CDF Highlights

a personal selection:

- ⋆ inclusive $\sigma \times BR$ for W/Z
- ⋆ $Z' \rightarrow \mu^+\mu^-$ Searches
- ⋆ top cross sections
- ⋆ $X(3872) \rightarrow J/\psi\,\pi^+\pi^-$

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Outline

Experience from Four CDF Muon-based Analyses

Key Elements:

- acceptance
- efficiency
- background
- momentum resolution

as appear in:

1. inclusive W and Z cross section measurements
2. searches for anomalous high-mass di-muon pairs
3. top cross sections
4. J/ψ signals

Inclusive W and Z Cross Section Measurements

We measure both the individual cross sections for

$$p\bar{p} \to W \to \ell\nu \qquad \text{and} \qquad p\bar{p} \to Z \to \ell^+\ell^-$$

and their ratio,

$$R = \frac{\sigma \times BR(W \to \ell\nu)}{\sigma \times BR(W \to \ell\nu)} = \left(\frac{\sigma(W)}{\sigma(Z)}\right) \times \frac{1}{Br(Z \to \ell^+\ell^-)} \times \frac{\Gamma(W \to \ell\nu)}{\Gamma_W^{\text{tot}}}$$

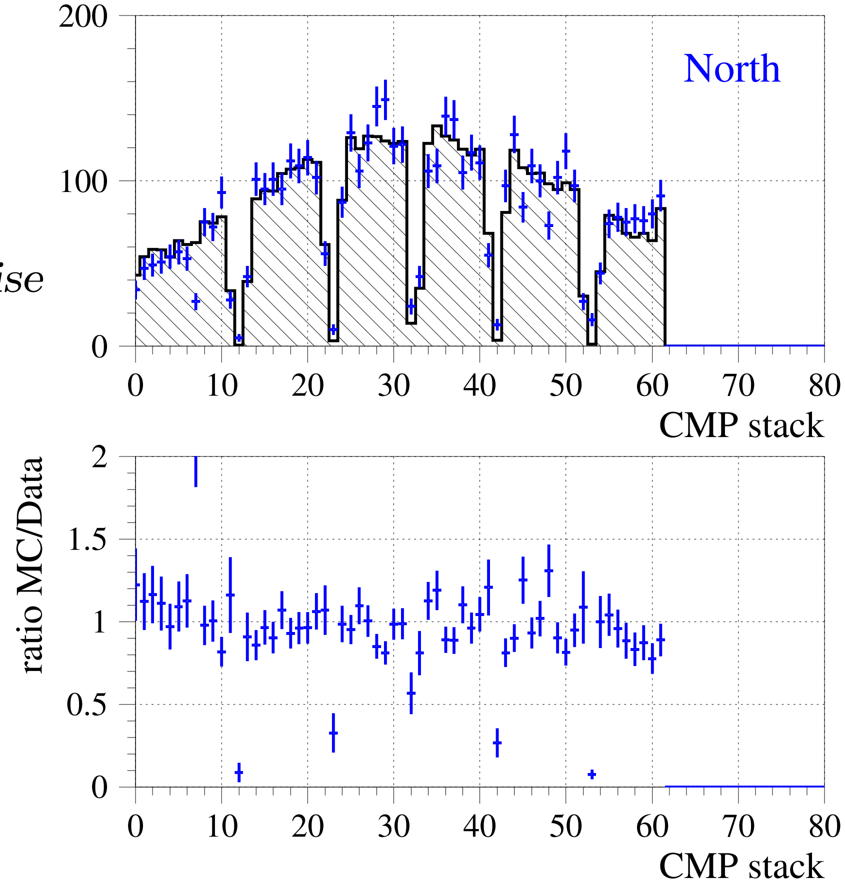
(We pursue both electron and muon channels simultaneously.)

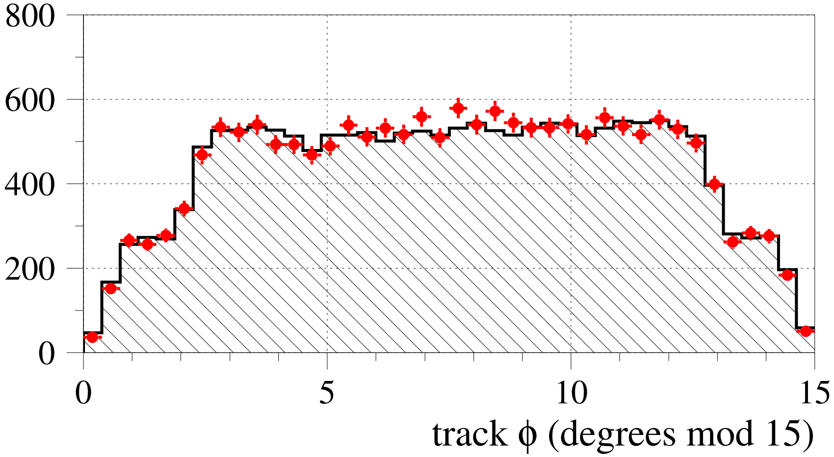
- gateway to top and searches for new physics
- a basic test of the Standard Model (QCD / parton distributions)
- extraction of W width
- future benchmark for luminosity

Our aim is a precision of 1 – 2% aside from the luminosity uncertainty.

Acceptance

- geometrical and kinematic
- accuracy depends on the fidelity of the detector description in the MC. *requires hard and careful work early on*
- individual chambers do malfunction. *discover them by appropriate direct comparisons of data and MC*
- good run lists require control of detector performance. *can be a long job – need to devise good procedure to track any time dependence that may arise*

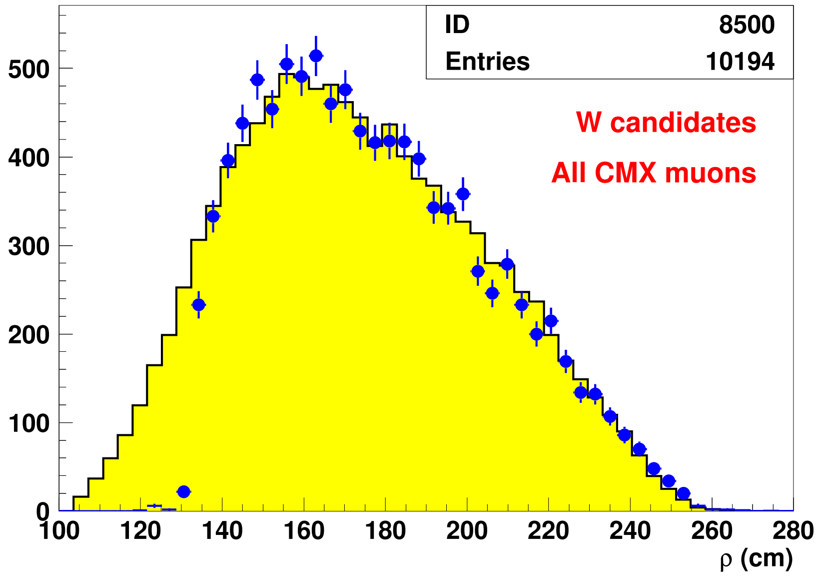




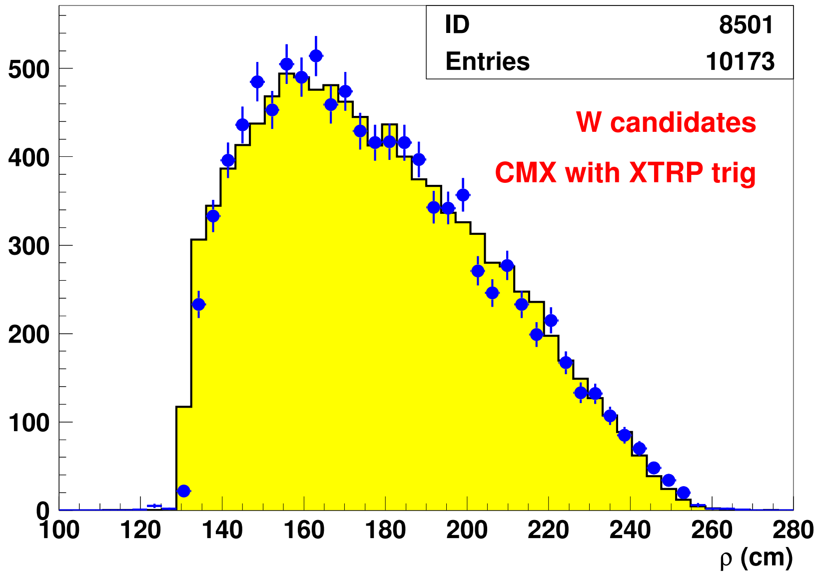
Efficiency

- several components
  - trigger
  - reconstruction
  - identification
  - isolation

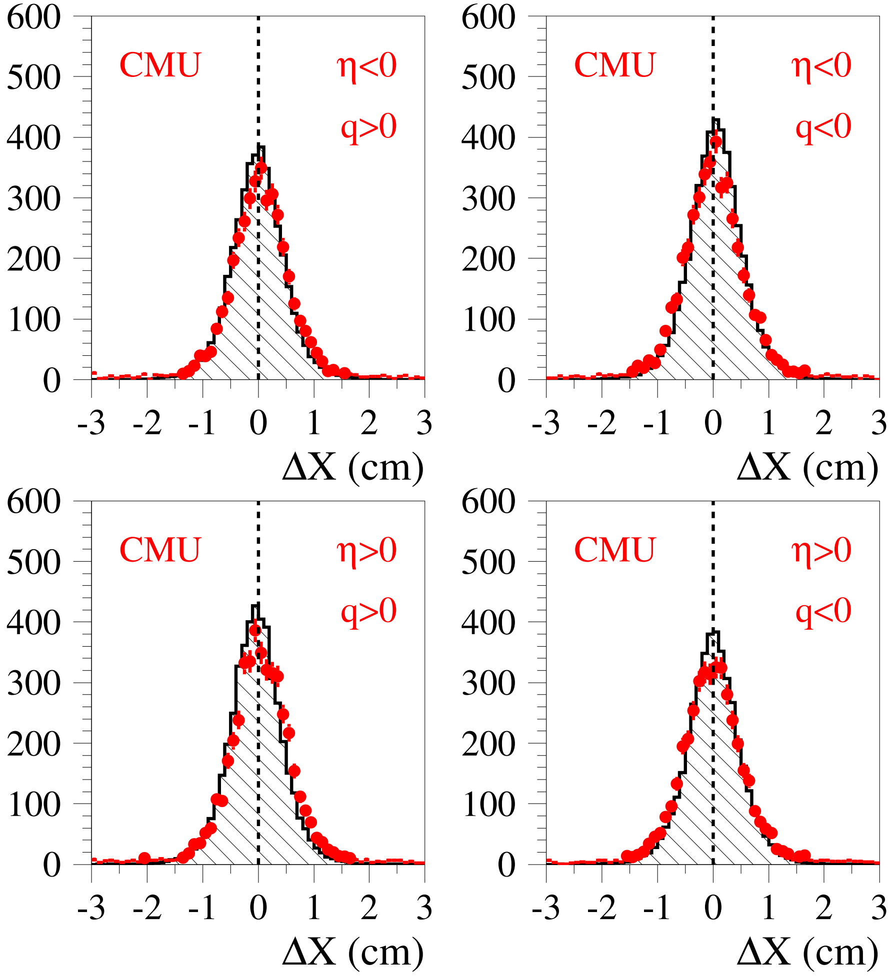
  watch out for correlations



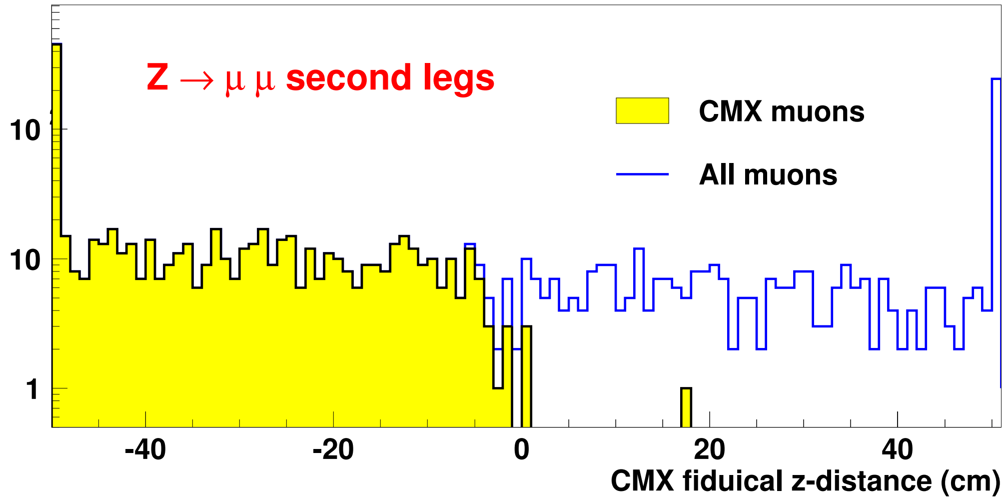
- measure directly from data for accuracy
  – otherwise you won't get it right.
- use tagged source of muons: $Z \rightarrow \mu^+\mu^-$
- uncertainties decrease as Z sample increases (They are mainly statistical.)
- We achieve $\delta\epsilon \sim 1\%$ for $72\mathrm{pb}^{-1}$



verify multiple scattering
and magnetic fields



Find the *actual* fiducial region.



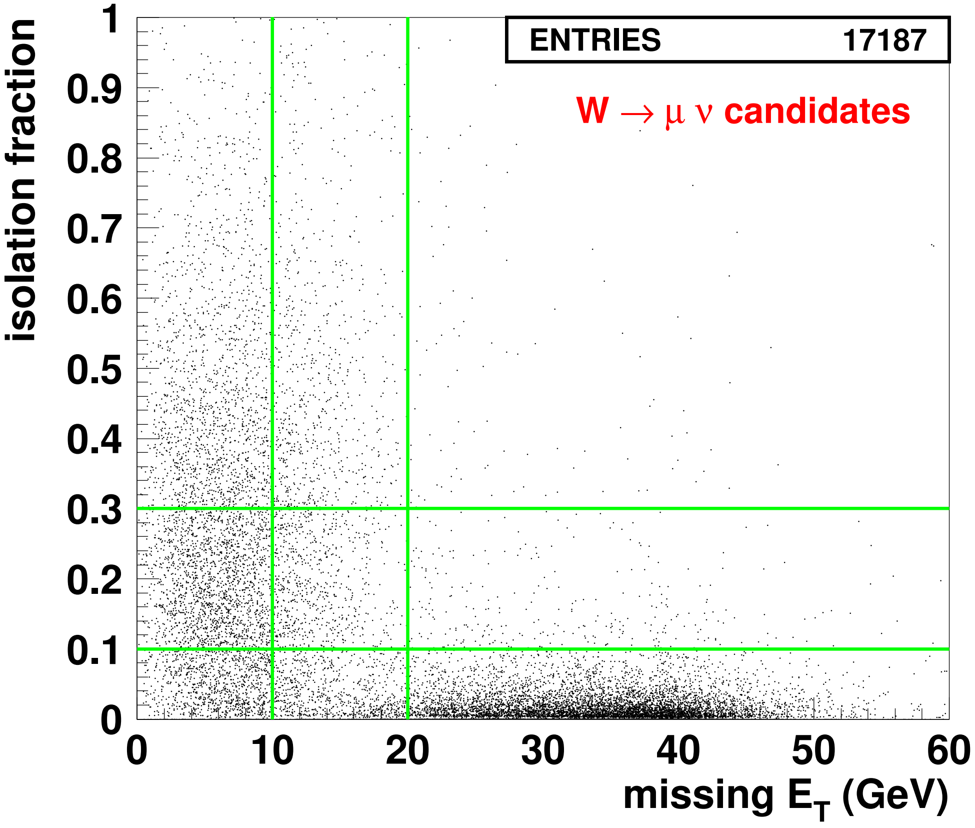
Backgrounds

There are three categories for this measurement:

1. electroweak backgrounds
   - ex: $Z \to \mu^+\mu^-$ in the $W \to \mu\nu$ channel
   - can be reliably calculated using simulations
   - di-boson production and $t\bar{t}$ quite small
2. multi-jet 'QCD' backgrounds.
   - muons not from weak bosons ($B \to D\mu\nu$ and $K^+ \to \mu^+\nu$)
   - hadrons that look like muons ('punch-through' and 'sail-through')
   - cross section huge, so eventually anything can happen. . .
   - these events are on the tails of tails of tails – *cannot be simulated reliably*
3. cosmic rays
   - huge raw rate at present luminosities
   - vast majority easily eliminated by demanding small impact parameters with respect to beam line (and proximity to event vertex)
   - employ timing capabilities of the COT to identify muon tracks which enter the chamber from outside (other timing devices available)
   - We have successfully eliminated cosmic rays – the challenge was to estimate how small they are in our sample!

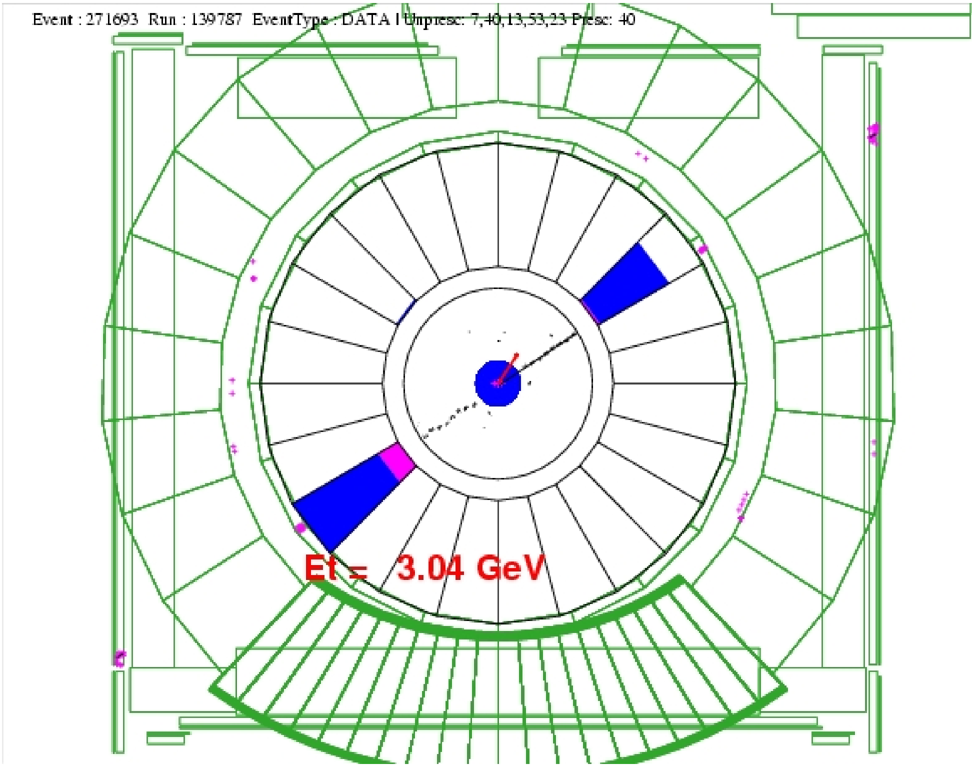
QCD BG

- Try to use 'isolation' (relative energy in a cone around the muon) and $\not{E}_T$ to define control regions.
- Assume these two quantities are uncorrelated for a given source.
- Important to correct for the *signal* which falls in the control regions.
- Estimated QCD contamination varies as we vary the boundaries of the control regions $\longrightarrow$ BAD!
  (This is tracked by the simulation.)
- We assign a large uncertainty ($\sim 25\%$) corresponding to this variation.



Cosmic Ray BG

- CR muons do not show the usual characteristics of reconstructed tracks because they typically are out-of-time (& out-of-place).
- We can exploit this to remove them.
- But what are the characteristics of the events which remain?
  In which ways are they 'biased' w.r.t the regular cosmic ray muons?
- This makes it difficult to use real data measure the efficiency of this set of analysis cuts for cosmic rays.

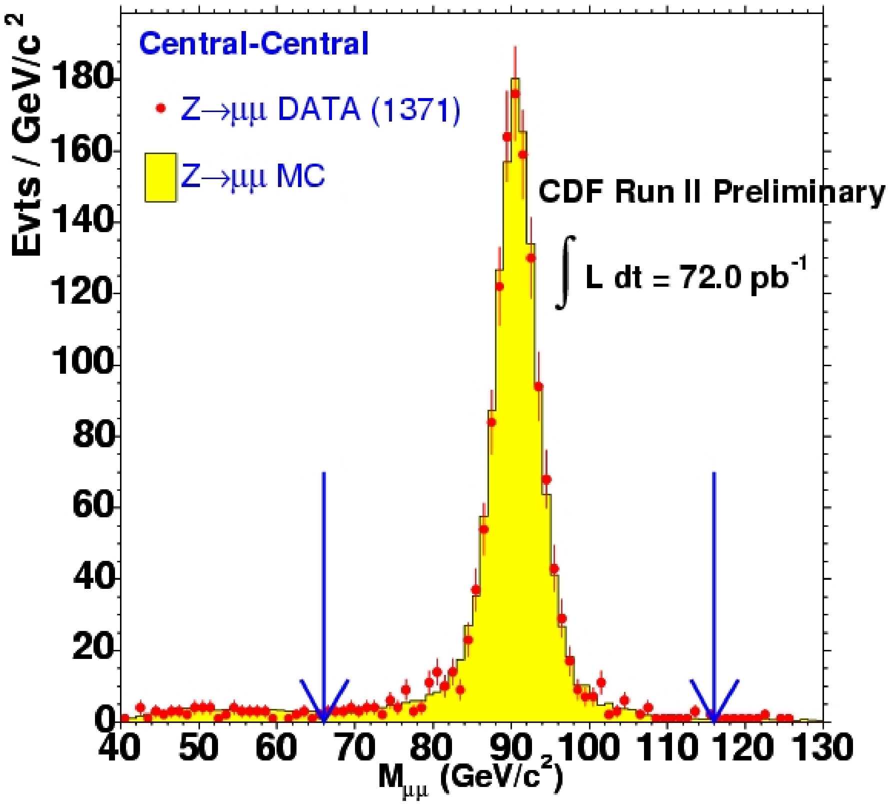


- useful handles:
  - presence of muon stubs opposite the reconstructed track
  - the back-to-back nature of cosmic rays
  - the unique impact parameter distribution
- in the end, very small contamination with a large uncertainty

Momentum Scale & Resolution

- enters as part of the (kinematic) acceptance
- tune the simulation to match the data (scale factor 0.997, no additional smearing)

$\longrightarrow$



- not especially crucial for this analysis $\delta A_W = 0.21\%$ and $\delta A_Z = 0.05\%$

Results

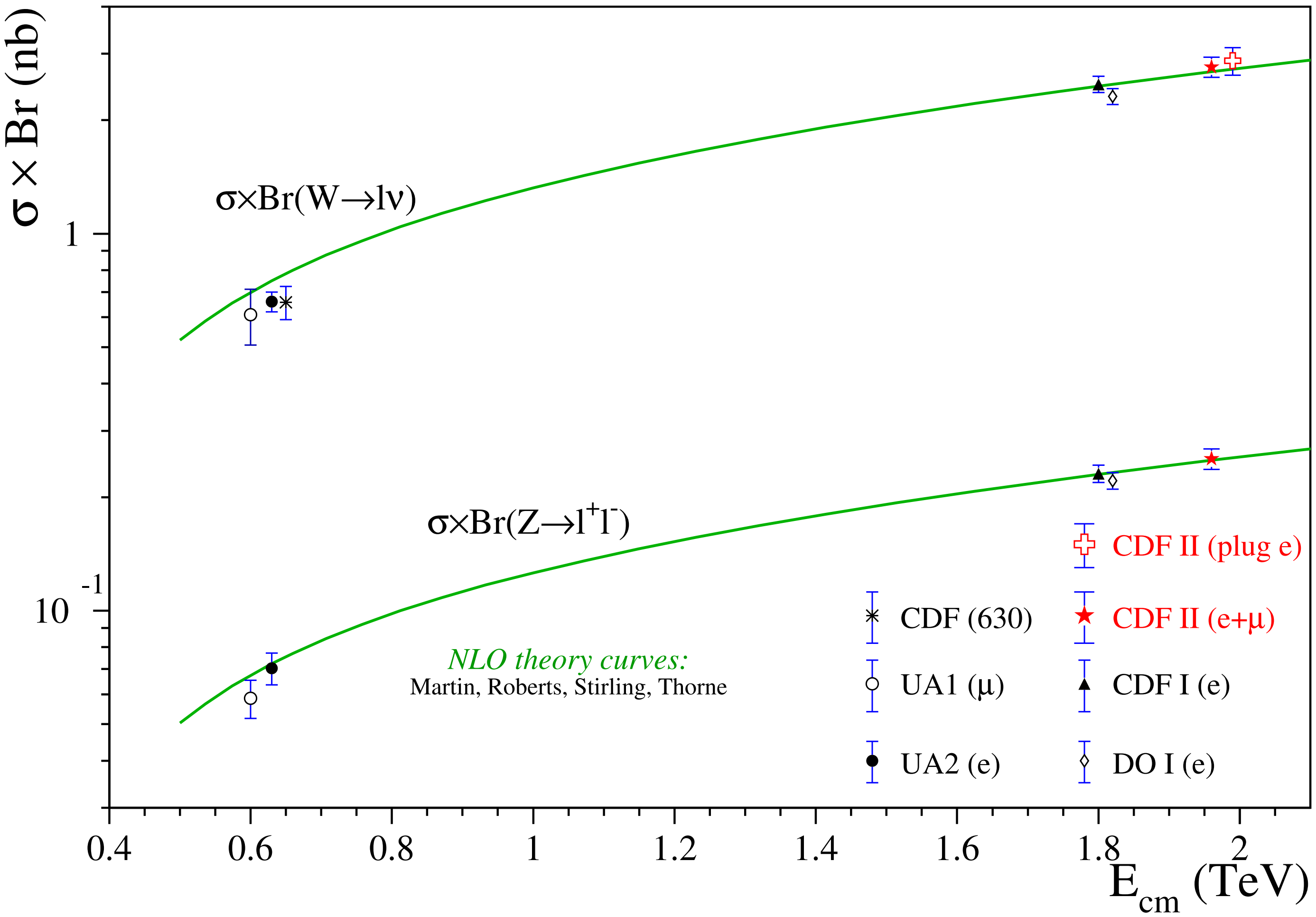
Putting all this and many other things together, we measure ($\mathcal{L} = 72.0\text{pb}^{-1}$):

$$
\begin{aligned}
\sigma \cdot Br(p\bar{p} \to W \to \mu\nu) &= 2772 \pm 16_{(\text{stat})} \,{}^{+64}_{-60}\,(\text{syst}) \pm 166_{(\text{lum})} \text{ pb} \\
\sigma \cdot Br(p\bar{p} \to W \to e\nu) &= 2782 \pm 14_{(\text{stat})} \,{}^{+61}_{-56}\,(\text{syst}) \pm 167_{(\text{lum})} \text{ pb} \\
\\
\sigma \cdot Br(p\bar{p} \to W \to \ell\nu) &= 2777 \pm 10_{(\text{stat})} \pm 52_{(\text{syst})} \pm 167_{(\text{lum})} \text{ pb}
\end{aligned}
$$

For the mass range 66 GeV $< M_{\ell^+\ell^-} <$ 106 GeV,

$$
\begin{aligned}
\sigma \cdot Br(p\bar{p} \to \gamma^*/Z \to \mu\nu) &= 248.9 \pm 5.9_{(\text{stat})} \,{}^{+7.0}_{-6.2}\,(\text{syst}) \pm 14.9_{(\text{lum})} \text{ pb} \\
\sigma \cdot Br(p\bar{p} \to \gamma^*/Z \to e\nu) &= 255.2 \pm 3.9_{(\text{stat})} \,{}^{+5.5}_{-5.4}\,(\text{syst}) \pm 15.3_{(\text{lum})} \text{ pb} \\
\\
\sigma \cdot Br(p\bar{p} \to \gamma^*/Z \to \ell\nu) &= 254.3 \pm 3.3_{(\text{stat})} \pm 4.3_{(\text{syst})} \pm 15.3_{(\text{lum})} \text{ pb}
\end{aligned}
$$

The precision is 2%, aside from a 6% luminosity uncertainty.



(These results will be released soon. . .)

One can extract W properties from the *ratio of cross sections*:

$$R = \frac{\sigma \cdot Br(p\bar{p} \to W \to \ell\nu)}{\sigma \cdot Br(p\bar{p} \to Z \to \ell^+\ell^-)} = \frac{\sigma(p\bar{p} \to W)}{\sigma(p\bar{p} \to Z)} \times \frac{\Gamma_Z}{\Gamma_Z(\ell^+\ell^-)} \times \frac{\Gamma_W(\ell\nu)}{\Gamma_W}$$

- We correct the $\ell^+\ell^-$ cross sections for γ^* exchange.
- We combined the individual R measurements rather than taking the ratio of combined cross sections.

$$R_\mu = 11.10 \pm 0.27_{(\mathrm{stat})} \pm 0.17_{(\mathrm{syst})}$$
$$R_e = 10.86 \pm 0.18_{(\mathrm{stat})} \pm 0.16_{(\mathrm{syst})}$$

$$R = 10.94 \pm 0.15_{(\mathrm{stat})} \pm 0.13_{(\mathrm{syst})}$$

The combined ratio is precise to 1.8% independent of the luminosity.

W leptonic branching ratio:

use the ratio of cross sections and $Br(Z \to \ell^+\ell^-)$:

$$Br(W \to \ell\nu) = 0.1093 \pm 0.0021$$

W Width:

now use the SM value for the leptonic partial width:

$$\Gamma_W = 2071 \pm 40 \text{ MeV}$$

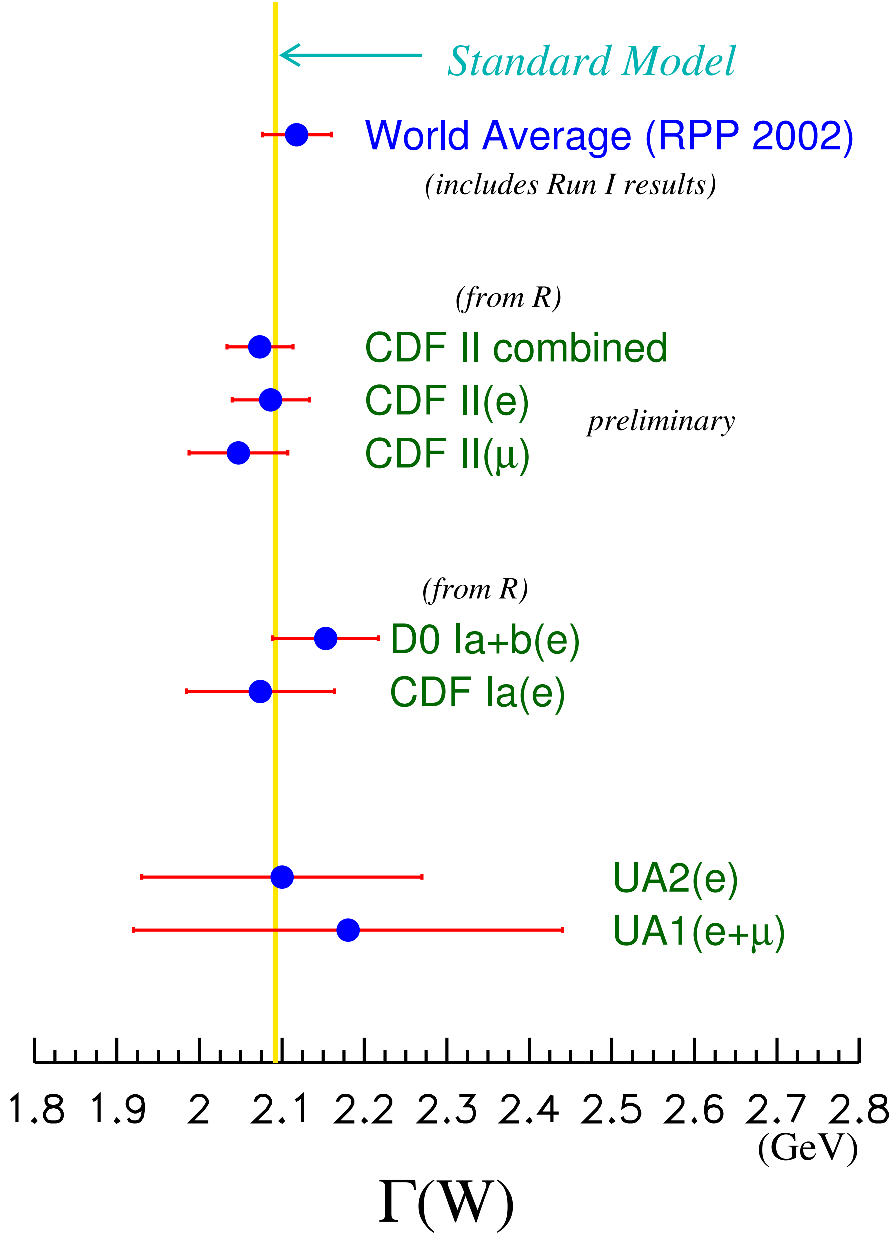
CKM Matrix Element V_{cs}:

Γ_W depends on a sum over two rows in the CKM matrix:

$$\Gamma_W = 3\Gamma_W^0 + 3\left(1 + \frac{\alpha_s}{\pi} + 1.409(\frac{\alpha_s}{\pi})^2 - 12.77(\frac{\alpha_s}{\pi})^3\right) \sum_{\text{[no top]}} |V_{qq'}|^2\,\Gamma_W^0.$$

We use PDG values for all of these except V_{cs}, and then impose our measurement of Γ_W to constrain V_{cs}

$$|V_{\mathrm{cs}}| = 0.962 \pm 0.030.$$



Summary of Γ_W^{tot}

The new CDF measurement is slightly more precise than the combined Run I results.

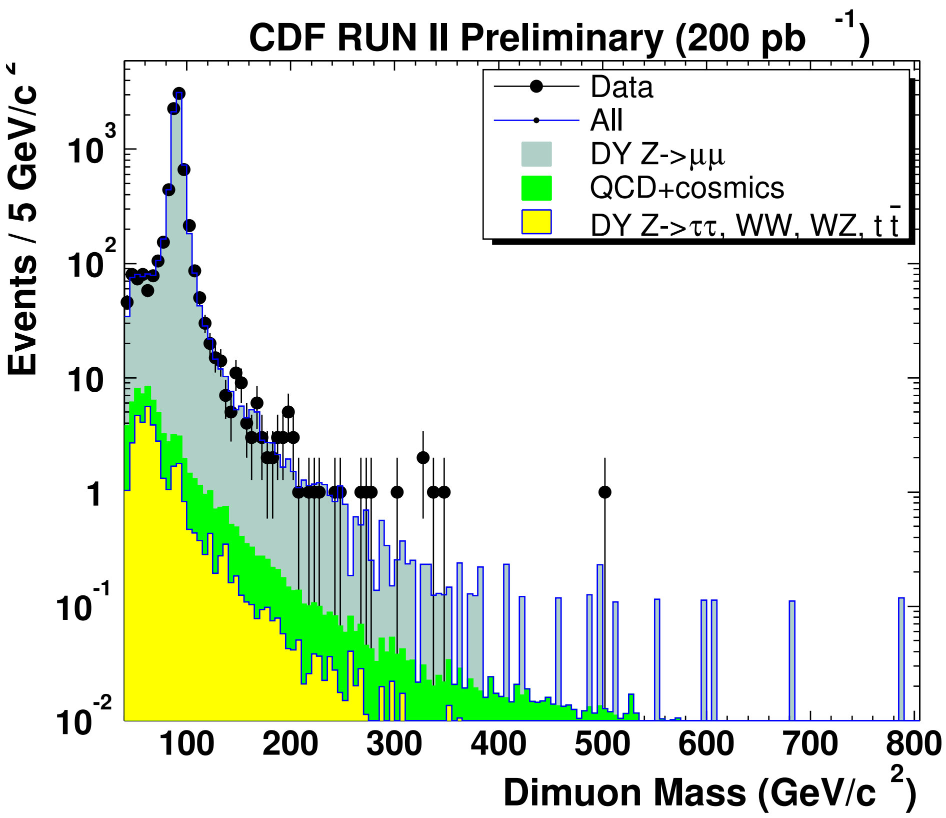
Search for Z''s

- Look well above the SM $Z \to \mu^+\mu^-$ peak.
  (Naturally, the analysis is very similar to the one just described.)

- Loosened some requirements to increase efficiency and acceptance.

- Here the emphasis will be on the backgrounds at high masses rather than on acceptances and efficiencies.
  - irreducible Drell-Yan background is well known
  - important to understand the *shape* of the QCD and CR backgrounds as a function of $M_{\mu\mu}$
  - use jet samples to study fakes
  - use dedicated CR runs (free from $p\bar{p}$ collisions!)

Mass spectrum for $\mathcal{L} = 200 \pm 12\ \text{pb}^{-1}$



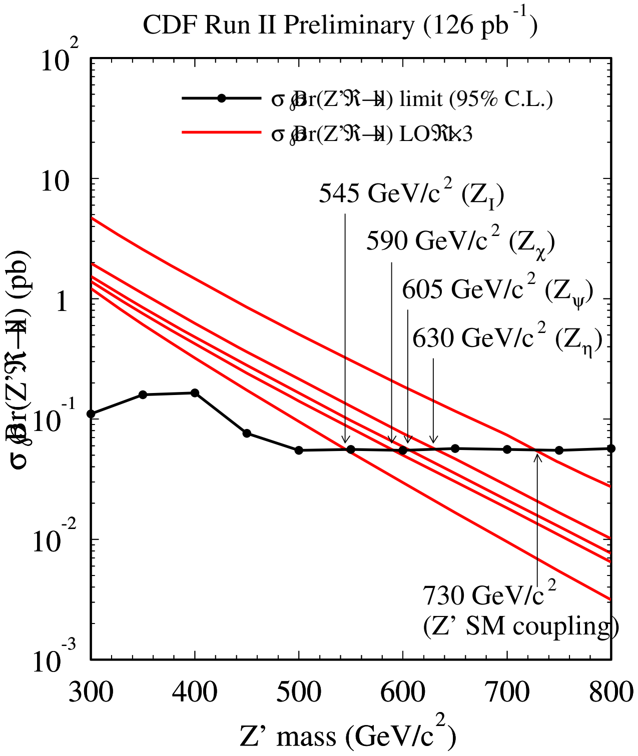
$M_{\ell^+\ell^-}^{(\min)}$	electrons		muons	
	expected	observed	expected	observed
150	n/a	n/a	55	58
200	70	71	21	18
250	27	30	9.5	9
300	11	14	5.2	6
350	4.6	8	3.2	1
400	2.0	2	2.3	1
450	0.9	0	1.8	1
500	n/a	n/a	1.2	1

The uncertainty on the total background estimate for, *e.g.*, $M_{\ell^+\ell^-} > 300$ GeV, is about 40% in the electron channel, and 25% in the muon channel.

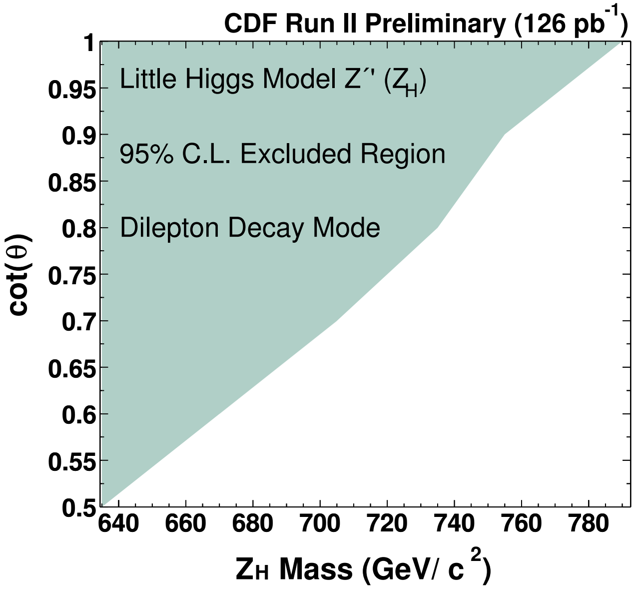
No *obvious* evidence for physics BSM.

example limits & exclusions

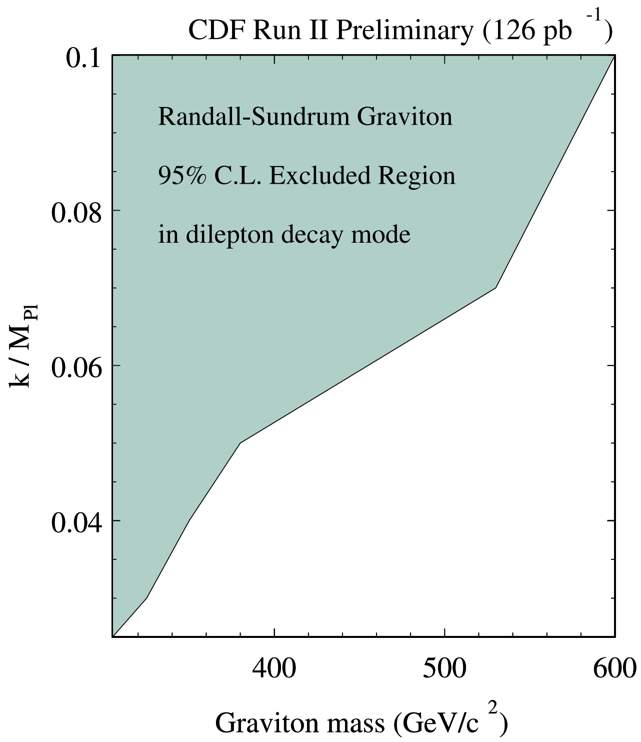
regular Z''s



little Higgs Z_H



RS gravitons



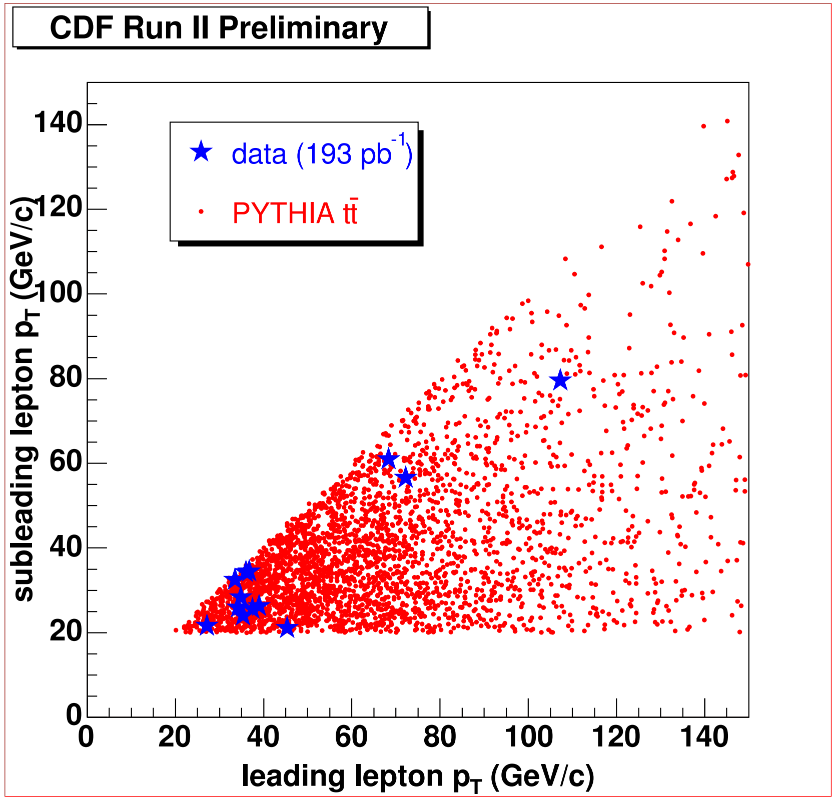
Note: The Z' signals tend to be quite narrow, while the graviton signals are broad. In this sense they cover more possibilities than one might realize.

Top Quark Production

- muons are important for both the di-lepton and the lepton+jets channels
- now fake muons are more difficult – the 'ISO' vs. 'MET' method won't work.
- Measure a 'fake rate' from jet samples.

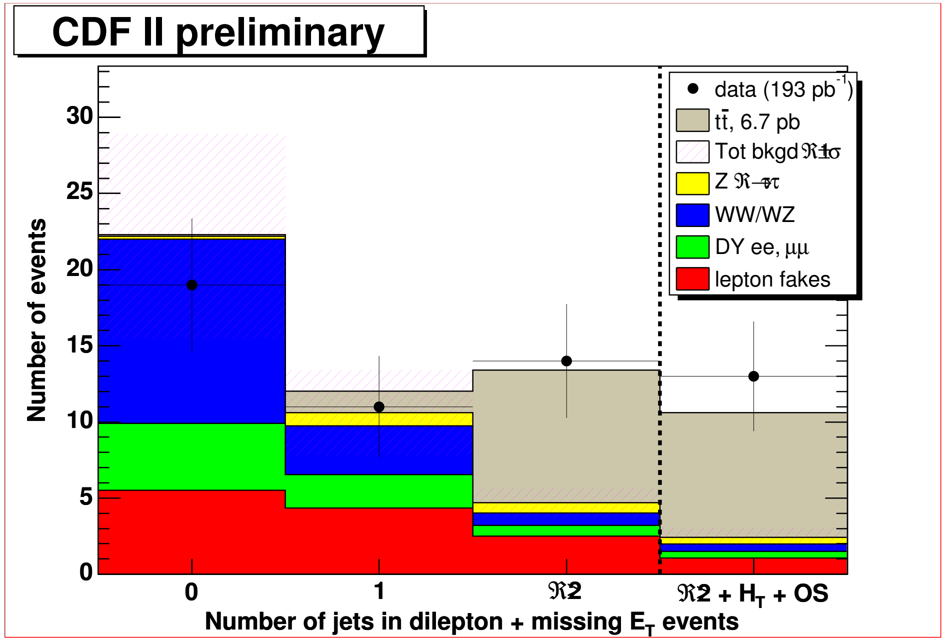
dilepton channel

	Events per 193 pb^{-1} after all cuts			
Source	ee	$\mu\mu$	$e\mu$	$\ell\ell$
WW/WZ	0.15 ± 0.06	0.12 ± 0.05	0.22 ± 0.09	0.49 ± 0.21
Drell-Yan	0.36 ± 0.28	0.07 ± 0.34	-	0.43 ± 0.44
$Z \to \tau\tau$	0.09 ± 0.03	0.11 ± 0.03	0.22 ± 0.07	0.42 ± 0.13
Fakes	0.30 ± 0.10	0.15 ± 0.05	0.62 ± 0.22	1.07 ± 0.35
Total Background	0.9 ± 0.3	0.4 ± 0.4	1.1 ± 0.2	2.4 ± 0.7
$t\bar{t}$ ($\sigma = 6.7$ pb)	1.9 ± 0.3	1.8 ± 0.3	4.5 ± 0.6	8.2 ± 1.1
Total SM expectation	2.8 ± 0.4	2.3 ± 0.5	5.5 ± 0.7	10.6 ± 1.4
Run II data	1	3	9	13



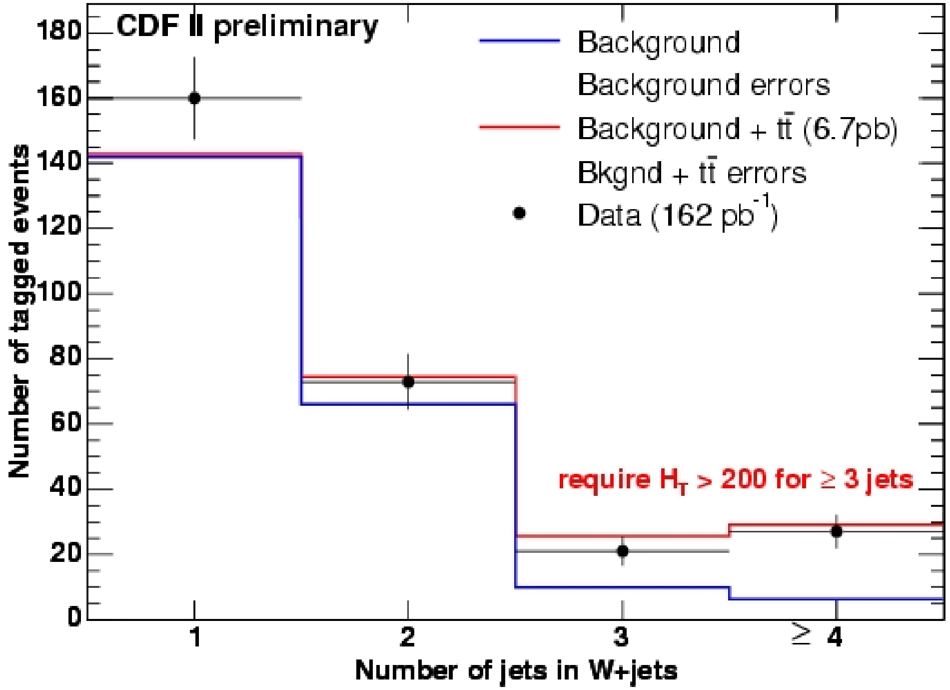
Clear confirmation of the Run I results –

di-leptons:



$$\sigma(t\bar{t}) = 8.7^{+3.9}_{-2.6} \pm 1.5 \text{ pb}$$

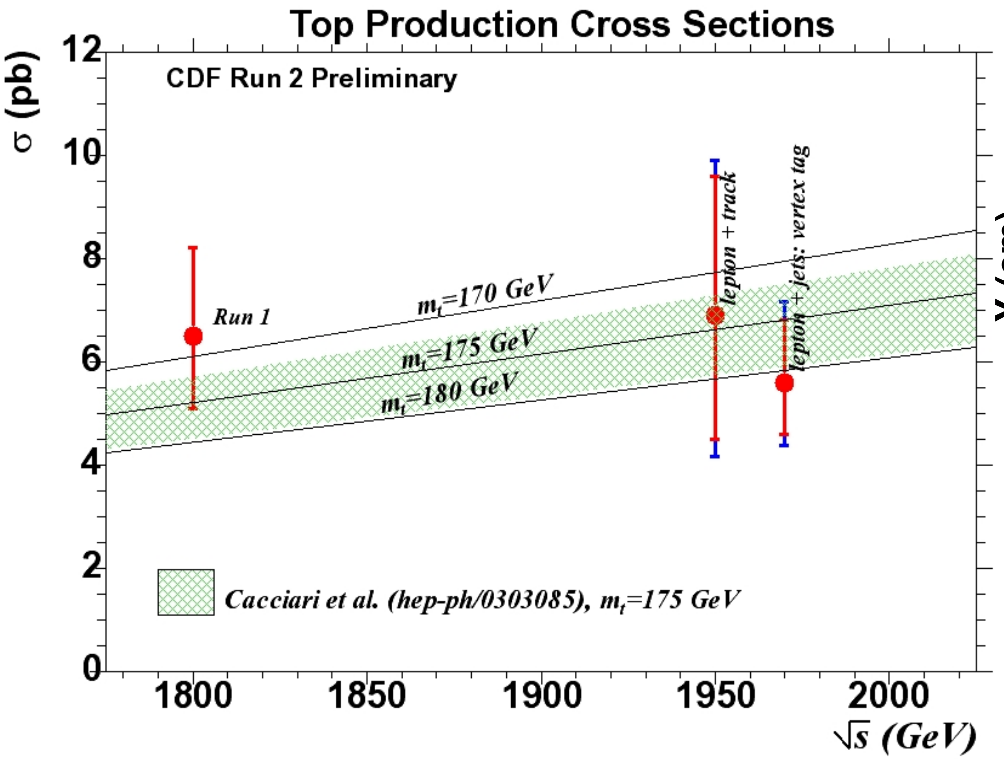
lepton + jets:

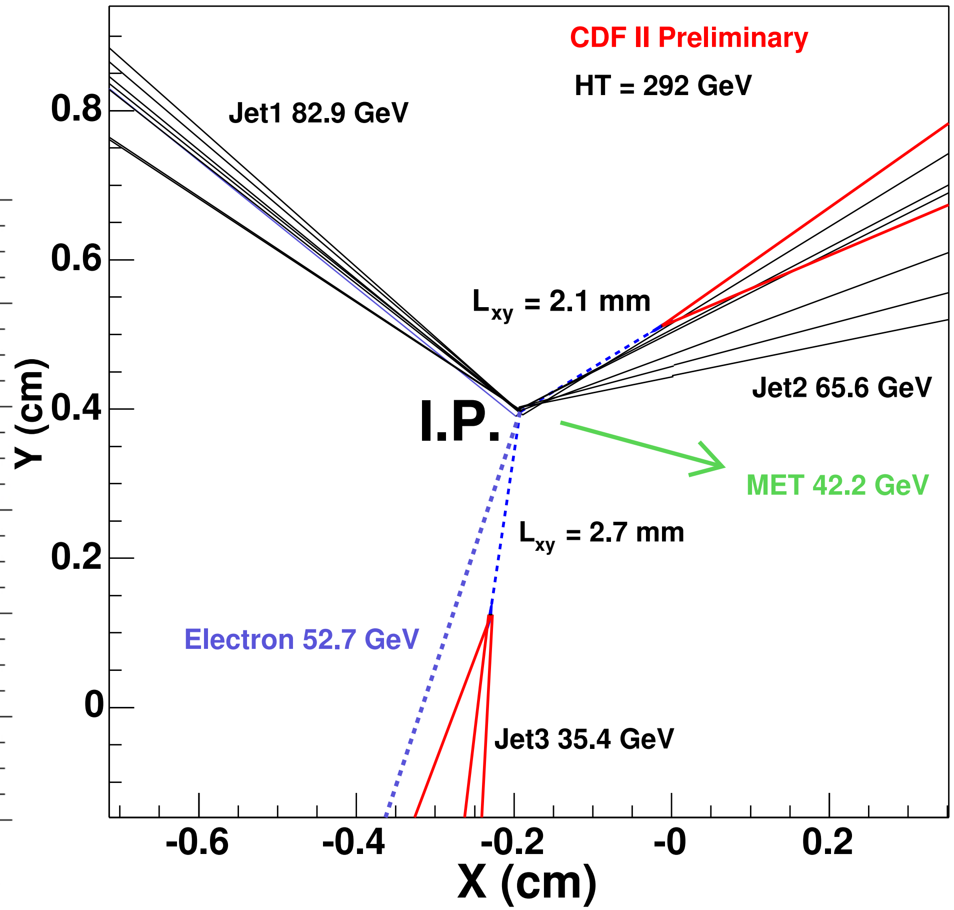


$$\sigma(t\bar{t}) = 5.3^{+1.3}_{-1.1}\ {}^{+1.2}_{-0.7} \text{ pb}$$

(Of course there are several other measurements. . .)

a comparison with Run I





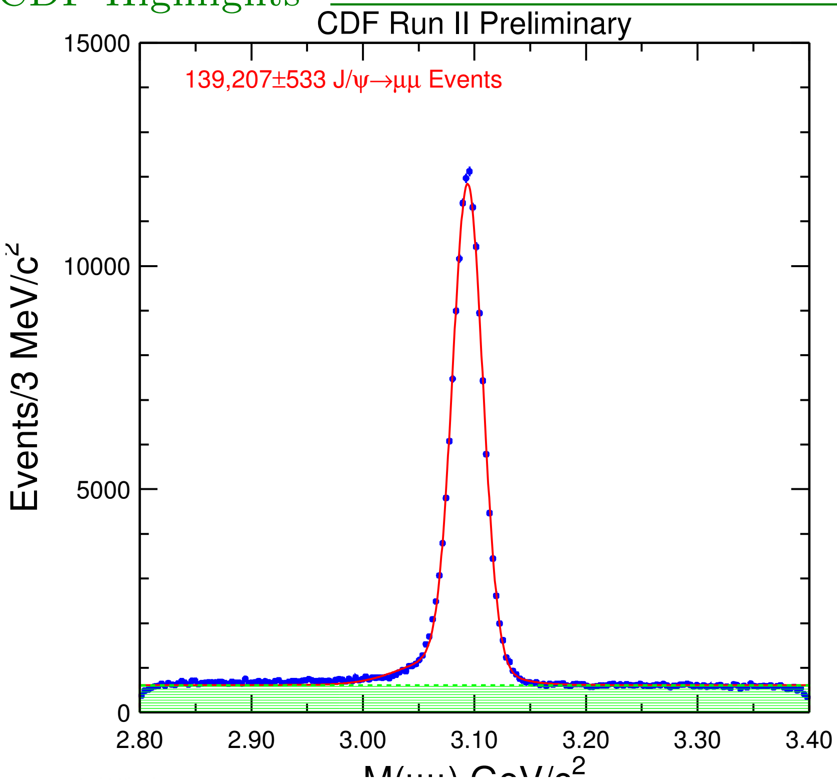
⋆ precision is already better

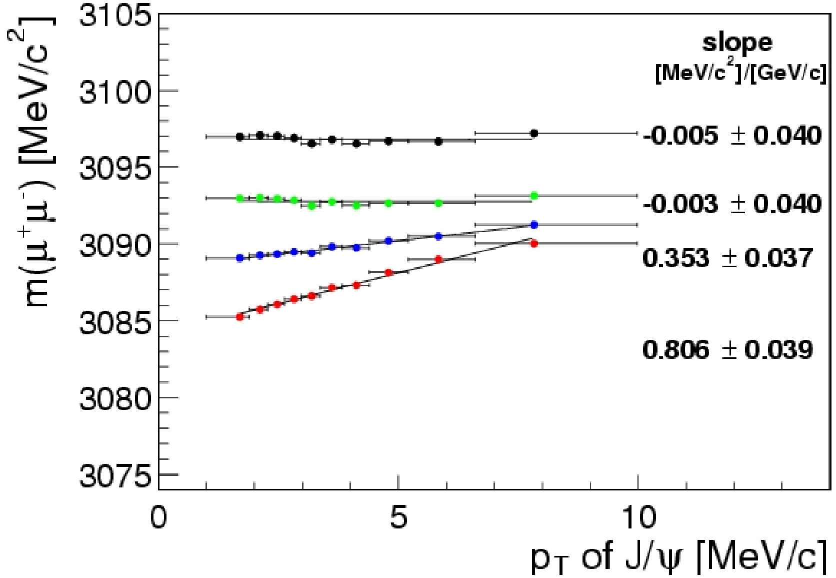
⋆ a gorgeous tagged event!

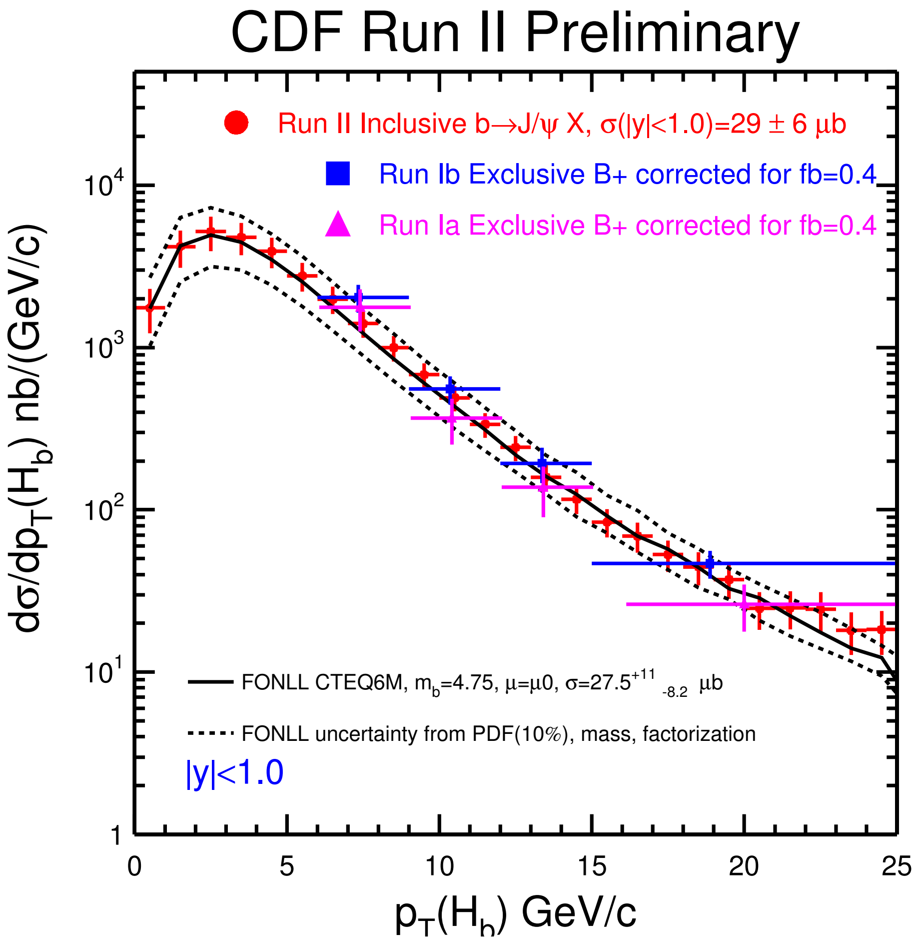
We are working now to combine measurements

Heavy Flavors & Spectroscopy

- There are **many** measurements and searches done in the heavy flavor sector which rely on identified muons. I can only mention one or two.
- This is not the main reason why we build high energy colliders, but we should never pass up opportunities to do physics even if unplanned!
- Of course, triggers are completely different and there are new and more difficult reconstruction & identification issues.
  - stub-track matching is less sharp $\rightarrow$ combinatorial issues
  - muons can range out $\rightarrow$ acceptance vs. p_T
  - more sensitive to details of the magnetic field & material description
  - much larger backgrounds from fake muons at these lower p_T
  - *etc.*
- The decay $J/\psi \rightarrow \mu^+\mu^-$ plays the same benchmark role as does $Z \rightarrow \mu^+\mu^-$.







Note the acceptance down to "zero" p_T and the much higher statistics.

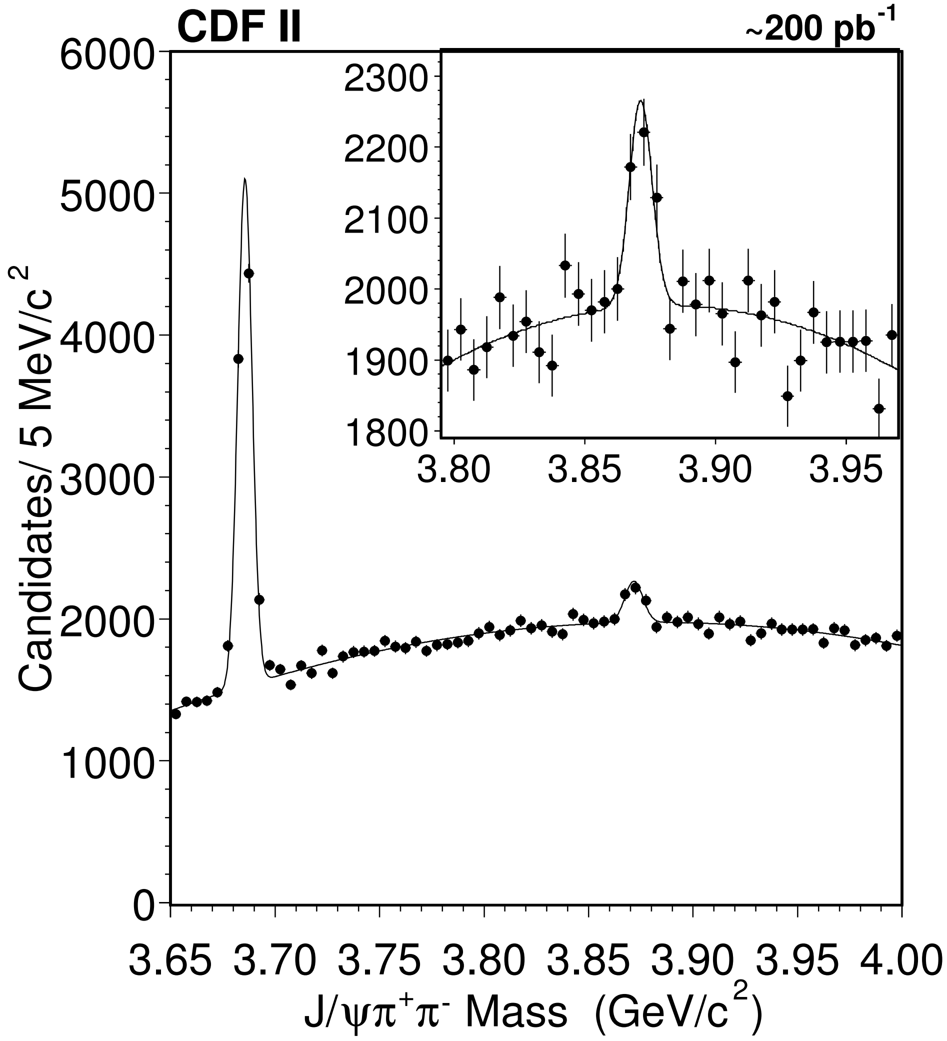
One can do many things with such a J/ψ sample...

for example, find the new particle $X(3872) \to J/\psi\pi^+\pi^-$.

The bump has a high significance.

Our fitted mass is $3871.2 \pm 0.7 \pm 0.4$ MeV which agrees well with the Belle mass.

There is a clear enhancement at larger $M_{\pi^+\pi^-}$.



Conclusions

from our experience from CDF muon-based analyses

- Detector, Software and Analysis are all intertwined, and any separation or categorization can lead to problems.

  (Phil and Ken made these same points – it must be true!)

- The proof of practically *any* analysis comes with the things that are difficult to simulate.

  (This is not e^+e^-!)

- The CDF and DØ Collaborations are devising ever better techniques to handle nasty problems with backgrounds, efficiency measurements, and triggering. This is where the 'fun' is.

  (This invention – and learning – will continue.)