Charmonium and Bottomonium Production

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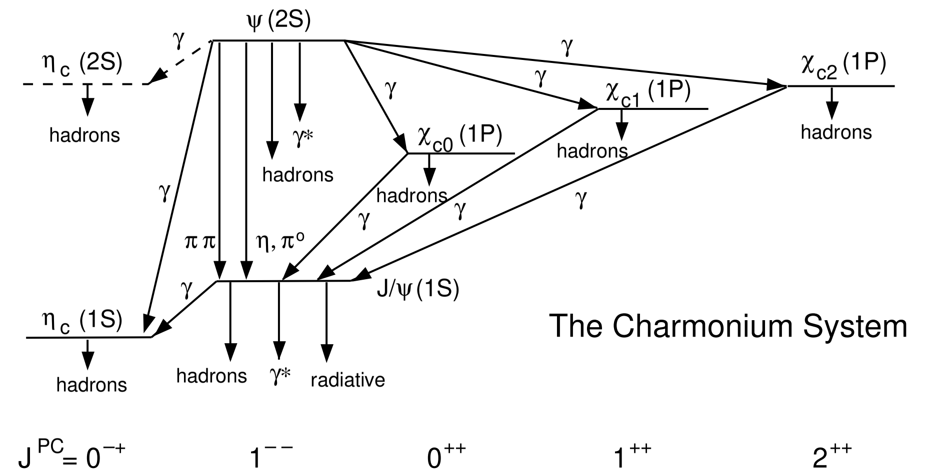
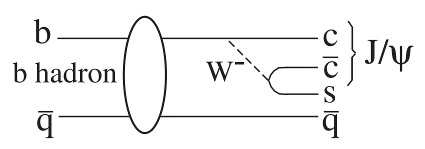
Charmonium Production



❐Dominant mechanism for the production of $\mathbf{c\bar{c}}$ in hadronic $\mathbf{Z}$ decays:

$$\mathbf{e^+e^- \to Z \to b\bar{b} \to [c\bar{c}] + X}$$



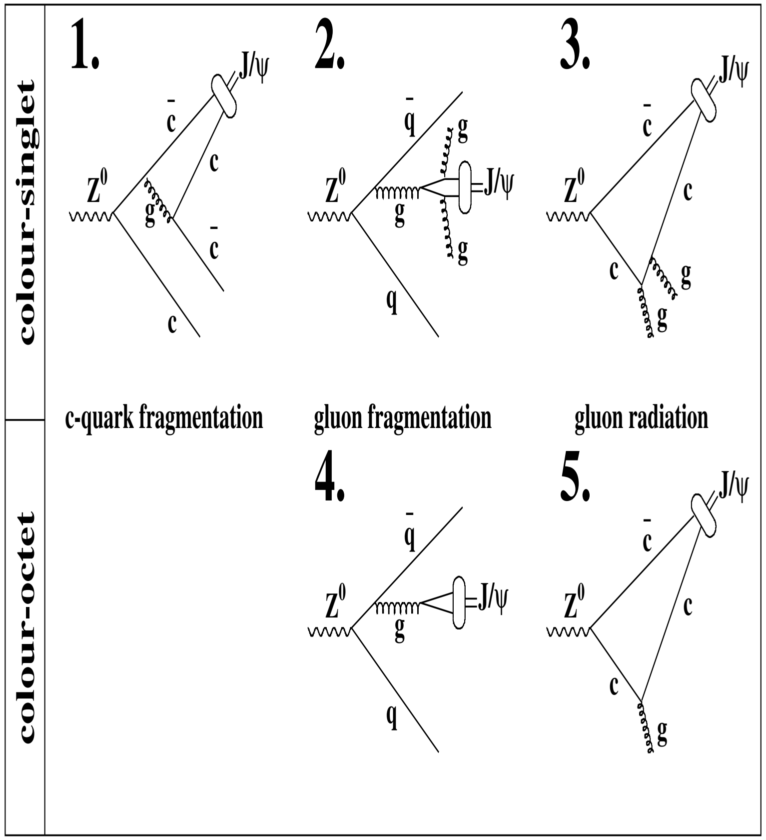
$$\mathbf{Br(b \to J/\psi + X) = 0.2 - 2.0\%}$$

Uncertainties

★ Heavy Quark Masses
★ Size of Higher order correction
★ Value of QCD scale $\mathbf{\Lambda}$
★ Non-Perturbative effects

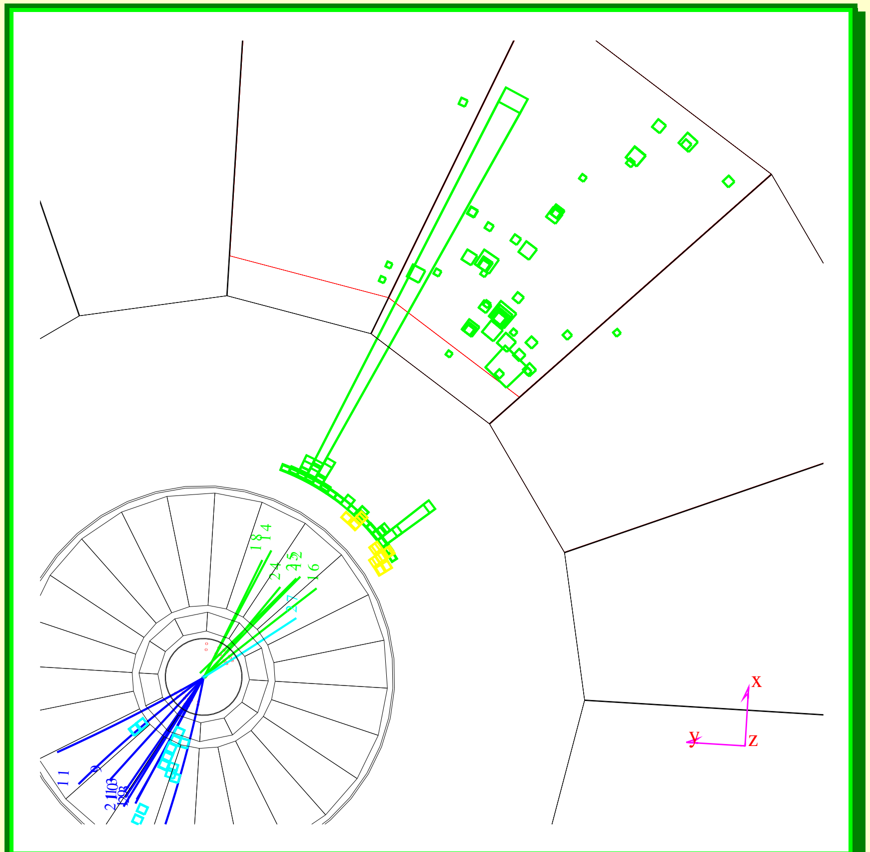
Charmonium Production

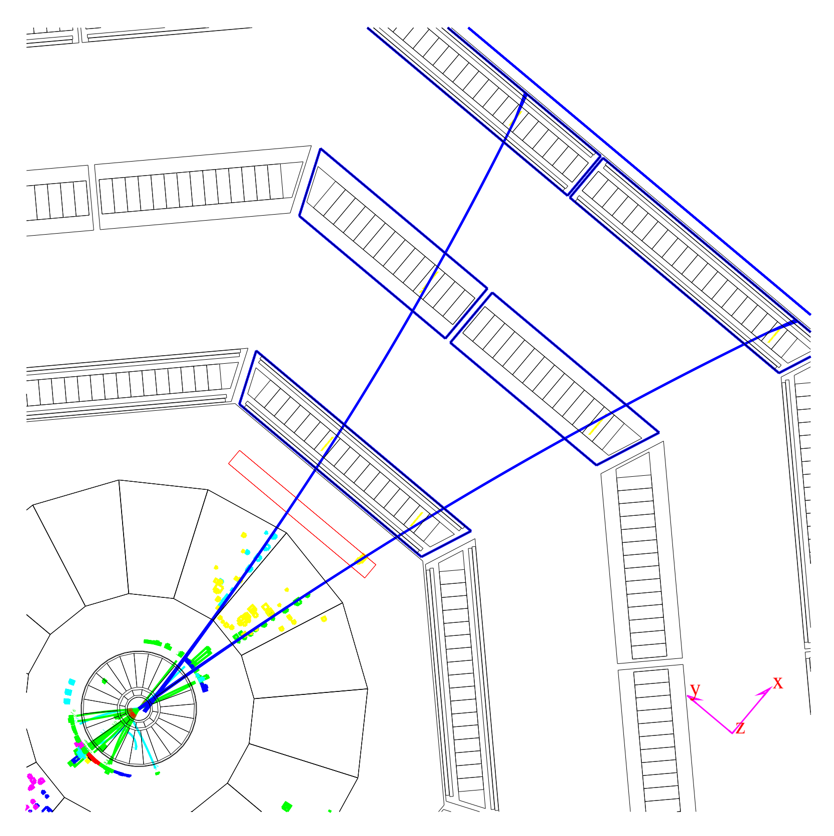
❒ Fragmentation



Production model	$\mathbf{Br(Z \to J/\psi X)}$ $(\times 10^{-4})$
1. $\mathbf{Z \to J/\psi c\bar{c}}$	**0.8**
2. $\mathbf{Z \to J/\psi q\bar{q}gg}$	**0.2**
3. $\mathbf{Z \to J/\psi gg}$	**0.005**
4. $\mathbf{Z \to J/\psi q\bar{q}}$	**1.9**
5. $\mathbf{Z \to J/\psi g}$	**0.002**
Total	$\approx$ **2.9**

Production of $J/\psi, \psi'$ at L3



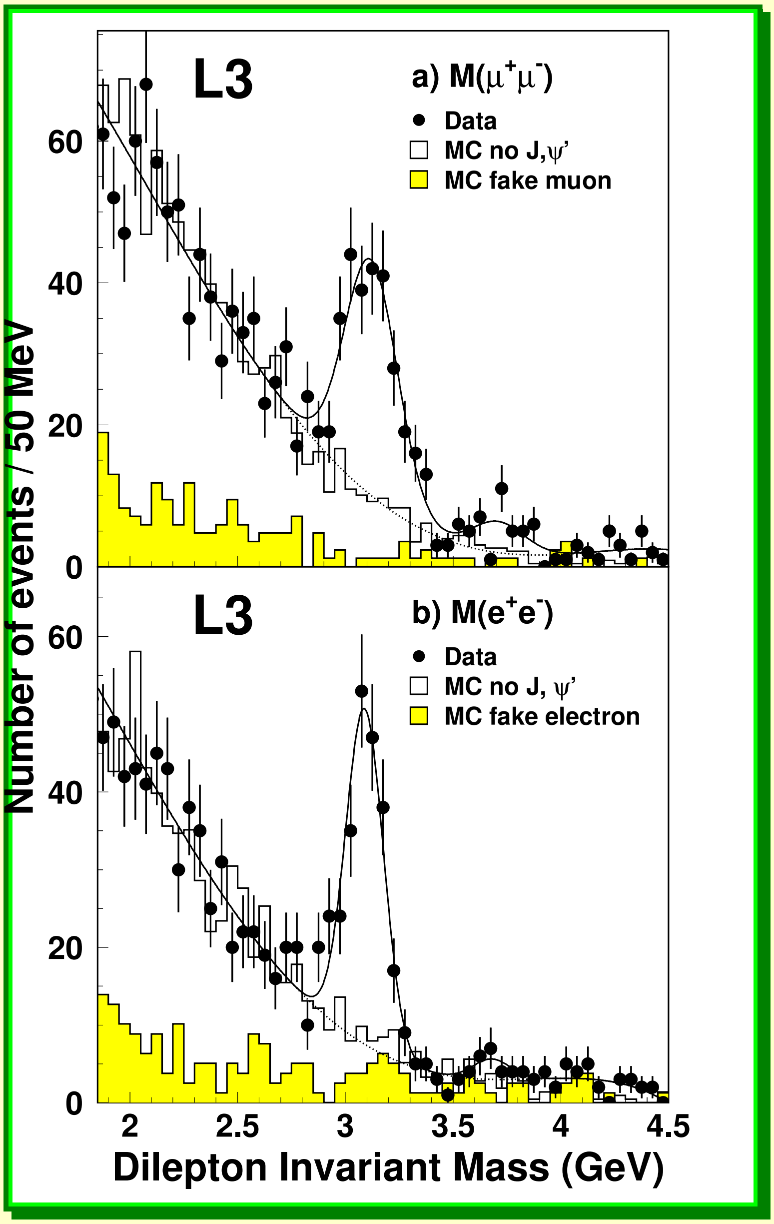


$J/\psi \rightarrow e^+e^-$

$J/\psi \rightarrow \mu^+\mu^-$

Production of $J/\psi, \psi'$ at L3

❒ Data events (91–94)   3.2 Million Hadronic Events



$$N_{J/\psi} = 241 \pm 25$$
$$N_{\psi'} = 27 \pm 10$$

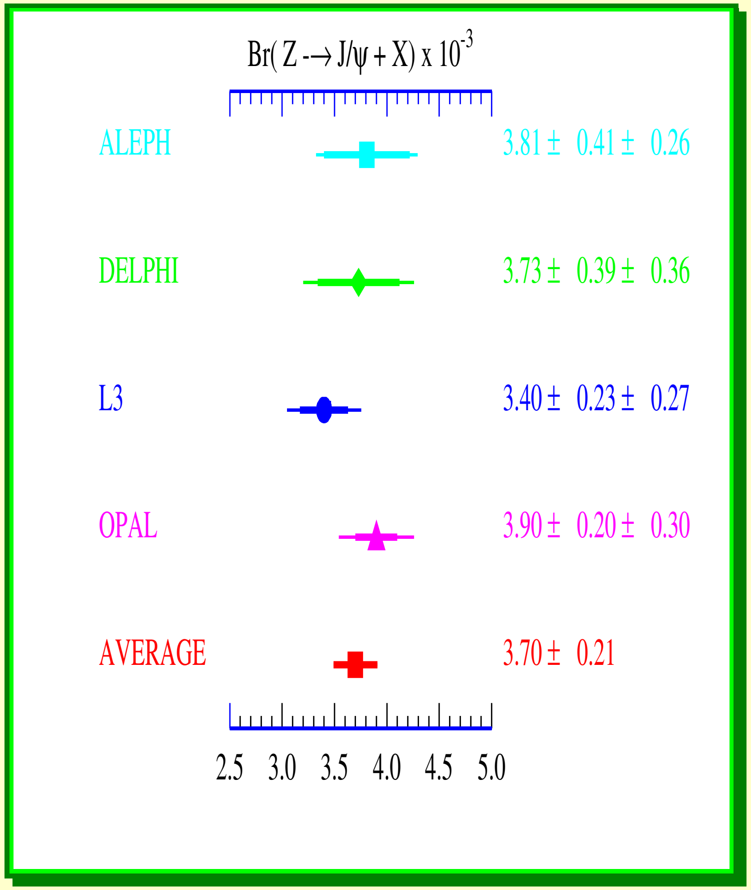
$$N_{J/\psi} = 200 \pm 18$$
$$N_{\psi'} = 11.6 \pm 6.6$$

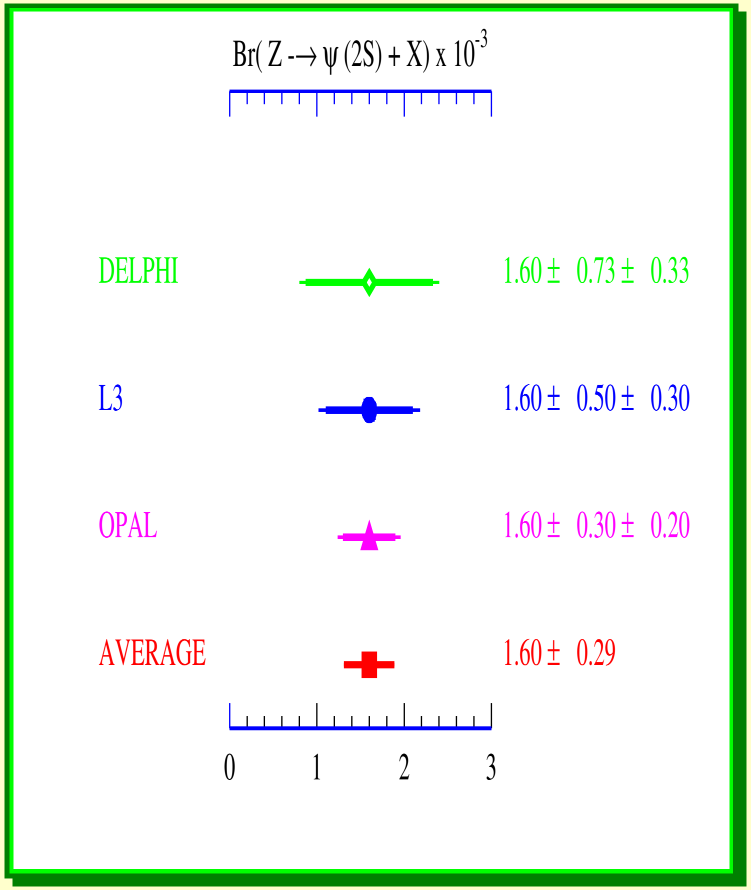
$$\mathrm{Br}(Z \to J/\psi + X) = (3.40 \pm 0.23 \pm 0.27) \times 10^{-3}$$

$$\mathrm{Br}(Z \to \psi' + X) = (1.60 \pm 0.50 \pm 0.30) \times 10^{-3}$$

(CERN PPE Preprint 97-44; 25 April 1997)

LEP Average

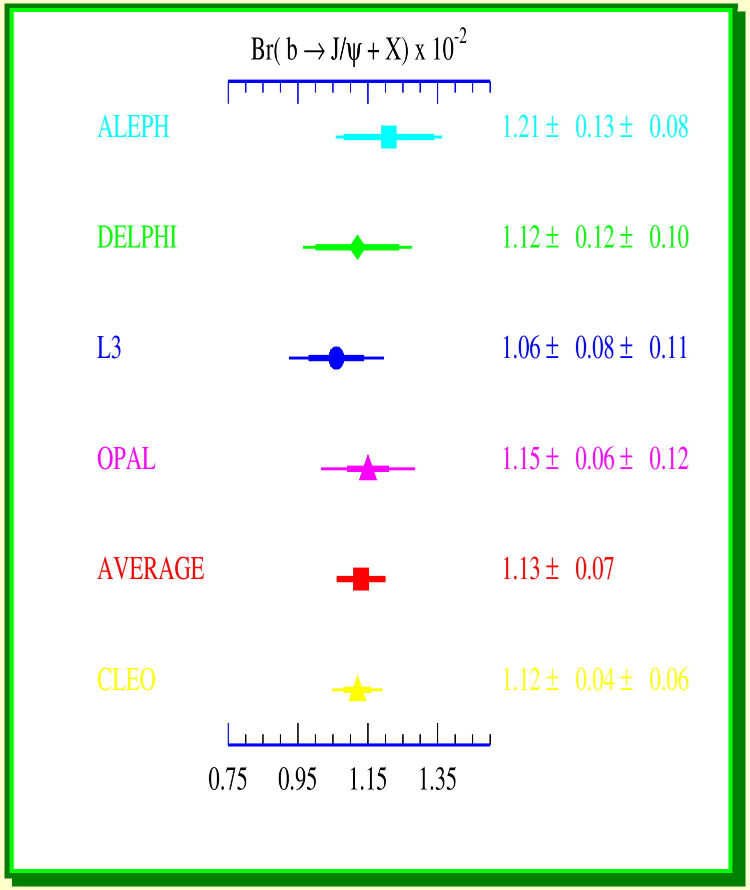




L3 Collaboration , PPE Preprint 97-44; 25 April 1997.
ALEPH Collaboration , Phys. Lett. B 295 (1992) 396.
DELPHI Collaboration , Phys. Lett. B 295 (1994) 109.
OPAL Collaboration , Z. Phys. C 70 (1996) 197.

$\mathbf{Br(b \rightarrow J/\psi + X)}$

❐ $\mathbf{Br(b \rightarrow J/\psi X) = \frac{\Gamma_Z}{2 \cdot \Gamma_{b\bar{b}}} \cdot Br(Z \rightarrow J/\psi X)}$



$\mathbf{Br(Z \rightarrow J/\psi_{prompt} X) \times 10^{-4}}$

- Neglected
- $\mathbf{7.7^{+6.3}_{-5.4}}$ (Measured)
- $\mathbf{2.0 \pm 2.0}$ (Assumption)
- $\mathbf{3.3^{+3.3}_{-1.6}}$ (Assumption)

Recent Measurement

★ Aleph Prel. $\mathbf{3.00 \pm 0.85}$

★ OPAL $\mathbf{1.90 \pm 0.99}$ Colour Singlet

★ OPAL $\mathbf{2.70 \pm 1.21}$ Colour Octet

CLEO Collaboration , Phys. Rev. D (1995) 2661.

χ_c Production

❐ Production of χ_c state in Z hadronic decays is also dominated by decays of b-hadrons with additional contribution from fragmentation.

☞ Colour Singlet Model	☞ Colour Octet Model
$\frac{Br(b\to\psi'+X)}{Br(b\to J/\psi+X)} \approx 0.25$	$\frac{Br(b\to\psi'+X)}{Br(b\to J/\psi+X)} \approx 0.25$
$\frac{Br(b\to\chi_{c1}+X)}{Br(b\to J/\psi+X)} \approx 0.2$	$\frac{Br(b\to\chi_{c1}+X)}{Br(b\to J/\psi+X)}$ ➠ No Calculation
χ_{c0}, χ_{c2} are forbidden	χ_{c0}, χ_{c2} are allowed

➠ Measurements of χ_c production Tests Hadronization Models.

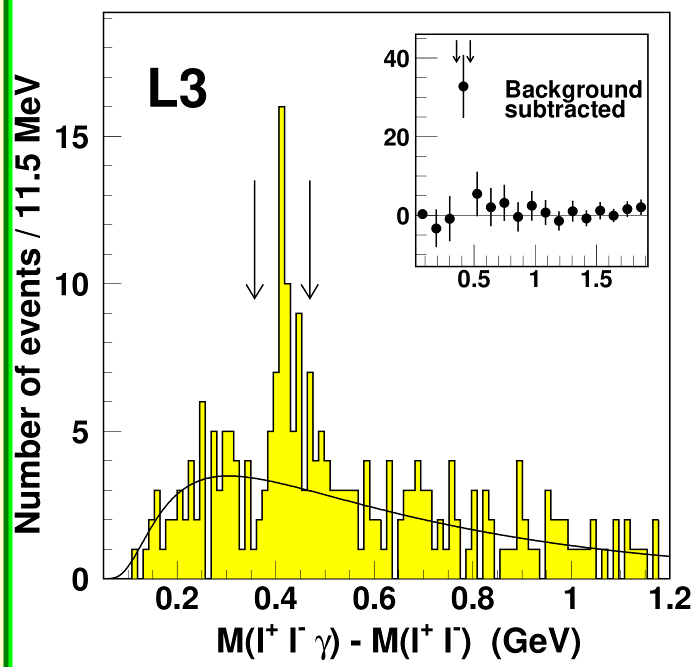
χ_c Production at L3

- $\chi_c \to J/\psi + \gamma$

➠ $Br(\chi_{c1} \to J/\psi + \gamma) = (27.3 \pm 1.6)\%$

- $2.8 < M_{\ell^+\ell^-} < 3.4$ GeV
- Associated γ

➠ $\Delta M = (414 \pm 56)$ MeV



$$\boxed{N_{\chi_{c1}} = 32.8 \pm 8}$$

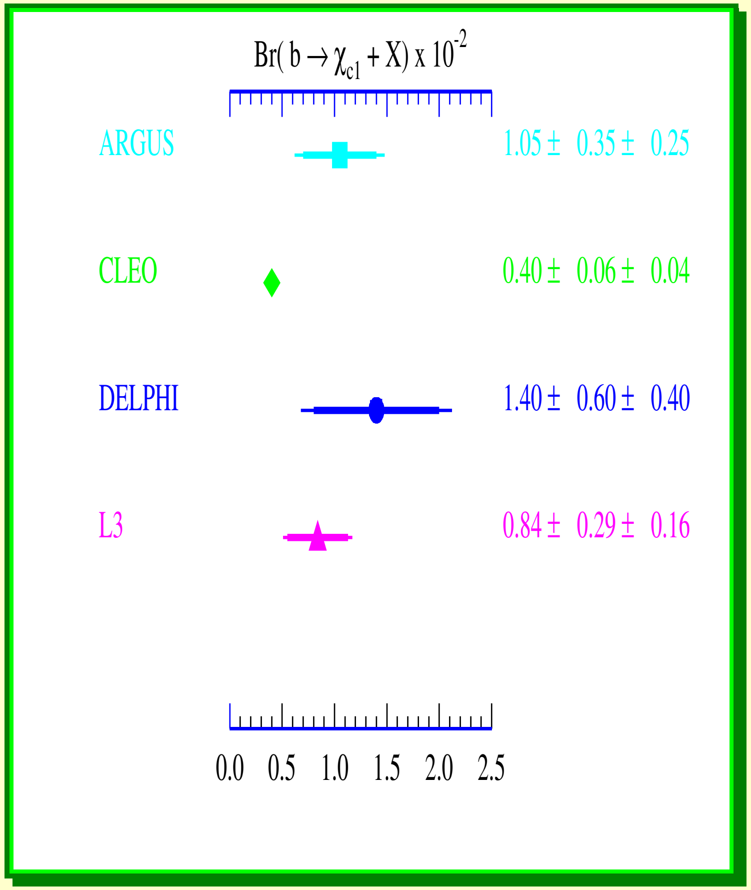
$\epsilon_{\chi_{c1}} = (8.1 \pm 0.4)\%$

$$\boxed{Br(Z \to \chi_{c1}X) = (2.7 \pm 0.6 \pm 0.5) \times 10^{-3}}$$

➠ Assuming $Br(Z \to \chi_{c1}X)_{prompt}$ is small

$$\boxed{Br(b \to \chi_{c1}X) = (0.84 \pm 0.20 \pm 0.16) \times 10^{-2}}$$

L3 results and comparisons



- $\mathbf{R^b_{\chi_{c1}} = \frac{Br(b\to\chi_{c1}+X)}{Br(b\to J/\psi+X)}}$
- Assuming all the $\mathbf{J/\psi}$ are decays of b

$$\boxed{\mathbf{R^b_{\chi_{c1}} = 0.75 \pm 0.19 \pm 0.15}}$$

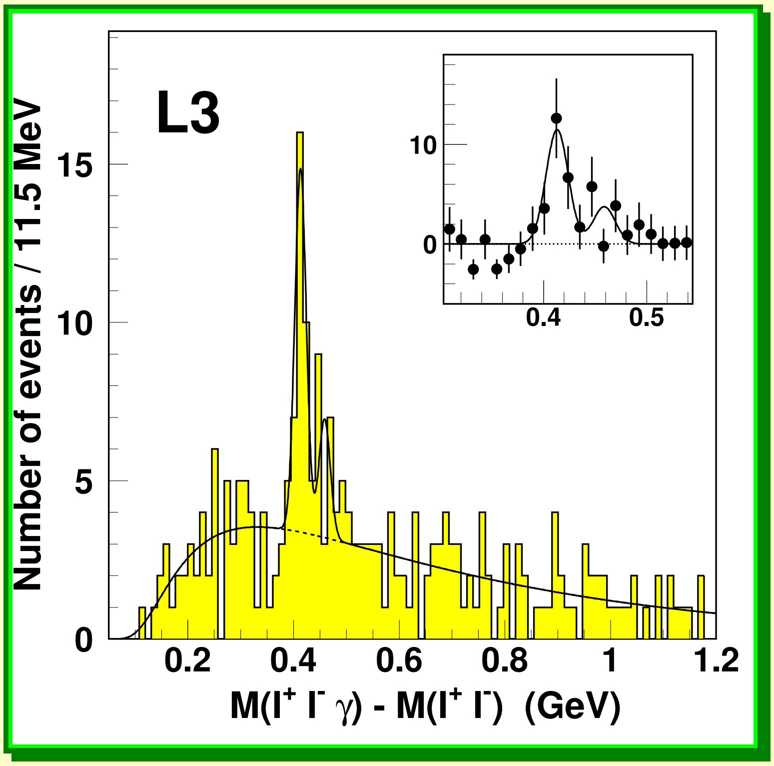
- Compared to theoretical prediction ($\mathbf{R^b_{\chi_{c1}} \approx 0.2}$)
- Significantly higher than the *Colour singlet Model*

ARGUS Collaboration , Phys. Lett. B 277 (1992) 209.
CLEO Collaboration , Phys. Rev. D 52 (1995) 2661.
DELPHI Collaboration , Phys. Lett. B 341 (1994) 109.
L3 Collaboration , CERN PPE Preprint 97-44; 25 April 1997.

Search for $\chi_{c2} \to J/\psi\gamma$

- χ_{c2} Forbidden in Colour Singlet Model
- Observation of χ_{c2} ➠ Colour Octet Model

- Unbinned Maximum-likelihood
- Two Gaussian constrained to same width and Mass difference of $M_{\chi_{c2}} - M_{\chi_{c1}}$



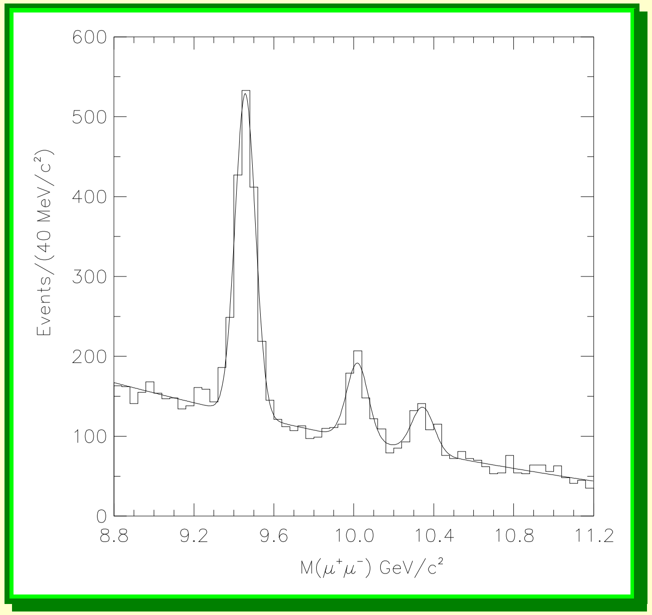
$$N_{\chi_{c1}} = 30.1^{+7.7}_{-7.0}$$

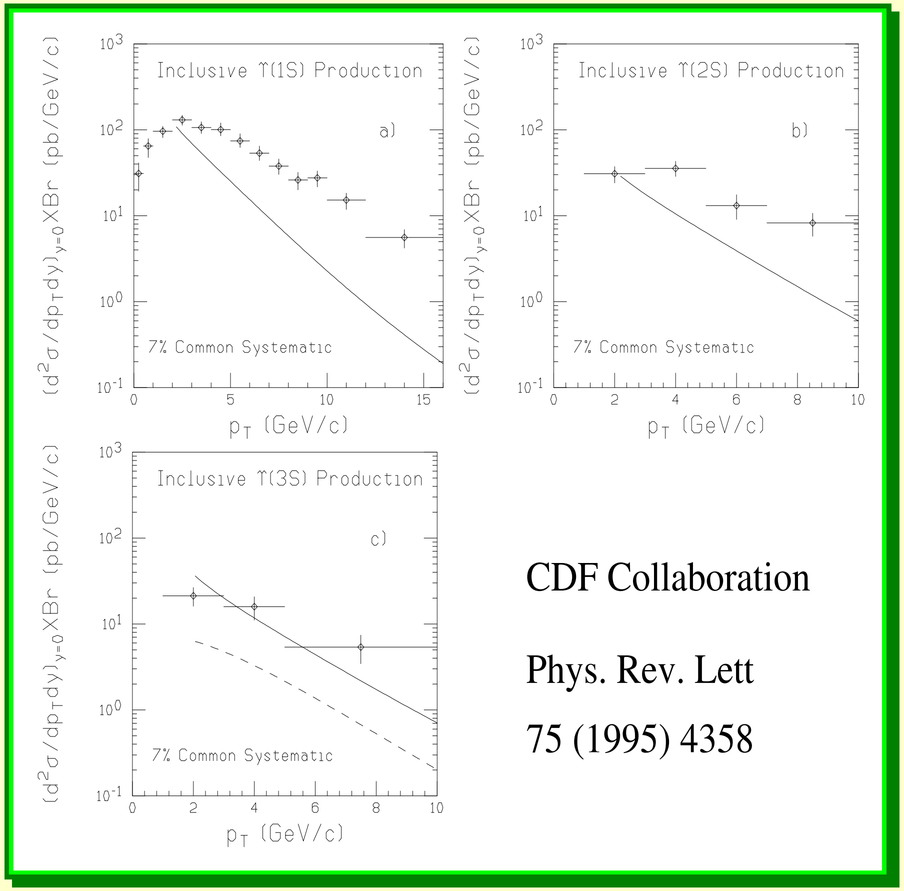
$$N_{\chi_{c2}} = 8.8^{+5.4}_{-4.6}$$

➠ $N_{\chi_{c1}}$ agreement with previous method ($N_{\chi_{c1}} = 32.8 \pm 8$)

$\boxed{Br(Z \to \chi_{c2} + X) < 3.2 \times 10^{-3}}$ ➠ 90% C.L.

The CDF Υ anomaly





CDF Collaboration

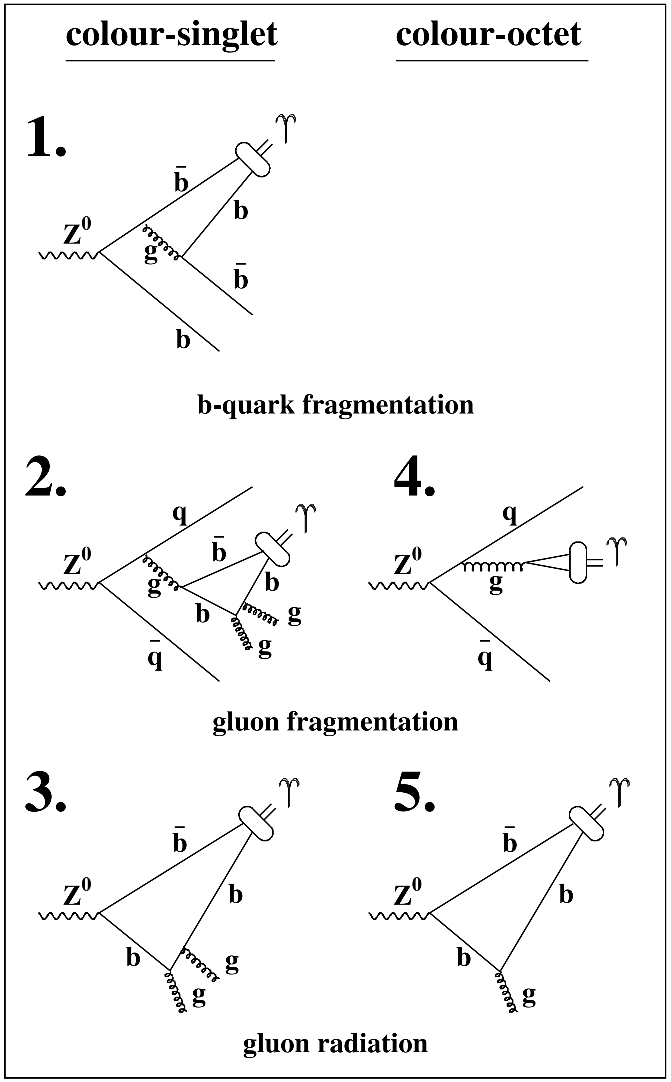
Phys. Rev. Lett 75 (1995) 4358

Measured rates much higher (factor ∼50) than predictions for *colour-singlet* processes

Discrepancies were resolved by including *colour-octet* processes

(∼100 theory papers in 2 years)

Υ production at LEP (theoretical)



Production model	$\mathrm{Br}(Z \to \Upsilon X)$ $(\times 10^{-5})$
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.)

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

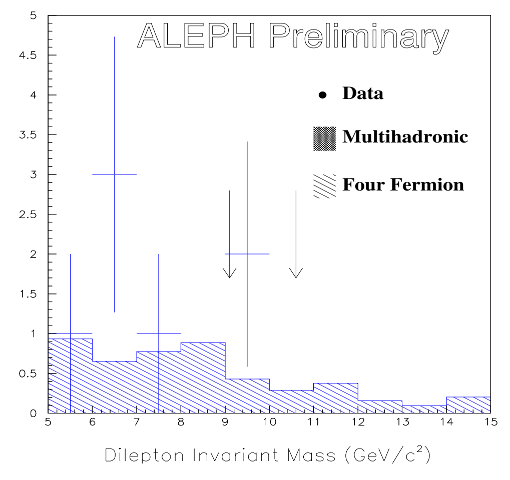
(for process **3.**)

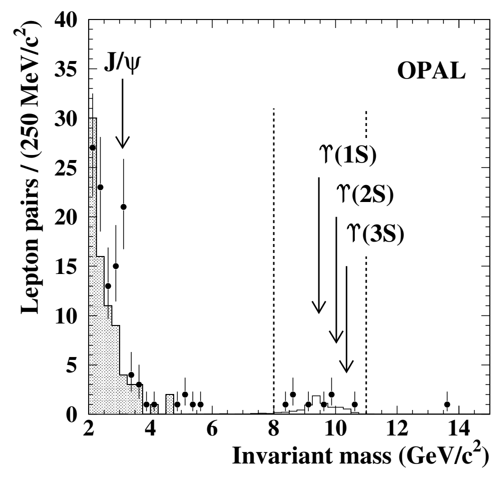
OPAL (Phys. Lett. B370 (1996) 185.)

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

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

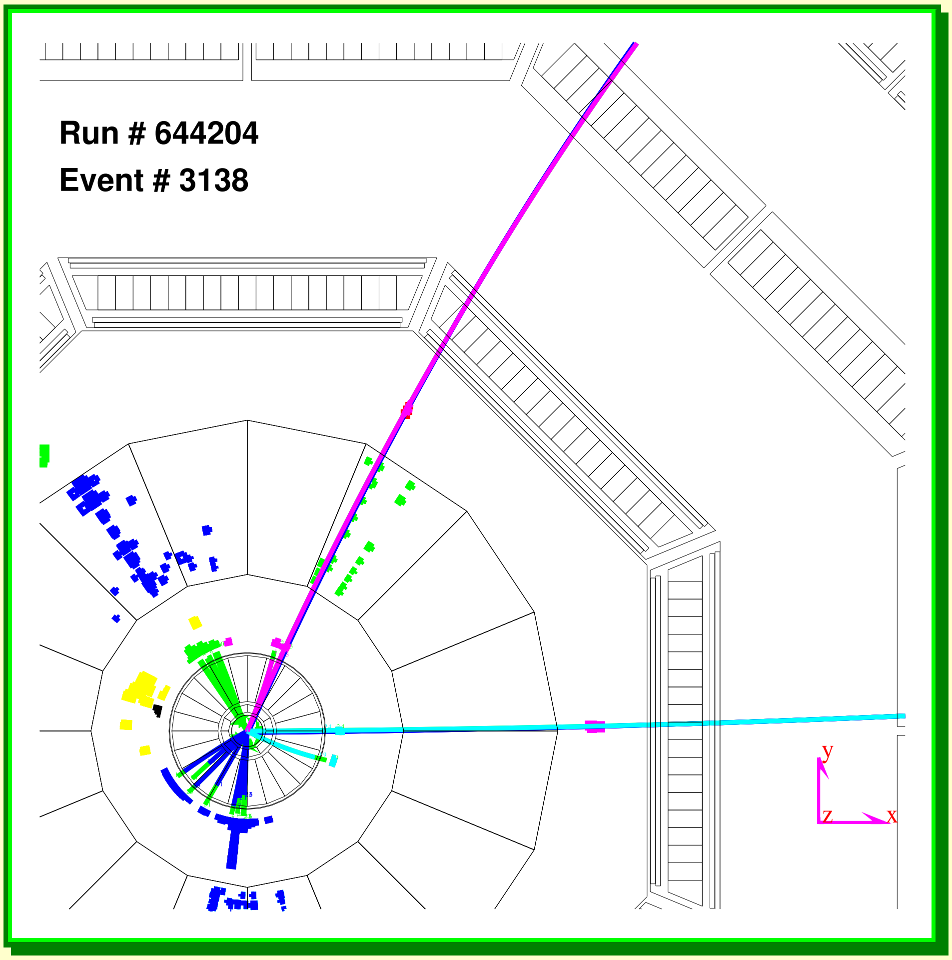
No attempts are made to separate $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$





L3 Selection of Υ

- Data events (91–95) 3,453,780

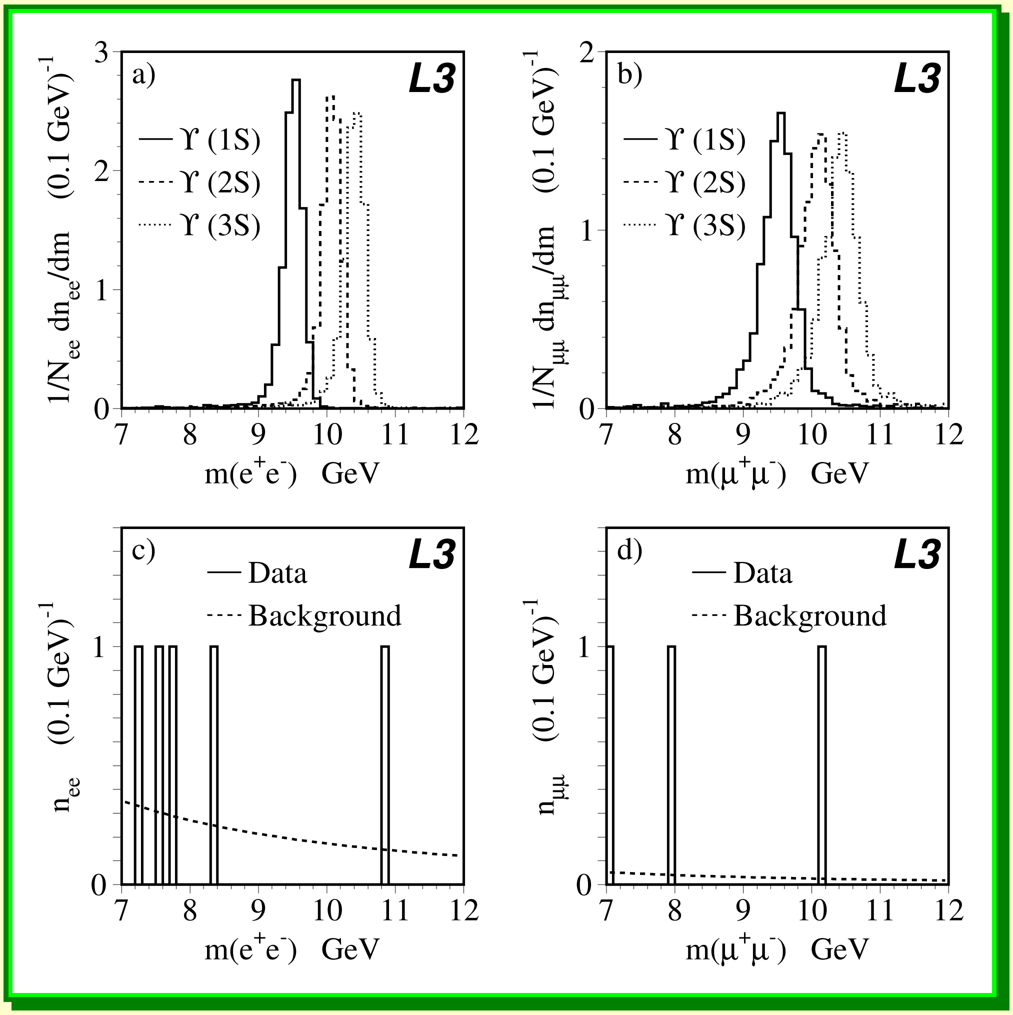


Υ production mechanism	$\epsilon\left(Z \to \Upsilon X; \Upsilon \to \ell^+\ell^-\right)$ [%]	
	e^+e^- channel	$\mu^+\mu^-$ channel
1. $Z \to \Upsilon b\bar{b}$	$37.4\pm0.6\pm5.0$	$21.2\pm0.5\pm2.6$
2. $Z \to \Upsilon q\bar{q}gg$	$25.5\pm0.6\pm3.4$	$14.3\pm0.5\pm1.7$
3. $Z \to \Upsilon gg$	$32.1\pm0.6\pm4.3$	$19.6\pm0.5\pm2.4$
4. $Z \to \Upsilon q\bar{q}$	$33.2\pm0.6\pm4.4$	$21.2\pm0.5\pm2.6$
5. $Z \to \Upsilon g$	$41.5\pm0.6\pm5.5$	$33.3\pm0.6\pm4.1$

Di-lepton mass spectra (L3)

- ❒ BGO Crystal calorimeter & Precision Muon spectrometer
- ➠ L3 resolves $\Upsilon(1S)$, $\Upsilon(2S)$ & $\Upsilon(3S)$

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



No evidence for Υ production at L3

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

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

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** $\epsilon_{\text{had}} = 0.99 \pm 0.01$
- $\boldsymbol{R_{\text{had}} = 0.6990 \pm 0.0015}$
- **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 $\mathbf{Br(Z \to \Upsilon X)} \times \mathbf{10^5}$ 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. $\boxed{\mathbf{Br(Z \to \Upsilon X) < 20 \times 10^{-5}}}$ ➠ 90% C.L.

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

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

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

Conclusions

- Charmonium Production
  - Inclusive / Prompt production of $\mathbf{J}/\psi$ and ψ' are in agreement with CLEO data and Colour Singlet Model
  - $\chi_\mathbf{c}$ production is higher than expected from Colour Singlet Model. Consistent with CLEO result within $\mathbf{1.5}\boldsymbol{\sigma}$
- Bottomonium Production
  - Results are consistent with the theoretical prediction
  - Consistency with the OPAL measurement is marginal
- Still Room for the improvements
  - Especially testing Colour Octet Model