Status of the Top Quark: Top Production Cross Section and Top Properties

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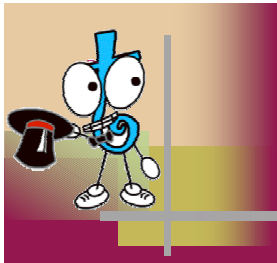
Les Rencontres de Physique de la Vallée d'Aoste

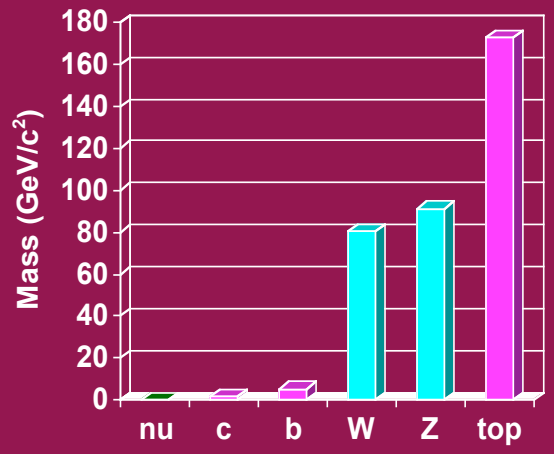
Friday March 10th 2006

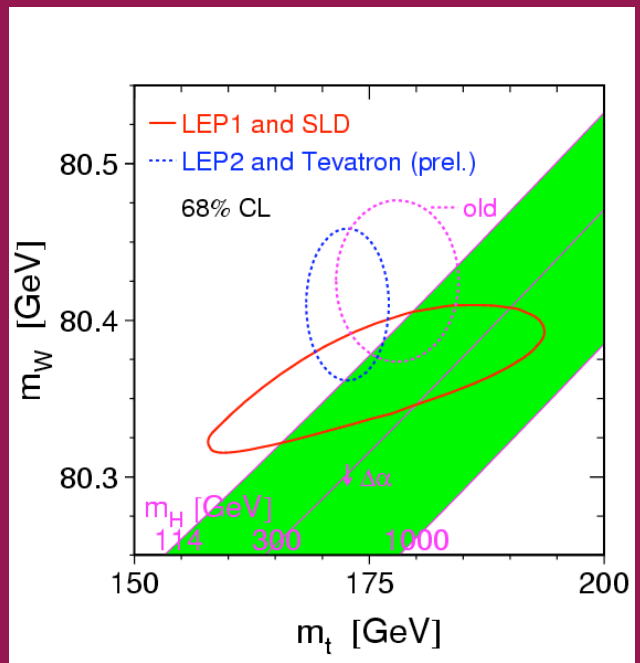


- Top quark discovered in 1995 by CDF and DØ
  - Not a surprise: SM quark sector now complete
- From discovery to:
  - Still discovery!
    - Single top production
    - Properties
    - Surprises
  - And precision:
    - Cross-sections
      - Now 12%!
    - Mass
      - Now <2%!

The "Big" Surprise:

- Large Top mass implications:
  - Top-Higgs Yukawa coupling~1
  - Largest radiative corrections to W mass
  - $\Rightarrow$ Connection to EWSB?
  - For m_t=175GeV/c^2, Γ~1.4GeV >>Λ_{QCD}
  - $\Rightarrow$ No top-hadrons or $t\bar{t}$-quarkonium
  - $\Rightarrow$ Top spin transferred to decay products

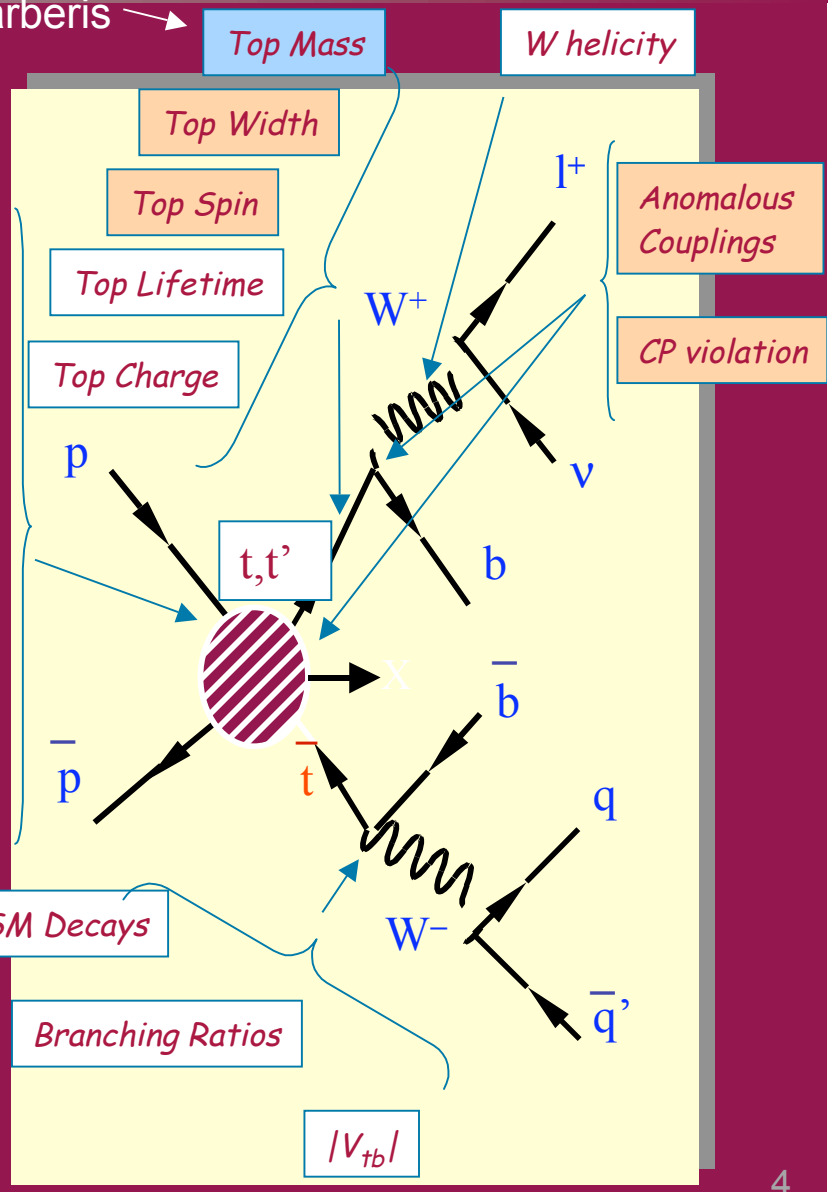


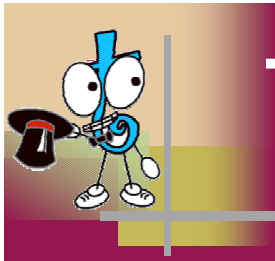


The Next Surprises?

Next talk given by Prof. Barberis →

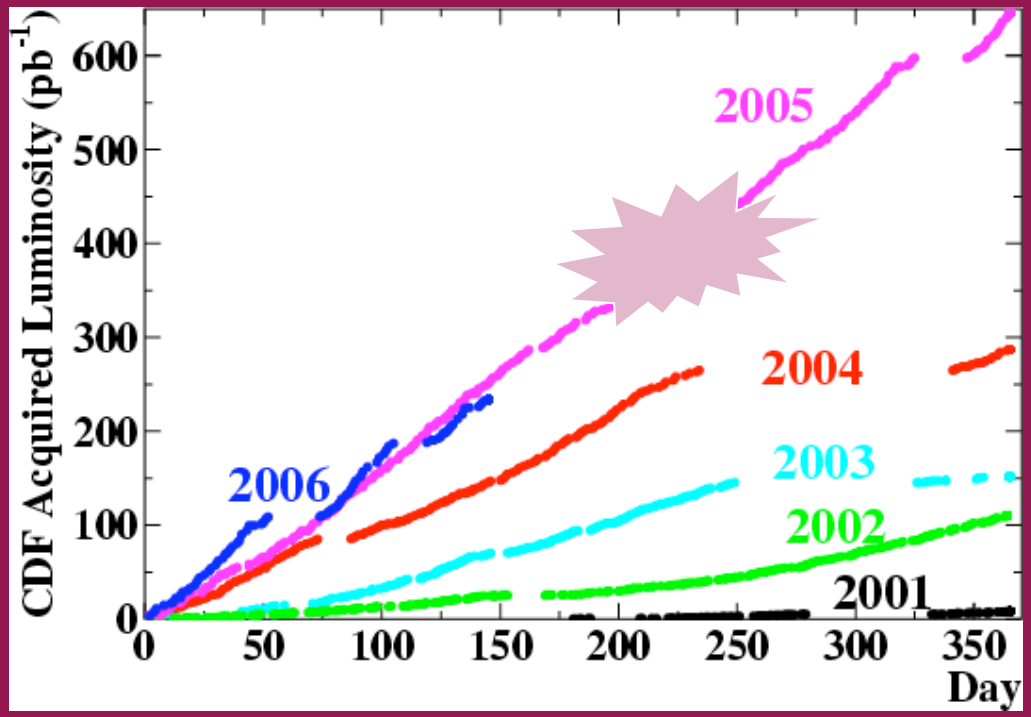
- Need precision measurements of top properties
- Tevatron is the only source of top quarks providing direct measurements!
- Outline: New results on:
  - Production Cross-section
  - Single Top search
  - t' search
  - Measurement of B(t→Wb)/B(t→Wq)
  - Search for Charged Higgs
  - Top Lifetime
  - Top Charge
  - W helicity





The Data Sample

- Accelerator doing very well
  - Record peak inst. luminosity
    - $1.8 \times 10^{32}/cm^2s$
    - If no further improvements:
      - $4fb^{-1}$ in 2009
  - Electron cooling on track
    - Could get $8fb^{-1}$ in 2009!
- Detectors doing well:
  - Upgrades finishing up to deal with luminosity increase coming in 2006
    - DØ installing silicon L0 now



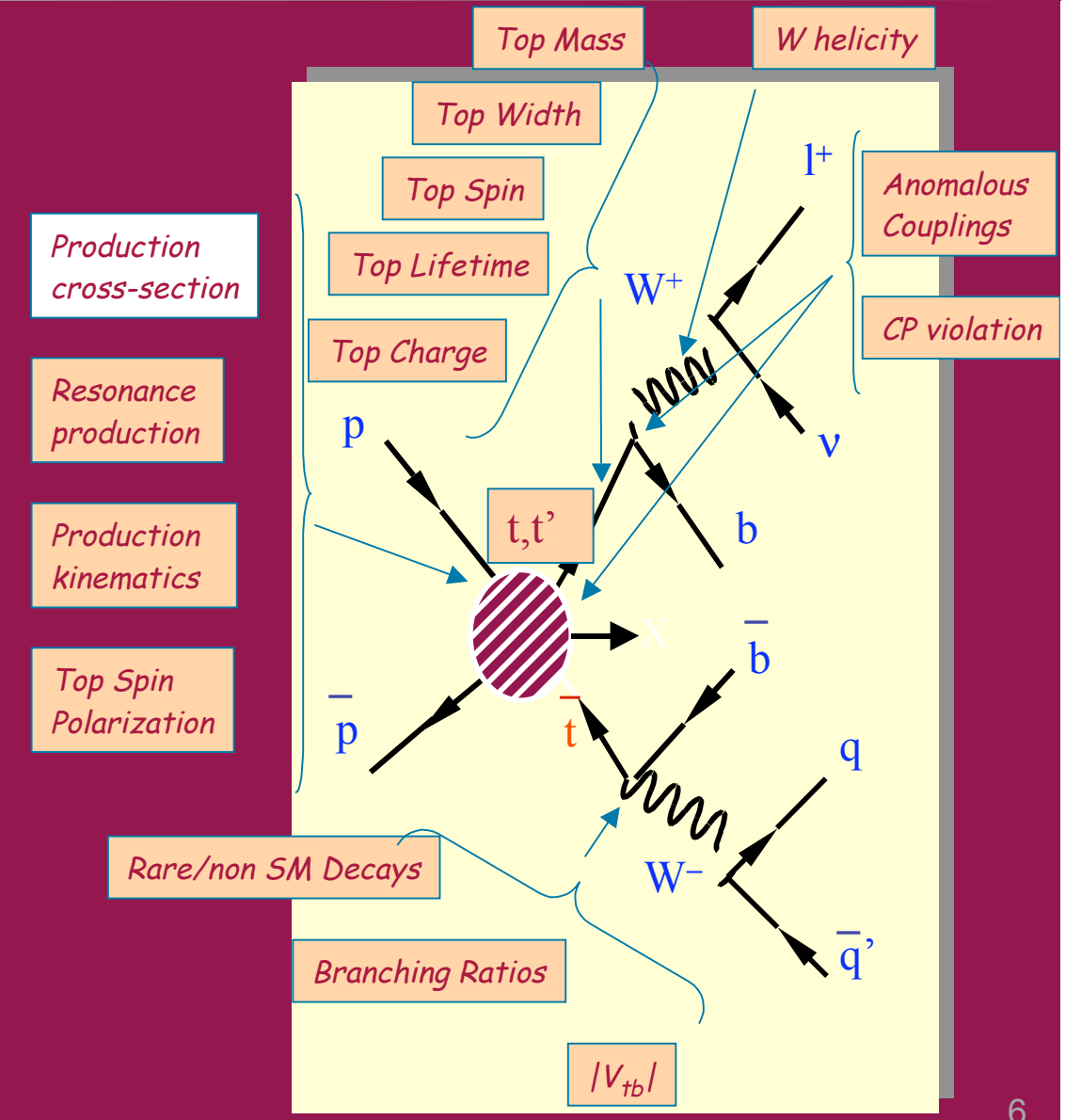
In this talk:

All very recent results!

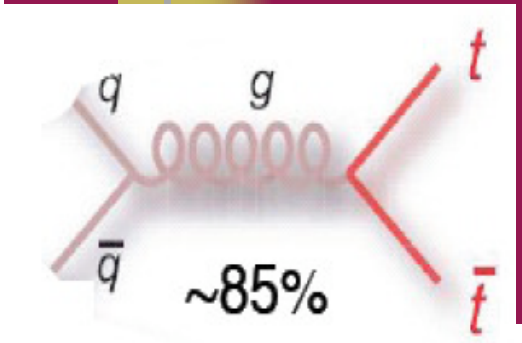
New! = never been shown before

Production Cross Section

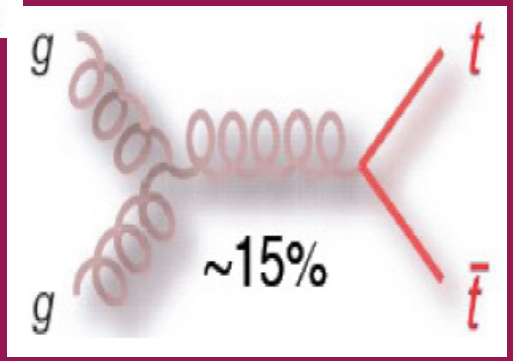
- Top pair production
- Single top production



Top Pair Production Cross Section



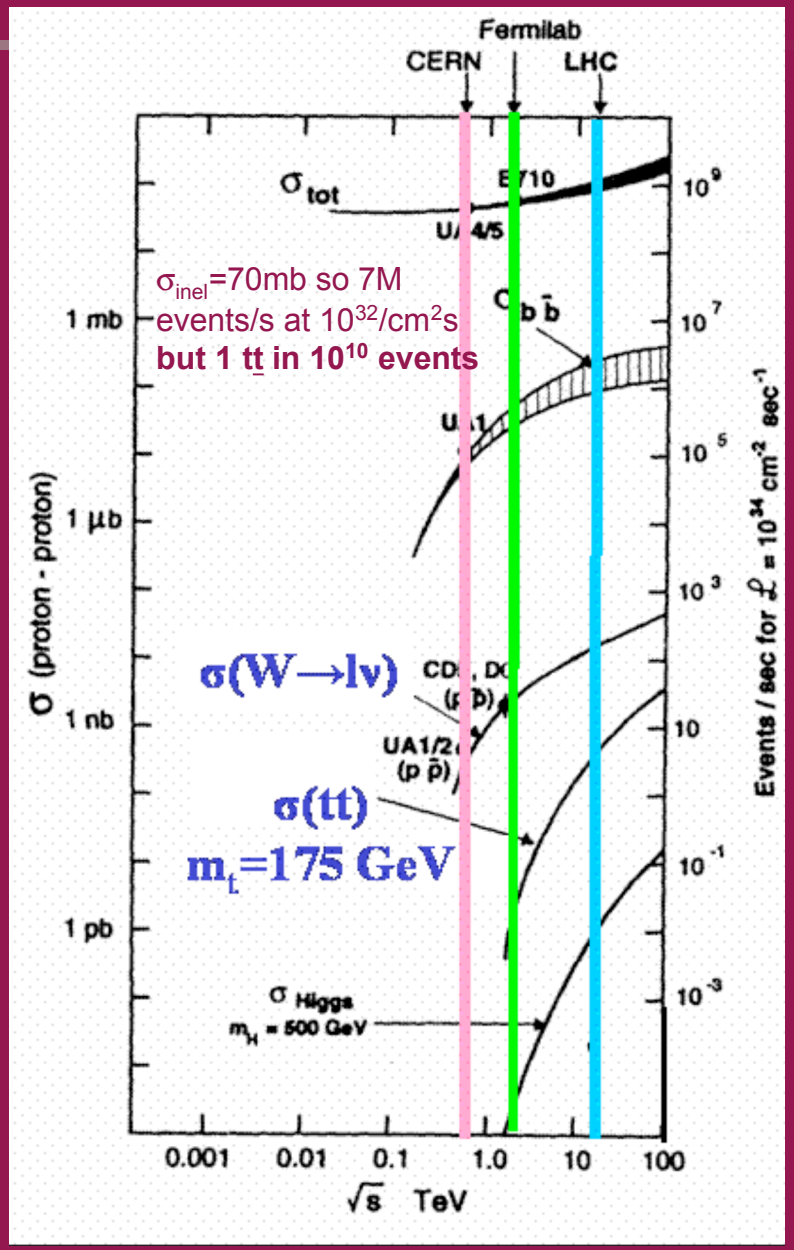
√s=1.96TeV



For m_t=175GeV/c^2

$\sigma_{t\bar{t}}$ (theo) ≅ 6.7± 0.8

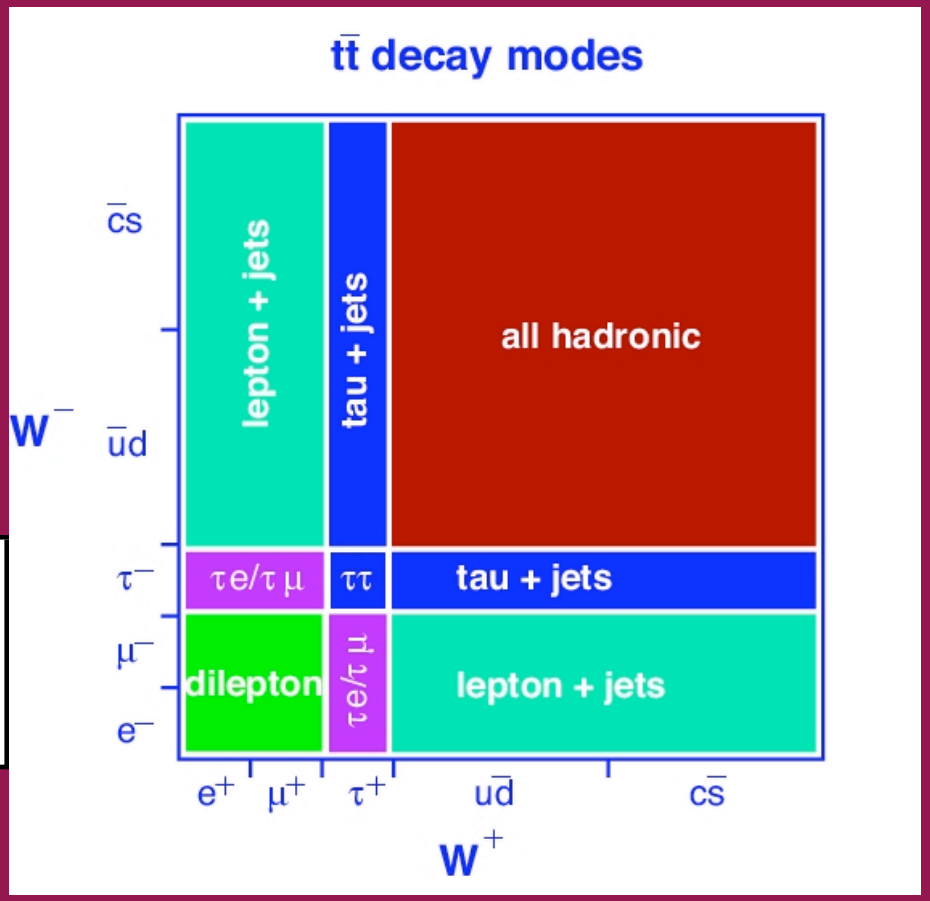
- $\sigma_{t\bar{t}}$ is crucial:
  - Window to NP
    - Look at all possible channels
  - Starting point for all properties analysis
  - $t\bar{t}$ is background for searches



Top Decay Channels

- $m_t > m_W + m_b$ so dominant decay $t \rightarrow Wb$
- If assume unitarity $B(t \rightarrow Wb) \sim 100\%$

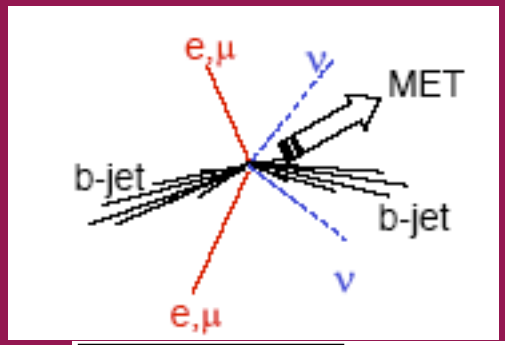
	BR	background
dilepton	~5%	low
lepton + jets	~30%	moderate
all hadronic	~65%	high



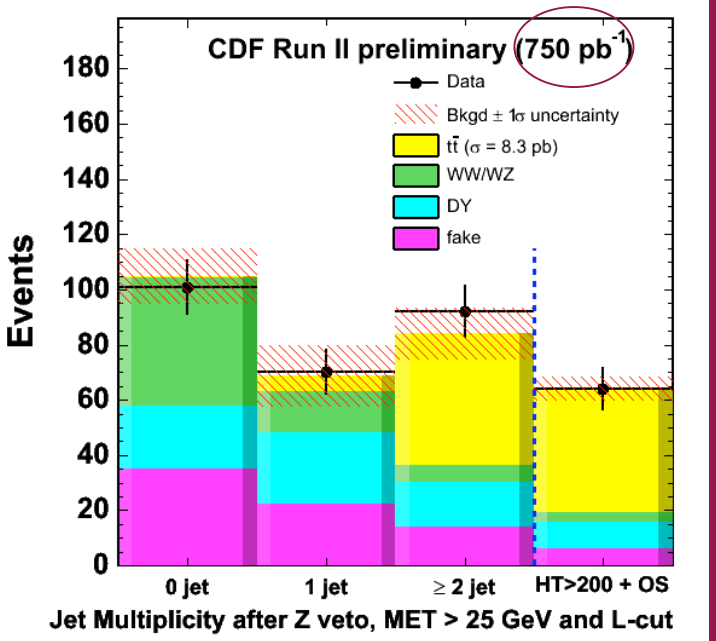
Dilepton Channel

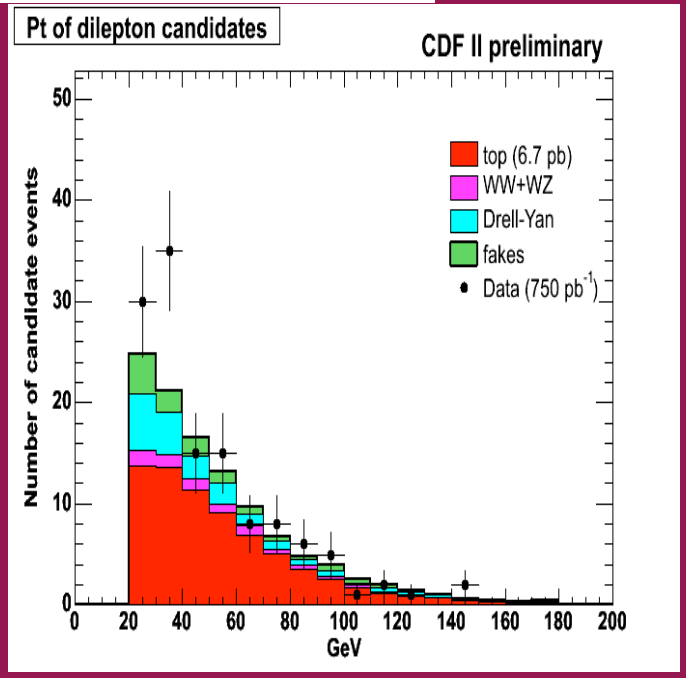
$$\sigma = \frac{N_{obs} - N_{backg}}{A \cdot L \cdot \varepsilon}$$

- Selection:
  - 2 leptons E_T>20GeV with opposite sign
  - >=2 jets E_T>15GeV
  - Missing E_T>25GeV (and away from any jet)
  - $H_T = p_{Tlep} + E_{Tjet} + ME_T$>200GeV



- Backgrounds:
  - Physics: WW/WZ/ZZ, $Z \rightarrow \tau\tau$
  - Instrumental: fake lepton

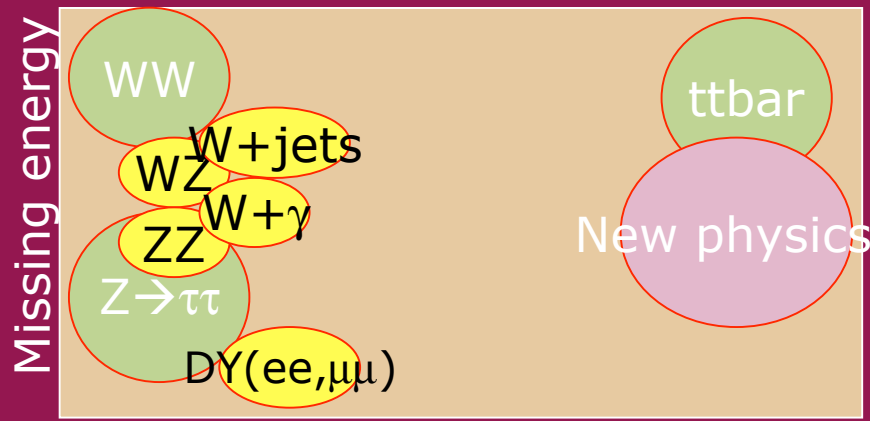




$\sigma(t\bar{t}) = 8.3 \pm 1.5\ (stat) \pm 1.0\ (syst) + 0.5\ (lumi)$ pb

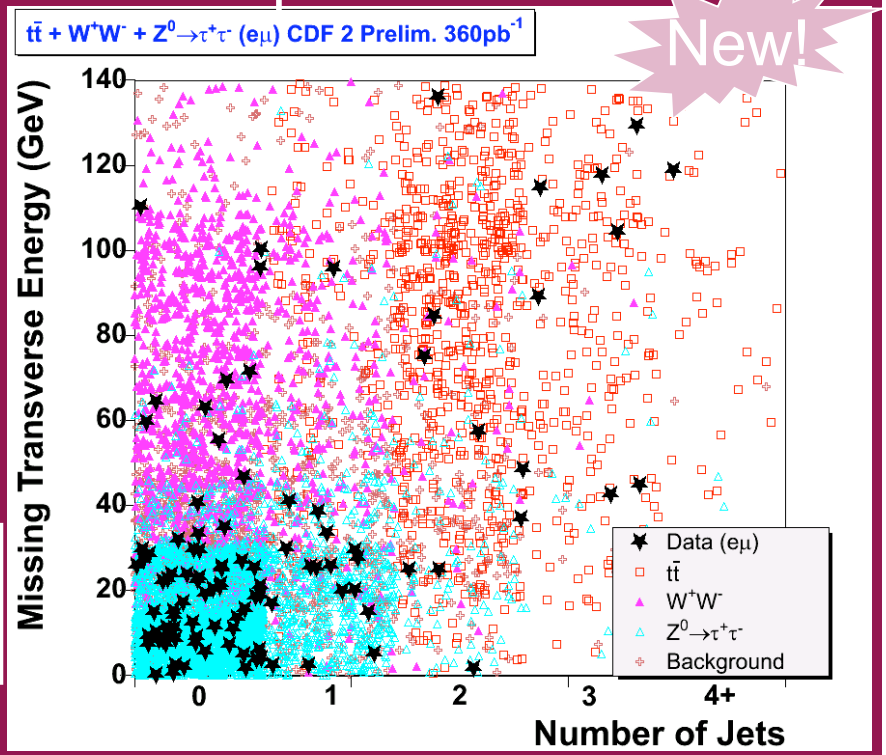
Dilepton Channel: Inclusive

- Higher statistical power with less purity than counting experiment



- Selection:
  - 2 leptons with P_T>20GeV/c with opposite sign
  - In ee,μμ channels: $ME_T^{sig} = \frac{ME_T}{\sqrt{\sum E_T}} > 2.0$

360pb^{-1}



ee + μμ + eμ fit (other σ fixed)

$$\sigma(t\bar{t}) = 6.6^{+2.2}_{-1.9}(\text{stat+acc.syst.})^{+0.5}_{-0.2}(\text{shape syst.})\,pb$$

$$\sigma(WW) = 15.4^{+5.1}_{-4.4}(\text{stat+acc.syst.})^{+0.8}_{-0.2}(\text{shape syst.})\,pb$$

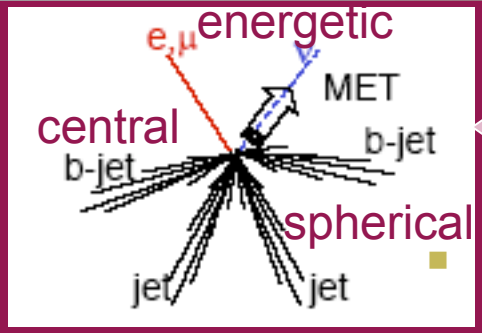
eμ fit (other σ fixed)

$$\sigma(Z \to \tau\tau) = 282^{+49}_{-44}(\text{stat+acc.syst.}) \pm 6(\text{shape syst.})\,pb$$

Next step: look for New Physics!

Lepton+Jets Channel: Kinematics

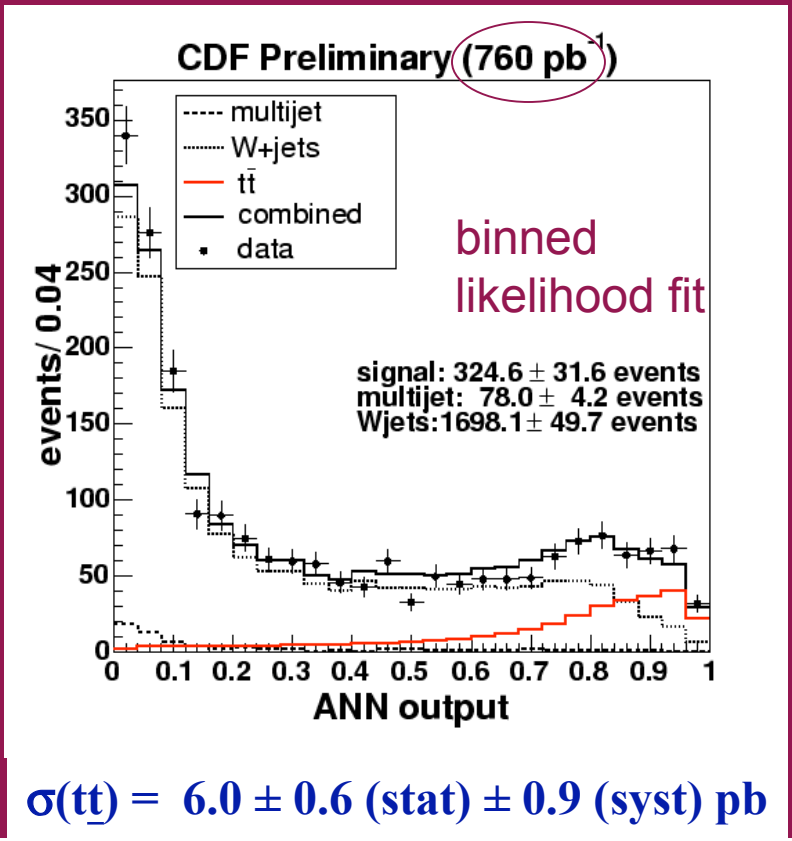
- Selection:
  - 1 lepton with p_T>20GeV/c
  - >=3 jets with p_T>15GeV/c



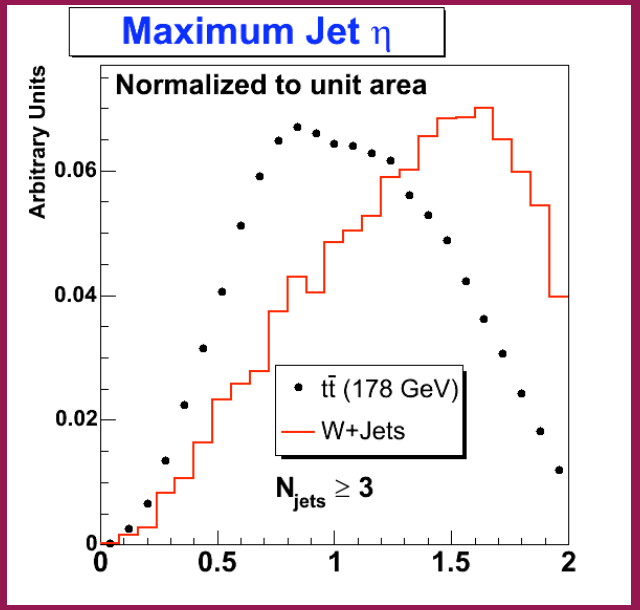
discriminate

- Backgrounds:
  - W+jets
  - QCD

7 kinematic variables in neural net



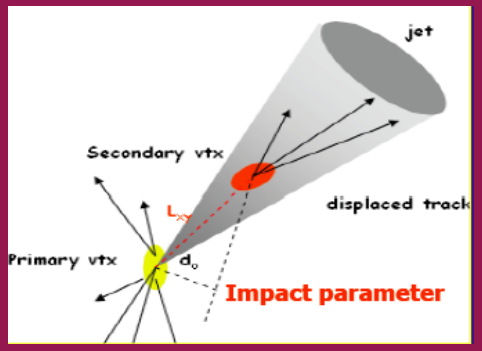
$\sigma(t\bar{t}) = 6.0 \pm 0.6\ (stat) \pm 0.9\ (syst)$ pb

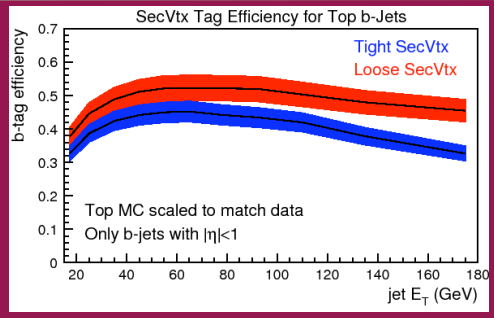


- Dominant systematics:
  - Jet E scale
  - W+jet Q^2 scale

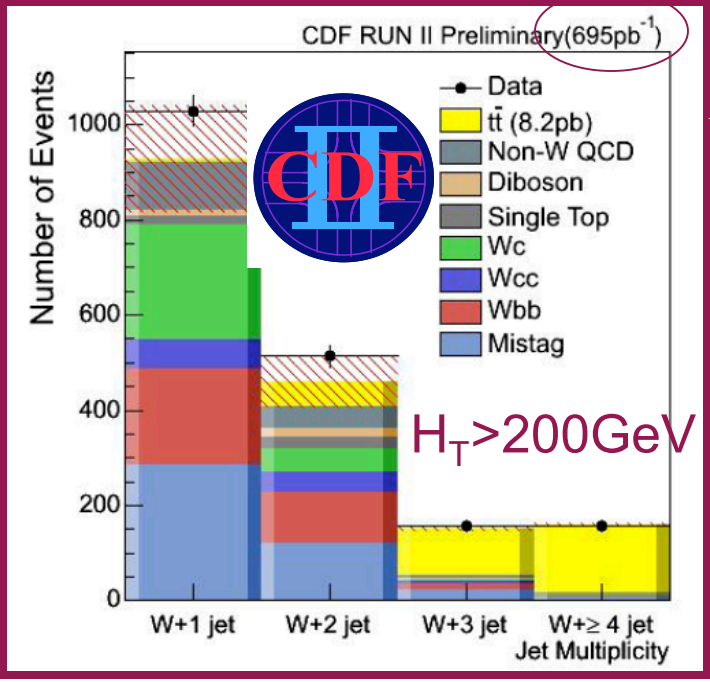
Lepton+Jets Channel: b Tagging

- Request b jet to be tagged for discrimination
  - Dominant systematic

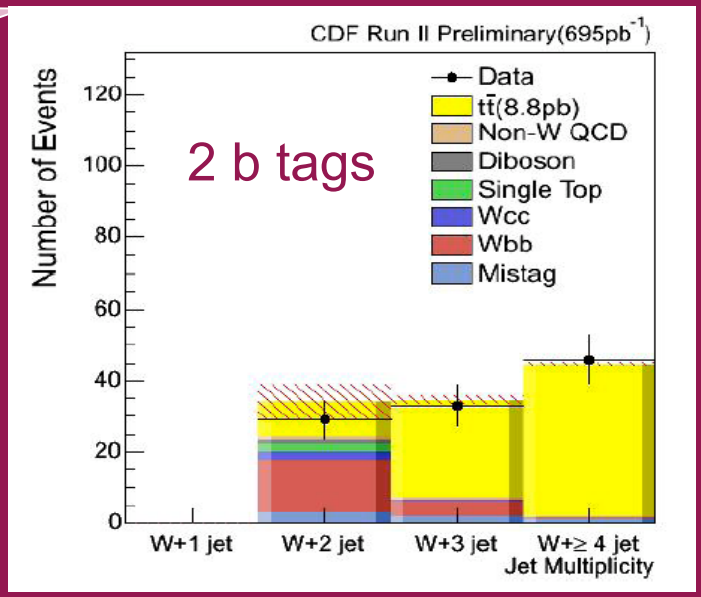




Tagging eff for b jets~50%
for c jets<10%
for light q jets < 0.05%



New!

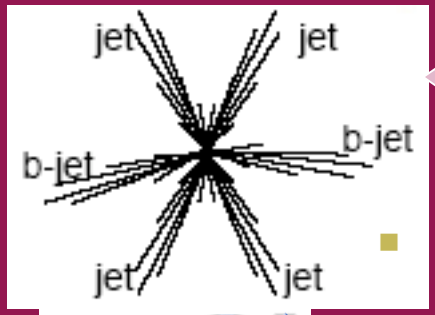


$\sigma(t\bar{t}) = 8.2 \pm 0.6\ (stat) \pm 1.1\ (syst)$ pb

$$\sigma(t\bar{t}) = 8.8^{+1.2}_{-1.1}(stat)^{+2.0}_{-1.3}(syst)\,pb$$

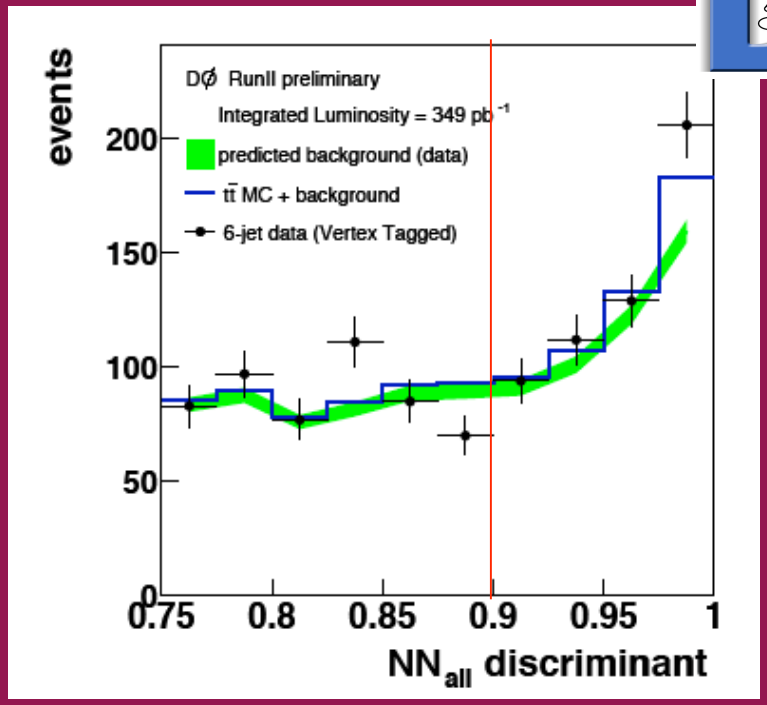
All Hadronic Channel

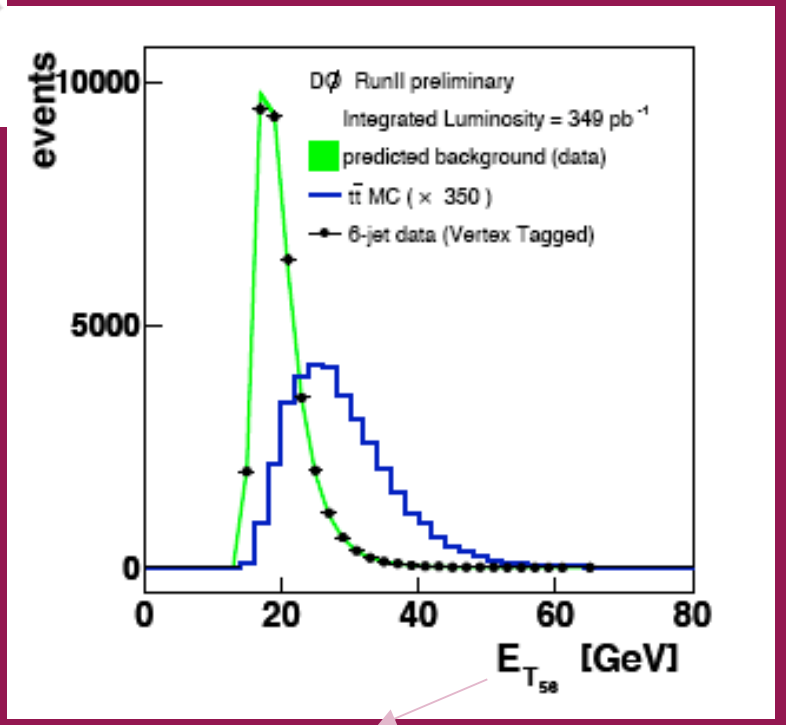
- Selection:
  - >=6 jets with pT>15GeV/c
  - >=1 b tagged
  - NN discriminant > 0.9



discriminate → Huge QCD background !

6 kinematic variables in neural net

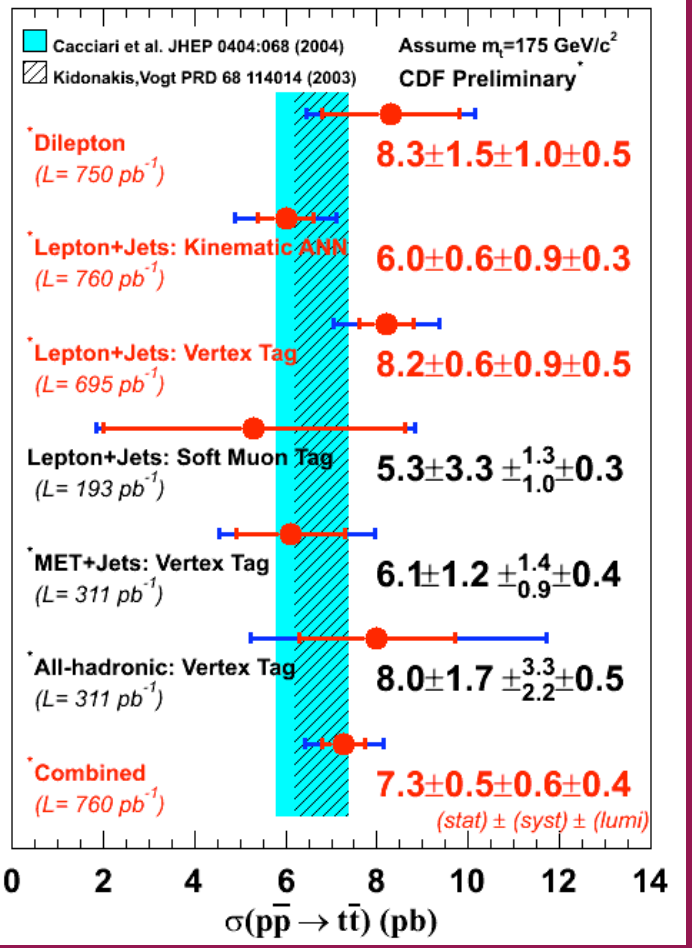


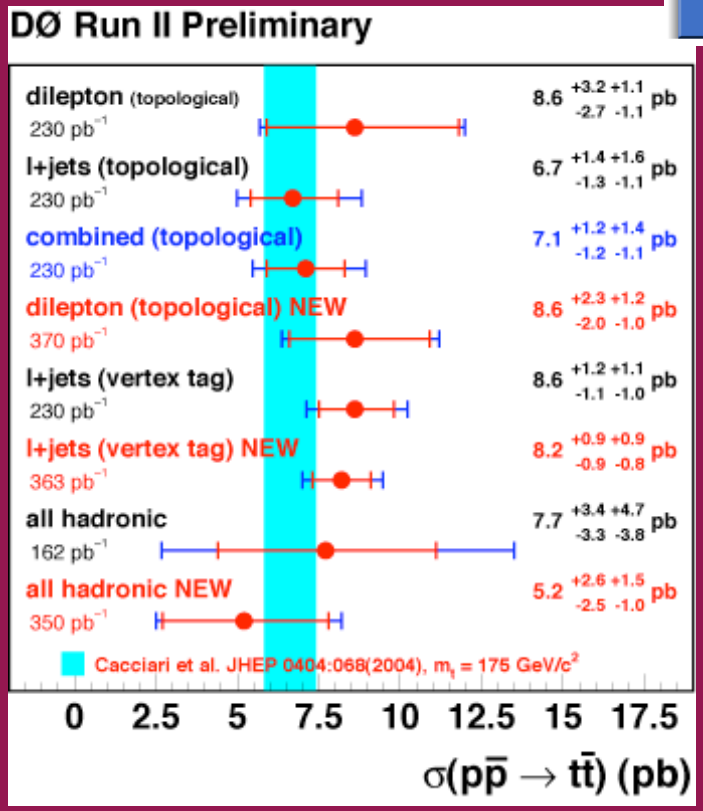


Geometric mean of 5th and 6th leading jet E_T

$$\sigma(t\bar{t}) = 5.2^{+2.6}_{-2.5}(stat)^{+1.5}_{-1.0}(syst) \pm 0.3(lumi)\,pb$$

Summary of Top Pair Production Cross Sections

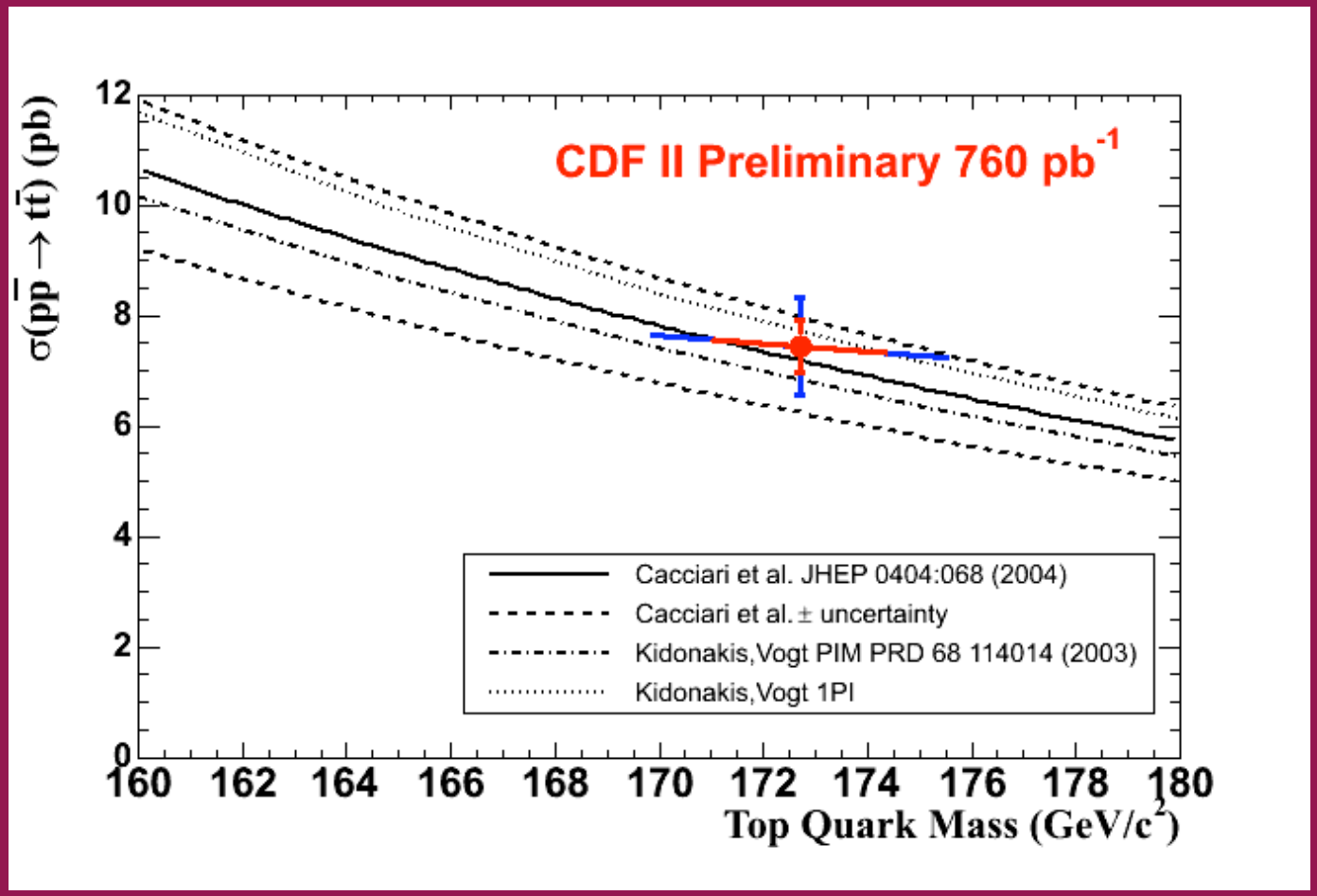




Red = new

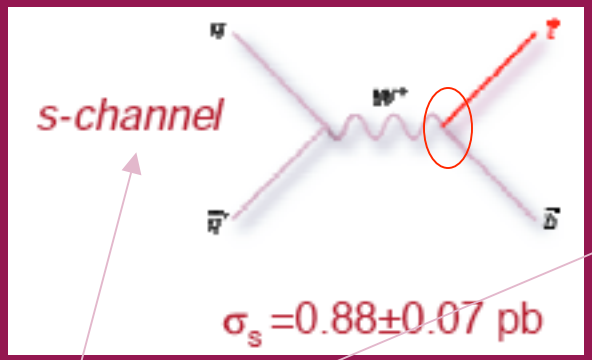
- Can already test theory estimate
- Soon can test among different channels

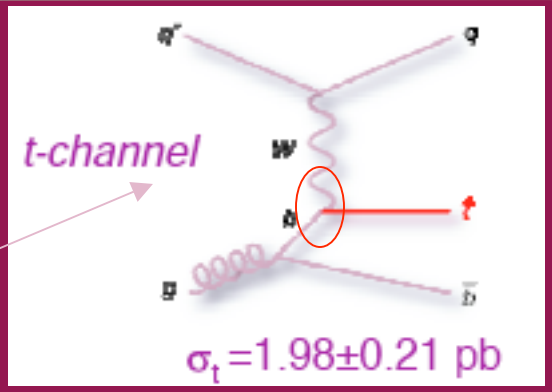
Summary of Top Pair Production Cross Sections



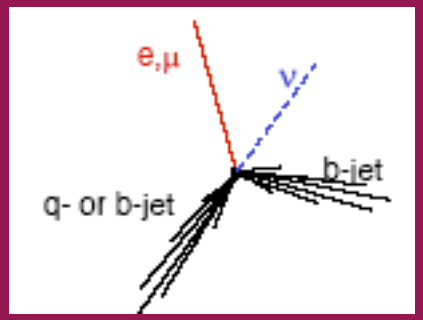
Single Top Production

- Electroweak production:





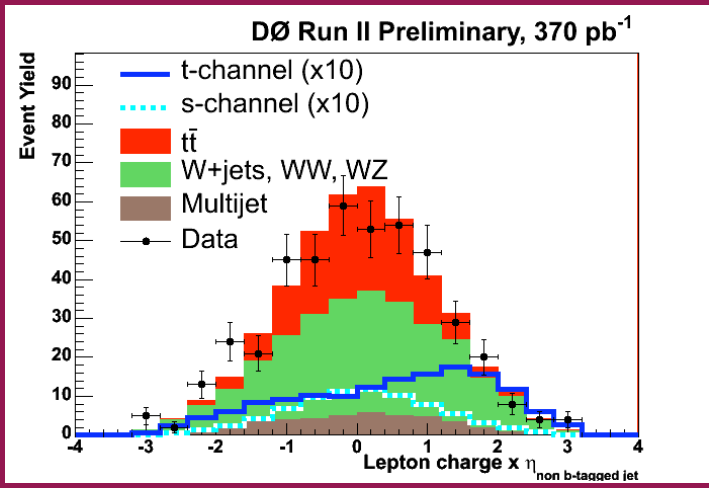
  - Different New Physics
    - New resonances
    - vs FCNC
  - Measurement of $|V_{tb}|$
  - Anomalous Wtb coupling



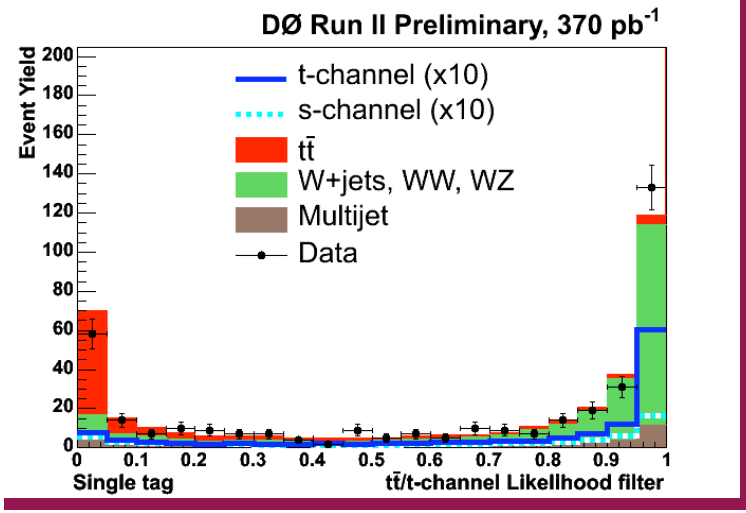
- Selection:
  - Same as Lepton+Jets with lower jet multiplicity
    - Use b tagging information
- Sophisticated discrimination against overwhelming backgrounds (W+jets and $t\bar{t}$):
  - Likelihood discriminants
  - Neural Nets
  - Decision trees
  - Etc.

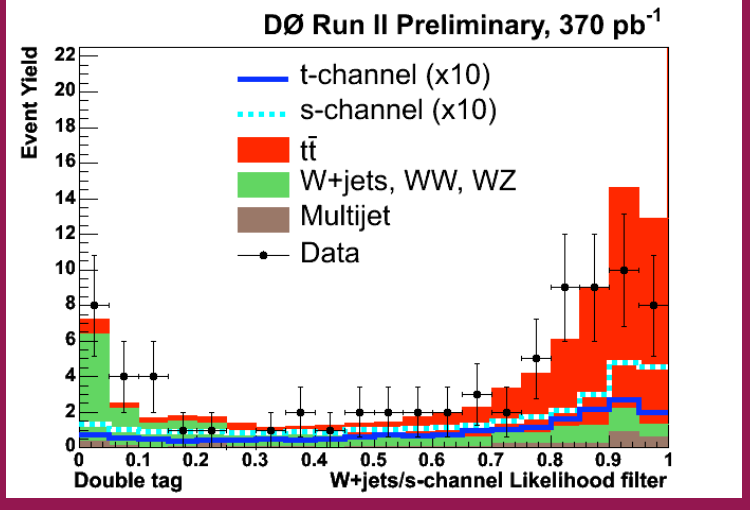
Single Top Production

- World's best limits: DØ likelihood discriminant analysis:
  - Different filters for t vs $t\bar{t}$ and t vs W+jets and e vs μ, and single tag (mostly t-channel) vs double-tag (mostly s-channel) :
    - 16 variables (leading jet p_T, 2nd leading jet p_T, $M_T(W)$, sphericity, Q(lepton)xη(untagged jet), etc.



	σ_s(pb)	σ_t(pb)
SM expectations (NLO)	0.88±0.07	1.92±0.21
95% upper limits observed (expected)	**5.0(3.3)**	**4.4(4.3)**



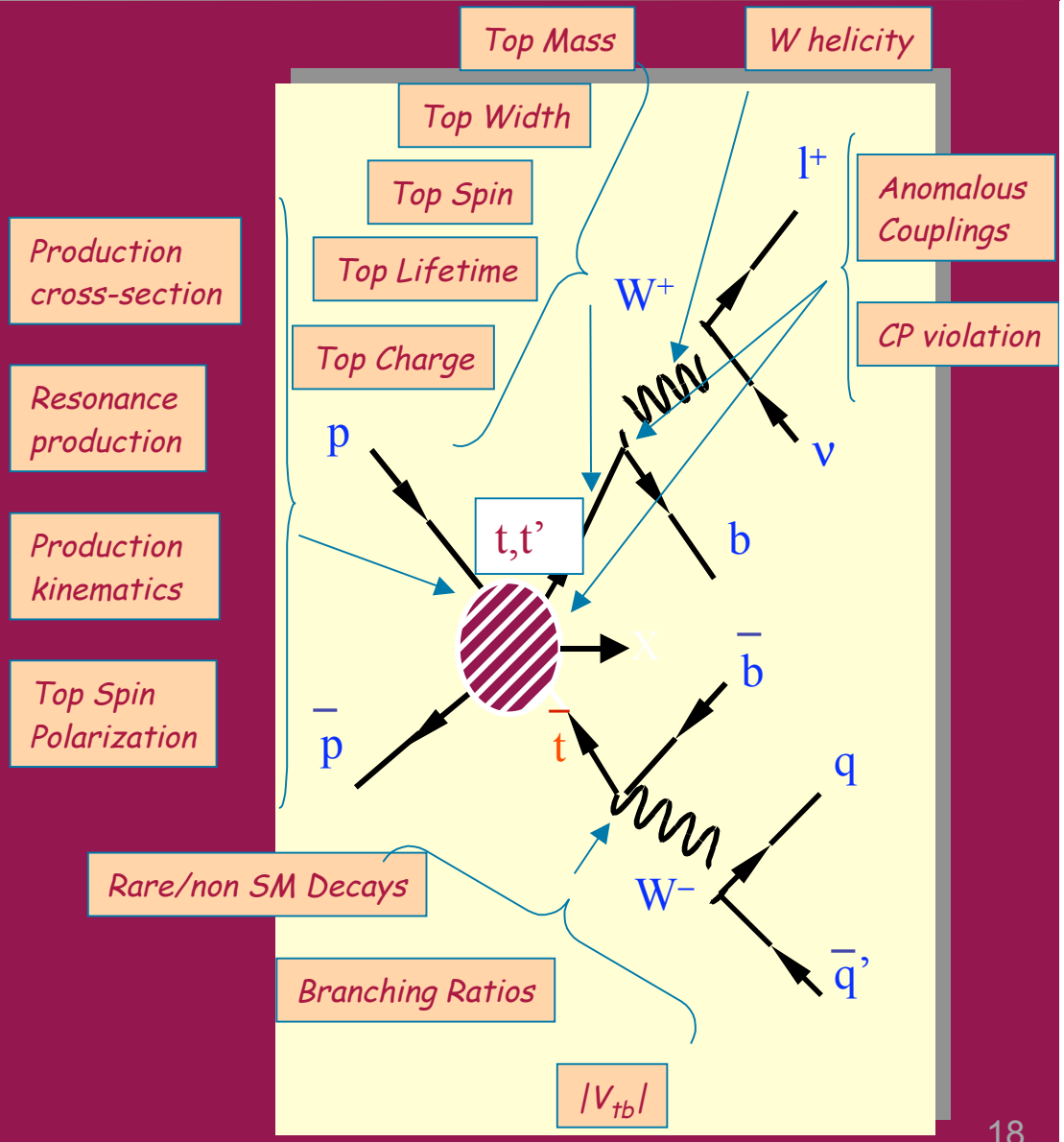


3σ evidence expected with <2fb^{-1}

CDF result with ~ 700pb^{-1} expected at Moriond QCD

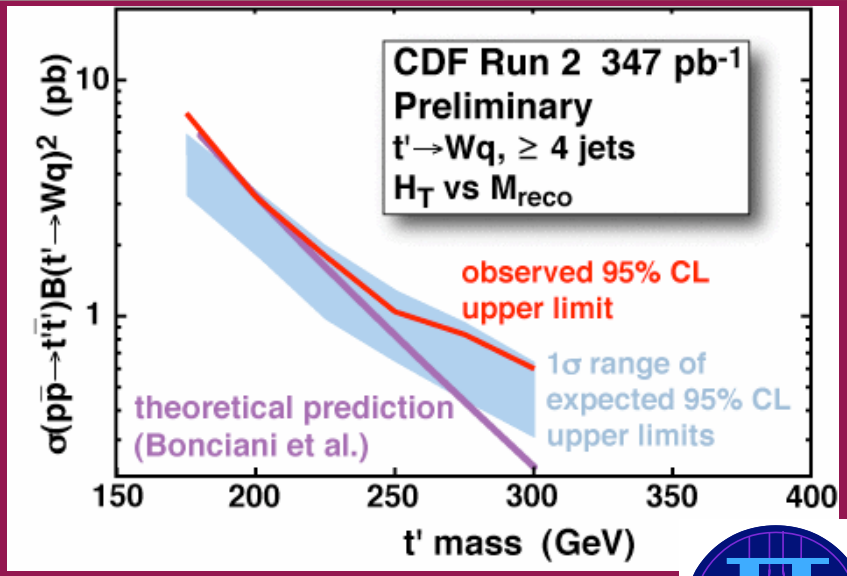
Any Additional Top Like Quark?

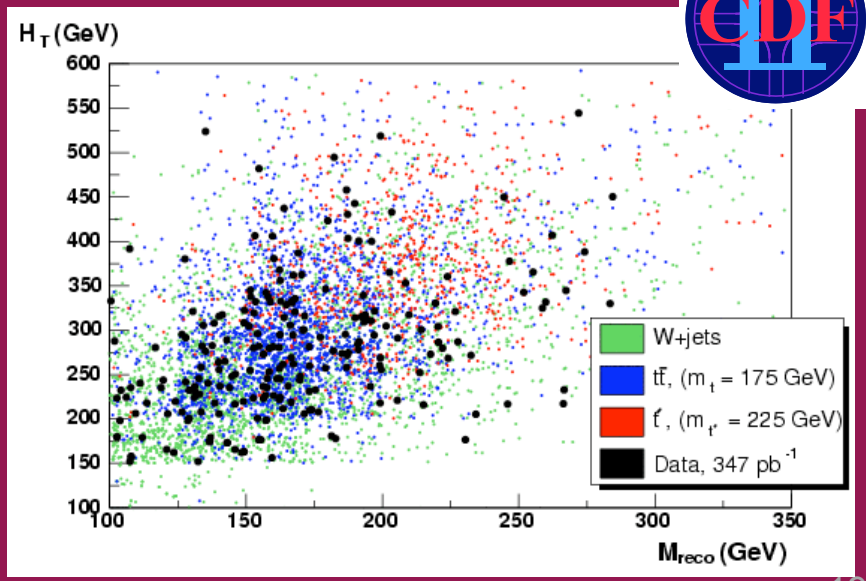
- t' search



Search for Heavy Quark t'→Wq

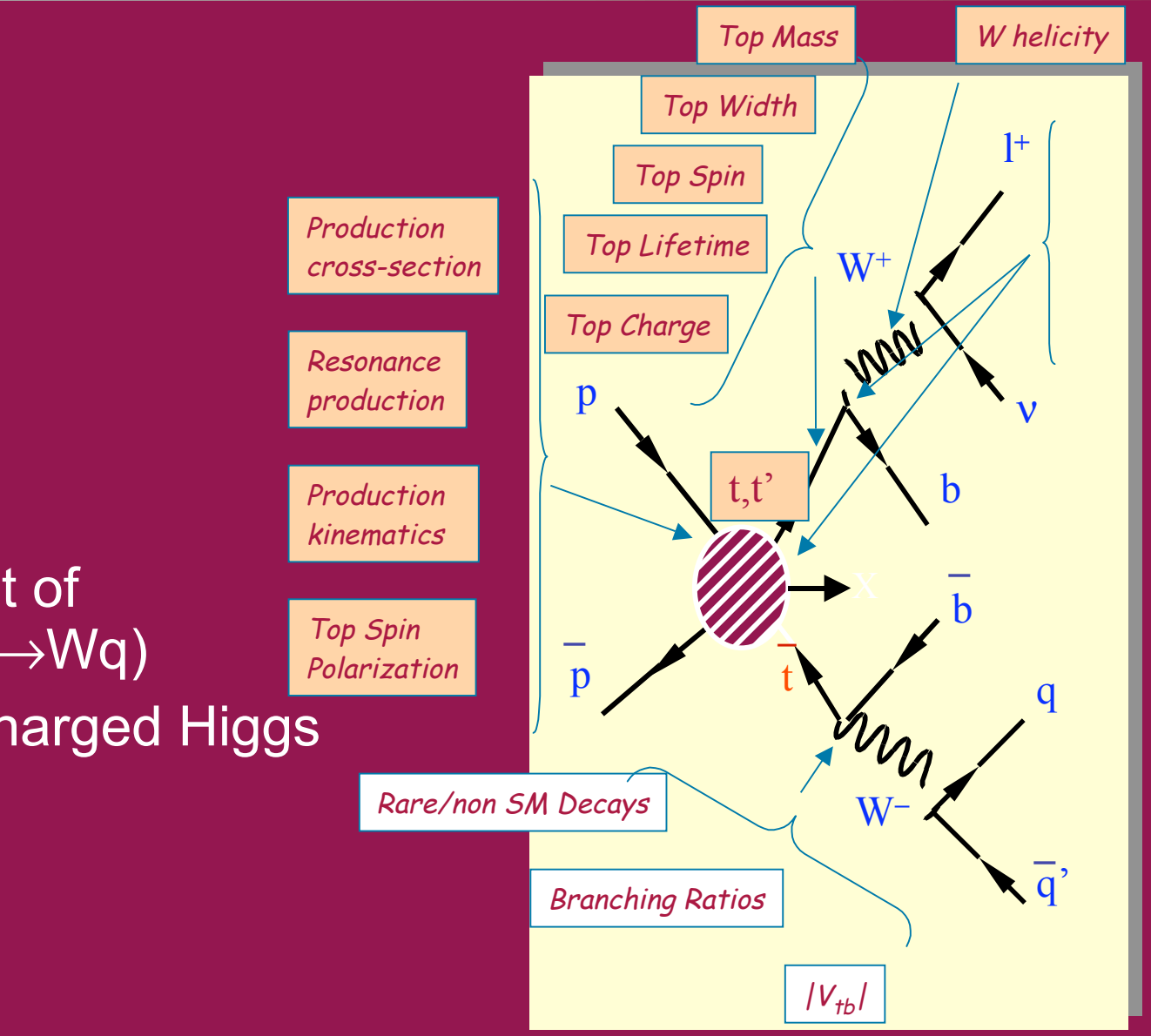
- Several theoretical scenarios:
  - Heavy 4th generation quark (He et. Al. Hep-ph/0102144)
  - "beautiful mirrors" models (Wagner et. Al. Hep-ph/0109097)
    - Consistent with EWK data
- CDF performs 2D fit: $H_T = \Sigma_{jets} E_T + E_{T,l} + ME_T$ and M_{reco} from χ^2 mass fit in Lepton + Jets channel
- Uses binned likelihood fit and Bayesian limit:
  - Rule out at 95% CL a t' with 196 GeV/c^2 < m(t') < 207 GeV/c^2
- ~700pb^{-1} measurement expected soon!





Does t →Wb only?

- Measurement of B(t→Wb)/B(t→Wq)
- Search for Charged Higgs



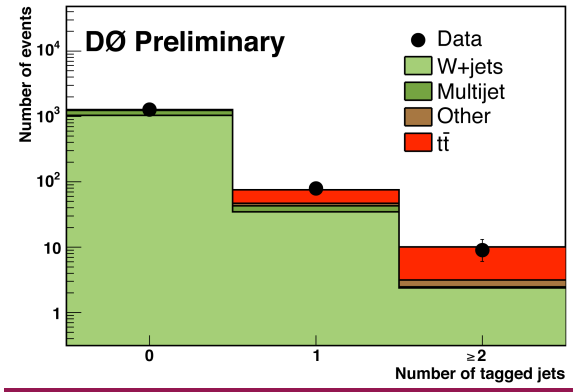
Measurement of B(t→Wb)/B(t→Wq)

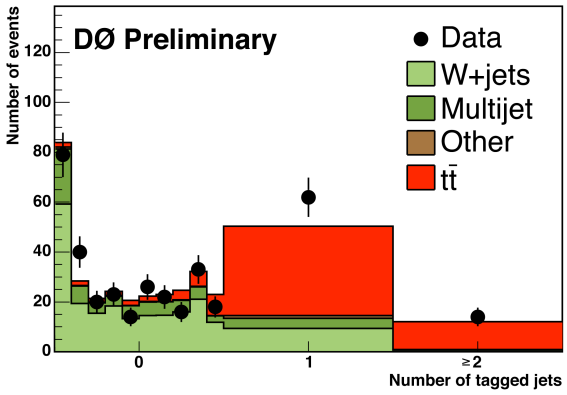
- In SM B(t→Wb)~1
  - If measure < 1: NP
    - In top decays or
    - In top backgrounds
- Single top measures B directly, $t\bar{t}$ measures R:

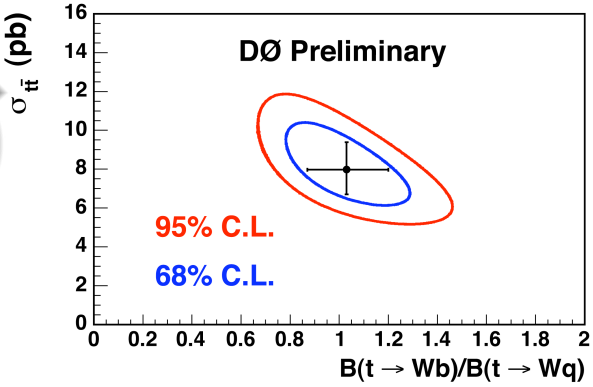
- DØ uses Lepton+Jets (3 and ≥ 4 jets) sample and fits number of 0, 1, ≥ 2 b tagged events
- 0 tag ≥ 4 jets sample: use a 4 variable discriminant

$$R = \frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{ts}|^2 + |V_{td}|^2 + |V_{tb}|^2} = |V_{tb}|^2 \sim 0.998$$

In SM







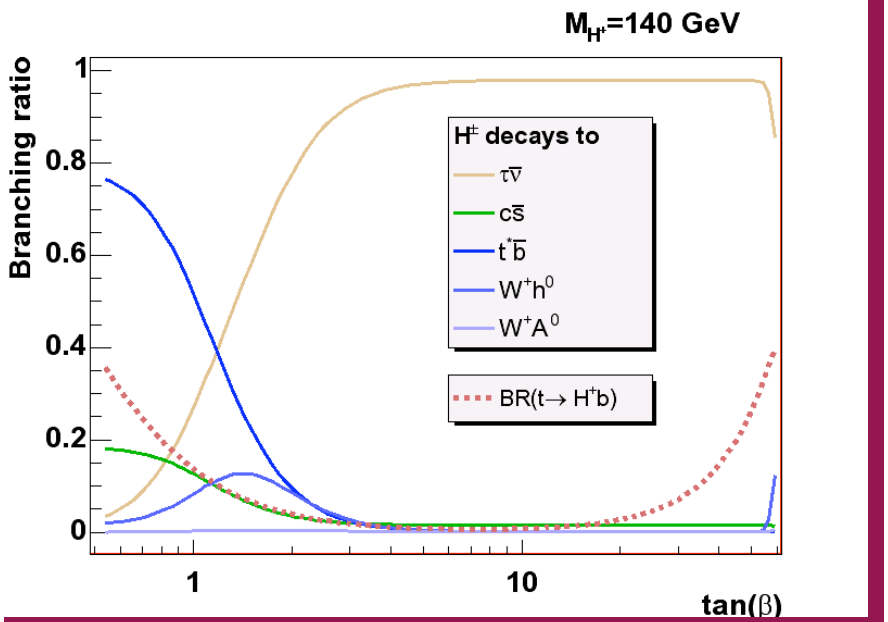
$$R = 1.03^{+0.19}_{-0.17}(stat + syst)$$

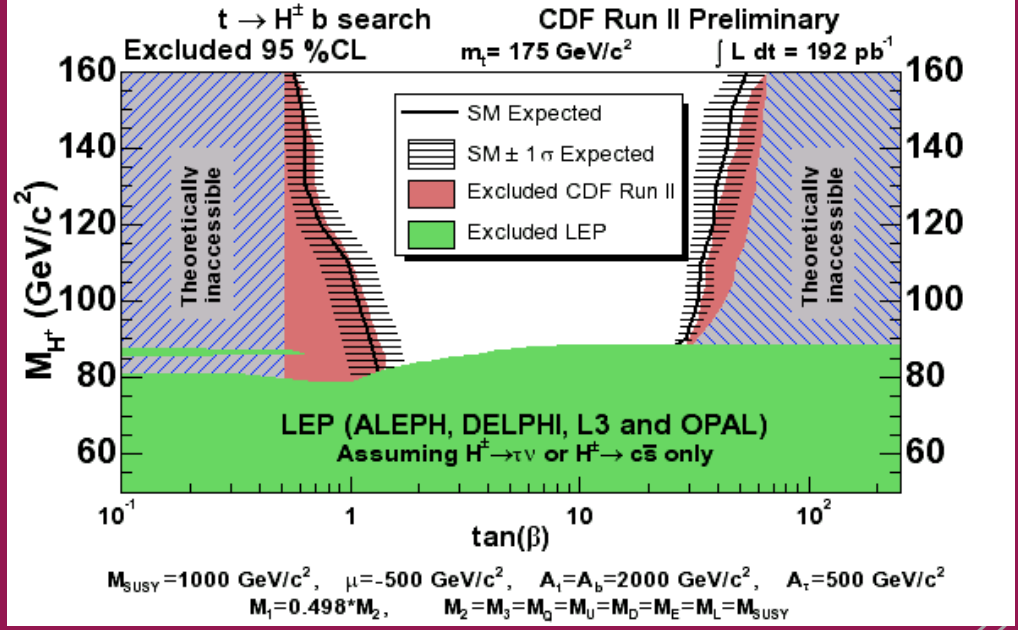
R>0.61 at 95%CL
$|V_{tb}|$>0.78 at 95%CL

N_{jet}=3 N_{jet}≥4

Search for Charged Higgs

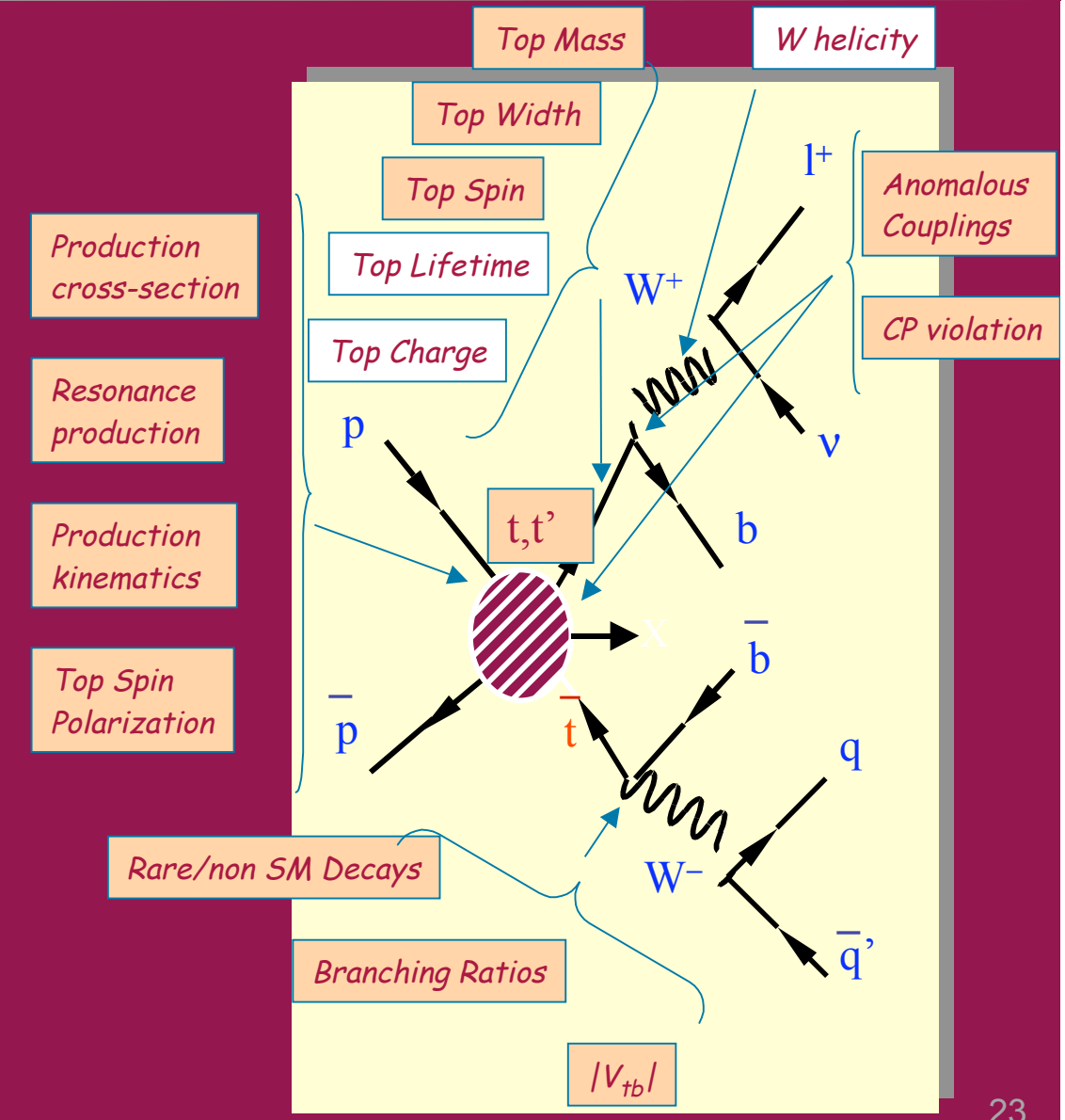
- Models with 2 H doublets: 5 Higgs bosons (h^0,H^0,A,$H^\pm$), $H^\pm$:
  - Direct production: small production rate, hard signature
  - Indirect production: top associated (if $m_{H\pm} < m_t - m_b$, $t \to H^\pm b$ competes with $t \to Wb$)
    - Maybe large production rates
    - Clean signature
- Various $H^\pm$ decays affect differently $\sigma_{t\bar{t}}$ in the various channels
  - Look for imbalance among dilepton, L+J(1,2 tags), L+τ

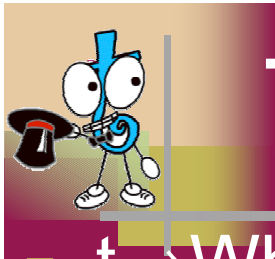




Is Top Really "True"?

- Top charge
- Top lifetime
- W helicity

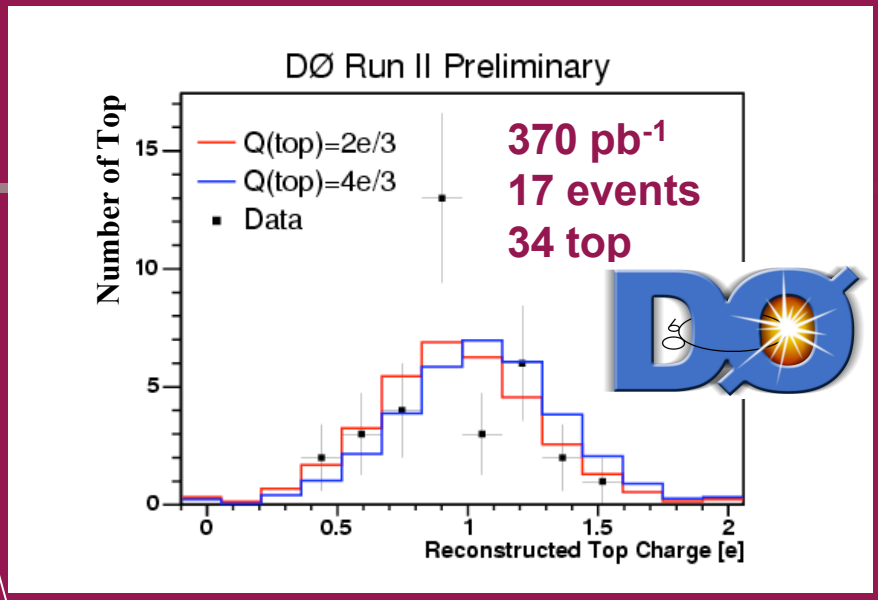


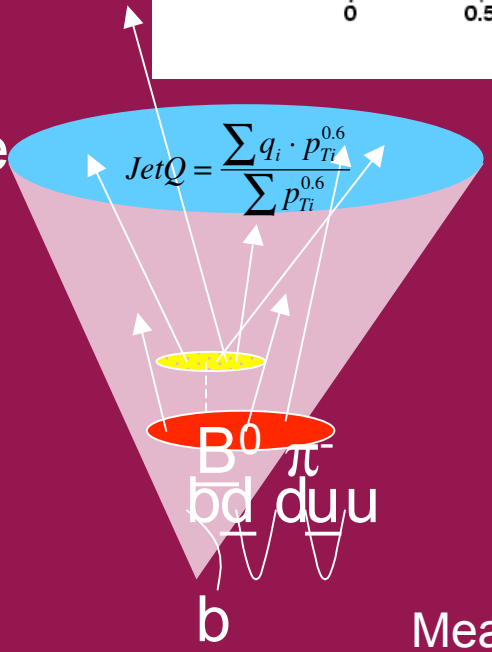


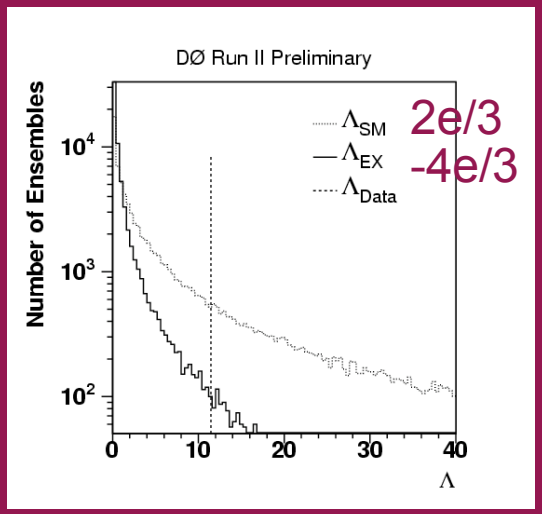
Top Charge

- $t \rightarrow Wb$ but W^+b or W^-b?
- Q=-4/3: exotic quark (PRD, hep-ph/9850131)
  - Accommodates better EWK fit (hep-ph/9909537)
  - True top quark would be at higher mass (~270GeV/c^2)
- DØ uses Lepton+Jets double-tag sample
  - χ^2 fit for pairing of leptonic b
  - JetQ for flavor tagging b jet
  - Likelihood ratio test:

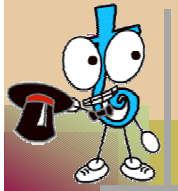
$$\Lambda = \frac{\Pi_i prob^{2e/3}(q_i)}{\Pi_i prob^{-4e/3}(q_i)}$$





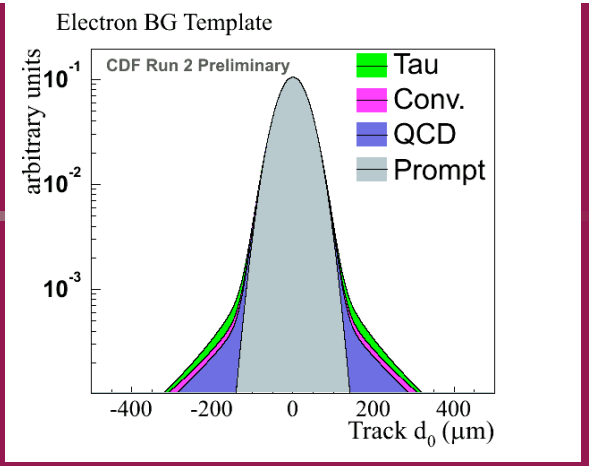


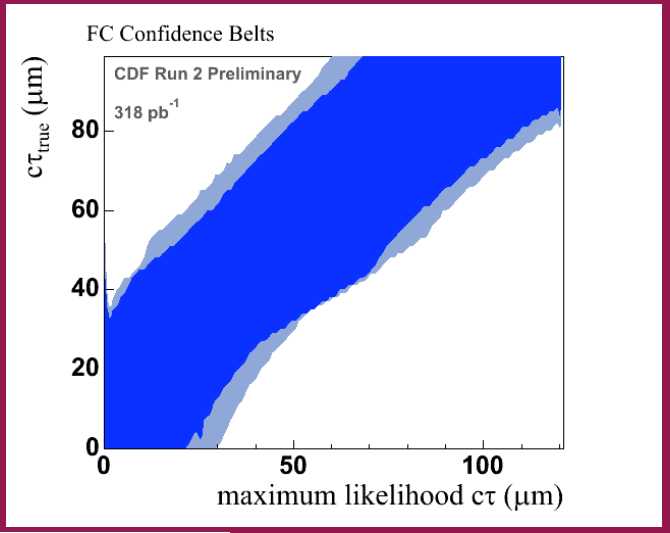
Measure Λ_{data} = 11.5
exclude -4e/3 hypothesis to 94% CL
exclude 2e/3 hypothesis to 66% CL

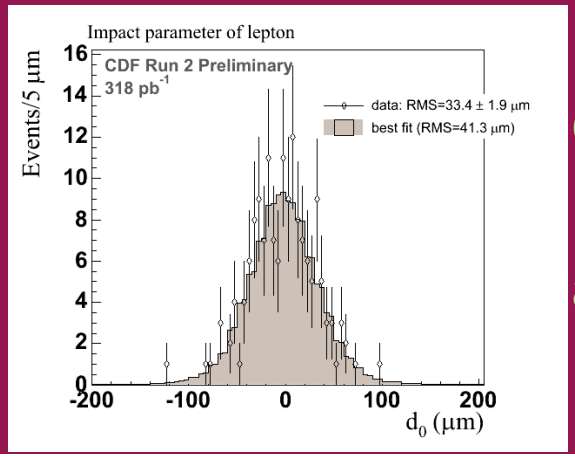


Top Lifetime

- SM top has $\tau \sim 10^{-24}$s
- Measuring lifetime
  - Sensitive to production mechanism from long lived particles
- CDF uses Lepton+Jets channel with b jet tagged
  - Measure lepton impact parameter (d_0)
- Backgrounds:
  - Prompt: W+jets, Drell-Yan, Diboson
  - Displaced lepton: W(Z) decaying to τ, Semileptonic b,c decays, photon conversion (failing filter)
- Calibration: use DY near Z resonance to get d_0 resolution



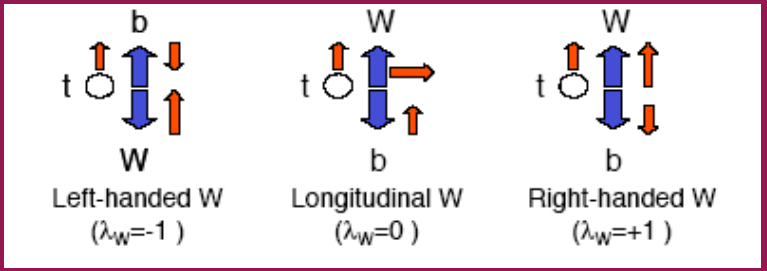


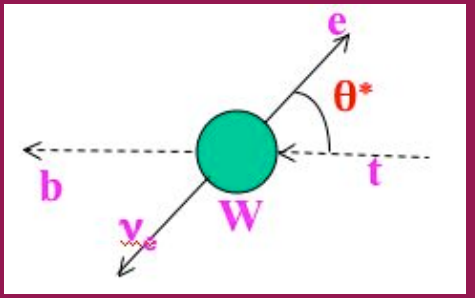


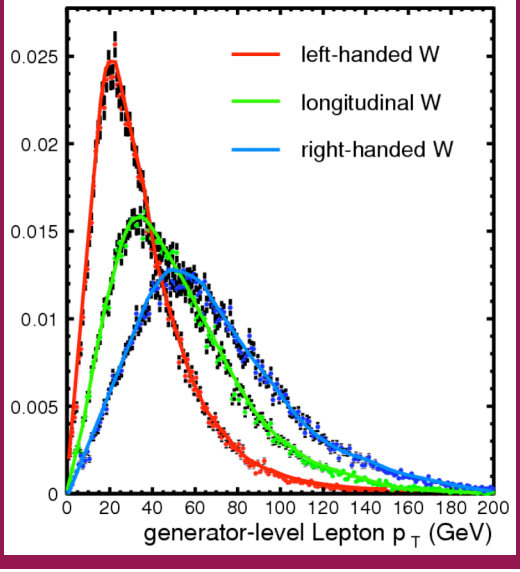
$c\tau_t < 52.5\mu m$
($\tau < 1.75 \times 10^{-13}$s)
at 95%CL

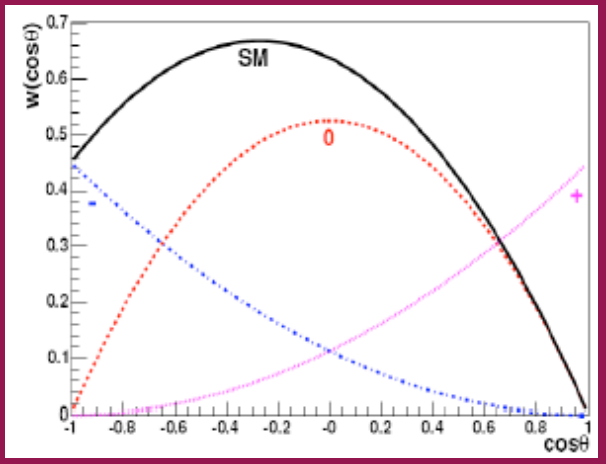
W Helicity

- In SM (V-A coupling of tWb) only 2 helicities allowed:
  - $f_+=0$, $f_-\sim0.3$, $f_0\sim0.7$
- DØ uses both the cosθ* (in Lepton+Jets)and lepton P_T (in dilepton) variables to measure f_+ (fix f_0)



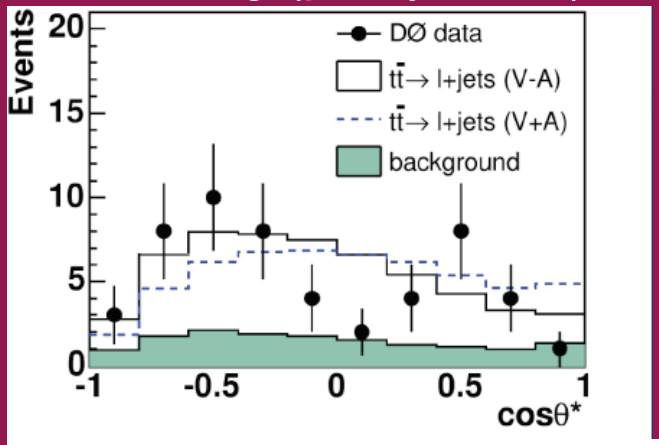




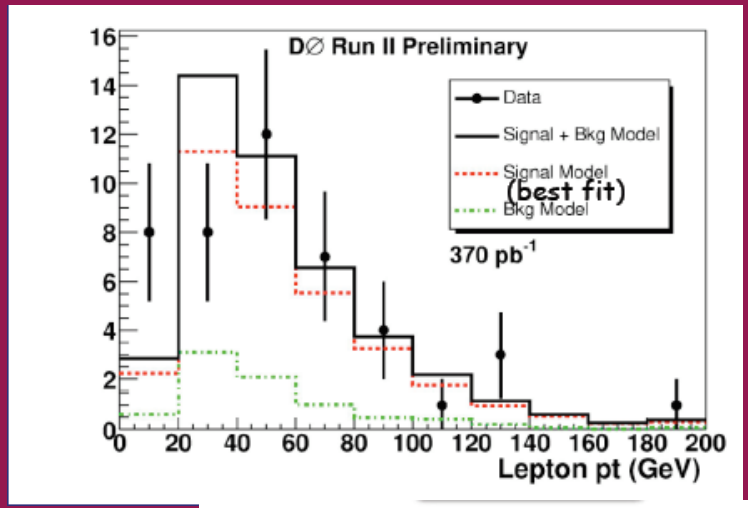


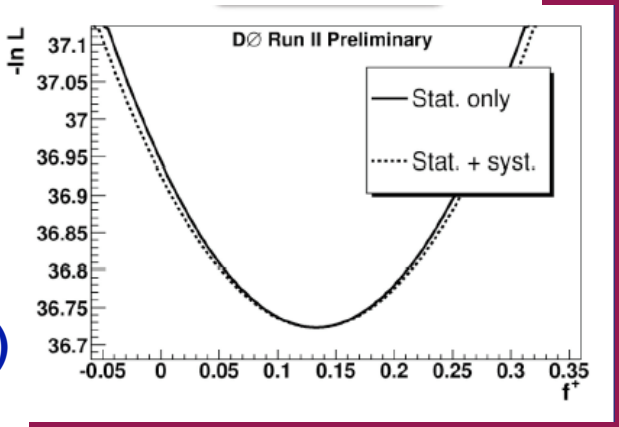
W Helicity

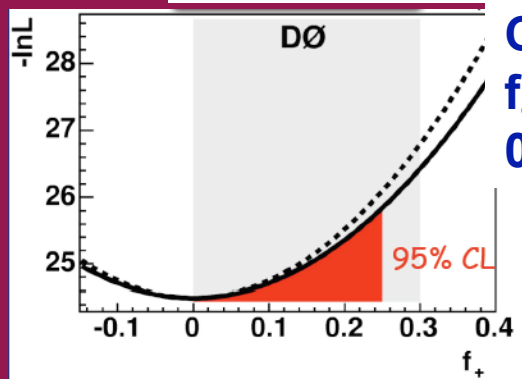
- Cosθ* in Lepton+Jets: (230pb^{-1})
  - 2 Template analysis:
    - B tagging used
    - Topological variables
  - χ^2 fit is used for lepton matching (purity: 60%)



- Lepton P_T in dilepton: (370pb^{-1})





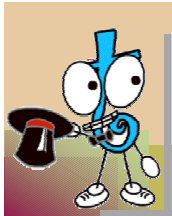


Combined result:
f_+ = 0.04 ± 0.11 (stat) ± 0.06 (syst)
0.0<f_+<0.25 at 95%CL

CDF combined (162pb^{-1}):
0.0<f_+<0.27 at 95%CL

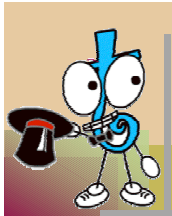
CDF Run I (109 pb^{-1}):
0.0<f_+<0.18 at 95%CL

$$f_0 = 0.74^{+0.22}_{-0.34}$$



Conclusions

- Pair production cross section: still consistent with SM and among channels
  - New era of being systematics limited
  - Meaningful comparison among channels around the corner!
- Single top production: observation coming very soon!
- Top properties (R, $H^{\pm}$, charge, lifetime, W helicity)
  - All consistent with SM top so far

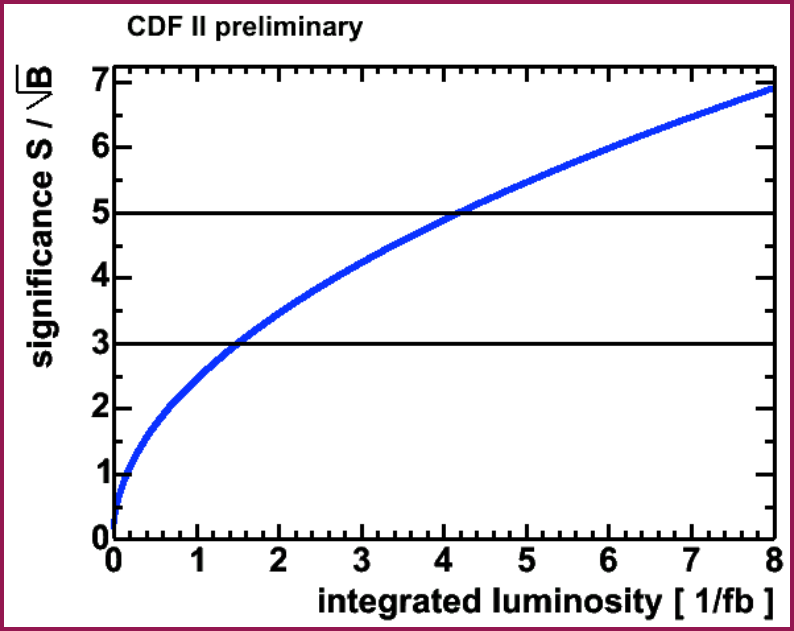


Shameless Publicity

- Tevatron and both CDF and D0 doing very well!
- Top physics is crucial!:
  - Likely related to EWSB
  - Rich analysis environment:
    - B tagging (and even flavor tagging!)
    - Various analysis technique
    - “Full” event reconstruction
- Current machine at the energy frontier!
  - CDF+D0: 95 papers (published or accepted or submitted) in Run II so far!
    - http://www-d0.fnal.gov/www_buffer/pub/Run2_publications.html
    - http://www-cdf.fnal.gov/physics/pub_run2/

Backup slides

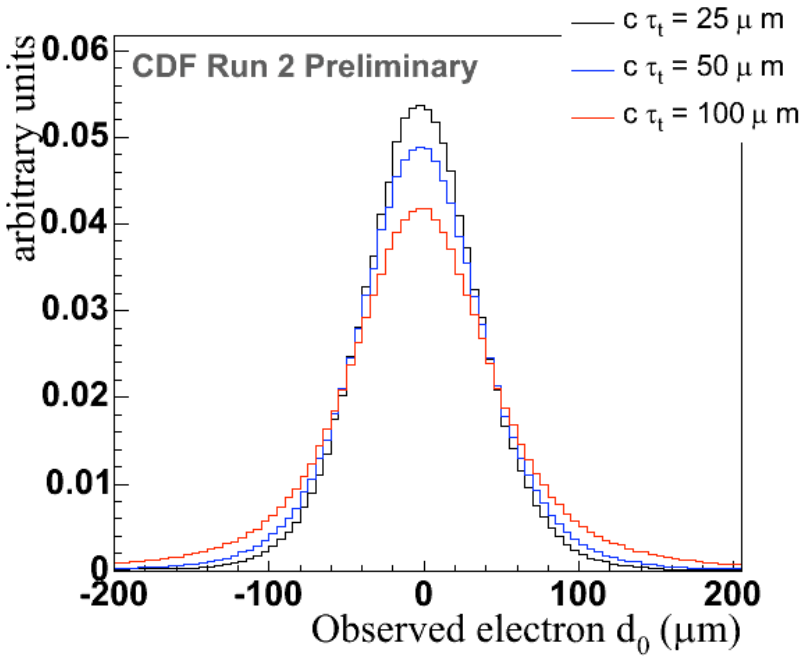
Single top projection



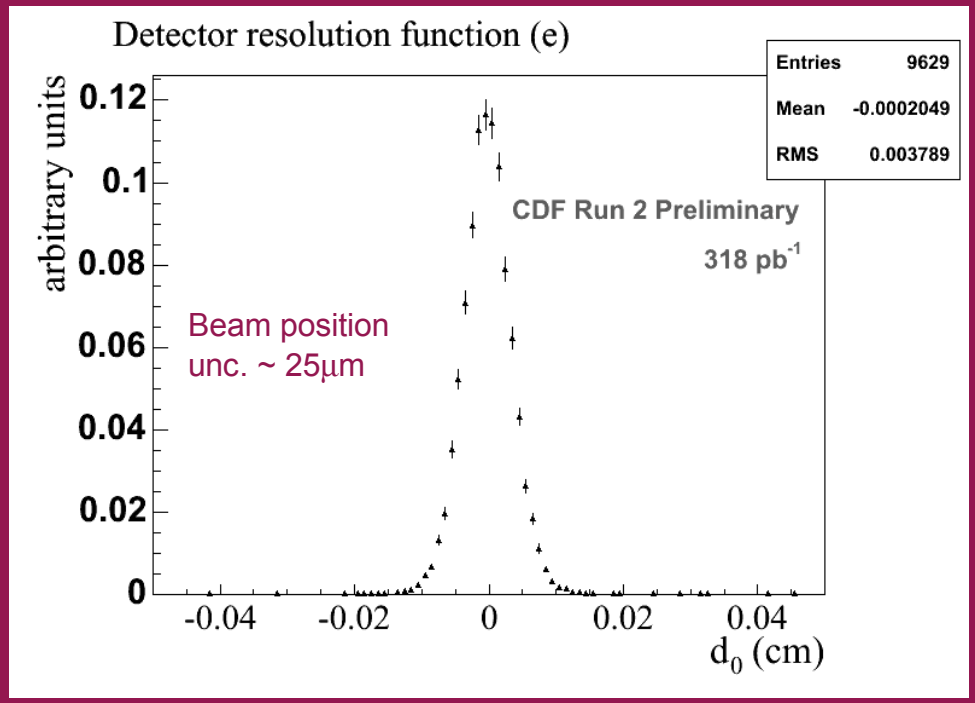
L+J b tag systematics

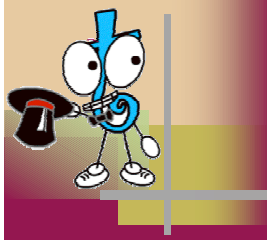
Source	Systematic (%)
b-tagging	6.5
Luminosity	6.0
PDF	5.8
Jet Energy Scale	3.0
ISR/FSR	2.6
Lepton Identification	2.0
Total	11.5

Top Lifetime

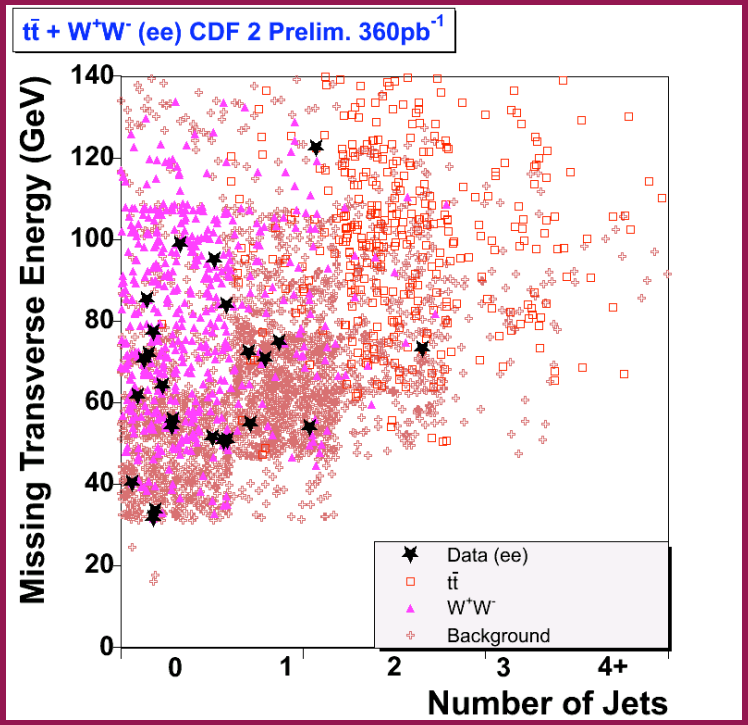


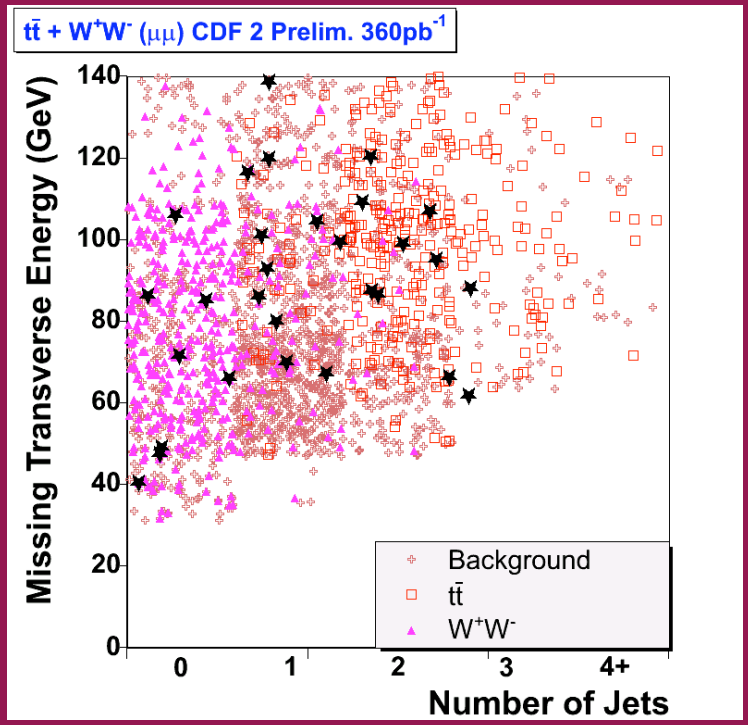
Top lifetime resolution

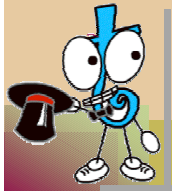




Back up slides

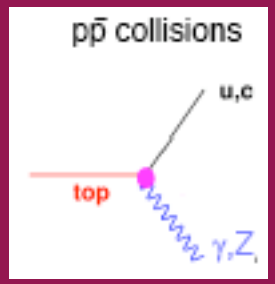


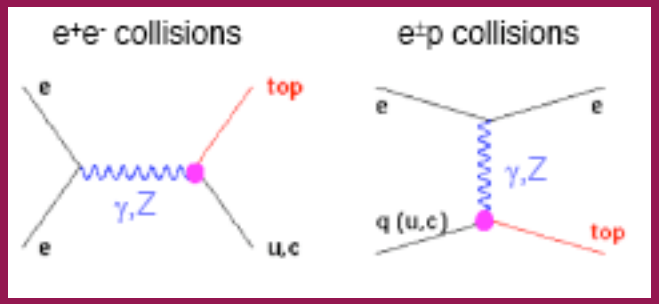




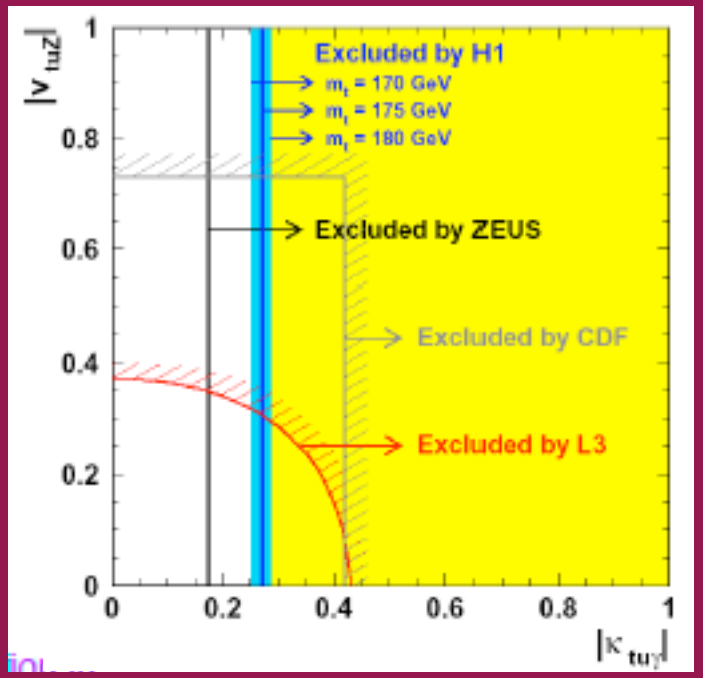
FCNC

- No FCNC at tree level in SM
- Enhancement in NP models





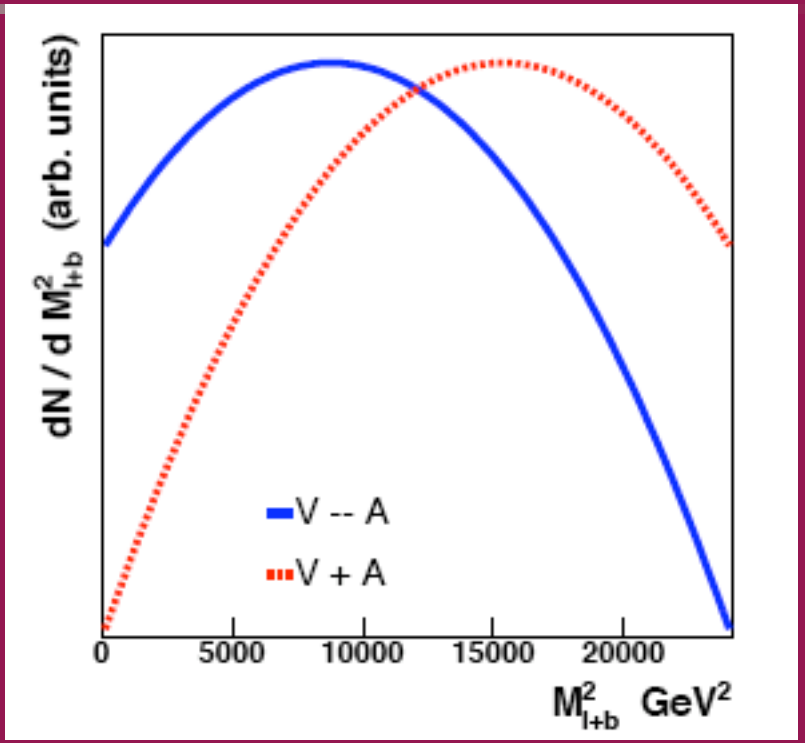
- H1: 2.2σ excess in leptonic channel
- CDF & D0 working on it

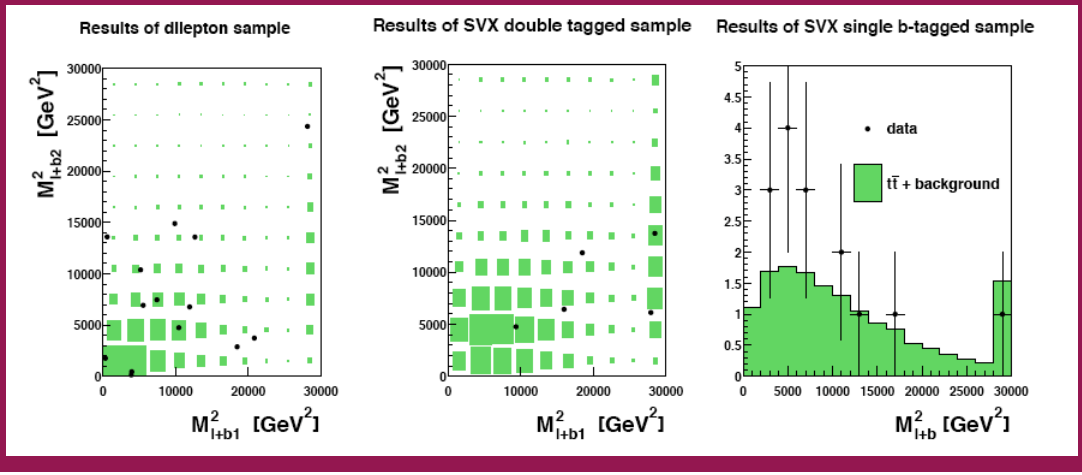


W helicity

- CDF Run I:
  - M^2_{lb} in dilepton and L+Jets channel
  - Combined with lepton p_T in dilepton (correlation: 0.4)

$$\cos\theta^* = \frac{p_\ell \cdot p_b - E_\ell E_b}{|\mathbf{p}_\ell||\mathbf{p}_b|} \simeq \frac{2M_{lb}{}^2}{m_t^2 - M_W^2} - 1,$$



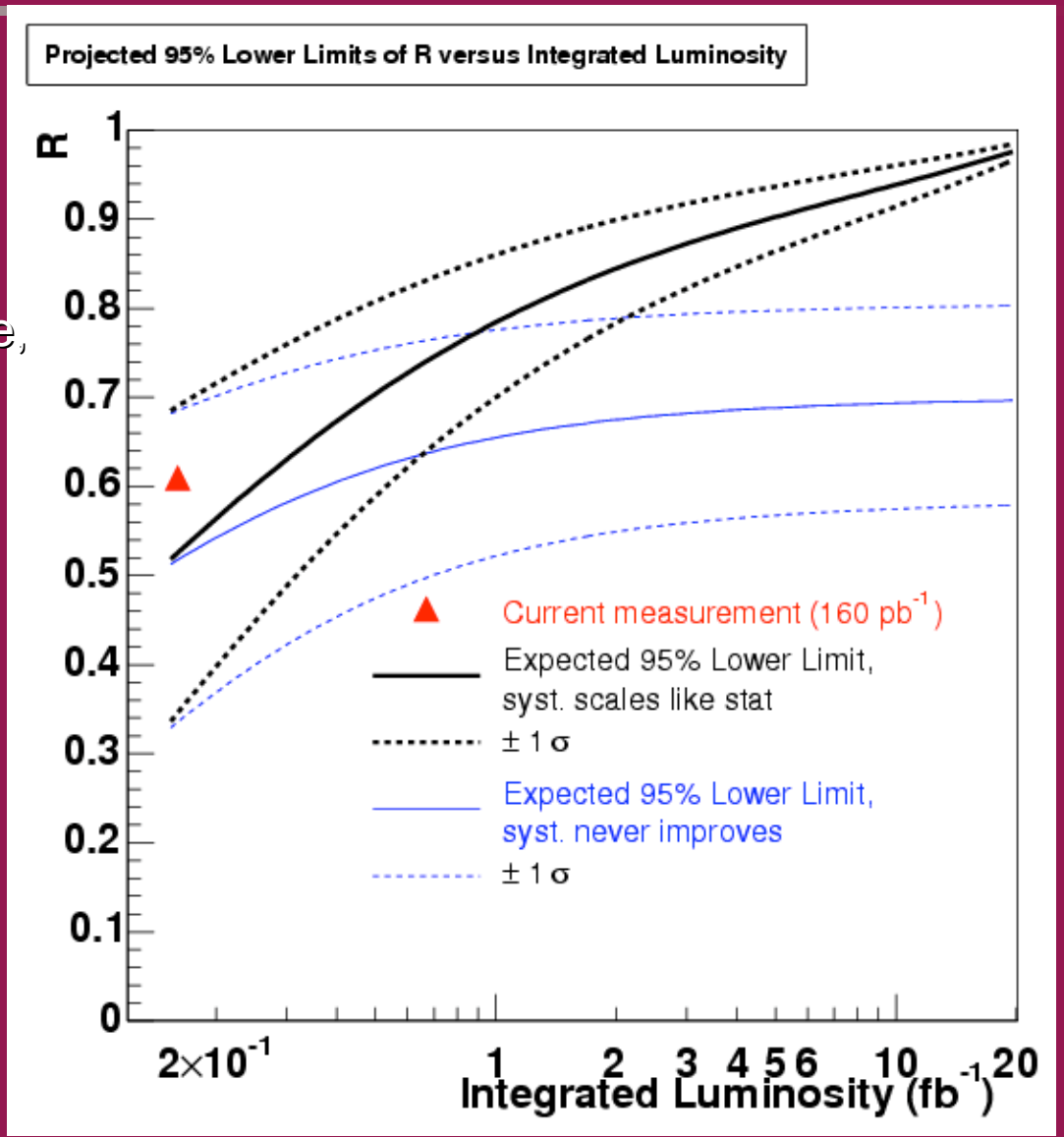


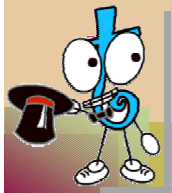
R measurement

Test 3 generations?

If $|V_{ts}| = 0.1$ and three generations,
➔ R = 0.99

If four generations and, for example,
$|V_{tb}| = 0.5$, ➔R = 0.96

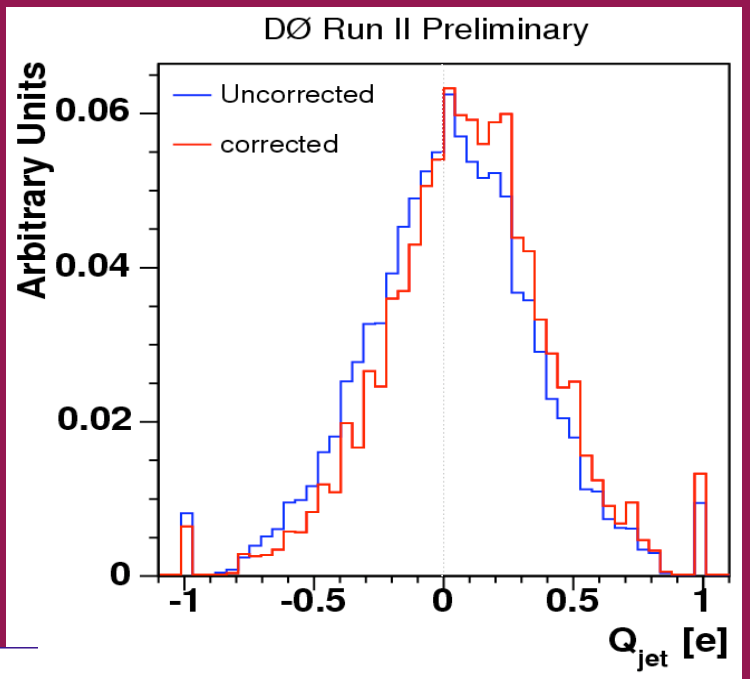




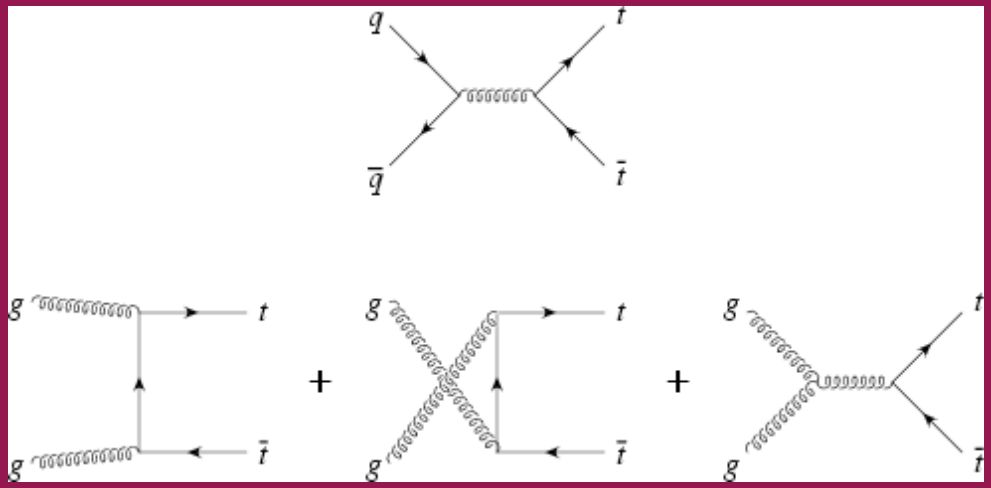
Top Charge

- $Q_1 = |q_l + q_b|$
- $Q_2 = |-q_l + q_B|$
- Corrections:
  - C-jet fraction (6%)
  - B mixing
  - Cascade decays

b jet charge



Source	Predicted C.L.	Observed C.L.
Stat. only.	96.9	98.7
+ Jet energy resolution	96.9	98.5
+ Jet energy calibration	97.0	98.6
+ Jet reconstruction	96.6	98.3
+ Jet charge corrections	94.9	97.4
+ b-jet production meachanism	94.5	97.0
+ η spectrum of b-jets	93.8	96.6
+ Top mass	92.4	96.1
+ p_T spectrum of b-jets	89.0	93.7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