Precision top physics at 100 TeV

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Motivation

We have not seen any new physics (the Higgs can be considered as *old physics*) so it must be heavy or elusive, if it is out there.

Apart from bump searches, historically it has been useful to look for deviations from the SM predictions.

Lately, precision physics has not given us many happy news, since most anomalies fade with time. But we should not give up.

Even at *discovery machines*, precision physics ~~can~~ must be done to search for heavy or elusive objects.

If new particles are heavy, their effects can be parameterised by a dim-6 effective Lagrangian

$$\mathcal{L} = \sum_x \frac{C_x}{\Lambda^2} O_x + \ldots$$

exception: light, elusive new physics

Which precision top physics at FHC?

Many, for example:

- the obvious: top chromo* moments
- the brute force: top FCNC, etc.
- the challenge: weak dipole moments

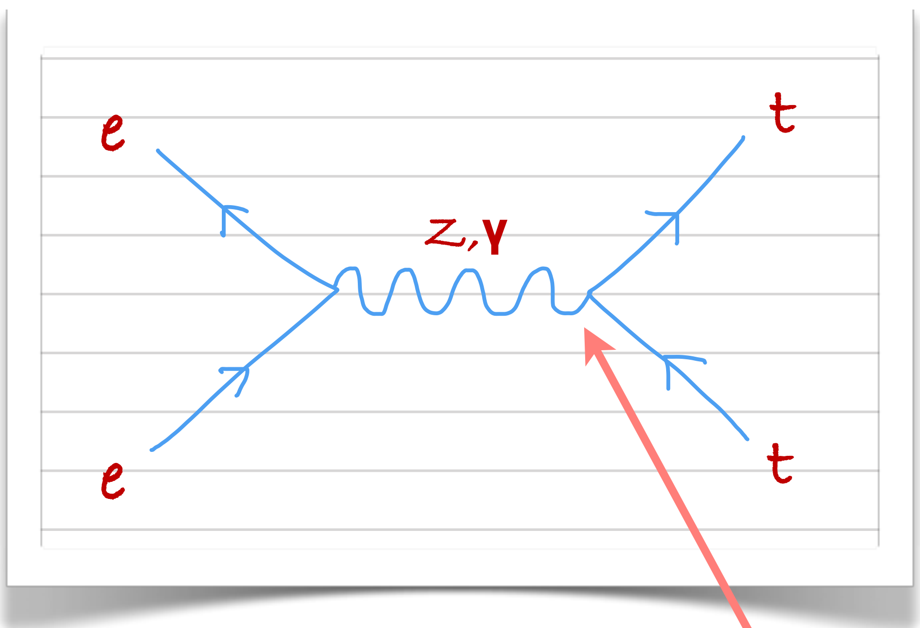
Flavour-diagonal BSM contributions are expected to be dominant because flavour is well described by the SM at low energies.

On the other hand, flavour-changing ones are easier to spot since they are suppressed in the SM.

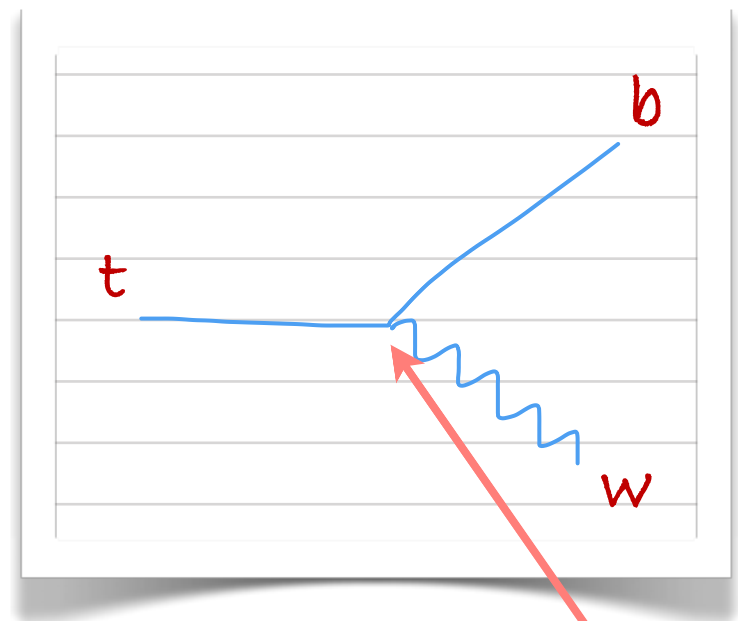
We illustrate the potential (and challenges) of FHC versus other colliders with an explicit example: top dipole moments.

Weak moments: the contenders

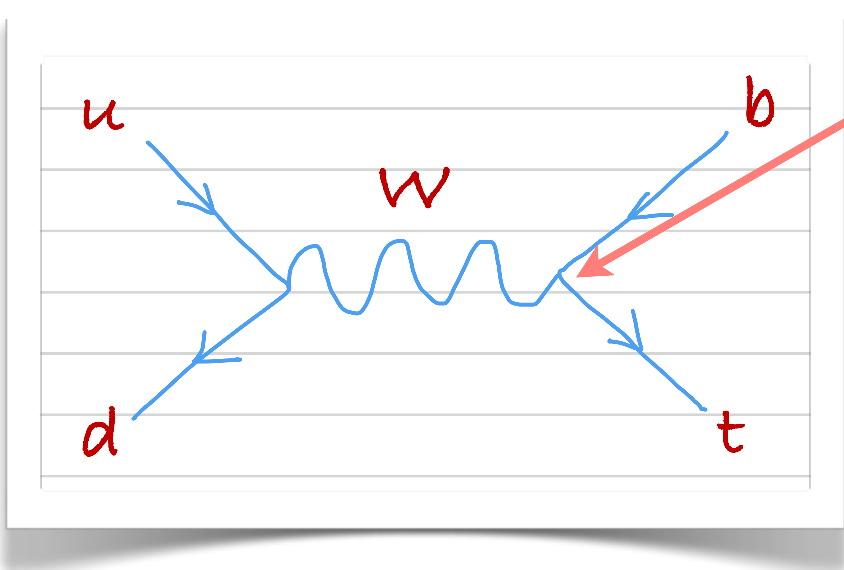
the old favorite: $t\bar{t}$ at ILC



the newcomer: $t\bar{t}$ at TLEP

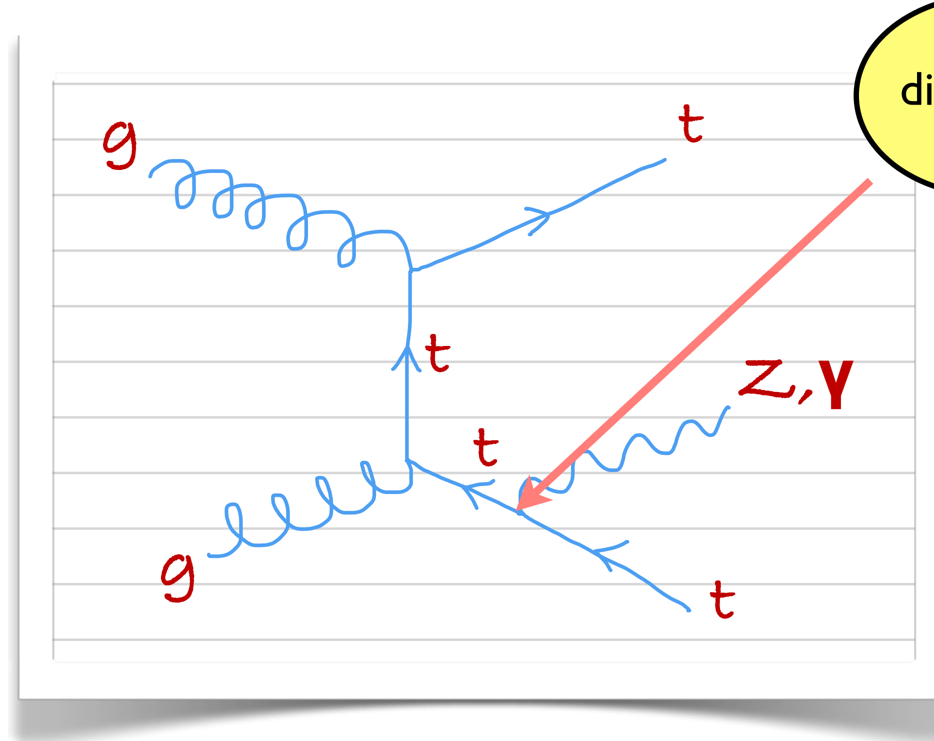


the underdog: $t\bar{b}$ at FHC



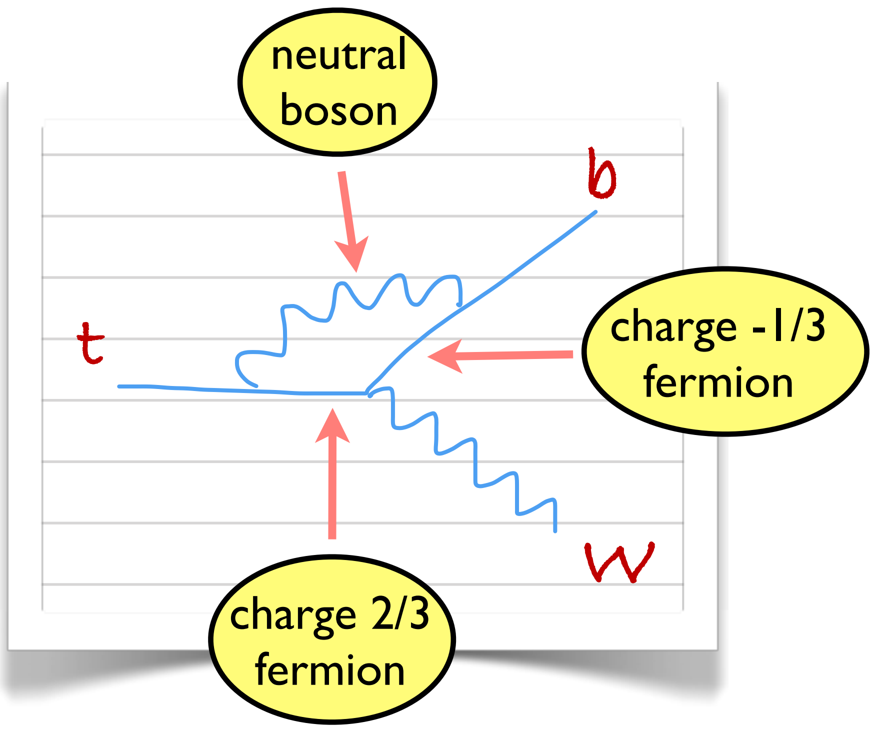
top dipole int here

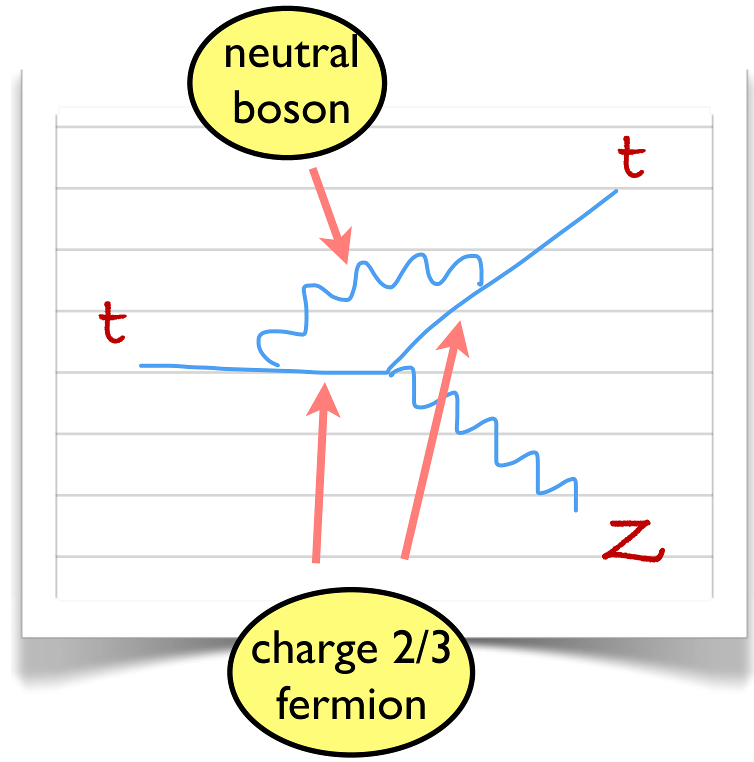
the other: $t\bar{t}Z/\gamma$ at FHC

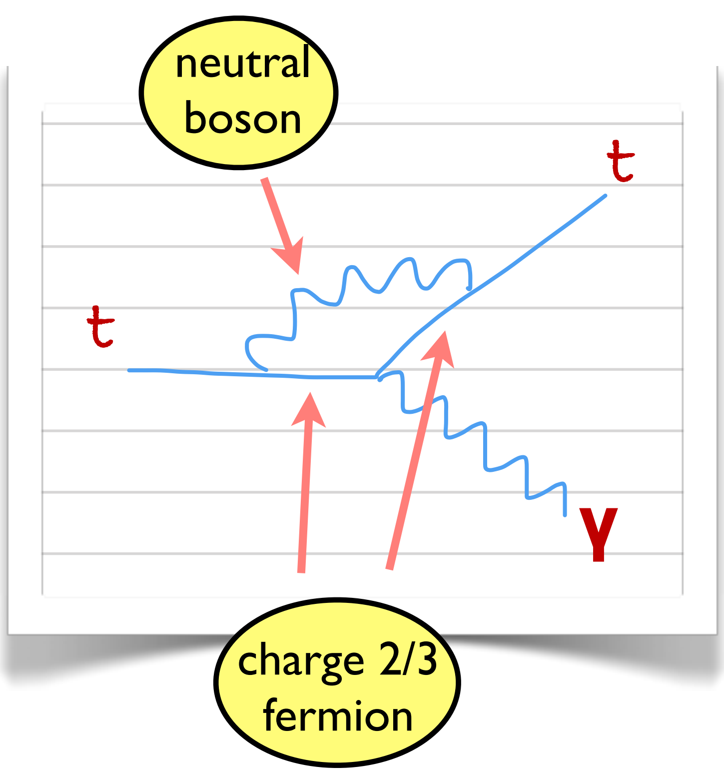


top dipole int here

In any BSM model you expect relations between the effective interactions generated *unless you tune parameters in order not to have it*







Focus on a specific operator giving top electroweak dipole moments

Effective field theory brings this argument into an explicit relation.

Wtb

$$-\frac{g}{\sqrt{2}}\bar{b}_L \frac{i\sigma^{\mu\nu}q_\nu}{M_W} g_R\, t_R\, W^-_\mu$$

$$g_R = \sqrt{2}\, C^{33}_{uW} \frac{v^2}{\Lambda^2}$$

Ztt

$$-\frac{g}{2c_W}\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{M_Z} d^Z_V\, t\, Z_\mu$$

$$d^Z_V = \sqrt{2}c_W\, \mathrm{Re}\, C^{33}_{uW} \frac{v^2}{\Lambda^2} + \text{other}$$

γtt

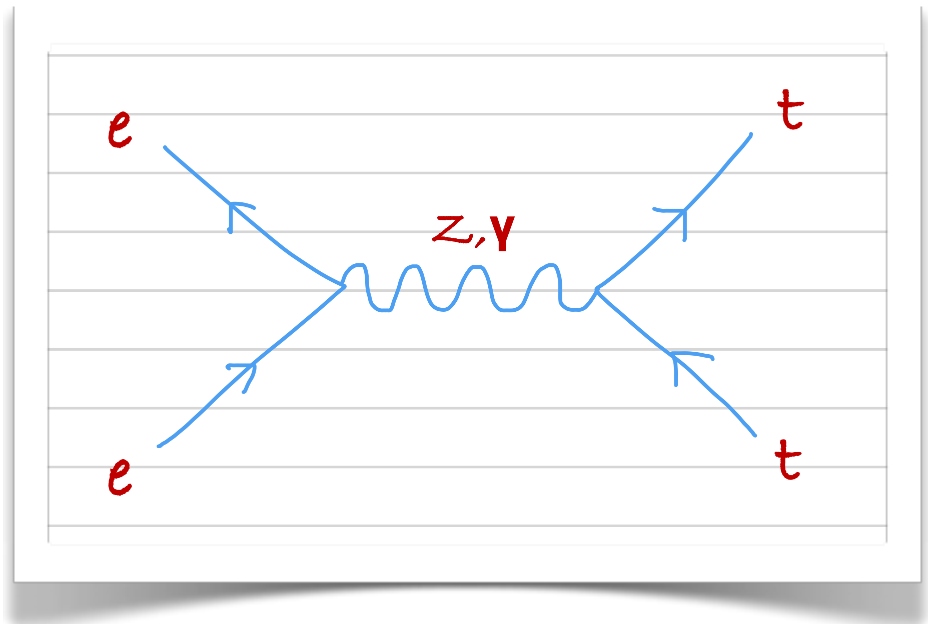
$$d^\gamma_V = \frac{\sqrt{2}}{e}s_W\, \mathrm{Re}\, C^{33}_{uW} \frac{v m_t}{\Lambda^2} + \text{other}$$

$$-e\bar{t}\,\frac{i\sigma^{\mu\nu}q_\nu}{m_t} d^\gamma_V\, t\, A_\mu$$

In this framework, results from differents processes can be compared and even combined, e.g. single top, $t\bar{t}$ and $t\bar{t}Z/\gamma$

1. ILC

Studies for precision physics (top in particular) span two centuries

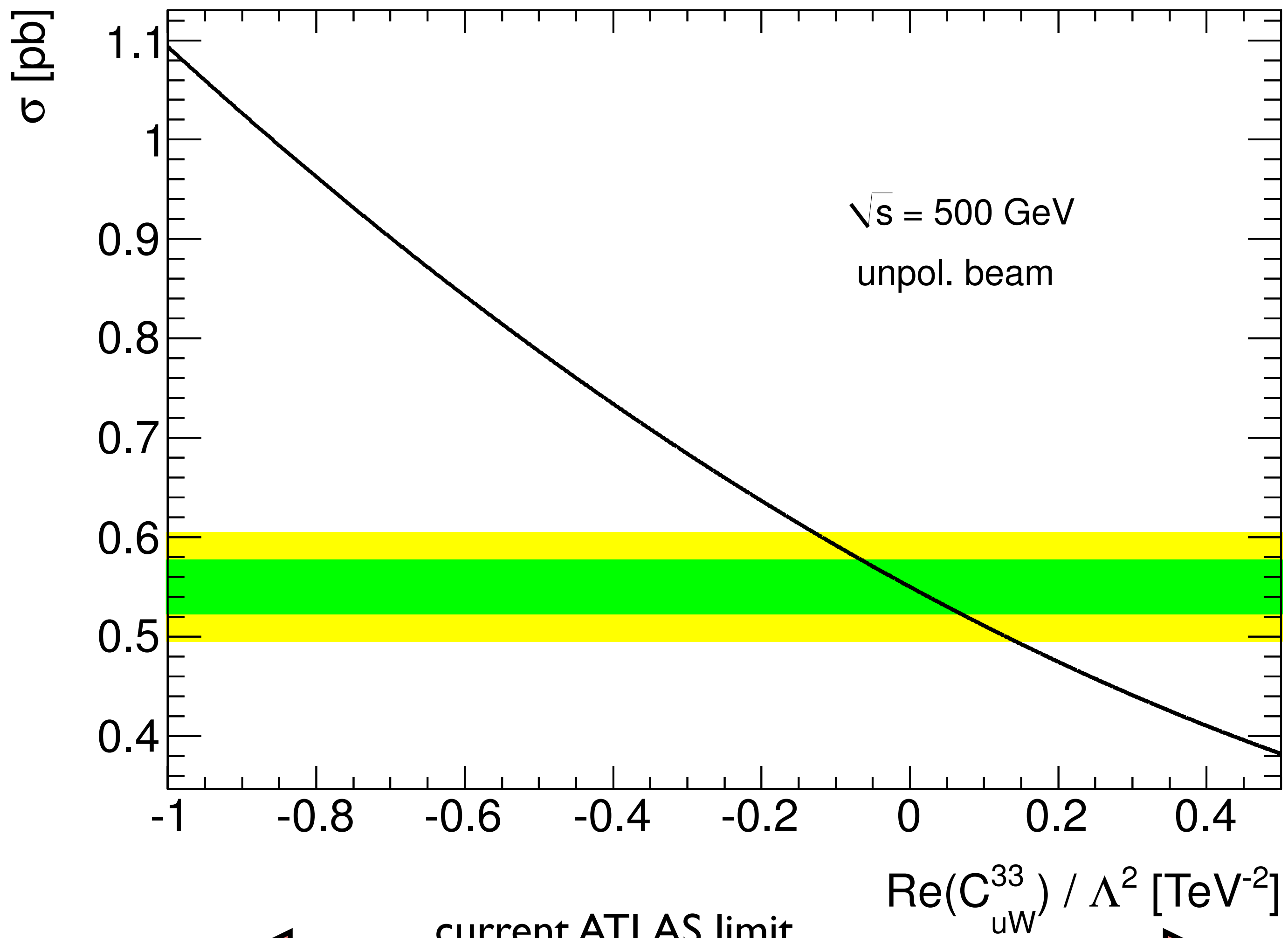


Top anomalous interactions can be probed in production & decay

- production: *Ztt*, γ*tt*, four-fermion
- decay: *Wtb*

Some of them are related by gauge invariance, as seen

Limit from cross section



JAAS et al.1206.1033

5% uncertainty

current ATLAS limit

L = 500 fb^{-1}
Br = 0.3, eff = 0.55

45K events

$$\frac{\Delta\sigma}{\sigma} = 0.0047$$

sys dominated: 5%?

$$\mathrm{Re}\, C^{33}_{uW}/\Lambda^2 \in [-0.128, 0.140]\ \mathrm{TeV}^{-2}$$

95% CL

$$\Lambda > 2.7\sqrt{\mathrm{Re}\, C}\ \mathrm{TeV}$$

… but why is the precision so good with so few tops?

The coupling has a momentum factor: $\bar{t} i \sigma^{\mu\nu} q_\nu t Z_\mu$

In top decays $q^2 = M_W^2$

At ILC $q^2 = s = 500^2\ \text{GeV}^2$

The ILC is not a top factory but has great sensitivity to weak dipole interactions [much less to CP-violating ones]

Compare O(0.1) sensitivity with projected LHC limits:

$$\mathrm{Re}\, C_{uW}^{33}/\Lambda^2 \in [-0.30, 0.30]\ \mathrm{TeV}^{-2}$$

II. TLEP

A precision top factory!!!

asymmetries used by ATLAS to investigate *Wtb*

1M tops
Br = 0.3, eff = 0.55 ⇒ 165K events ⇒ $\Delta A_{+} = 0.002$, $\Delta A_{-} = 0.0013$

now assuming sys-free

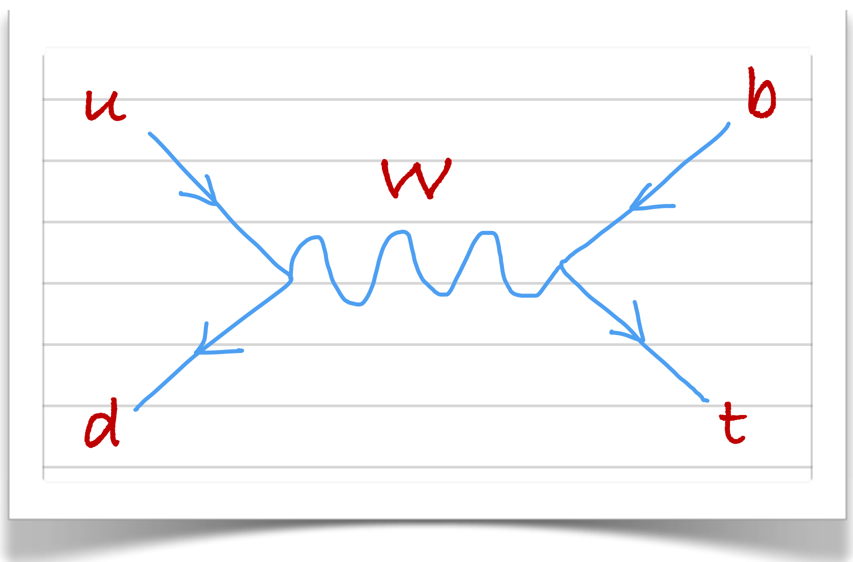
$$\mathrm{Re}\, C_{uW}^{33}/\Lambda^2 \in [-0.083, 0.083]\ \mathrm{TeV}^{-2}$$ 95% CL

$$\Lambda > 3.5\sqrt{\mathrm{Re}\, C}\ \mathrm{TeV}$$

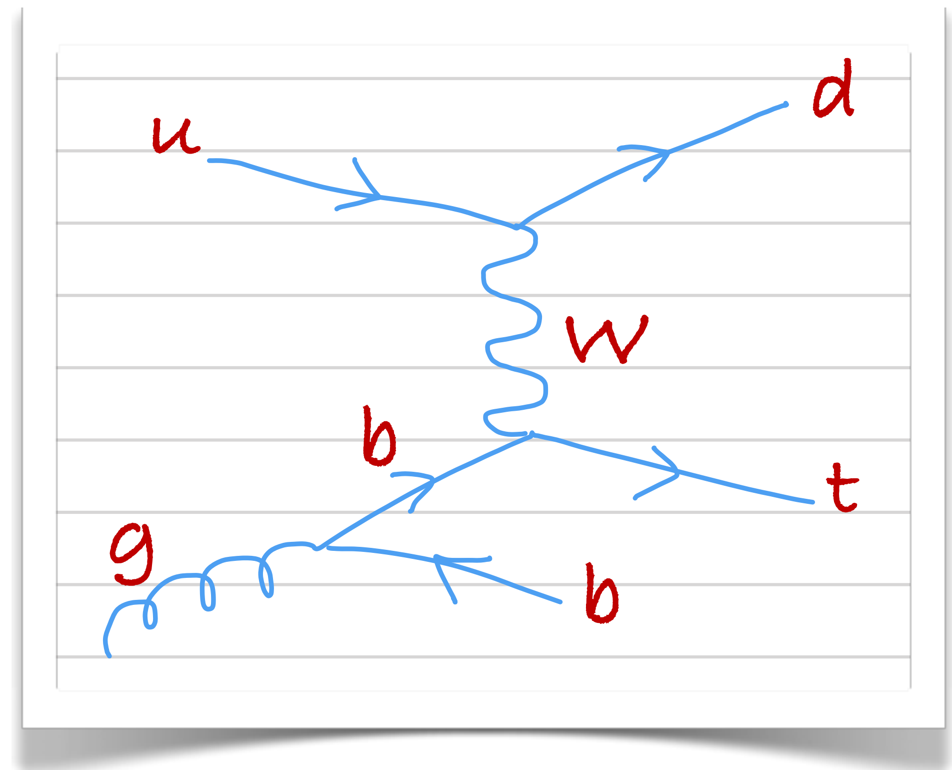
Precise measurements with many tops will likely be unbeatable for renormalisable γ^{μ} interactions

III. FHC

If you want high q^2, this is your collider!



but also



- high q^2 means a top and a bottom with high invariant mass, possibly there will be extra jets
- one has to set some additional cuts to suppress t-channel

Why suppress t-channel? Isn't it a signal?

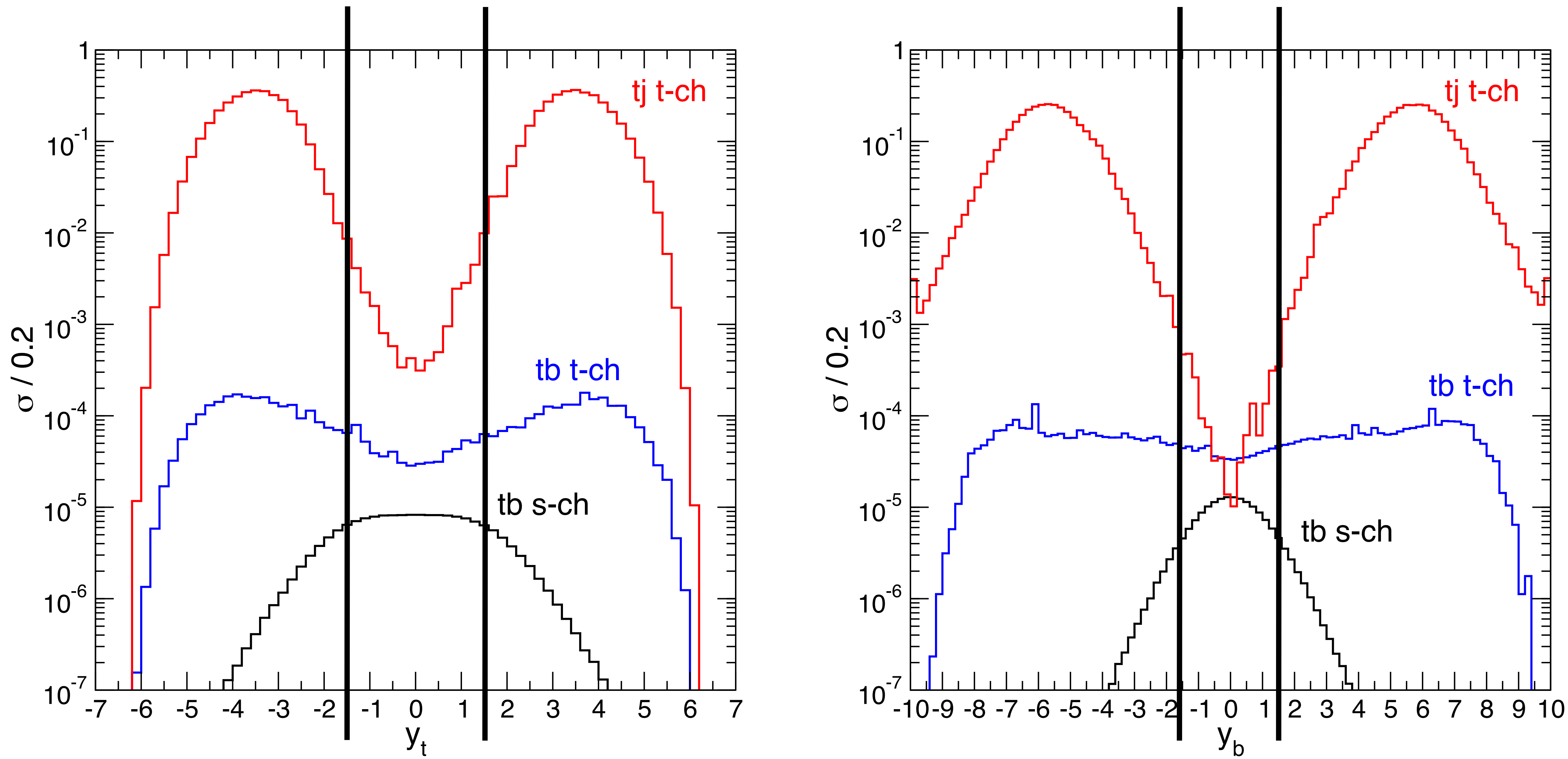
The dependence of cross section on the SM coupling and anomalous couplings is

$$\sigma = \sigma_{\rm SM}|V_{tb}|^2 + \sigma_{\rm int}\,{\rm Re}\,V_{tb}^* g_R + \sigma_{\rm quad}\,|g_R|^2$$

and at high q^2 the sensitivity to anomalous couplings is given by $\sigma_{\rm quad} / \sigma_{\rm SM}$ which is much larger for *s*-channel

⇒ exploit that *s*-channel is more central to enhance the total $\sigma_{\rm quad} / \sigma_{\rm SM}$

Rapidity distributions for m_{tb} > 10 TeV



Ask $m_{tb} > 10$ TeV, $y_t < 1.5$, $y_b < 1.5$

these numbers determine the sensitivity

$V_{tb} = 1$

tb s-ch

$\sigma = 71$ ab $(1 - 7.24 \, \text{Re}\, g_R + 17400 \, |g_R|^2)$ top

$\sigma = 26$ ab $(1 - 7.17 \, \text{Re}\, g_R + 16300 \, |g_R|^2)$ antitop

tb t-ch

$\sigma = 212$ ab $(1 - 2.88 \, \text{Re}\, g_R + 12200 \, |g_R|^2)$ top

$\sigma = 91$ ab $(1 - 0.690 \, \text{Re}\, g_R + 3150 \, |g_R|^2)$ antitop

not so bad: decent sensitivity

tj t-ch [miss b]

$\sigma = 1027$ ab $(1 - 0.894 \, \text{Re}\, g_R + 3970 \, |g_R|^2)$ top

$\sigma = 401$ ab $(1 + 0.554 \, \text{Re}\, g_R + 5060 \, |g_R|^2)$ antitop

background if *j* mistagged as *b*

$t\bar{t}$

$\sigma = 11$ fb

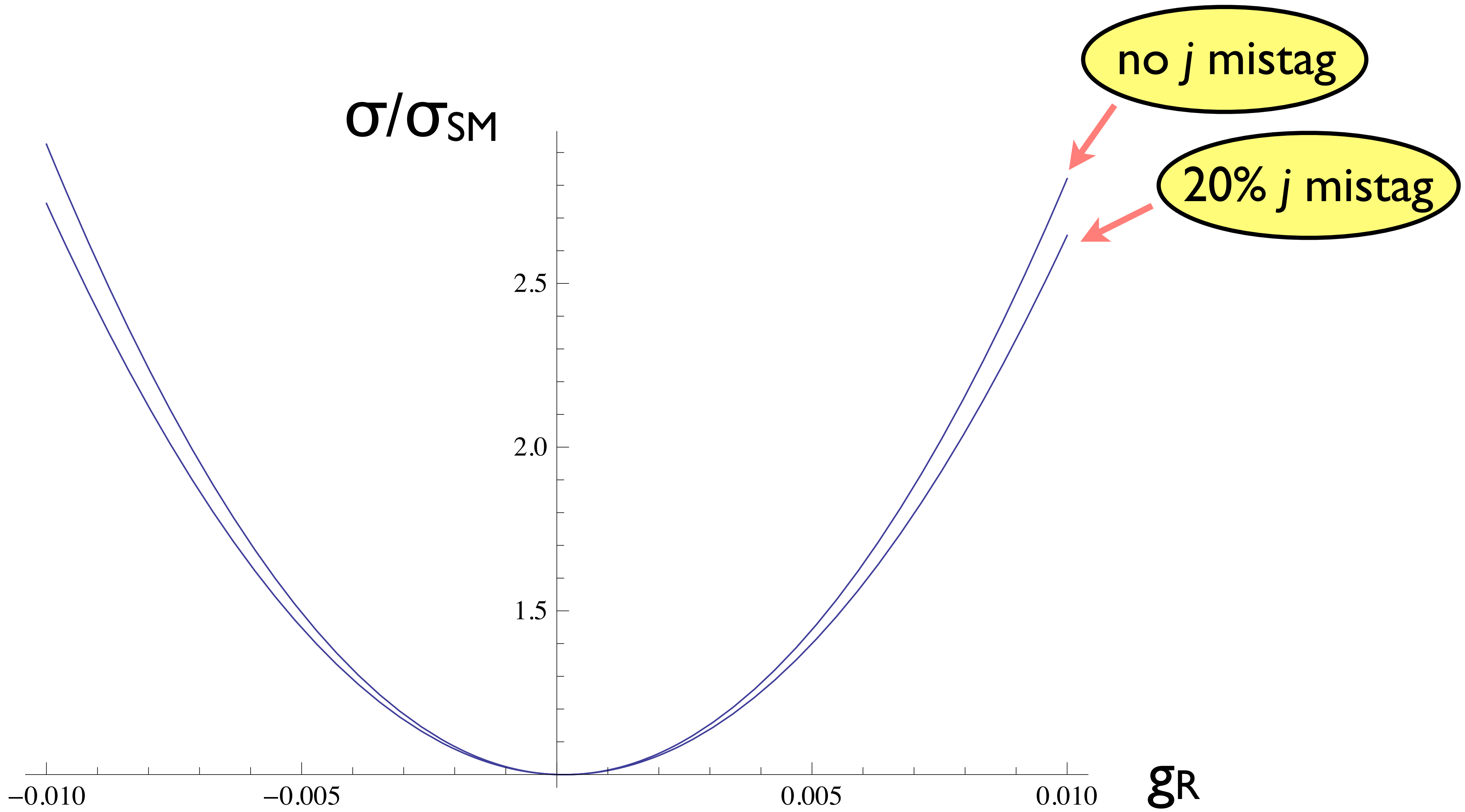
background if *t* mistagged as *b*

Shopping list of measurements

- Total # events → one needs 30x rejection of $t\bar{t}$ to have S/B = 1 in which case the sensitivity is reduced to 1/2
- # top - # antitop → eliminates $t\bar{t}$ background [except for stat. unc.]
- (# top - # antitop) / total # events → reduced systematics but also reduced dependence on anomalous couplings
- A_{FB} top, A_{FB} antitop, A_{FB} total → little dependence, cancellations among processes, very sensitive to mistag rates
- top polarisation → one can measure lepton E / top jet E but not spectacular

→ concentrate on # top - # antitop

tops - # antitops



L = 10 ab^{-1} → 4K # top - # antitop
7K events → stat error 1%

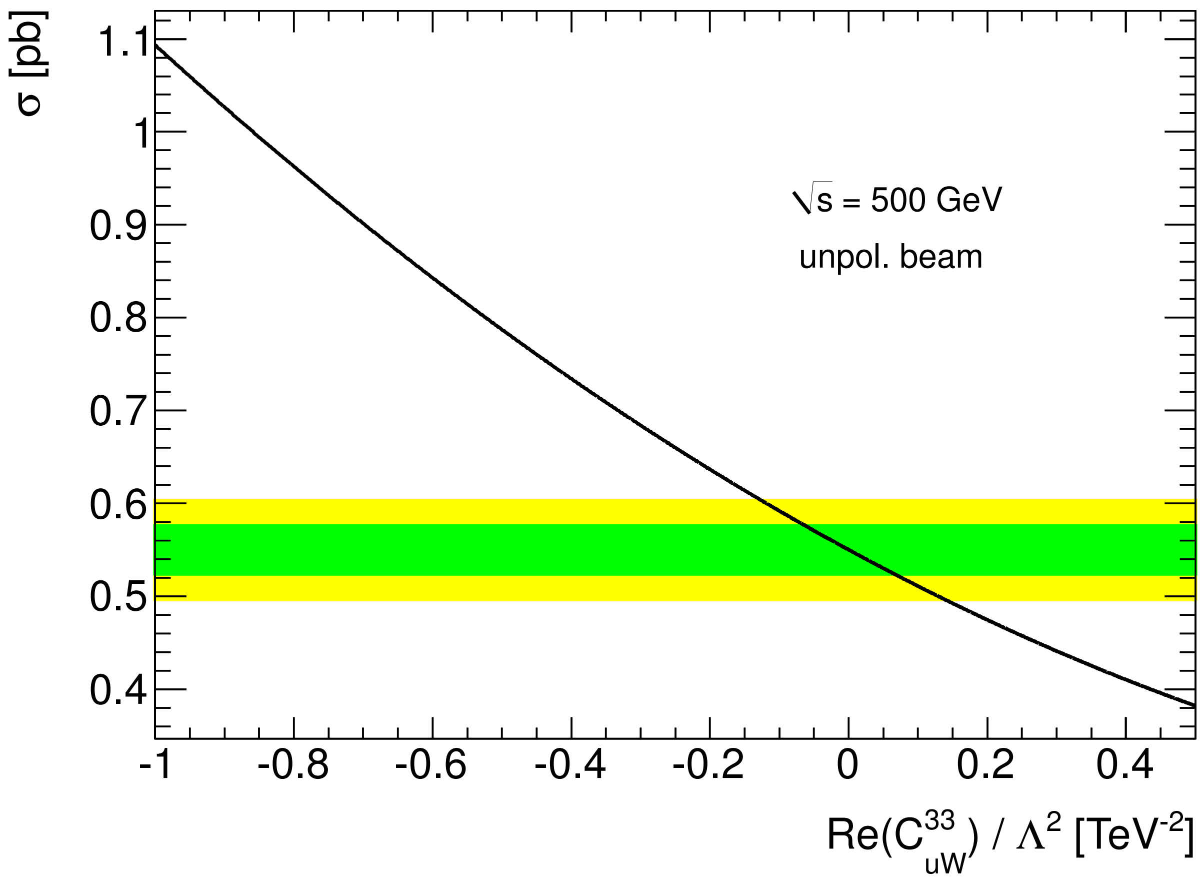
1% t mistag

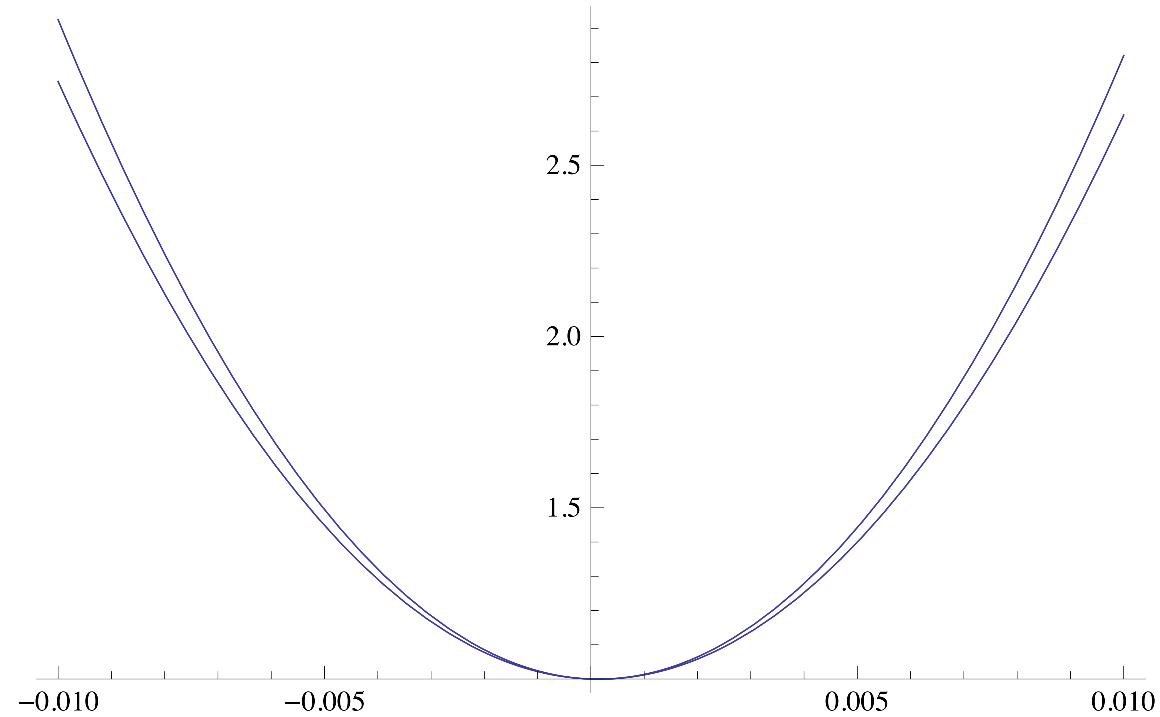
sys dominated: 20%?

$$\mathrm{Re}\, C_{uW}^{33}/\Lambda^2 \in [-0.043, 0.046]\ \mathrm{TeV}^{-2}$$

$$\Lambda > 4.7\sqrt{C}\ \mathrm{TeV}$$

Don't miss this!





sensitive to *Re C*

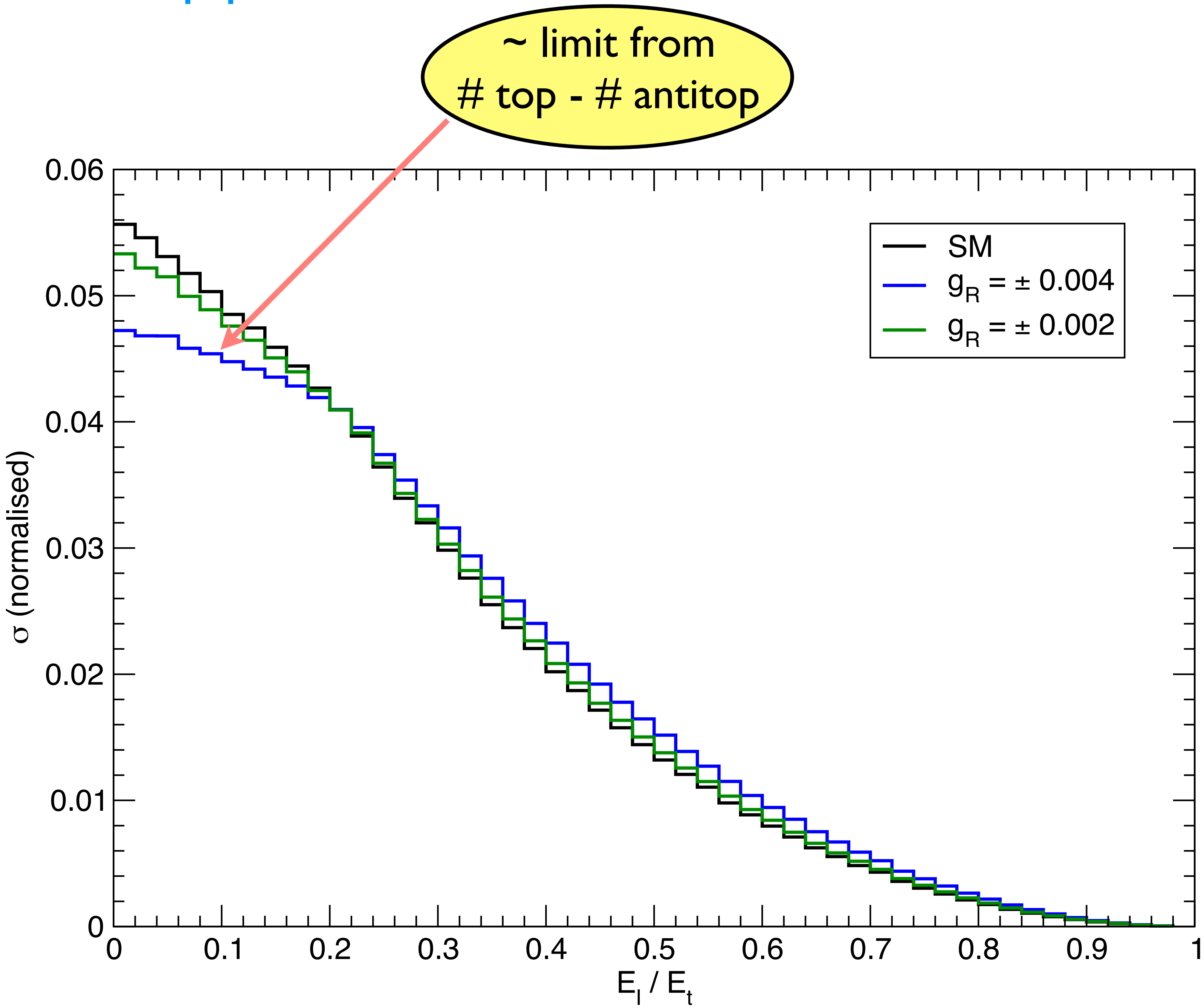
magnetic-like dipole moments

sensitive to $|C|^2$

electric-like dipole moments too

probe CP-violating quantity via CP-conserving observable

Comment on top polarisation effects



The usual statement "the top decays before it can form hadrons, so its spin is preserved" that we have read 10^2 times in papers, applies no longer.

1 conclusion & 4 comments

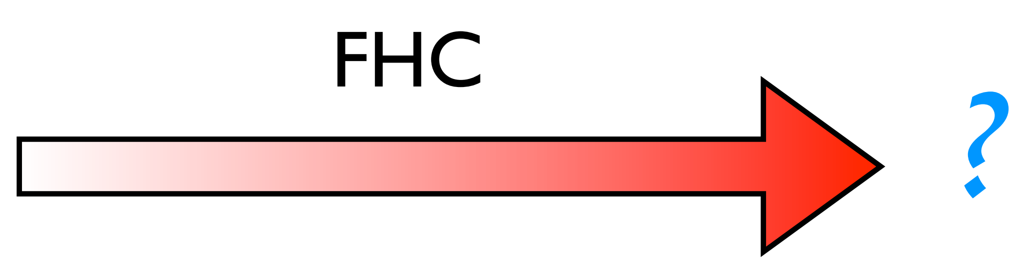
- High energy hadronic machines are good for high q^2 (obvious) but not necessarily in strong interaction processes.
- We have used effective operators for the sake of comparison, but dipole moments can arise from elusive low-scale physics too.
- Or if the top quark is not point-like, an even more exotic possibility.
- Many other examples not covered here which are interesting too and deserve specific work.
- Besides, we should not forget that we have a *Present* Hadron Collider that has not been fully exploited and several of these measurements could be done now.

ADDITIONAL MATERIAL

Top FCNC

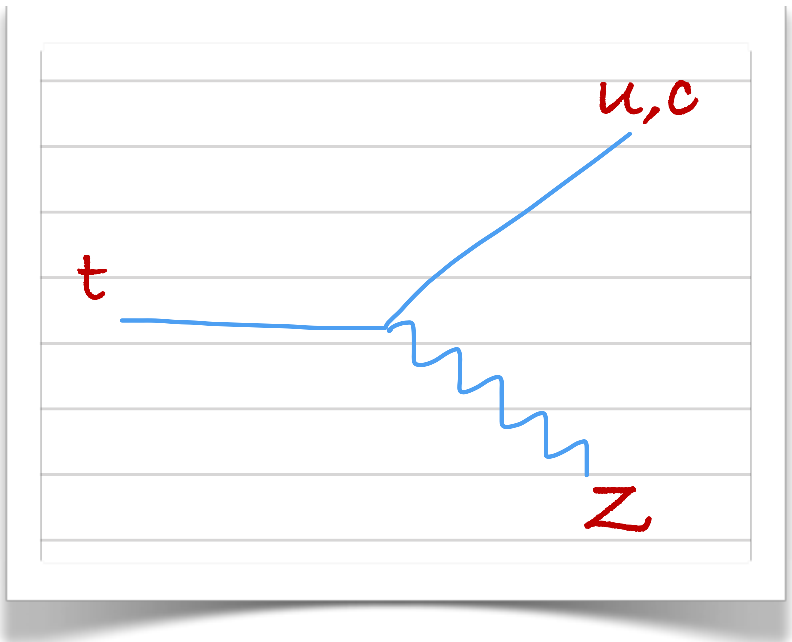
An all-time classic, popular within theorists and experimentalists as well, from LEP to LHC, including HERA and Tevatron

	exp. limit	LHC reach	SM
$t \to cZ$	$5 \cdot 10^{-4}$ [CMS]	10^{-5}	10^{-14}
$t \to c\gamma$	$2 \cdot 10^{-3}$ [CMS]	10^{-5}	$5 \cdot 10^{-14}$
$t \to cg$	$2 \cdot 10^{-4}$ [ATLAS]	10^{-5}	$5 \cdot 10^{-12}$
$t \to cH$	$8 \cdot 10^{-3}$ [ATLAS]	10^{-5}	$3 \cdot 10^{-15}$



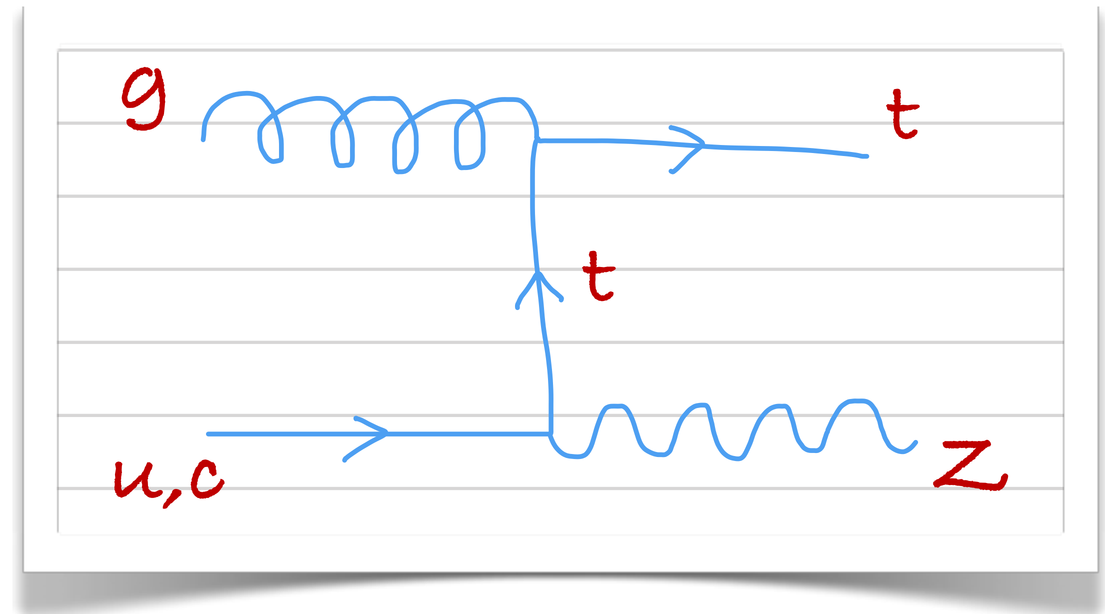
How to probe FCNC at hadron colliders

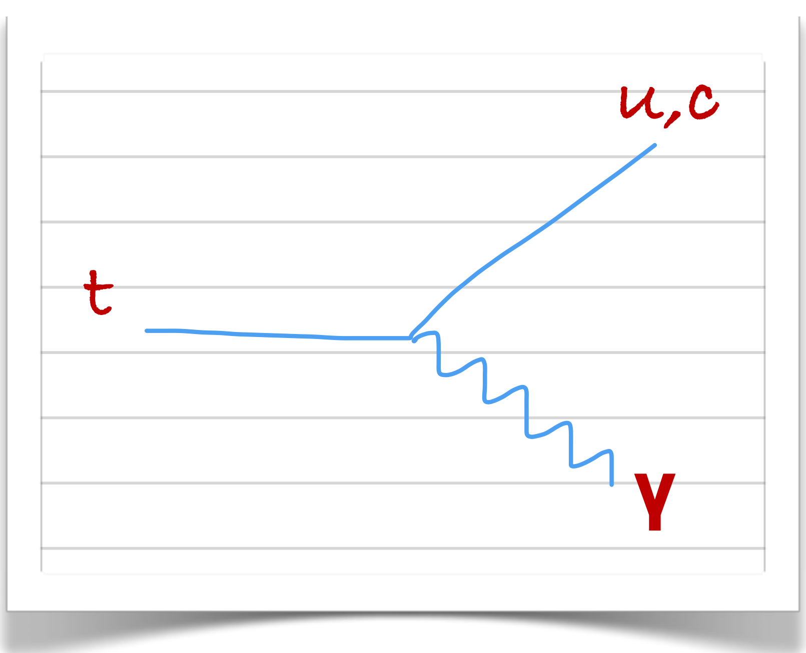
ATLAS CMS



Ztu / Ztc

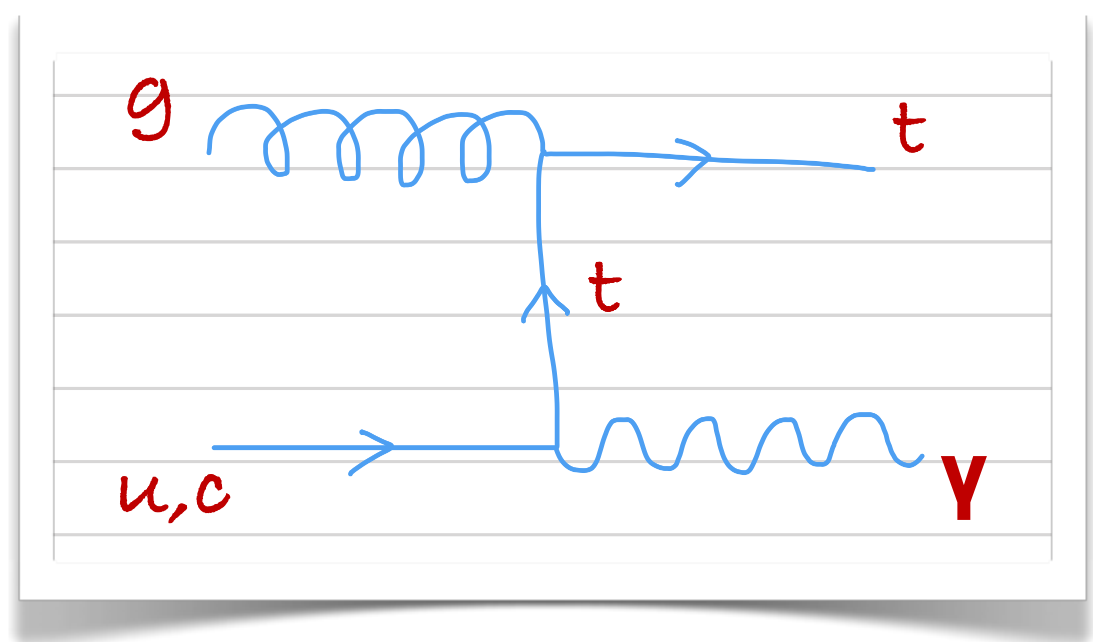
CMS



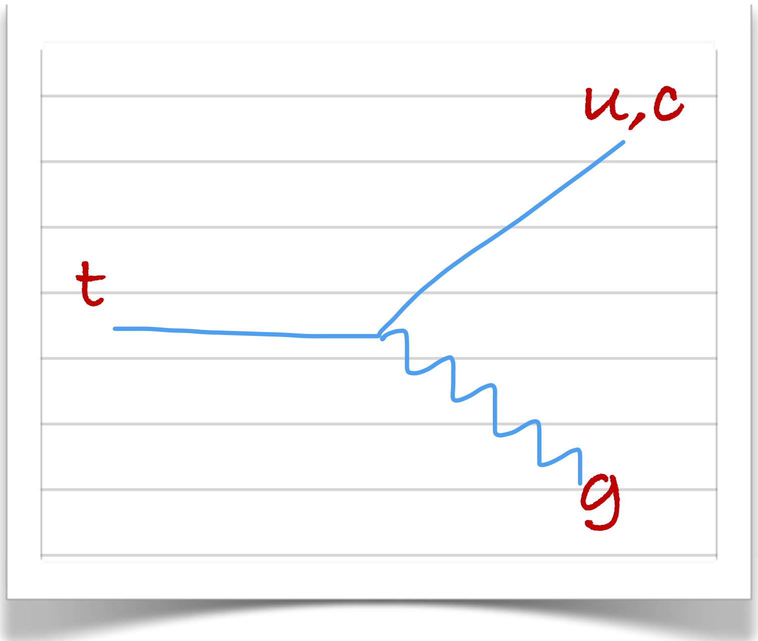


γtu / γtc

CMS

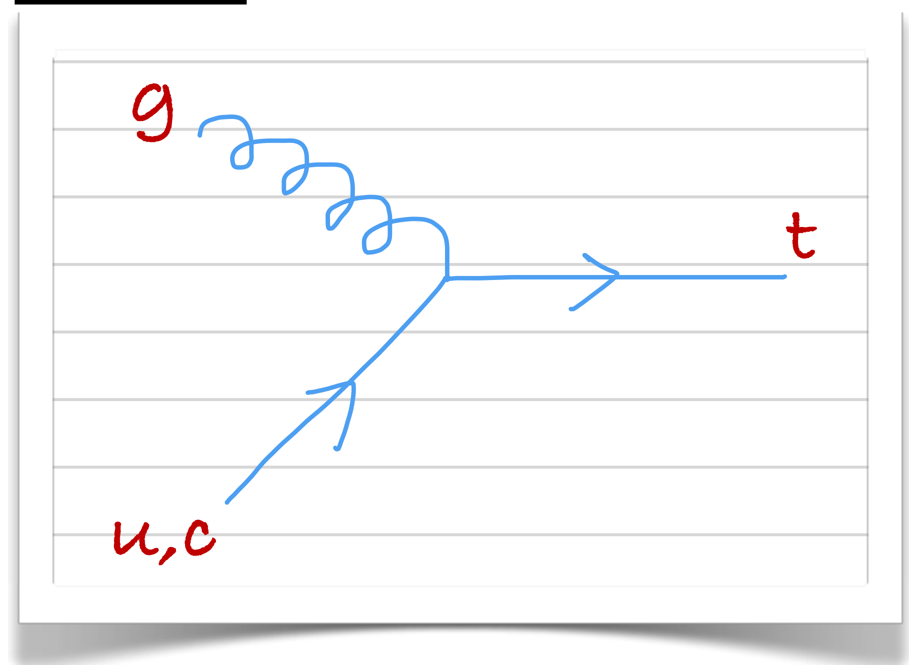


How to probe FCNC at hadron colliders

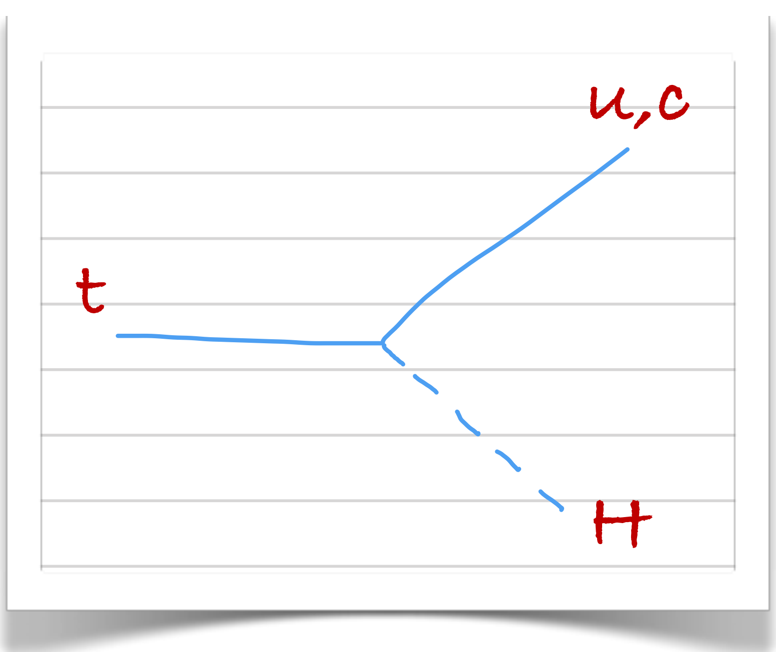


gtu / gtc

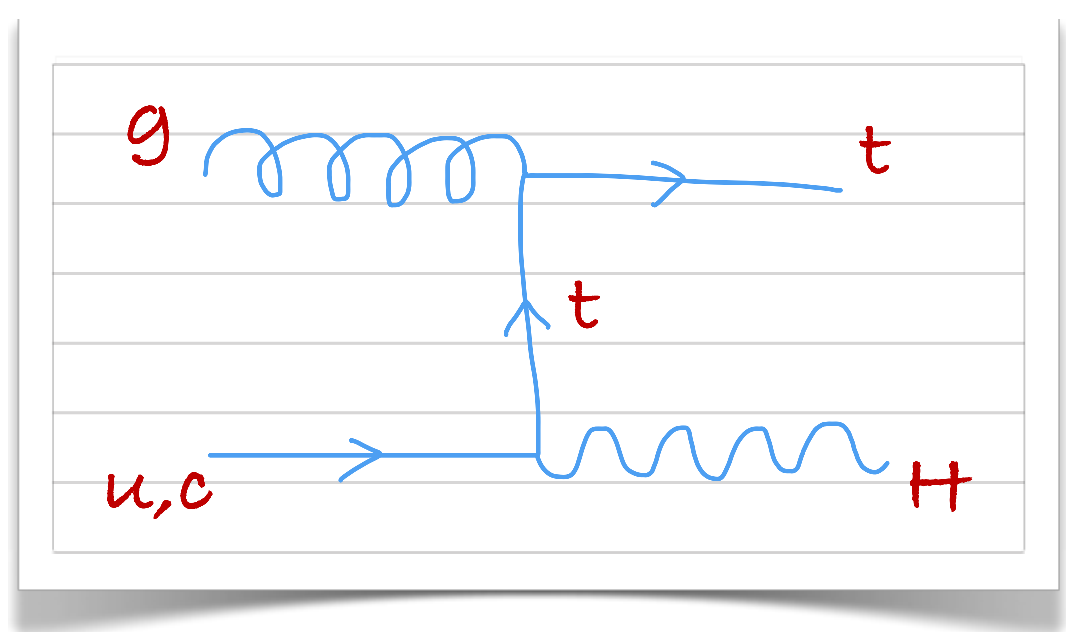
ATLAS



ATLAS



Htu / Htc



Extrapolations to 100 TeV

- Naive rescaling by $1/\sqrt{N}$ of the expected LHC limits
- Ignore FCNC with up quark, for brevity
- Limits rather conservative, since one can also extract limits from tails
- Luminosity: 10 ab^{-1}

	exp. limit	LHC reach	Est. 100 TeV	SM
$t \to cZ$	$5 \cdot 10^{-4}$ [CMS]	10^{-5}	10^{-7}	10^{-14}
$t \to c\gamma$	$2 \cdot 10^{-3}$ [CMS]	10^{-5}	10^{-7}	$5 \cdot 10^{-14}$
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$t \to cH$	$8 \cdot 10^{-3}$ [ATLAS]	10^{-5}	10^{-7}	$3 \cdot 10^{-15}$