Searches for Narrow di-Muon Resonances at Hadron Colliders

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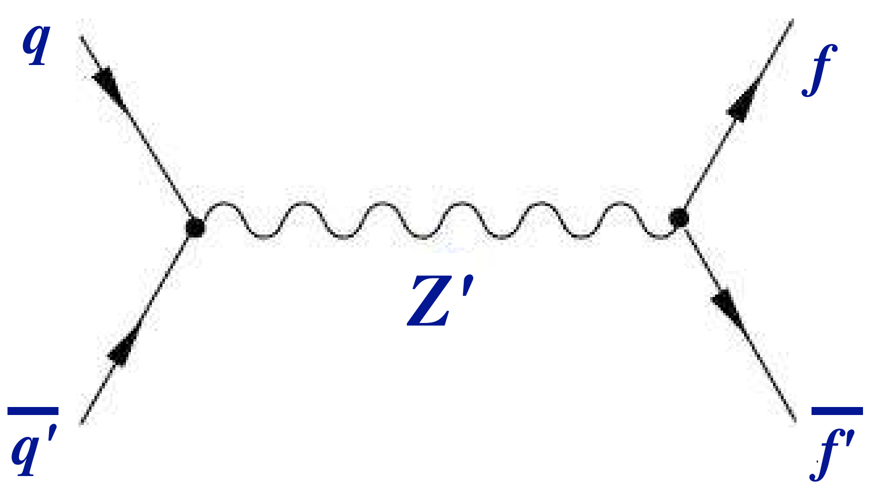
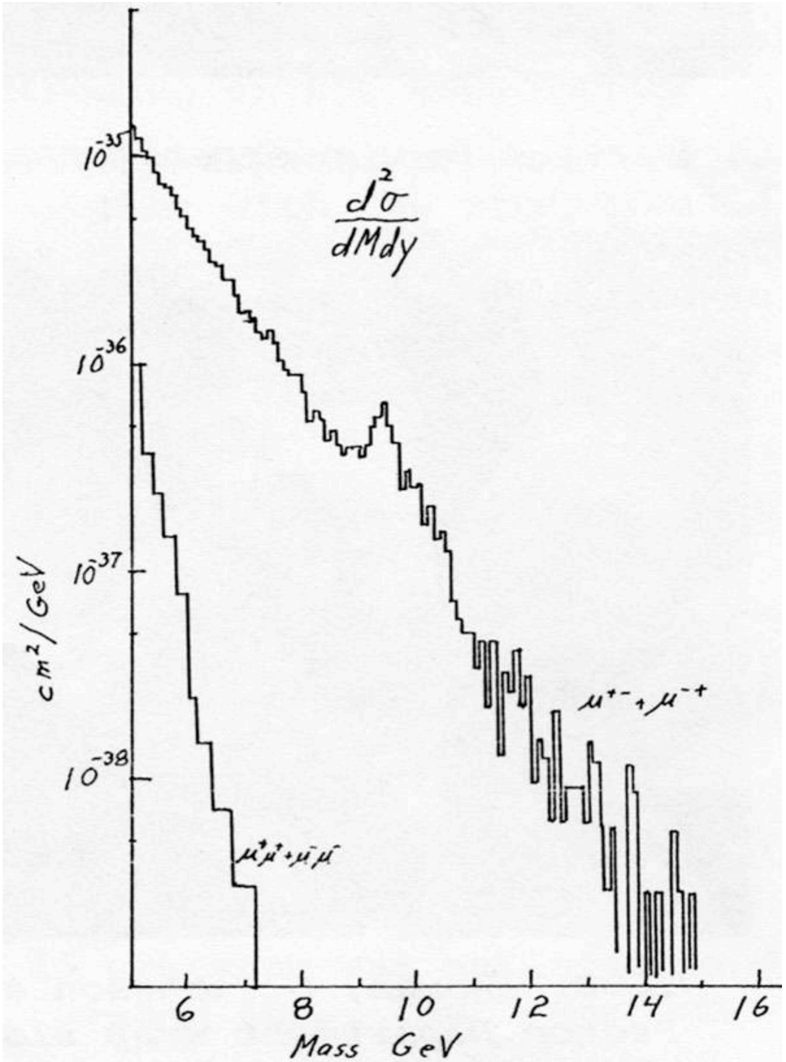
- motivations
- new techniques from CDF
- traditional Z' searches at the Tevatron
- searches at the LHC
- conclusions

Introduction & Motivation

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

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



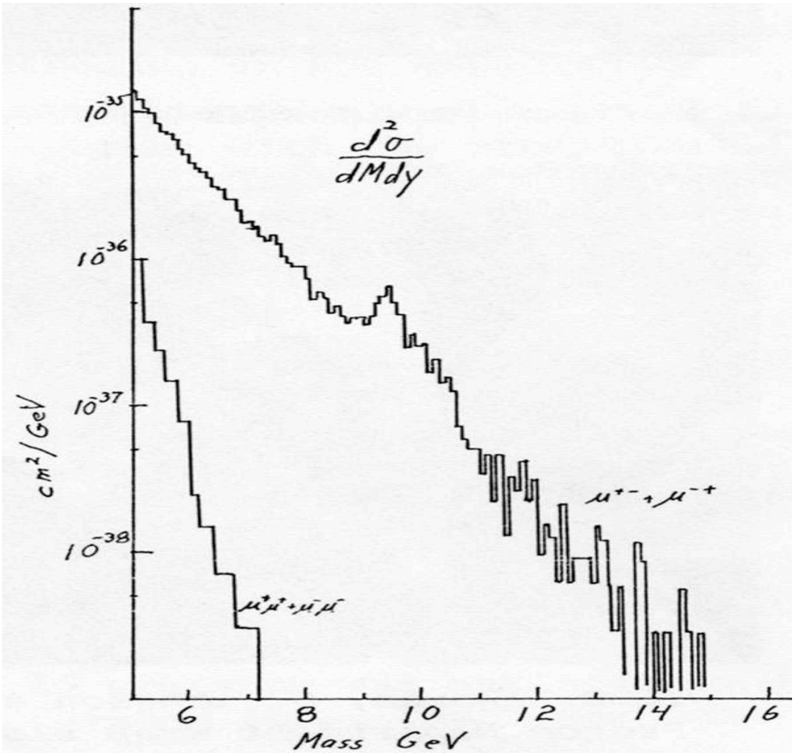


Motivations

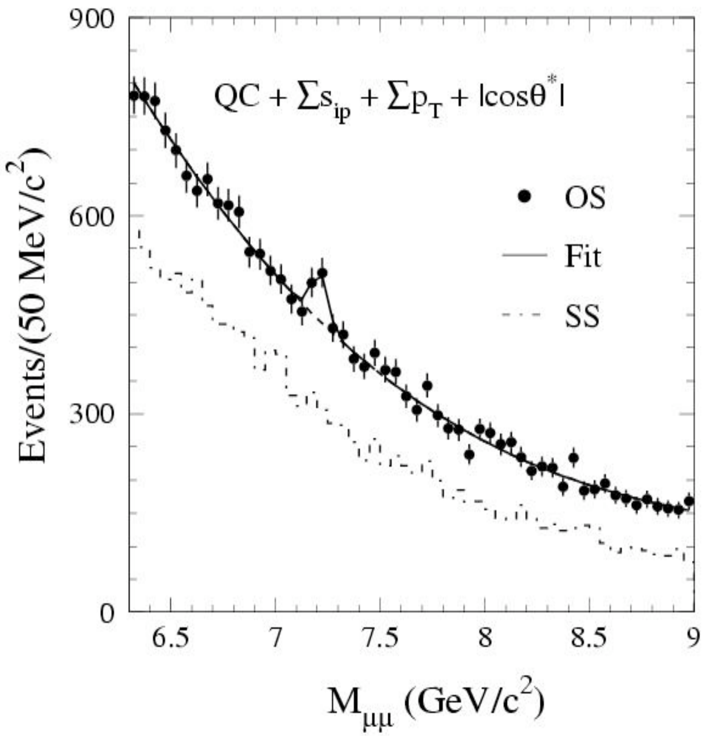
Basic: We have lots of nice data – unique data – we should look at it in any many ways as we can think of!

Fancy: Theorists may talk about light sbottom resonances, or weakly-coupled Z' bosons, *etc. etc*...

Internal: A hint of a signal was observed in the Run I data.



CDF Run I Data



A new technique from CDF

Method

Previously, people binned the mass spectrum and looked for bumps.

If the "signal" falls on the boundary between bins – tough luck!

Physicists have used unbinned fitting methods for years.

We should use an unbinned method to hunt for bumps.

What is needed:

- parametrization of the continuum (background)
- parametrization for the bump (signal)
- measure of the significance of any bump that is found, or method to set limits on any signal as a function of its mass...

This is what we do, in some detail:

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

Implicit assumptions:

- any signal would be narrow compared to the width of the region
- the signal would be small compared to the total BG in the region
- the background has no sharp features within the mass region

Data and Event Selection

event selection:

- data taken with a special low-p_T di-muon trigger : $\approx 200\ \mathrm{pb}^{-1}$
- offline, demand two opposite-sign muons with $p_T > 5$ GeV and $M_{\mu\mu} > 3.8$ GeV
- muons must be "isolated" - small calorimeter energy in a cone around each muon
- reject cosmic rays using timing information from the drift chamber
- small alignment corrections to remove p_T bias in the real data

muon selection:

- both muons must have good track "stubs" in the muon chambers
- the match to a high-quality drift-chamber track must be good
- muon identification:
  - calorimeter energy consistent with min-I particle
  - impact parameter consistent with the beam line

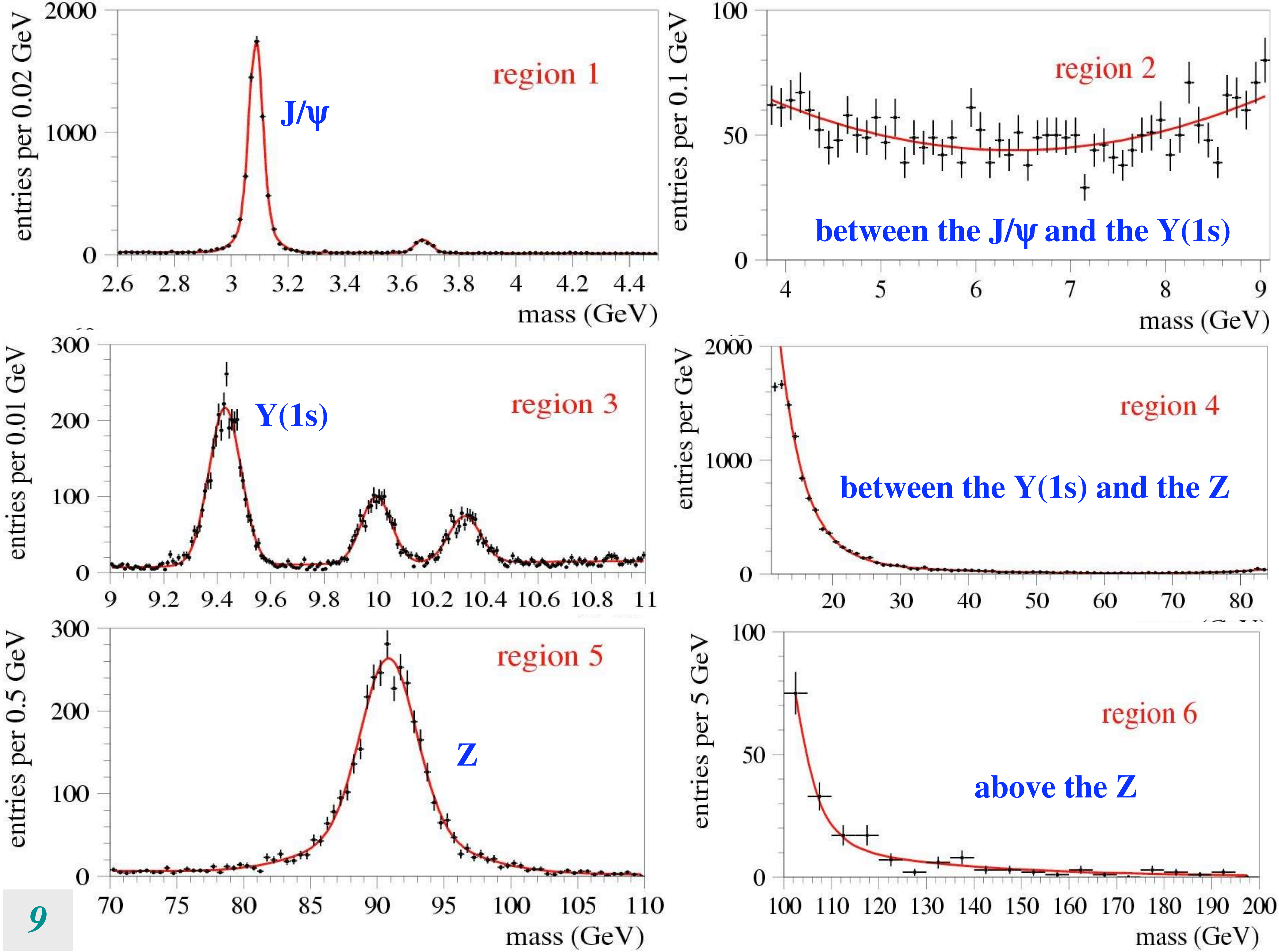
Six Mass Ranges

- We defined six mass ranges:
  three with resonances and three with smooth distributions

1)	J/psi	2.6 - 4.5 GeV
2)	4-9	3.8 - 9.1 GeV
3)	Upsilon	9 - 14 GeV
4)	13-84	13 - 84 GeV
5)	Z	70 - 110 GeV
6)	high	100 - 200 GeV

provide good calibration signals (1, 3, 5)

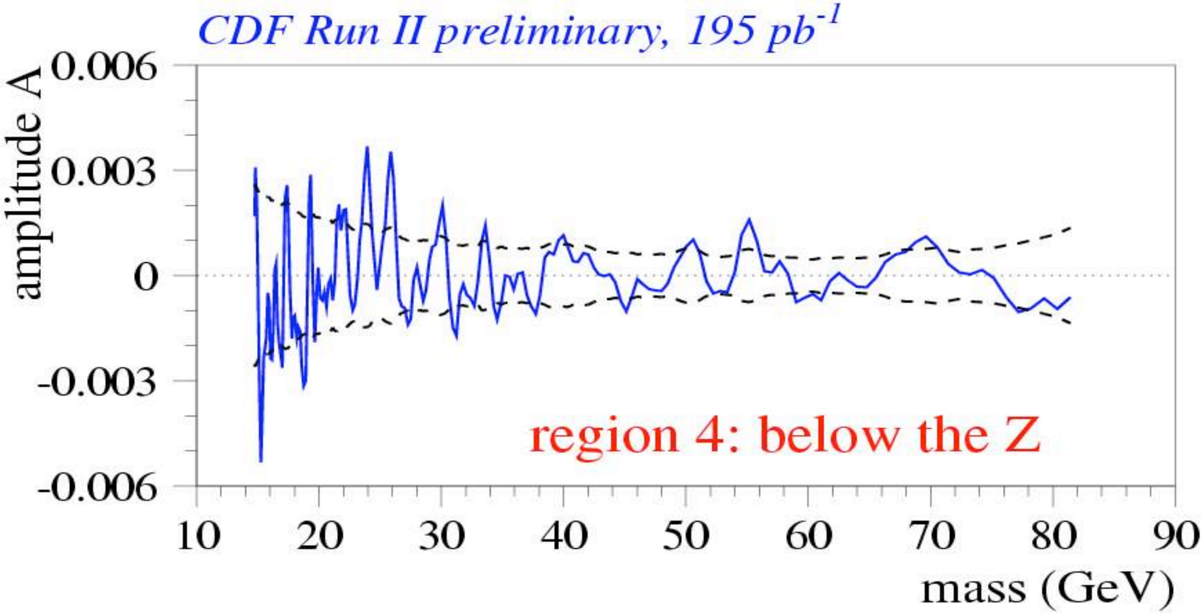
- We fit these to appropriate empirical functions.
  - use an unbinned likelihood fit
- Above 200 GeV demands a different technique – *in progress*.

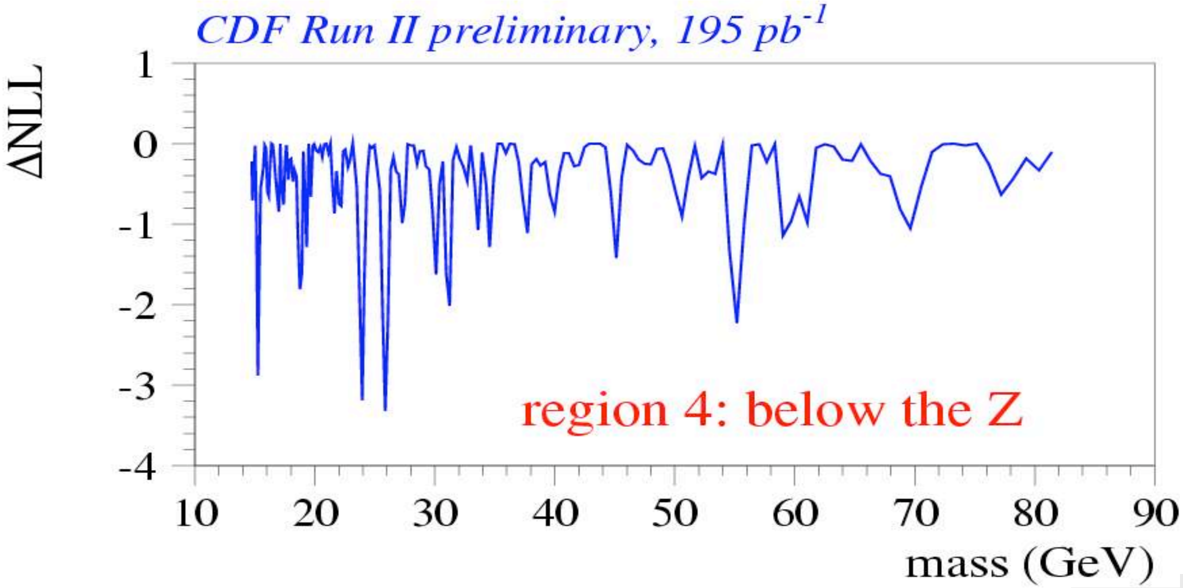


region 1
J/ψ
entries per 0.02 GeV
mass (GeV)
region 2
between the J/ψ and the Y(1s)
entries per 0.1 GeV
mass (GeV)
region 3
Y(1s)
entries per 0.01 GeV
region 4
between the Y(1s) and the Z
entries per GeV
region 5
Z
entries per 0.5 GeV
mass (GeV)
region 6
above the Z
entries per 5 GeV
mass (GeV)

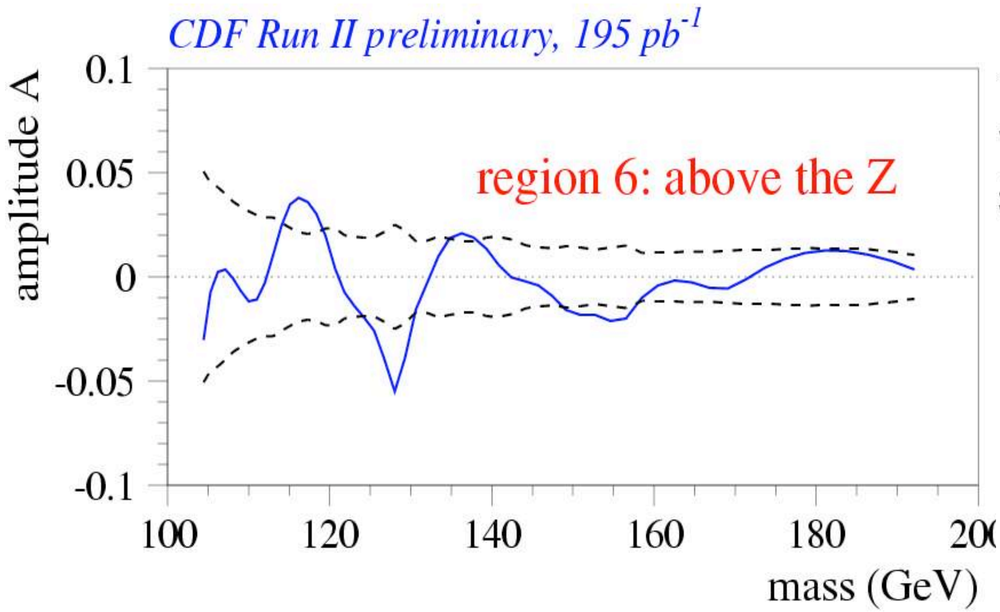
Example: Scanning Region 4

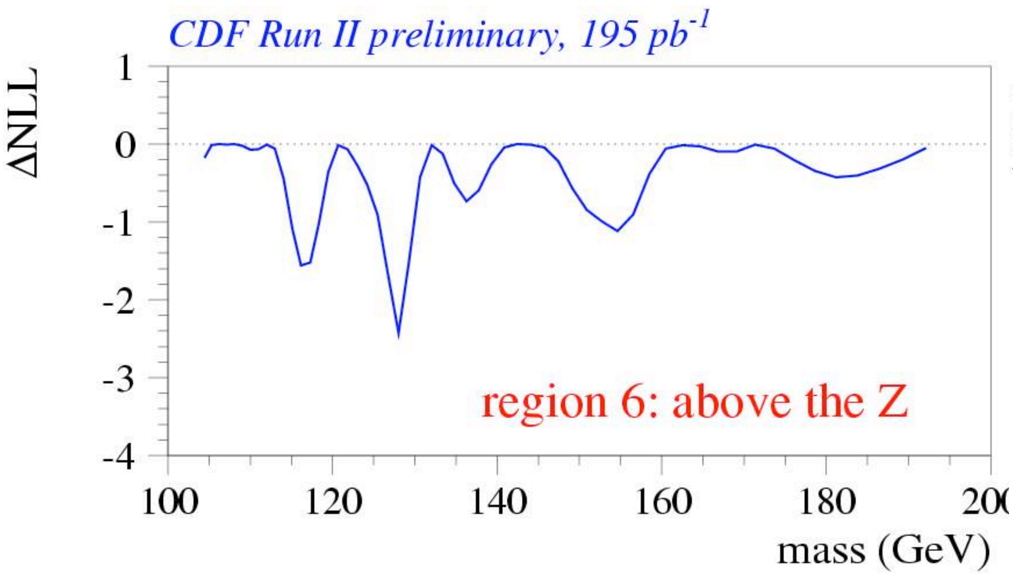
- *mass range 13 – 84 GeV*
- *parametrize as a sum of three exponentials*
- *Increasing spacing reflects the quadratic increase of σ_M with M.*
- *Dashed lines show the calculated uncertainty on the amplitude.*
- *No signs of a new peak.*



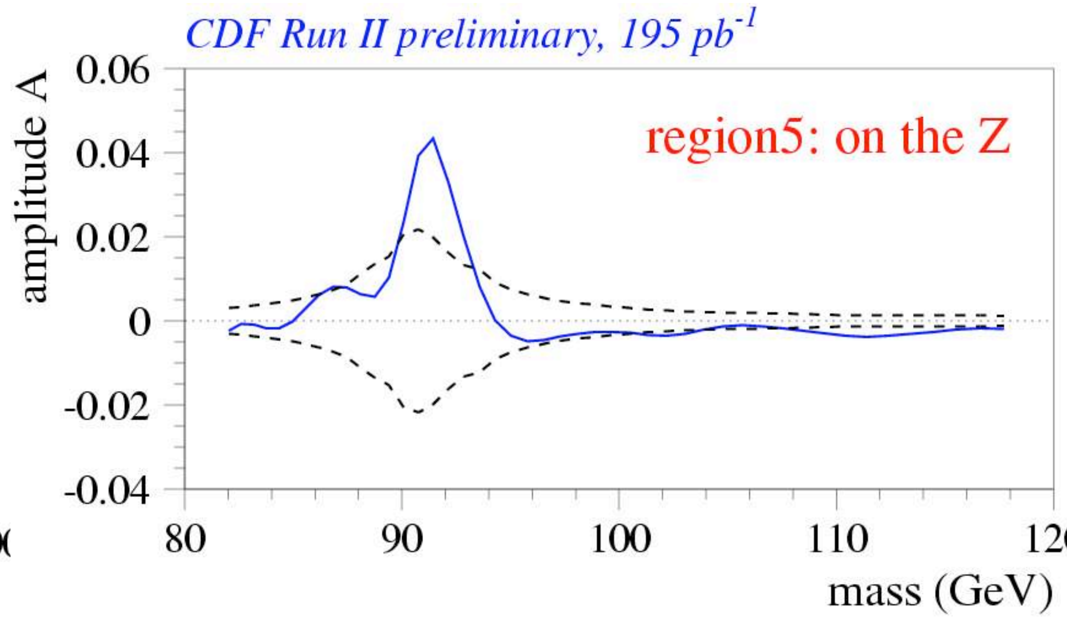


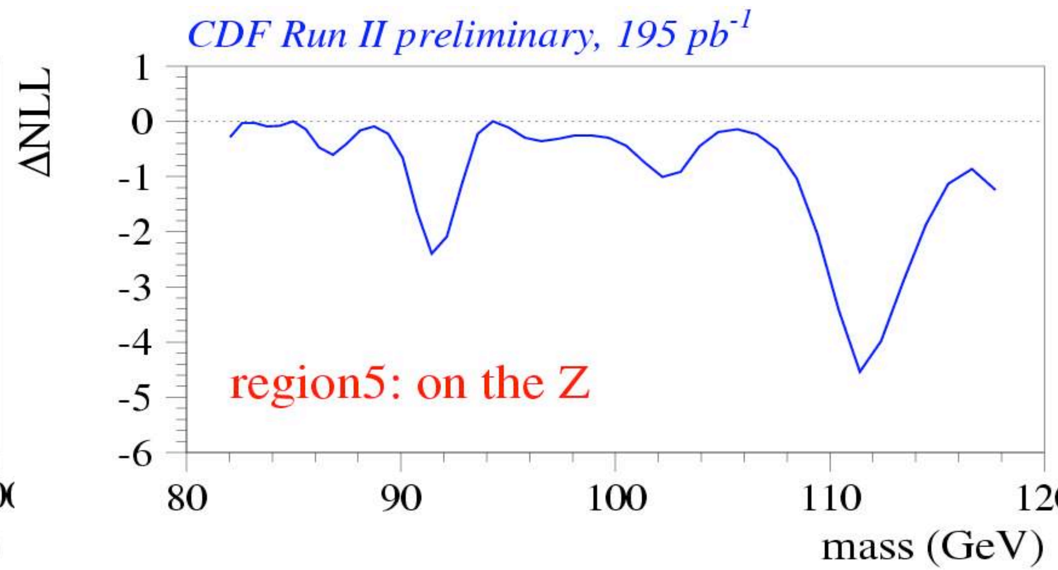
above the Z





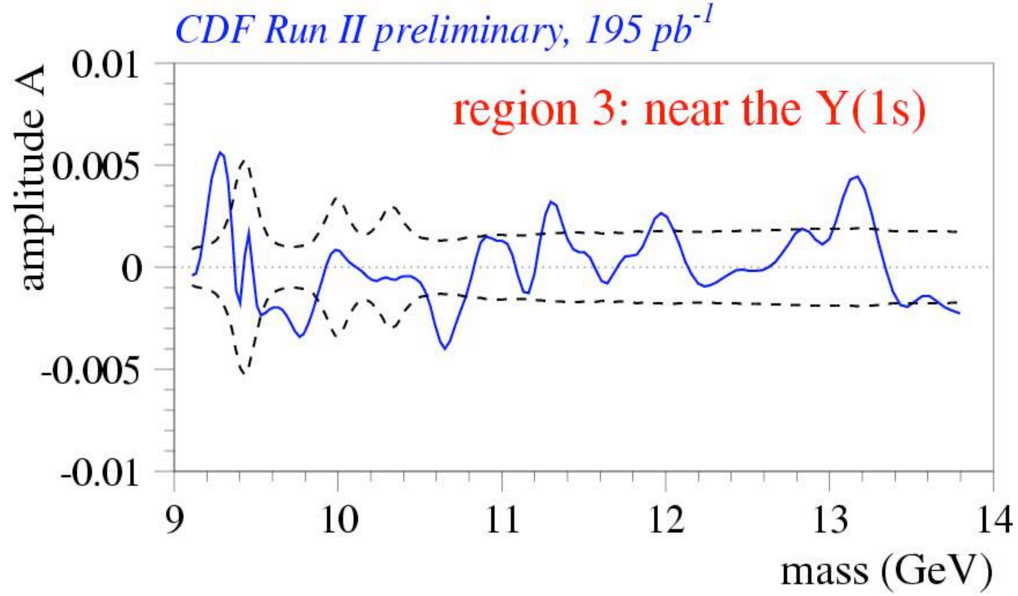
on the Z

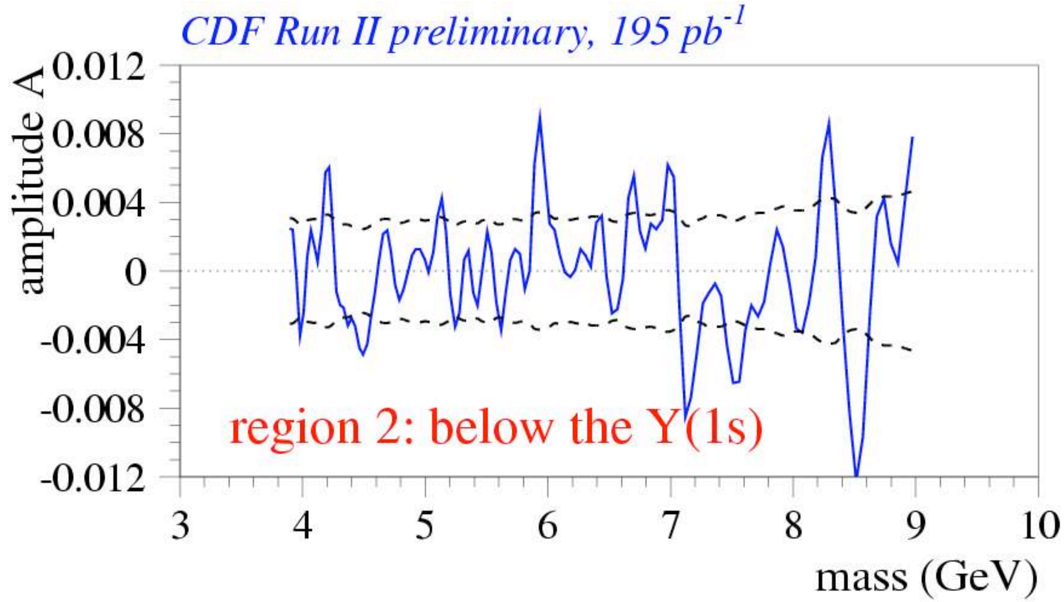


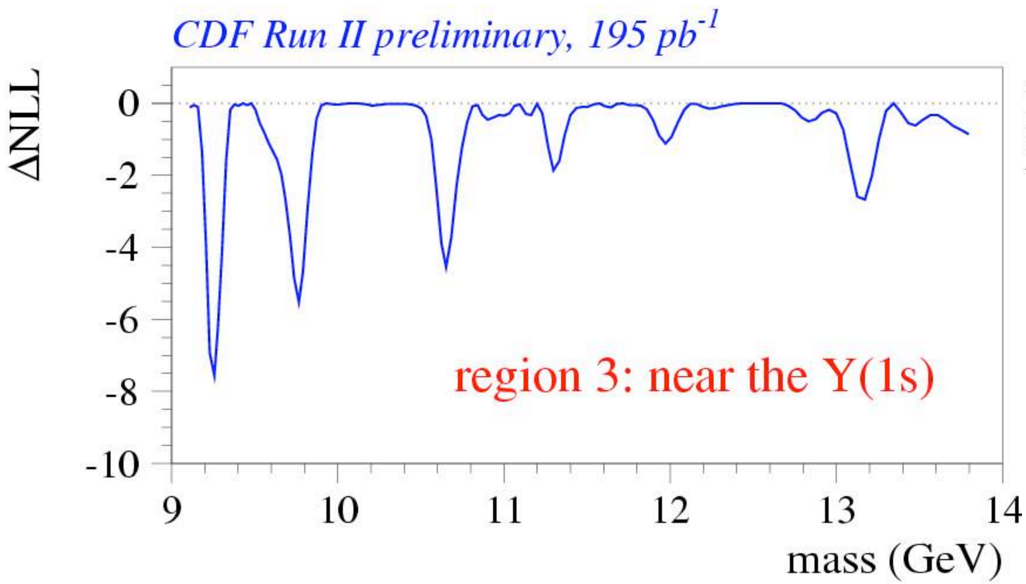


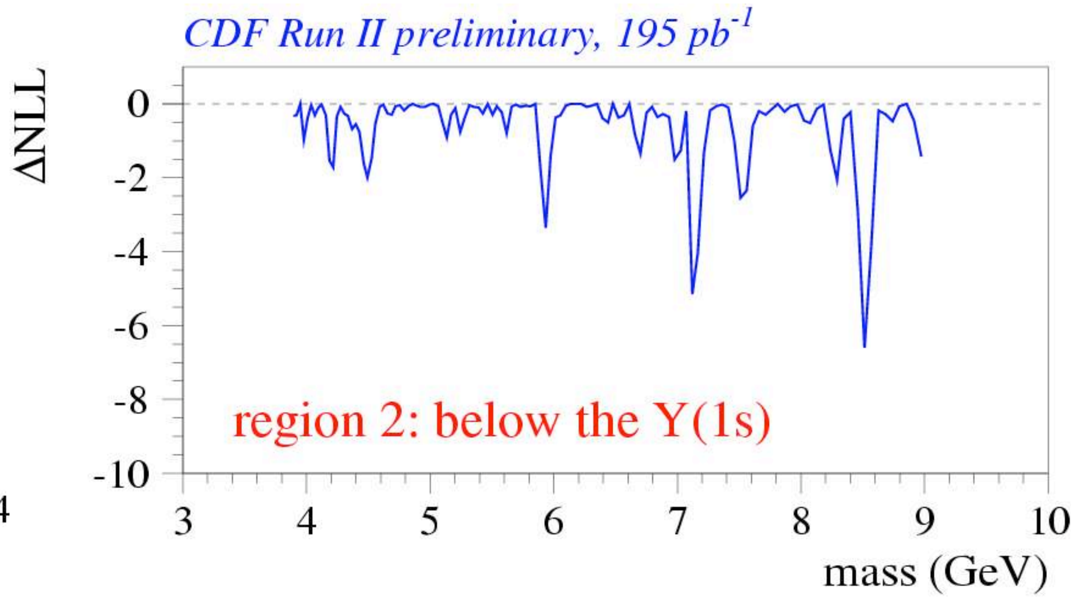
near the Υ(1s) and Υ(2s)

below the Υ(1s)





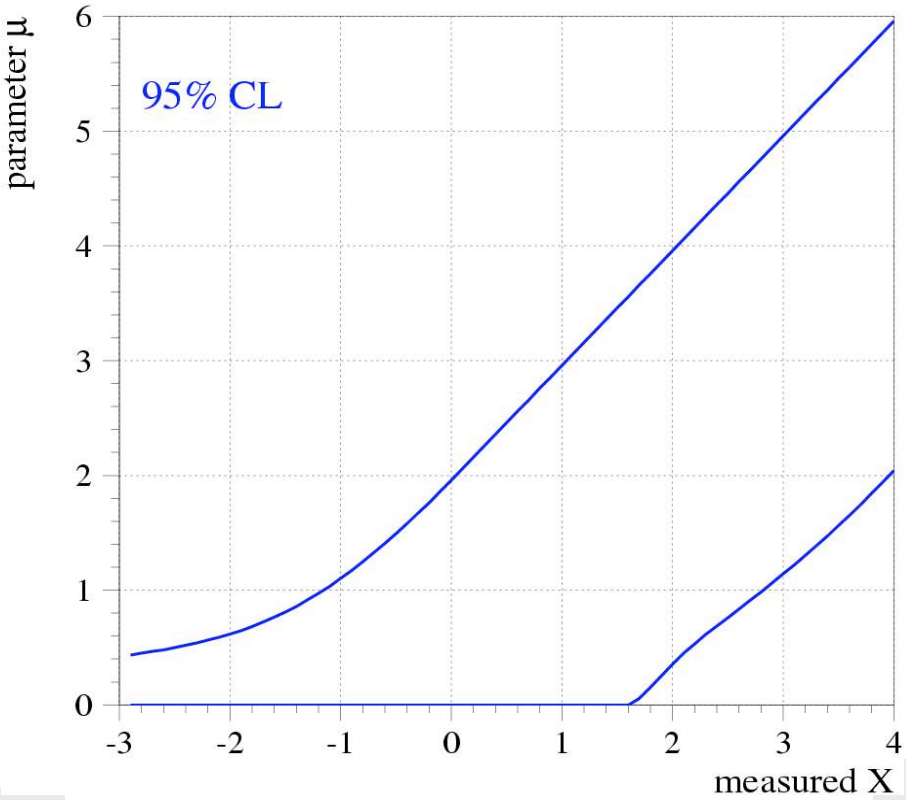




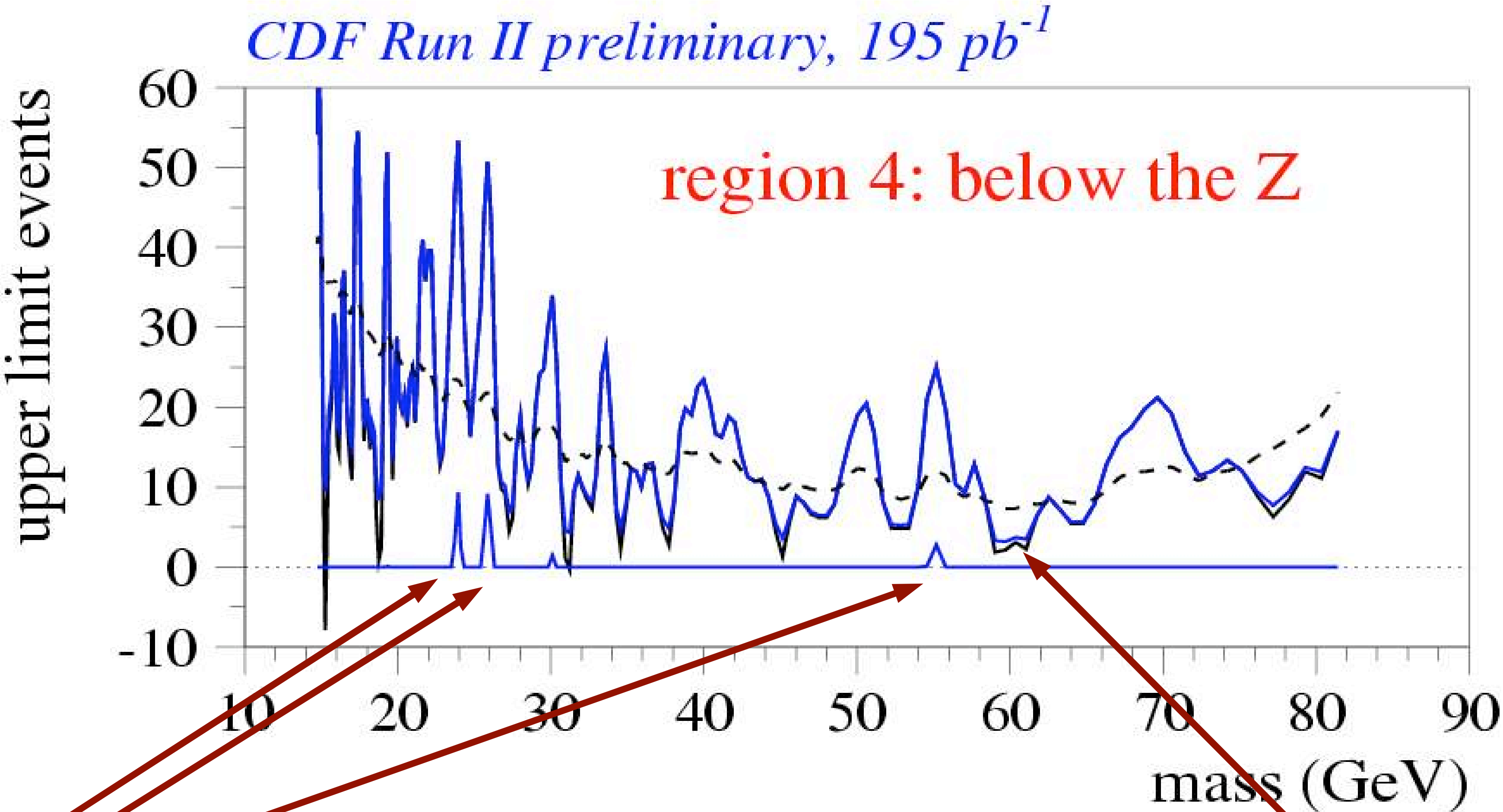
Feldman-Cousins Prescription

- We have employed the Feldman-Cousins prescription, which is recommended by the PDG and others:
  Gary Feldman & Robert Cousins, Phys. Rev. D57 (1998) 3873
- This allows us to convert an amplitude which can be negative into a number of signal events, which cannot be negative.

- Here is the proto-typical case
- The measured X stands for our amplitude, which may turn out to be negative.
- The parameter μ stands for the number of signal events, which cannot be negative.
- This prescription uses time-honored statistical methods to define “confidence belts” for μ as a function of X.
- Given a value for X, one inverts the map to obtain a range of m values at the given CL.



This shows the Feldman-Cousins 95% confidence belt for N_{ev}

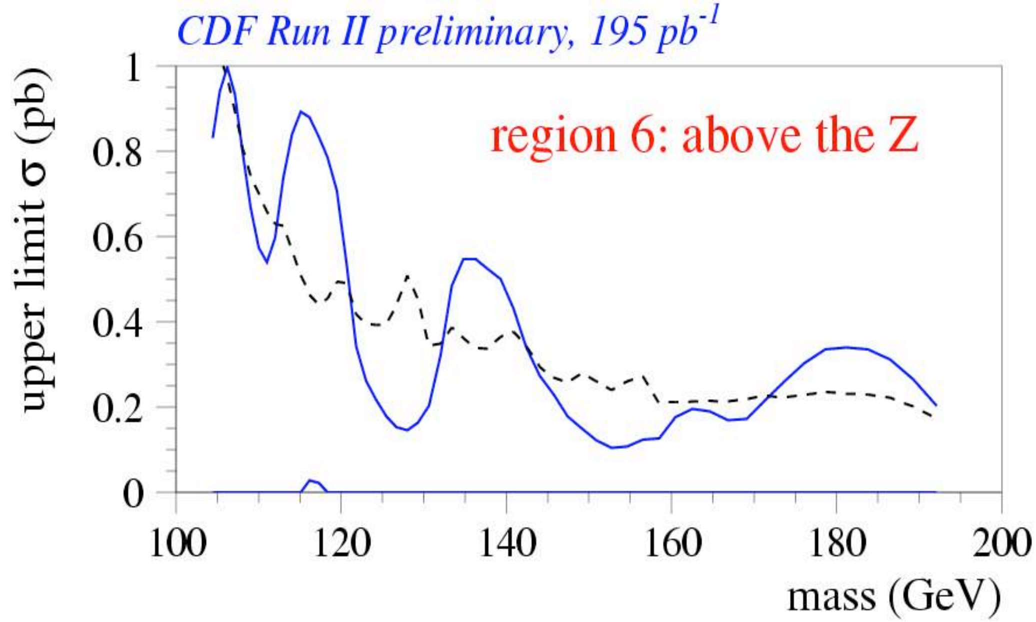


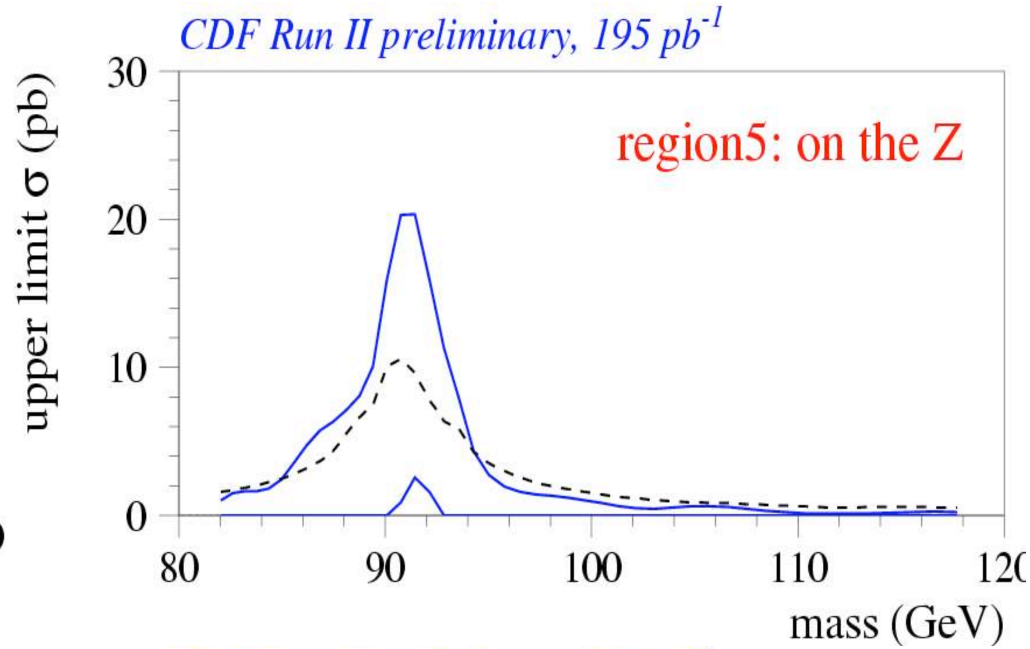
Notice there are mass values for which there is a "lower limit".
This is to be be expected in the Feldman-Cousins method.
At 95% CL, the data do not favor zero signal – this does not mean a signal is present.
Notice, also, that where there is a downward fluctuation, the limit on N_{ev} is not negative.

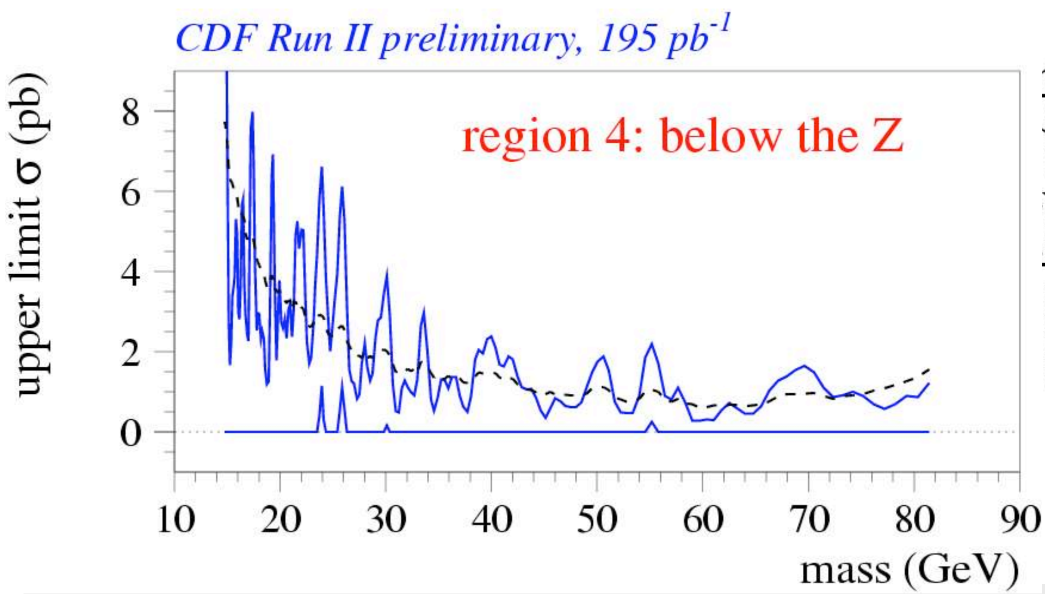
Obtaining a cross-section:

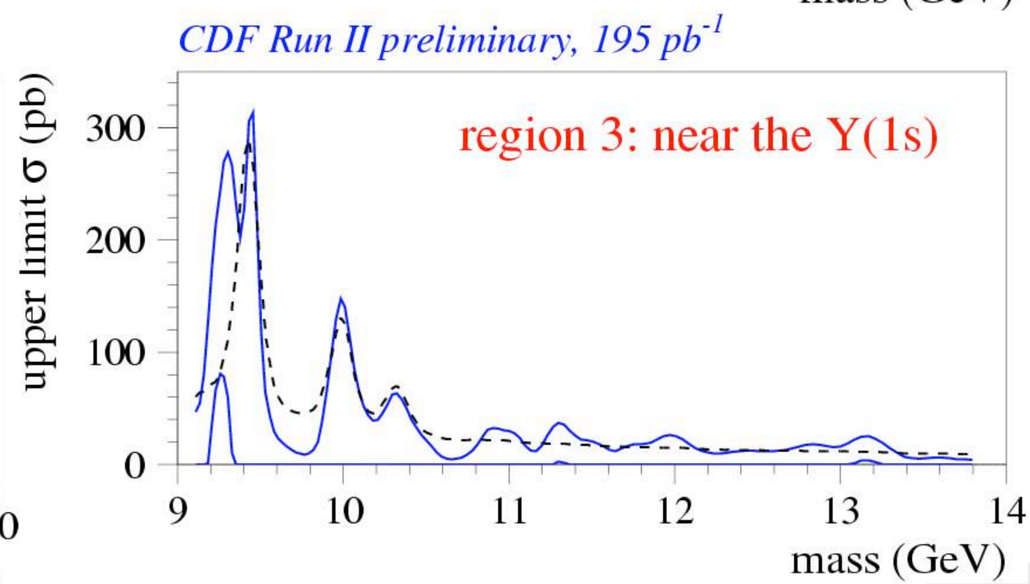
- There will be both upper and lower limits, in general.
- set the normalization $(L \times \varepsilon)$ using the Z – peak
- take variation of acceptance with mass into account
- take systematics into account
  - various terms are taken to be Gaussian
    - mass-dependent efficiencies
    - mass-dependent acceptance
    - mass resolution
    - overall normalization
  - total varies 8 – 26 % depending on the mass
  - impact on the limit is not large

95% Feldman-Cousins confidence belts for σ×Br:









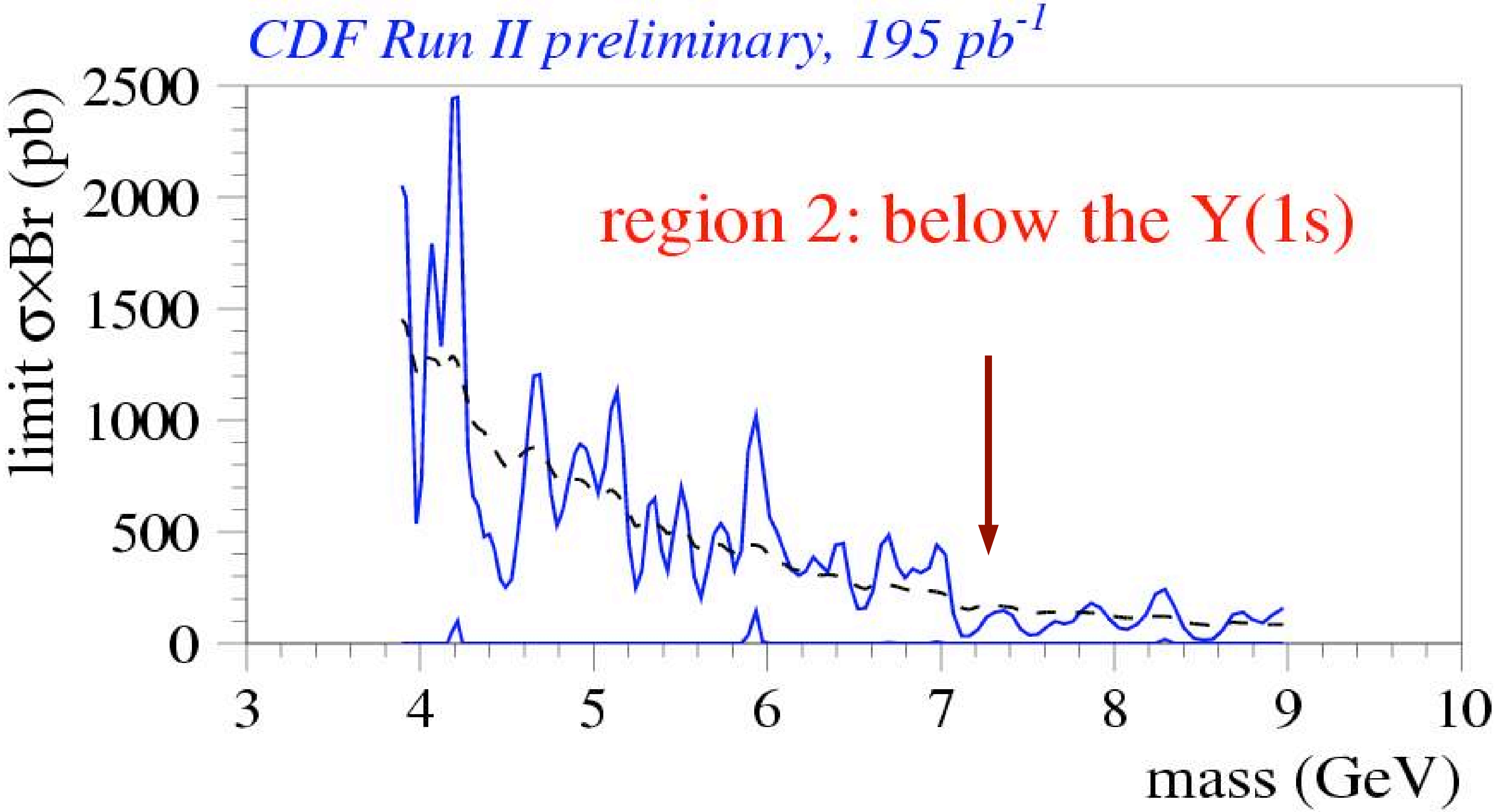
Region 2 – special

(3.8 – 9.1 GeV)

- These events are generally below the trigger threshold.
- The acceptance falls rapidly below about M = 10 GeV.
- Only the high transverse-momentum (q_T) pairs are accepted.
- The acceptance depends on the process assumed:
  - Drell-Yan – like (appropriate perhaps for new gauge bosons)
  - Upsilon – like (appropriate perhaps for new bound states)
  - something else?
- CDF is implementing a special low-p_T di-muon trigger to solve this difficulty.
- For now, work with the data that we have, and accept some model-dependence. Keep this in mind!

First, consider a Drell-Yan – like process.

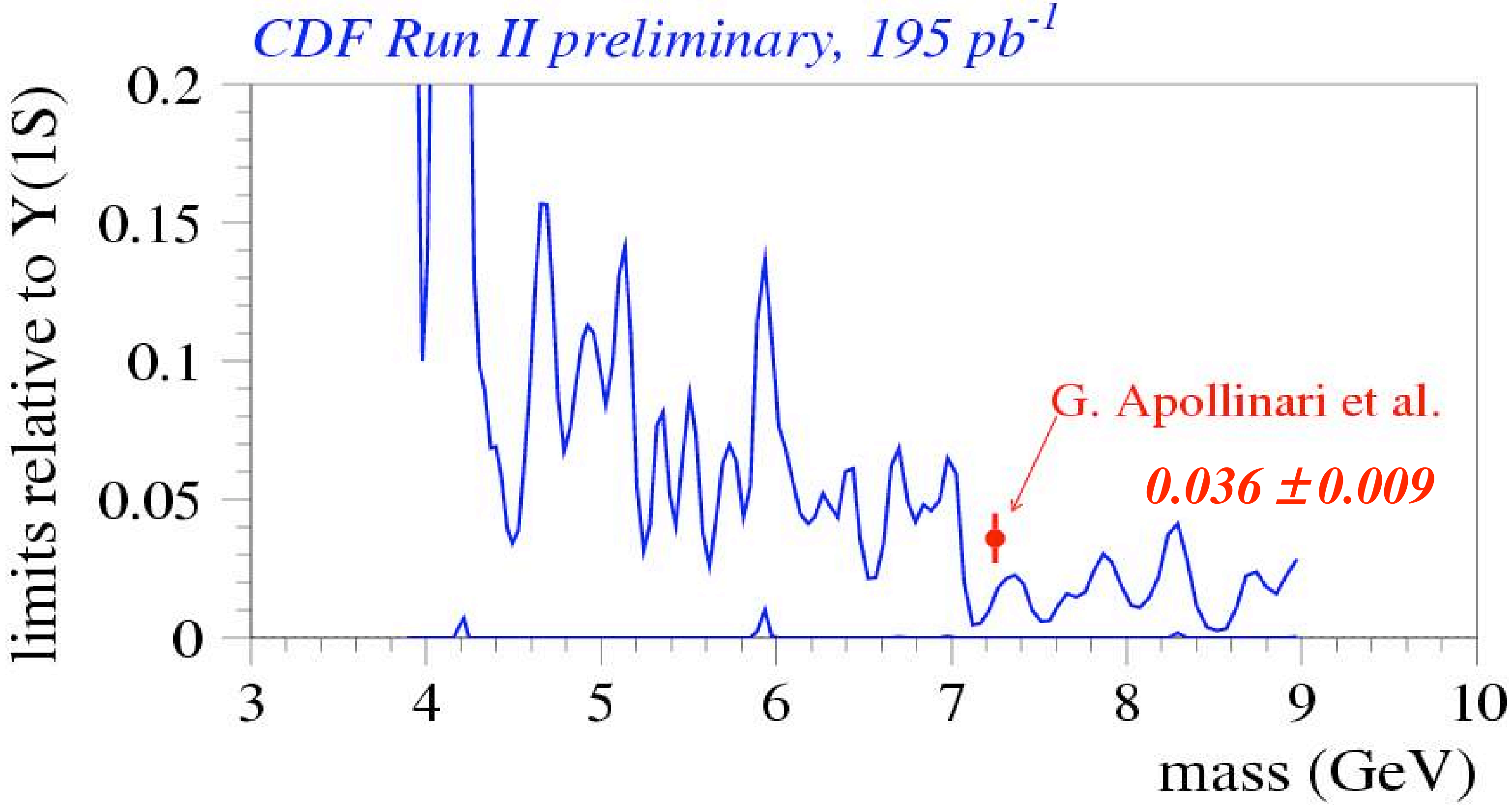
95% Feldman-Cousins confidence belt for $\sigma \times$ Br in region 2:



The peak seen by G. Apollinari *et al.* with Run I data fell at mass 7.25 GeV.
Their result works out to $\sigma \times$ Br $\approx$ 201 pb assuming a Drell-Yan – like production process.

If we consider the second model:

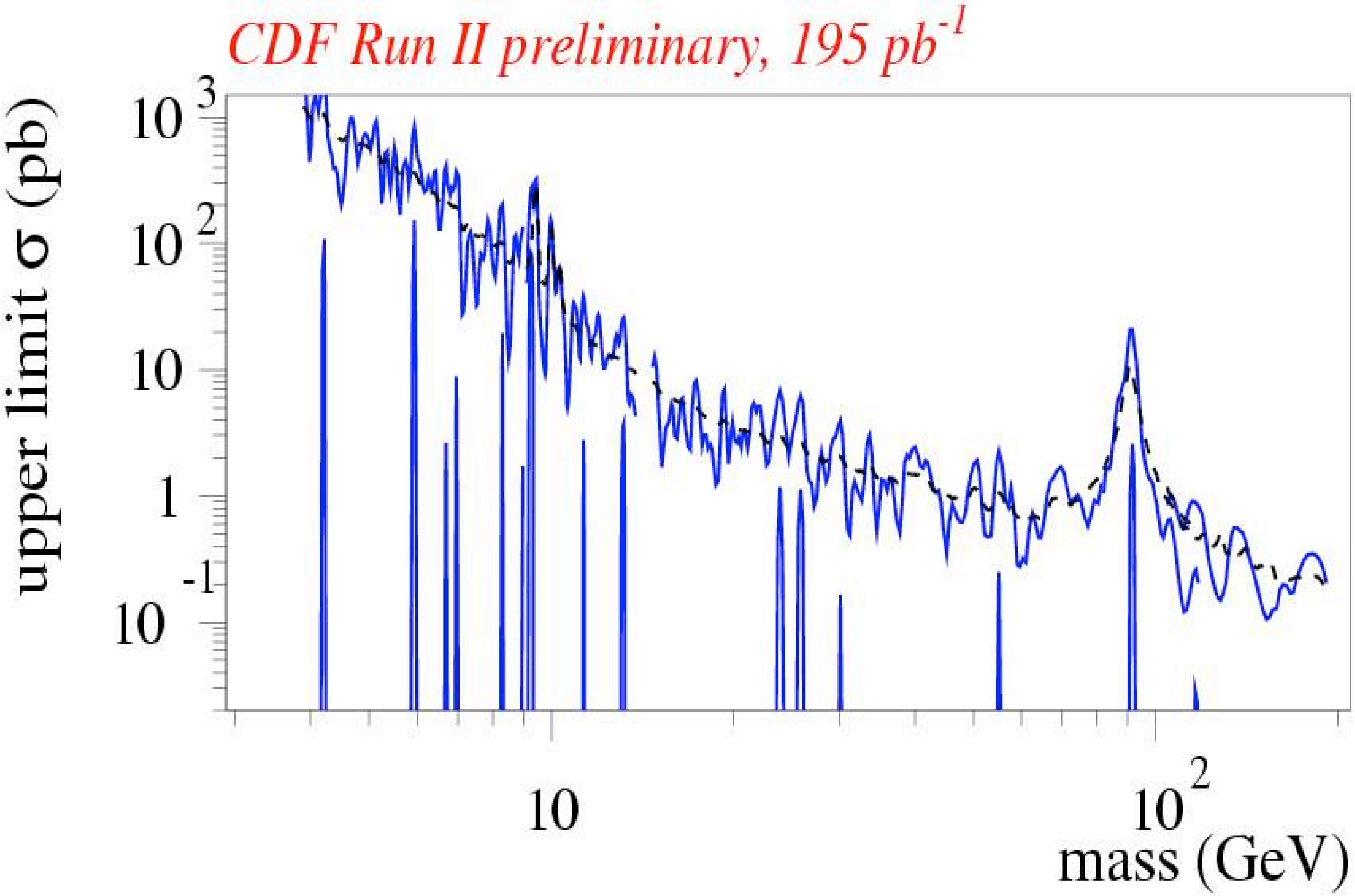
→ **plot the limits relative to Y(1S) production.**



$$\frac{\sigma \times Br(x \rightarrow \mu^+ \mu^-)}{\sigma \times Br(Y(1S) \rightarrow \mu^+ \mu^-)} < 0.018$$

at 95% CL

95% Feldman-Cousins confidence belt for $\sigma \times Br$ for the range 4 – 200 GeV:

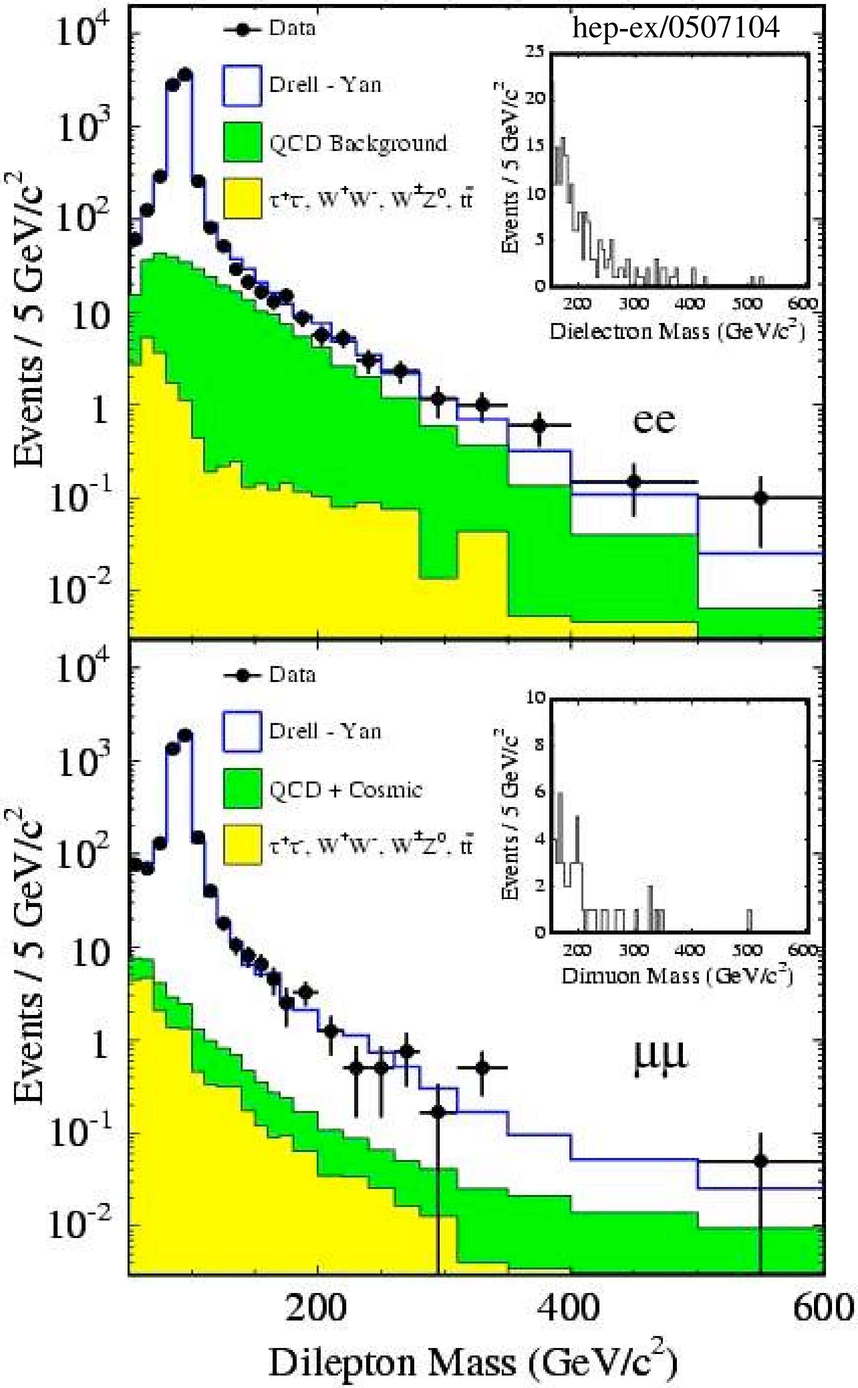


CDF Run II *preliminary*

- Five mass regions have been scanned, encompassing the range 4 GeV up to 200 GeV, for 195 pb^{-1}.
- There is no sign of new physics anywhere.
  We have derived cross section limits using Feldman-Cousins.
- The Run I observation at 7.25 GeV is not confirmed.
- We will add more data very soon.
- We will also tackle the region above 200 GeV.

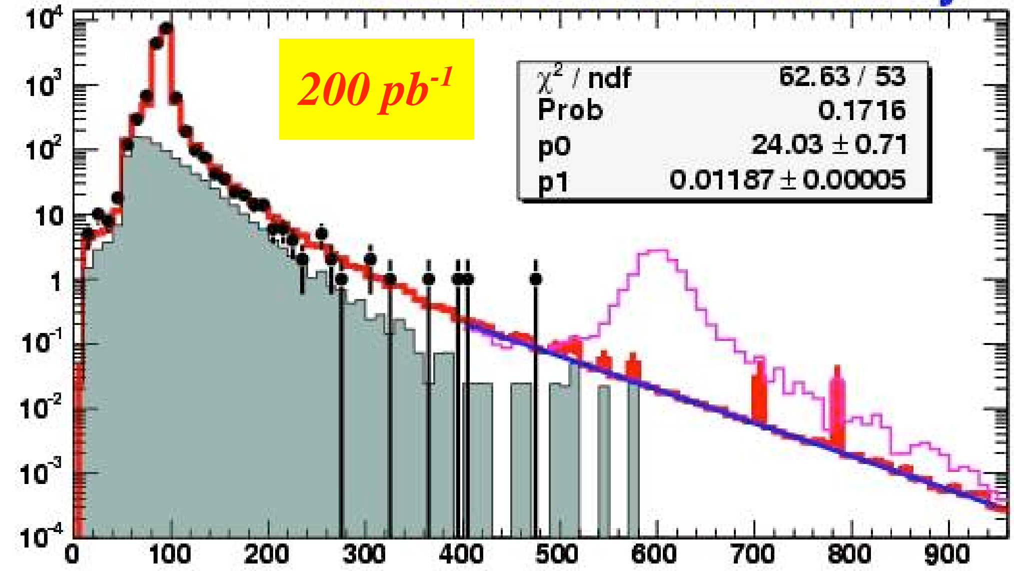
More Traditional Searches for high-mass Z' at the Tevatron

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

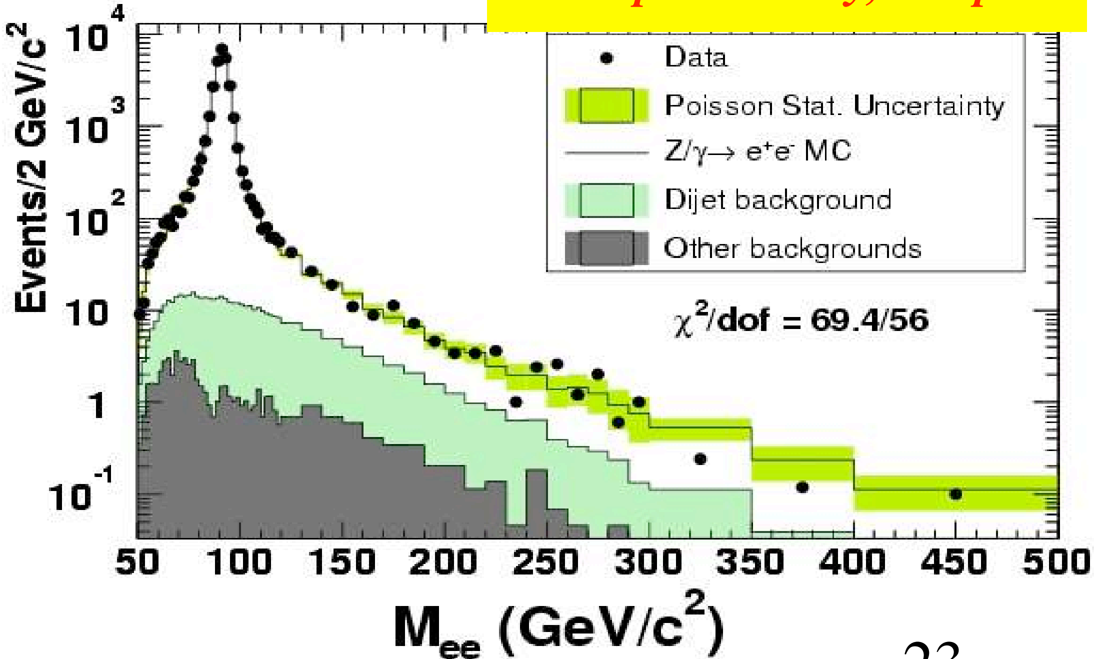


diEM Mass Spectrum

DØ Run II Preliminary



CDF preliminary, 448 pb^{-1}

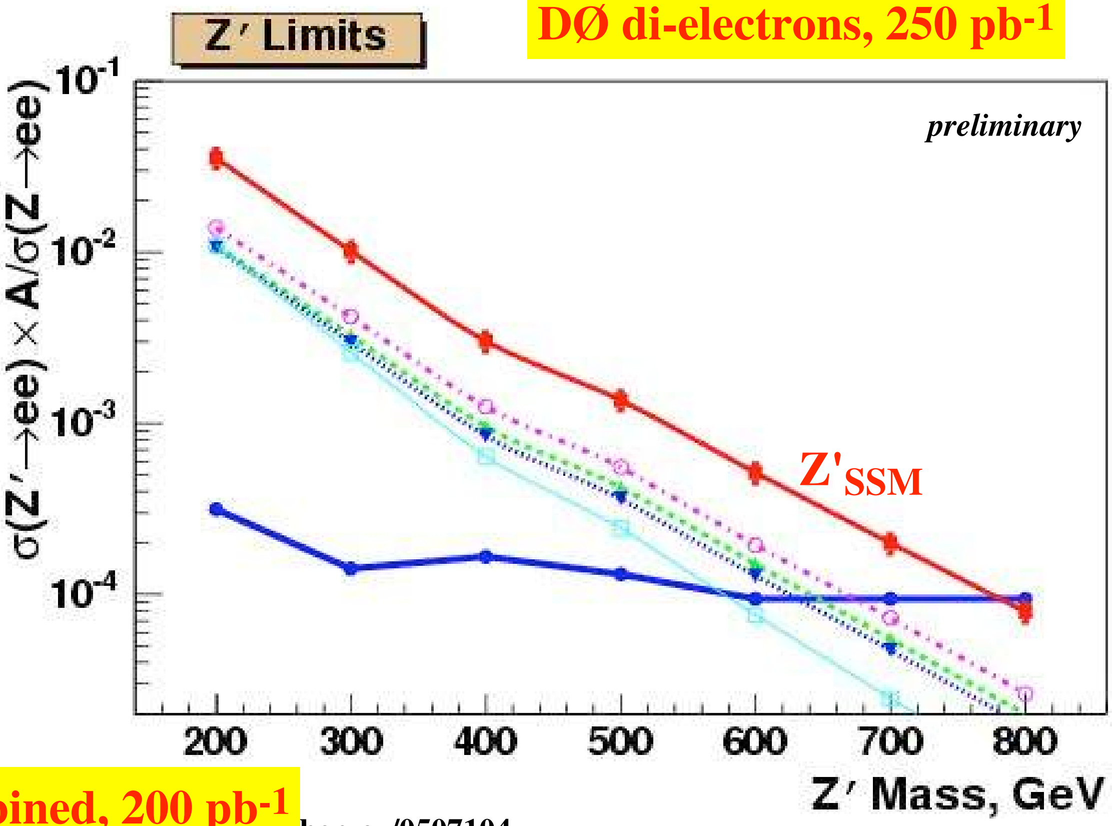


Actual
upper limits on Z' production

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

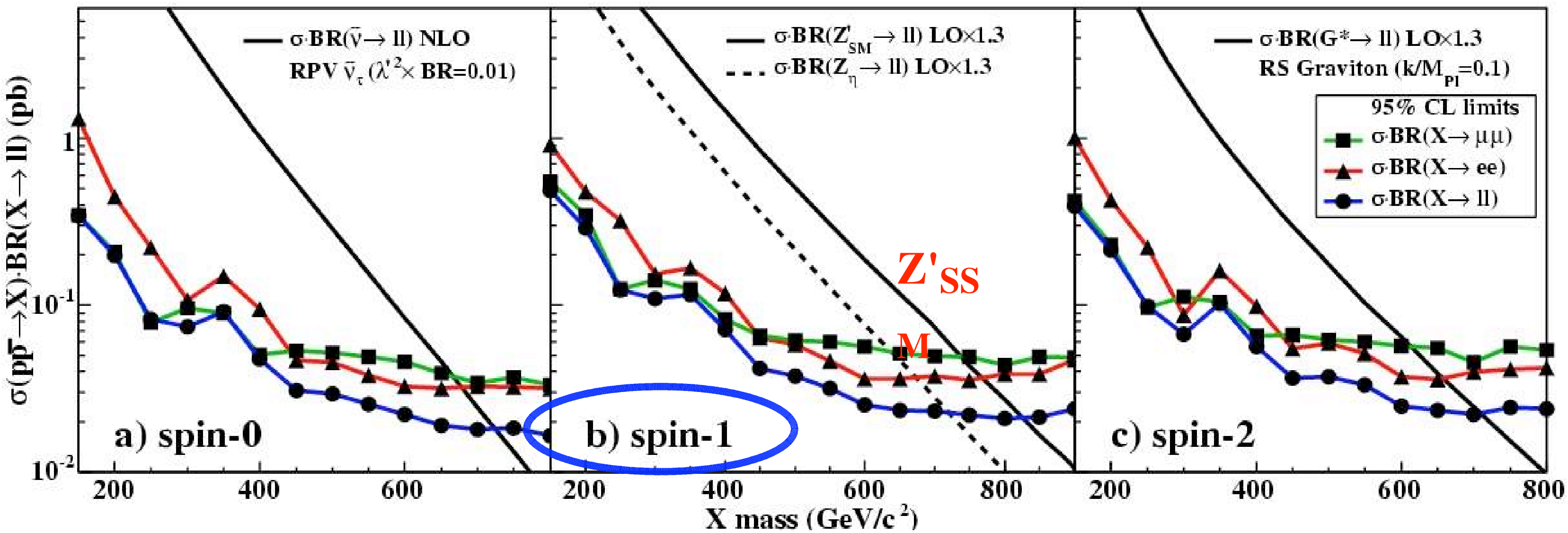
Both experiments achieve
σ x BR < 24 fb at 95% CL

DØ di-electrons, 250 pb^{-1}

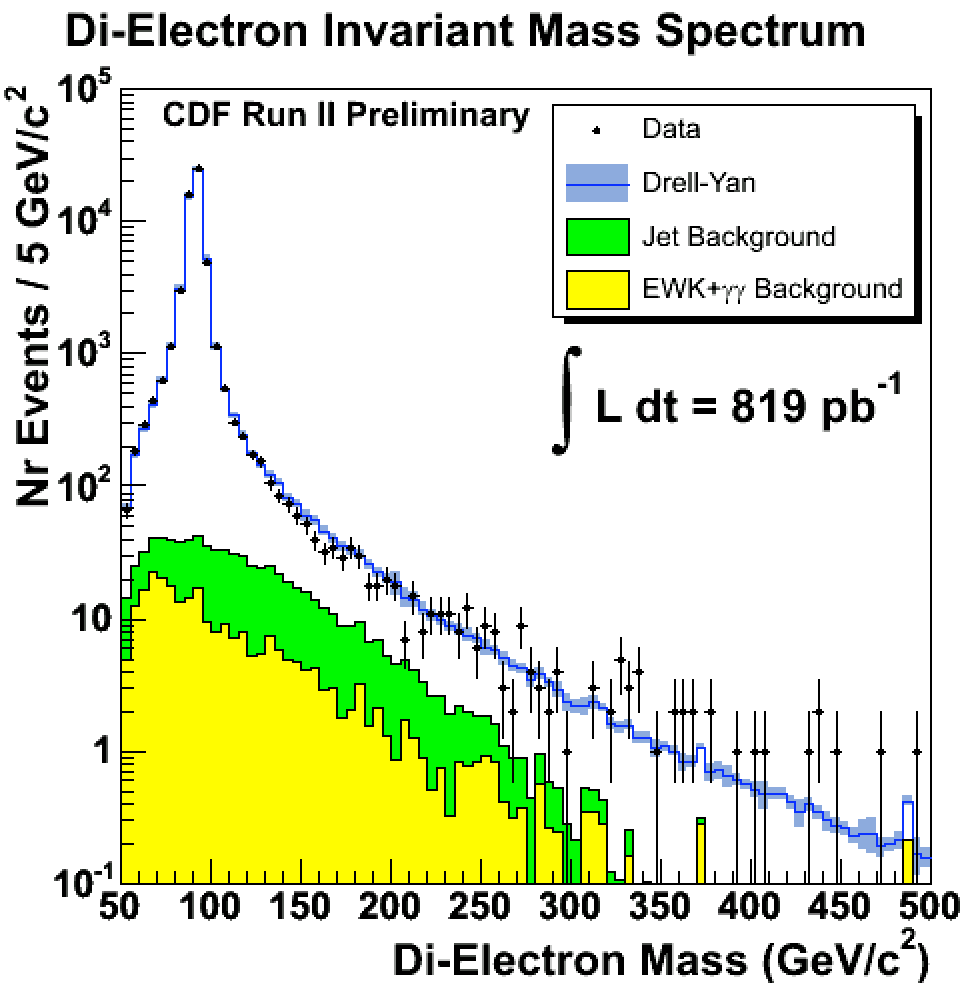


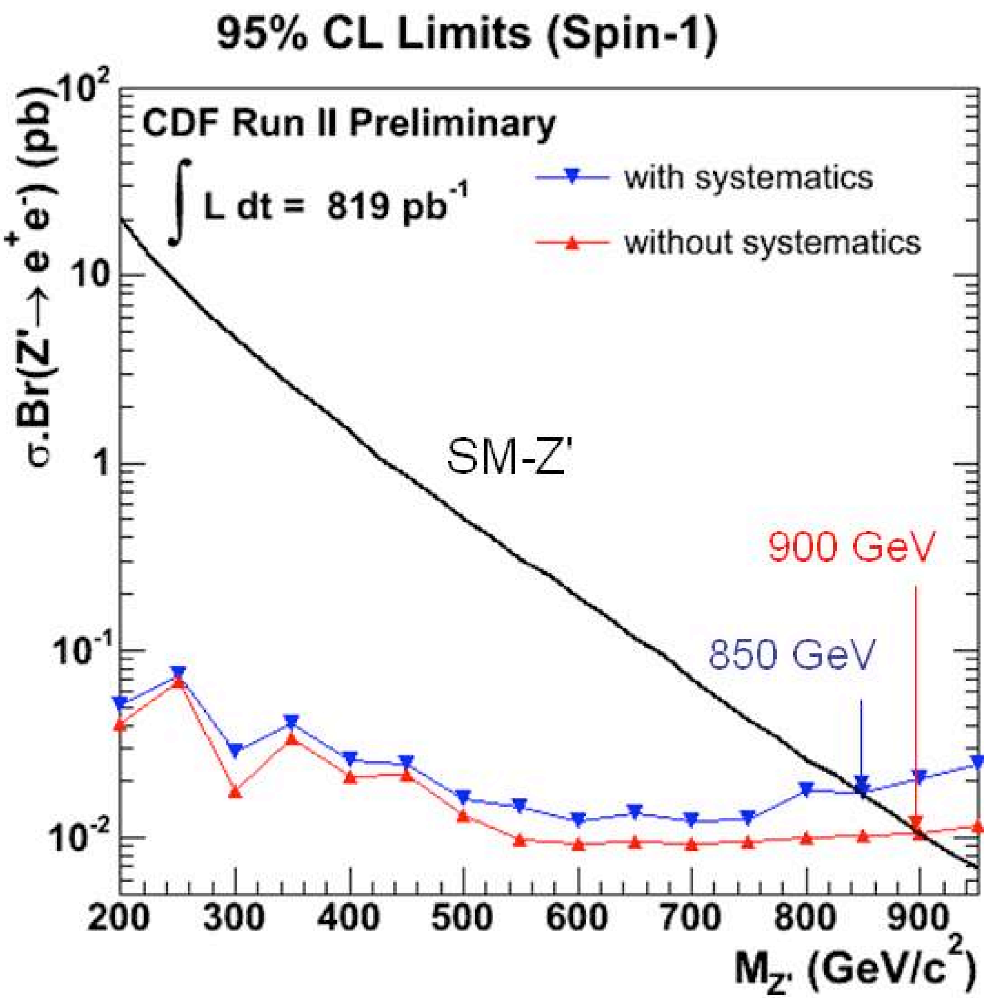
CDF, di-electrons and di-muons combined, 200 pb^{-1}

hep-ex/0507104



CDF update – preliminary results in the electron channel w/ 819 pb^{-1}





M > 850 GeV at 95% CL, for a sequential Z'

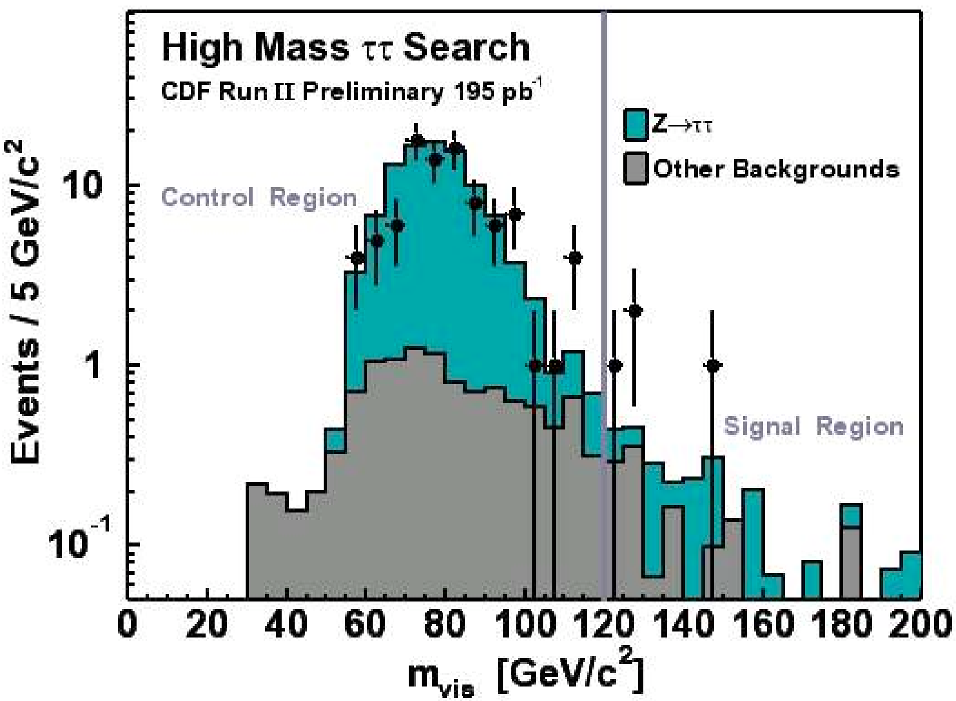
Just a quick word about τ's ....

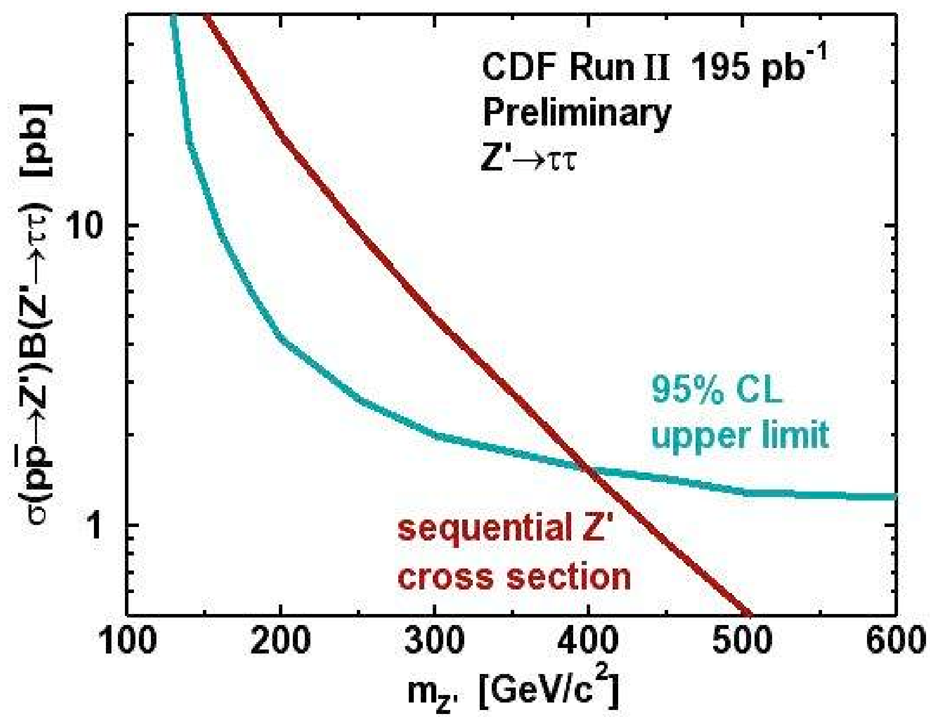
Z' decays to tau's are much harder to identify, of course, so this channel does not play a central role in the search for Z' bosons.

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

CDF published, 195 pb^{-1}

hep-ex/0506034





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:

hep-ex/0602045

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

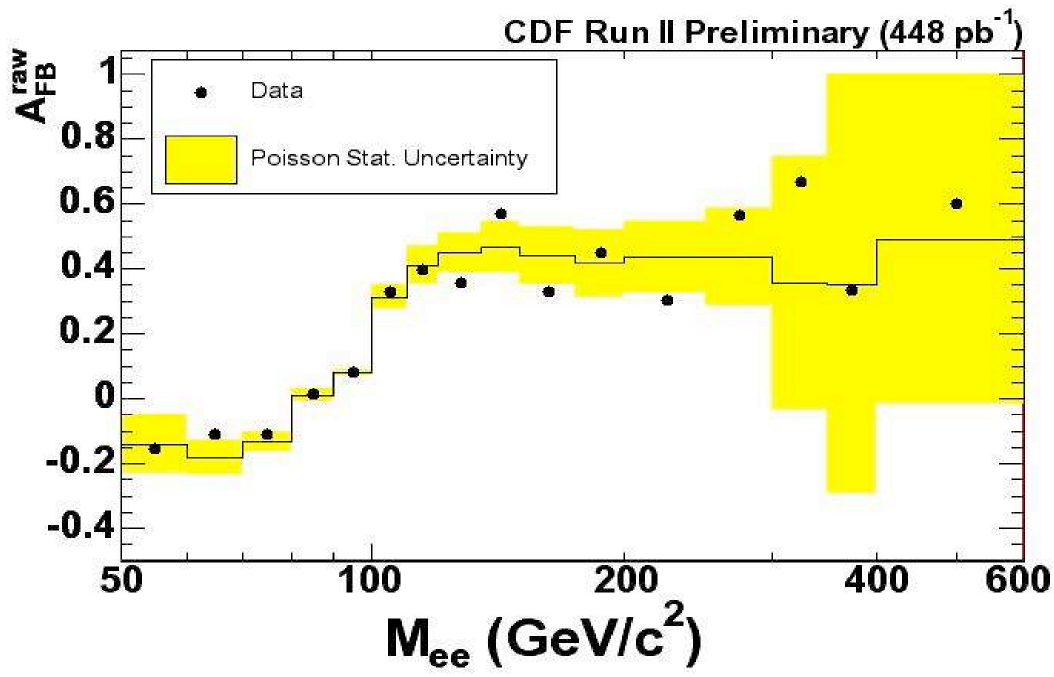
The presence of a Z' generally shifts A_{FB} depending on couplings and the Z' width.

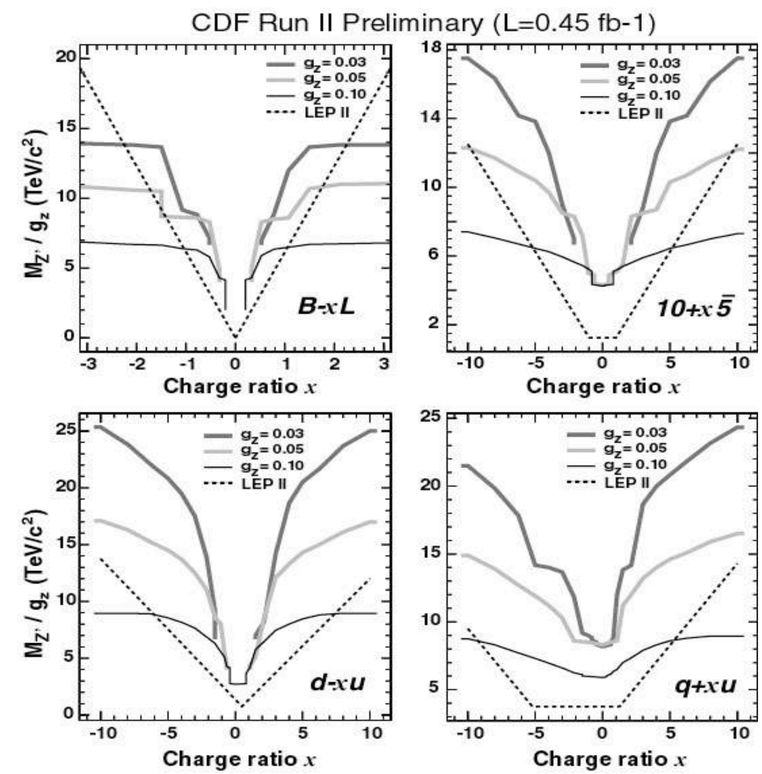
A “model-independent” formulation is quite helpful here...

Including the angular information boosts the sensitivity of the analysis – it is the same as 25% more luminosity (roughly).

$M > 850$ GeV for sequential Z'

(from 448 pb^{-1}, same as mass-only search with 819 pb^{-1}.)





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

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

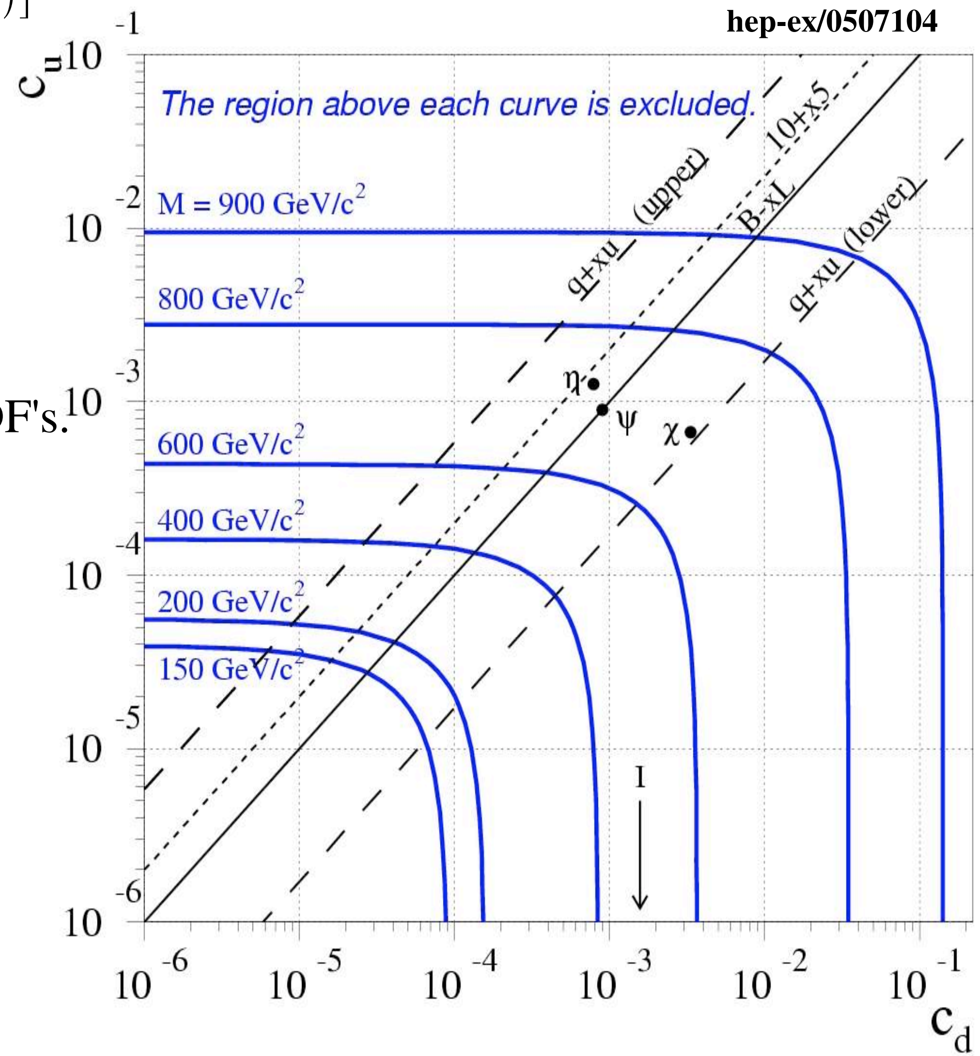
$$\sigma(Z')=\frac{\pi}{48\,s}\left[c_u w_u(s,M_{Z'})+c_d w_d(s,M_{Z'})\right]$$

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

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



LHC Studies

LHC Studies

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

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:

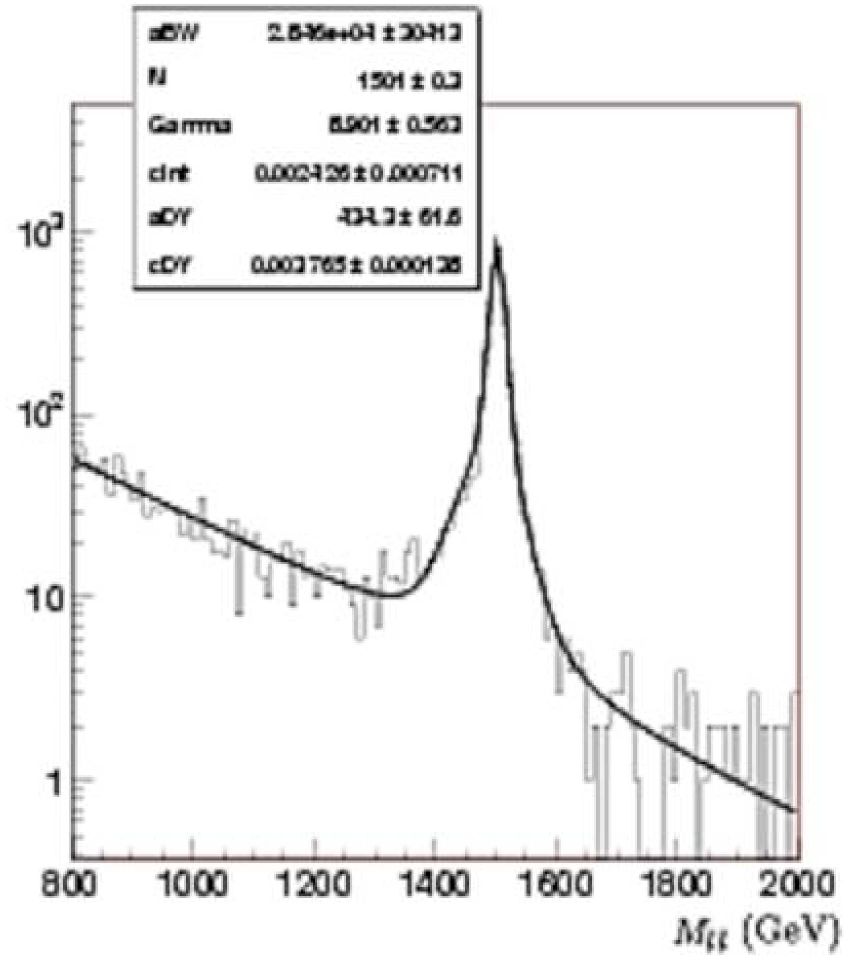
- recognize muons which radiate a lot like electrons (at the TeV scale...)
- delicacy exercised with the electron isolation criteria

Experimentalists are trying to approach the problem of finding and studying di-lepton resonances with several physics scenarios in mind: Z' , KK-excitations, etc.

I will restrict my discussion to some particularly interesting developments in CMS, but it should be understood that similar work has been done in ATLAS, too.

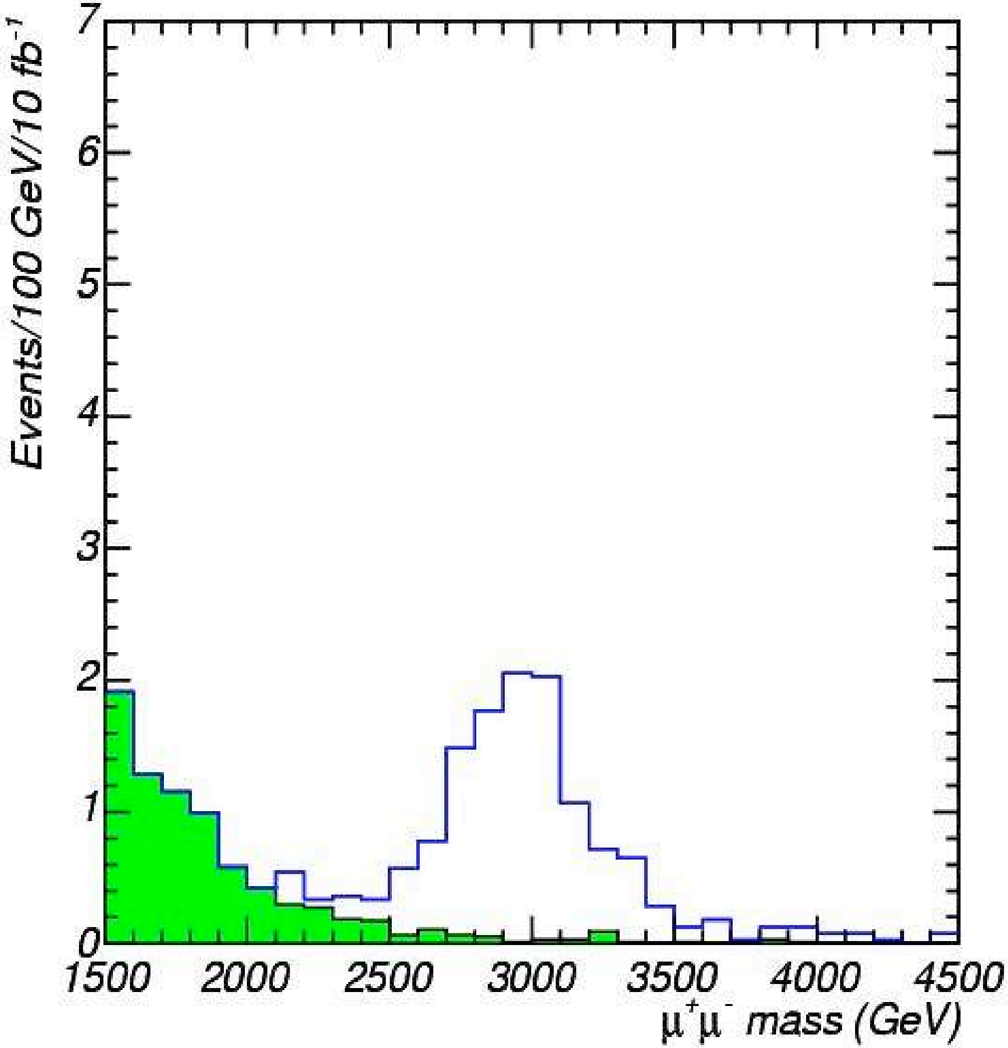
Here are some examples of imagined signals at the LHC:

ATLAS, di-electrons PUB-2005-010



(a) Z'_η model - $M = 1.5$ TeV

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

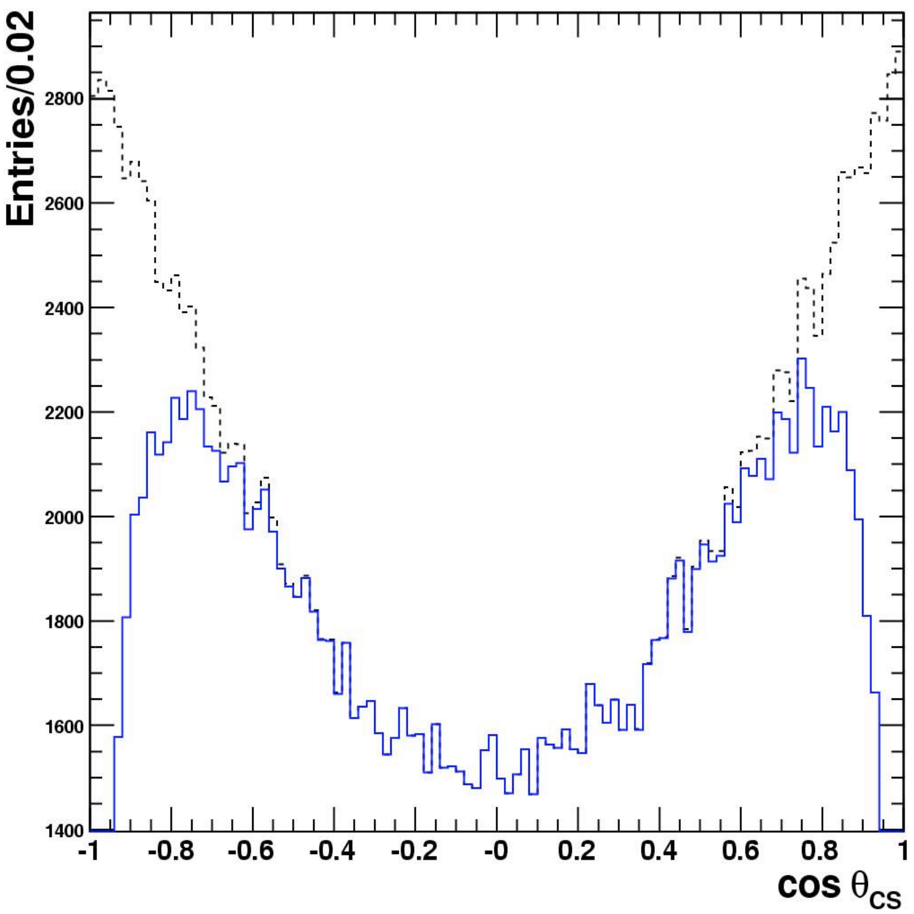


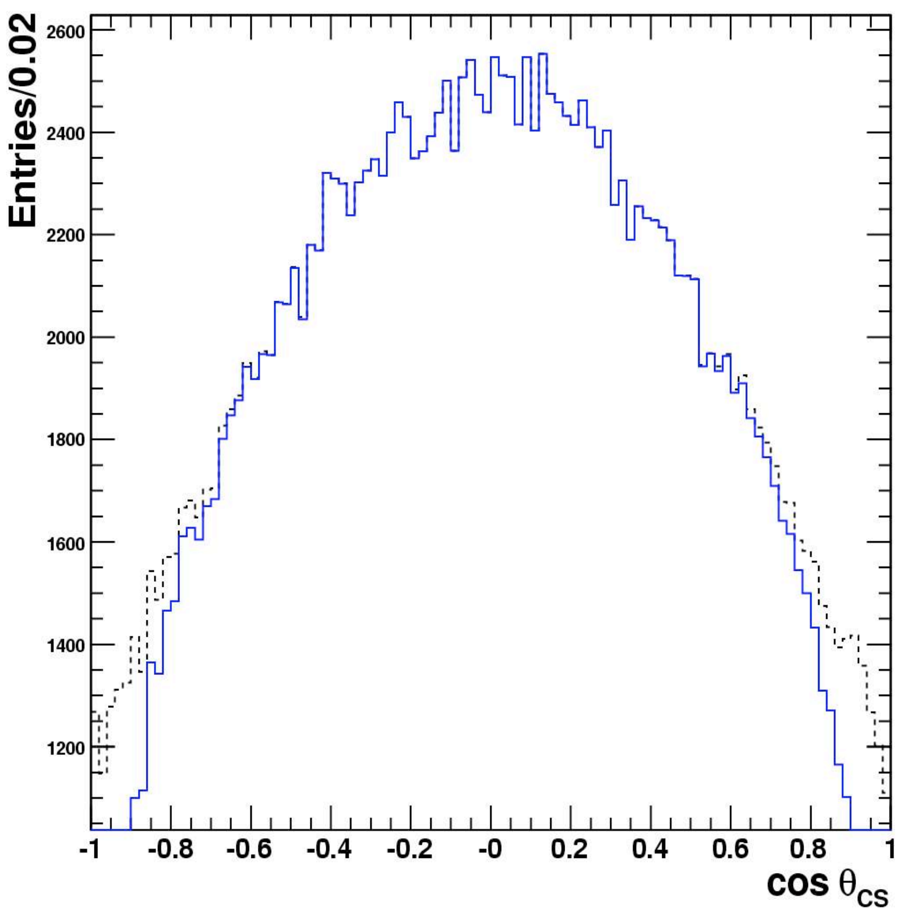
Is it spin-1 or spin-2? (or even spin-0?)

spin hypothesis testing

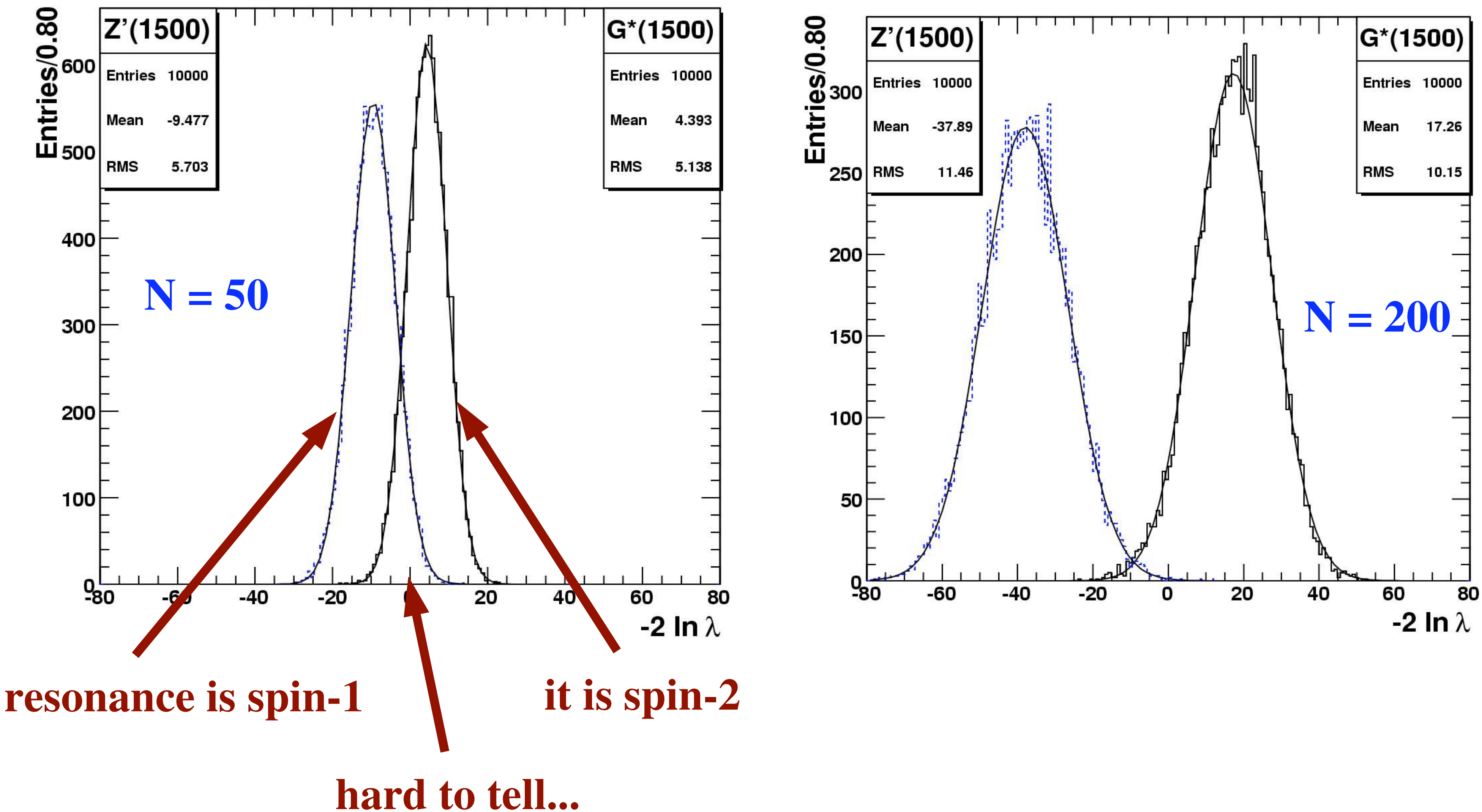
R. Cousins et al., JHEP 11 (2005) 046

The angular distribution of the muons in the resonance rest frame is the key:





Work with the ratio of likelihoods to test the two hypotheses:



Conclusion: discrimination at 68% CL requires only a few dozen events.
Spin-0 is somewhat more difficult, but still resolvable.

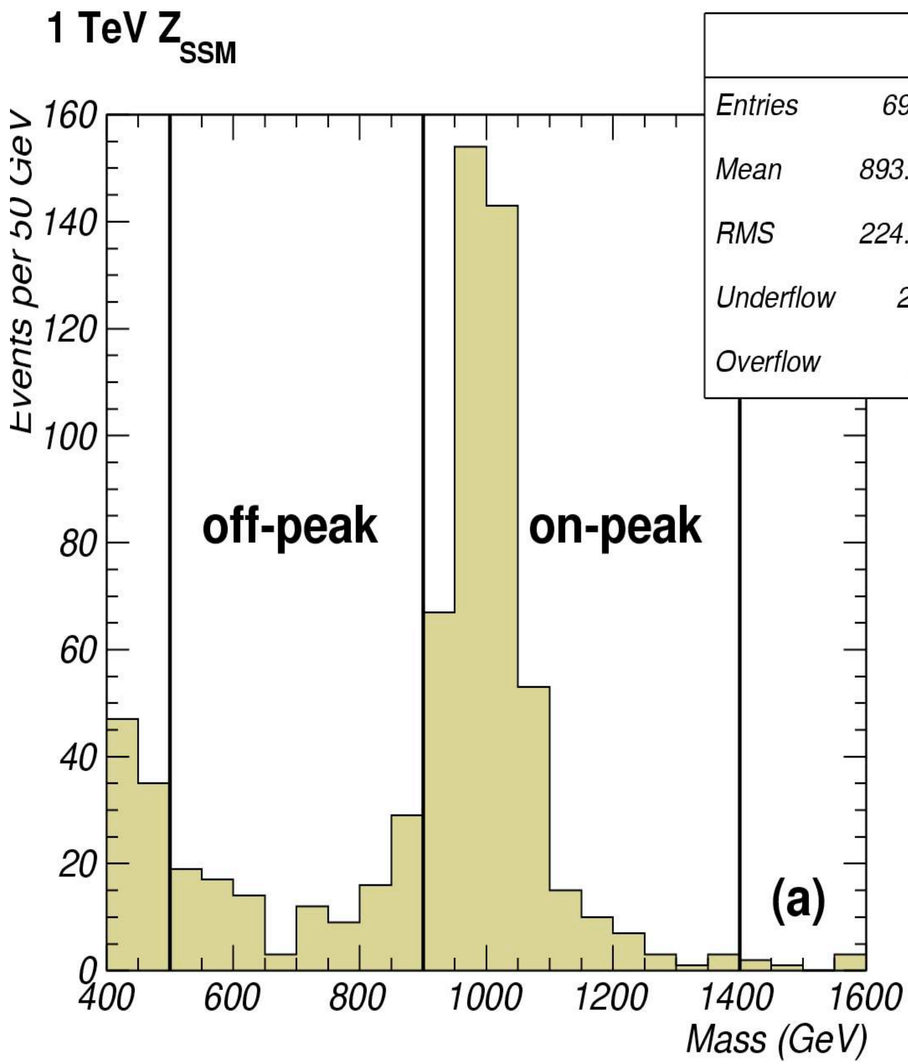
R. Cousins et al., JHEP 11 (2005) 046

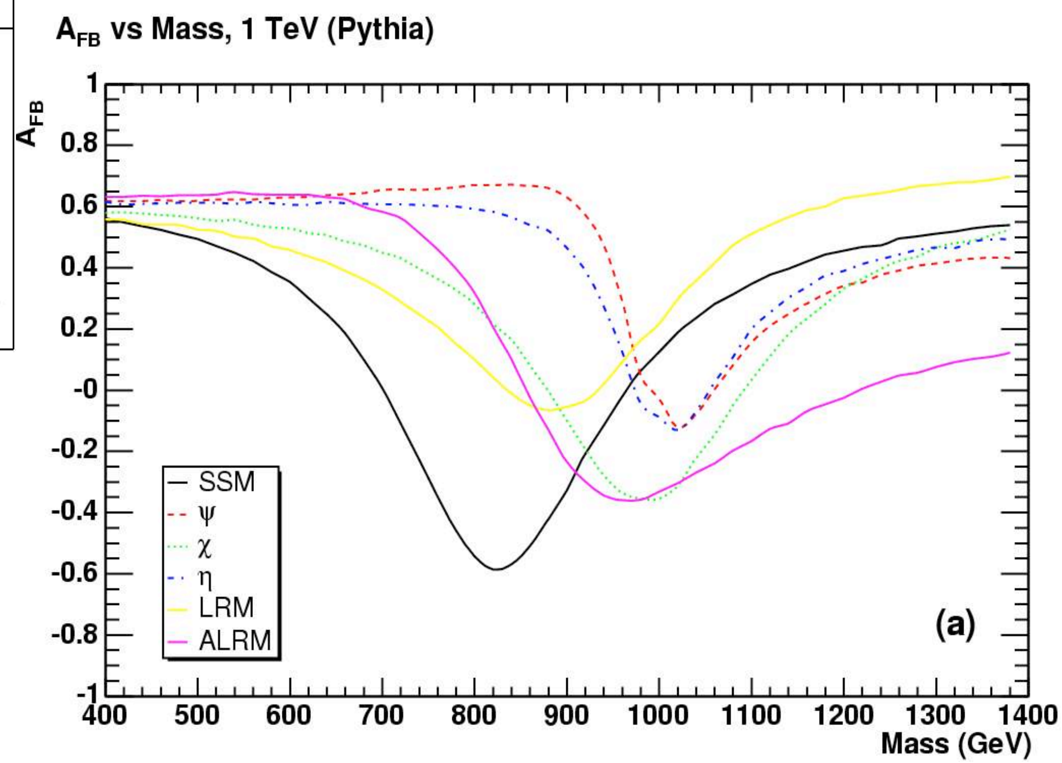
What about the forward-backward asymmetry, A_{FB} ?

R. Cousins et al., CMS NOTE 2005/022

Can help a lot to distinguish – constrain – models.

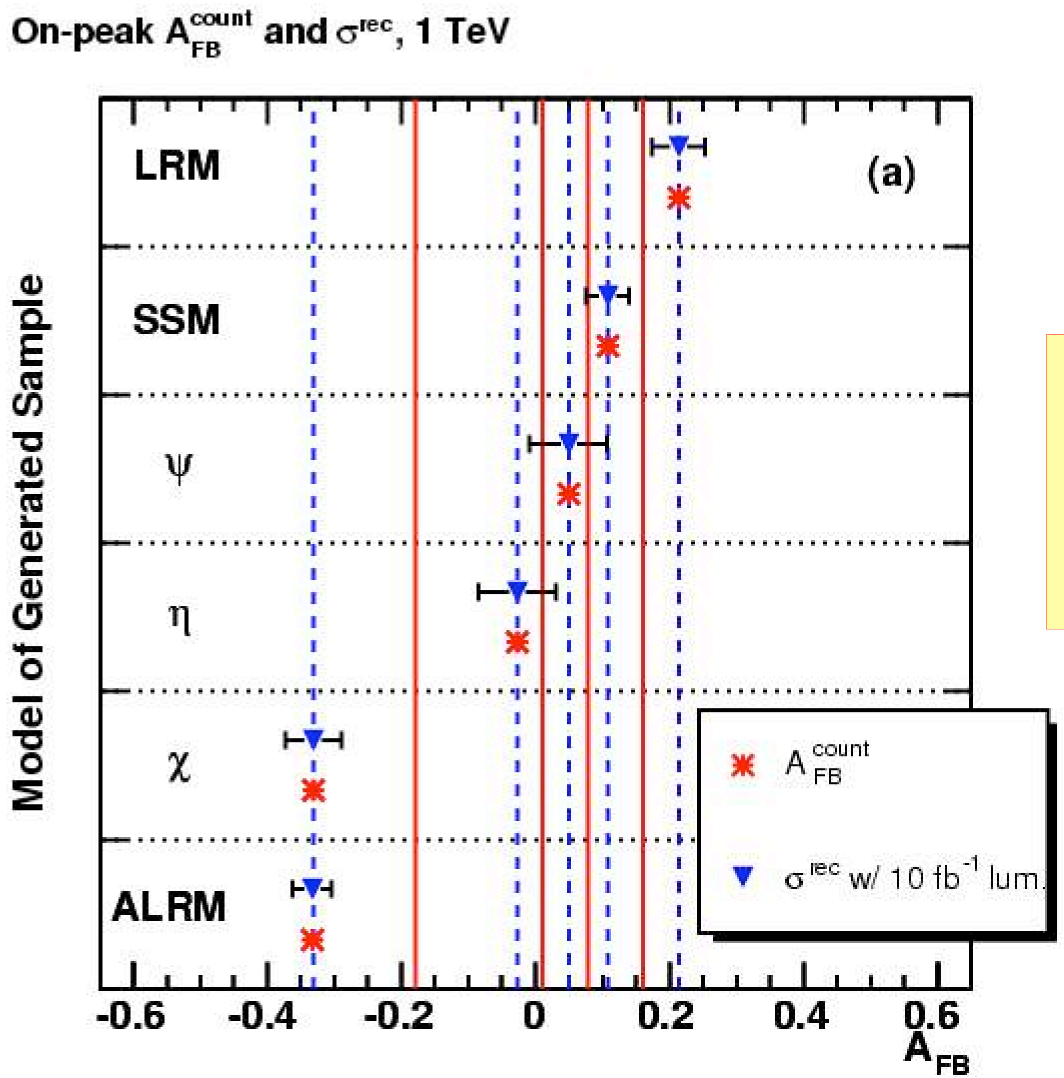
Difficult due to acceptance limitations, and mis-tagging at high masses.





AFB for 1 TeV Z' can be measured to a few percent off- and on-peak.

Get a handle on models by pair-wise hypothesis testing:



M = 1 TeV

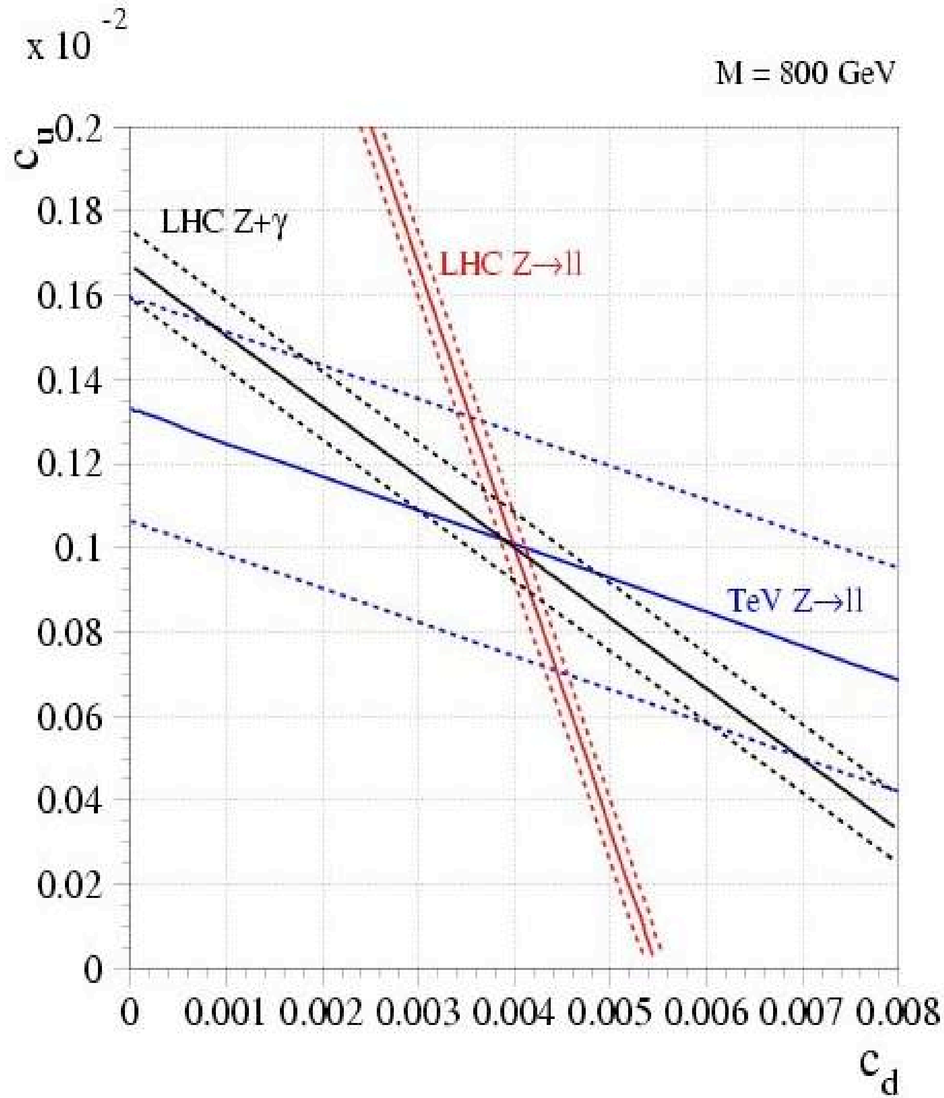
Pairs of models can be distinguished at the 2 – 4 σ level with 10 fb^{-1}.

Naturally, higher states require more luminosity.

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

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

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



The intersection of constraints pins down c_u and c_d!

Notice the synergy between Tevatron and LHC!

Another option is to consider the reaction

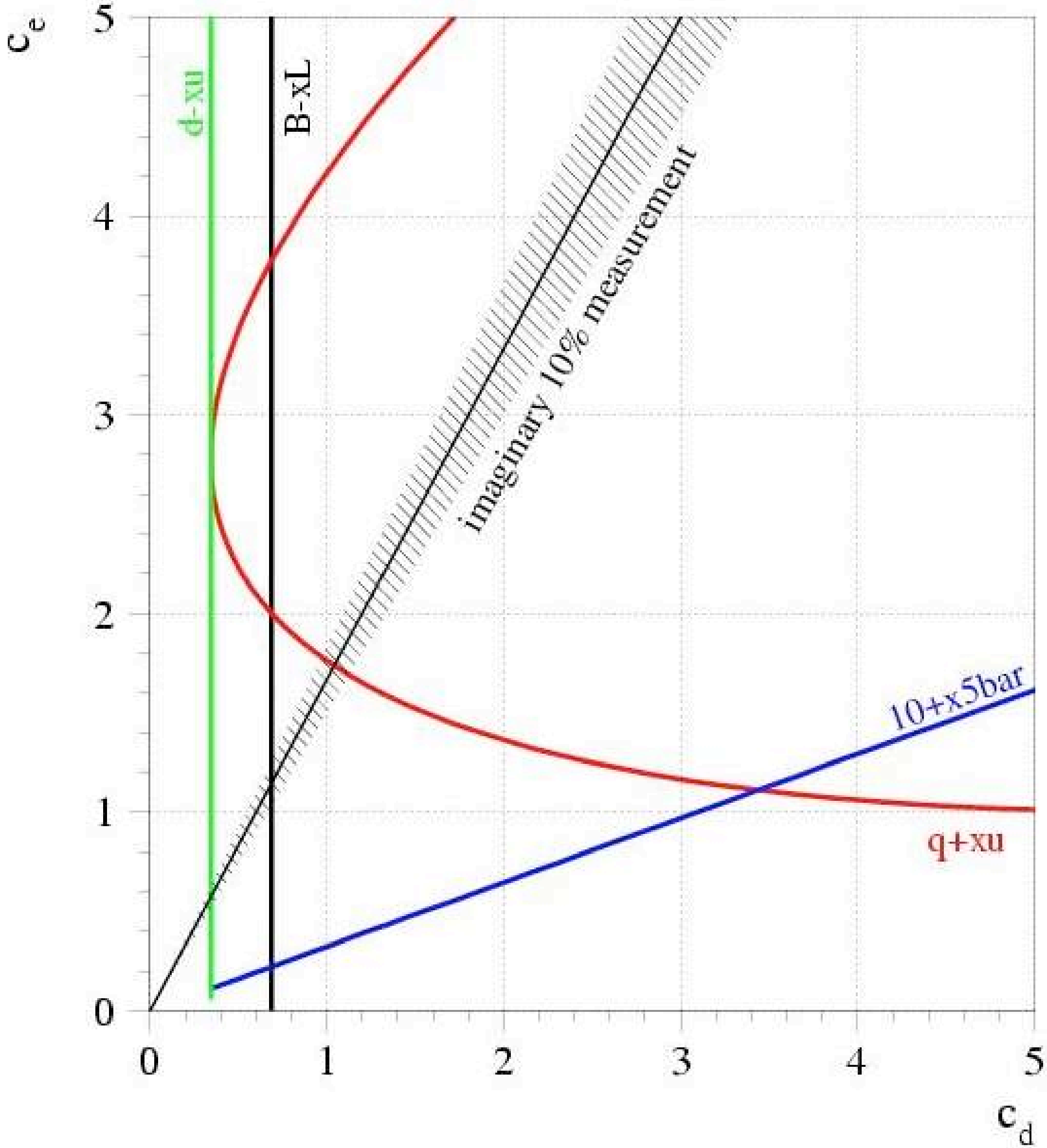
$$pp \to Z' + \gamma$$

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.

New ideas and techniques are expanding the scope.

Studies for the LHC experiments show impressive capabilities

with a "modest" amount of luminosity.

$\rightarrow$ well past simple parton-level estimates by now !!

The model-independent approach provides an effective platform

for combining various data to constrain Z' properties.

$\rightarrow$ will be advocated for LHC, too !

Back-up Slides

ΔNLL is 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.

$$\Delta NLL = NLL(background+peak) - NLL(background)$$

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

Canonically, for a single mass value,

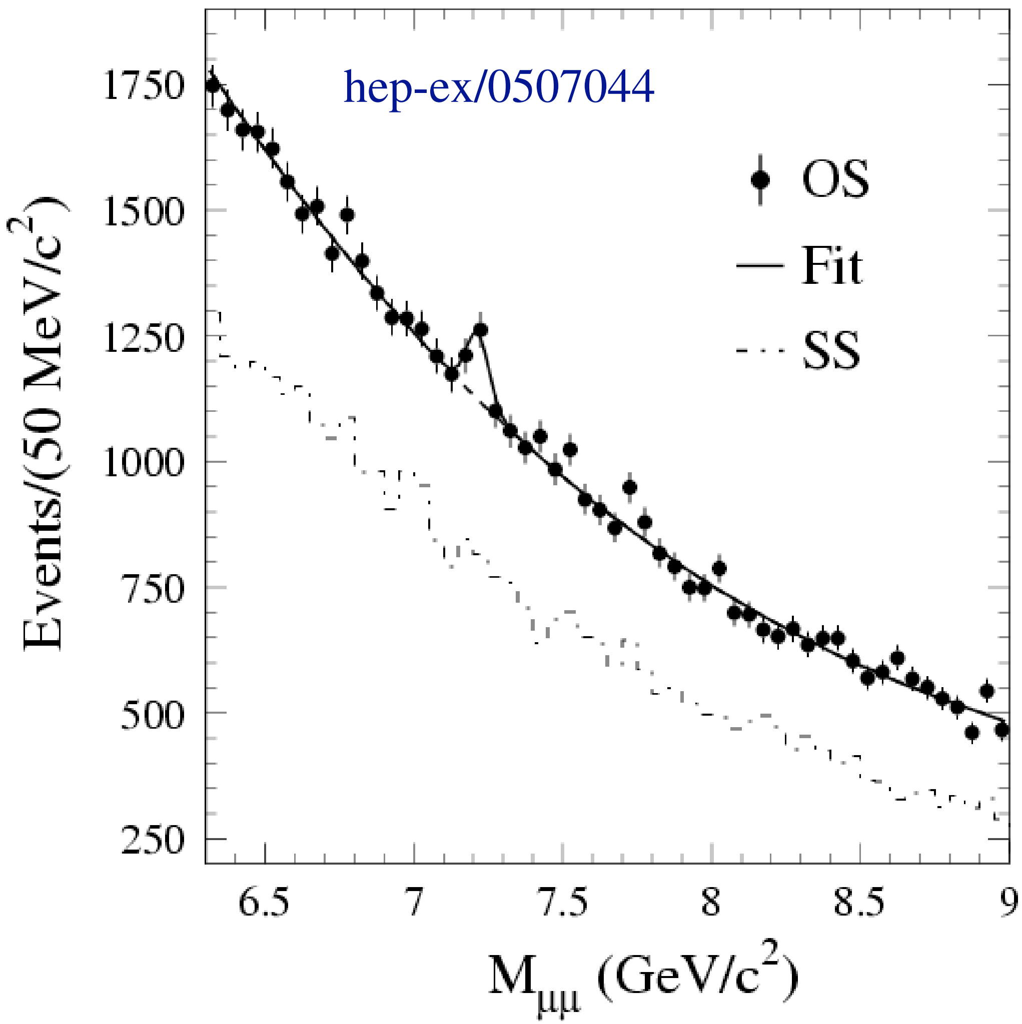
ΔNLL = 0.5 corresponds to 1σ

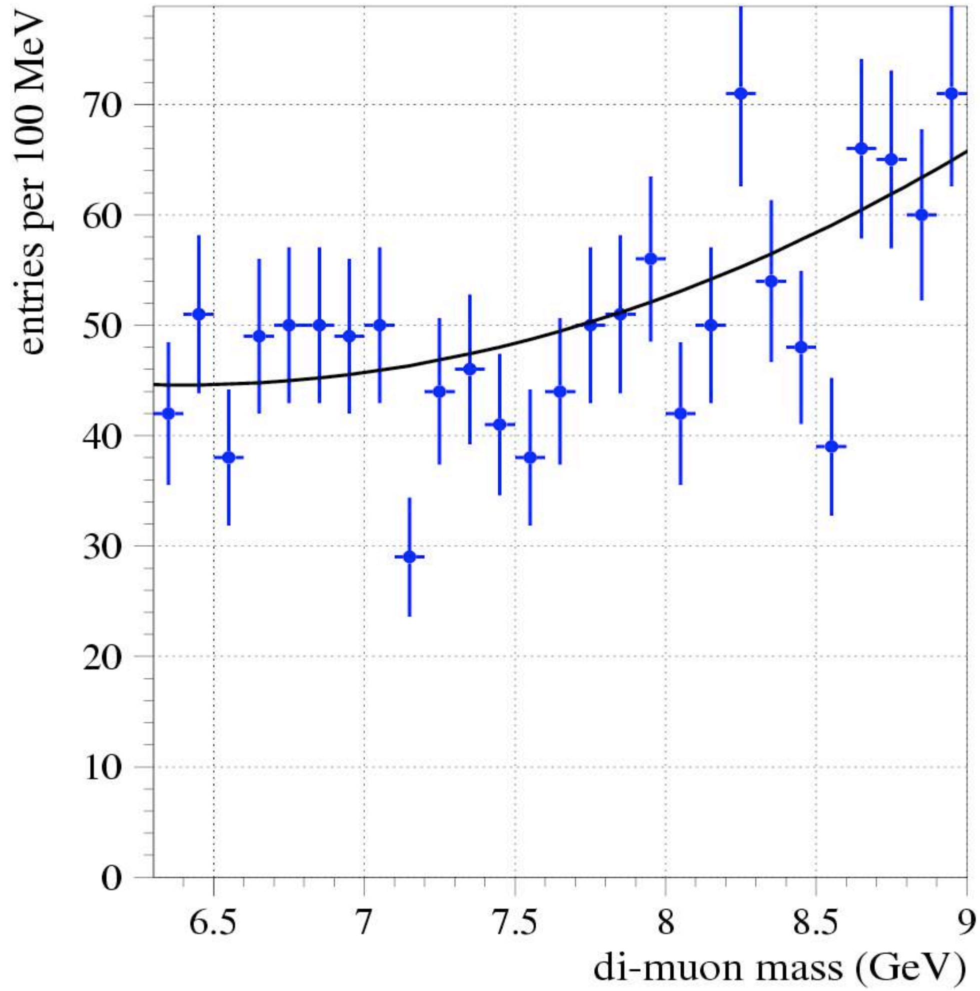
ΔNLL = 2.0 corresponds to 2σ

ΔNLL = 4.5 corresponds to 3σ

ΔNLL = 12.5 corresponds to 5σ

However, when scanning a given mass range, one must take into account the dilution factor.





- **110 pb^{-1} from Run I**
- **events in peak: 250 ± 61**
- **some special cuts to clean the sample**

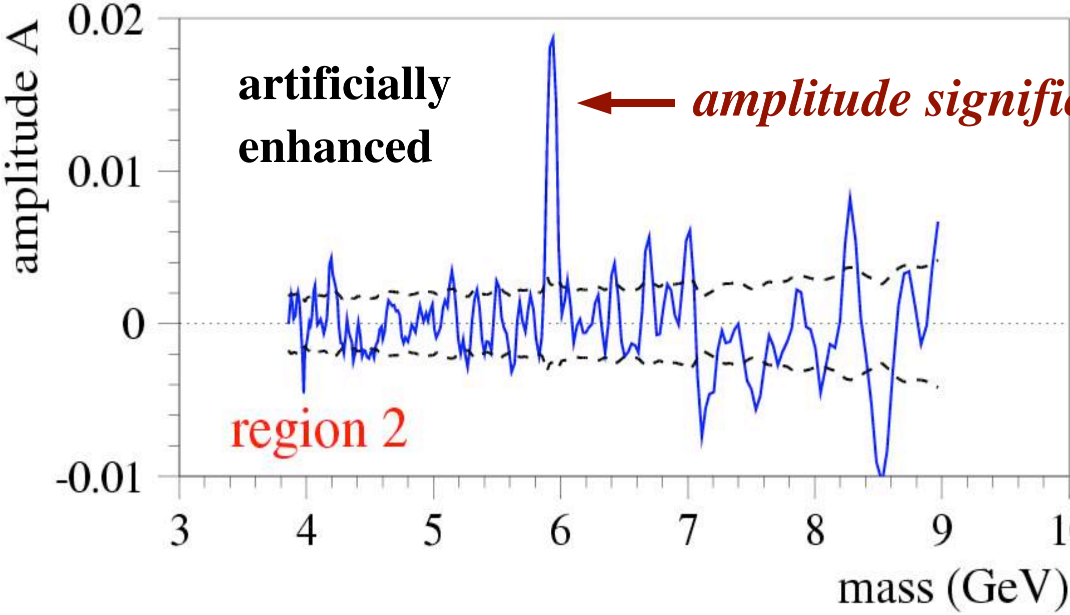
$$\frac{\sigma \times Br(\epsilon \to \mu\,\mu)}{\sigma \times Br(\Upsilon \to \mu\,\mu)} = (3.6 \pm 0.9)\%$$

- **195 pb^{-1} from Run II**
- **no peak; upper limit is 12 events**
- **would expect about 30 events**
- **sample not cleaned**

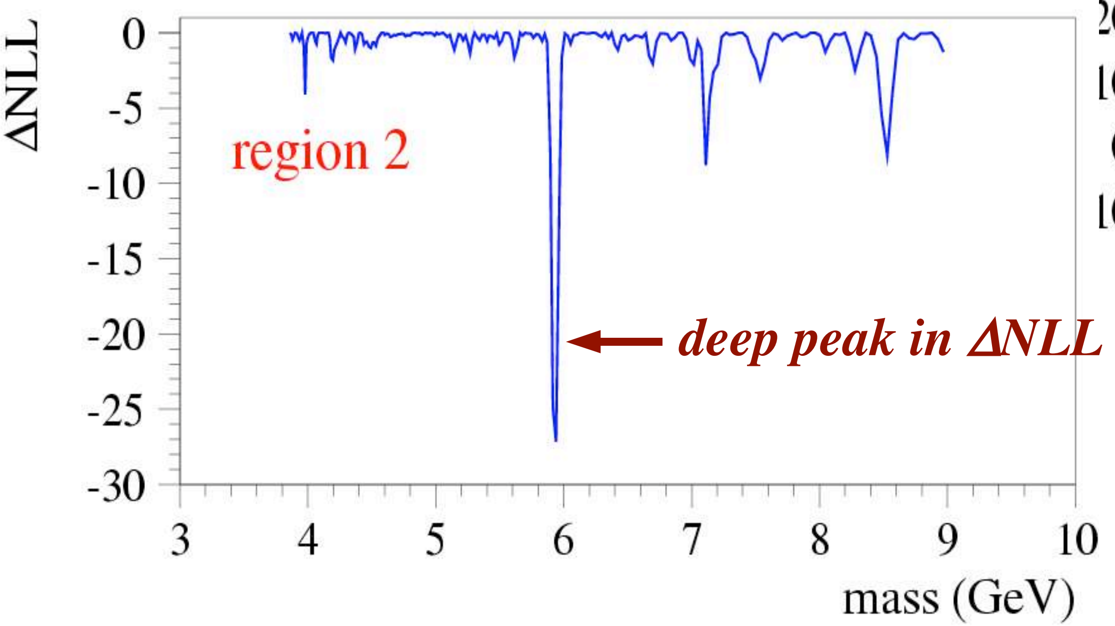
$$\frac{\sigma \times Br(\epsilon \to \mu\,\mu)}{\sigma \times Br(\Upsilon \to \mu\,\mu)} < 1.6\%$$

at 95% CL

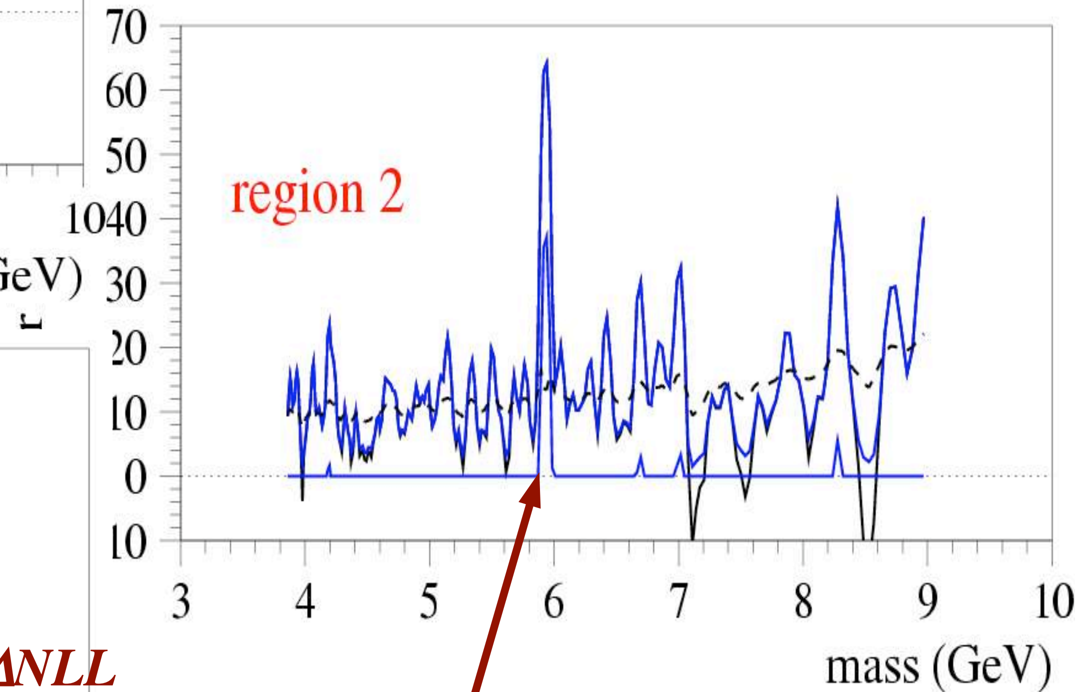
Suppose the "peak" at 5.92 GeV were a signal:



amplitude significantly above zero



deep peak in ΔNLL



Feldman-Cousins belt clearly deviates from zero signal events.

Acceptance Estimate

- We used a generator-simulation and applied simple kinematic and geometric cuts to estimate the acceptance *vs.* mass.
- We have shown elsewhere that this seems to agree well with full simulation.