Top and EW phsycis at hadron collider(Tevatron/CDF)

Yuji Takeuchi
University of Tsukuba

基研研究会「素粒子高エネルギーフロンティアでの物理」@ 京都大学基礎物理学研究所

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Outline

- Overview of Electroweak Physics
- EW Physics Results from CDF Run II
- Overview of Top Physics
- Top Physics Results and Prospects in CDF
- Summary

Electroweak Physics Overview

Results of EW Physics from CDF Run II

- Cross section measurements
  $W \to \ell\nu \quad (\ell = e, \mu, \tau)$
  $Z^0 \to \ell^+\ell^- \quad (\ell = e, \mu)$
- Forward-Backward asymmetry: $A_{\rm FB}$
- W pair production
  $W^+W^- \to \ell\nu\ell\nu$
- Standard Model consistency checks
  $\sigma(W \to \tau\nu)/\sigma(W \to e\nu)$
  $\Rightarrow$ extract g_τ/g_e
  $R = \sigma(W \to \ell\nu)/\sigma(Z^0 \to \ell^+\ell^-) \quad (\ell = e, \mu)$
  $\Rightarrow$ extract $\Gamma(W)$

Expected Yeilds for $2\,\mathrm{fb}^{-1}$

Sample	Run I	Run IIa
$W \to \ell\nu$	77k	2300k
$Z^0 \to \ell^+\ell^-$	10k	202k
WV $(W \to \ell\nu,\ V = W, \gamma, Z)$	90	1800
ZV $(Z \to \ell\ell,\ V = W, \gamma, Z)$	30	500

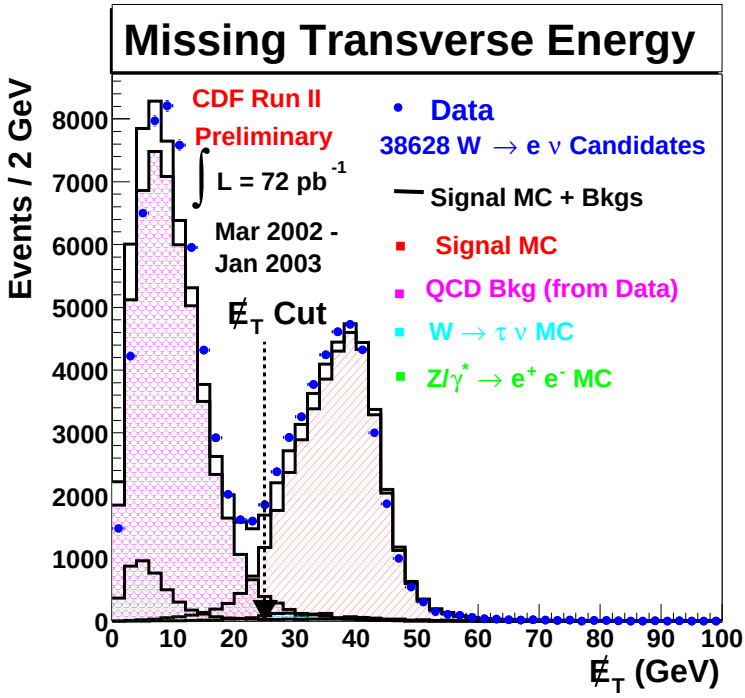
$\sigma_W \cdot \mathrm{Br}(W \to e\nu_e)$ (Run II)

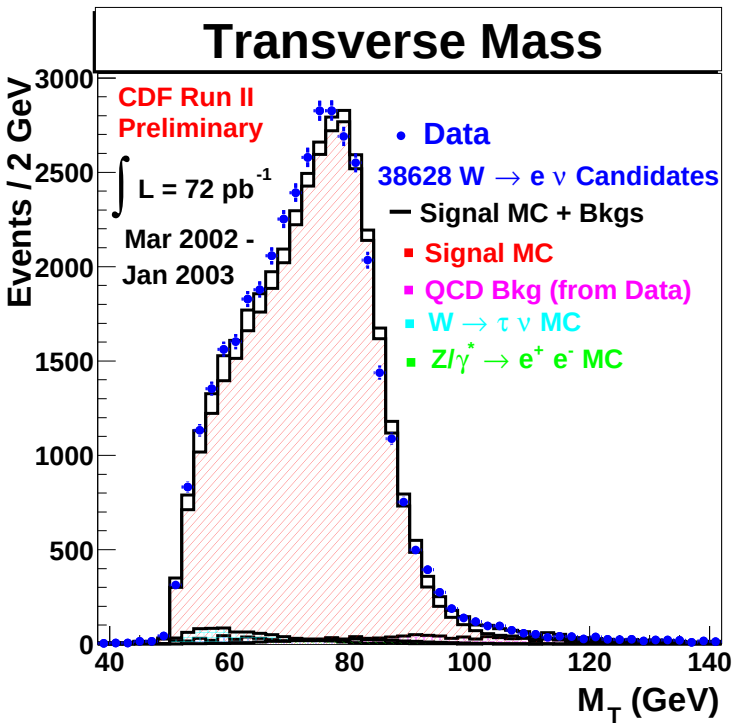
Event selection

1 electron

- Isolated
- High p_T
- Central

$\not\!\!E_T > 25\,\mathrm{GeV}$





Candidates

- 38628

Luminosity

- $\sim 72\,\mathrm{pb}^{-1}$

Backgrounds

- $\sim 6.4\%$

QCD	3.4%
$W \to \tau\nu$	2.0%
$Z \to ee$	0.9%

$$\sigma \cdot \mathrm{Br}(W \to e\nu) = 2.64 \pm 0.01_{\mathrm{stat}} \pm 0.09_{\mathrm{syst}} \pm 0.16_{\mathrm{lum}}\,\mathrm{nb}$$

Preliminary

$$\Updownarrow$$

$2.69 \pm 0.10\,\mathrm{nb}$ (NNLO at $\sqrt{s} = 1.96\,\mathrm{TeV}$)

$\sigma_W \cdot \mathrm{Br}(W \to \mu\nu_\mu)$ (Run II)

Event selection

- 1 isolated high p_T central μ
- $\not\!\!E_T > 20\,\mathrm{GeV}$
- Z^0-veto
- Cosmic veto

Candidates

- 21599

Luminosity

- $\sim 72\,\mathrm{pb}^{-1}$

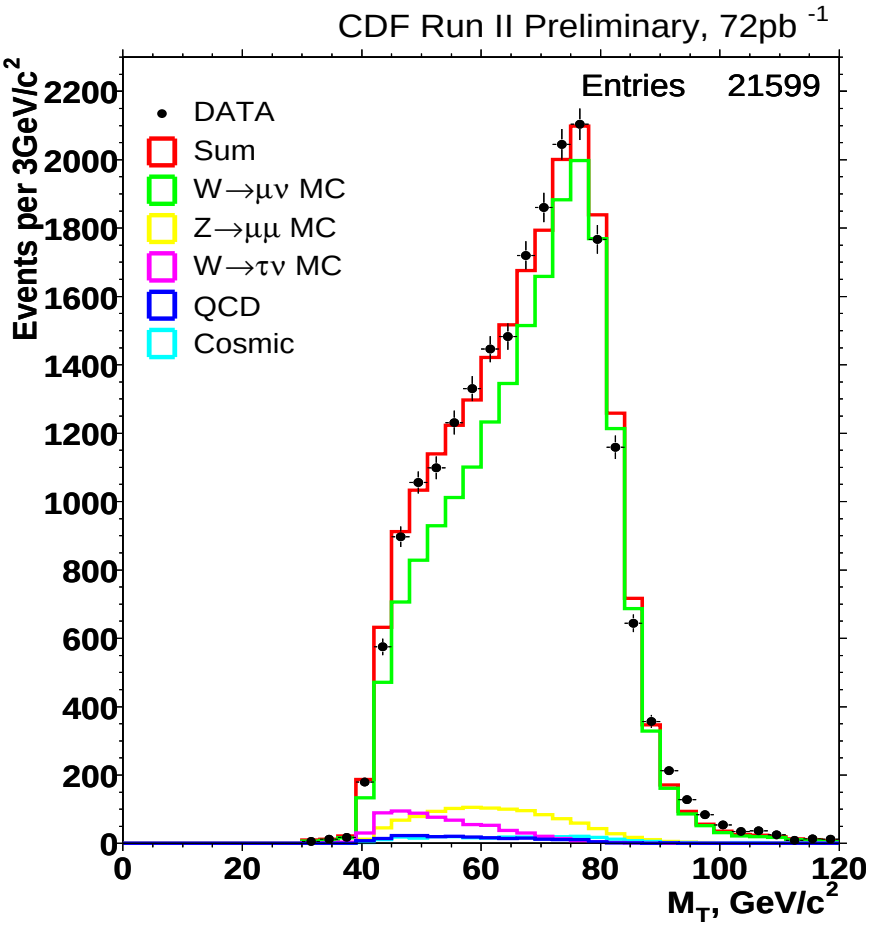
B.G.($\sim 11\%$)

$Z \to \mu\mu$ 5.3%

$W \to \tau\nu$ 3.2%

cosimic 1.3%

QCD 1.0%



$$\sigma \cdot \mathrm{Br}(W \to \mu\nu) = 2.64 \pm 0.02_{\mathrm{stat}} \pm 0.12_{\mathrm{syst}} \pm 0.16_{\mathrm{lum}}\,\mathrm{nb}$$

Preliminary

$\sigma \cdot \mathrm{Br}(W \to \tau\nu_\tau)$ (Run II)

Event selection

- 1 isolated (cal+track) high E_T central τ
- $\not\!\!E_T > 25\,\mathrm{GeV}$
- e removal

Candidates

- 2345

Luminosity

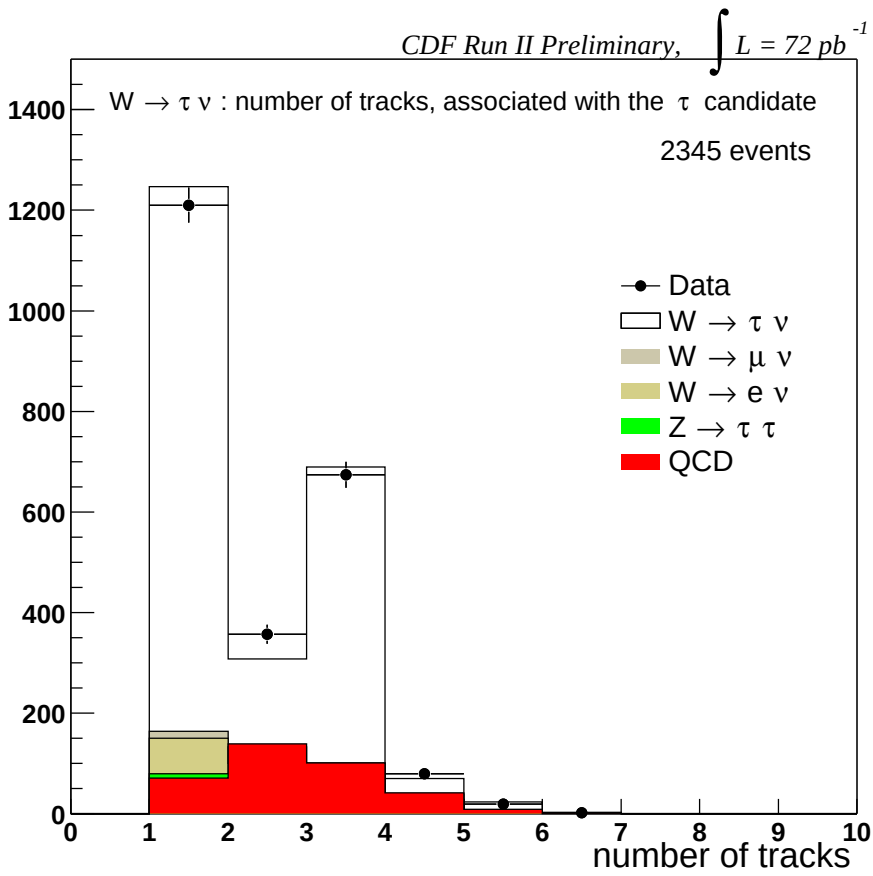
- $\sim 72\,\mathrm{pb}^{-1}$

B.G.($\sim 26\%$)

QCD 15%

$W \to e\nu$ 4%

$W \to \mu\nu$ 4%

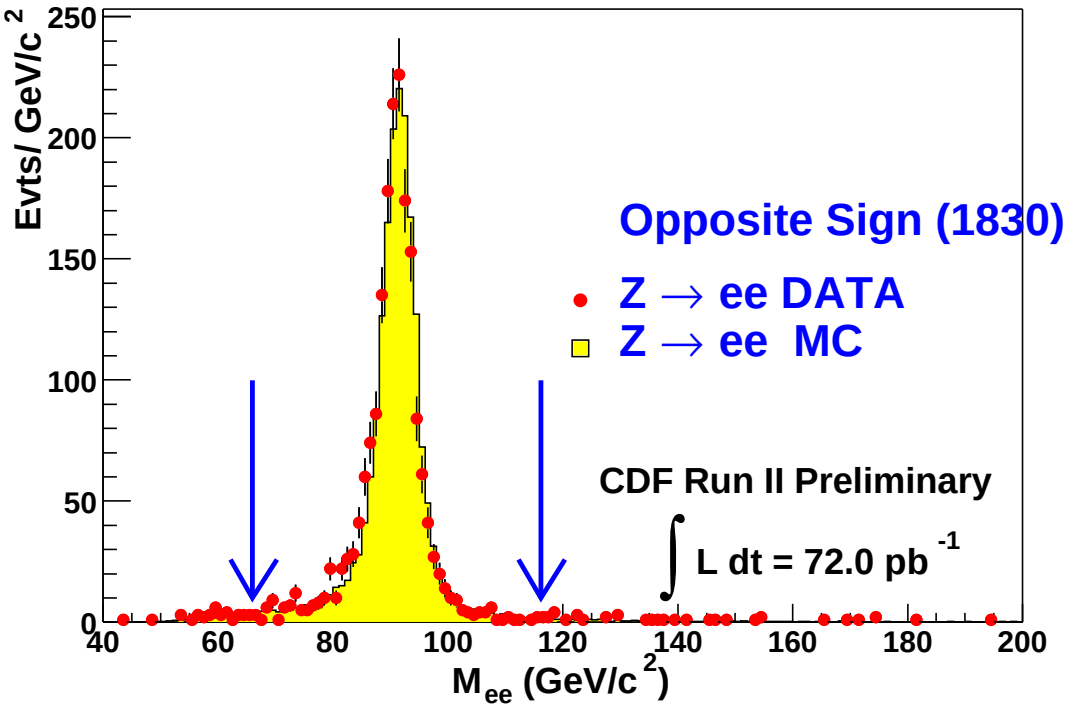


$$\sigma \cdot \mathrm{Br}(W \to \tau\nu) = 2.62 \pm 0.07_{\mathrm{stat}} \pm 0.21_{\mathrm{syst}} \pm 0.16_{\mathrm{lum}}\ \mathrm{nb}$$

Preliminary

$\sigma_Z \cdot \mathrm{Br}(Z^0 \to e^+e^-)$ (Run II)

- Event selection
  - 2 isolated high p_T central e's
- 1830 candidates in $\sim 72\,\mathrm{pb}^{-1}$
- Backgrounds $\sim 0.5\%$ $(8.7 \pm 4.7_{\mathrm{stat}} \pm 2.4_{\mathrm{syst}})$



$$\sigma_Z \cdot \mathrm{Br}(Z^0 \to e^+e^-) = 267 \pm 6_{\mathrm{stat}} \pm 15_{\mathrm{syst}} \pm 16_{\mathrm{lum}}\,\mathrm{pb}$$

Preliminary

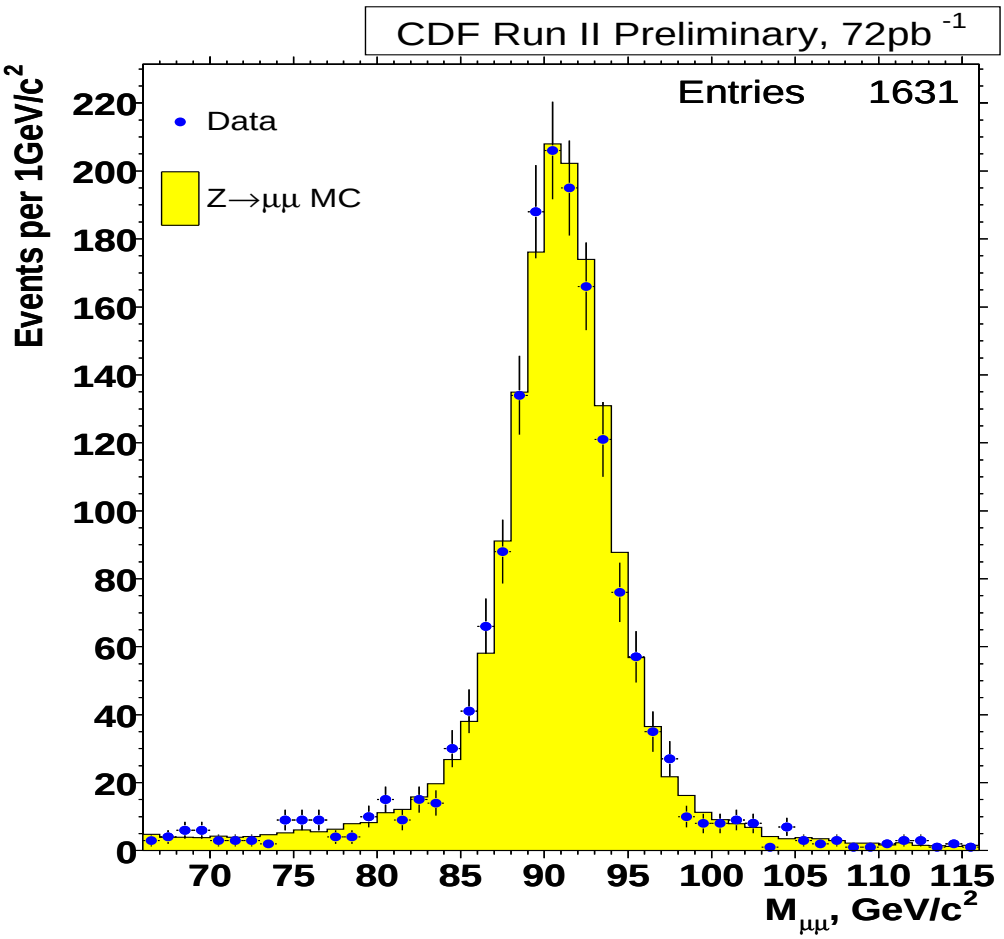
$$\Updownarrow$$

$250.2\,\mathrm{pb}$ (NNLO at $\sqrt{s} = 1.96\,\mathrm{TeV}$)

$\sigma_Z \cdot \mathrm{Br}(Z^0 \to \mu^+\mu^-)$ (Run II)

- ▷ Event selection
  - ☐ 1 isolated high p_T central μ
  - ☐ A second isolated high p_T track:

    $E_{\mathrm{EM}} < 2\mathrm{GeV}$ & $E_{\mathrm{HAD}} < 6\mathrm{GeV}$
  - ☐ Cosmic veto
- ▷ 1632 candidates in $\sim 72\,\mathrm{pb}^{-1}$
- ▷ Backgrounds $\sim 0.8\%$



$$\sigma_Z \cdot \mathrm{Br}(Z^0 \to \mu^+\mu^-) = 246 \pm 6_{\mathrm{stat}} \pm 12_{\mathrm{syst}} \pm 15_{\mathrm{lum}}\,\mathrm{pb}$$

Preliminary

Standard Model consistency checks

Lepton universality

e, μ, and τ have the same couplings

$$\sigma(W\to\tau\nu)/\sigma(W\to e\nu) = 0.99 \pm 0.04_{\rm stat} \pm 0.07_{\rm syst}$$

$$\Rightarrow g_\tau/g_e = 0.99 \pm 0.02_{\rm stat} \pm 0.4_{\rm syst}$$ CDF Run II reliminary

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$\Gamma(W)$

$$\mathcal{R}_\ell \equiv \frac{\sigma_W \cdot {\rm Br}(W\to\ell\nu)}{\sigma_Z \cdot {\rm Br}(Z\to\ell\ell)} = \frac{\sigma_W}{\sigma_Z}\cdot\frac{\Gamma(W\to\ell\nu)}{\Gamma(W)}\cdot\frac{\Gamma(Z)}{\Gamma(Z\to\ell\ell)}$$

electron channel:

$$\mathcal{R}_e = 9.88 \pm 0.24_{\rm stat} \pm 0.47_{\rm syst}$$ CDF Run II Preliminary

$$\Rightarrow \Gamma(W) = 2.29 \pm 0.06_{\rm stat} \pm 0.10_{\rm syst}\,[{\rm GeV}]$$

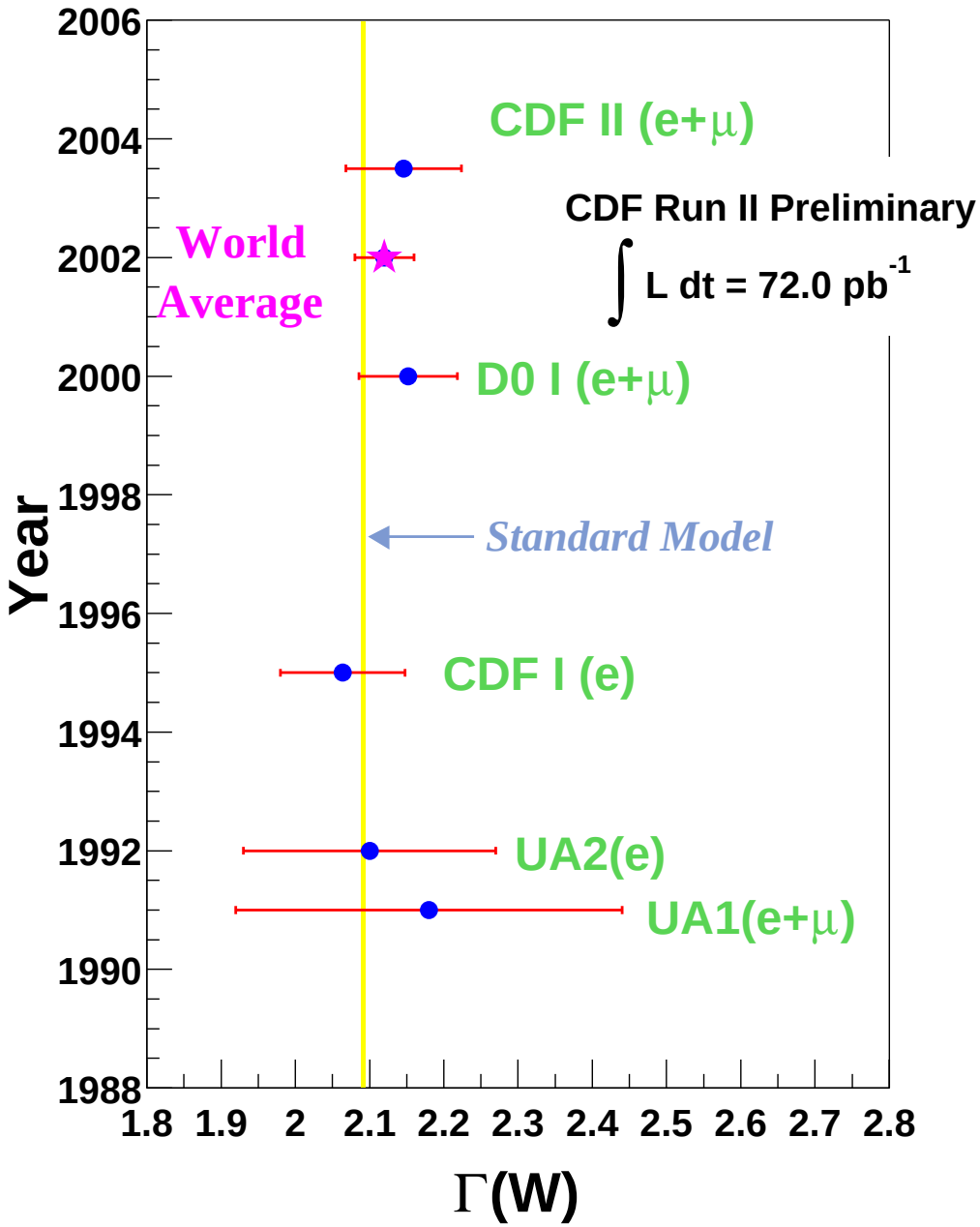
μ channel:

$$\mathcal{R}_\mu = 10.69 \pm 0.27_{\rm stat} \pm 0.33_{\rm syst}$$ CDF Run II Preliminary

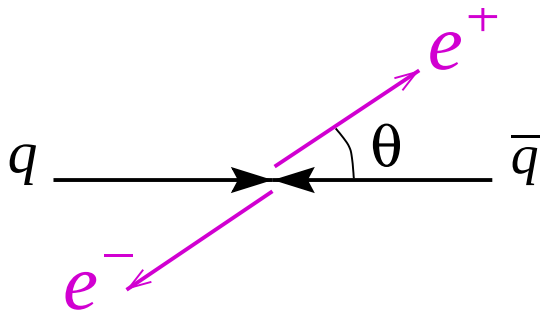
$$\Rightarrow \Gamma(W) = 2.11 \pm 0.05_{\rm stat} \pm 0.07_{\rm syst}\,[{\rm GeV}]$$

PDG: $\Gamma(W) = 2.118 \pm 0.042\,[{\rm GeV}]$

Summary of $\Gamma(W)$ measurement



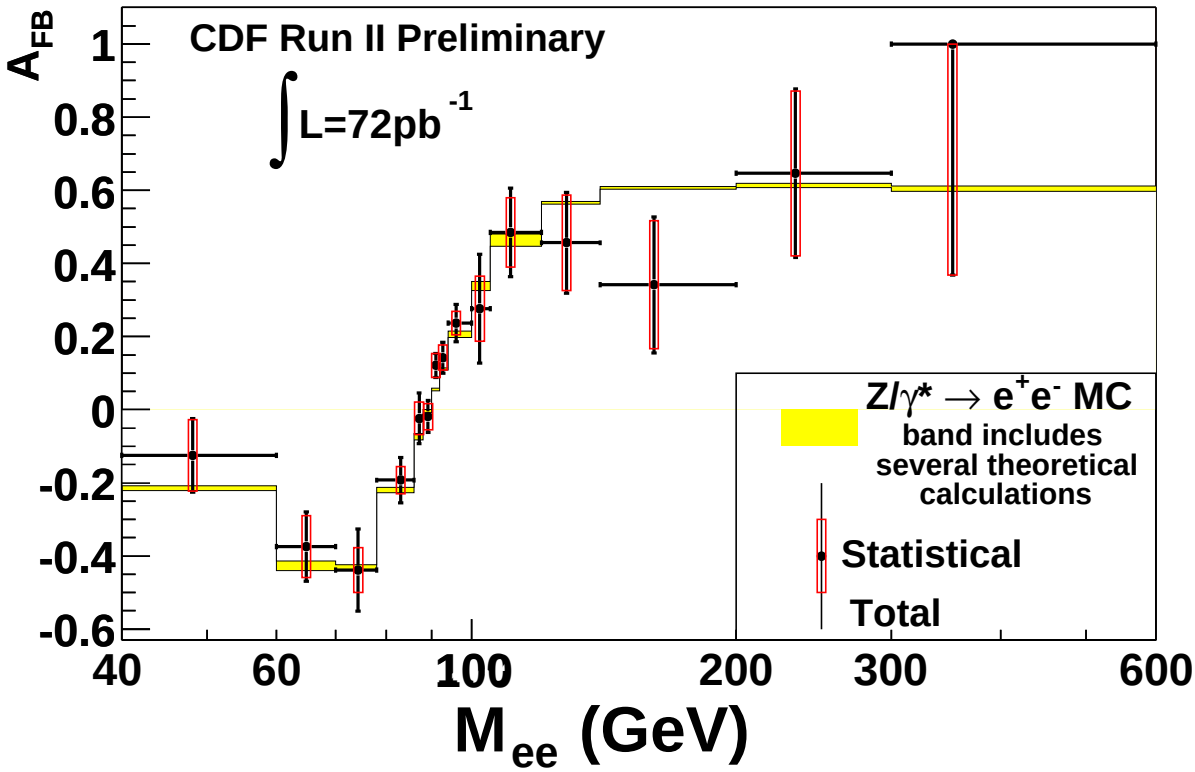
$A_{\rm FB}$ with $Z^0 \to e^+e^-$ (Run II)



$$\frac{d\sigma(q\bar{q} \to Z/\gamma \to e^+e^-)}{d\cos\theta} = A(1+\cos^2\theta) + B\cos\theta$$

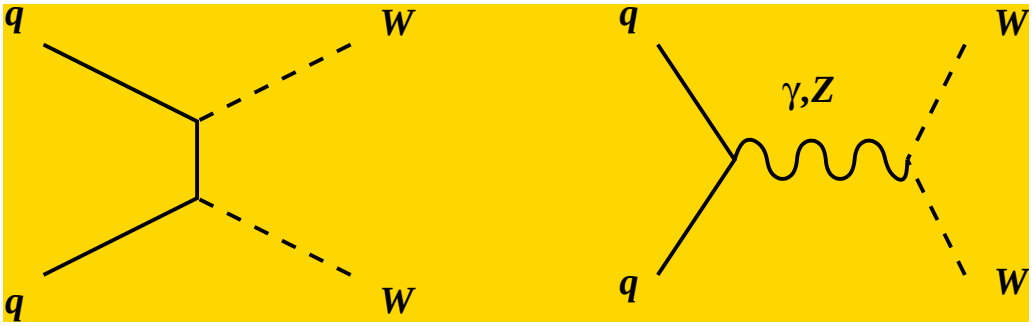
Forward-Backward asymmetry $A_{\rm FB}$

$$A_{\rm FB} \equiv \frac{N_F - N_B}{N_F + N_B} = \frac{\sigma_{\cos\theta>0} - \sigma_{\cos\theta<0}}{\sigma_{\cos\theta>0} + \sigma_{\cos\theta<0}} = \frac{3B}{8A}$$



Relative strengths of V,A $\Rightarrow$ Extract $\sin^2\theta_W$

W^+W^- pair production



dilepton channel: $W^+W^- \to \ell\nu\ell\nu$

CDF Run I

$N_{\rm obs} = 5 \quad N_{\rm BG} = 1.2 \pm 0.3 \quad \int \mathcal{L}\,dt = 106\,{\rm pb}^{-1}$

$\sigma_{WW} = 10.2^{+6.3}_{-5.1}({\rm stat}) \pm 1.6({\rm syst})\,{\rm pb}$

CDF Run II

Event selection

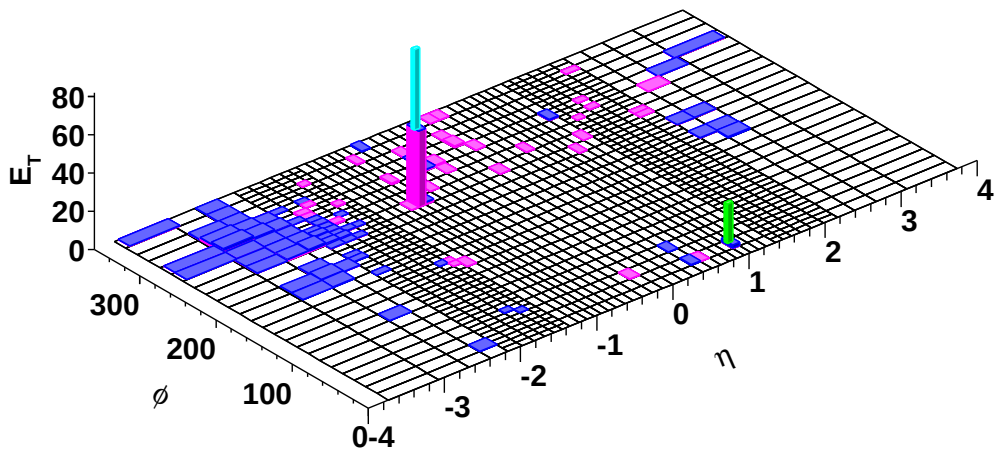
- Two high p_T isolated μ or e with opposite charge
- $\not\!\!E_T > 25{\rm GeV},\ \Delta\phi(\not\!\!E_T, \ell/j) > 20^\circ$
- Z veto
- Jet veto to reject $t\bar{t}$

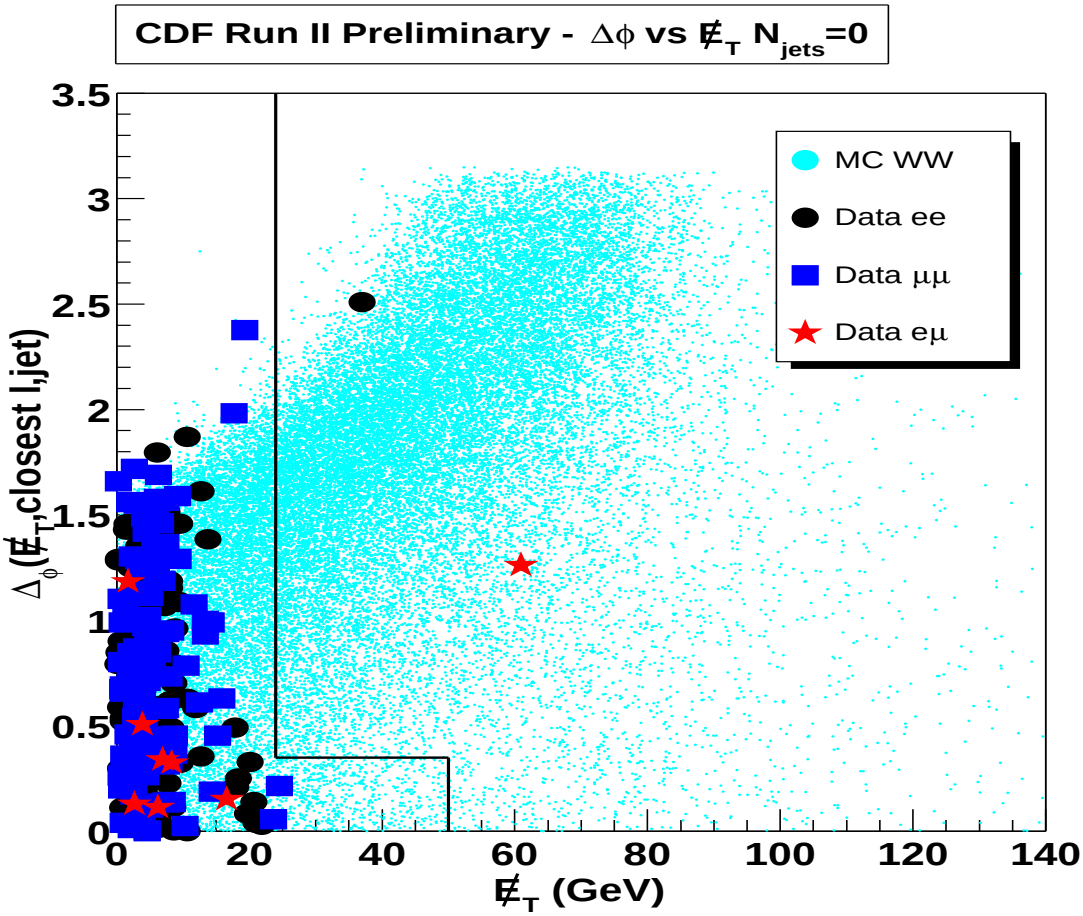
CDF Run II Preliminary

Source	ee	$\mu\mu$	$e\mu$	$\ell\ell$
BG	0.29 ± 0.13	0.47 ± 0.19	0.77 ± 0.60	1.53 ± 0.64
$WW \to \ell\nu\ell\nu$	0.55 ± 0.13	0.66 ± 0.15	1.58 ± 0.36	2.79 ± 0.62
$N_{\rm observe}$	1	0	1	2

$\int \mathcal{L}dt = \sim 72\,{\rm pb}^{-1}$

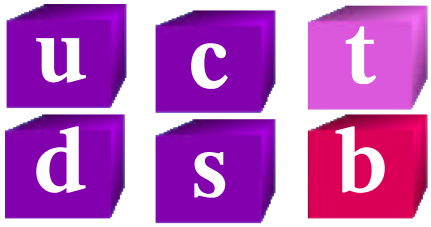
A $W^+W^- \to e\nu\mu\nu$ candidate





Top Physics Overview

- Partner of b-quark in SU(2) doublet of weak isospin in the third generation.



- Mass: $M_t \approx 175\,\mathrm{GeV}/c^2$
  Width: $\Gamma_t \simeq 1.42\,\mathrm{GeV}$

- Top quark decays before hadronization.

- Yukawa coupling $\sqrt{2}\frac{m_t}{v} \approx 1$
  $\Rightarrow$ Special role in electroweak symmetry breaking?

- Experimentlly established by CDF and D$\varnothing$ in 1995

CDF : F. Abe *et al.* Phys. Rev. Lett. 74 (1995) 2626

D0 : S. Abachi *et al.* Phys. Rev. Lett. 74 (1995) 2632

Top Quark Production at Tevatron

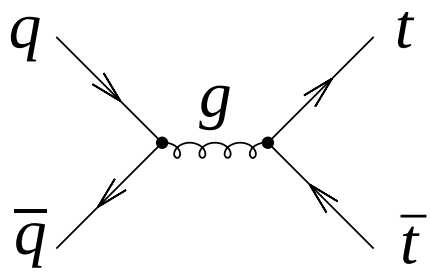
$t\bar{t}$ pair production thru. strong interaction

$\sigma(t\bar{t}) \sim 5\,\mathrm{pb}$ at $\sqrt{s} = 1.8\,\mathrm{TeV}$

$\sim 7\,\mathrm{pb}$ at $\sqrt{s} = 1.96\,\mathrm{TeV}$

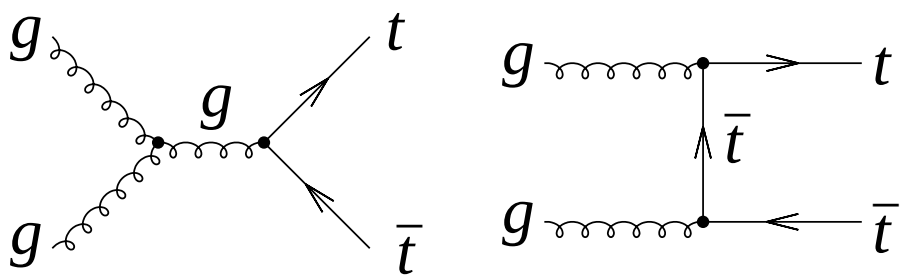
$q\bar{q}$ annihiration

$\sim 90\%$(Run I) $\sim 85\%$(Run II)



gluon fusion

$\sim 10\%$(Run I) $\sim 15\%$(Run II)

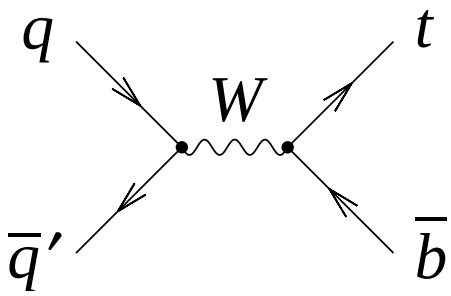


Single-top production via EW interaction

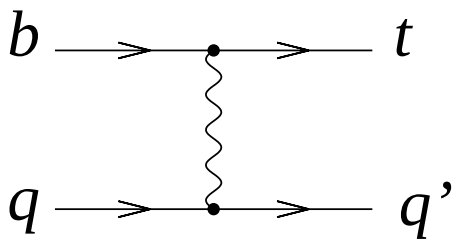
$\sigma(\text{single}-t) \sim 2.4\,\text{pb}$ at $\sqrt{s} = 1.8\,\text{TeV}$

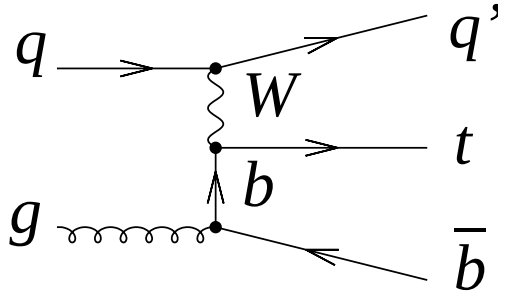
$\sim 3\,\text{pb}$ at $\sqrt{s} = 1.96\,\text{TeV}$

s-channel W^* $\sim 32\%$(Run I)



t-channel $\sim 62\%$(Run I)





W-gluon fusion

Dominant contributions:

s-channel and W-gluon fusion

3 classes of signal in $t\bar{t}$ production

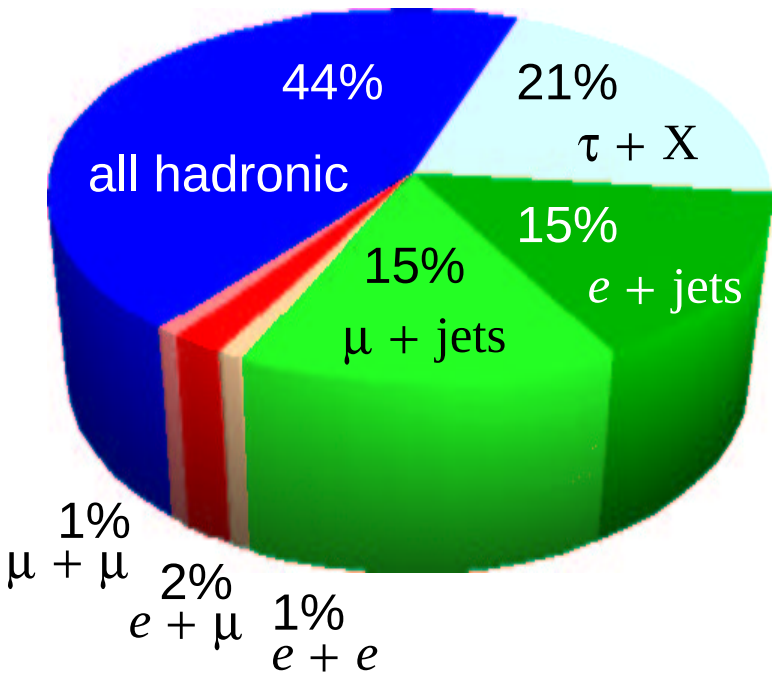
Top quark goes W+b at a rate of $\sim$100%:

$$\mathrm{Br}(t \to W^+ b) \simeq 1$$

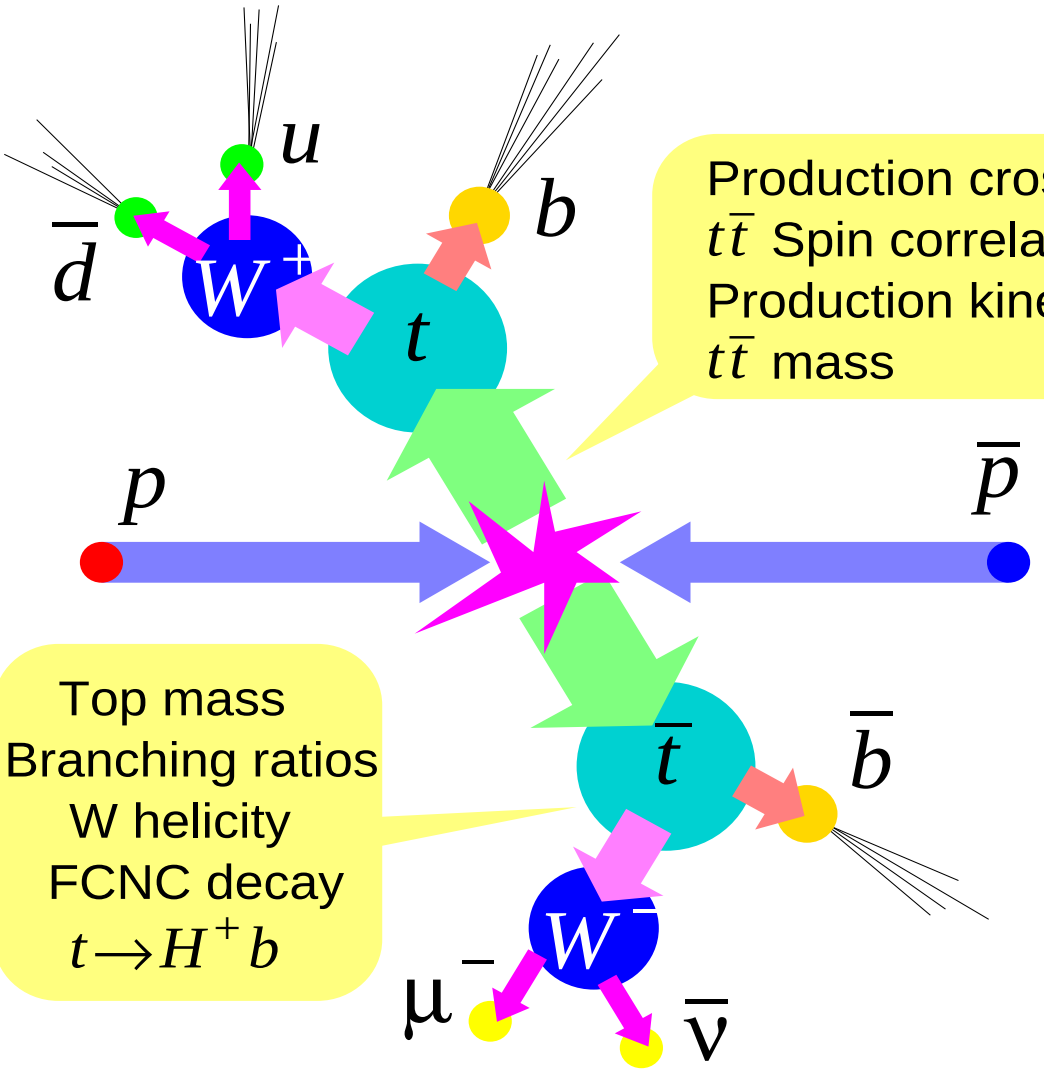
Decay channels of $t\bar{t}$ pair

$t \to W^+ b$				
	$\hookrightarrow$	$\ell^+\nu$	$q\bar{q}'$	$\ell^+\nu$	$q\bar{q}'$
$\bar{t} \to W^- \bar{b}$				
	$\hookrightarrow$	$\ell^-\bar{\nu}$	$\ell^-\bar{\nu}$	$q\bar{q}'$	$q\bar{q}'$

Fraction of decay channels of $t\bar{t}$



Topics on Top Physics at Tevatron



Production cross section
$t\bar{t}$ Spin correlations
Production kinematics
$t\bar{t}$ mass

Top mass
Branching ratios
W helicity
FCNC decay
$t \to H^+ b$

Single top production
Polarized top

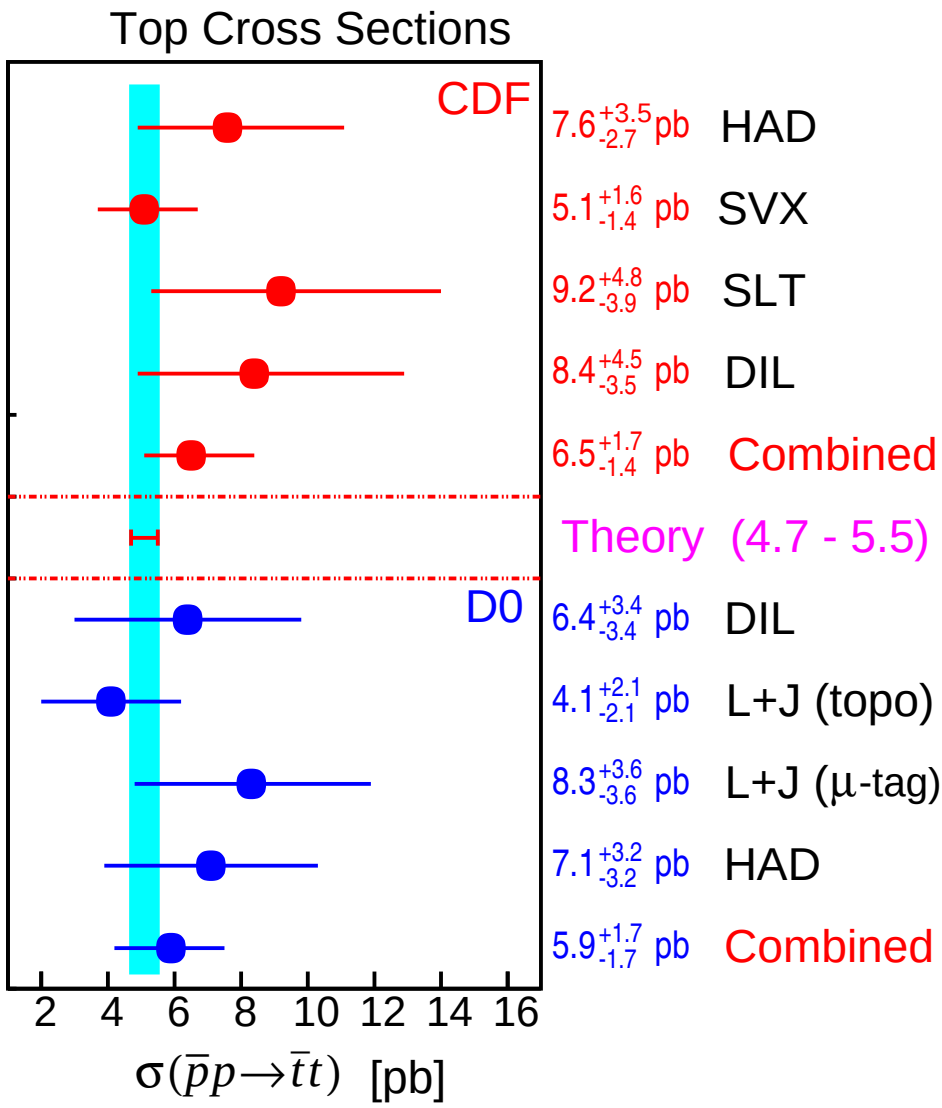
Results from Run IIa !!

- $\sigma_{t\bar{t}}$ in dilepton channel
- $\sigma_{t\bar{t}}$ in $\ell + \text{jets}$ channel
- Top mass measurement in $\ell + \text{jets}$ channel

$t\bar{t}$ production cross section

- Test of perturbative QCD predictions.
- Counting experiment: $\sigma_{t\bar{t}} = \dfrac{N_{\rm obs} - B}{\epsilon_{\rm tot} \int dt\, \mathcal{L}}$

Run I



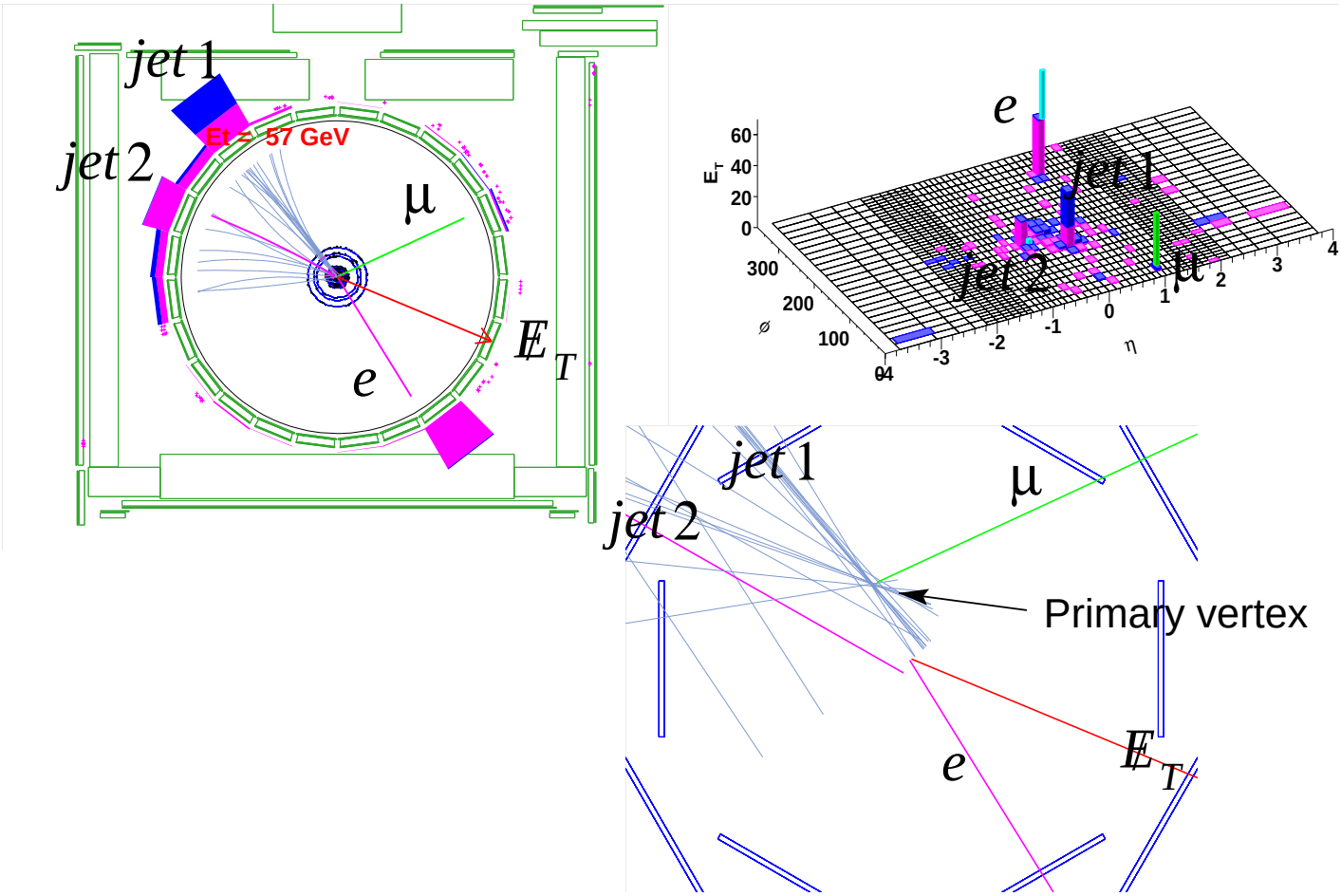
$\sigma_{t\bar{t}} = 6.5^{+1.7}_{-1.4}\,\mathrm{pb}$ at $\sqrt{s} = 1.8\,\mathrm{TeV}$ (CDF Run I)

In good agreement with predictions.

$t\bar{t}$ production cross section (Run II)

$\sigma_{t\bar{t}}$ in dilepton channel

A dilepton candidate



Run 156484 Event 3099305

$E_T(e) = 34\,\mathrm{GeV}$

$E_T(\mu) = 36\,\mathrm{GeV}$

$E_T(\mathrm{jets}) = 57, 28\,\mathrm{GeV}$

$\not\!\!E_T = 55\,\mathrm{GeV}$

$M_{e\mu} = 47\,\mathrm{GeV}$

$H_T = 227\,\mathrm{GeV}$

Event selection

- 2 isolated high p_T central ℓ's
- Veto Z, cosimics
- $\not\!\!E_T > 25\,\mathrm{GeV}$
- 2 jets
- $H_T > 200\,\mathrm{GeV}$

Candidates

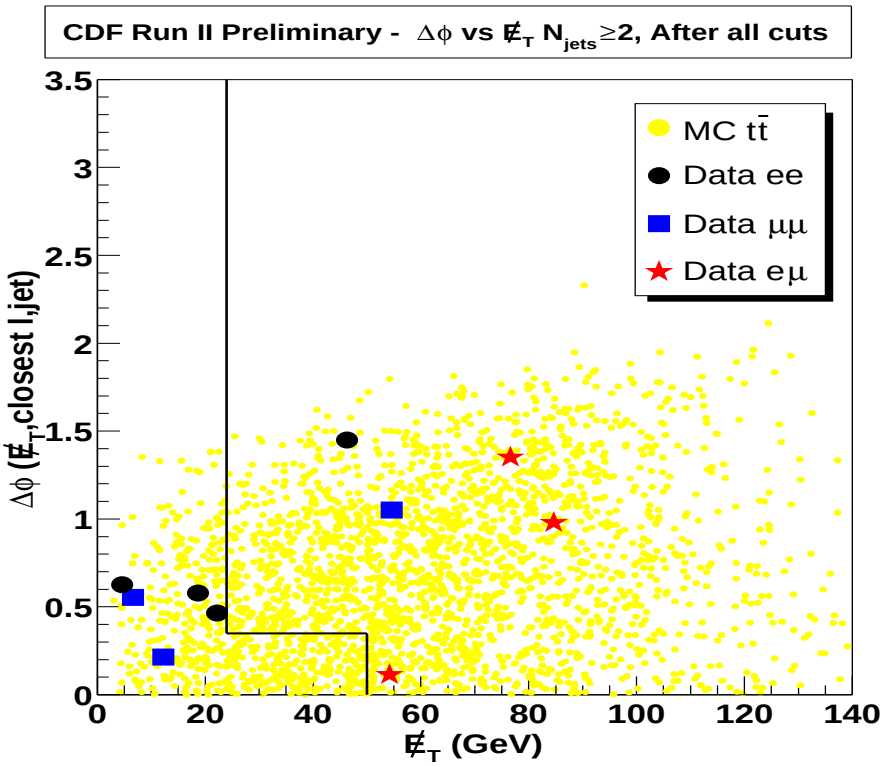
- 5

Luminosity

- $\sim 72\,\mathrm{pb}^{-1}$

B.G.

- 0.30 ± 0.12



$$\sigma_{t\bar{t}} = 13.2 \pm 5.9_{\mathrm{stat}} \pm 1.5_{\mathrm{syst}}\,\mathrm{pb}$$

⇕ Preliminary

$6.70^{+0.71}_{-0.88}\,\mathrm{pb}$ (NLO at $\sqrt{s} = 1.96\,\mathrm{TeV}$)

$\sigma_{t\bar{t}}$ in $\ell + \mathrm{jets}$ channel

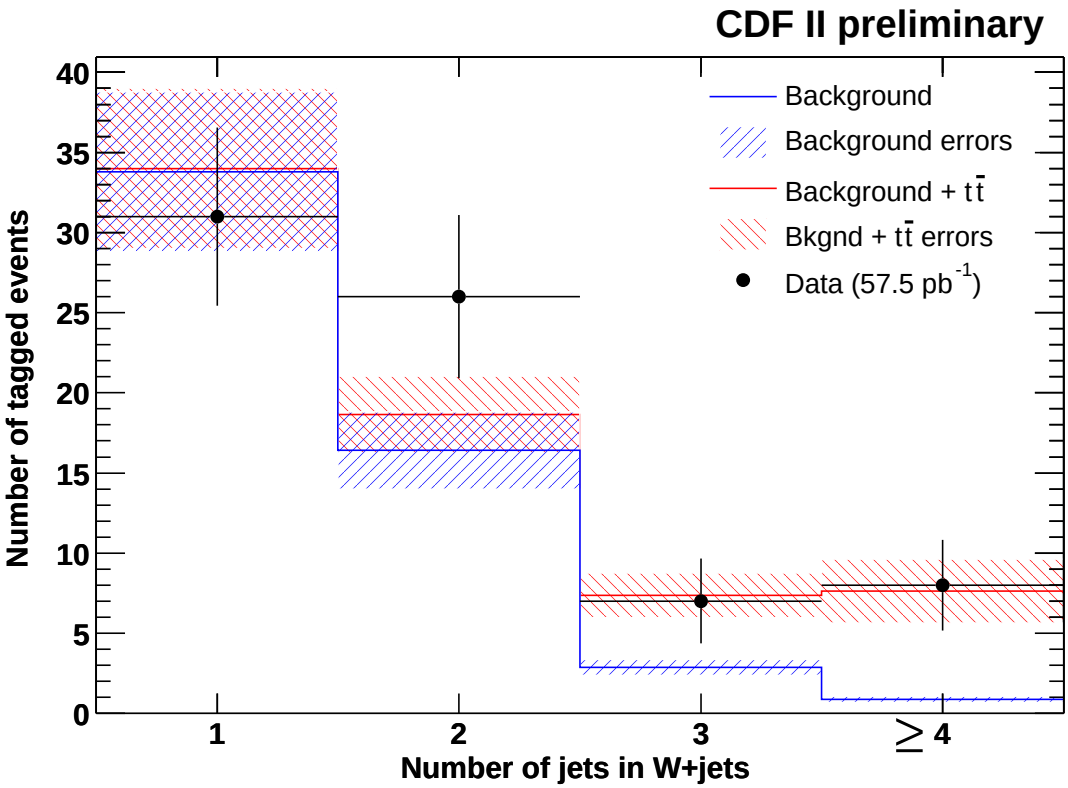
Event selection

- 1 isolated high p_T central ℓ
- Veto Z, cosimics
- $\not\!\!E_T > 20\,\mathrm{GeV}$
- $N_{\mathrm{jets}} \geqslant 3$
  $N_{\mathrm{SecVtx-tag}} \geqslant 1$

Candidates
- 15

Luminosity
- $\sim 57.5\,\mathrm{pb}^{-1}$

B.G.
- 3.8 ± 0.5



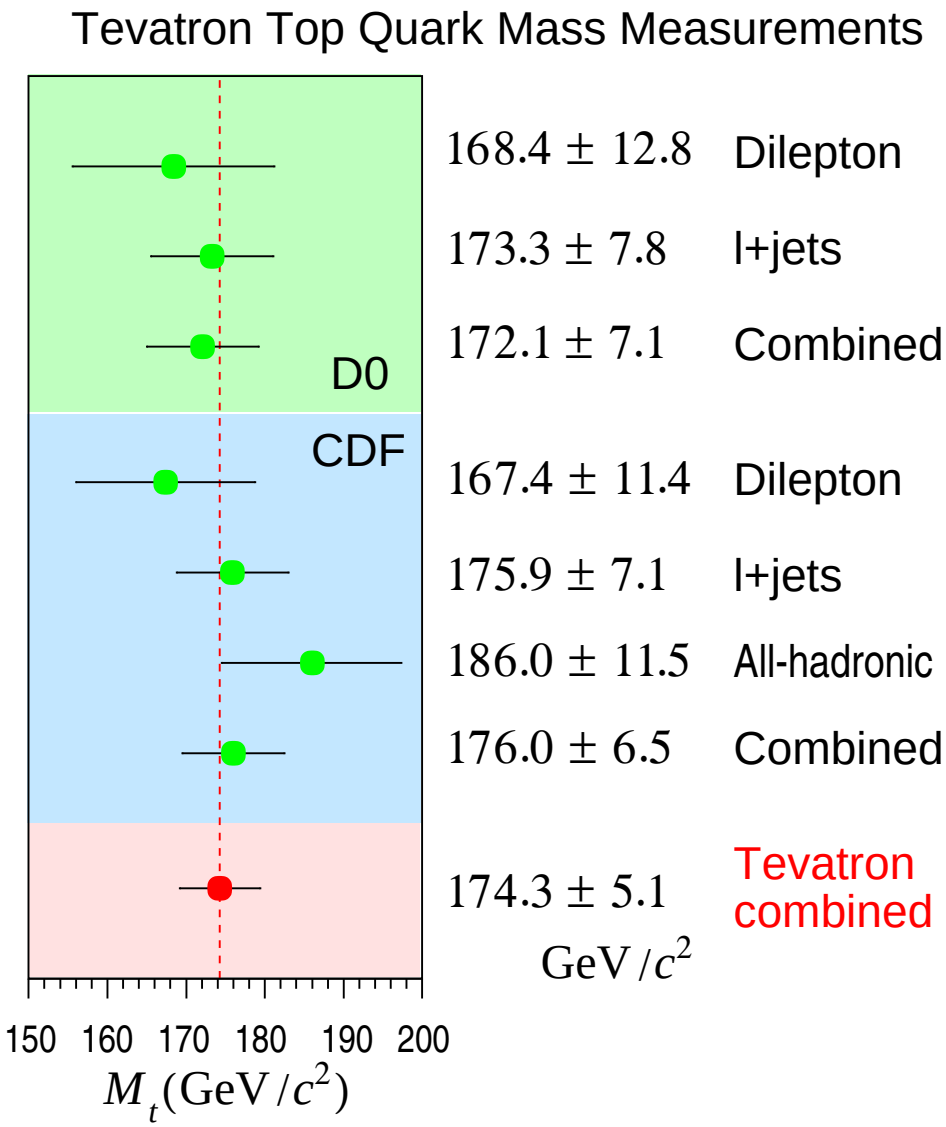
$$\sigma_{t\bar{t}} = 5.3 \pm 1.9_{\mathrm{stat}} \pm 0.8_{\mathrm{syst}}\,\mathrm{pb}$$

⇕ Preliminary

$6.70^{+0.71}_{-0.88}\,\mathrm{pb}$ (NLO at $\sqrt{s} = 1.96\,\mathrm{TeV}$)

Top quark mass

Run I



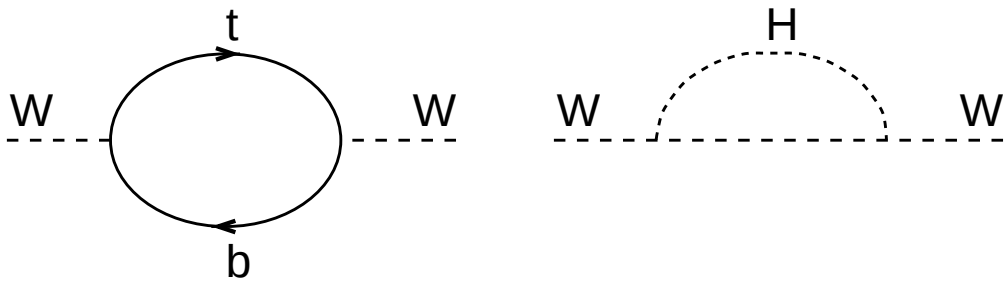
The combind result of CDF in Run I is:

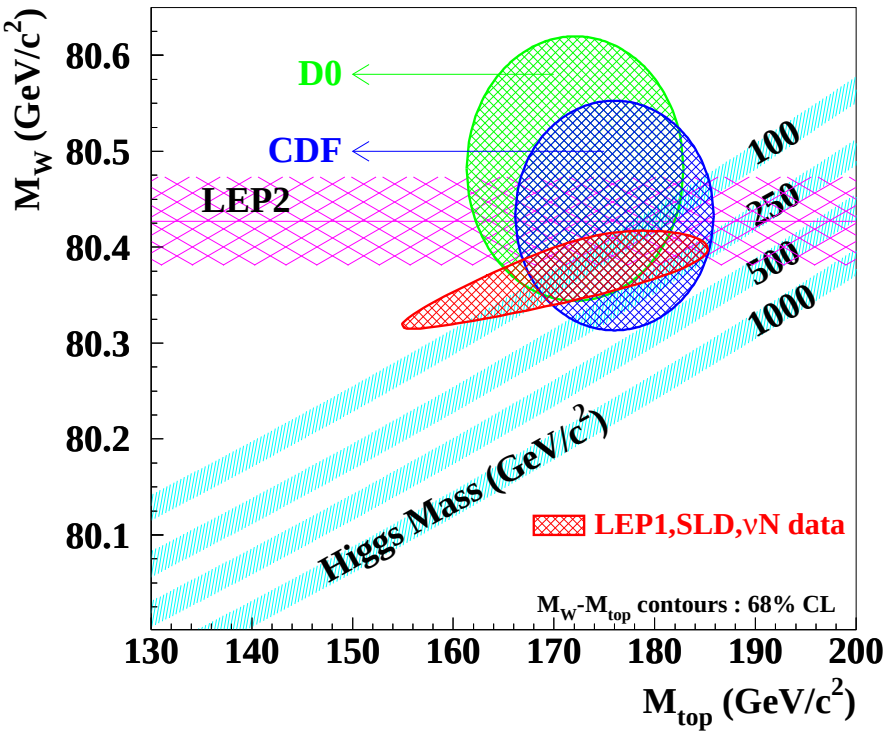
$M_t = 176.0 \pm 6.5\,\mathrm{GeV}/c^2$ (Run I)

What is the top quark mass for?

- Important parameter for predictions of SM via radiative corrections.
- Measurements of M_W and m_t constrain M_H.

$$\delta M_W = f(m_t^2, \log M_H)$$





(Run I)

Top mass measurement in CDF Run II

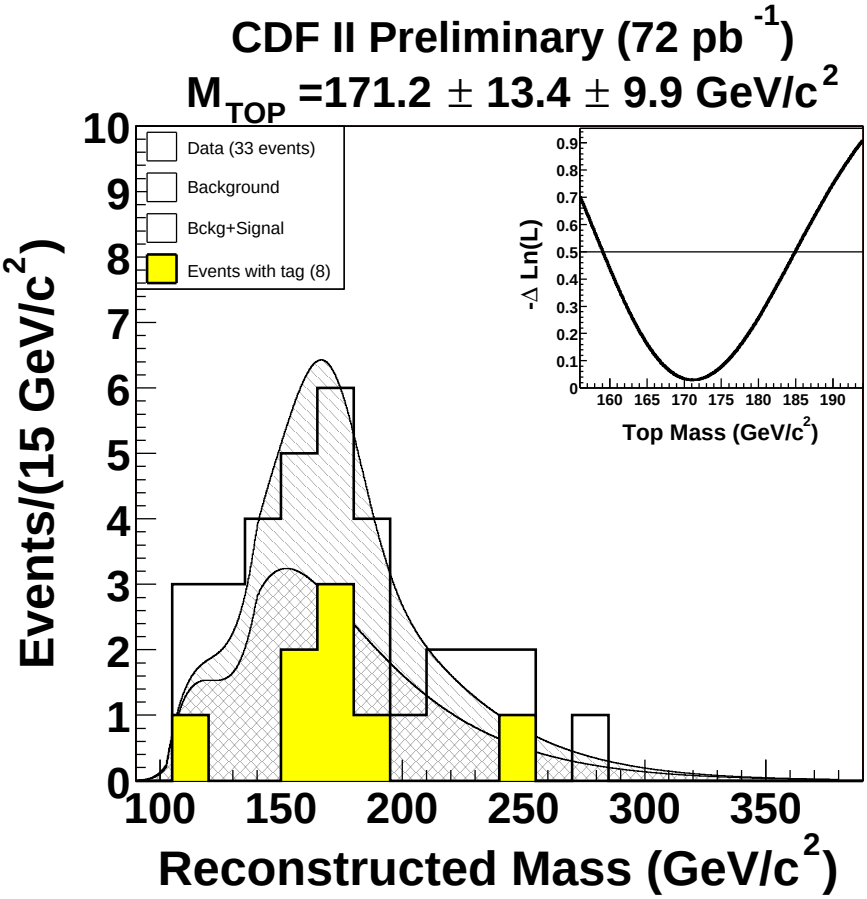
Use pre-SecVtx-tagged $\ell + 4\mathrm{jets}$ sample

How do we extract m_t in a $\ell + \mathrm{jets}$ event?

→ Use 2C constrained χ^2 fitting with
$M_{\ell\nu} = M_{jj'} = M_W$, $M_{\ell\nu b} = M_{bjj'} = M_t$ (4 constraint)
M_t, p_z^ν (2 unknown)

→ But we don't know which jet is which.
24 combinations:
12 permutations for the jet assignment
each permutation has 2 solutions for neutrino p_z^ν

→ Choose the best one with lowest χ^2



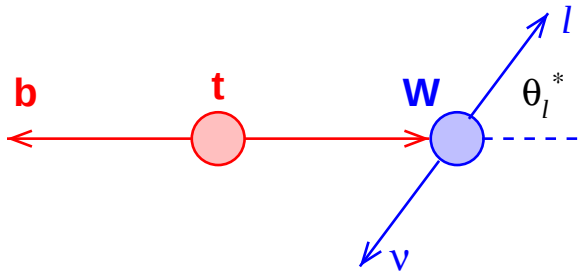
$M_{\mathrm{top}} = 171.2 \pm 13.4 \pm 9.9\,\mathrm{GeV}/c^2$ CDF Run II Preliminary

W helicity in top decays (Run I)

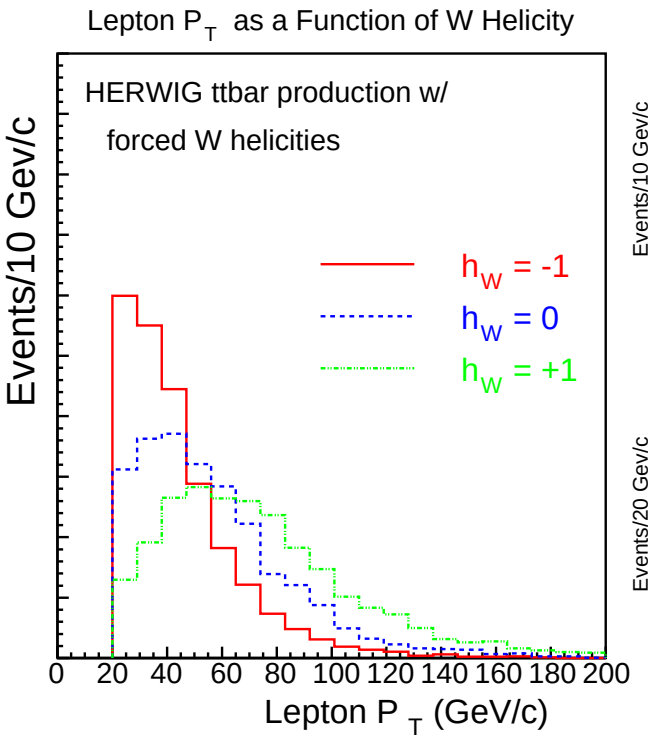
In SM(V-A), top quark decays only to longitudinally polarized or left-handed W.

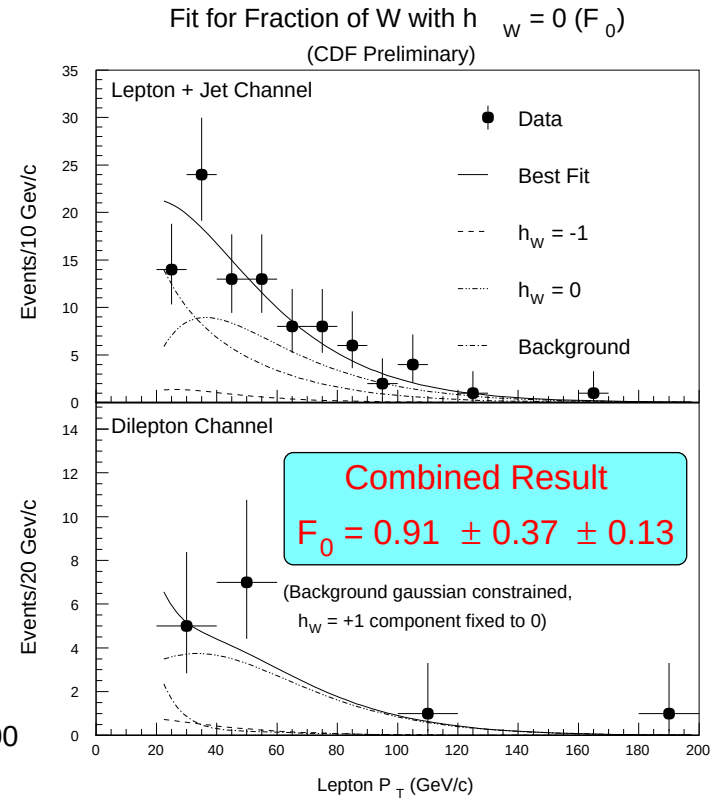
$$h_W = 0 \text{ or } -1 \qquad \frac{\mathrm{Br}(t \to bW_{\mathrm{long}})}{\mathrm{Br}(t \to bW_{\mathrm{left}})} = \frac{1}{2}\left(\frac{m_t}{m_W}\right)^2 = \frac{0.70}{0.30}$$

Lepton P_T distributions in $t \to b\ell\nu$ distinguish the three helicity states of W.



$$|\mathfrak{M}(W_{\mathrm{left}})|^2 \propto \frac{1}{4}(1-\cos\theta_l^*)^2$$
$$|\mathfrak{M}(W_{\mathrm{long}})|^2 \propto \frac{1}{2}(\sin\theta_l^*)^2$$
$$|\mathfrak{M}(W_{\mathrm{right}})|^2 \propto \frac{1}{4}(1+\cos\theta_l^*)^2$$





CDF Run I Results		SM
$\mathcal{F}_{\mathrm{long}} = 0.91 \pm 0.37(\mathrm{stat}) \pm 0.12(\mathrm{syst})$	$\Longleftrightarrow$	~ 0.7
$\mathcal{F}_{\mathrm{right}} = 0.11 \pm 0.15(\mathrm{stat}) \pm 0.06(\mathrm{syst})$		0

Single top search (Run I)

♣ Direct measurement of $|V_{\rm tb}|$ of EW vertex t-W-b.

♣ Two dominant production processes at Tevatron.

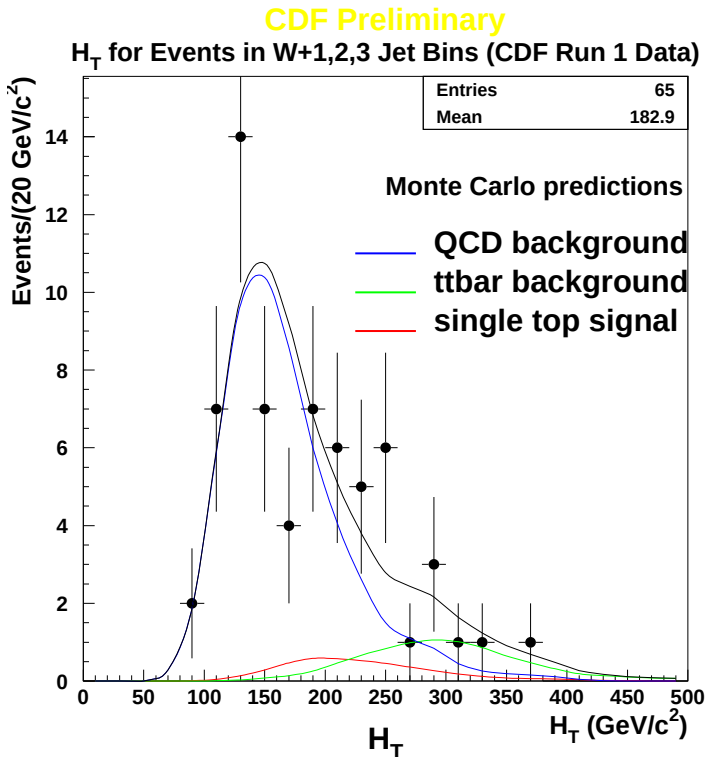
- W-gluon fusion:
  Hard b-jet, W decay, (soft b-jet), light q jet
- s-channel W^*:
  2 hard b-jets, W decay

Event signiture: W decay + n jets(one or two b-tagged)

→ After all event selections, look at

$$H_t \equiv |\not\!\!E_T| + |E_T(\ell)| + \sum |E_T(\text{all jets})|$$

→ Unbinned maximum likelihood fit to H_t distribution.



$\sigma(Wg + W^*) < 14\,\text{pb}$ (Run I)

Other results on top physics (Run I)

- Branching ratio $R = \frac{\mathrm{Br}(t \to \mathrm{Wb})}{\mathrm{Br}(t \to \mathrm{Wq})}$.

  $R = 0.94^{+0.31}_{-0.24}$ $\quad |V_{\mathrm{tb}}| = 0.97^{+0.16}_{-0.12}$

  (assuming 3 generations)

- Search for FCNC top quark decays.

  strongly GIM suppressed in the SM:

  - $p\bar{p} \to t\bar{t} + X$ with $t \to W + b$ and $\bar{t} \to \bar{u}/\bar{c} + \gamma$

    $\mathrm{Br}(t \to u/c + \gamma) < 3.2\%$ (95%CL)

  - $p\bar{p} \to t\bar{t} + X$ with $t \to W + b$ and $\bar{t} \to \bar{u}/\bar{c} + Z^0$

    $\mathrm{Br}(t \to u/c + Z^0) < 33\%$ (95%CL)

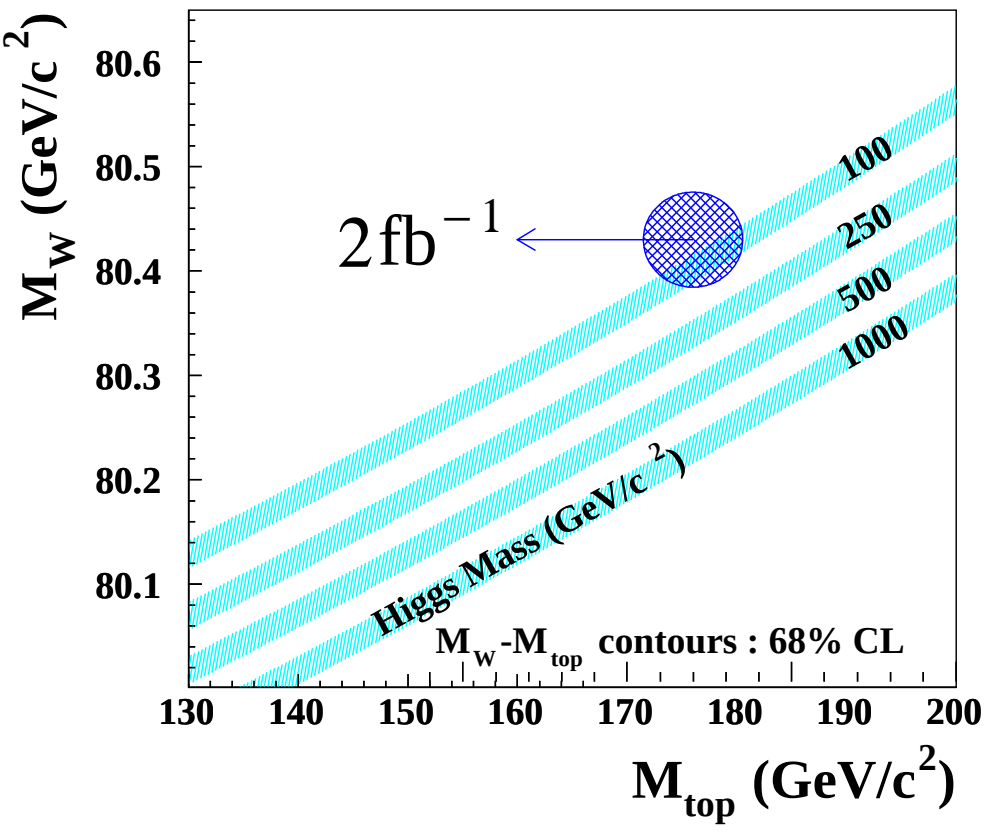
Run II Prospects

Run IIa luminosity goal is $2\ \mathrm{fb}^{-1}$. This means at least 20x higher statistics.

Top quark mass

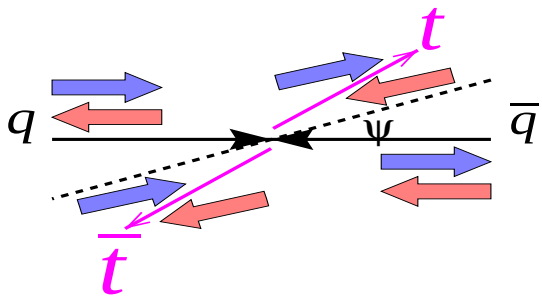
$\Rightarrow \delta M_t$: $6.5\,\mathrm{GeV}/c^2$(Run I) $\rightarrow$ $2{-}3\,\mathrm{GeV}/c^2$(Run IIa)

$\Rightarrow$ Constraint for higgs mass: $\delta M_h/M_h \sim 40\%$



$t\bar{t}$ spin correlations

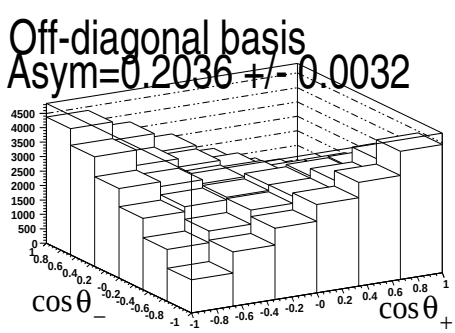
- $\sim 90\%$ of $t\bar{t}$ pairs produced at Tevatron come from $q\bar{q}$ annihilation.
  - Only like-spin combinations in $t\bar{t}$, if we take an optimal spin quantization basis.



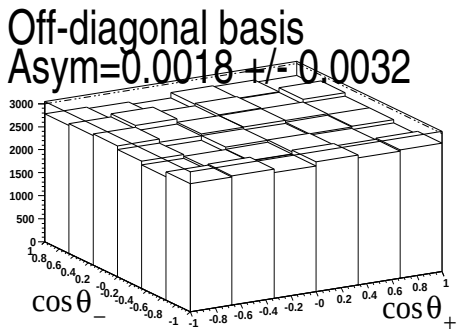
"Off-diagonal basis"

- Top quark decays before losing the spin information at production.
  - Top spin can be measured by lepton flight direction in top the rest frame.

Herwig ver6.5 generator level



w/ Spin correlation



w/o Spin correlation

  - Experimental proof of the top life time shorter than the spin-flip time

- Run IIa will provide up a good opportunity for observing the $t\bar{t}$ spin correlations.

Top quark yields summary

	Run I	Run IIa	Run IIb
CM Energy (TeV)	1.8	1.96	1.96
Integrated Luminosity (fb^{-1})	0.11	2.0	15.0
Production			
$\sigma_{t\bar{t}}$ (pb)	5.0	7.0	7.0
$\sigma_{\mathrm{single}\,t}$ (pb)	2.5	3.4	3.4
Number of $t\bar{t}$ produced	500	14000	105000
Number of single t produced	250	7000	52500
Yields			
dilepton channel	4	150	1100
$N(t\bar{t} \to \ell + \geqslant 3j)(\geqslant 1\ b$-tag)	25	1400	10000
$N(t\bar{t} \to \ell + \geqslant 4j)(2\ b$-tag)	5	600	4500
$N(\mathrm{single\ t})$ ($W + 2j$ w/ 1 b-tag)	3	140	1000

Expected uncertainties of measurements

		Run I	Run IIa	Run IIb
Mass	m_t	$6.6\,\mathrm{GeV}$	2-3 GeV	1-2 GeV
cross section	$\sigma_{t\bar{t}}$	25%	10%	5%
W helicity	$\mathcal{F}_0$	0.4	0.09	0.04
	$\mathcal{F}_+$	0.15	0.03	0.01
$R \equiv \frac{B(t \to Wb)}{B(t \to \mathrm{Wq})}$		30%	4.5%	0.8%
$\sigma_{\mathrm{single}-t}$		--	20%	8%
$\lvert V_{\mathrm{tb}} \rvert$ from single-t		--	12%	5%
FCNC decay	$B(t \to \gamma q)$	< 0.03	?	?
	$B(t \to \mathrm{Zq})$	< 0.3	< 0.02	?

Summary

- Run IIa is at the process of reestablishing measurements of basic physics
  - ♣ W/Z Cross Sections and Ratios
  - ♣ $t\bar{t}$ Cross Section
  - ♣ Top quark mass
- We are ready for the next step
  - ♣ W mass
  - ♣ Top quark properties
  - ♣ ...
- By this summer we hope to have $\sim 200\,\mathrm{pb}^{-1}$.
  - ♣ Run I physics with higher statics
  - ♣ ...
- Goal for Run IIa is $2\,\mathrm{fb}^{-1}$
- Run II is promised to be prolific of top quarks, and will give us much information about top quark before LHC.