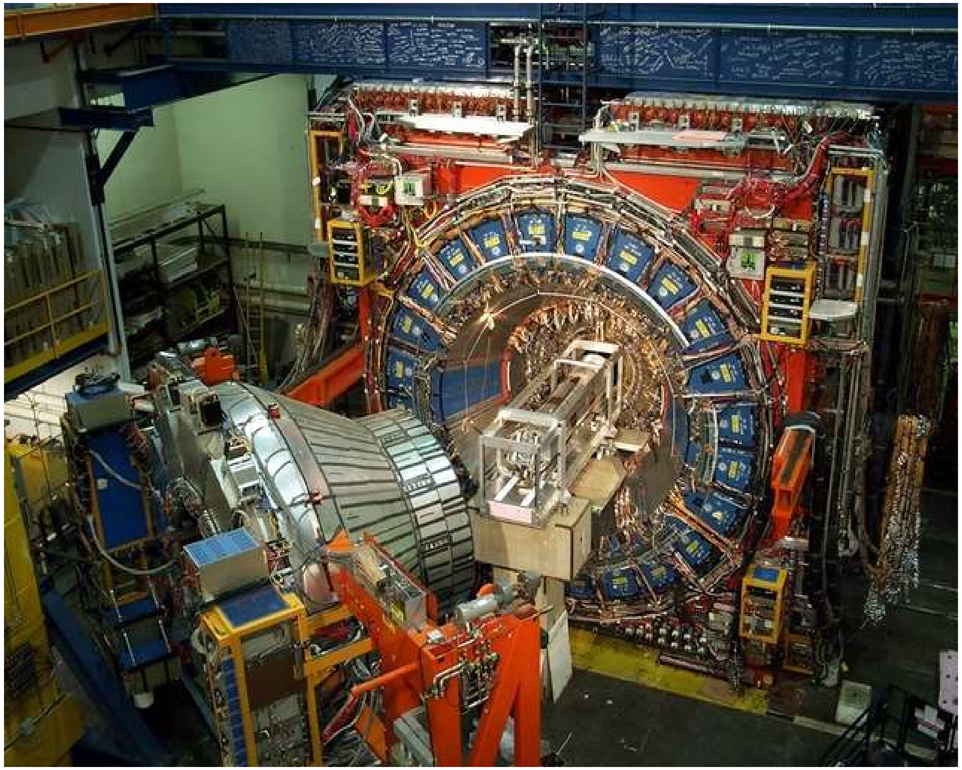
Z' at the Tevatron and LHC: Lessons and Synergy

CDF Detector, physics output 1985 - 2008?



CMS Muon Endcap, physics starts 2008?

Michael Schmitt / Northwestern (CDF & CMS)
TeV4LHC Session 4, Fermilab
October 20, 2005

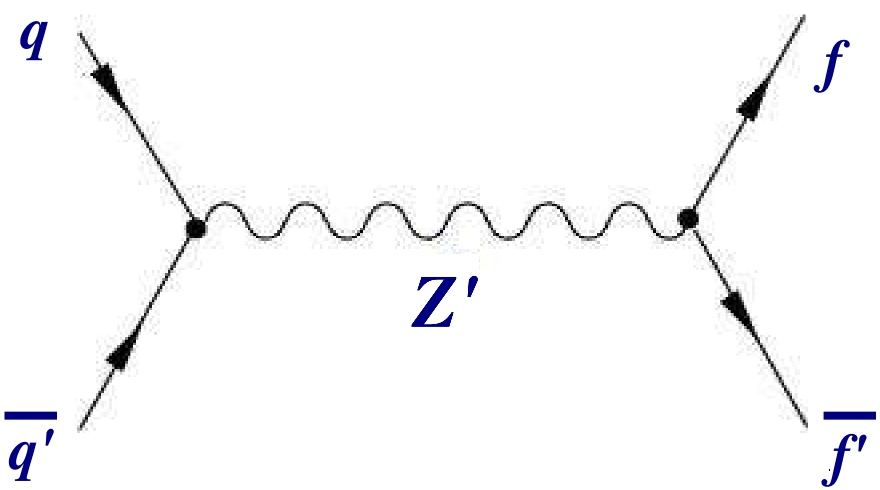
Outline

- **Introduction and Motivation – Scope of this Talk**
- **Synopsis of Results from DØ & CDF, and of Studies from ATLAS & CMS**
- **Lessons to be Learned, Synergy between the Machines**
- **The Cutting Edge – The Best Way to Handle the Data?**
- **Conclusions**

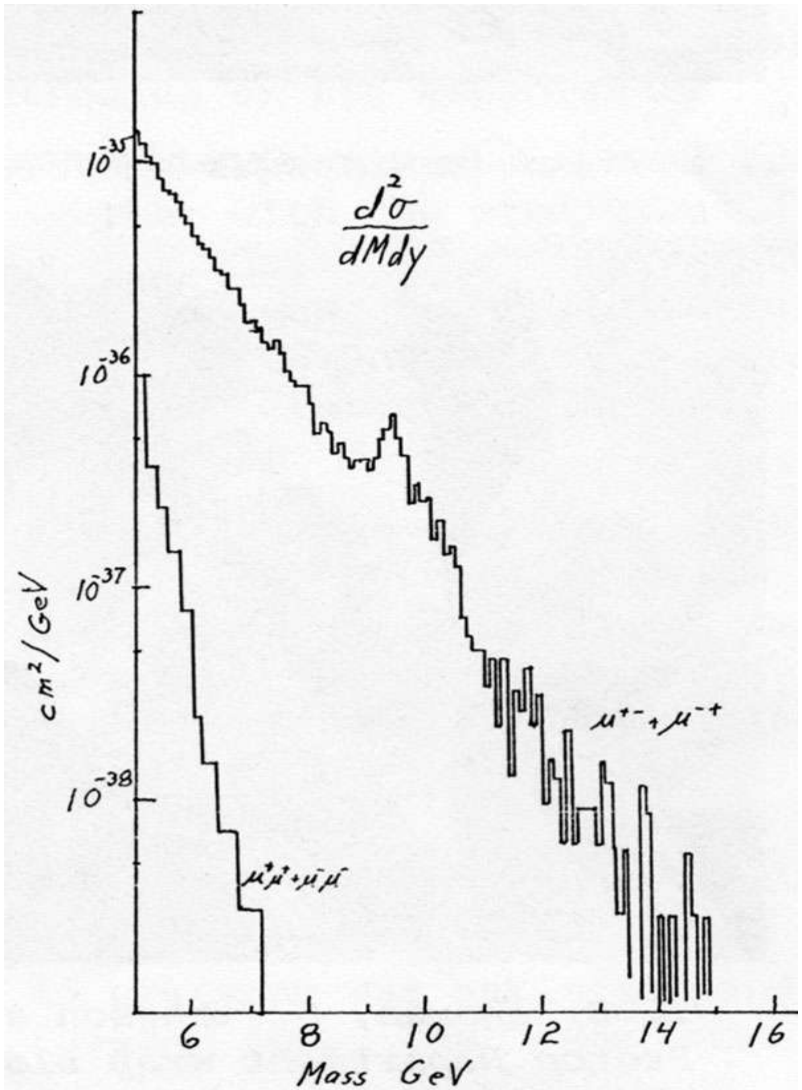
Introduction & Motivation

This talk will favor an empirical, “bottom-up” approach.
I will ignore beautiful theoretical motivations...

Here are two “views” of what ***Z'*** *is:*



We will assume spin-1 and negligible lifetime -
this would have to be confirmed by real data, of course...



Four Approaches to the Data

(1) Look for a numerical excess above the Drell-Yan continuum.

Choose a minimum di-lepton mass, compare N_{obs} to N_{exp}.

(2) Test specific models using mass templates

These serve as benchmarks: Z_{SSM}, various E_6 GUT incarnations, little Higgs Z'

(3) New: attempt a (more) model-independent approach

Spurred by Carena, Daleo, Dobrescu & Tait: Phys. Rev. D70 (2004) 093009 - "CDDT"

(4) Revived: Simple Bump Hunting!

Absolutely no theory at all – just statistical techniques.

Experimental Synopsis

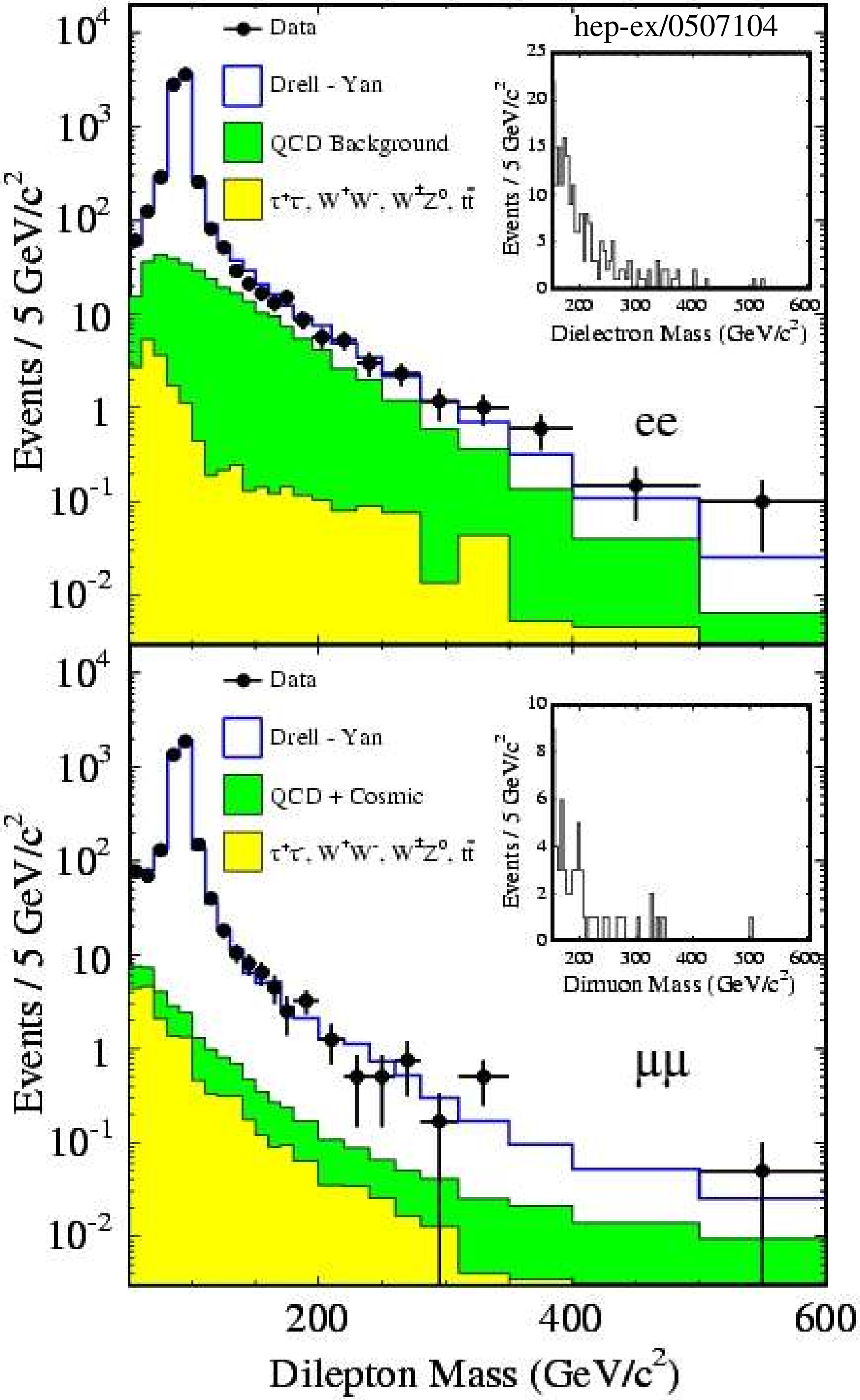
Select events with two isolated high-p_T leptons of the same flavor (e or μ) and opposite charge.

Examine the di-lepton invariant mass distribution:
- dominated by the Z peak and Drell-Yan
- worry about fake leptons
  * QCD di-jets with two jets looking like leptons
  * W + jet(s) with a leptonic W decay and one jet looking like a lepton
  * γ + jet(s) with the photon looking like an electron and the jet faking an electron
- "electroweak" backgrounds (WW, WZ, ZZ, tt) are tiny and can be estimated w/ simulations

If you find a peak, then
1. quantify its significance
2. measure the production rate: σ x BR

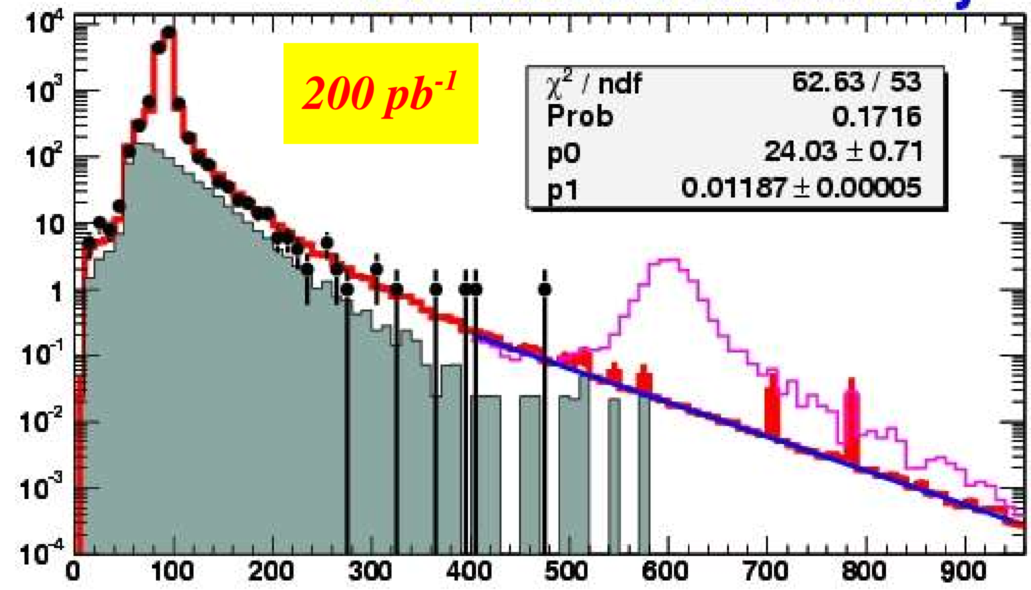
If you don't find a peak, then
1. derive an upper limit on the production rate: σ x BR
2. constrain popular models or better, constrain combinations of couplings and charges

CDF Run II, 200 pb^{-1}, published.

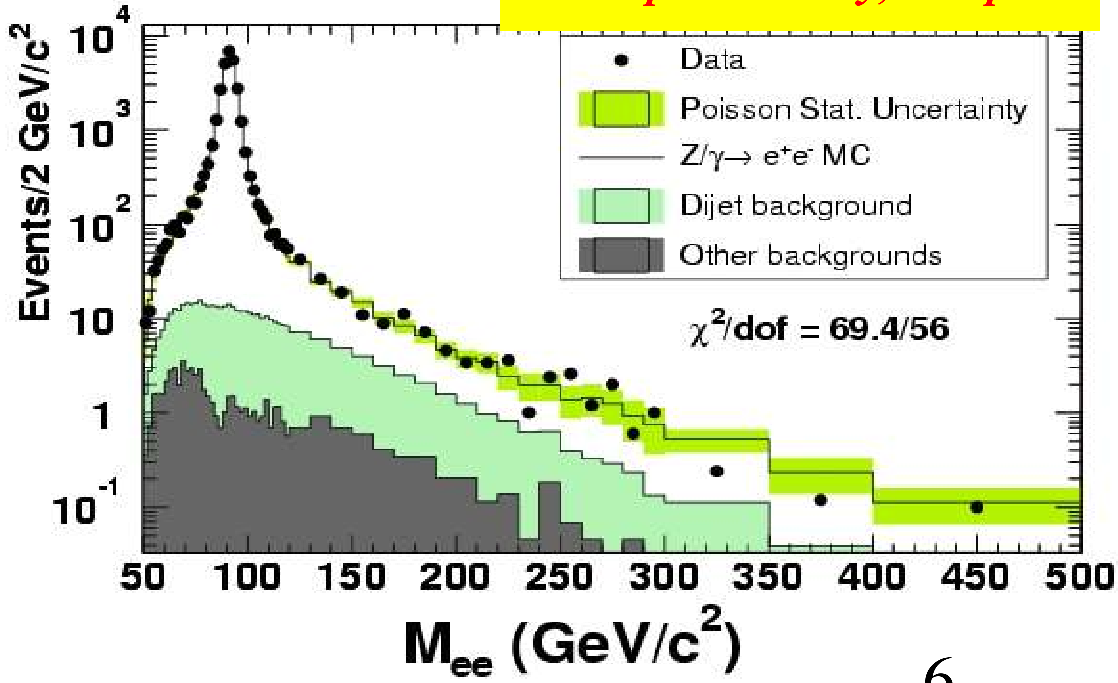


diEM Mass Spectrum

DØ Run II Preliminary

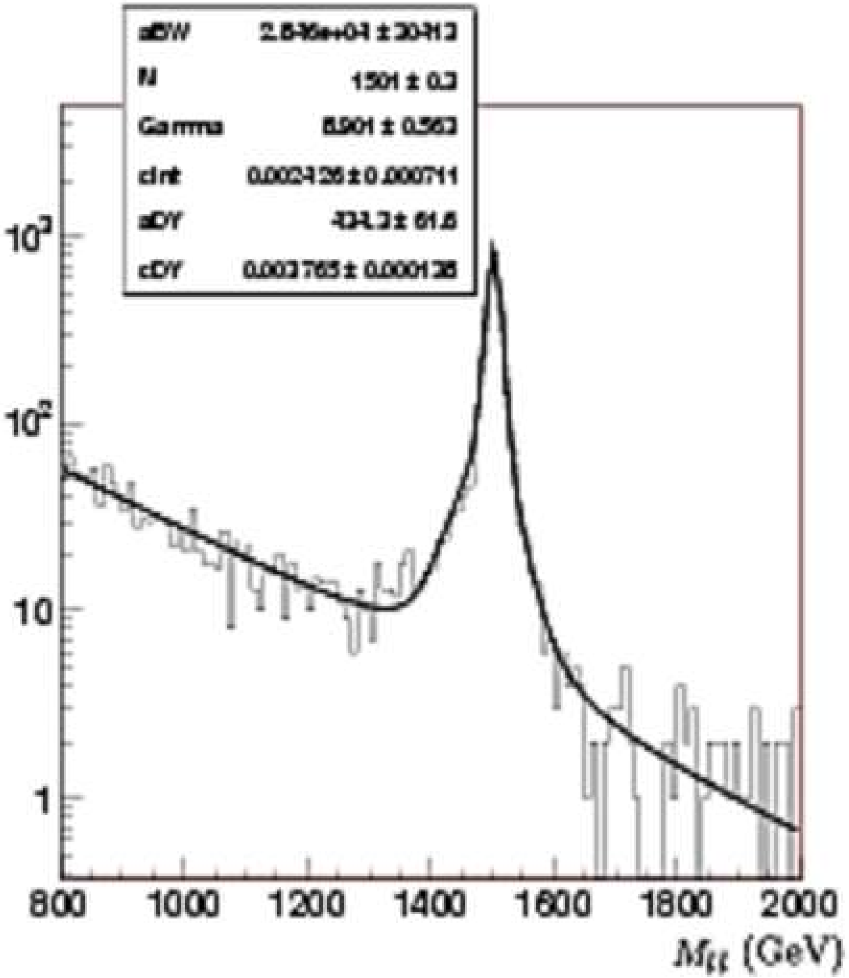


CDF preliminary, 448 pb^{-1}



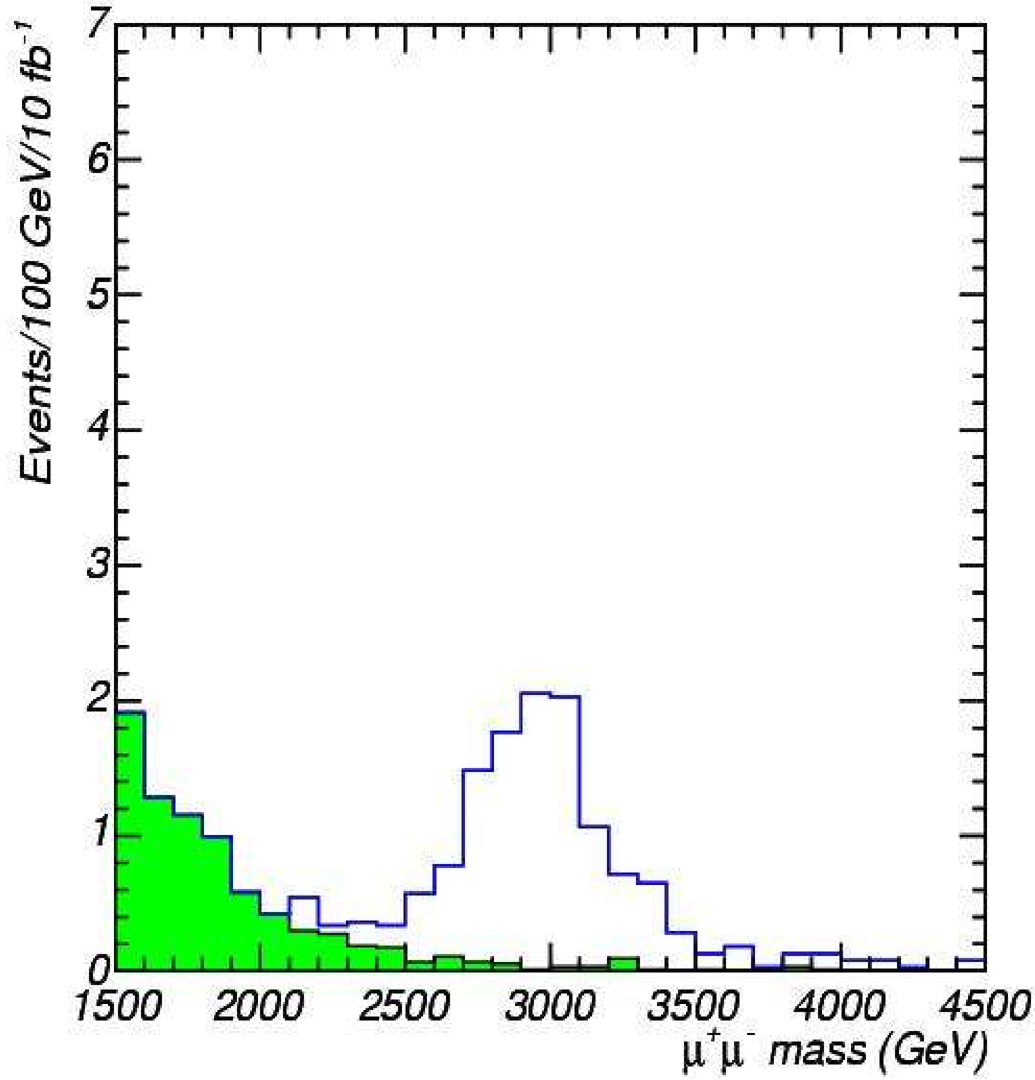
Here are some examples of imagined signals at the LHC:

ATLAS, di-electrons PUB-2005-010



(a) Z'_η model - $M = 1.5$ TeV

CMS, di-muons, 10 fb^{-1}, NOTE 2005/002



How do DØ and CDF Set Limits?

First, is there any overall excess?

minimum mass	CDF ee		CDF mm		D0 mm	
	exp.	obs.	exp.	obs.	exp.	obs.
150	213 +/- 99	205	55 +/- 2	58	85	73
200	78 +/- 33	84	21 +/- 1	18	-	-
210	-	-	-	-	25	24
300	14 +/- 4	22	5.2 +/- 0.3	6	6.4	5

If not, then compute the upper limit on the signal:

- define mass windows assuming very small natural width
- compute the 95% CL upper limit on the number of signal events
- convert into σ x BR using acceptance and efficiency estimates
- combine e and μ channels

From the point of view of the experimenter, this is the end result!

- one might compare this to $(\sigma \text{ x BR})_{\text{model X}}$ to constrain the model...

(but the models are not the important thing, (σ x BR) is....)

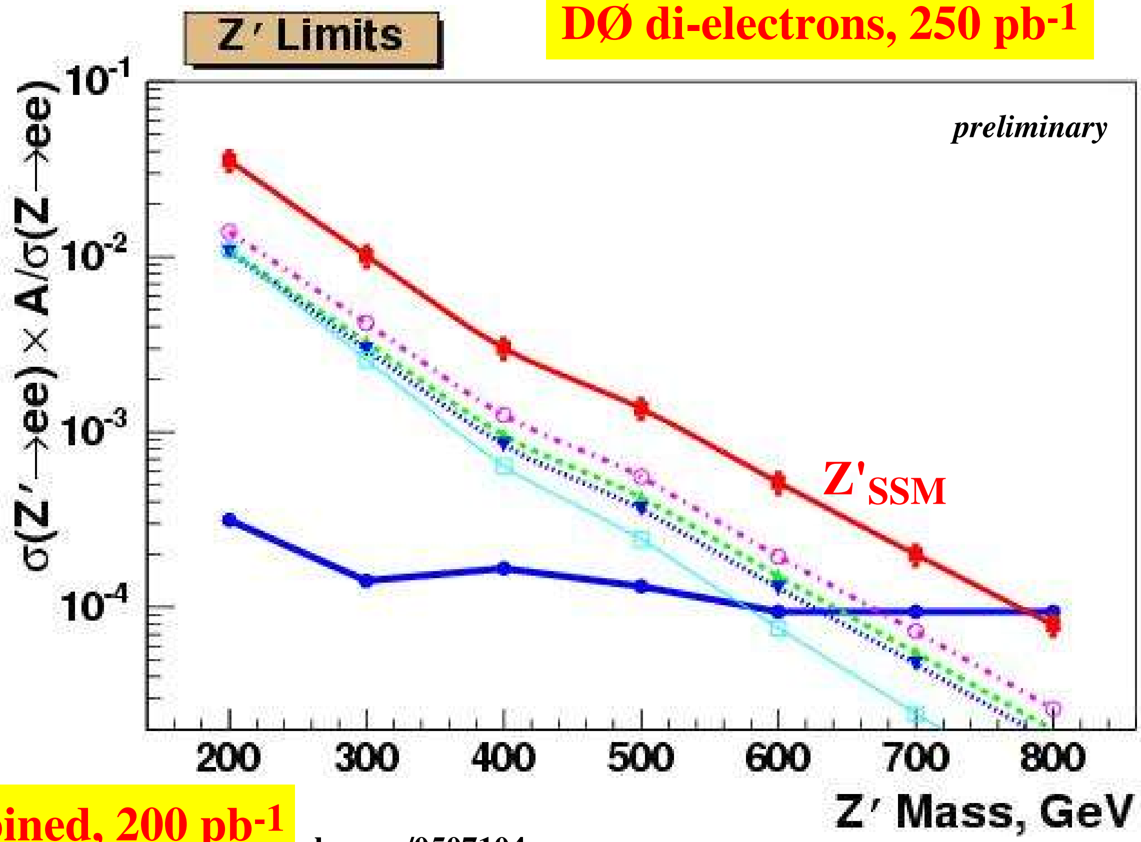
Actual

upper limits on Z' production

DØ works with the ratio of signal to SM Z cross sections.

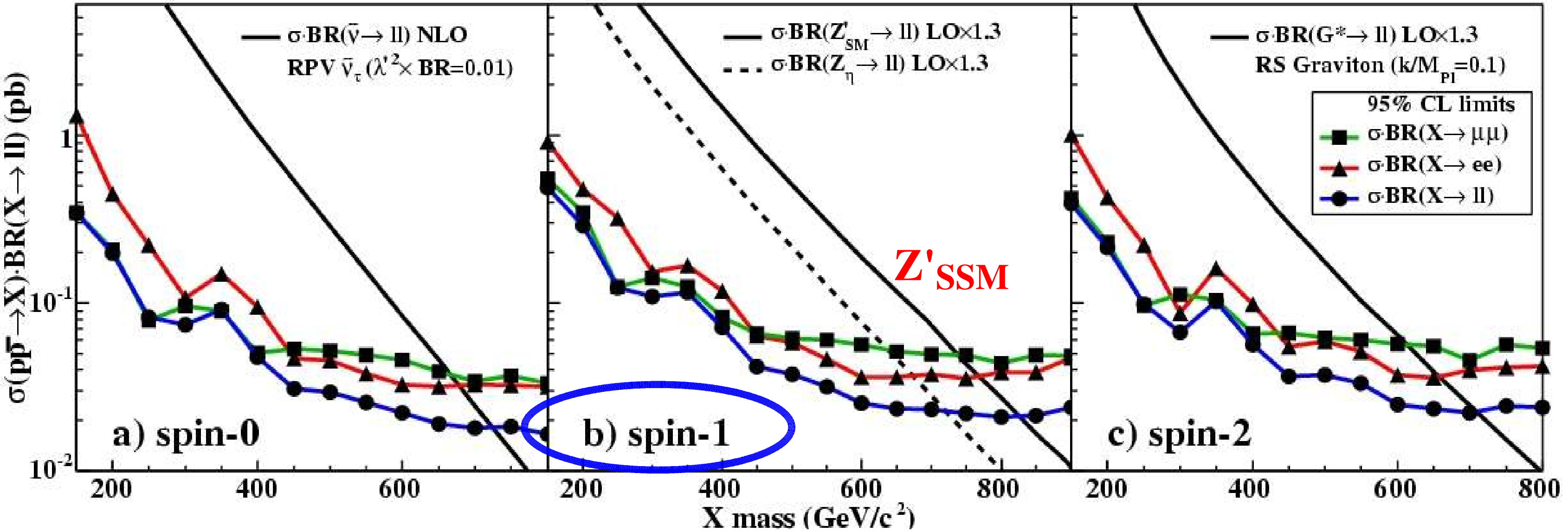
Both experiments achieve σ x BR < 24 fb at 95% CL

DØ di-electrons, 250 pb^{-1}



CDF, di-electrons and di-muons combined, 200 pb^{-1}

hep-ex/0507104



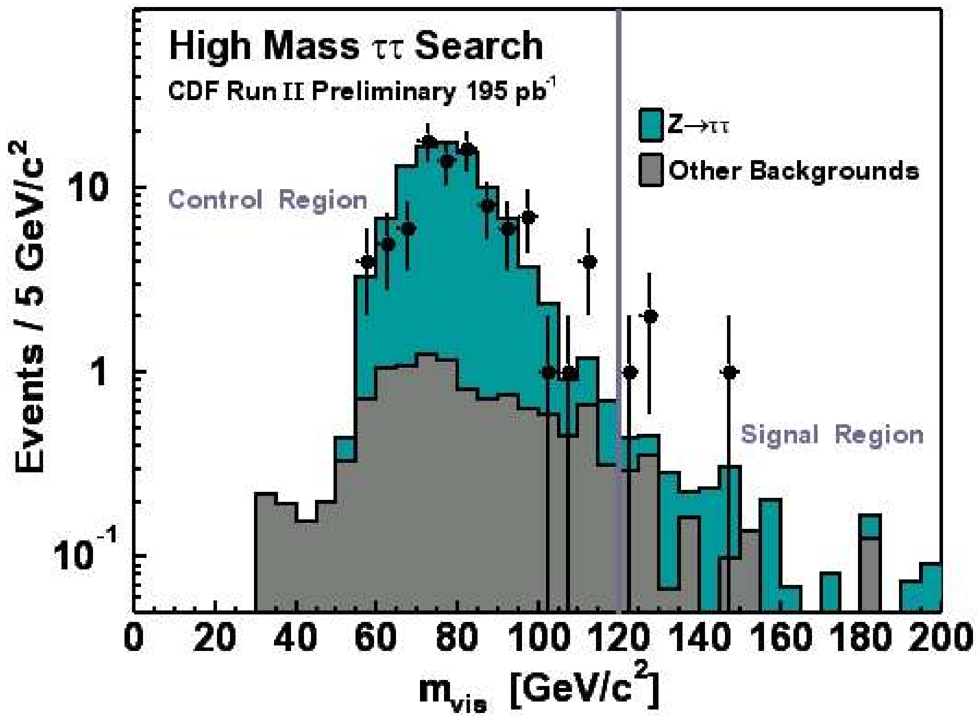
Just a quick word about τ's ....

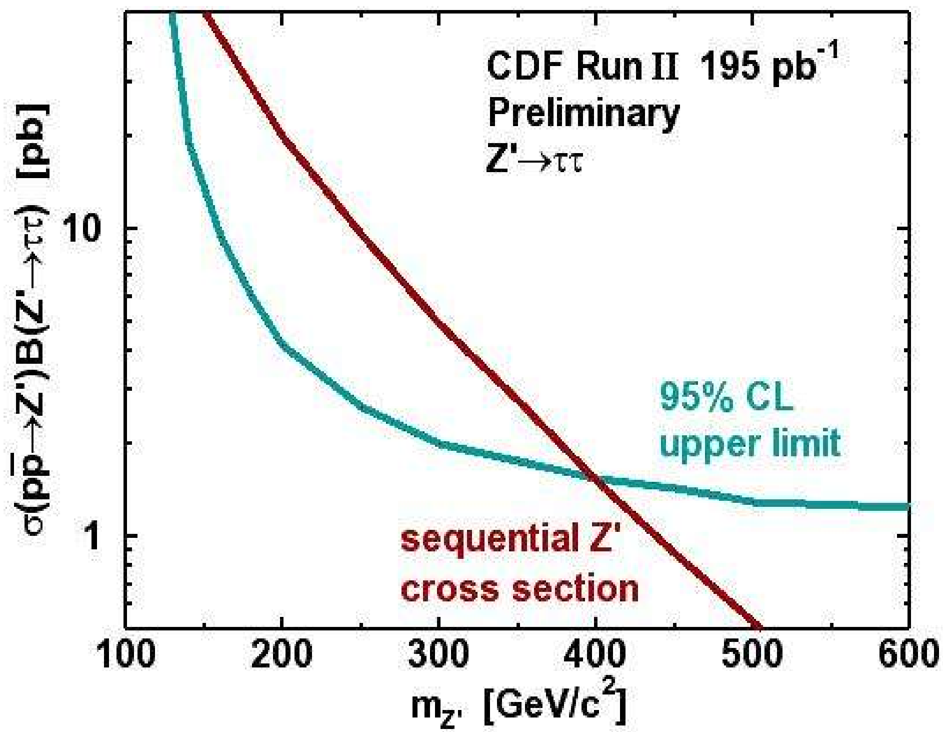
Z' decays to tau's are much harder to identify, of course, so this channel does not play a central role in the search for Z' bosons.

That said, it would be extremely important if couplings were not generation-independent!

CDF published, 195 pb⁻¹

hep-ex/0506034





LHC Studies

CMS has emphasized the di-muon channel, at ATLAS, the di-electron channel.

This reflects the relative strengths of the two detectors vis-a-vis resolution.

Some (not all) of the simulations have been fairly realistic.

- CMS: include effects of chamber mis-alignment – major impact on mass resolution
- ATLAS: include effects of shower correction algorithms including rad've tails

This has already lead to some innovations:

- recognize muons which radiate a lot like electrons (at the TeV scale...)
- delicacy exercised with the electron isolation criteria

Of course there are estimates of mass reach and of the luminosity required for discovery.

Roughly speaking, 100 fb^{-1} gets you in the <u>5 TeV</u> mass region.

Lessons & Challenges

lepton reconstruction and selection:

- "loose" selections helped a lot to boost acceptance
  - *has this been pursued yet, for the LHC?*
- isolation criteria are crucial at the Tevatron
  - *will this be a complicated issue at the LHC?*
- new problems at LHC, such as the behavior of TeV muons
- methods to measure efficiencies directly from data
  - *how will we extrapolate from high to very high p_T?*

energy and momentum scale:

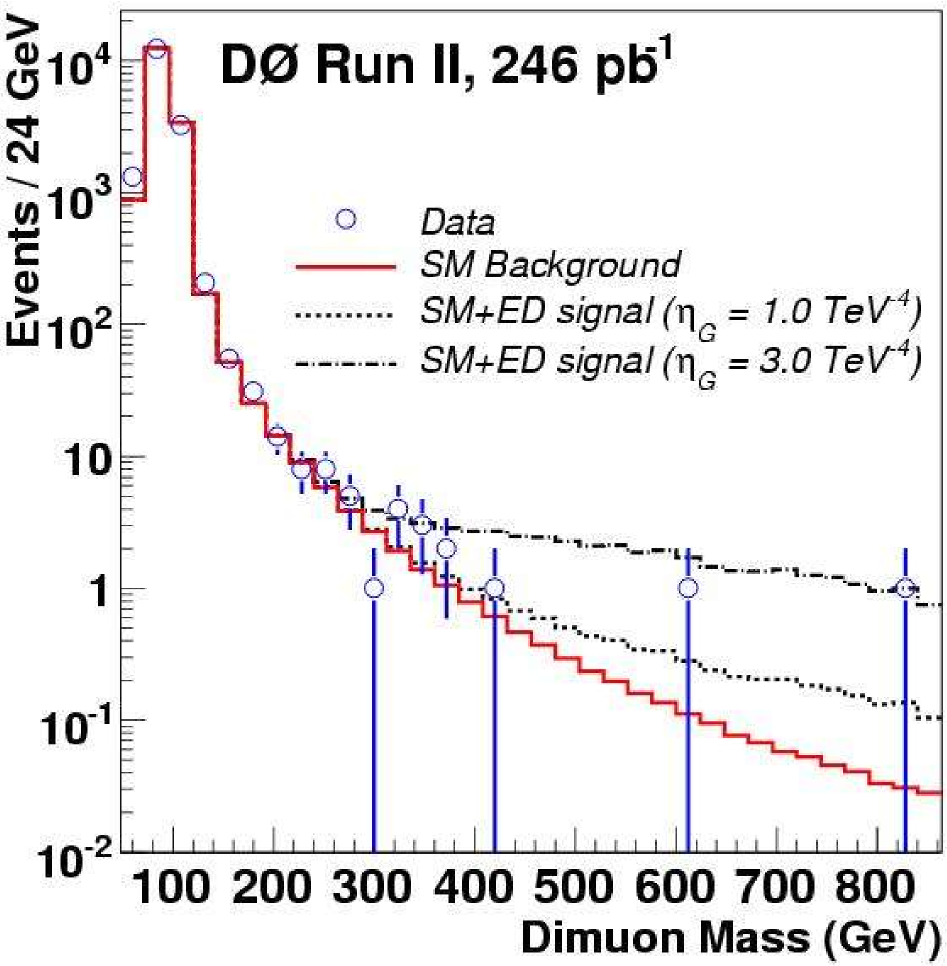
- how to extrapolate scale set by the Z peak to high scales?
  - *linearity of the calorimeter & tracker is the issue*
- tails of the resolution function are crucial – how to keep them under control?
  - *can apply clever techniques such as momentum balance devised by DØ*

background estimation:

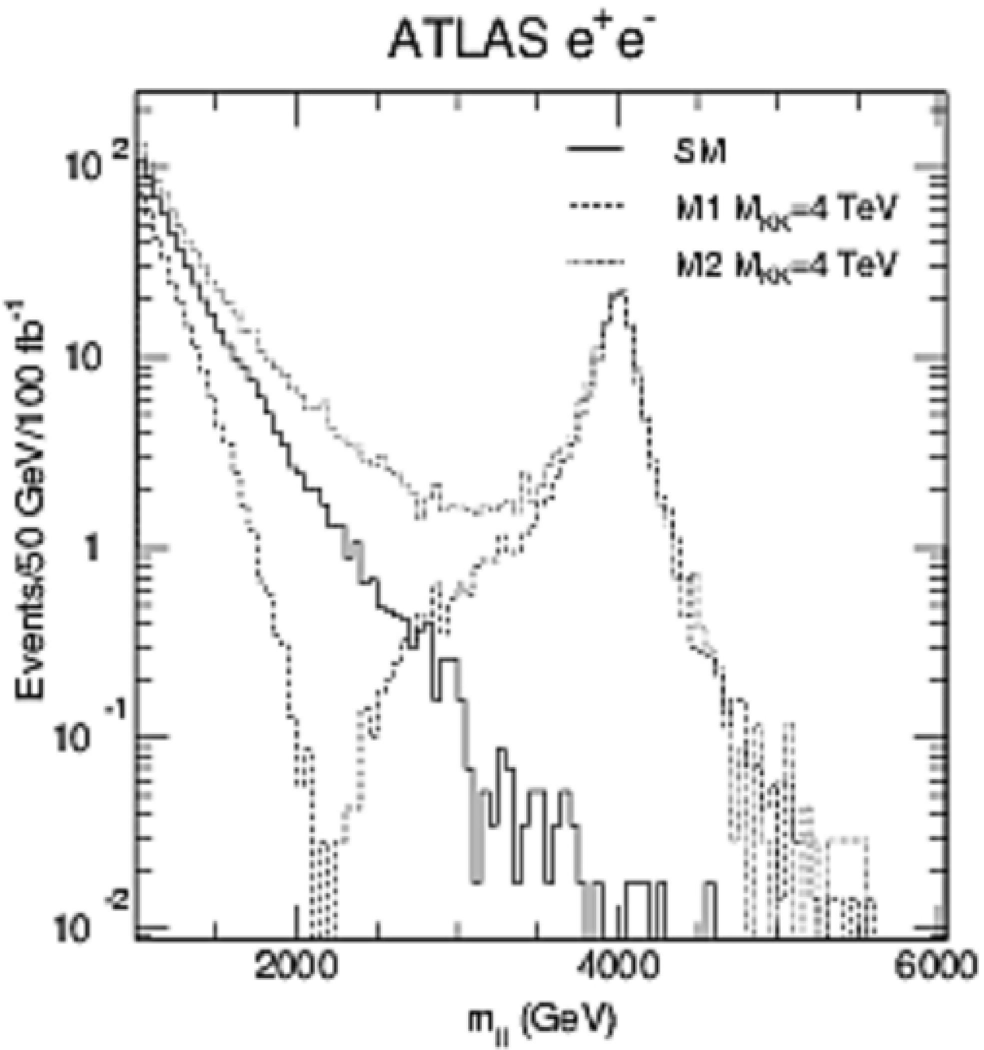
- **Drell-Yan constitutes 90 – 95%, so shape must be understood well!**
  - Tevatron uses Z-peak for normalization
    - *can this work at the LHC?*
  - must use mass-dependent K-factors
    - *can the Tevatron verify these?*
  - PDF's influence level and shape
    - *Tevatron constraints will improve*
    - *LHC will also provide constraints*
    - *methods to quantify uncertainties*
  - electroweak corrections are predicted to be large (U. Baur)
    - *can these be verified using Tevatron data?*
- **QCD events, producing 1 or 2 fake leptons**
  - not to be estimated from simulation!
  - not easy to estimate from the data: pitfalls
    - *same-sign methods require charge correlation – not obvious*
    - *fake rates can be biased by selection criteria*
- **electroweak backgrounds are very small – use simulations**

DØ published

hep-ex/0506063



Azuelos & Polesello, Eur. Phys. J C39, s2, s1 (2004)



Watch out for the size and shape of the Drell-Yan tail!

detector stability and simulation:

- LHC will use a wealth of test beam data
- plans for in situ calibrations under development
  - *must specify necessary triggers to collect calibration data*
- much harder to tune the underlying event, and pile-up
  - *studies and tunes with Tevatron data should be most useful*

statistical methods:

- how to integrate over the systematic uncertainties?
- how to correlate uncertainties between channels
- challenge for *discovery* may be trickier than for *limits*
- eventually we hope to be making measurements!

Perhaps the easiest approach is just to "bump hunt."

This approach is under development at CDF and CMS.

- Parametrize the background in some intuitive way.
- Determine the background parameters by maximizing the likelihood for the background.
- Slide a Gaussian across a given region in small steps (typically, one sigma on the mass resolution), and for each step, determine the amplitude which maximizes a signal+background likelihood.
- Compare the NLL (negative log-likelihood) for signal+background to that for the background alone.
- If the improvement is significant, and if the amplitude for the Gaussian is positive, then investigate!!

Fitting for a peak + background:

Given a description of the background, we can look for a peak at some (arbitrary) spot within the mass range.

We use a single Gaussian with width = mass resolution, and use the amplitude to indicate whether a signal is present or not.

$$\mathcal{P}(x) = a\,G(x,\sigma) + (1-a)\,B(x)$$

The Gaussian G(x,σ) and the background B(x) are normalized to unity.

For each arbitrary mass value μ, we find the value for a which optimizes the probability (NLL).

A positive value for a which is significantly different from zero indicates a real peak.

ΔNLL as an indicator for significance:

NLL = "negative log-likelihood"

We use a comparison of the NLL to indicate the significance of a given a at a given mass value μ.

$$\Delta \text{NLL} = \text{NLL(background+peak)} - \text{NLL(background)}$$

Canonically,

ΔNLL = 0.5 corresponds to 1σ

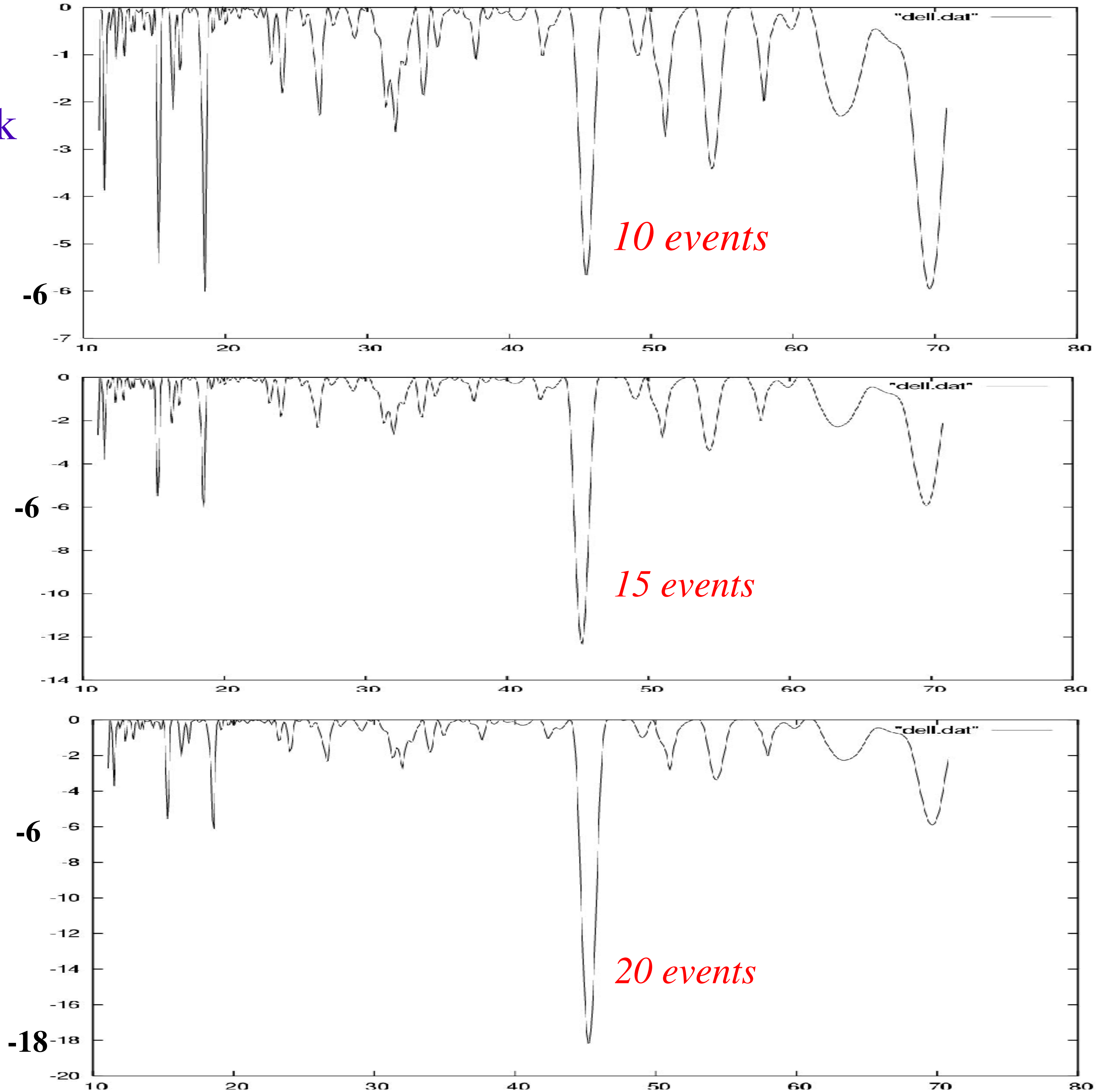
ΔNLL = 2.0 corresponds to 2σ

ΔNLL = 4.5 corresponds to 3σ

ΔNLL = 12.5 corresponds to 5σ

Naturally, one must distinguish between $a > 0$ and $a < 0$!

Add in a fake peak to show that the method clearly indicates a signal.

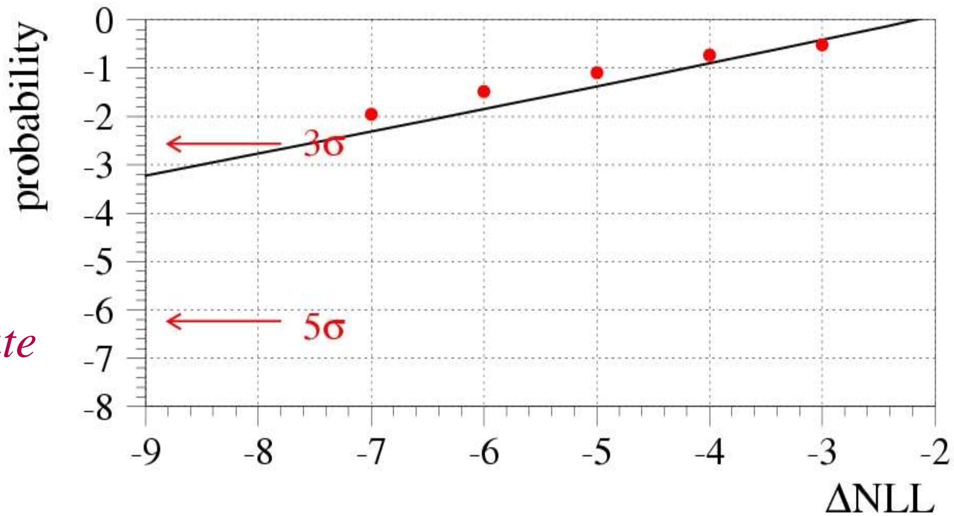


How do we assess the significance of any bump?

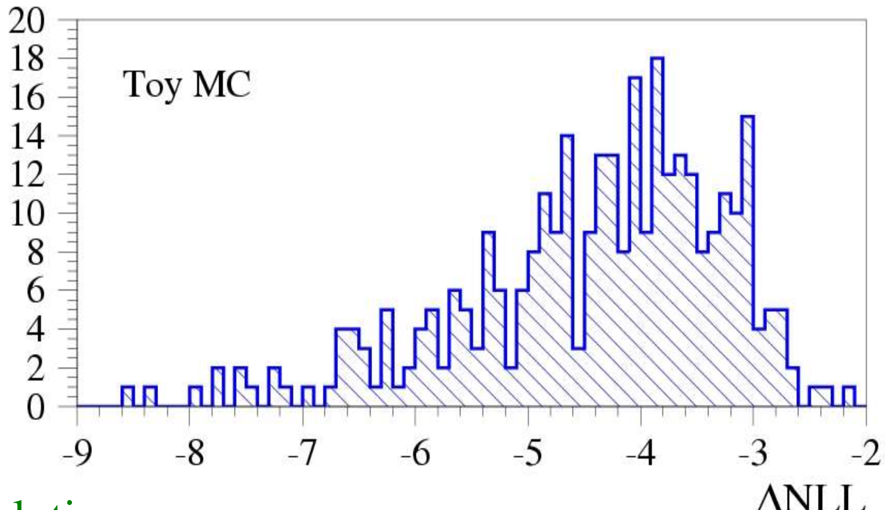
The issue is that we have many opportunities to catch an upward fluctuation of the background.
The canonical statement $\Delta NLL = \sigma^2/2$ applies to just one "trial."

If a given interval is spanned by *N* steps of σ (the mass resolution), then the probability to observe a given ΔNLL is increased roughly by *N/4*.

probability for the background to fluctuate upward and produce a given ΔNLL



distribution of ΔNLL
from toy MC
(positive amplitude only)



Naturally this depends on the given range and the mass resolution.

The Cutting Edge

Suppose we observe a narrow peak at the Tevatron and/or at the LHC.   What then?

We do not simply want to test various benchmarks.

A more empirical approach is needed: What kind of Z' is it?

A recent study by *Carena, Daleo, Dobrescu and Tait* (CDDT) leads the way.

Phys. Rev. D70 (2004) 093009

Their approach has been presented several times
- time for only one or two points
- in use by CDF in two contexts

CDDT discuss the phenomenology of Z' arising from generic GUT's.

Applying only a few very general theoretical considerations, they identify four distinct "model lines" which cover broad classes of Z' models.

Each model line depends only on a few parameters:

- the mass of the resonance ($M_{Z'}$)
- the overall coupling constant (g_z)
- a free dimensionless parameter, x, which determines the fermion charges

Instead of testing 1, or 4, or 6, or 7 different specific Z' models, one places constraints on g_z and x for a given $M_{Z'}$.

This formalism allows constraints from e^+e^- machines and from hadron colliders to be compared directly.

So far, applications have been made by CDF to:

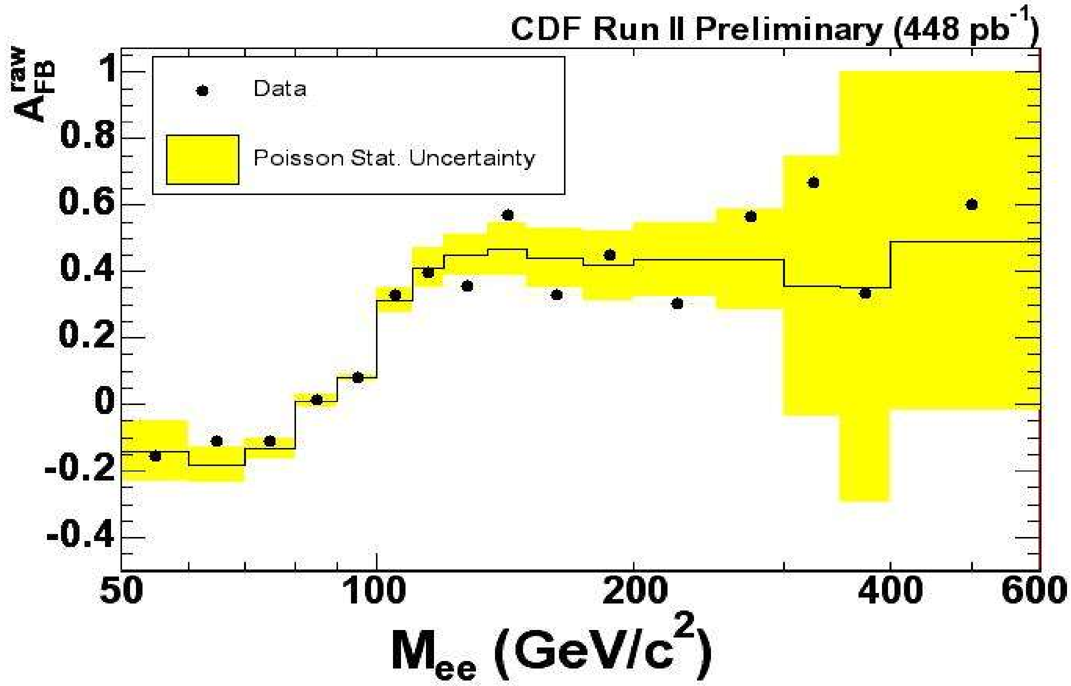
- forward-backward asymmetry
- cross section limits

CDF recent di-electron results:

The forward-backward asymmetry has been measured as a function of M_{ee}.

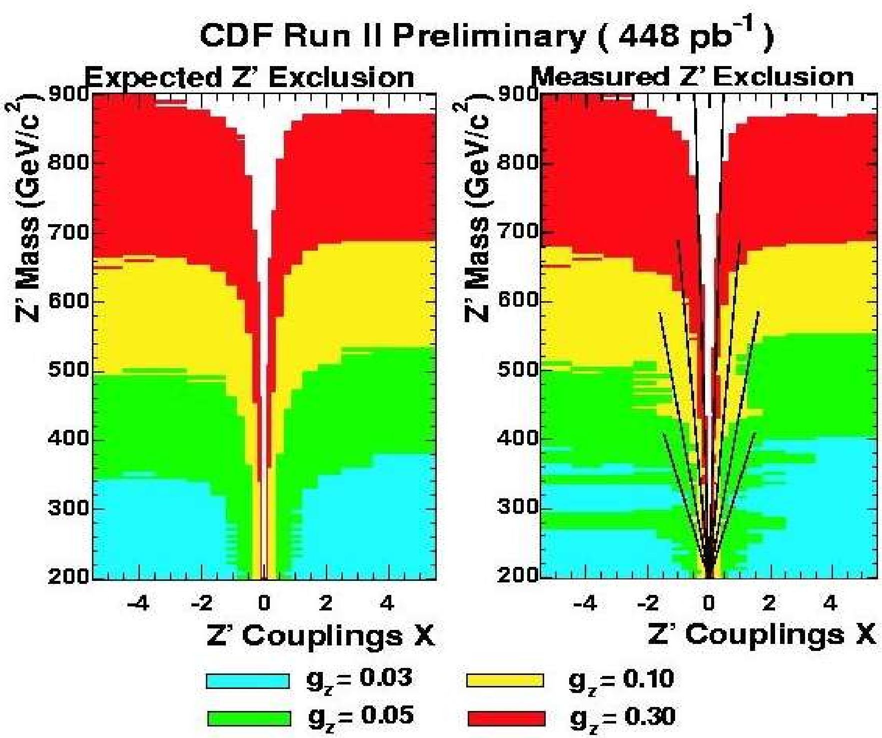
The presence of a Z' generally shifts A_{FB} depending on couplings and the Z' width.

A "model-independent" formulation is quite helpful here...

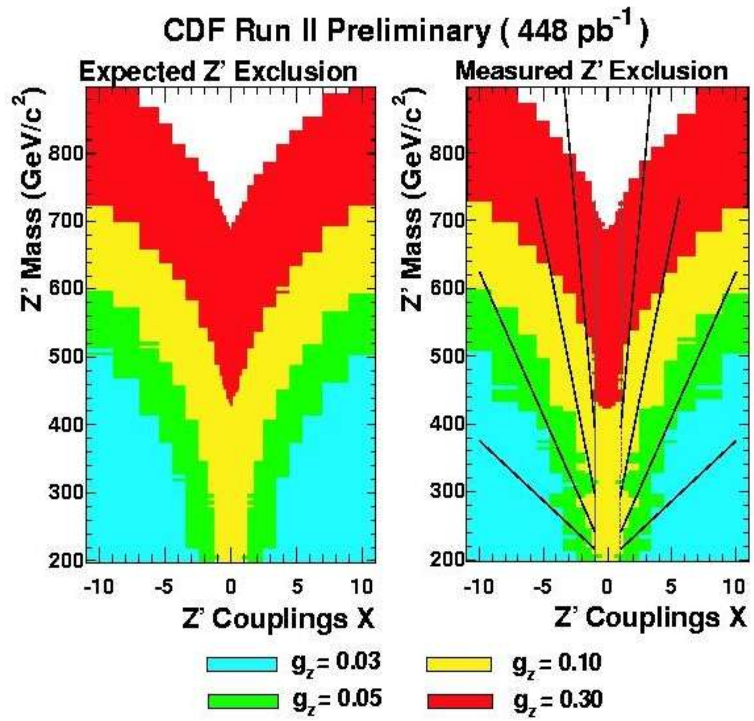


These are two out of four examples.

***B-xL* models**



10+$x\bar{5}$ models



CDF constraints coming from the upper limit on the cross section:

CDDT factorize the cross section in terms of model parameters and kinematic factors:

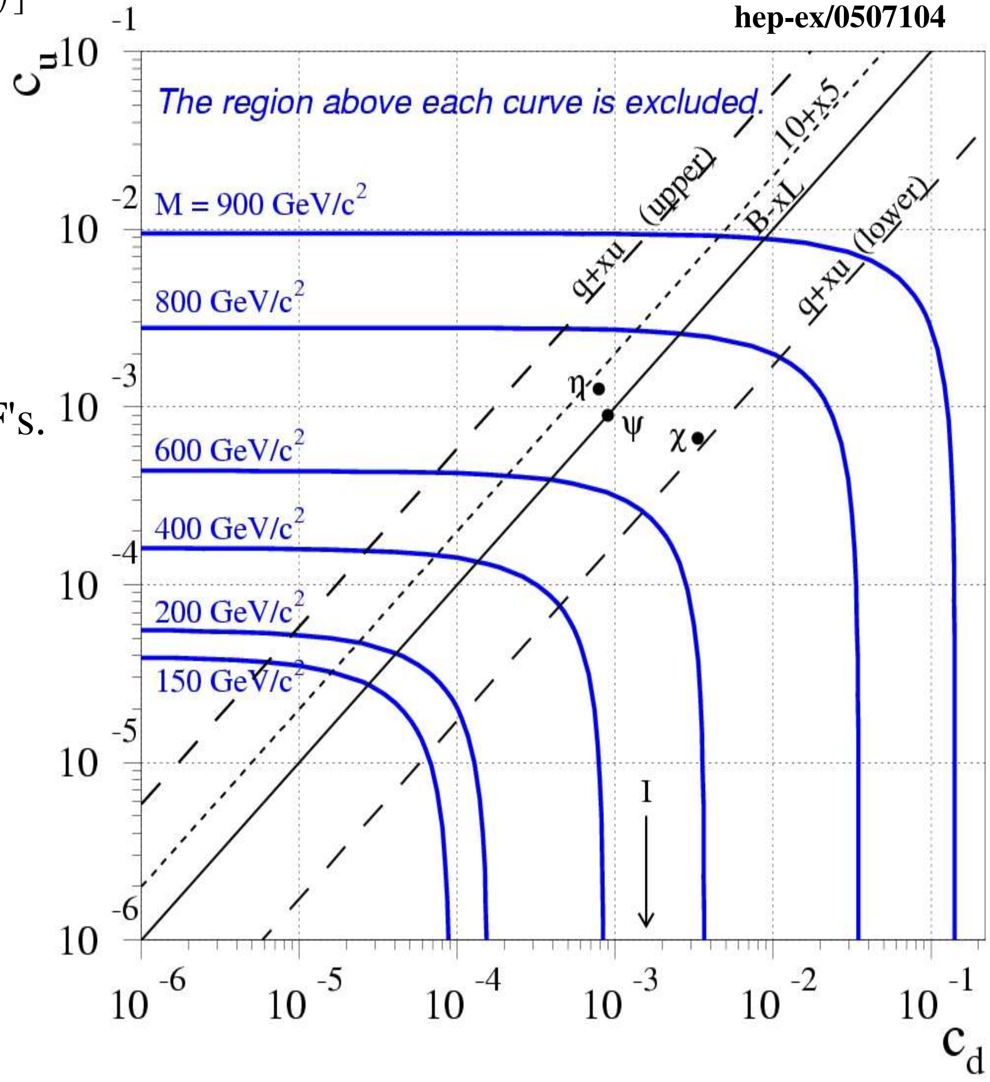
$$\sigma(Z') = \frac{\pi}{48\,s}\left[c_u w_u(s, M_{Z'}) + c_d w_d(s, M_{Z'})\right]$$

$$c_{u,d} = g_z^2\,(z_q^2 + z_{u,d}^2)\,Br(Z' \to l\,l)$$

The factors w_u and w_d encapsulate the integrals over the parton fluxes.
They can be computed and depend only on the PDF's.

An upper limit on $\sigma(Z')$ translates directly into limits on the "charge factors" c_u and c_d.

hep-ex/0507104



The constants w_u and w_d are different at the LHC and the Tevatron.

Example ($M_{Z'} = 800$ GeV): TEV: $w_u = 1.134, \quad w_d = 0.091$
LHC: $w_u = 2404, \quad w_d = 1613$

A given Z' model (with mass $M_{Z'}$ & coupling g_z) will show up as different contours in the (c_u, c_d) plane:

<ins>The intersection of constraints pins down c_u and c_d!</ins>

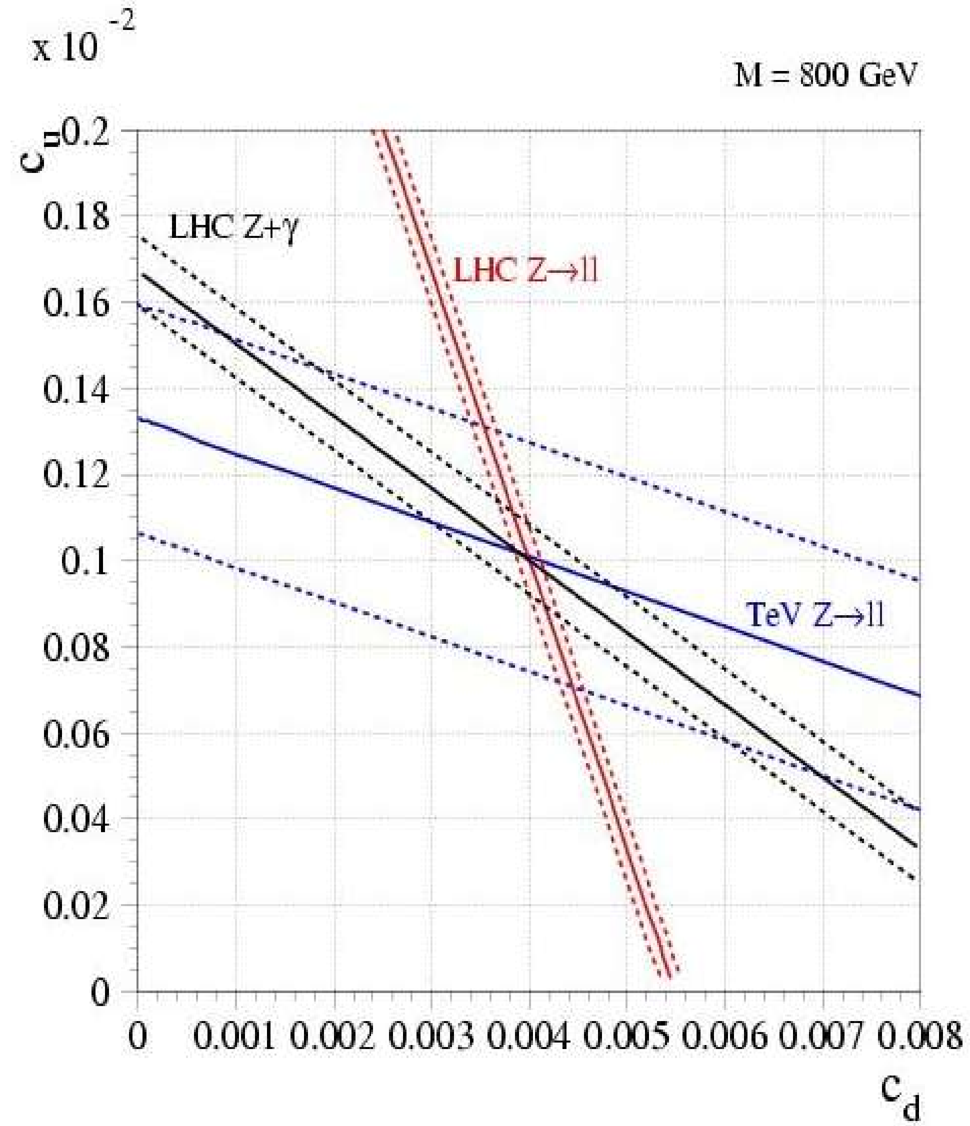
Notice the synergy between Tevatron and LHC!

Another option is to consider the reaction

$$pp \to Z' + \gamma$$

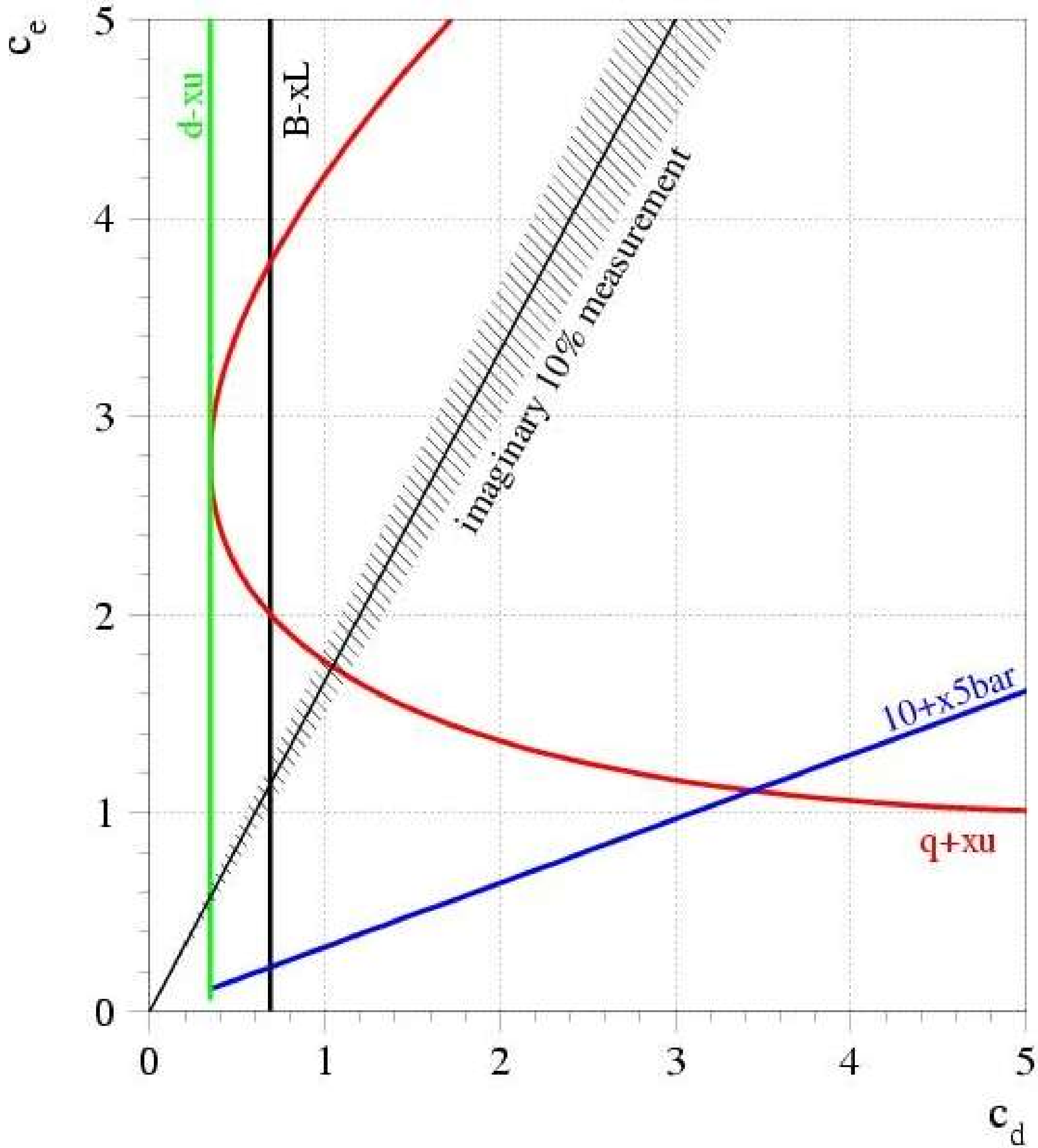
which tags the u-quarks more than the d-quarks.

(Work is in progress to obtain fairly realistic estimates of constraints.)



Finally, if a Z' peak could be seen in bb or tt final states, then more constraints result from the comparison of leptonic and hadronic final states.

$$R_b = \frac{\sigma \times Br(Z' \to bb)}{\sigma \times Br(Z' \to e^+ e^-)}$$



There are four model lines.

Each curve is parametrized by x.

As x changes, so do the relative leptonic and hadronic branching ratios:

$$R_b = \frac{3(z_q^2 + z_d^2)(1+\alpha_s/\pi)}{z_l^2 + z_e^2}$$

If c_d were already known, then this measurement would allow one to infer the value of x.

No study has been made as to the accuracy with which R_b could be measured.

Conclusions

Real results on Z' are coming from the Tevatron:
the DØ and CDF analyses are in a mature stage.

Experience gained gives valuable lessons for the LHC,
and challenges at the LHC could be mitigated with Tevatron studies.

The model-independent approach provides an effective platform
for combining various data to constrain Z' properties.