Upsilon Production in hadronic Z decays

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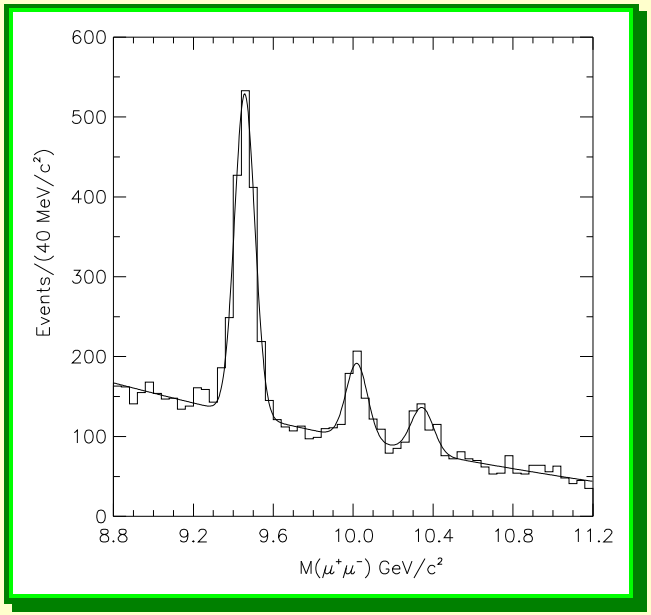
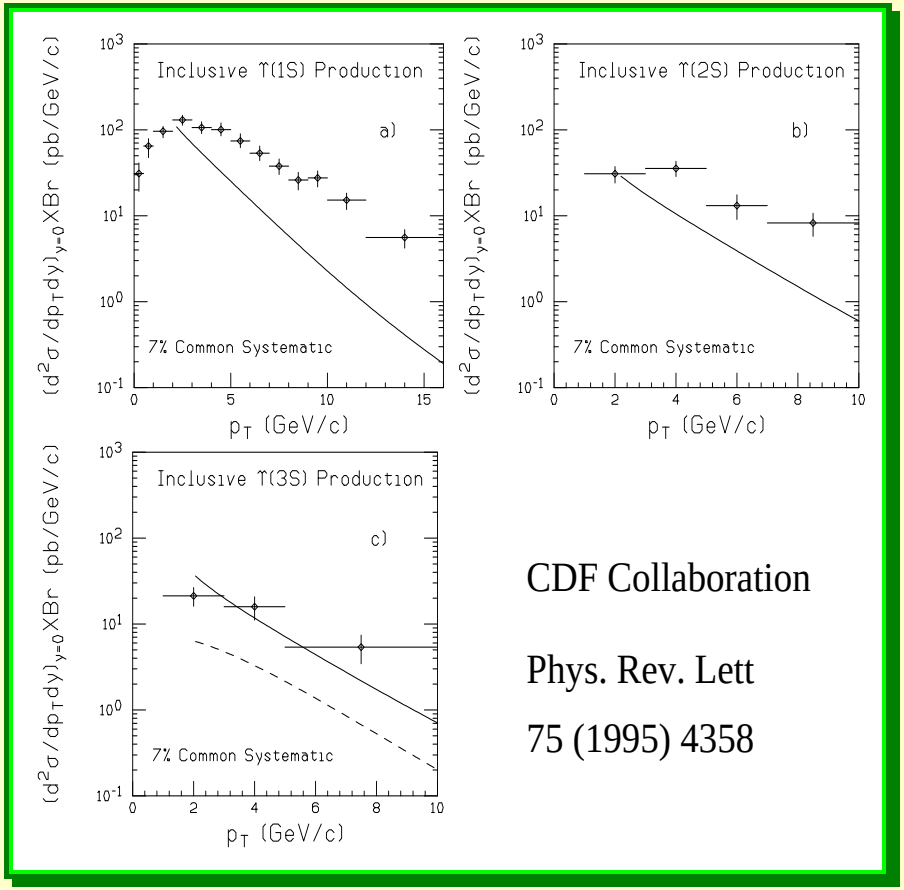
HADRON'97
24–30 August 1997
Brookhaven, USA

- Motivation
- Υ production at LEP
- L3 Υ analysis
- Results and conclusions

Motivation: The CDF Υ anomaly



Measured rates much higher than predictions for *colour-singlet* processes



CDF Collaboration

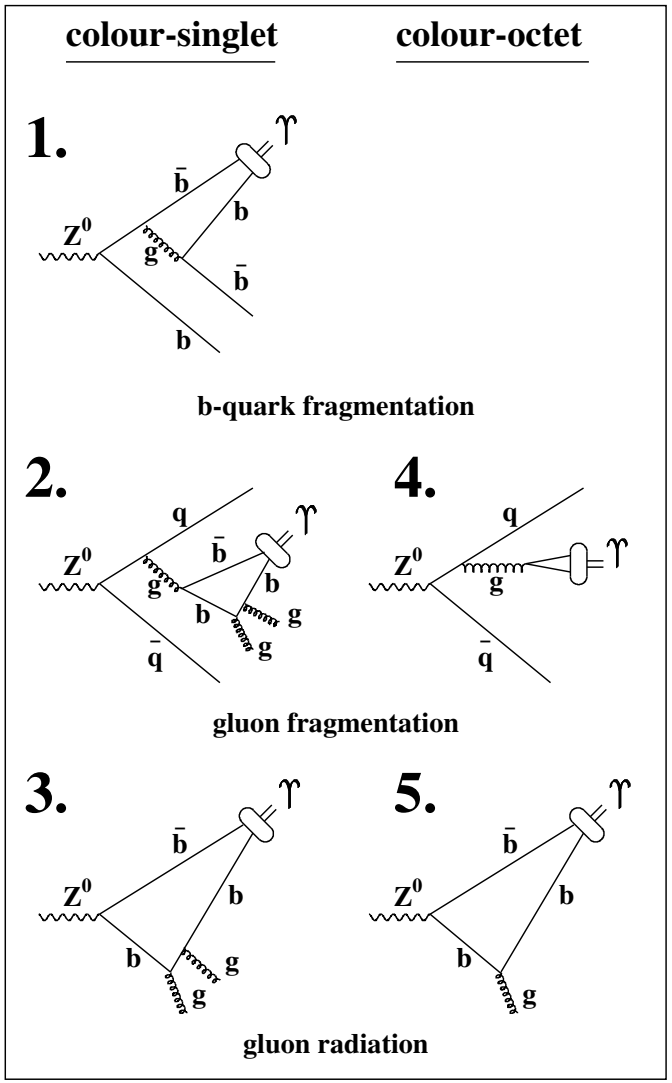
Phys. Rev. Lett

75 (1995) 4358

Discrepancies were resolved by including *colour-octet* processes

(∼100 theory papers in 2 years)

Υ production at LEP (theoretical)



Production model	$\mathbf{Br(Z \to \Upsilon X)}$ $(\times 10^{-5})$
1. $Z \to \Upsilon b\bar{b}$	1.6
2. $Z \to \Upsilon q\bar{q}gg$	0.07
3. $Z \to \Upsilon gg$	0.05
4. $Z \to \Upsilon q\bar{q}$	4.1
5. $Z \to \Upsilon g$	0.1

Dominated by colour octet process (4.)

($\approx 75\%$ of total rate)

Υ production at LEP (experimental)

ALEPH (ICHEP 96, Warsaw)

$$\mathbf{Br(Z \to \Upsilon X) < 7.3x10^{-5}}$$

("colour octet" process considered)

DELPHI (Z.Phys. C69 (1996) 575.)

$$\mathbf{Br(Z \to \Upsilon X) < 20x10^{-5}}$$

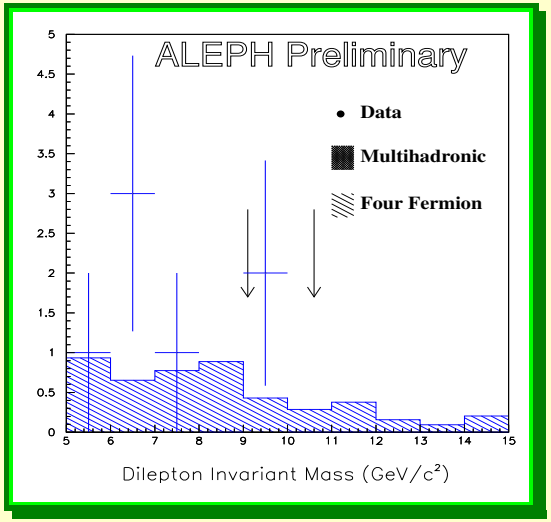
(for process **3.**)

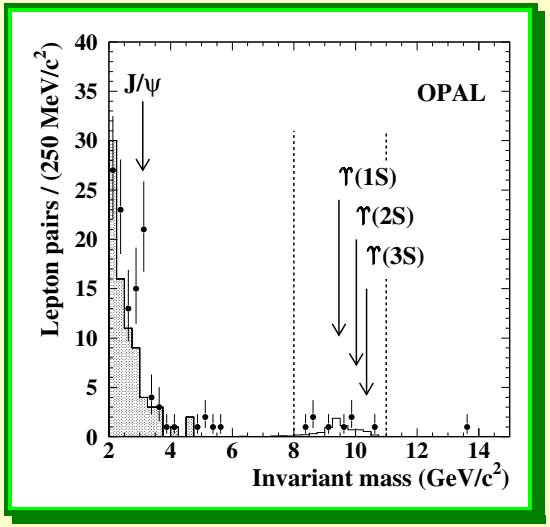
OPAL (Phys. Lett. B370 (1996) 185.)

$$\mathbf{Br(Z \to \Upsilon X) = (10 \pm 4 \pm 1) \times 10^{-5}}$$

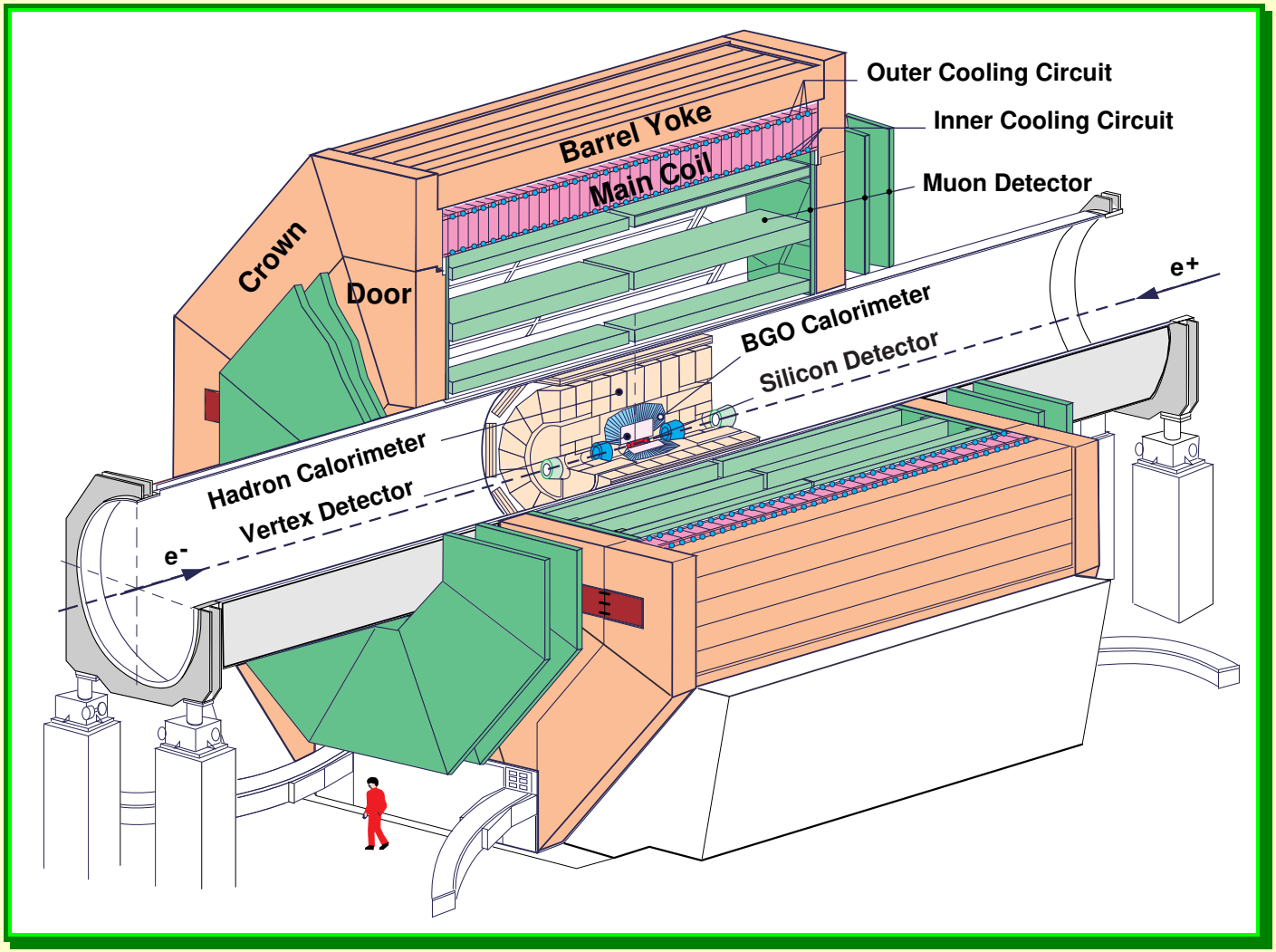
(weighted average of processes **1.–5.**)

No attempts are made to separate
$\mathbf{\Upsilon(1S)}$, $\mathbf{\Upsilon(2S)}$, and $\mathbf{\Upsilon(3S)}$



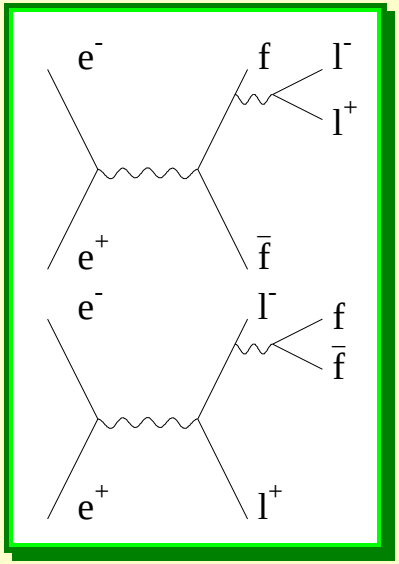


The L3 Detector at LEP



L3 Υ Analysis

- **Data** events (91–95) 3,453,780
- **MC** events:
  - $Z \to q\bar{q}$ 6,967,957
  - Υ production processes: 5,000/model
    $Z \to \Upsilon X \to \ell^+\ell^- X$
  - Four-fermion events
    (main background)
    $e^+e^- \to e^+e^- q\bar{q}$ 1,000/channel
    $e^+e^- \to \mu^+\mu^- q\bar{q}$ 500/channel



L3 Υ Selection

e^+e^- identification

- ✔ electromagnetic shower in calorimeter
- ✔ good match between BGO cluster and track in tracking chamber

$\mu^+\mu^-$ identification

- ✔ well measured track in muon chambers
- ✔ muon track compatible with interaction point

e^+e^- kinematics

$$|\cos\theta| < 0.97$$
$$E_e > 4 \text{ GeV}$$
$$\alpha_{(e-Jet)} > 10^\circ$$
$$\psi_{e^+e^-} < 90^\circ$$

$\mu^+\mu^-$ kinematics

$$|\cos\theta| < 0.81$$
$$|p_\mu| > 3 \text{ GeV}$$
$$\alpha_{(\mu-Jet)} > 15^\circ$$
$$\psi_{\mu^+\mu^-} < 90^\circ$$

Υ production mechanism	$\epsilon\left(Z \to \Upsilon X; \Upsilon \to \ell^+\ell^-\right)$ [%]	
	e^+e^- channel	$\mu^+\mu^-$ channel
1. $Z \to \Upsilon b\bar{b}$	$37.4 \pm 0.6 \pm 5.0$	$21.2 \pm 0.5 \pm 2.6$
2. $Z \to \Upsilon q\bar{q}gg$	$25.5 \pm 0.6 \pm 3.4$	$14.3 \pm 0.5 \pm 1.7$
3. $Z \to \Upsilon gg$	$32.1 \pm 0.6 \pm 4.3$	$19.6 \pm 0.5 \pm 2.4$
4. $Z \to \Upsilon q\bar{q}$	$33.2 \pm 0.6 \pm 4.4$	$21.2 \pm 0.5 \pm 2.6$
5. $Z \to \Upsilon g$	$41.5 \pm 0.6 \pm 5.5$	$33.3 \pm 0.6 \pm 4.1$

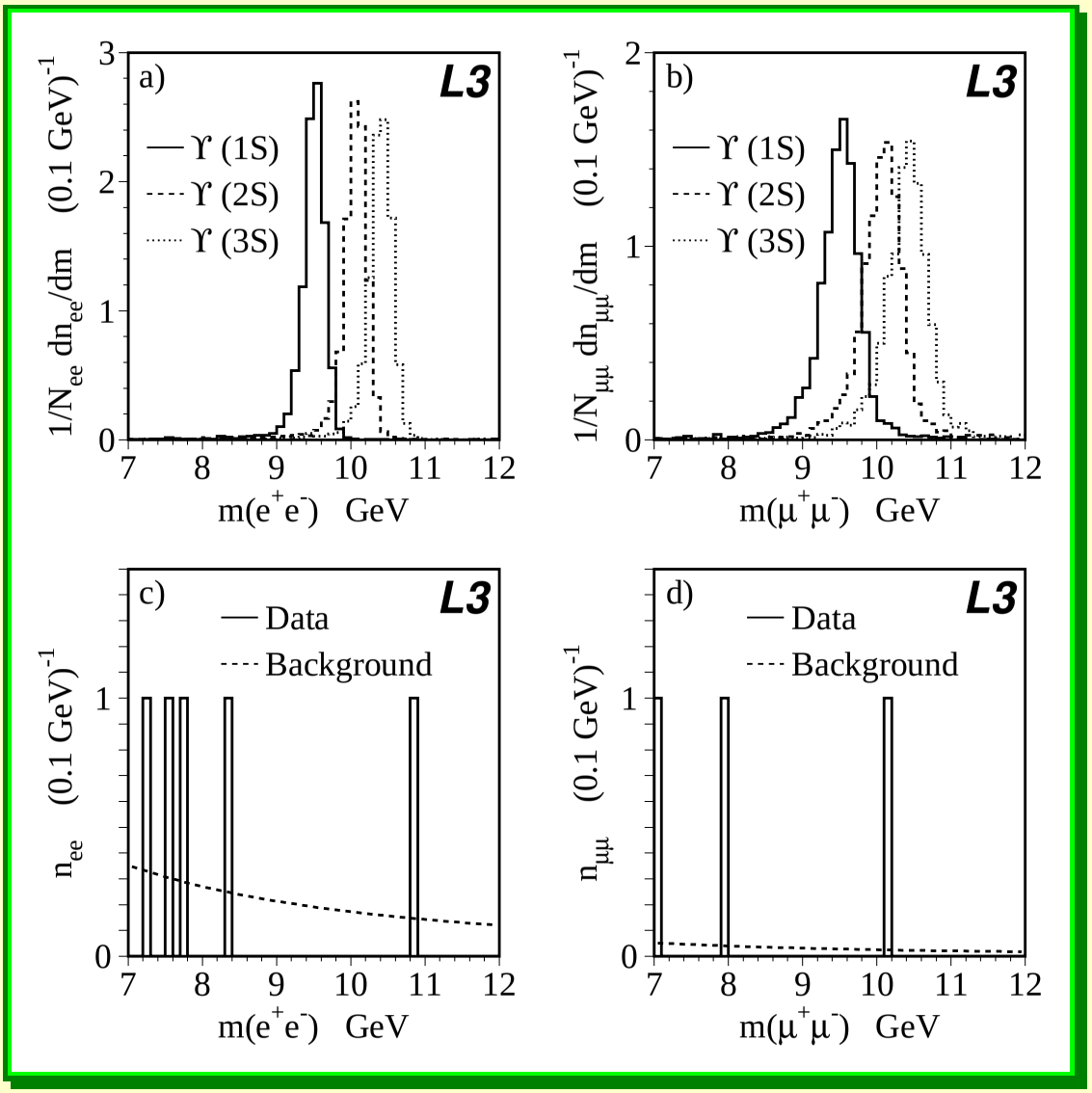
$\Rightarrow$ must consider each process seperately

Di-lepton mass spectra (L3)

❒ BGO Crystal calorimeter & Precision Muon spectrometer

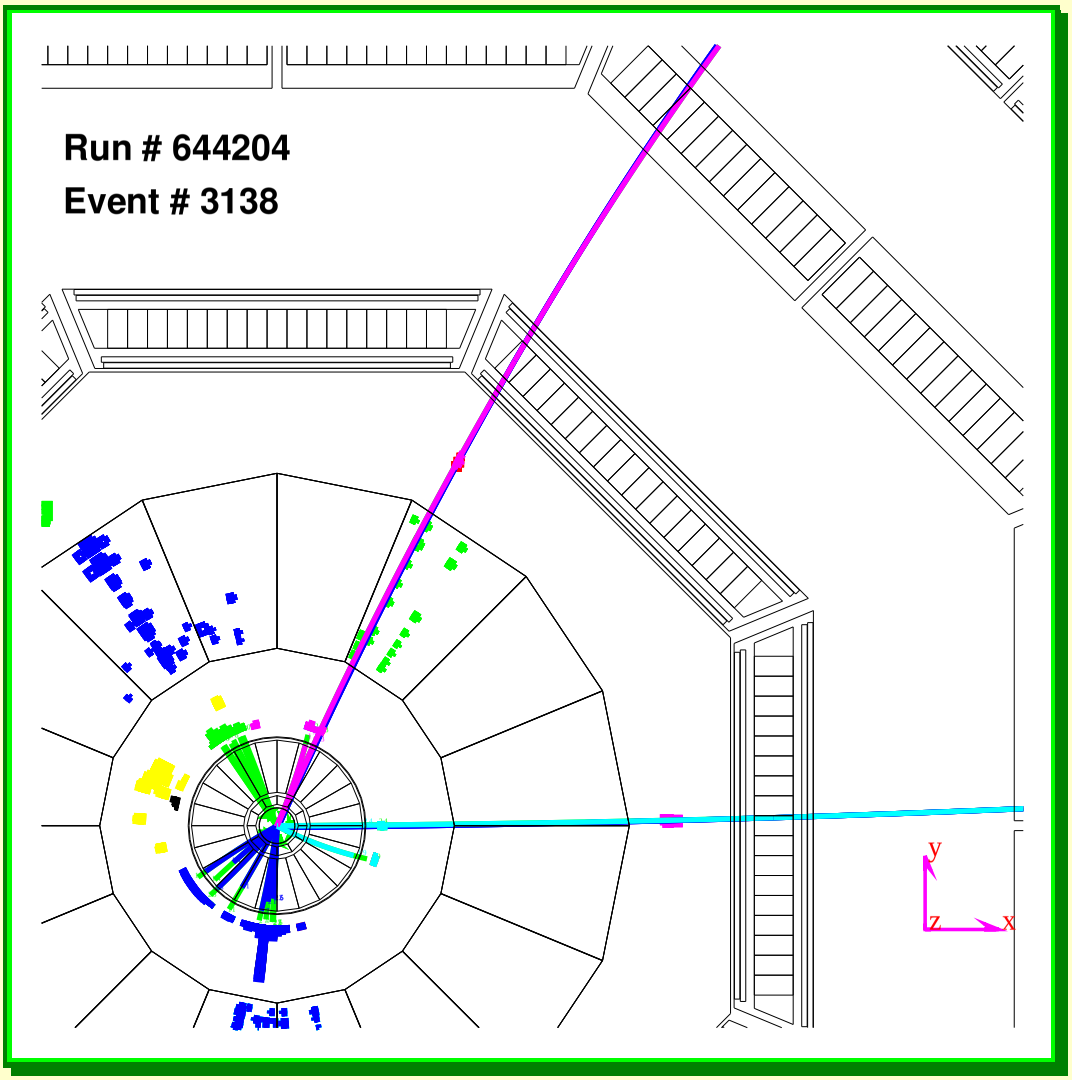
➠ L3 resolves $\Upsilon(1S)$,$\Upsilon(2S)$ & $\Upsilon(3S)$

$\sigma(m_{ee}) \approx 100\,\text{MeV}$ $\sigma(m_{\mu\mu}) \approx 235\,\text{MeV}$



No evidence for Υ production at L3

$\Upsilon \to \mu^+\mu^-$ Candidate



$$
\begin{aligned}
M_{\mu\mu} &= 10.15 \text{ GeV} \\
P_{\mu 1} &= 19.28 \text{ GeV} \\
P_{\mu 2} &= 4.69 \text{ GeV}
\end{aligned}
$$

Limits on $\mathrm{Br}(\mathrm{Z} \to \Upsilon X)$

$$\mathcal{L} = \prod_{i=1}^{n_{\mathrm{channels}}} \prod_{j=1}^{n_{\mathrm{bins}}} \frac{\mathrm{e}^{-(\mu_{\mathrm{bkg}}^{ij}+\mu_{\Upsilon}^{ij})}(\mu_{\mathrm{bkg}}^{ij}+\mu_{\Upsilon}^{ij})^{N_{ij}}}{N_{ij}!}$$

Systematic errors included (numerically):

- Υ **selection efficiencies** – statistical and systematic (allowing for correlations)
- Υ **branching ratios** ($\mathrm{Br}(\Upsilon(2\mathrm{S}) \to \mathrm{e}^+\mathrm{e}^-)$ and $\mathrm{Br}(\Upsilon(2\mathrm{S}) \to \mu^+\mu^-)$ completely correlated as are $\mathrm{Br}(\Upsilon(3\mathrm{S}) \to \mathrm{e}^+\mathrm{e}^-)$ and $\mathrm{Br}(\Upsilon(3\mathrm{S}) \to \mu^+\mu^-)$)
- **Background** – hadronic and 4-fermion, statistical and systematic errors (allowing for correlations)
- **hadronic selection efficiency** $\epsilon_{\mathrm{had}} = 0.99 \pm 0.01$
- $R_{\mathrm{had}} = 0.6990 \pm 0.0015$
- **Invariant mass scale and resolution** – correct with $\mathrm{Z} \to \mathrm{e}^+\mathrm{e}^-, \mu^+\mu^-, \tau^+\tau^-, \mathrm{e}^+\mathrm{e}^-\mathrm{e}^+\mathrm{e}^-$ events and π^0 peak. Verify with $\mathrm{J}/\psi \to \mathrm{e}^+\mathrm{e}^-/\mu^+\mu^-$
- **Fit ranges and binning** – no effect
- Υ **polarisation**
- Υ **and** χ_{b} **feed-down**

L3 results and comparisons

Υ production mechanism	Upper limit on $\mathbf{Br(Z \to \Upsilon X) \times 10^5}$ at the 95% C.L.			
	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	Average Υ
1. $\mathbf{Z \to \Upsilon b\bar{b}}$	5.4	13.5	9.0	7.4
2. $\mathbf{Z \to \Upsilon q\bar{q}gg}$	7.8	16.3	13.0	10.5
3. $\mathbf{Z \to \Upsilon gg}$	6.0	14.1	9.9	8.0
4. $\mathbf{Z \to \Upsilon q\bar{q}}$	5.5	14.0	9.5	7.6
5. $\mathbf{Z \to \Upsilon g}$	3.9	10.3	6.9	5.4
Combined model	5.5	13.9	9.4	7.6

DELPHI process 3. $\mathbf{Br(Z \to \Upsilon X) < 20 \times 10^{-5}}$ ➠ 90% C.L.

ALEPH process 4. (no systematics) $\mathbf{Br(Z \to \Upsilon X) < 7.3 \times 10^{-5}}$ ➠ 95% C.L.

OPAL (sum of all processes) $\mathbf{Br(Z \to \Upsilon X) = (10 \pm 4 \pm 1) \times 10^{-5}}$

Theory (sum of all processes) $\mathbf{Br(Z \to \Upsilon X) = 5.9 \times 10^{-5}}$

Conclusions

- Υ production especially interesting for testing theoretical QCD models
- No evidence for Υ Production at L3
- Results are consistent with the theoretical predictions
- Consistency with the OPAL measurement is marginal