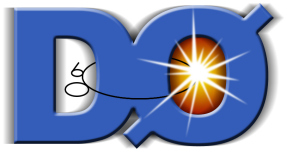
Searches for rare/BSM top decays (Tevatron)

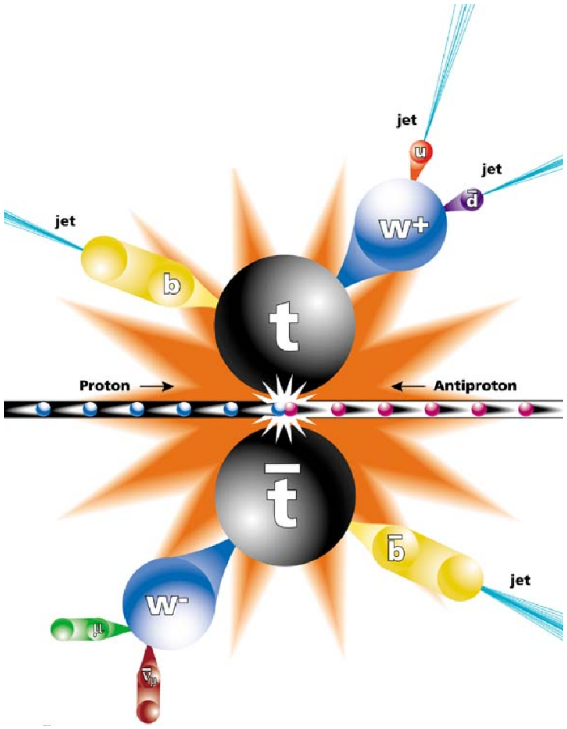


Daniel Wicke
Bergische Universität Wuppertal
for the CDF and DØ collaborations

Introduction and Outline

Top quark decay by modified interactions or new particles:

- EIm interaction $\rightarrow$ Charge, $tt\gamma$
- Weak interaction $\rightarrow$ Wtb, Ztq and Higgs
- BSM particles $\rightarrow$ Charged Higgs
- Strong interaction $\rightarrow$ Colour flow



go from rare to BSM to strong force

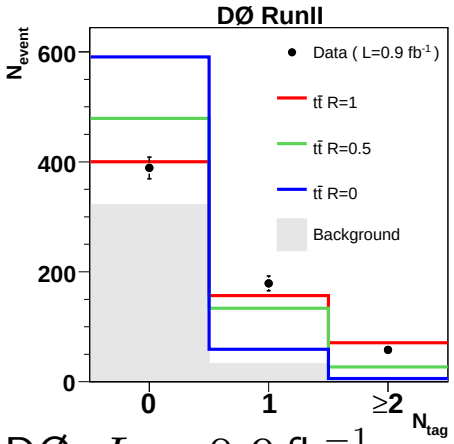
Top Quark Width

Significant BSM contributions should alter the top quark width (SM: $1.34\,\text{GeV}$)

Direct measurements — CDF

- Reconstructed top quark mass distribution $4.3\,\text{fb}^{-1} \rightarrow \Gamma_t < 7.5\,\text{GeV}$

Combination of Branching Fraction with t-channel Single Top — DØ



DØ, $L = 0.9\,\text{fb}^{-1}$

Top pairs: amount of 0,1 and 2 identified b-Jets

$$R = \frac{B(t \rightarrow Wb)}{B(t \rightarrow Wq)} = 0.97 \pm 0.09$$

Single Top:

$\Gamma_t = \Gamma_t(t \rightarrow Wb)/R$ with $\Gamma_t(t \rightarrow Wb) \propto \sigma_{1t,\ t-\text{channel}}$

$1 - 2.3\,\text{fb}^{-1}$: $\Gamma_t = 1.99^{+0.69}_{-0.55}\,\text{GeV}$

Gross picture of top quark decay as expected

Rare Processes

Photon Radiation in Top Pair Events CDF $6.0\,\mathrm{fb}^{-1}$

Semileptonic selection

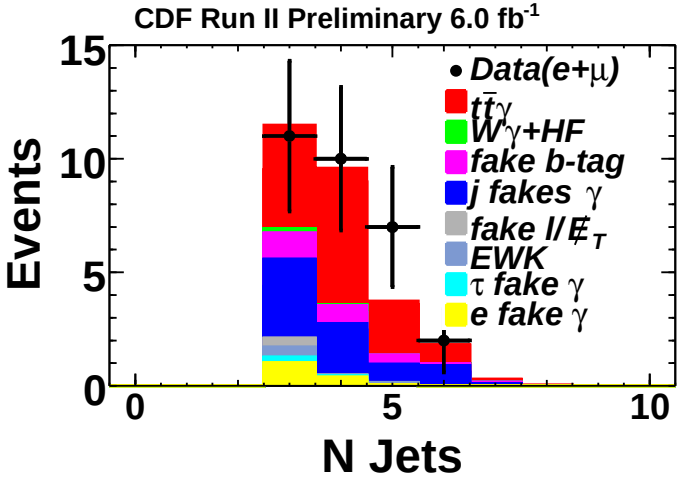
- lepton, $\not\!\!E_T$, at least 3 jets one b-tag
- $H_T > 200\,\mathrm{GeV}$

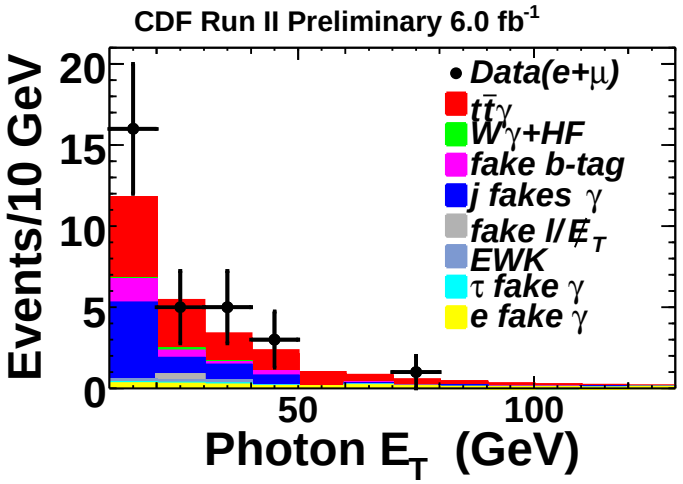
\+ isolated energetic photon

Background estimates

- photon fake rate from jets events (as function of $\not\!\!E_T$)
- rate of fake b-tags from $b\bar{b}$ configurations

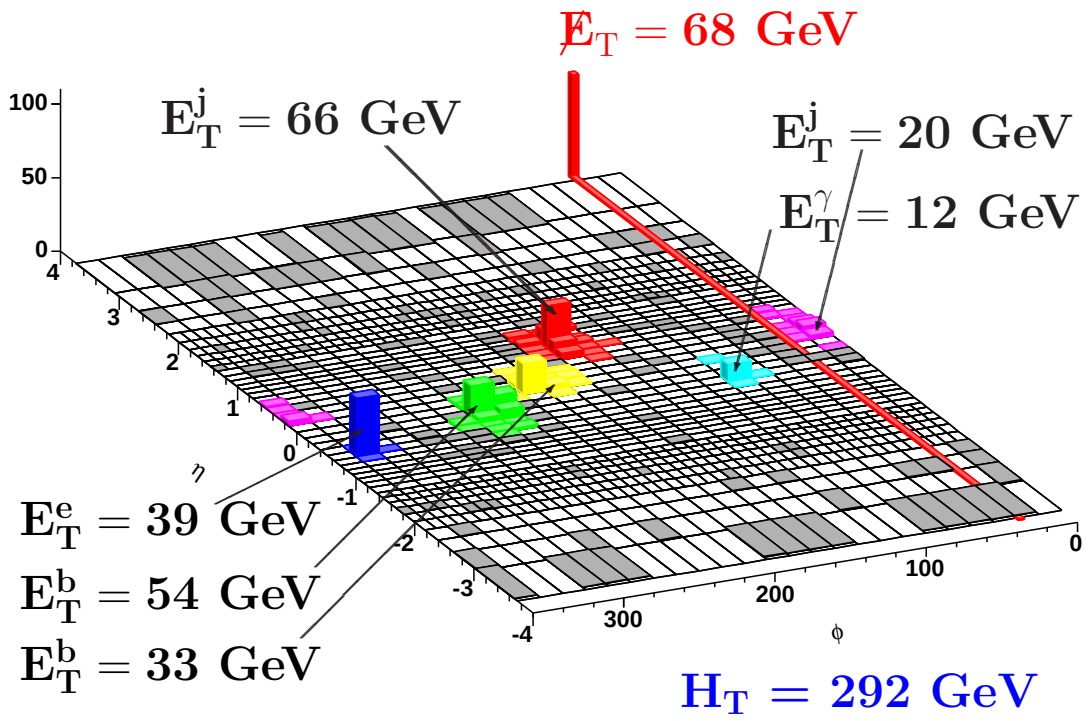
applied to events without photon/b-tag requirement, respectively





Photon Radiation in Top Pair Events (2) CDF $6.0\,\mathrm{fb}^{-1}$

A total of 30 candidate events observed

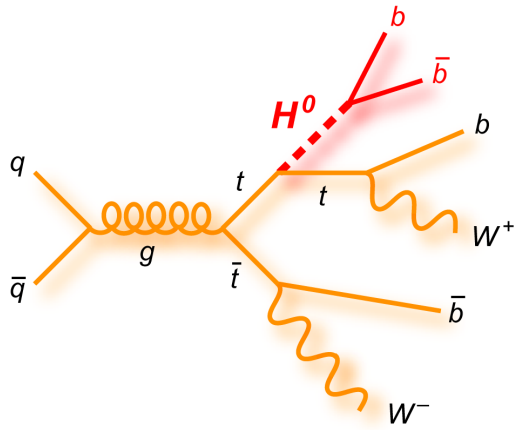


$\sigma_{t\bar{t}\gamma} = 0.18 \pm 0.08\mathrm{pb}$ SM: 0.17pb (NLO from Madgraph+K-faktor)

p-value: 0.0015 (3.0σ)

Associated Higgs Production

- Check of the top quark's Yukawa coupling
- Enhancements possible
  - in 2HDM (e.g. MSSM) for low $\tan\beta$
  - anomalous contributions to top-Yukawa coupling
  - in presence of a quark singlett T.

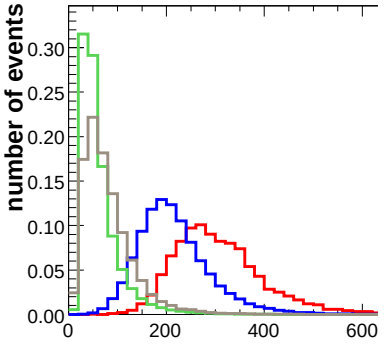


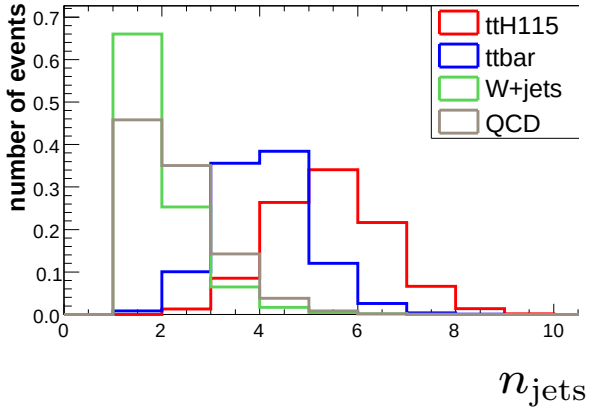
Signature

In semileptonic top decay ℓ, $\not\!\!E_T$, 4 b- and 2 light-jets

Signal to background discrimination

- DØ: H_T and n_{jets} most sensitive





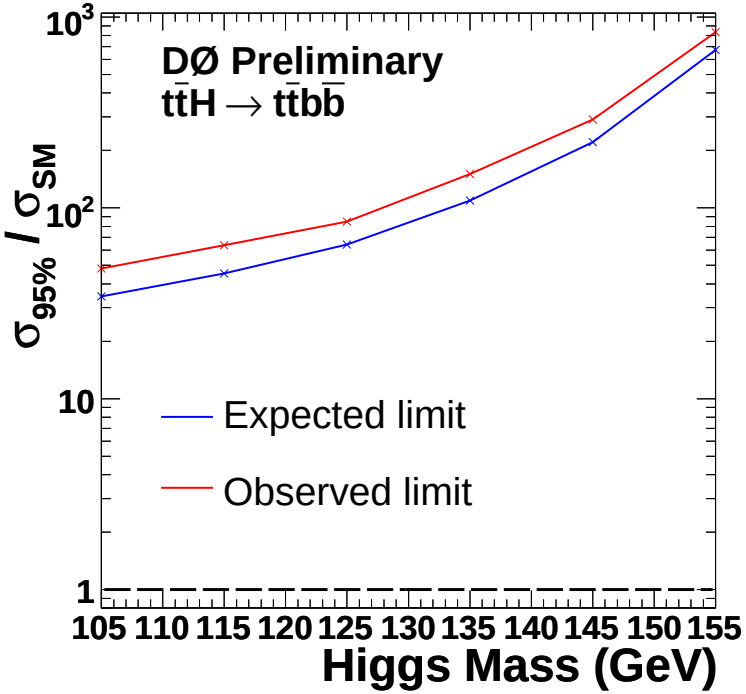
Associated Higgs

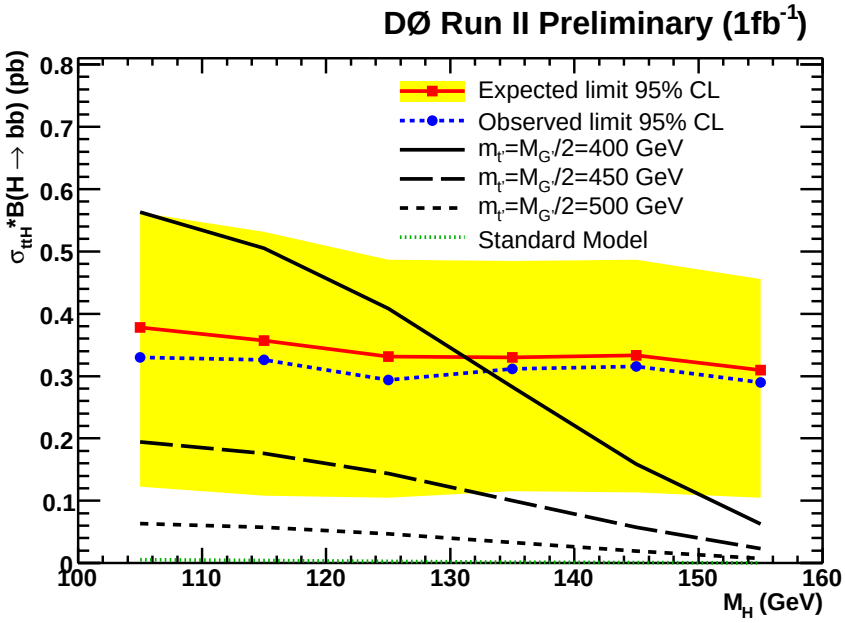
DØ, 2.1 fb^{-1}

$\ell, \not\!\!E_T$, at least 4 jets

- sub-channels 4, ≥ 5 jets
  1, 2, ≥ 3 b-tags

- Limits on $\sigma_{ttH}\mathcal{B}(H \to bb)$
- Compared to BSM models
  - Here: G' with t'





Associated Higgs

$\ell, \not\!\!E_T$, at least 4 jets

Signal to background discrimination

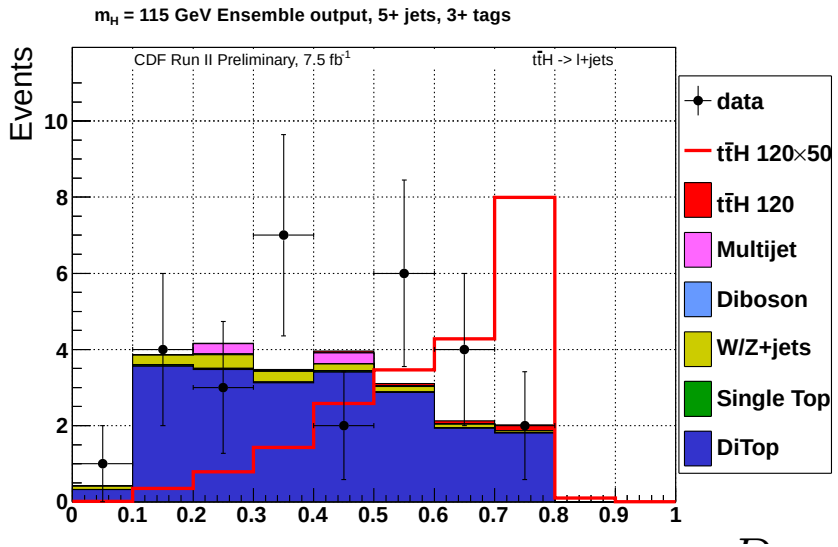
- Ensemble of neural networks
  - 1000 networks for each M_H value
  - each network with random set of 10 of 22 observables
  - including H_T and n_{jets}
- Combination of network outputs Supra-Bayesian method

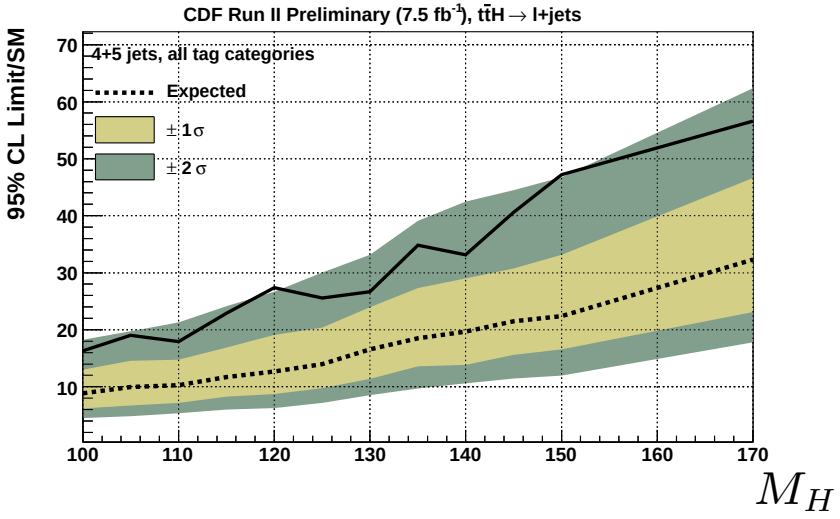
Major systematics:

- Process cross-section & JES

At $M_H = 115\,\text{GeV}$ exclude $> 22.9 \cdot \sigma_{\text{SM}}$

Lepton+jets CDF, $7.5\,\text{fb}^{-1}$





Associated Higgs

Nolepton CDF, $5.7\,\text{fb}^{-1}$

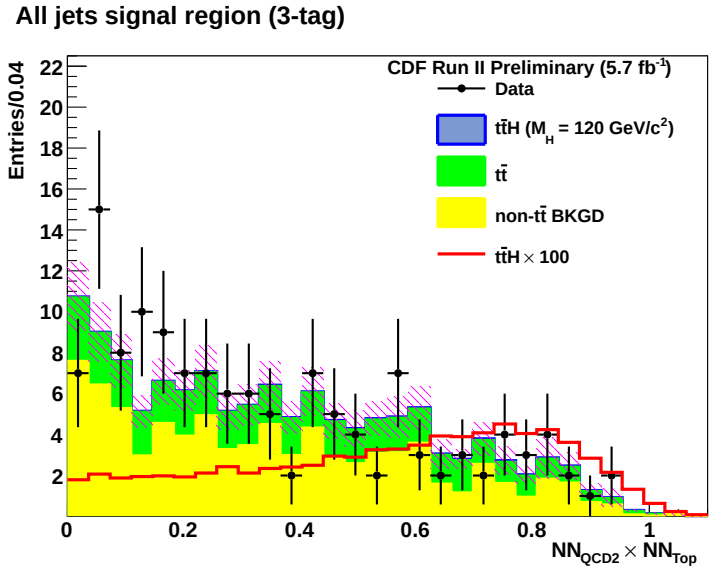
$\not\!\!E_T$, at least 5 jets (but no charged lepton)

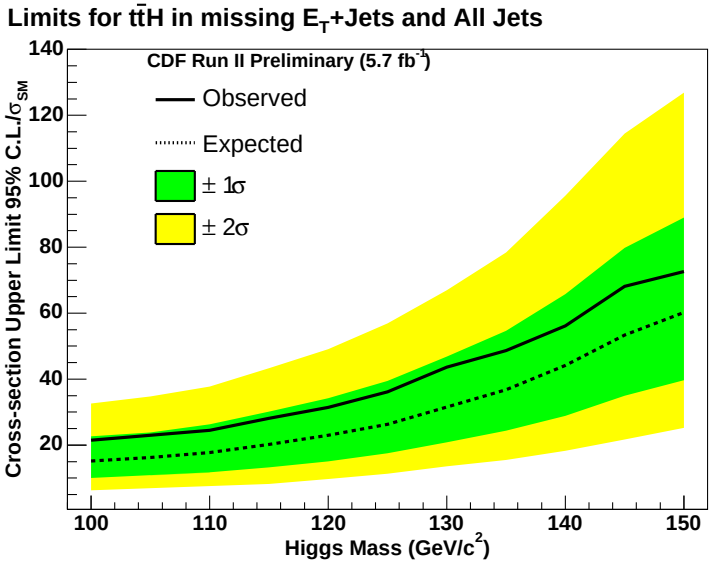
- $p_T > 50(40)\,\text{GeV}$ for (2nd) leading jet
- $H_T > 300\,\text{GeV}$
- Additional QCD suppression with NNs

Signal to background discrimination

- NN with 13 input variables

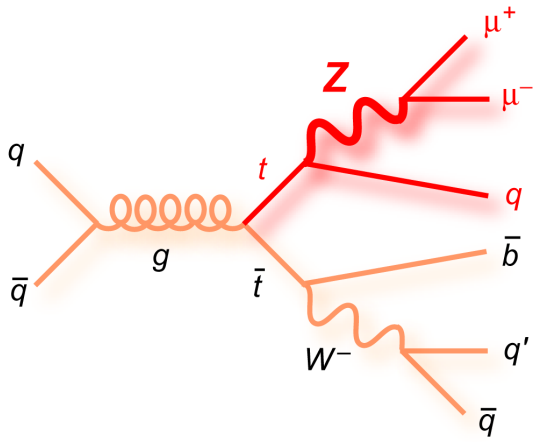
At $M_H = 115\,\text{GeV}$ exclude $> 28.1 \cdot \sigma_{\text{SM}}$





Flavour Changing Neutral Currents

- SM expects $B(t \to Zq) \sim 10^{-14}$
- BSM physics may yield measurable contribution



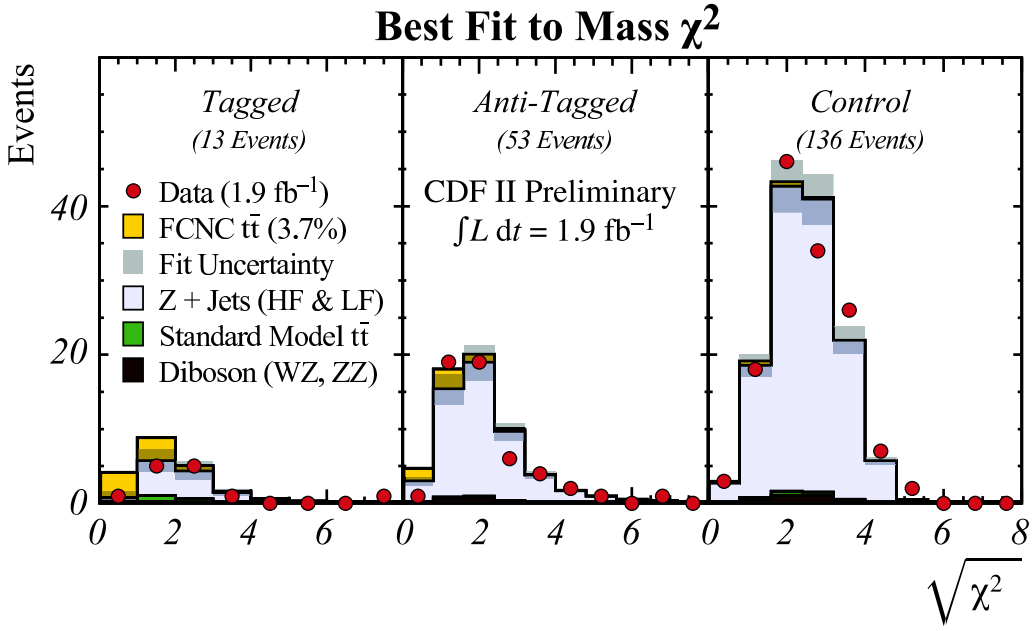
Dilepton Analysis, CDF $1.9\,\text{fb}^{-1}$

Selection: e^+e^- und $\mu^+\mu^- + 4$jets, $M_{\ell\ell} \approx M_Z$

Observable: χ^2 from mass constraints (Reconstructed Z, W and top masses)

Fit of signal and SM simulation to χ^2-distribution from data

$B(t \to Zq) < 3.7\%$ (95% C.L.)



Trilepton Analysis

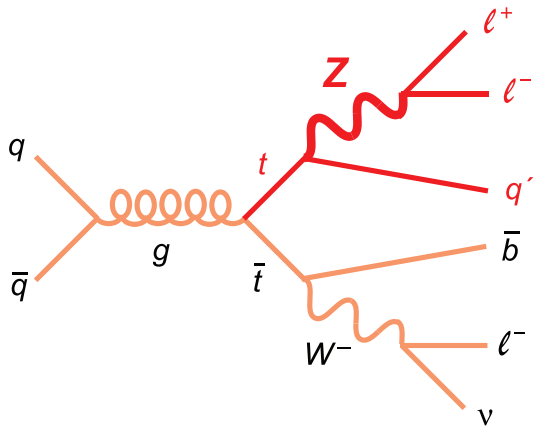
DØ $4.1\,\mathrm{fb}^{-1}$

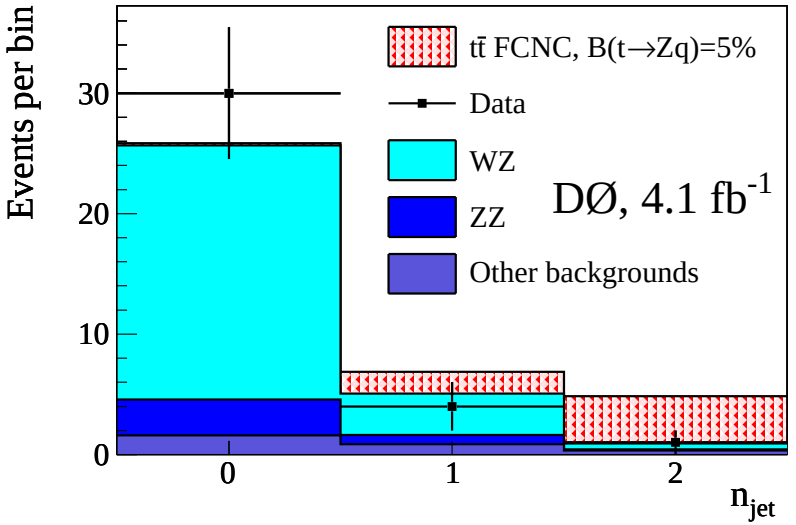
Selection: 3ℓ, $\not\!\!E_T$ and possibly jets.

- 4 channels: eee, $ee\mu$, $\mu\mu e$, $\mu\mu\mu$
- At least one $\ell^+\ell^-$ pair with $M_{\ell\ell} \approx M_Z$ (channel dependent distance cut)
- assignment of leptons to Z and W
  $\sim 100\%$ correct for $ee\mu$ and $\mu\mu e$
  $\sim 90\%$ correct for eee and $\mu\mu\mu$.

Background estimates

- WZ, ZZ and $t\bar{t}$ from simulation
- Z+jets and $Z\gamma$ contribution from data





Trilepton Analysis (2)

DØ $4.1\,\mathrm{fb}^{-1}$

Signal to background separation

- H_T
- $m_t^{\mathrm{rec}} = M(\ell^+\ell^- j)$

  use jet that yields m_t^{rec} closest to $172.5\,\mathrm{GeV}$

Result

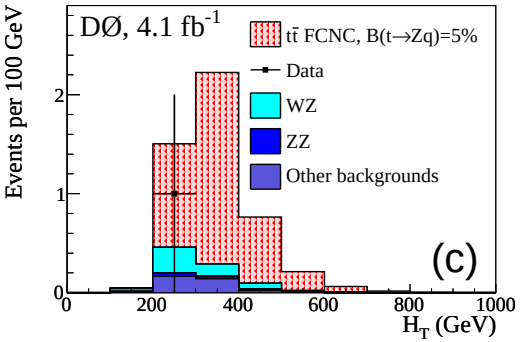
$B(t \to Zq) < 3.2\%$

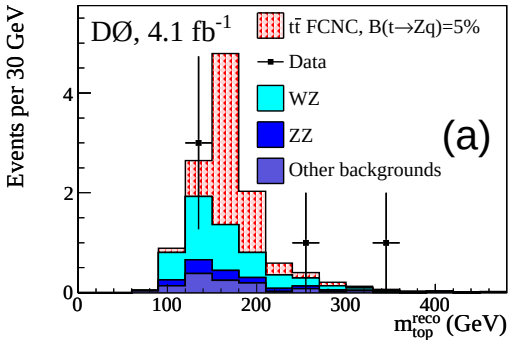
Expected $B(t \to Zq) < 3.8\%$

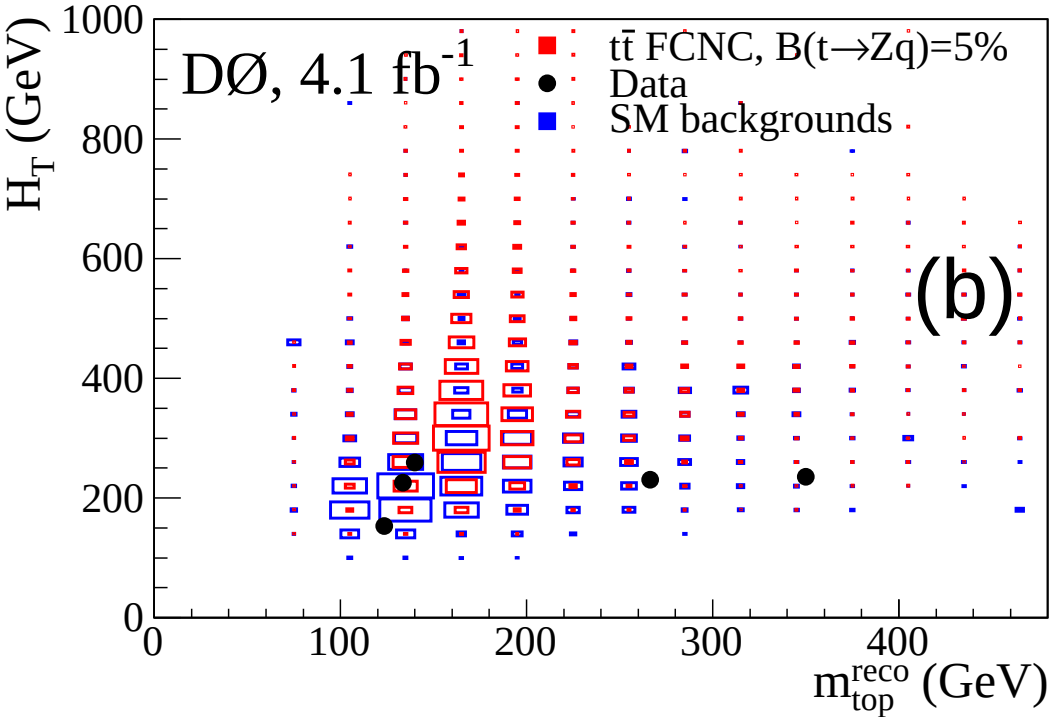
Couplings

$v_{tqZ} < 0.19 \quad (q = u, c)$

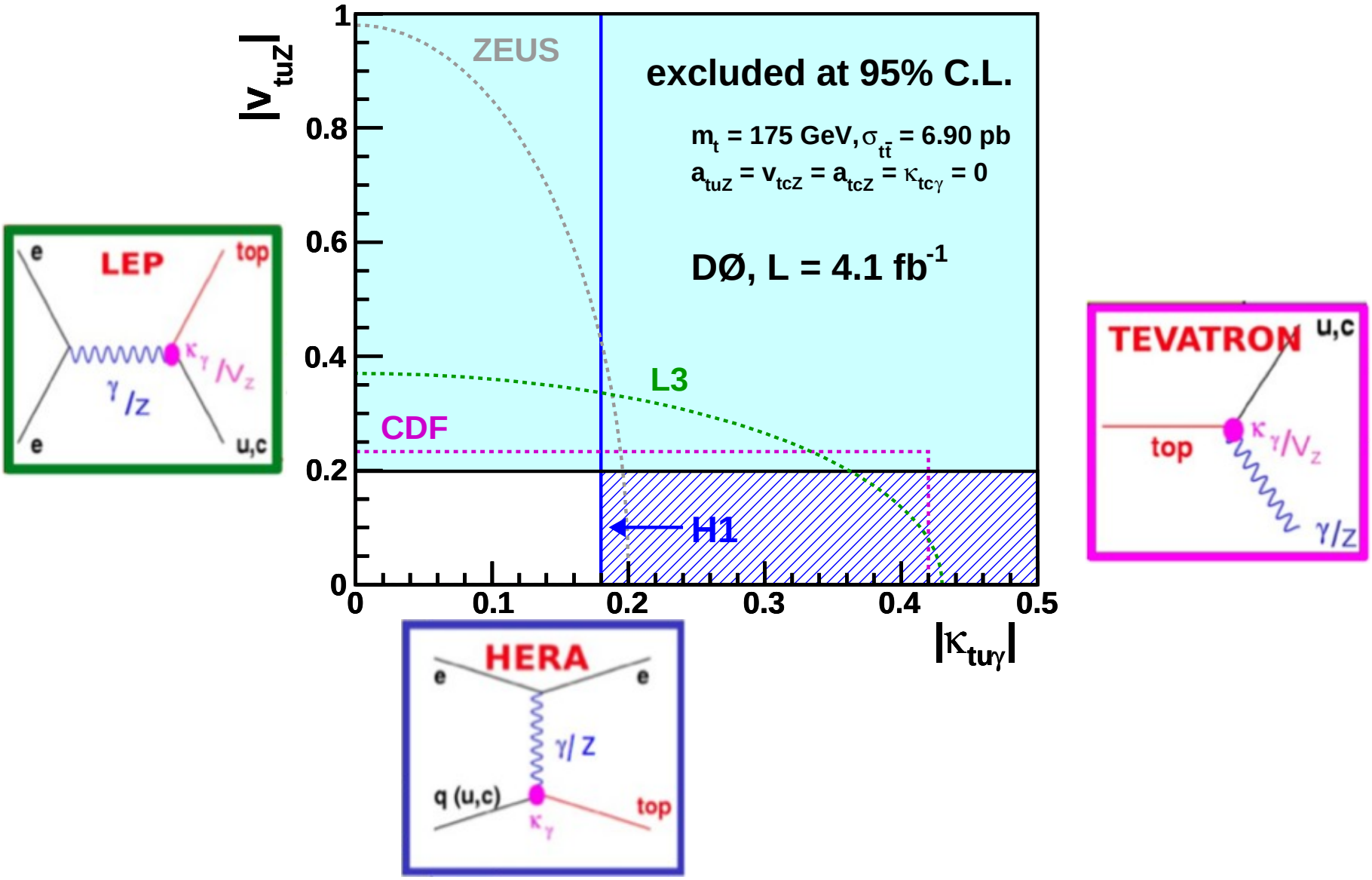
for only one non-vanishing coupling







Summary of FCNC in Top Quark Decays



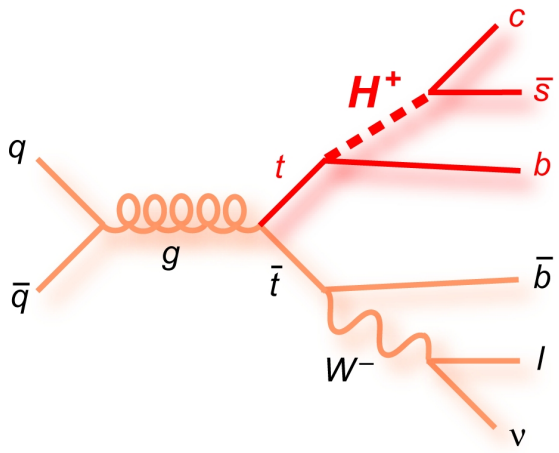
BSM Particles

Decay to Charged Higgs Boson

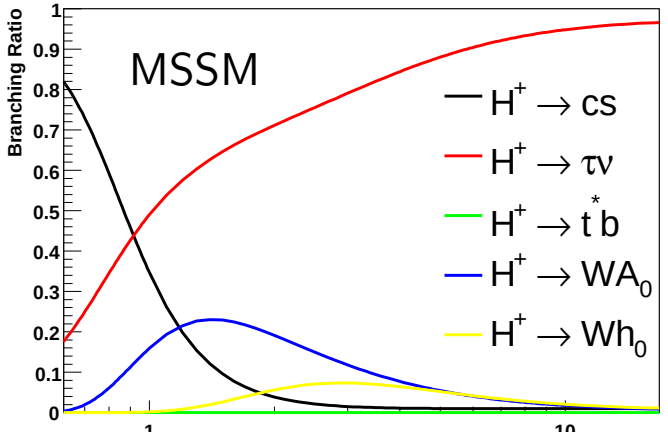
New particles in the decay alter deduced $\sigma_{t\bar{t}}$ depending on decay channel

$$\sigma^{C}_{t\bar{t}} = \sigma_{t\bar{t}} \cdot \frac{B^{\mathrm{BSM}}(t\bar{t} \to C)}{B^{\mathrm{SM}}(t\bar{t} \to C)}$$

$C = \ell$+jets, Dilepton, tauonic



- Check cross-section ratios
- Consider decay $t \to bH^{\pm}$
  - with $H^{\pm} \to cs$, leptophobic $H^{\pm}$
  - with $H^{\pm} \to \tau\nu$, tauonic $H^{\pm}$
- Within MSSM relevant
  - leptophobic: at low $\tan\beta$
  - tauonic: at high $\tan\beta$



$\tan\beta$

Leptophobic Charged Higgs

DØ $1\,\mathrm{fb}^{-1}$

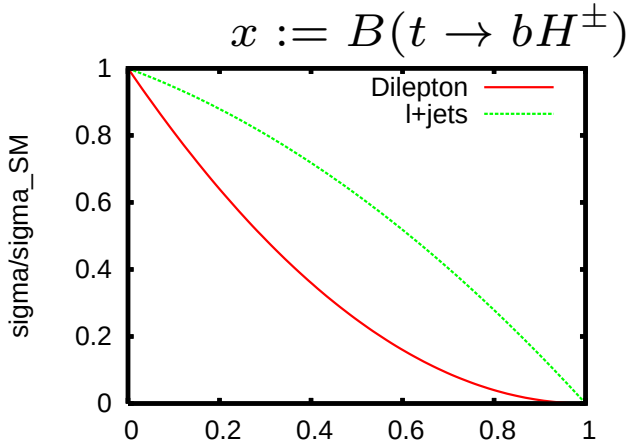
Sensitivity from semileptonic to dilepton cross-section

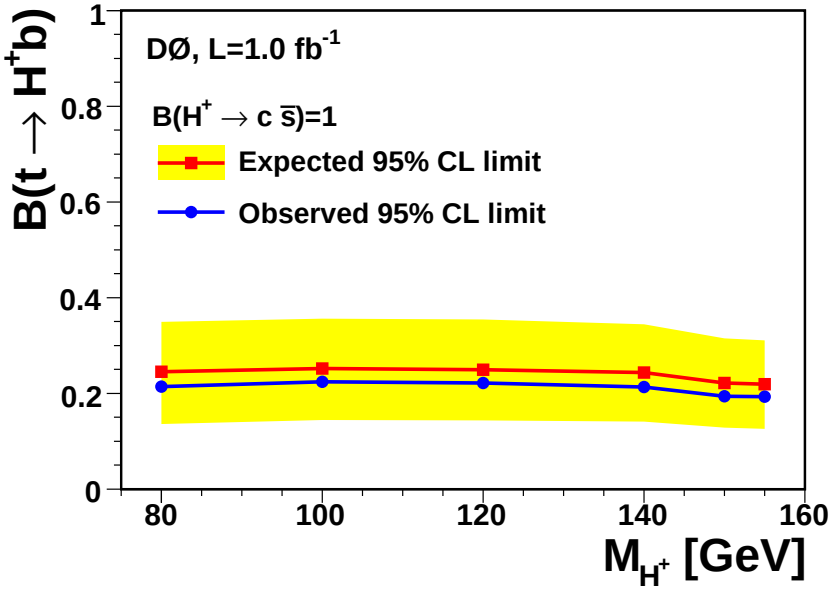
- $B(H^{\pm} \to cs) = 100\%$
  - semileptonic decay enhanced
  - dileptonic decay reduced
- fix $\sigma_{t\bar{t}}$ at nominal value (7.48pb)
- maximise likelihood wrt $B(t \to bH^{\pm})$

Dominating systematics:

- uncertainty of assumed $\sigma_{t\bar{t}}$, luminosity and b-tagging

Limits obtained w/ Feldman-Cousins:





Leptophobic Charged Higgs

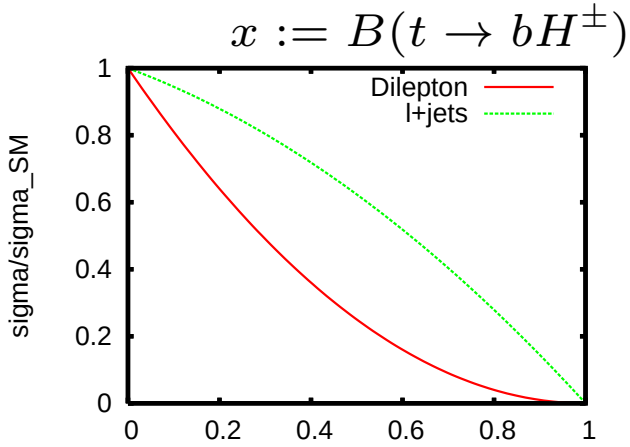
DØ 1 fb^{-1}

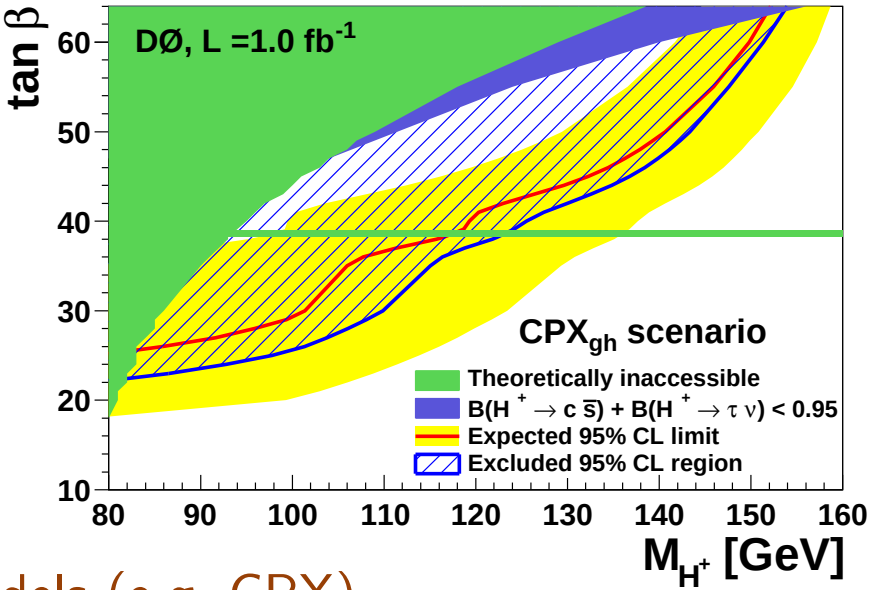
Sensitivity from semileptonic to dilepton cross-section

- $B(H^{\pm} \to cs) = 100\%$
  - semileptonic decay enhanced
  - dileptonic decay reduced

- fix $\sigma_{t\bar{t}}$ at nominal value (7.48pb)

- maximise likelihood wrt $B(t \to bH^{\pm})$





Dominating systematics:

- uncertainty of assumed $\sigma_{t\bar{t}}$, luminosity and b-tagging

Limits obtained w/ Feldman-Cousins

... transfered to exlcusions for specific models (e.g. CPX)

Leptophobic Charged Higgs

CDF $2.2\,\mathrm{fb}^{-1}$

Bump search in dijet mass in ℓ+jets

- Reconstruct (fit) decay kinematics w/ contraints
  - top quark mass
  - leptonic W-mass
- Fifth jet in p_T joined with closest other jet if $\Delta R < 1.0$

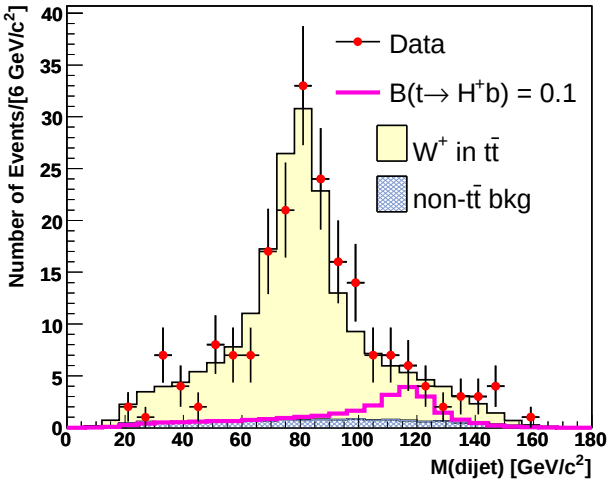
$\Rightarrow$ Obtain M(dijet) with assignment of best χ^2

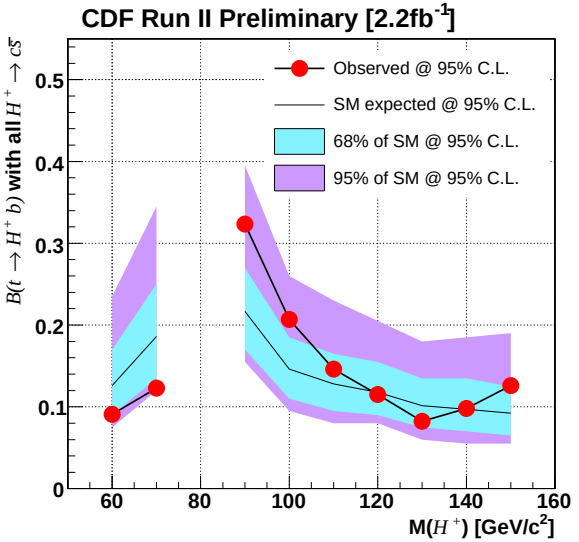
- Binned likelihood to extract $B(t \to bH^{\pm})$

Dominating uncertainties

- Simulation
- JES (for $M_{H^{\pm}} \simeq M_W$)

Limits also applicable to $H^{\pm} \to ud$



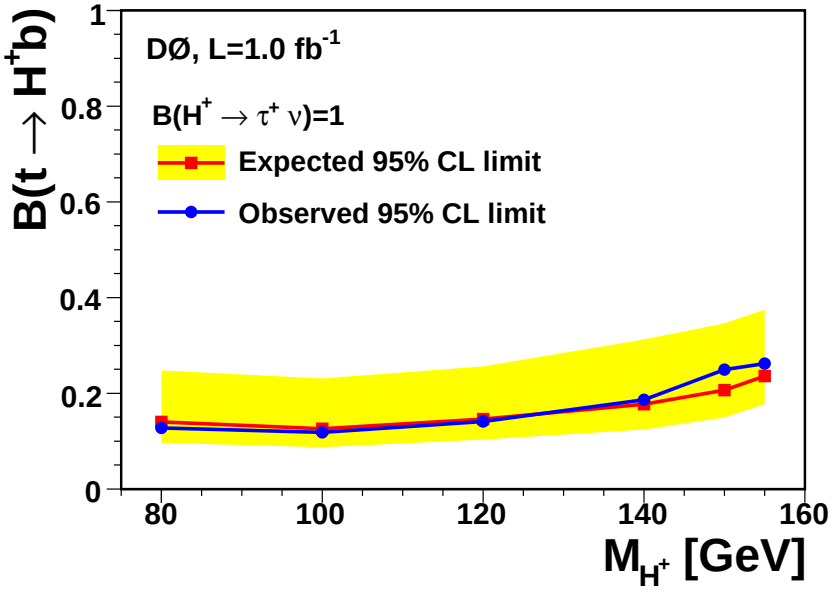


Tauonic Charged Higgs

DØ $1\,\mathrm{fb}^{-1}$

Differences between dilepton and lepton+τ yields sensitivity to total cross-section

- maximise likelihood simultaneously wrt $B(t \to bH^{\pm})$ and $\sigma_{t\bar{t}}$
- reduces assumptions



Systematics:

- luminosity reduced
- multijet description dominates

Limits w/ Feldman-Cousins for a range of $M_{H^{\pm}}$

CP Odd Higgs

CDF 2.7 fb^{-1}

In next-to-minimal SSM additional CP-odd Higgs bosons occur

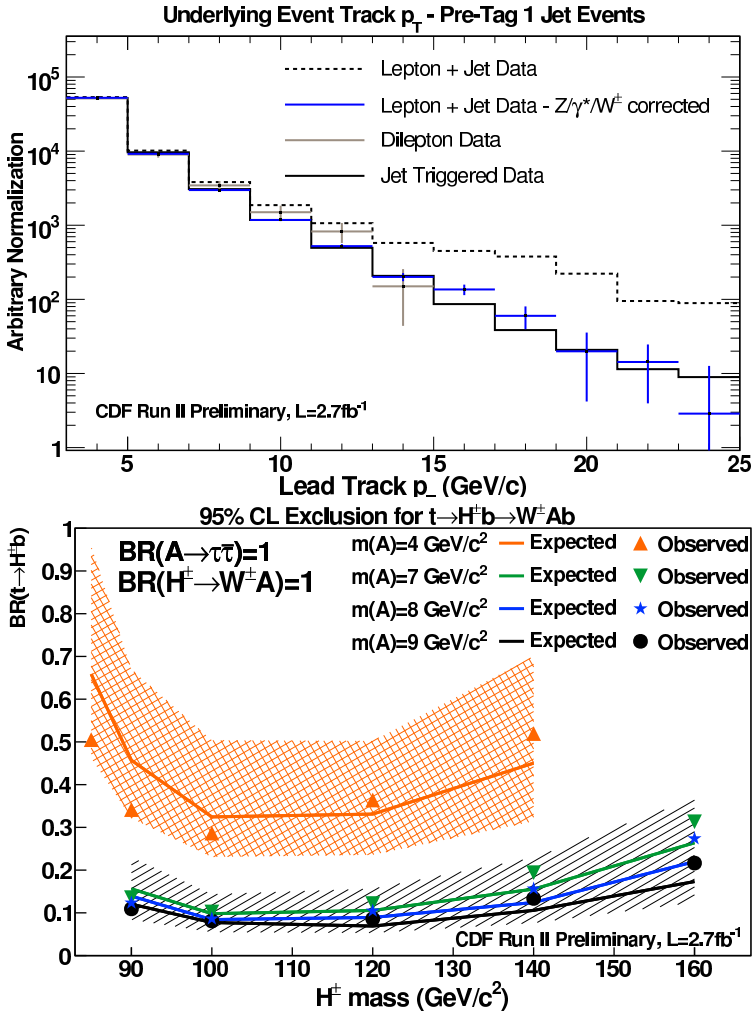
$t \to H^{\pm} b \to W^{\pm} a_1^0 b$

- for $m_{a_1^0} < 2m_b$ likely decay is $a_1^0 \to \tau^+\tau^-$
- decay products have low momenta
  $\Rightarrow$ undetected in other $t\bar{t}$ analyses

Analysis

- $t\bar{t}$ semileptonic selection
- require additional soft tracks (from taus)
- cross-checks for soft tracks in control regions

Limits on $B(t \to bH^{\pm})$ for various m_a



Colour Flow in Top Pair Decays

Verify colour singlet structure of hadronically decaying W in top decays

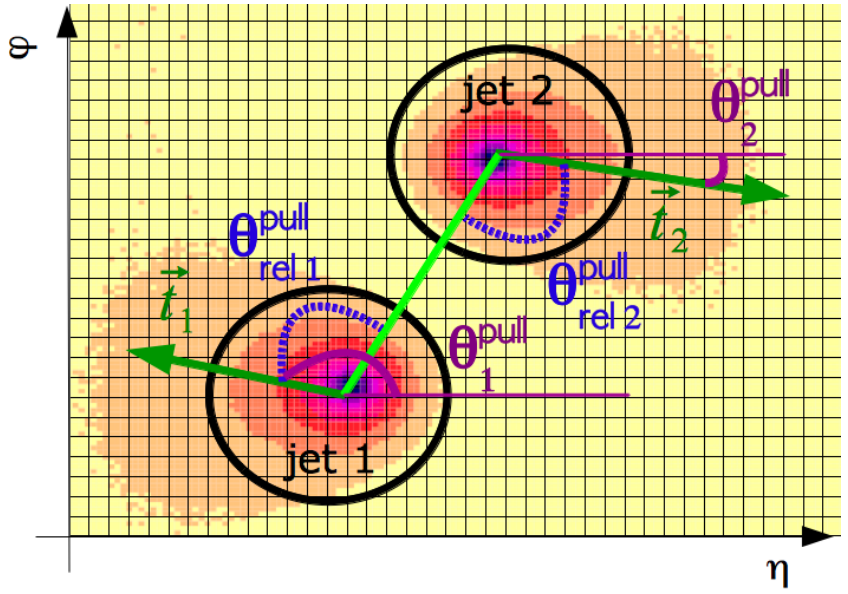
- distinguish from colour octet
- applicable to separate e.g. $Z(H \to b\bar{b})$ from $Z(g \to b\bar{b})$

Observables

Jet Pull:
Sum energy and distance weighted cell directions (in η and φ)

$$\vec{t} = \frac{1}{E_T^{\text{jet}}} \sum_{\text{Cal.cells}} E_{T,i} \, |r_i| \, \vec{r}_i$$

Relative Jet Pull:
Angle between $\vec{t}$ and connection to additional jet: $\theta^{\text{pull}}_{\text{rel},i}$.



Color Flow Analysis

Selection

- Consider ℓ+jets sample with 2 (loose) b-tags
- 90% pure top pairs

Signal expectaton:

- W-jets point to each other
- b-jets point away from each other

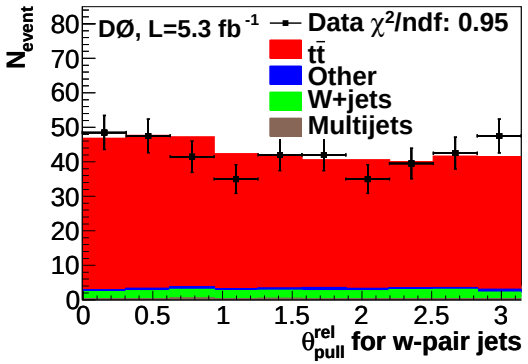
Control sample rather flat.

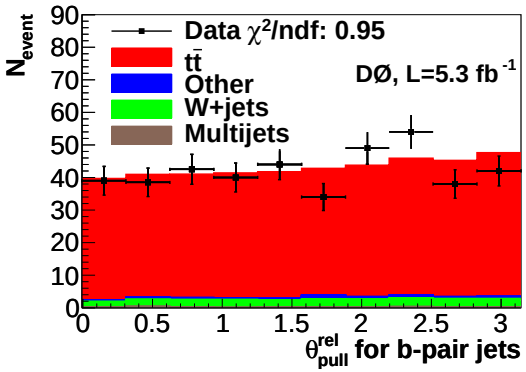
Rel. jet pulls shows qualitatively expected behaviour

Signal sample: no b-tags

w-pairs b-pairs

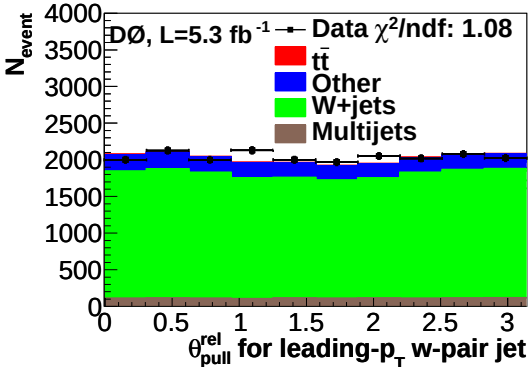
$|m_{jj} - M_W| < 30$ GeV

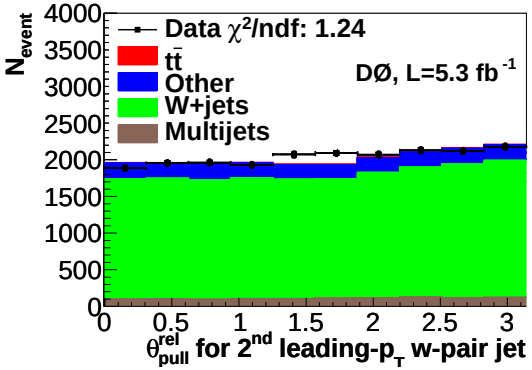




Control sample: no b-tags

$\theta_{\mathrm{rel}}^{\mathrm{pull}}$ of leading jet second leading jet



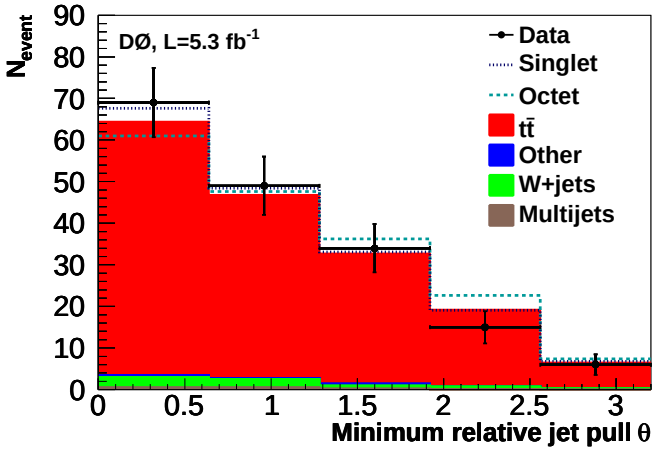


Color Flow: Result

D0 $5.3\,\mathrm{fb}^{-1}$

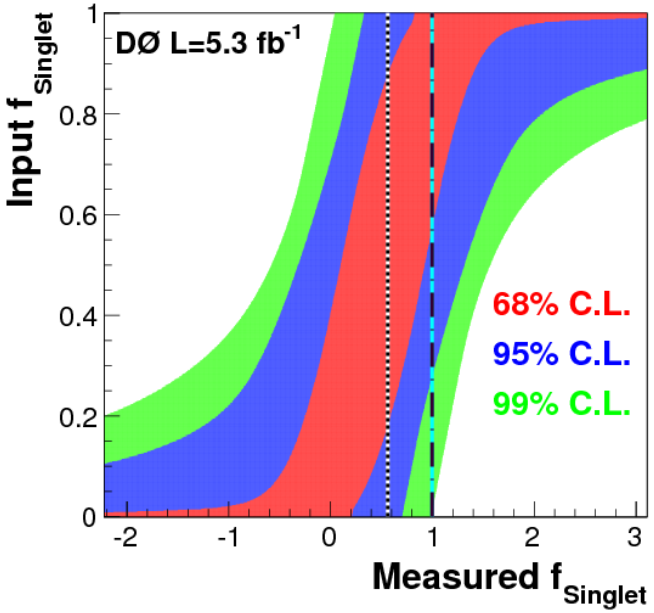
Selection of $\theta^{\mathrm{pull}}_{\mathrm{rel}}$:

- $\Delta R > 2$: $\theta^{\mathrm{pull}}_{\mathrm{rel}}$ of leading p_T jet
- $\Delta R < 2$ both $|\eta_d| < 1$: use smaller $\theta^{\mathrm{pull}}_{\mathrm{rel}}$.
- $\Delta R < 2$ one $|\eta_d| < 1$: $\theta^{\mathrm{pull}}_{\mathrm{rel}}$ of jet with $|\eta_d| < 1$.



Dominating Systematics

- Signal shapes (**1** vs. **8**): $\delta f_{\mathrm{Singlet}} = \pm 0.118$
- Jet pull reconstruction: $\delta f_{\mathrm{Singlet}} = ^{+0.100}_{-0.093}$



Simultaneously determine singlet vs octet fract. and top quark pair cross-section

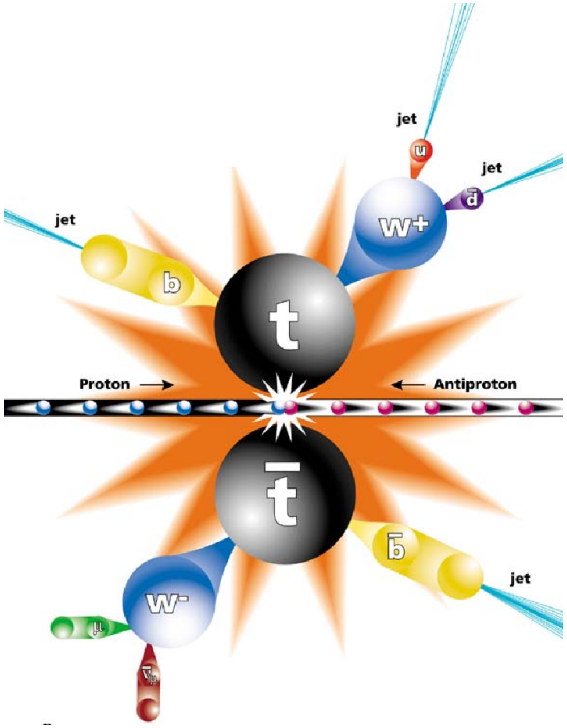
$$f_{\mathrm{Singlet}} = 0.56 \pm 0.36_{\mathrm{stat}} \pm 0.22_{\mathrm{syst}}$$

consistent with SM $f_{\mathrm{Singlet}} = 1$

Summary and Conclusions

Searches for rare and BSM top quark decays

- Top Quark Width (35% uncertainty)
- Rare processes
  - Photon radiation in top pairs (3σ evidence)
  - ttH ($\sigma_{\mathrm{Limit}} \lesssim 23\sigma_{\mathrm{SM}}$ at $M_H = 115\,\mathrm{GeV}$)
  - FCNC in top decays ($B < 3.2\%$)
- Decays with BSM particles
  - Charged Higgs ($B \lesssim 10...20\%$)
- Colour structure



Top quark decay is verified to the few percent level