Run 2 at CDF:
results from top quark and electroweak measurements, and new physics searches

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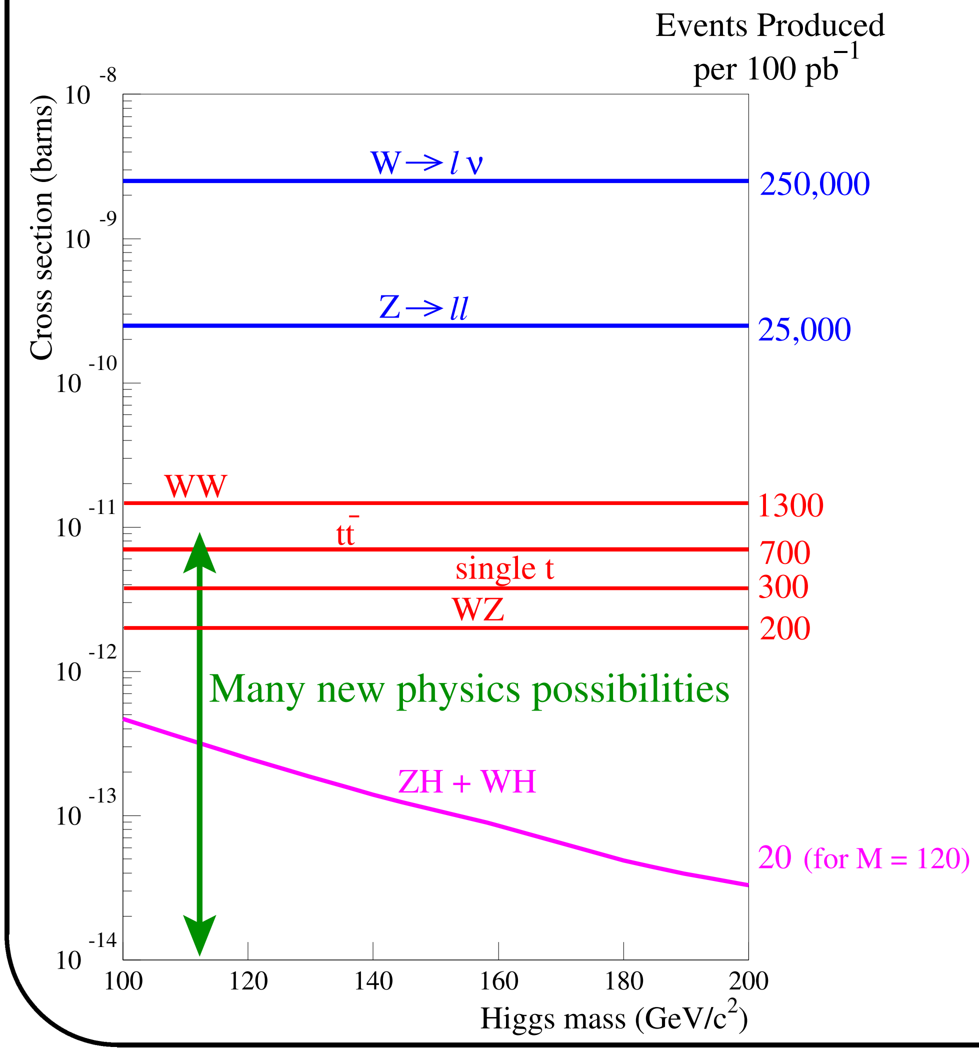
Outline

- Introduction
- CDF detector and performance in Run II
- W's, Z's, and other Electroweak measurements
- Top quark studies
- Higgs and new physics searches
- Summary

Introduction

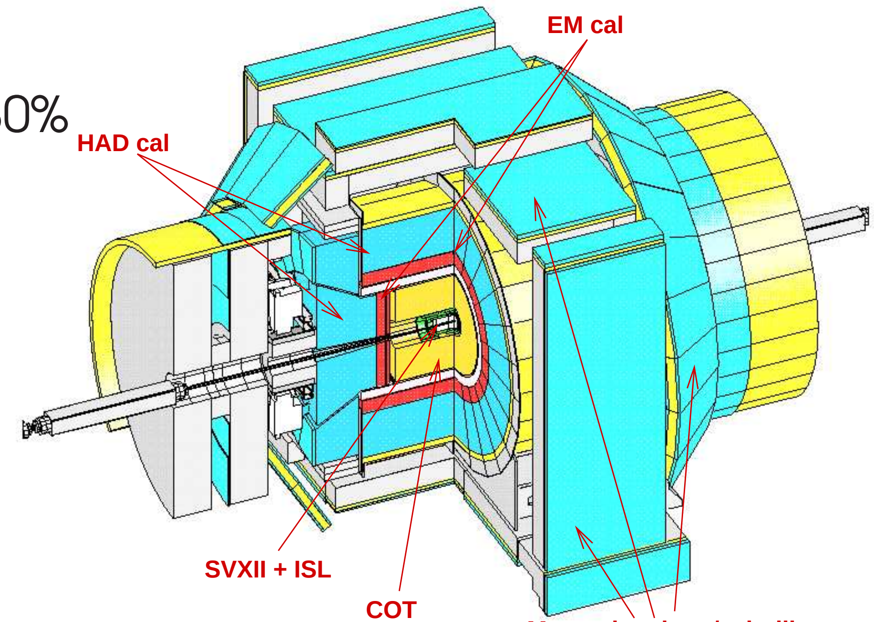
High-P_T physics at CDF now in high gear $\Rightarrow$ exciting next few years



- W's, Z's: Large cross sections
  $\Rightarrow$ high statistics
  $\Rightarrow$ precision measurements
- Top: Cross section $\sim$ 7 pb
  $\Rightarrow$ soon entering phase of highly anticipated precision measurements
- Dibosons: σ's $\sim$ few pb
  $\Rightarrow$ beginning program of important SM tests
- Higgs, new physics: foundations built from the above analyses crucial for optimal searches

The CDF Run II Detector

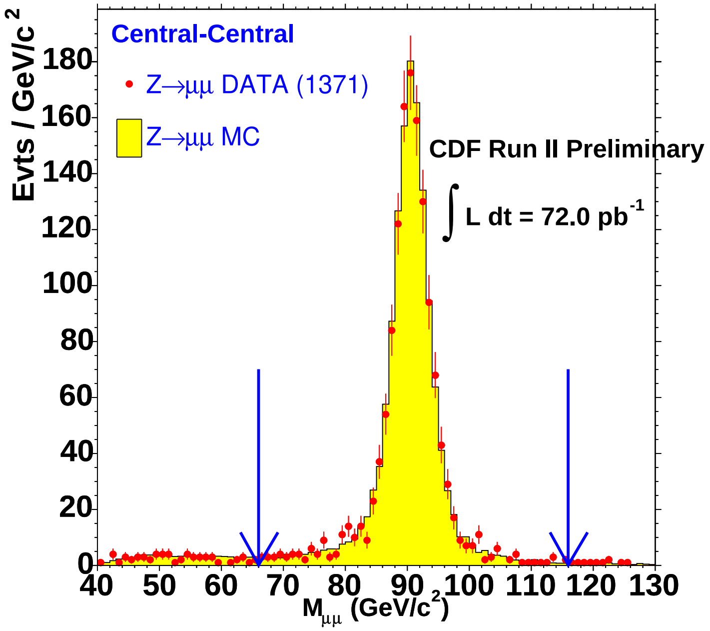
- Detector performing well
  - Data taking efficiency $\sim$ 80%
  - Recent CDF analyses based on $\sim 200\,\mathrm{pb}^{-1}$ (Mar 2002 - Aug 2003)
  - Expect another $\sim 400\,\mathrm{pb}^{-1}$ within next year

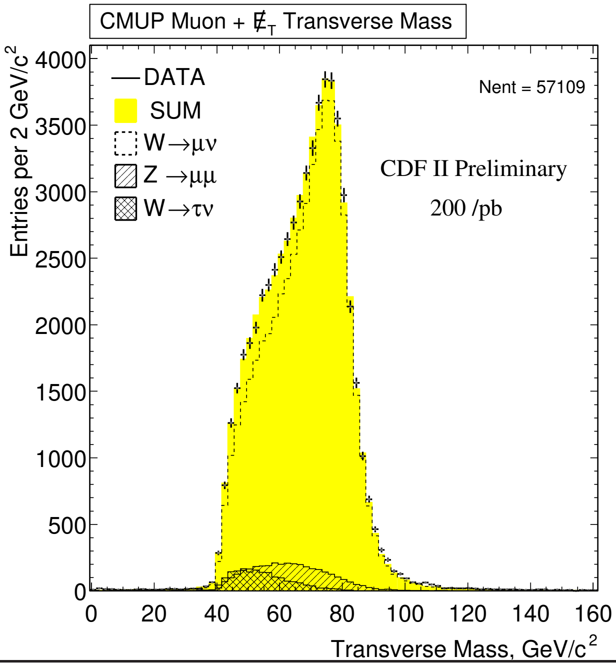


- New in Run II:
  - Front-end DAQ, Trigger system (L1 track, L2 displaced track)
  - Tracking system (8 layers of Si out to $|\eta| < 2.0$, COT)
  - Forward calorimeters ($1.0 < |\eta| < 3.6$)
  - Extended muon coverage (out to $|\eta| < 1.5$)
  - Run 2 upgrades greatly extend physics reach

W and Z cross-sections

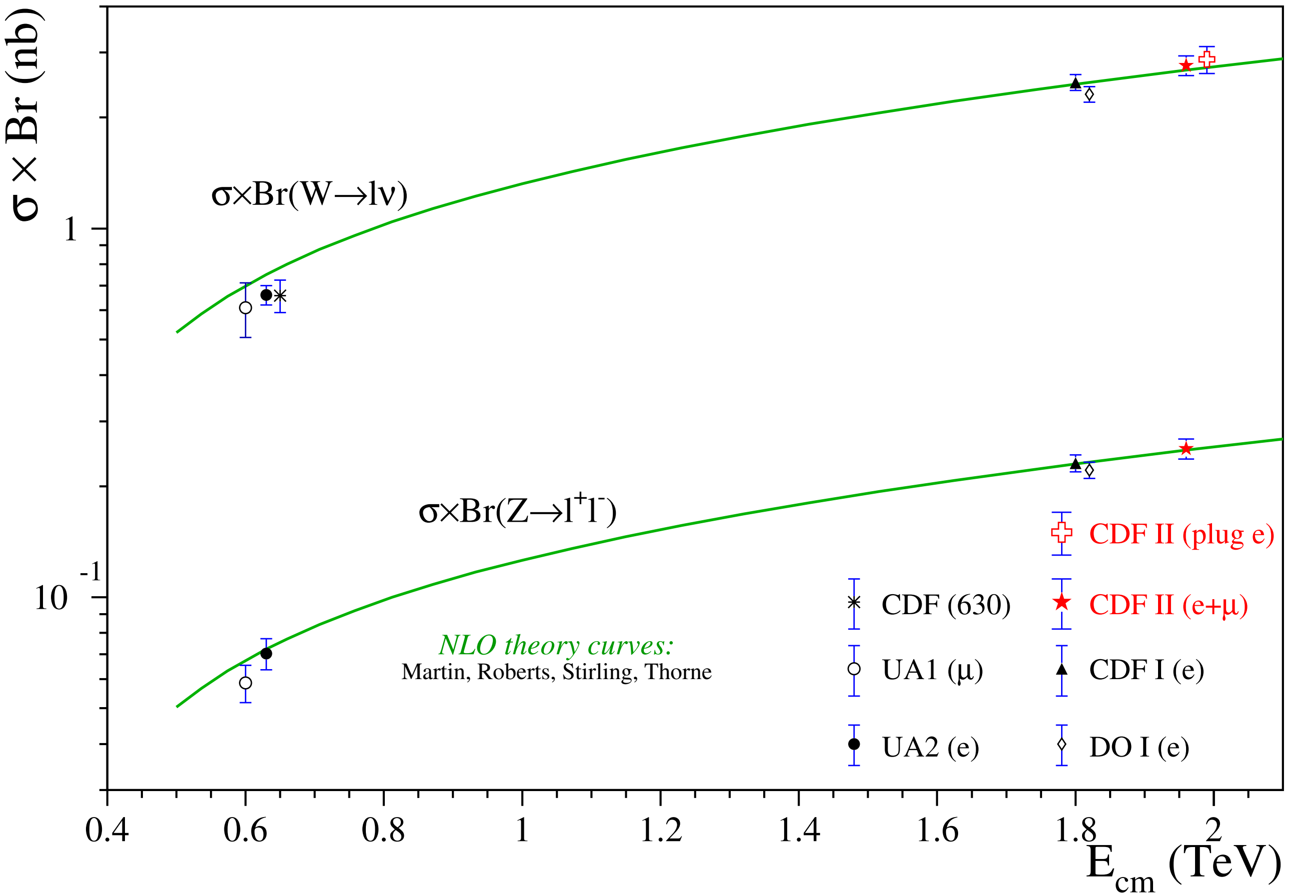
- Precision measurements done using W and Z leptonic decays
  - Yardstick for validation of all high-P_T lepton analyses
  - Important for calibration of energy/momentum scales





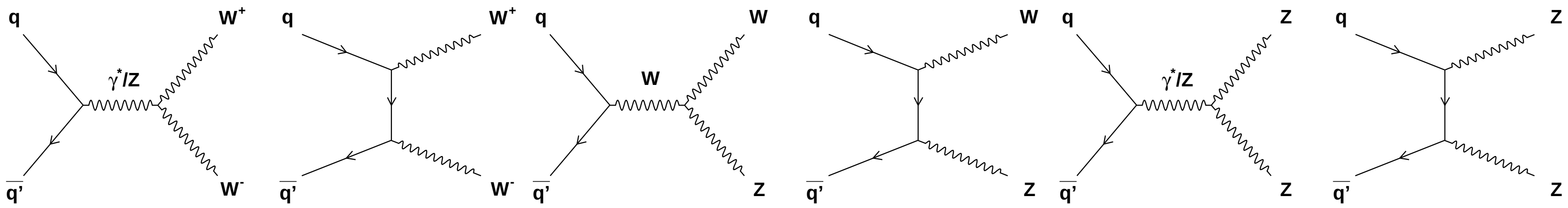
	CDF Run 2 measurement (pb)	SM value
$\sigma \times BR(W \to \ell\nu)$	$2777 \pm 10_{\text{(stat)}} \pm 52_{\text{(syst)}} \pm 167_{\text{(lum)}}$	2690 ± 50
$\sigma \times BR(Z \to \ell\ell)$	$254.3 \pm 3.3_{\text{(stat)}} \pm 4.3_{\text{(syst)}} \pm 15.3_{\text{(lum)}}$	252 ± 5

W and Z cross-sections (cont.)



- W/Z cross-sections, and related quantities, consistent with calculations
- Updates/combinations with all available data soon

Diboson Production



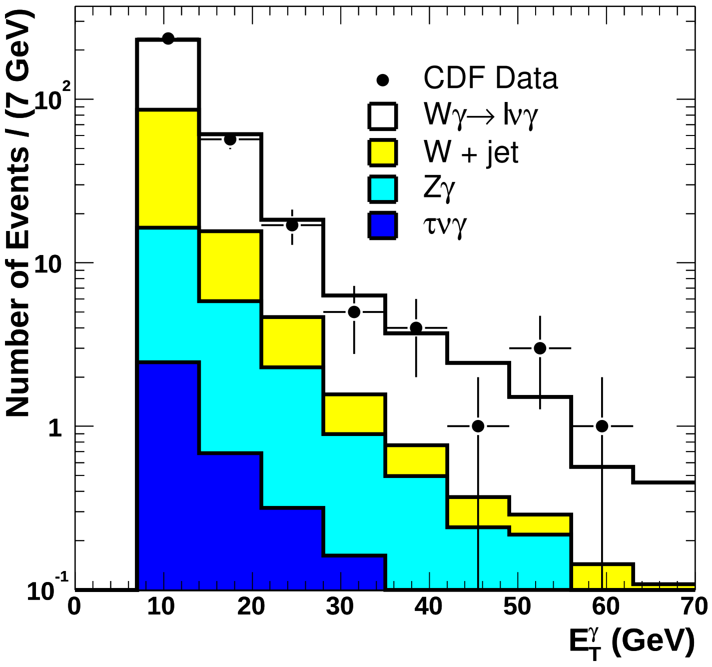
- Direct test of triple gauge boson couplings
  - Higher mean P_T of W/Z's and leptons $\Rightarrow$ Anomalous couplings
- We have measured production cross-sections for:
  $W\gamma$, $Z\gamma$, WW, WZ, ZZ
  using the leptonic decays of the W and Z
- Studies of anomalous couplings now in progress
- Provides an important foundation for Higgs searches

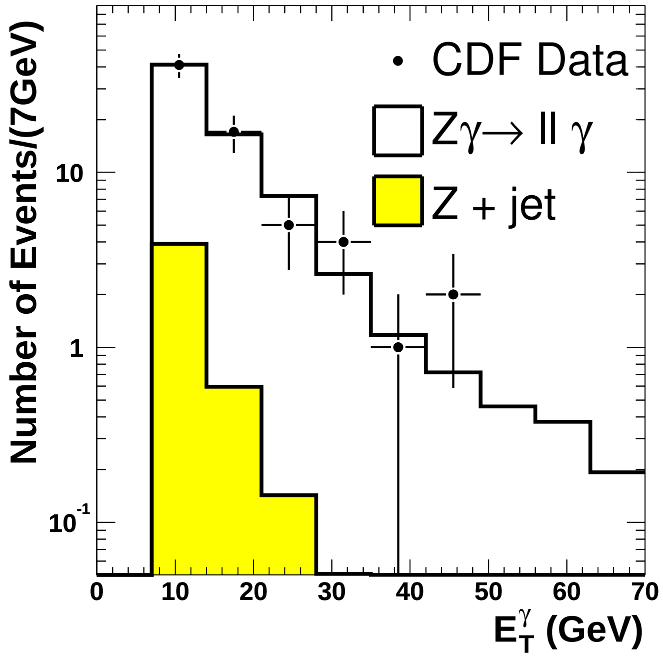
Diboson Results: $W/Z+\gamma$

- Data well described over large range of photon E_T's

	Run 2 measurement ($E_T^\gamma > 7$ GeV) (pb)	SM value
$\sigma(W\gamma)\times BR(W\to\ell\nu)$	$19.7\pm1.7_{(\mathrm{stat})}\pm2.0_{(\mathrm{syst})}\pm1.1_{(\mathrm{lum})}$	19.3 ± 1.4
$\sigma(Z\gamma)\times BR(Z\to\ell\ell)$	$5.3\pm0.6_{(\mathrm{stat})}\pm0.3_{(\mathrm{syst})}\pm0.3_{(\mathrm{lum})}$	5.4 ± 0.3

- Next, with more data, and with WW, test SM couplings



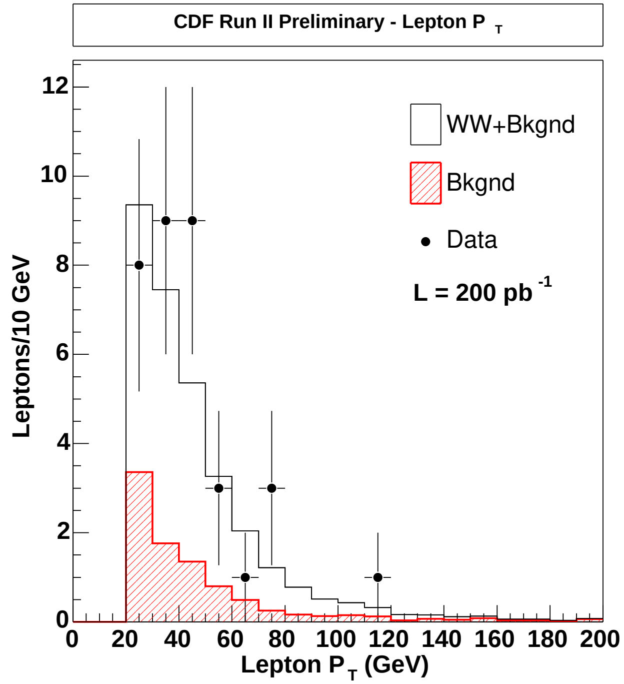


Diboson Results: WW, WZ, ZZ

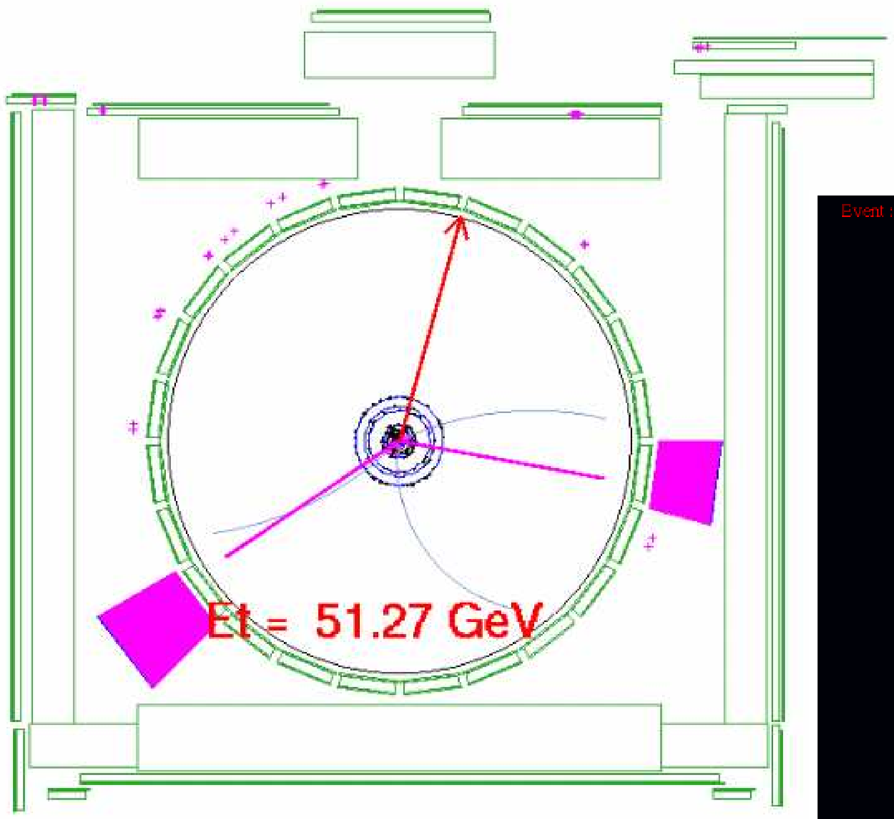
- Use leptonic decays of the vector bosons $\rightarrow$ high-P_T e/μ's, missing E_T

	σ_{theory} (pb)	Observe	Background	Measured σ (pb)
WW	12.5	17 (TT) 39 (TL)	4.8 ± 0.7 16 ± 1	$14.3^{+5.6}_{-4.9}(\mathrm{stat}) \pm 1.6_{(\mathrm{syst})} \pm 0.9_{(\mathrm{lum})}$ $19.4 \pm 5.1_{(\mathrm{stat})} \pm 3.5_{(\mathrm{syst})} \pm 1.2_{(\mathrm{lum})}$
WZ + ZZ	3.8 + 1.4	4	2.3 ± 0.4	< 13.9 at 95% CL

- Evidence for WW in Run 1 now confirmed in Run 2
- Cannot yet claim WZ and ZZ observation but a couple of nice candidates...
- next; better optimize, use additional decay channels (including $Z \rightarrow b\bar{b}$)

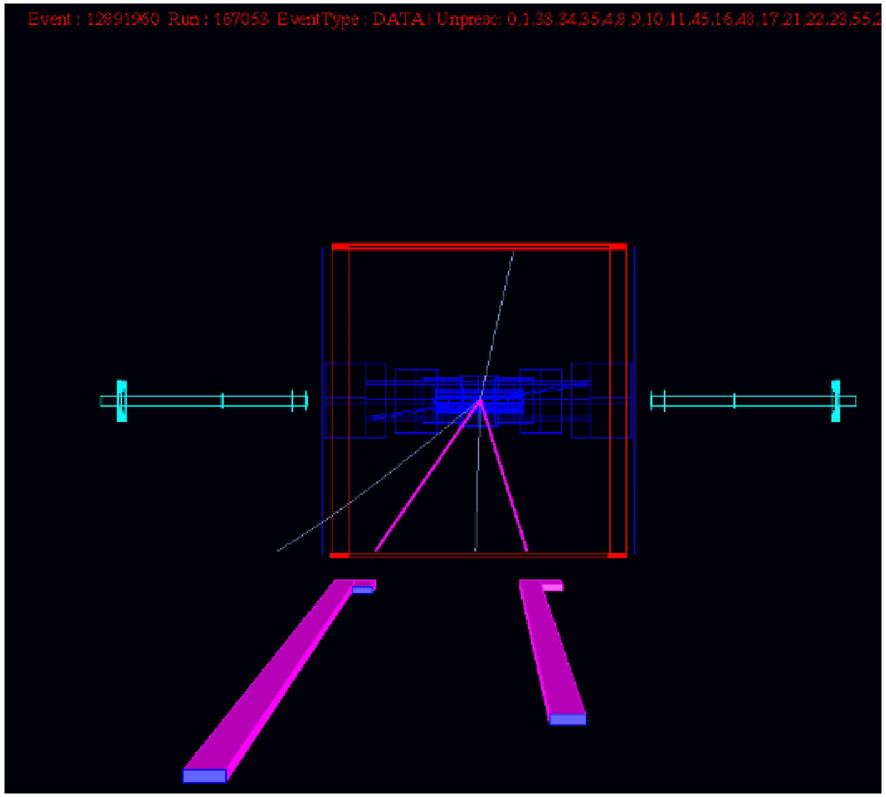


$WW \to e\nu e\nu$ or $ZZ \to ee\nu\nu$?



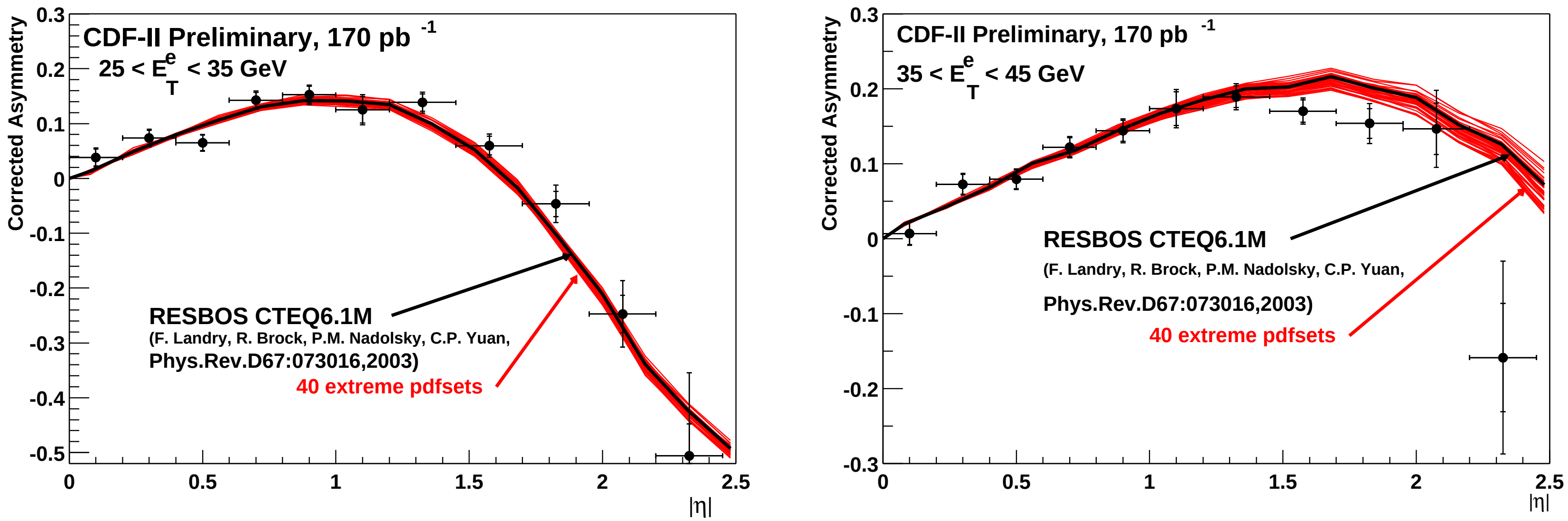
$M_{ee} = 88\ \mathrm{GeV}/c^2$

Missing $E_T \sim 50$ GeV



$W \to e\nu$ charge asymmetry

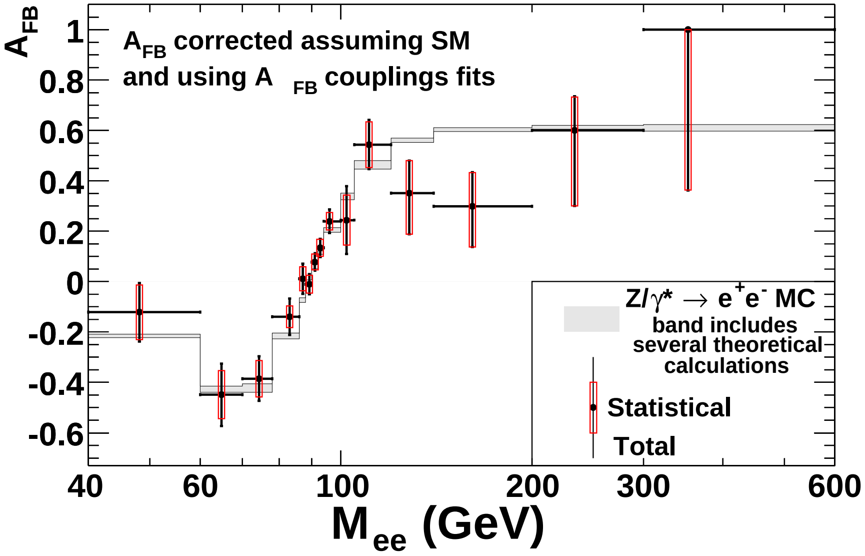
- Provides important constraints to PDF's
- Higher u momentum $\Rightarrow$ W^+ boosted in p direction
  W^- boosted in $\bar{p}$ direction
- Forward electron identification crucial $\to$ use Silicon



- Indication of higher P_T data having more PDF discrimination than prediction (CTEQ6.1 with RESBOS NLO)

Lots of other electroweak activity.....

- Measurement of forward-backward asymmetry of $Z/\gamma^* \to e^+e^-$
  - Direct probe of Z, γ couplings
  - Deviations could signify interference from new physics
  - $\sim 2\sigma$ effect seen in Run 1
  - High mass reach unique to Tevatron
  - In Run 2 $(72\,\mathrm{pb}^{-1})$ see agreement with SM

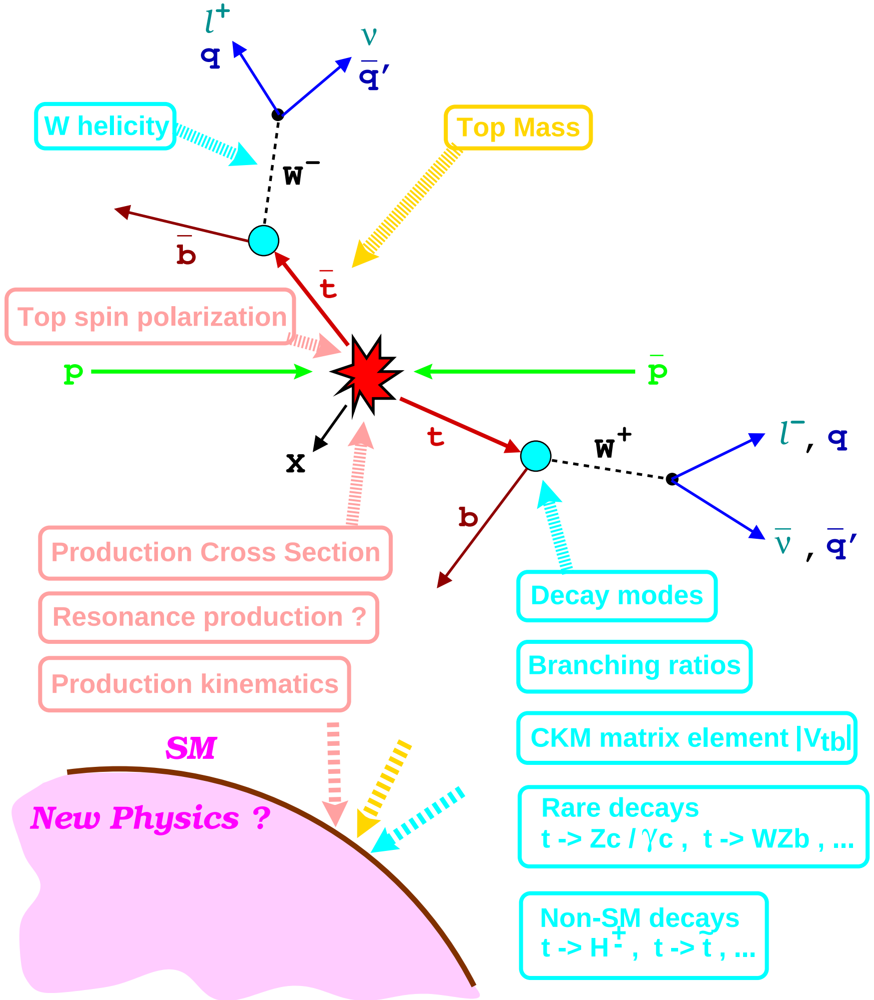


- W/Z cross-sections using tau leptons
  - $\sigma(W) \times BR(W \to \tau\nu) = 2.62 \pm 0.07(\mathrm{stat}) \pm 0.21(\mathrm{syst}) \pm 0.16(\mathrm{lum}) \quad (72\,\mathrm{pb}^{-1})$
  - Provides baseline for all analyses using tau's

- W mass: Requires meticulous understanding of detector responses, resolutions, and backgrounds. Preliminary results ready $\sim$ August

Measuring the Top Quark

- The top quark remains the most intriguing particle we have discovered
- Large Mass $\Rightarrow$ intimate connection with EWSB ?
- Top measurements still statistically limited
- Main Run 2 priority to measure as many top quark properties, in as many ways, and as best we can, not only as a test of the SM, but to exploit the top quark potential to lead us to new physics

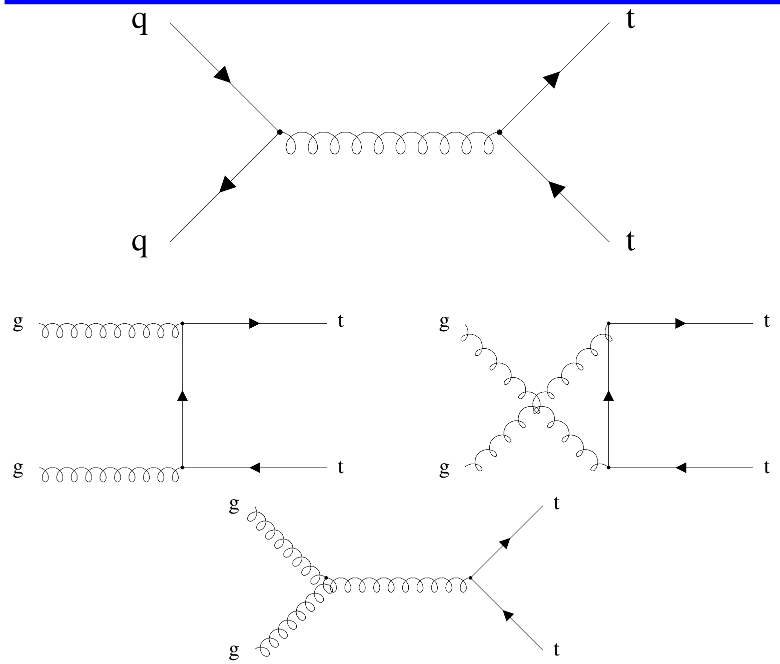


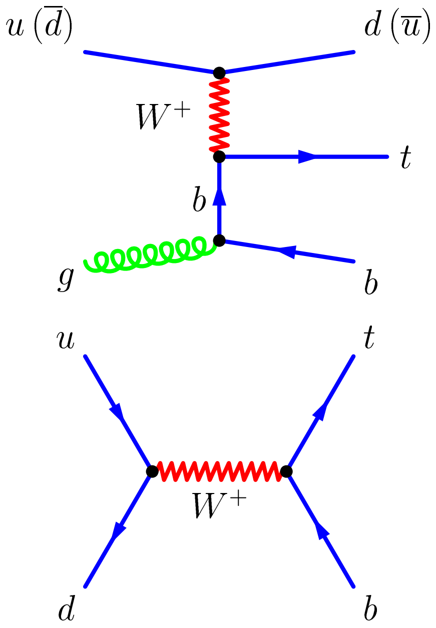
- The Tevatron is the only place to do this for several more years

Top Quark Production

Top quarks can be produced:

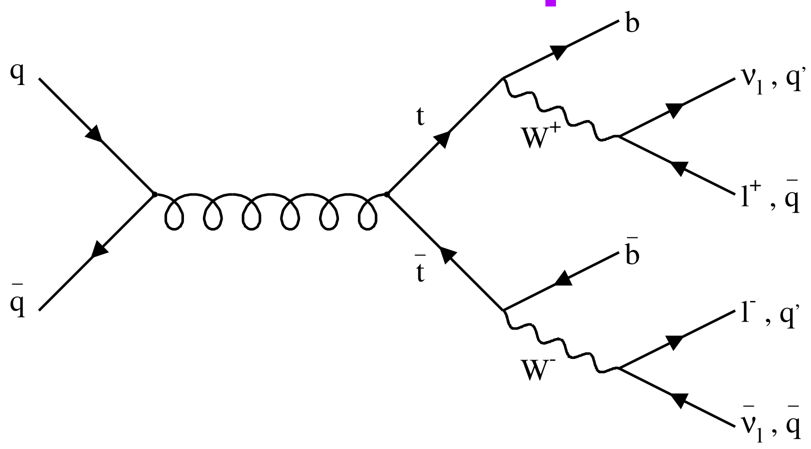
In pairs via the strong interaction	singly via the electroweak interaction





$\sigma \sim 7$ pb (40% increase over Run 1) Many Run 2 measurements	$\sigma \sim 3$ pb Not (yet) observed

Top Decays



$\mathrm{BR}(t \to Wb) \sim 100\%$
$\mathrm{BR}(W \to \ell\nu) = 3/9$
$\mathrm{BR}(W \to q\bar{q}') = 6/9$

We consider the following decay channels for measurements:

- Dilepton: 2 high-P_T e's or μ's, 2 high-E_T jets, large Missing E_T
  BR = 5%
- Tau-dilepton: 1 e or μ, 1 hadronic τ, 2 high-E_T jets, large Missing E_T
  BR = 5%
- Lepton + Jets: 1 high-P_T e or μ, 4 jets (2 b's), large Missing E_T
  BR = 30%
- All-hadronic: 6 jets (2 b's): BR = 44%

Top expectations in Run 2

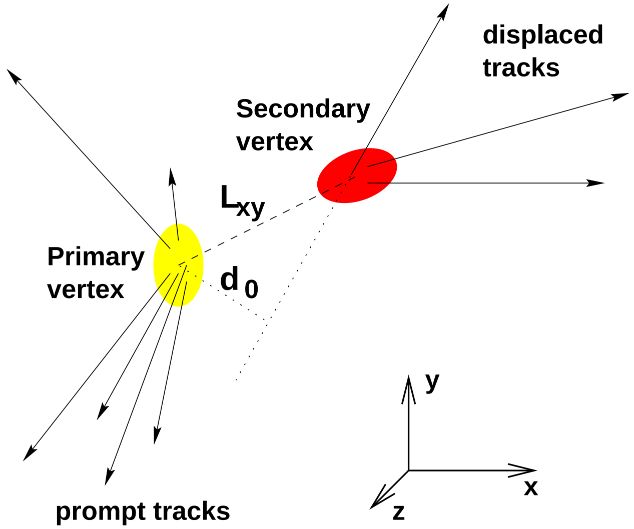
	σ (pb) @ 2 TeV	Events produced per 200 pb^{-1}
$q\bar{q} \rightarrow t\bar{t}$ (90%) $gg \rightarrow t\bar{t}$ (10%)	6.7 ± 0.3	70 (dilepton) 400 (lepton + jets) 600 (all-hadronic)
$q\bar{q} \rightarrow W^* \rightarrow tb$ (30%) $qb \rightarrow q't$ (70%)	2.9 ± 0.3	130 (lepton + jets)

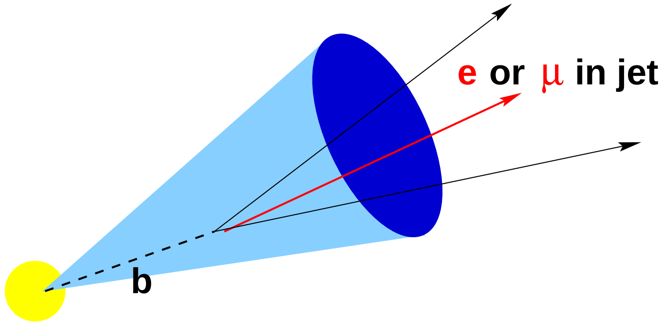
- Detection efficiencies $\Rightarrow$
  expect to observe 10 - 20% of events produced

Heavy Flavour tagging

- Lepton + jets and all-hadronic decay channels rely heavily on identification of B hadron decays to reduce backgrounds

Measure secondary vertex: B's travel $\sim 3\,mm$ before decay	Identify low-P_T muon in jet: BR($b \to \ell\nu c$) $\sim$ 20%

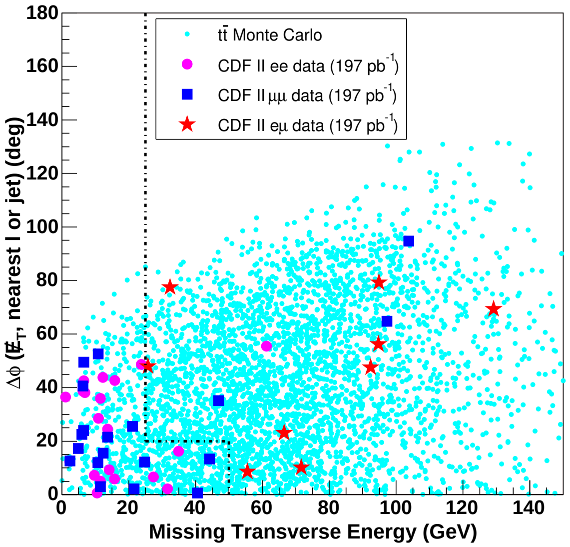




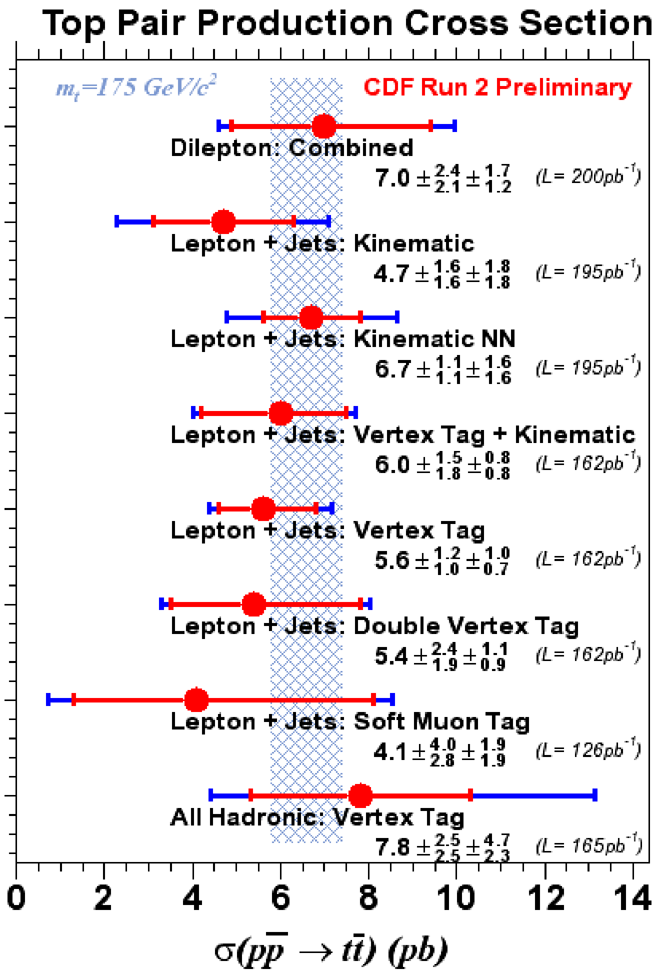
Top event tag efficiency $\sim 55\%$ False tag rate $\sim 0.5\%$ Relies on excellent Si performance	Top event tag efficiency $\sim 15\%$ False tag rate $\sim 0.6\% \times N_{track}$

Run 2 Top Cross-sections

- Many different avenues taken
- All sensitive to, and test, different aspects of top production
- E.g. $ee + e\mu + \mu\mu$: cleanest channel
  mild $e\mu$ anomaly seen in Run 1
  Run 2: expect 5 $ee + \mu\mu$, 5.5 $e\mu$

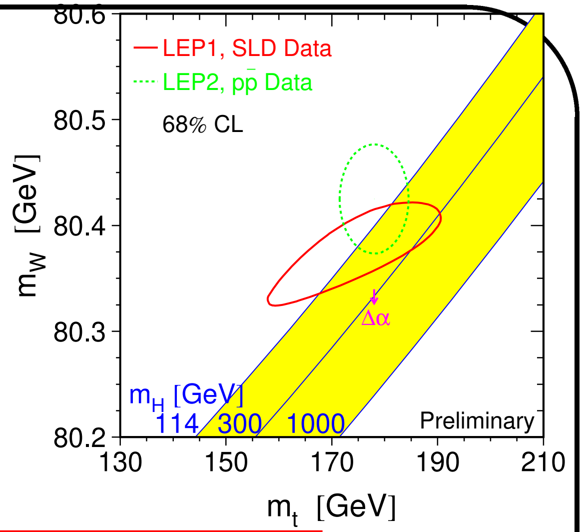


Observe:
1 ee
3 $\mu\mu$
9 $e\mu$



- Combine all results for best precision
- goal to achieve 10% result after 2 fb^{-1} (also expect ~ 100 $t\bar{t} \to dileptons$!)

Top Mass in Run 2

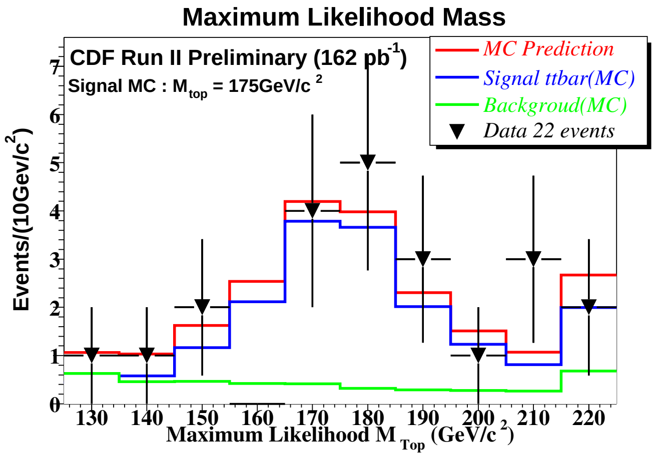


- Precision measurement constrains Higgs sector:
  ± 1 GeV in M_{top} $\Rightarrow$ ± 5 GeV in best fit M_{higgs}
- Different methods use different assumptions and event information
  - Using b-tagged lepton + jets events
    Dynamical Likelihood: $\boxed{M_{top} = 177.8^{+4.5}_{-5.0}(\mathrm{stat}) \pm 6.2(\mathrm{syst})\mathrm{GeV}/c^2}$

(Template: $M_{top} = 174.9^{+7.1}_{-7.7} \pm 6.5\,\mathrm{GeV}/c^2$ Multivariate: $M_{top} = 179.6^{+6.4}_{-6.3} \pm 6.8\,\mathrm{GeV}/c^2$)

  - From dilepton events: $\boxed{M_{top} = 175 \pm 17(\mathrm{stat}) \pm 8(\mathrm{syst})\mathrm{GeV}/c^2}$ $(126\,\mathrm{pb}^{-1})$

- c.f. Run 1 CDF + DØ world average:
  $178.0 \pm 4.3\ \mathrm{GeV}/c^2$
- Near future improvements in simulation, jet energy scale, and finally combining all information, will give significant improvements. Longer term goal to achieve $\Delta M_{top} \sim 3$ GeV. Please stand by.....



Top Physics Outlook

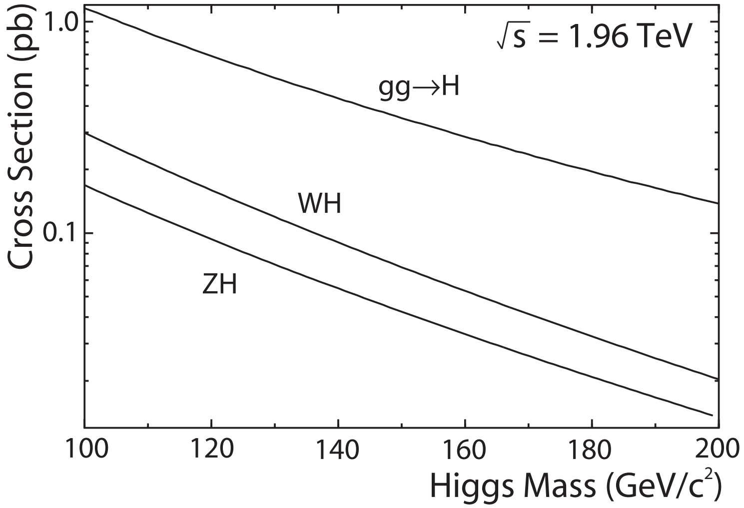
- Many other measurements with initial results and in progress:
  - Searches for single top: Cross-section a direct test of the Wtb coupling: Current Run 2 result: < 13.7 pb @ 95% CL (combined)
  - W helicity
  - Measurements of BR's
  - Tau-dilepton channel
  - Search for high mass particles decaying to $t\bar{t}$
  - Search for rare decays
  - Top quark spin
- Submitted first top paper (dilepton cross-section), with many to follow this summer
- Now entering first period of precision top measurements: anomalies, surprises, could be important clues to mass generation in the universe, and/or other new physics

Searches for the Higgs

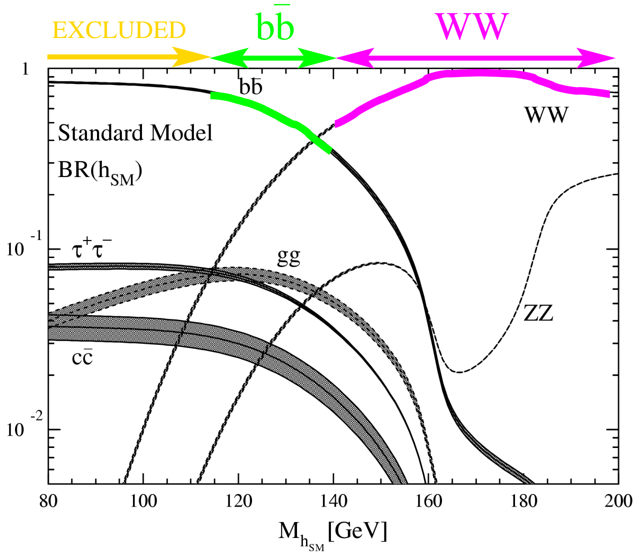
- The Higgs boson is crucial to our understanding of EWSB
- The Standard Model Higgs is used as a benchmark for our discovery potential. Currently:
  - $M_H > 114\,\mathrm{GeV}/c^2$ (95% CL) (from direct LEP searches)
  - $M_H < 251\,\mathrm{GeV}/c^2$ (95% CL) (from fit to electroweak data)
  - With 5 fb^{-1} $\Rightarrow$ can exclude SM Higgs up to $\sim 130\,\mathrm{GeV}/c^2$
    $\Rightarrow$ possibly achieve a 3σ result for $M_H \sim 115\,\mathrm{GeV}/c^2$
- However, there exist many additional Higgs bosons in a variety of other models, some of which we are more sensitive to
- Many analyses underway at CDF:
  - Deep understanding of backgrounds and signal required
  - Rely heavily on tools and experience from related analyses
  - Some promising ideas emerging to increase sensitivity

SM Higgs Overview

- Production



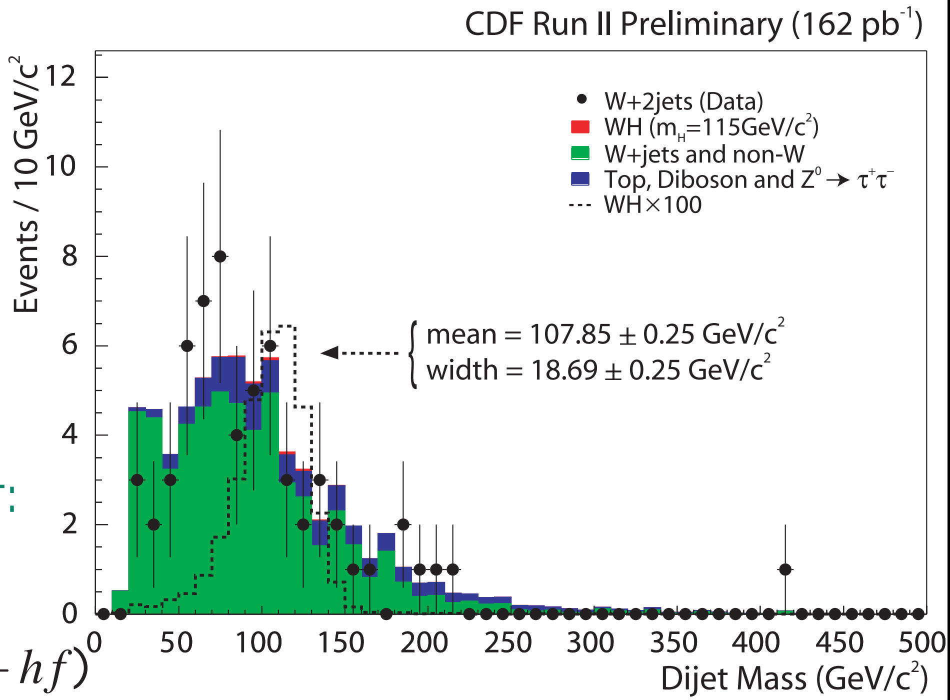
- Decay



- Low mass Higgs searches require associated vector boson production for sensitivity
- For $M_H > 140\,\mathrm{GeV}/c^2$ WW decay mode predominant
  $\Rightarrow$ significant gain from $gg \to H$
- E.g. $M_H = 115$: 7 $q\bar{q}' \to WH \to \ell\nu b\bar{b}$ events produced in 200 pb^{-1}
  $M_H = 180$: 40 $gg \to H \to WW^*$, 2.0 with $WW \to \ell\nu\ell\nu$

Run 2 Higgs search using $WH \to \ell\nu b\bar{b}$

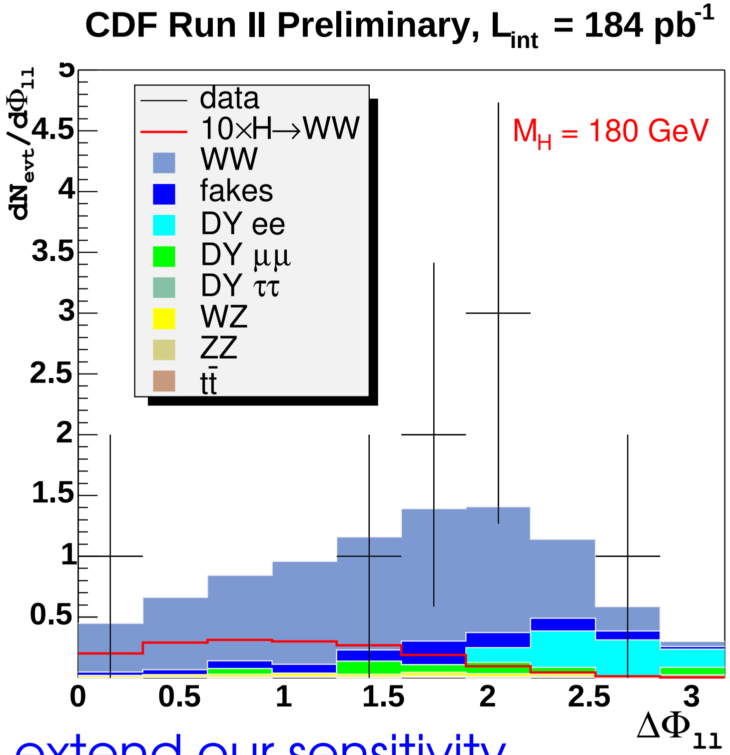
- Utilizes many of the tools and experience from the $t\bar{t}$ "lepton + jets" analyses
- Select events with:
  - 1 high-P_T lepton
  - Large missing E_T
  - 2 jets (≥ 1 b-tag)
- For $M_H = 115\,\mathrm{GeV}/c^2$, expect:
  - 0.7 $WH \to \ell\nu b\bar{b}$ events
  - 60 Background (40% $W + hf$)
  - Observe 62 events



- Use shape of resulting dijet mass distribution to set limits
- Dijet mass resolution and b-tagging efficiency important features

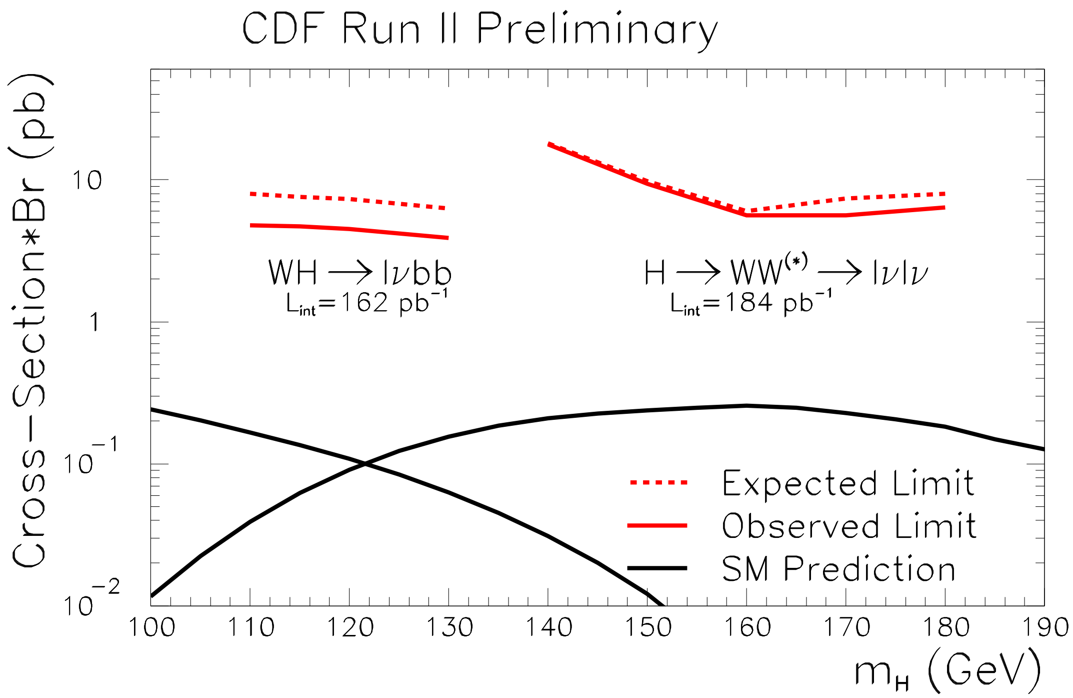
Run 2 Higgs search using $H \rightarrow WW^* \rightarrow \ell\nu\,\ell\nu$

- Small branching ratio but extremely clean signal
- Borrows extensively from WW analysis, but with:
  - $M_{\ell\ell} < M_H/2$
  - $\Delta\phi(\ell,\ell)$ good discriminator from backgrounds $\Rightarrow$ use distribution to set limits
- For $M_H = 180\,\mathrm{GeV}/c^2$, expect:
  - 0.2 $H \rightarrow WW$ events
  - 8.9 Background (75% WW)
  - Observe 8 events



- Progress being made on ways to extend our sensitivity and include other production and decay mechanisms

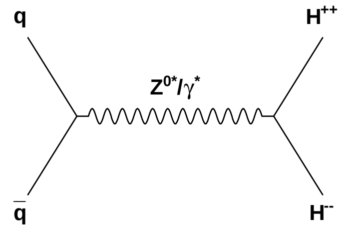
Run 2 SM Higgs results



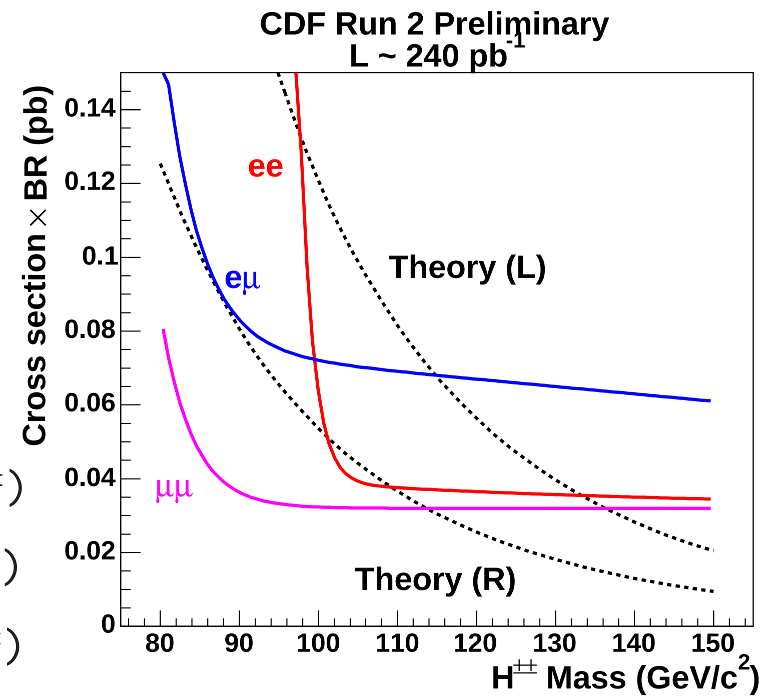
- Limits now better than in Run 1 ($H \to WW$ new to Run 2)
- But this is just the beginning....
  - Improvements in jet energy resolution and b-tagging
  - Combine with other WH and ZH decay channels for low mass Higgs
  - $WH \to WWW$, $ZH \to ZWW$ with many decay channels

Search for doubly-charged Higgs

- Beyond SM, low mass $H^{\pm\pm}$ (< 1 TeV) predicted by some models



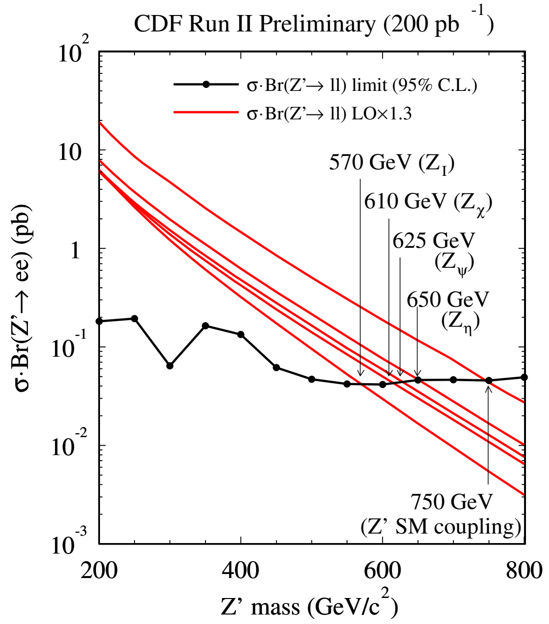
- $H^{\pm\pm}$ decay to same-sign leptons $\Rightarrow$ backgrounds very small
- For $M_{H^{\pm\pm}} = 120\,\mathrm{GeV}/c^2$, expect:
  - 5 $H_L^{\pm\pm} \to e^\pm e^\pm, \mu^\pm\mu^\pm$ events
    2.5 $H_L^{\pm\pm} \to e^\pm\mu^\pm$ events
  - 1.0 background evt (50% ee)
  - 0 events observed



- Obtain limits (at 95% CL) of:
  - $M_{H^{\pm\pm}} > 136\,\mathrm{GeV}/c^2 \quad (H_L^{\pm\pm} \to \mu^\pm\mu^\pm)$
  - $M_{H^{\pm\pm}} > 133\,\mathrm{GeV}/c^2 \quad (H_L^{\pm\pm} \to e^\pm e^\pm)$
  - $M_{H^{\pm\pm}} > 115\,\mathrm{GeV}/c^2 \quad (H_L^{\pm\pm} \to e^\pm\mu^\pm)$
- One of several interesting Higgs searches outside the SM

Many more new physics searches at CDF

- A myriad of searches underway, many with results from $200\,\mathrm{pb}^{-1}$, covering a large spectrum of new physics ideas
  - Other Higgs's: SUSY models, Quasi-stable doubly charged
  - Magnetic monopoles
  - many different SUSY searches
  - GMSB: anomalous $\gamma\gamma$ + Missing E_T
  - high mass Z', W'
  - Leptoquarks
  - excited leptons
  - signatures of extra dimensions



- Already 18 Run 2 new physics results completed and on the path toward publication – many more to follow
- **Leaving no stone unturned → if it's there, we will find it !**

Summary

- Run 2 is leading us into a fascinating next few years

  Precision measurements from W's and Z's

  $\Downarrow$

  Testing the SM with Top and Dibosons

  $\Downarrow$

  Direct and indirect searches for the Higgs and new physics

- A flurry of activity in many areas – already several Run 2 high-P_T analyses either submitted for publication or close to it

- Keep checking our public analysis web pages for details of all our latest results

- We are exploring what the universe looked like after $\sim 10^{-12}$s !
  (and when its temperature was $\sim 10^{16}$K)
  This is largely unknown territory; who knows what we might find...