Top quark properties
(except for FB asymmetry, polarization, spin correlations, W helicity, mass)

Christian Schwanenberger

University of Manchester

on behalf of

36th International Conference on High-Energy Physics
Melbourne
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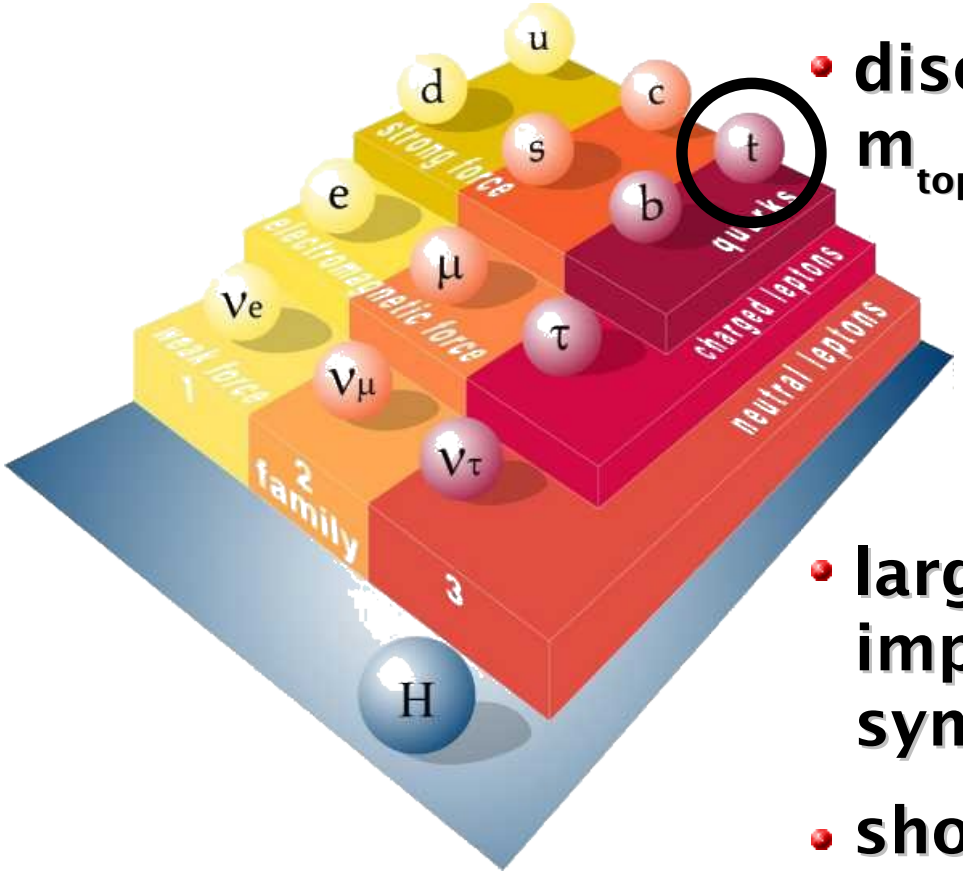
The Top Quark



- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: m_{top} ~ gold atom

couplings

- large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?
- short lifetime: $\tau \sim 5 \cdot 10^{-25}$s $\ll \Lambda^{-1}_{QCD}$: decays before fragmenting → observe "naked" quark

$\Gamma_t = 1/\tau$

Is the top quark the particle as predicted by the SM?

Outline

Top quark decay branching ratios

Width and lifetime

Top quark couplings (FCNC)

Conclusions

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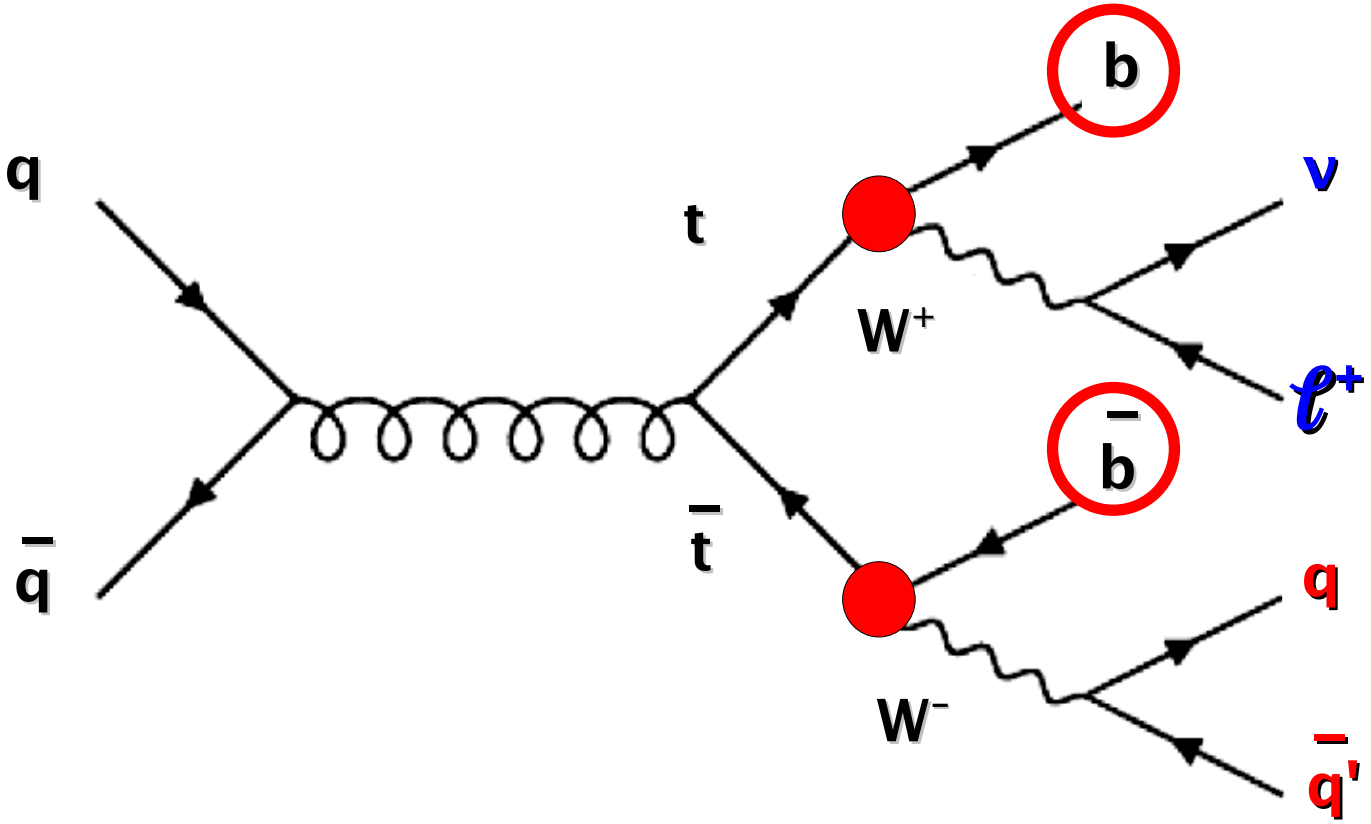
Top quark couplings



Measurement of Branching Fractions

$$R = \frac{B(t \to Wb)}{B(t \to Wq)}$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Standard Model:

$$R_{SM} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} = |V_{tb}|^2 \approx 1$$

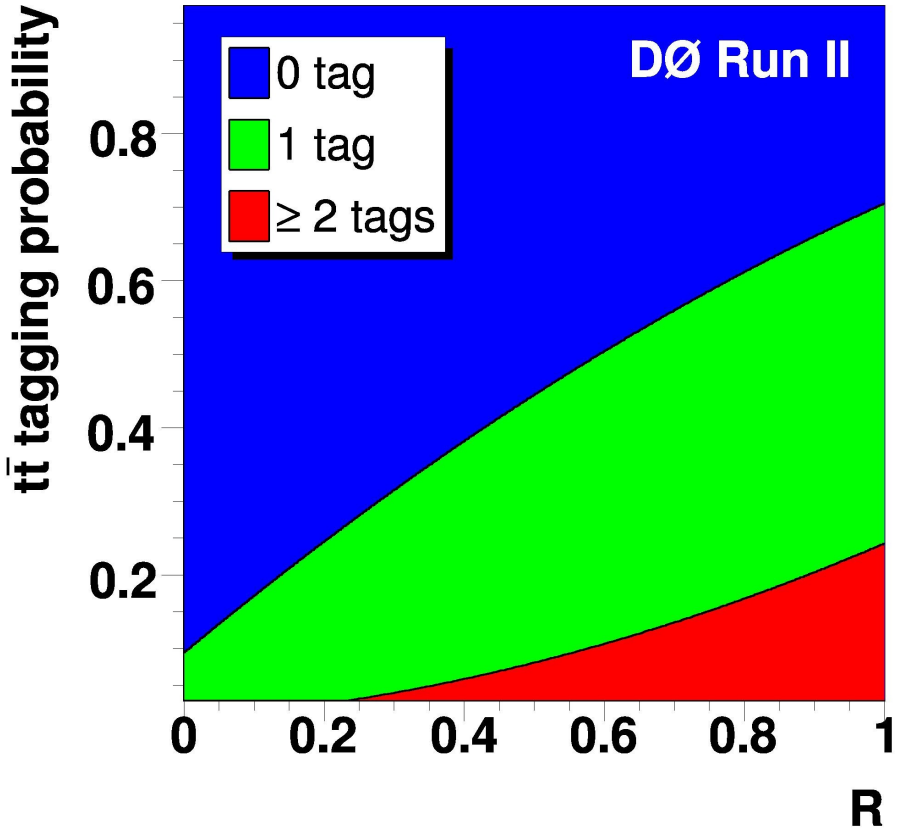
unitarity of CKM matrix

beyond SM:

R ≠ 1

e.g. decay into 4th generation quark: R<1
sensitive to b disappearance

R changes fractions of b-tagged jets:



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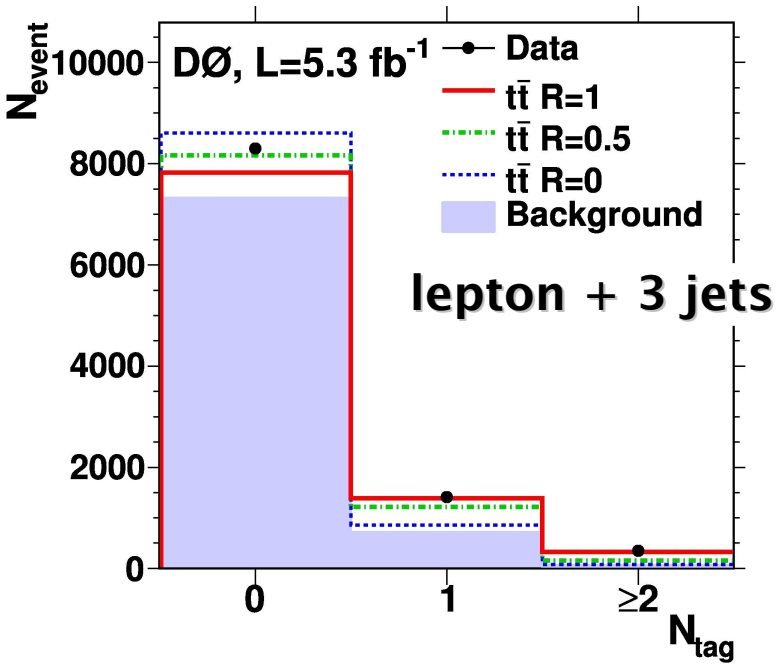
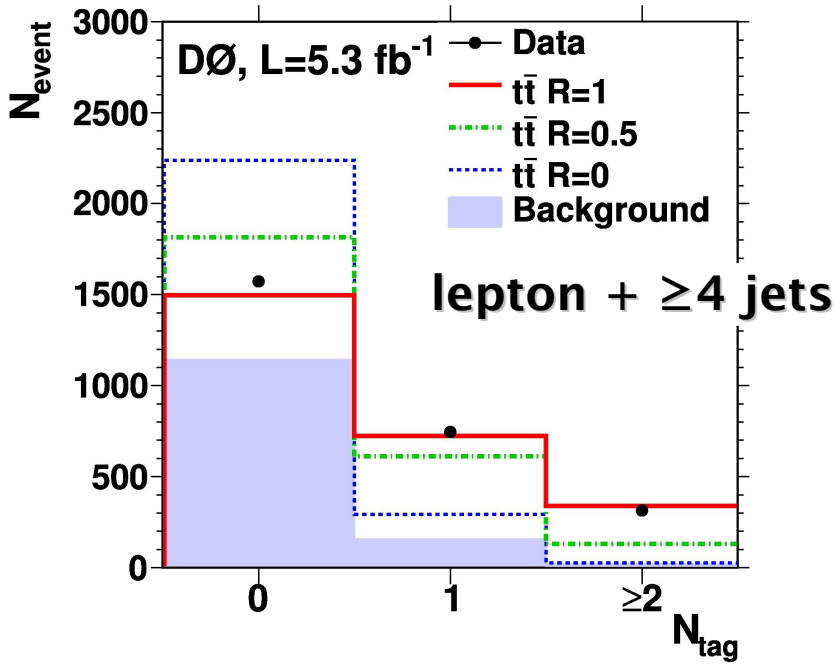
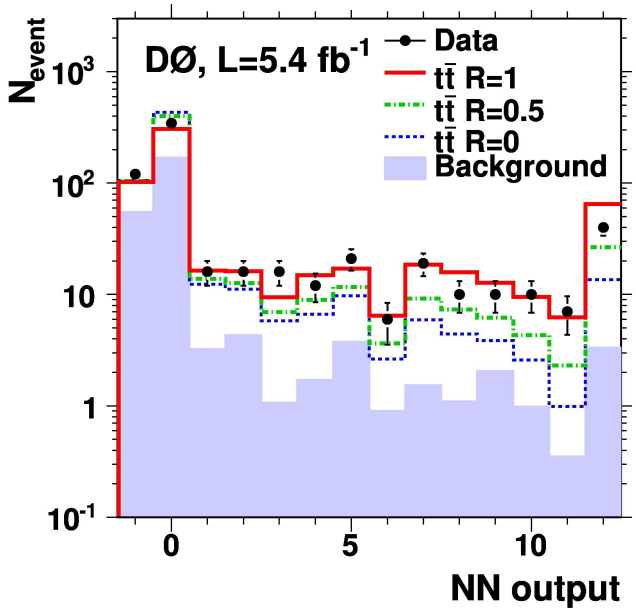






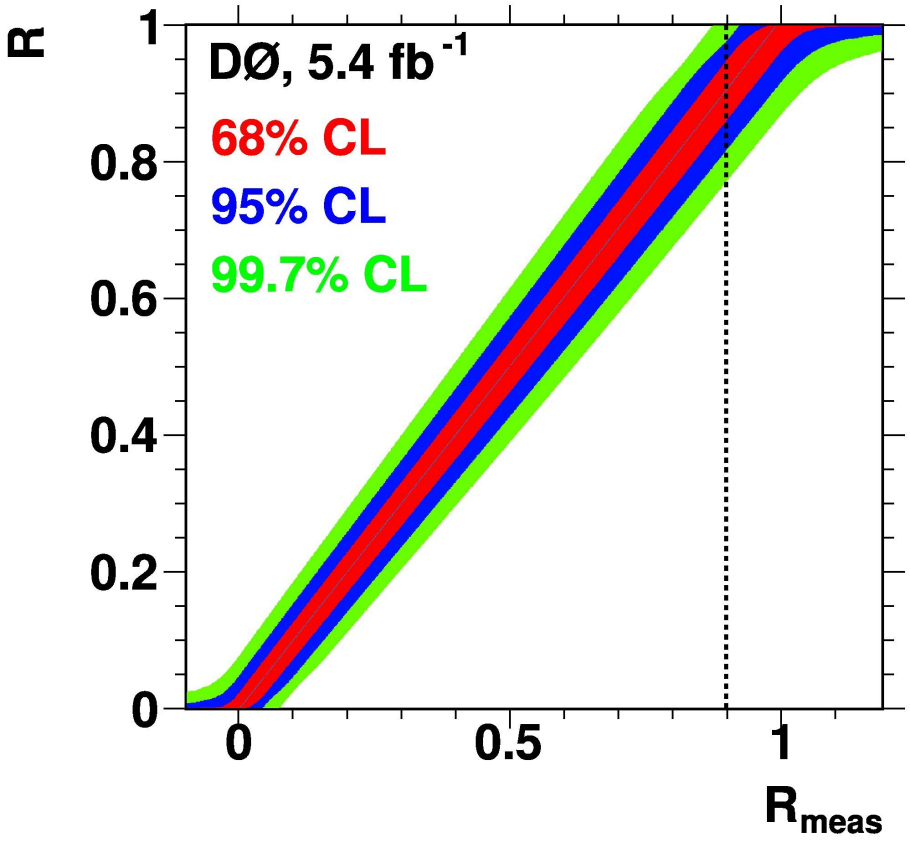
topological information and b-tagging

dilepton

Simultaneous Measurement of σ and R

Maximize total Likelihood function simultaneously for branching ratio R and top pair production cross section

Phys. Rev. Lett. 107, 121802 (2011)



$R = 0.90 \pm 0.04$ (stat+syst)

using unitarity of CKM matrix:

$0.90 < |V_{tb}| < 0.99$ @ 95% C.L.

$\sigma_{t\bar{t}} = 7.74^{+0.67}_{-0.57}$ (stat+syst) pb

⇒ agrees with SM within 2.5σ

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Top quark decay branching ratios

Width and lifetime

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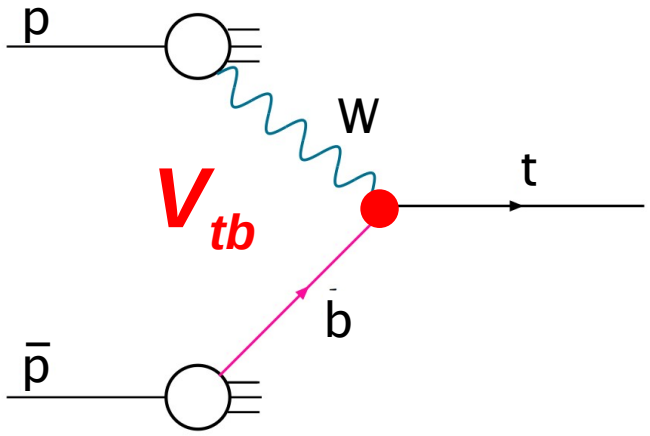
Top Decay Width

- **indirect determination (direct extraction not sensitive enough)**

t-channel cross section:

σ(t-channel) = 2.26 ± 0.12 pb
approximate NNNLO, m_t = 172.5 GeV



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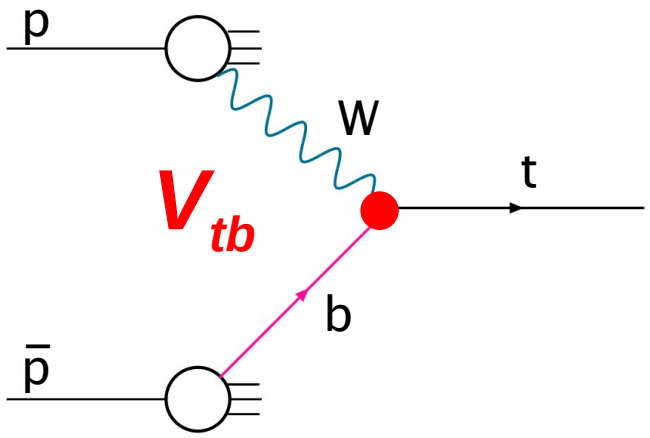
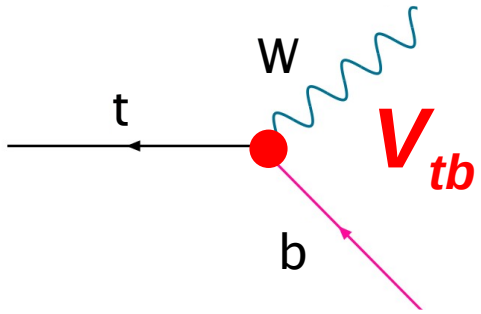


partial decay width:

$\Gamma(t \to Wb) = 1.33$ GeV

NLO, $m_t = 172.5$ GeV



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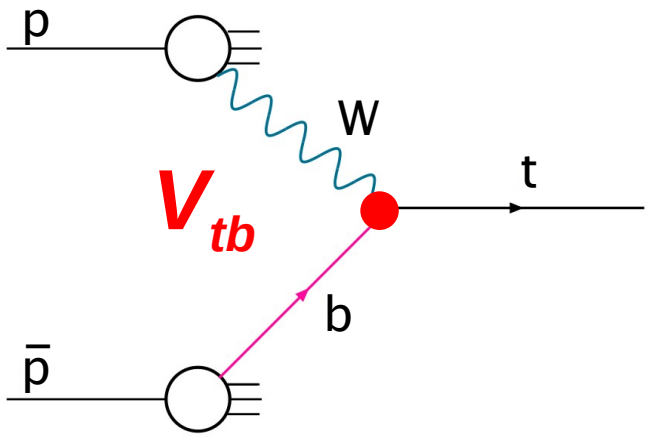
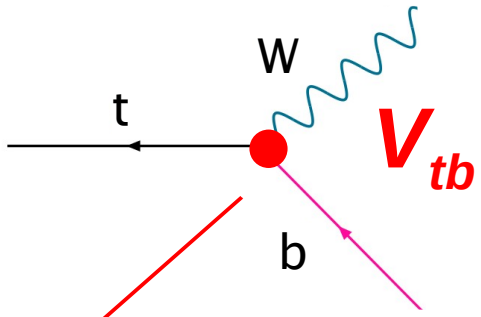




$$\Gamma_t = \frac{\Gamma(t \to Wb)}{\mathcal{B}(t \to Wb)}$$

← $t\bar{t}$ production

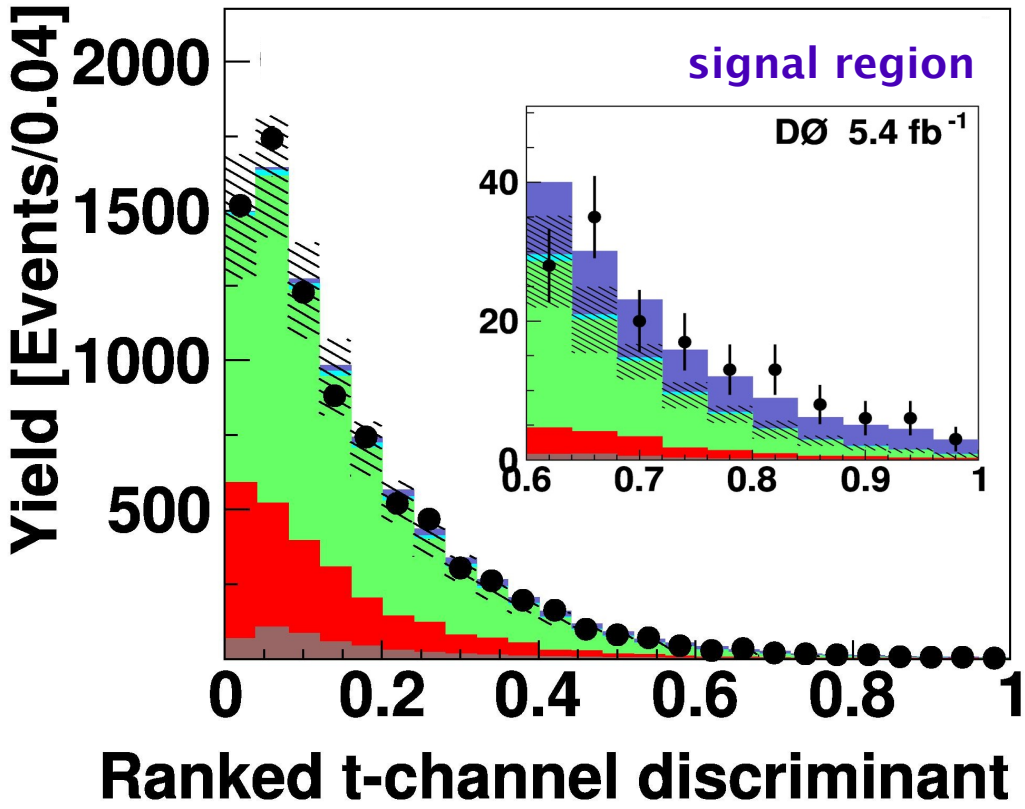
- **combine both measurements**
- **assume that coupling in top production and decay is the same**

Observation of t-Channel Production

- remove s/t channel constraint which could be changed by new physics
- train multivariate analysis for t-channel
- measure t-channel and s-channel simultaneously

Phys. Lett. B 705, 313 (2011)

observation with 5.5σ



$$\sigma(p\bar{p} \rightarrow tqb + X) = 2.90 \pm 0.59 \text{ pb}$$

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m_t =172.5 GeV

Top Decay Width

t-channel cross section:

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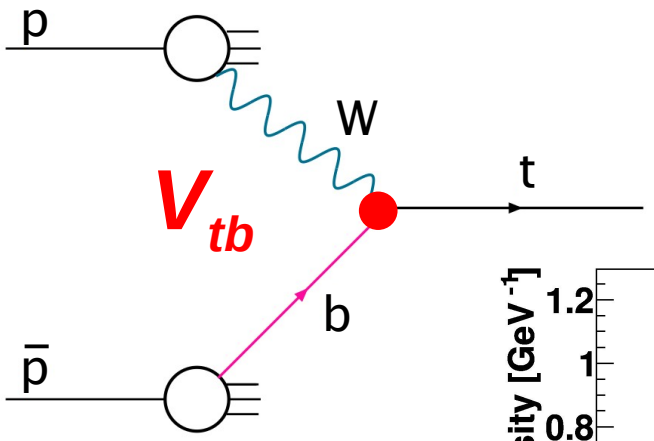
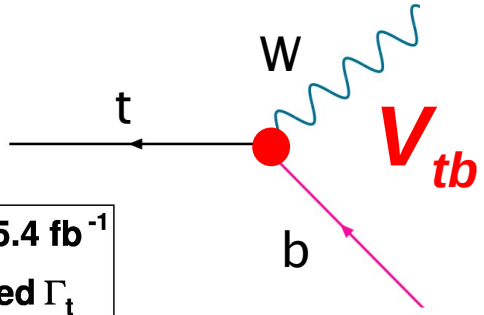
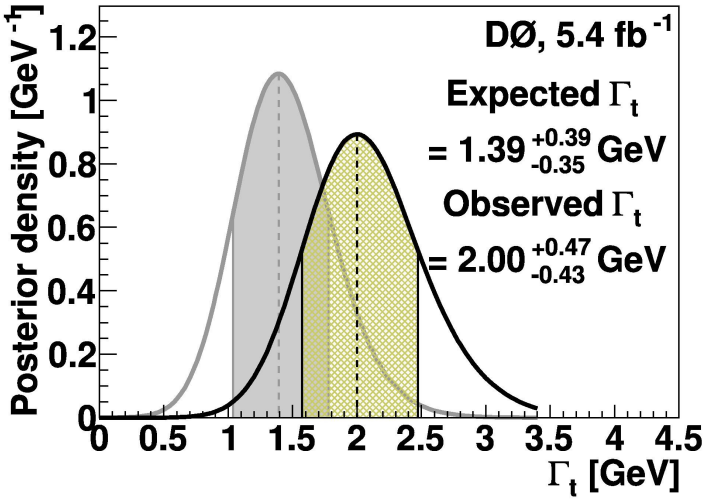


partial decay width:

R= 0.90±0.04 (stat+syst)





Phys. Rev. D84 012008 (2011)

$$\Gamma_t = 2.00^{+0.47}_{-0.43} \text{ GeV}$$

$$\tau_t = (3.29^{+0.90}_{-0.63}) \times 10^{-25} \text{ s}$$

$\Longrightarrow$ **most precise determination**

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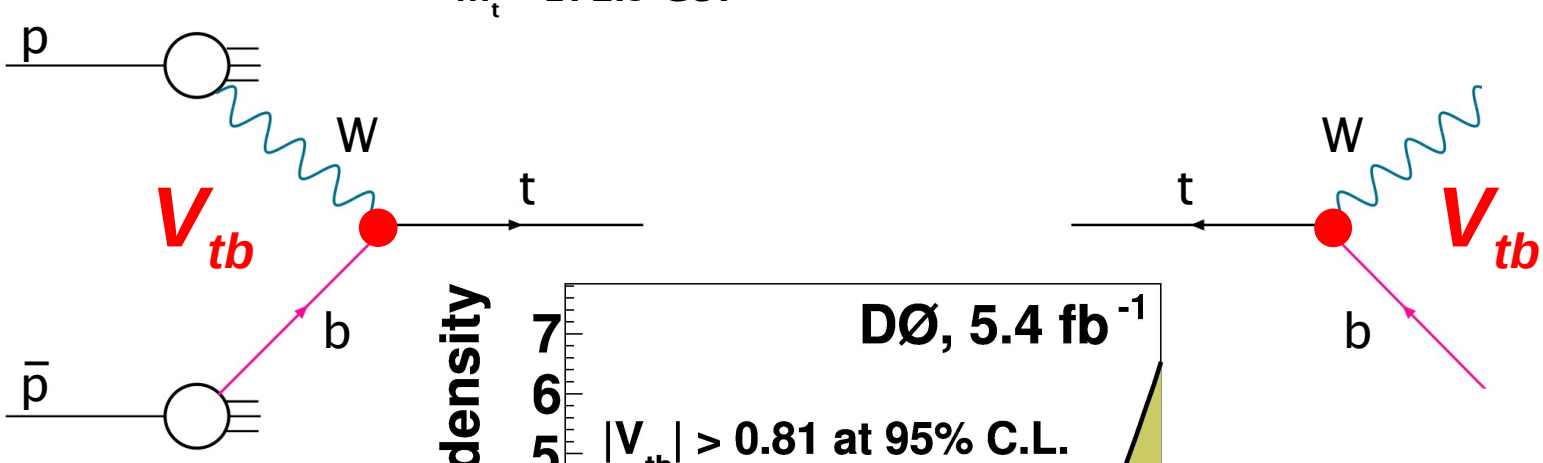

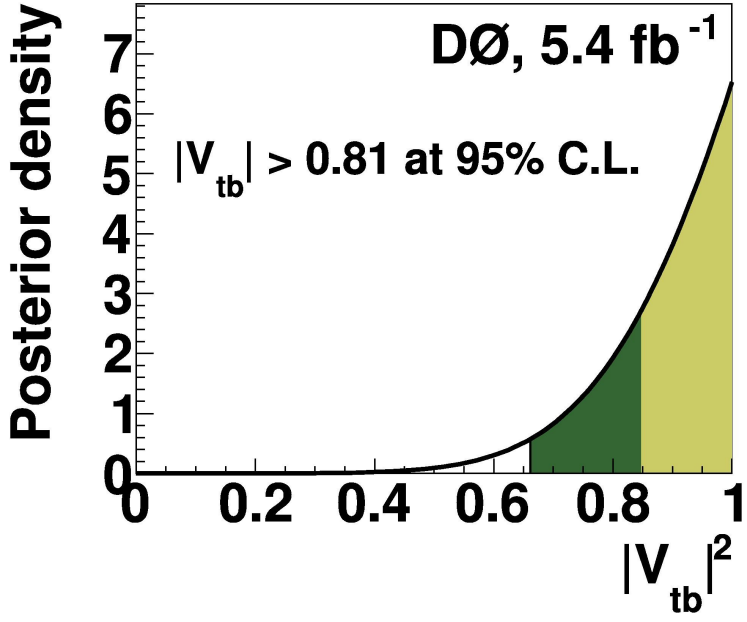

$|V_{tb}| > 0.81$ at the 95% C.L.

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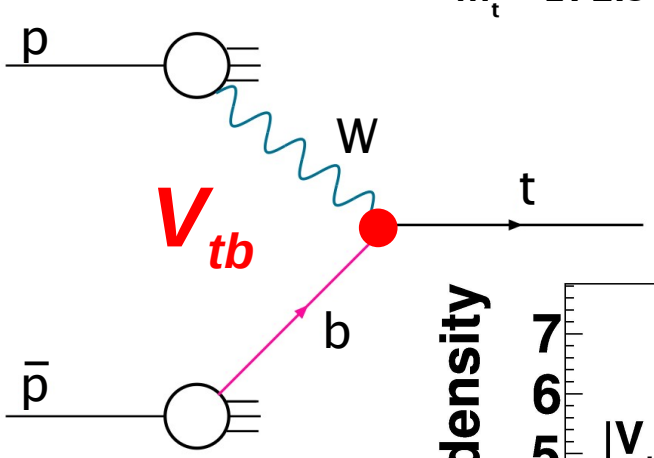

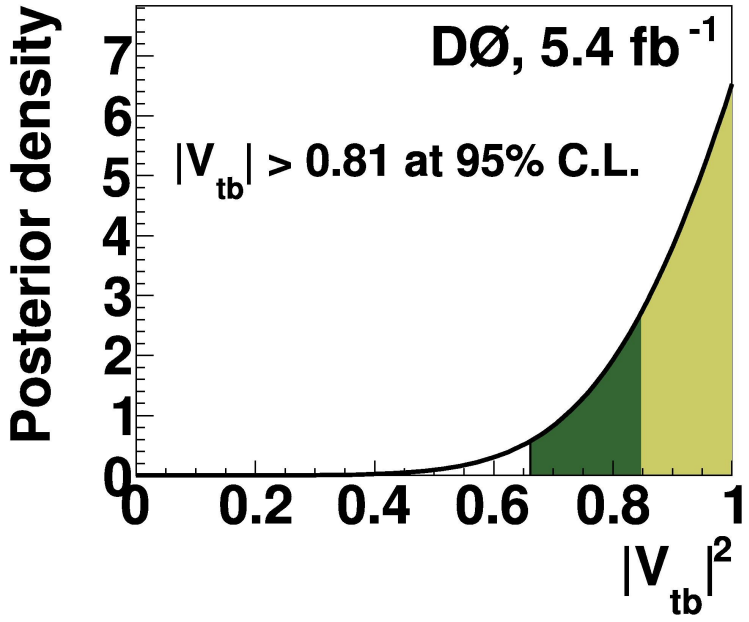

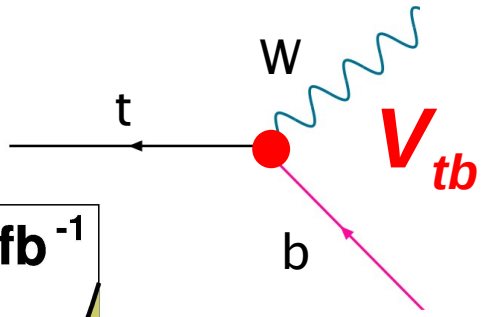

4th generation b' quark:

$$m_{b'} > m_t - m_W$$

$$|V_{td}|, |V_{ts}| \ll 1$$

$$|V_{tb'}|^2 = 1 - |V_{tb}|^2$$

$|V_{tb}| > 0.81$ at the 95% C.L.

$|V_{tb'}| < 0.59$ at 95% C.L.

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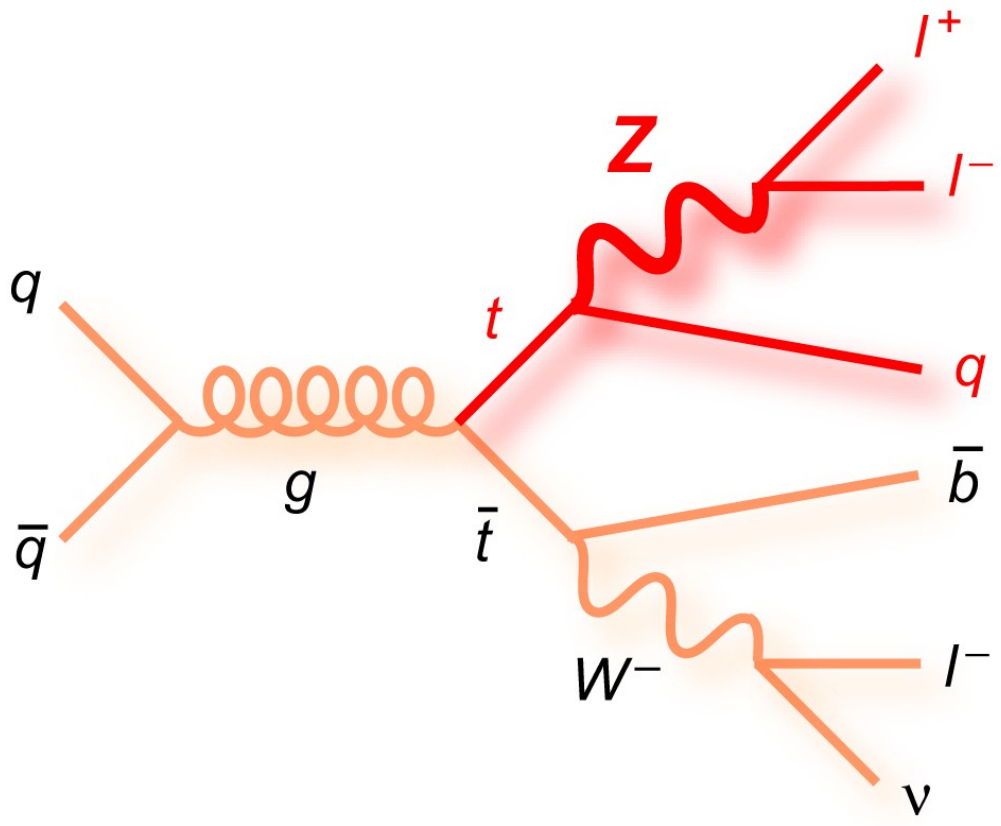
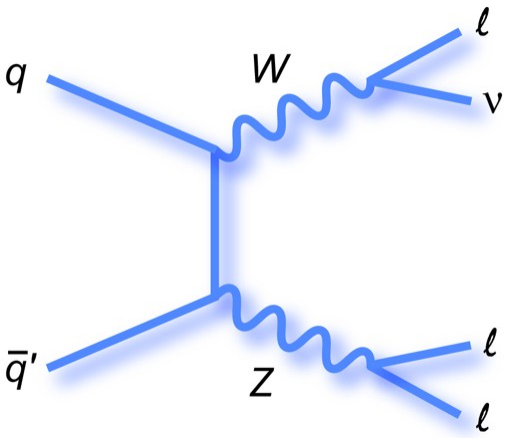
Search for FCNC in Top Quark Decays

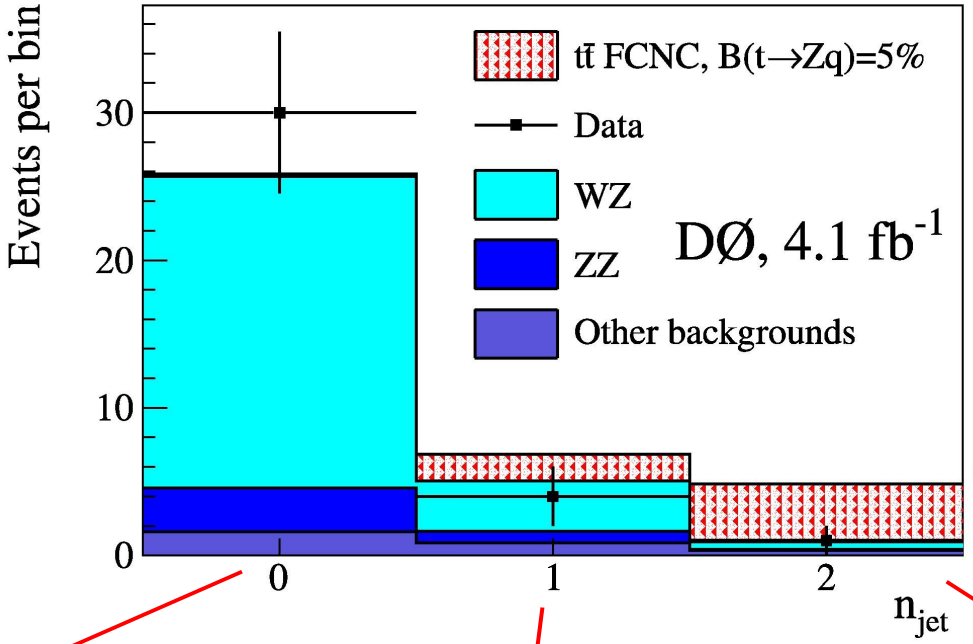
$$\mathcal{L}_{FCNC} = \frac{e}{2\sin\theta_W \cos\theta_W}\,\bar{t}\gamma_\mu(v_Z - a_Z\gamma_5)qZ^\mu + h.c.$$

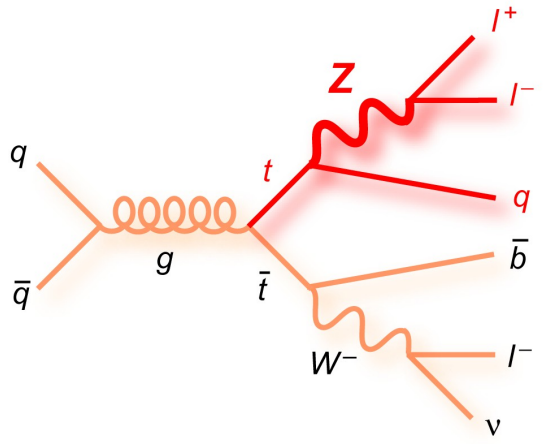


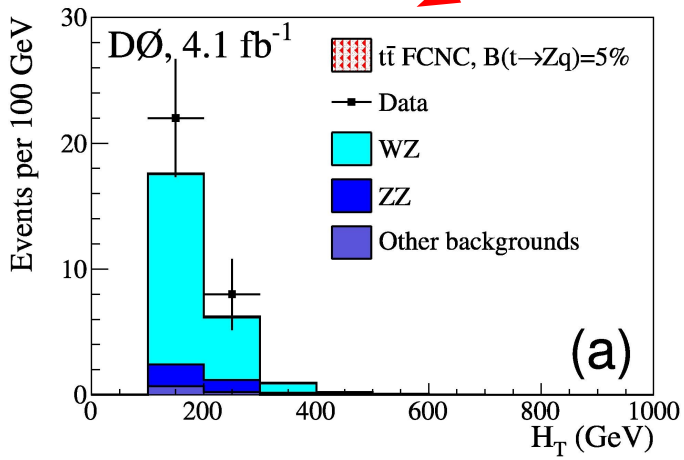
- **select 3 leptons, missing transverse momentum, 2 jets**

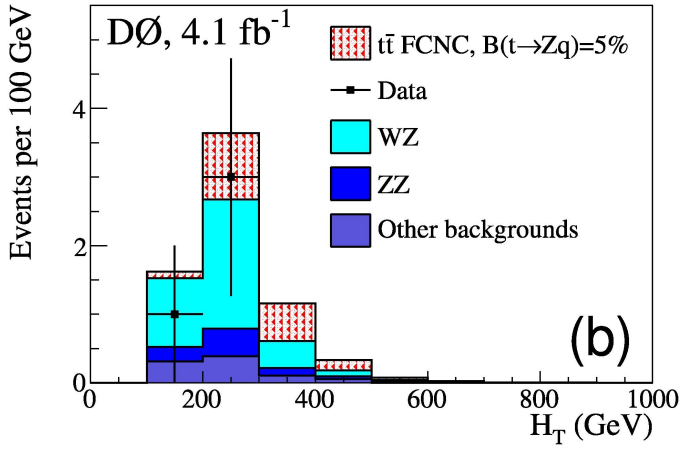
Search for FCNC in Top Quark Decays

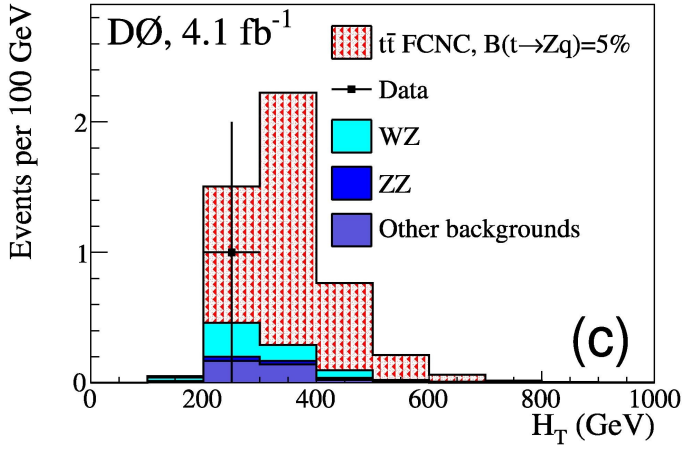






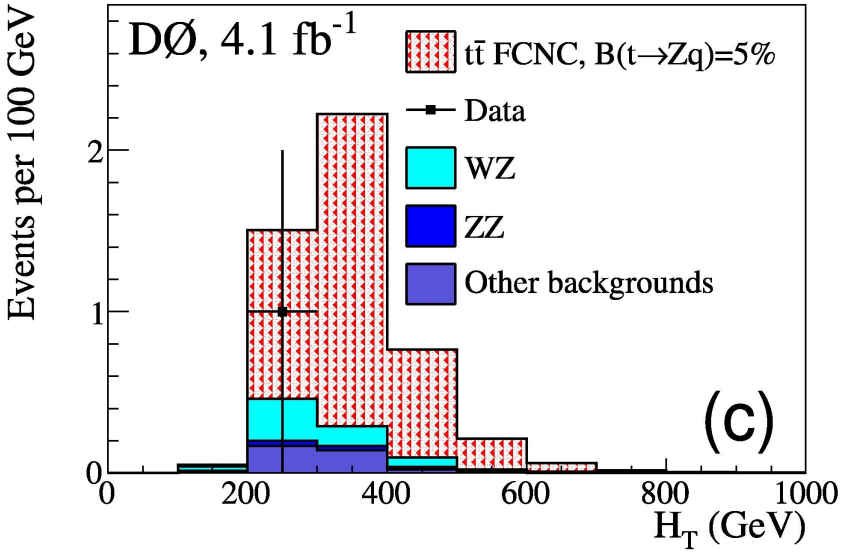


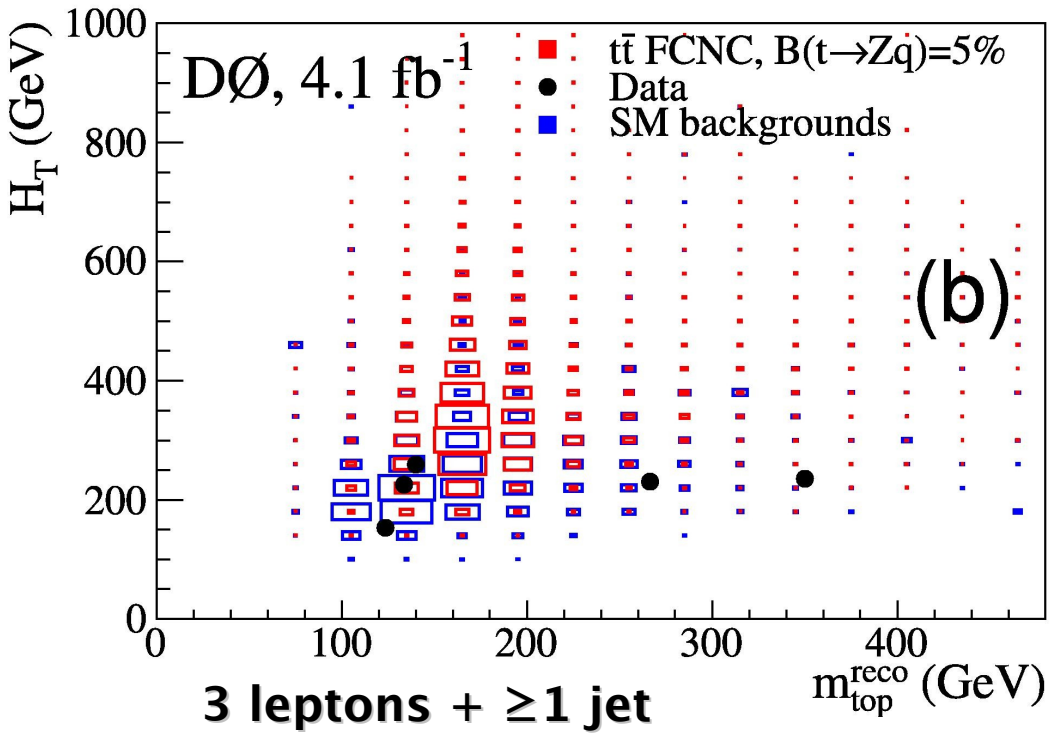


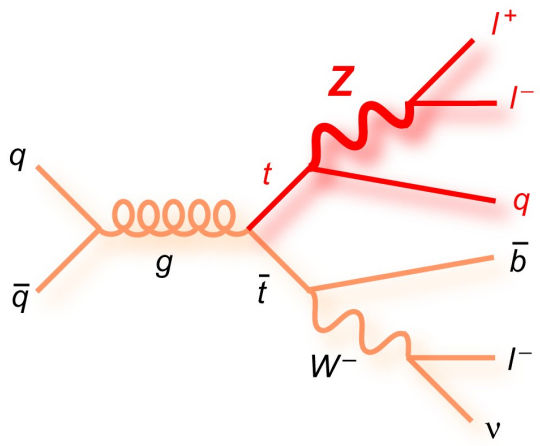


3 leptons + 0 jets | **3 leptons + 1 jet** | **3 leptons + ≥2 jets**

Search for FCNC in Top Quark Decays

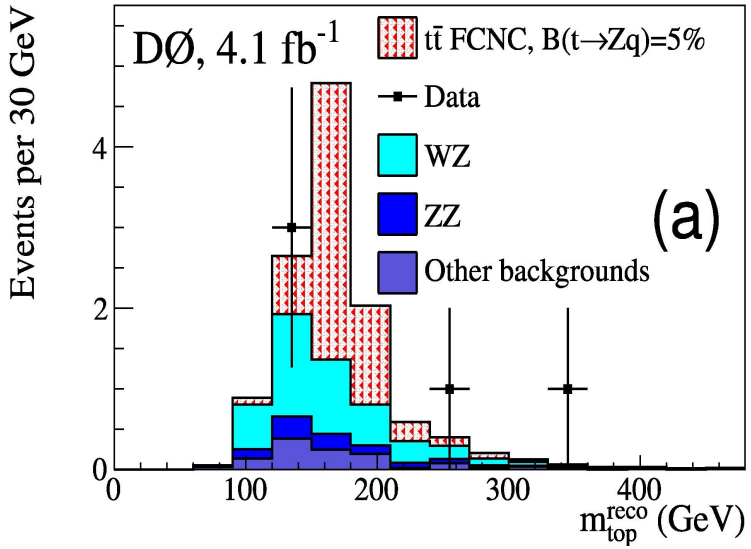






m_{top}^{reco}

3 leptons + ≥1 jet

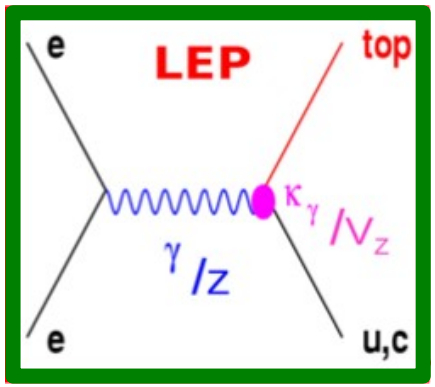


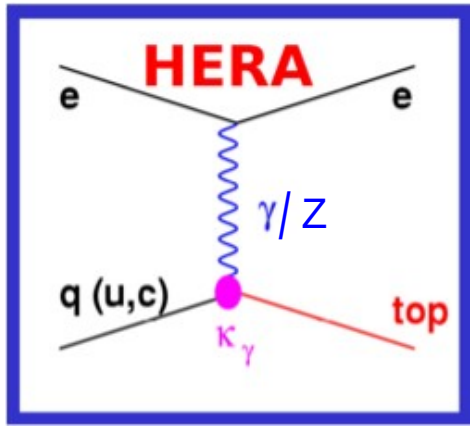
Phys. Lett. B701, 313 (2011)

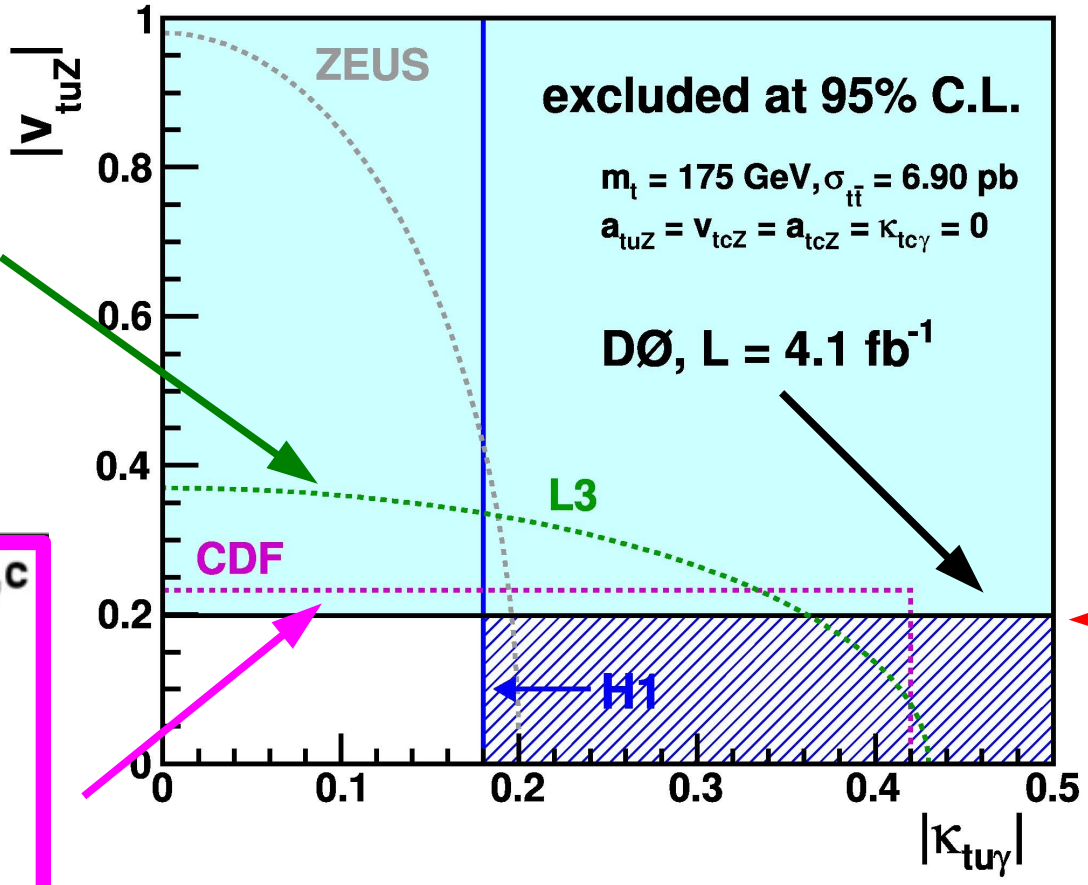
95% C.L.

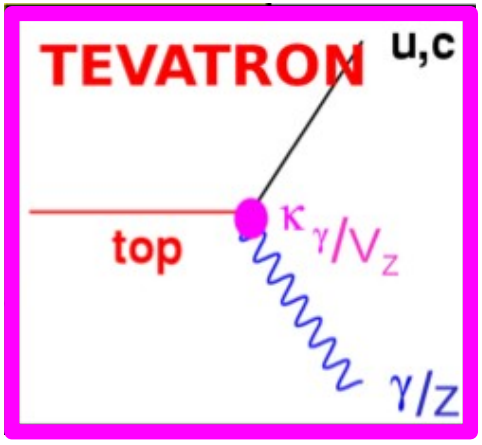
B(t→Zq) < 3.2% (3.8% expected)

Excluded Regions by Colliders









world's best limit

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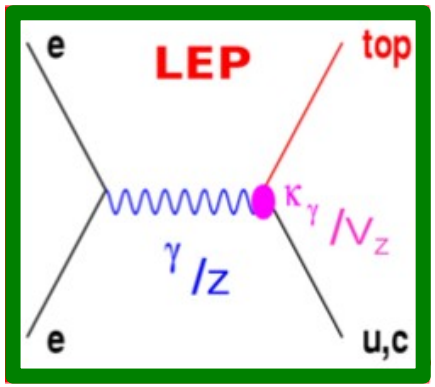

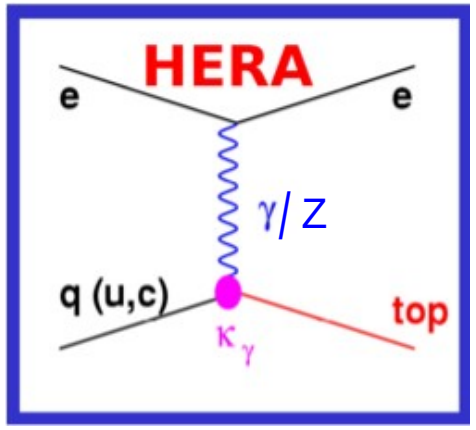

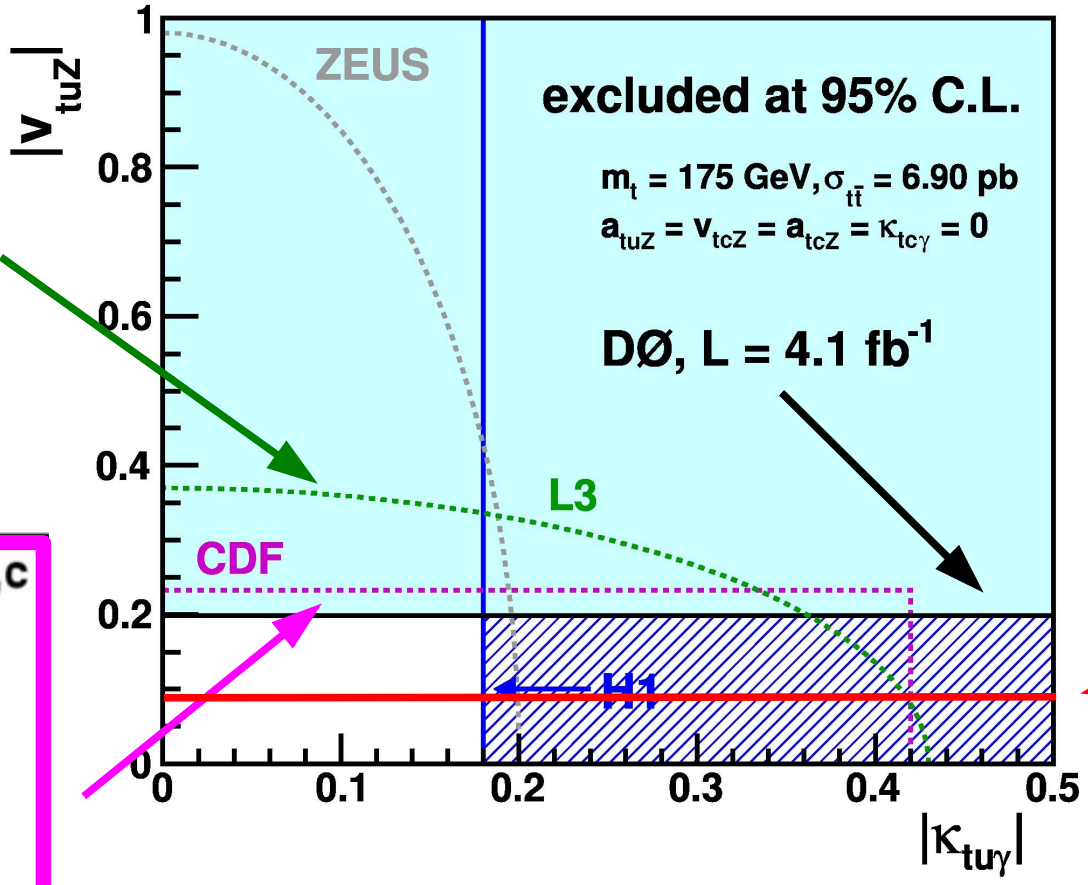

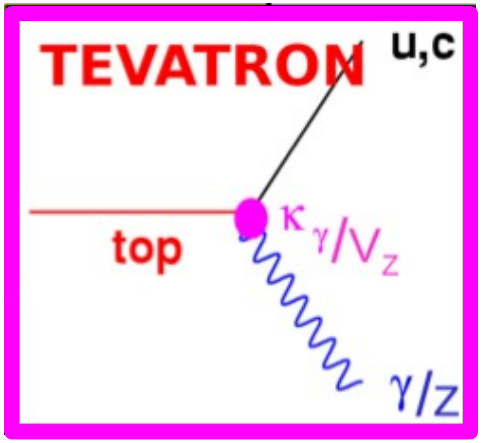

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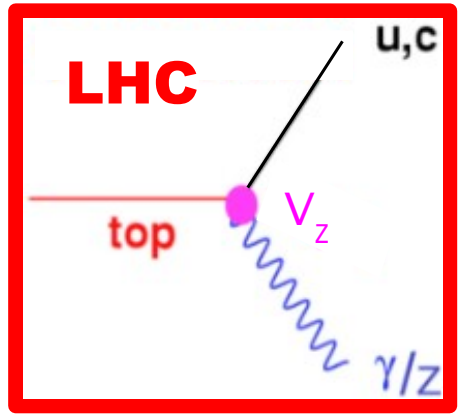

arXiv:1206.0257

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Conclusions: Top Quark Properties

- many high precision measurements
- competitive (mass) and complementary (spin correlations, FB asymmetry) to LHC

Property		Measurement	SM Prediction	Lumi (fb^{-1})
$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)	$p\bar{p} \to t\bar{t}$	CDF: $7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb	$7.46^{+0.48}_{-0.67}$ pb	up to 4.6
		D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb		5.6
σ_{tbq} (for $M_t = 172.5$ GeV)	$p\bar{p} \to t\bar{t}$	CDF: 0.8 ± 0.4 pb ($M_t = 175$ GeV)	2.26 ± 0.12 pb	3.2
		D0: 2.90 ± 0.59 pb		5.4
σ_{tb} (for $M_t = 172.5$ GeV)	$p\bar{p} \to tb$	CDF: $1.8^{+0.7}_{-0.5}$ pb ($M_t = 175$ GeV)	1.04 ± 0.04 pb	3.2
		D0: $0.68^{+0.38}_{-0.35}$ pb		5.4
$R = B(t \to Wb)/B(t \to Wq)$		CDF: > 0.61 @ 95% CL	1	0.2
		D0: 0.90 ± 0.04		5.4
$\lvert V_{tb} \rvert$		CDF: $\lvert V_{tb} \rvert = 0.96 \pm 0.09(\text{stat} + \text{sys}) \pm 0.05(\text{theory})$	1	7.5
		D0: $0.81 < \lvert V_{tb} \rvert < 1$		5.4
$\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$	$p\bar{p} \to t\bar{t}$	CDF: $0.07^{+0.15}_{-0.07}$	0.18	1
$\sigma_{t\bar{t}\gamma}$ (for $M_t = 172.5$ GeV)	$p\bar{p} \to t\bar{t}\gamma$	CDF: $0.18 \pm 0.08(\text{stat} + \text{syst} + \text{lumi})$ pb	0.17 ± 0.03 pb	6.0
M_t		Tev: 173.2 ± 0.9 GeV	-	up to 5.8
$M_t - M_{\bar{t}}$		CDF: $-1.95 \pm 1.11(\text{stat}) \pm 0.59(\text{syst})$ GeV	0	8.7
		D0: $0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$ GeV		3.6
W helicity fraction		Tev: $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$	0.7	up to 5.4
Charge		CDF: -4/3 excluded @ 95% CL	2/3	5.6
		D0: $\lvert q \rvert = 4/3$ excluded @ 92% CL		0.37
Γ_t		CDF: < 7.6 GeV @ 95% CL	1.26 GeV	4.3
		D0: $1.99^{+0.69}_{-0.55}$ GeV		up to 2.3
spin correlation	$p\bar{p} \to t\bar{t}$, beam	CDF: $0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$	$0.777^{+0.027}_{-0.042}$	5.3
		D0: $0.66 \pm 0.23(\text{stat} + \text{sys})$		5.4
Charge asymmetry	$p\bar{p} \to t\bar{t}$	CDF: $0.162 \pm 0.041(\text{stat}) \pm 0.022(\text{syst})$	0.06	8.7
		D0: 0.196 ± 0.065		5.4

F. Deliot

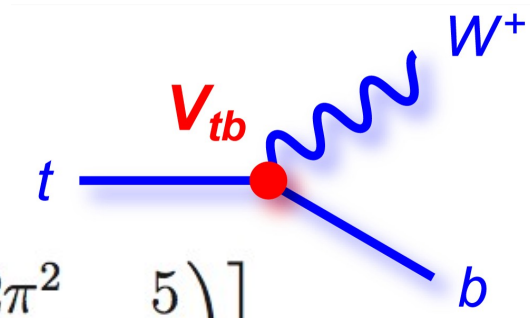
FCNC

Top quark behaves as predicted by SM

Backup

Top Quark Width

LO: $\Gamma_t^0 = \frac{G_F m_t^3}{8\pi\sqrt{2}}$

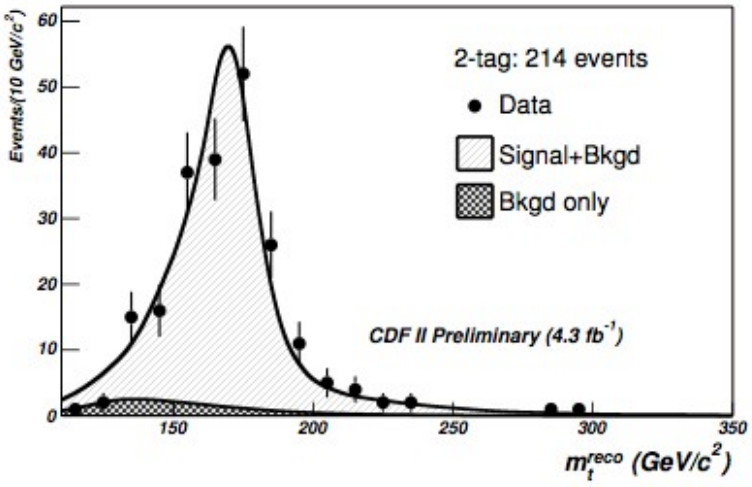


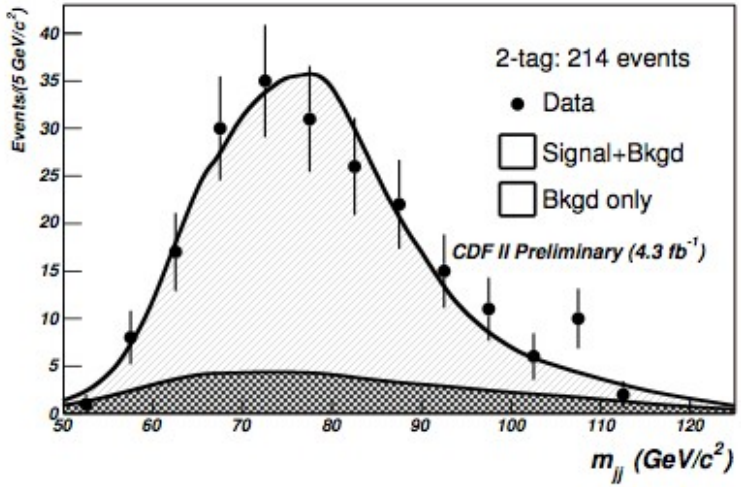
NLO: $\Gamma_t = \Gamma_t^0 \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right) \left[1 - \frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right]$

$\Gamma_t = 1.26$ GeV for $m_t = 170$ GeV

CDF Conference Note 10035

CDF : $\Gamma_t < 7.5$ GeV (2-dimensional template fit)

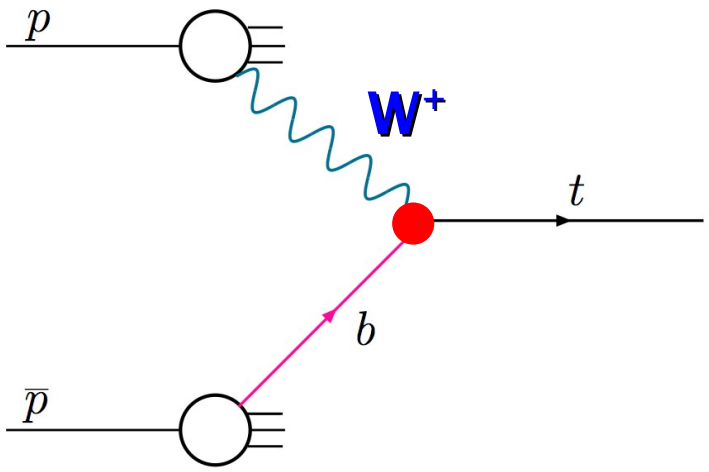




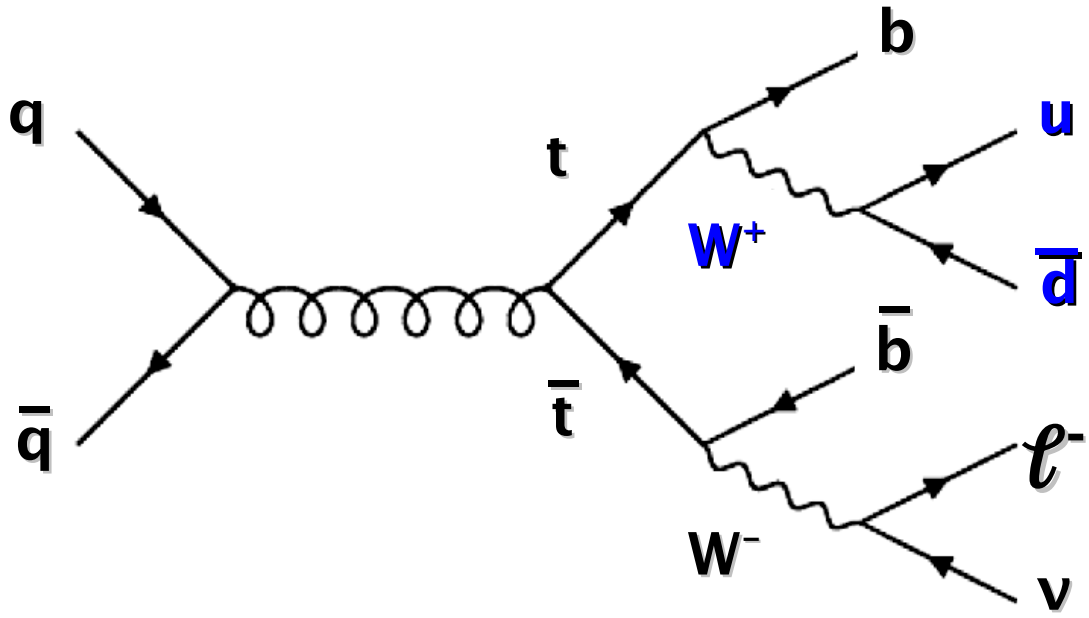
⟹ **model independent but not really sensitve**

Sensitivity to New Physics (I)

t-channel cross section:



branching ratio B(t→Wb):



$$\Gamma_t = \frac{\sigma(t\text{−channel})\ \Gamma(t \to Wb)_{\rm SM}}{\mathcal{B}(t \to Wb)\ \sigma(t\text{−channel})_{\rm SM}}$$

Combined Method

Source	$\sigma_{t\bar{t}}$ [pb]	Offset [pb]	$+\sigma$ [pb]	$-\sigma$ [pb]
Statistical only	7.58		+0.24	−0.24
Muon identification		−0.04	+0.05	−0.05
Electron identification		+0.14	+0.12	−0.12
Triggers		-0.09	+0.09	−0.11
Background normalization		+0.00	+0.07	−0.06
Signal modeling		−0.06	+0.23	−0.21
b-tagging		−0.14	+0.12	−0.12
Monte Carlo statistics		−0.01	+0.06	−0.06
Fake background		−0.01	+0.06	−0.04
f_H		−0.00	+0.02	−0.02
Jet energy scale		−0.03	+0.00	−0.00
Jet reconstruction and identification		+0.18	+0.18	−0.17
Luminosity		+0.12	+0.51	−0.44
Template statistics		+0.00	+0.03	−0.03
Other		+0.01	+0.14	−0.13
Total systematics			+0.65	−0.58
Fit result	7.78		+0.77	−0.64

m_{top} = 172.5 GeV

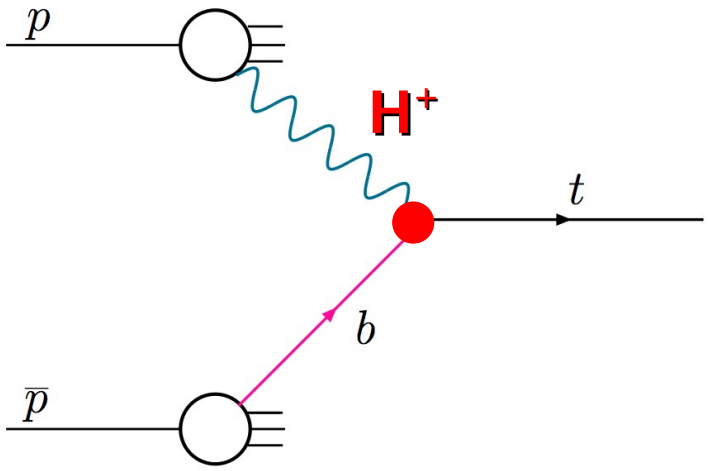
$$\sigma_{t\bar{t}} = 7.78^{+0.77}_{-0.64}\ \text{(stat+syst+lumi) pb}$$

±9%

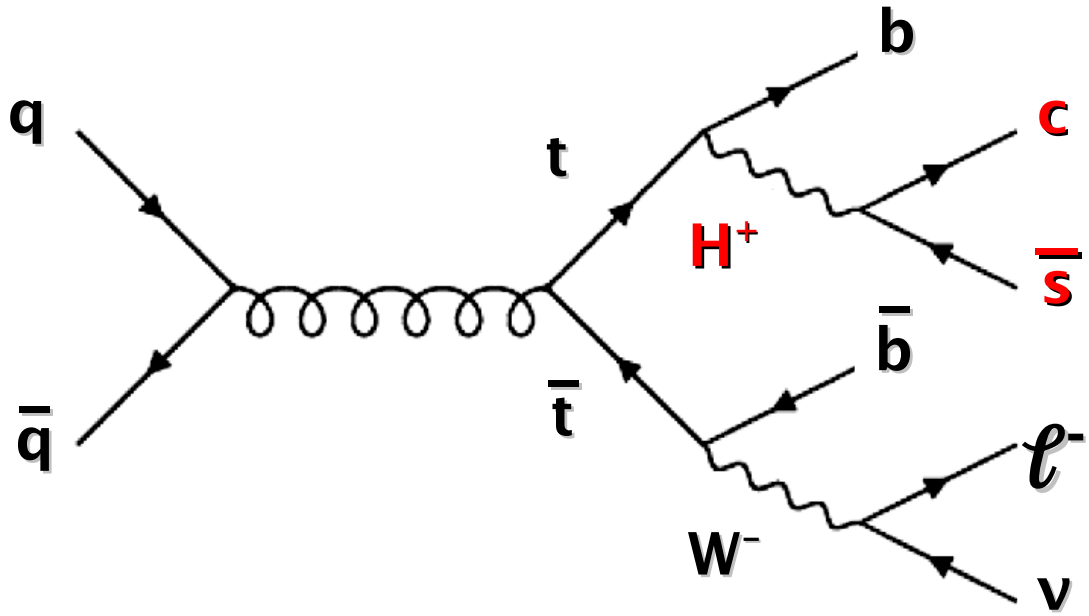
Sensitivity to New Physics (I)

example: charged Higgs with $m_{H+} < m_t - m_b$

t-channel cross section:



branching ratio B(t→Wb):

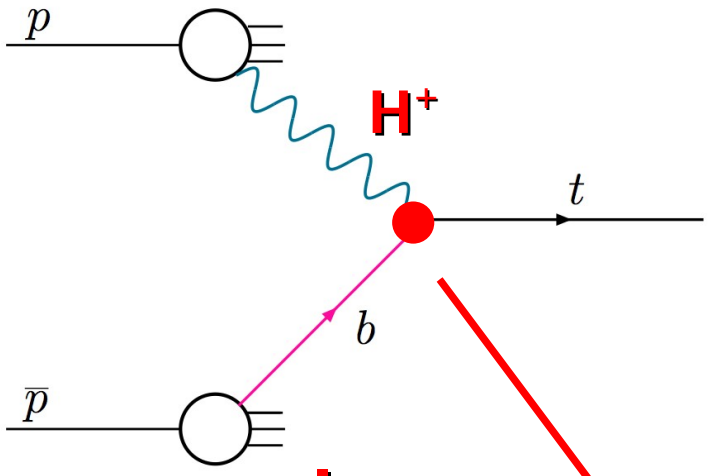


$$\Gamma_t = \frac{\sigma(t\text{−channel})\ \Gamma(t \to Wb)_{\mathrm{SM}}}{\mathcal{B}(t \to Wb)\ \sigma(t\text{−channel})_{\mathrm{SM}}}$$

Sensitivity to New Physics (I)

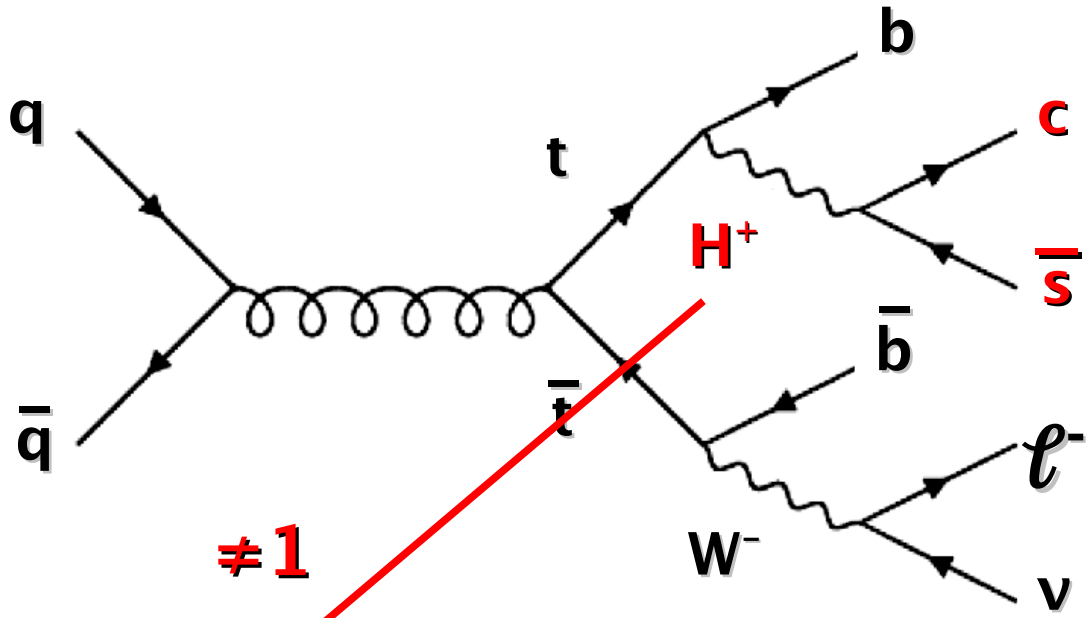
example: charged Higgs with $m_{H+} < m_t - m_b$

t-channel cross section:



larger

branching ratio B(t→Wb):



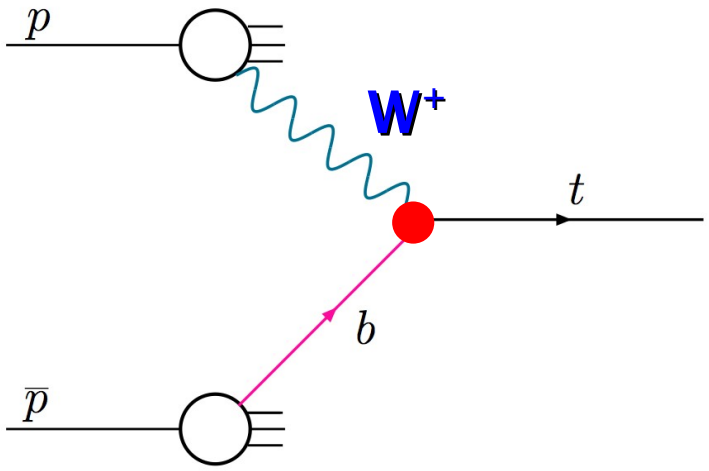
≠1

$$\Gamma_t = \frac{\sigma(t\text{−channel})\,\Gamma(t \to Wb)_{\mathrm{SM}}}{\mathcal{B}(t \to Wb)\,\sigma(t\text{−channel})_{\mathrm{SM}}}$$

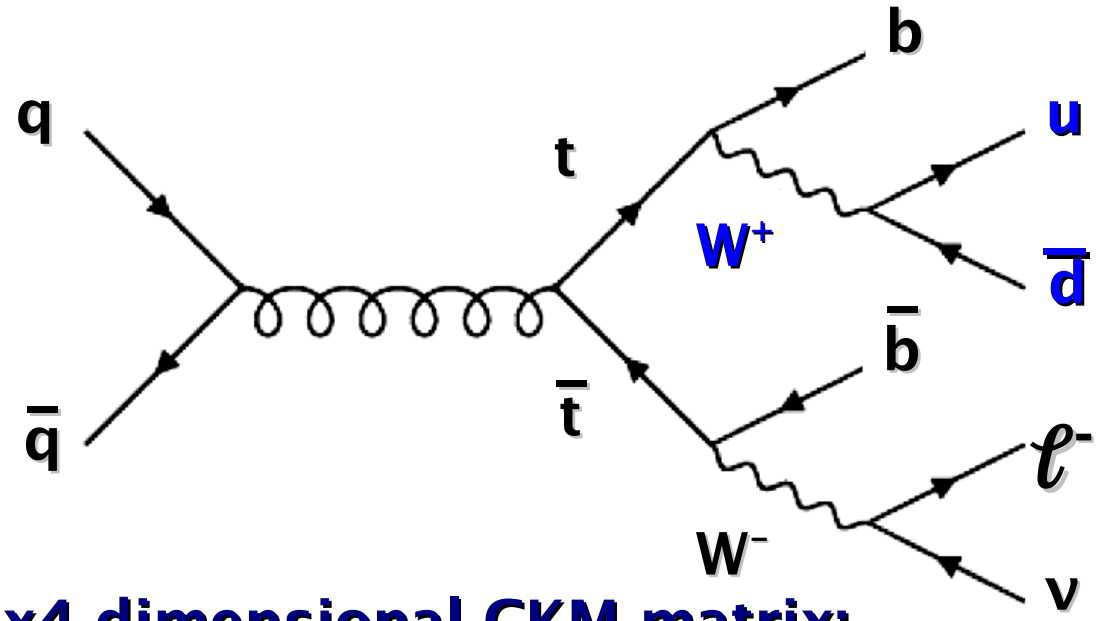
Sensitivity to New Physics (II)

example: 4th generation b' quark with $m_{b'} > m_t - m_W$

t-channel cross section:



branching ratio B(t→Wb):

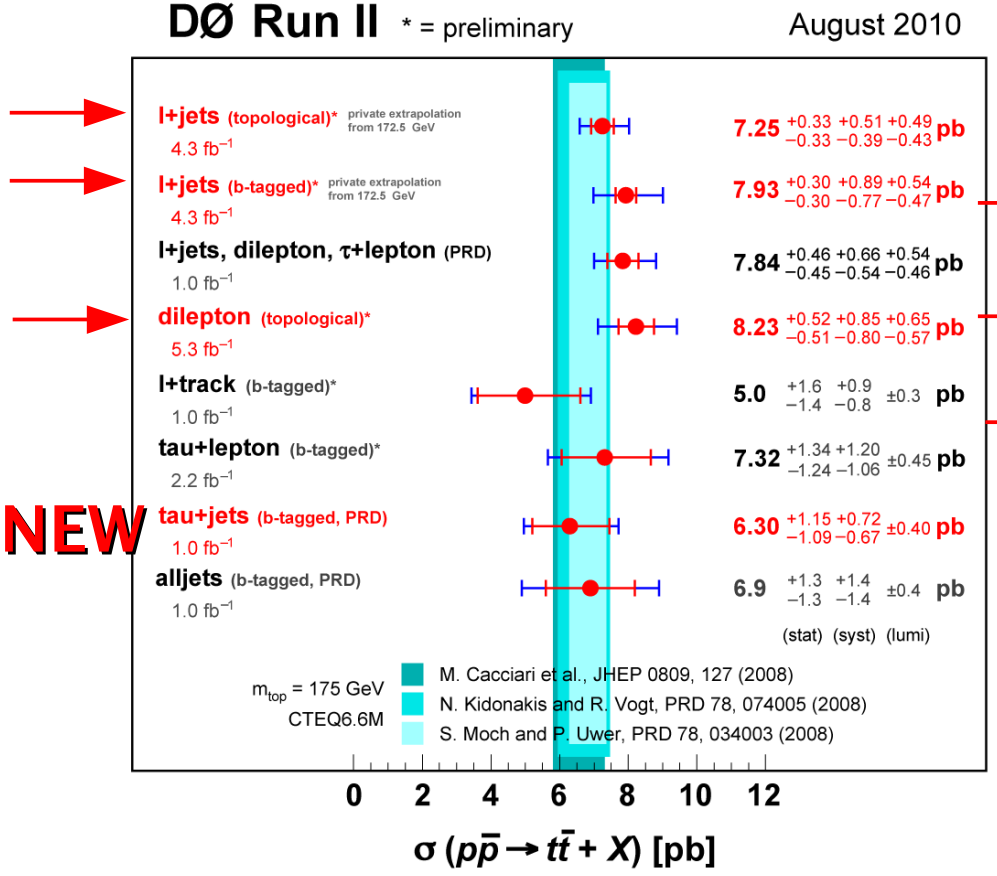


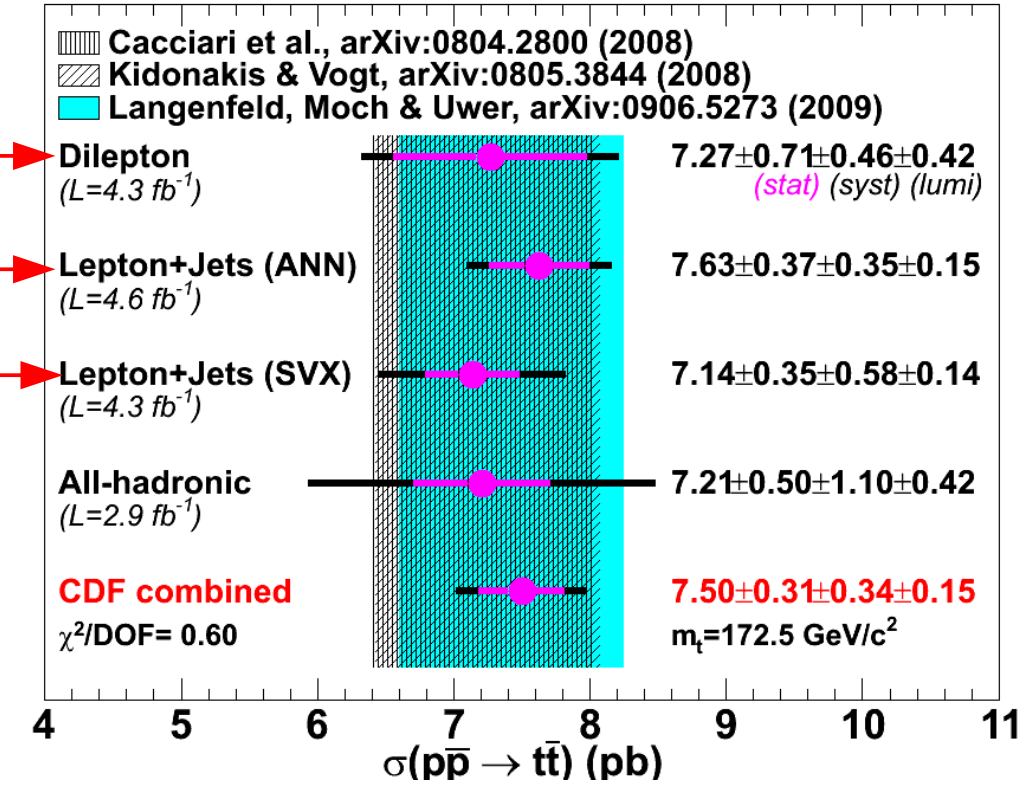
assume unitarity of the new 4x4 dimensional CKM matrix:
$|V_{tb}|^2 + |V_{tb'}|^2 = 1$ and $|V_{td}|$, $|V_{ts}|$ small
using a flat prior for $0 \leq |V_{tb}| \leq 1$

$$|V_{tb'}| < 0.59 \text{ at } 95\% \text{ C.L.}$$

first such limit

Top Pair Production Cross Sections





NEW MET+2, 3, ≥ 4 jets (orthogonal)

all channels measured except for τ_{had} τ_{had}

combination: ±6% !

⇒ **good agreement with SM in all channels**