Searches for New Physics in the Top Quark Samples at CDF

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ATLAS CSC T7 MEETING

(Talk given in SUSY07 on behalf of the
CDF Collaboration → arXiv:0709.2264v1 [hep-ex])

MOTIVATION

Top is MASSIVE $\mathbf{M_{TOP}}$ = 170.9 ± 1.8 GeV/c^2 (TEWG hep-ex/0703034)

Decays before hadronization $\Gamma_t = 1.4\,GeV \Rightarrow \tau/\Gamma_t \approx 5\times10^{-25}s << \tau/\Lambda_{QCD} \approx 3\times10^{-24}s$

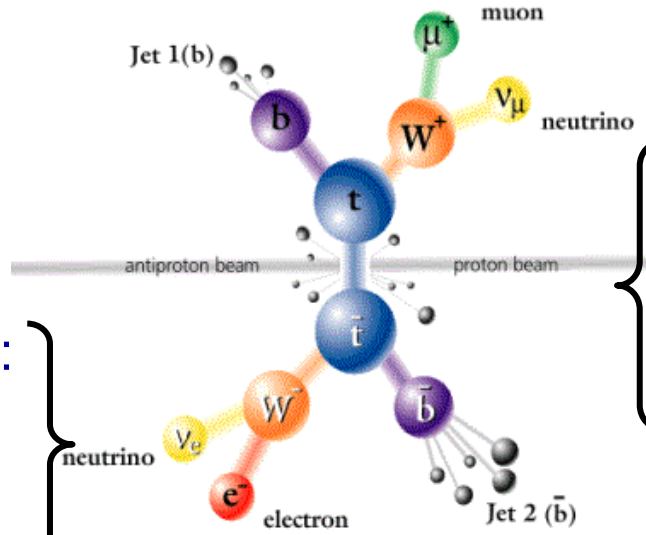
→Spin information transferred to decay products

Special role in EWSB?

→Top Yukawa coupling to Higgs is "natural" (~1)

→M_{top} together with M_W constrains M_{Higgs}

New physics in the top quark samples ?



Searches in the production:

σ_{tt} , $\sigma(gg\rightarrow tt)/\sigma(qq\rightarrow tt)$

$Z' \rightarrow tt$

$t' \rightarrow Wb$

Searches in the decay:

Top charge.

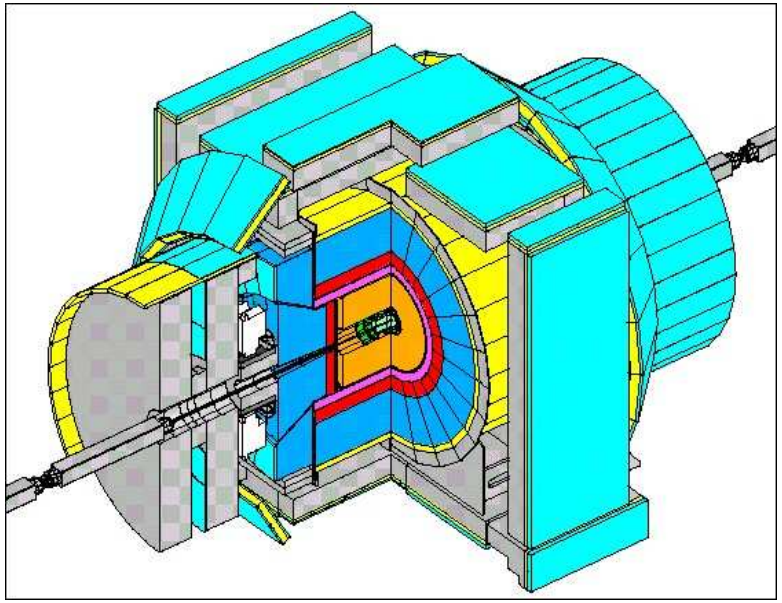
FCNC $t\rightarrow Zq$

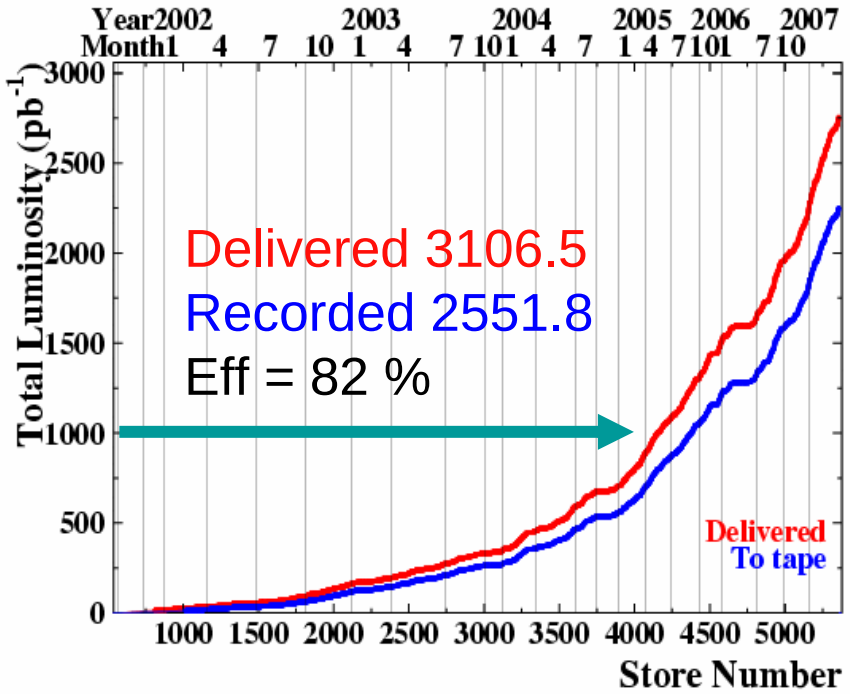
W helicity

THE EXPERIMENTAL SETUP

- The CDF II detector:
  - Excellent tracking system:
    - Drift chamber: Central Outer Tracker.
    - Inner silicon detector: → essencial for b-tagging and vertexing.
  - EM and HAD calorimeters.
  - MUON systems.

- TEVATRON RUN II:
  - Proton-Antiproton Synchrotron
  - $\sqrt{s}$ = 1.96 TeV
  - Aim for 6-8 fb^{-1} by 2009.
- Searches for new physics in ~1 fb^{-1} top quark samples



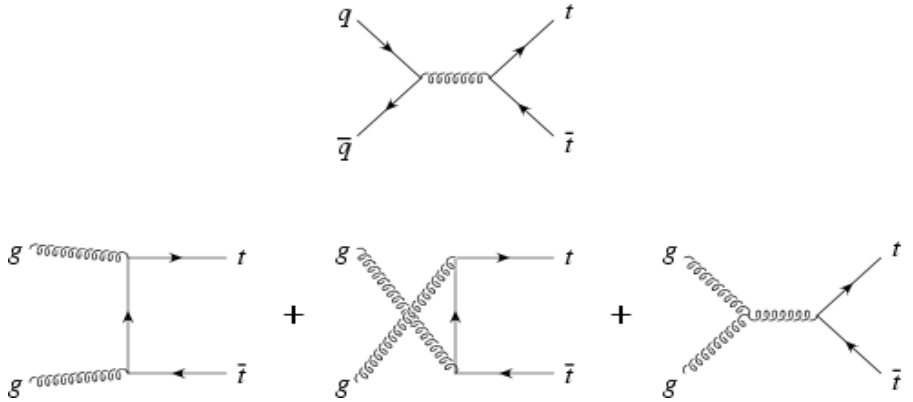


TOP PHYSICS require a good understanding of the entire detector

TOP QUARK PRODUCTION & DECAY

Produce in pairs via strong interaction

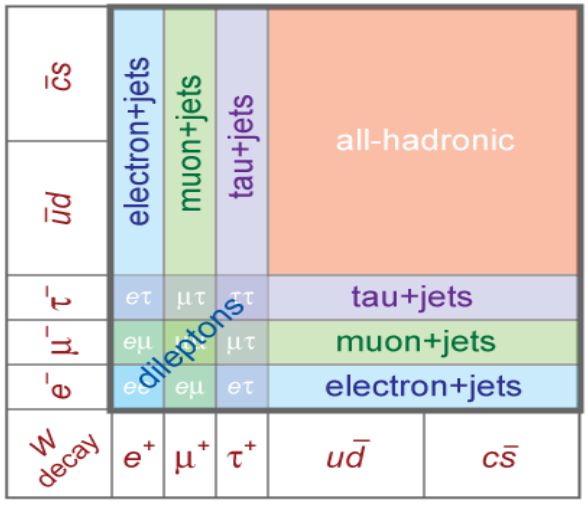
At √s=1.96 (14) TeV:
85 (10) ±5% qq
15 (90) ±5% gg



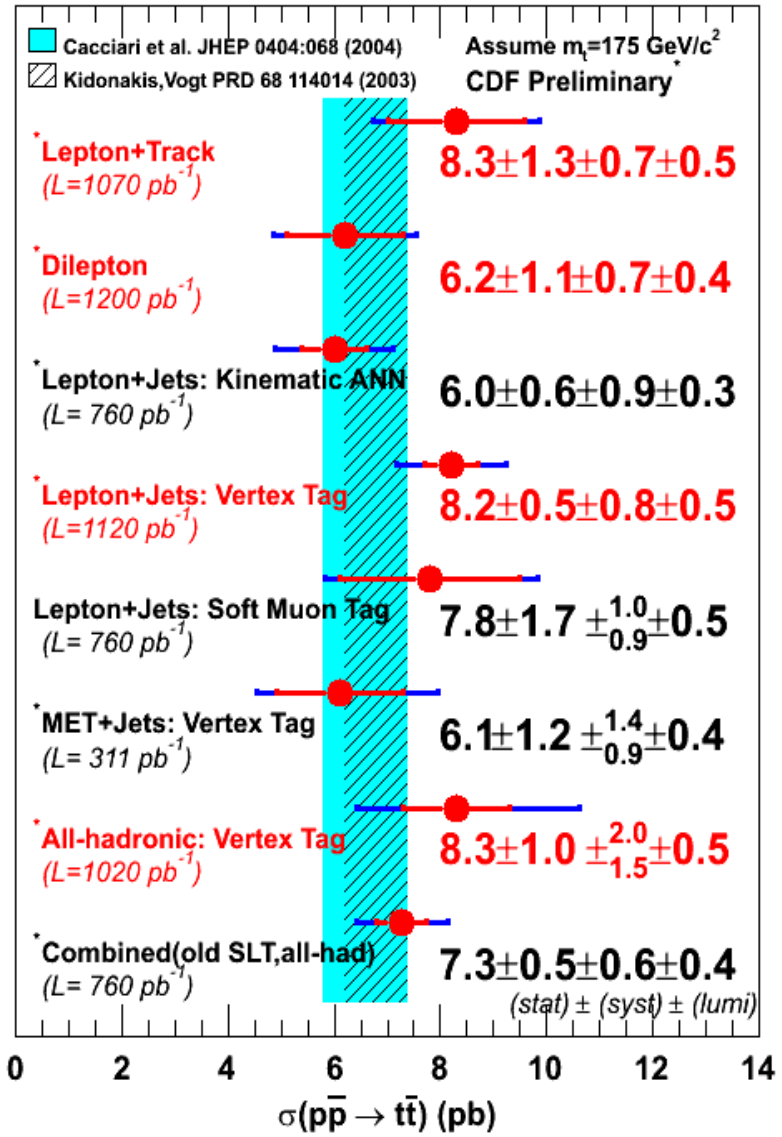
Decay via electroweak interaction ~100% BR(t→W⁺b)

tt → W(→lν)bW(→lν)b (e+μ: 5%)
low background, low yield
→ DILEPTON SAMPLE
tt → W(→lν)bW(→qq)b (e+μ:35%)
background moderate, medium yield
→ LEPTON PLUS JETS SAMPLE
tt → W(→qq)bW(→qq)b all hadronic (45%)
high background, high yield

Top Pair Decay Channels



σ(pp-bar→tt-bar) MEASUREMENTS



σ_{tt} measured in ALL final states:

- Independent top quark samples with different non-SM sensitivities.

$\sigma_{t\bar{t}}$ (CDF) ≅ 7.3 ± 0.9 pb

Cacciari et al. JHEP 0404:068 (2004)
Kidonakis & Vogt PRD 68 114014 (2003)

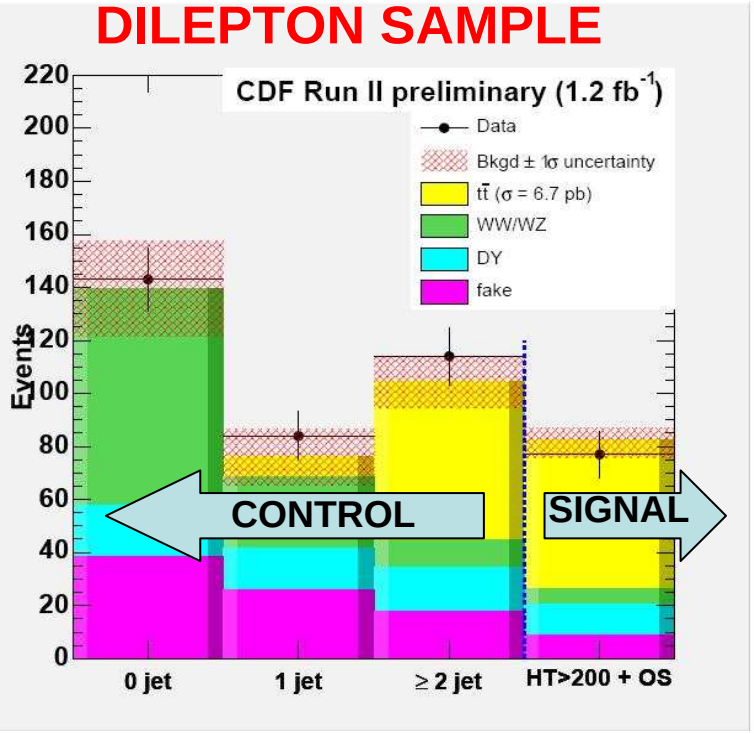
$\sigma_{t\bar{t}}$ (NLO-THEO) ≅ 6.7± 0.8 pb

(M_{TOP}=175GeV/c²)

12% ACCURACY: THEORY & EXPERIMENT

THE ~1 fb^{-1} TOP QUARK SAMPLES

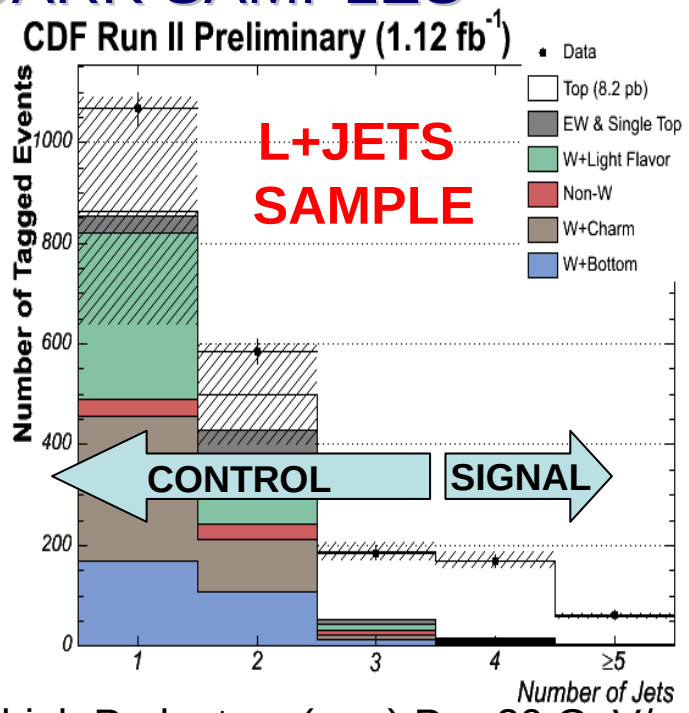
DILEPTON SAMPLE



- 2 high P_T leptons (e,μ) P_T> 20 GeV/c
- 2 high E_T jets.
- High Missing E_T

Total Backgr.	25.6±5.5
tt-bar (σ=6.7pb)	55.9±4.3
Total SM	81.5±8.9
DATA	77

L+JETS SAMPLE



- 1 high P_T lepton (e,μ) P_T> 20 GeV/c
- ≥4 high E_T jets.
- High Missing E_T
- B-tagging with secondary vertex.

	4 jets	≥5 jets
Total Backgr.	16.7 ± 5.9	4.7 ± 1.7
tt-bar (σ=6.7pb)	153.5 ± 15.6	53.6 ± 5.5
Total SM	170 ± 17	58 ± 6
DATA	169	62

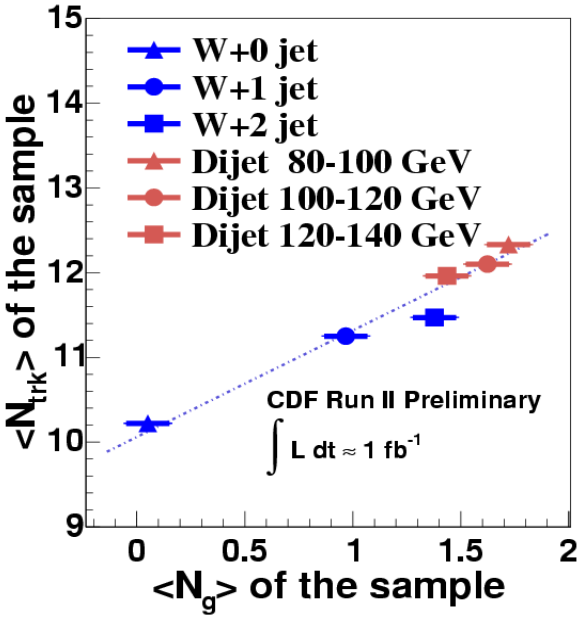
$\sigma(gg \rightarrow tt)/\sigma(pp \rightarrow tt)$: $\langle N_{TRK} \rangle$ VS $\langle N_{gluon} \rangle$

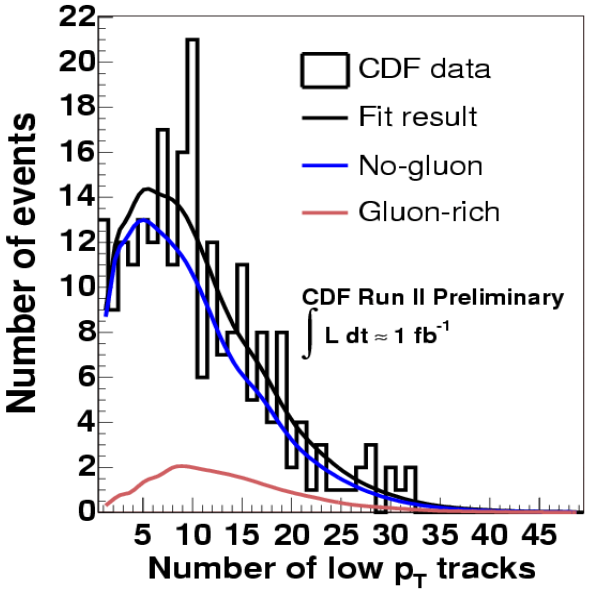
Sensitive to new top production & decay mechanisms simultaneously.

G.L Kane and S. Mrenna Phys. Rev. Lett.77: 3502-3505 (1996)

Top quark from gluino decays and top quark decays to stops

PRINCIPLE: gg→tt tends to have more underlying event activity w.r.t qq→tt



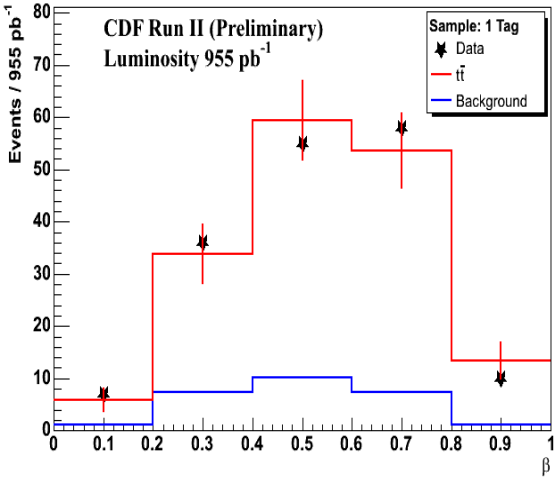


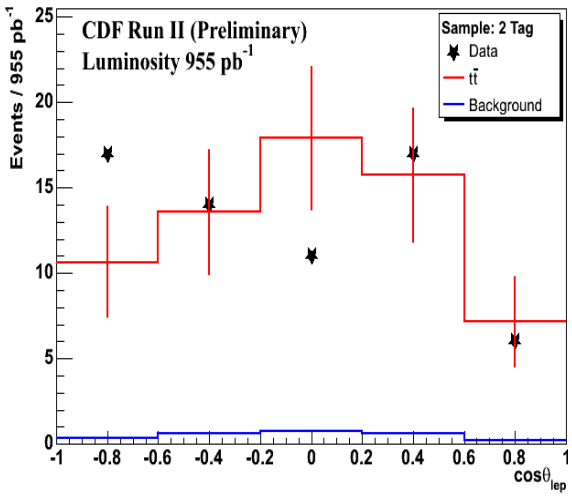
Calibrate $\langle N_{TRK} \rangle$ (low P_T tracks) vs. $\langle N_g \rangle$ correlation with W+jets and dijet data.
Fit W+jets (b-tagged) data to $\langle N_{TRK} \rangle$ templates: gluon-rich (DIJET 80-100 GeV)
no-gluon (W+0 jets)

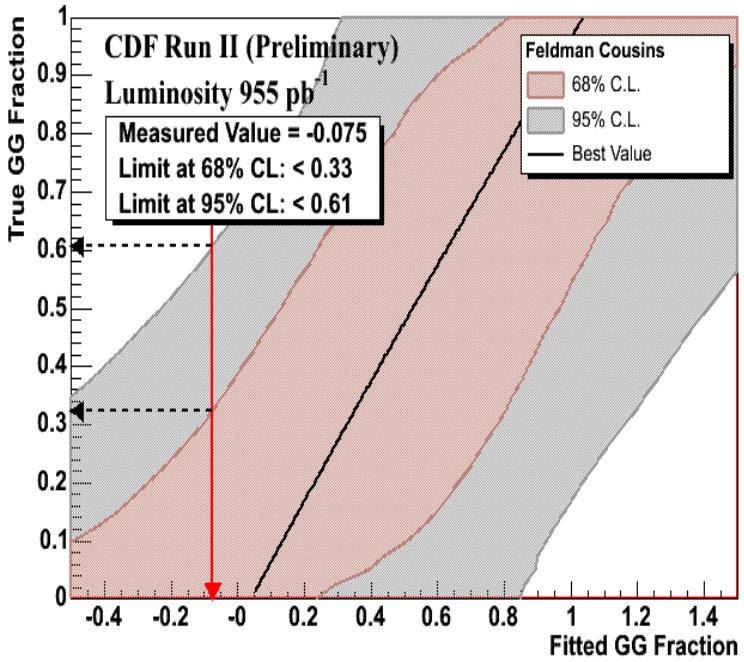
$$\sigma(gg \rightarrow t\bar{t}) / \sigma(p\bar{p} \rightarrow t\bar{t}) = 0.07 \pm 0.14(stat) \pm 0.07(syst)$$

σ(gg→tt)/σ(pp →tt):neural network

- PRINCIPLE: gg (qq-bar) tt-bar events tend to be produced with unlike (like) spin.
- Use NN with 8 input variables:
  - 2 in the tt-bar reference frame: β and angle top quark-incoming parton.
    - kinematic information from the production.
  - 6 angles between decay products in the "off-diagonal" bases
    - spin correlation information from the decay.
- Fit data to templates built from the NN output shapes.



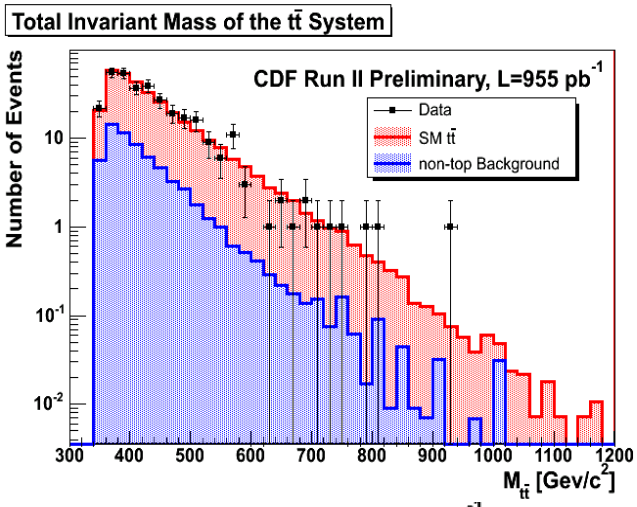




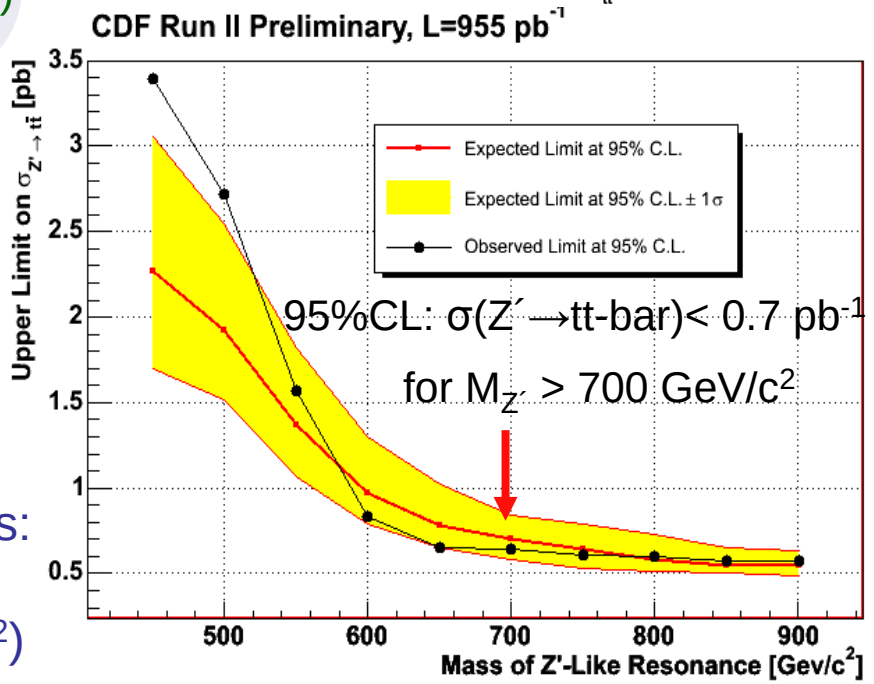
$$\sigma(gg \to t\bar{t}) / \sigma(p\bar{p} \to t\bar{t}) < 0.61 \,@\, 95\%\ CL$$

Search for resonant top pair production

- Sensitive to new resonant t-tbar production mechanisms:
  - Extended Gauge Theories
    - (A. Leike, Phys. Rep. 317, 143, 1999. hep-ph/9805494)
  - KK states of the gluon , Z
    - (J. Rosner, CERN-TH/96-169, 1996, B. Lillie, hep-ph/0701166)
  - Topcolor
    - (C. Hill, S. Park, PRD49, 4454, 1994)



- Search for narrow width Z' (1.2% of the mass) with same coupling as Z0
  - no resonant interference with the s channel gluon production.

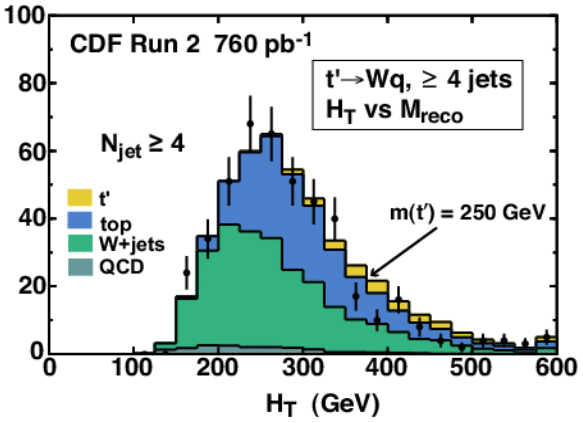


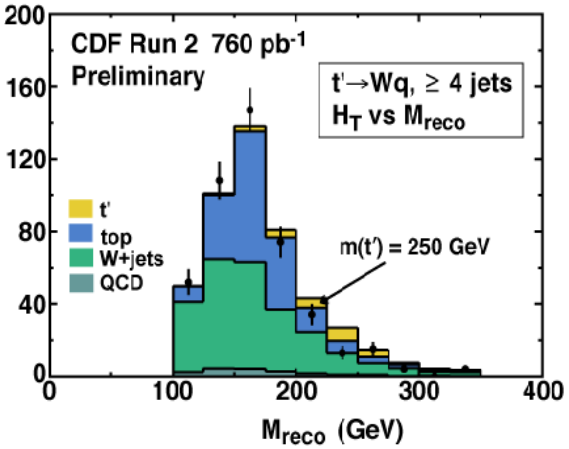
- Reconstruct Mtt-bar with kinematic fitter.
- Binned likelihood fit of data to 3 templates:
  - SM tt-bar, Z'→tt-bar,non tt-bar
  - Range of Z' masses (450-900 GeV/c^2)

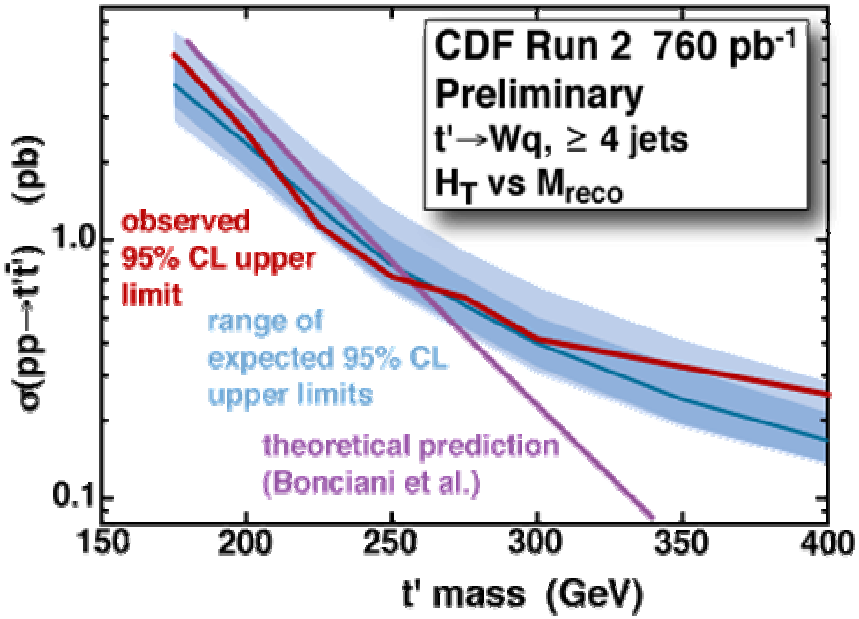
Search for a Heavy Top t´→Wb

•Hypothesis: t´ is pair-produced strongly, heavier than SM top quark, decay to Wb.
- •2HD models and N=2 SUSY models can accomodate a heavier 4th fermion generation with $m_{Z/2} < m_f < m_{Higgs}$ (hep-ph/0102144,hep-ph/0111028)
- •Other models: “Beautiful mirrows” (hep-ph/0109097)

•Data fitted to templates (t´, top, background) with 2D binned likelihood (H_T and M_{RECO})

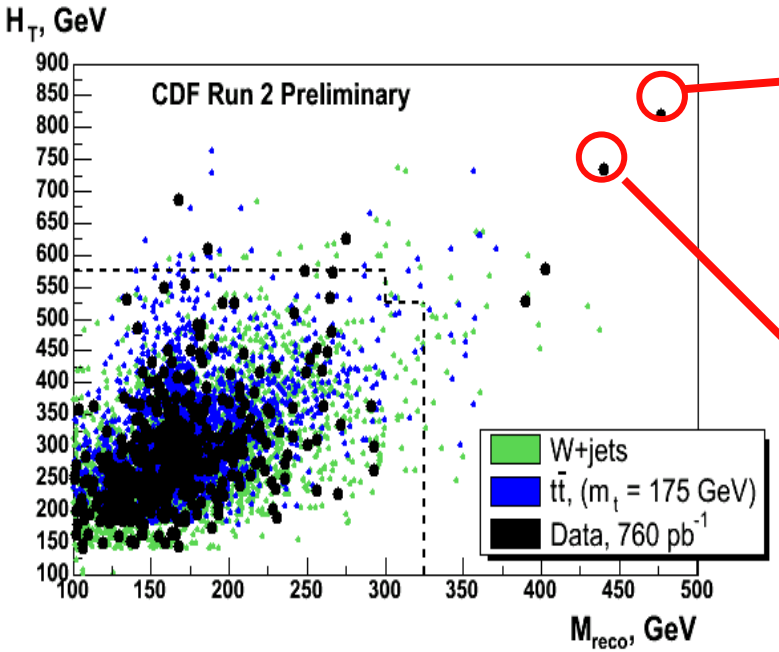


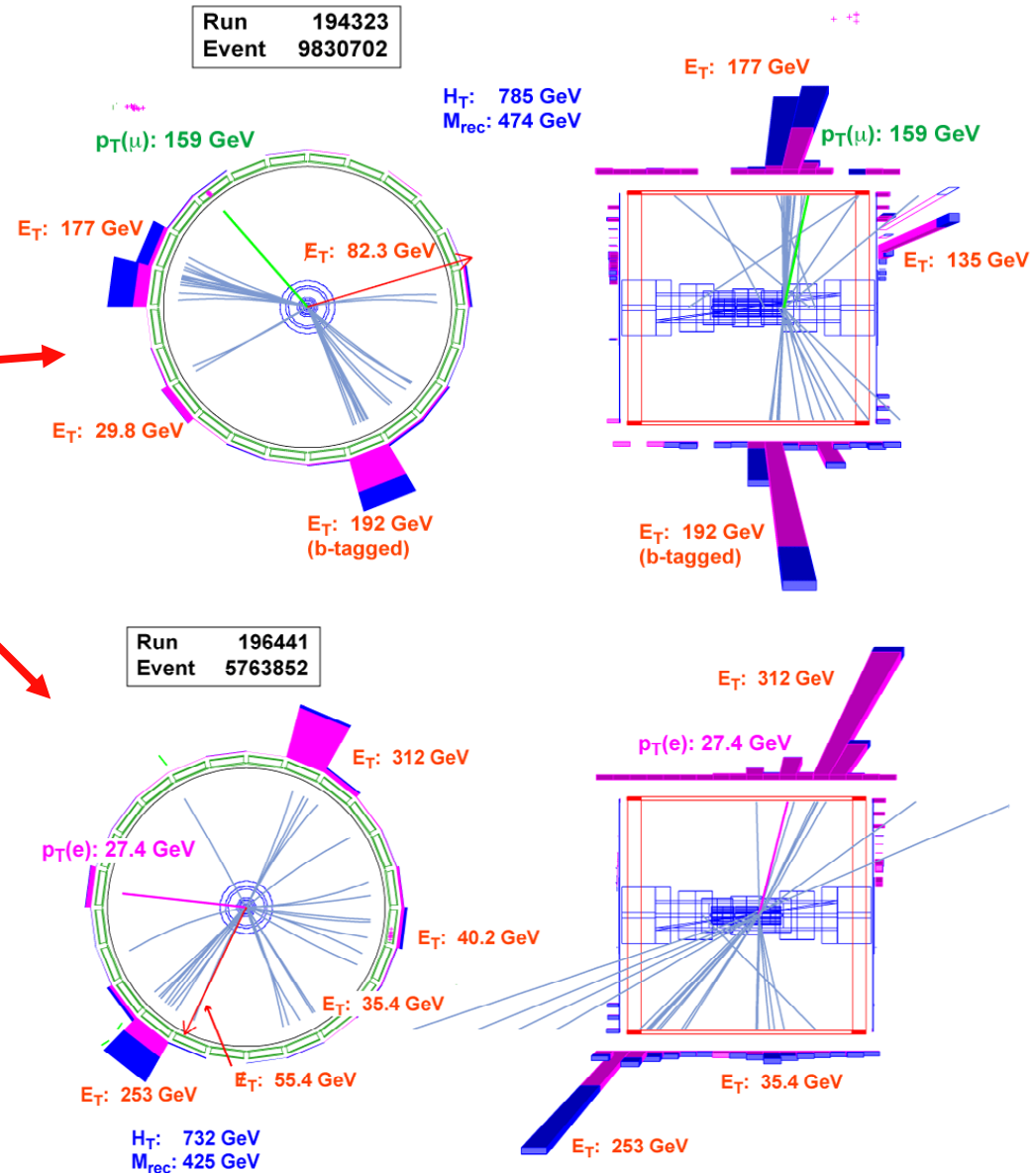




$$m_{t'} < 256\ GeV/c^2\ @\ 95\%CL$$

Event Displays: high H_T high M_{REC} candidates

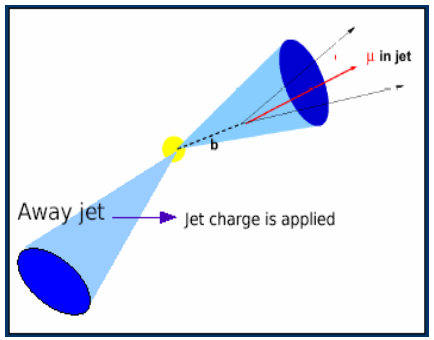




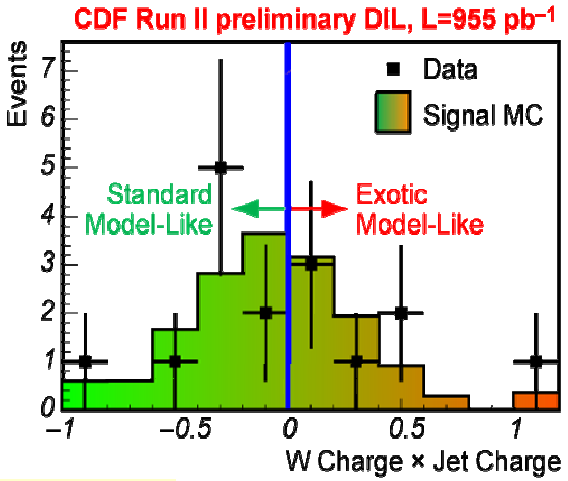
Top quark charge: +2/3 or -4/3 ?

- Hypothesis: Top quark charge = -4e/3
  - New exotic quark part of a fourth generation. D.Chang et al. PRD 59, 09153(99)
- A challenging experimental method:
  - Jet Charge algorithm:

$$Q_{bjet} = \frac{\sum_i q_i^{track} \left(p_i^{track} \cdot \hat{a}_{jet} \right)^{0.5}}{\sum_i \left(p_i^{track} \cdot \hat{a}_{jet} \right)^{0.5}}$$



  - Calibration with dijet data bb-bar enriched
  - "Purity":= probability of correctly pairing Wb and getting the correct flavor of b-jet
  - Counting experiment:
    - 62 Standard Model-like (SM)
    - 48 Exotic Model-like (XM)
  - Likelihood versus f+= Fraction of pairs with charge 2e/3 in data.
  - Result:

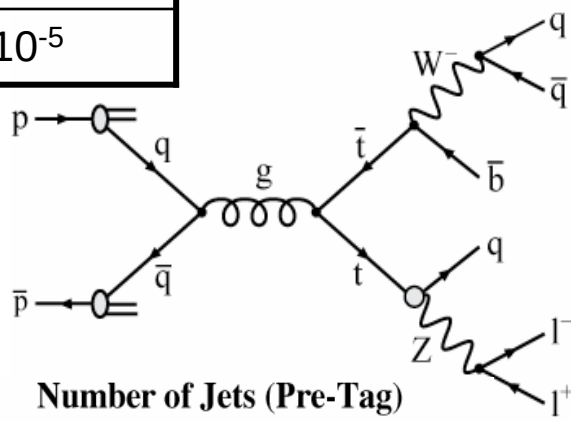


Consistent with charge 2e/3 hypothesis
Exclude charge -4e/3 hypothesis at 81% confidence

Search for the FCNC decay t→Zq

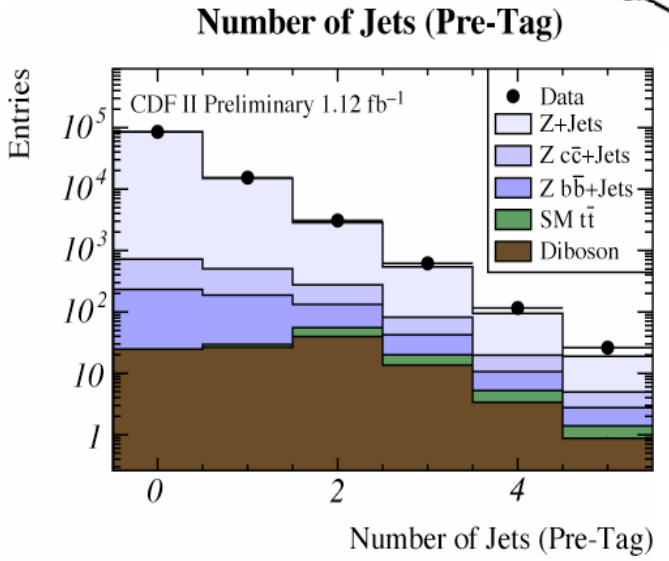
- SM: Top quark FCNC highly suppressed (GIM mechanism and CKM suppression)
- Beyond SM scenarios enhance top FCN decays providing observable BR´s
- J. A. Aguilar-Saavedra Acta Phys. Polon. B35 (2004) 2695-2710, hep-ph/0409342

Model	SM	Q=2/3 quark singlets	2HDM	MSSM	RPV-SUSY
BR(t→qZ)	~10^{-14}	~ 10^{-4}	~ 10^{-7}	~ 10^{-6}	~ 10^{-5}



- Blind search in tt → Zq Wb
  - Z → e^+e^-,$\mu^+\mu^-$ (clean signature)
  - 4 jets (larger BR of hadronic W → qq')
  - Two separate signal regions: zero b-tags – one or more b-tag

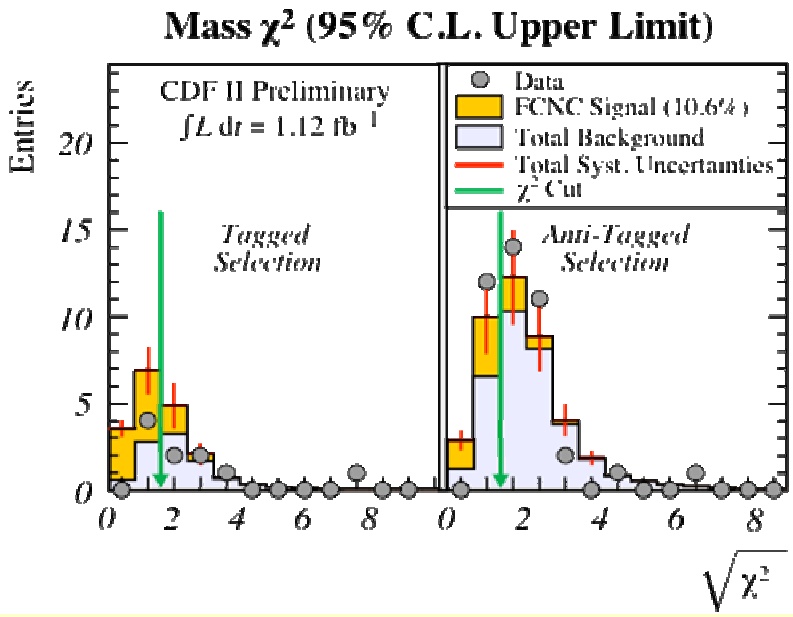
- Backgrounds: from data-driven and MC methods
  - Dominant background: Z+Jets production
  - Smaller backgrounds: tt and diboson (WZ, ZZ)



Search for the FCNC decay t→Zq (Cont´)

- Optimize event selection for best expected limit
  - Strongest discriminator: Mass χ^2 : reconstructed W, SM Top and NON-SM FCNC Top masses

$$\chi^2 = \left(\frac{m_{W,\mathrm{rec}} - m_{W,\mathrm{PDG}}}{\sigma_{W,rec}}\right)^2 + \left(\frac{m_{t\to Wb,\mathrm{rec}} - m_{t,\mathrm{PDG}}}{\sigma_{t\to Wb}}\right)^2 + \left(\frac{m_{t\to Zq,\mathrm{rec}} - m_{t,\mathrm{PDG}}}{\sigma_{t\to Zq}}\right)^2$$



- Unblinding after optimization: observed numbers events consistent with background

Selection	Observed	Expected
Base Selection	141	130±28
Base Selection (Tagged)	17	20±6
Anti-Tagged Selection	12	7.7±1.8
Tagged Selection	4	3.2±1.1

$$B(t \to Zq) < 10.6\% @ 95\%\ C.L$$

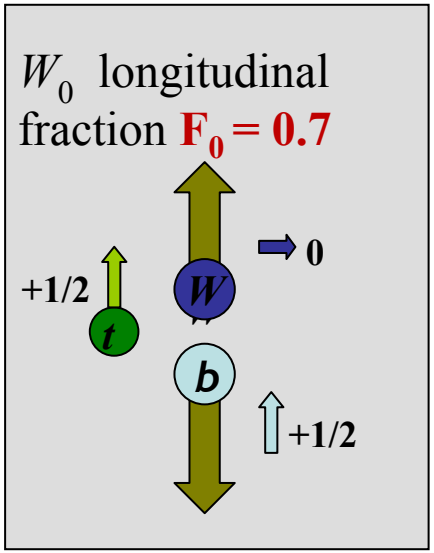
- New world´s best limit: improves previous limit by 25% (13.7% from non-observation of $e^+e^- \to tq$ at LEP,L3)

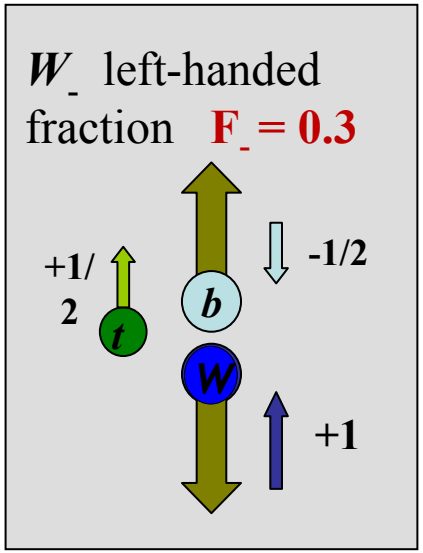
W Helicity in Top Quark Decays

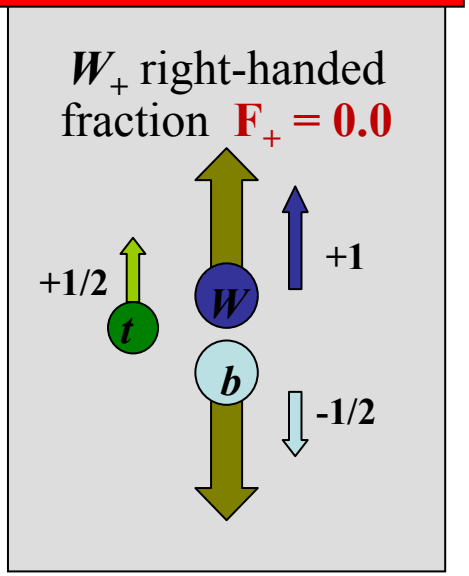
SM: Top quark decays via weak interaction to spin-1 W^+ boson and spin-1/2 b quark
→ V-A coupling like all other fermions:

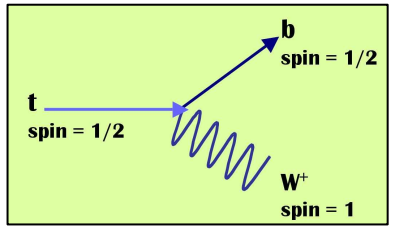
$$\frac{-ig}{2\sqrt{2}}\bar{t}\gamma^{\mu}(1-\gamma^{5})V_{tb}bW_{\mu}$$

V+A is Suppressed in the SM







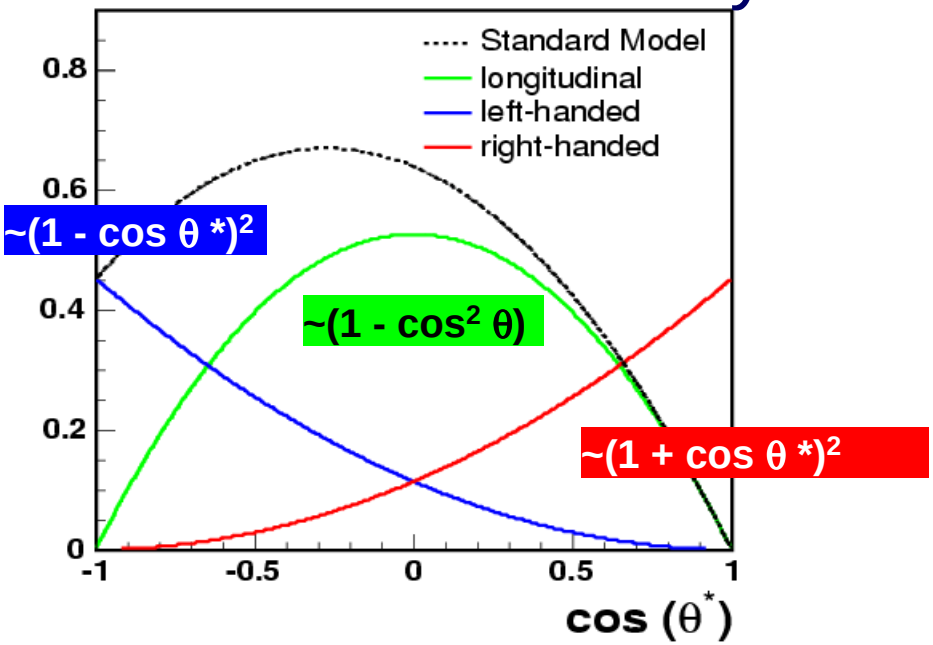


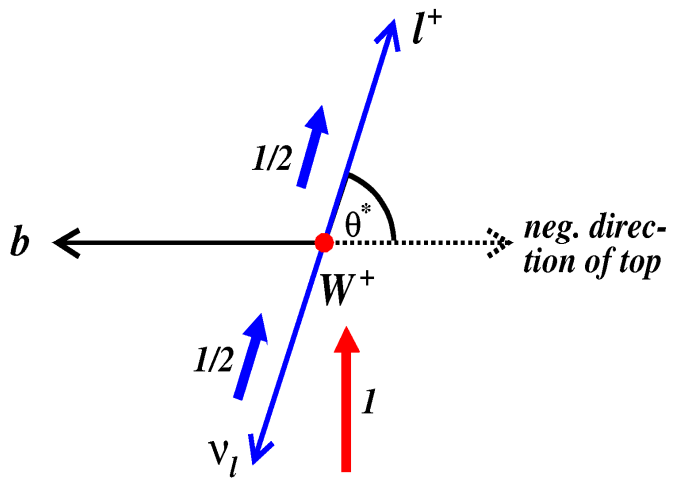
In general, t-W-b coupling can have form-factors of type: V-A (standard model), V+A and Magnetic-moment G.L. Kane, G.A. Ladinsky, C.P. Yuan Phys. Rev. D 45, 124 (1992)

The presence of V+A could signal new physics: Left-right symmetric models? Mirror fermions?

Beg, Mohapatra et al. **Phys.Rev.Lett.38:1252, 1977**
Triantaphyllou: **J.Phys.G26:99,2000**
Tait,Yuan, He et al.:**Phys.Rev.D62:011702,2000, Phys.Rev.D65:053002,2002**

W-helicity: cosθ*method





$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{4}(1-\cos^2\theta^*)F^0 + \frac{3}{8}(1-\cos\theta^*)^2 F^- + \frac{3}{8}(1+\cos\theta^*)^2 F^+$$

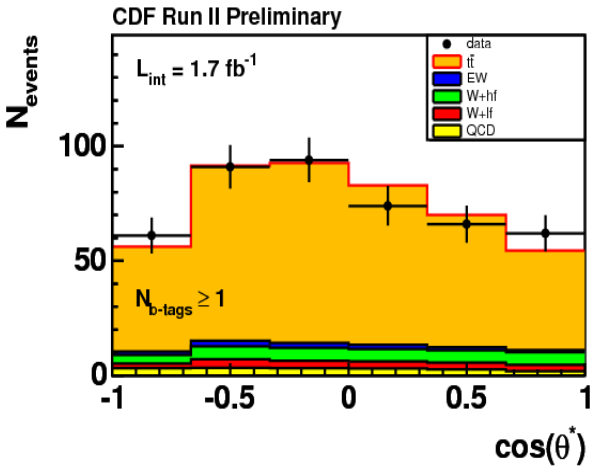
- L+JETS sample with $N_{JETS} \geq 4$ and ≥ 1 btag.
- tt-bar kinematics fully reconstructed.
- Extract $\cos\theta^*$ by boosting lepton and top into W rest frame.
- Two methods to extract F_0 and F_+ (next two slides)
- 3 set of results:
  - 1-Parameter-fit: F_0 fixed to 0.7 → Test possible V+A contribution in weak interactions
  - 1-Parameter-fit: F_+ fixed to 0. → Test possible anomalous couplings (non zero-magnetic moment couplings)
  - 2-Parameter-fit ➔ MODEL INDEPENDENT

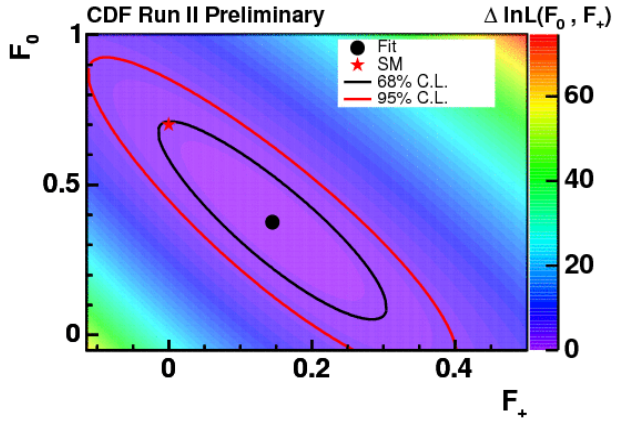
W-helicity: cosθ*method (I) 1.73 fb^{-1}

FIRST METHOD TO EXTRACT F_0 AND F_+

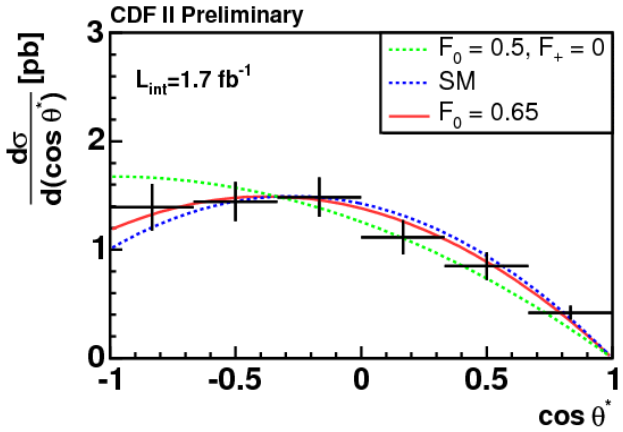
- Binned likelihood fitter:
  - Fits data to signal and background templates.
  - Signal Templates: from theoretical principles

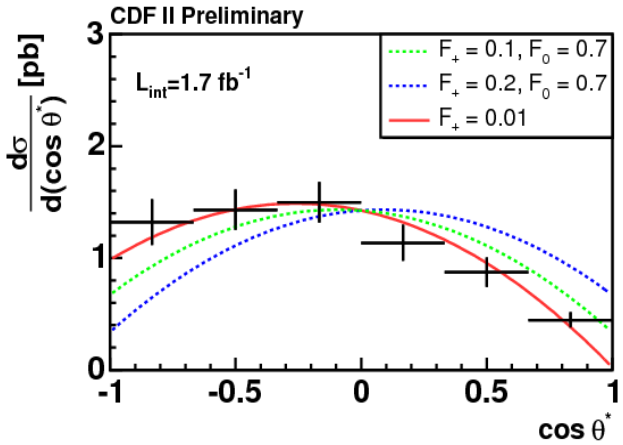
corrected for detector efficiency and resolution





Unfolding of measured distribution:
Background substraction of data.
Correct for acceptance and resolution effects: f(F_0,F_+)





F_0=0.38 ± 0.22$_{stat}$ ± 0.07$_{syst}$ and F_+=0.15 ± 0.10$_{stat}$ ± 0.04$_{syst}$

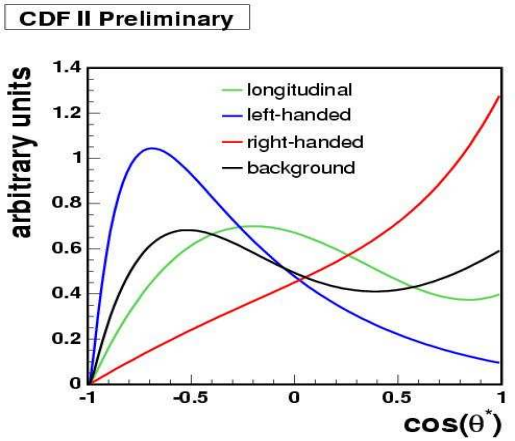
F_0=0.65 ± 0.10$_{stat}$ ± 0.06$_{syst}$ with F_+=0

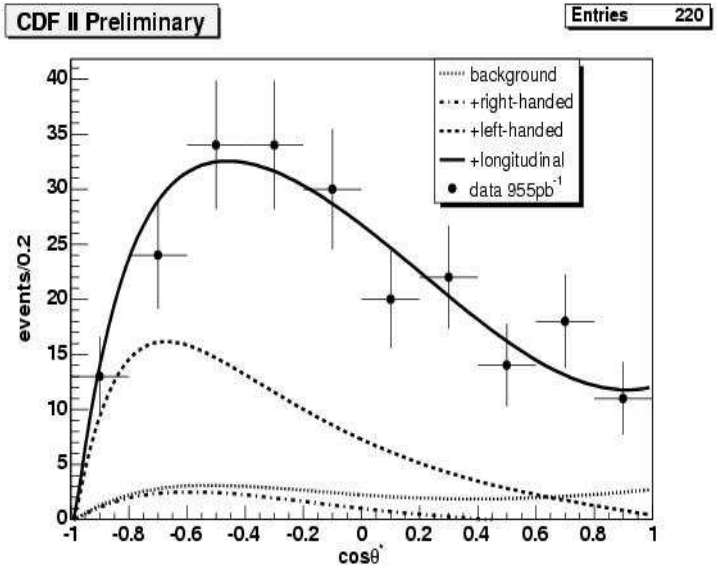
F_+=-0.01± 0. 05$_{stat}$ ± 0.03$_{syst}$ with F_0=0.7 f_+< 0.12 @95% CL

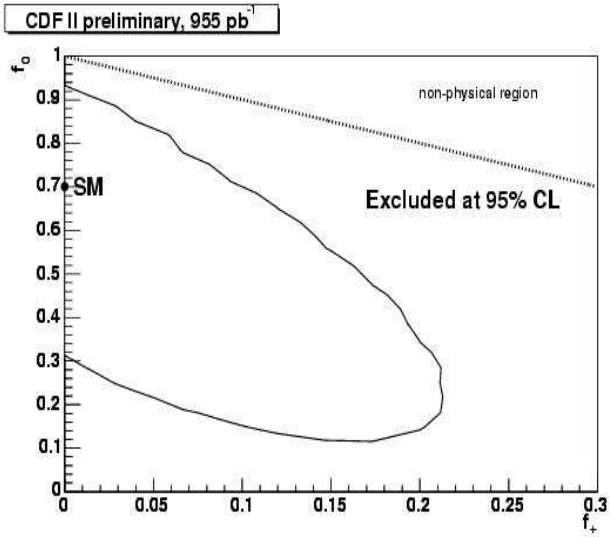
W-helicity: cosθ*method (II) 1 fb^{-1}

SECOND METHOD TO EXTRACT F_0 AND F_+

- Unbinned likelihood fitter.
- Fits data to signal and MC shapes:
  - 3rd order polinomial times exponent parameterizations from templates.







$F_0 = 0.74 \pm 0.25_{stat} \pm 0.06_{syst}$ and $F_+ = -0.06 \pm 0.10_{stat} \pm 0.03_{syst}$

$F_0 = 0.61 \pm 0.12_{stat} \pm 0.06_{syst}$ with $F_+ = 0$

$F_+ = -0.06 \pm 0.06_{stat} \pm 0.03_{syst}$ with $F_0 = 0.7$ $\quad f_+ < 0.11$ @95% CL

CONCLUSIONS AND PROSPECTS

- The CDF top quark samples with L = 1.1 – 1.2 fb^{-1} have been reestablished:
  - Top pair production cross section has been measured and found in good agreement with QCD-NLO predictions.

- A lot of challenging and creative "ALTERNATIVE" searches have been performed on the CDF top quark samples in order to find NEW PHYSICS.
  - New production mechanisms: resonances, t´, etc
  - New decay mechanisms: FCNC t→Zq
  - Search for deviations in SM values of measured top properties: charge, W helicity.
  - For the time being are very statistical limitted, but the methodology is in place.
  - 2fb^{-1} analyses coming by the end of summer.

NO EVIDENCE OF NEW PHYSICS IN THE 1 fb^{-1} CDF TOP QUARK SAMPLES

- All the ongoing CDF analysis techniques described can be applied to search for new physics in the TEVATRON PHASE OF THE LHC (early LHC data 0.1-1 fb^{-1})
  - Background methods for total rates and shapes.
  - Determination of systematic uncertainties.
  - Statistical machinery to extract limits.

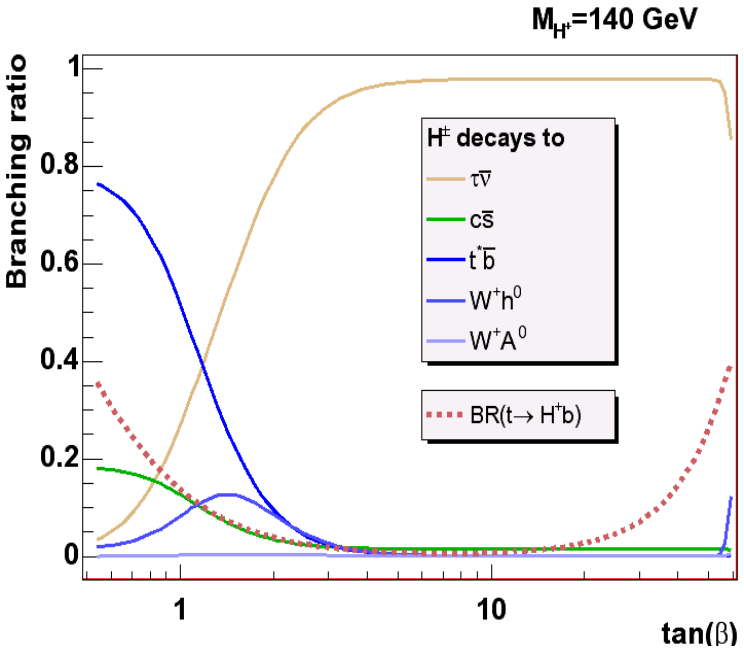
Backup slides.

Charged Higgs from Top quark decays

Branching ratio for $t \to H^+ b$ significant (>10%) for small and large tanβ

H^+ decays differently than W^+:

- $H^+ \to \tau^+ \upsilon_\tau$ enhanced if high tanβ:
  - Excess of taus
- $H^+ \to t^* b \to W^+ bb$ for high $m(H^+)$ if low tanβ:
  - Mimics SM signature but observe more b-tags
- $H^+ \to cs$: defect all channels.



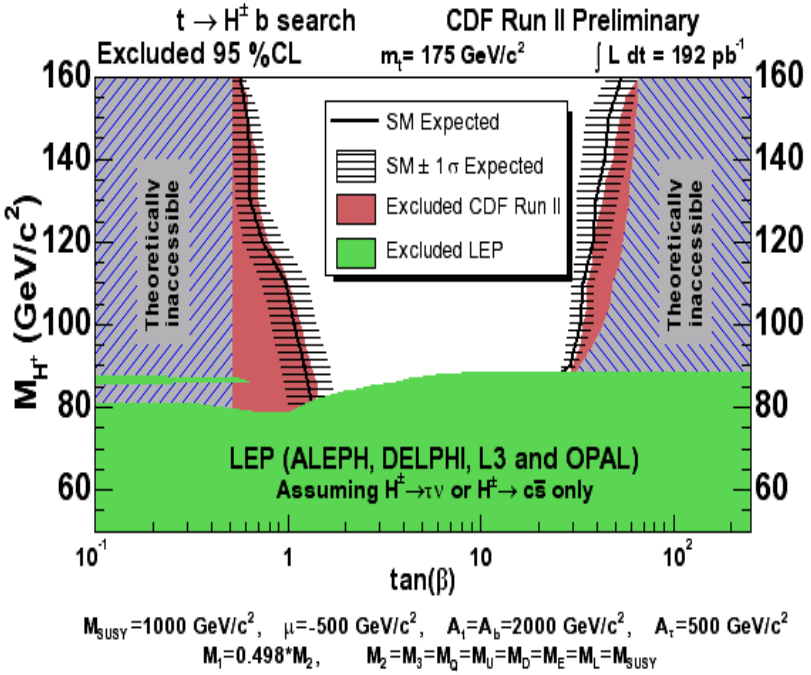
Compare number of observed events in 4 ttbar final states:

dilepton, $e\tau_h$ + $\mu\tau_h$,

lepton+jets with single b-tag, and lepton+jets with double b-tags

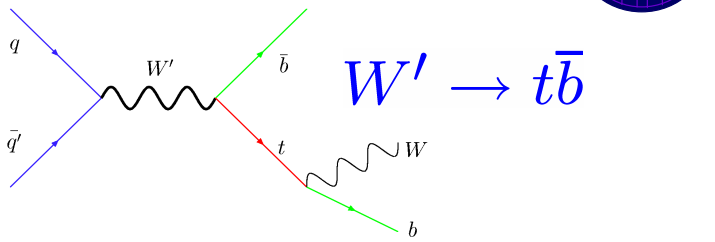
(Phys. Rev. Lett 96,042003)

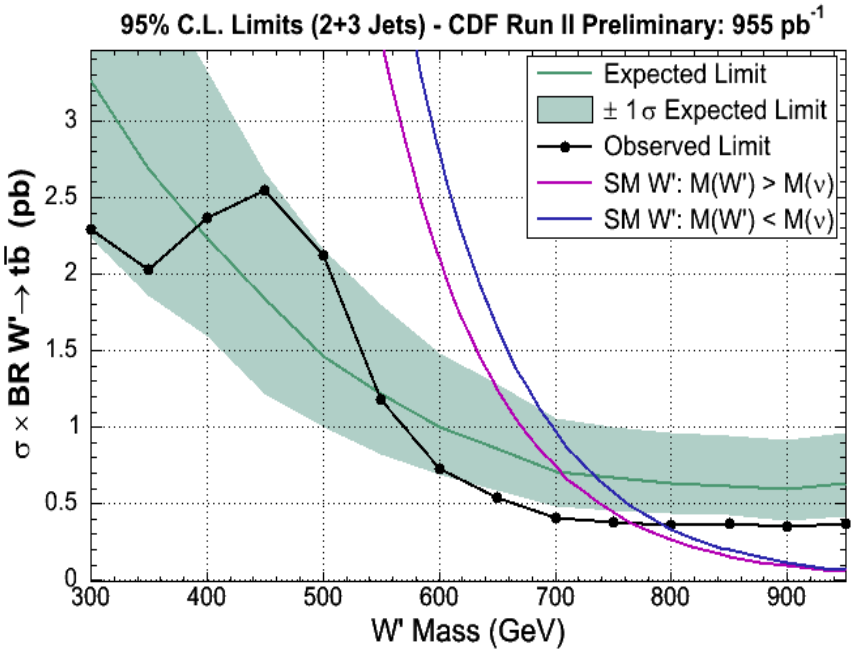
Limits on BR(t->H^+b)

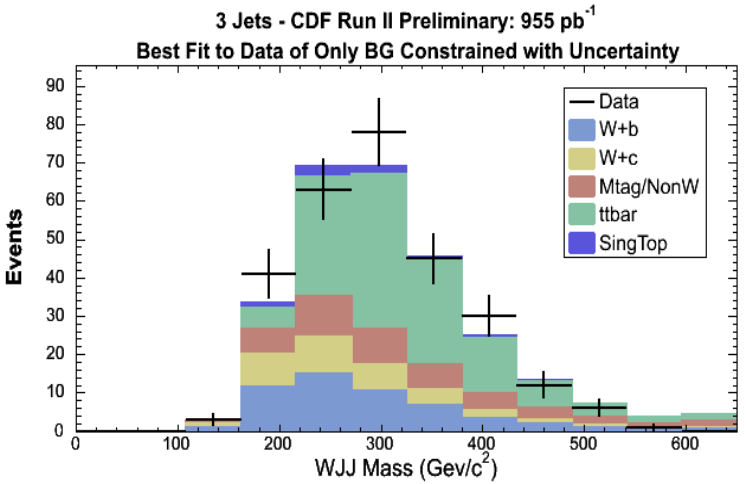


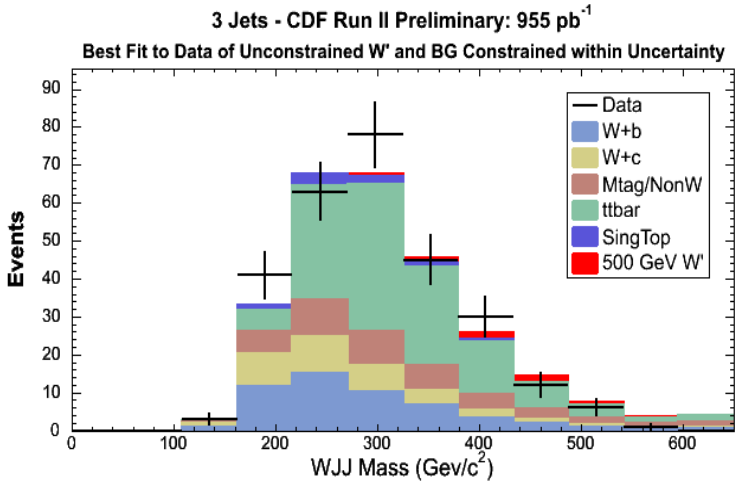
W´-like resonances in the tb-bar decay channel.

- Beyond SM models predict massive W-like bosons describing resonant tb production:
  - Extra dimensions, PL B538, 406 (2002)
  - Top Color PL B385,304 (1996)
- Single Top analysis methods applied to search for a narrow peak in M_{WJJ}
- Set limits on W' production and it's coupling to fermion.

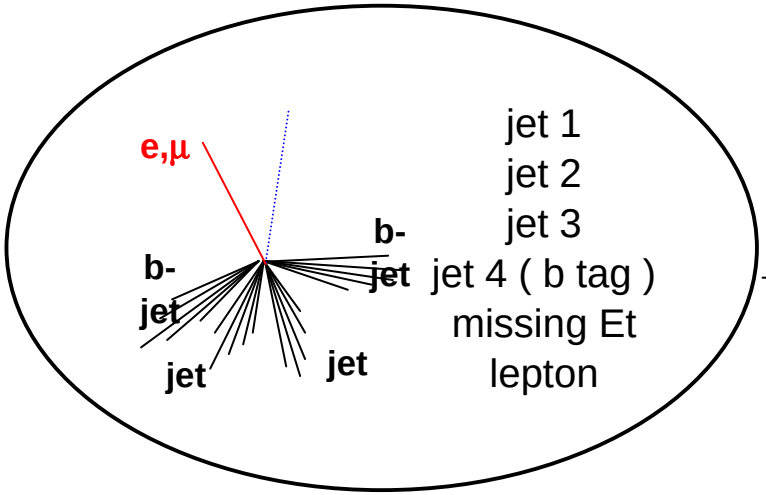








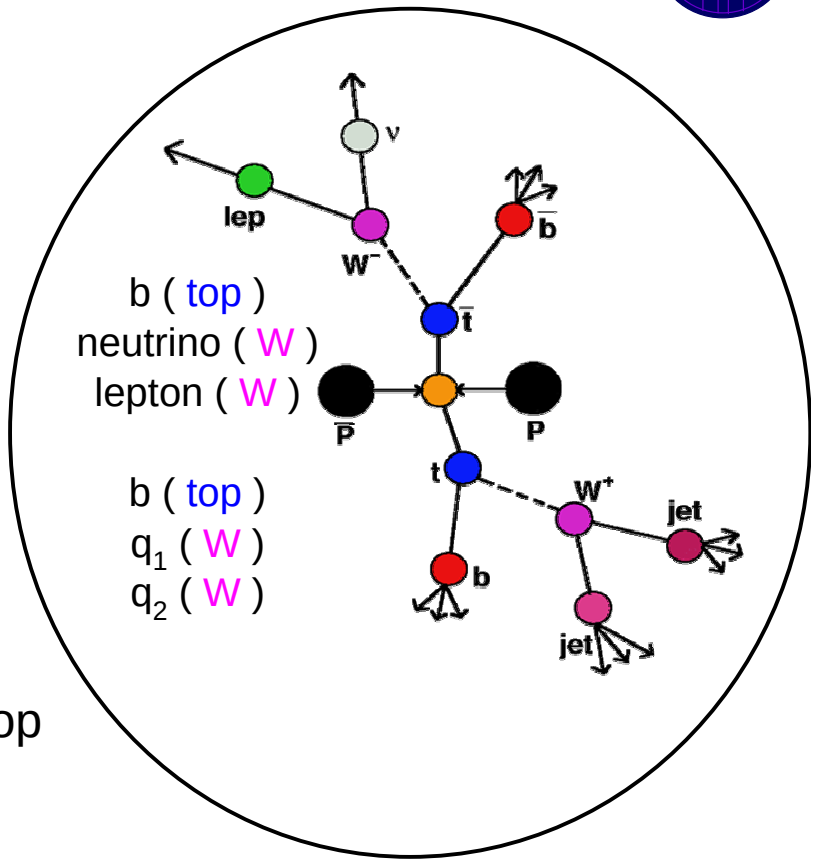
A COMMON TOOL: THE "TOP MASS" KINEMATIC FITTER



jet 1
jet 2
jet 3
jet 4 (b tag)
missing Et
lepton

24: 0 btags
12: 1 b-tag
4: 2 b-tags

χ^2



b (top)
neutrino (W)
lepton (W)

b (top)
q_1 (W)
q_2 (W)

- Reconstruction of kinematics:
  - Constrain jet-jet mass to W mass.
  - Constrain lepton-neutrino mass to W mass
  - Constrain b-lepton-neutrino and b-jet-jet to Top masses.
  - Top mass equal to anti-top mass
  - Lowest χ2 gives correct combination in 70% of the cases

$$\chi^2 = \sum_{i=\lambda,4jets} \frac{(p_T^{i,fit} - p_I^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_j^{UE,meas})^2}{\sigma_{UE}^2} + \frac{(M_{lv} - M_W)^2}{\Gamma_W^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{blv} - m_t^{reco})^2}{\Gamma_t^2} + \frac{(M_{bjj} - m_t^{reco})^2}{\Gamma_t^2}$$