Apparent Excess in $e^+e^- \to$ hadrons

hep-ex/0401034

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9 - February - 2004

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1.Motivation

We are talking about the cross section for the **inclusive** process

$$\boxed{e^+e^- \longrightarrow \text{hadrons.}}$$

This has been measured many times over the decades – *PEP*, *PETRA*, *TRISTAN*, *LEP*, etc. The selection is very loose in order to avoid systematic uncertainties from the acceptance.

It is known that both the LEP 2 and the LEP 1 measurements fall above the SM prediction – but the significance is not high.

Why not check the lower energy data to see what they say?

2. The Data

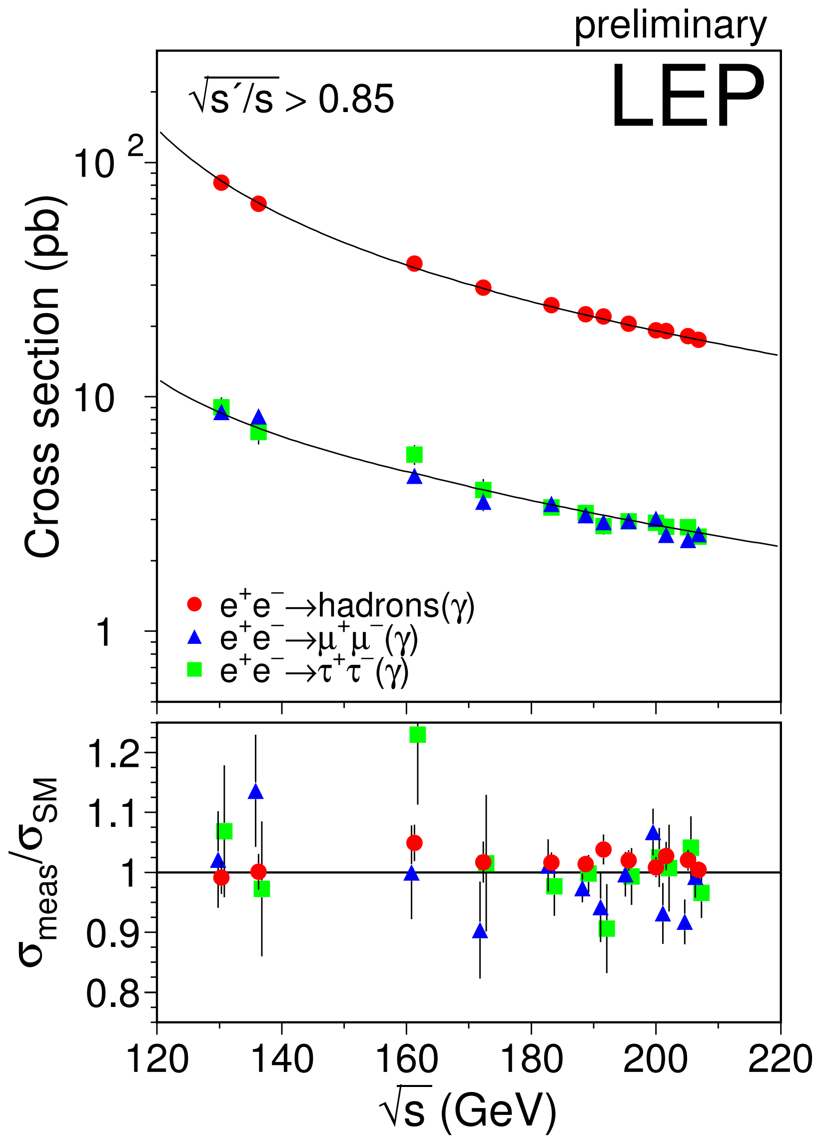
Starting from the top down,
we have first the LEP 2 Data:

$$130 \text{ GeV} < \sqrt{s} < 209 \text{ GeV},$$

where $\sqrt{s}$ is the center-of-mass energy,
$\sqrt{s} = E_{\rm cm} = 2 \times E_{\rm beam}$.

LEP 2 ran at twelve center-of-mass energies over several years.

These plots are from the LEPEWWG.

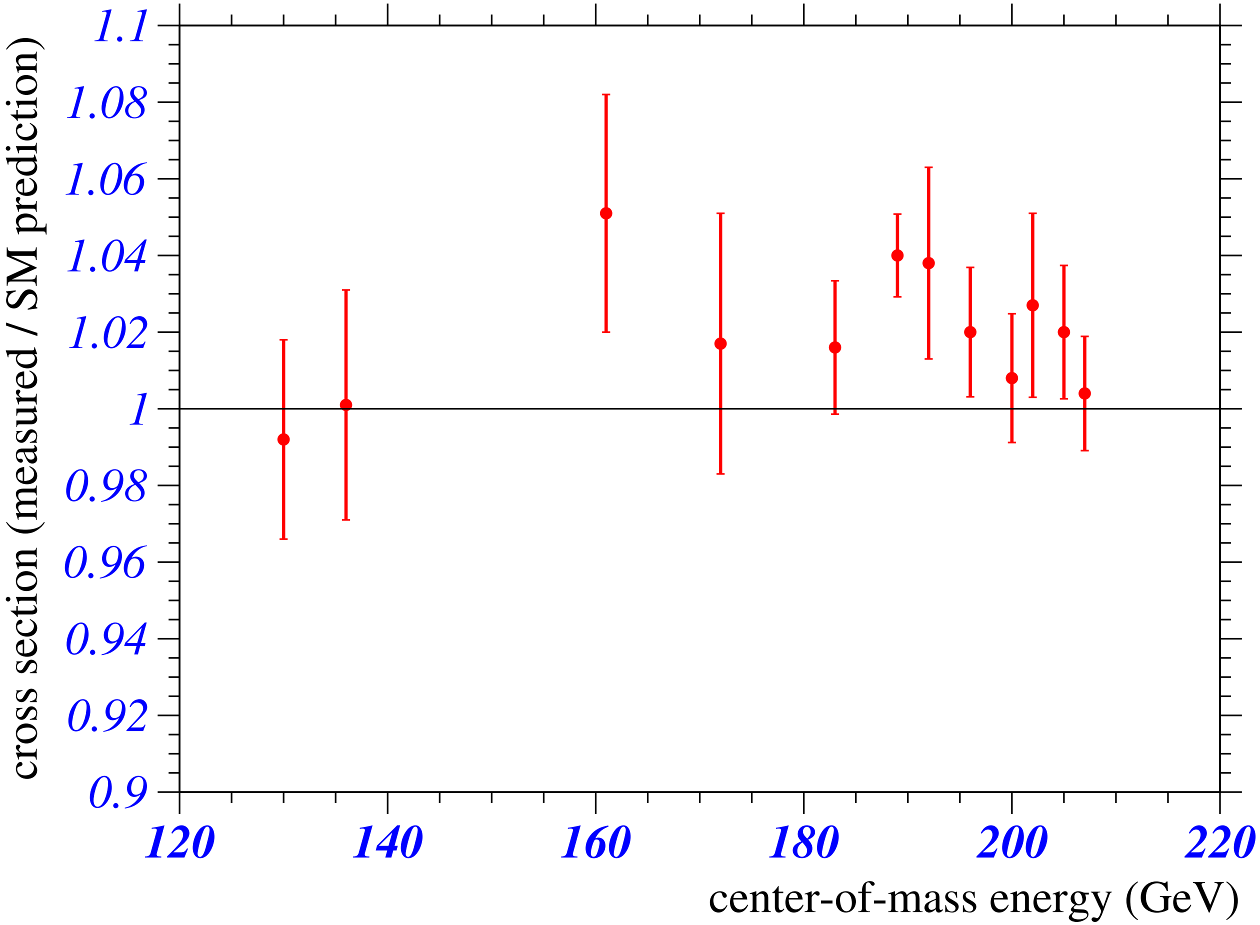


Here are the measurements and the SM predictions:

energy	combined measurement	SM prediction	difference	deviation
91.187	41540 ± 37	41478	62	1.68
130	82.1 ± 2.2	82.8	-0.7	-0.32
136	66.7 ± 2.0	66.6	0.1	0.05
161	37.0 ± 1.1	35.2	1.8	1.64
172	29.23 ± 0.99	28.74	0.49	0.49
183	24.59 ± 0.42	24.20	0.39	0.92
189	22.47 ± 0.24	22.16	0.31	1.29
192	22.05 ± 0.53	21.24	0.81	1.53
196	20.53 ± 0.34	20.13	0.40	1.18
200	19.25 ± 0.32	19.09	0.16	0.50
202	19.07 ± 0.44	18.57	0.50	1.13
205	18.17 ± 0.31	17.81	0.36	1.16
207	17.49 ± 0.26	17.42	0.07	0.27

Notice that nearly all points show a positive difference.

We can replot these data as the ratio: *(Measured/Predicted)*



It is clearly interesting to quantify the overall “excess.”

One very simple way to compare the data to the prediction in an overall sense is to compute the **mean deviation** as follows:

- Let the measurements be y_i with uncertainties η_i.
  (We will take the measurements to be fullly independent, which means that the uncertainties are uncorrelated, for now. We return to correlations shortly...)
- Let the theoretical prediction be y^{SM}, which is understood to be a function of $\sqrt{s}$.
- Then the mean deviation is simply

$$\bar{\Delta} \equiv \sum_{i=1}^{N} \left(\frac{y_i - y^{\mathrm{SM}}}{\eta_i^2} \right) \Big/ \sum_{i=1}^{N} \left(\frac{1}{\eta_i^2} \right) \qquad \text{and} \qquad \sigma_{\bar{\Delta}} \equiv \left[\sum_{i=1}^{N} \left(\frac{1}{\eta_i^2} \right) \right]^{-1/2} . \quad (1)$$

- The traditional "goodness" measure is χ^2 as follows:

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{y_i - y^{\mathrm{SM}}}{\eta_i} \right)^2 \quad (2)$$

- For the LEP 2 data we have $\chi^2 = 12.2$, $\bar{\Delta} = 0.32$ pb and $\bar{\Delta}/\sigma_{\bar{\Delta}} = 2.8$ which means there is a 2.8 s.d. excess in this set alone!?!
  And, what about $\chi^2 = 12.2$ for 12 d.o.f.?

So why hasn't there been a lot of attention payed for this?

$\longrightarrow$ This treatment is too naive – correlations DO matter.

The correct expression for the χ^2 is the contraction of the inverse covariance matrix:

$$\chi^2 = \sum_{i,j=1}^{N} (y_i - y^{\mathrm{SM}})\,(\mathbf{C}^{-1})_{ij}\,(y_j - y^{\mathrm{SM}}) \qquad \mathbf{C} \equiv \begin{pmatrix} \sigma_1^2 & \rho_{12}\sigma_1\sigma_2 & \rho_{13}\sigma_1\sigma_3 \\ \rho_{12}\sigma_1\sigma_2 & \sigma_2^2 & \rho_{23}\sigma_2\sigma_3 \\ \rho_{13}\sigma_1\sigma_3 & \rho_{23}\sigma_2\sigma_3 & \sigma_3^2 \end{pmatrix}$$

- The LEPEWWG provide the complete correlation matrix as well as the errors (as listed in the table above) so it is straight forward to re-compute the χ^2.
- In general, $\rho_{ij} = 0.05$–0.2, so the correlations are not large.
- The upshot is that the signficance is 1.8σ instead of 2.8σ (which is also what the LEPEWWG report).

$\longrightarrow$ *One should look at other data sets…*

More Data

$\sigma(e^+e^- \to \text{ hadrons})$

was also measured at LEP 1.

There are many measurements around the Z peak, spanning $88 < \sqrt{s} < 92$ GeV.

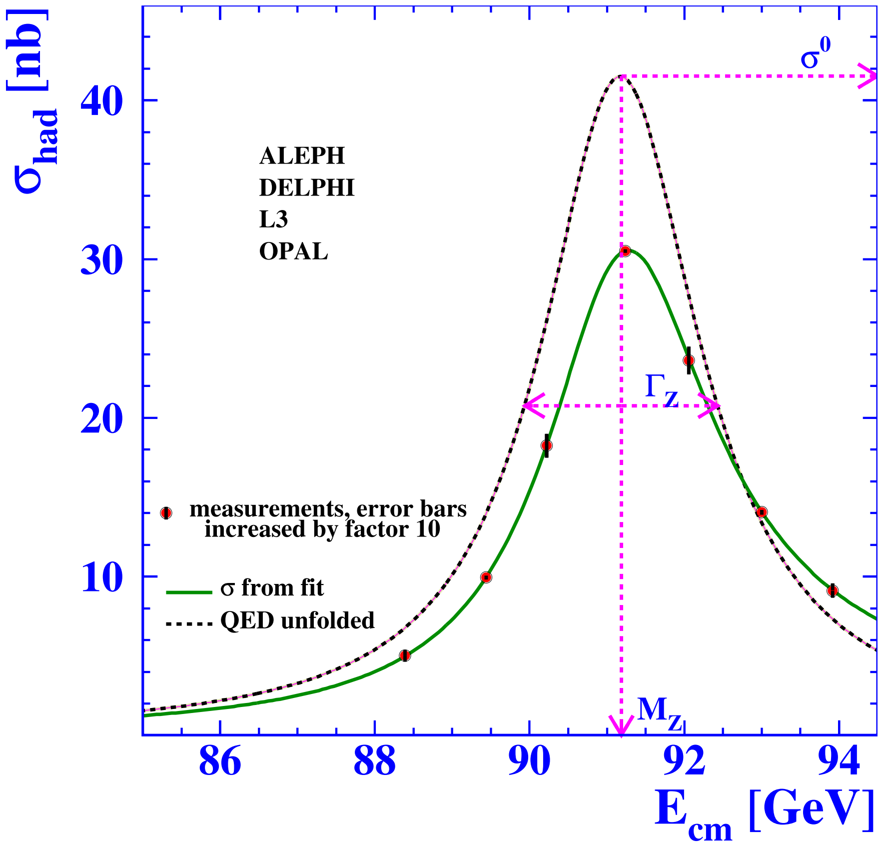
These have been combined into one number:

$$\sigma^0_{\text{had}} = 41540 \pm 37 \text{ pb}$$

to be compared to

41478 pb in the SM.

From the LEPEWWG:



$\Delta = 62 \pm 37$ pb equiv. $1.7\sigma \implies$ also a small excess. . .

Any More Data?

Yes!

There are hundreds of cross section measurements made before the advent of LEP.

Do they show any excess?

Utilize a recent compilation by Zenin, *et al.*. (QED corrections already applied.)

Set a somewhat arbitrary cutoff $\sqrt{s} > 20$ GeV to avoid measurements with larger errors and problems with the theoretical prediction.

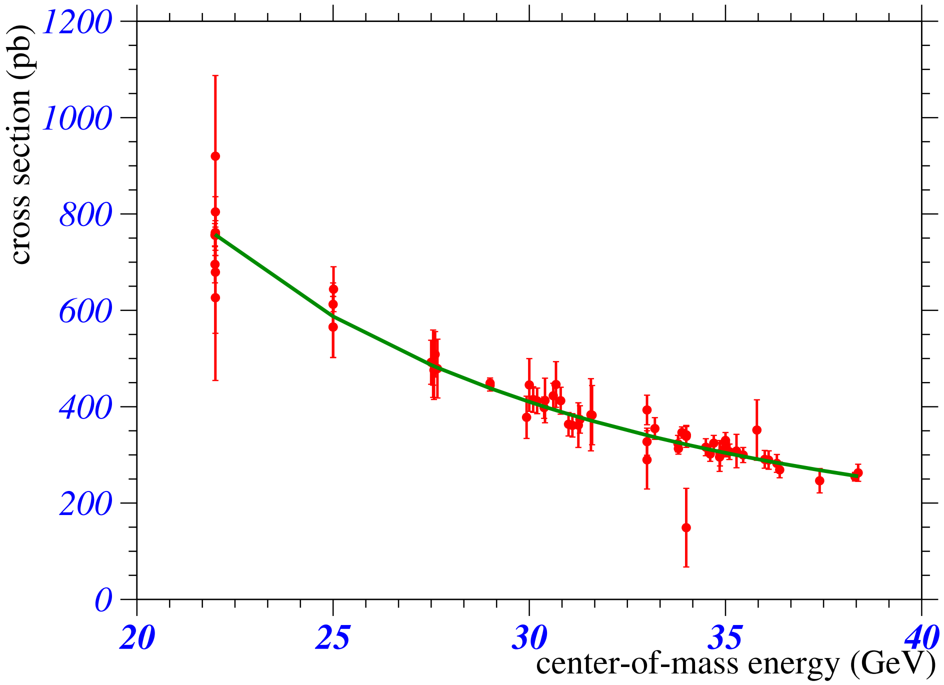
$$\begin{array}{rr} 1 & 20 < \sqrt{s} < 40 \text{ GeV} \\ 2 & 40 < \sqrt{s} < 70 \text{ GeV} \\ 3 & 88 < \sqrt{s} < 93 \text{ GeV} \\ 4 & 130 < \sqrt{s} < 210 \text{ GeV} \end{array}$$

The first region is dominated by photon exchange, the second feels the influence of Z exchange, the third is dominated by the Z peak, and the fourth has roughly equal contributions from both γ^* and Z^*.

There are many measurements, experiments and calculations.

If there is an excess everywhere...

Region 1

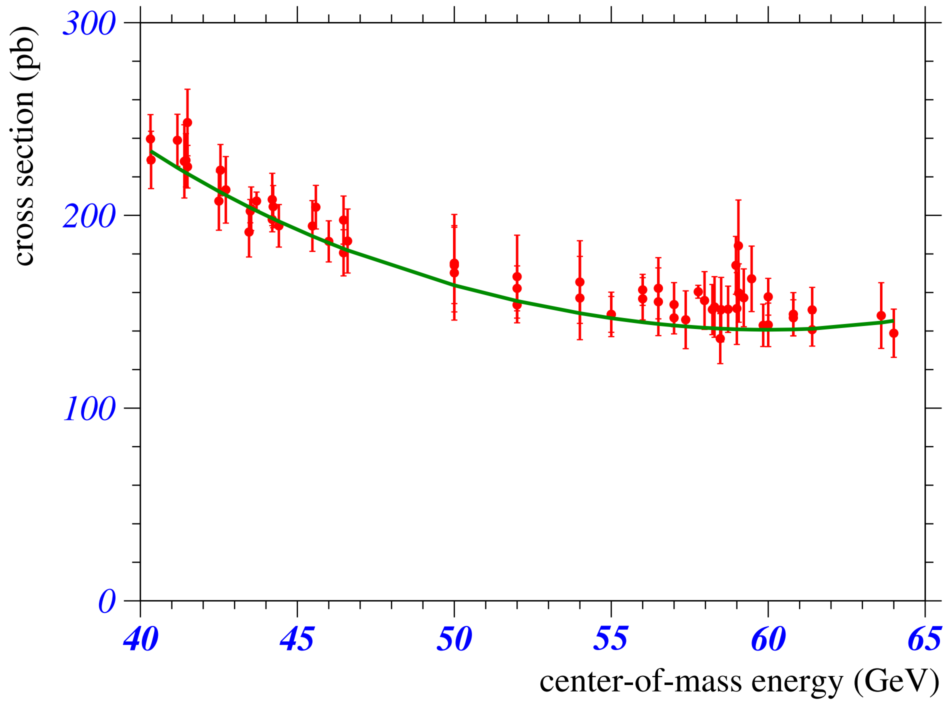


67 data points $\chi^2 = 50$

$\bar{\Delta} = 6.7$ pb, $\sigma_{\bar{\Delta}} = 2.5$ pb

$\Longrightarrow$ 2.9 s.d.

Region 2



63 data points $\chi^2 = 55$

$\bar{\Delta} = 7.9$ pb, $\sigma_{\bar{\Delta}} = 1.4$ pb

$\Longrightarrow$ 2.8 s.d.

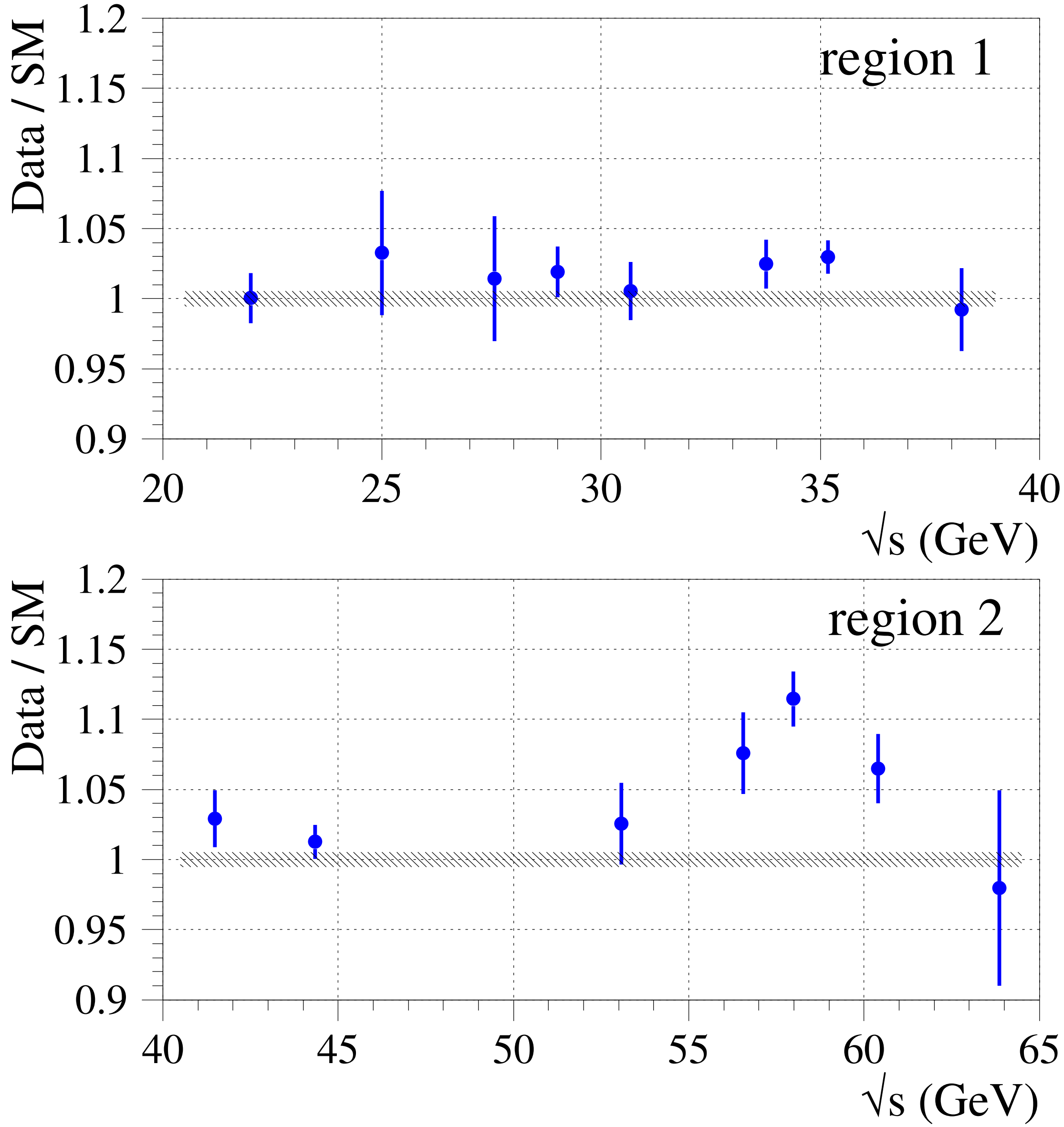
But it is hard to see the excess...

rebin

Combine data in ~ 1 GeV bins as a visual aid.

Plot the ratio

(Measured/Predicted):



3. Method

If we accept the statement that there is an overall excess everywhere, how to we combine the results from the four regions?

Use a likelihood method.

Instead of χ^2, which did not tell us anything, use:

$$\mathcal{P} \equiv \prod_{I=1}^{N} \frac{1}{\sqrt{2\pi}\,\eta_i} \exp\left(-\frac{1}{2\eta_i^2} (y_i - (y^{\rm SM} + \alpha y^{\rm NP}))^2 \right). \tag{3}$$

(In fact it is more convenient to work with $\mathcal{F} \equiv -\ln \mathcal{P}$.)

The term $\alpha\, y^{\rm NP}$ represents a contribution from new physics:

$$y^{\rm NP}(s) \equiv (10 \text{ pb}) \times \frac{(30 \text{ GeV})^2}{s} \tag{4}$$

Compare $\mathcal{F}_{\rm min}$ to $\mathcal{F}$ for the SM alone ($\alpha = 0$). Improvement when a nonzero "new physics" contribution is included? This improvement can be described by

$$\text{SD} = \sqrt{2\left[\mathcal{F}(0) - \mathcal{F}(\alpha_{\rm best})\right]} \tag{5}$$

The results are:

region	α_{best}	$\mathcal{F}(\alpha_{\text{best}})$	$\mathcal{F}(0)$	S.D.
1	0.74	21.89	25.23	2.58
2	1.80	25.52	37.50	4.90
3	57.3	0	1.404	1.68
4	1.37	2.00	6.12	2.87
net	1.183	53.446	70.255	5.80

- Notice that S.D. is the same as $\bar{\Delta}/\sigma_{\bar{\Delta}}$ from before.
- Regions 1, 2 and 4 suggest $\alpha \sim 1$ but region 3 is much higher.
- The *net* significance is nearly 6σ!
- NB: correlations & theoretical uncertainties not taken into account.

4. The Standard Model Prediction

This is an elementary calculation, at the Born level.

Improved Born approximation employes running coupling constants and masses, and a QCD correction for the final state.

In the 1990's it was crucial to make these SM calculations as accurate as humanly possible. One of the leading efforts is ZFITTER which has been cross checked with other high quality codes.

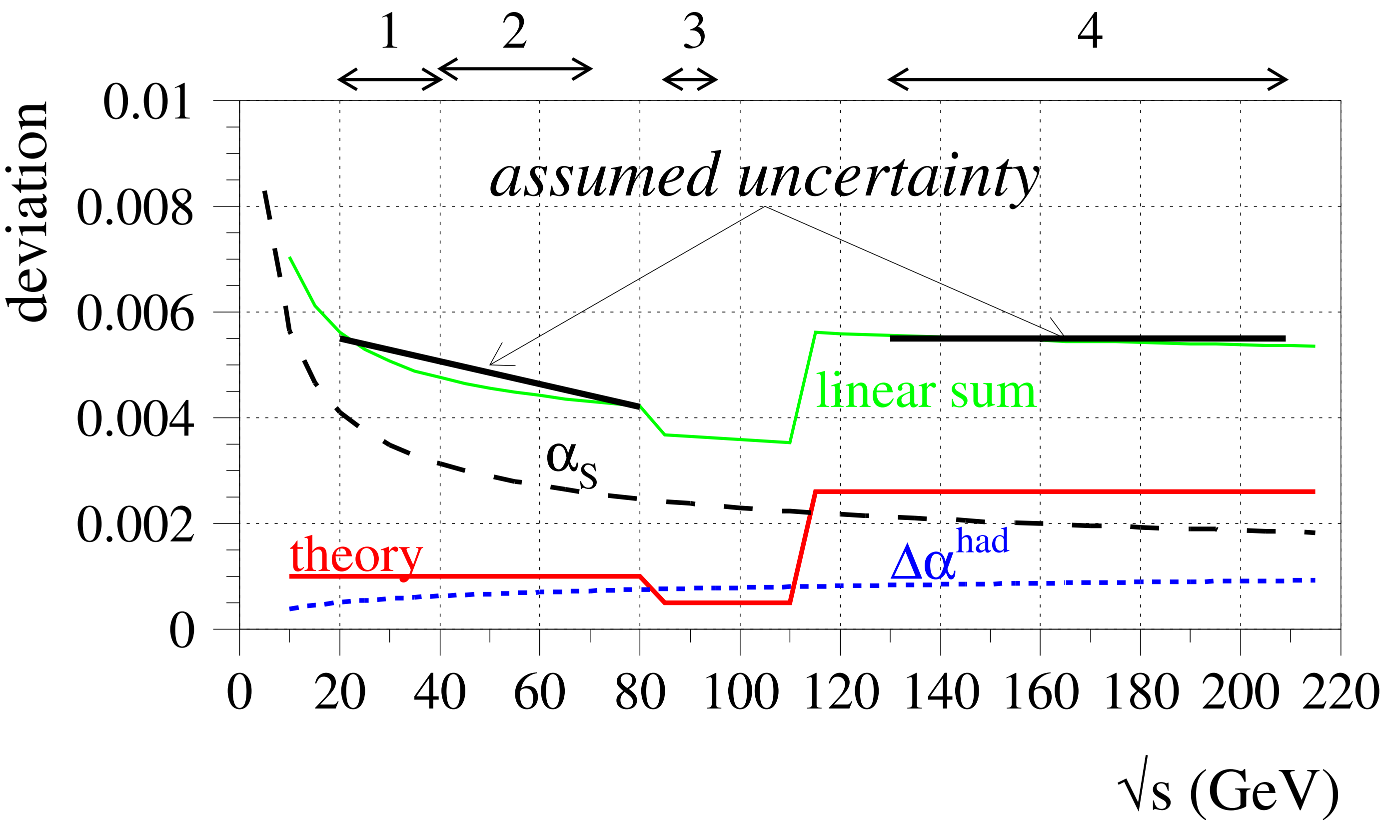
The LEPEWWG uses ZFITTER by default, and I use their numbers for regions 3 & 4.

For regions 1 & 2, I run ZFITTER myself. I also wrote my own code to compute $\sigma(e^+e^- \to \text{ hadrons})$ from scratch as a tool for understanding theoretical uncertainties.

Theoretical Uncertainties

- The numerical accuracy of ZFITTER is estimated to be 0.2% or better.
- The uncertainty from $\alpha_{\mathrm{QED}}(s)$ is estimated using the conservative uncertianty assigned by Jegerlehner on $\Delta\alpha^{(\mathrm{had})}$.
- Take $\delta(\sigma)/\sigma \sim 2\,\delta(\alpha_{\mathrm{QED}})/\alpha_{\mathrm{QED}}$.
  This covers uncertainties in running $\sin^2\theta_W$.
- For running α_S, *double the usual uncertainty*, which should cover how α_S might change in presence of new physics. This dominates.
- Uncertainty from HO QCD corrections is negligible.
- Uncertainties from input parameters are negligible.

Take the *linear sum* of these already conservative uncertainties.



The heavy lines represent what we used in the calculation.

They are <u>not</u> negligible.

Incorporate this in the likelihood function.

One could argue that these are over-estimated by a factor of about 2.

Modify the likelihood function – include multiplier ρ for y^{SM}:

$$\mathcal{P} \equiv \left[\prod_{I=1}^{N} \exp\left(-\frac{1}{2\eta_i^2}(y_i - (\rho y^{\mathrm{SM}} + \alpha y^{\mathrm{NP}}))^2\right)\right] \times \exp\left(-\frac{1}{2\eta_\rho^2}(\rho - 1)^2\right) \tag{6}$$

$\mathcal{F}$ is now a function of α <u>and</u> ρ.

The optimal $\mathcal{F}$ will not change.

But when $\alpha = 0$ (which represents the case of the SM with no new NP), ρ imparts a degree of freedom which will allow $\mathcal{F}$ to decrease, so $\Delta\mathcal{F} = \mathcal{F}(\alpha = 0) - \mathcal{F}_{\mathrm{min}}$ will diminish.

Result: 6σ becomes 4σ.

We also need to take into account error correlations...

For region 4 (LEP 2) this was already discussed.

For regions 1 & 2, it is much trickier.

- the data appear in 21 publications
- assume correlations hold for the data from a given publication
- correlations should not be very large, because:
  - stat errors usually are large
  - detector issues dominate the syst error
  - different groups use different methods
- take one-half the systematic uncertainty to be correlated
- impact on $\Delta\mathcal{F}$ is small.

Result: net significance becomes 3.9σ.

Conclusion: the apparent excess survives the more careful treatment.

5. Results

The simple $1/s$ ansatz is special because it assumes the Z plays no role.

From the combined α value, we can infer that "new physics" is contributing

$$y^{\mathrm{SM}}(s) = (11.8 \pm 2.0 \text{ pb}) \times \frac{(30 \text{ GeV})^2}{s}$$

(This is 3% of the total hadronic cross section.)

At $\sqrt{s} = 30$ GeV, a muon has cross section of 110 pb, a charge -1/3 quark has 40 pb.

$\longrightarrow$There must be a suppression by about a factor of 4.

One possibility is spin – a scalar quark has a cross section typically four times smaller than a quark, well above threshold.

There already are arguments why a light scalar bottom quark might exist, put forward by the Argonne theory group.

Light Scalar Bottom Model

- mass range: 2 – 6 GeV
- decay: promptly via R-parity violation

$$\tilde{b}_1 \longrightarrow \bar{u}\bar{s}$$

  The anti-quarks hadronize and the event is hadronic.

- charge is -1/3 so coupling to the photon is fixed
- there are "right" and "left" interaction eigenstates which mix to form the mass eigenstates.
  The mixing parameter, $\cos\theta_{\tilde{b}_1}$, is not known – a free parameter.
  It is possible to have zero coupling to the Z.
  We will use the data to constrain the mixing $\cos\theta_{\tilde{b}_1}$.

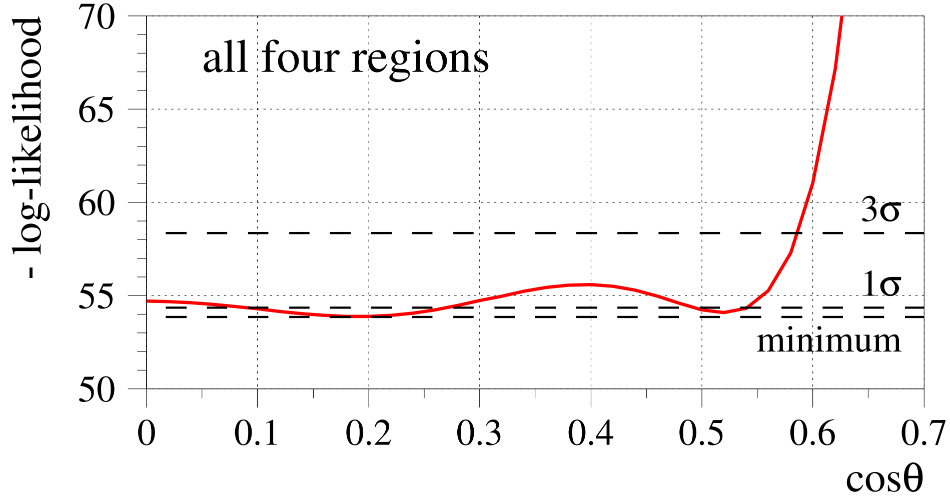
The negative log-likelihood function is now a function of two parameters related to the "new physics" part:

1. α turns y^{NP} on and off
2. $\cos\theta_{\tilde{b}_1}$ controls the contribution of the Z

First fix $\alpha = 1$ and vary $\cos\theta_{\tilde{b}_1}$.

Regions 1 & 2 have little impact.

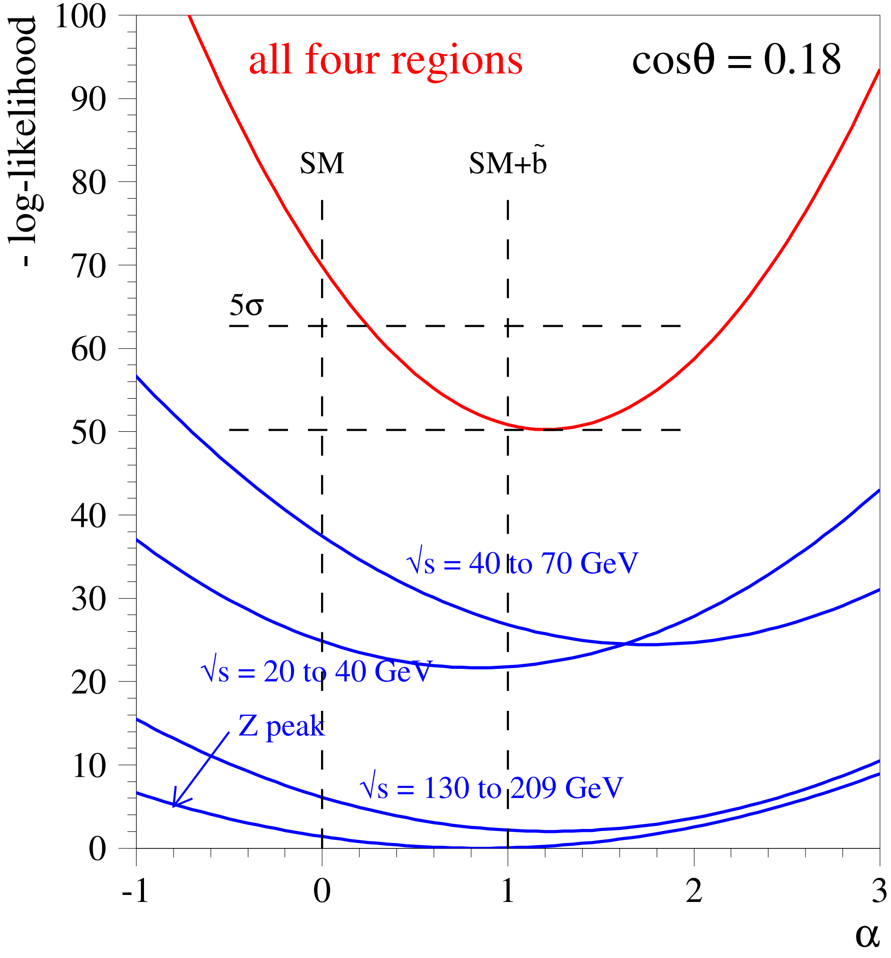
Regions 3 & 4 give similar results which disallow $\cos\theta_{\tilde{b}_1} > 0.6$.



The data favor $\cos\theta_{\tilde{b}_1} = 0.18$, so we take that as fixed.

Vary α one region at a time – blue lines.
Vary α for all regions together – red.

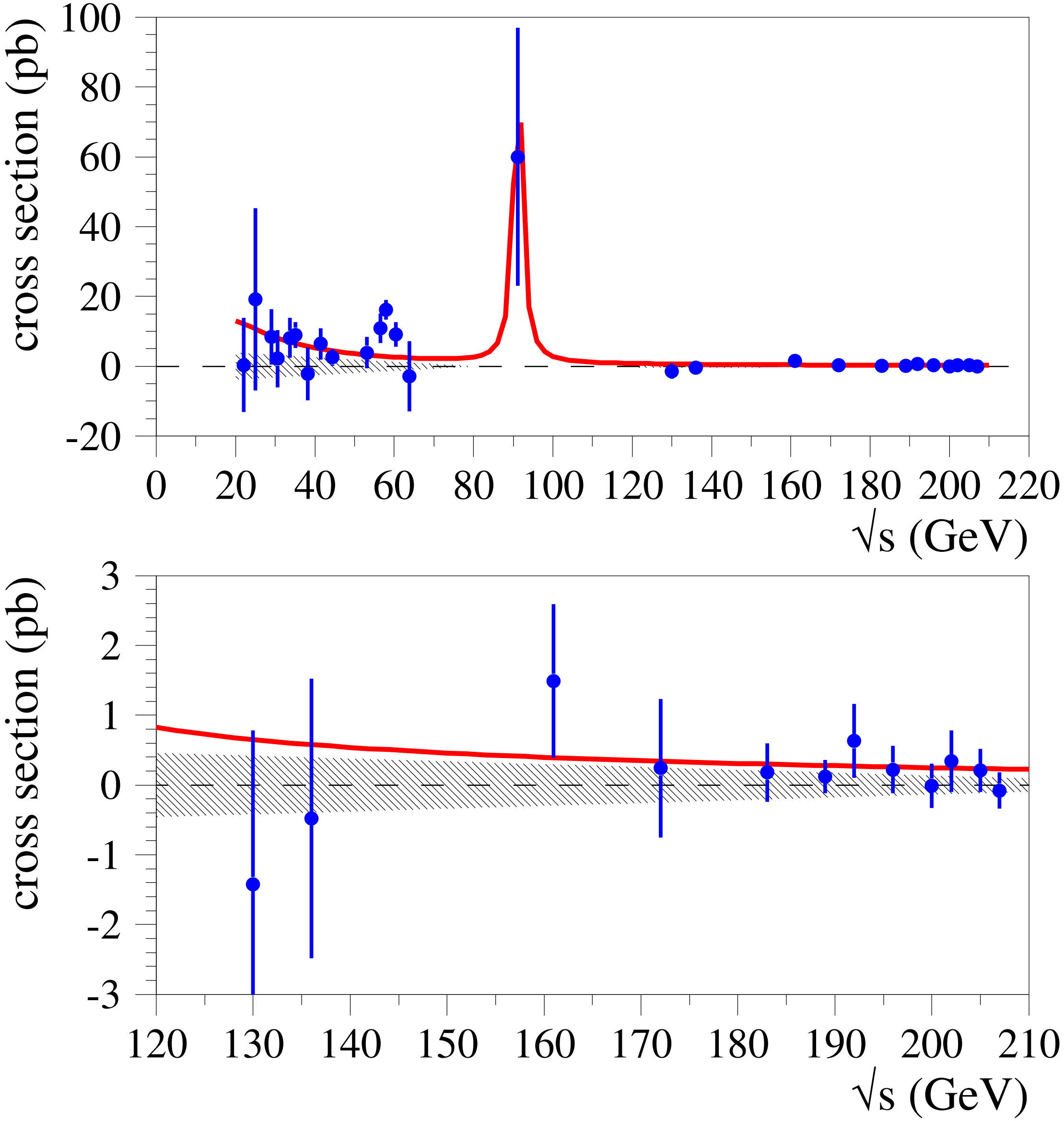
1. All four regions contribute to α_{best}.
2. α_{best} is consistent with the best α in each region.
3. α_{best} is consistent with 1.



After taking theoretical uncertianties and correlations into account,

the statistical significance is 4.3σ.

Here is a depiction of the sum SM + light $\tilde{b}_1$ compared to data:



Another Ansatz: high mass Z'

There would be no new final states, only new exchange matrix elements.

If we ignore interference terms, then $y^{\mathrm{NP}} \propto s$.

(It is probably not a good idea to ignore interference terms –
this needs to be revisited. . .)

Upshot: a linear rise in s is not supported by the data.
Regions 1 & 2 are contradicted by region 4.

6. Conclusions & Directions for Future Research

1. There is an apparent excess in $e^+e^- \to$ hadrons with a signficance of more than 4.3σ, conservatively estimated.

2. The "excess" fits well the expectation for a light $\tilde{b}_1$, coincidentally.

3. This is <u>not</u> proof that light sbottoms exist!

4. A heavy Z' does not fit the data when interference is ignored.

5. To do:
   (a) improve the Z' analysis
   (b) consider the "bump" at $\sqrt{s} \approx 57$ GeV
   (c) perform a full fit to the LEP 1 data
   (d) check impact of correlated systematics from below the Z in more detail