Searches for New Physics in the Top Quark Samples at CDF

15th International Conference on Supersymmetry and the Unification of Fundamental Interactions

Parallel session: "ALTERNATIVES"

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MOTIVATION

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

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

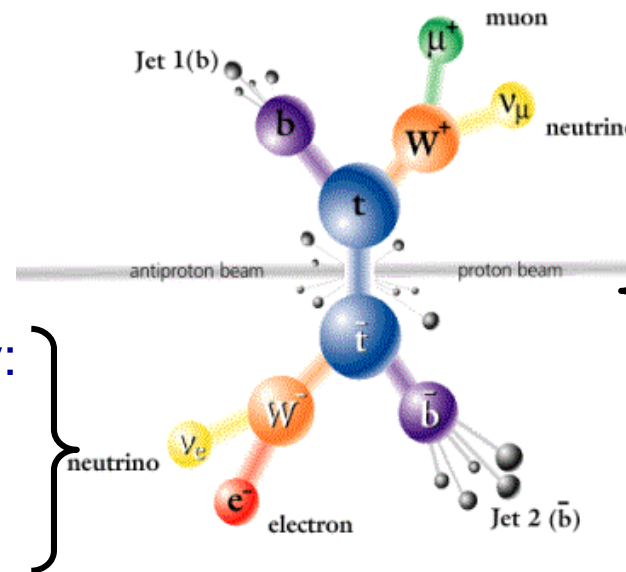$\rightarrow$Spin information transferred to decay products

Special role in EWSB?

$\rightarrow$Top Yukawa coupling to Higgs is "natural" (~1)

$\rightarrow$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
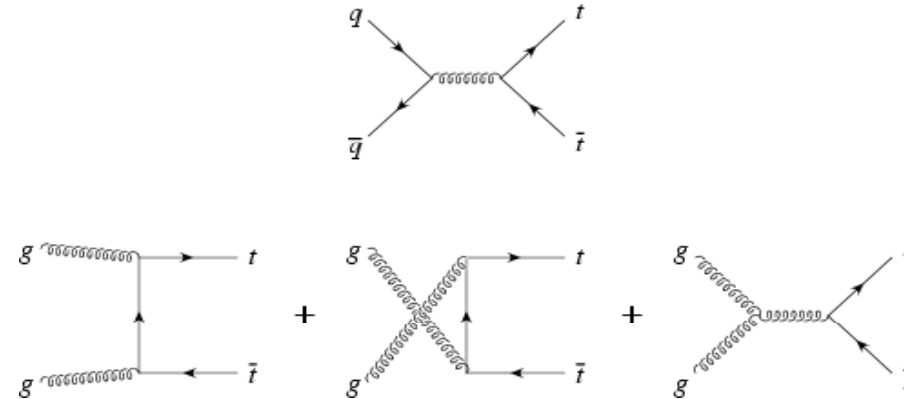

Delivered 3106.5
Recorded 2551.8
Eff = 82 %
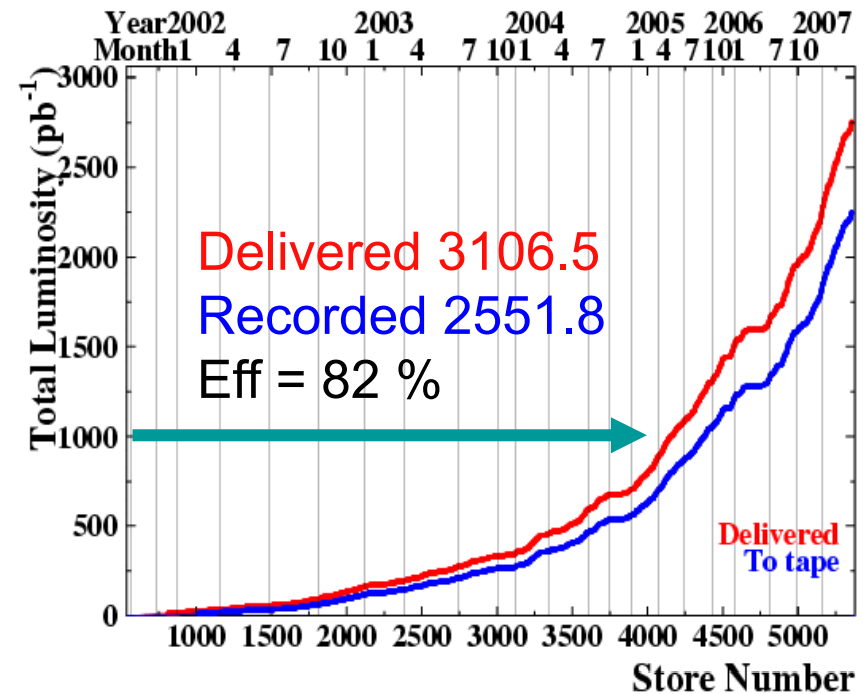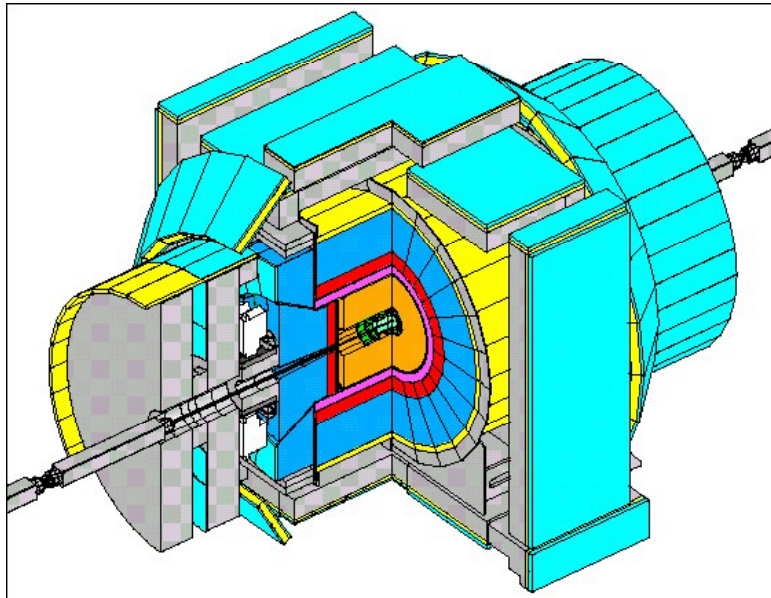
TOP PHYSICS require a good understanding of the entire detector

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

W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$
$\bar{c}s$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{u}d$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{\tau}$	$e\tau$	$\mu\tau$	$\tau\tau$	tau+jets	
μ^-	$e\mu$	$\mu\mu$	$\mu\tau$	muon+jets	
e^-	ee	$e\mu$	$e\tau$	electron+jets	

σ(pp-bar→tt-bar) MEASUREMENTS

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

Assume $m_t = 175$ GeV/c^2
CDF Preliminary

Lepton+Track (L=1070 pb^{-1}): $8.3 \pm 1.3 \pm 0.7 \pm 0.5$

Dilepton (L=1200 pb^{-1}): $6.2 \pm 1.1 \pm 0.7 \pm 0.4$

Lepton+Jets: Kinematic ANN (L= 760 pb^{-1}): $6.0 \pm 0.6 \pm 0.9 \pm 0.3$

Lepton+Jets: Vertex Tag (L=1120 pb^{-1}): $8.2 \pm 0.5 \pm 0.8 \pm 0.5$

Lepton+Jets: Soft Muon Tag (L= 760 pb^{-1}): $7.8 \pm 1.7 \,{}^{+1.0}_{-0.9} \pm 0.5$

MET+Jets: Vertex Tag (L= 311 pb^{-1}): $6.1 \pm 1.2 \,{}^{+1.4}_{-0.9} \pm 0.4$

All-hadronic: Vertex Tag (L=1020 pb^{-1}): $8.3 \pm 1.0 \,{}^{+2.0}_{-1.5} \pm 0.5$

Combined(old SLT,all-had) (L= 760 pb^{-1}): $7.3 \pm 0.5 \pm 0.6 \pm 0.4$

(stat) ± (syst) ± (lumi)

$\sigma(p\bar{p} \to t\bar{t})$ (pb)

σ_{tt} measured in ALL final states:
- Independent top quark samples with different non-SM sensitivities.

$\sigma_{t\underline{t}}$ (CDF) $\cong 7.3 \pm 0.9$ pb

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

$\sigma_{t\underline{t}}$ (NLO-THEO) $\cong 6.7 \pm 0.8$ pb

(M_{TOP}=175GeV/c^2)

12% ACCURACY: THEORY & EXPERIMENT

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

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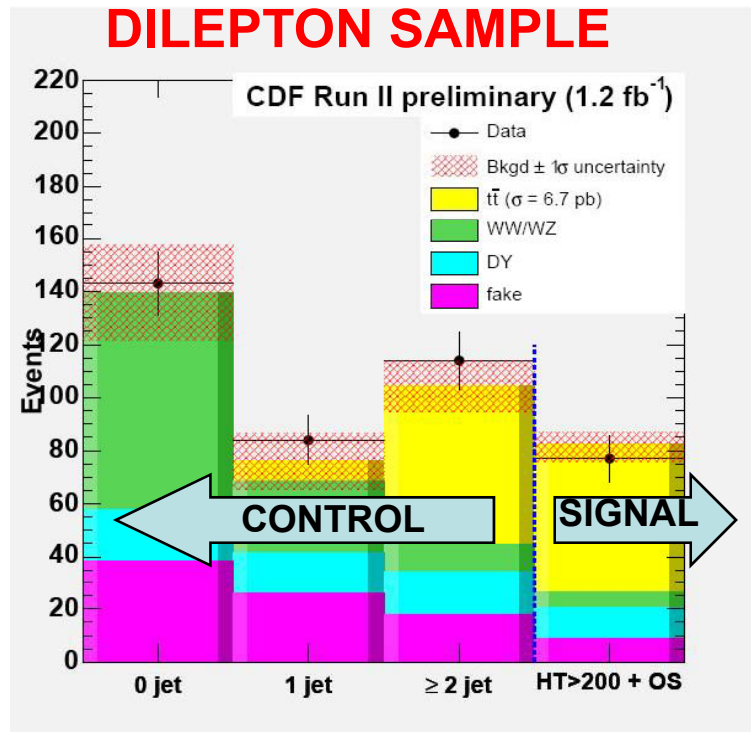
- 2 high P_T leptons (e,μ) P_T> 20 GeV/c
- 2 high E_T jets.
- High Missing E_T

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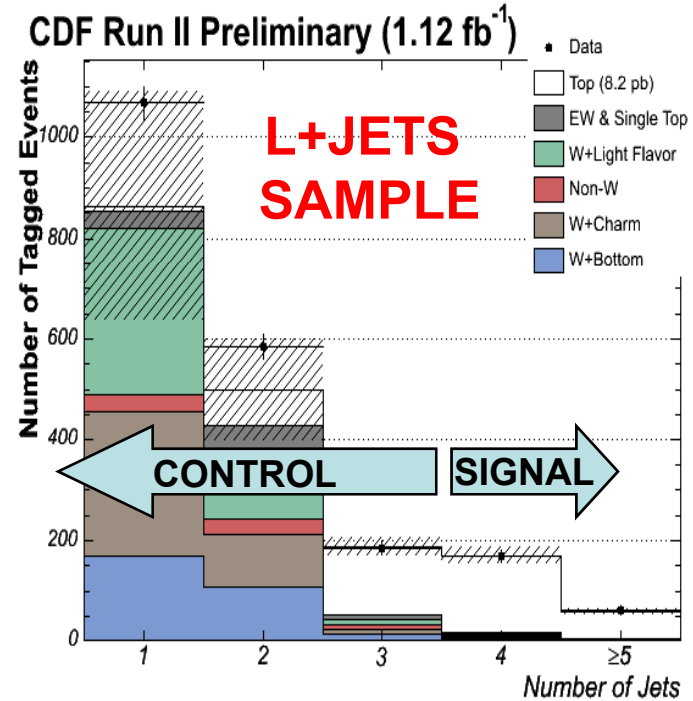
- 1 high P_T lepton (e,μ) P_T> 20 GeV/c
- ≥4 high E_T jets.
- High Missing E_T
- B-tagging with secondary vertex.

	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

$\sigma(gg \to tt)/\sigma(pp \to tt)$: $<N_{TRK}>$ VS $<N_{gluon}>$

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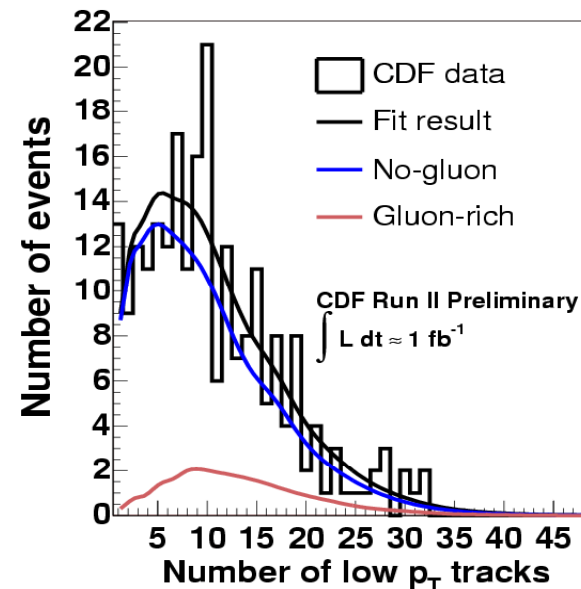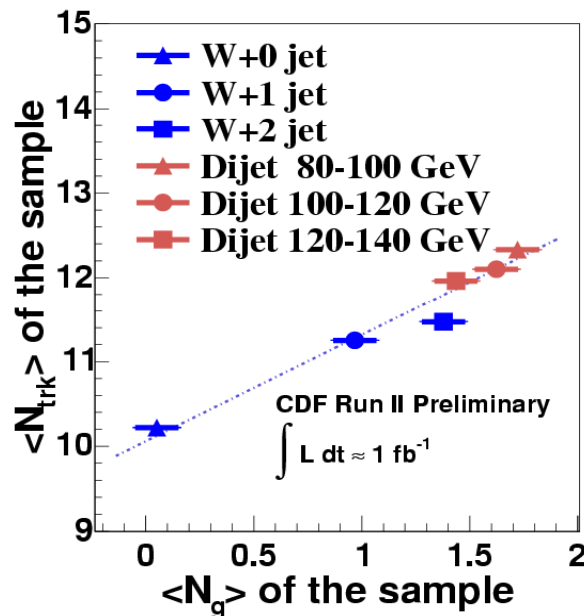
Calibrate $<N_{TRK}>$ (low P_T tracks) vs. $<N_g>$ correlation with W+jets and dijet data.
Fit W+jets (b-tagged) data to $<N_{TRK}>$ templates: gluon-rich (DIJET 80-100 GeV)
no-gluon (W+0 jets)

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

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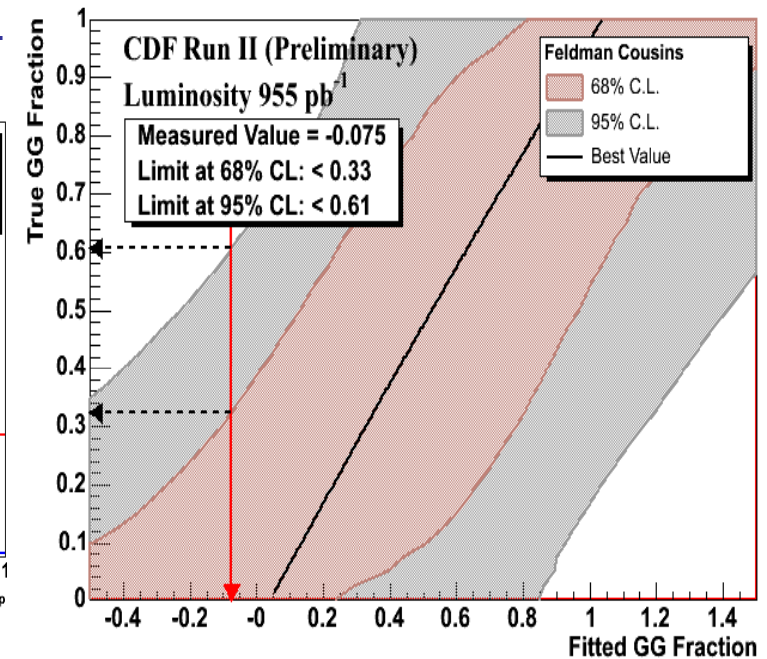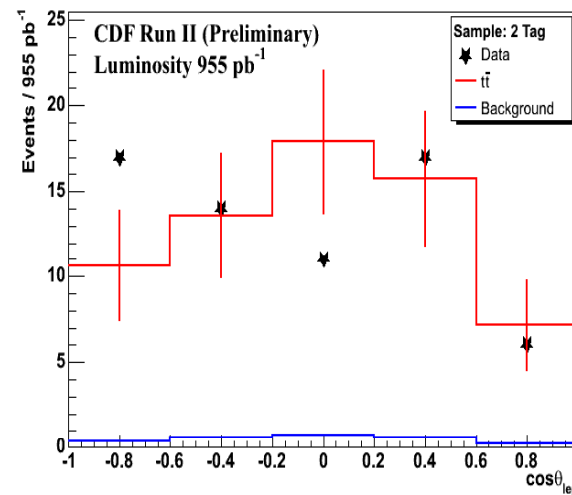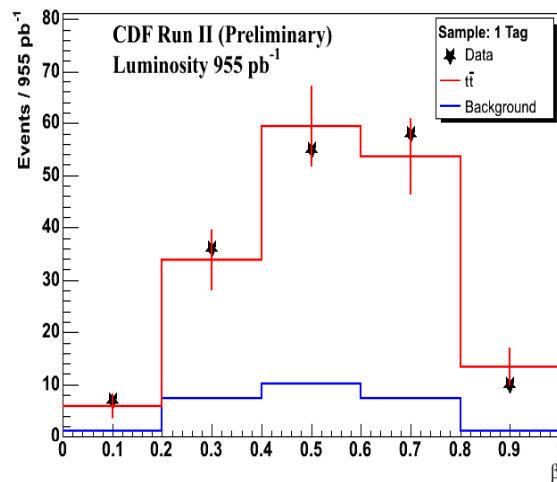
$$\sigma(gg \to t\bar{t}) / \sigma(p\bar{p} \to t\bar{t}) < 0.61 @ 95\% \ CL$$

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)

95%CL: σ(Z´→tt-bar)< 0.7 pb^{-1}

for $M_{Z'}$ > 700 GeV/c^2
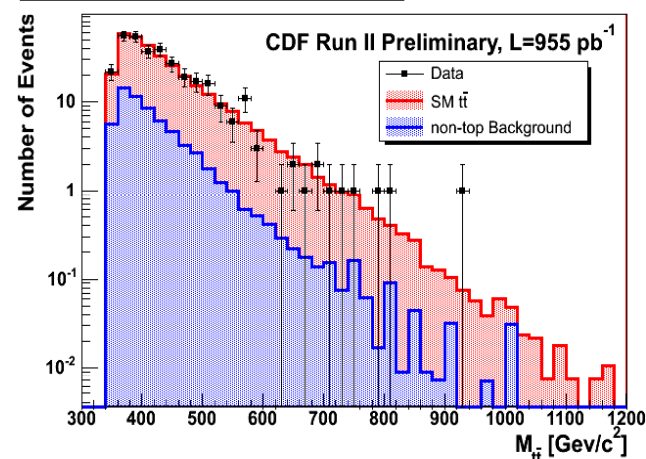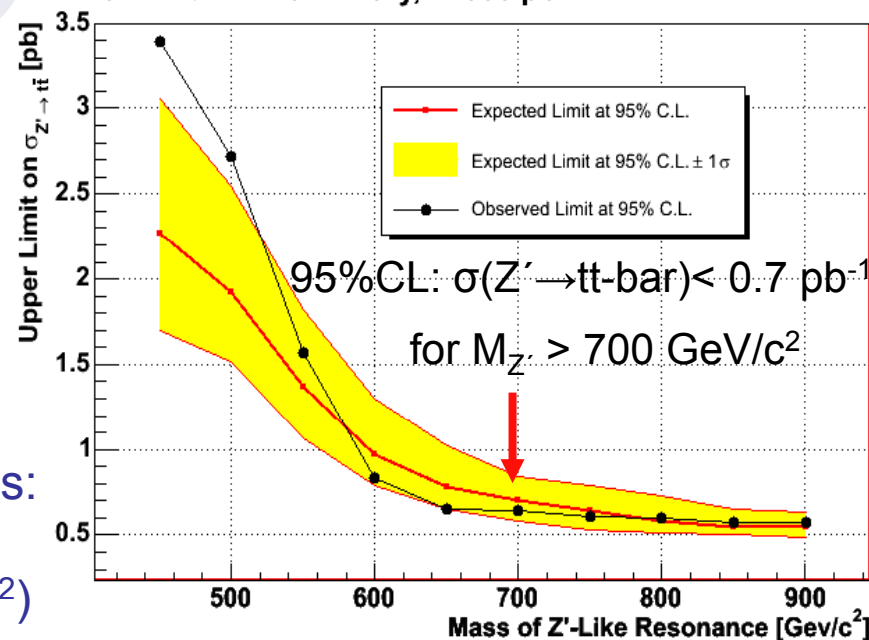
Search for a Heavy Top t´→Wb

- 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$_{RECO}$)
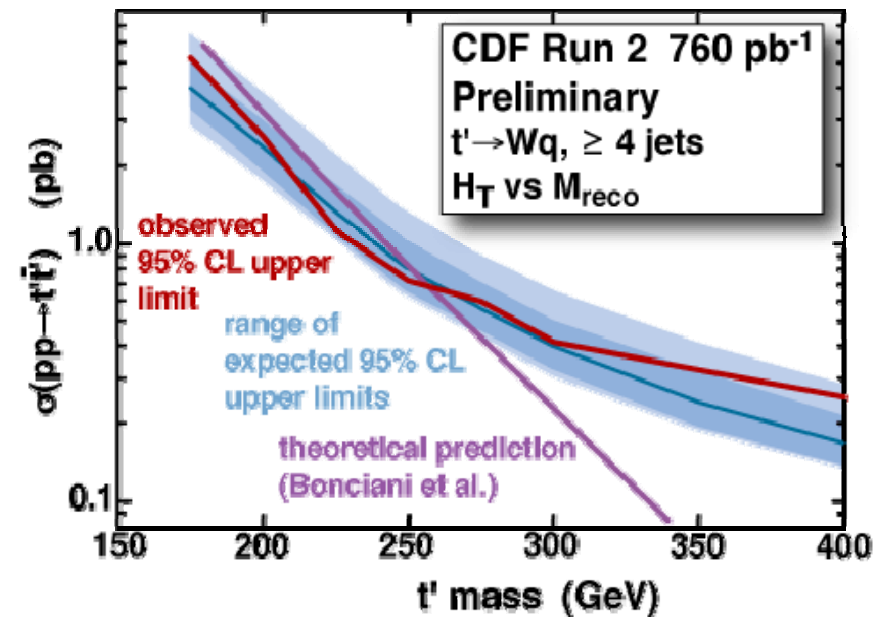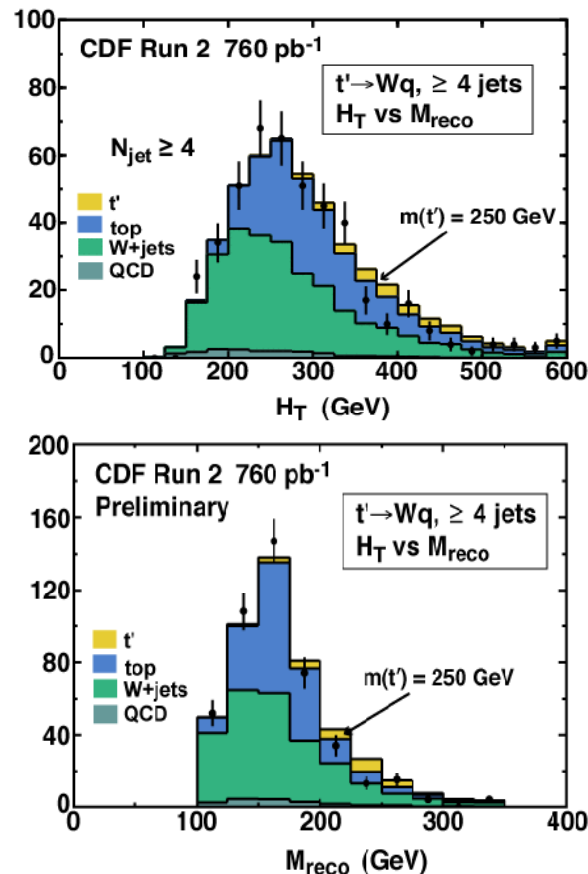
$$m_{t'} > 256\, GeV/c^2 \,@\, 95\% CL$$

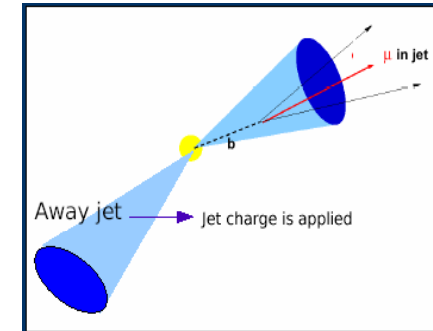# Event Displays: high H_T high M_{REC} candidates
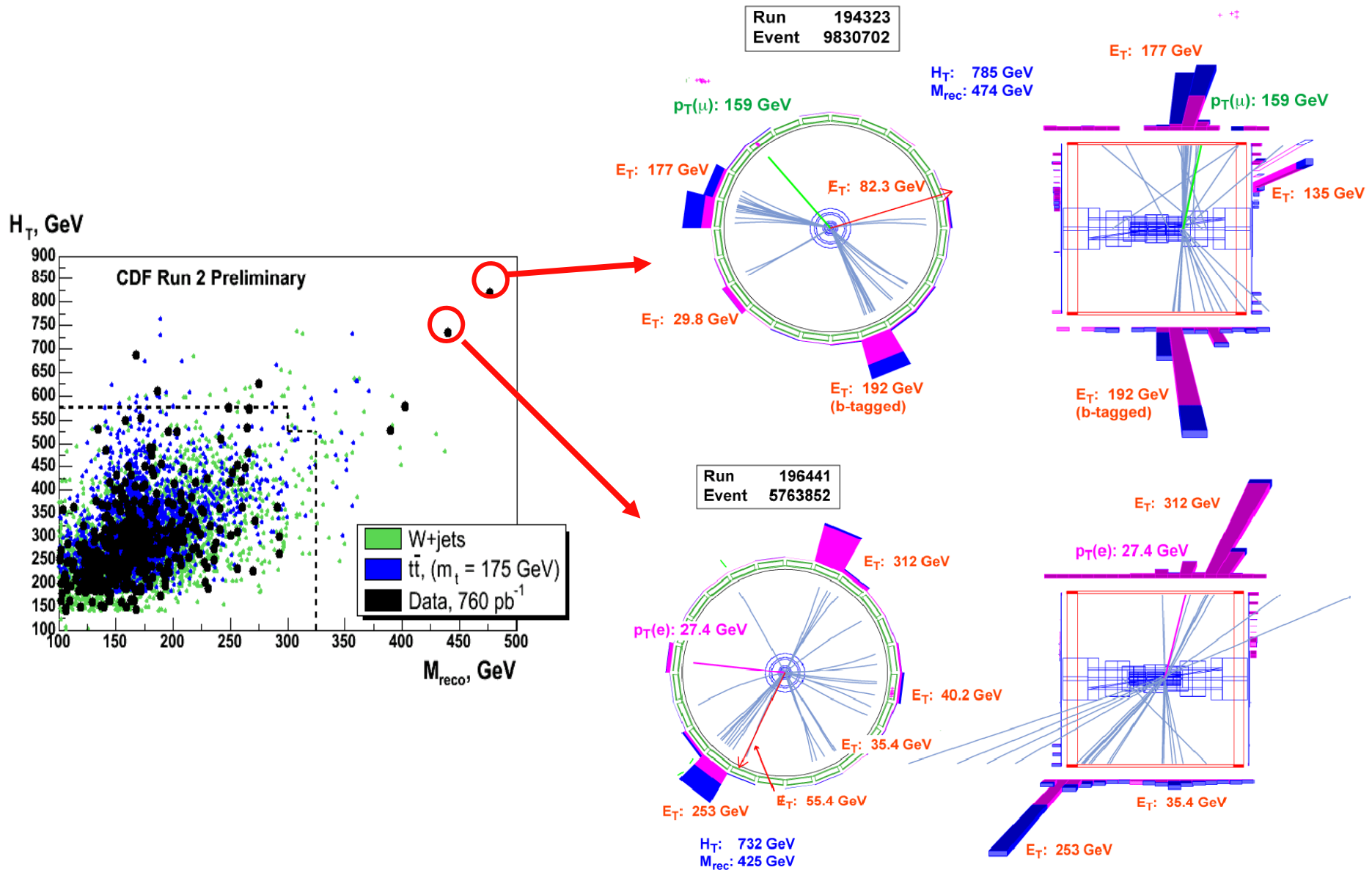
Top quark charge: +2/3 or -4/3 ?

- 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:

$$Q_{bjet} = \frac{\sum_i q_i^{track} \left(\vec{p}_i^{\,track} . \hat{a}_{jet} \right)^{0.5}}{\sum_i \left(\vec{p}_i^{\,track} . \hat{a}_{jet} \right)^{0.5}}$$

- 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
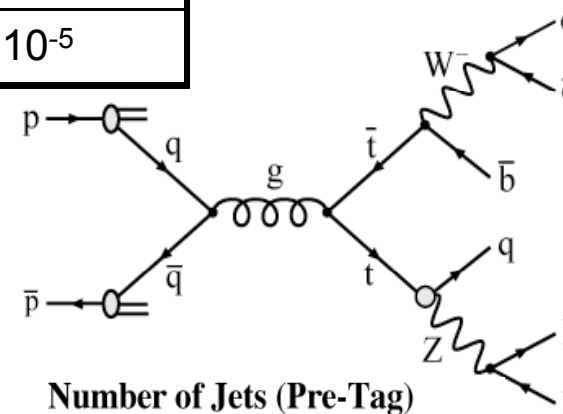**Exclude charge -4e/3 hypothesis at 81% confidence**
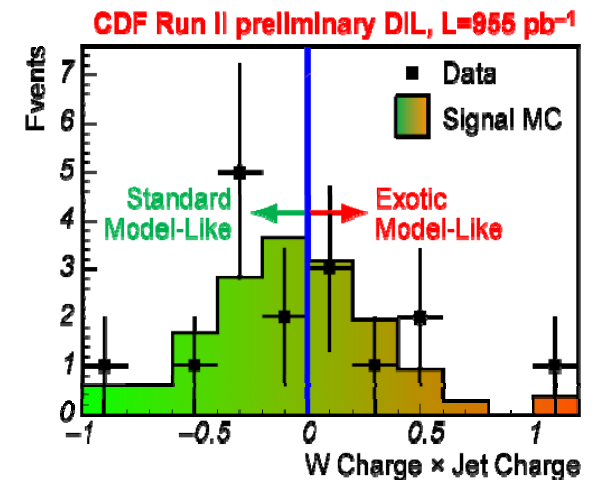
Search for the FCNC decay t→Zq
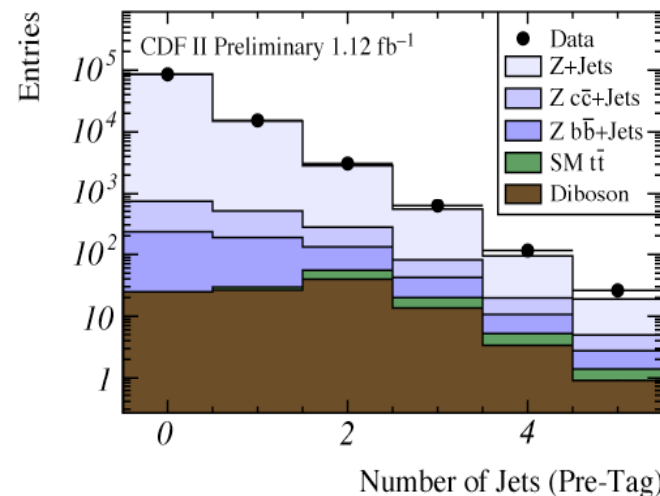
- SM: Top quark FCNC highly suppressed (GIM mechanism and CKM suppression)
- Beyond SM scenarios enhance top FCN decays providing observable BR´s
- Acta Phys. Polon. B35 (2004) 2695-2710, hep-ph/0409342

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
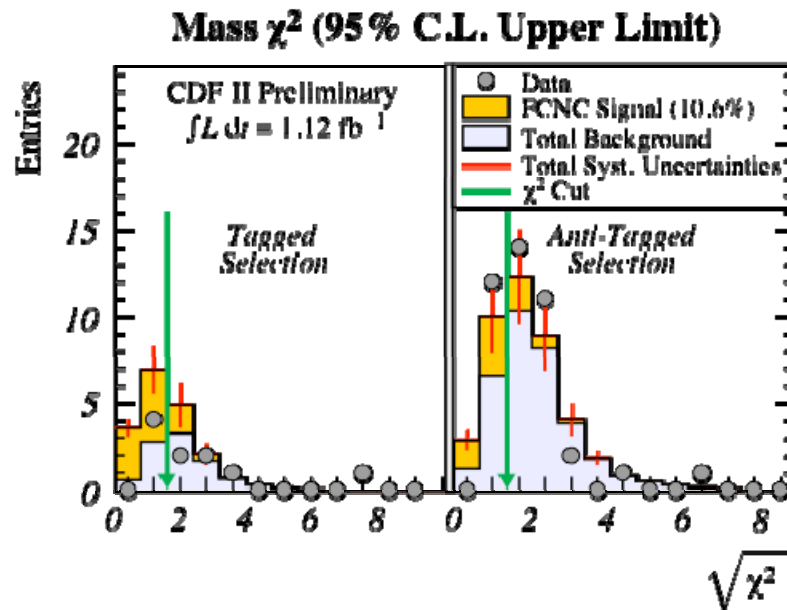 - Smaller backgrounds: tt and diboson (WZ, ZZ)

Number of Jets (Pre-Tag)

CDF II Preliminary 1.12 fb^{-1}

- Data
- Z+Jets
- Z $c\bar{c}$+Jets
- Z $b\bar{b}$+Jets
- SM t$\bar{t}$
- Diboson

Number of Jets (Pre-Tag)

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

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

Mass χ^2 (95% C.L. Upper Limit)

CDF II Preliminary
$\int L\,dt = 1.12\ fb^{-1}$

- Data
- FCNC Signal (10.6%)
- Total Background
- Total Syst. Uncertainties
- χ^2 Cut

Tagged Selection

Anti-Tagged Selection

- Unblinding after optimization: observed numbers events consistent with background

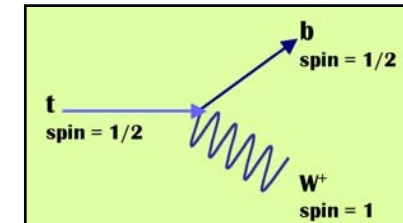| Selection	Observed	Expected
Base Selection	141	130±28
Base Selection (Tagged)	17	20±6
Anti-Tagged Selection	12	7.7+1.8
Tagged Selection	4	3.2±1.1

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

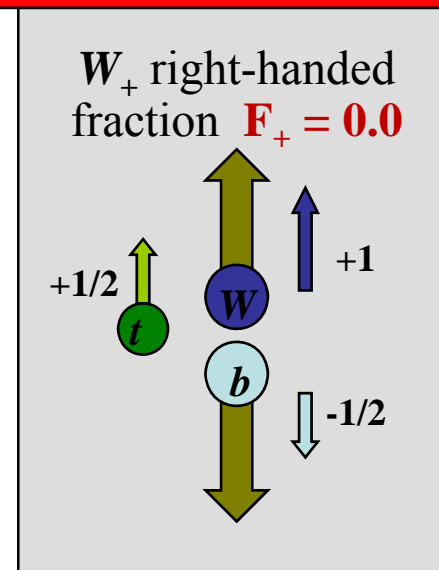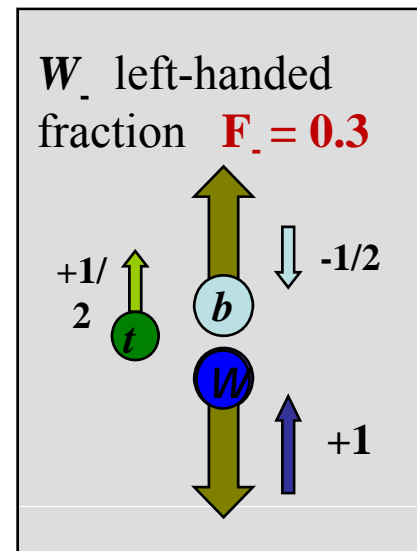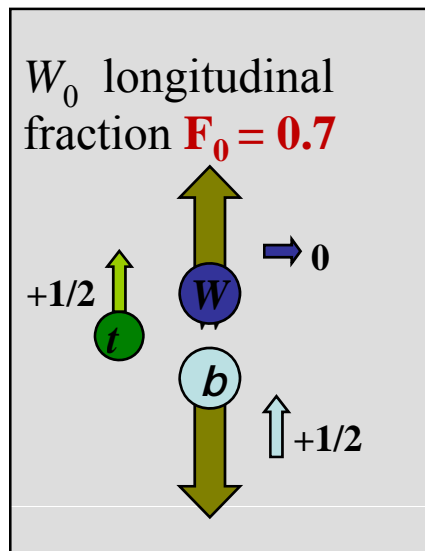- New world´s best limit: improves previous limit by 25% (13.7% from non-observation of $e^+e^- \to tq$ at LEP,L3)

W Helicity in Top Quark Decays

SM: Top quark decays via weak interaction to spin-1 W^+ boson and spin-1/2 b quark
$\rightarrow$ 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

W_0 longitudinal fraction $F_0 = 0.7$

W_- left-handed fraction $F_- = 0.3$

W_+ right-handed fraction $F_+ = 0.0$

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)
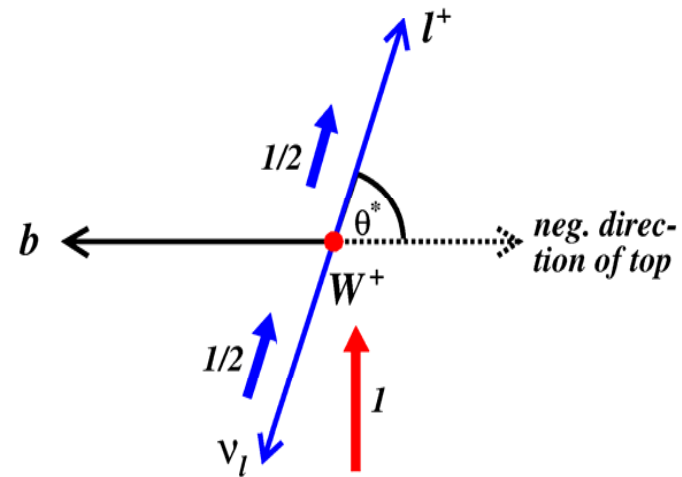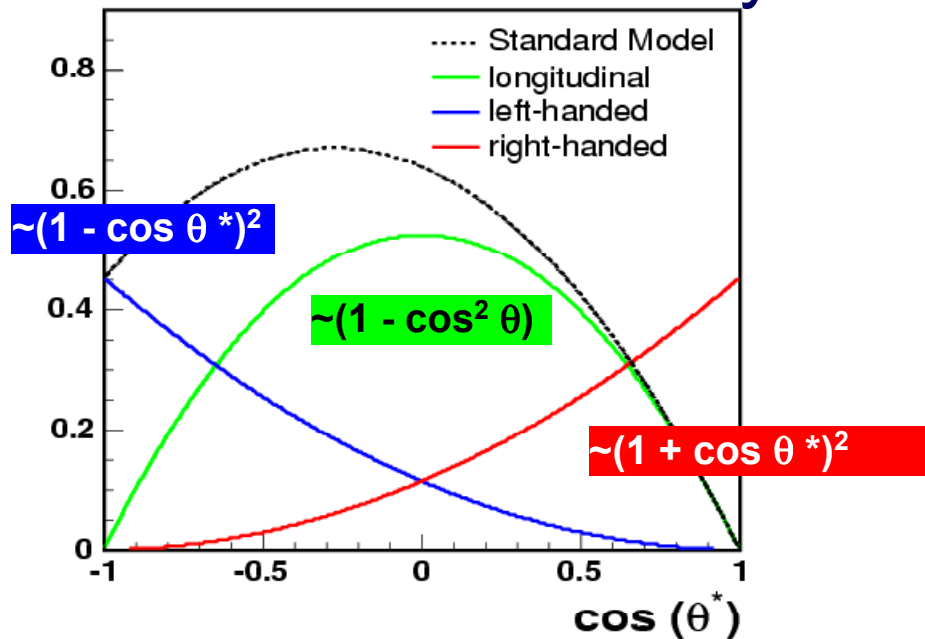
The presence of V+A could signal new physics: Left-right symmetric models? Mirror fermions?
Beg, Mohapatra et al. **Phys.Rev.Lett.38:1252, 1977**
Triantaphyllou: **J.Phys.G26:99,2000**
Tait,Yuan, He et al.:**Phys.Rev.D62:011702,2000, Phys.Rev.D65:053002,2002**

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 cosθ* 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

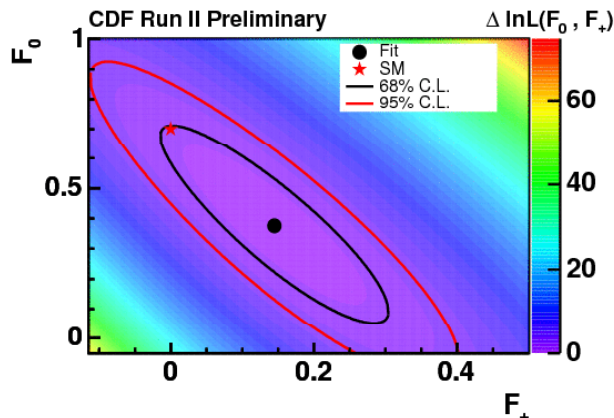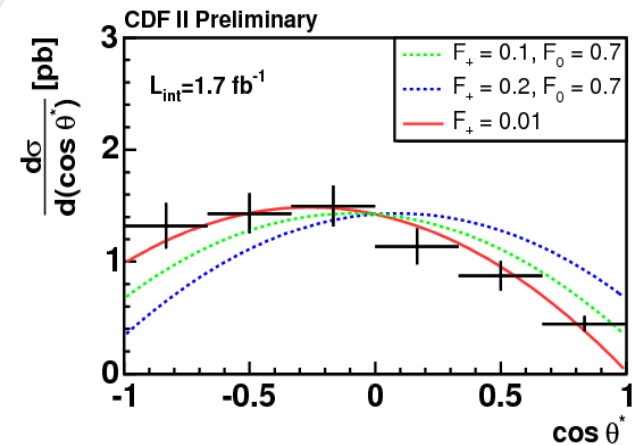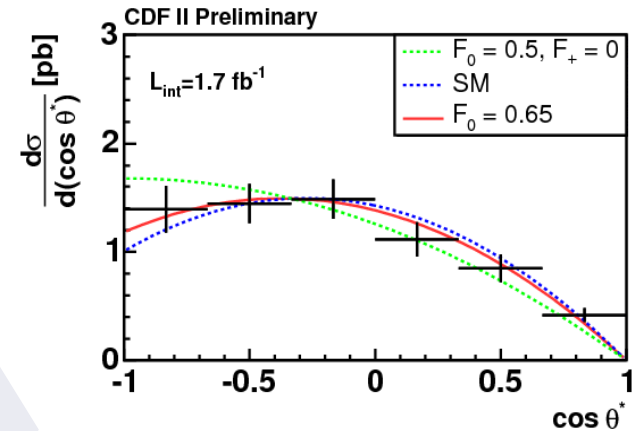# W-helicity: $\cos\theta^*$ method (I) 1.73 fb^{-1}

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
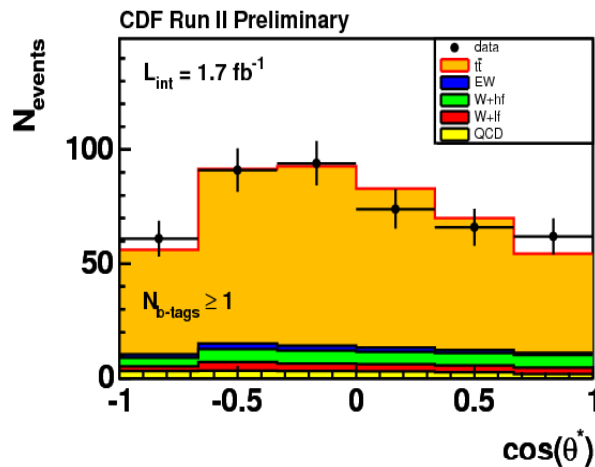
Unfolding of measured distribution:
Correct for efficiency and resolution effects.

$f_0 = 0.38 \pm 0.22_{stat} \pm 0.07_{syst}$ and $f_+ = 0.15 \pm 0.10_{stat} \pm 0.04_{syst}$

$f_0 = 0.65 \pm 0.10_{stat} \pm 0.06_{syst}$ with $f_+ = 0$

$f_+ = -0.01 \pm 0.05_{stat} \pm 0.03_{syst}$ with $f_0 = 0.7$ $f_+ < 0.12$ @95% CL

W-helicity: $\cos\theta^*$ method (II) 1 fb^{-1}
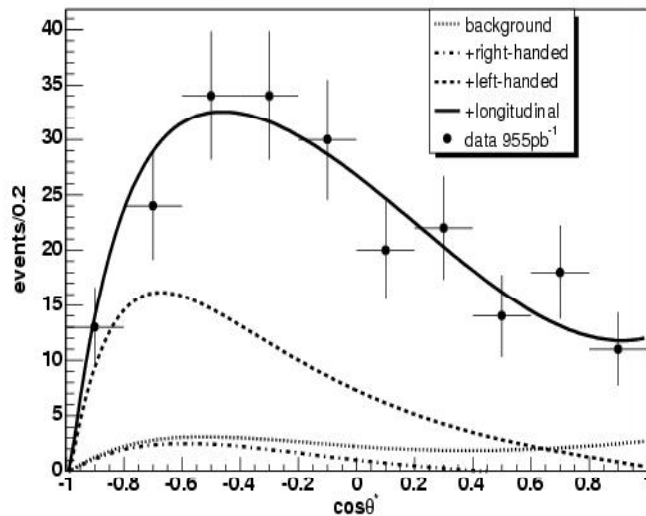
SECOND METHOD TO EXTRACT F_0 AND F_+

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

CDF II Preliminary
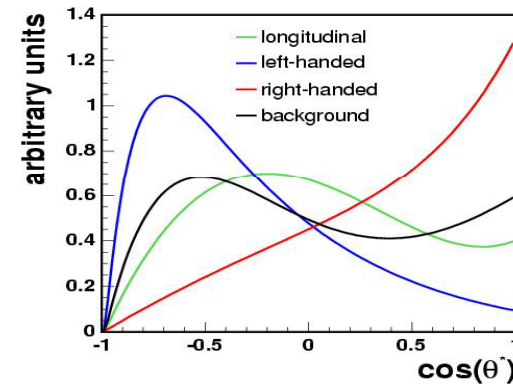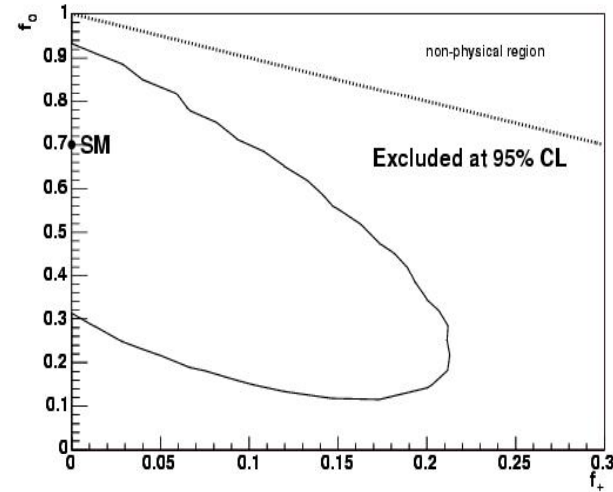

$f_0 = 0.74 \pm 0.25_{stat} \pm 0.06_{syst}$ and $f_+ = -0.06 \pm 0.10_{stat} \pm 0.03_{syst}$

$f_0 = 0.61 \pm 0.12_{stat} \pm 0.06_{syst}$ with $f_+ = 0$

$f_+ = -0.06 \pm 0.06_{stat} \pm 0.03_{syst}$ with $f_0 = 0.7$ $f_+ < 0.11$ @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.
    - <u>2fb^{-1} analyses coming by the end of summer.</u>

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

- <u>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})</u>
    - 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→H⁺b significant (>10%) for small and large tanβ

H⁺ decays differently than W⁺:

- H⁺→τ⁺υ_τ enhanced if high tanβ:
  - Excess of taus
- H⁺→t*b→W⁺bb for high m(H⁺) if low tanβ:
  - Mimics SM signature but observe more b-tags
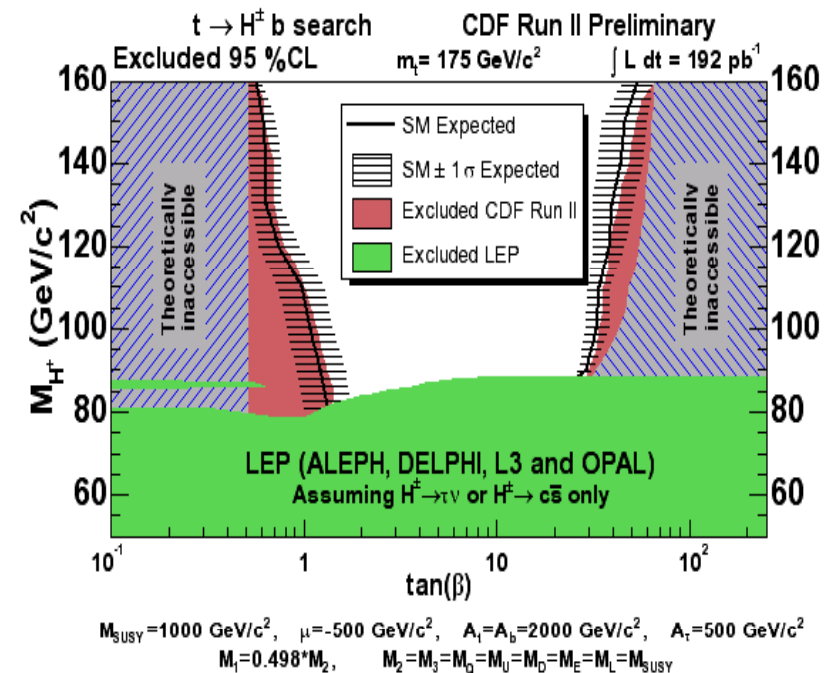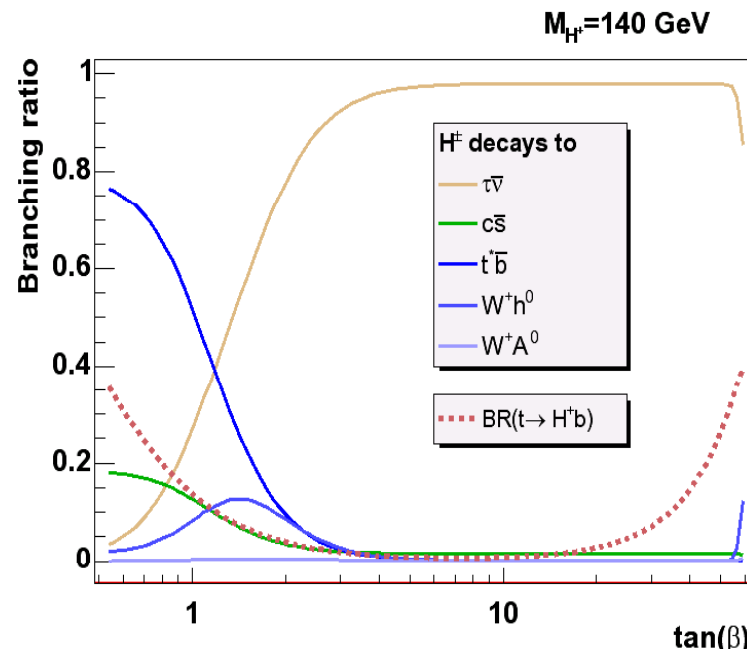- H⁺→cs: defect all channels.

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
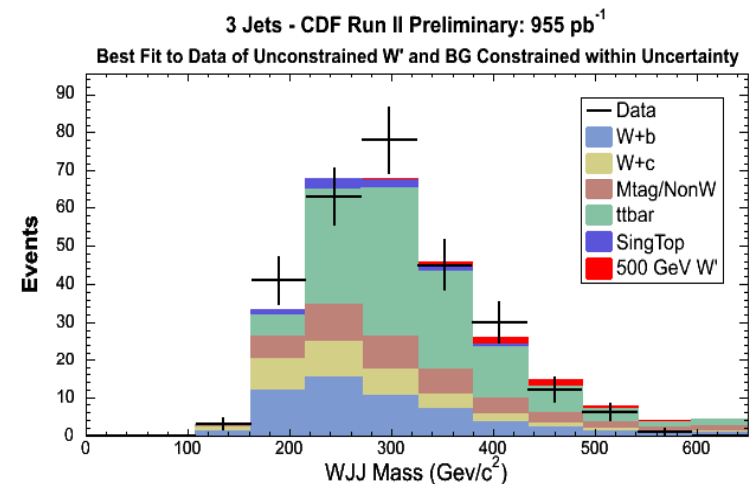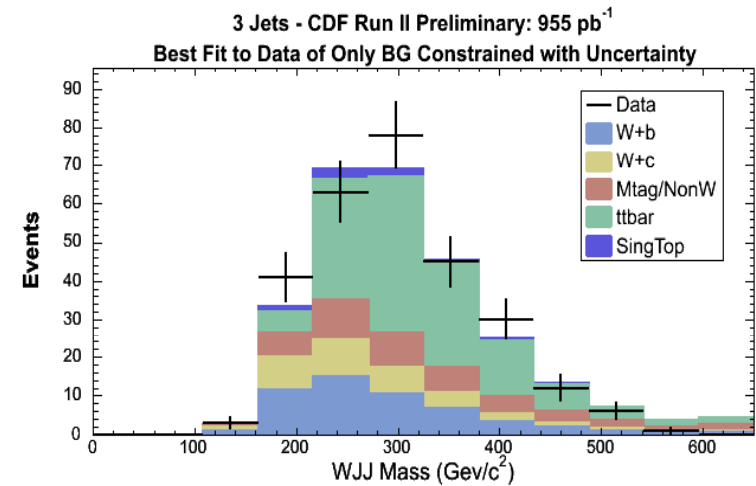
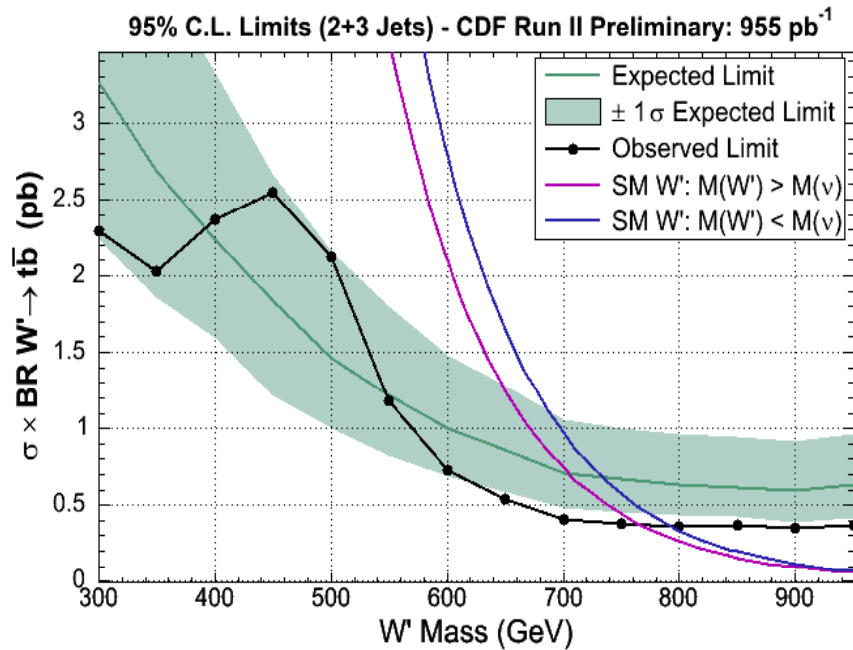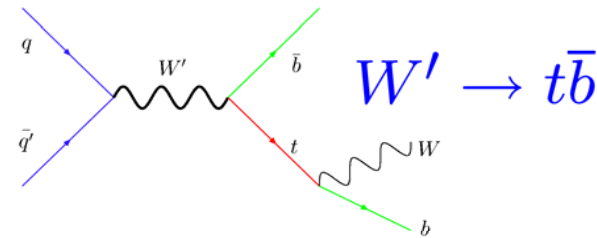(Phys. Rev. Lett 96,042003)

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)

$$W' \to t\bar{b}$$

- 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.

3 Jets - CDF Run II Preliminary: 955 pb⁻¹
Best Fit to Data of Only BG Constrained with Uncertainty

95% C.L. Limits (2+3 Jets) - CDF Run II Preliminary: 955 pb⁻¹

- Expected Limit
- ± 1σ Expected Limit
- Observed Limit
- SM W': M(W') > M(ν)
- SM W': M(W') < M(ν)

3 Jets - CDF Run II Preliminary: 955 pb⁻¹
Best Fit to Data of Unconstrained W' and BG Constrained within Uncertainty

A COMMON TOOL: THE "TOP MASS" KINEMATIC FITTER

jet 1
jet 2
jet 3
jet 4 (b tag)
missing Et
lepton
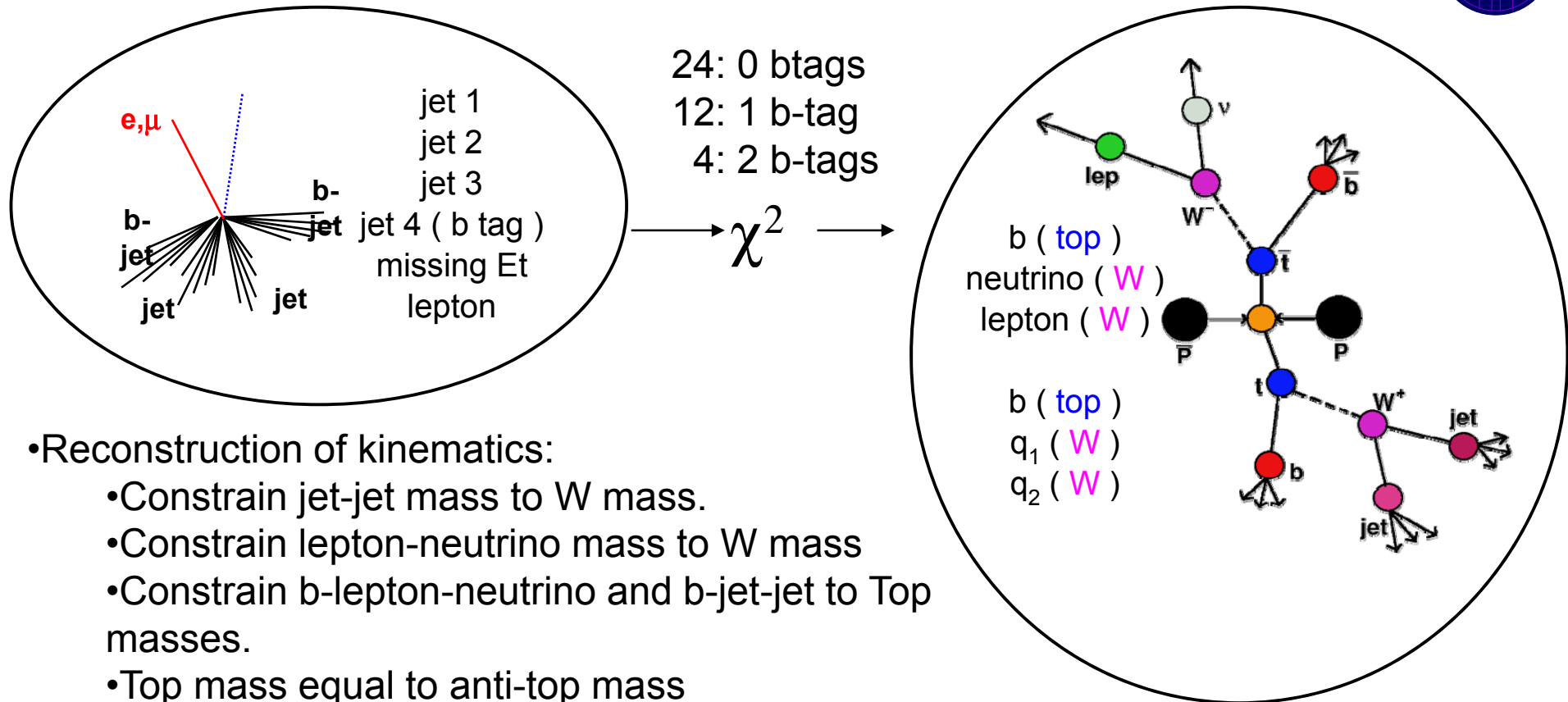
24: 0 btags
12: 1 b-tag
4: 2 b-tags

$\xrightarrow{} \chi^2 \xrightarrow{}$

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

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