Measuring Top Quark Properties at the Tevatron

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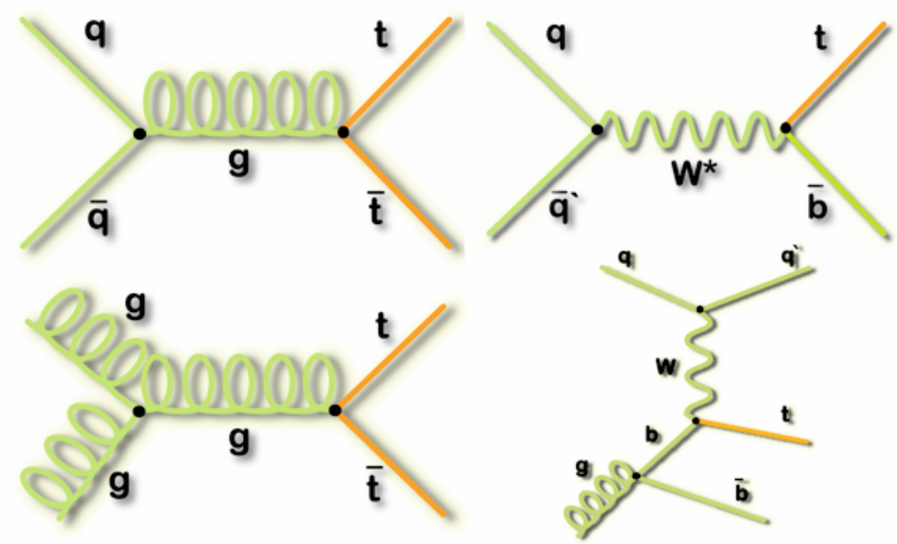
On behalf of the CDF & D0 Experiments

HCP 2010 Toronto, Canada

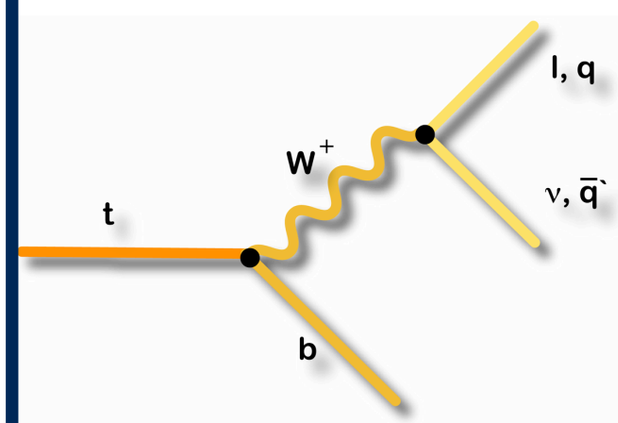
Top Physics at the Tevatron

How is Top Produced



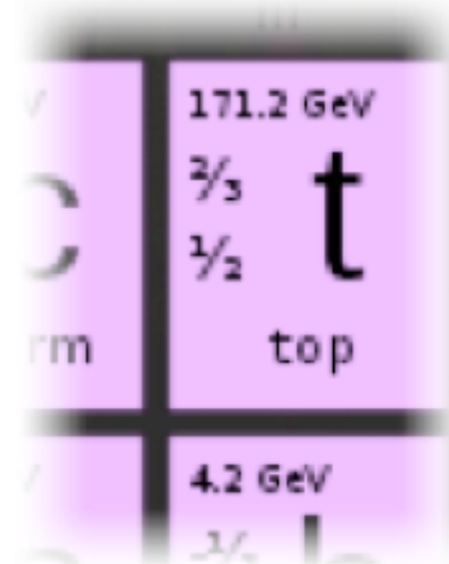
- Strong Force σ_{tt}
- Electroweak σ_t , σ_s

How Does Top Decay



- V-A
- V_{TB}

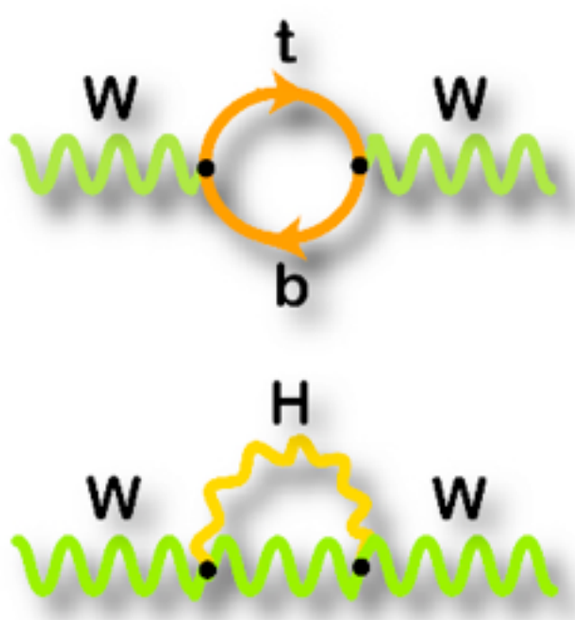
What are Top's Intrinsic Properties

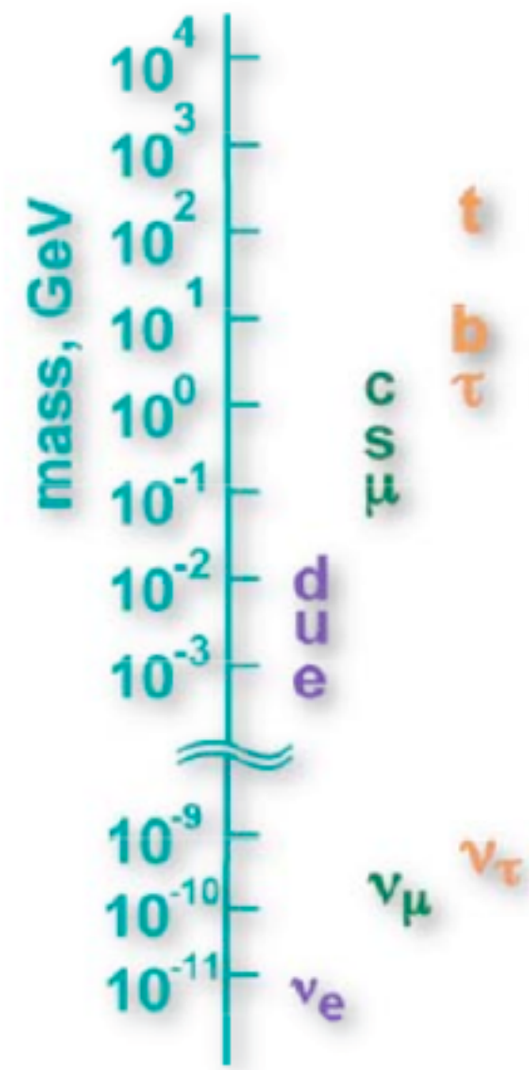


- Mass
- Width
- Spin
- Charge

Top Mass

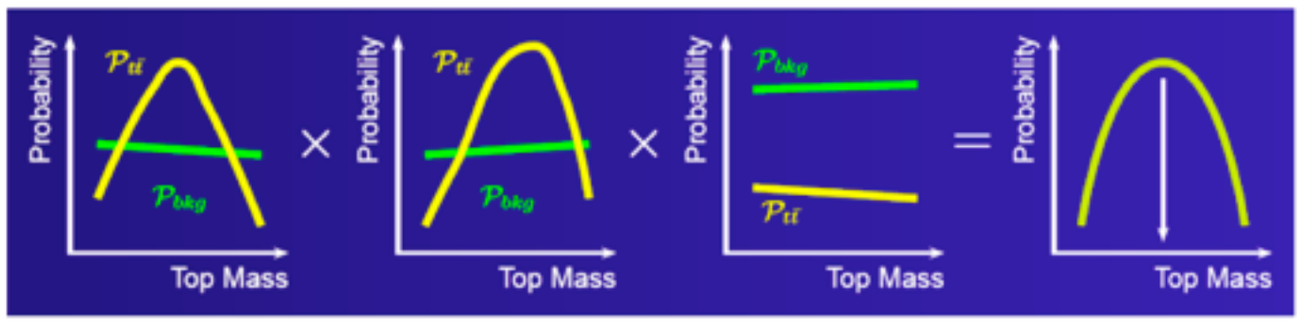
- **Free parameter in the SM**
- **Combined with the measured W mass constrains the mass of the Higgs through radiative corrections**

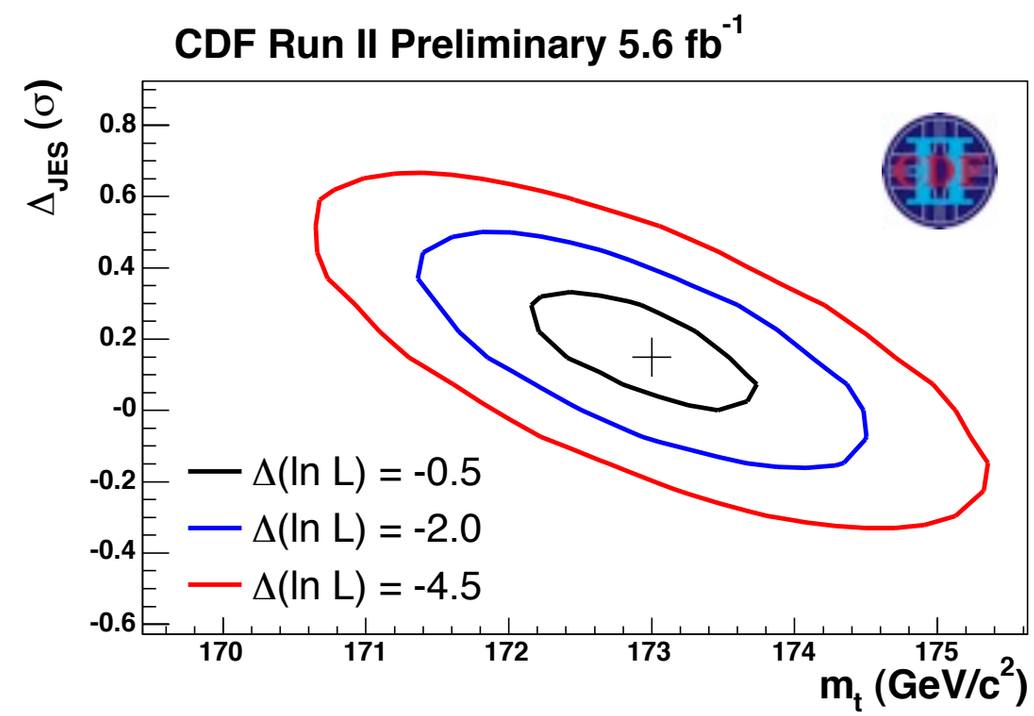




Top Mass

- **Matrix Element Technique: The probability of being signal or background is calculated per event as a function of M_t**





- **Multiply event probabilities to extract the most likely mass**

- **Jet Energy Scale is reduced by measuring simultaneously with M_t**

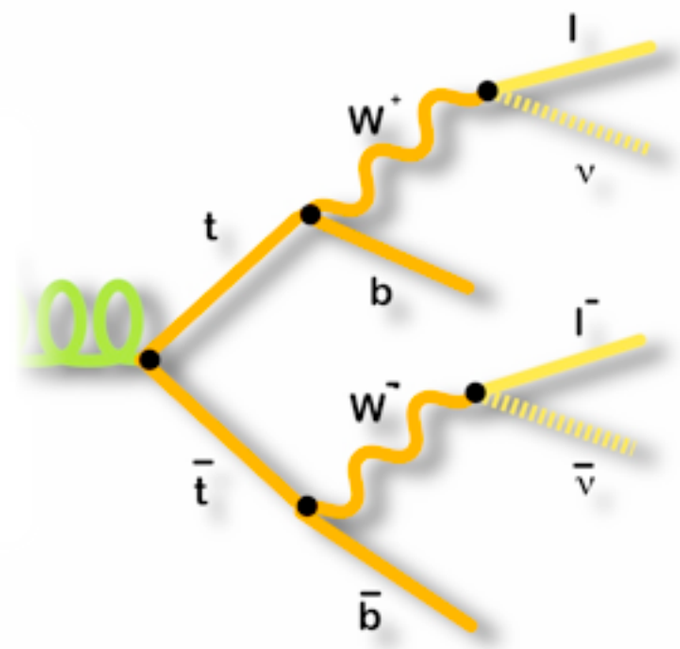
M_t = 173.0 ± 0.9$_{stat+JES}$ ± 0.9$_{sys}$ GeV/c^2

5.6 fb^{-1}

ΔM / M ~ 0.7 %

Top Mass in Dileptons

- **Use a kinematic reconstruction technique to measure the mass**
- **Two neutrinos in the final state lead to an under-constrained system**
- **Missing transverse momentum in the data is compared with the expected kinematics of the two unobserved neutrinos as a function of top mass**



$M_t = 173.3 \pm 2.4_{stat} \pm 2.1_{sys}$ GeV/c^2

$\Delta M / M \sim 1.8$ %

5.3 fb^{-1}

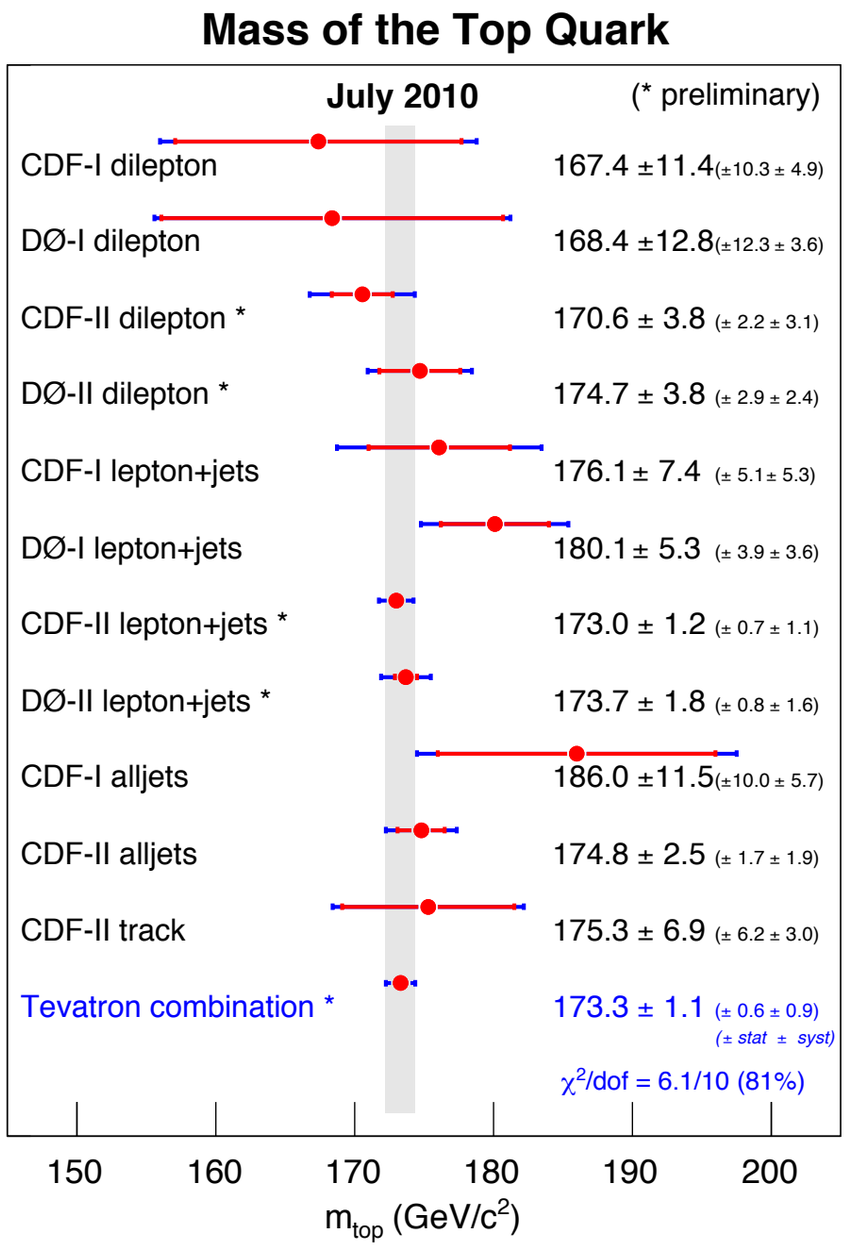
Top Mass Combination

- **Tevatron Combination updated this July - includes 11 results**
- **Statistical Uncertainty on Jet Energy Scale is largest systematics (~ 0.46 GeV)**
- **Good agreement across both experiments and channels**

M_t = 173.3 ± 1.1 GeV/c^2

ΔM / M ~ 0.6 %

up to 5.6 fb^{-1}

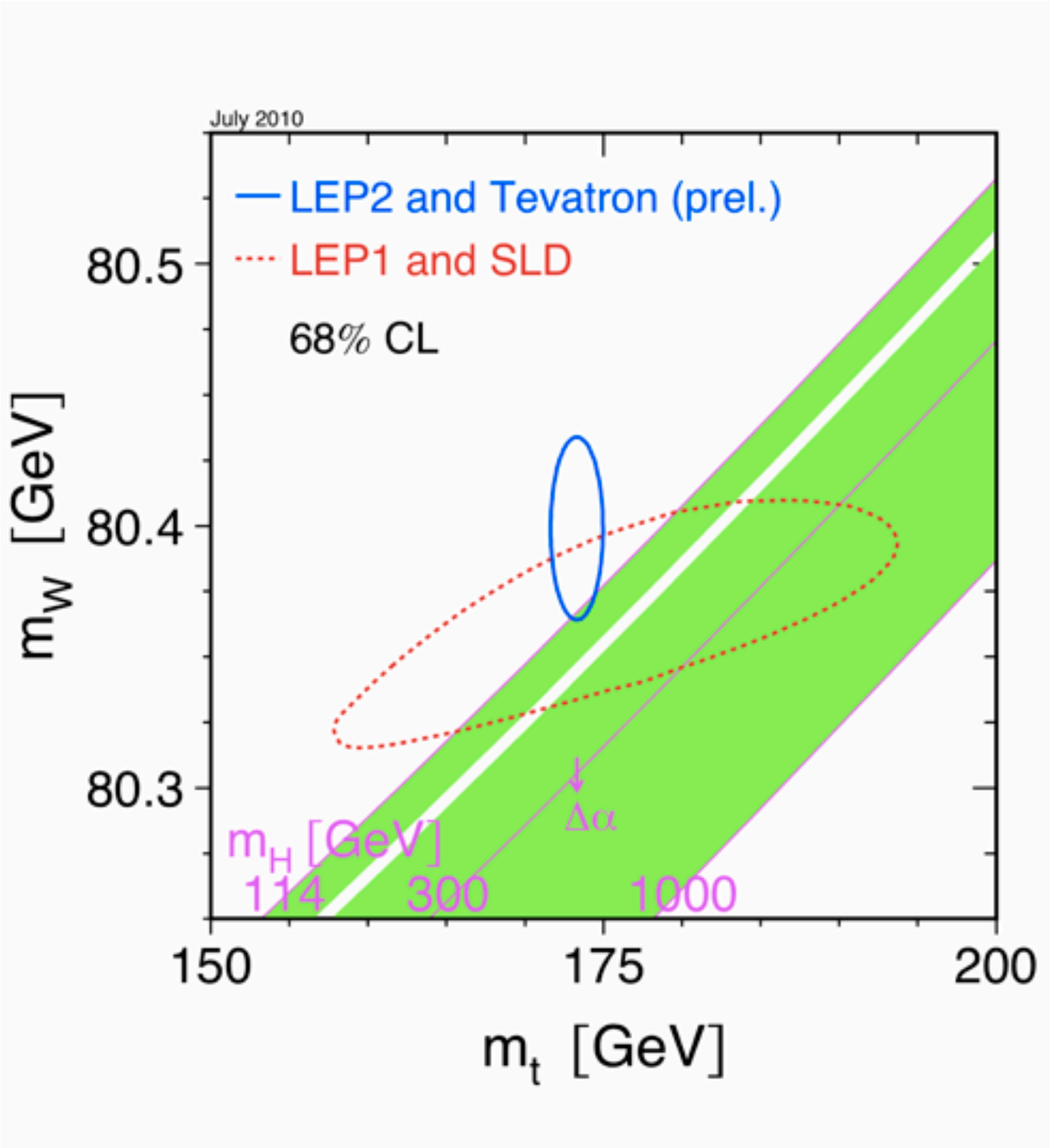


Back to the Higgs

Electroweak Fit

$M_H = 89^{+35}_{-26}$ GeV

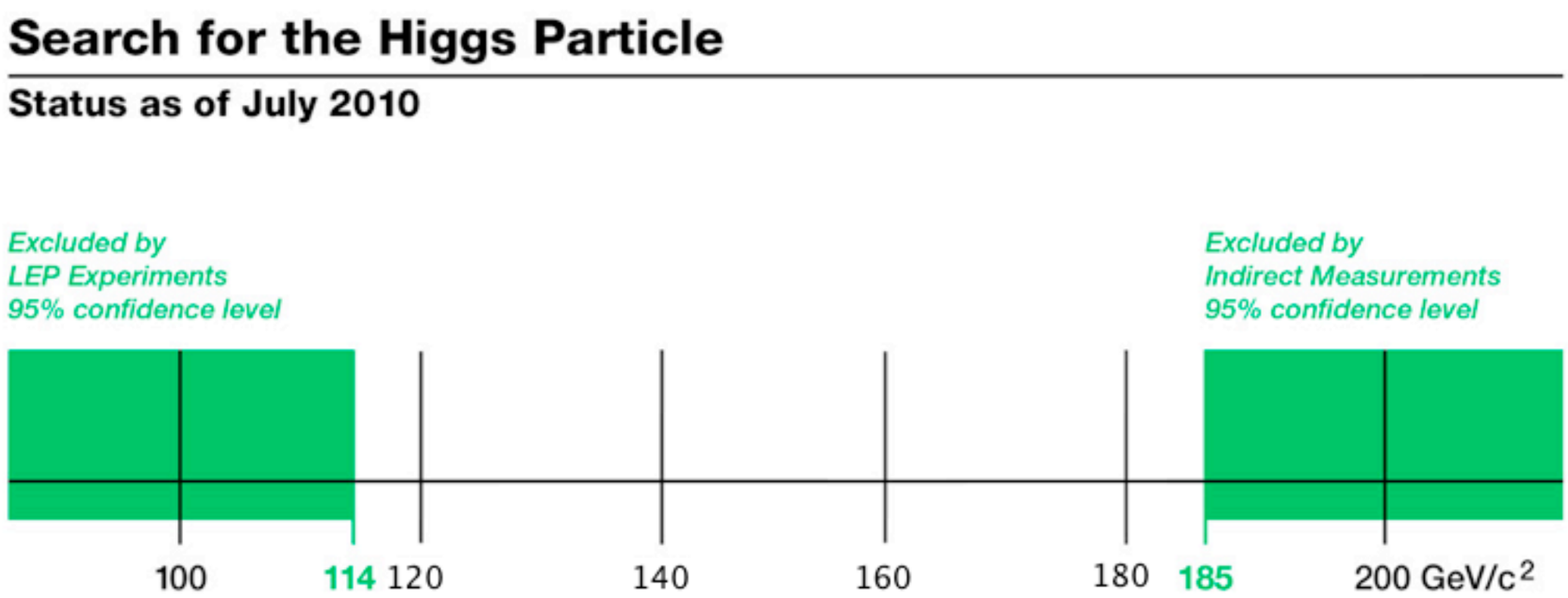
$M_H < 158$ GeV @ 95% CL



Back to the Higgs

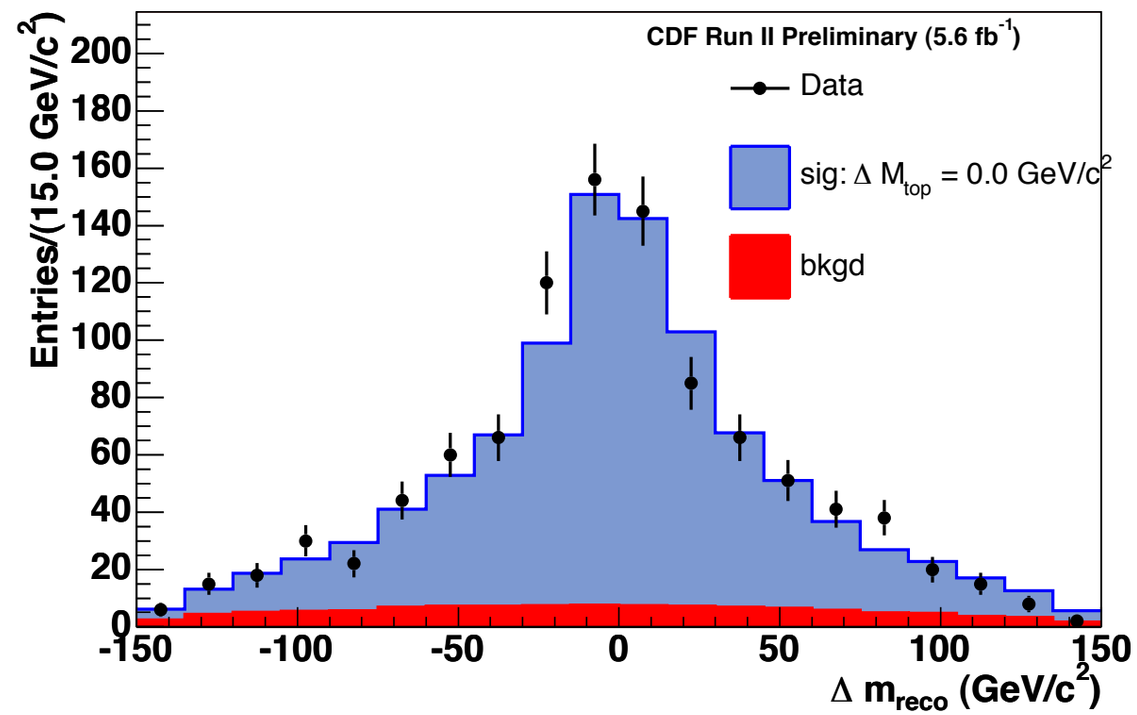
Including LEP Direct Search Limit

M_H < 185 GeV @ 95% CL



Top Anti-Top Mass Difference

- If CPT is conserved, $M_t = M_{\bar{t}}$
- Mass measurements until now have held this assumption
- Similar techniques to mass measurements



$\Delta M = -3.3 \pm 1.7$ GeV

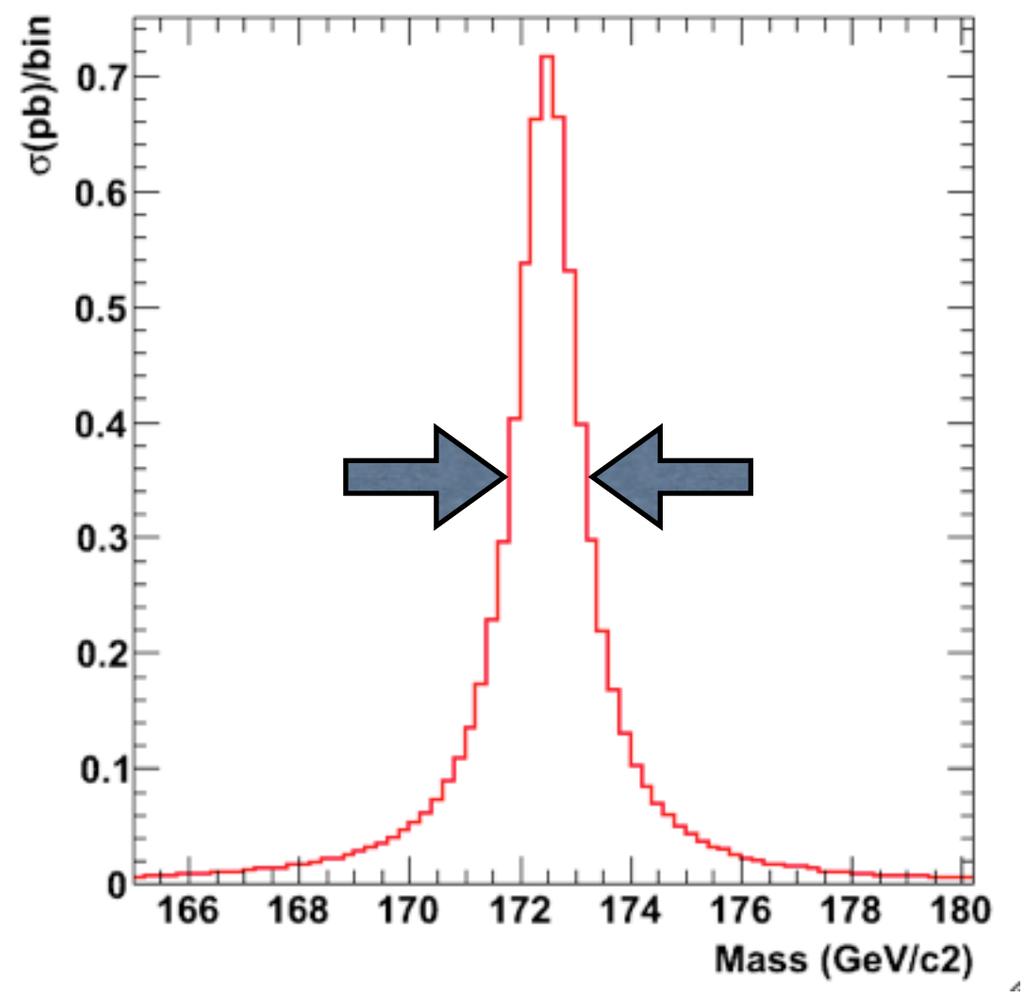
5.6 fb^{-1}

$\Delta M = +3.8 \pm 3.7$ GeV

1 fb^{-1}

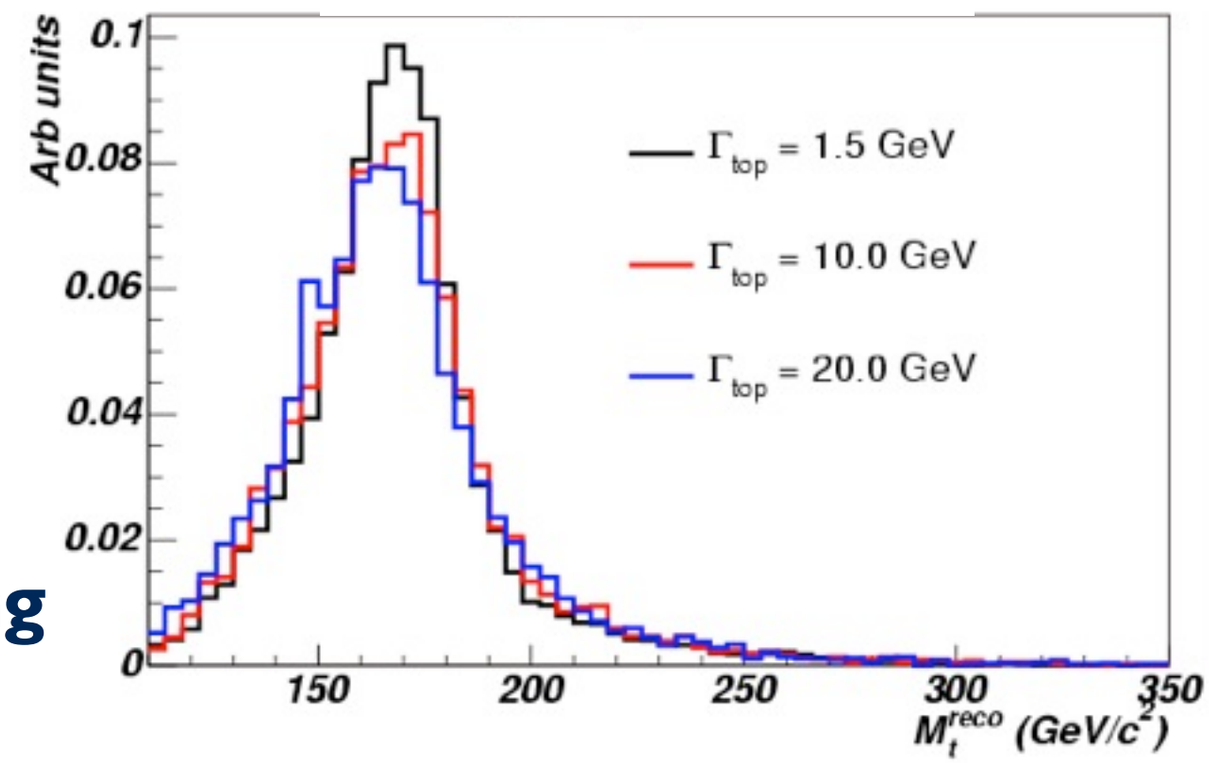
Top Width

- Top decays very quickly, which has interesting ramifications for how we observe it
  - No direct detection - we infer its properties from decay products
  - Spin information is passed to it's decay products
- SM predicts Γ_t = 1.3 GeV



Top Width

- **Complementary measurements done by CDF & D0**
- **Direct measurement:**
  - **Reconstruct top mass event-by-event**
  - **Extract width from fitting data to templates**



Γ_t < 7.5 GeV @ 95% CL

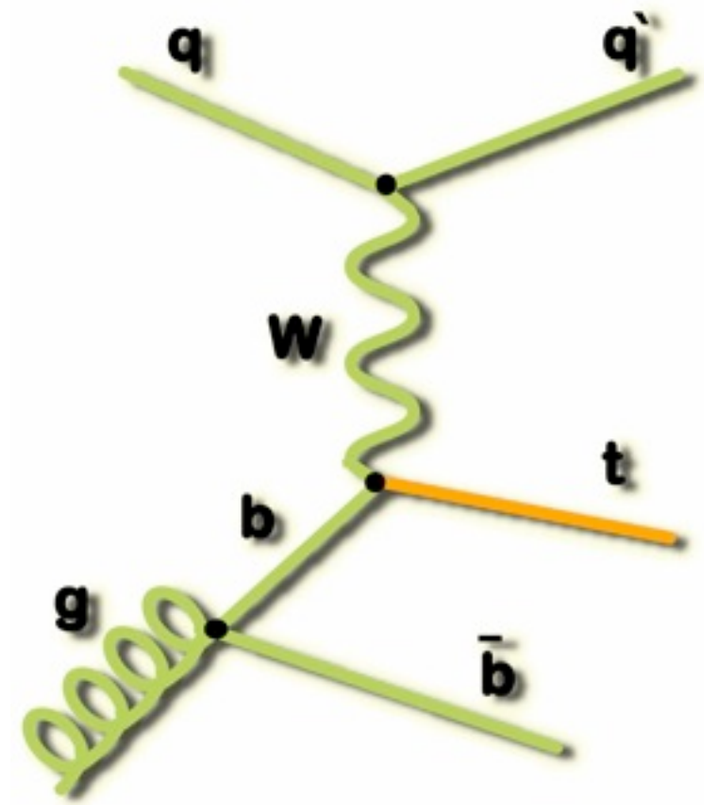
4.3 fb^{-1}

Γ_t^{SM} = 1.3 GeV

Top Width

- **Indirect measurement:**
  - **Use measured t-channel top cross-section and branching ratio t→Wb / t→Wq**

$$\Gamma_t = \frac{\sigma(t-ch)}{Br(t \to bW)} \cdot \frac{\Gamma(t \to bW)_{SM}}{\sigma(t-ch)_{SM}}$$



$\Gamma_t = 2.05^{+0.57}_{-0.52}$ GeV

4.3 fb^{-1}

$\tau_t = (3 \pm 1) \times 10^{-25}$ s

Spin Correlations

- **Top decays before hadronization - spin information passed to decay products**

- **SM predicts top pairs produced mostly in opposite-spin states at the Tevatron**

$$\kappa = \frac{\mathbf{N}_{\downarrow\uparrow} + \mathbf{N}_{\uparrow\downarrow} - \mathbf{N}_{\uparrow\uparrow} - \mathbf{N}_{\downarrow\downarrow}}{\mathbf{N}_{\downarrow\uparrow} + \mathbf{N}_{\uparrow\downarrow} + \mathbf{N}_{\uparrow\uparrow} + \mathbf{N}_{\downarrow\downarrow}} \approx \mathbf{0.78}$$

- **Several effects probed: spin, width, qq/gg production**

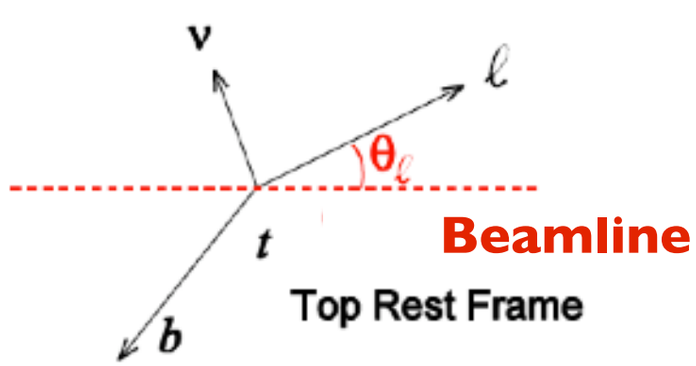
Spin Correlations

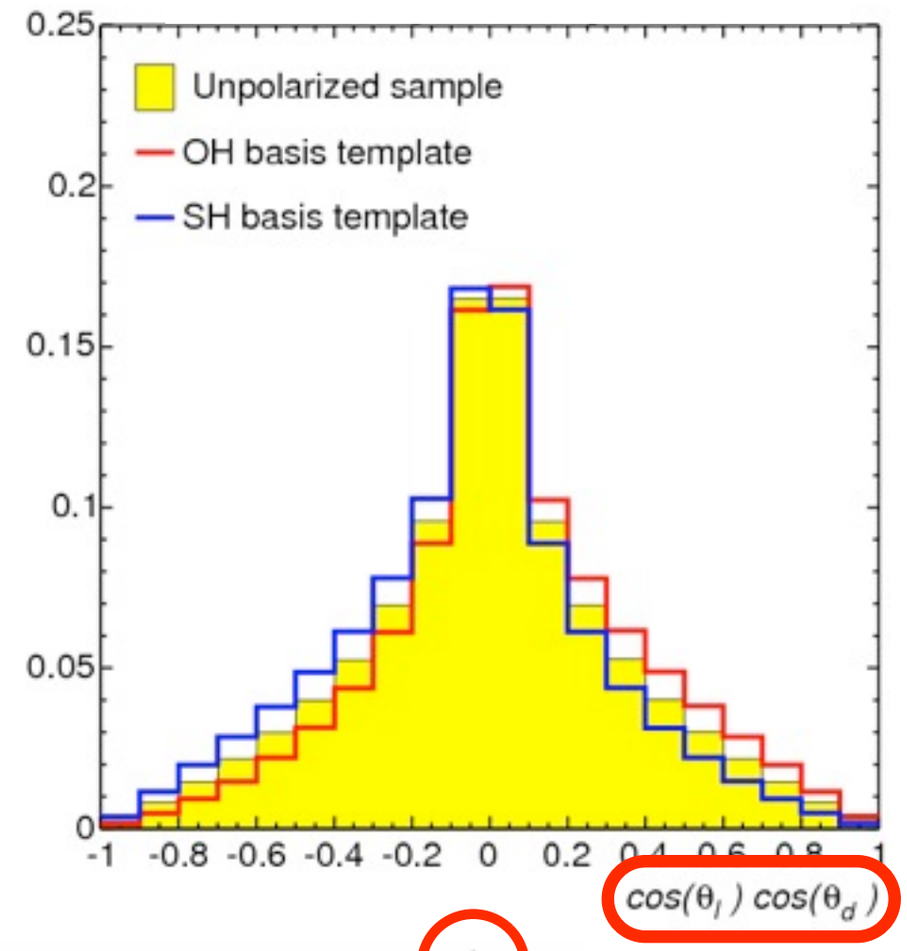
$$\kappa = \frac{N_{\downarrow\uparrow} + N_{\uparrow\downarrow} - N_{\uparrow\uparrow} - N_{\downarrow\downarrow}}{N_{\downarrow\uparrow} + N_{\uparrow\downarrow} + N_{\uparrow\uparrow} + N_{\downarrow\downarrow}}$$

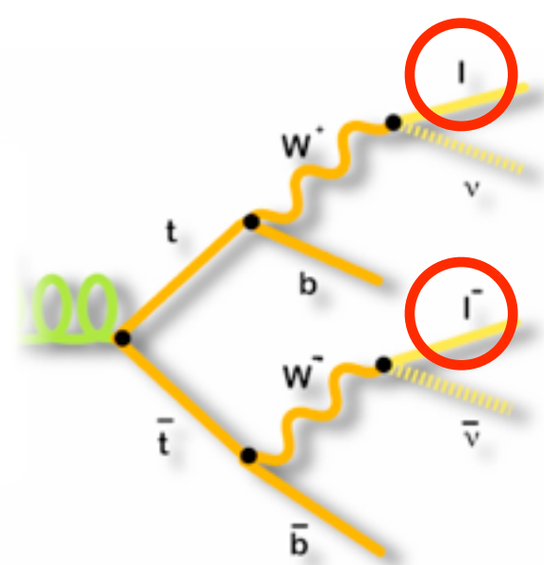
- **κ related to decay products angle through:**

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta^+ d\cos\theta^-} = \frac{1 + \kappa \cos\theta^+ \cos\theta^-}{4}$$

- **where**







Dileptons

Spin Correlations

$$\kappa = \frac{N_{\downarrow\uparrow} + N_{\uparrow\downarrow} - N_{\uparrow\uparrow} - N_{\downarrow\downarrow}}{N_{\downarrow\uparrow} + N_{\uparrow\downarrow} + N_{\uparrow\uparrow} + N_{\downarrow\downarrow}}$$

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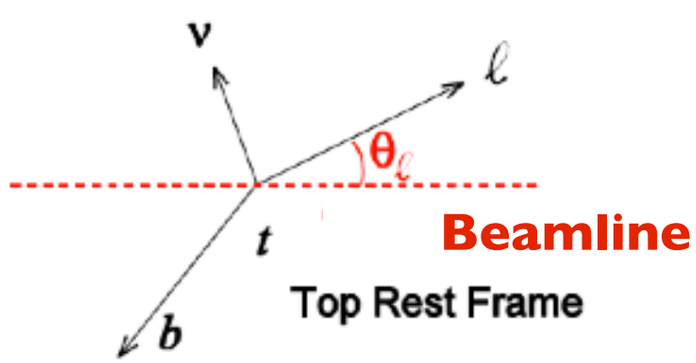
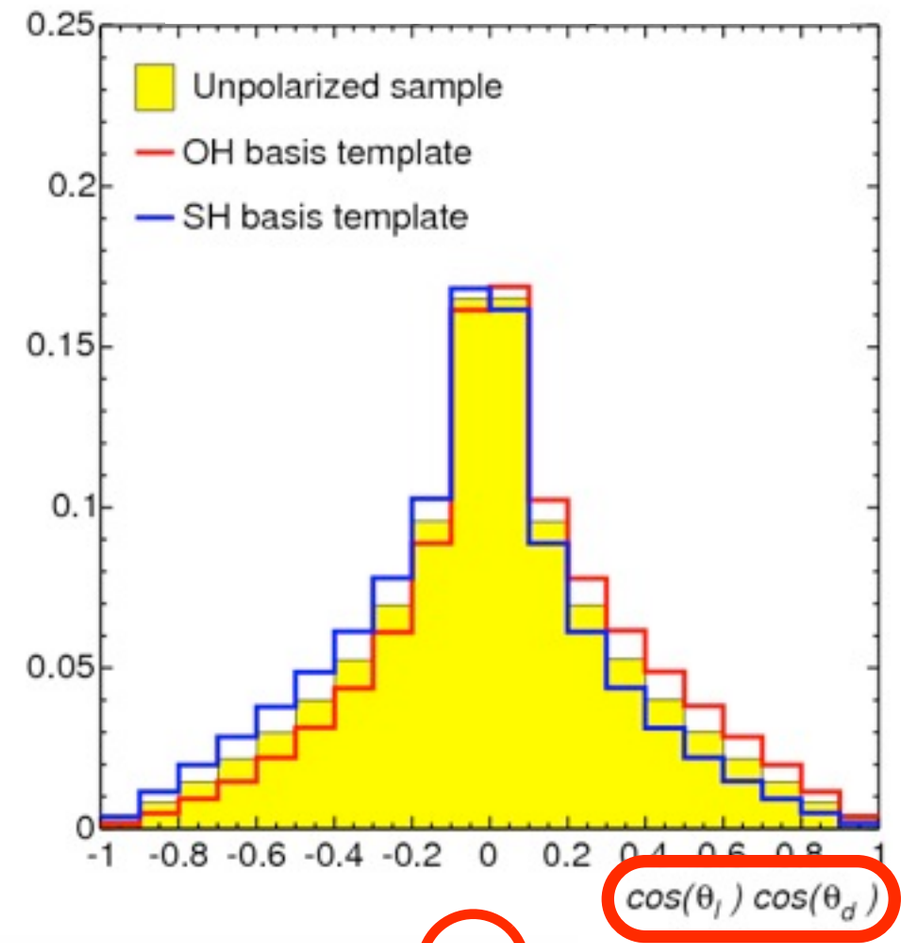
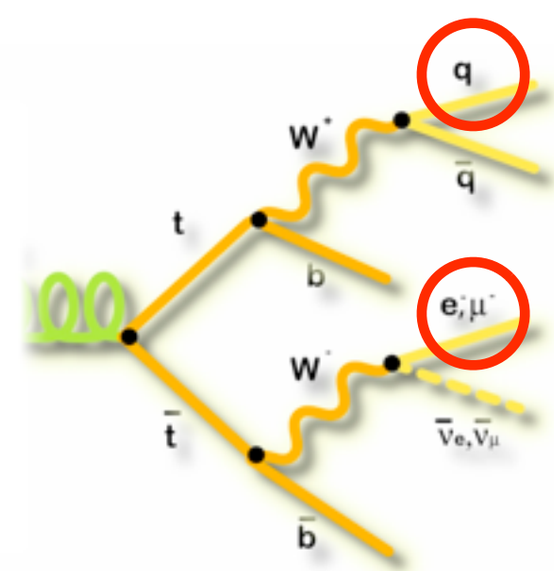


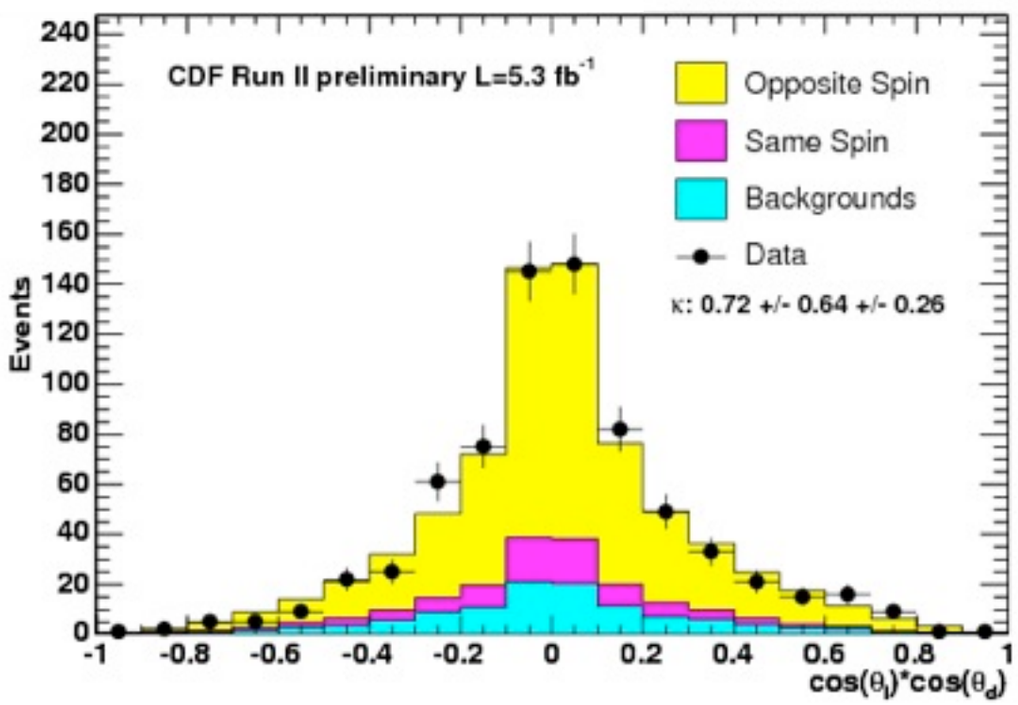




Lep+Jets

Spin Correlations

Lepton+Jets Channel

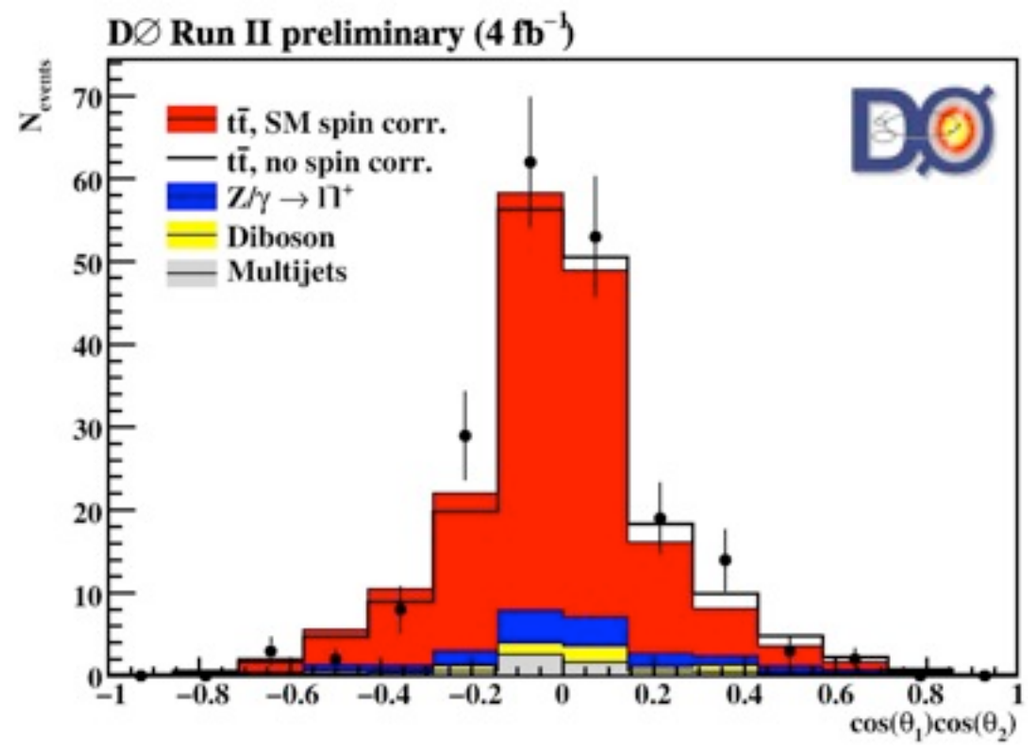


$\kappa = 0.7 \pm 0.6_{stat} \pm 0.3_{syst}$

5 fb^{-1}

$\kappa^{sm} = 0.78$

Di-lepton Channel



$\kappa = -0.2^{+0.6}_{-0.5}$

4 fb^{-1}

$\kappa = 0.3^{+0.6}_{-0.8}$

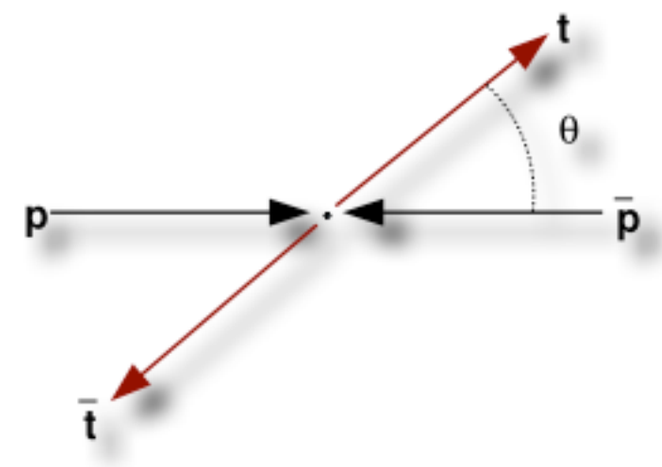
3 fb^{-1}

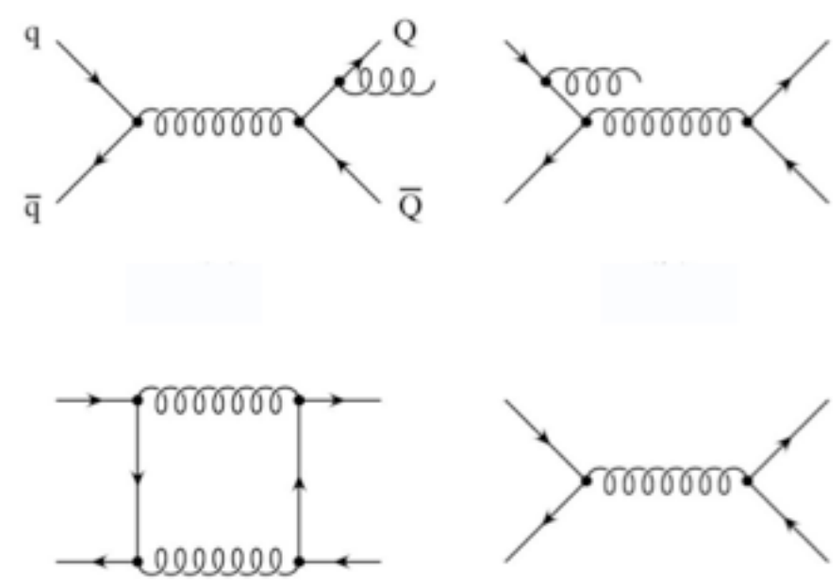
Forward Backward Asymmetry

- **Test of discrete symmetries of the strong interaction at high energy**
- **Tevatron is special: $p\bar{p}$ collider**
  - **NLO QCD predicts small asymmetry from $q\bar{q} \rightarrow t\bar{t}$**

$$A_{FB} = \frac{N_{\cos\Theta>0} - N_{\cos\Theta<0}}{N_{\cos\Theta>0} + N_{\cos\Theta<0}} \approx 6\%$$

  - **Ideally suited to discover new big gluons with axial vector coupling**





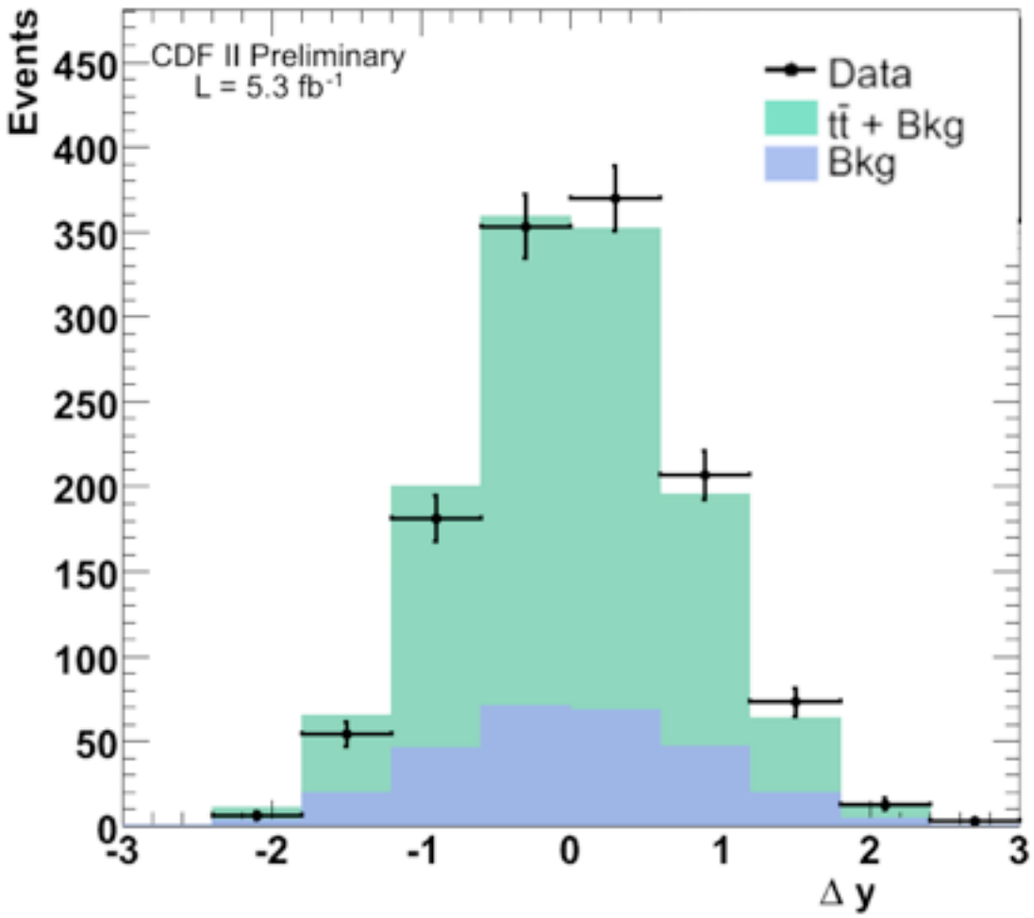
Top Quark A_{FB}

- **Reconstruct the rapidity of top and anti-top quarks**

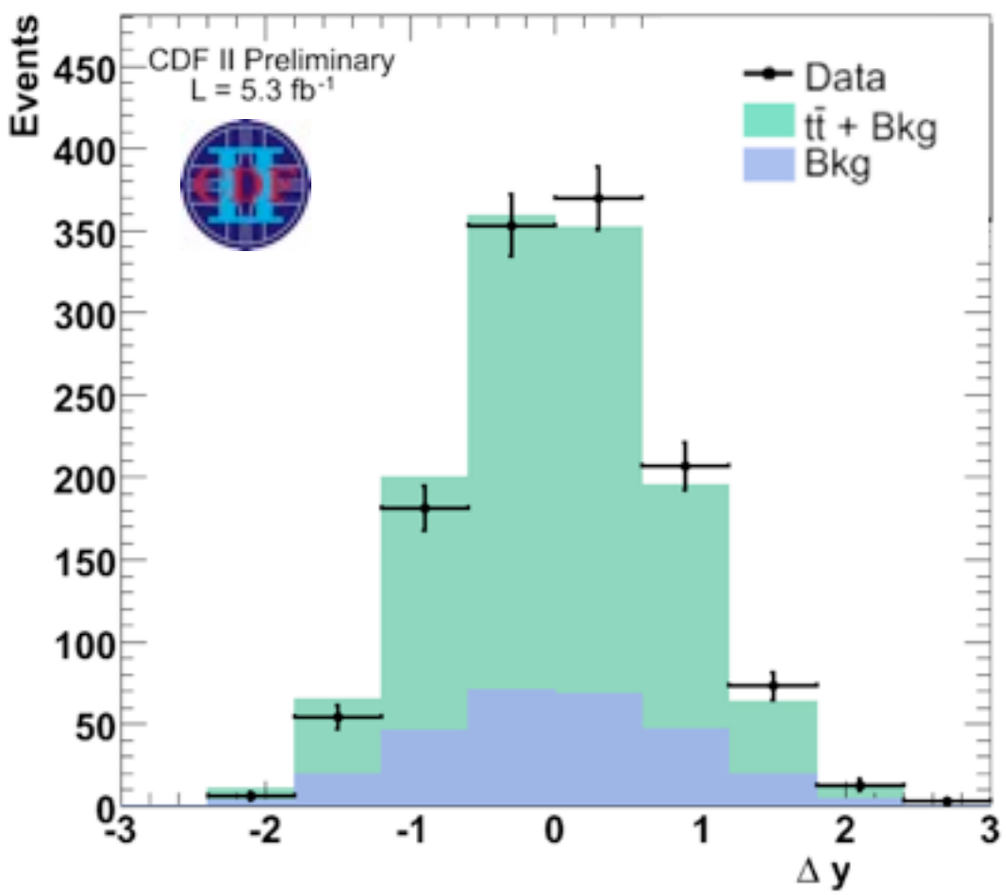
- **$\cos\Theta_{t\bar{t}} \propto Y_t - Y_{\bar{t}} = \Delta Y$**

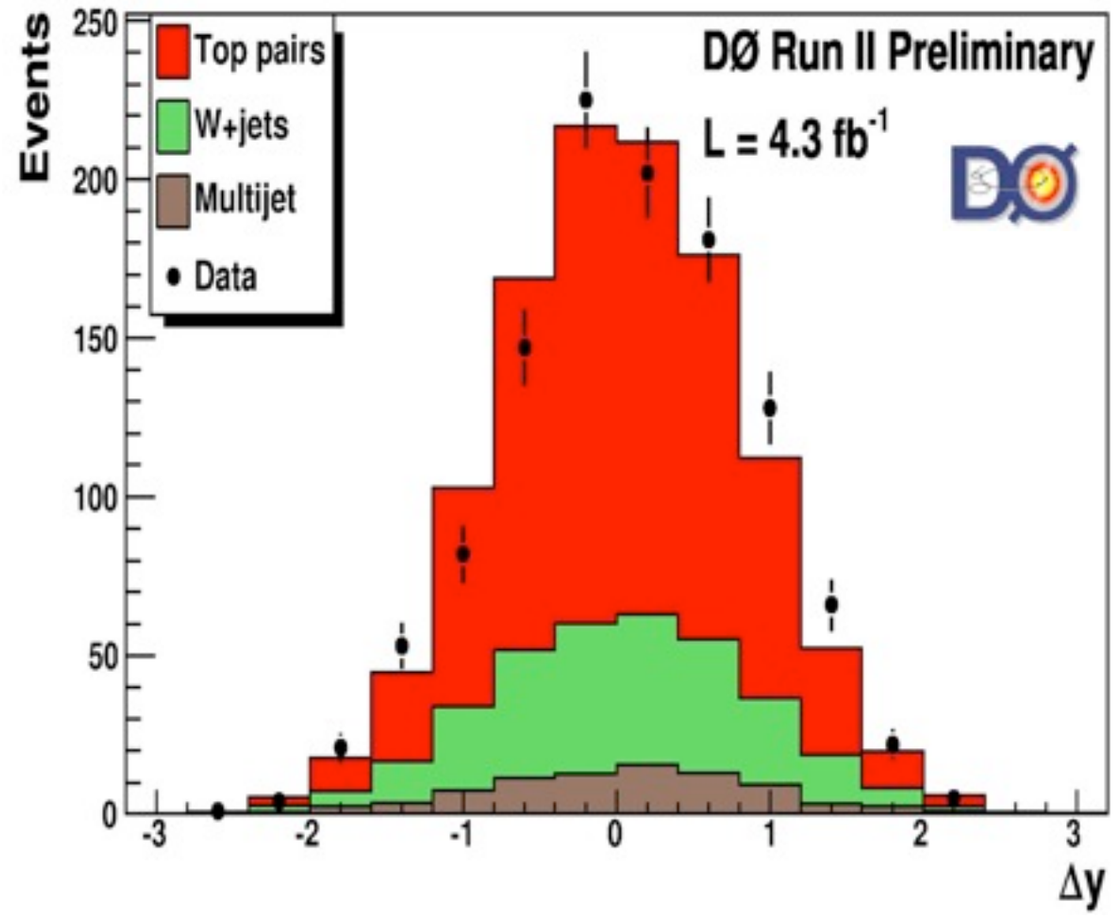
$$A_{FB} = \frac{N_{\Delta Y>0} - N_{\Delta Y<0}}{N_{\Delta Y>0} + N_{\Delta Y<0}}$$

- **A_{FB} is then corrected for backgrounds, acceptance, and mis-reconstruction**



Top Quark A_{FB}





$A_{FB} = 16 \pm 7_{stat+sys}$ %

5.3 fb^{-1}

$A_{FB}^{SM} = 6 \pm 2$ %

$A_{FB}^{data-bkg} = 8 \pm 4_{stat+sys}$ %

4.3 fb^{-1}

$A_{FB}^{mc@nlo} = 1^{+2.0}_{-1.0}$ %

Top Quark A_{FB}

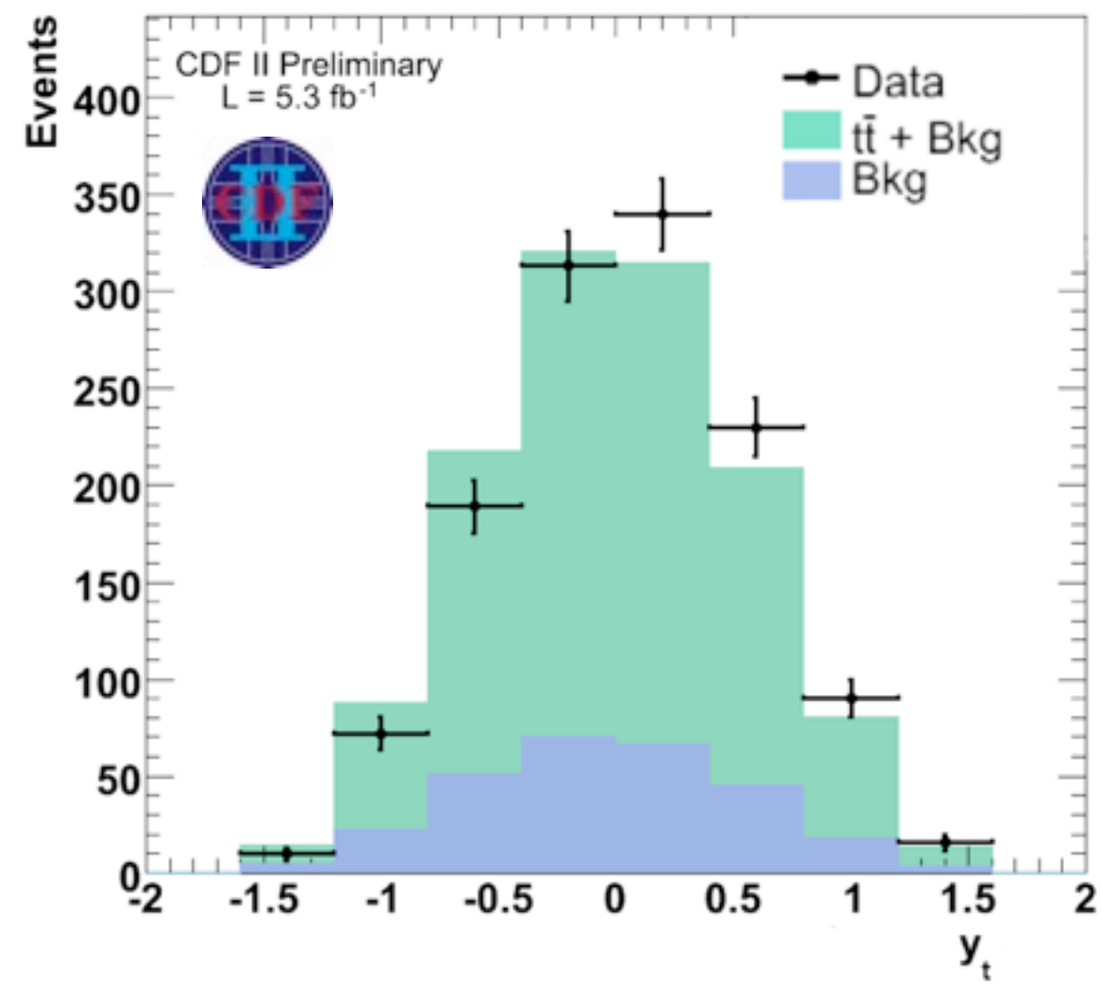
- **Alternatively, the asymmetry is measured in the $p\bar{p}$ frame using only top or anti-top**
  - **Better resolution on production angle**
  - **PDF dilutes expected asymmetry**

A_{FB} = 15 ± 5$_{stat+sys}$ %

3σ

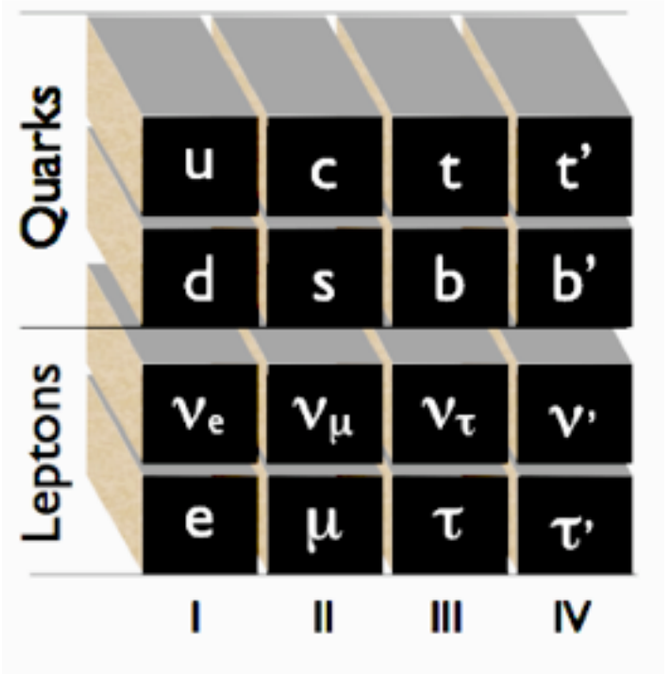
5.3 fb^{-1}

A_{FB}^{SM} = 5.0 ± 1.5 %



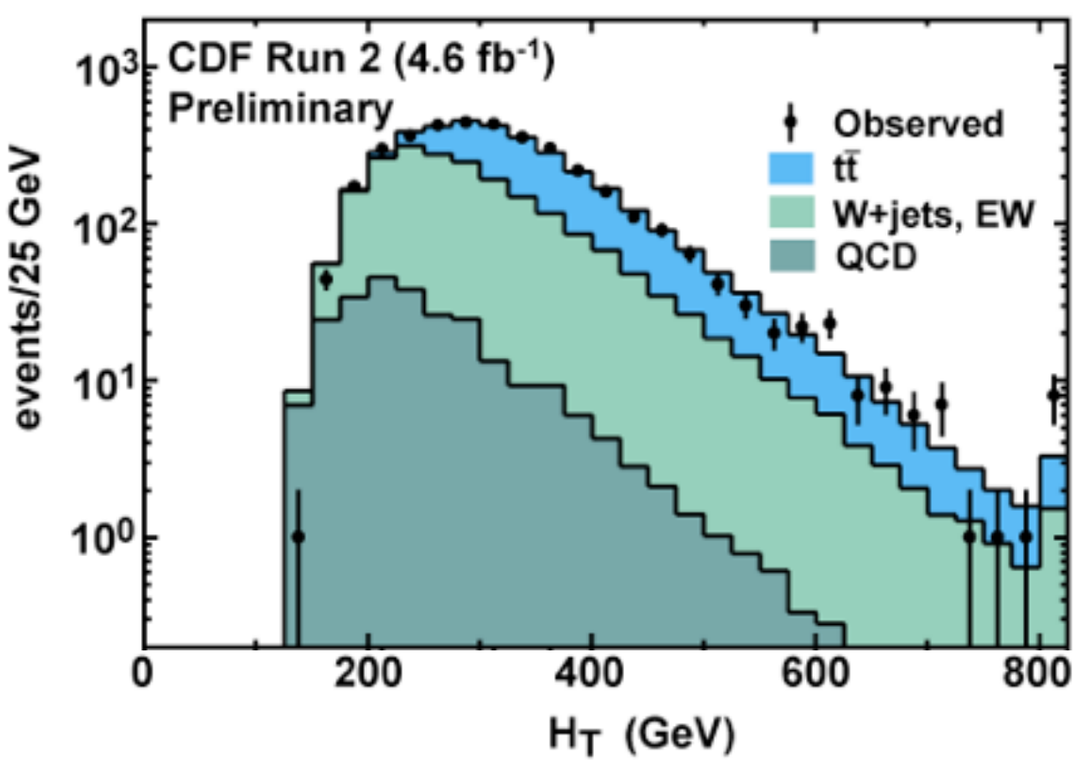
Searching for a 4th Generation

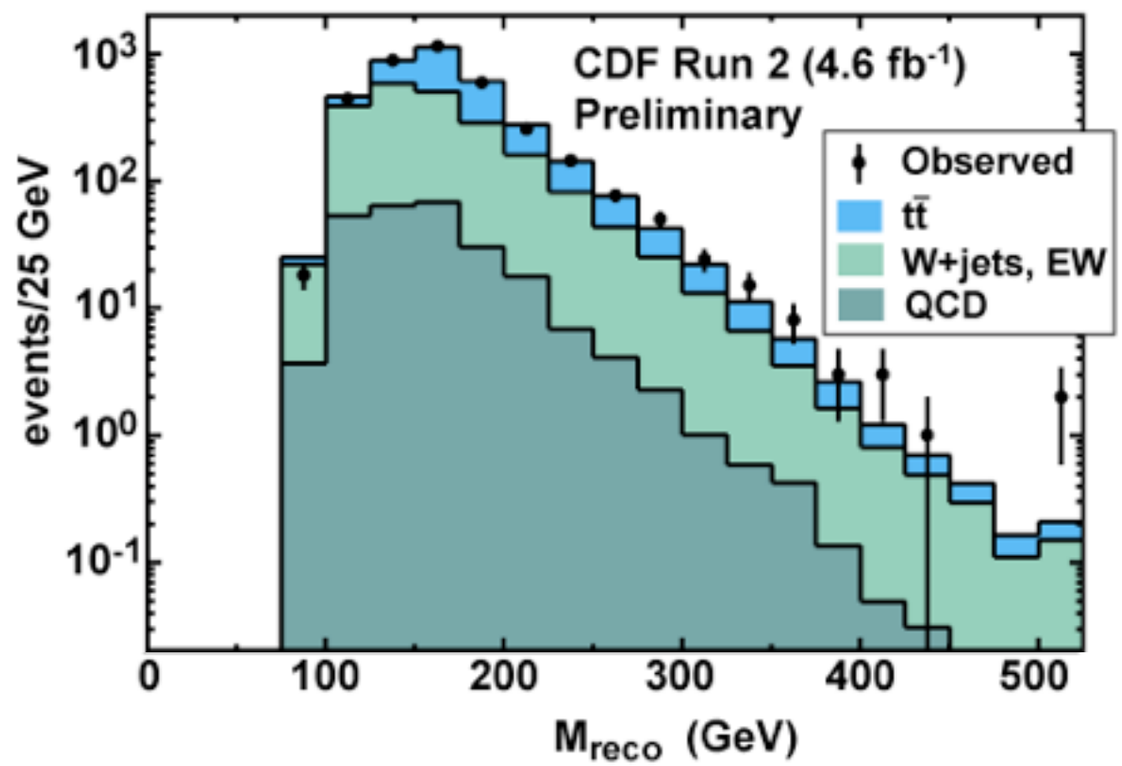
- **Why are there only 3 generations?**
- **No theoretical reason, only experiment**
  - ***Electroweak Constraints***
  - ***Flavor Physics Measurements***
  - ***Direct Searches***
- **Tevatron explores phase space beyond these limits**



Searching for t´

- **Experimentally we treat t´ as just a more massive top quark (t´ → Wq)**
- **Use reconstructed t´ mass and the scalar sum of the transverse energy in the event (H_T)**





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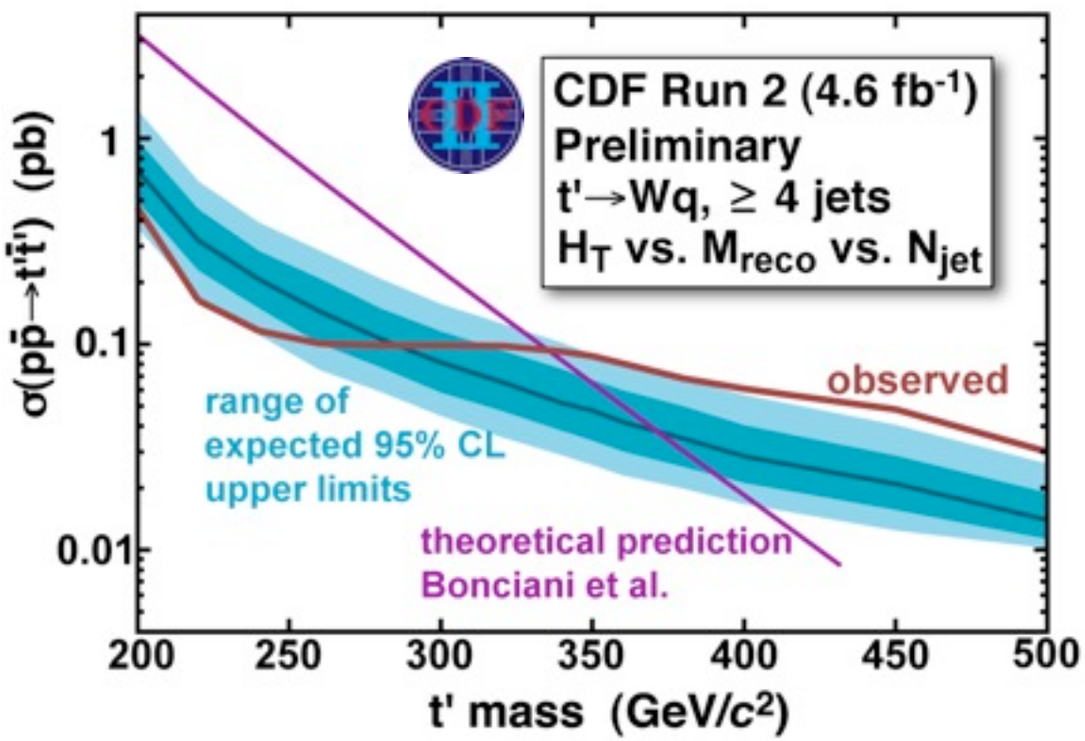
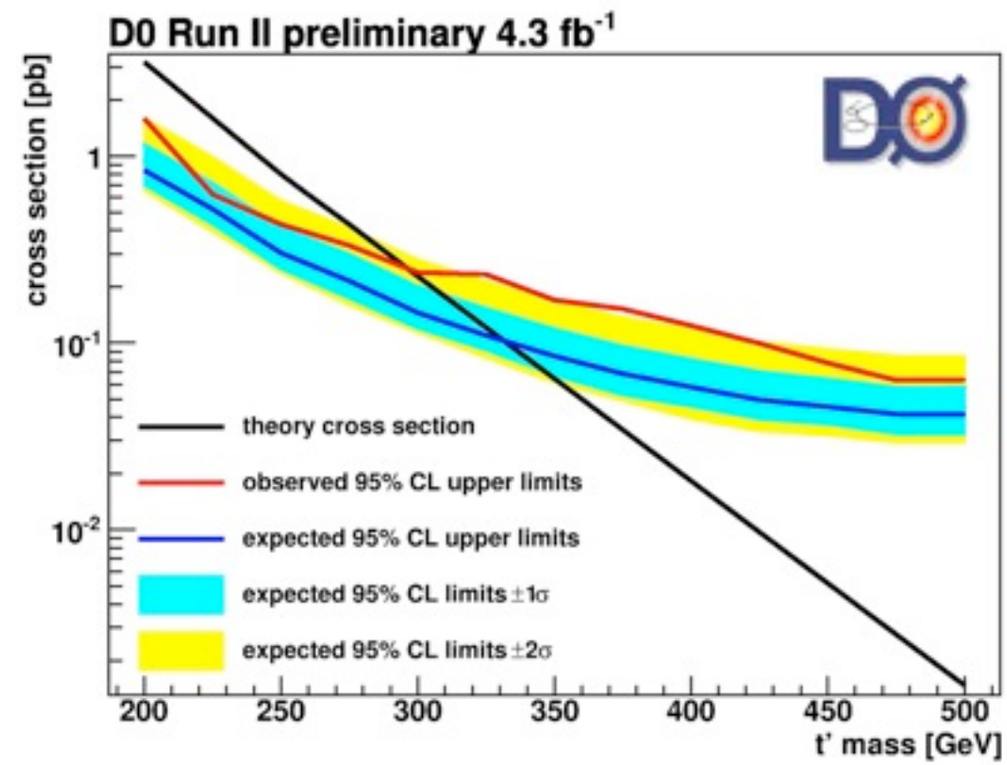




$M_{t'}$ < 335 GeV @ 95 % CL

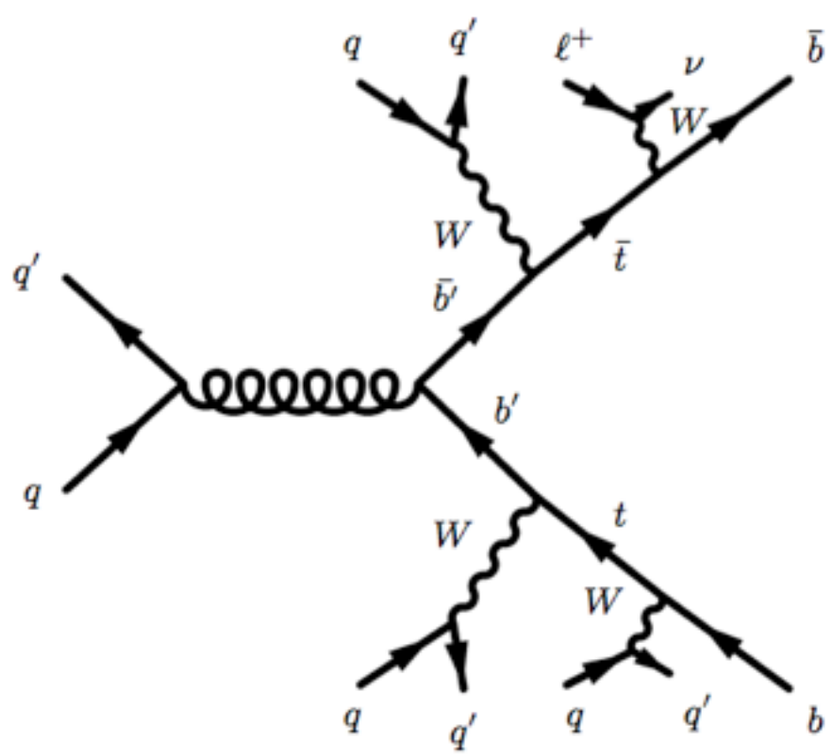
4.6 fb^{-1}

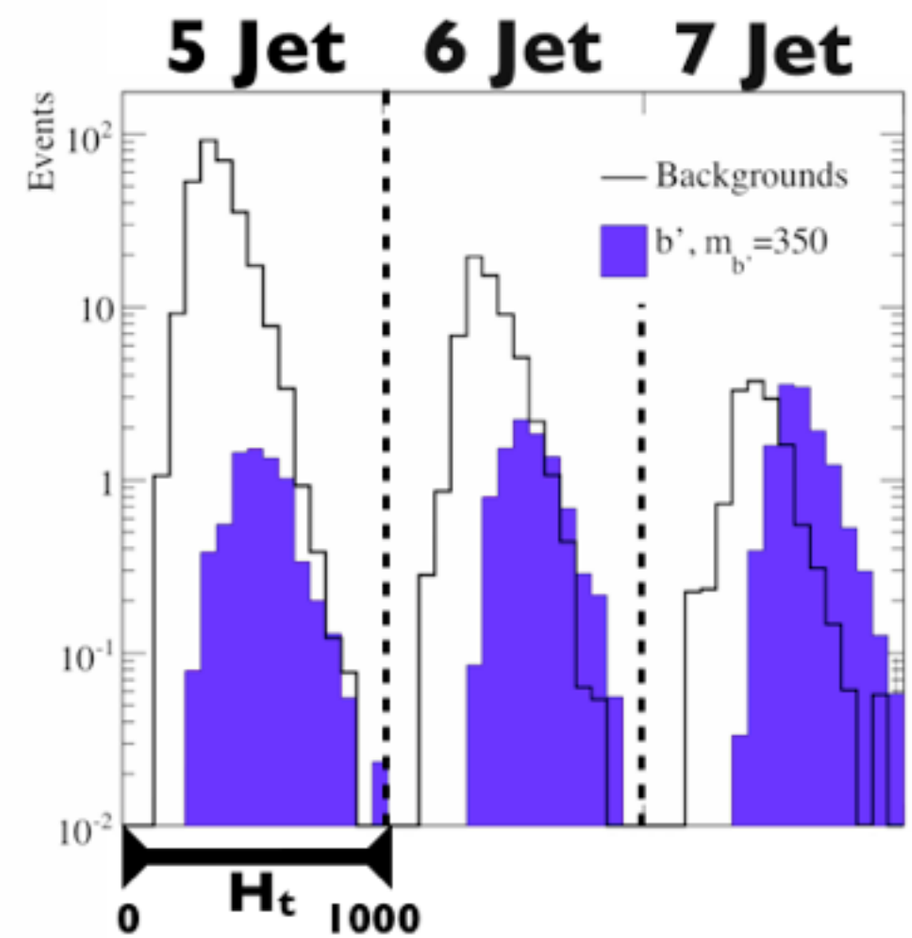
$M_{t'}$ < 296 GeV @ 95 % CL

4.3 fb^{-1}

Searching for b´

- Similarly, we can search for b´ → tW
- Signature is very energetic, jetty events: search in high H_T, high jet multiplicity
- Largest background is $t\bar{t}$+jets





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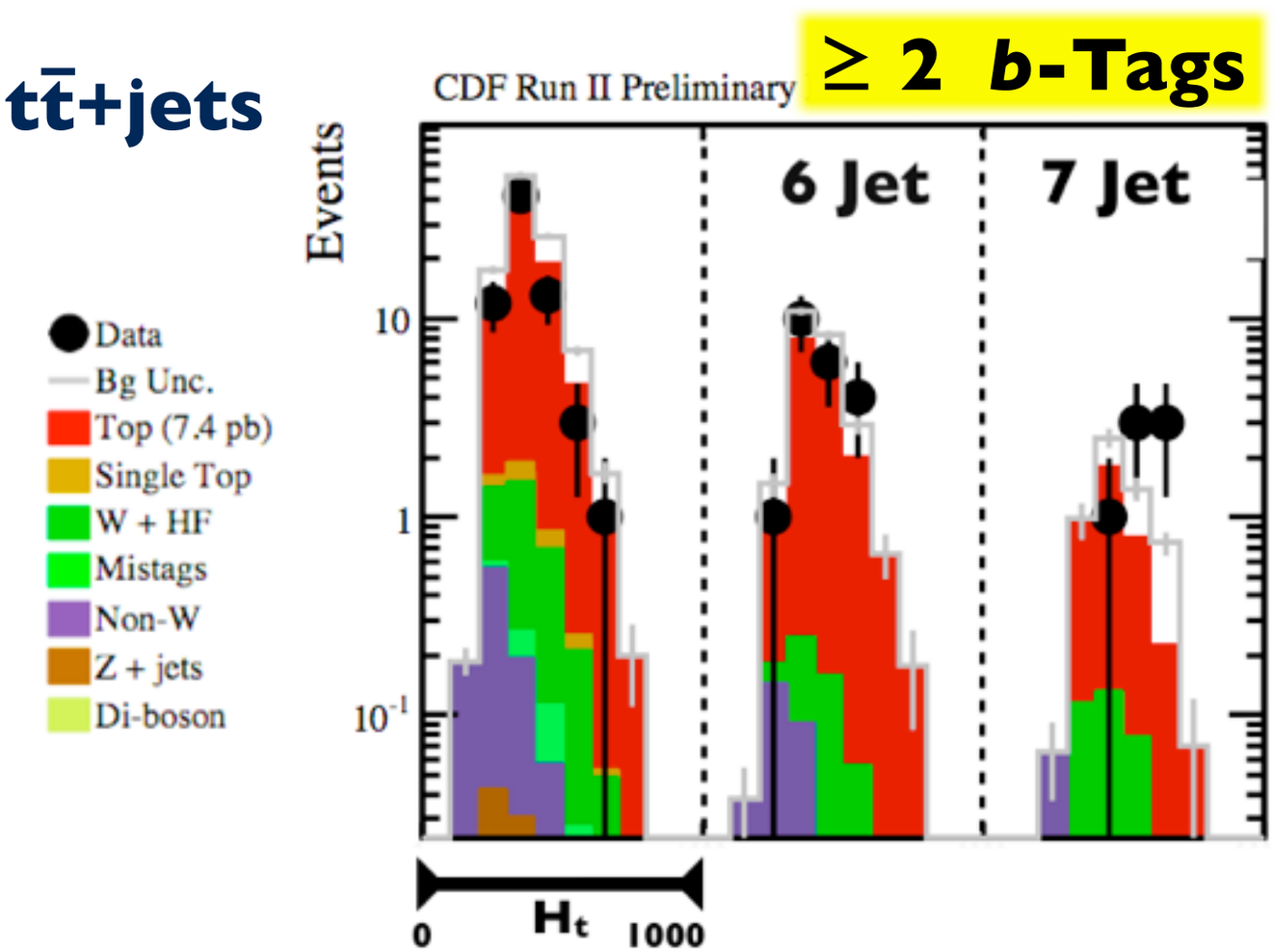

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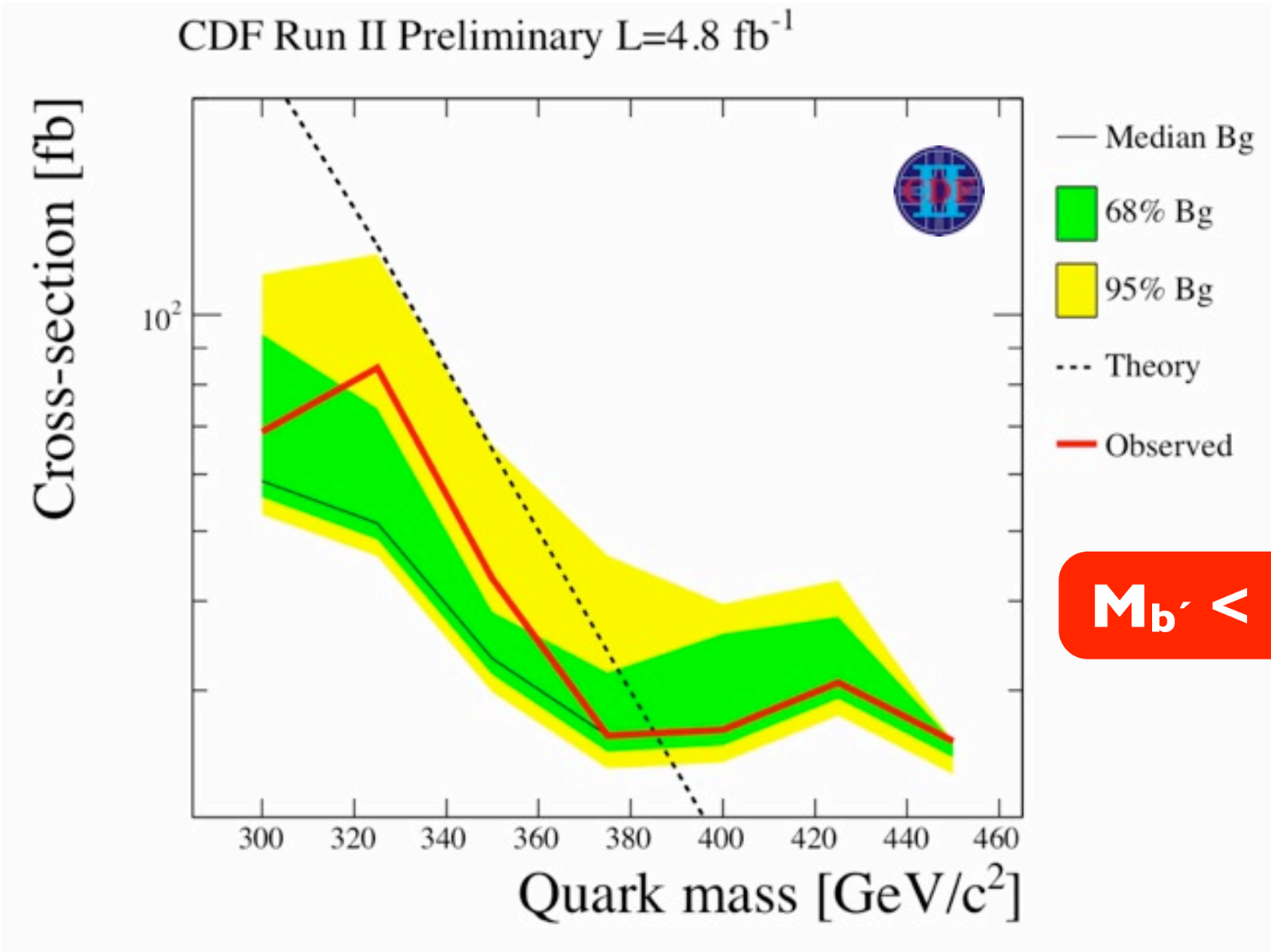
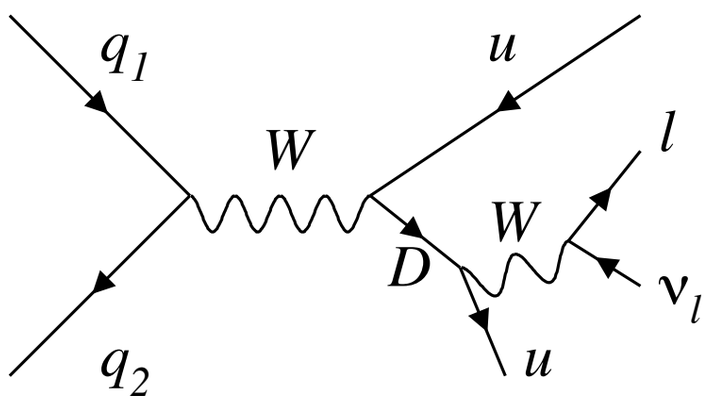


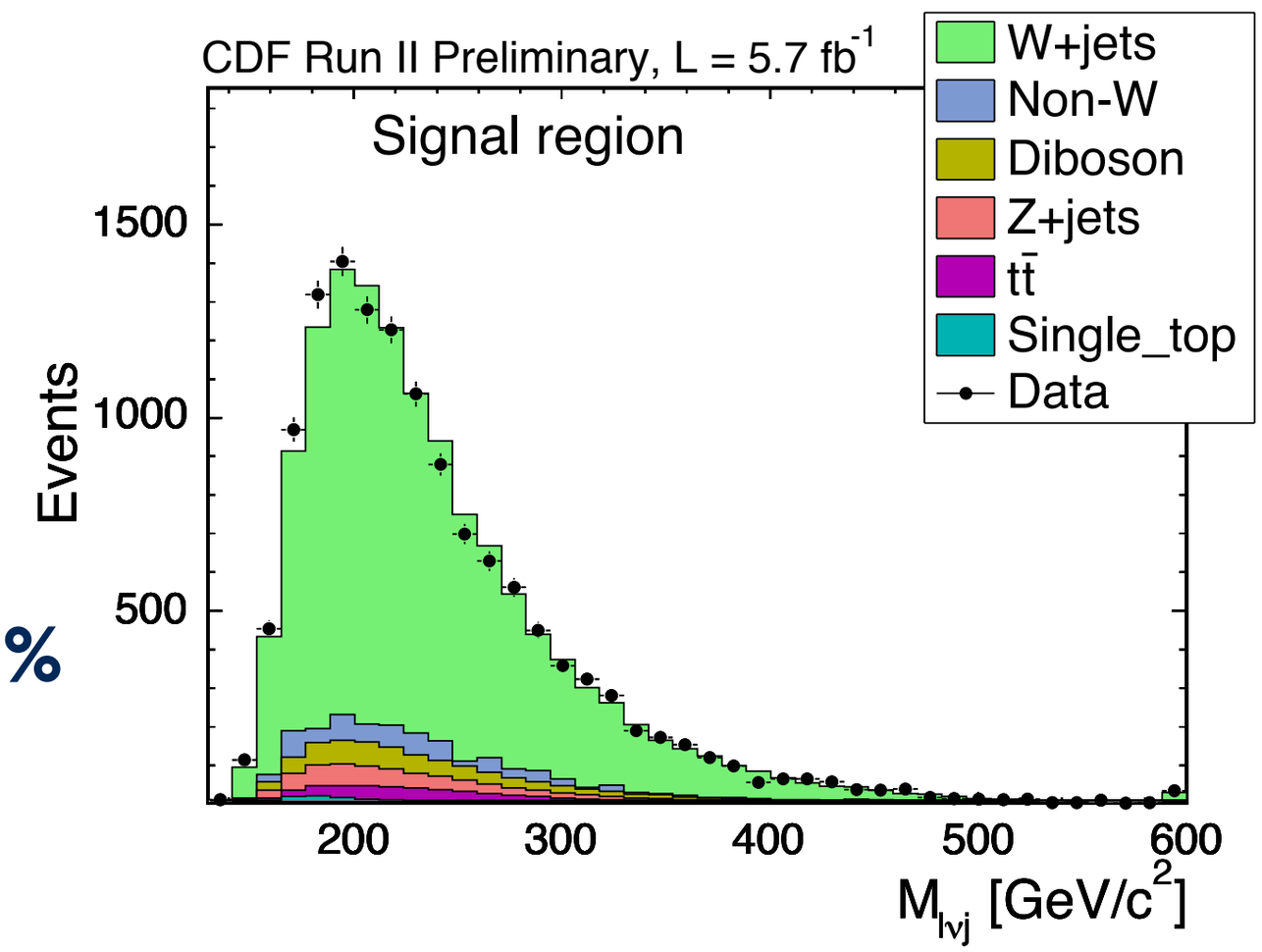
$M_{b´}$ < 385 GeV @ 95 % CL

~ 5 fb^{-1}

Search for Singly Produced Heavy Quarks

- **Searching for single production of new heavy quarks via charged-current interaction**





- **Assume BR(Q→Wq) 100%**
- **Search in $M_{l\upsilon j}$**

Search for Singly Produced Heavy Quarks

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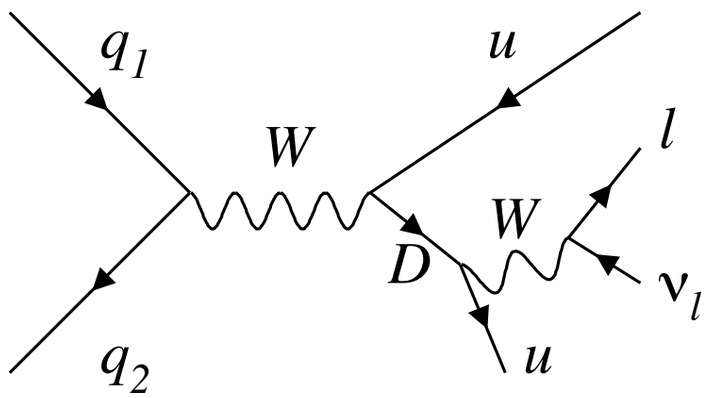

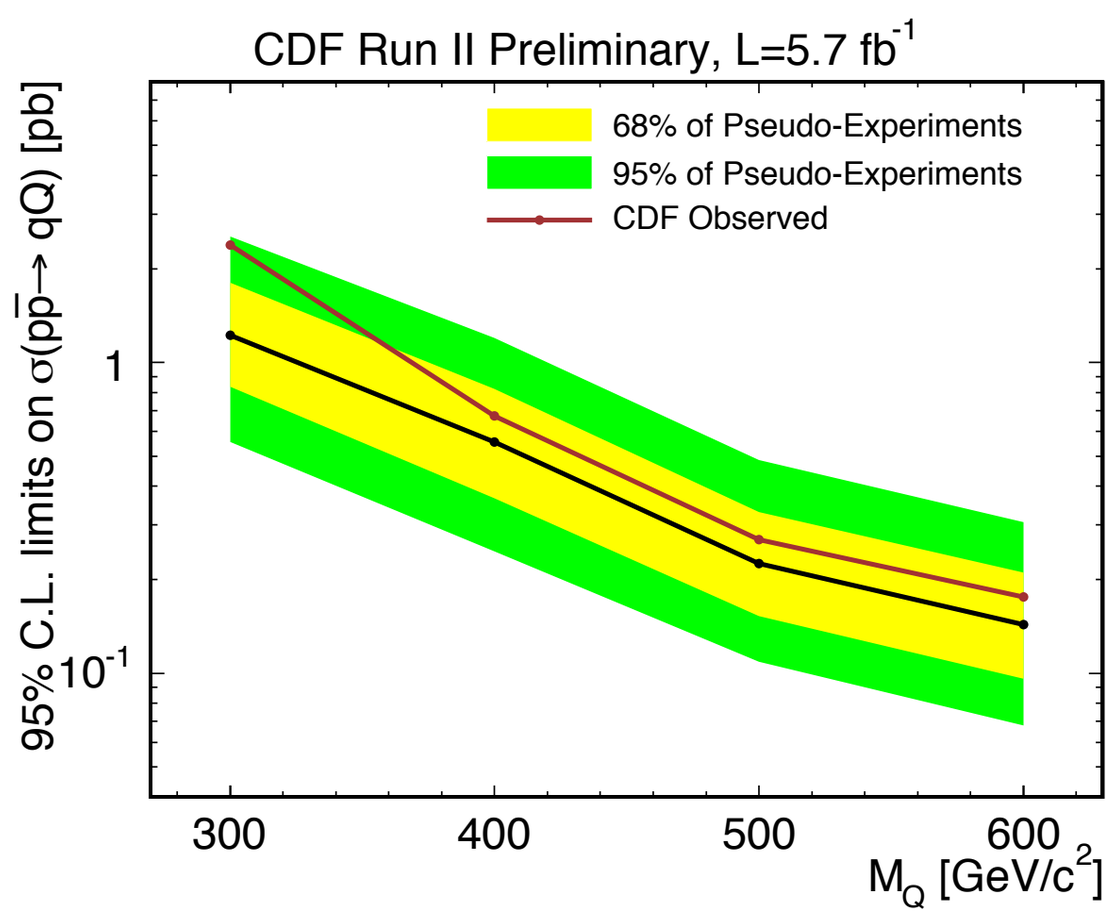

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Top Physics at the Tevatron

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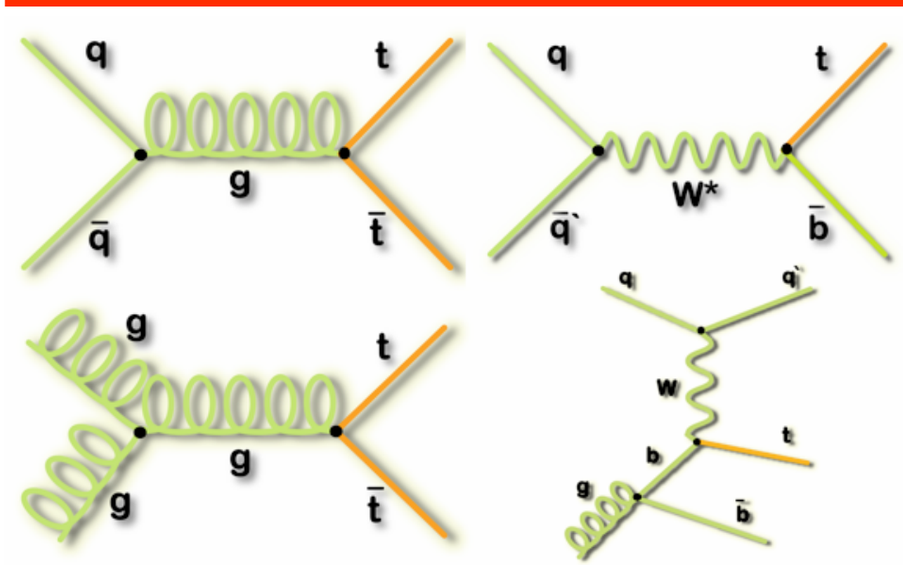

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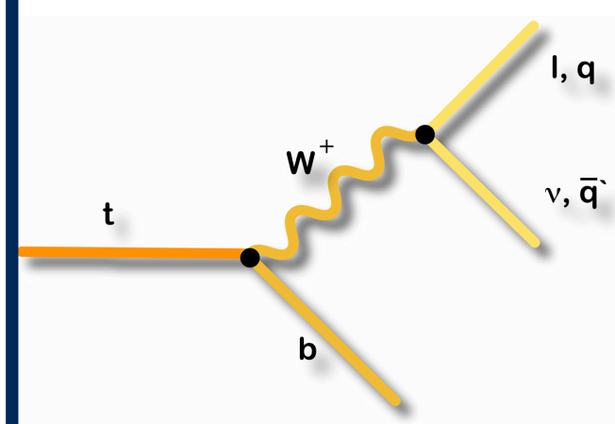
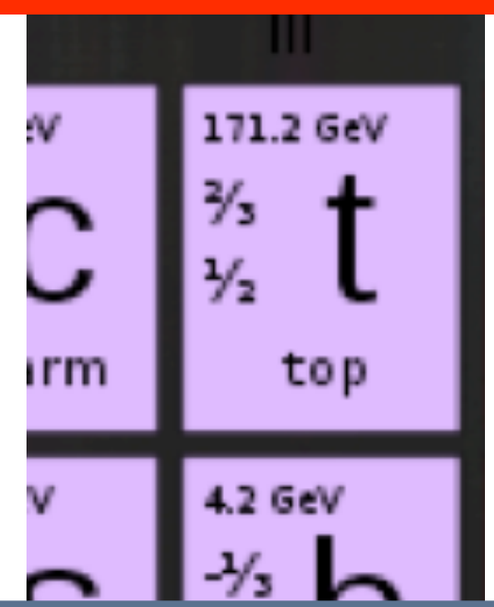


- V-A
- V_{TB}

What are Top's Intrinsic Properties



- Mass
- Width
- Spin
- Charge

Top Physics at the Tevatron

How is Top Produced	How Does Top Decay	What are Top's Intrinsic Properties
$\sigma_{tt} = 7.50$ $\delta \sim 6\ \%$	$F_0 = 0.88$ $\delta \sim 10\ \%$	$M_t = 173.3$ $\delta \sim 0.6\ \%$
$\sigma_{s+t} = 2.8$ $\delta \sim 19\ \%$	$F_+ = -0.15$ $\delta \sim 10\ \%$	$\Gamma_t = 2.1$ $\delta \sim 25\ \%$
$\sigma_t = 3.1$ $\delta \sim 30\ \%$	$V_{tb} = 0.88$ $\delta \sim 9\ \%$	$\kappa = 0.7$ sig ~ 1 σ
		$q \neq -4/3$ @ 95%CL
• Strong Force σ_{tt} • Electroweak σ_t, σ_s	• V-A • V_{TB}	• Mass • Width • Spin • Charge

Prospects for the Future

How is Top Produced

$\sigma_{tt} = 7.50$	$\delta \sim 6\ \%$
$\sigma_{s+t} = 2.8$	$\delta \sim 19\ \%$
$\sigma_{t} = 3.1$	$\delta \sim 30\ \%$

- Strong Force σ_{tt}
- Electroweak σ_t , σ_s

- **Systematically limited in only one channel (lepton+jets)**
- **Tevatron combination coming...**

Prospects for the Future

How is Top Produced	How Does Top Decay	What are Top's Intrinsic Properties
σ_{tt} = 7.50 δ ~ 6 %	F_0 = 0.88 δ ~ 10 %	M_t =173.3 δ ~ 0.6 %
σ_{s+t} = 2.8 δ ~ 19 %	F_+ = -0.15 δ ~ 10 %	Γ_t = 2.1 δ ~ 25 %
σ_t = 3.1 δ ~ 30 %	V_{tb} = 0.88 δ ~ 9 %	κ = 0.7 sig ~ 1 σ
		q ≠ -4/3 @ 95%CL

- All inter-related and statistically limited (~ 2-3 fb^{-1})
- Can be done side-by-side with WH→lυbb searches

Prospects for the Future

How is Top Produced	How Does Top Decay	What are Top's Intrinsic Properties
σ_{tt} = 7.50 δ ~ 6 %	F_0 = 0.88 δ ~ 10 %	M_t =173.3 δ ~ 0.6 %
σ_{s+t} = 2.8 δ ~ 19 %	F_+ = -0.15 δ ~ 10 %	Γ_t = 2.1 δ ~ 25 %
σ_t = 3.1 δ ~ 30 %	V_{tb} = 0.88 δ ~ 9 %	κ = 0.7 sig ~ 1 σ
		q ≠ -4/3 @ 95%CL

- Statistically limited (~ 3 fb^{-1})
- Tevatron combination coming...

Prospects for the Future

- **Better measurements in multiple channels as a cross check**
- **Spin-off measurements such as $\Delta M = M_{top} - M_{antitop}$**

What are Top's Intrinsic Properties

M_t =173.3	$\delta \sim 0.6$ %
Γ_t = 2.1	$\delta \sim 25$ %
κ = 0.7	sig ~ 1 σ
$q \neq -4/3$	@ 95%CL

- Mass
- Width
- Spin
- Charge

Prospects for the Future

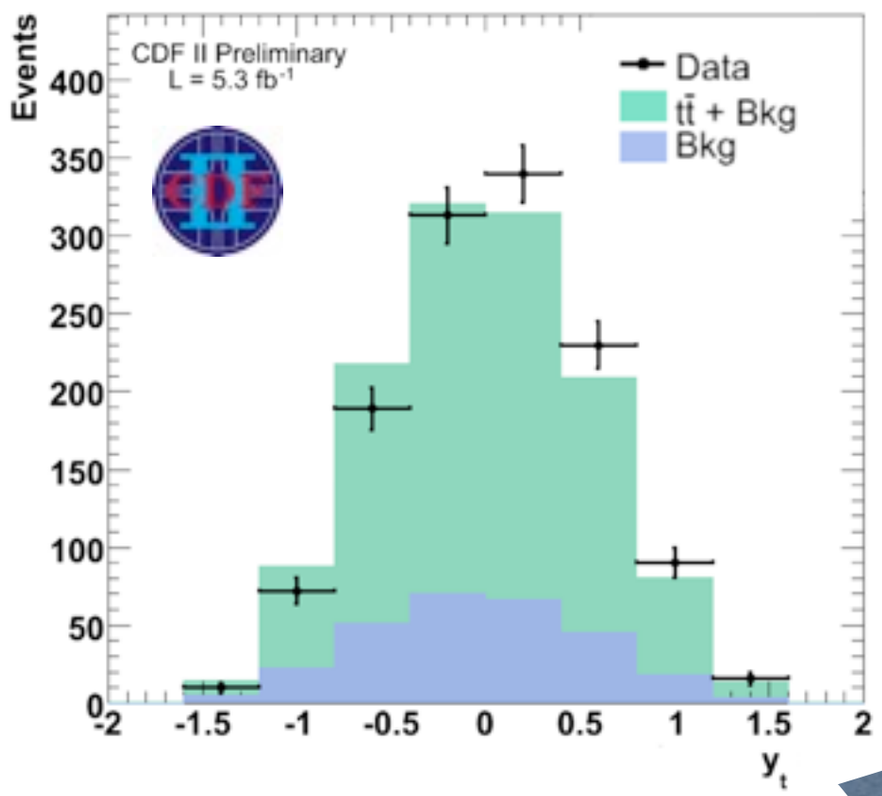
- **Statistically limited (~ 3-5 fb^{-1})**
- **Large effort underway: 4 measurements across both experiments**
- **Tevatron Combination**
- **Aiming for 3σ evidence in combination**

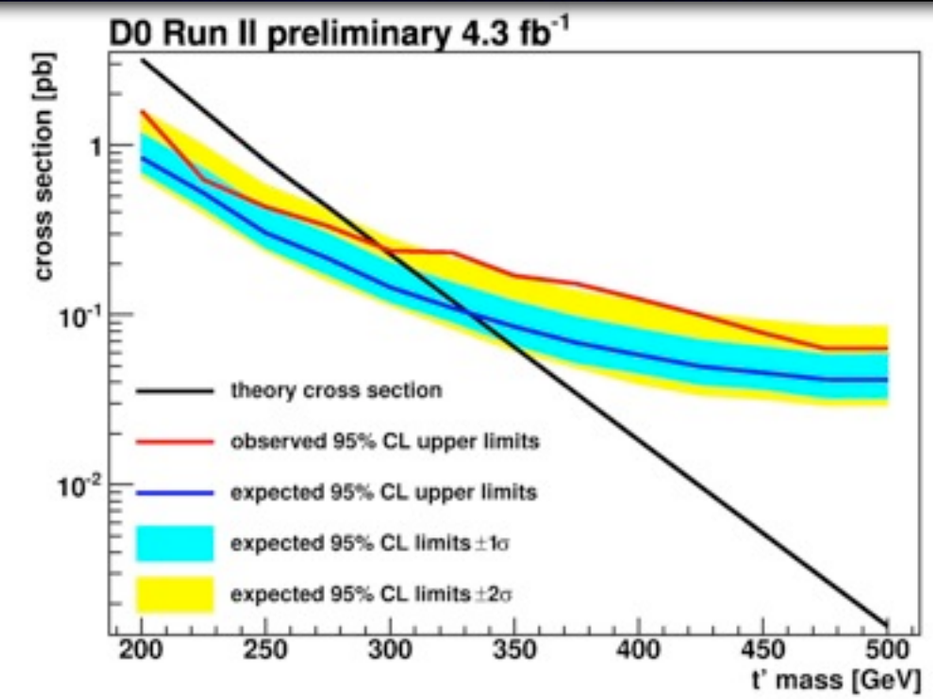
What are Top's Intrinsic Properties

M_t =173.3	δ ~ 0.6 %
Γ_t = 2.1	δ ~ 25 %
κ = 0.7	sig ~ 1 σ
q ≠ -4/3	@ 95%CL

- Mass
- Width
- Spin
- Charge

Maybe a Surprise?



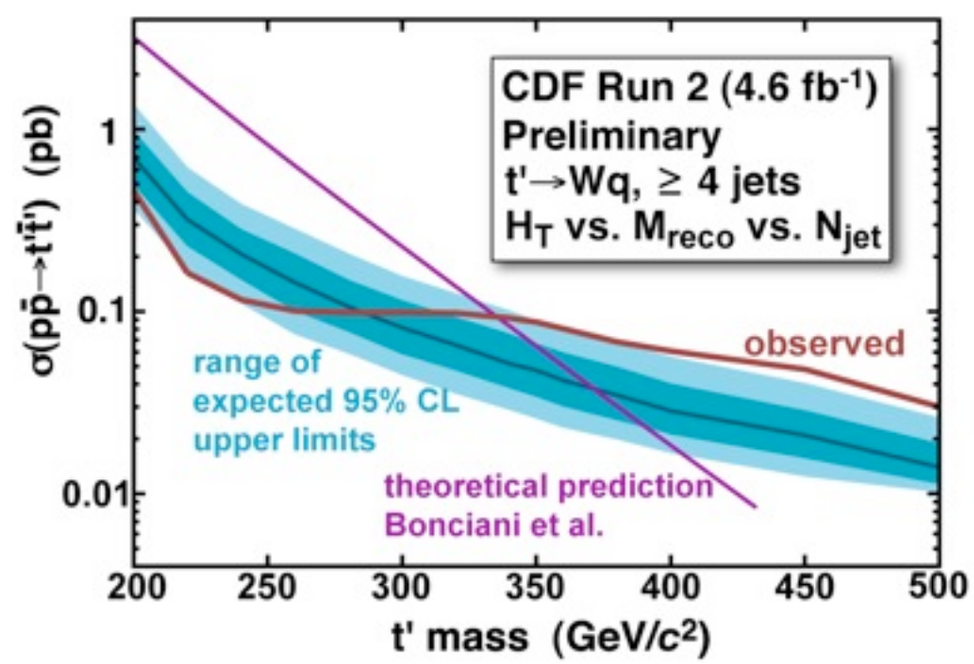


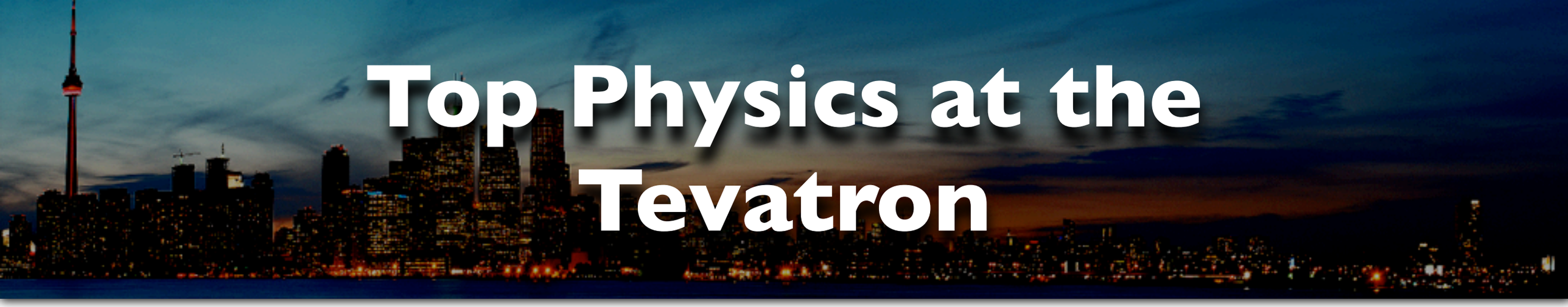
3σ

$A_{FB} = 15 \pm 5_{stat+sys}$ %

5.3 fb^{-1}

$A_{FB}^{SM} = 5.0 \pm 1.5$ %





Top Physics at the Tevatron

Never leave that till tomorrow which you can do today

- Benjamin Franklin