Searches for New Physics in the Top Quark Samples at CDF

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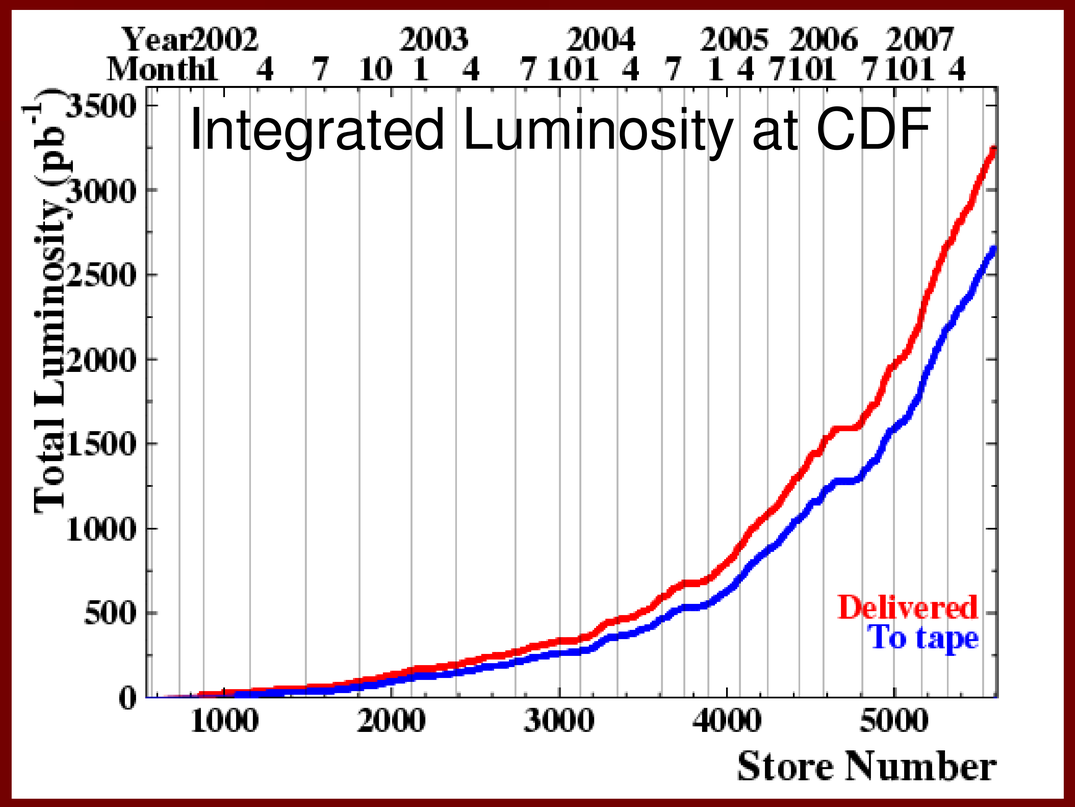
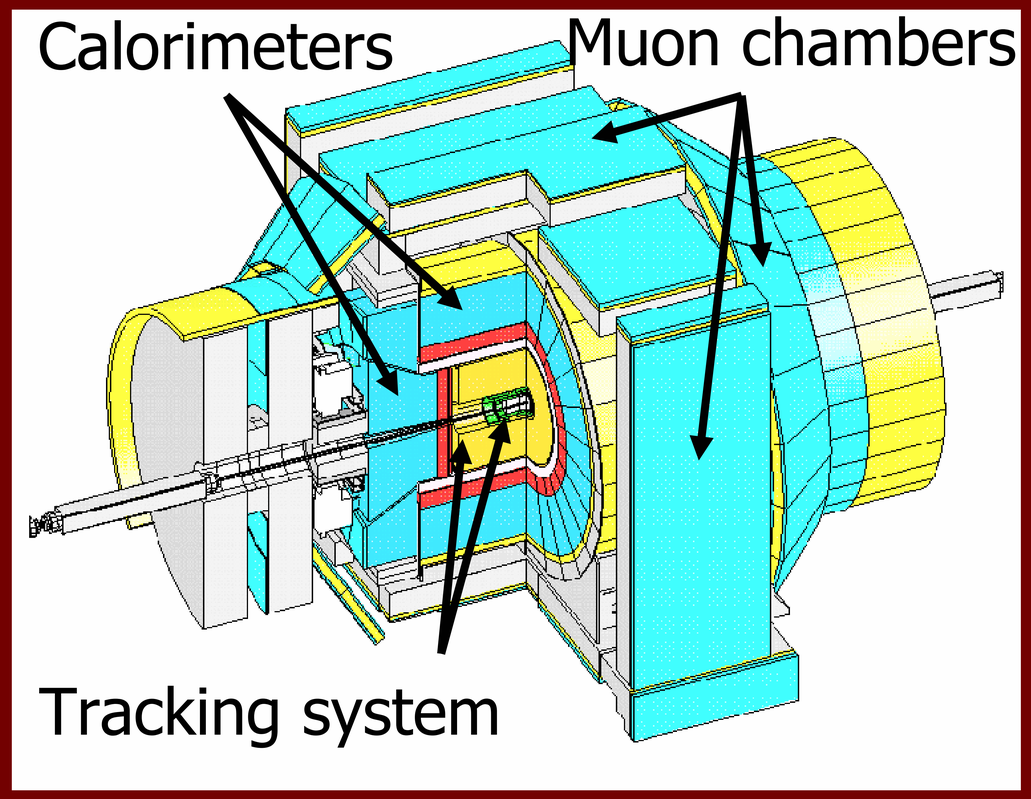
Motivations

- Top quark is really massive
  - Yukawa coupling to Higgs near unity
  - Special role in EWSB?
  - Sensitivity to physics beyond SM?
- Lot of top properties still to be tested
  - Top charge, width, couplings
  - Production mechanism
- Samples getting larger and well understood
  - Direct searches for new phenomena

The Tevatron and CDF

- Proton-antiproton collider
  - $\sqrt{s}$ = 1.96 TeV
  - Record luminosity $2.9 \times 10^{32} cm^{-2} s^{-1}$
  - Aim to collect 6-8 fb^{-1} by 2009
- Only top factory in the world





- Tracking system
  - charged particles and b-tagging
- EM and HAD calorimeters
  - electrons and jets
- Muon chambers

Top Production at the Tevatron

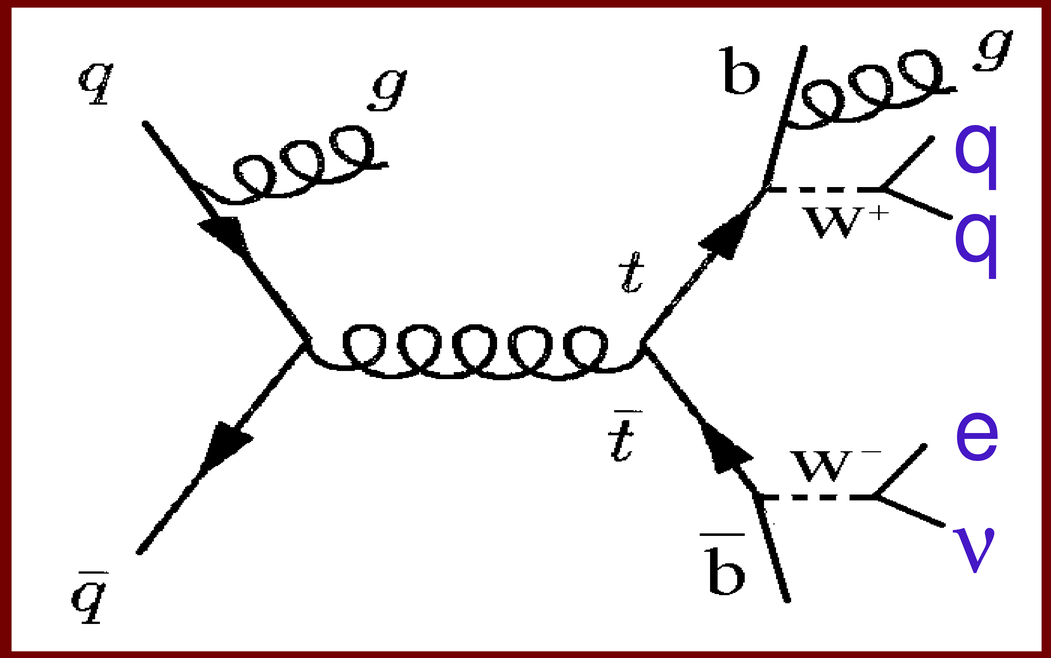
- Pair production via strong interaction dominant

  σ_{NLO} ($p\bar{p} \rightarrow t\bar{t}$) $\cong$ 6.7± 0.8 pb

  for m_t = 175 GeV/c^2

  Cacciari et al. JHEP 0404:068 (2004)

  Kidonakis & Vogt PRD 68 114014 (2003)



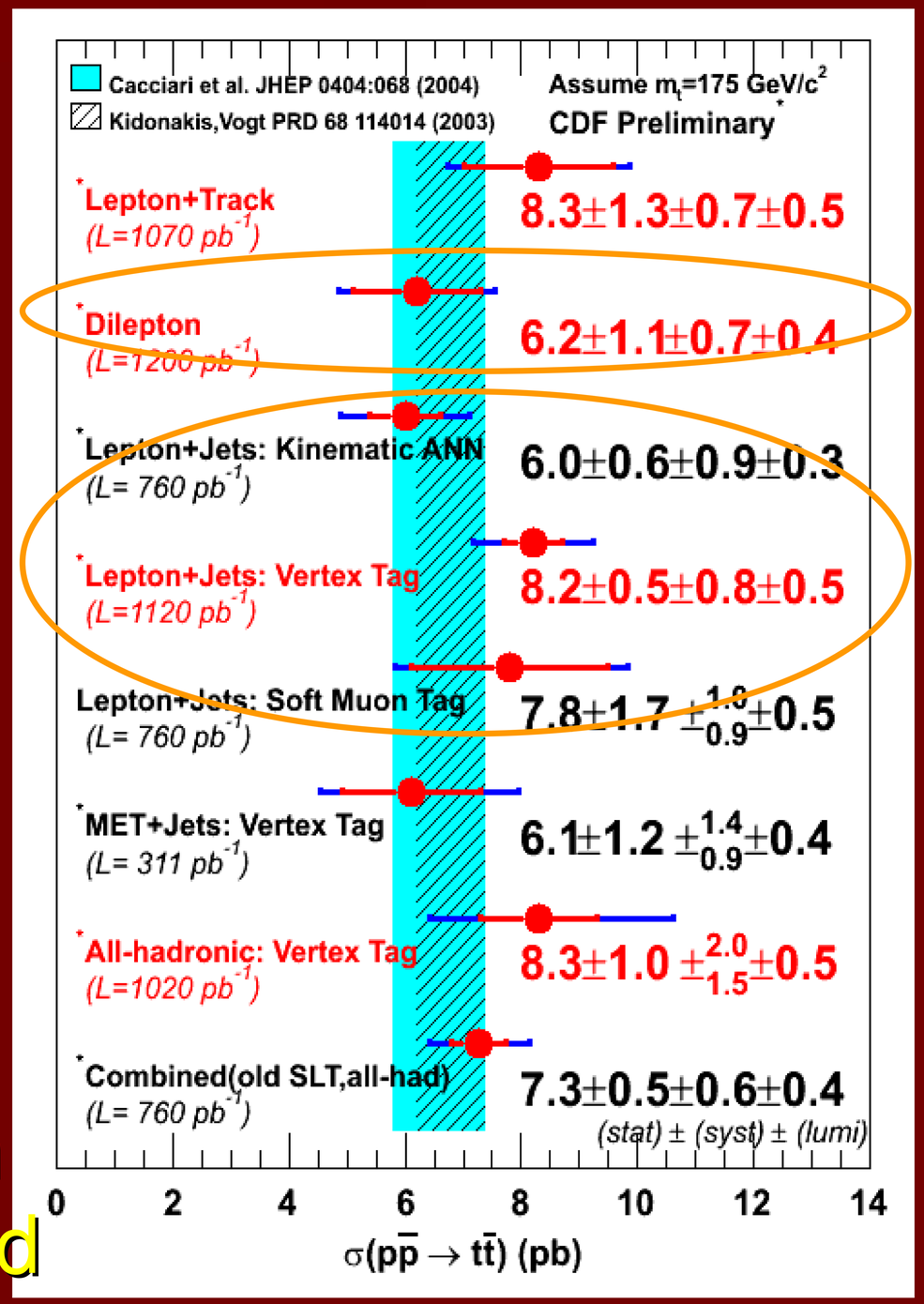
- Decay via electroweak interaction BR(t→Wb) ≈100%
- Observed final states given by W boson decay

  Dilepton: tt → lvlvbb (5%)
  Lepton+jets: tt → lvqqbb (30%)
  Hadronic: tt → qqqqbb (45%)

  } l=electron or muon

Top Quark Samples at CDF

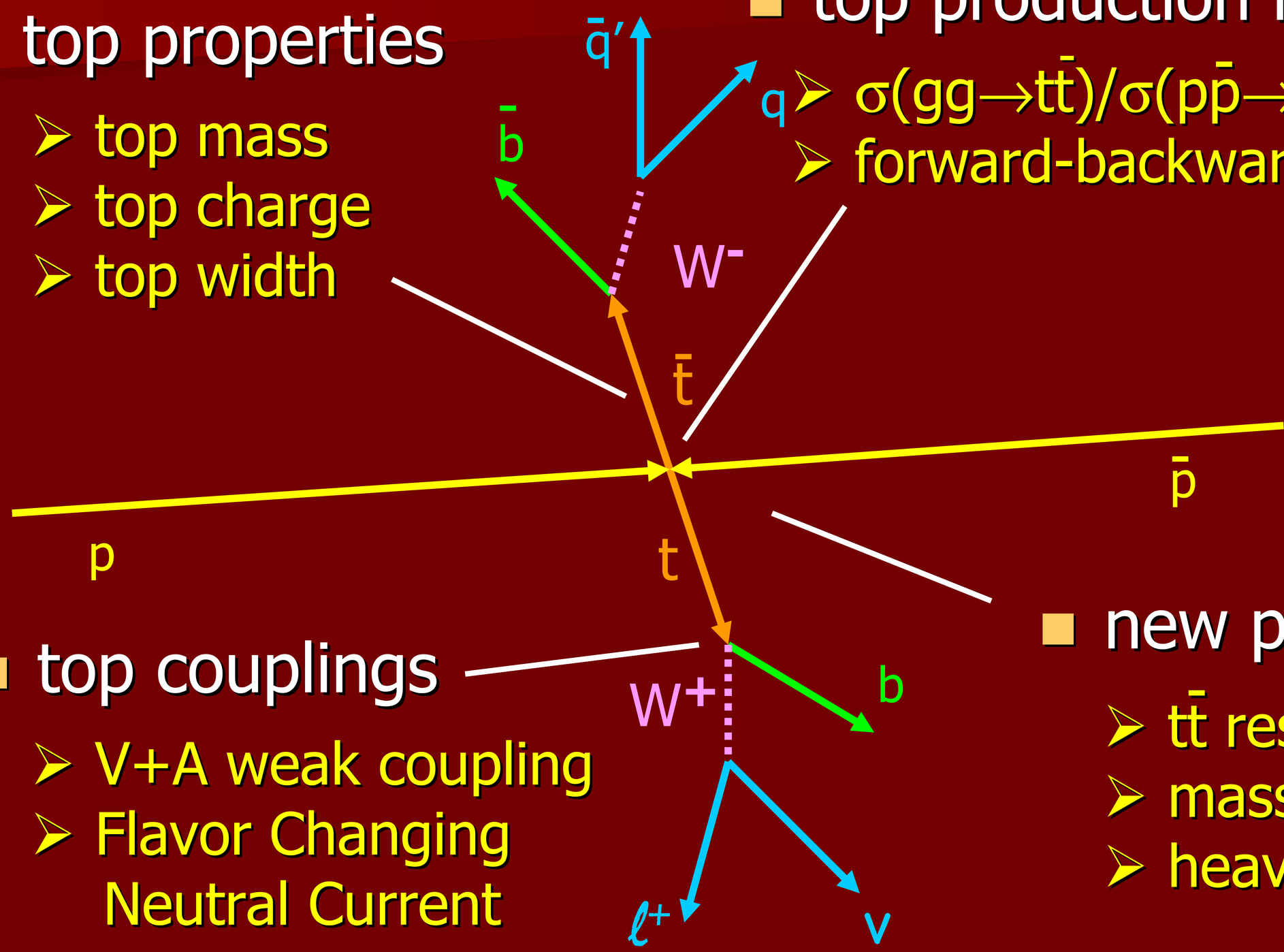
- Dilepton sample
  - Two high-P_T isolated leptons
  - Two high-E_T jets
  - Large missing transverse energy
- Lepton+jets sample
  - One high-P_T isolated lepton
  - ≥ 4 high-E_T jets (≥1 b-tagged)
  - Large missing transverse energy
- About 1-1.7 fb^{-1} analyzed
- Cross section measured
  - Good agreement with SM prediction
  - Sample composition well understood



What Can We Test?

- top properties
  - top mass
  - top charge
  - top width

- top production mechanism
  - $\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$
  - forward-backward asymmetry



- top couplings
  - V+A weak coupling
  - Flavor Changing Neutral Current

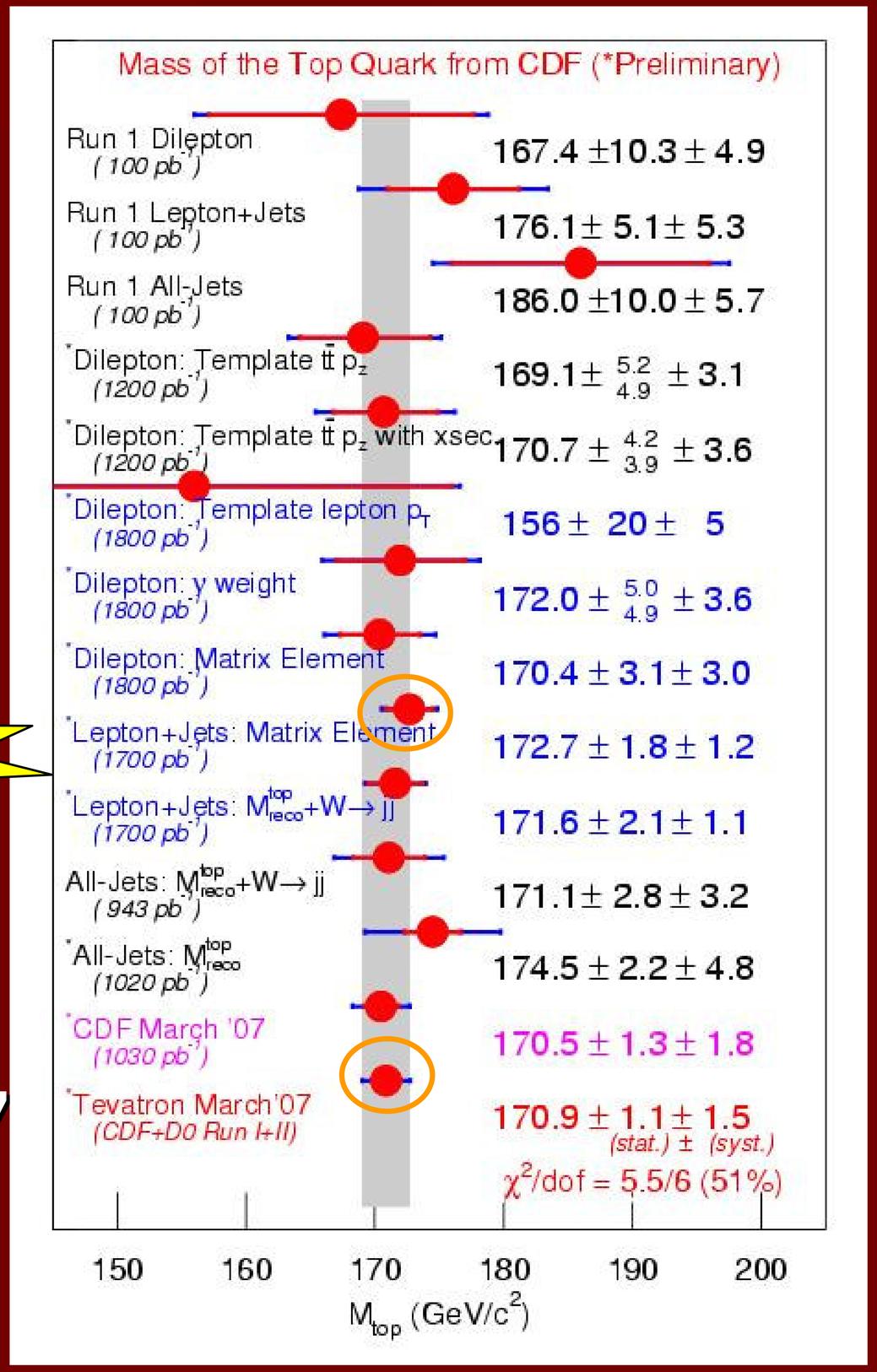
- new particles
  - $t\bar{t}$ resonances
  - massive t′
  - heavy W′

Top Quark Properties

Top Quark Mass

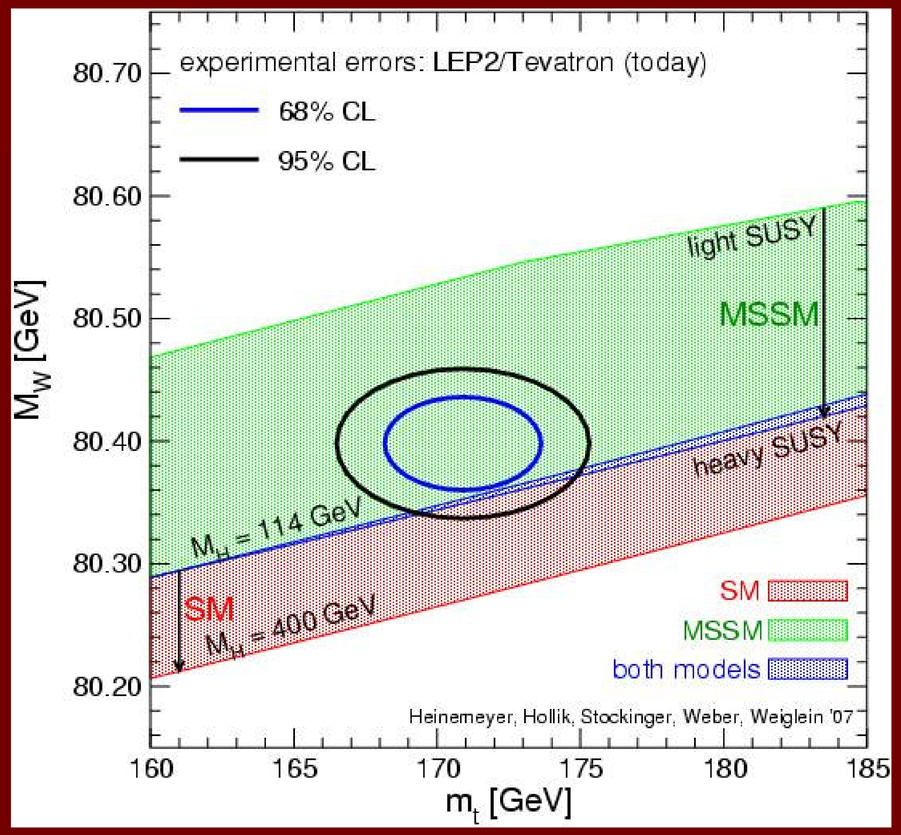
- Challenging measurement
  - final state reconstruction
  - jet energy measurement
  - neutrinos undetected
- Best world measurement
  lepton+jets channel:
  $m_t = 172.7 \pm 2.1$ GeV/c^2
- Tevatron combination March'07
  $m_t = 170.9 \pm 1.8$ GeV/c^2

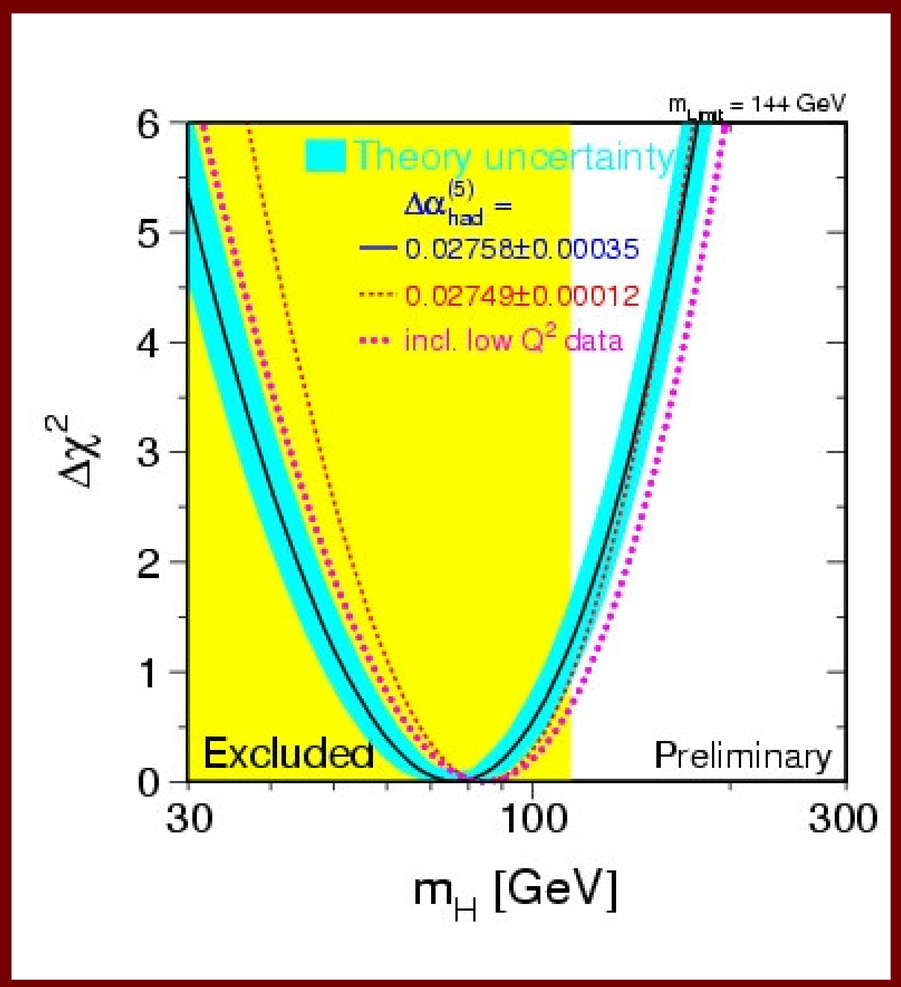
New!!!



Constraints on Higgs Boson Mass

- Top mass (together with W) mass measurements allow to constrain Higgs boson mass through radiative corrections





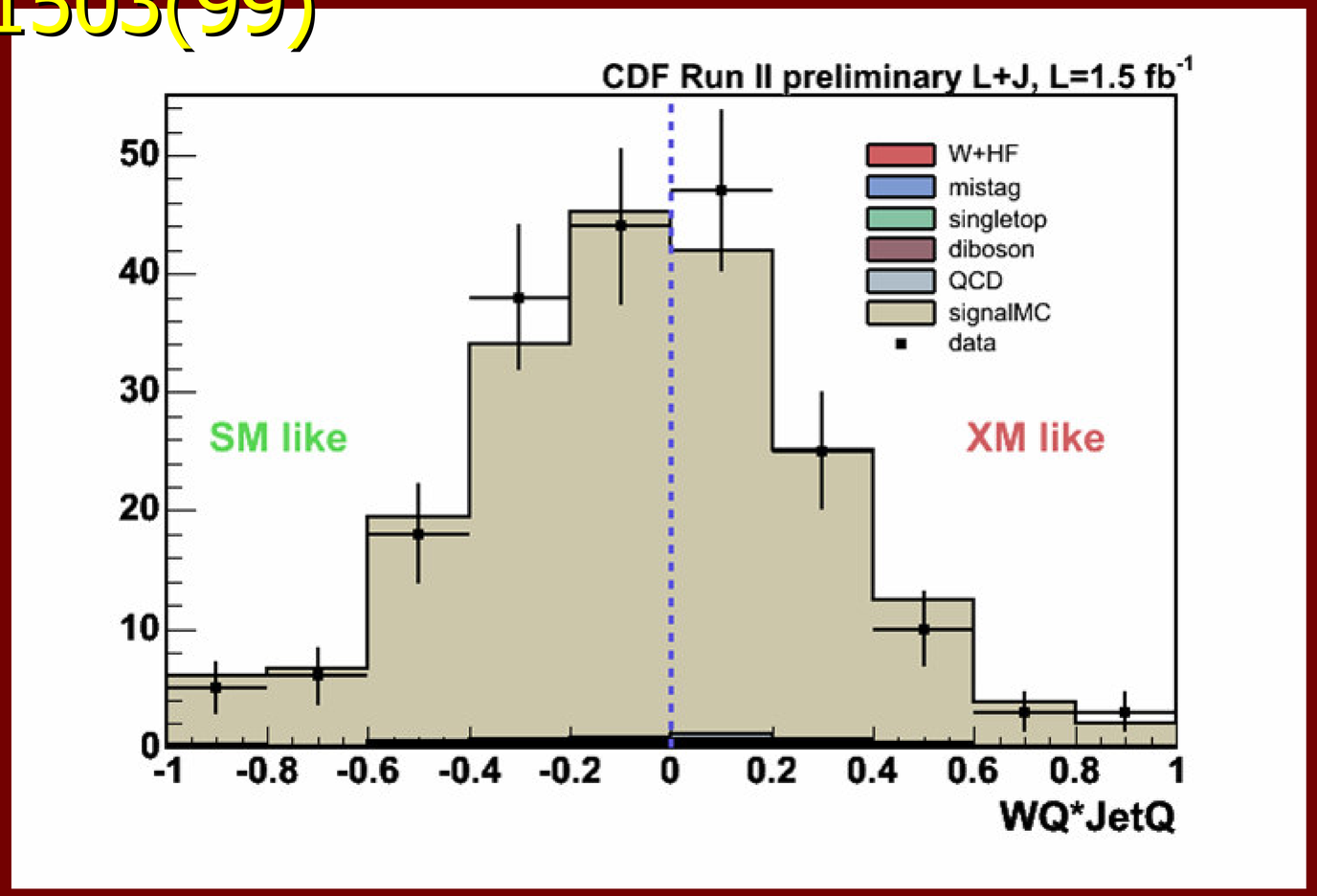
- Electroweak fit to SM Higgs boson mass using latest Tevatron combination:

$M_H = 76^{+33}_{-24}$ GeV/c^2

$M_H < 144$ GeV/c^2 @ 95% CL

Top Charge: +2/3 or -4/3?

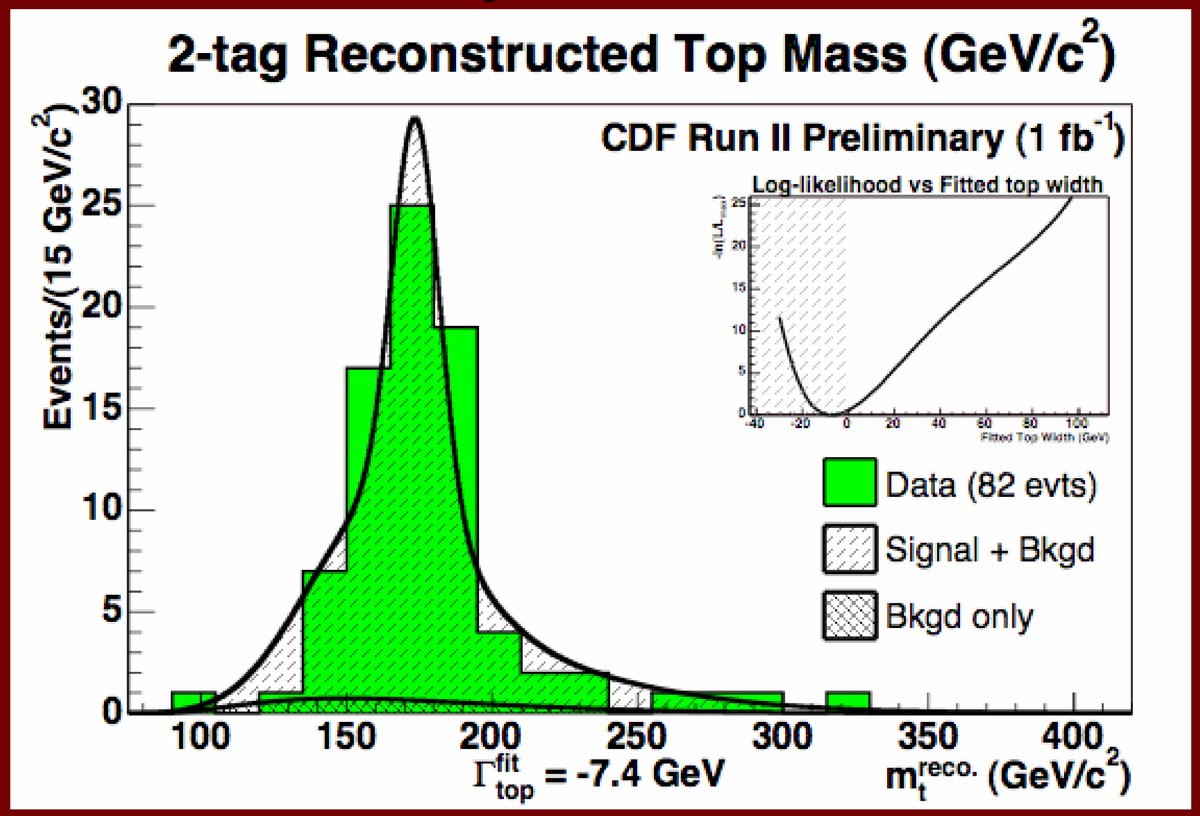
- Suggestions for a fourth generation quark with Q=-4/3
  D. Chang et al. PRD 59 091503(99)
- Top charge reconstructed from decay product $t \rightarrow Wb$
  - W charge from leptonic decay $W^{\pm} \rightarrow \ell^{\pm}\nu$
  - b flavor from charged tracks information in jet

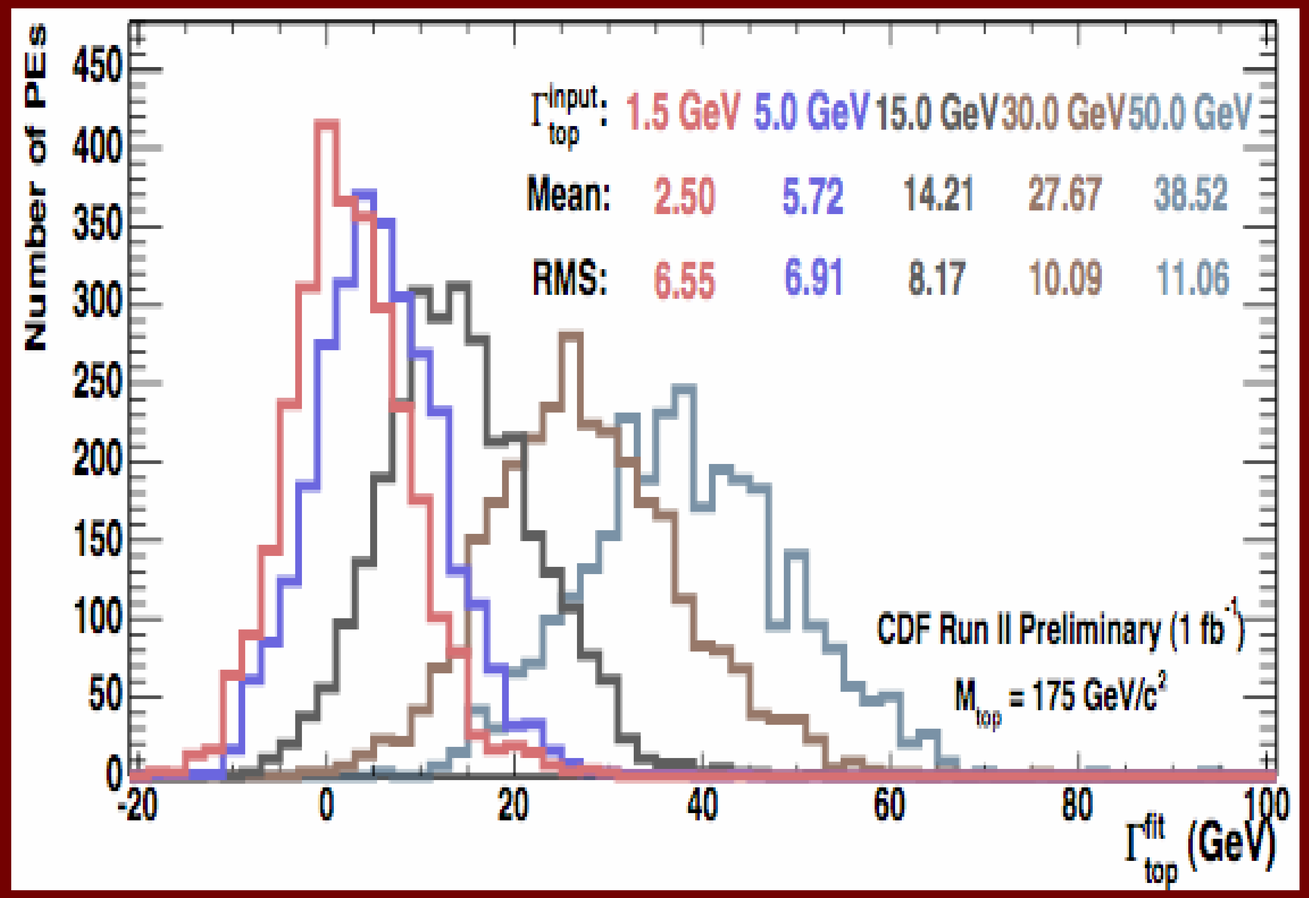


- Observed charge distribution tested vs Q=+2/3 and Q=- 4/3 hypotheses
  - data consistent with a SM top hypotesis
  - exotic quark excluded at 87% CL

Top Quark Width

- Top lifetime in SM extremely short ($\tau_t \sim 4\times10^{-25}$s)
- Top mass spectrum sensitive to top width: templetes fit to extract Γ_t



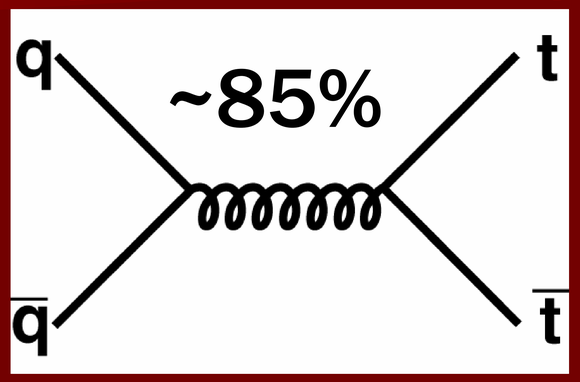


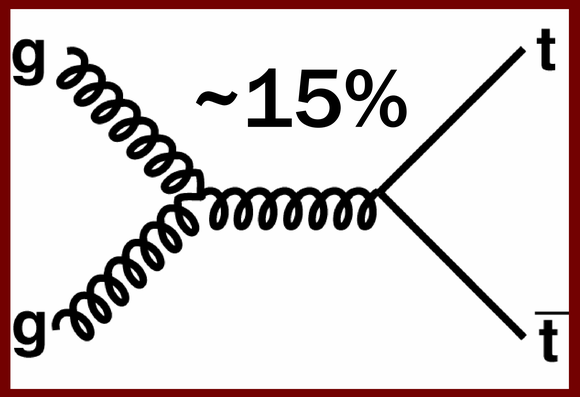
- Compare Γ_t^{fit} to results from pseudo-experiments
  - $\Gamma_t < 12.7$ GeV @ 95% CL
  - $\tau_t > 5.2\times10^{-26}$ s @ 95% CL

Top Production Mechanism

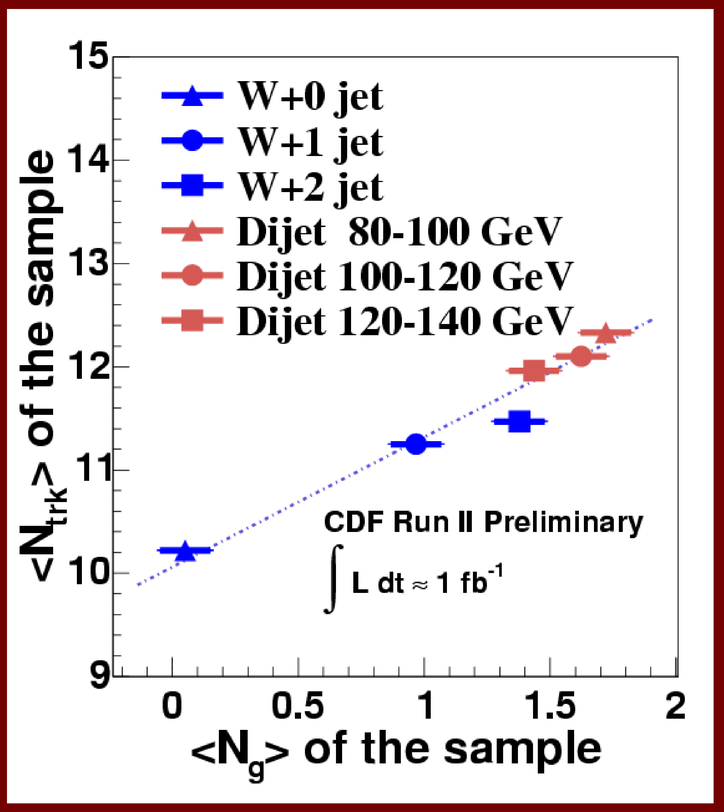
$\sigma(gg\to t\bar{t})/\sigma(p\bar{p}\to t\bar{t})$

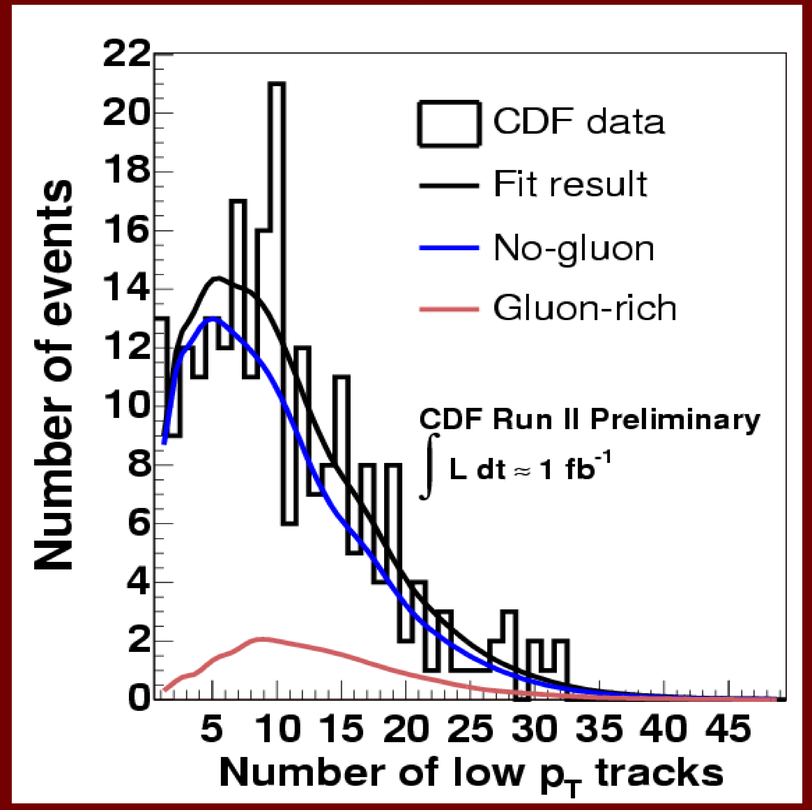
- Fraction of $t\bar{t}$ events from gluon fusion provides
  - test perturbative QCD
  - sensitivity to new top production and decay





- First idea: radiation from gluons tends to carry low P fraction



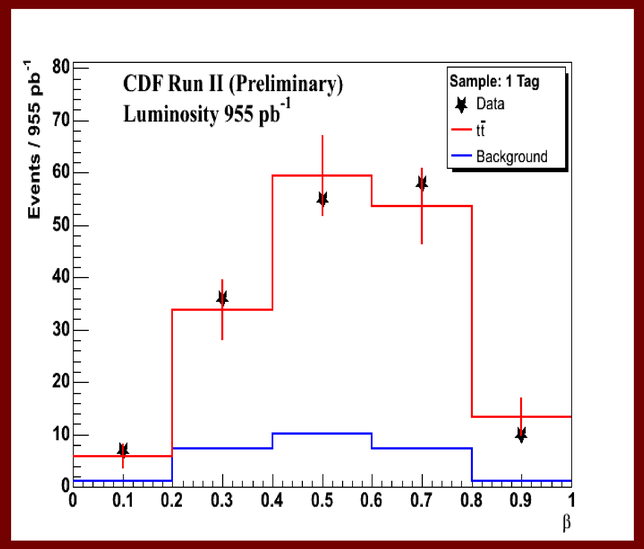


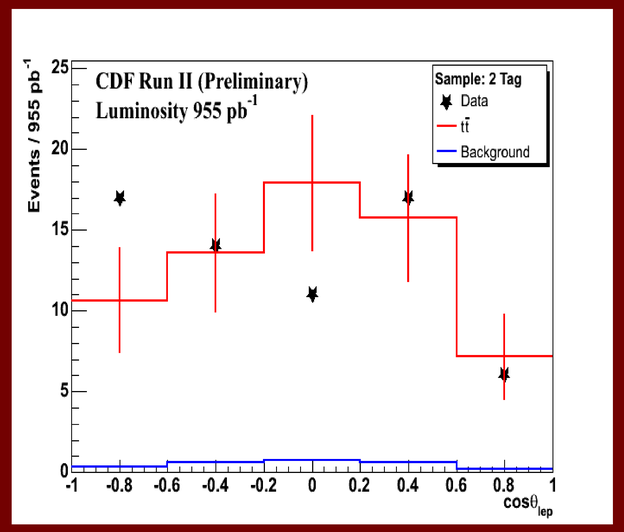
- Low-P_T track multiplicity measured in no-gluon and gluon-rich samples
- Fitting data distribution to $\langle N_{TRK}\rangle$ templates

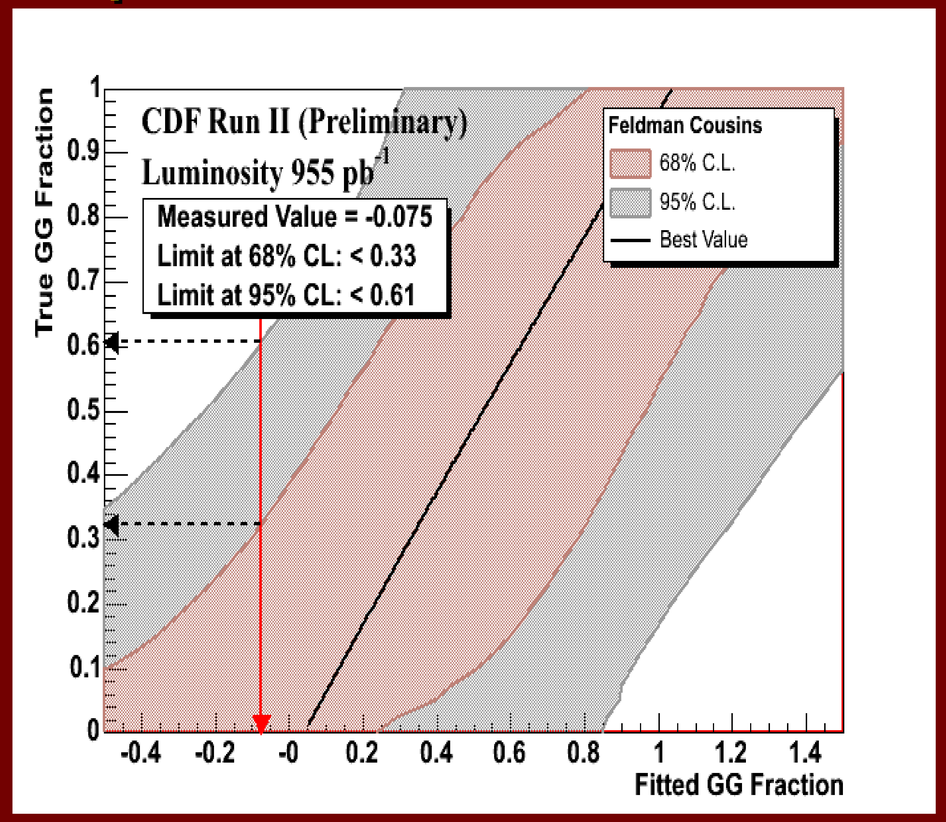
$$\sigma(gg\to t\bar{t})/\sigma(p\bar{p}\to t\bar{t}) = 0.07 \pm 0.16$$

$\sigma(gg\rightarrow t\bar{t})/\sigma(p\bar{p}\rightarrow t\bar{t})$

- Second idea: top-antitop spin correlation
  - like-sign in gluon fusion production
  - unlike-sign in $q\bar{q}$ annihilation
- Neural Network approach:
  - 2 kinematic variables describing the production in $t\bar{t}$ frame
  - 6 angles between decay products → spin correlation
- Fitting data to NN output shapes





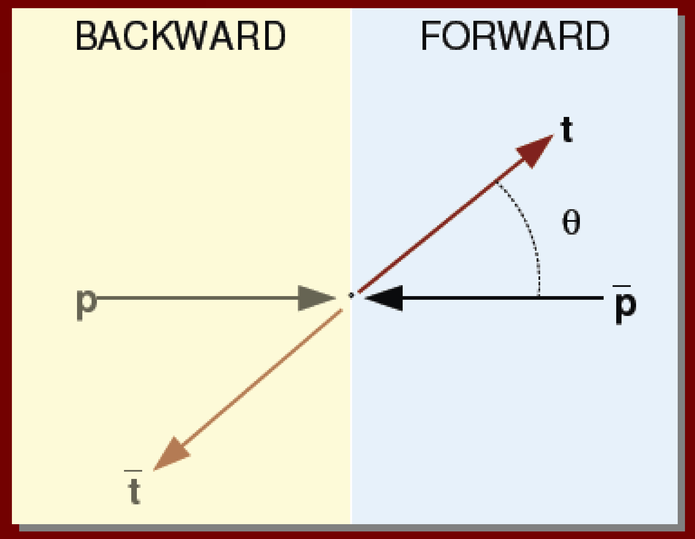


$\sigma(gg\rightarrow t\bar{t})/\sigma(p\bar{p}\rightarrow t\bar{t})<0.33$ @ 68% CL

Forward-Backward Asymmetry

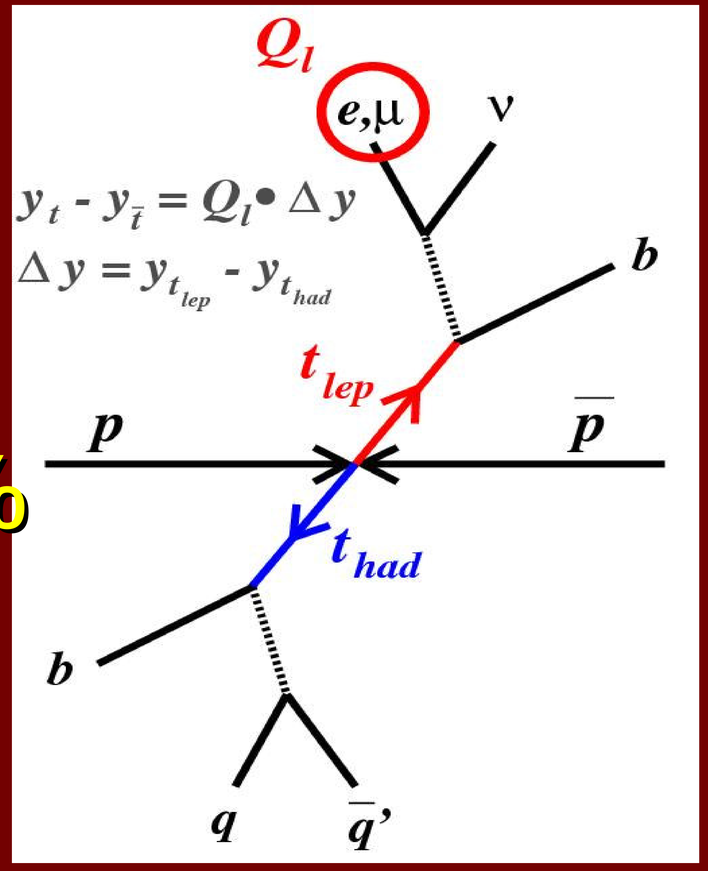
- Production diagrams interference

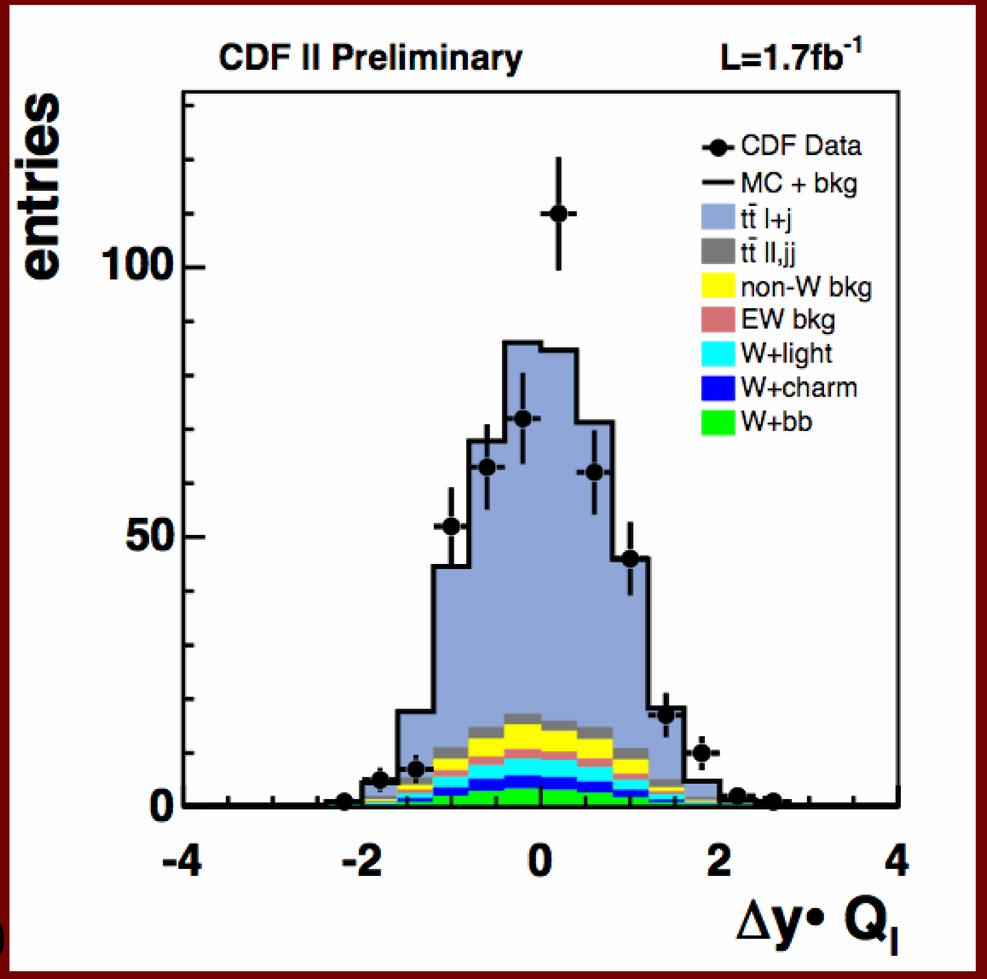
$$A_{fb} = \frac{N_t(\cos\theta) - N_{\bar{t}}(\cos\theta)}{N_t(\cos\theta) + N_{\bar{t}}(\cos\theta)}$$



- 4-6% asymmetry expected at NLO
- Use $\Delta Y^* Q_l$ in lepton+jets sample:

$A_{\Delta Y^* Q}^{NLO} \sim 4\text{-}7\%$



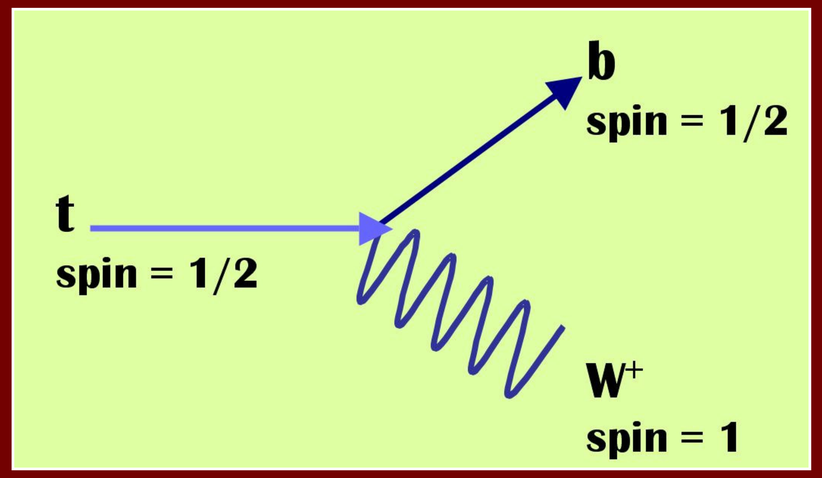


$A_{fb} = 28 \pm 13(\text{stat}) \pm 5(\text{syst})\ \%$

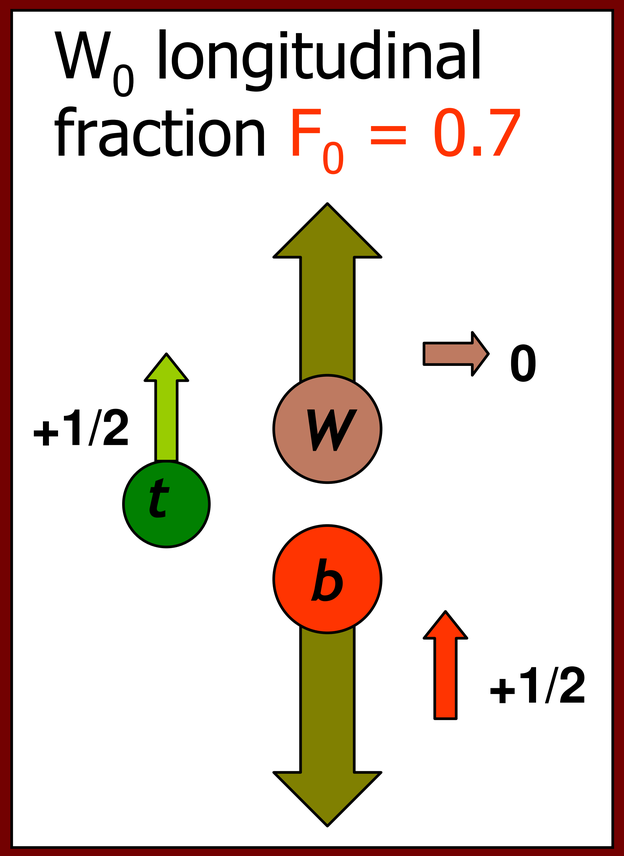
Searches for Non-SM Top Couplings

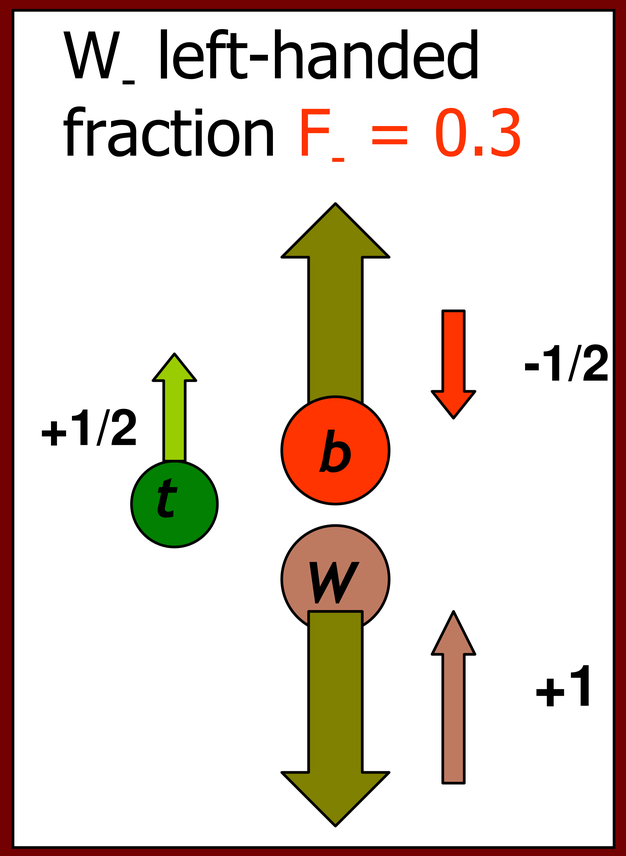
Right-Handed Weak Coupling

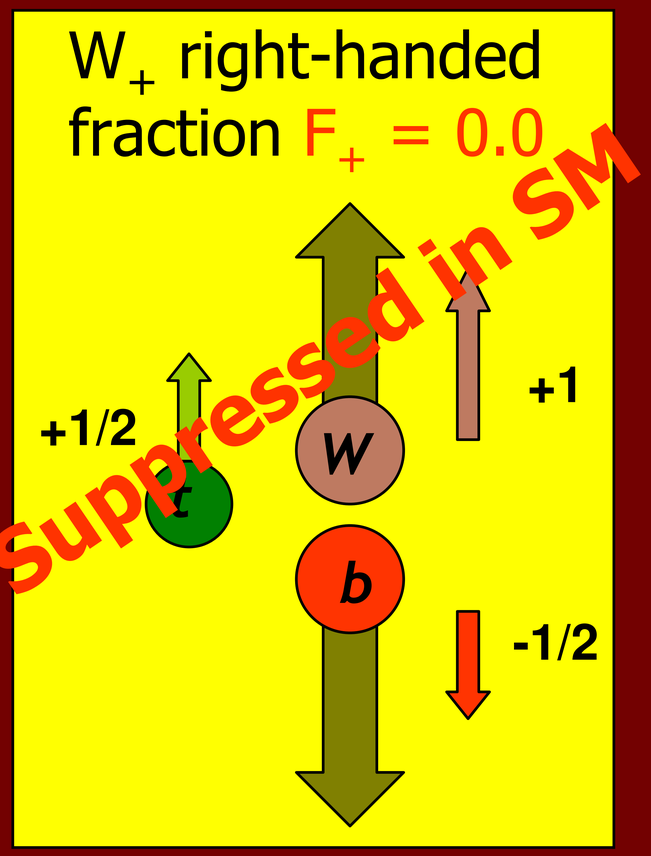
- V+A coupling signal of new physics
  - Left-right symmetry, PRL 38,1252(1977)
  - Mirror particles, J.Phys.G 26,99 (2000)
  - Beautiful mirrors, PRD 65,53002,(2002)



- V-A character of top decay tested by W helicity

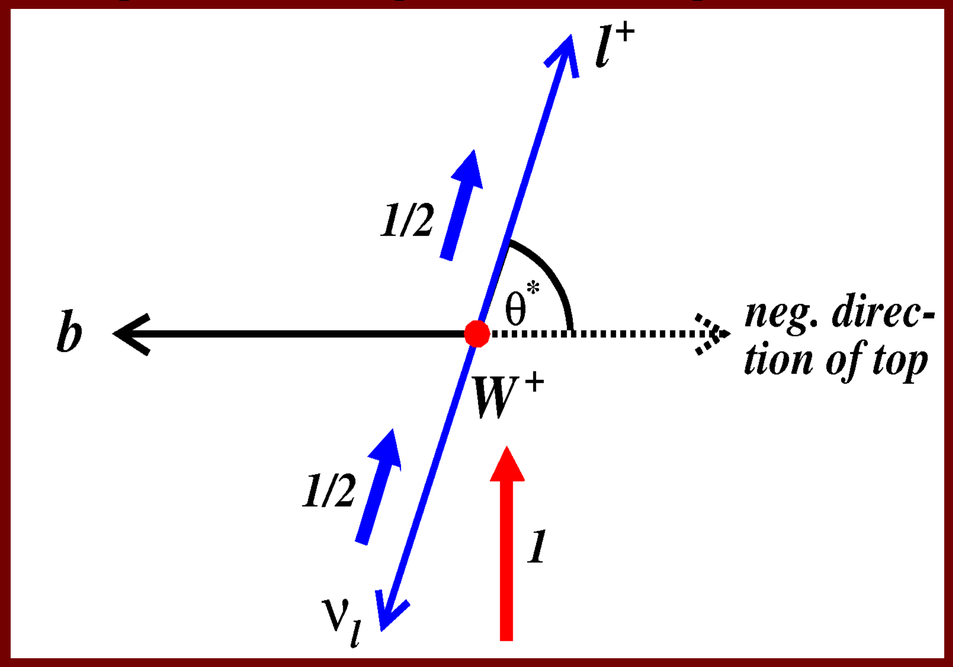


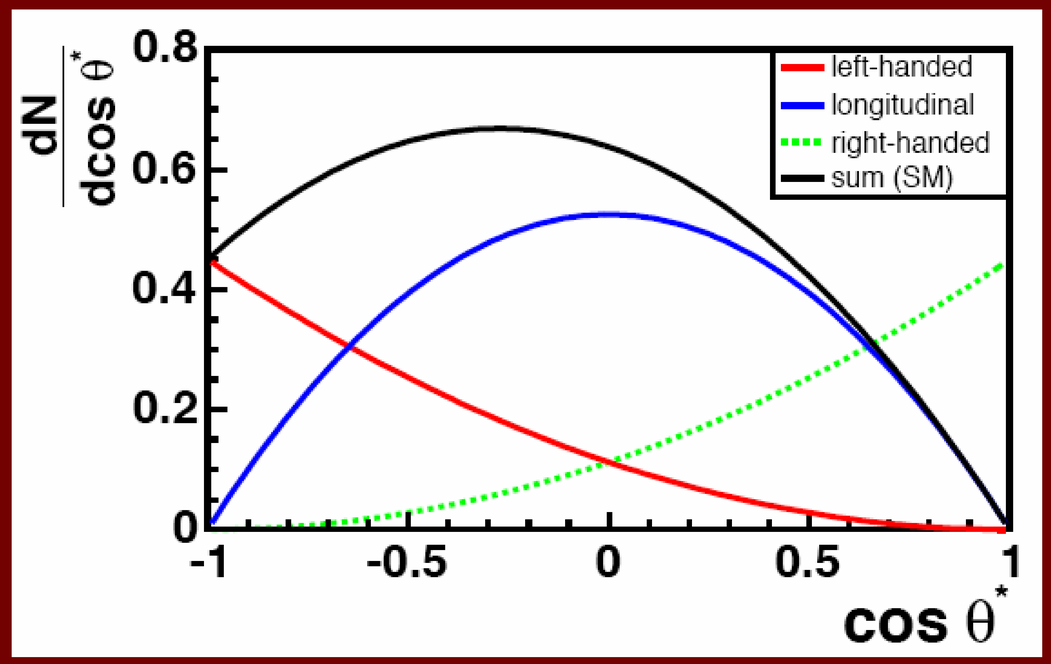




W Helicity in Top Decay

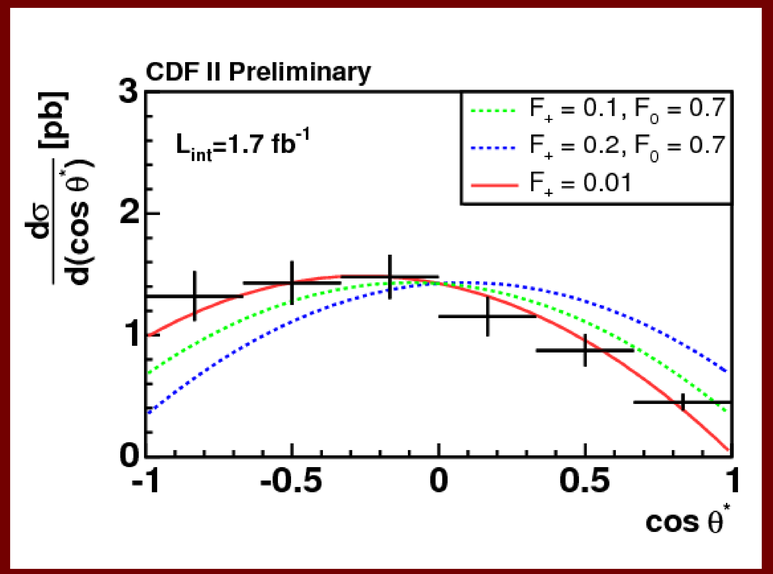
- Two variables sensitive to W helicity in top decays
- $\cos\theta^*$ = angle between lepton and top in W rest frame:
  - Left-handed $\sim \frac{3}{8}(1-\cos\theta^*)^2$
  - Longitudinal $\sim \frac{3}{4}(1-\cos^2\theta^*)$
  - Right-handed $\sim \frac{3}{8}(1+\cos\theta^*)^2$
- Mass of the charged lepton - b quark system:
  - $M_{lb}^2 \approx \frac{1}{2}(m_t^2 - m_W^2)\cos\theta^*$

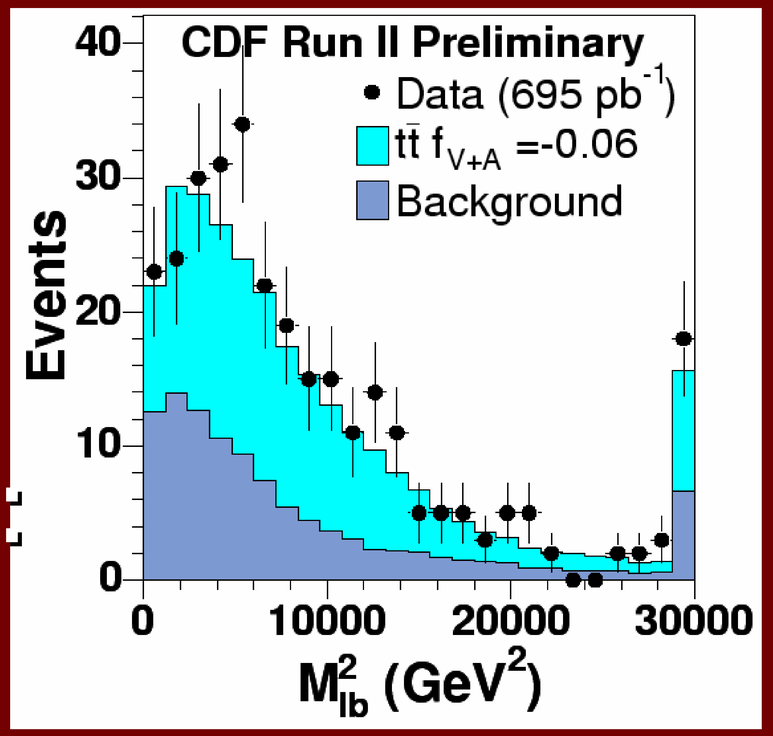




W Helicity Results

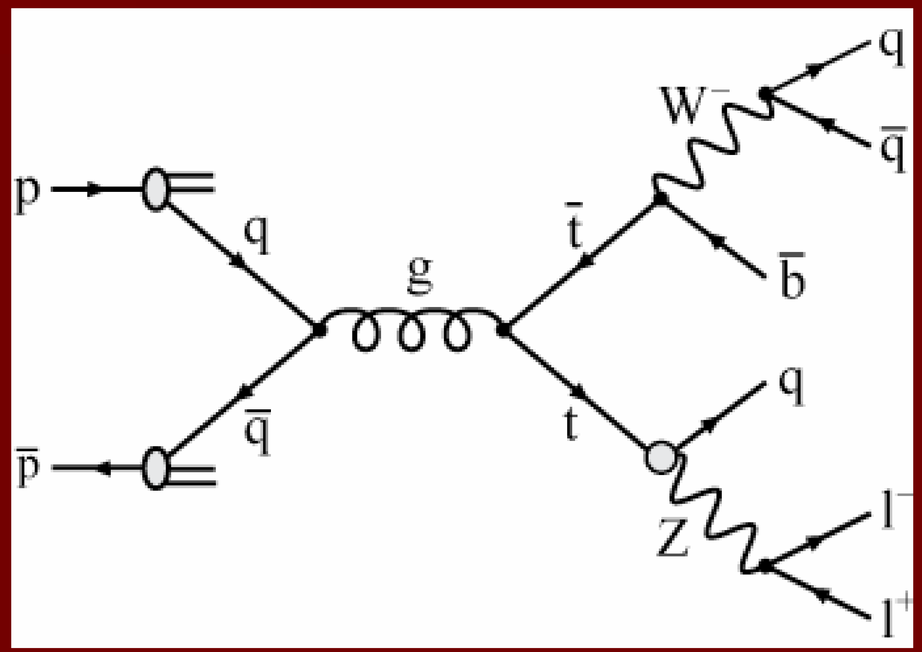
- Different fitting techniques in cosθ* analysis
- Binned fit to theoretical shapes:
  - $f_0 = 0.38 \pm 0.22$ (stat) ± 0.07 (syst)
    $f_+ = 0.38 \pm 0.22$ (stat) ± 0.07 (syst)
  - $f_+ < 0.12$ @ 95% CL ($f_0 = 0.7$ fixed)
- Unbinned fit to Monte Carlo shapes:
  - $f_0 = 0.61 \pm 0.20$ (stat) ± 0.03 (syst)
    $f_+ = -0.02 \pm 0.08$ (stat) ± 0.03 (syst)
  - $f_+ < 0.07$ @ 95% CL ($f_0 = 0.7$ fixed)
- Using M_{lb} to measure fraction of V+A:
  - $f_+ < 0.09$ @ 95% CL ($f_0 = 0.7$ fixed)

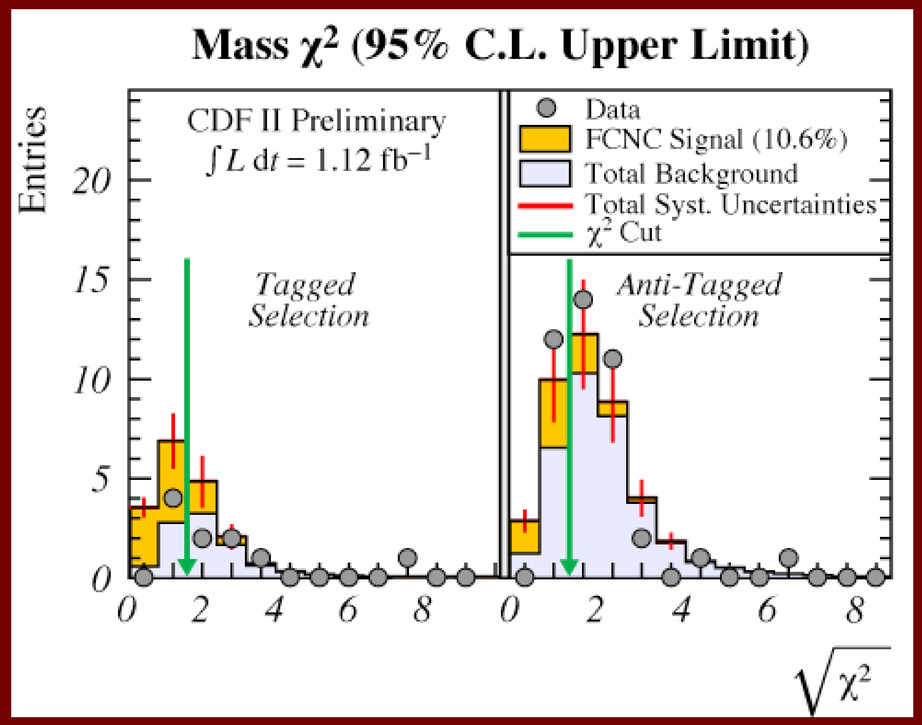




FCNC: $t \to Zq$

- In SM $BR(t \to Zq) = O(10^{-14})$
- BSM scenarios allow BR up to $O(10^{-2})$
  - J.A.Aguilar-Saavedra, Acta Phys.Polon.B35, 2695-2710
- LEP limit $BR(t \to Zq) < 13.7\%$
- Counting experiment $t\bar{t} \to Zq\,W\bar{b}$
  - $Z \to l^+l^-$
  - $W \to q\bar{q}'$
  - χ^2 of kinematic fit to top mass best discriminator
- No excess observed
  $BR(t \to Zq) < 10.6\%$ @ 95% CL





Searches for New Particles

$t\bar{t}$ Resonances

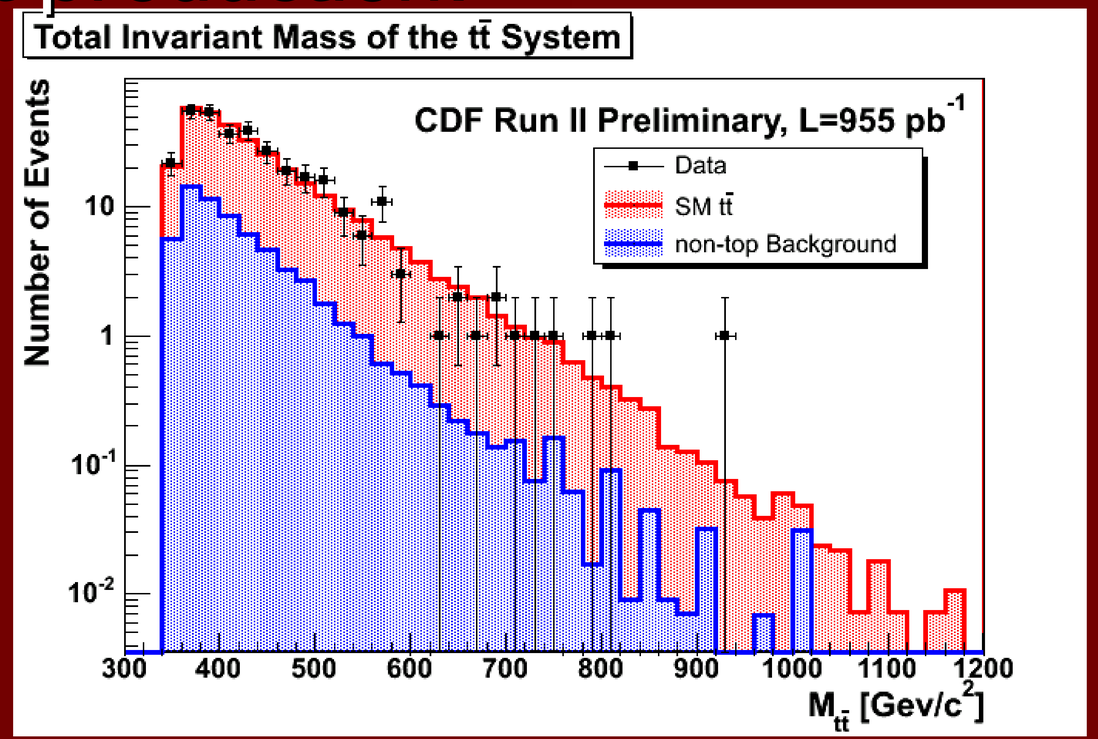
- Several models suggest $t\bar{t}$ resonant production:
  - Extended gauge theories
    - A.Leike, Phys.Rep.317,143(1999)
  - KK states of gluons or Z
    - B.Lillie et al.,arXiv:hep-ph/0701166
    - R.Rizzo,Phys.Rev.D61,055005(2000)
  - Axigluons and Topcolor
    - L.Sehgal et al.,Phys.Lett.B200(1988)
    - C.Hill et al.,Phys.Rev.D49,4454(1994)
- Fit to reconstructed $t\bar{t}$ mass

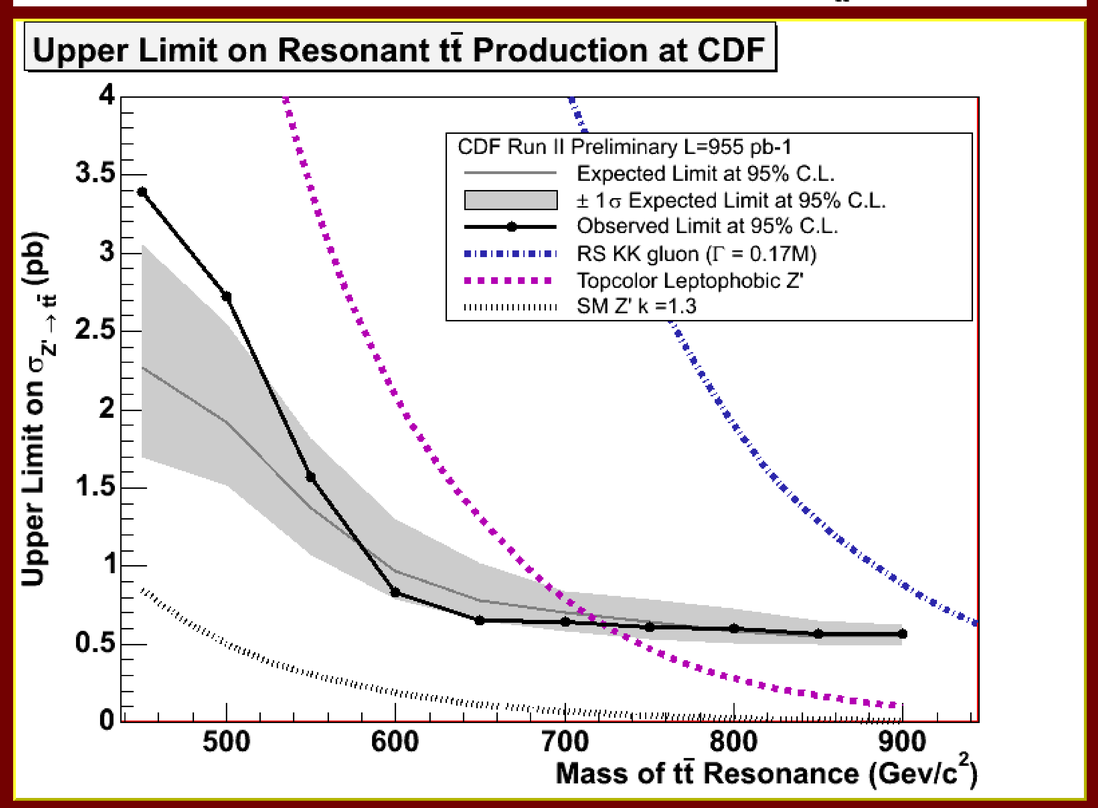
  Model: narrow Z′ ($\Gamma_{Z'} \sim 1.2\%\ M_{Z'}$)

  no interference with s-channel $t\bar{t}$
- No deviation from SM observed

  $\sigma\ (Z' \rightarrow t\bar{t}) < 0.7$ pb @ 95% CL

  for $M_{Z'} > 700$ GeV/c^2

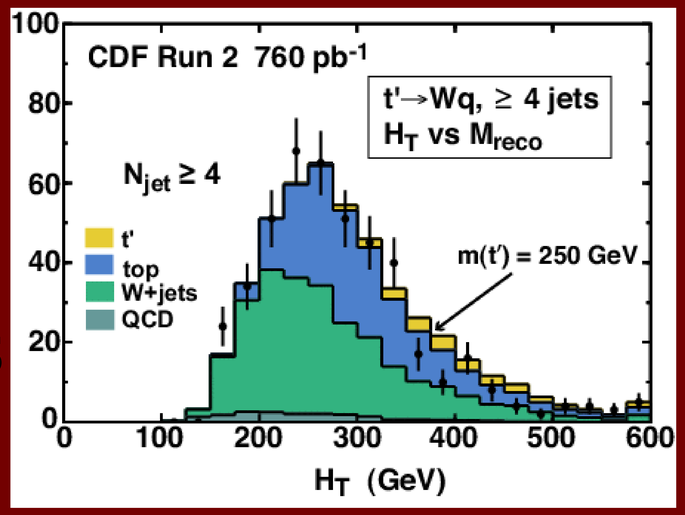


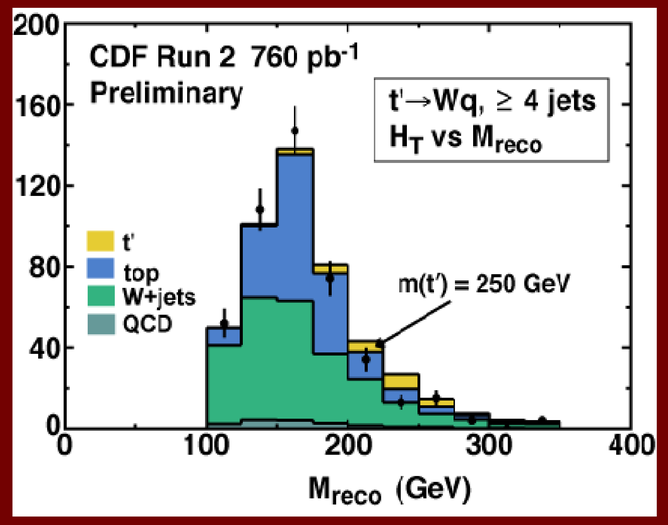


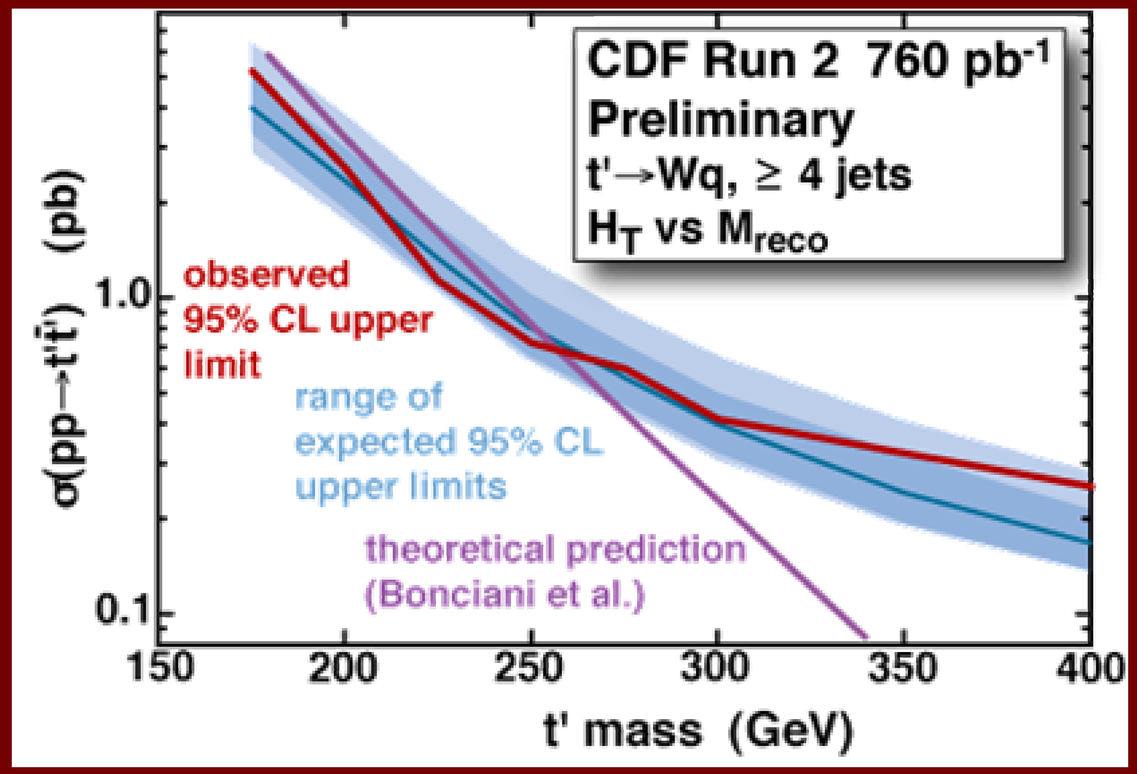
Search for Massive t′ → Wb

- 4th generation of heavy fermions compatible with EWK data
  - N=2 SUSY models: H.J.He et al., arXiv:hep-ph/0102144
  - "Beautiful mirrors" model: C.Wagner et al., arXiv:hep-ph/0109097

- 2-dim likelihood fit to data
  - H_T: sum of transverse energy of all objects in final state
  - Mreco: Wb reconstructed mass



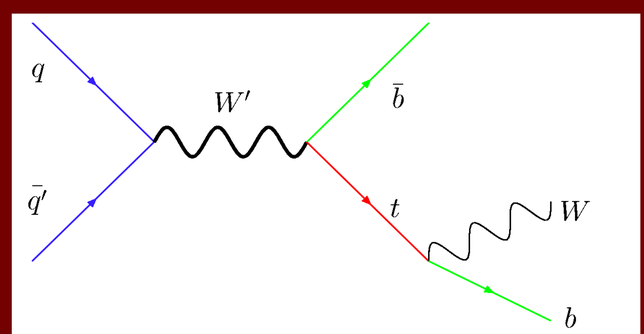




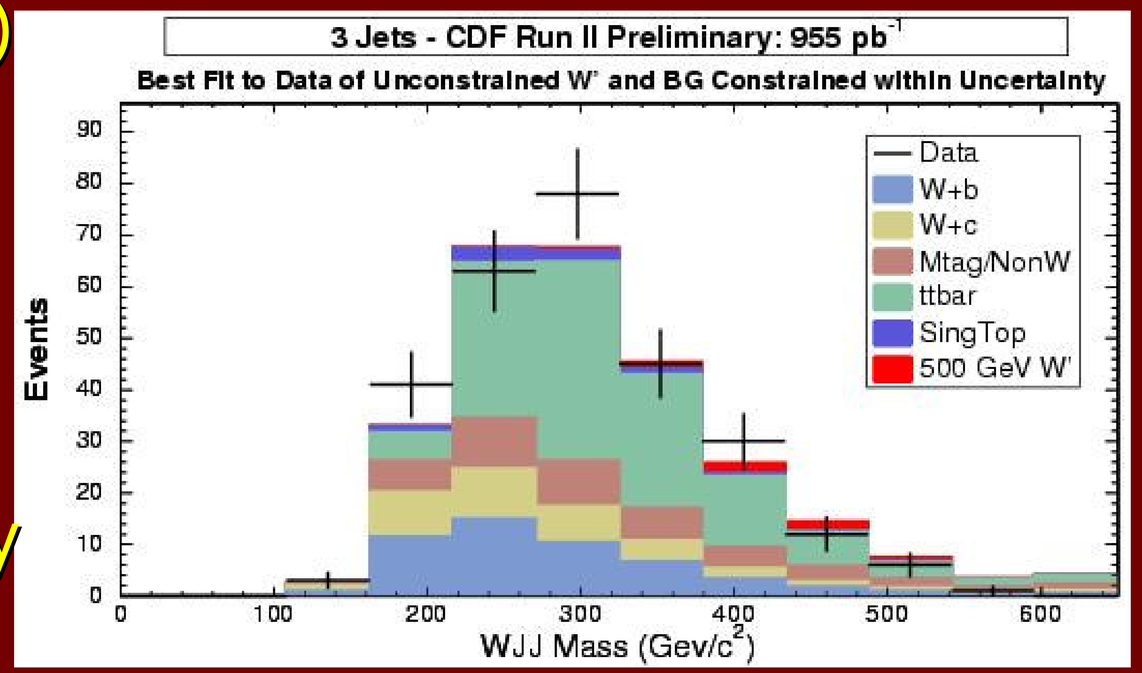
- No evidence for t′ observed
  - Set 95% CL upper limit on $\sigma(p\bar{p}\rightarrow t'\bar{t}') \times BR(t'\rightarrow Wb)^2$
  - $m_{t'}>256$ GeV/c^2 @ 95% CL

Heavy W' Production

- Search for W-like heavy boson decaying to a top-bottom pair
  - Extra dimensions: PRD 74, 75008(2006)
  - Little Higgs: arXiv:hep-ph/051212
  - Topcolor: PL B385, 304(1996)
- Single top production signature:

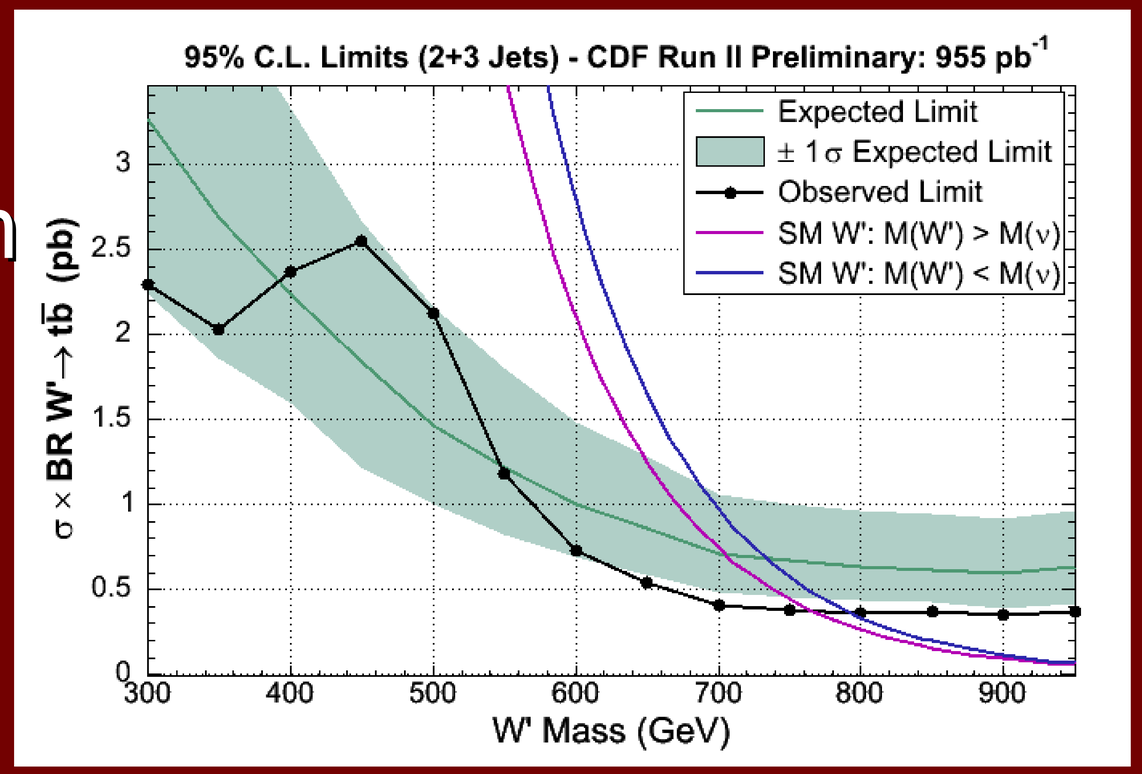


  - Charged lepton
  - Large missing energy
  - Two jets



- No evidence for W' boson in reconstructed M_{wbb} mass spectrum
- Limits on W' production and its couplings to fermions

  $\sigma \cdot BR(W' \rightarrow tb) < 0.4$ pb @ 95% CL for $M_{W'} > 700$ GeV/c^2



Conclusions

- The CDF top quark samples in 1-1.7 fb^{-1} of $p\bar{p}$ collision data at the Tevatron have been established and well understood
- Lot of precision measurements and first results in searches for new physics have been achieved
- Beginning to have sensitivity to unexpected top quark properties and new phenomena in our samples

Backup Slides

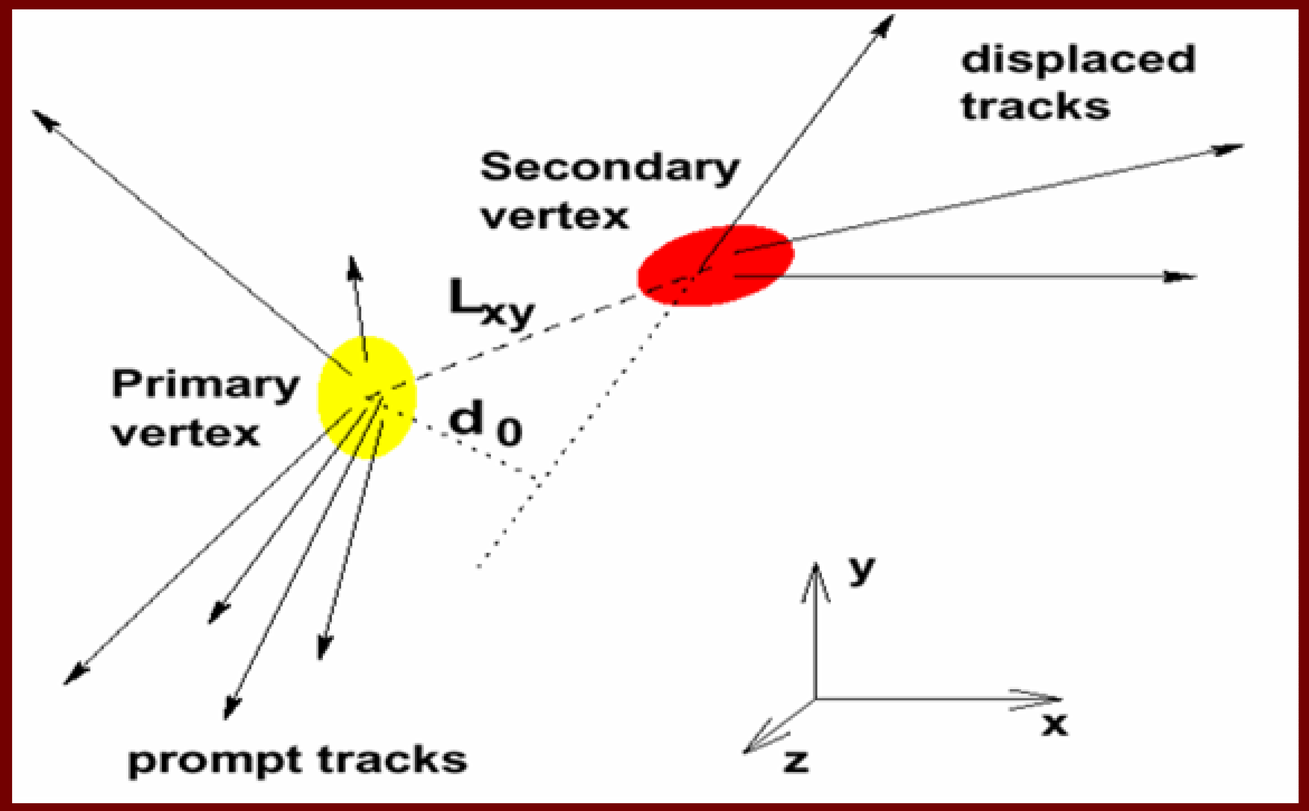
b Quark Tagging

- Tagging the b quark improves parton-jet assignments:

  lepton+jets: 1 tag → 6 combinations, 2 tags → 2 combinations
- Requiring a b tagged jet also reduces background contamination
- B hadrons are long lived

  Jet tagging efficiency → 42%

  False tag rate → 0.5%



Best Top Mass Measurement

- Matrix Element Method with in situ jet calibration
- Build event likelihood as a function of m_t and JES

Normalization factor

Sum over parton jet assignament

Matrix element

Integration over phase space

$$L(\vec{y} \mid m_t, JES) = \frac{1}{N(m_t)} \frac{1}{A(m_t, JES)} \sum_{i=1}^{24} w_i \int \frac{f(x_1) f(x_2)}{FF} TF(\vec{y} \cdot JES \mid \vec{x}) \mid M_{eff}(m_t, \vec{x}) \mid^2 d\Phi(\vec{x})$$

Acceptance

b-tag weight

PDFs

Transfer function connecting partons to jets

- Sum over events and background subtraction

$$\log L_{tot}(m_t, JES) = \sum_i (\log L(y_i \mid mt, JES) - f_{bg}(y_i) \log L(bg \mid m_t, JES))$$

- Top mass extracted by maximizing profile likelihood

$$L_{prof}(m_t) = \max_{j \in JES} L_{tot}(m_t, j)$$

Kinematic Fit

- Lowest χ^2 parton-jet assignamnt used in analyses

Fluctuate momenta according to their resolution

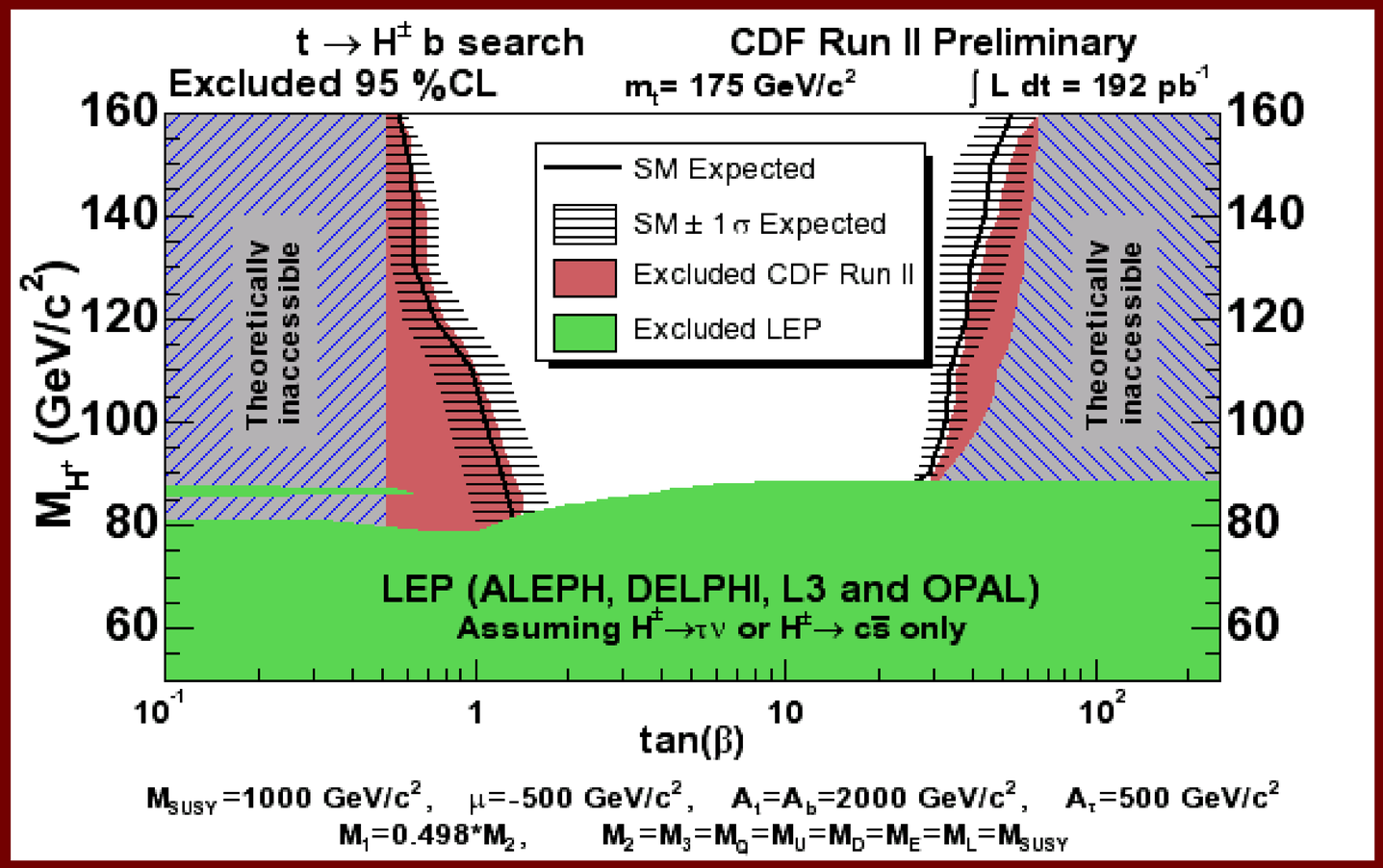
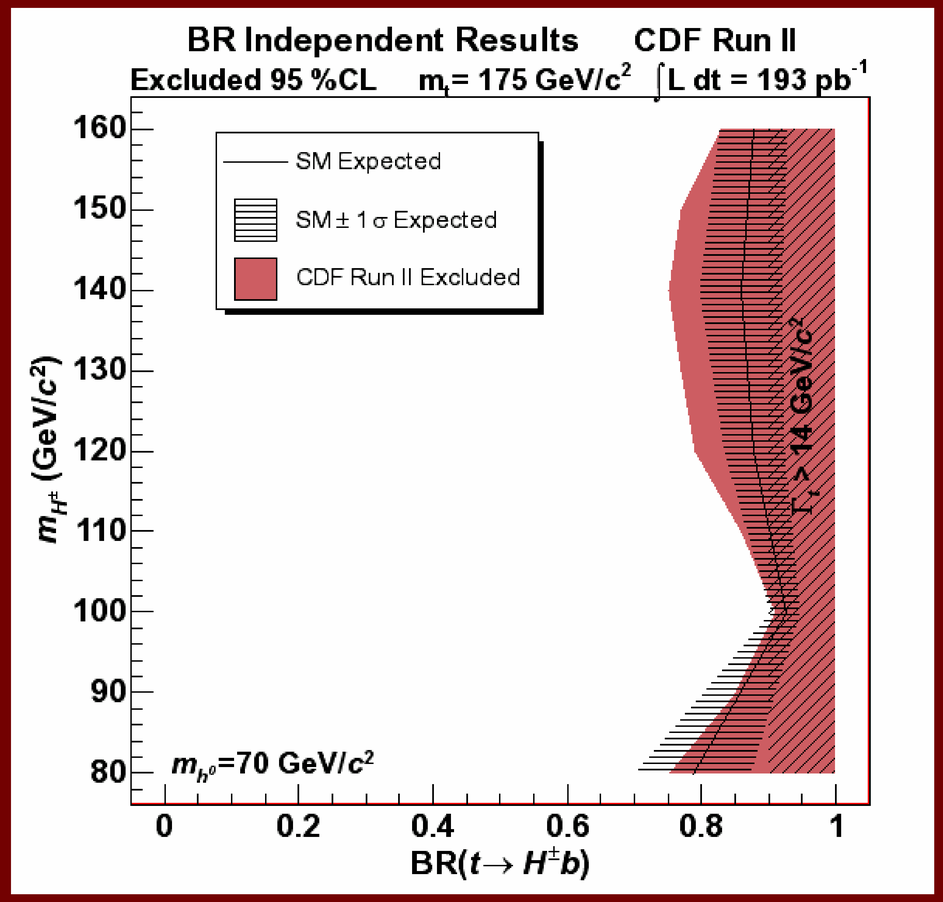
$$\chi^2 = \sum_{i=\ell,4\text{ jets}} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_j^{UE,meas})^2}{\sigma_j^2}$$

$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_t)^2}{\Gamma_t^2} + \frac{(M_{b\ell\nu} - M_t)^2}{\Gamma_t^2}$$

Constrain on W masses

t and $\bar{t}$ have the same mass M_t

- Correct combination in 70% of the cases

Search for $t \rightarrow H^+b$

- SMMS predicts large BR($t \rightarrow H^+b$) (>10%) for small and large β
- Four different channels considered: $H^+ \rightarrow \bar{\tau}\nu$, $c\bar{s}$, $t^*\bar{b}$, W^+h^0
- Compare predictions to data to set limits on M_{H^+} - tan(β) plane
- Scan all combinations of H^+ BR's to set model independent limits on BR($t \rightarrow H^+b$)