W BR's and Drell-Yan

1. *Measurements of W branching ratios*
2. *Drell-Yan and Searches for Z''s*
3. *Concluding Remarks*

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FNAL Workshop: "From Zero to Z^0"

Cross Section Measurements

Cross sections ($\times BR$) are measured for the following processes ($\ell = e$ or μ):

1. inclusive $p\bar{p} \rightarrow W$, $W \rightarrow \ell\nu$
2. inclusive $p\bar{p} \rightarrow \gamma^*/Z$, $\gamma^*/Z \rightarrow \ell^+\ell^-$

The selection is fairly simple:

- one well-indentified, isolated, high$-p_T$ lepton
- $\not{E}_T$ or a second lepton/track acc: channel
- minor cuts to reduce specific backgrounds

The challenge is in the control of systematics

- *acceptances:* many factors, incl. PDF's, theory $d\sigma/dy$, precise detector description
- *efficiencies:* measured from data, limited by typ. Z statistics
- *backgrounds:* multi-jet ('QCD') background difficult to estimate; others small
- *luminosity:* by far the largest uncertainty ($\sim 6\%$)

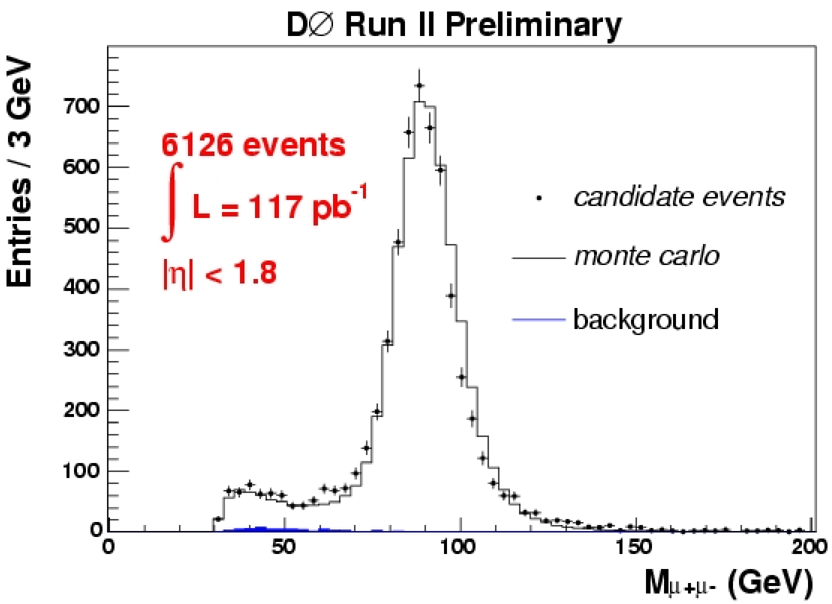
The goal is $\sim 1 - 2\%$ (aside from luminosity)

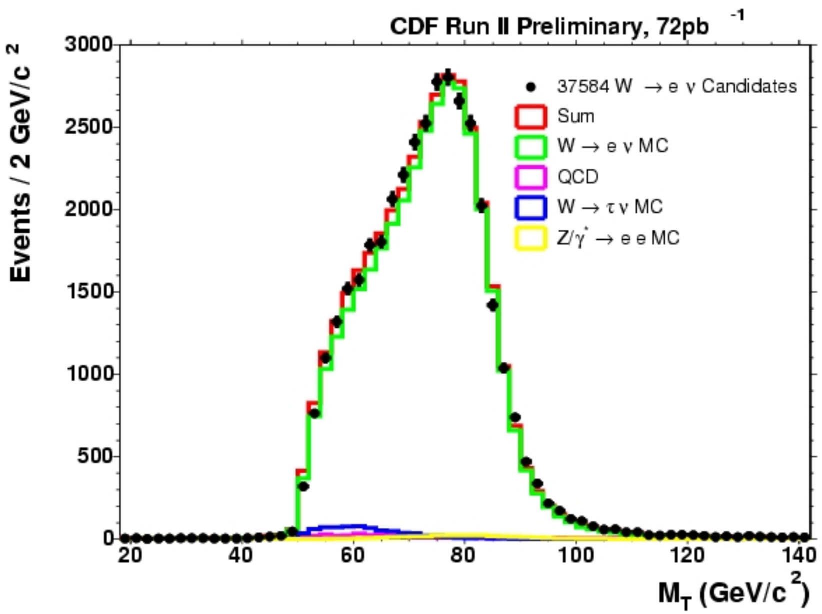
Preliminary Measurements Run II

CDF	$W \to e\nu$ (C)	72 pb^{-1}	$2782 \pm 14 \pm 58 \pm 167$
	$W \to \mu\nu$	72 pb^{-1}	$2772 \pm 16 \pm 62 \pm 166$
	$W \to \ell\nu$	72 pb^{-1}	$2777 \pm 10 \pm 52 \pm 167$
	$W \to e\nu$ (P)	72 pb^{-1}	$2874 \pm 34 \pm 167 \pm 172$
	$W \to \tau\nu$	72 pb^{-1}	$2620 \pm 70 \pm 210 \pm 160$
DØ	$W \to e\nu$	42 pb^{-1}	$2844 \pm 21 \pm 128 \pm 284$
	$W \to \mu\nu$	17 pb^{-1}	$3226 \pm 128 \pm 100 \pm 322$
CDF	$\gamma^*/Z \to e^+e^-$ (CP)	72 pb^{-1}	$255.2 \pm 3.9 \pm 5.5 \pm 15.3$
	$\gamma^*/Z \to \mu^+\mu^-$	72 pb^{-1}	$248.9 \pm 5.9 \pm 6.6 \pm 14.9$
	$\gamma^*/Z \to \ell^+\ell^-$	72 pb^{-1}	$254.3 \pm 3.3 \pm 4.3 \pm 15.3$
DØ	$\gamma^*/Z \to e^+e^-$	42 pb^{-1}	$2755.2 \pm 9 \pm 9 \pm 28$
	$\gamma^*/Z \to \mu^+\mu^-$	117 pb^{-1}	$261.8 \pm 5.0 \pm 8.9 \pm 26.2$

Notes:

1. units are pb.
2. errors are stat, syst, and luminosity. I have symmetrized some for readability.
3. The 'ℓ' values are the combined e(C) + μ.





- Evidently, the signals are very clear.
- Backgrounds are very low (couple percent).
- Systematics dominated already with a few tens of pb.
- How to utilize these measurements despite the large luminosity uncertainty?
  (Alternatively, turn these into luminosity standards. . .)

Ratio, R, Measurements

Consider the ratio of these leptonic rates:

$$R \equiv \frac{\sigma(p\bar{p} \to W) \times B(W \to \ell\nu)}{\sigma(p\bar{p} \to Z) \times B(Z \to \ell^+\ell^-)} = \frac{N_W(1-b_W)\, A_Z\, \epsilon_Z}{N_Z(1-b_Z)\, A_W\, \epsilon_W}$$

- Many experimental uncertainties cancel in the ratio
  - luminosity cancels perfectly
  - lepton efficiencies tend to cancel
  - PDF uncertainties greatly reduced
- Use theoretical calculation for the ratio of production cross sections.
  - NLO and NNLO available from two groups
  - theoretical uncertainties cancel in the ratio: $< 0.5\%$ total, incl. PDF's
- $B(Z \to \ell^+\ell^-)$ is very well known, from LEP.

From CDF data,

$$R = 10.93 \pm 0.15_{\mathrm{stat}} \pm 0.14_{\mathrm{syst}}$$

which is precise to 1.8%.

Tevatron value for $B(W \to \ell\nu)$

Use the CDF R value to extract

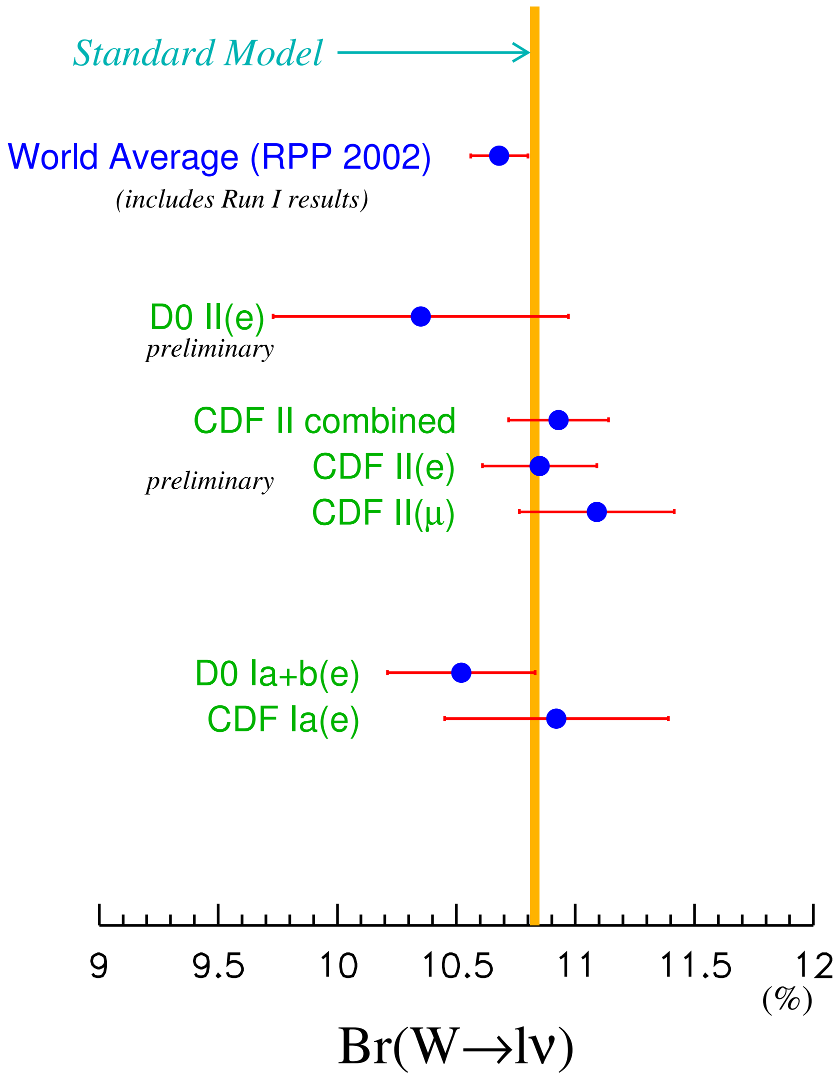
$$B(W \to \ell\nu) = 0.1093 \pm 0.0021$$

compare to WA (2002)

$$B(W \to \ell\nu) = 0.1068 \pm 0.0012$$

and to SM value

$$B(W \to \ell\nu) = 0.1082 \pm 0.0002$$



How much might this measurement yet improve?

- anticipate factor **30** more data yet to come
  $\longrightarrow$ stat error will vanish
  $\longrightarrow$ will trade stat power for lower systematics
- leading systematics are
  1. efficiencies, which come from data
  2. detailed description of the detector, driven by data
  3. PDF's, which might improve with other measurements, and which might be reduced by careful control of acceptances
  4. other systematics can be handled more carefully

A factor 3–4 reduction in the total error seems possible.

LEP Measurements of $B(W \to \ell\nu)$

4 Expt's measure all W decays

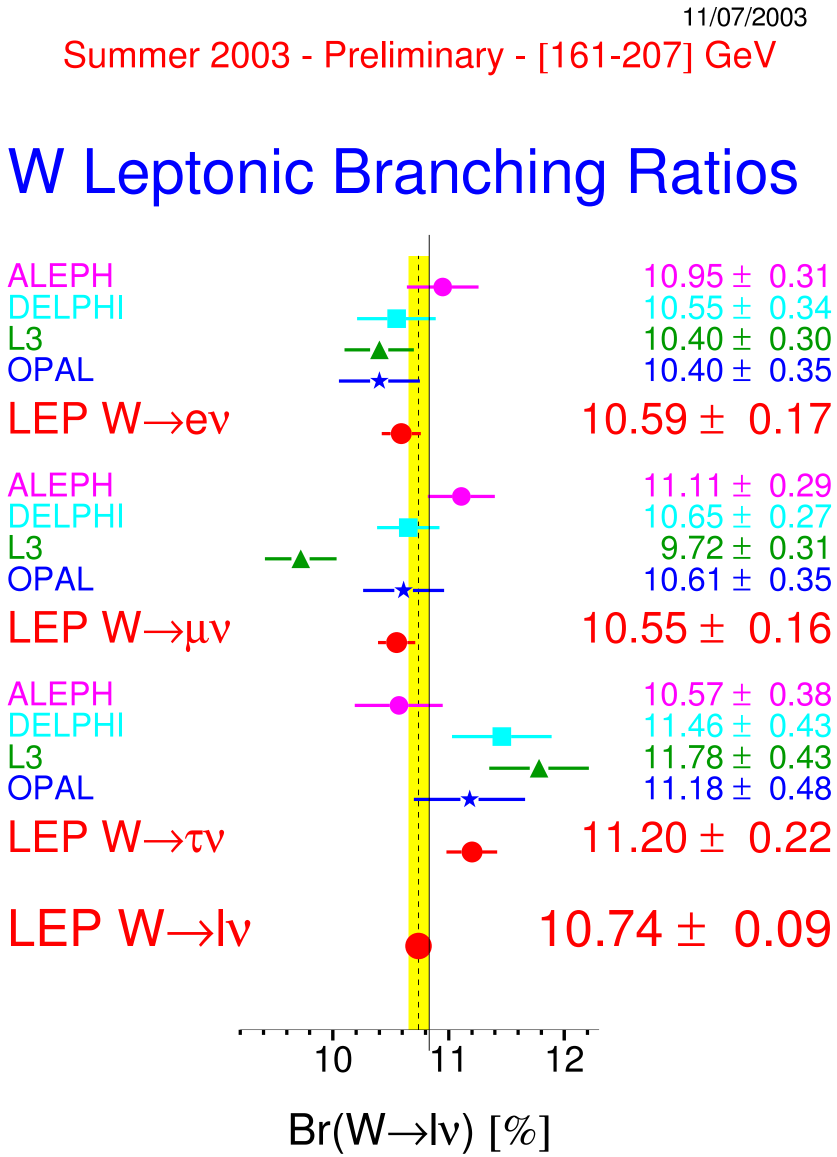
$B(W \to \ell\nu)$ is obtained directly from counting selected events – essentially no auxilliary inputs.

combined values takes correlations into account:

$$
\begin{aligned}
B(W \to e\nu) &= 0.1059 \pm 0.0017 \\
B(W \to \mu\nu) &= 0.1055 \pm 0.0016 \\
B(W \to \tau\nu) &= 0.1120 \pm 0.0022
\end{aligned}
$$

or, assuming e-μ-τ universality,

$$B(W \to \ell\nu) = 0.1074 \pm 0.0009$$



What can we do with a very precise measurement of $B(W \to \ell\nu)$?

$\boxed{1}$ Convert $B(W \to \ell\nu)$ to $\Gamma_W^{\rm tot}$ using a theoretical value for $\Gamma_W^{\rm lept}$.

From the CDF measurement alone, and with $\Gamma_W^{\rm lept} = 226.5 \pm 0.4$ MeV,

$$\Gamma_W^{\rm tot} = 2071 \pm 40 \text{ MeV}$$

to be compared to 2118 ± 42 MeV (WA) and 2092 ± 2 (SM).

LEP direct measurement gives $\Gamma_W^{\rm tot} = 2150 \pm 91$ MeV, and the Run I direct measurement is $\Gamma_W^{\rm tot} = 2115 \pm 105$ MeV.

$\boxed{2}$ In SM, $B(W \to \ell\nu)$ depends on certain CKM matrix elements:

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

It turns out that $|V_{\rm cs}|$ contributes most of the uncertainty for this prediction, and we can use $\Gamma_W^{\rm tot}$ to constrain $|V_{\rm cs}|$.

$$\begin{aligned} |V_{\rm cs}| &= 0.962 \pm 0.030 \qquad (\text{CDF, unofficial}) \\ |V_{\rm cs}| &= 0.989 \pm 0.014 \qquad (\text{LEP}) \end{aligned}$$

(Measurements from leptonic D_s decays have 10% uncertainties.)

Drell-Yan

The measurements of $B(W \to \ell\nu)$ do not provide important constaints on the electroweak sector of the SM.

For that, one needs to study the neutal current: Drell-Yan.

Two avenues at present:

1. study asymmetry of $p\bar{p} \to \ell^+\ell^-$ as a function of $M_{\ell\ell}$
2. study the $M_{\ell\ell}$ dependence of the cross section
   $\longrightarrow$ look at high-mass to Z-pole ratio of rates

Once high masses come into play, one also becomes alert to the possibility of *direct contributions* from new physics (such as Z''s or large extra dimensions...).

This is the exclusive provence of the Tevatron – the asymmetry measurements at LEP & SLD were completed years ago.

$A_{\rm FB}$ at the Tevatron

- Mature analysis carried out by CDF, profiting from the greatly extended coverage of the calorimetry (Run II upgrade).

- measure the asymmetry in bins of $M_{\ell\ell}$:

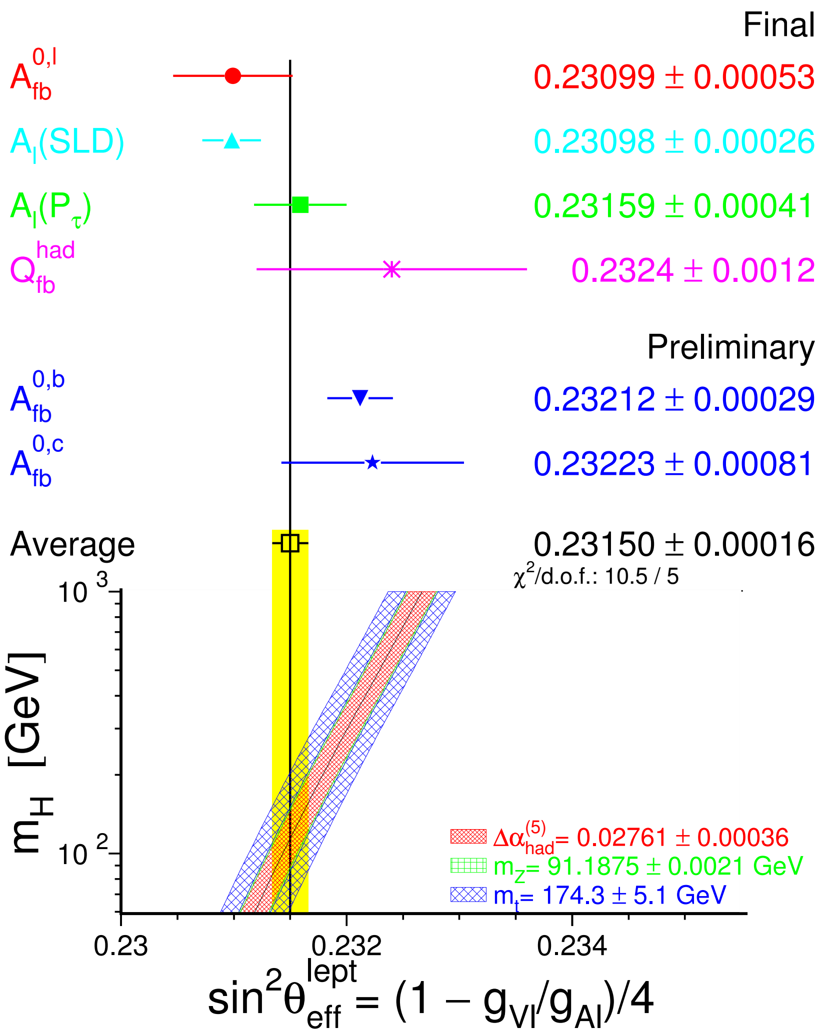
$$A_{\rm FB} = \frac{\sigma(\cos\theta > 0) - \sigma(\cos\theta < 0)}{\sigma(\text{all} \ \ \cos\theta)}$$

- enjoys low systematics

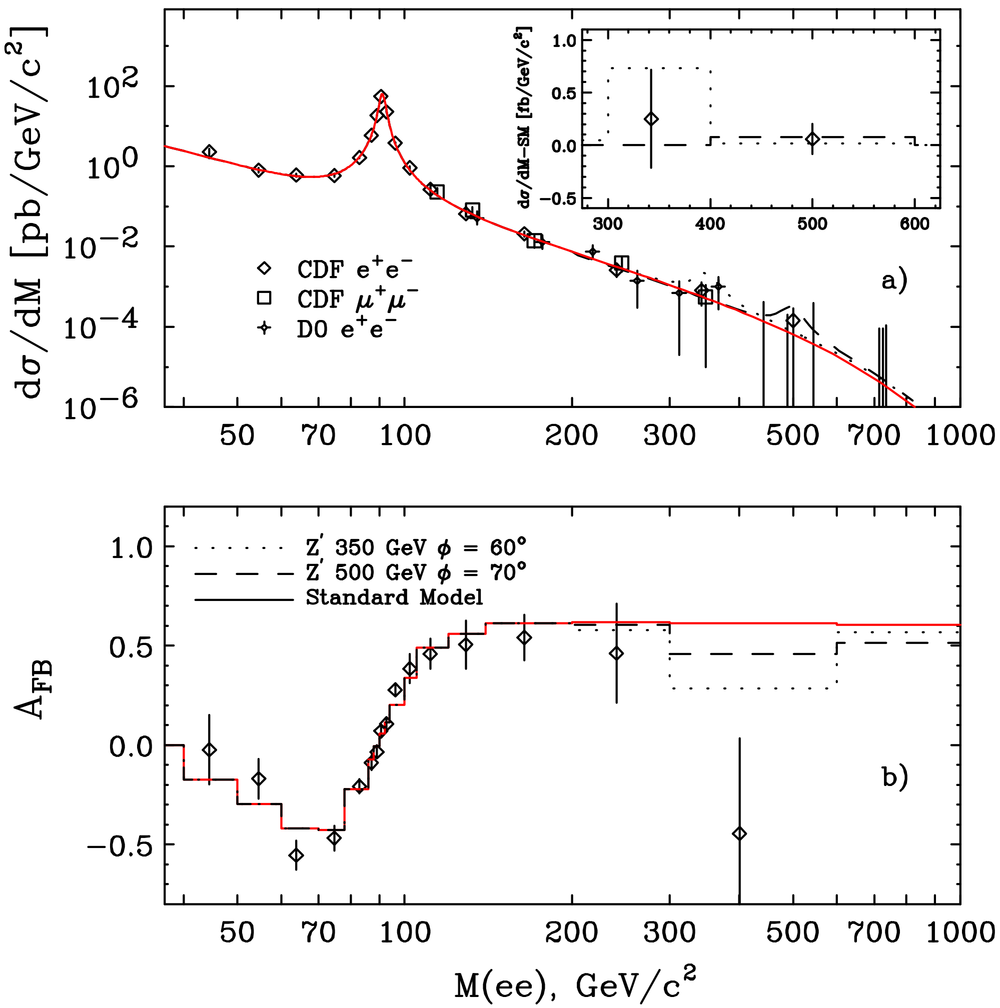
- sensitive to NC couplings, though messier than in e^+e^- colliders

- can observe behavior of $A_{\rm FB}$ to much higher masses than at LEP 2

- particular interest comes from:
  1. 'problem' with e^+e^- asymmetry measurements *(leptonic vs. hadronic)*
  2. interesting 'wiggle' from CDF Run I data $\longrightarrow$ $M_{\ell\ell} \sim 400 - 500 \ GeV$



LEPEWWG – `hep-ex/30312023`



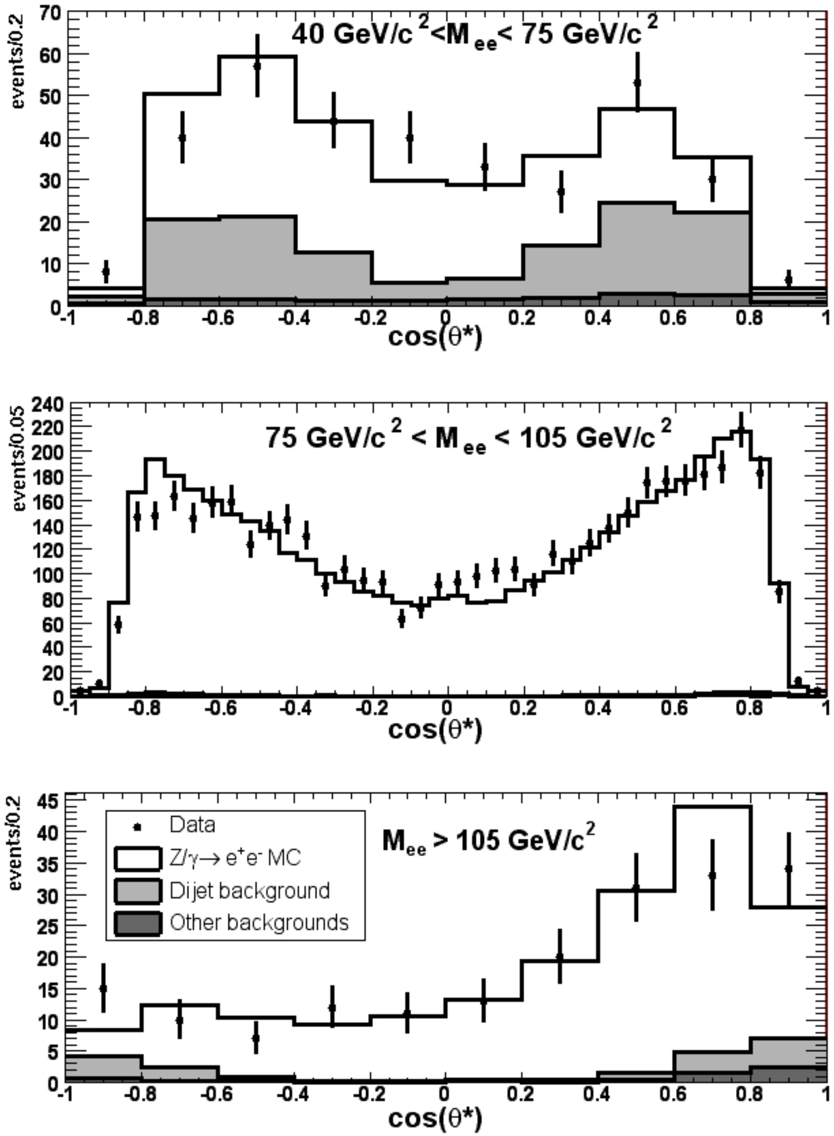
CDF Collab. PRL **87** (2001) 131802

Build on the existing CDF analysis for $\sigma \times Br(p\bar{p} \to Z \to e^+e^-)$.

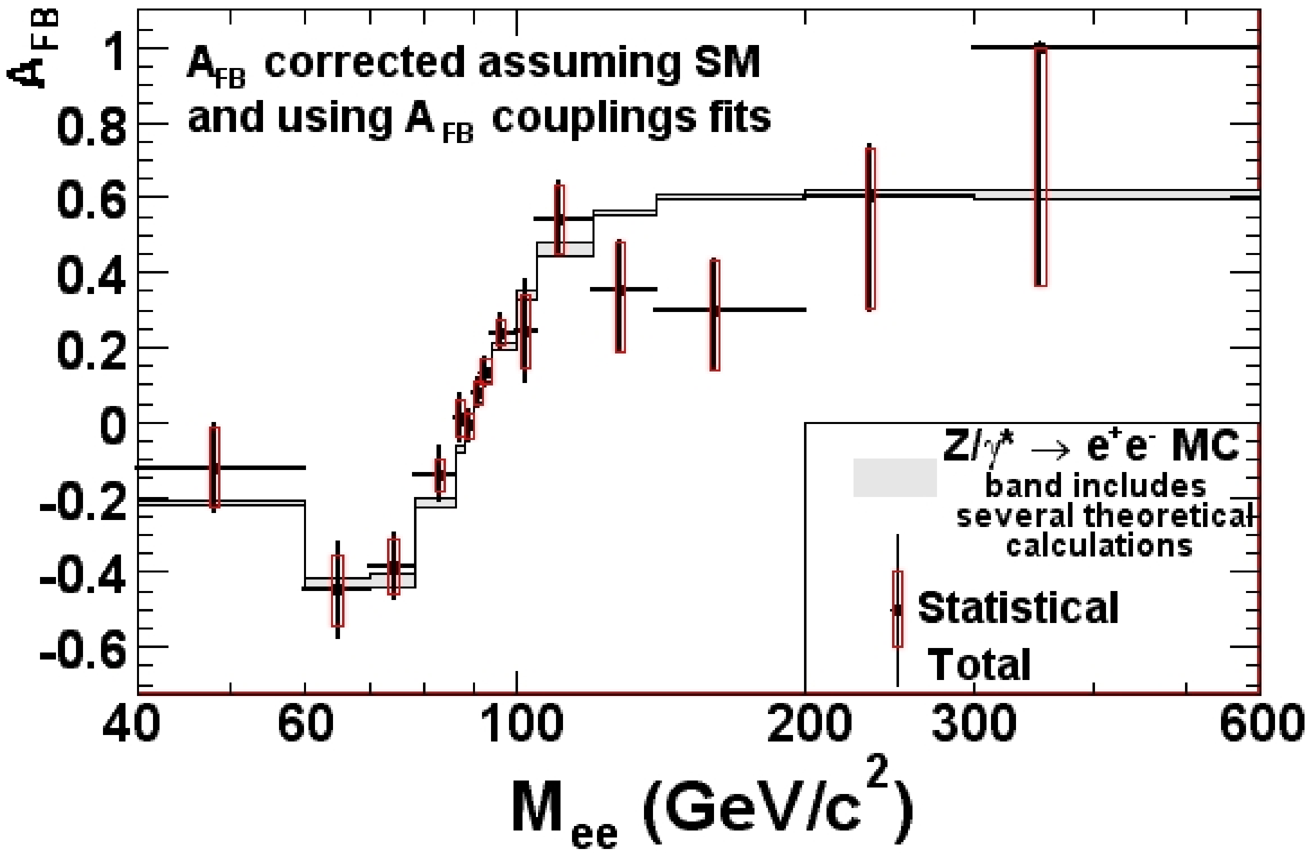
Special emphasis on

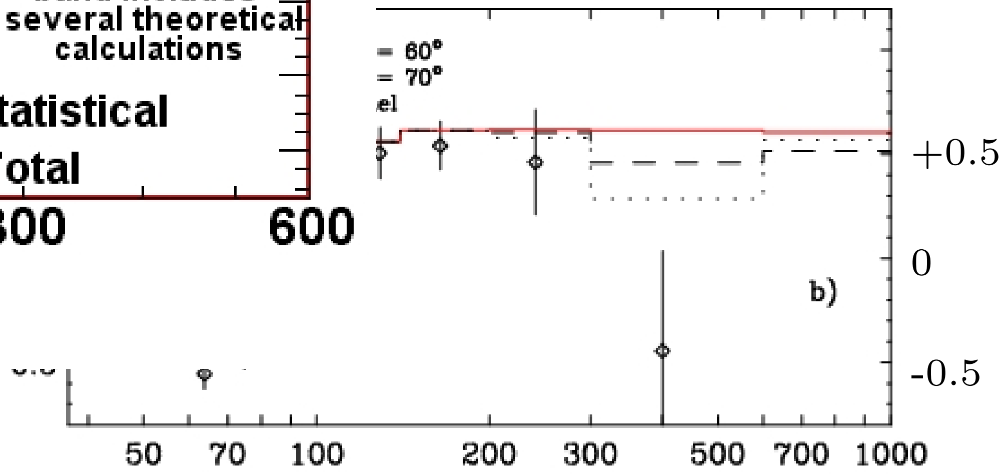
- di-electron mass resolution
  - $\longrightarrow$ mass migration matrix
- acceptance as a function of $\cos\theta^*$
  - $\longrightarrow$ depends on assumed couplings
  - $\longrightarrow$ watch out for bias towards MC values!
- background estimates for high $M_{\ell\ell}$

Raw distributions already show clear evidence for the asymmetry!



The CDF preliminary result is, for 70 pb^{-1}:

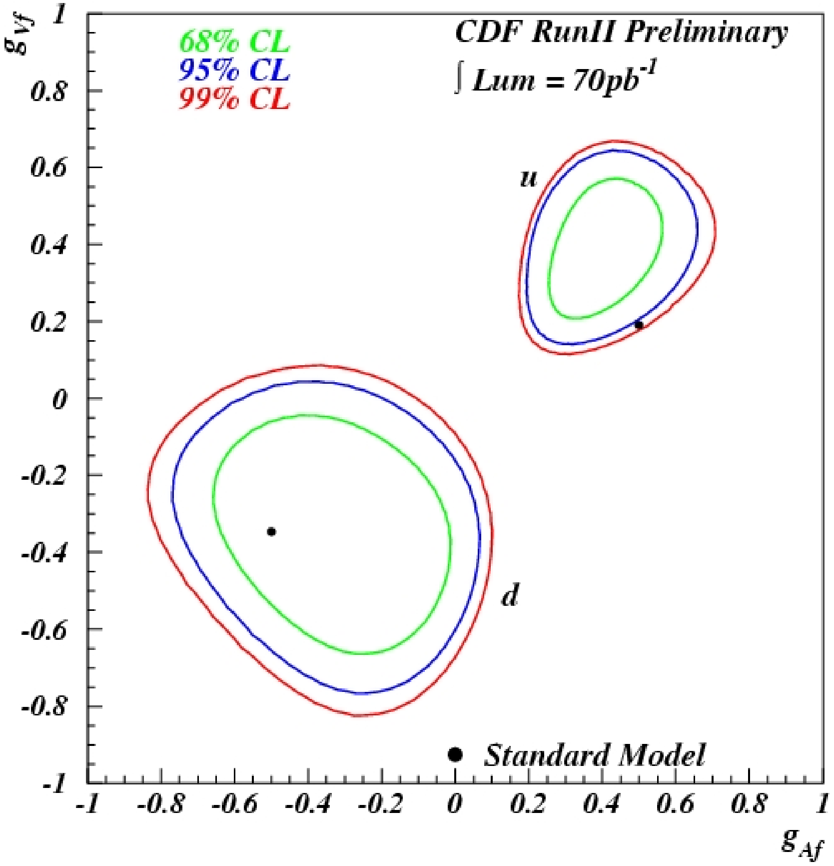




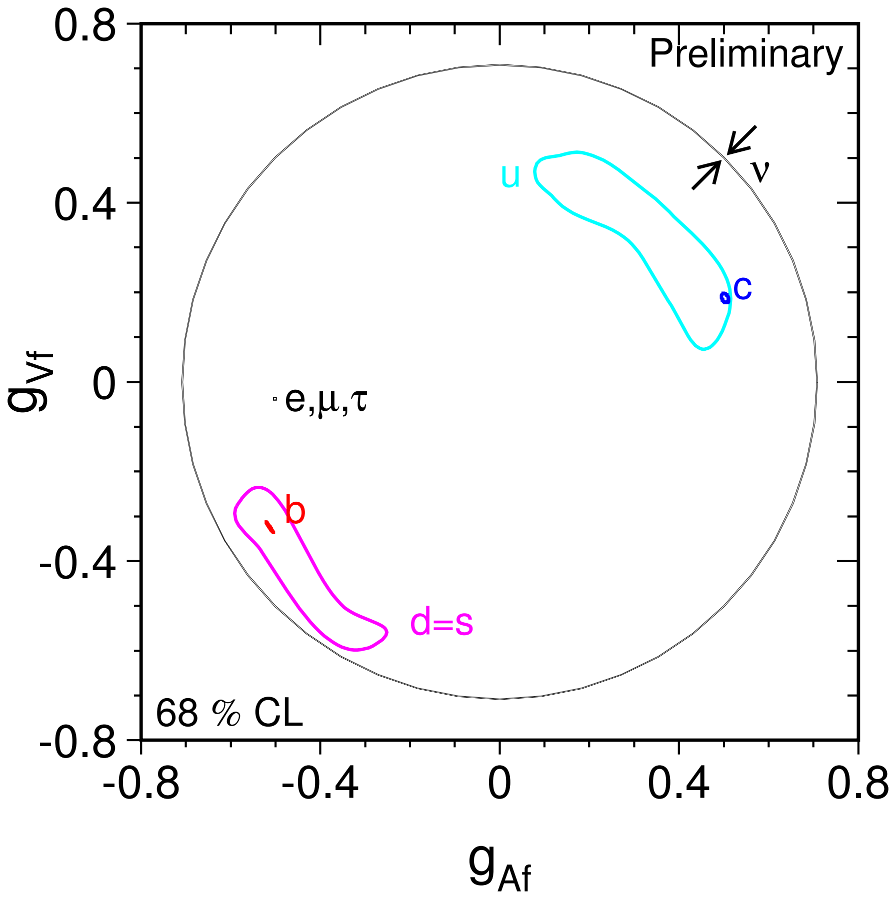
$A_{\rm FB}$ is NOT low for $M_{\ell\ell} \sim 400$ GeV.

(The SM couplings are used for this plot.)

An extension of this analysis extracts the u and d-quark couplings to the Z:



Errors on u_L, u_R, d_L, d_R are about ten times PDG values.
$\sin^2\theta_W = 0.2238 \pm 0.0046 \pm 0.0020$



LEP constraints on quark couplings

Probably the most interesting thing is to combine TEVATRON + LEP...

$A_{\rm FB}$ at the LHC

It has long been planned to measure $\sin^2\theta_W$ very precisely using $A_{\rm FB}$.

This was studied by the working group on electroweak physics `(hep-ph/0003275)`

Currently, $\sin^2\theta_W = 0.23151 \pm 0.00017$ prec $\sim 7\times 10^{-4}$

At the LHC, for $\mathcal{L}\sim 100$ fb^{-1}, $Z\to\ell^+\ell^-$ samples will be on the order of 10^8 events!
$\longrightarrow$ stat precision $\sim 1.4\times 10^{-4}$

Main systematic will come from PDF's.
May need to constrain these with LHC data in order to achieve super-low systematics.

Mass Spectrum – Searching for Enhancements

This is basically an open search for 'bumps' or 'shoulders':
One has to ask only the basic questions:

- Is the peak narrow (*e.g.*, Z' from GUT's, technicolor) or broad (LED)
- How are the couplings to fermions relative to the SM?
- Can one combine e and μ?

The only important experimental issue is the background at high $M_{\ell\ell}$.

There is a lot of activity here, both on CDF and on DØ. I will highlight the DØ analysis as it is particularly elegant, and uses $> 200\ \mathrm{pb}^{-1}$ of di-electron data.

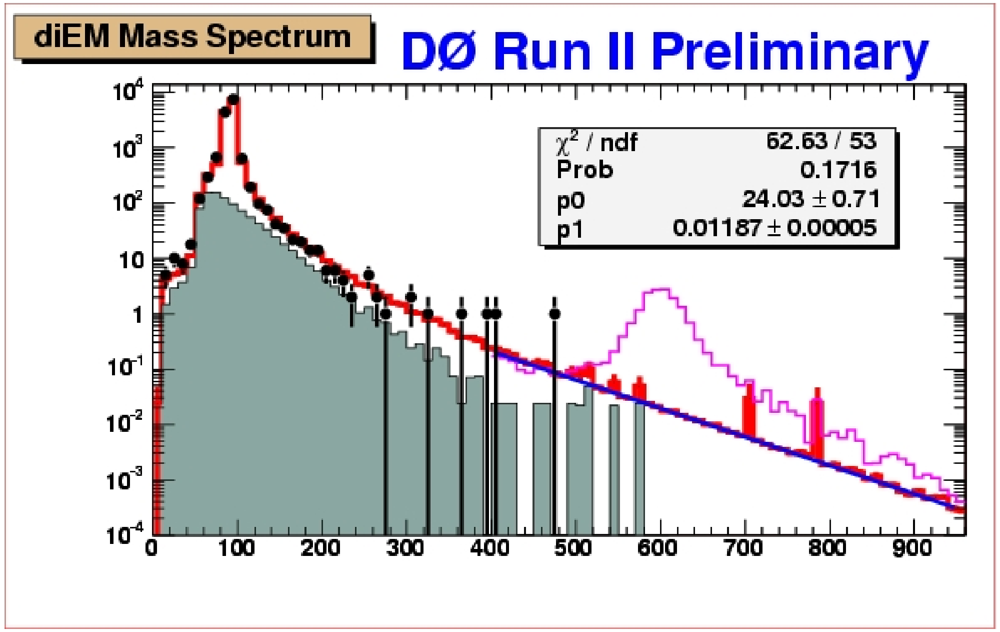
⋆ In particular, they use the Z peak to normalize their data and their SM predictions, which brings significant reductions in systematic uncertainties.

In essence, use another kind of R:

$$R = \frac{\sigma(M_{\ell\ell} > M_{\ell\ell}^{\mathrm{min}})}{\sigma(M_{\ell\ell}\ \text{near}\ M_Z)}$$

Examples:

sequential Z'



e.g., mass window around 400 GeV, expect 1.19 ± 0.12, observe 2.

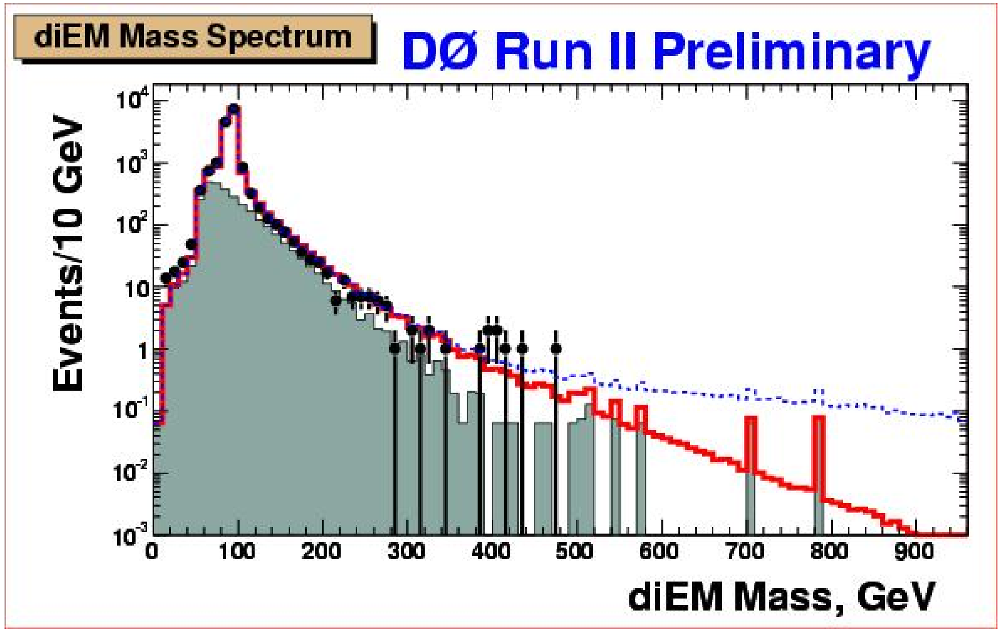
ratio limit 1.66×10^{-4} equiv. 42 fb

$M_{Z'} > 780$ GeV (seq.)

Limits in E_6 models range from

$M_{Z'} > 575$ GeV to $M_{Z'} > 650$ GeV

large extra dimensions

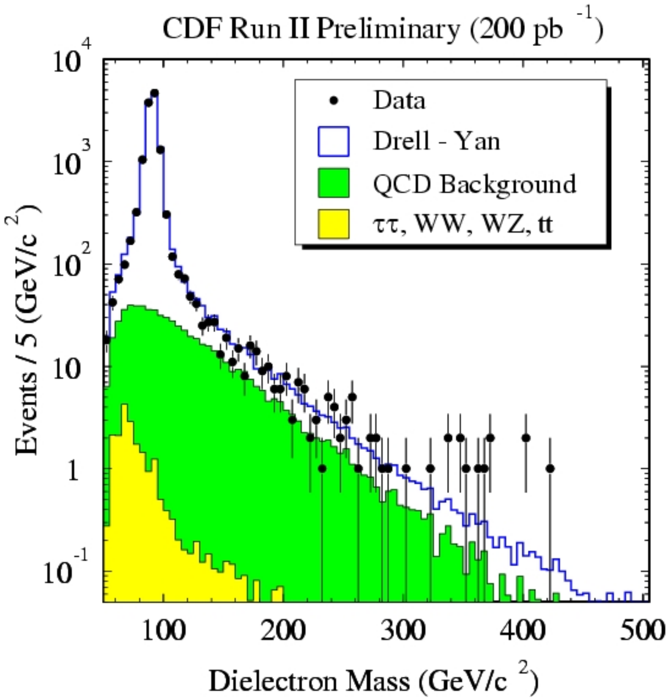


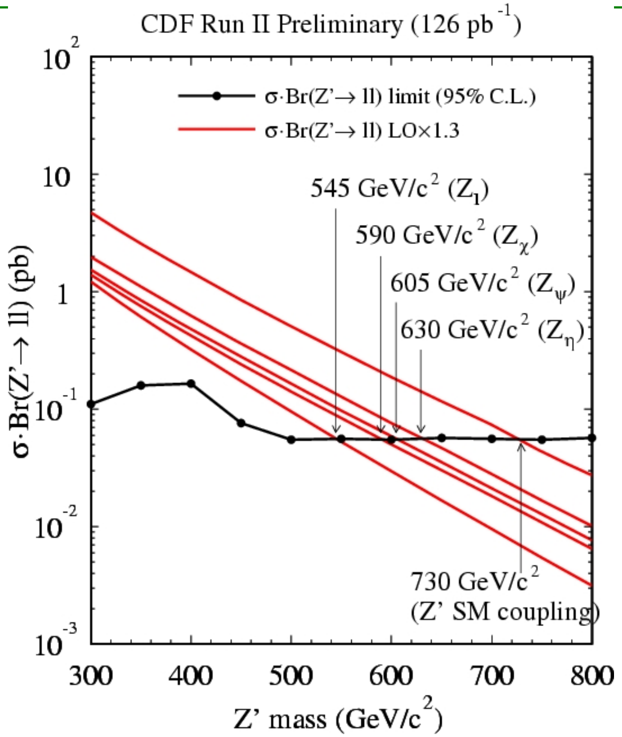
This includes di-photons.

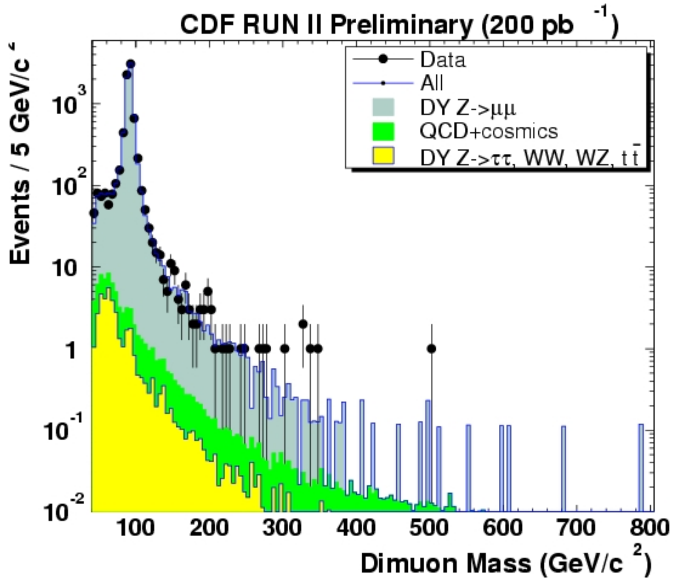
Bi-dimension LL fit $(M_{\ell\ell}, \cos\theta^*)$

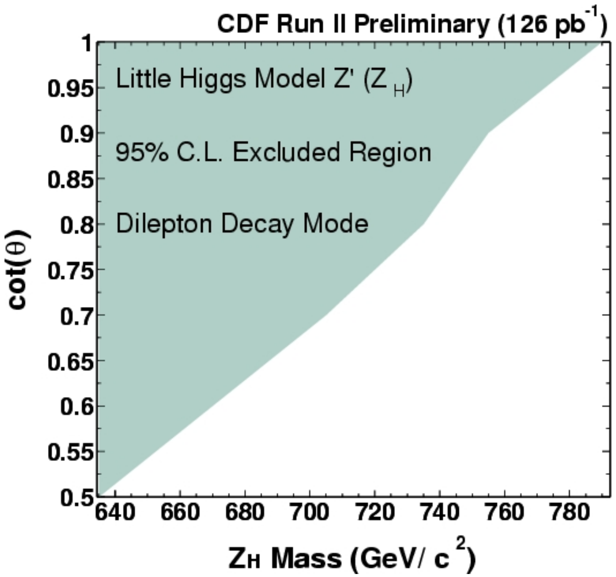
fund. scale $M_S > 1.10$ TeV (Hewett conv.)

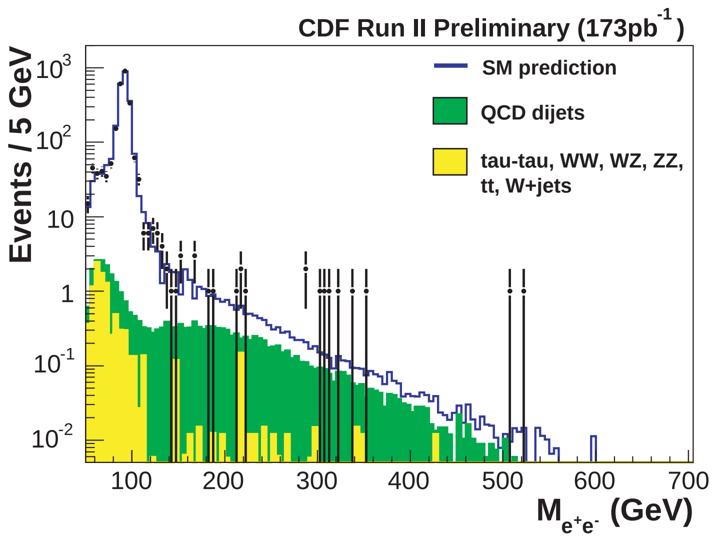
combine with Run I: $M_S > 1.28$ TeV !

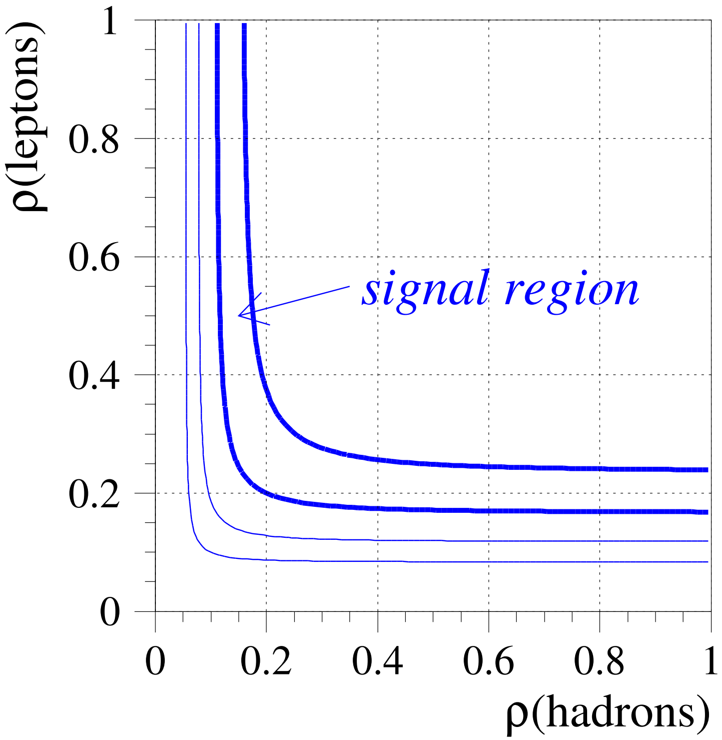

CDF Run II Preliminary (200 pb^{-1})
Data
Drell - Yan
QCD Background
ττ, WW, WZ, tt
Events / 5 (GeV/c^2)
Dielectron Mass (GeV/c^2)


CDF Run II Preliminary (126 pb^{-1})
σ·Br(Z'→ ll) limit (95% C.L.)
σ·Br(Z'→ ll) LO×1.3
545 GeV/c^2 (Z_I)
590 GeV/c^2 (Z_χ)
605 GeV/c^2 (Z_ψ)
630 GeV/c^2 (Z_η)
730 GeV/c^2
(Z' SM coupling)
σ·Br(Z'→ ll) (pb)
Z' mass (GeV/c^2)


CDF RUN II Preliminary (200 pb^{-1})
Data
All
DY Z->μμ
QCD+cosmics
DY Z->ττ, WW, WZ, tt
Events / 5 GeV/c^2
Dimuon Mass (GeV/c^2)


CDF Run II Preliminary (126 pb^{-1})
Little Higgs Model Z' (Z_H)
95% C.L. Excluded Region
Dilepton Decay Mode
cot(θ)
ZH Mass (GeV/ c^2)





There is also a mass distribution from CDF in which *both* electrons are at small angles to the beam: $\longrightarrow$ interesting accumulation $M_{\ell\ell} \sim 300$ GeV ?

expected: 2.5 ± 0.7 events, observe 8, prob = 1%

One can ask about a Z' with reduced couplings to fermions, (factors ρ_q and ρ_ℓ for quarks and leptons)

A 'signal' around 300 GeV would have, roughly

$$\frac{\sigma(Z')}{\sigma(Z^{(\mathrm{seq})})} = 0.06 \pm 0.02$$

leading to a specific region in the (ρ_q, ρ_ℓ) plane.

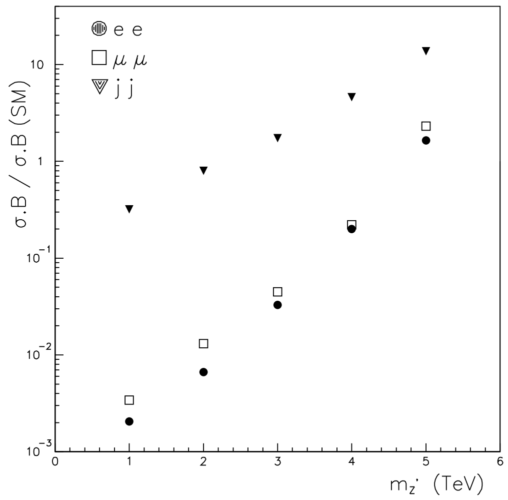
This is, however, totally excluded by the central electron result.

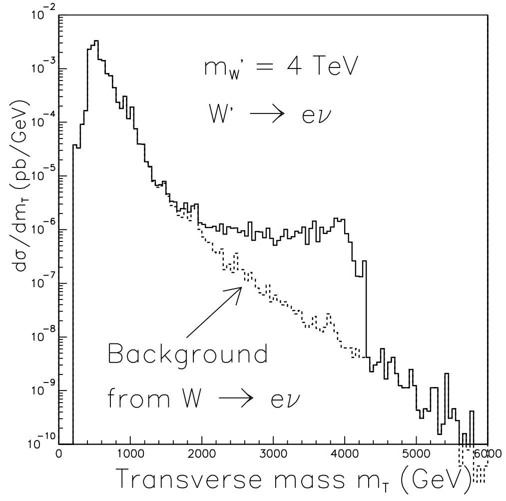
Z' Searches at Future Colliders

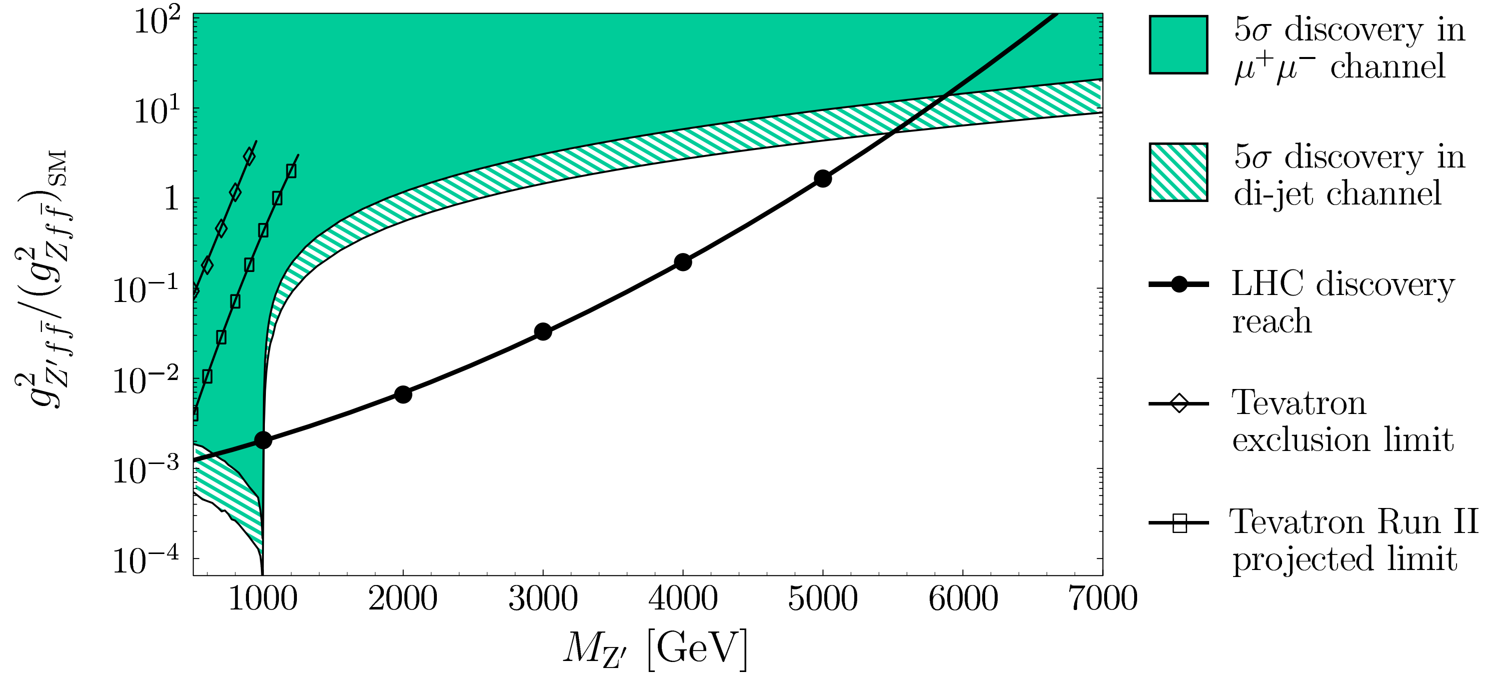
LHC reach for $Z^{(\mathrm{seq})} \to e^+e^-$ is about 5 TeV.

A.Freitas (FNAL) has discussed searching for *weakly-coupled* Z' bosons at a future LC, and perhaps measuring the couplings. `(hep-ph/0403288)`

Notice limits vs. $M_{\ell\ell}$ from Tevatron data, too.







Summary & Conclusion

LEP

We are seeing (perhaps) the effectively final values for most electroweak parameters (even if they are labeled 'preliminary' in some cases).

Tevatron

The analysis of inclusive W and Z signals (& others) is making serious progress

- cross sections to $\sim 1\%$
- W properties will surpass LEP in a couple years
- A_{FB} beyond Run I, extraction of quark couplings
- new territory in *e.g.* Z' searches

There is *a lot* that one can do with 2–4–8 fb^{-1} (even if the Higgs is out of reach).

Future Colliders

These hold fantastic promise, acc: studies.

But it will be many years before we can realize this potential...