Search for Narrow di-Muon Resonances

Tevatron Run II

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for the
CDF Collaboration

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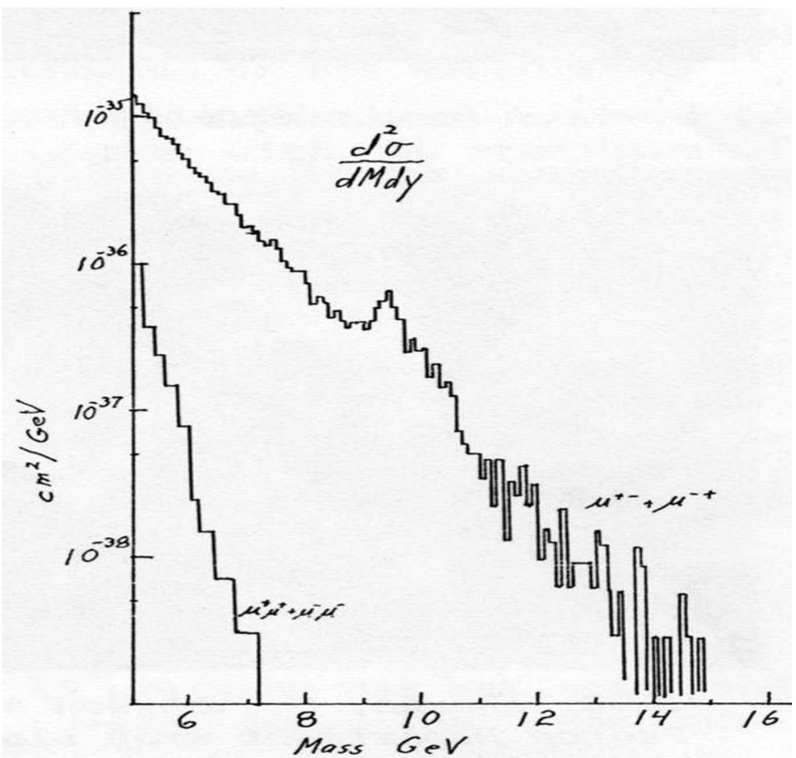
- motivations
- unbinned likelihood technique
- data sample and event selection
- scanning for bumps
- cross-section limits
- summary and conclusions

Motivations

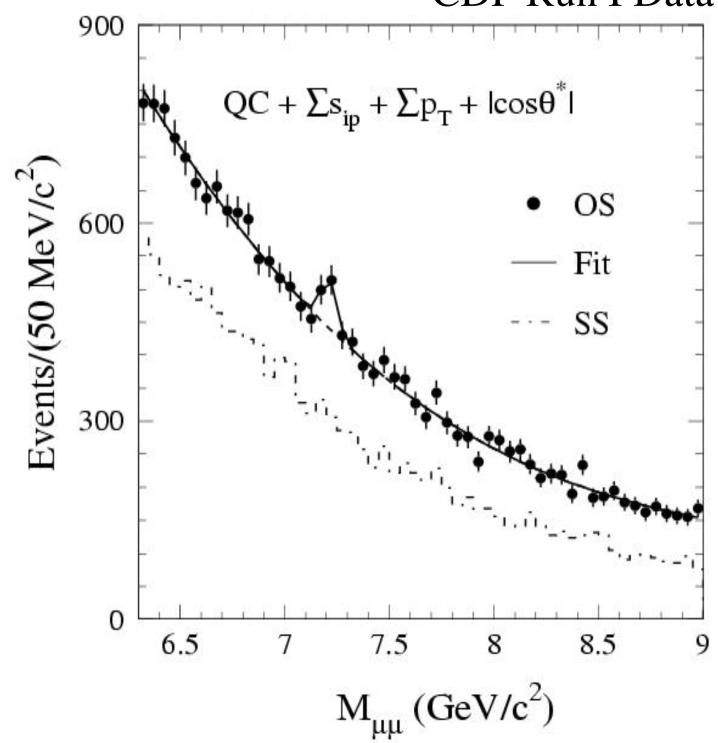
Basic: We have lots of nice data – unique data – we should look at it in any many ways as we can think of!

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



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

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.

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

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.

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

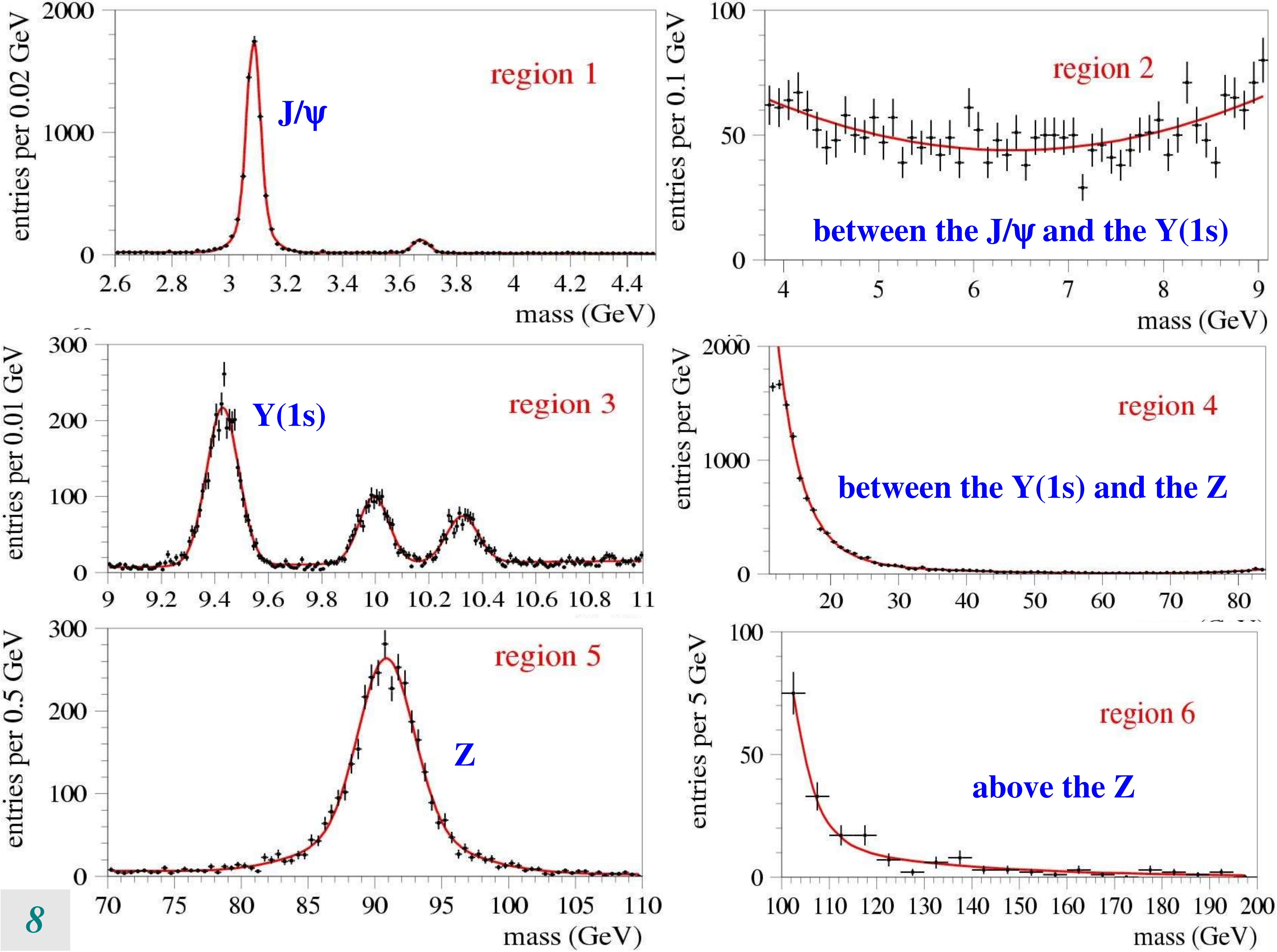
Six Mass Ranges

- 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)

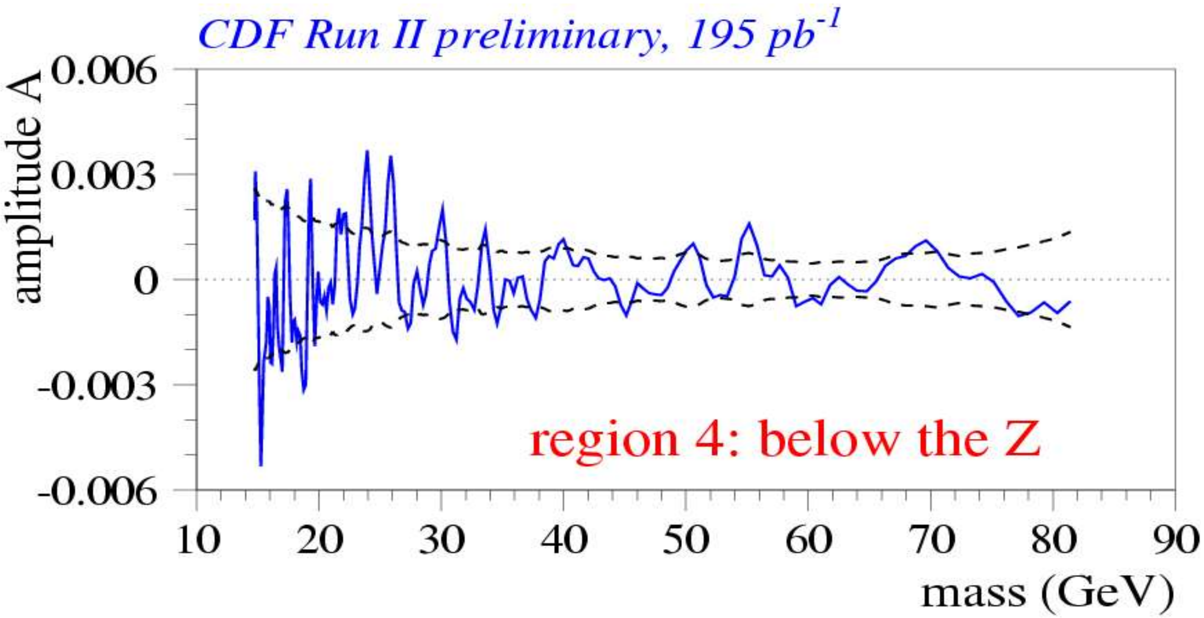
- We fit these to appropriate empirical functions.
  - use an unbinned likelihood fit
- Above 200 GeV demands a different technique – *in progress*.

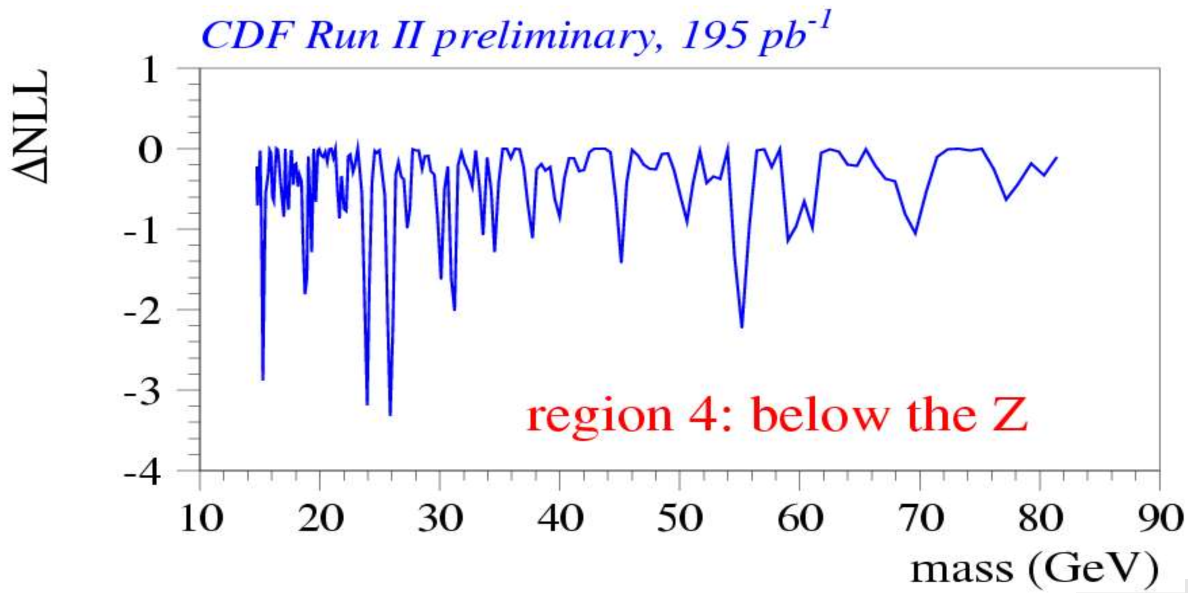


region 1
J/ψ
entries per 0.02 GeV
mass (GeV)
region 2
between the J/ψ and the Y(1s)
entries per 0.1 GeV
mass (GeV)
region 3
Y(1s)
entries per 0.01 GeV
region 4
between the Y(1s) and the Z
entries per GeV
region 5
Z
entries per 0.5 GeV
mass (GeV)
region 6
above the Z
entries per 5 GeV
mass (GeV)

Example: Scanning Region 4

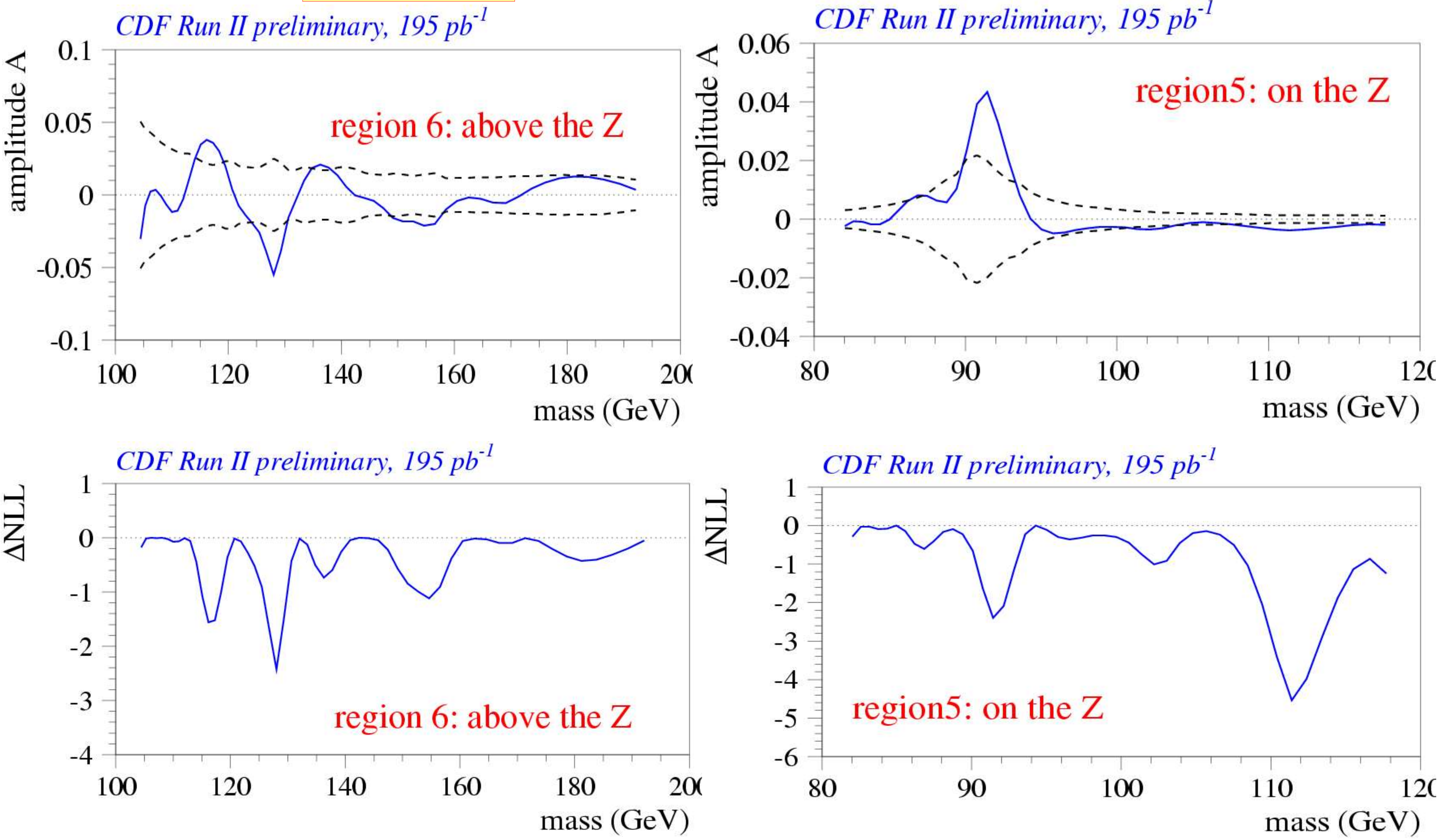
- *mass range 13 – 84 GeV*
- *parametrize as a sum of three exponentials*
- *Increasing spacing reflects the quadratic increase of σ_M with M.*
- *Dashed lines show the calculated uncertainty on the amplitude.*
- *No signs of a new peak.*





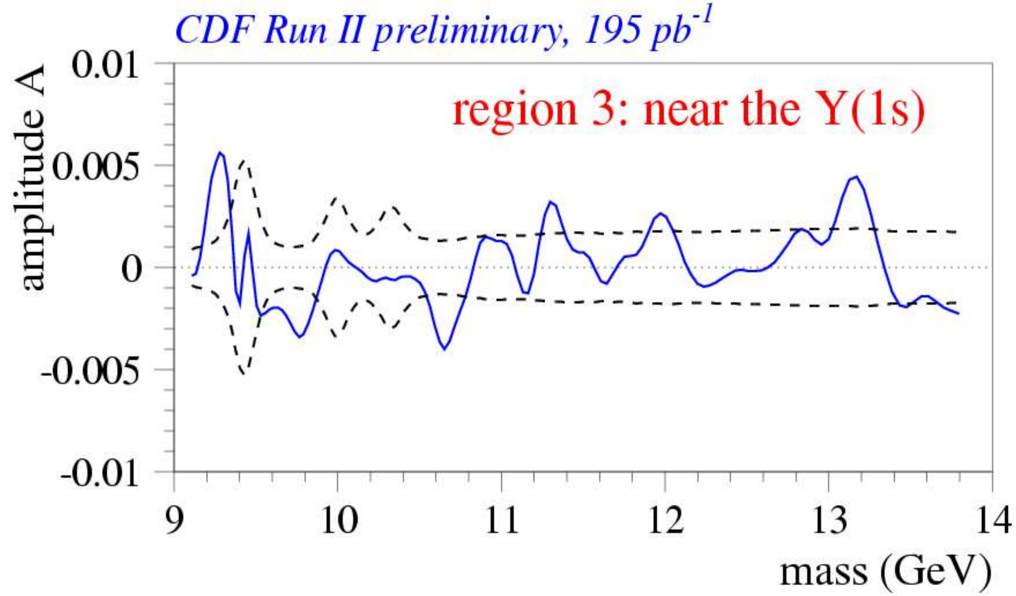
above the Z

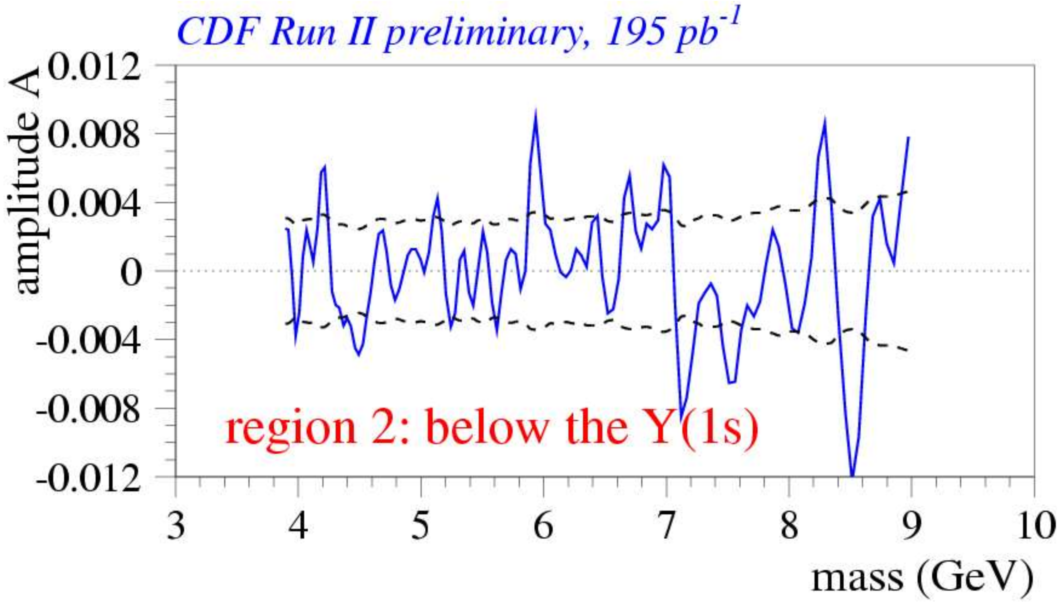
on the Z

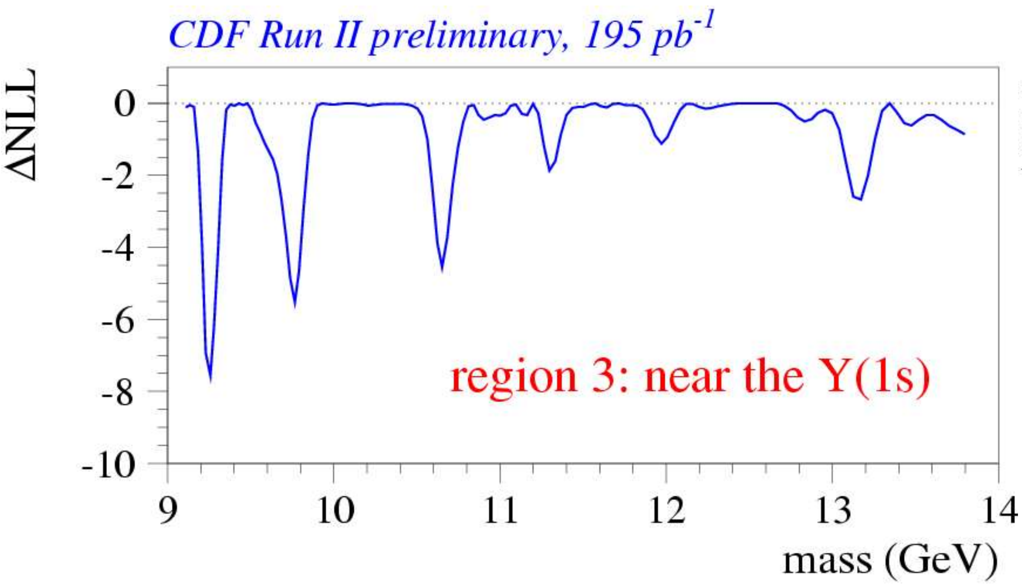


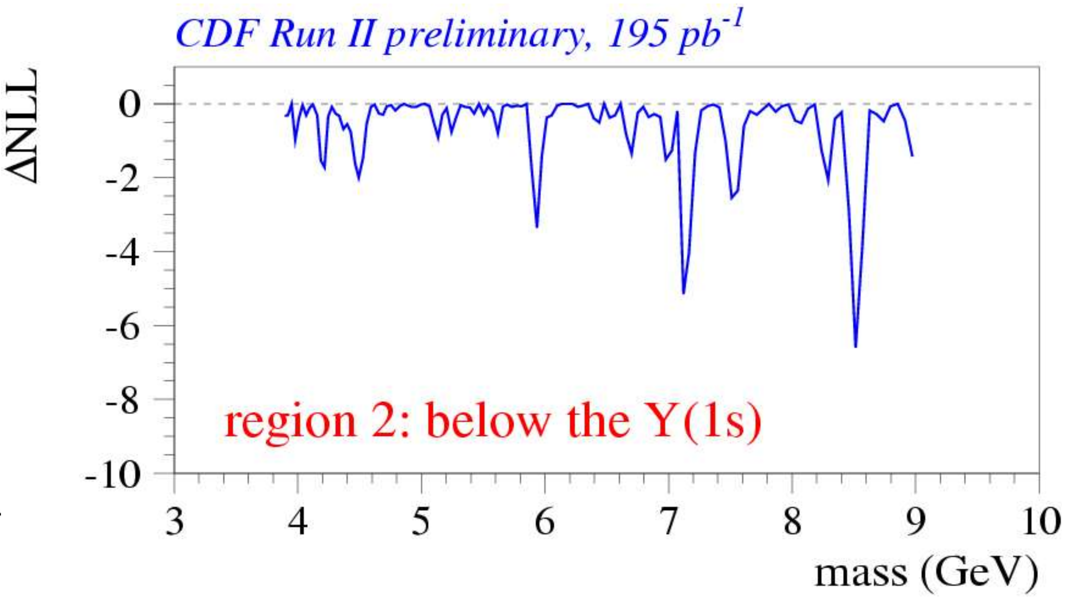
near the Υ(1s) and Υ(2s)

below the Υ(1s)



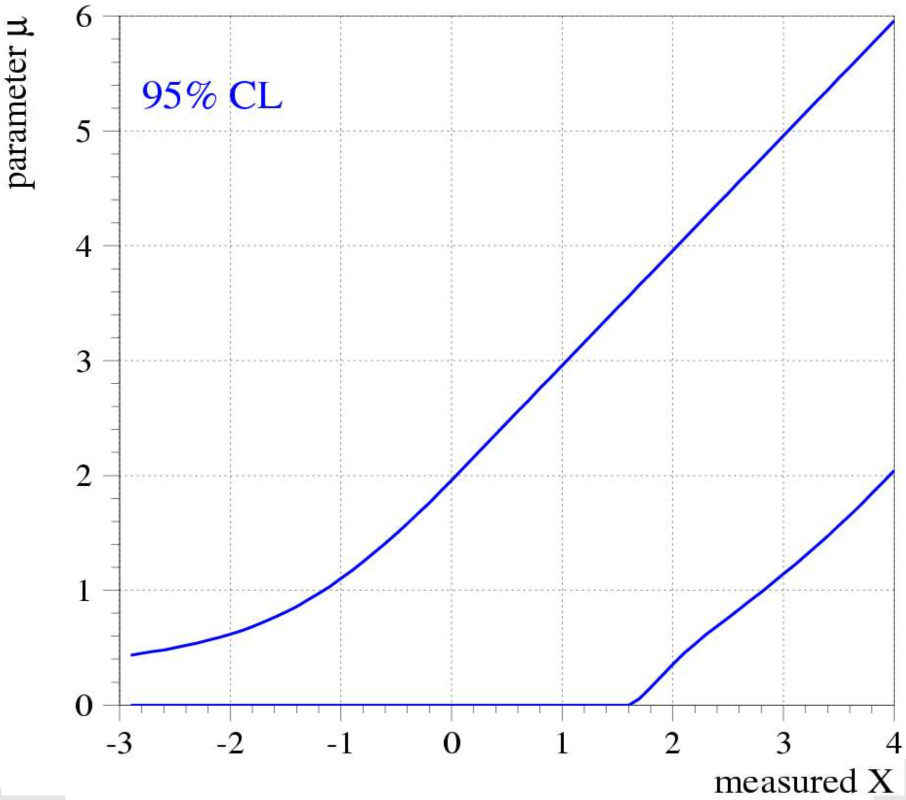






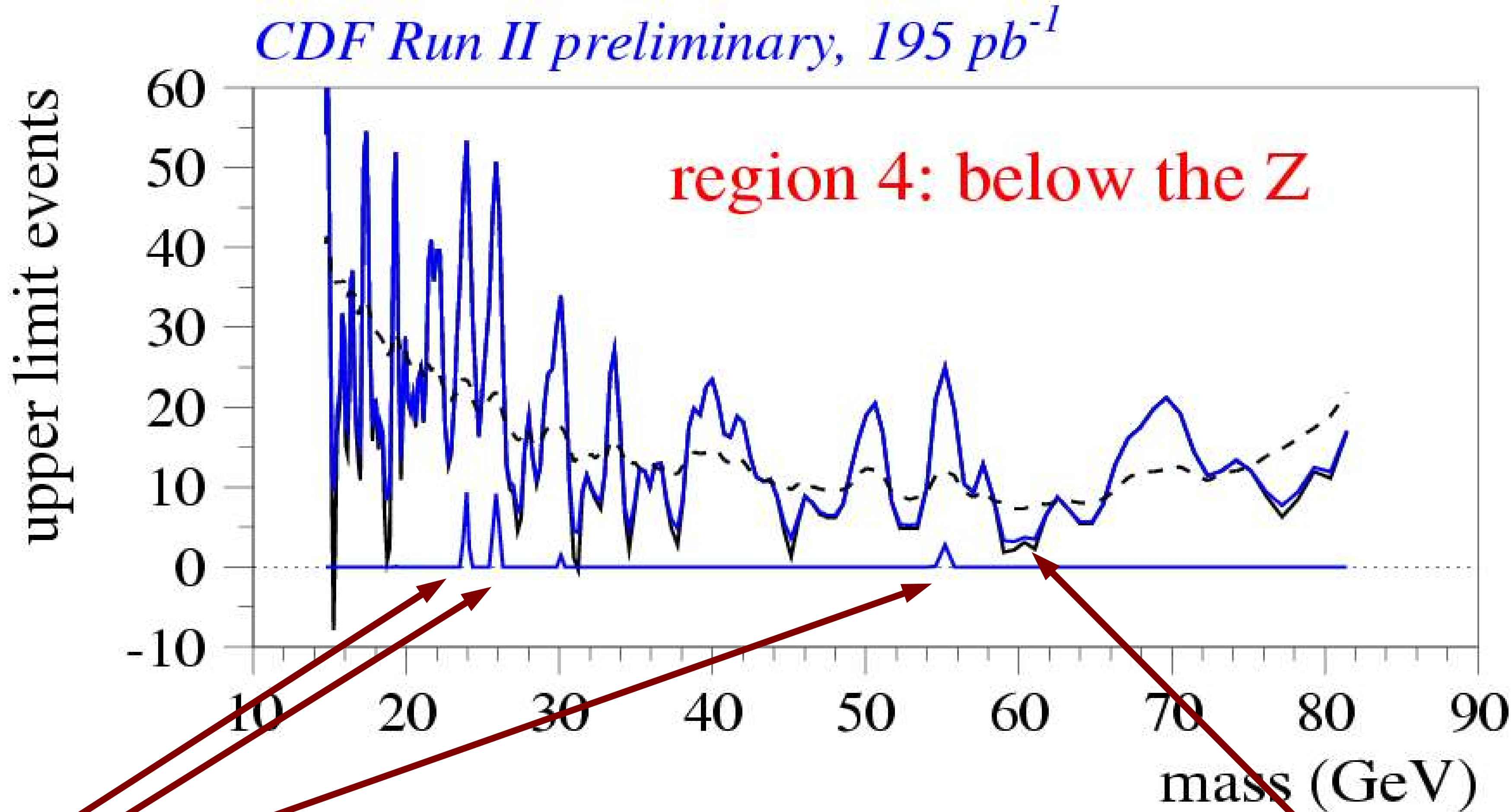
Feldman-Cousins Prescription

- 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}

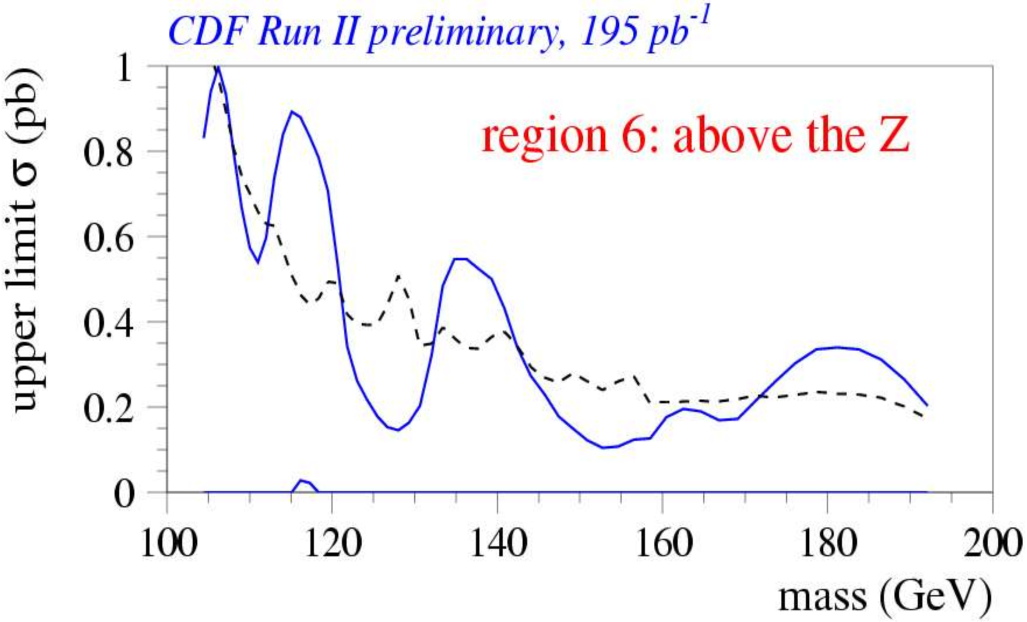


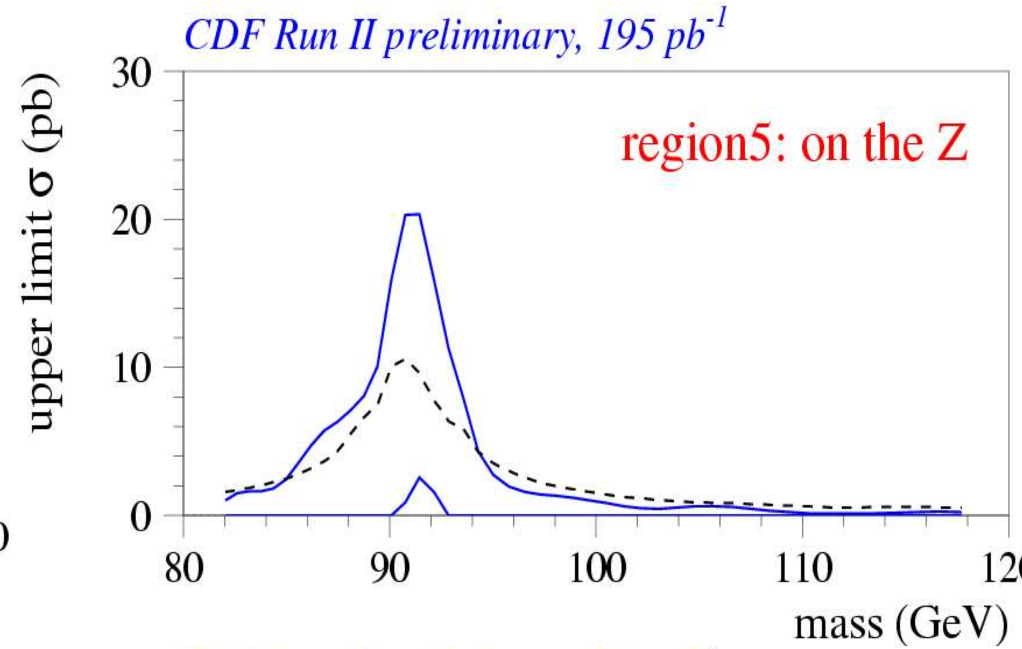
Notice there are mass values for which there is a "lower limit".
This is to be be expected in the Feldman-Cousins method.
At 95% CL, the data do not favor zero signal – this does not mean a signal is present.
Notice, also, that where there is a downward fluctuation, the limit on N_{ev} is not negative.

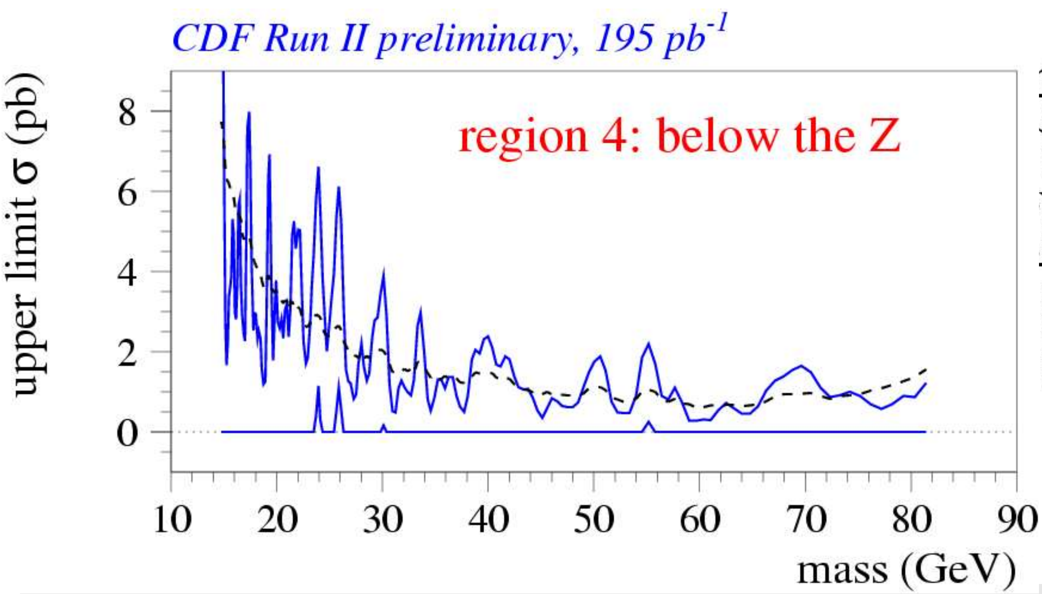
Obtaining a cross-section:

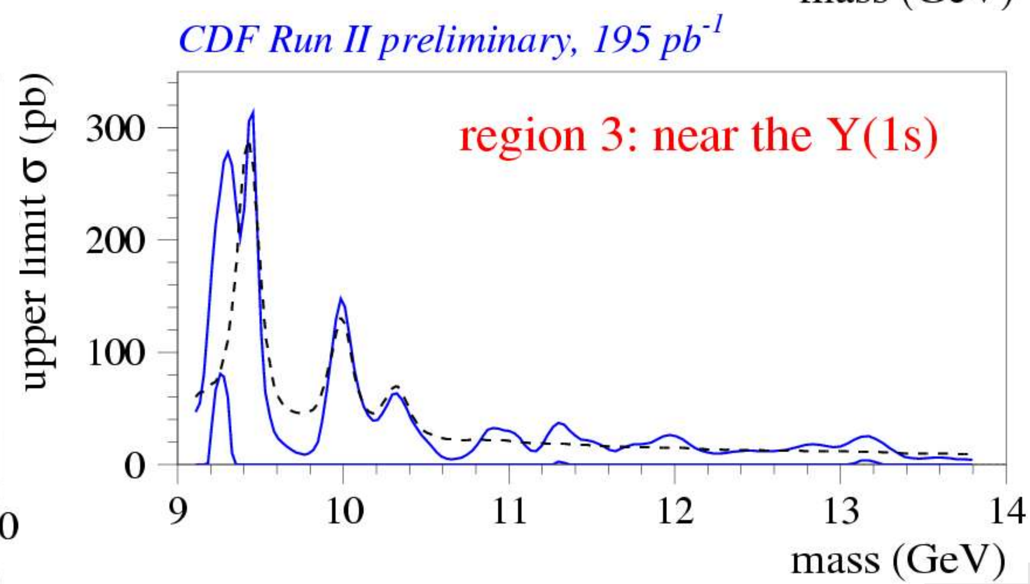
- There will be both upper and lower limits, in general.
- set the normalization ($L \times \varepsilon$) using the Z – peak
- take variation of acceptance with mass into account
- take systematics into account
  - various terms are taken to be Gaussian
    - mass-dependent efficiencies
    - mass-dependent 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:









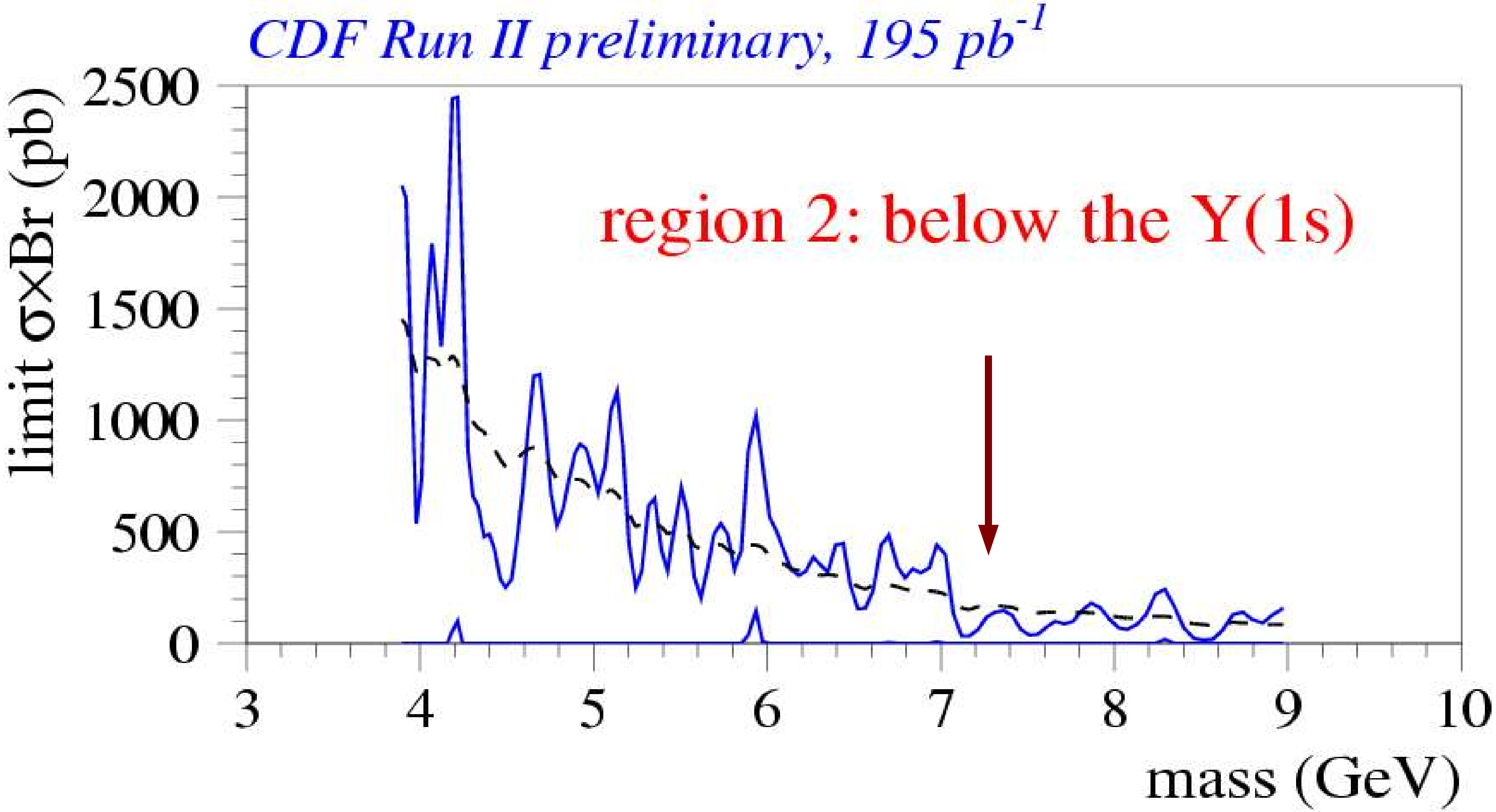
Region 2 – special

(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.

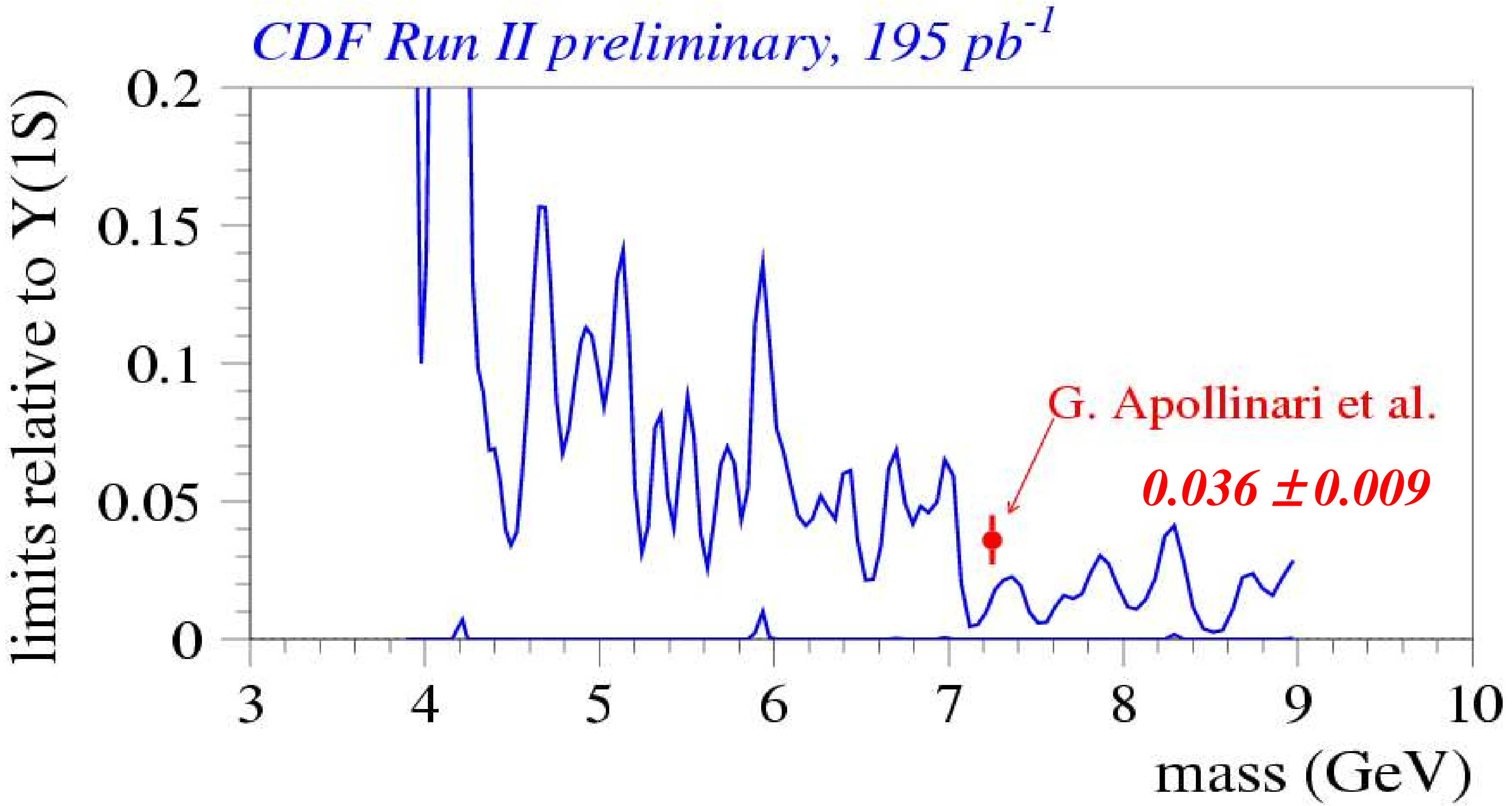
95% Feldman-Cousins confidence belt for $\sigma \times \mathrm{Br}$ in region 2:



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

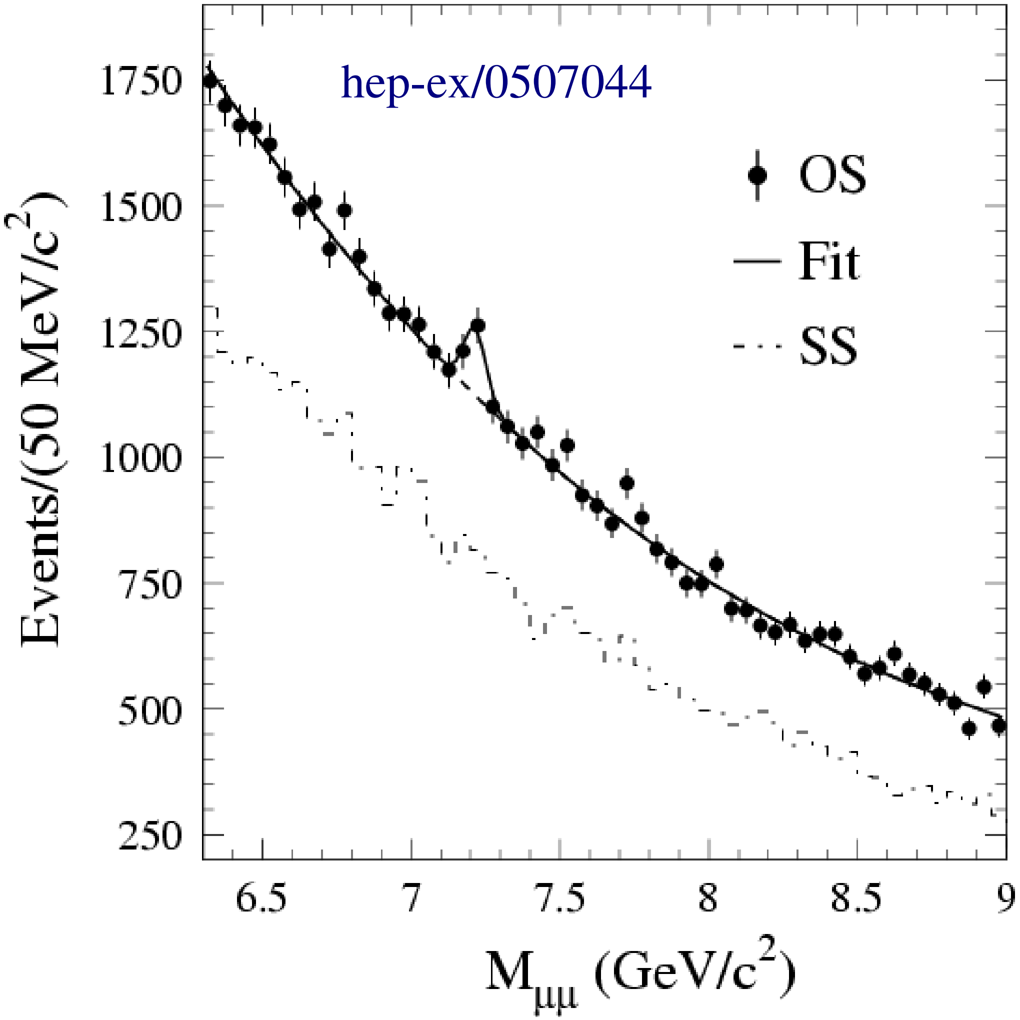
If we consider the second model:

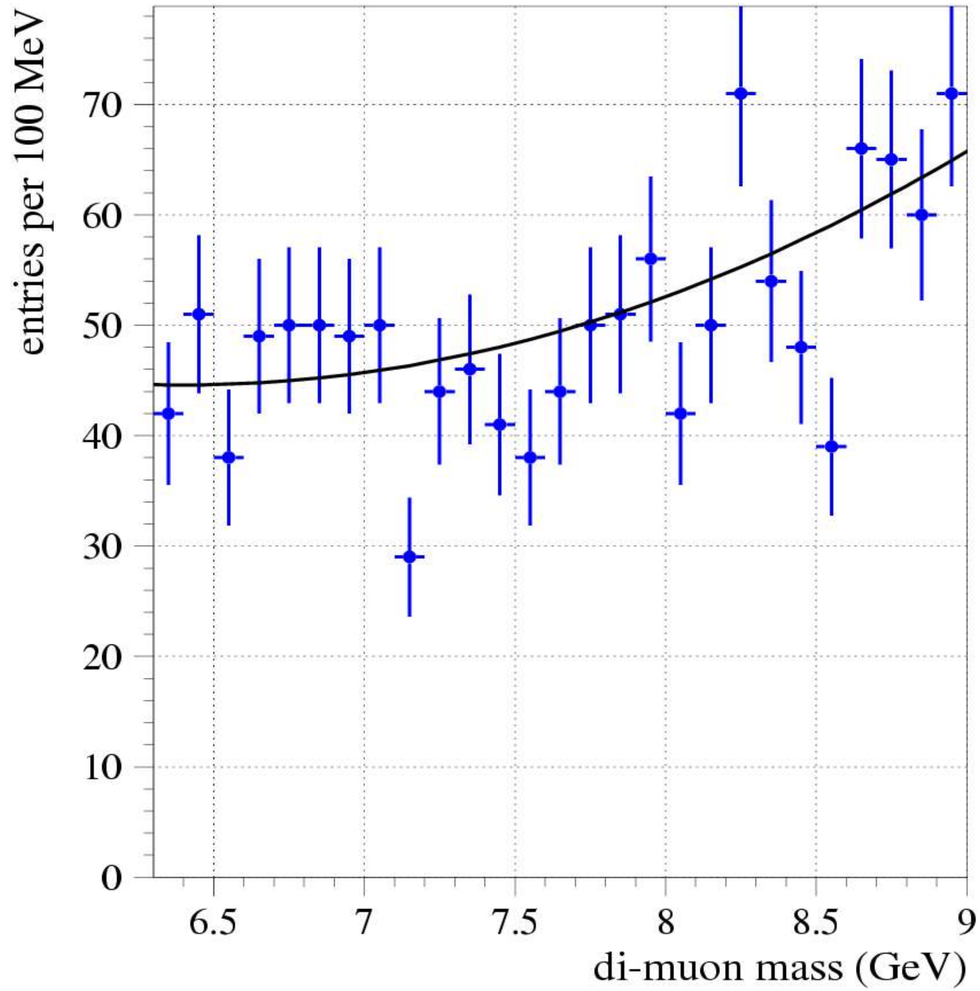
plot the limits relative to Υ(1S) production.



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

at 95% CL





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

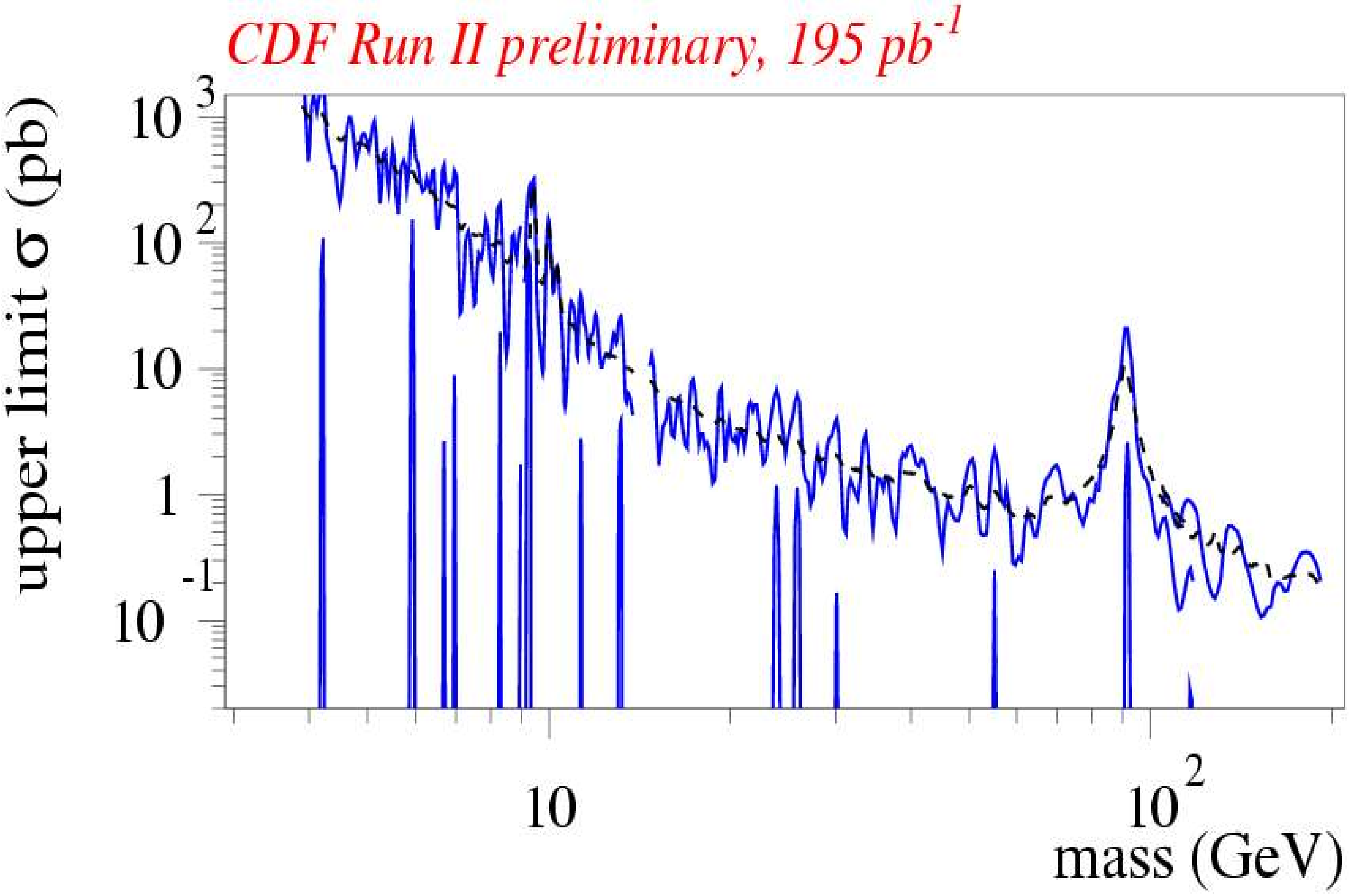
$$\frac{\sigma \times Br(\epsilon \to \mu\mu)}{\sigma \times Br(\Upsilon \to \mu\mu)} = (3.6 \pm 0.9)\%$$

- **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

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



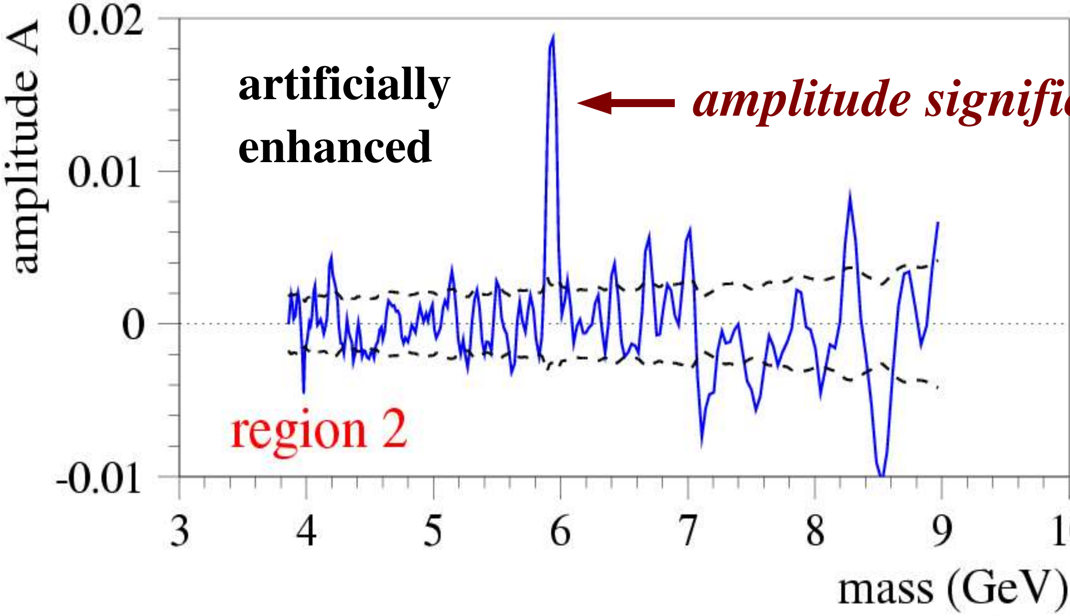
Summary & Conclusions

CDF Run II *preliminary*

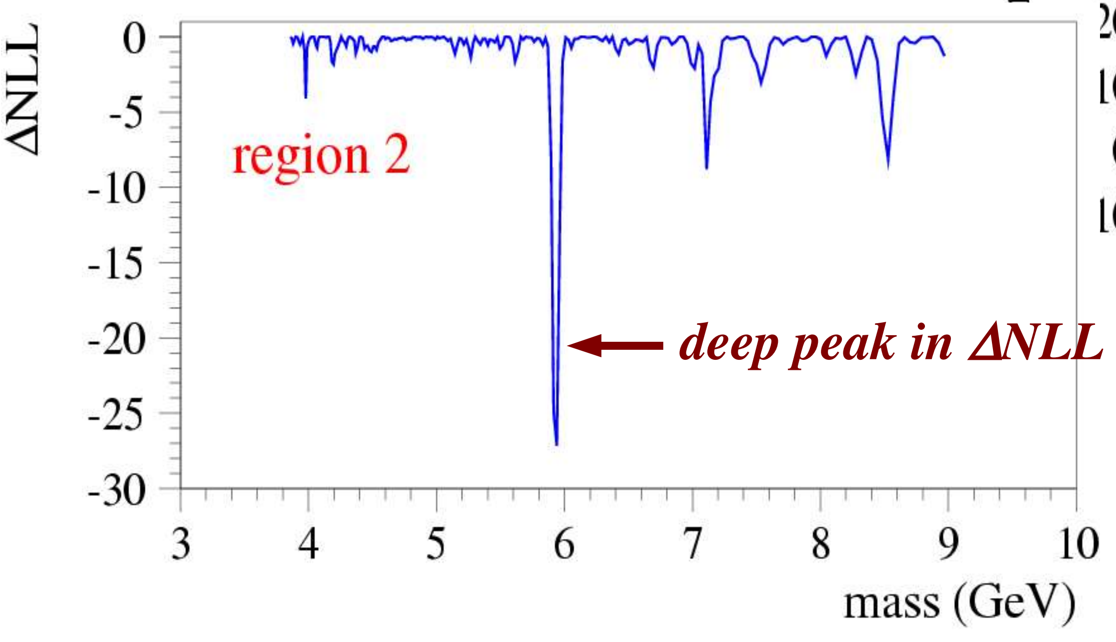
- Five mass regions have been scanned, encompassing the range 4 GeV up to 200 GeV, for 195 pb^{-1}.
- There is no sign of new physics anywhere.
  We have derived cross section limits using Feldman-Cousins.
- The Run I observation at 7.25 GeV is not confirmed.
- We will add more data very soon.
- We will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

Back-up Slides

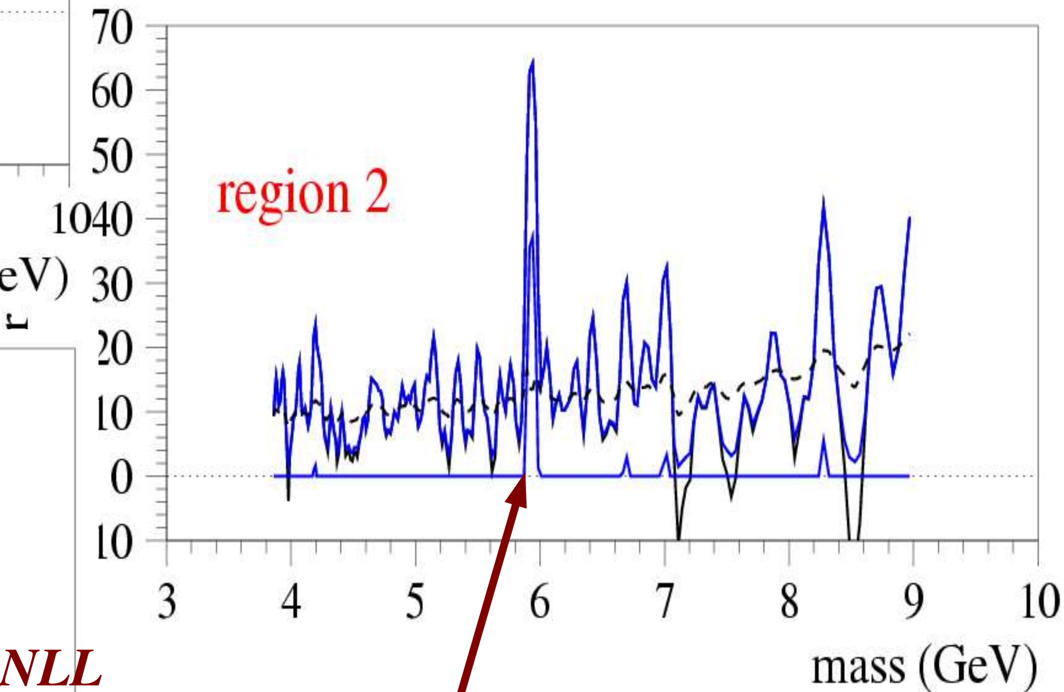
Suppose the "peak" at 5.92 GeV were a signal:



amplitude significantly above zero



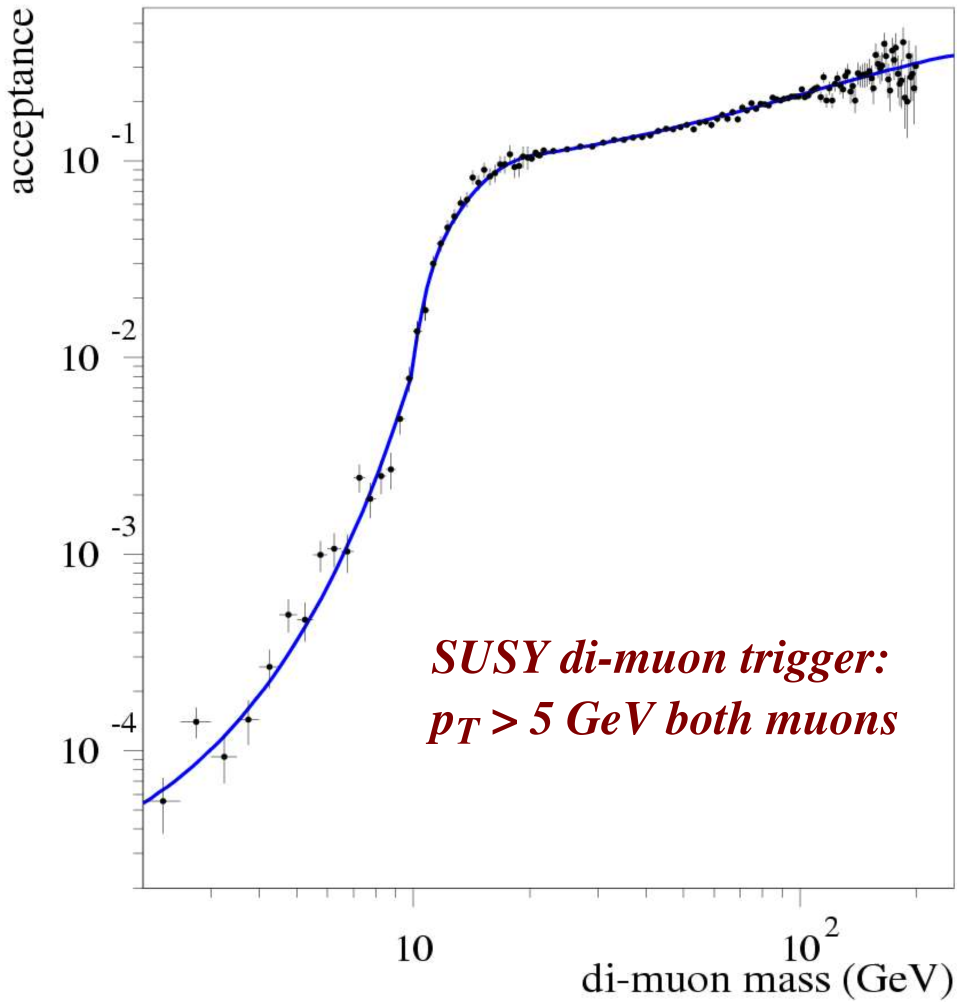
deep peak in ΔNLL

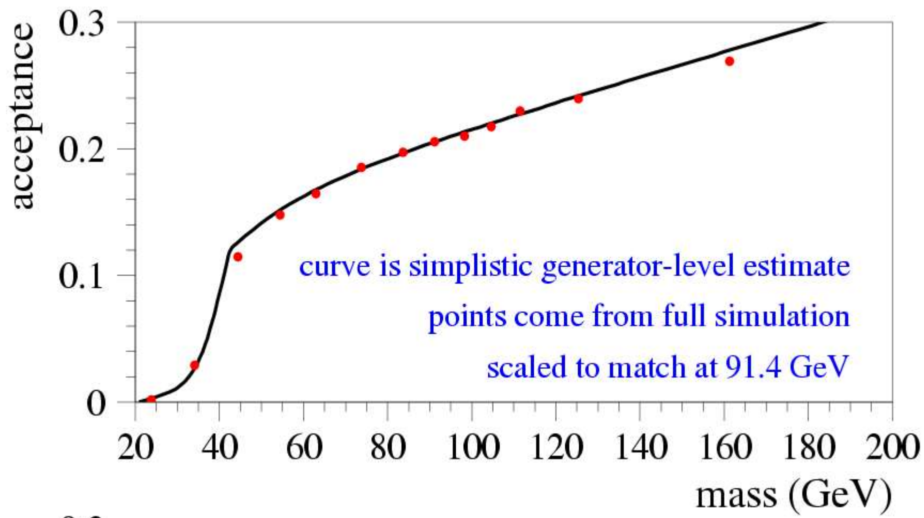


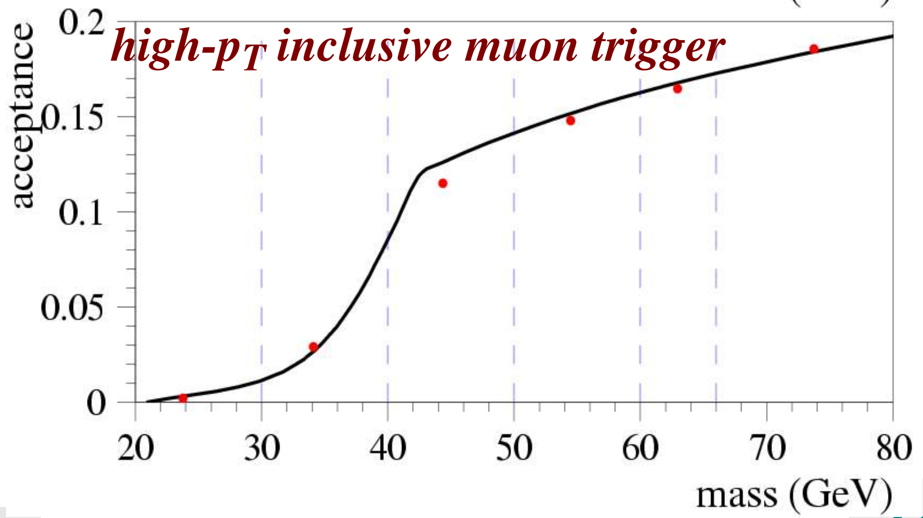
Feldman-Cousins belt clearly deviates from zero signal events.

Acceptance Estimate

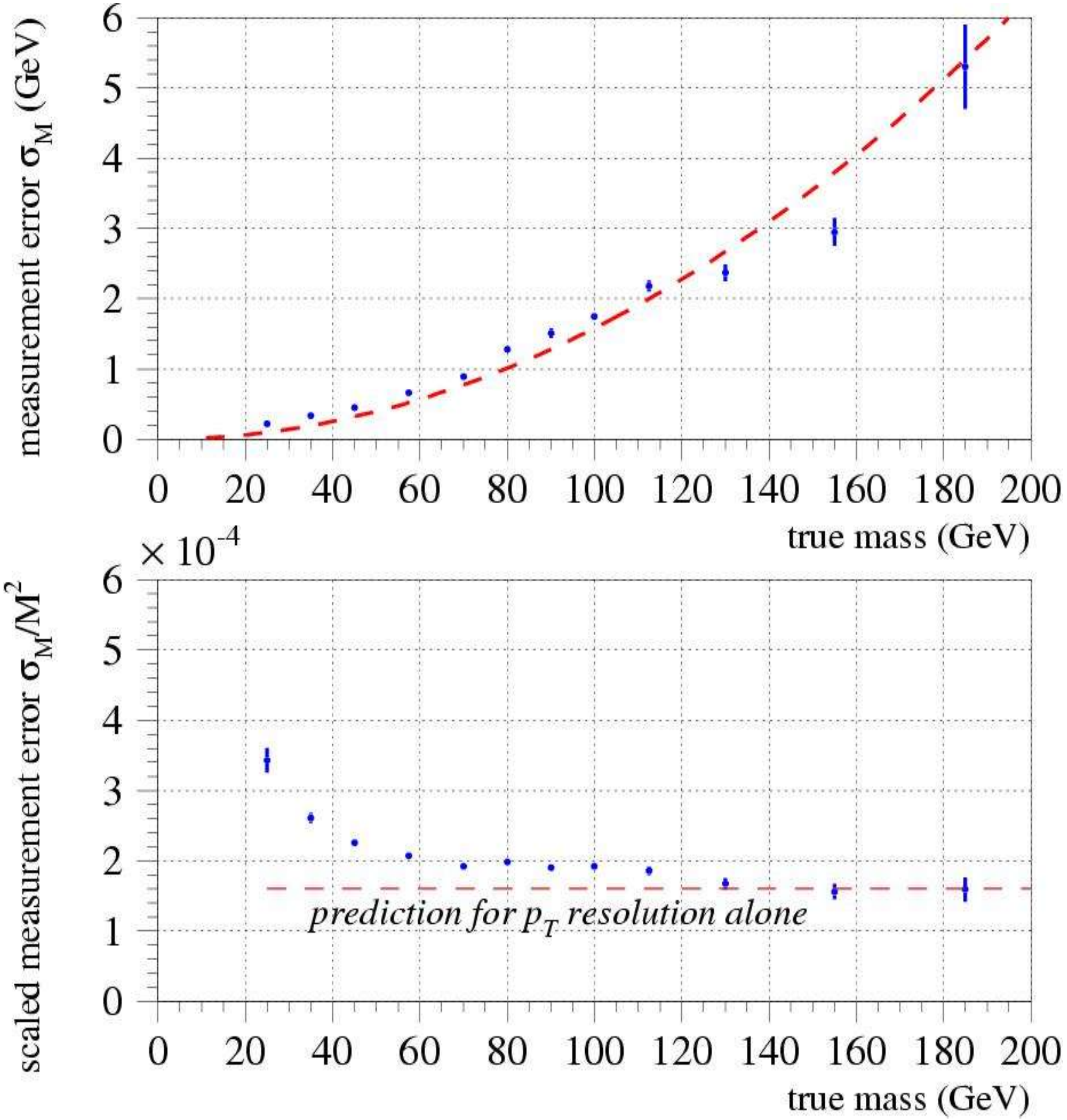
- We used a generator-simulation and applied simple kinematic and geometric cuts to estimate the acceptance *vs.* mass.
- We have shown elsewhere that this seems to agree well with full simulation.







$$\frac{\sigma_M}{M^2} = (1.6\times10^{-4}) + (2.4\times10^{-4})\exp(-(M-20)/20)$$



cdf7560

Check the fitted masses:

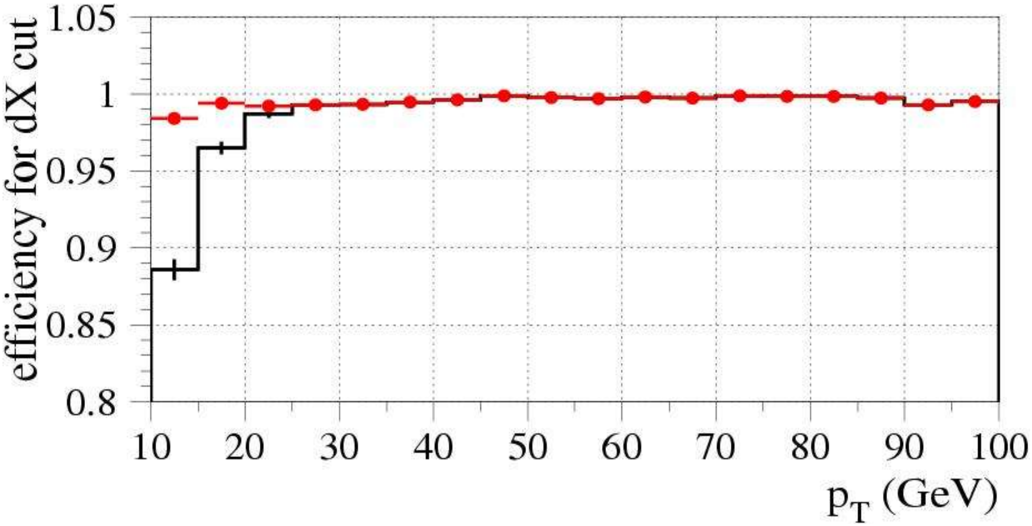
fit	PDG	ratio
3.0864 ± 0.0005 GeV	3.0969 GeV	0.997
3.6742 ± 0.0020 GeV	3.6860 GeV	0.997
9.4291 ± 0.0008 GeV	9.4603 GeV	0.997
9.9951 ± 0.0019 GeV	10.0233 GeV	0.997
10.325 ± 0.002 GeV	10.356 GeV	0.997

Normalization:

- statistical uncertainty is 1.7%
- systematic error on the measurement of σ(Z) is 2.2%
- we ignore the uncertainty on the luminosity since this cancels out
- total uncertainty is 2.8% for all masses

Efficiency:

- sliding ΔX and isolation cuts reduce/remove p_T dependence of ID efficiency
- assume 1% for $p_T > 10$ GeV
- not tested for $p_T < 10$ GeV – assign a conservative 5% uncertainty
- the uncertainty as a function of mass will be, roughly, twice that.



from cdf7560

Acceptance:

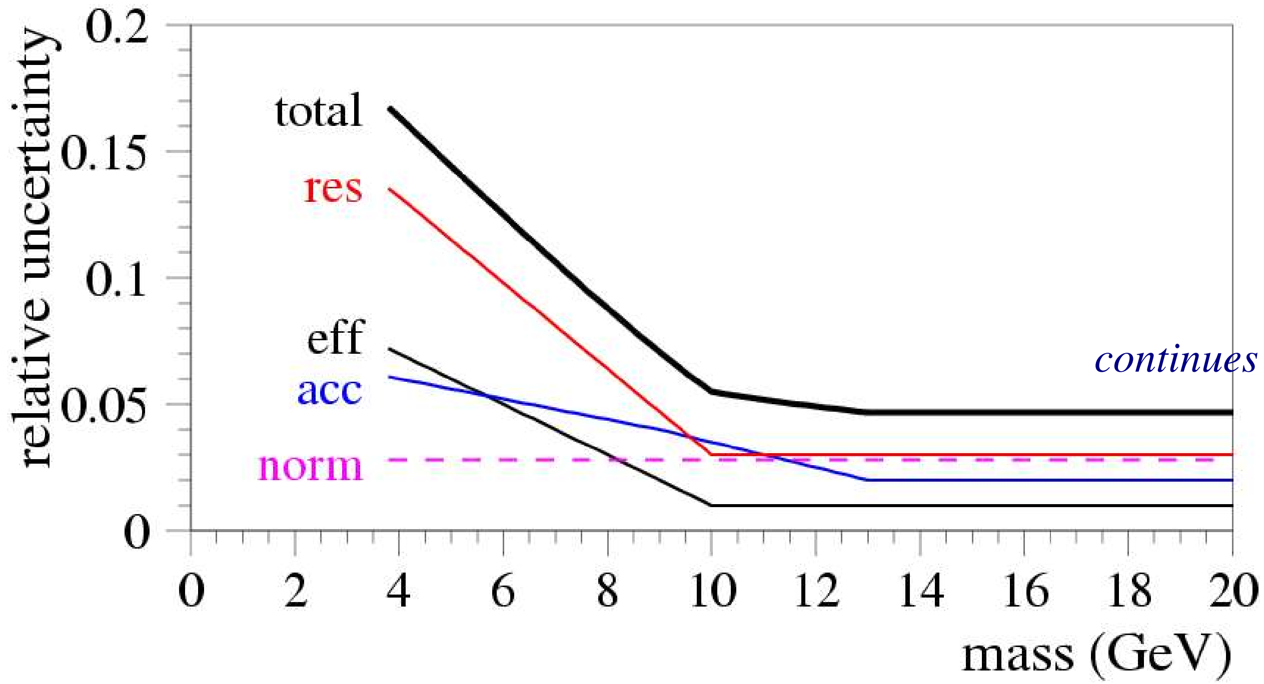
- since we normalize to the Z-peak, absolute acceptance does not matter
- uncertainties would come from PDF's and veracity of the theory
- in cdf7560 we evaluated the PDF uncertainty using CTEQ6M
- we verified the generator-level PYTHIA distribution using REBOS, PHOZPRMS
- still need to repeat these studies for $M_{\mu\mu} < 20$ GeV
- assign linearly decreasing uncertainty: typ. 6% region 2, 3% region 4, 2% region 6

Mass Resolution:

- detailed MC studies of mass resolution were carried out for cdf7560
- conservative variations of tails: 3% uncertainty on yields for $M_{\mu\mu} > 20$ GeV
- use known resonances for explicit tests:
  - J/psi: fitted width – 0.024 GeV, predicted 0.024 GeV
  - Υ(1S): fitted width – 0.060 GeV, predicted 0.061 GeV
  - Z-peak: fitted width – 2.0 GeV, predicted 1.4 GeV

Overall Systematic Uncertainty:

- add these together in quadrature to obtain a total systematic uncertainty:

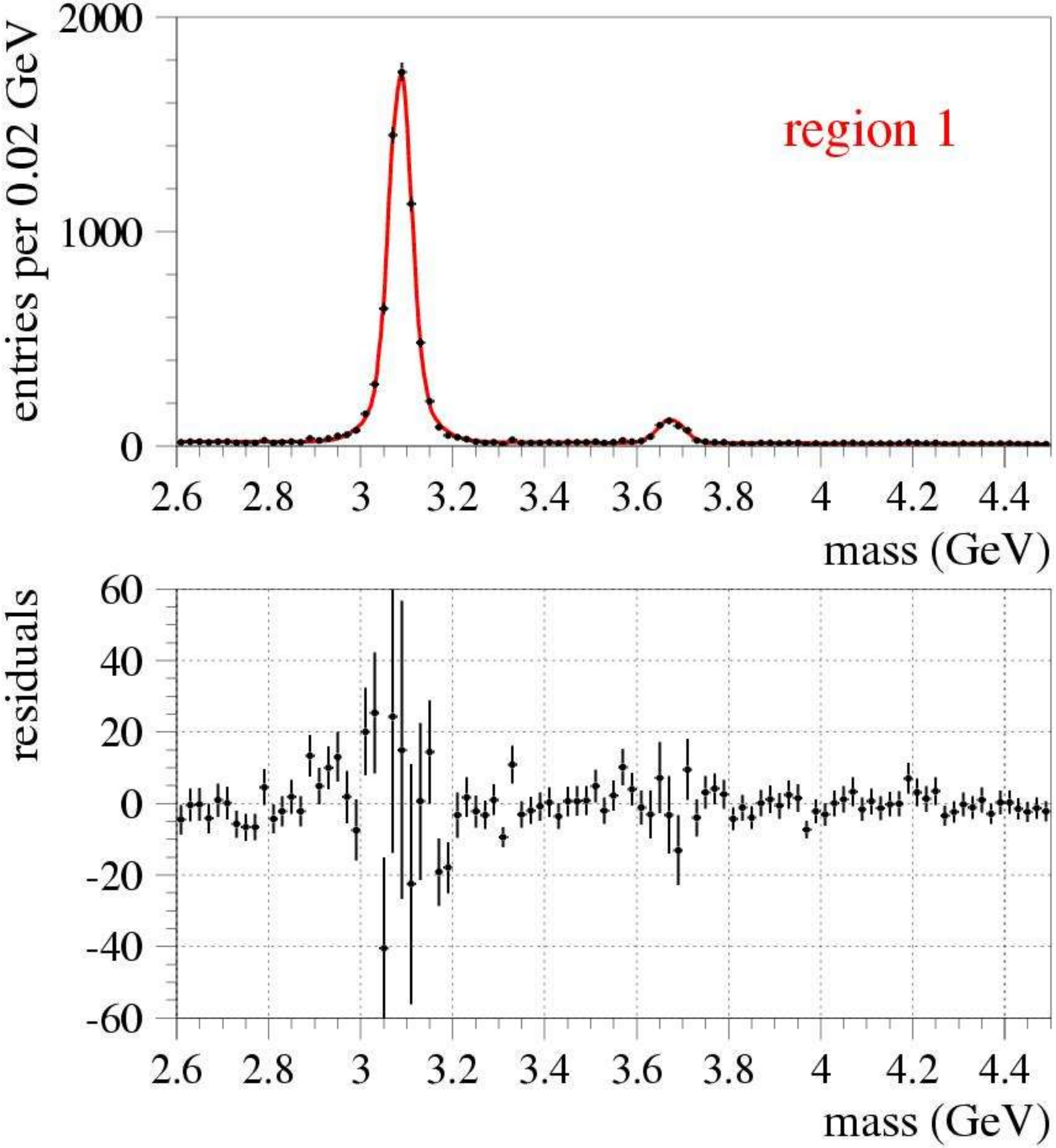


continues at 4.7% above 20 GeV

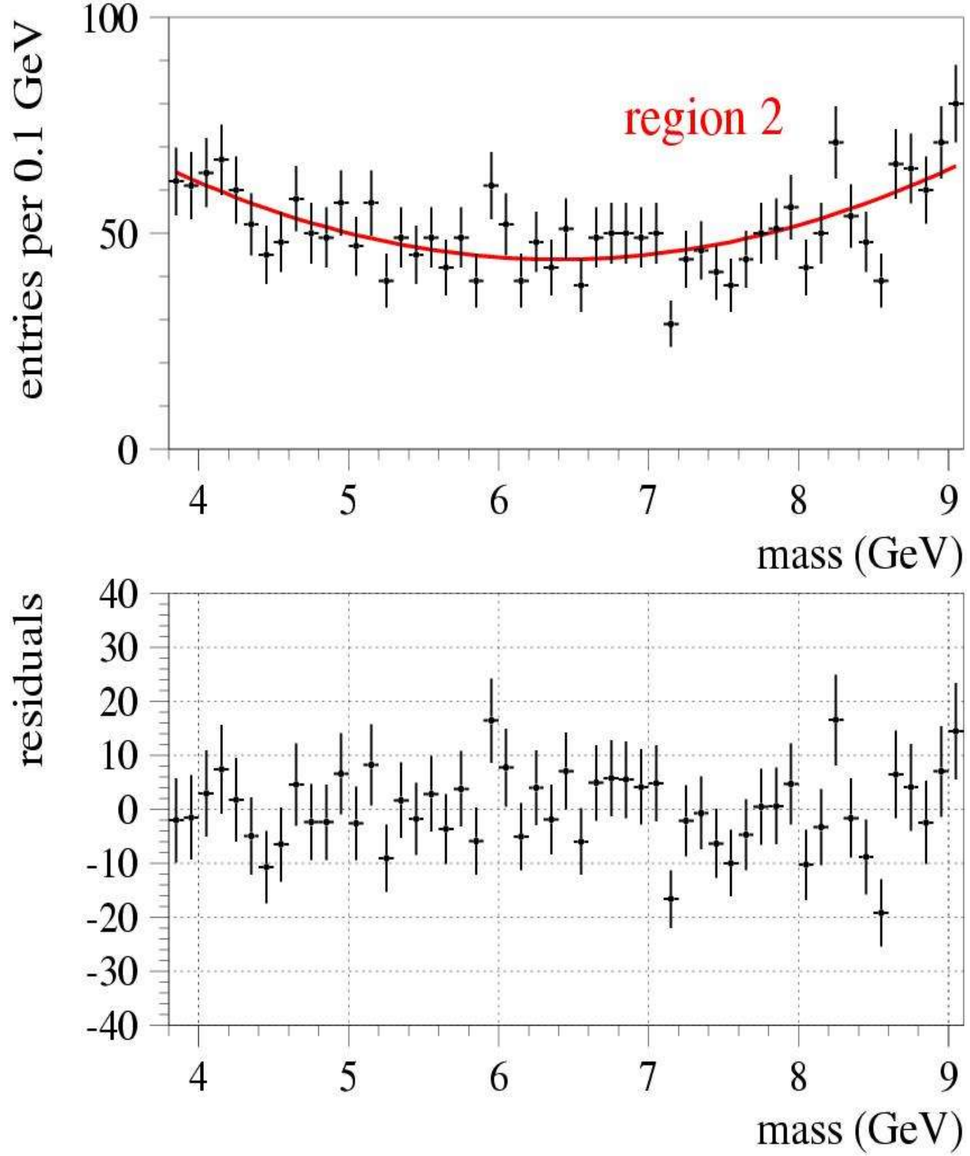
Impact:

- given definition of the cross section, syst unc κ adds in quadrature to ampl. unc.
- input "X" to Feldman-Cousins is increased by about (1 + κ)
- impact on cross section limits is about (1 + κ) too.

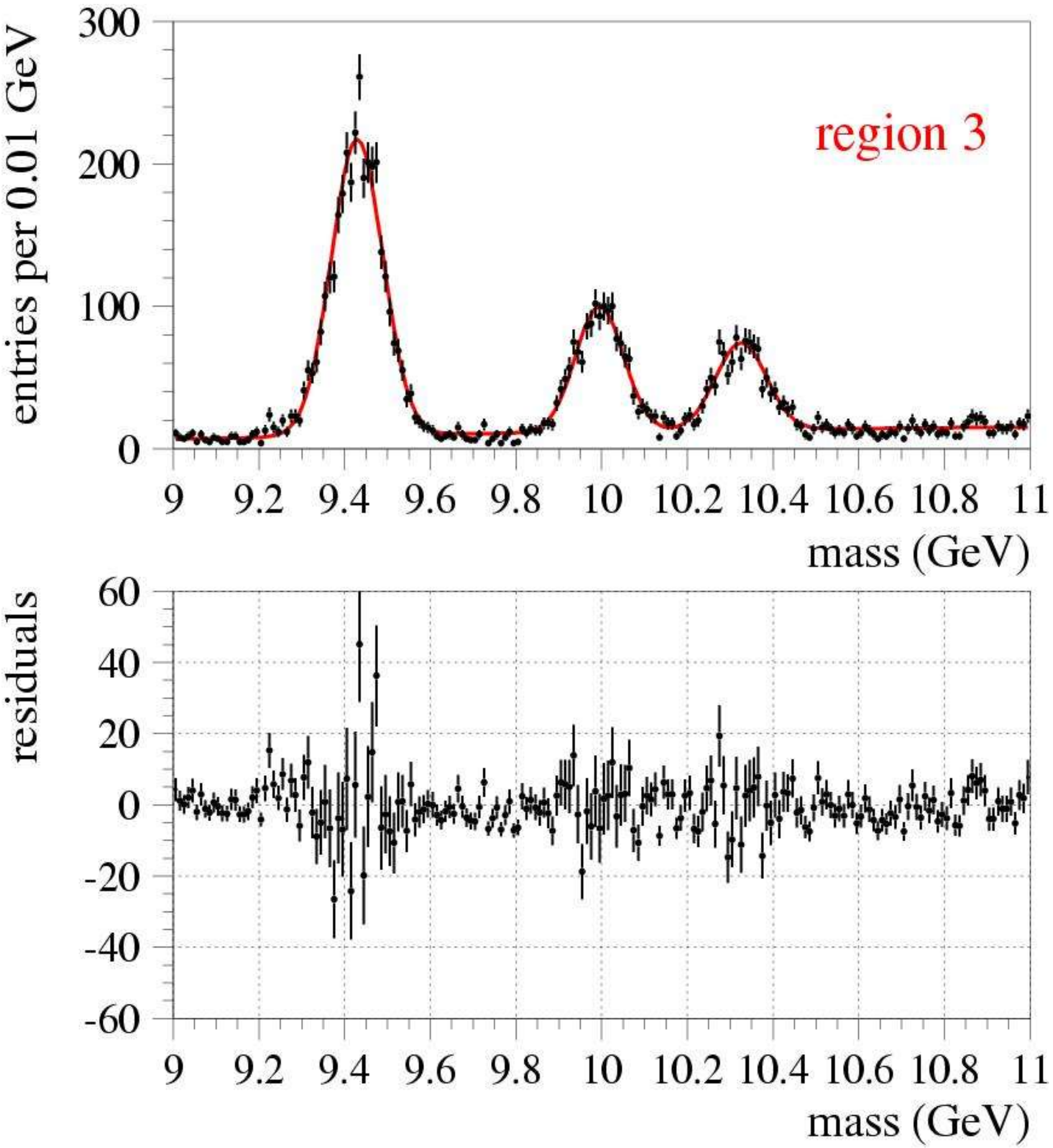
3 Gaussians + linear term



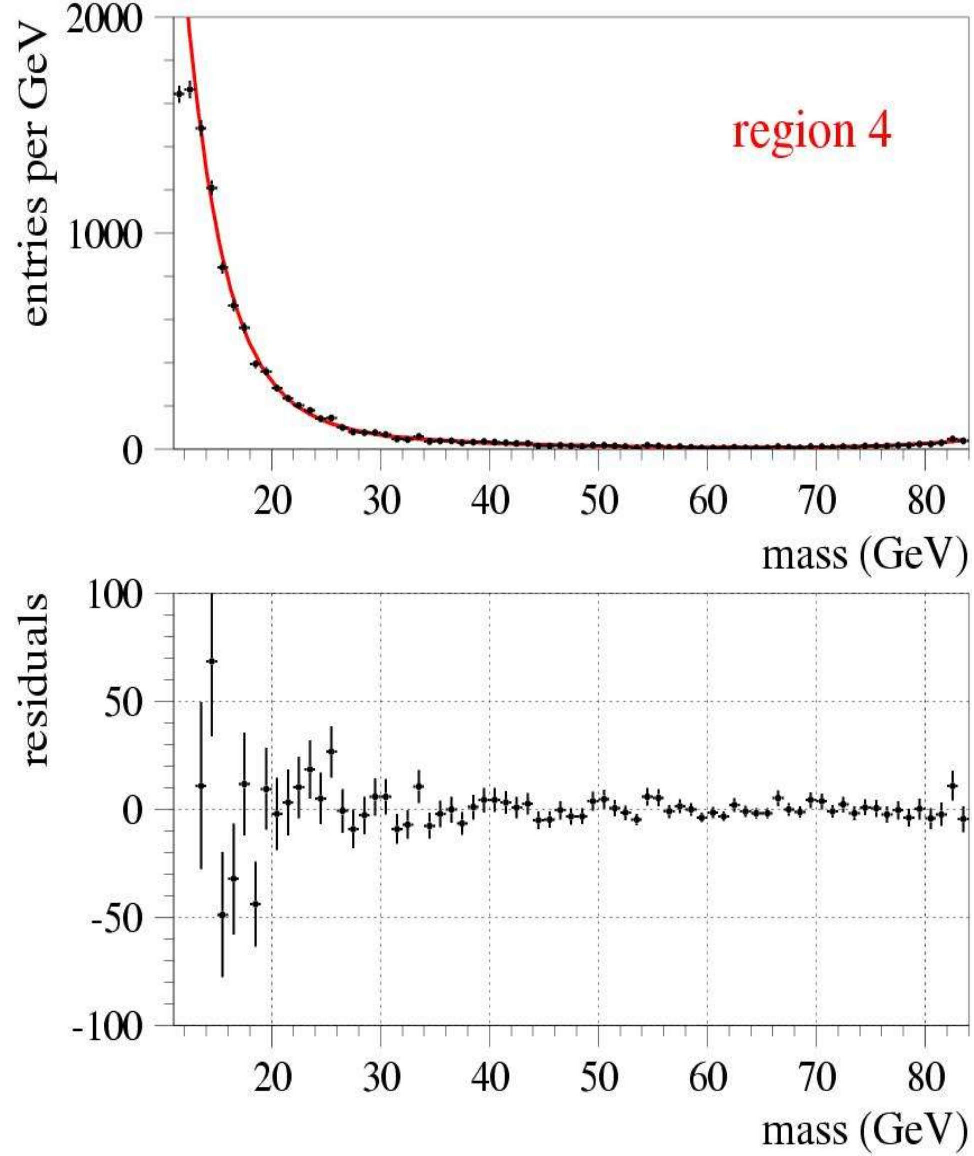
parabola



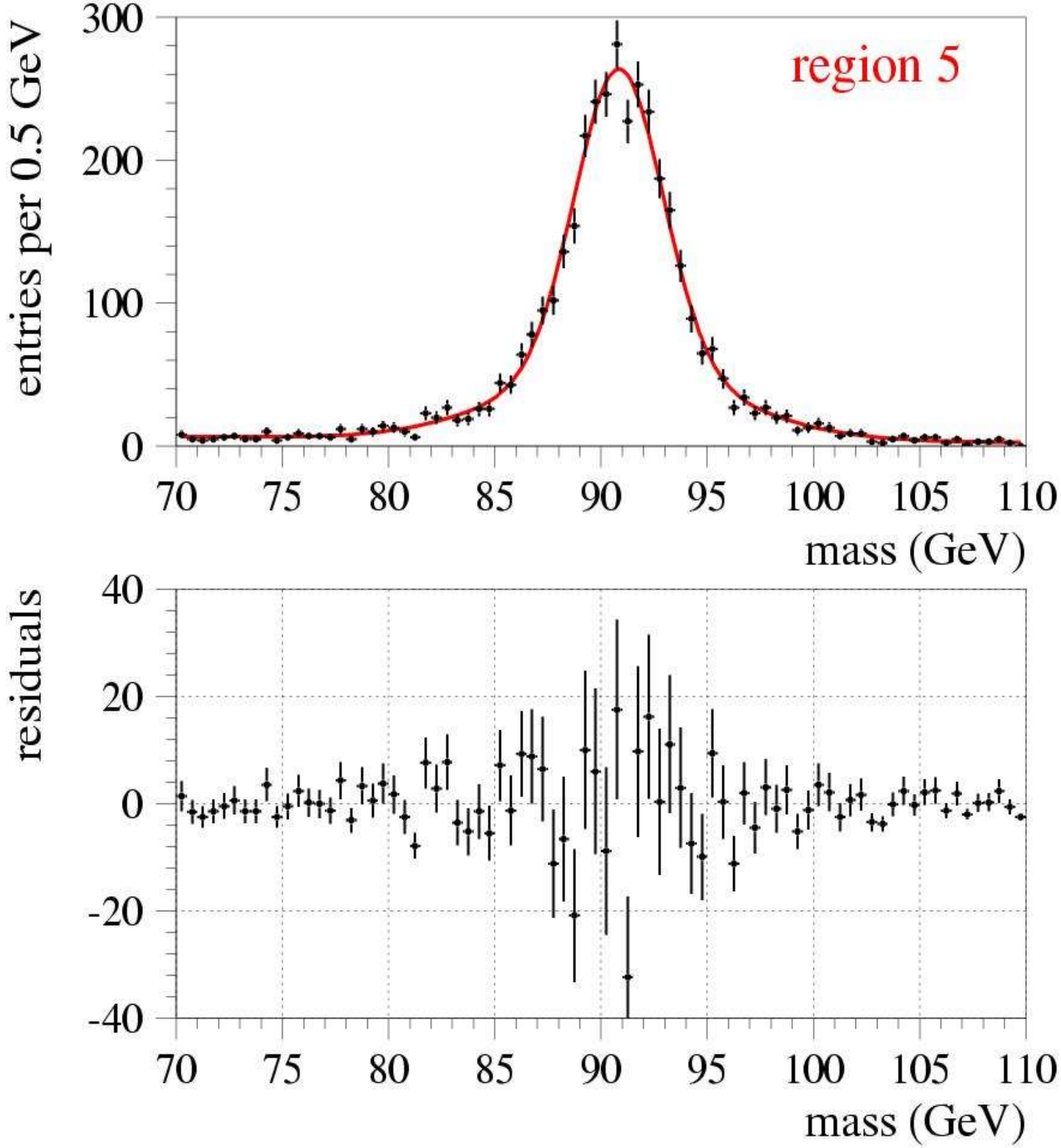
3 Gaussians plus parabola



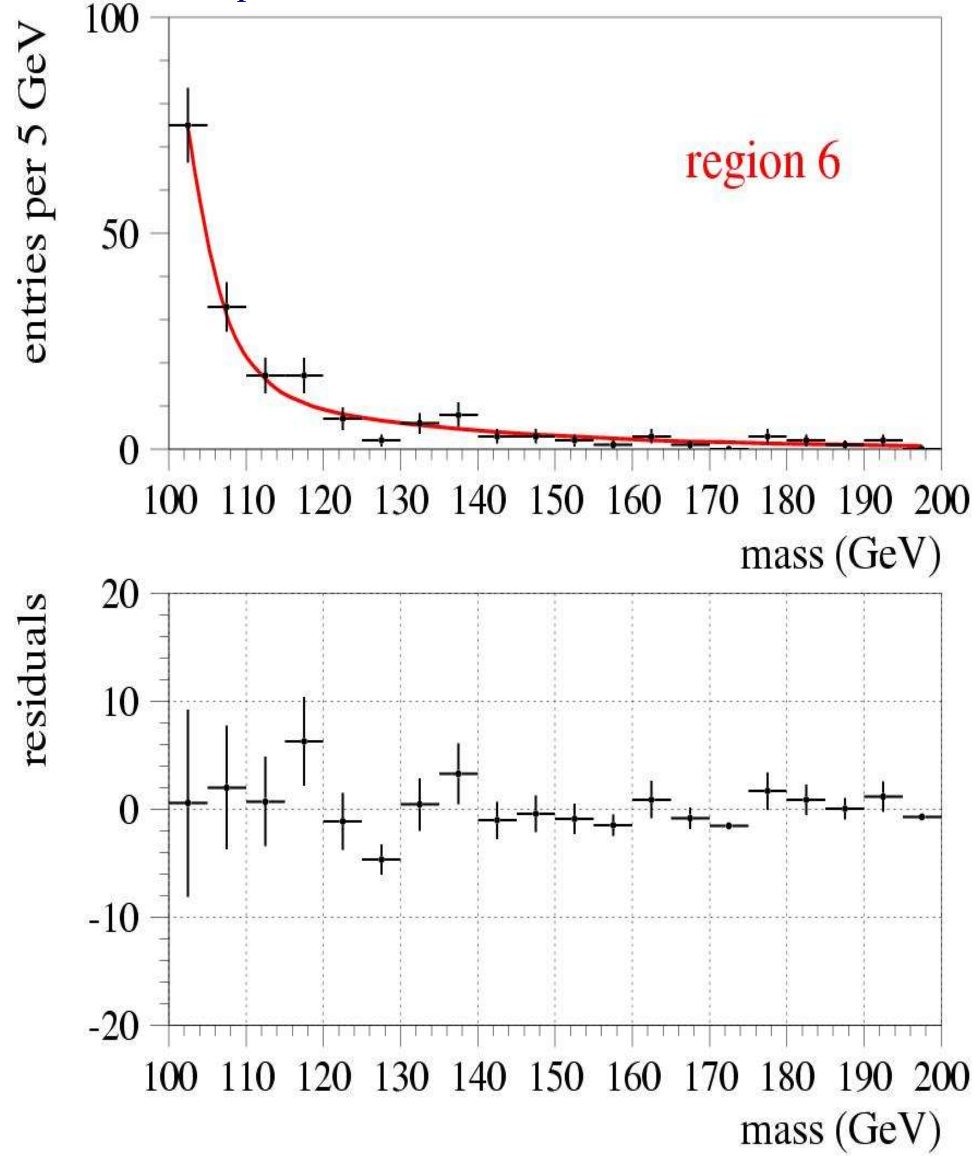
3 exponentials



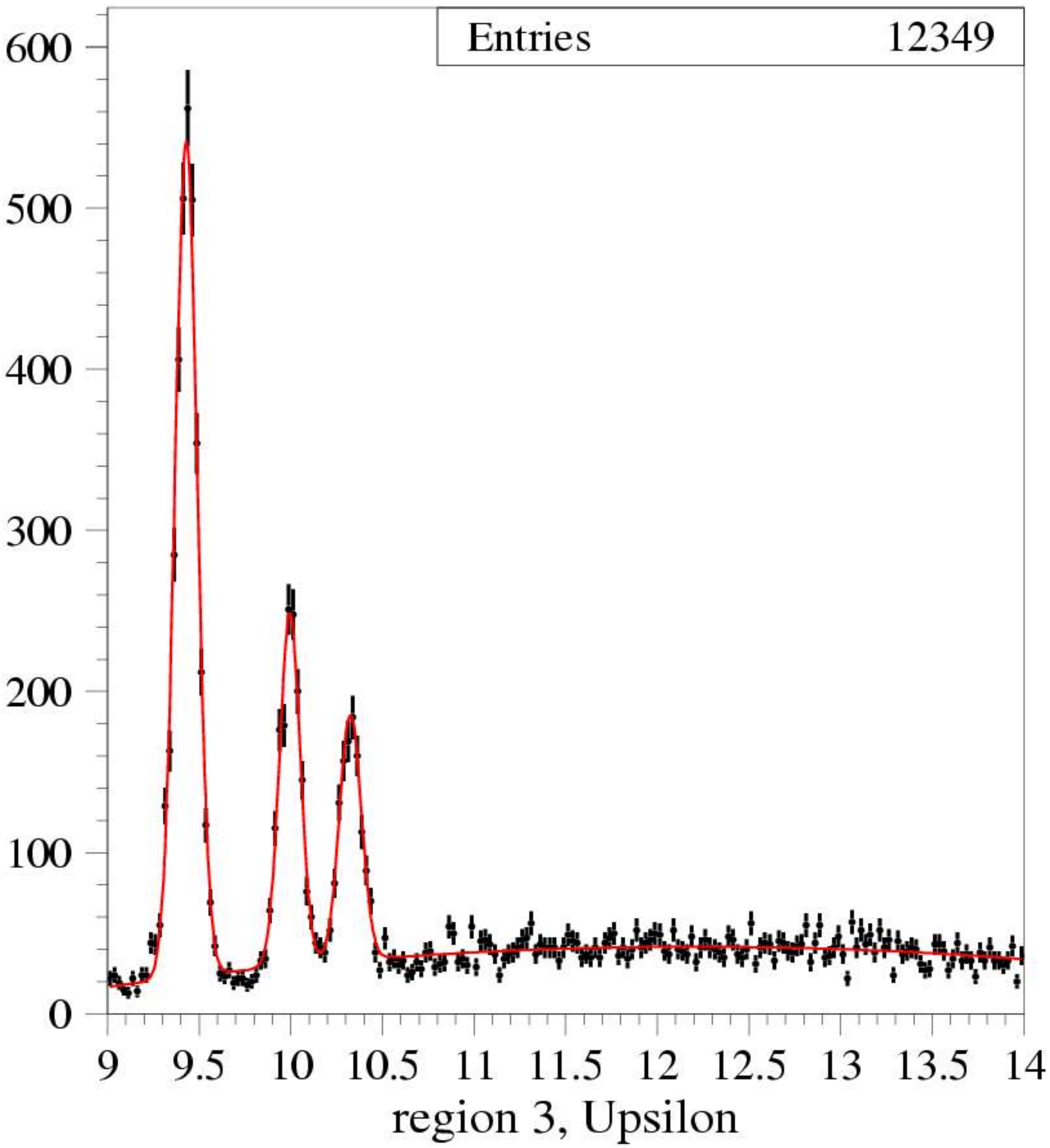
2 Gaussians plus linear term



2 exponentials



3 Gaussians plus parabola



Number of events in this region: 12349
Number of Y(1S): 3134, acc: fit.
Check yield by counting and simple sideband subtraction: 3165 ± 61.
"purity" is 0.091

Count events in 3σ window around 7.25 GeV: 82
predicted: 90
Simple upper limit:
(82-90) + 1.96×√(90) = 10.6
Feldman-Cousins gives 12.

acceptance at 9.34 GeV: 0.0060
acceptance at 7.25 GeV: 0.0015

$$\frac{\sigma \times Br(\epsilon \rightarrow \mu\mu)}{\sigma \times Br(\Upsilon \rightarrow \mu\mu)} = \frac{12}{3134} \times \frac{0.0060}{0.0015} = 0.015$$

If you inflate this by 20% for mass resolution: 0.018.