TOP QUARK PHYSICS at the Terascale

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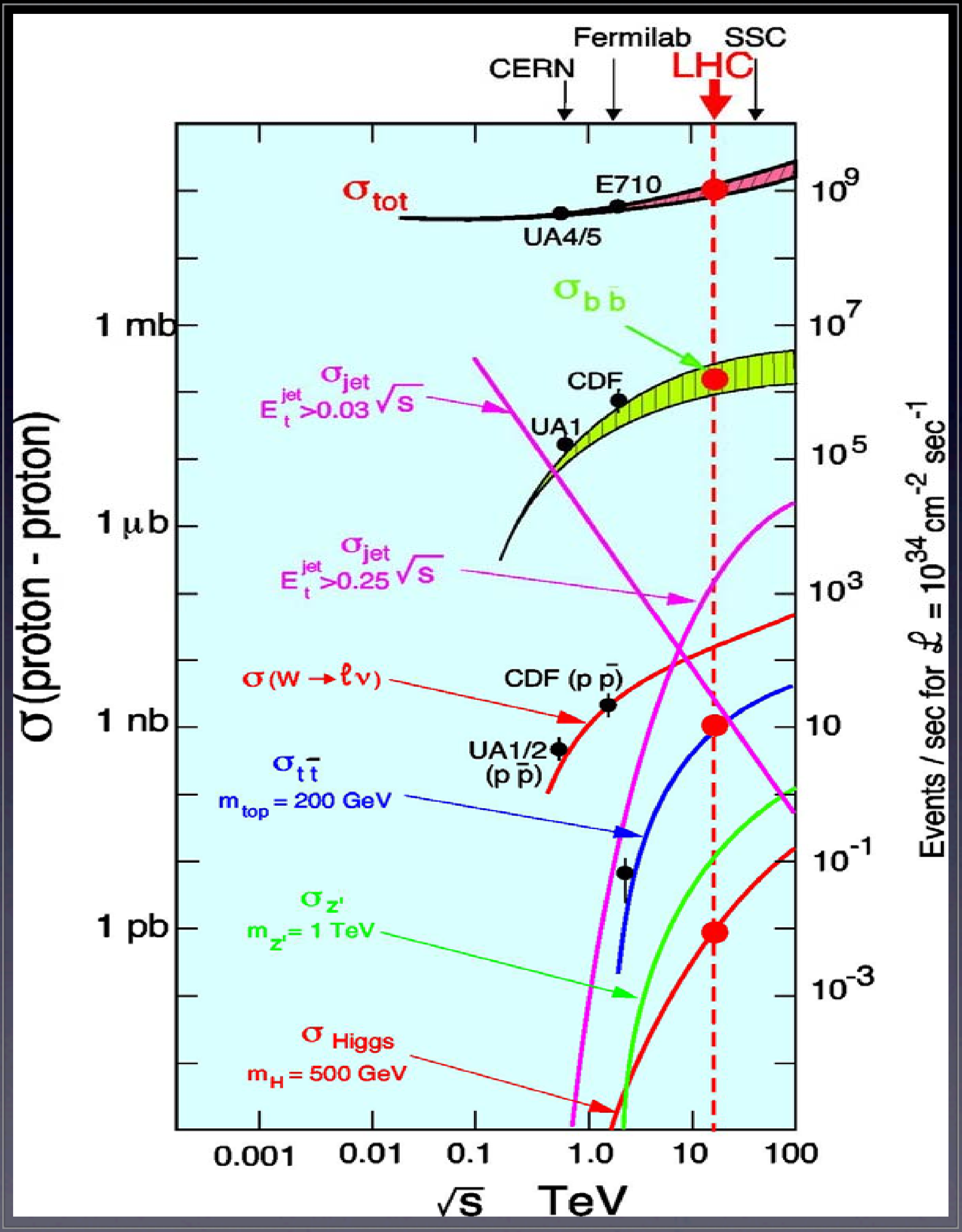
Mini-LHC Workshop @ IHEP March 28, 2012

LHC: a top factory



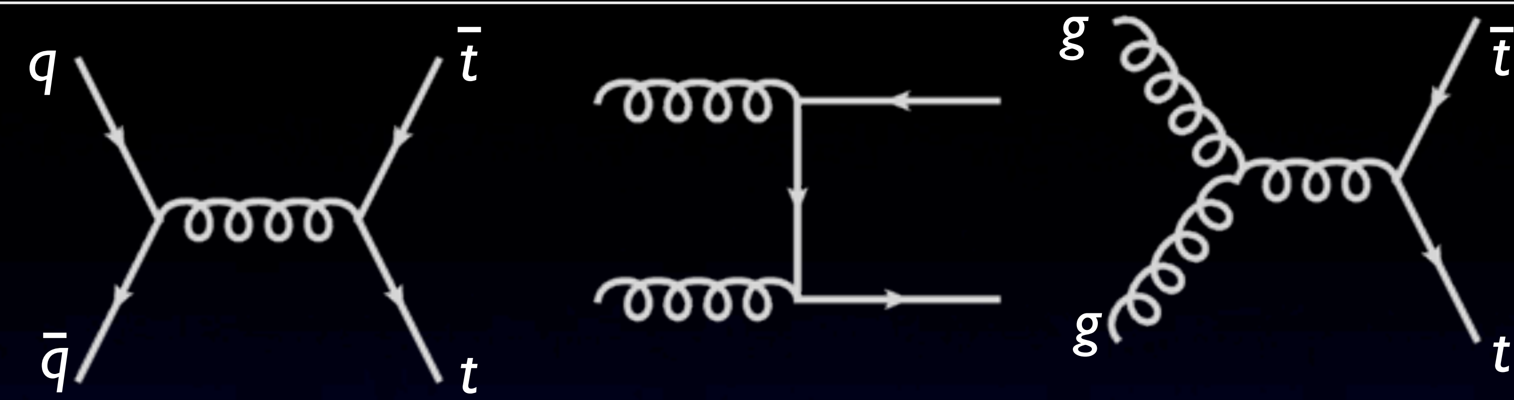
Rate for $\mathcal{L} = 10^{34}\mathrm{cm}^{-2}s^{-1}$

★ bottom quark pairs:	5×10^6/s
★ top quark pairs:	10/s
★ $W \to \ell\nu$:	150/s
★ $Z \to \ell\ell$:	15/s
★ Higgs boson (150GeV):	0.2/s
★ Gluino, Squarks (1TeV):	0.03/s

163,000 top quark pair
76,000 single top

7TeV, 1fb^{-1}

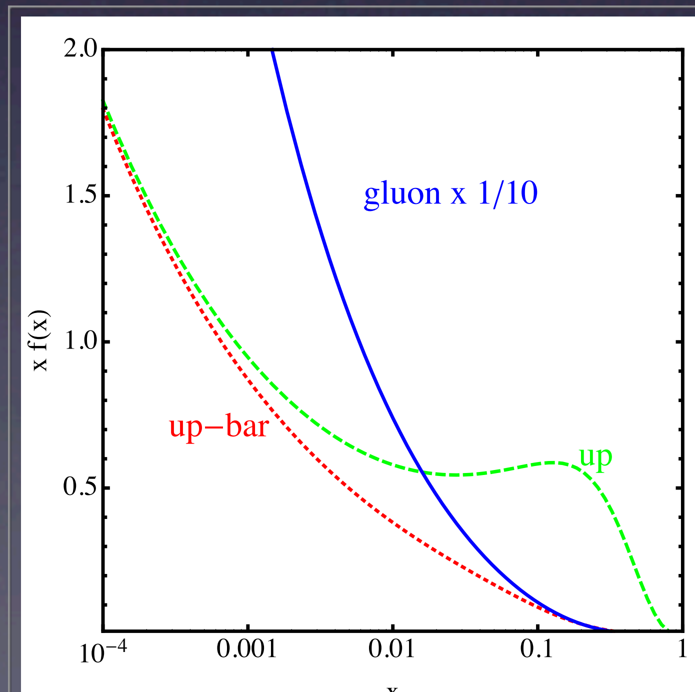
Top quark pair production



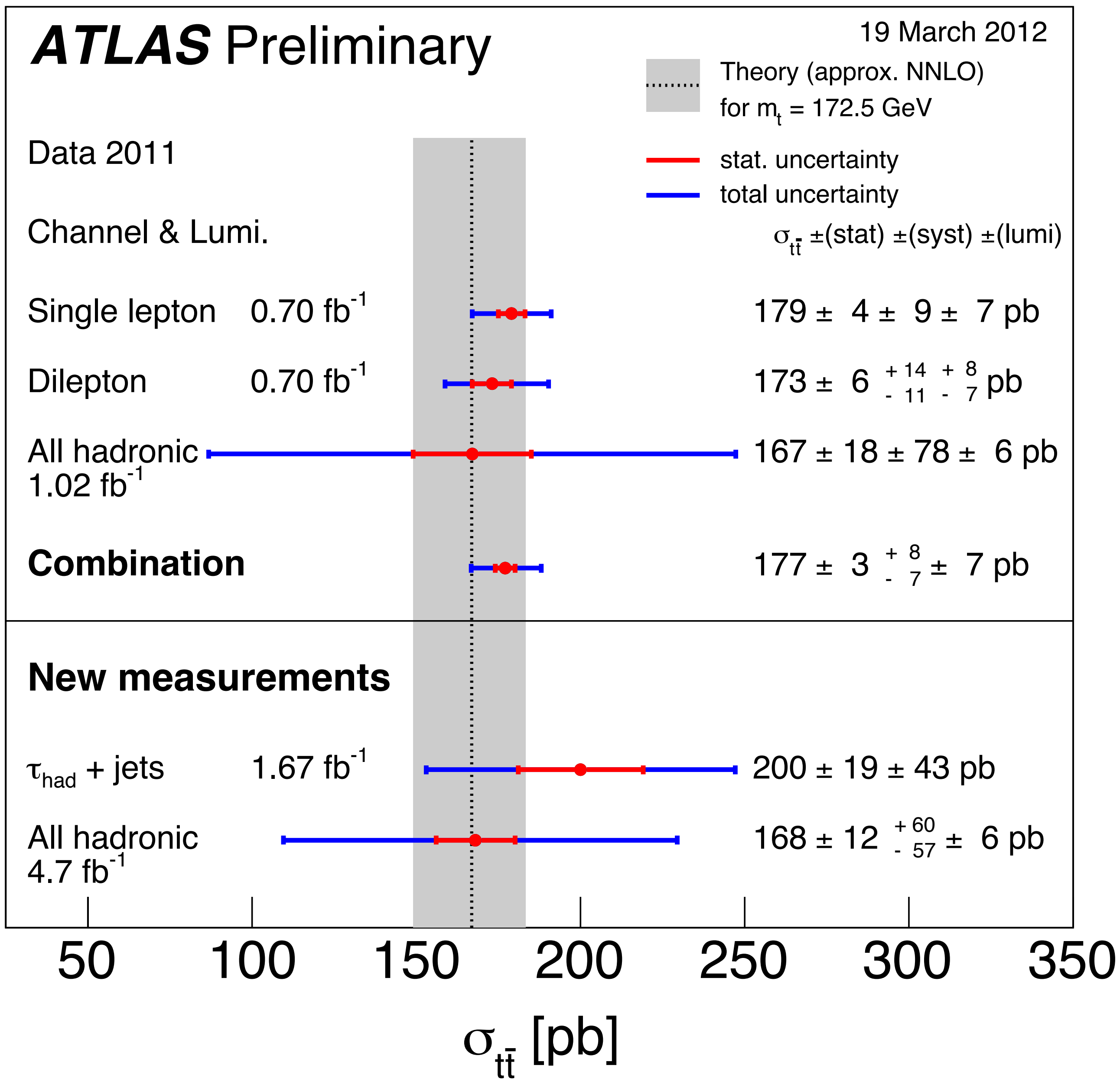
Tevatron:	**90%**	10%
LHC (7TeV):	20%	80%
LHC (14TeV):	10%	**90%**

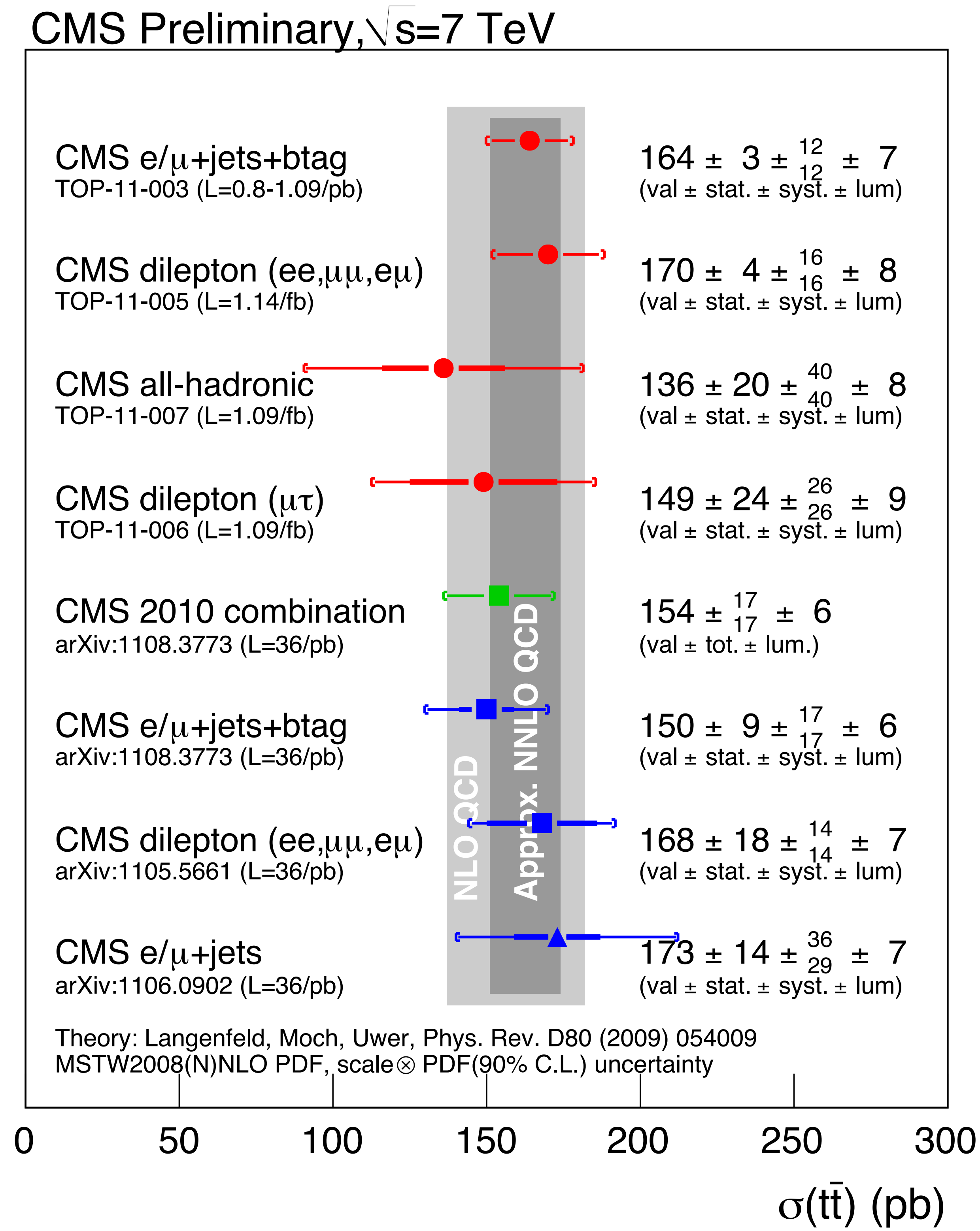
- Major backgrounds to almost all kinds of BSM
- Sensitive to different NP ➡ *qq* or *gg* initial state ?

NLO + threshold res. (NLL): Moch Uwer, Cacciari et al; Kidonakis, Vogt
NNLL extensions at threshold: Czakon et al; Beneke et al; Ahrens et al
Partial results at NNLL QCD: Czakon; Bonciani et al
ttbar + jet at NLO: Dittmaier et al; Melikov, Schulze
ttbar + bb Bredenstein et al, Bevilacqua et al
ttbar + jet with top decay at NLO: Melnikov, Schulze;
with weak interference corr. Bernreuther, Si
ttbar spin correlations: Mahlon, Parke; Bernreuther, Si



Top pair production cross section





~10-20% uncertainties

Top-quark spin correlation

arXiv: 1203.4081

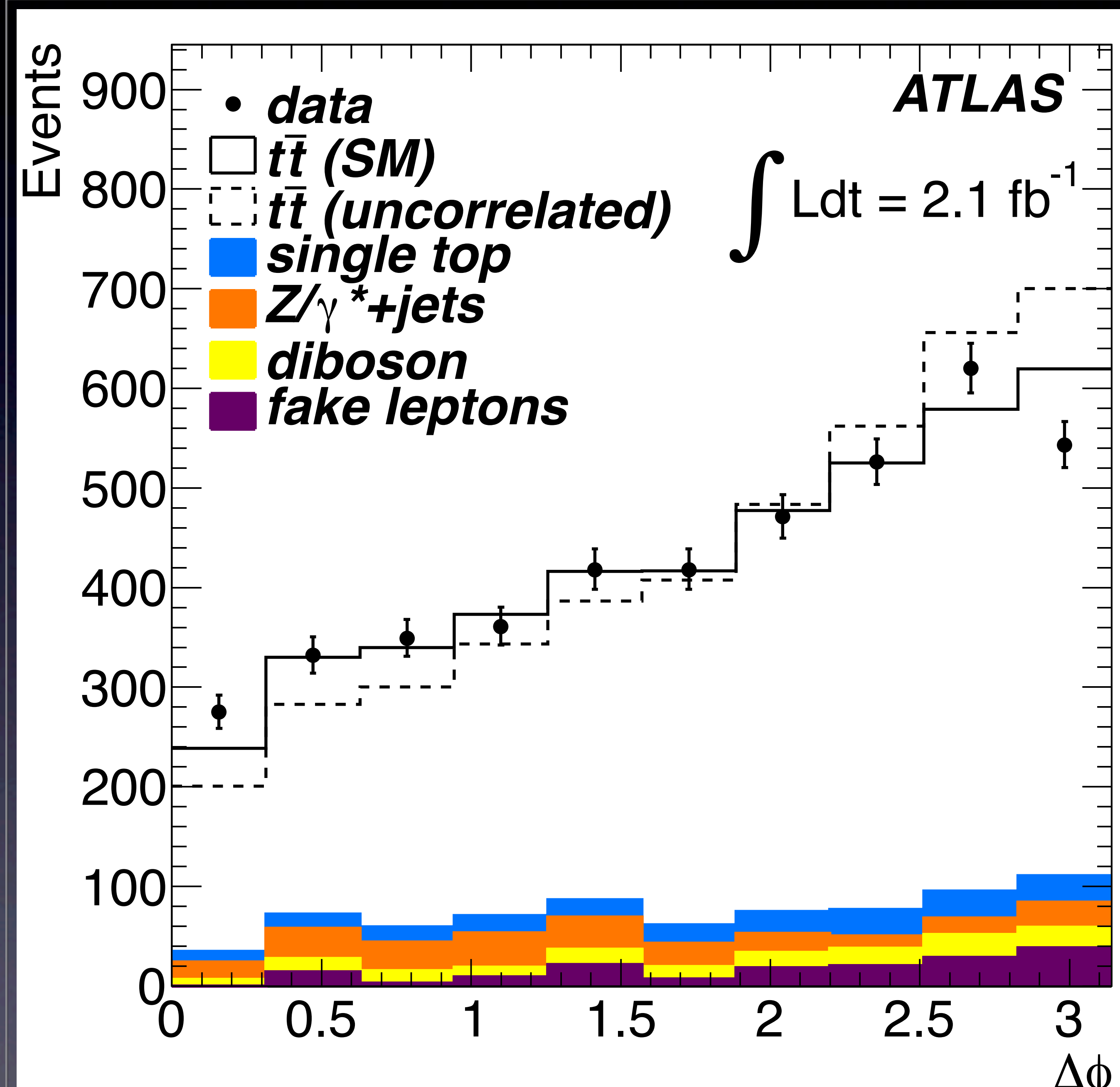
- Spin correlation in top-pair production confirmed by ATLAS (7 TeV, 2.1fb^{-1})

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

$$A_{\text{helicity}} = 0.40^{+0.09}_{-0.08}$$

SM theory predictions:
Bernreuther and Z. G. Si, NPB837 (201) 90
Bernreuther, Brandenburg, Z. G. Si, P. Uwer, PRL 87 (2011) 242002
Bernreuther, Brandenburg, Z. G. Si, P. Uwer, NPB 690 (2004) 81

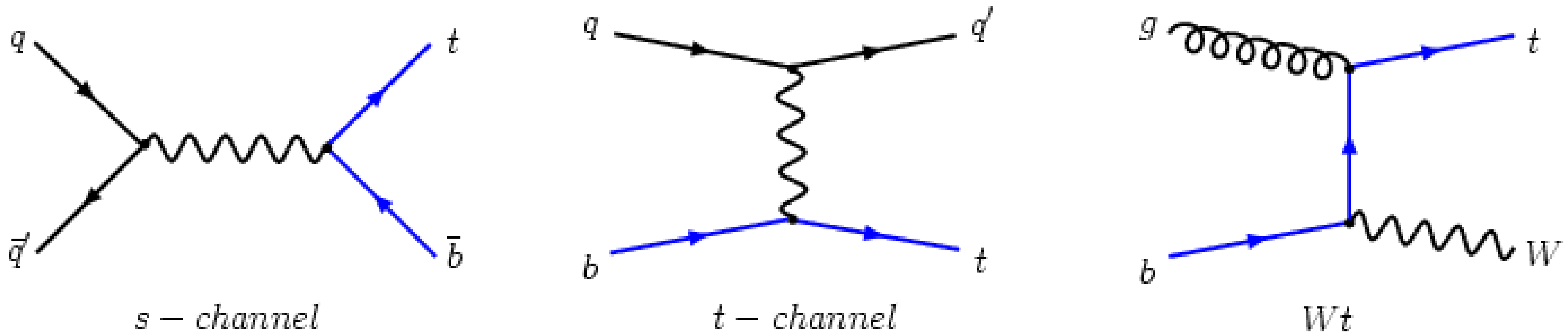
- Evidence seen by D0 at 3.2 sigma (2012)



NP effects in ttbar spin correlation, J. J. Cao, Wang, Wu, Yang, PRD84 (2011) 074001

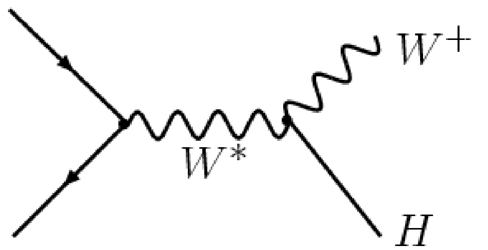
Single top production

Single top quarks are produced through interactions involving a W boson and b quark

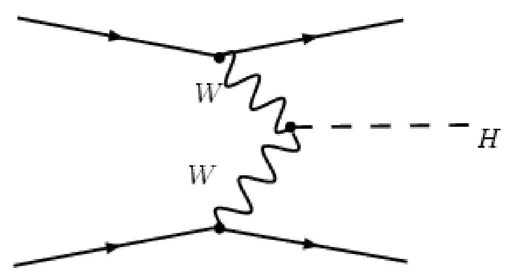


At tree level there are three modes:

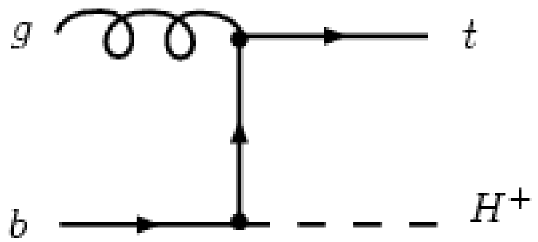
- s-channel W exchange ($Q^2 = p_W^2 > 0$)
  - Large rate at Tevatron Run II, small rate at LHC
  - background for SM Higgs seaches



- t-channel W exchange ($Q^2 = p_W^2 < 0$)
  - Dominant rate at Tevatron Run II and LHC
  - helping out with W-fusion Higgs searches

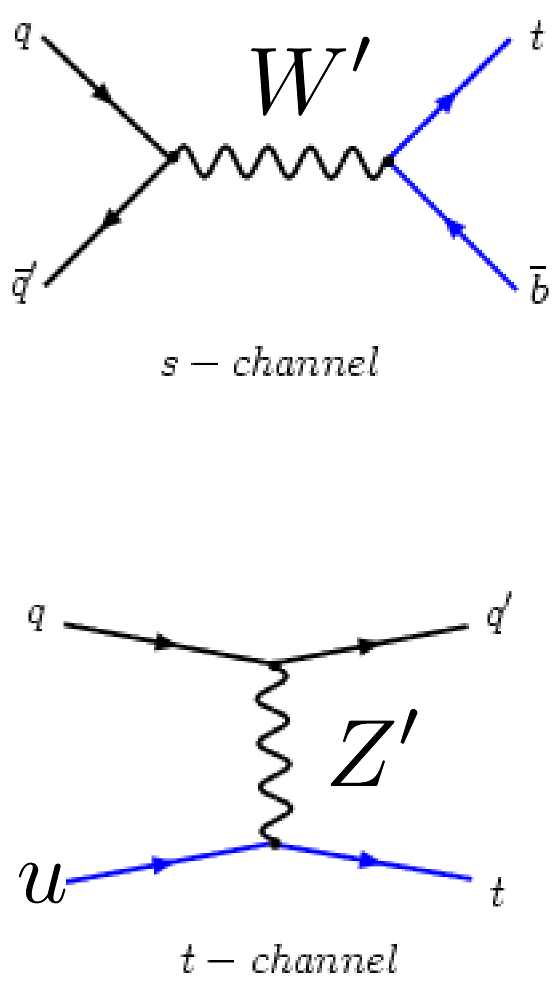


- Wt associated production ($Q^2 = p_W^2 = m_W^2$)
  - Very tiny rate at Tevatron Run II, large rate at LHC
  - background to $gb \to H^+ t$ at LHC

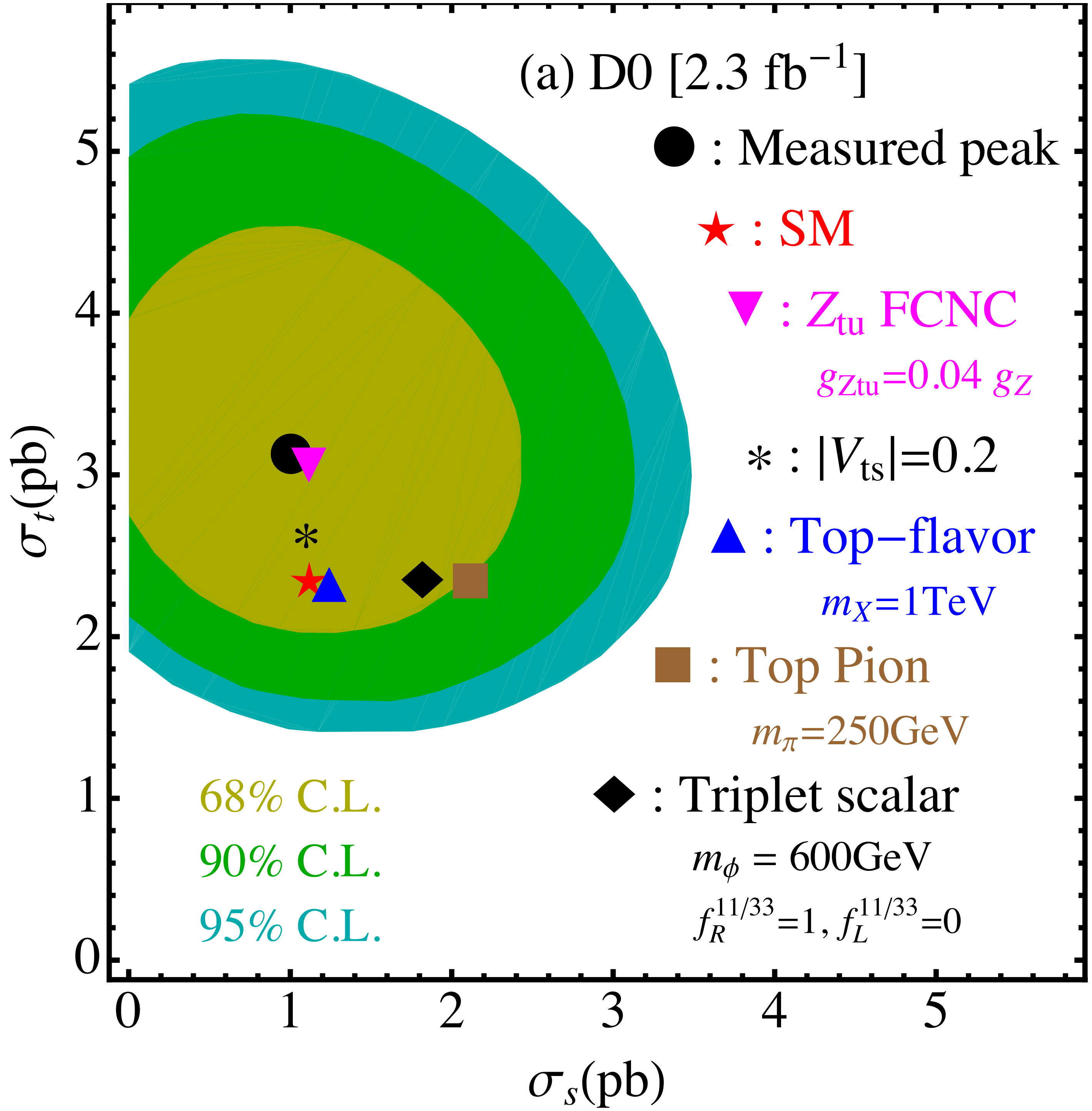


Single-top production and NP

Single top production is sensitive to new physics



Tait, Yuan PRD63, 014018 (2001)



Single-top measurements

$$\sigma_{t-\text{ch.}} = 70.2 \pm 5.2(\text{stat.}) \pm 10.4(\text{syst.}) \pm 3.4(\text{lumi.})\ \text{pb} \qquad (\text{combined})$$

$$|V_{\text{tb}}| = \sqrt{\frac{\sigma_{t-\text{ch.}}}{\sigma^{\text{th}}_{t-\text{ch.}}}} = 1.04 \pm 0.09\,(\text{exp.}) \pm 0.02\,(\text{th.})$$

Differential X-section at NLO:

Shou-Hua Zhu, PLB524 (2002) 283

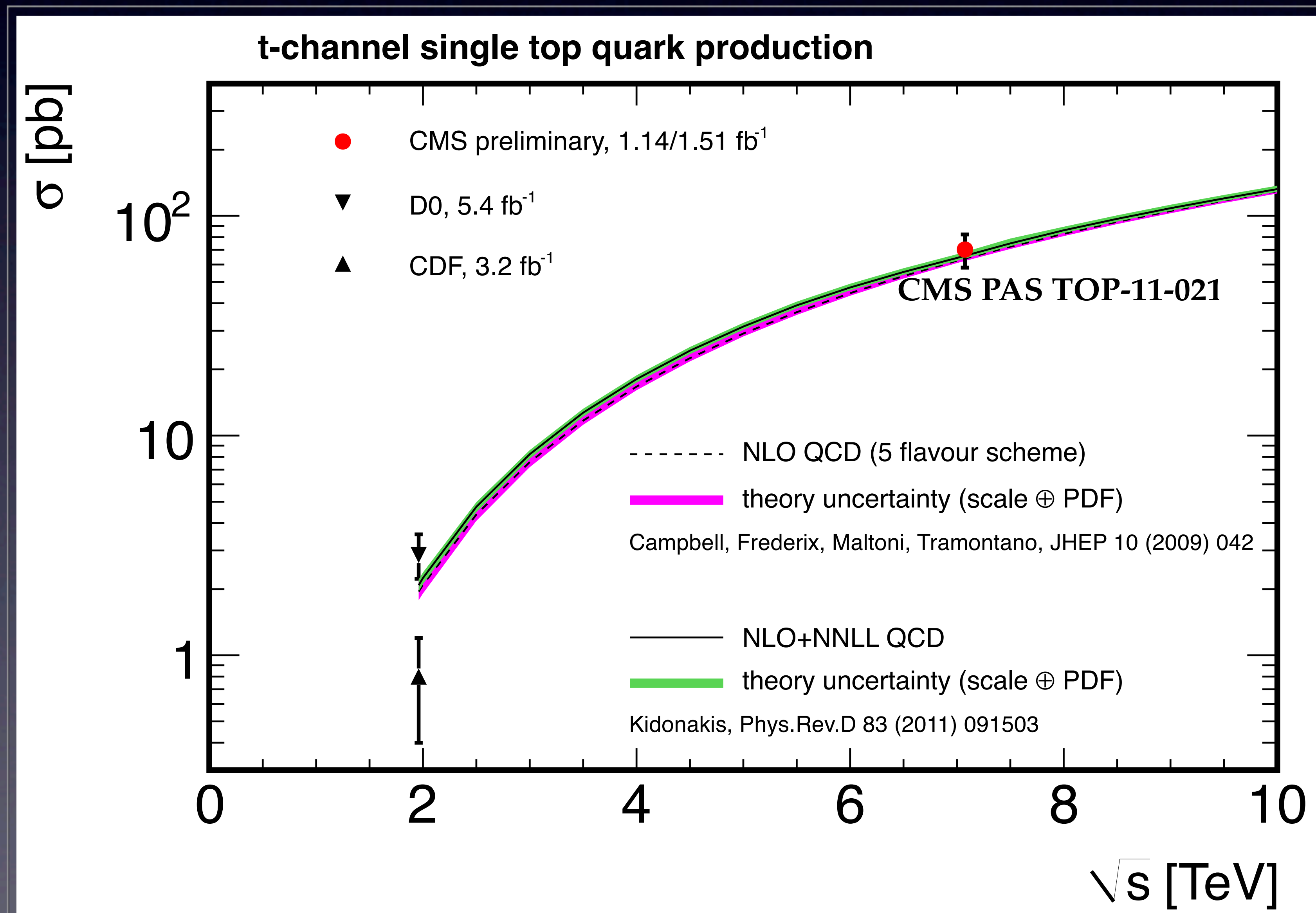
Harris, et al, PRD66 (2002) 054024

J. Campbell, et al, PRD70 (2004) 094012

QHC et al, PRD71 (2005) 054022, 054023,PRD72 (2005)094027

Frixione, et al, JHEP 0807 (2008) 029

J. Campbell, et al, PRL102 (2009) 182003



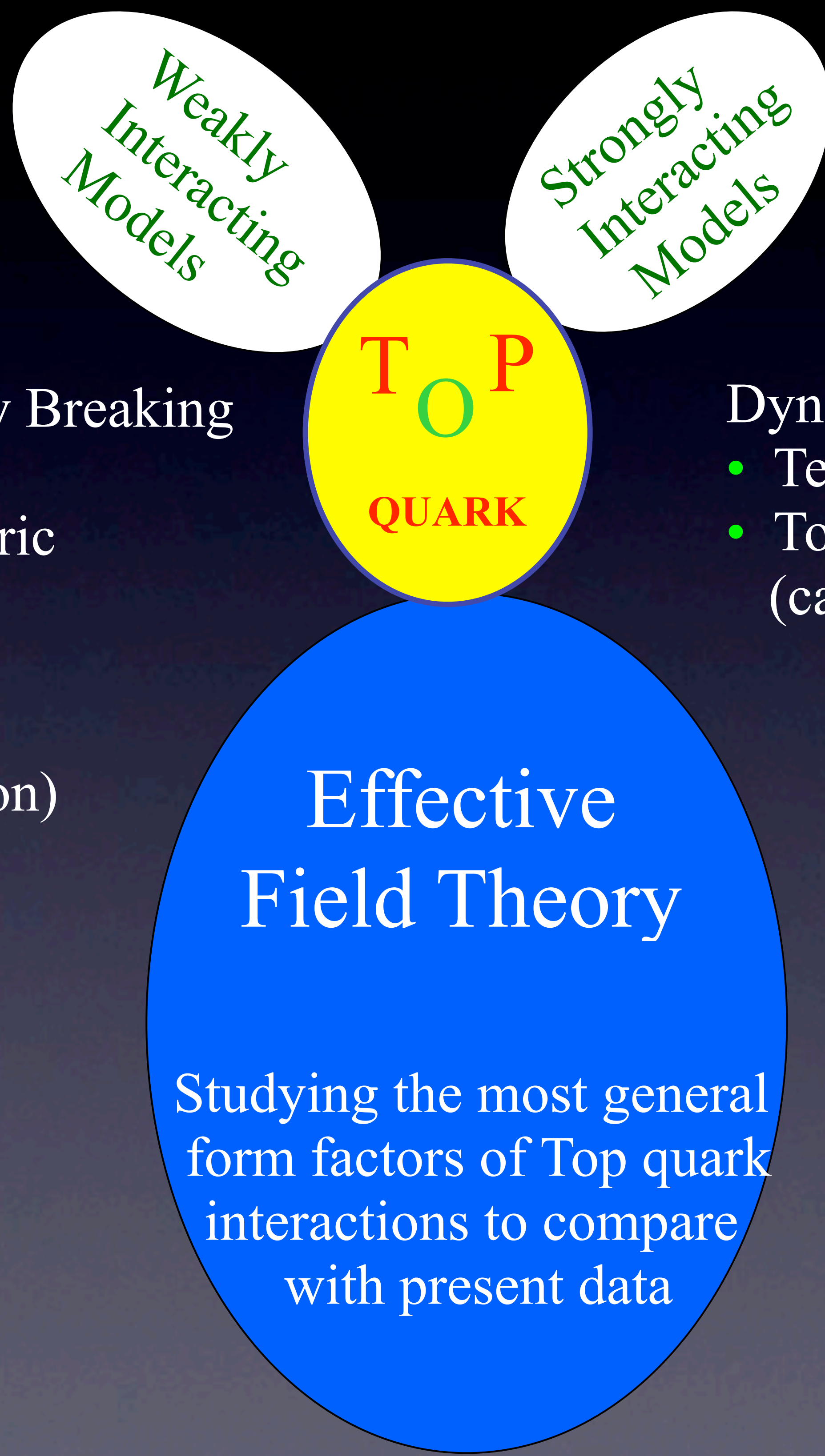
Precision measurements of top-quark physics

Top quark and EWSB

Top Down

Spontaneously Symmetry Breaking

- Minimal Supersymmetric Standard Model with Radiative EWSB and soft SUSY-breaking (elementary Higgs boson)



Dynamical Symmetry Breaking

- Technicolor
- TopColor / Condensate / Seesaw Models (can have composite Higgs bosons)

Bottom Up

Top-down approach

- Hundreds of proposal of BSM:

  - Weakly coupled model at TeV scale
    Introduce new particles to cancel SM "Divergences"

    Top partners, new vectors or scalars (strongly coupled to top quark)

  - Strongly coupled model at TeV scale
    New strong dynamics emerge at ~TeV

    Top-quark condensation, colorons. (Top quark is composited.)

  - New space-time structure
    Extra dimensions to lower the Planck scale to TeV

    KK excitations.

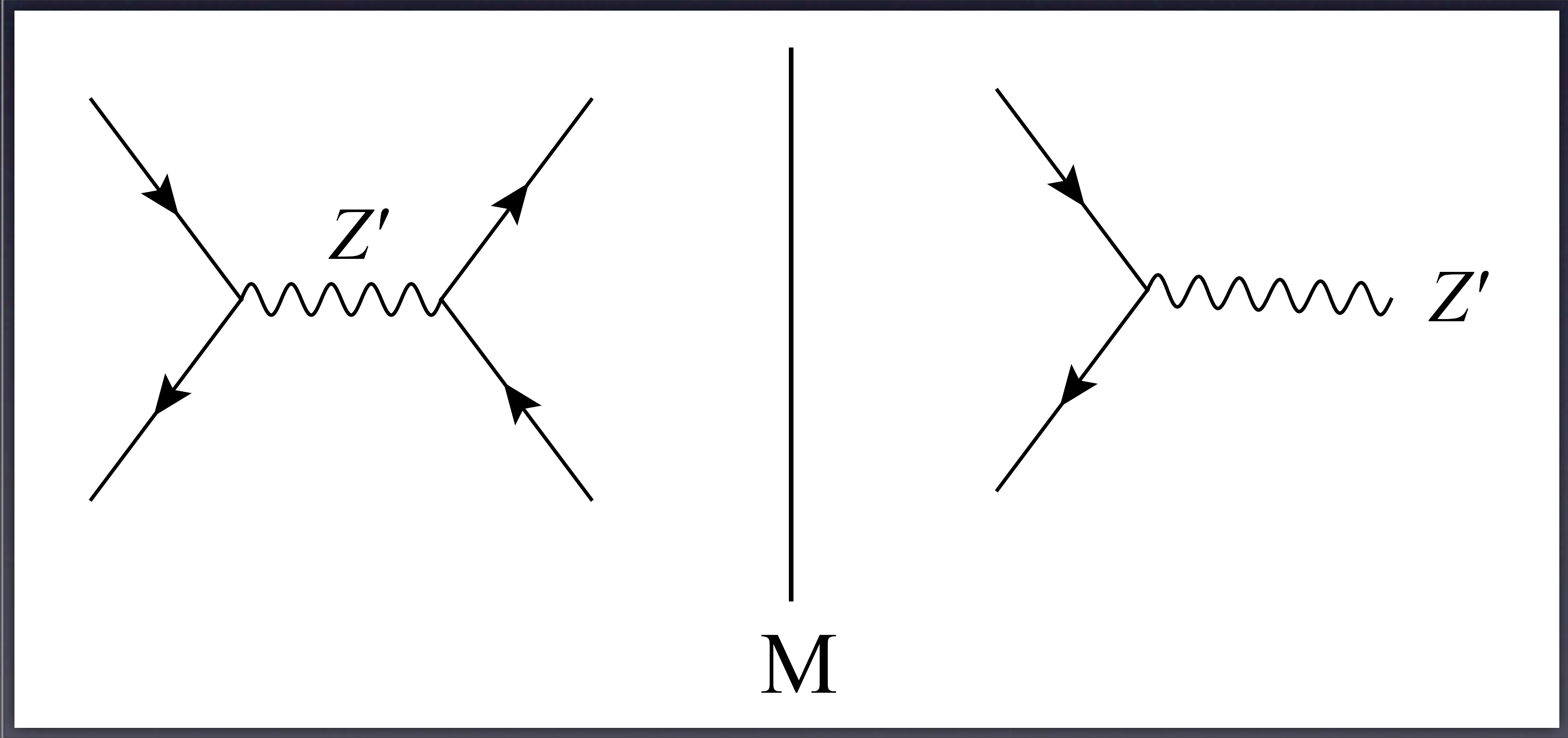
Bottom-up approach

- EFT: a powerful tool to probe NP

S. Weinberg, Physica A96, 327 (1979)
W. Buchmuller and D. Wyler, Nucl. Phys. B268, 621 (1986)

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{NP}^2} \sum_i (c_i \mathcal{O}_i + h.c.) + \cdots$$

- Example: Z-prime



What can we learn from top-quark?

- What is the mass of Higgs boson?
- Do we understand heavy flavor production in perturbative QCD?
- Are there more than three generations?
- Are there any new gauge bosons?
- Does top quark have the expected couplings?
- ……

What can we learn from top quark?

* Questions

What is the Higgs boson mass?

Do we understand heavy flavor production in QCD?

Are there more than three fermion generations?

Are there new massive particles?

Does top quark have the expected couplings?

* Measurements

Top quark mass

Top quark pair production cross section

Charge asymmetry of top pair

$m_{t\bar{t}}$ distribution

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Search for t-prime quark

Searches for $H^+ \to t\bar{b}$ or $t \to H^+\bar{b}$

Constraints on Wtb coupling

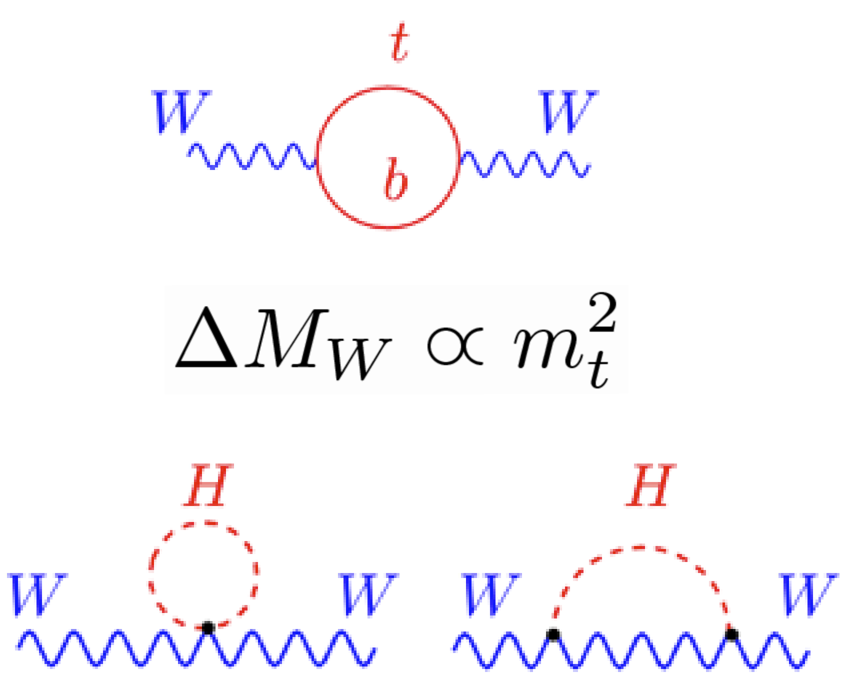
W boson helicity

Search for FCNC top interaction

W, Top and Higgs masses

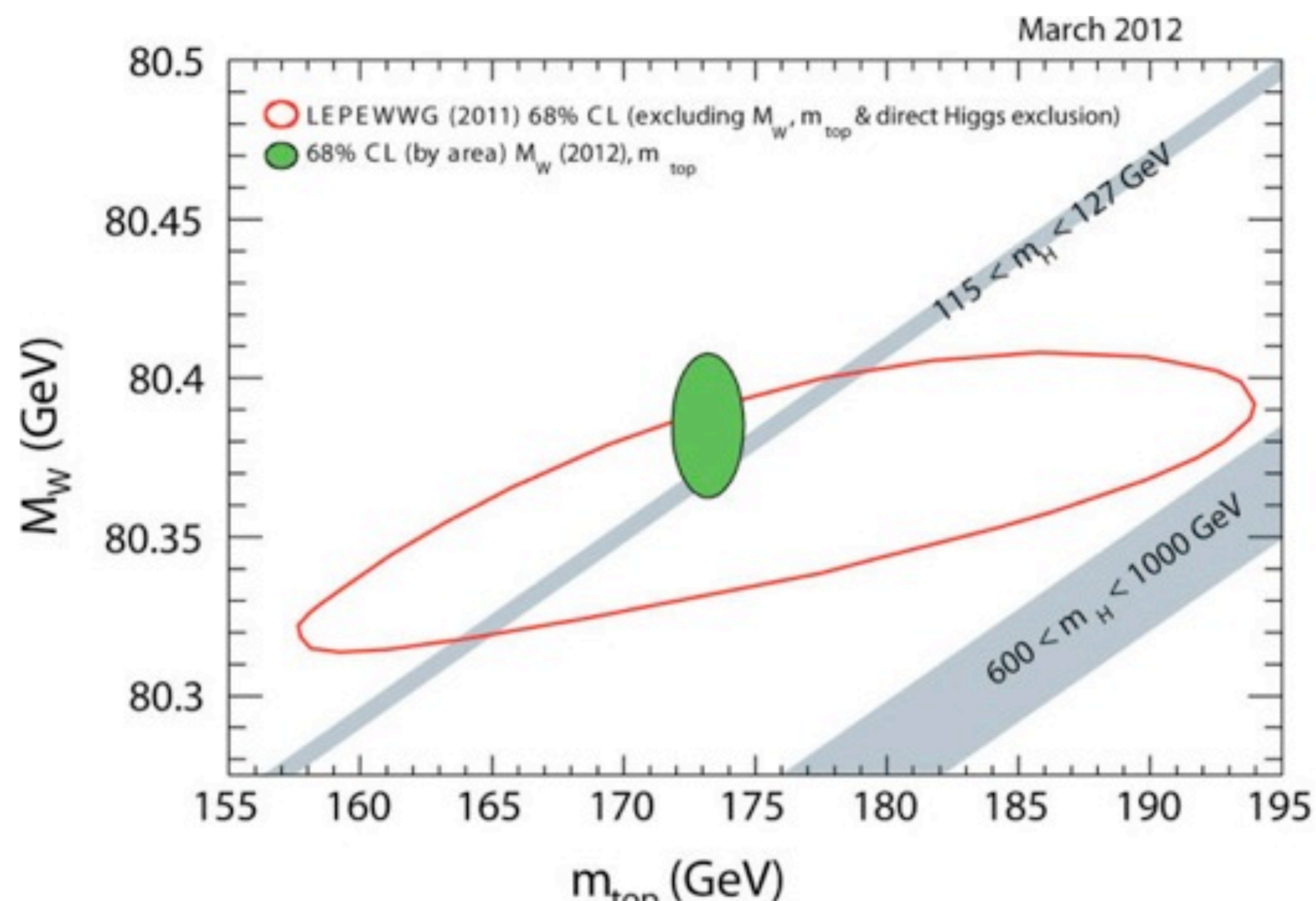
- Accurate measurements of m_t and m_W give Higgs boson less space to hide

$$M_W = 80.3827 - 0.0579 \ln\left(\frac{M_H}{100\ \text{GeV}}\right) - 0.008 \ln^2\left(\frac{M_H}{100\ \text{GeV}}\right)$$
$$+0.543\left(\left(\frac{m_t}{175\ \text{GeV}}\right)^2 - 1\right) - 0.517\left(\frac{\Delta\alpha^{(5)}_{had}(M_Z)}{0.0280} - 1\right) - 0.085\left(\frac{\alpha_s(M_Z)}{0.118} - 1\right)$$



$$\Delta M_W \propto m_t^2$$

$$\Delta M_W \propto \ln m_H^2$$



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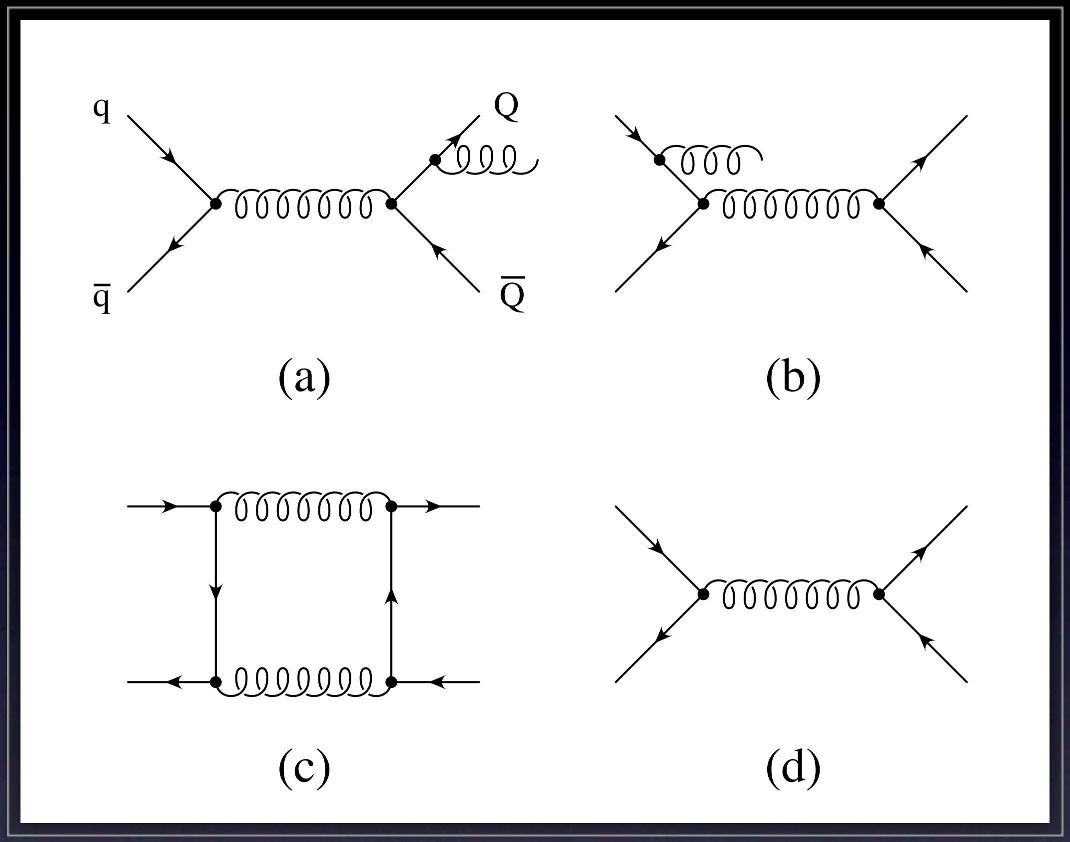
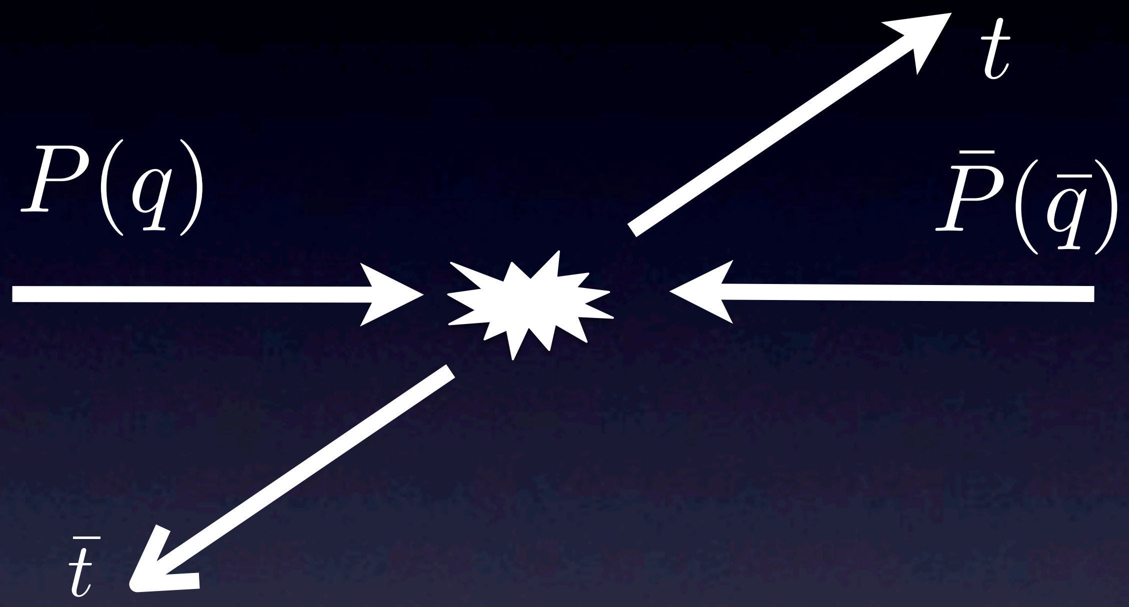
Top-quark F-B asymmetry in the SM

- A charge asymmetry arises at NLO



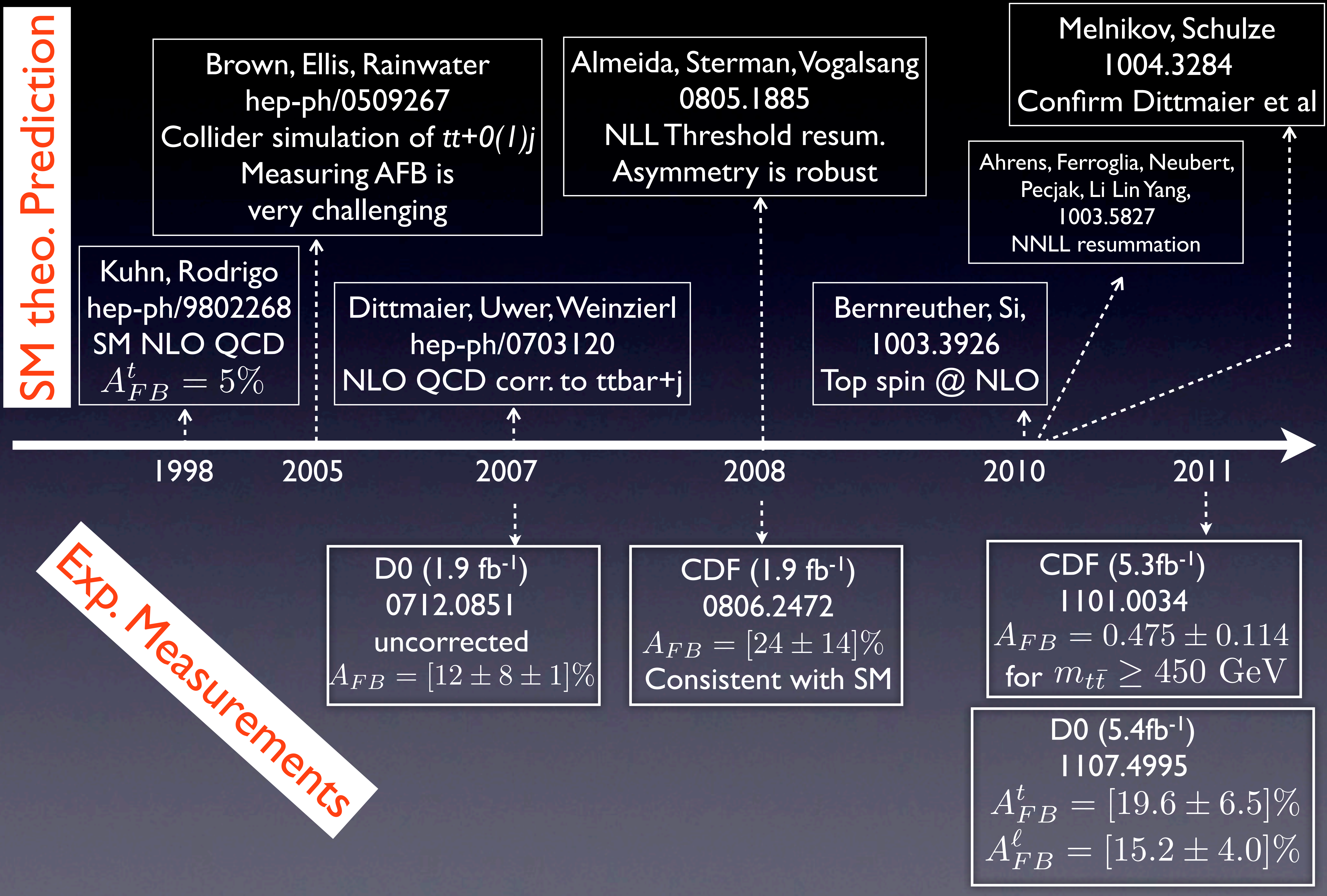


Top quarks are produced along the direction of the incoming quark

$$A^{p\bar{p}} = \frac{N_t(y>0) - N_{\bar{t}}(y>0)}{N_t(y>0) + N_{\bar{t}}(y>0)} = 0.051(6)$$

$$A^{t\bar{t}} = \frac{N(\Delta y>0) - N(\Delta y<0)}{N(\Delta y>0) + N(\Delta y<0)} = 0.078(9) \quad \Delta y = y_t - y_{\bar{t}}$$

Timeline of top-quark A_{FB}



Timeline of A_{FB}^{t} and NP models

s-channel

Ferrario, Rodrigo
Axigluon
0809.3353

Antunan, Kuhn, Rodrigo
Axigluon
0709.1652

Frampton, Shu, Wang
Axigluon
0911.2955

Ferrario, Rodrigo
chiral G'
0906.5541

Djouadi, Moreau, Richard, singh
KK Gluon
0906.0604

EFT

QHC et al
Effective coupling
(G', Z', W', H^0, H^+)
1003.3461

Jung, Ko, Lee, Nam
EFT
0912.1105

2007, 2008 — 2009 — 2010, 2011

t-channel

Jung, Murayama, Pierce, Wells
FCNC Z-prime
0907.4112

Cheung, Keung, Yuan
FC W-prime
0908.2589

Shu, Tait, Wang
Color Sextet/triplet scalar
0911.3237

Arhrib, Benbrik, Chen
Color Sextet/triplet scalar
0911.4875

J. Cao, Heng, Wu, Yang
$\not{R}$-SUSY and TC2
0912.1447

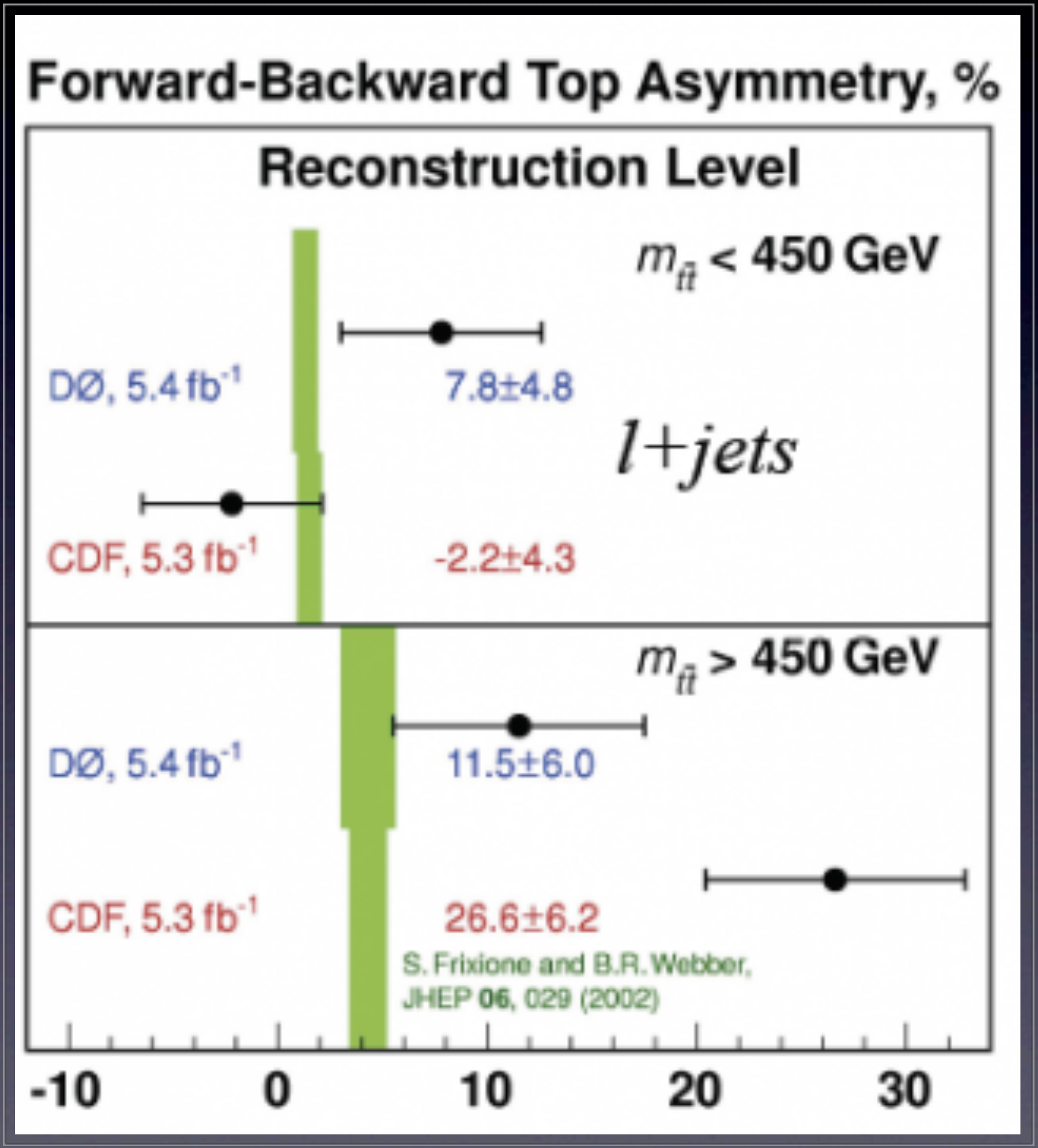
NLO QCD

Xiao, Wang, Zhu,
NLO QCD to Z-prime
1006.2510

Yan, Wang, Shao, Li
NLO QCD to W-prime
1110.6684

Shao, Li, et al
NLO QCD to EFT
1107.4012

A^{ℓ}_{FB} versus A^{t}_{FB}



D0: $A^{t}_{FB} = 0.196 \pm 0.065$

$A^{\ell}_{FB} = 0.152 \pm 0.040$

$$\left.\frac{A^{\ell}_{FB}}{A^{t}_{FB}}\right|_{\mathrm{D0}} \sim \frac{3}{4}$$

SM: $A^{t}_{FB} = 0.051 \pm 0.001$

$A^{\ell}_{FB} = 0.021 \pm 0.001$

$$\left.\frac{A^{\ell}_{FB}}{A^{t}_{FB}}\right|_{\mathrm{SM}} \sim \frac{1}{2} \quad ?$$

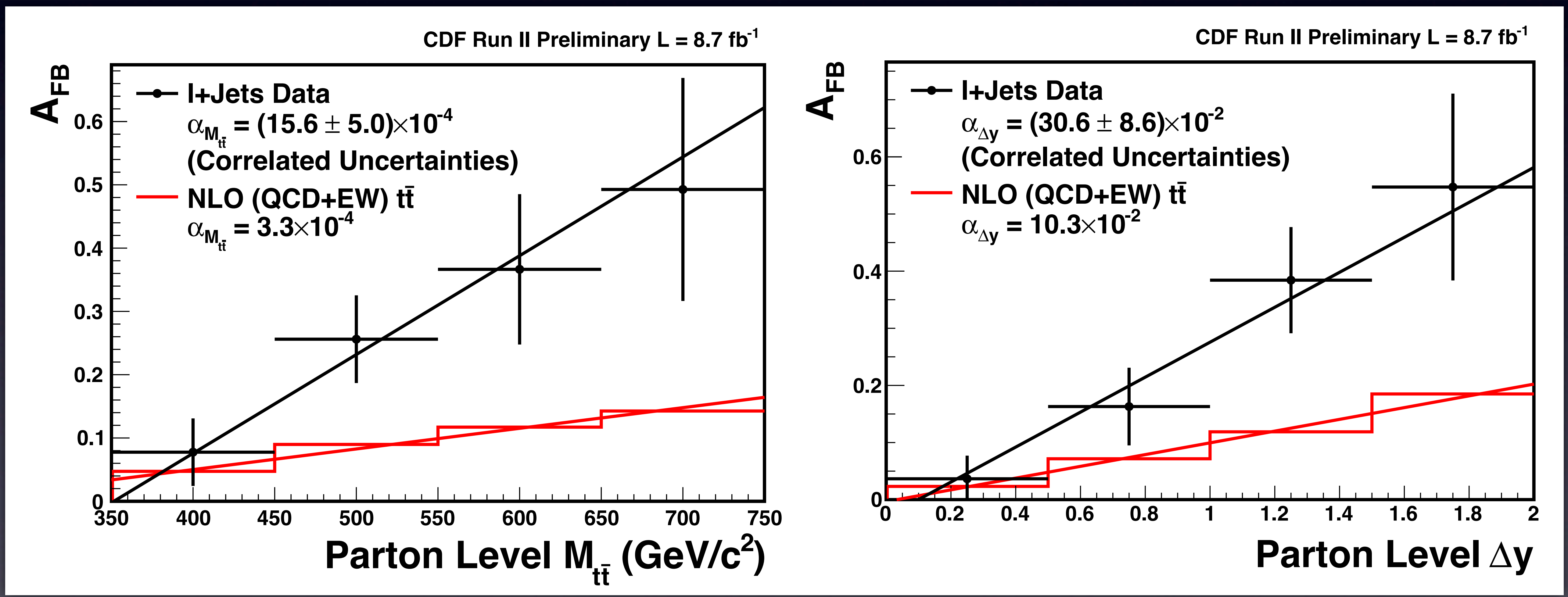
Bernreuther, Zong-Guo Si, NPB837 (2010) 90

CDF data (8.7 fb^{-1})

- "Linear" dependence of A_{FB} on m_{tt}

$$A_{FB}^{\text{inclusive}} = 0.162 \pm 0.041 \pm 0.022$$

$$A_{FB}^{\text{NLO+EW}} = 0.066$$



CDF data (8.7 fb^{-1})

- A^ℓ_{FB} vs A^t_{FB}

Beware: before unfolding

$$\left.\frac{A^\ell_{FB}}{A^t_{FB}}\right|_{<450} \sim \frac{3}{2} \; ?$$

$$\left.\frac{A^\ell_{FB}}{A^t_{FB}}\right|_{>450} \sim \frac{3}{5}$$

$$\left.\frac{A^\ell_{FB}}{A^t_{FB}}\right|_{\text{inc}} \sim \frac{3}{4}$$

A^ℓ_{FB}

CDF Run II Preliminary L = 8.7 fb^{-1}

$M_{t\bar{t}}$	Data $A_{\rm FB}$ (± [stat.+syst.])	NLO (QCD+EW) $t\bar{t}$ $A_{\rm FB}$
Inclusive	0.066 ± 0.025	0.016
$<$ 450GeV/c^2	0.037 ± 0.031	0.007
$\geq$ 450GeV/c^2	0.116 ± 0.042	0.032

Measured and expected asymmetries in $q \cdot \eta_{lep}$. after background subtraction

A^t_{FB}

CDF Run II Preliminary L = 8.7 fb^{-1}

Sample	$A_{\rm FB}$ (± [stat.+syst.]) Inclusive	$A_{\rm FB}$ (± [stat.+syst.]) $M_{t\bar{t}} <$ 450GeV/c^2	$A_{\rm FB}$ (± [stat.+syst.]) $M_{t\bar{t}} \geq$ 450GeV/c^2
All Data	0.085 ± 0.025	0.025 ± 0.031	0.198 ± 0.043
Positive Leptons	0.100 ± 0.037	0.044 ± 0.046	0.198 ± 0.060
Negative Leptons	0.071 ± 0.035	0.008 ± 0.043	0.198 ± 0.059
Exactly 0 b-tags	0.056 ± 0.052	0.079 ± 0.066	0.005 ± 0.085
Exactly 1 b-tags	0.103 ± 0.030	0.039 ± 0.037	0.226 ± 0.050
At least 2 b-tags	0.034 ± 0.046	-0.014 ± 0.057	0.122 ± 0.077
Electron Events	0.058 ± 0.038	-0.018 ± 0.048	0.199 ± 0.062
Muon Events	0.107 ± 0.034	0.060 ± 0.041	0.197 ± 0.057

.E XII: Measured asymmetries after background subtraction in various subsets of the

A^{ℓ}_{FB} versus A^{t}_{FB}

Berger, QHC, Chen, Yu, Zhang, PRL 108 (2012) 072002

- A^{t}_{FB} and A^{ℓ}_{FB} is connected by the top-quark and charged lepton spin correlation.

$$A^{\ell}_{FB} \approx \rho_{t_L} A^{t_L}_{FB} \times \left(2\mathcal{R}^{t_L}_{C} - 1\right) + \rho_{t_R} A^{t_R}_{FB} \times \left(2\mathcal{R}^{t_R}_{C} - 1\right)$$

★ $\rho_{t_L} \ll \rho_{t_R}$

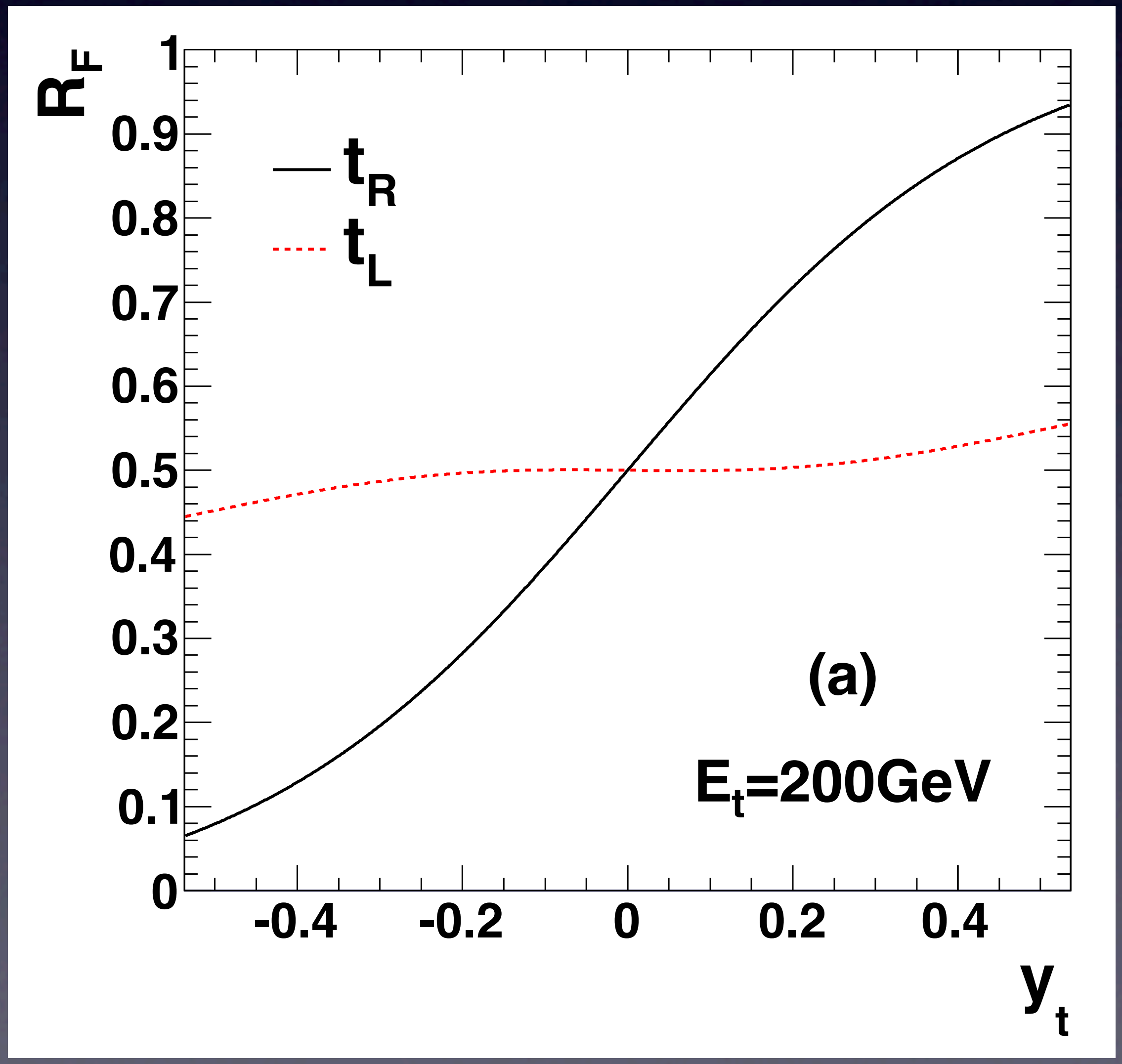
$$A^{\ell}_{FB} \lesssim \frac{1}{2} A^{t}_{FB}$$

★ $\rho_{t_L} = \rho_{t_R}$

$$A^{\ell}_{FB} \lesssim \frac{1}{2} A^{t}_{FB}$$

★ $\rho_{t_L} \gg \rho_{t_R}$

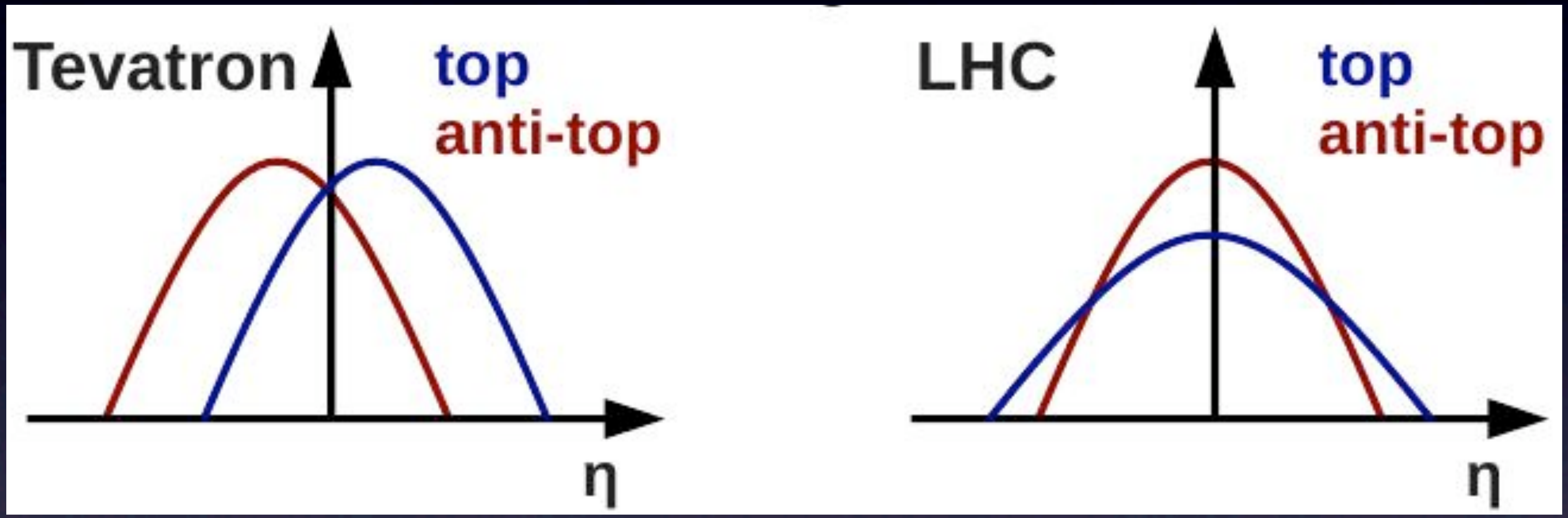
$$A^{\ell}_{FB} \gtrsim \frac{1}{2} A^{t}_{FB}$$



Top charge asymmetry at the LHC

- A_C definition

$$A_C^{t\bar{t}} = \frac{\sigma(\Delta y > 0) - \sigma(\Delta y < 0)}{\sigma(\Delta y > 0) + \sigma(\Delta y < 0)}$$



$$\Delta y^{\text{Tev}} = y_t - y_{\bar{t}} \qquad \Delta y^{\text{LHC}} = |y_t| - |y_{\bar{t}}|$$

- One side asymmetry (You-Kai Wang, Bo Xiao, Shou-Hua Zhu, 1008.2685)

$$A_{\text{OFB}} = \frac{\sigma(\Delta Y > 0) - \sigma(\Delta Y < 0)}{\sigma(\Delta Y > 0) + \sigma(\Delta Y < 0)} \Big|_{P^z_{t\bar{t}} > P^z_{\text{cut}}, M_{t\bar{t}} > M_{\text{cut}}}$$

Difficulty: gg fusion is dominant and symmetric

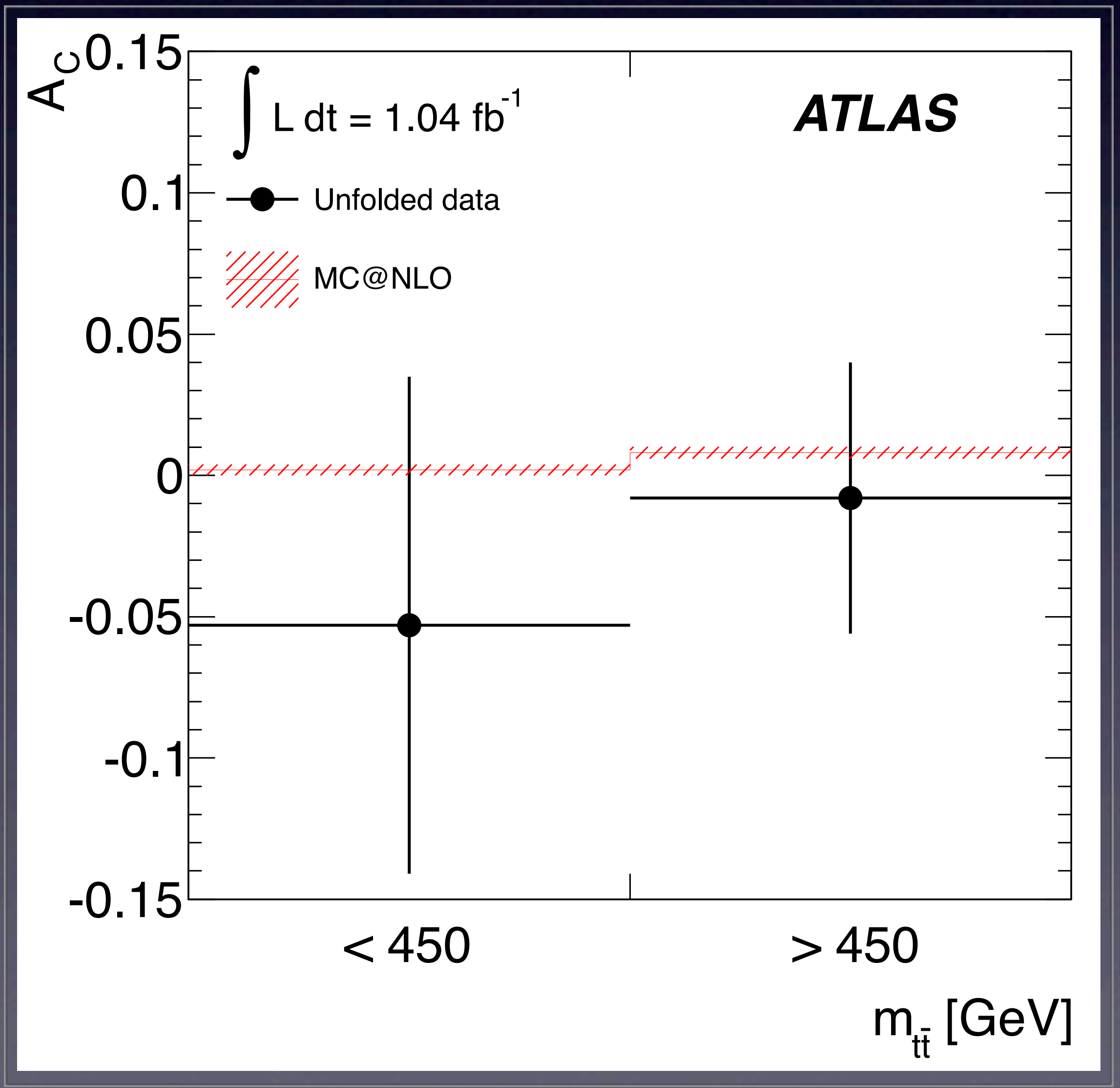
Top charge asymmetry at the LHC

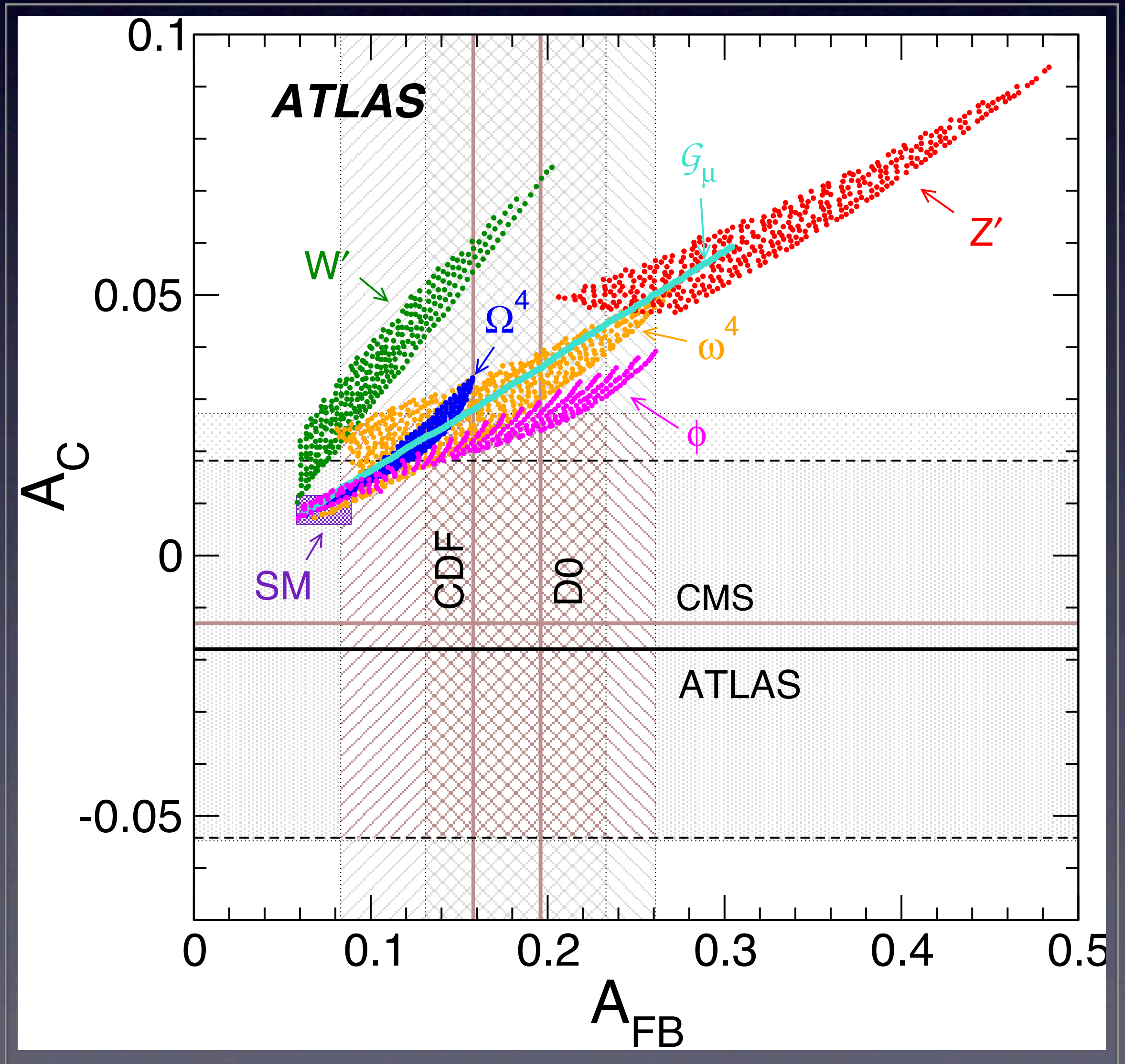
- "lepton + jets" channel

ATLAS (1.04 fb^{-1}): $A_C = -0.018 \pm 0.028 \pm 0.023$ 1203.4211

CMS (1.09 fb^{-1}): $A_C = -0.013 \pm 0.026^{+0.026}_{-0.021}$ CMS PAS TOP-11-014

MC@NLO: $A_C = 0.006 \pm 0.002$





What can we learn from top quark?

* Questions

- What is the Higgs boson mass?
- Do we understand heavy flavor production in QCD?
- Are there more than three fermion generations?
- Are there new massive particles?
- Does top quark have the expected couplings?

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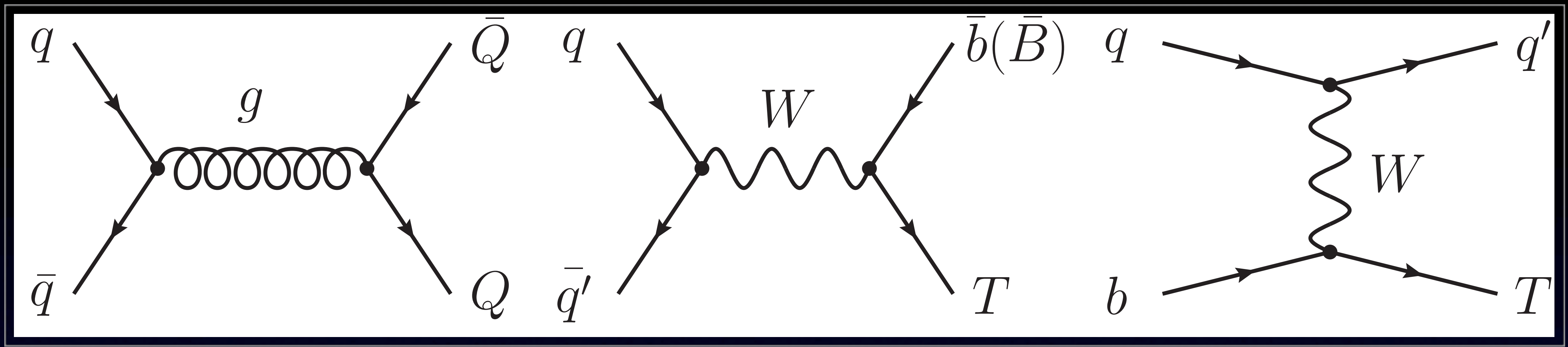
Motivation for heavy quark

- Natural NP models always have non-trial couplings between tops and new physics:

  Higgsless, Little Higgs, RS, SUSY, TC, ...

- New heavy quark loops stabilize EWSB
- New heavy quark condensates to form BCS type EWSB
- New heavy quark explains B_S and other flavor puzzles
- New heavy quark explains CP violation and Baryon asymmetry
- ...

Heavy Quark production



- Pair production via QCD

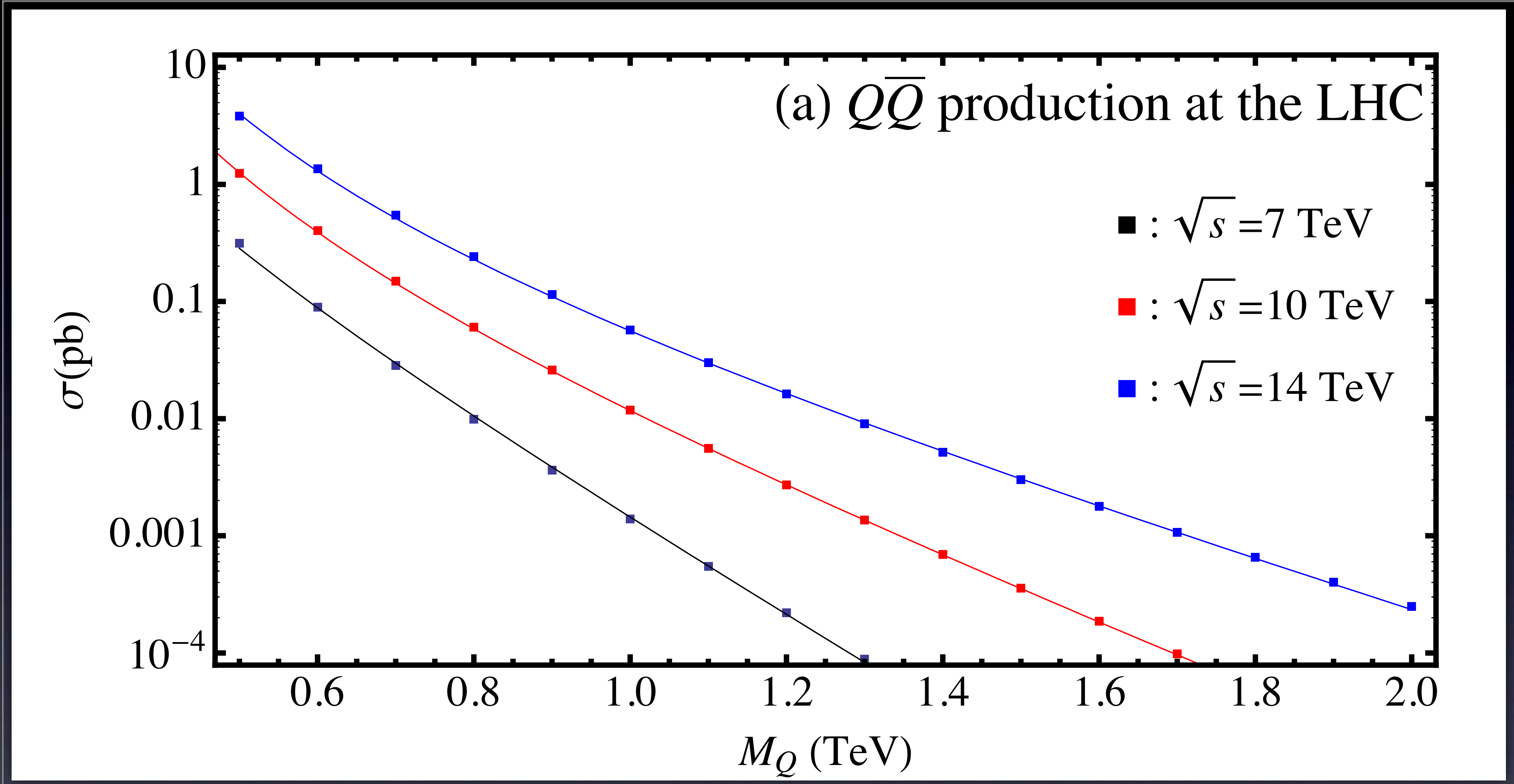
  - Major discovery channel for small M_Q
  - Sensitive to decay BRs, but not the couplings.

- Single production via EW

  - Determine the weak coupling strength of heavy quark
  - Probe the mixing of SM quarks and heavy quarks
  - Depend upon quark flavors

Heavy quark production at NLO

Berger, QHC, PRD81 (2010) 035006

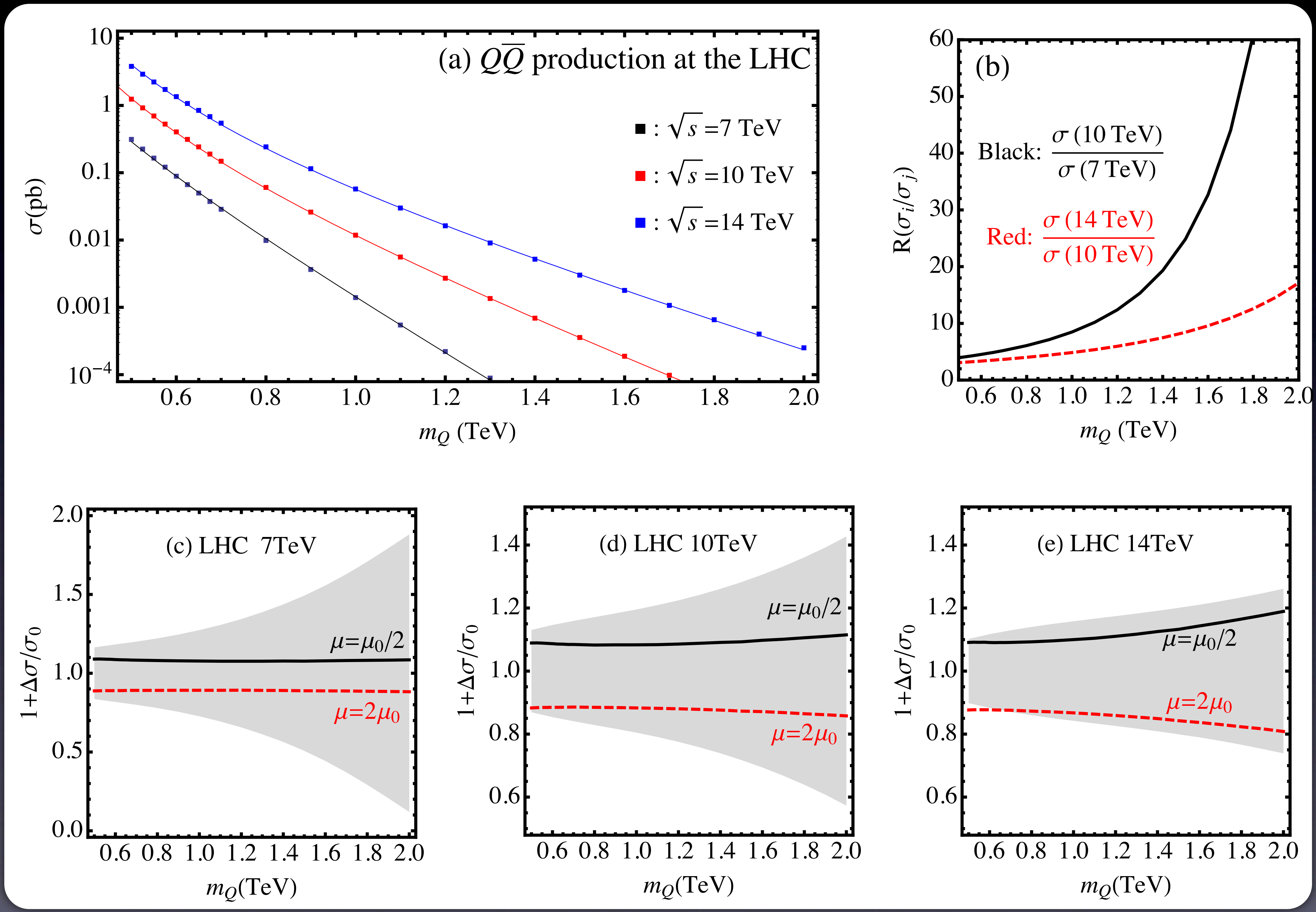


7 TeV: $$\log\left[\frac{\sigma}{\text{pb}}\right] = 0.84569\left(\frac{m_Q}{\text{TeV}}\right)^{-1} + 1.48655 - 8.87048\left(\frac{m_Q}{\text{TeV}}\right)$$

14 TeV: $$\log\left[\frac{\sigma}{\text{pb}}\right] = 2.03833\left(\frac{m_Q}{\text{TeV}}\right)^{-1} - 0.45930 - 4.45853\left(\frac{m_Q}{\text{TeV}}\right)$$

Heavy quark production at NLO

Berger, QHC, PRD81 (2010) 035006



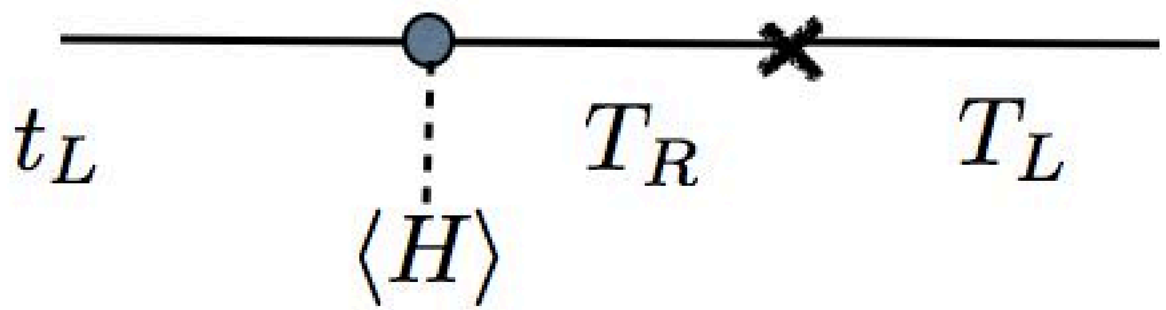
$$\mu_0 = m_Q$$

Heavy quark mixing

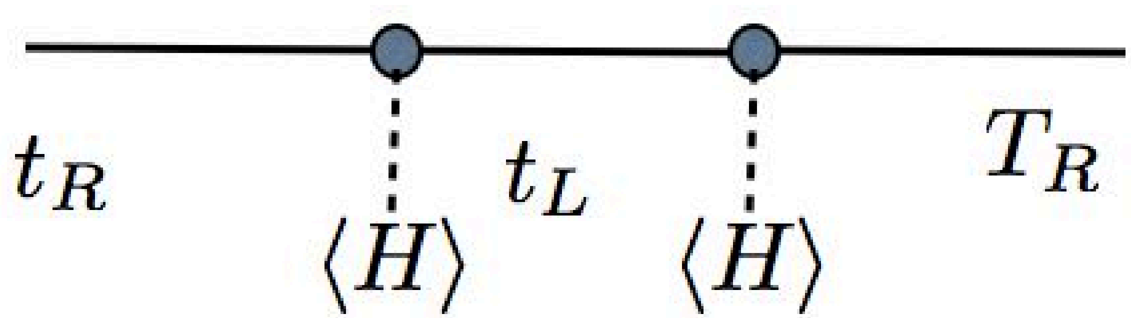
- Heavy quark talks to SM through mass mixing

  (1) Singlet/Triplet vector-like quark mass mixing

$$\mathcal{L} = -y_t v \bar{t}_L t_R - \lambda v \bar{t}_L T_R - M \bar{T}_L T_R + h.c.$$



$$\sin\theta_L \sim \lambda \frac{v}{M}$$



$$\sin\theta_R \sim y_t \lambda \frac{v^2}{M^2}$$

$$\sin\theta_R = \frac{y_t v}{M} \sin\theta_L$$

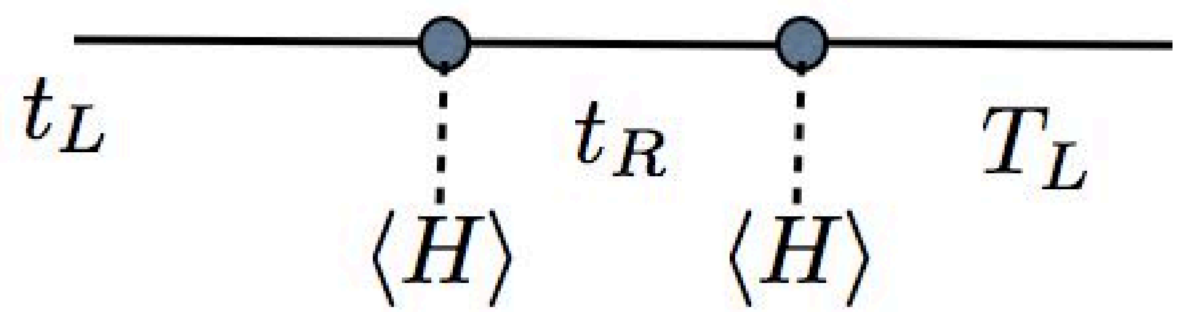
Mainly left-handed mixing

Heavy quark mixing

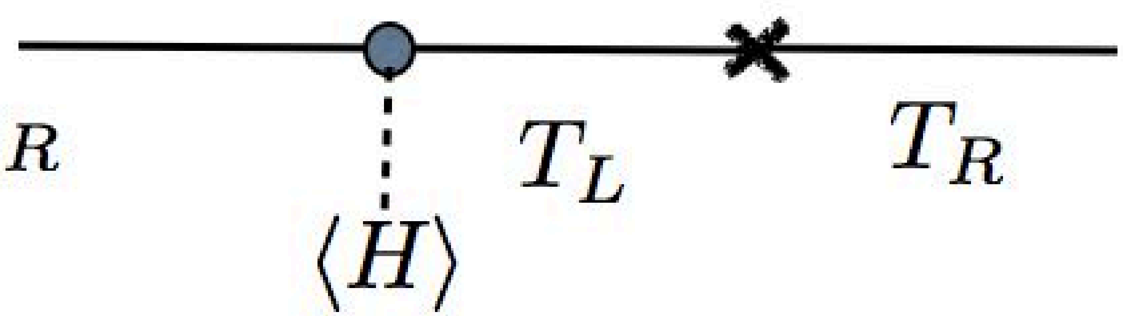
- Heavy quark talks to SM through mass mixing

(2) Doublet vector-like quark mass mixing

$$\mathcal{L} = -y_t v \bar{t}_L t_R - \lambda v \bar{T}_L t_R - M \bar{T}_L T_R + h.c.$$



$$\sin\theta_L \sim y_t \lambda \frac{v^2}{M^2}$$



$$\sin\theta_R \sim \lambda \frac{v}{M}$$

$$\sin\theta_L = \frac{y_t v}{M} \sin\theta_R$$

Mainly right-handed mixing

Heavy quark mixing

- CKM mixing with the top quark (4th gen, chiral doublet)

$$-\mathcal{L}_Q = Y_U^{ij}\bar{Q}_L\tilde{\Phi}U_R + Y_D^{ij}\bar{Q}_L\Phi D_R + h.c.$$

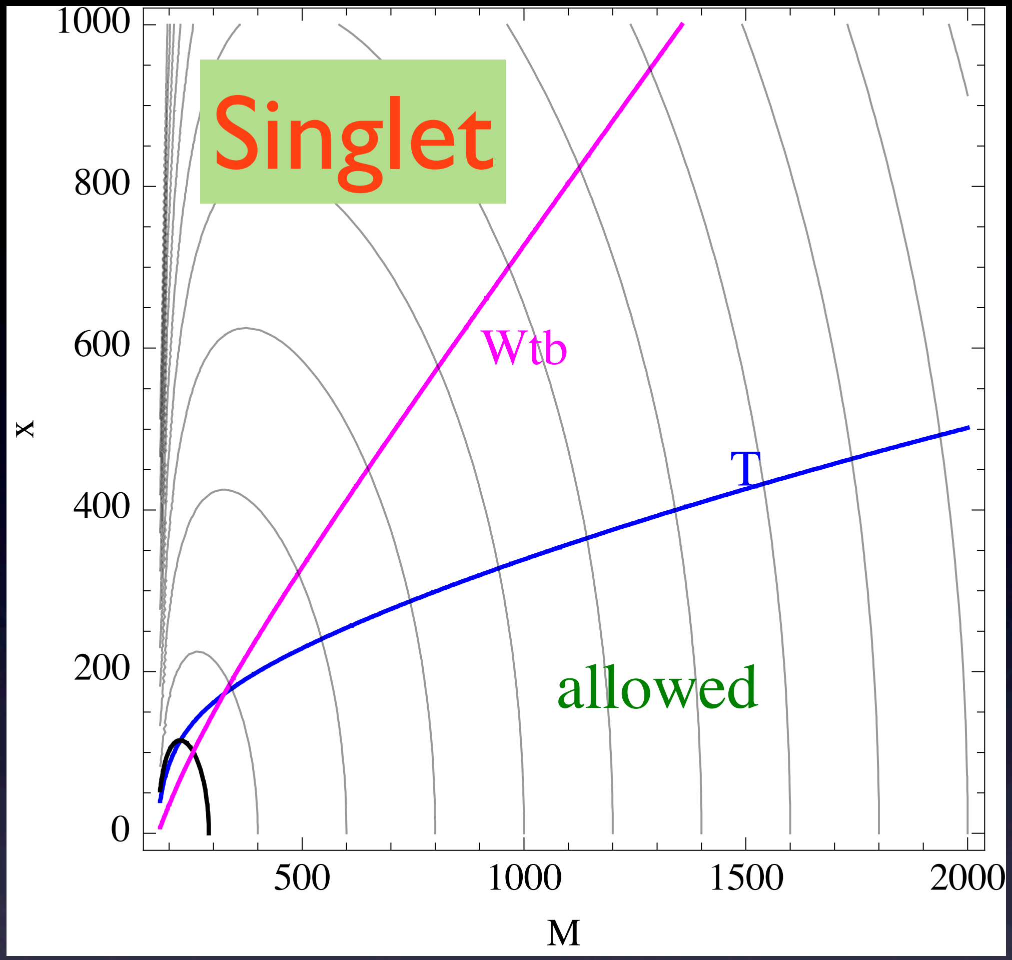
$$U = (u,c,t,T)^T \quad D = (d,s,b,B)^T \quad Q = \begin{pmatrix} U \\ D \end{pmatrix}$$

$$V_{CKM}^{3\times 3} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.9738 & 0.225 & 0.0039 \\ 0.22 & > 0.85 & 0.041 \\ < 0.14 & < 0.5 & > 0.78 \end{pmatrix}$$

$$V_{CKM}^{4\times 4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ud_4} \\ V_{cd} & V_{cs} & V_{cb} & V_{cd_4} \\ V_{td} & V_{ts} & V_{tb} & V_{td_4} \\ V_{u_4 d} & V_{u_4 s} & V_{u_4 b} & V_{u_4 d_4} \end{pmatrix} = \begin{pmatrix} 0.9738 & 0.225 & 0.0039 & < 0.06 \\ 0.22 & 0.96 & 0.041 & < 0.22 \\ < 0.1 & < 0.2 & > 0.78 & < 0.65 \\ < 0.1 & < 0.22 & < 0.65 & > 0.78 \end{pmatrix}$$

Indirect constraints

- S, T parameters
- Zbb corrections
- Wtb coupling

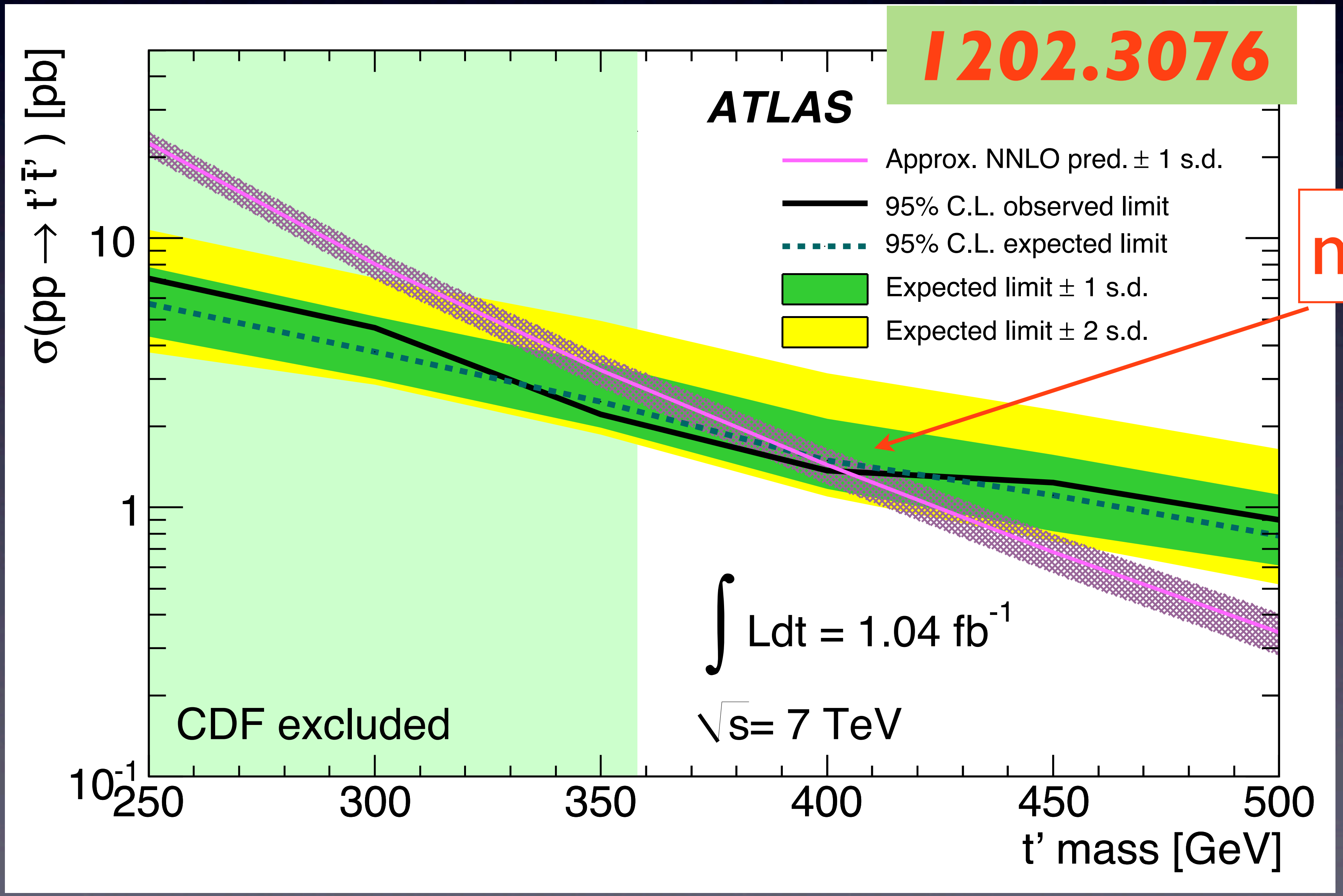


Cacciapaglia et al, JHEP 11(2010) 159

- b to s gamma
- Other flavor constraints (B, Charm)
- Higgs search limits (heavy quark loop)
- WW scattering and Unitarity

t-prime searches

- T-prime pair production with Br(t'-> Wb)=1 (same topology as ttbar in the SM)
  - "lepton+jets" channel (*at least 3 jets, 1 charged leptons, large MET, at leasting one jet is b-tagged*)

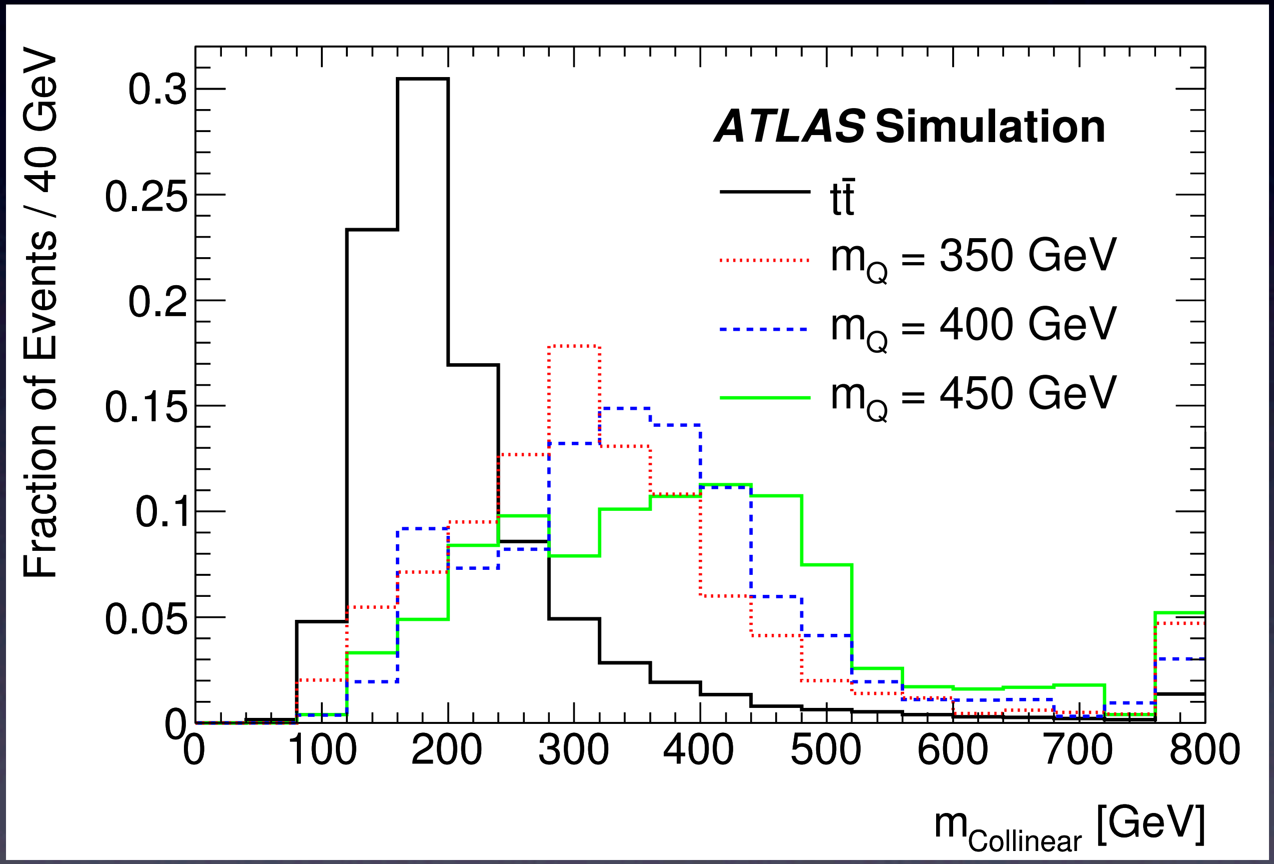


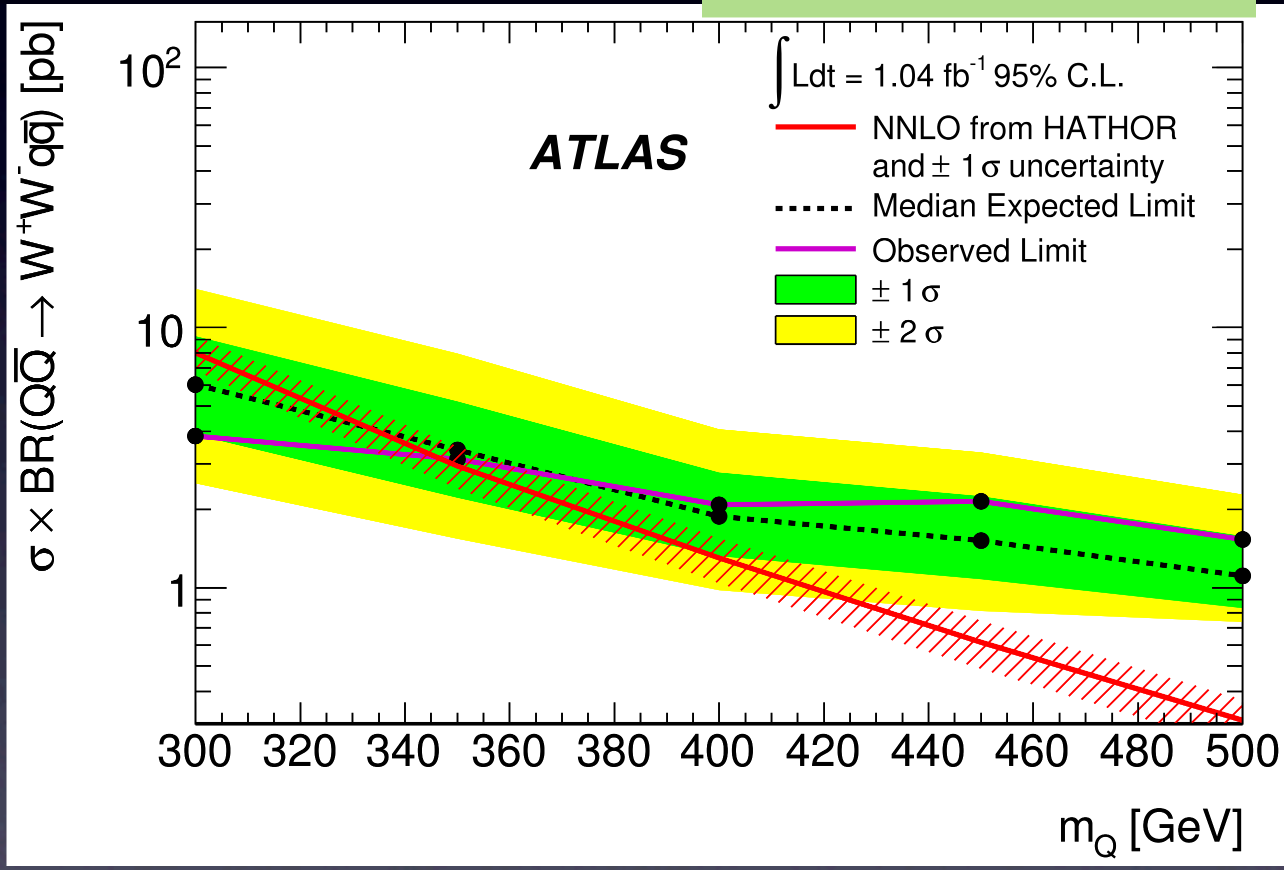
Heavy quark (t-prime) searches

- T-prime pair production with Br(Q->Wq)=1 (same topology as ttbar in the SM)

  - "di-leptons+jets" channel (*at least 2 jets, 2 charged leptons, large MET*)

1202.3389





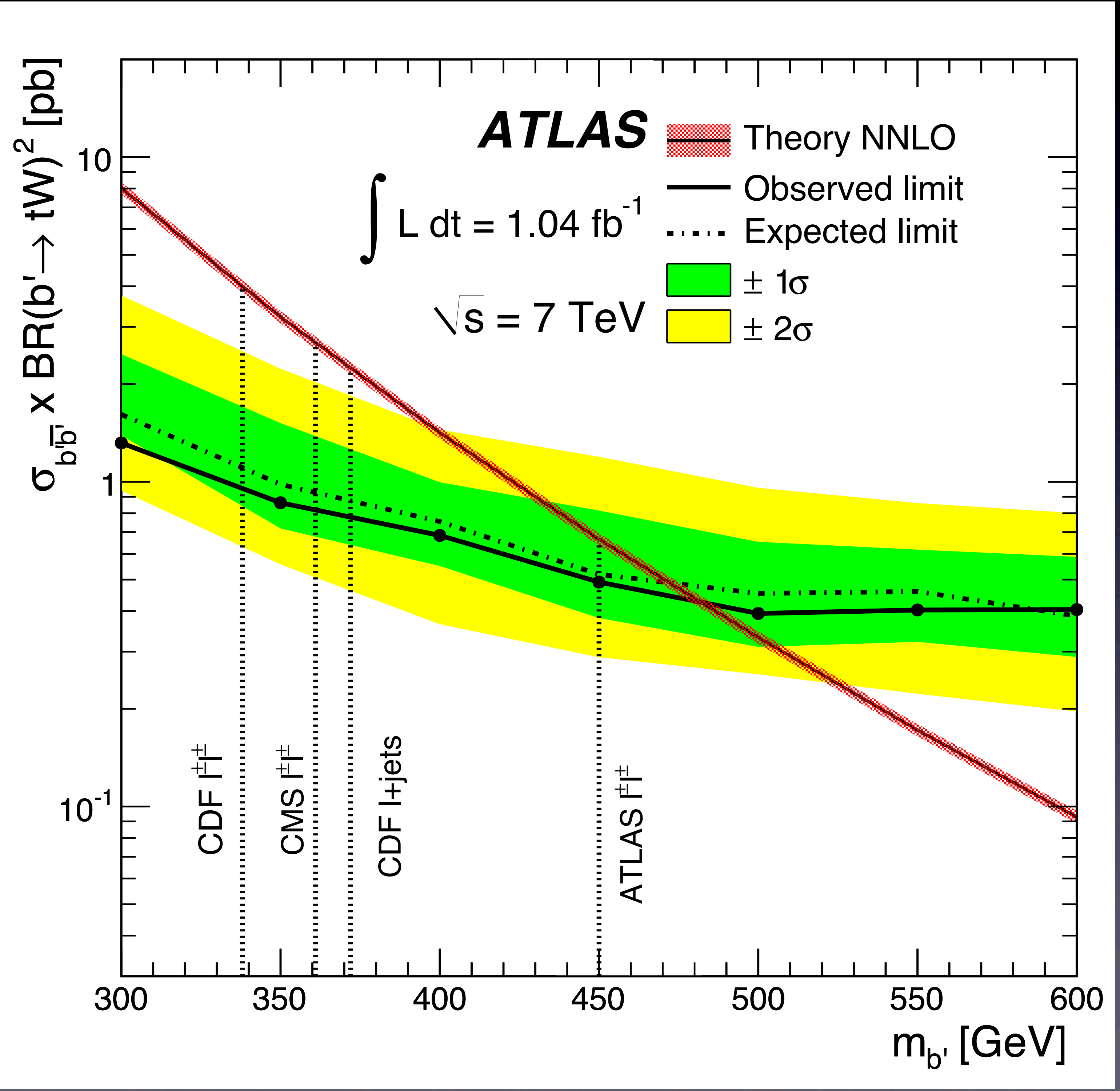
Collinear approximation is used to reconstruct the two invisible neutrinos.

$m_Q > 335$GeV

CMS ($4.7fb^{-1}$): $M_{T'} > 552$ GeV

B-prime quark searches

$$b'\bar{b}' \to W^- t W^+ \bar{t} \to b\bar{b} W^+ W^- W^+ W^- \to l^\pm \nu b\bar{b} q\bar{q} q\bar{q} q\bar{q}.$$



1202.6540

Expected and observed exclusion upper limits at 95% C.L.

$m_{b'} > 480$ GeV

What can we learn from top quark?

* Questions

  - What is the Higgs boson mass?
  - Do we understand heavy flavor production in QCD?
  - Are there more than three fermion generations?
  - Are there new massive particles?
  - Does top quark have the expected couplings?

* Measurements

  - Top quark mass
  - Top quark pair production cross section
  - Charge asymmetry of top pair
  - $m_{t\bar{t}}$ distribution
  - Single top production
  - Search for t-prime quark
  - Searches for $H^+ \to t\bar{b}$ or $t \to H^+\bar{b}$
  - Constraints on Wtb coupling
  - W boson helicity
  - Search for FCNC top interaction

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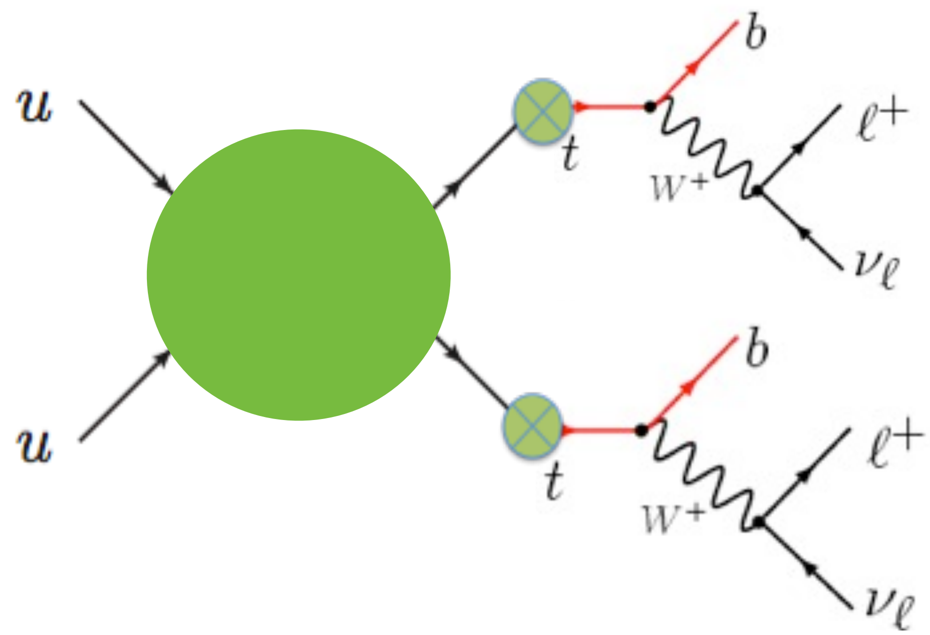
Same-sign top quark pair
(Exotic color resonance or FCNC interaction)

★ same-sign top production



✳ Potentially large cross section

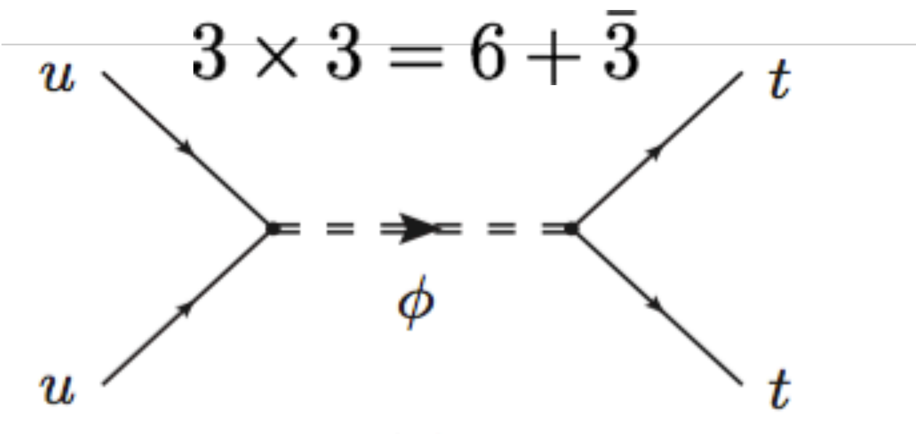
✳ Signature: same-sign charged lepton pair, b-jets, and large MET

✳ top quark polarization can be measured.

Berger, QHC, et al, PRL105 (2010) 181802

★ s-channel resonance

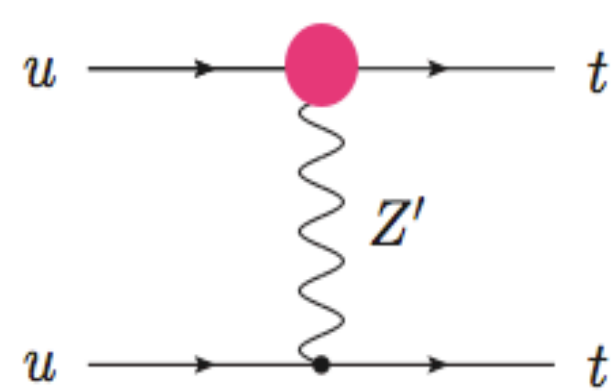
Quark-quark initial states can produce color sextet and anti-triplet resonances



Berger, QHC, et al, PRL106 (2011) 201801

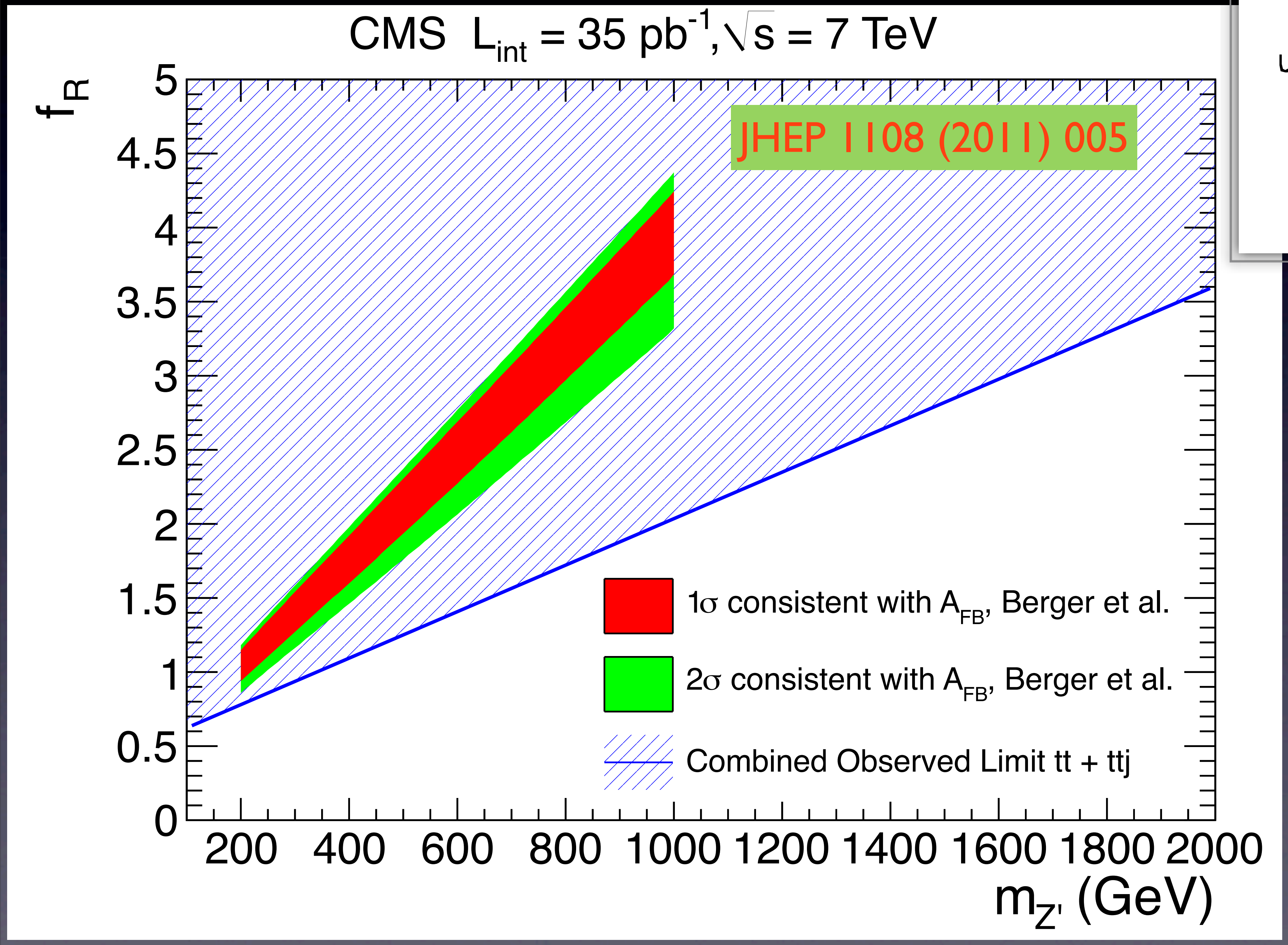
★ t-channel process

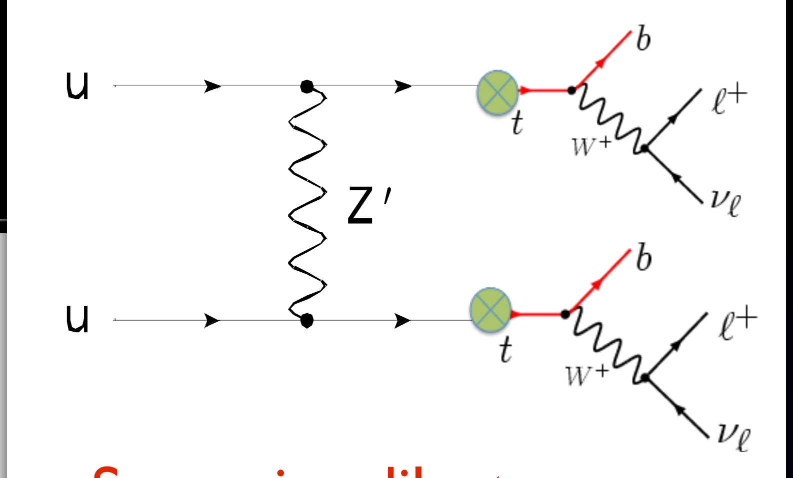
Flavor changing neutral current Z-prime



Searches for same-sign top pair

Tevatron: $\sigma(tt) < 0.4\text{pb}$





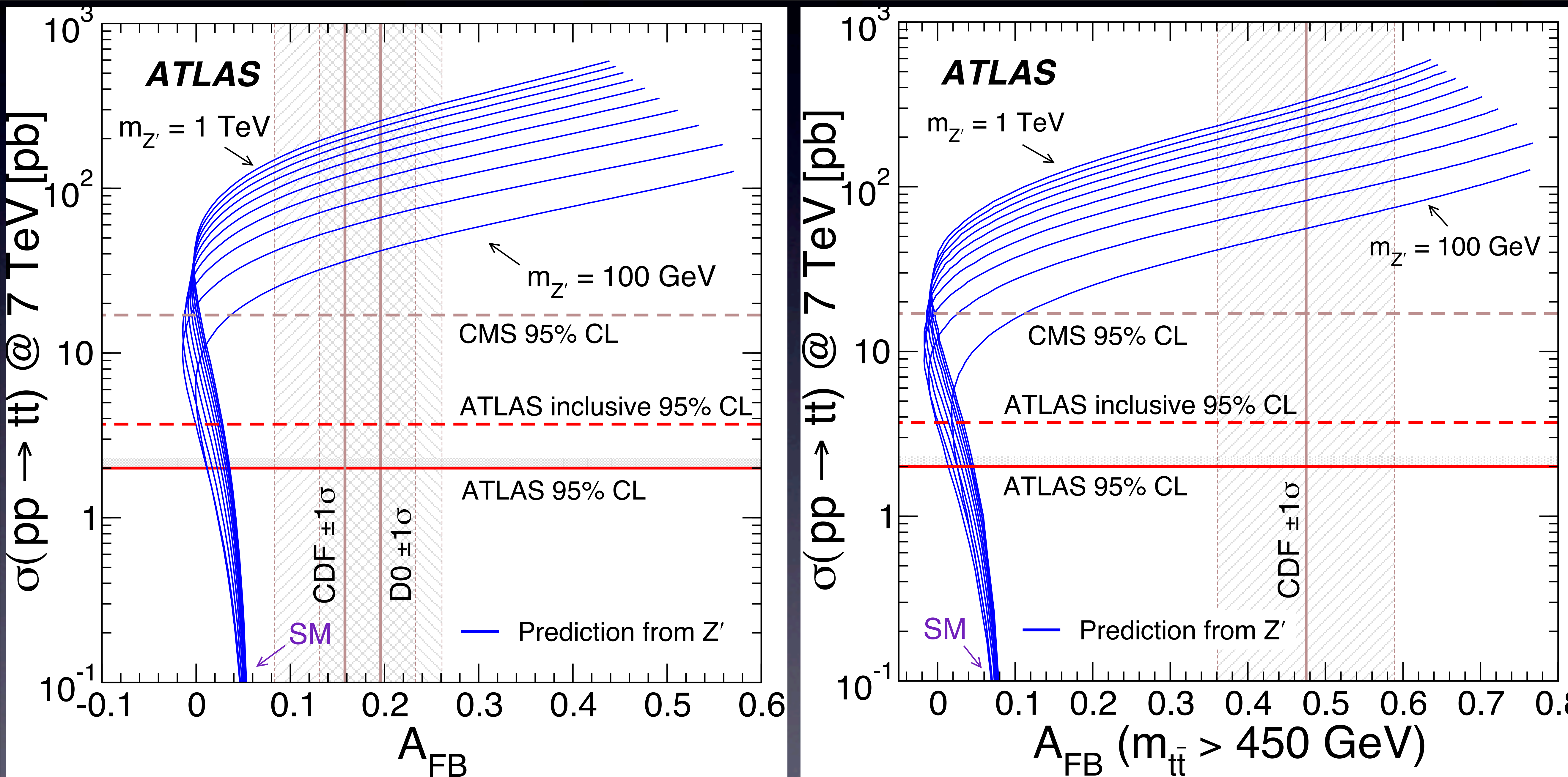
Same-sign dileptons are predicted.

ATLAS (Sep 26, 2011):
similar results
ATLAS-Conf-2011-139

Searches for same-sign top pair

- ATLAS (7TeV, 1.04fb^{-1})

1202.5520



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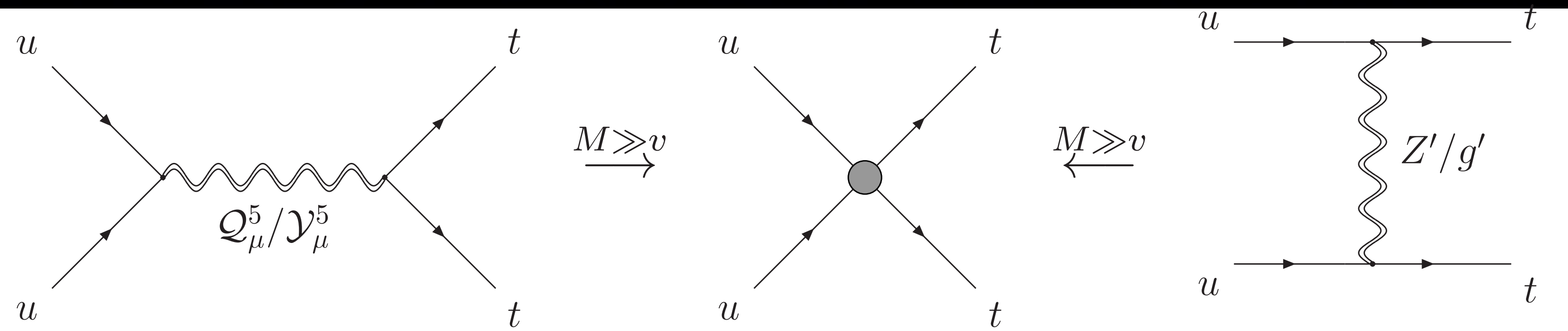
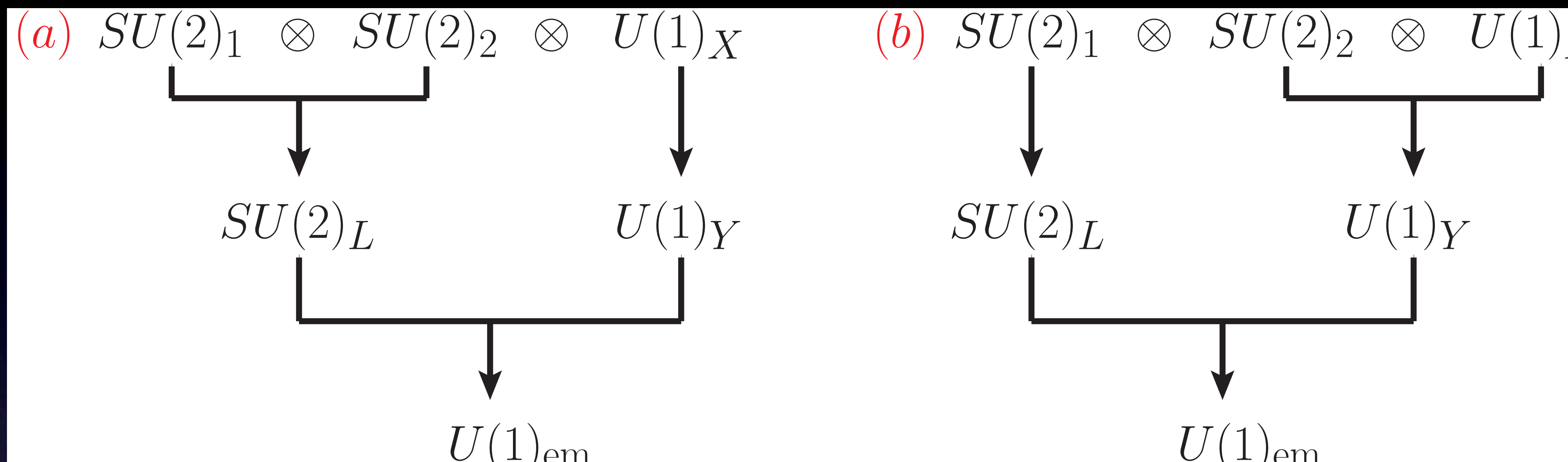


$$\mathcal{L}_{4F} = \frac{1}{2}\frac{C_{LL}}{\Lambda^2}(\bar{u}_L\gamma^\mu t_L)(\bar{u}_L\gamma_\mu t_L) + \frac{1}{2}\frac{C_{RR}}{\Lambda^2}(\bar{u}_R\gamma^\mu t_R)(\bar{u}_R\gamma_\mu t_R)$$
$$-\frac{1}{2}\frac{C_{LR}}{\Lambda^2}(\bar{u}_L\gamma^\mu t_L)(\bar{u}_R\gamma_\mu t_R) - \frac{1}{2}\frac{C'_{LR}}{\Lambda^2}(\bar{u}_{La}\gamma^\mu t_{Lb})(\bar{u}_{Rb}\gamma_\mu t_{Ra}) + \text{h.c.}\,,$$

Label	Spin	Quantum numbers	Limit	Mass Limit
$\mathcal{B}_\mu$	1	$(1,1)_0$	$\|g_{13}\|/\Lambda < 0.57$ TeV^{-1}	1.7 TeV
$\mathcal{W}_\mu$	1	$(1,3)_0$	$\|g_{13}\|/\Lambda < 0.57$ TeV^{-1}	1.7 TeV
$\mathcal{G}_\mu$	1	$(8,1)_0$	$\|g_{13}\|/\Lambda < 0.99$ TeV^{-1}	1.0 TeV
$\mathcal{H}_\mu$	1	$(8,3)_0$	$\|g_{13}\|/\Lambda < 0.99$ TeV^{-1}	1.0 TeV
$\mathcal{Q}^5_\mu$	1	$(3,2)_{-\frac{5}{6}}$	$\|g_{11}g_{33}\|/\Lambda^2 < 0.34$ TeV^{-2}	1.7 TeV
$\mathcal{Y}^5_\mu$	1	$(\bar{6},2)_{-\frac{5}{6}}$	$\|g_{11}g_{33}\|/\Lambda^2 < 0.63$ TeV^{-2}	1.3 TeV
ϕ	0	$(1,2)_{-\frac{1}{2}}$	$\|g^u_{13}g^u_{31}\|/\Lambda^2 < 0.92$ TeV^{-2}	1.1 TeV
Φ	0	$(8,2)_{-\frac{1}{2}}$	$\|g^u_{13}g^u_{31}\|/\Lambda^2 < 1.8$ TeV^{-2}	0.8 TeV
Ω^4	0	$(\bar{6},1)_{-\frac{4}{3}}$	$\|g_{11}g_{33}\|/\Lambda^2 < 0.33$ TeV^{-2}	1.8 TeV
Σ	0	$(\bar{6},3)_{-\frac{1}{3}}$	$\|g_{11}g_{33}\|/\Lambda^2 < 0.16$ TeV^{-2}	2.5 TeV

Extra gauge bosons (Z-prime and W-prime)

- Minimal model with both W-prime and Z-prime



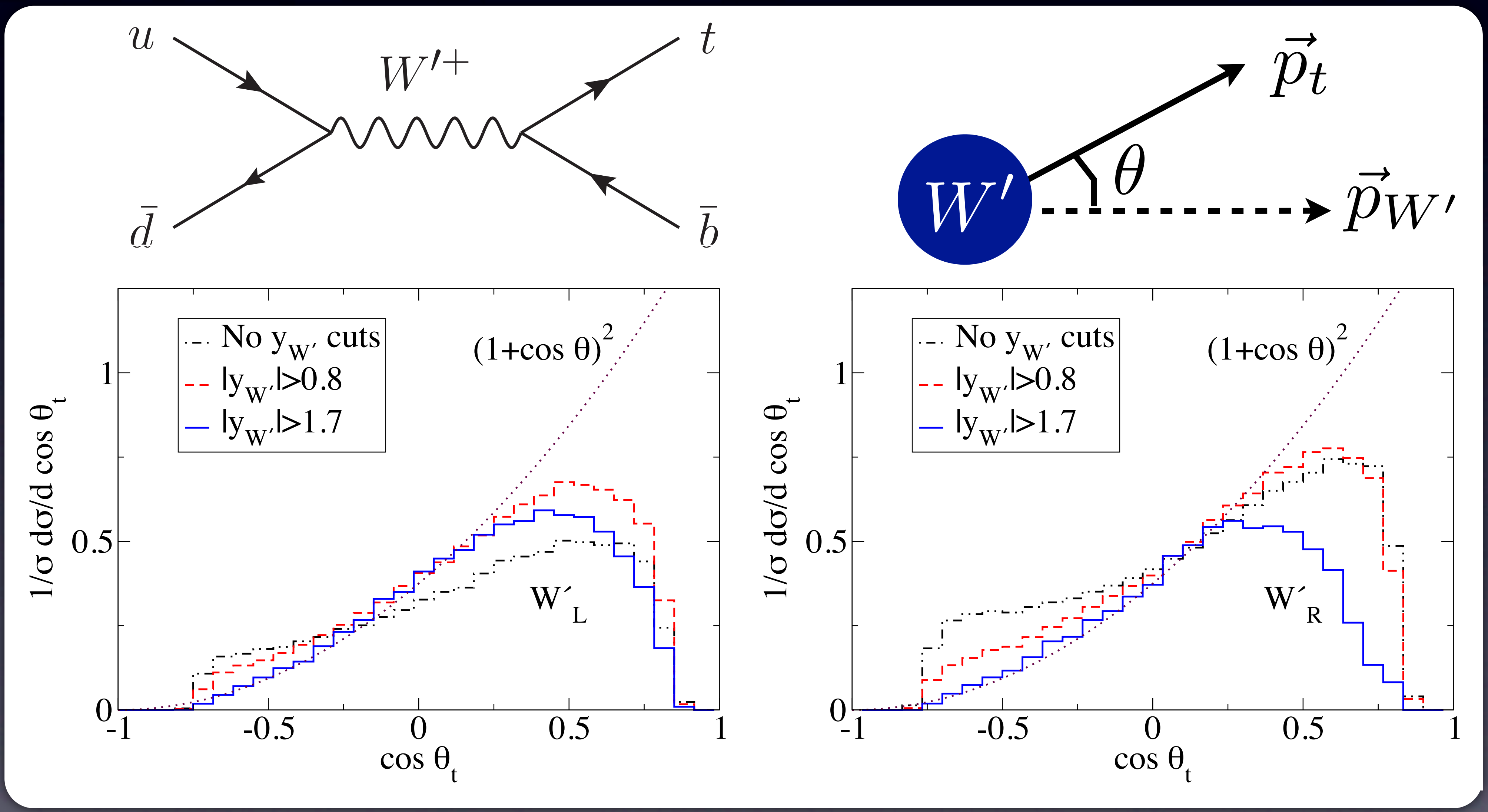
Hsieh, Schmitz, Jiang-Hao Yu, and Yuan, Phys. Rev. D 82, 035011 (2010)

Model	$SU(2)_1$	$SU(2)_2$	$U(1)_X$
Left-right (LR)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} u_R \\ d_R \end{pmatrix}, \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$	$\frac{1}{6}$ for quarks, $-\frac{1}{2}$ for leptons.
Leptophobic (LP)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} u_R \\ d_R \end{pmatrix}$	$\frac{1}{6}$ for quarks, $Y_{\rm SM}$ for leptons.
Hadrophobic (HP)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$	$Y_{\rm SM}$ for quarks, $-\frac{1}{2}$ for leptons.
Fermiophobic (FP)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$		$Y_{\rm SM}$ for all fermions.
Ununified (UU)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$Y_{\rm SM}$ for all fermions.
Nonuniversal (NU)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{1^{\rm st},2^{\rm nd}}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{1^{\rm st},2^{\rm nd}}$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{3^{\rm rd}}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{3^{\rm rd}}$	$Y_{\rm SM}$ for all fermions.

Measuring W'-t-b and Z'-t-t couplings

★ At the LEP and the Tevatron, the forward-backward asymmetry is used to investigate the chirality of the couplings.

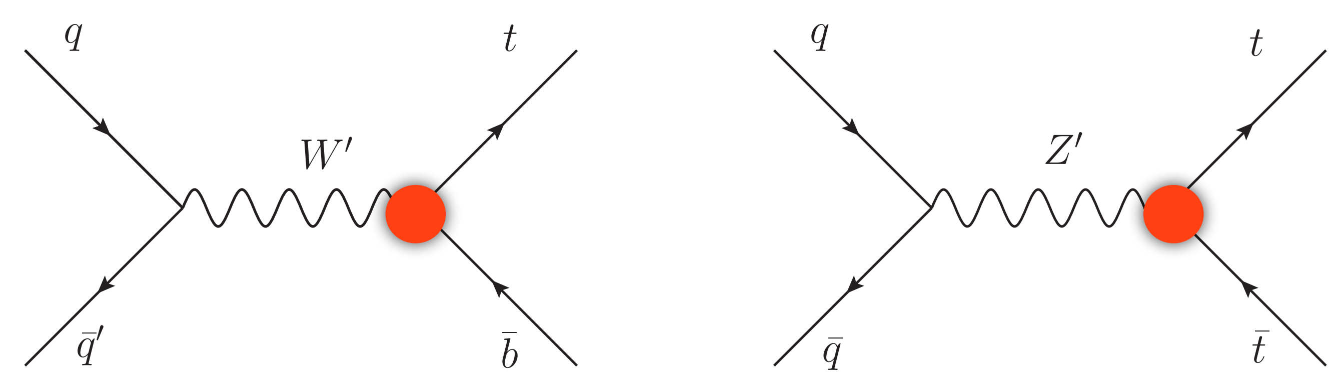
★ Forward direction is **NOT** well defined at the LHC (a proton-proton machine).



Gopalakrishna, Han, Lewis, Si, Zhou, Phys Rev D82 (2010) 115020

Extra gauge bosons (Z-prime and W-prime)

Gopalakrishna, Han, Lewis, Si, Zhou, Phys Rev D82 (2010) 115020
Berger, QHC, Chen, Zhang, Phys.Rev. D83 (2011) 114026



Top-quark polarization depends on how the top-quark is gauged under new gauge symmetry, *or*, the handness of W'-t-b and Z'-t-t couplings.

Hsieh, Schmitz, Jiang-Hao Yu, and Yuan, Phys. Rev. D 82, 035011 (2010)

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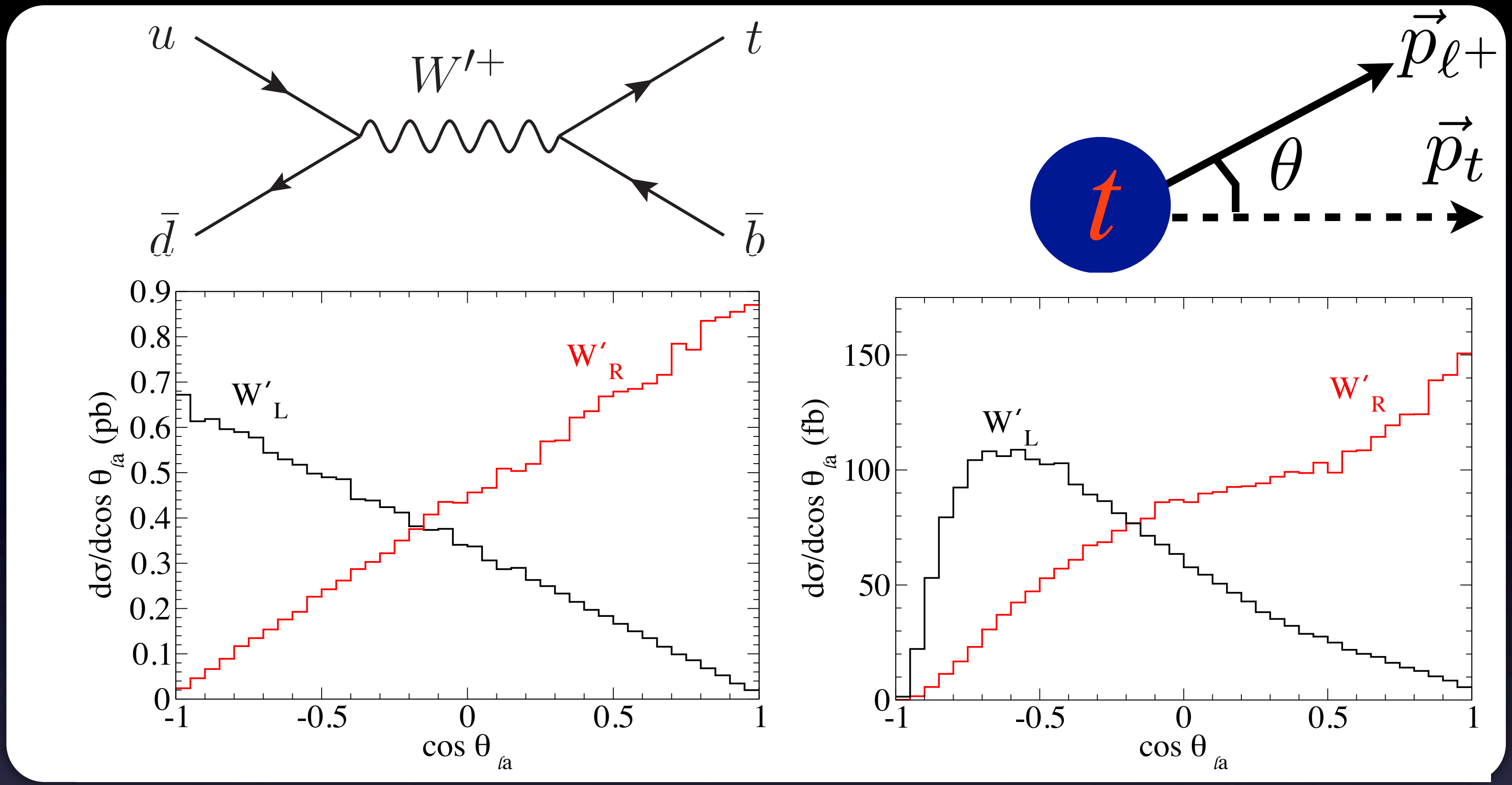
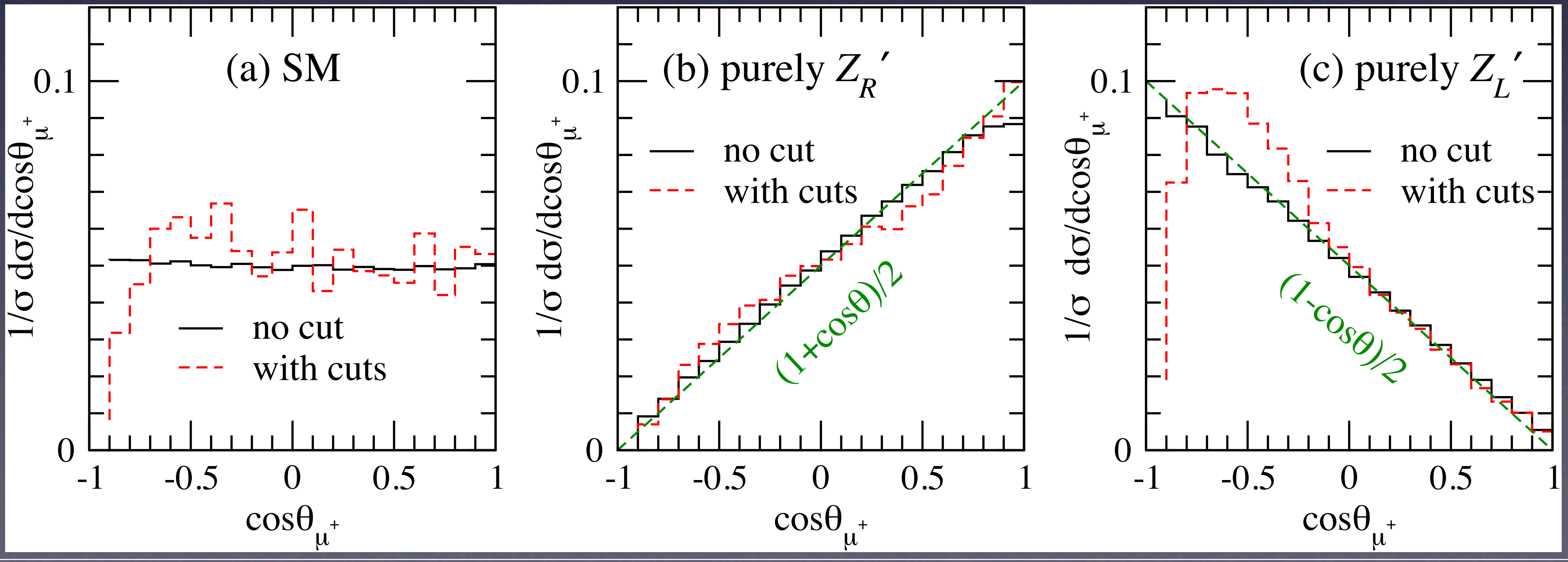
Measuring W'-t-b and Z'-t-t couplings

★ Top polarization can probe the handness of W'-t-b coupling.



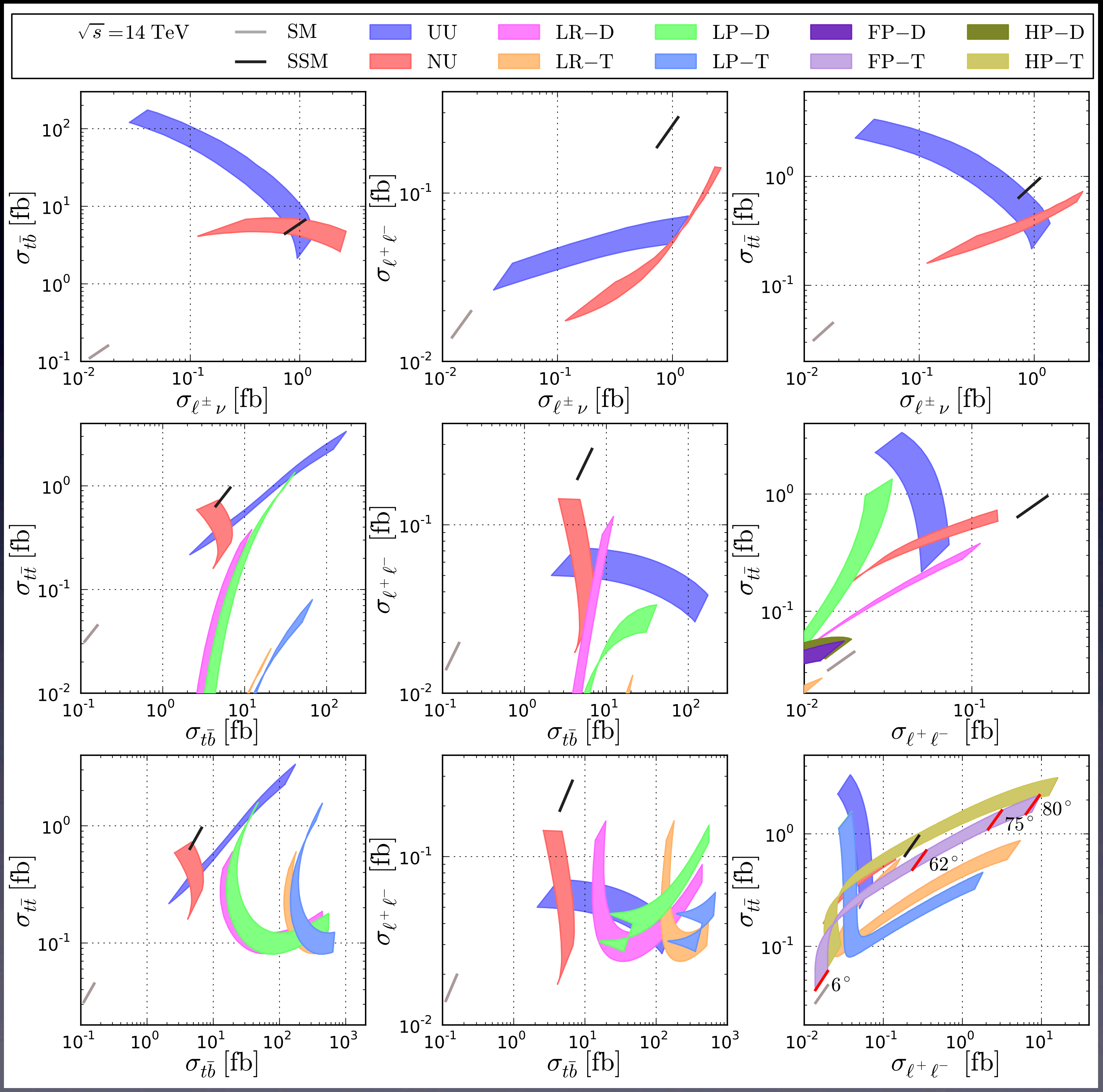
Gopalakrishna, Han, Lewis, Si, Zhou, PRD82 (2010) 115020

★ Top polarization can probe the handness of Z'-t-t coupling.



Berger, QHC, Chen, Zhang, PRD83 (2011) 114026

Extra gauge bosons (Z-prime and W-prime)



$$m_{W'} = 4.0 \pm 0.1\text{TeV}$$

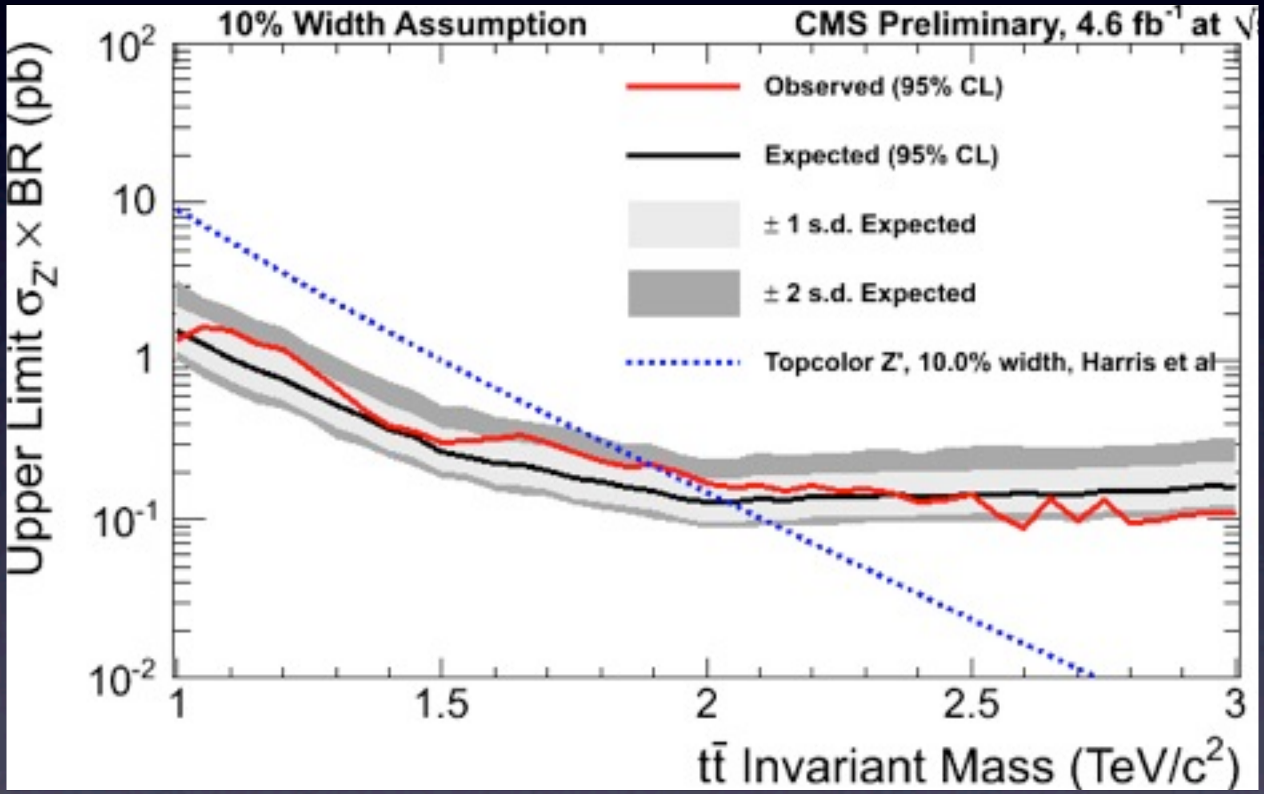
$$m_{Z'} = 4.0 \pm 0.1\text{TeV}$$

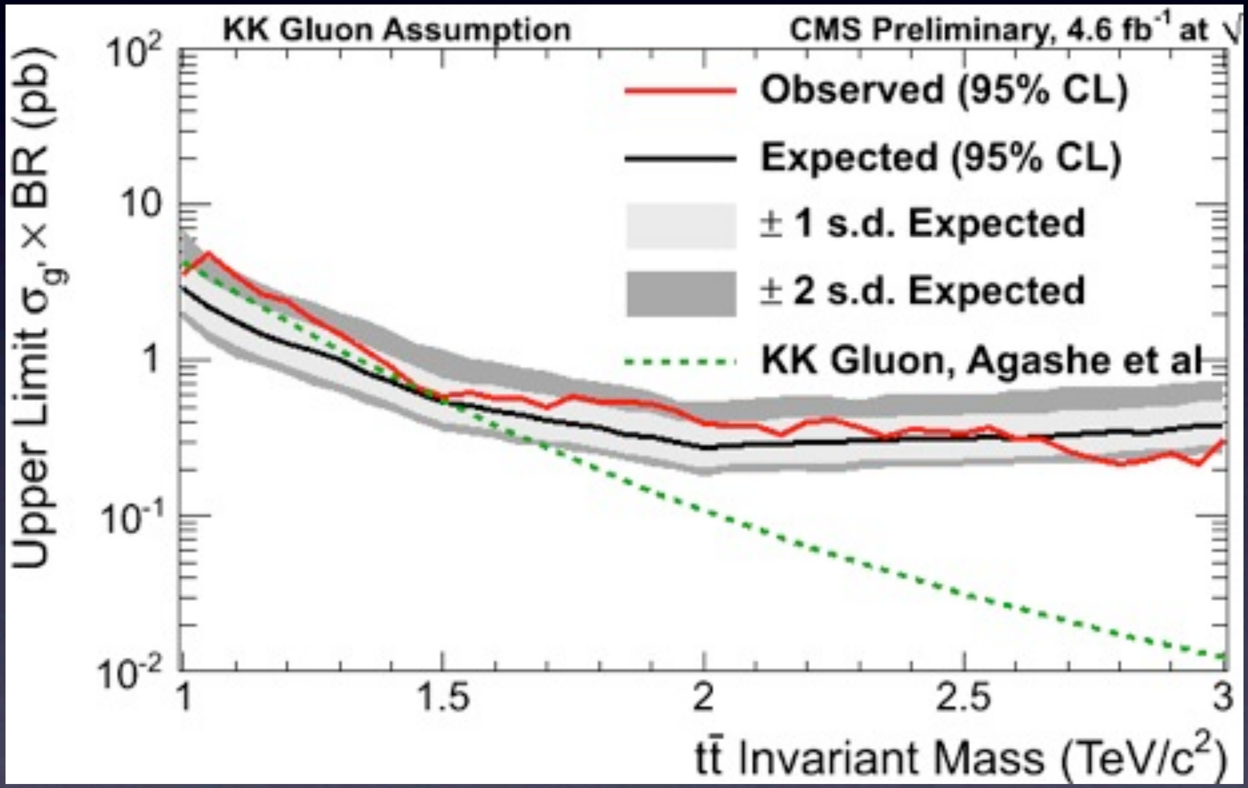
Jezo, Klasen, Schienbein
1203.5314

Searches for Z-prime in ttbar

- BSM ttbar production in boosted all-hadronic final state

(CMS, Feb 2012)

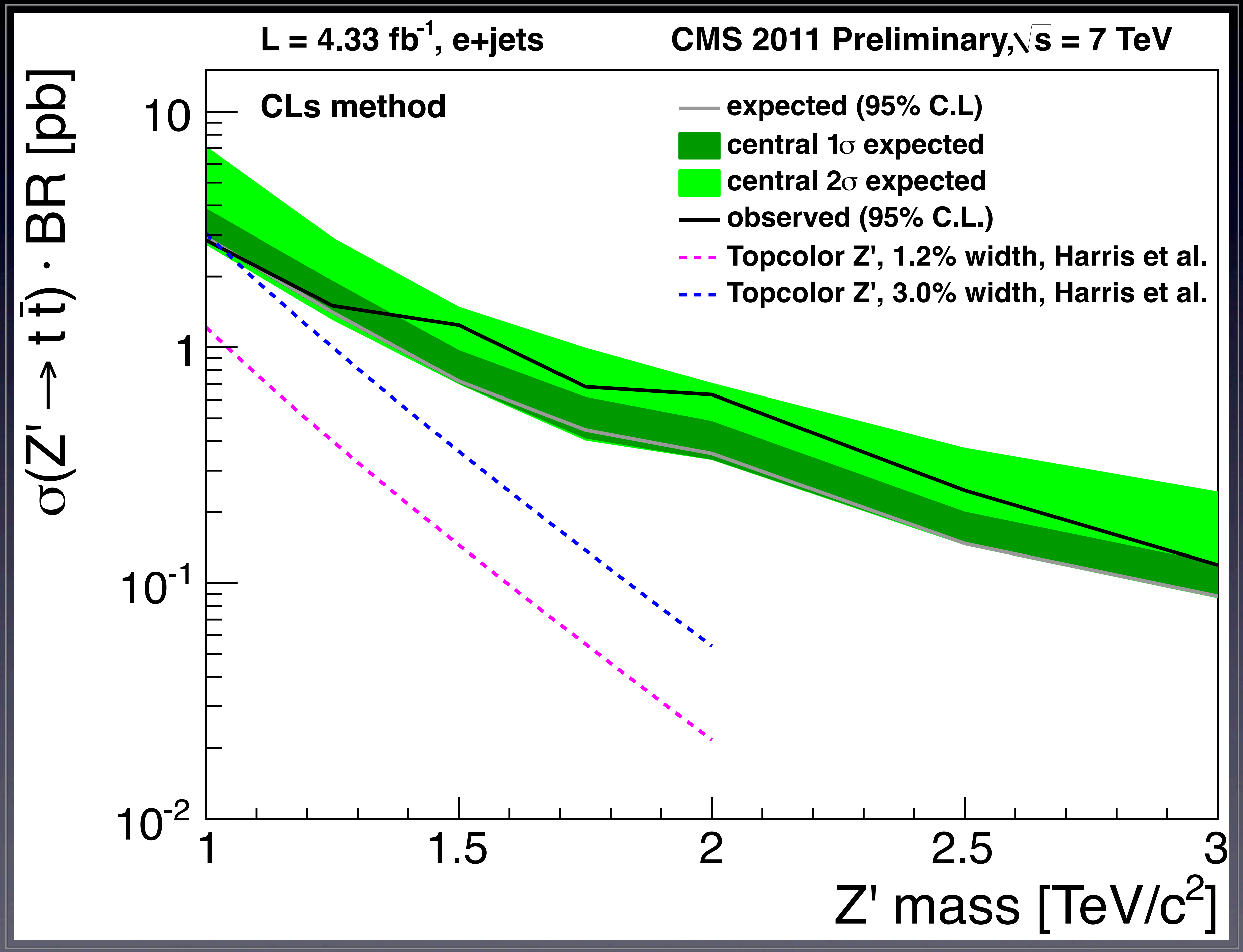




Searches for Z-prime in ttbar

- "electron+jets" channels (CMS, 4.33 fb^{-1})

CMS PAS EXO-11-092



What can we learn from top quark?

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- Do we understand heavy flavor production in QCD?
- Are there more than three fermion generations?
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- Does top quark have the expected couplings?

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Top-quark EFT

Zhang, Willenbrock, PRD83 (2011) 034006

- CP-even operators *(linear realization as EWPT prefers a light Higgs)*

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

$$O_{qq}^{(8,1)} = \frac{1}{4}(\bar{q}^i \gamma_\mu \lambda^A q^j)(\bar{q}\gamma^\mu \lambda^A q) \qquad O_{qq}^{(8,3)} = \frac{1}{4}(\bar{q}^i \gamma_\mu \tau^I \lambda^A q^j)(\bar{q}\gamma^\mu \tau^I \lambda^A q)$$

$$O_{ut}^{(8)} = \frac{1}{4}(\bar{u}^i \gamma_\mu \lambda^A u^j)(\bar{t}\gamma^\mu \lambda^A t) \qquad O_{dt}^{(8)} = \frac{1}{4}(\bar{d}^i \gamma_\mu \lambda^A d^j)(\bar{t}\gamma^\mu \lambda^A t)$$

$$O_{qu}^{(1)} = (\bar{q}u^i)(\bar{u}^j q) \qquad O_{qd}^{(1)} = (\bar{q}d^i)(\bar{d}^j q)$$

$$O_{qt}^{(1)} = (\bar{q}^i t)(\bar{t} q^j)$$

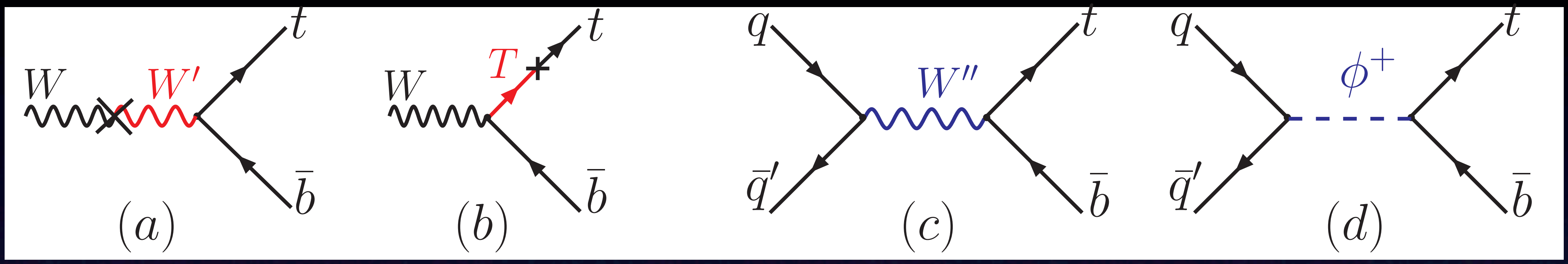
- CP-odd operators

operator	process
$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W_{\mu\nu}^I$ (with imaginary coefficient)	top decay, single top
$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G_{\mu\nu}^A$ (with imaginary coefficient)	single top, $q\bar{q}, gg \to t\bar{t}$
$O_{\tilde{G}} = f_{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$gg \to t\bar{t}$
$O_{\phi\tilde{G}} = \frac{1}{2}(\phi^+\phi) \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$gg \to t\bar{t}$

Single top quark production

- Tree-level induced operators only

QHC, J. Wudka, C.-P. Yuan, Phys.Lett.B658:50(2007)



$$\mathcal{O}^{(3)}_{\phi q} = i\left(\phi^\dagger \tau^I D_\mu \phi\right)\left(\bar{q}_h \gamma^\mu \tau^I q_h\right) + h.c.$$

$$\mathcal{O}_{\phi\phi} = i\left(\phi^\dagger \epsilon D_\mu \phi\right)\left(\bar{t}\gamma^\mu b\right) + h.c.$$

$$\mathcal{O}^{(3)}_{qq} = \frac{1}{2}\left(\bar{q}_l \gamma_\mu \tau^I q_l\right)\left(\bar{q}_h \gamma^\mu \tau^I q_h\right)$$

$$\mathcal{O}^{(1)}_{qu} = \left(\bar{q}_l t_R\right)\left(\bar{u}_R q_l\right)$$

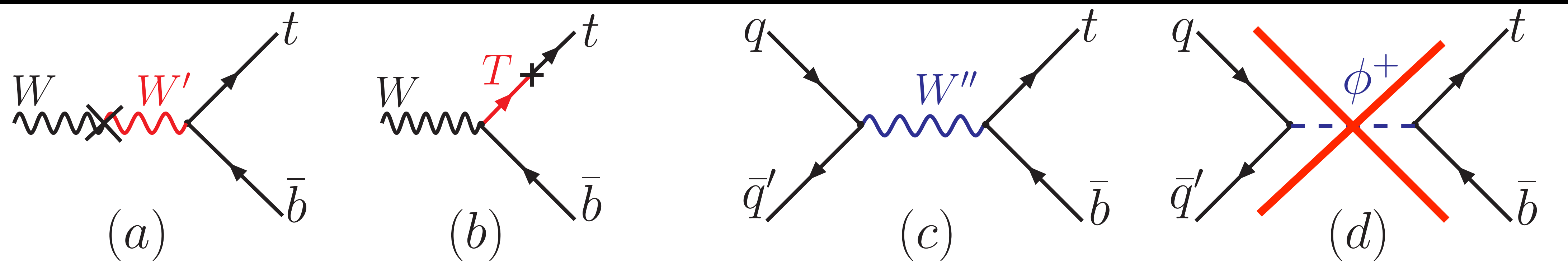
$$\mathcal{O}^{(1)}_{qq} = \left(\bar{q}^i_l t_R\right)\left(\bar{q}^j_l b_R\right)\epsilon_{ij}$$

$$q_l = \begin{pmatrix} u \\ d \end{pmatrix}_L \qquad q_h = \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$u_R\ t_R$, $d_R\ b_R$: singlet

ϕ : Higgs doublet

Single top quark production



Does not interfere with the SM channel

Upon symmetry breaking

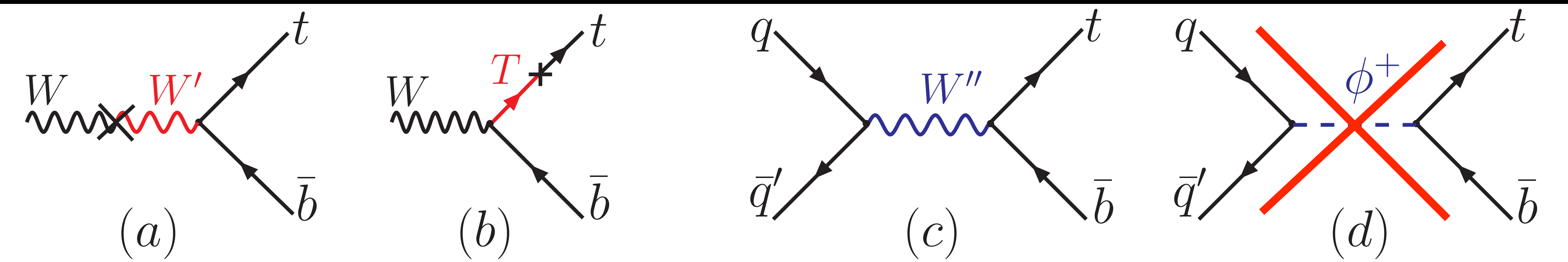
$$\phi = \frac{v+h}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$\mathcal{O}_{Wtb} = \frac{g}{\sqrt{2}} \left\{ \bar{t}\gamma^{\mu} \left(\mathcal{F}_L P_L + \mathcal{F}_R P_R \right) b W_{\mu}^{+} + h.c. \right\}$$

$$\mathcal{O}_{4f} = \mathcal{G}_{4f} \frac{1}{v^2} \left(\bar{Q}' \gamma^{\mu} P_L Q \right) \left(\bar{b} \gamma_{\mu} P_L t \right) + h.c.$$

$$\mathcal{F}_L = \frac{C_{\phi q}^{(3)} v^2}{\Lambda^2} \qquad \mathcal{F}_R = \frac{C_{\phi\phi} v^2}{2\Lambda^2} \qquad \mathcal{G}_{4f} = \frac{C_{\phi q}^{(3)} v^2}{2\Lambda^2}$$

Single top quark production



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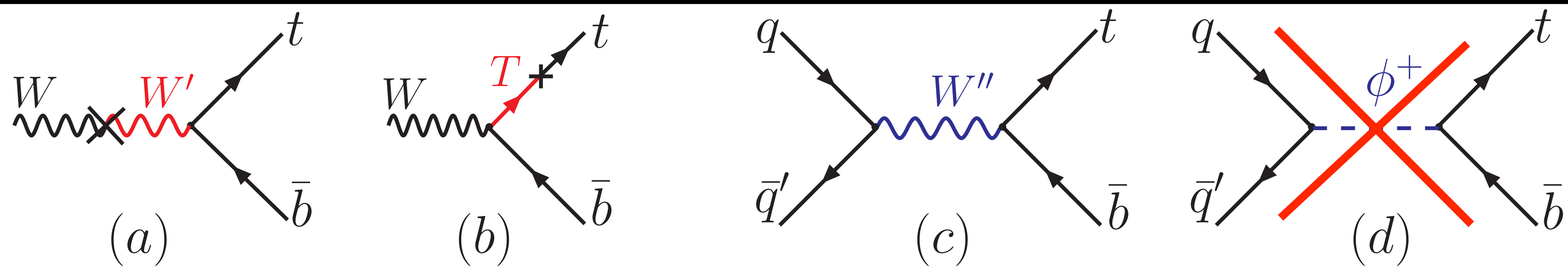

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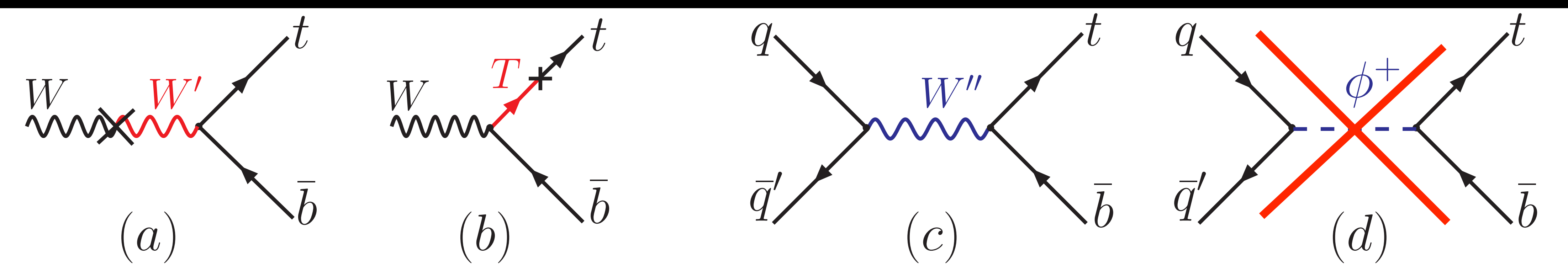

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$b \to s\gamma$

$-0.0007 < \mathcal{F}_R < 0.0025$

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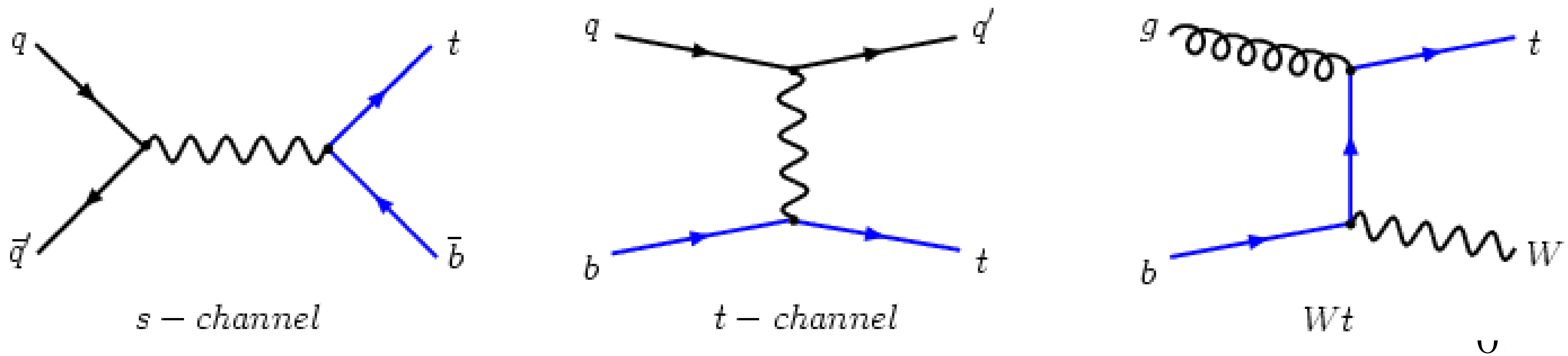
Single top quark production

Inclusive cross sections:

$$\sigma_{tW} = \sigma^0_{tW}\left(1 + 4\mathcal{F}_L\right),$$
$$\sigma_s = \sigma^0_s\left(1 + 4\mathcal{F}_L + 19.69\mathcal{G}_{4f}\right),$$
$$\sigma_t = \sigma^0_t\left(1 + 4\mathcal{F}_L - 3.06\mathcal{G}_{4f}\right),$$



Single top quark production

- **Inclusive cross sections:**

$$\begin{aligned}\sigma_{tW} &= \sigma^0_{tW}\left(1+4\mathcal{F}_L\right),\\ \sigma_s &= \sigma^0_s\left(1+4\mathcal{F}_L+19.69\mathcal{G}_{4f}\right),\\ \sigma_t &= \sigma^0_t\left(1+4\mathcal{F}_L-3.06\mathcal{G}_{4f}\right),\end{aligned}$$

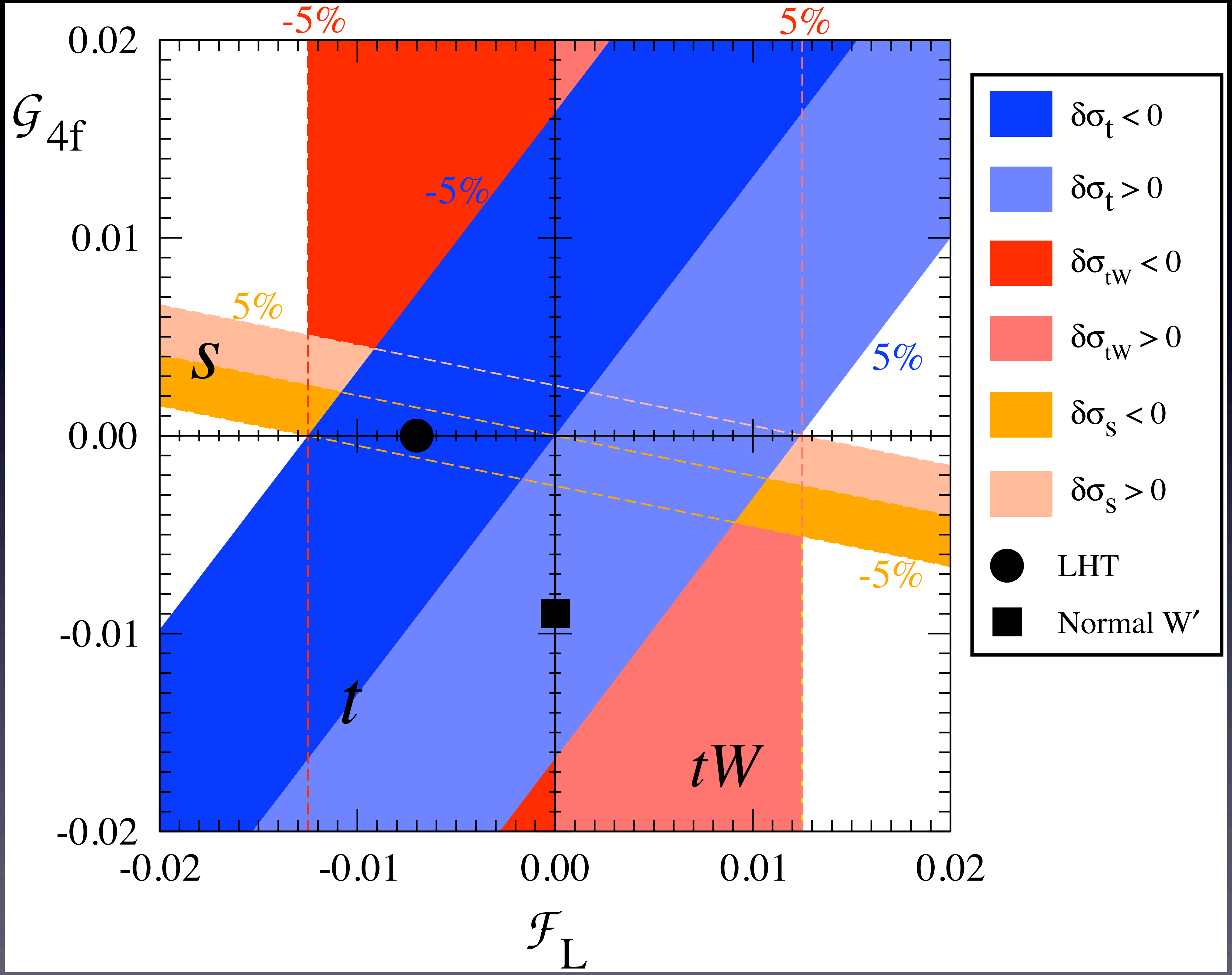
- **Cross section sum rules:**

$$\frac{\sigma_s}{\sigma^0_s}+6.43\frac{\sigma_t}{\sigma^0_t}=7.43\frac{\sigma_{tW}}{\sigma^0_{tW}}$$

$\mathcal{G}_{4f}=0$ $\rightarrow$ $$\frac{\sigma_s}{\sigma^0_s}=\frac{\sigma_t}{\sigma^0_t}=\frac{\sigma_{tW}}{\sigma^0_{tW}}$$

$\mathcal{F}_L=0$ $\rightarrow$ $$\frac{\sigma_s}{\sigma^0_s}+6.43\frac{\sigma_t}{\sigma^0_t}=0$$

Single top quark production



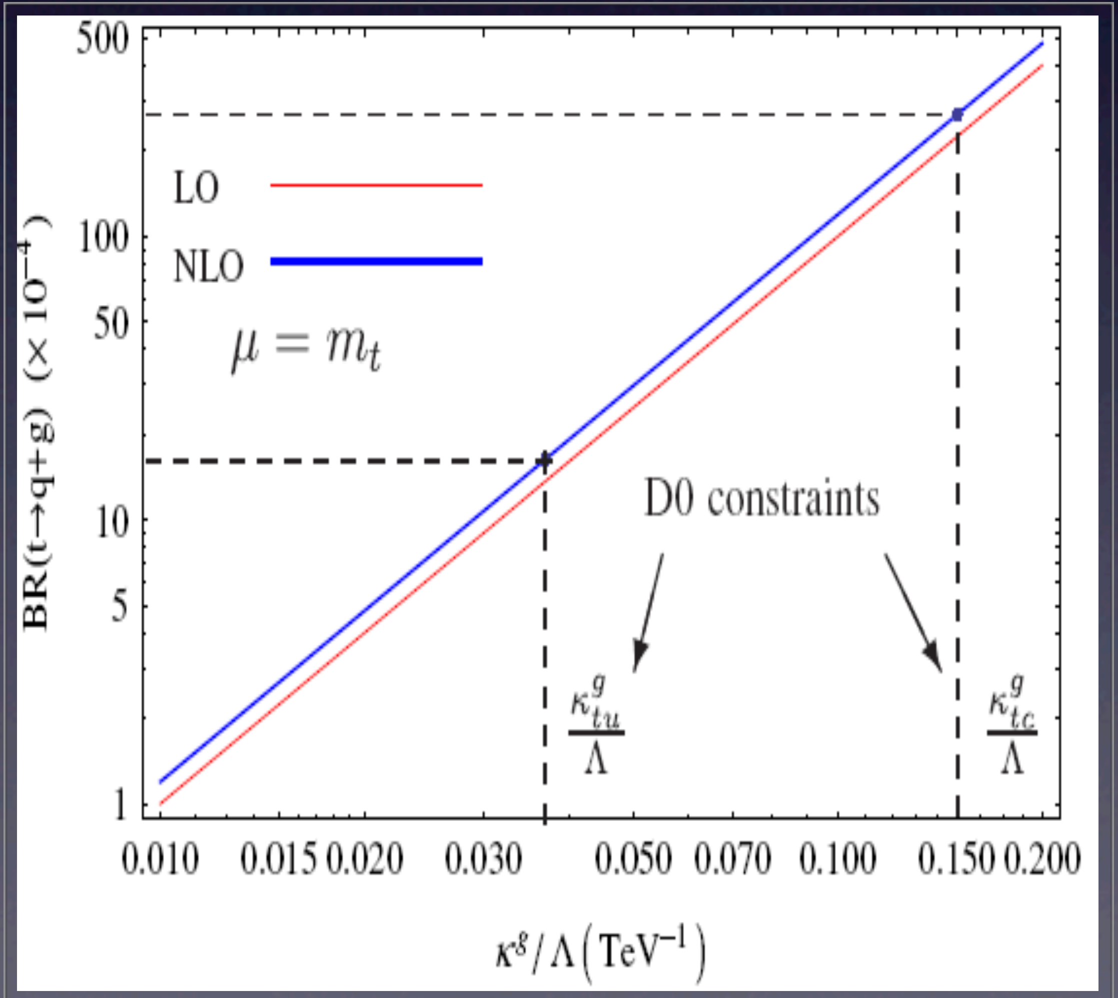
Direct top-quark production

- $gq \to t$ induced by anomalous g-q-t FCNC coupling

$$\mathcal{L} = g_s \sum_{q=u,c} \frac{\kappa_{tqg}}{\Lambda} \bar{t}\sigma^{\mu\nu} T^a (f_q^L P_L + f_q^R P_R) q G^a_{\mu\nu} + h.c.$$

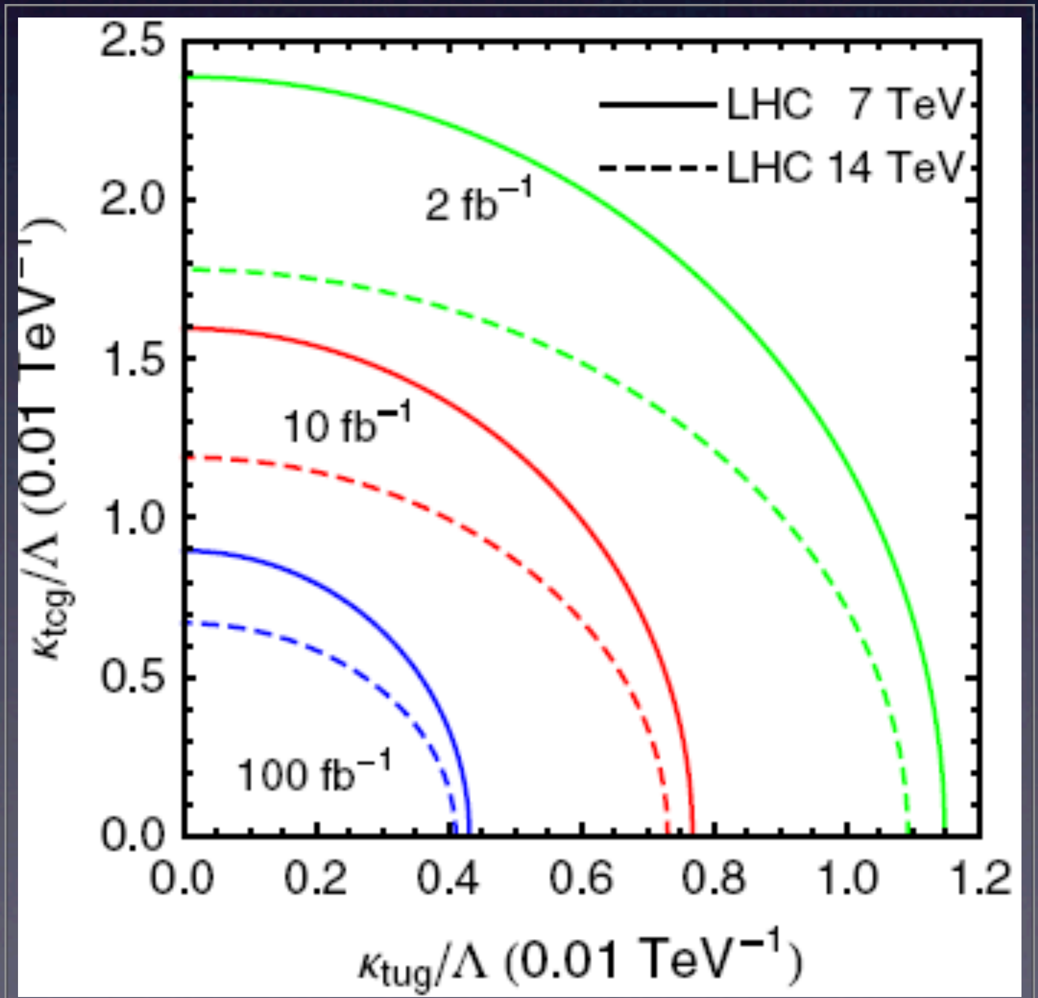
★ NLO QCD corrections to top rare decay (K_F~1.2)

J. J. Zhang, C. S. Li, Gao, Zhang, Li
PRL 102 (2009) 072001



★ NLO QCD corrections (K_F~1.3-1.5) and promising at the LHC

Gao, C. S. Li, Yang, Zhang,
PRL 107 (2011) 092002



Anomalous gtt coupling in LHT

$$\mathcal{L}_{gtt} = -ig_s T^a \bar{t}\Gamma^\mu t$$

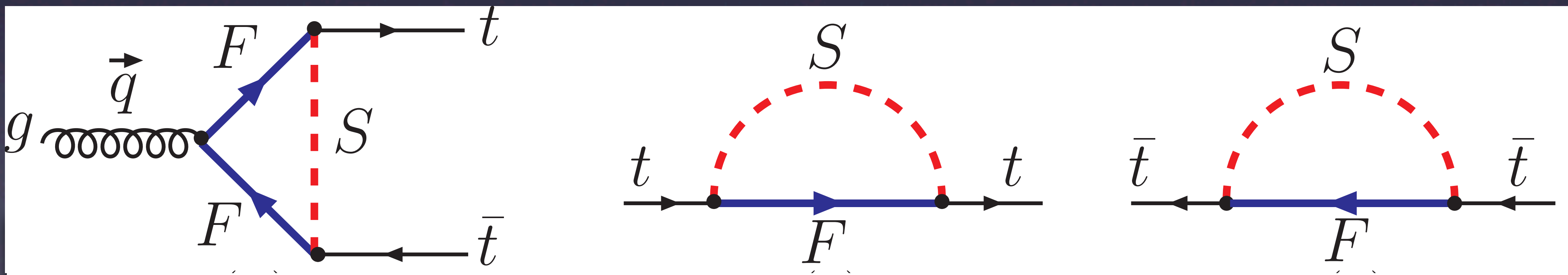
QHC, Chen, Larios, Yuan, PRD79 (2009) 015004

$$\Gamma^\mu = (1+\alpha)\gamma^\mu + i\beta\sigma^{\mu\nu}q_\nu + \xi\left(\gamma^\mu - \frac{2m_t}{\hat{s}}q^\mu\right)\gamma_5$$

- cross section

$$\hat{\sigma} = \frac{8\pi\alpha_s^2}{27\hat{s}^2}\sqrt{1-\frac{4m_t^2}{\hat{s}}}\left\{\hat{s} + 2m_t^2 + 2\Re\left[(\hat{s}+2m_t^2)\alpha + 3m_t\hat{s}\,\beta\right]\right\}$$

- LHT model

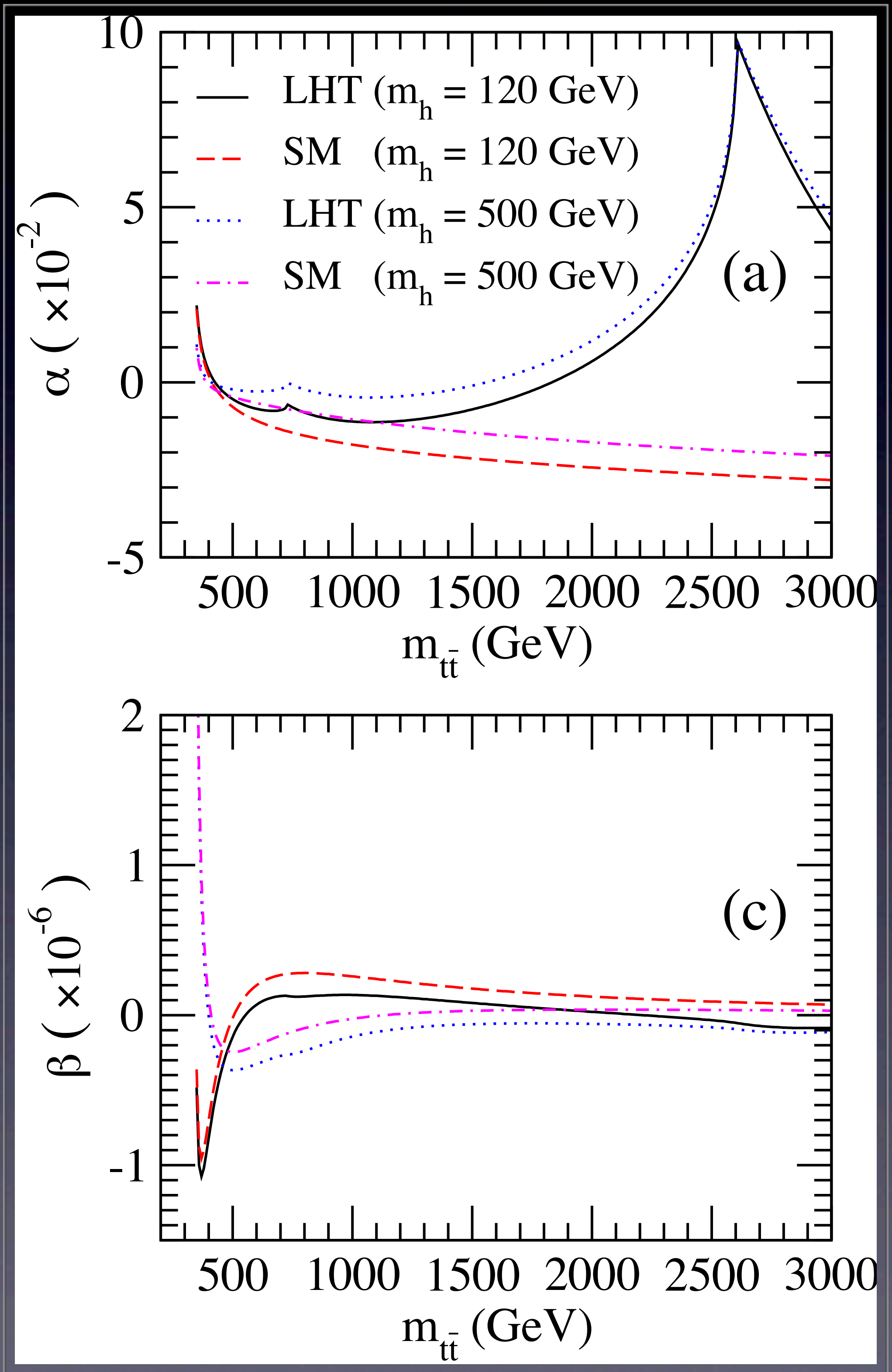


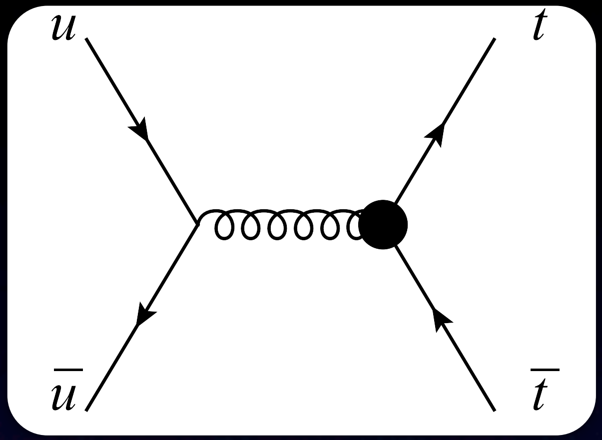
$$m_{T_+} = 1302\,\text{GeV}, \quad m_{T_-} = 364\,\text{GeV},$$

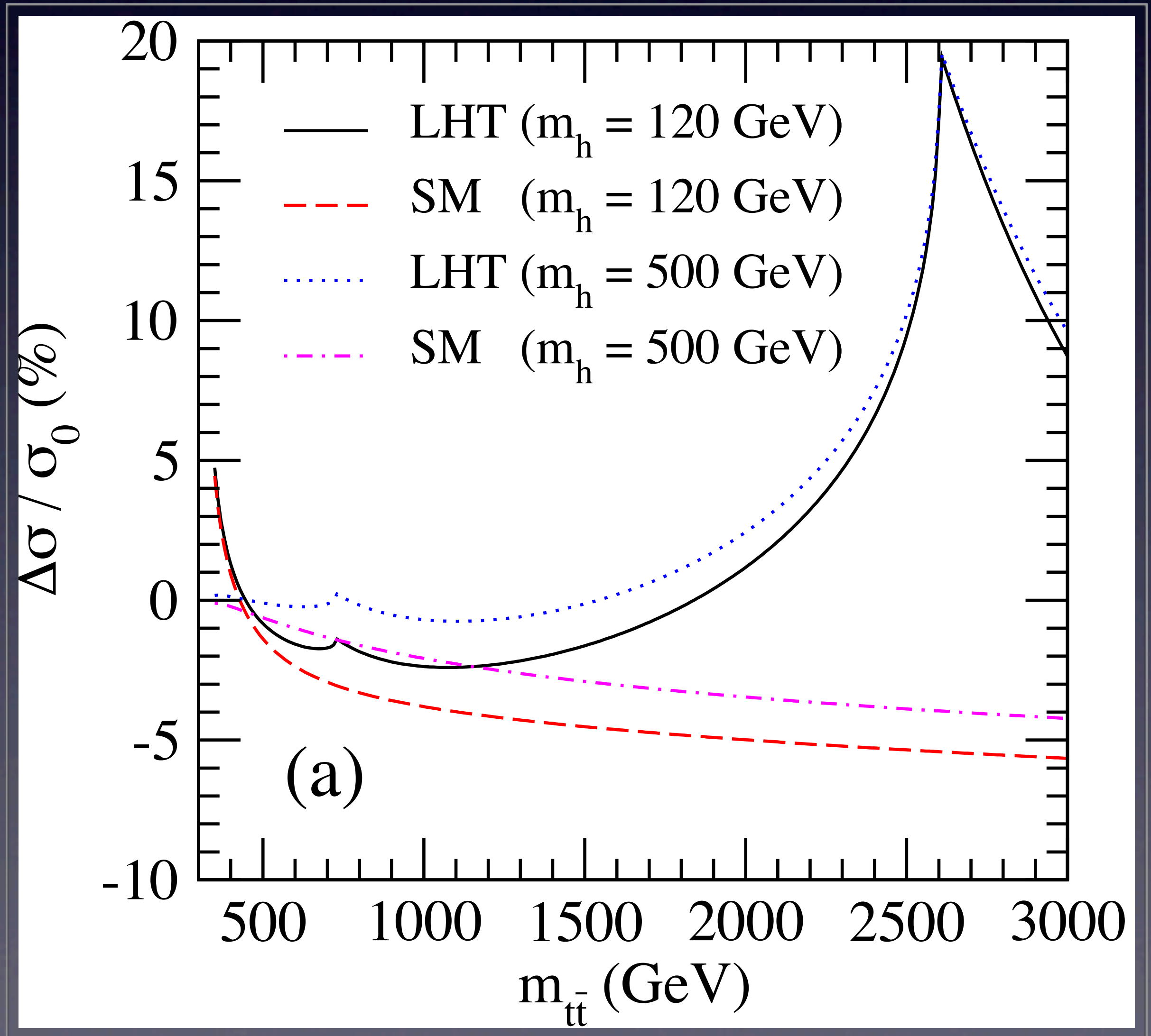
$$m_{t_-} \simeq m_{b_-} = 3536\,\text{GeV}, \quad m_{\omega^{\pm,0}} = 327\,\text{GeV}, \quad m_\eta = 78\,\text{GeV}$$

Anomalous gtt coupling in LHT

- anomalous couplings
- Impact on ttbar production







Summary

As we know,
There are known knowns.
There are things we know we know.
We also know
There are known unknowns.
That is to say
We know there are somethings
We do not know.
But there are also unknown unknowns,
The ones we don't know
We don't know.


Secretary of Defense
Donald H. Rumsfeld

--- Feb 12, 2002, Department of Defense news briefing

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(to be honest, I don't think nature would be so nice)

Stay hungry. Stay foolish.

by Stewart Brand,
The Whole Earth Epilog, 1974

Tree-level induced dim-6 operators

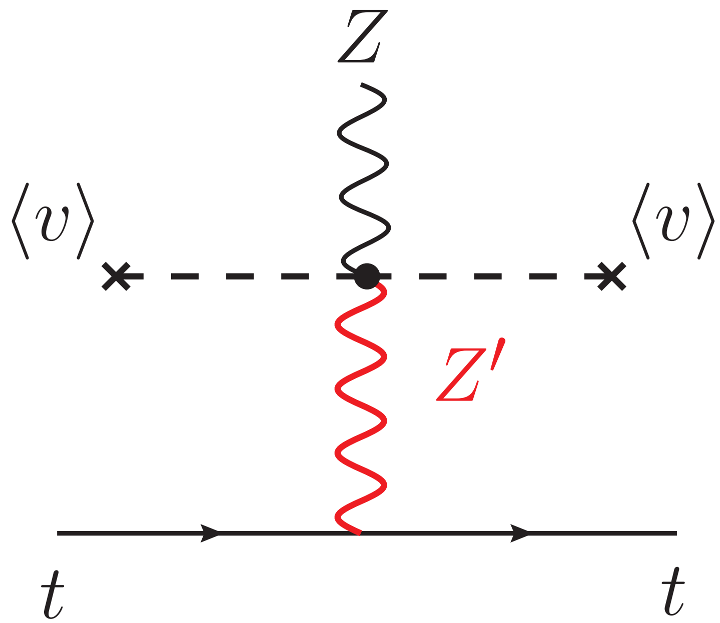
Ed L. Berger, QHC, Ian Low, Phys.Rev.D80:074020(2009)

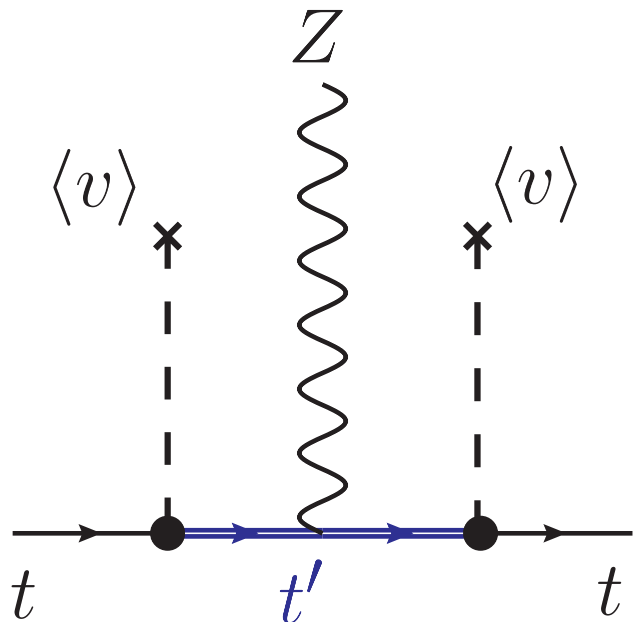
$$\mathcal{O}^{(1)}_{\phi q} = i\left(\phi^\dagger D_\mu \phi\right)\left(\bar{q}\gamma^\mu q\right),$$
$$\mathcal{O}^{(3)}_{\phi q} = i\left(\phi^\dagger \tau^I D_\mu \phi\right)\left(\bar{q}\gamma^\mu \tau^I q\right),$$
$$\mathcal{O}_{\phi t} = i\left(\phi^\dagger D_\mu \phi\right)\left(\bar{t}_R\gamma^\mu t_R\right),$$
$$\mathcal{O}_{\phi b} = i\left(\phi^\dagger D_\mu \phi\right)\left(\bar{b}_R\gamma^\mu b_R\right),$$
$$\mathcal{O}_{\phi \phi} = \left(\phi^\dagger \epsilon D_\mu \phi\right)\left(\bar{t}_R\gamma^\mu b_R\right),$$

$$q = \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$t_R \quad b_R$

ϕ : Higgs doublet





Effective Wtb, Ztt and Zbb couplings

$$\mathcal{O}_{Wtb} = \frac{c^{(3)}_{\phi q} v^2}{\Lambda^2} \frac{g_2}{\sqrt{2}} W^+_\mu \bar{t}_L \gamma^\mu b_L - \frac{c_{\phi\phi} v^2}{2\Lambda^2} \frac{g_2}{\sqrt{2}} W^+_\mu \bar{t}_R \gamma^\mu b_R + h.c.$$

$$\mathcal{O}_{Zt\bar{t}} = \frac{\left(c^{(3)}_{\phi q} - c^{(1)}_{\phi q}\right) v^2}{\Lambda^2} \frac{\sqrt{g_1^2 + g_2^2}}{2} Z_\mu \bar{t}_L \gamma^\mu t_L - \frac{c_{\phi t} v^2}{\Lambda^2} \frac{\sqrt{g_1^2 + g_2^2}}{2} Z_\mu \bar{t}_R \gamma^\mu t_R$$

$$\mathcal{O}_{Zb\bar{b}} = -\frac{\left(c^{(1)}_{\phi q} + c^{(3)}_{\phi q}\right) v^2}{\Lambda^2} \frac{\sqrt{g_1^2 + g_2^2}}{2} Z_\mu \bar{b}_L \gamma^\mu b_L - \frac{c_{\phi b} v^2}{\Lambda^2} \frac{\sqrt{g_1^2 + g_2^2}}{2} Z_\mu \bar{b}_R \gamma^\mu b_R$$

Effective Wtb, Ztt and Zbb couplings

$b \to s\gamma$

$-0.0007 < \frac{c_{\phi\phi} v^2}{2\Lambda^2} < 0.0025$

B. Grzadkowski and M. Misiak, Phys. rev. D78, 077501 (2008)

$$\mathcal{O}_{Wtb} = \frac{c_{\phi q}^{(3)} v^2}{\Lambda^2} \frac{g_2}{\sqrt{2}} W_\mu^+ \bar{t}_L \gamma^\mu b_L - \frac{c_{\phi\phi} v^2}{2\Lambda^2} \frac{g_2}{\sqrt{2}} W_\mu^+ \bar{t}_R \gamma^\mu b_R + h.c.$$

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R_b and $A^{(b)}_{FB}$

$\frac{\delta g_{Zb_L b_L}}{g^{\rm SM}_{Zb_L b_L}} \leq 0.25\%$

$\rightarrow$ $c^{(3)}_{\phi q} + c^{(1)}_{\phi q} \simeq 0$

J. Alcaraz et al, arXiv:hep-ex/0511027

Effective Wtb, Zt$\bar{t}$ and Zb$\bar{b}$ couplings

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R_b and $A_{FB}^{(b)}$

$$\frac{\delta g_{Zb_L b_L}}{g^{\rm SM}_{Zb_L b_L}} \leq 0.25\%$$

$\Rightarrow$

$$c_{\phi q}^{(3)} + c_{\phi q}^{(1)} \simeq 0$$

J. Alcaraz et al, arXiv:hep-ex/0511027

Effective Wtb, Ztt and Zbb couplings

- New parameterization of couplings

$$\mathcal{O}_{Wtb} = \frac{g}{\sqrt{2}} \mathcal{F}_L W^+_\mu \bar{t}_L \gamma^\mu b_L + h.c. \ ,$$

$$\mathcal{O}_{Zt\bar{t}} = \frac{g}{2c_w} Z_\mu \left(2\mathcal{F}_L \bar{t}_L \gamma^\mu t_L + \mathcal{F}_R \bar{t}_R \gamma^\mu t_R\right)$$

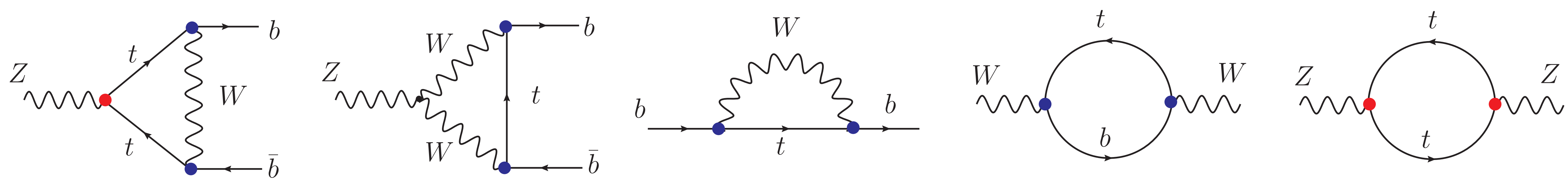
- The coefficients of the left-handed neutral and charged currents are related,

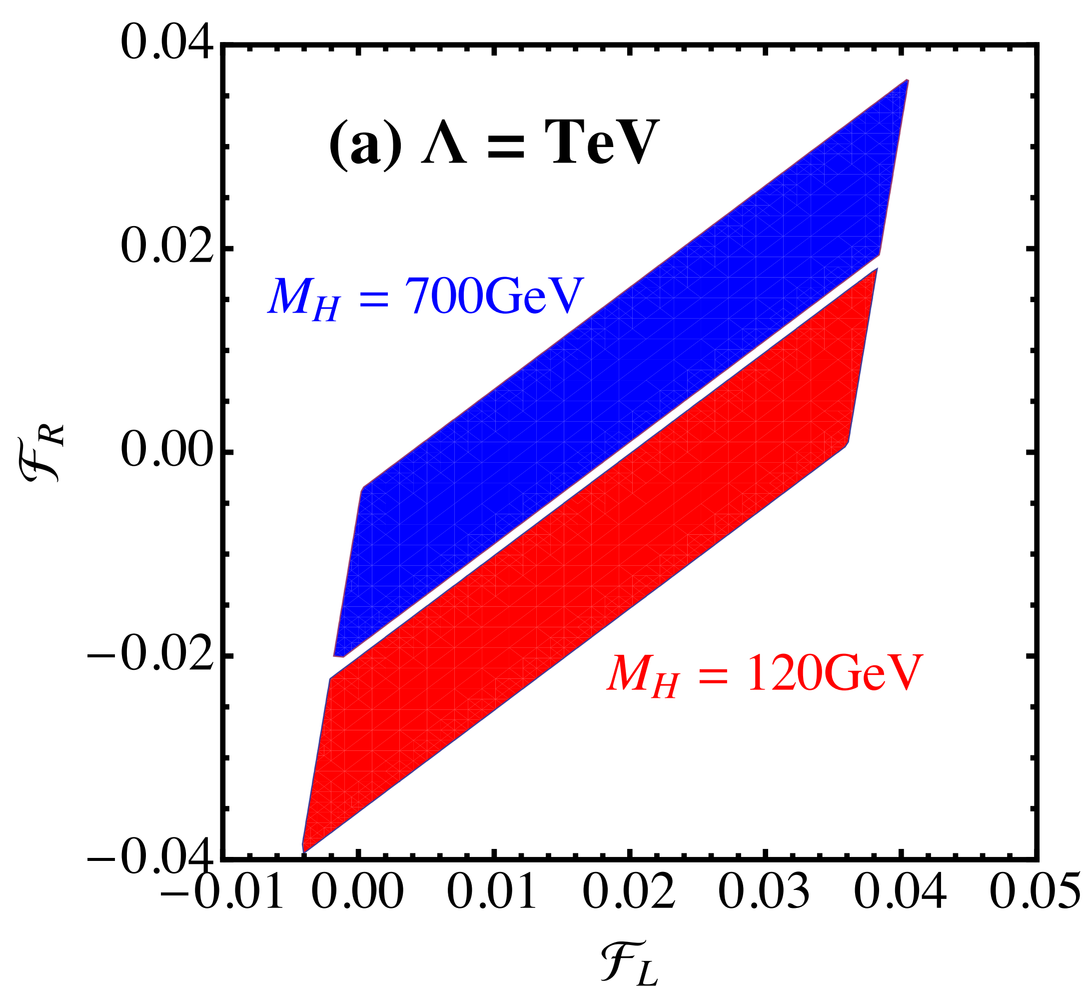
$$g^L_{Zt\bar{t}} = 2 g^L_{Wtb} = 2\mathcal{F}_L$$

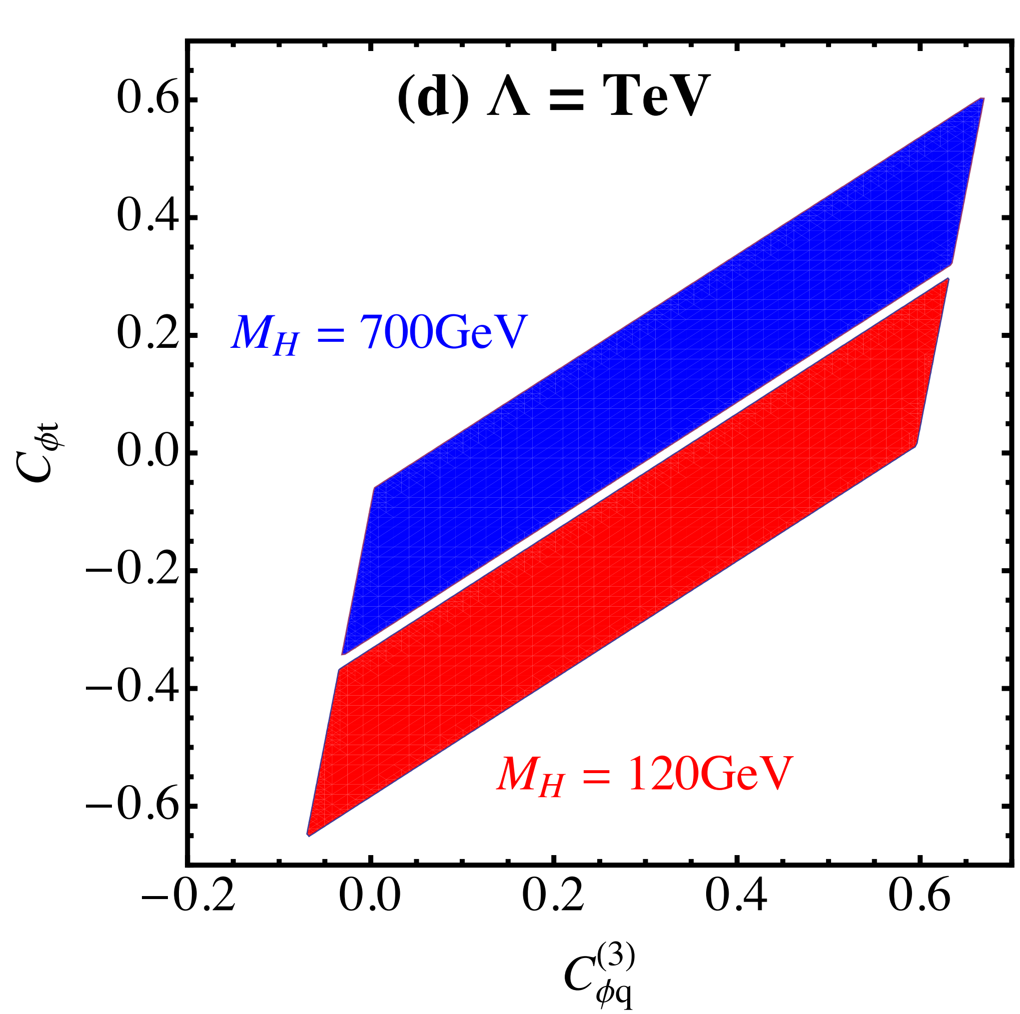
which is predicted by the EW gauge symmetry after the stringent constraint on $Zb_L b_L$ imposed.

Electroweak constraints

- Indirect constraint from LEP II Zbb precision measurements

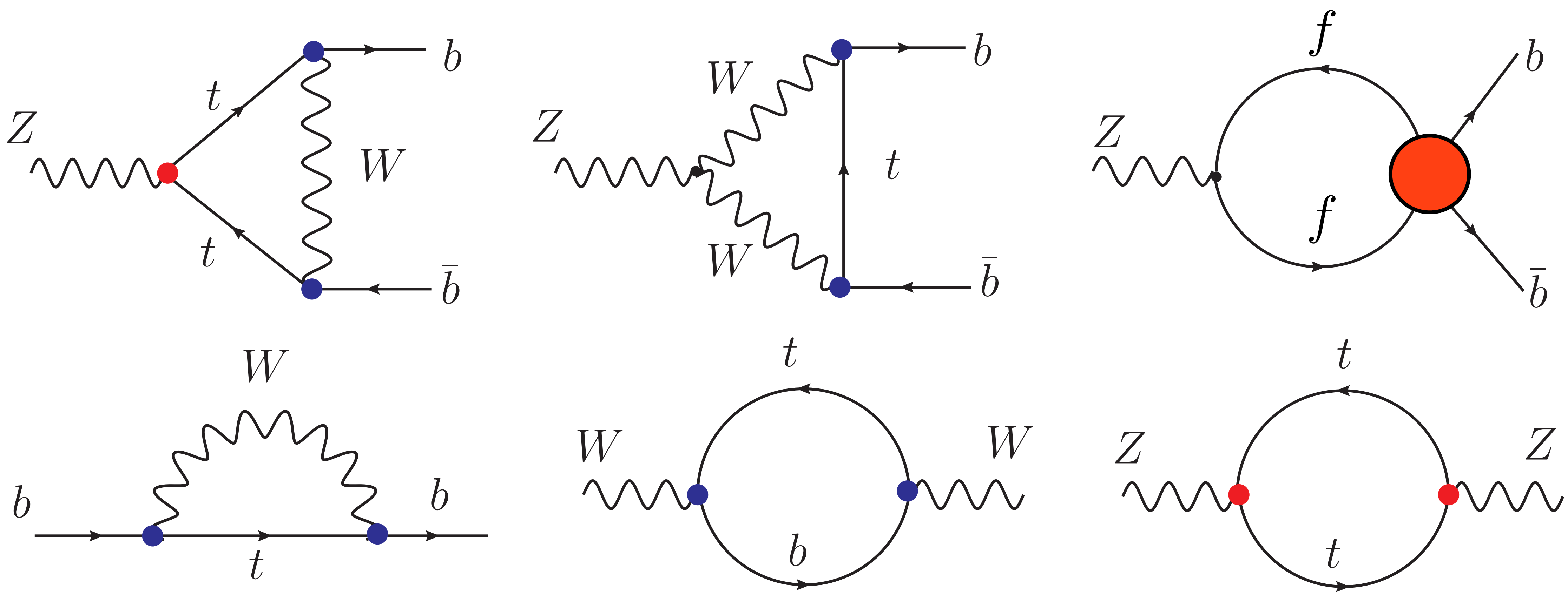






Electroweak constraints

- Including four-fermion operator might relax the tight constraint.



How to probe such an correlation?

$$\mathcal{O}_{Wtb} = \frac{g}{\sqrt{2}}\mathcal{F}_L W^+_\mu \bar{t}_L\gamma^\mu b_L + h.c. \ ,$$

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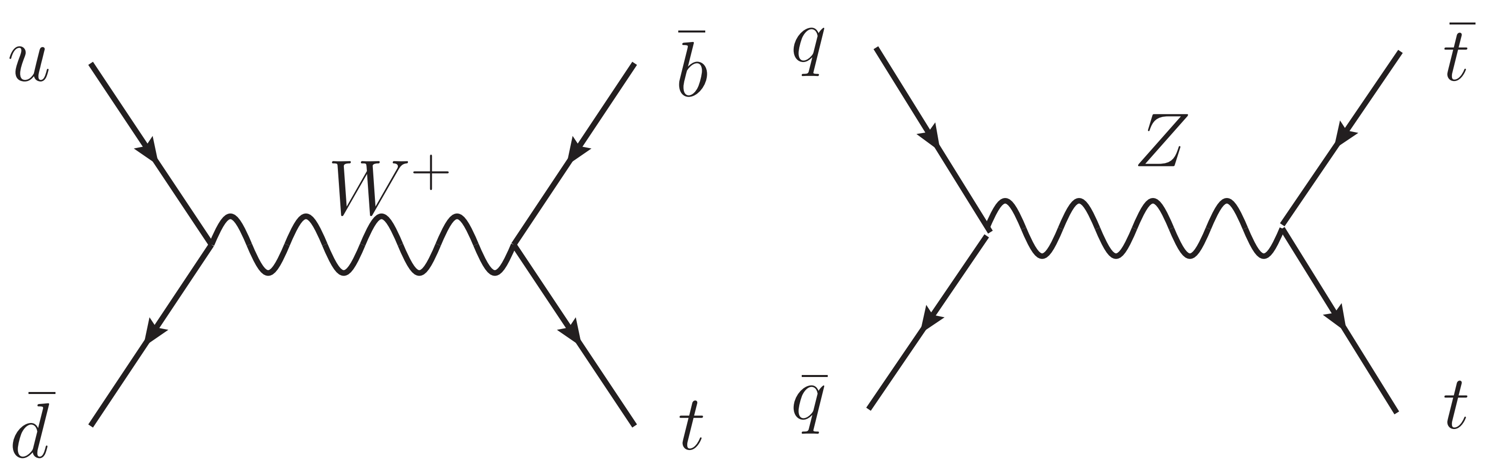
- At the Large Hadron Collider



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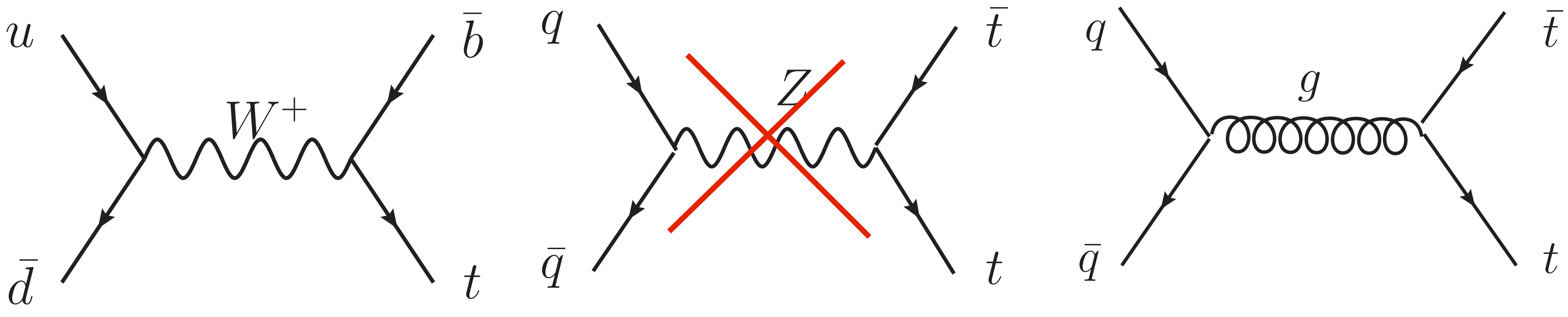

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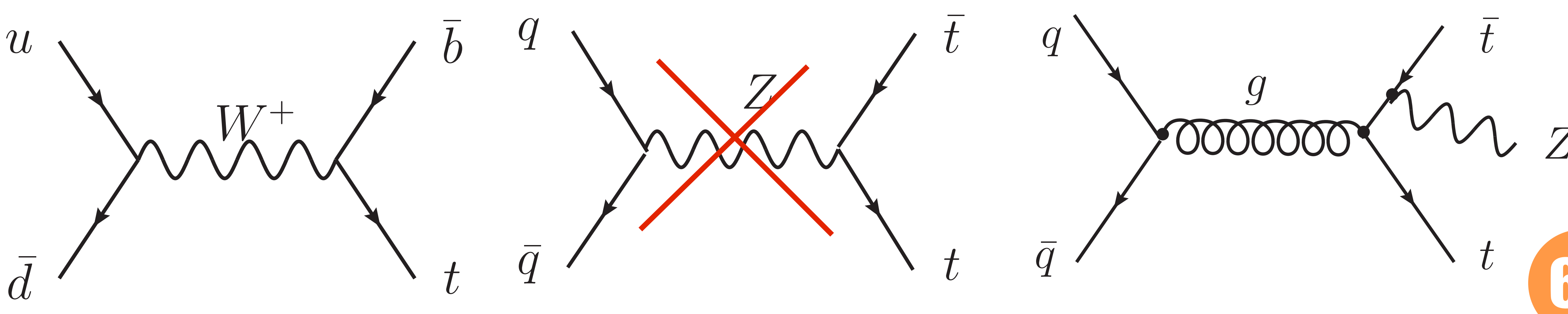
U. Baur, A. Juste, L.H. Orr, D. Rainwater
Phys.Rev.D71:054013,2005;
Phys. Rev.D73:034016,2006



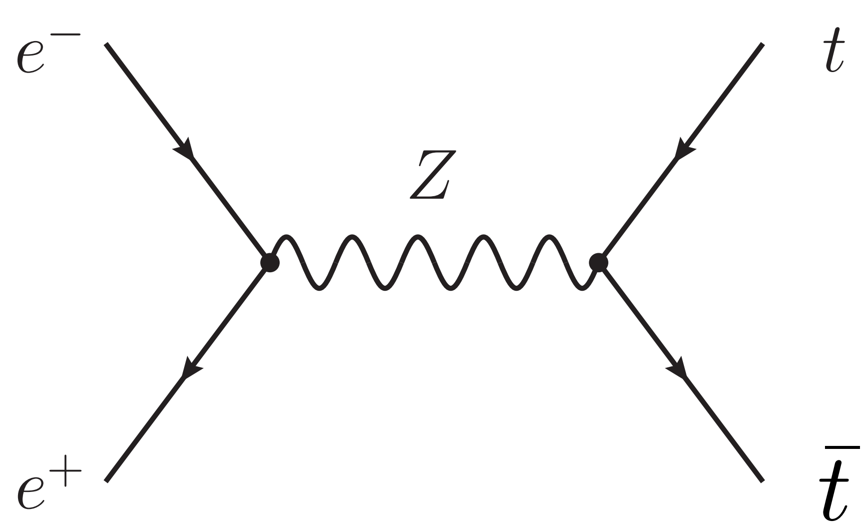
How to probe such an correlation?

$$\mathcal{O}_{Wtb} = \frac{g}{\sqrt{2}} \mathcal{F}_L W^+_\mu \bar{t}_L \gamma^\mu b_L + h.c. \; ,$$

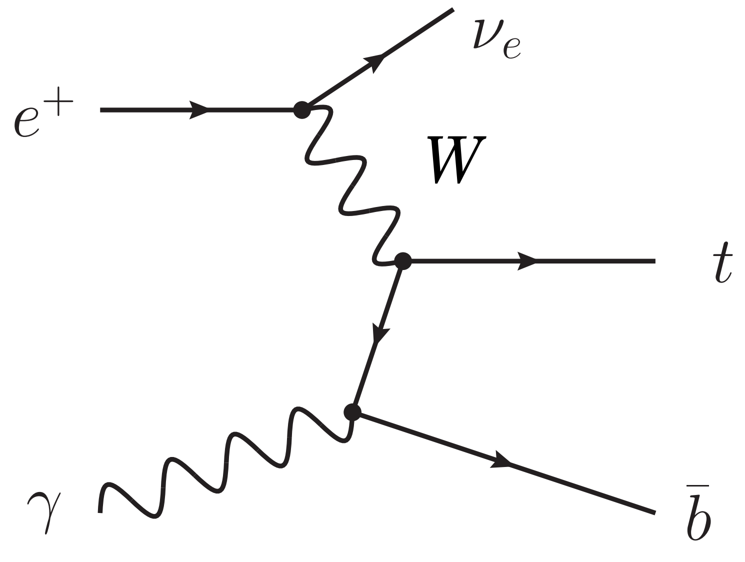
$$\mathcal{O}_{Zt\bar{t}} = \frac{g}{2c_w} Z_\mu \left(2\mathcal{F}_L \bar{t}_L \gamma^\mu t_L + \mathcal{F}_R \bar{t}_R \gamma^\mu t_R\right)$$

At the Linear Collider

P. Batra, T. Tait,
Phys.Rev.D74:054021,2006



QHC, J. Wudka,
Phys.Rev.D74:094015,2006



Impact of anomalous couplings on $\sigma(t)$ and $\sigma(zt\bar{t})$

- **Inclusive cross sections of single-t and Ztt productions:**

$$\sigma_t = \sigma_t^0 \left[1 + 2\mathcal{F}_L + 2\delta V_{tb} + \mathcal{O}\left(\mathcal{F}_L^2, \delta V_{tb}^2\right)\right],$$

$$\sigma_{Zt\bar{t}} = \sigma_{Zt\bar{t}}^0 \left[1 + 4.4\mathcal{F}_L - 1.5\mathcal{F}_R + \mathcal{O}\left(\mathcal{F}_L^2,\ \mathcal{F}_R^2,\ \mathcal{F}_L\mathcal{F}_R\right)\right]$$

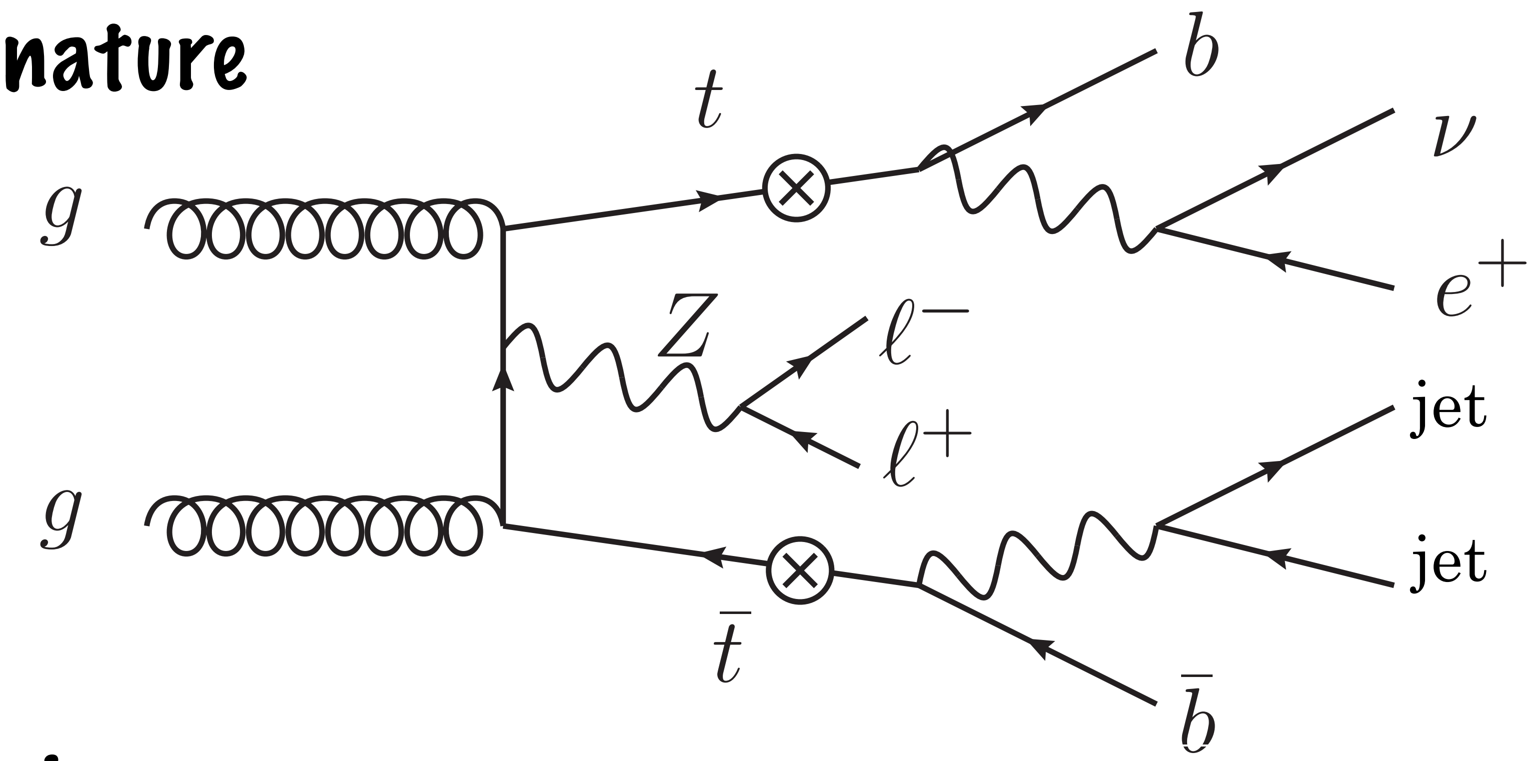
$$\delta\sigma = (\sigma - \sigma^0)/\sigma^0 \qquad \delta V_{tb} = |V_{tb}|^{(\exp)} - |V_{tb}|^{(\mathrm{SM})}$$

$$\boxed{\delta V_{tb} = -0.23\delta\sigma_{Zt\bar{t}} + 0.5\delta\sigma_t - 0.34\mathcal{F}_R}$$

Note: Vtb cannot be extracted out from single top production alone.

LHC phenomenology study

- Collider signature



- Backgrounds

$$PP \to Zt\bar{b} + jj$$

$$PP \to Z\bar{t}b + jj$$

$$PP \to WZb\bar{b}jj$$

LHC phenomenology study

- **Basic kinematics cuts:**

$$p_T^\ell > 15\,\text{GeV}, \quad |\eta_\ell| < 2.5, \quad p_T^b > 20\,\text{GeV}, \quad |\eta_b| < 2.5,$$

$$p_T^j > 15\,\text{GeV}, \quad |\eta_j| < 2.5, \quad \not{E}_T > 20\,\text{GeV},$$

$$\Delta R(j,\, j) > 0.4, \quad \Delta R(j,\, \ell) > 0.4, \quad \Delta R(j,\, b) > 0.4, \quad \Delta R(b,\, b) > 0.4.$$

- **b-tagging:**

$$\epsilon_b = 0.57 \times \tanh\left(\frac{p_T^b}{35\,\text{GeV}}\right)$$

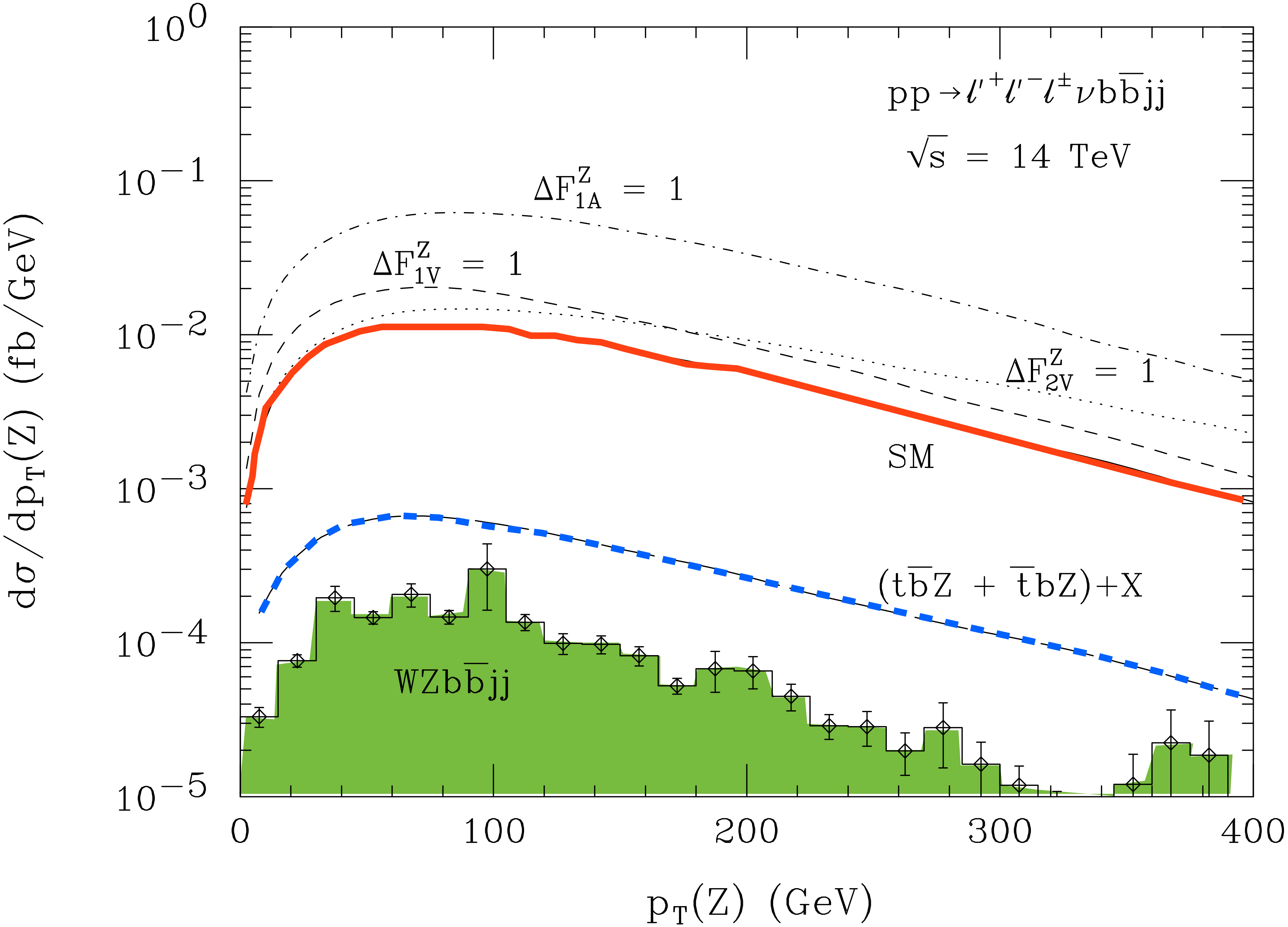
- **Detector smearing effects:**

$$\frac{\Delta E}{E} = \frac{50\%}{\sqrt{E/\text{GeV}}}$$

- **Z-boson mass window cuts:**

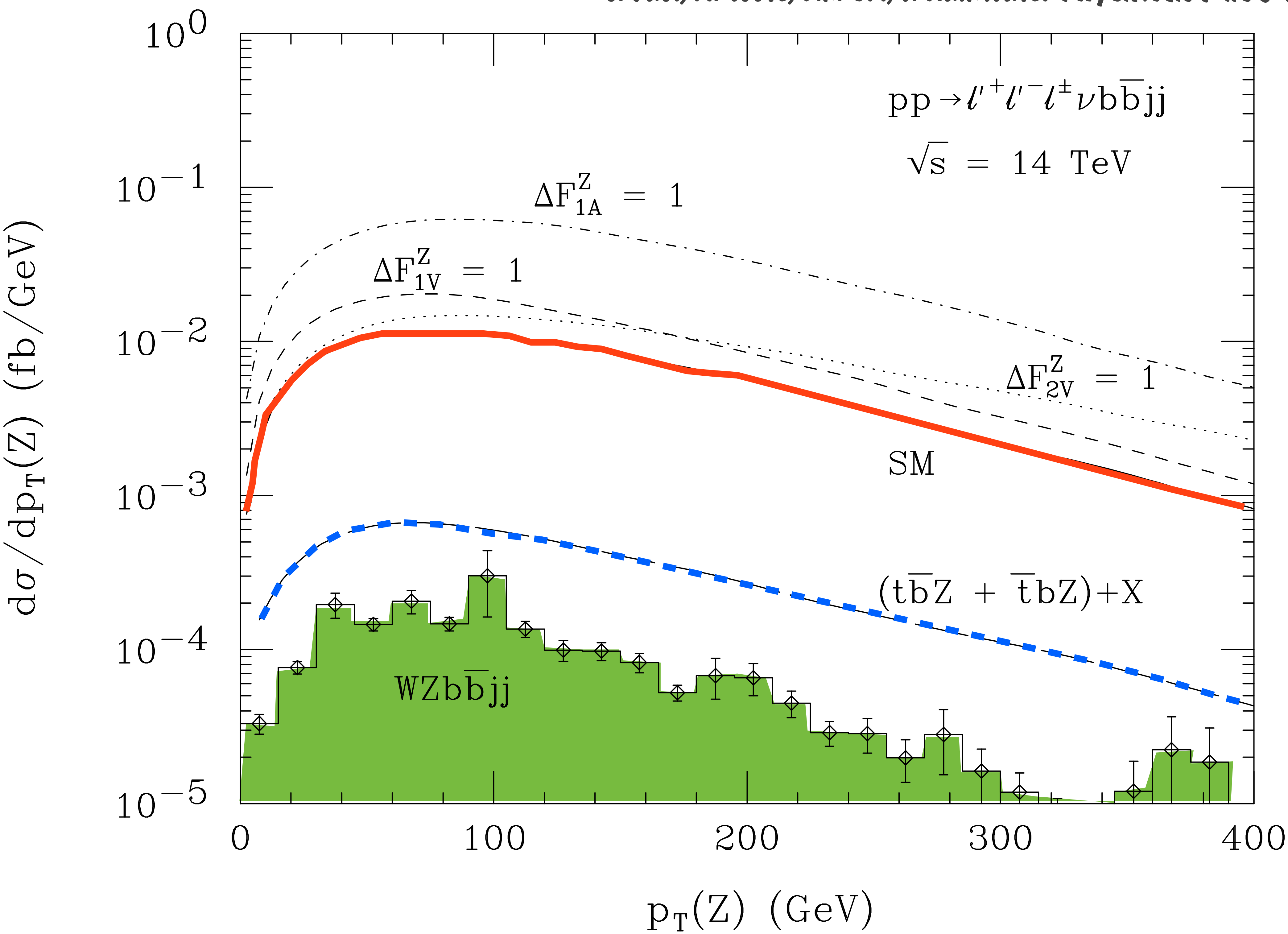
$$|m_{\ell'^+\ell'^-} - m_Z| < 10\,\text{GeV}$$

Cross section of Signal and Background

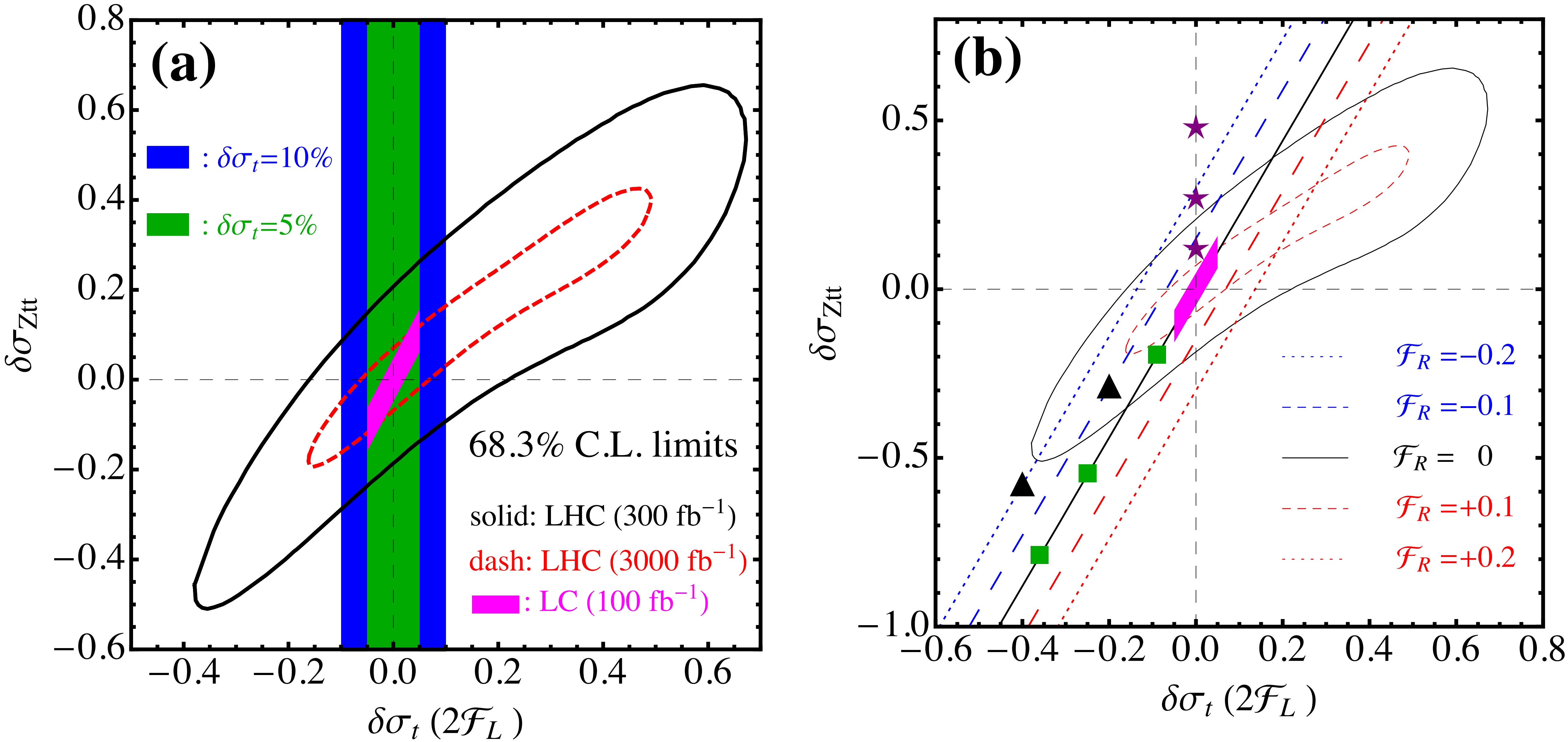


Cross section of Signal and Background

U. Baur, A. Juste, L.H. Orr, D. Rainwater Phys.Rev.D71:054013,2005



Measuring anomalous couplings at LHC



■ : left-handed t-prime

★ : right-handed t-prime

▲ : chiral 4th generation