R Measurements at High Q^2

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Outline

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2. Previous Results
3. Recent Results
   - BES R Measurement
   - CLEO Measurement
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5. Future?

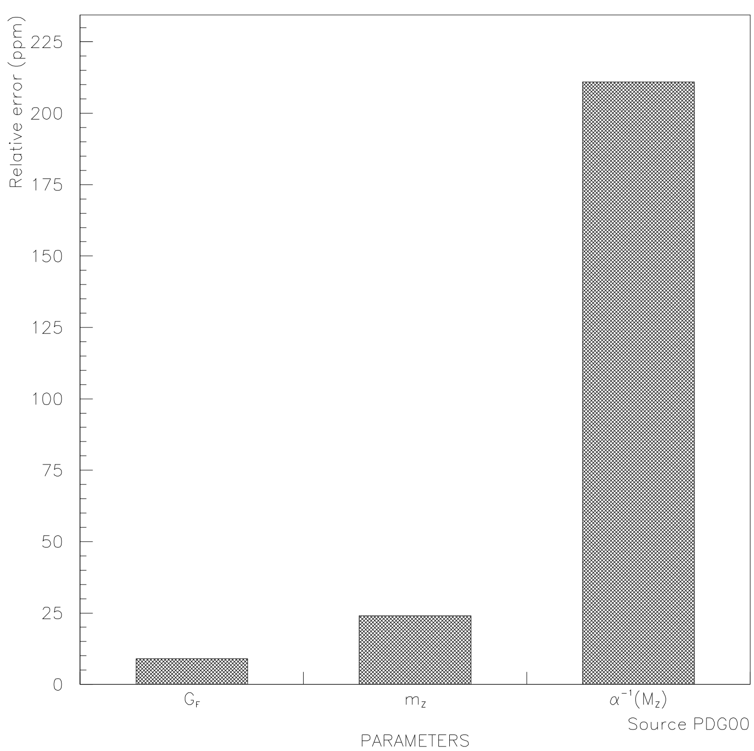
Introduction

$$R(s) = \frac{\sigma_{tot}(e^+e^- \to hadrons)}{\sigma_{tot}(e^+e^- \to \mu^+\mu^-)}$$

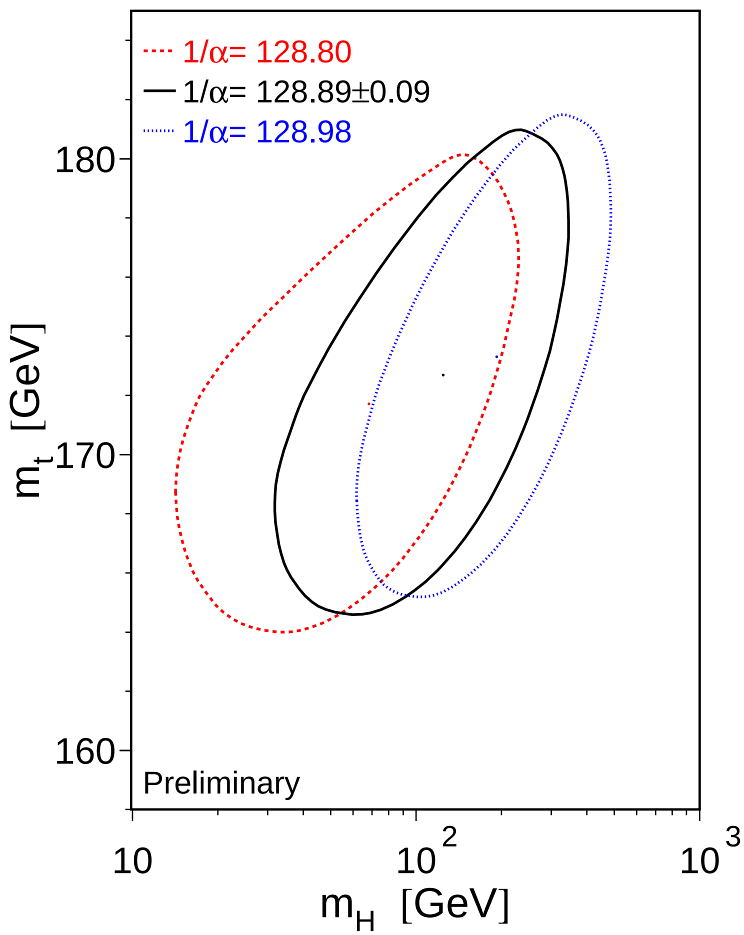
Improved R values are extremely important:

- Uncertainties in R limit the precision of $\alpha\left(m_Z^2\right)$.

The error on $\alpha\left(m_Z^2\right)$ is a limiting element in tests of the Standard Model.

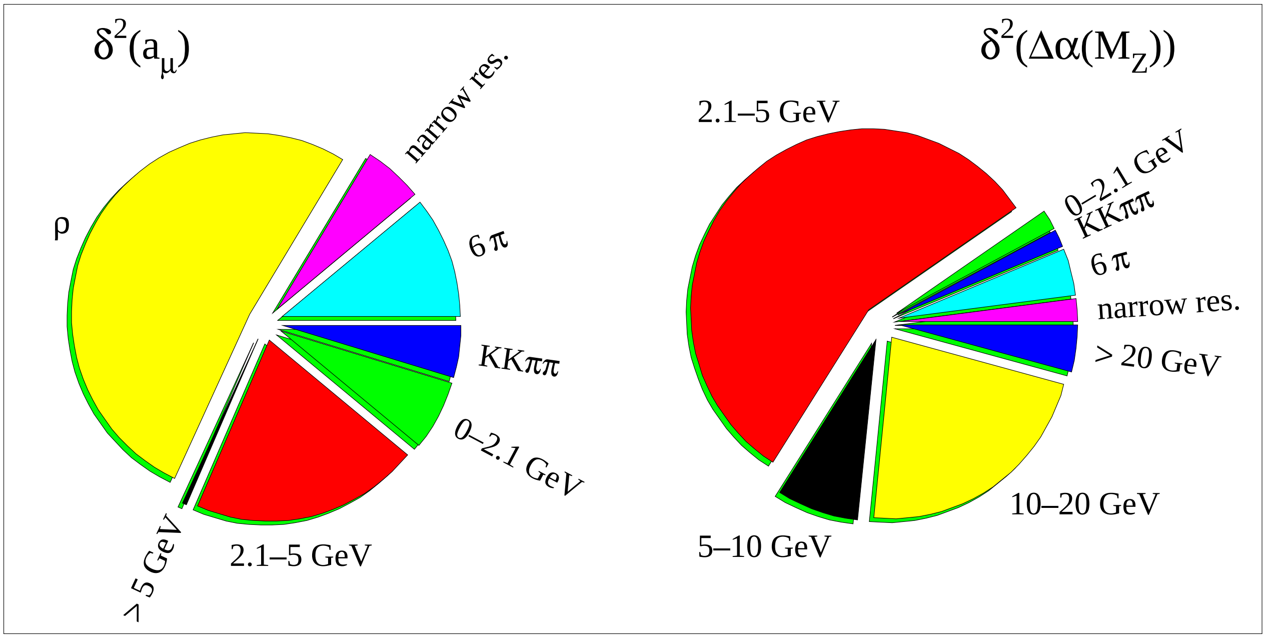


- The Higgs mass determined from radiative corrections in the standard model is very sensitive to the uncertainty in $\alpha(M_Z^2)$.



SM fit to m_t and m_H with $\alpha(M_Z^2)$ varying by $\pm\sigma$.
B. Pietrzyk and H. Burkhard (1997).

- For the interpretation of $a_\mu = (g-2)/2$.
Most of the theoretical uncertainty due to R.

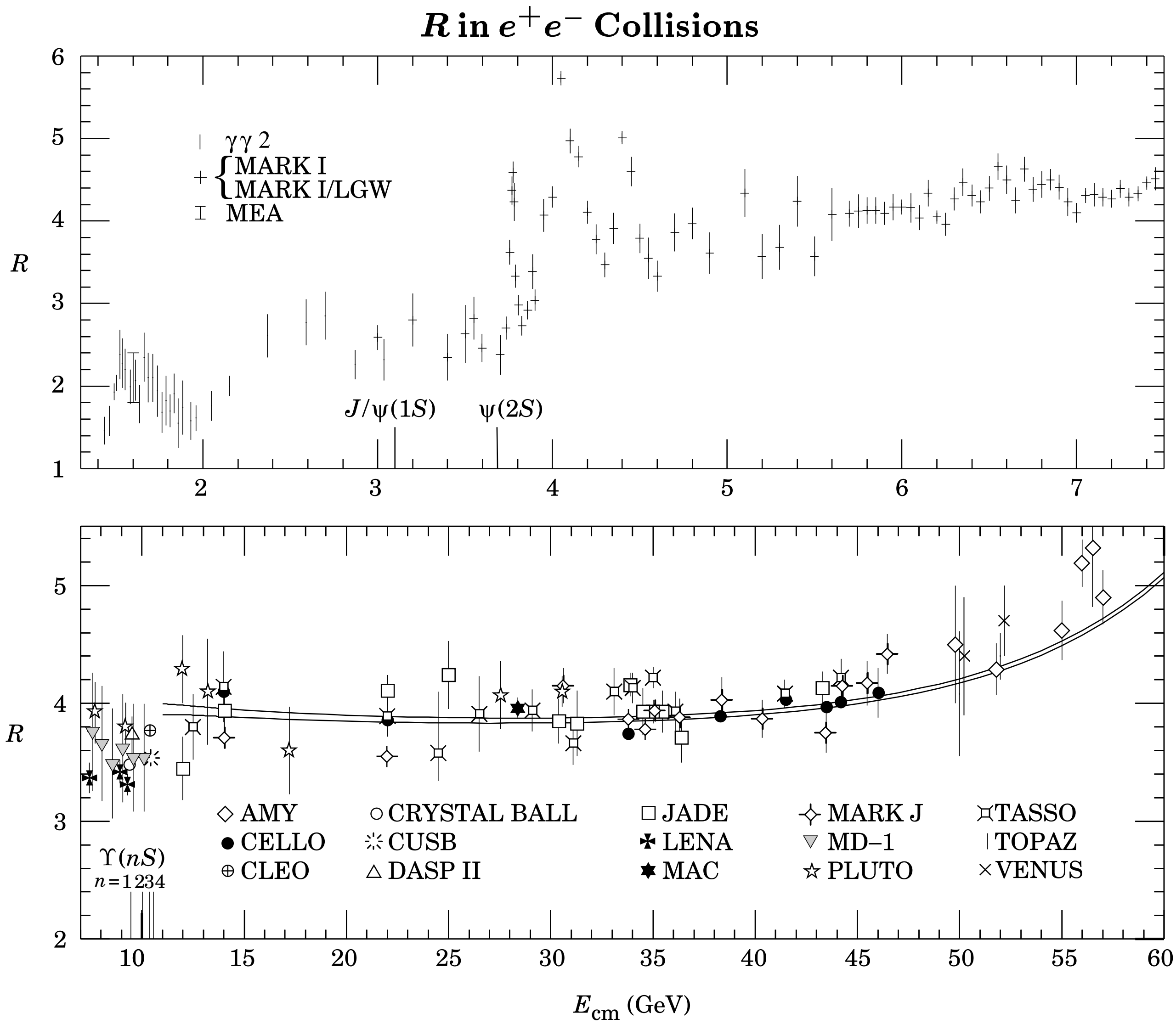


H. Burkhardt and B. Pietrzyk, *Phys. Lett.* B356, 398 (1995).

Previous Measurements

PDG2000 - Selected measurements.

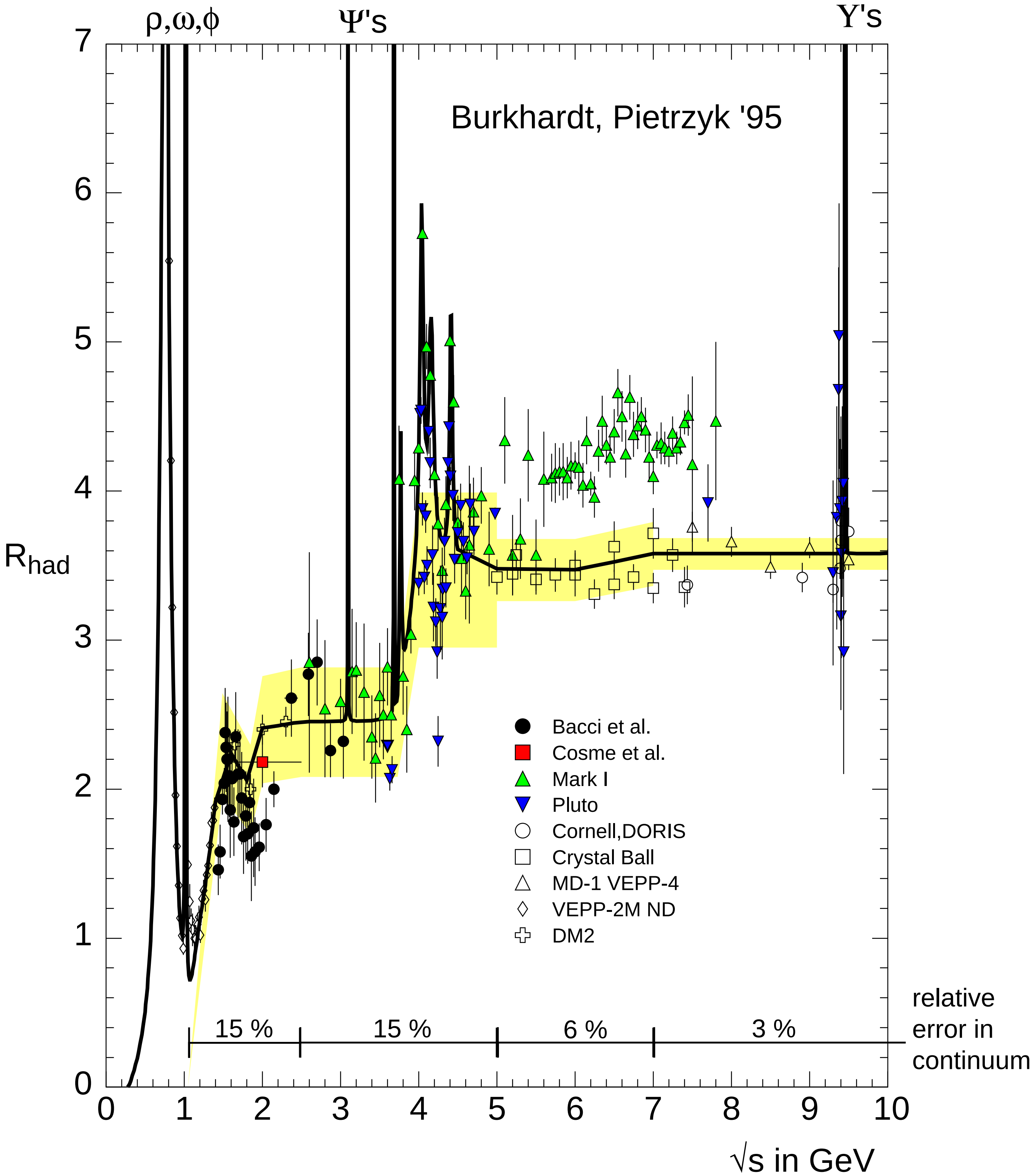
Systematic normalization error (5 - 20 %) not included.



Concentrate on $m_{J/\psi} < E_{\rm cm} < 12$ GeV

- PQCD can be used at high energies. (curves: M. Dine and J. Sapirstein, Phys. Rev. Lett. **43**, 668 (1979).)
- Theory driven approaches go much lower in energy.

Collaboration	Reference
AMY	T. Mori et al., Phys. Lett. B218, 499 (1989)
CELLO	H.J. Behrend et al., Phys. Lett. 144B, 297 (1984) H.J. Behrend et al., Phys. Lett. 183B, 400 (1987)
CLEO	R. Giles et al., Phys. Rev. D29, 1285 (1984) D. Besson et al., Phys. Rev. Lett. 54, 381 (1985)
CUSB	E. Rice et al., Phys. Rev. Lett. 48, 906 (1982)
CRYSTAL BALL	A. Osterheld et al., SLAC PUB 4160 (1986) C. Edwards et al., SLAC PUB 5160 (1990) Z. Jakubowski et al., Z. Phys. C40, 49 (1988)
DASP	R. Brandelik et al., Phys. Lett. 76B, 361 (1978)
DASP II	Phys. Lett. 116B, 383 (1982)
DCI	G. Cosme et al., Nucl. Phys. B152, 215 (1979)
DHHM	P. Bock et al., Z. Phys. C6, 125 (1980)
$\gamma\gamma 2$	C. Bacci et al., Phys. Lett. 86B, 234 (1979)
HRS	D. Bender et al., Phys. Rev. D31, 1 (1985)
JADE	W. Bartel et al., Phys. Lett. 129B, 145 (1983) W. Bartel et al., Phys. Lett. 160B, 337 (1985)
LENA	B. Niczyporuk et al., Z. Phys. C15, 299 (1982)
MAC	E. Fernandez et al., Phys. Rev. D31, 1537 (1985)
MARK J	B. Adeva et al., Phys. Rev. Lett. 50, 799 (1983) B. Adeva et al., Phys. Rev. D34, 681 (1986)
MARK I	J.L. Siegrist et al., Phys. Rev. D26, 969 (1982)
MARK I + Pb G. Wall	P.A. Rapidis et al., Phys. Rev. Lett. 39,526 (1977) P.A. Rapidis, thesis, SLAC Report 220 (1979)
MD 1	A.E. Blinov et al., Z. Phys. C70, 31 (1996)
MEA	B. Esposito et al., Lett. Nuovo Cimento 19, 21 (1977)
PLUTO	A. Backer, thesis, DESY F3377/03 (1977) C. Gerke, thesis, Hamburg Univ. (1979) Ch. Berger et al., Phys. Lett. 81B, 410 (1979) W. Lackas, thesis, DESY Pluto81/11 (1981)
TASSO	R. Brandelik et al., Phys. Lett. 113B, 499 (1982) M. Althoff et al., Phys. Lett. 138B, 441 (1984)
TOPAZ	I. Adachi et al., Phys. Rev. Lett. 60, 97 (1988)
VENUS	H. Yoshida et al., Phys. Lett. 198B, 570 (1987)



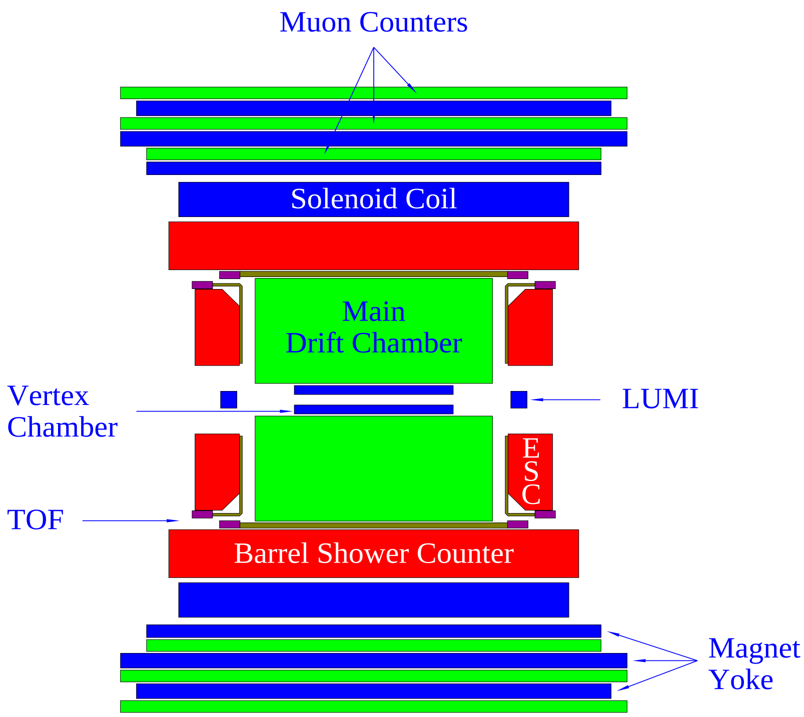
ρ,ω,φ
Ψ's
Υ's
Burkhardt, Pietrzyk '95
R_had
Bacci et al.
Cosme et al.
Mark I
Pluto
Cornell,DORIS
Crystal Ball
MD-1 VEPP-4
VEPP-2M ND
DM2
15 %
15 %
6 %
3 %
relative
error in
continuum
0
1
2
3
4
5
6
7
8
9
10
√s in GeV

BES R Measurement

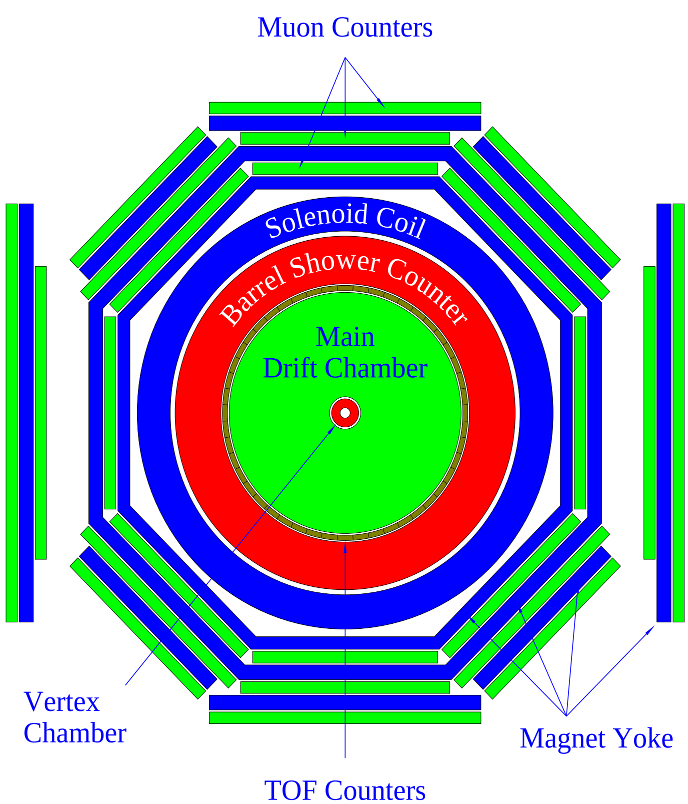
BES-II (Upgraded Beijing Spectrometer)

- General purpose solenoidal detector at Beijing Electron Positron Collider (BEPC).
- CM energy range from 2 to 5 GeV.
- Energy spread: 1.0 MeV
- Luminosity at J/ψ energy $\sim 4\times10^{30}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$.
- Detector Performance.

Subdetector	Performance
VC	$\sigma_{xy} \sim 100\ \mu\mathrm{m}$
MDC	$\sigma_{xy} \sim 200\ \mu\mathrm{m}$ $\sigma p/p \sim 1.8\%\sqrt{1+p^2}$ $\sigma_{dE/dx} \sim 8.4\%$
TOF	$\sigma_T \sim 180$ ps $\sigma_Z \sim 3$ cm
BSC	$\sigma E/E \sim 21\%/\sqrt{E}$ $\sigma_Z \sim 2.5$ cm
μ counter	$\sigma_{r\phi} \sim 3$ cm $\sigma_Z \sim 9$ cm



Side view of the BES detector



End view of the BES detector

Determination of R

Experimentally:

$$R = \frac{\sigma^0_{had}}{\sigma^0_{\mu\mu}} = \frac{N_{obs} - N_{bg}}{\sigma^0_{\mu\mu} \cdot \epsilon_{had} \cdot \epsilon_{trig} \cdot (1+\delta) \cdot L}$$

$$N_{bg} = N_{cr} + N_{bm} + N_{ll} + N_{\gamma\gamma}$$

$$\sigma^0_{\mu\mu}(s) = 4\pi\alpha^2/3s$$

Runs

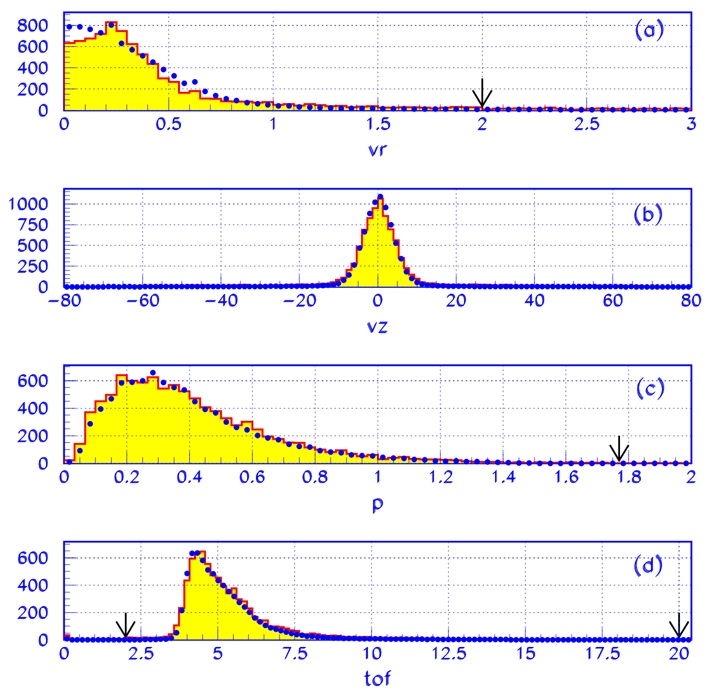
- In 1998 we performed an initial measurement of R using six scan points: 2.6, 3.2, 3.4, 3.55, 4.6, and 5.0 GeV.
- In 1999, we measured 85 scan points. ~ 1000 events/pt. Took $\sim$5 months.

Year	E (GeV)	Pts	Single Beam Pts	Separated Beam Pts	Time Spent (days)
1998	2.6 - 5.0	6	1	6	40
1999	2.0 - 4.8	85	7	24	105

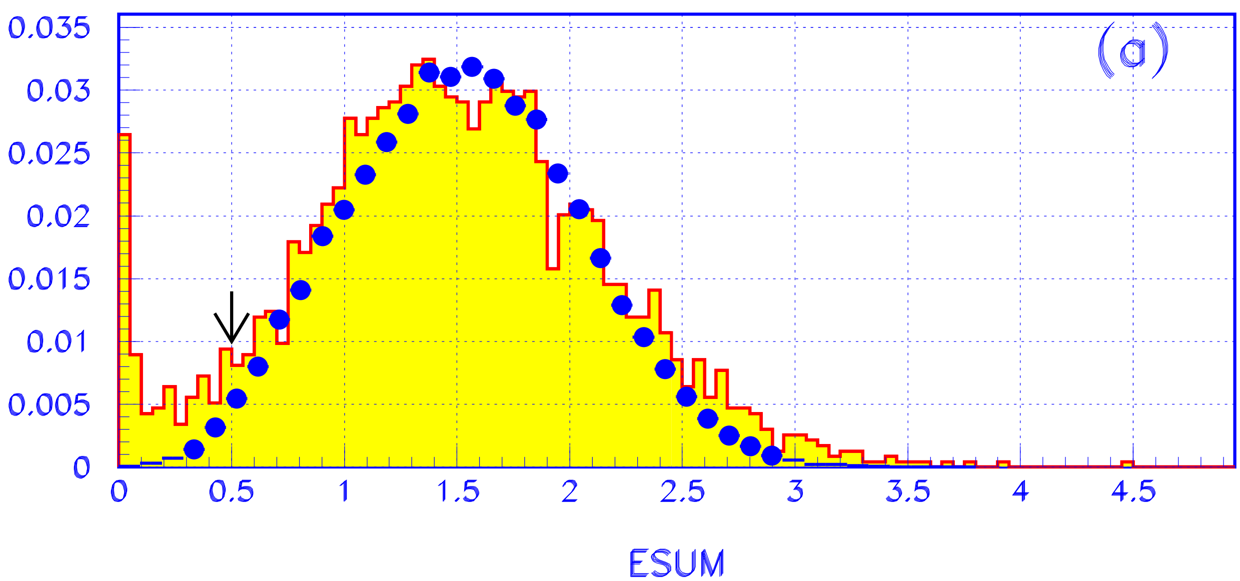
Event Selection

- Remove apparent Bhabhas.
- Track level cuts: require good tracks from IP. Remove cosmic rays and beam-gas.

Type	Cuts
Time	$2 < t < t_{\text{proton}} + 5\sigma_{\text{TOF}}$
Space (mfit = 2)	$r_o < 2.0$ cm $\lvert z_o\rvert < 18$ cm
Energy (BSC)	$E < 0.6E_{\text{beam}}$
Momentum	$p < p_{\text{beam}} + 5\sigma_p$ $\lvert\cos\theta\rvert < 0.84$



- Event level cuts:
  Remove beam-gas, two-photon, ee, $\mu\mu$, etc.
  - require $\geq$ 2tracks with at ≥ 1 good helix fit.
  - total deposited energy $> 0.28\ E_{beam}$.
  - tracks don't all point in the same direction in z.
  - for 2-prongs: tracks must NOT be back-to-back and have at least 2 isolated neutral tracks.



- Systematic error: part determined by varying cuts.

Backgrounds

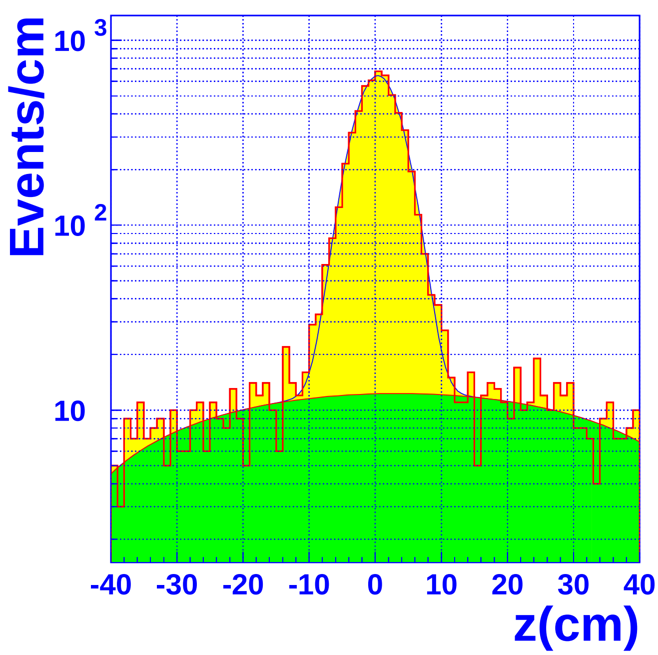
Cosmic rays, lepton pairs, two photon, and beam associated - subtract $\tau\tau$ and two photon.

Largest background: beam associated N_{bm}

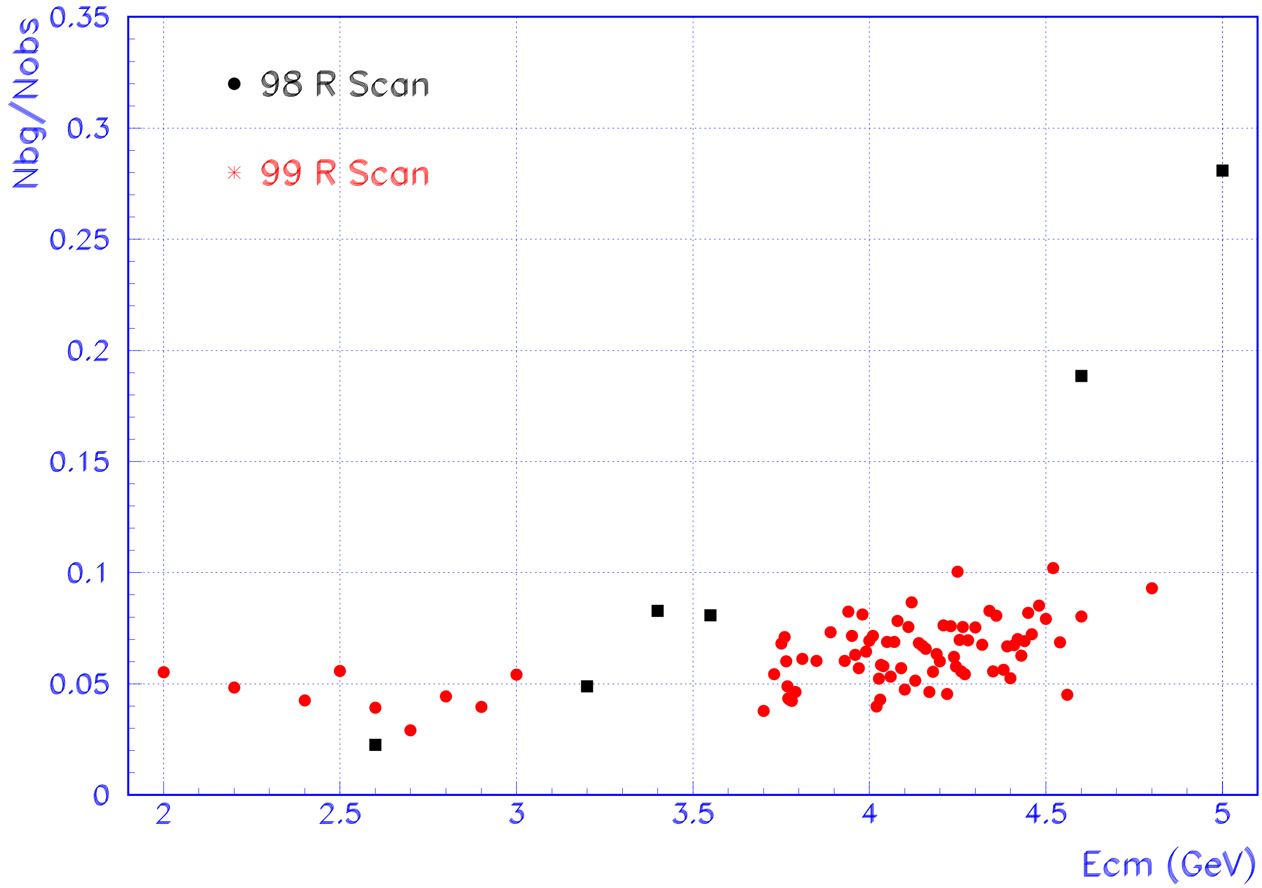
- Determine using separated beam runs. $N_{bm} = f N_{SB}$, where

$$f = \frac{\int_{col} (P \cdot I)_{col} dt}{\int_{sep} (P \cdot I)_{sep} dt}$$

- For 1999 data, also use vertex distribution. Fit with Gaussian + 2nd order polynomial.



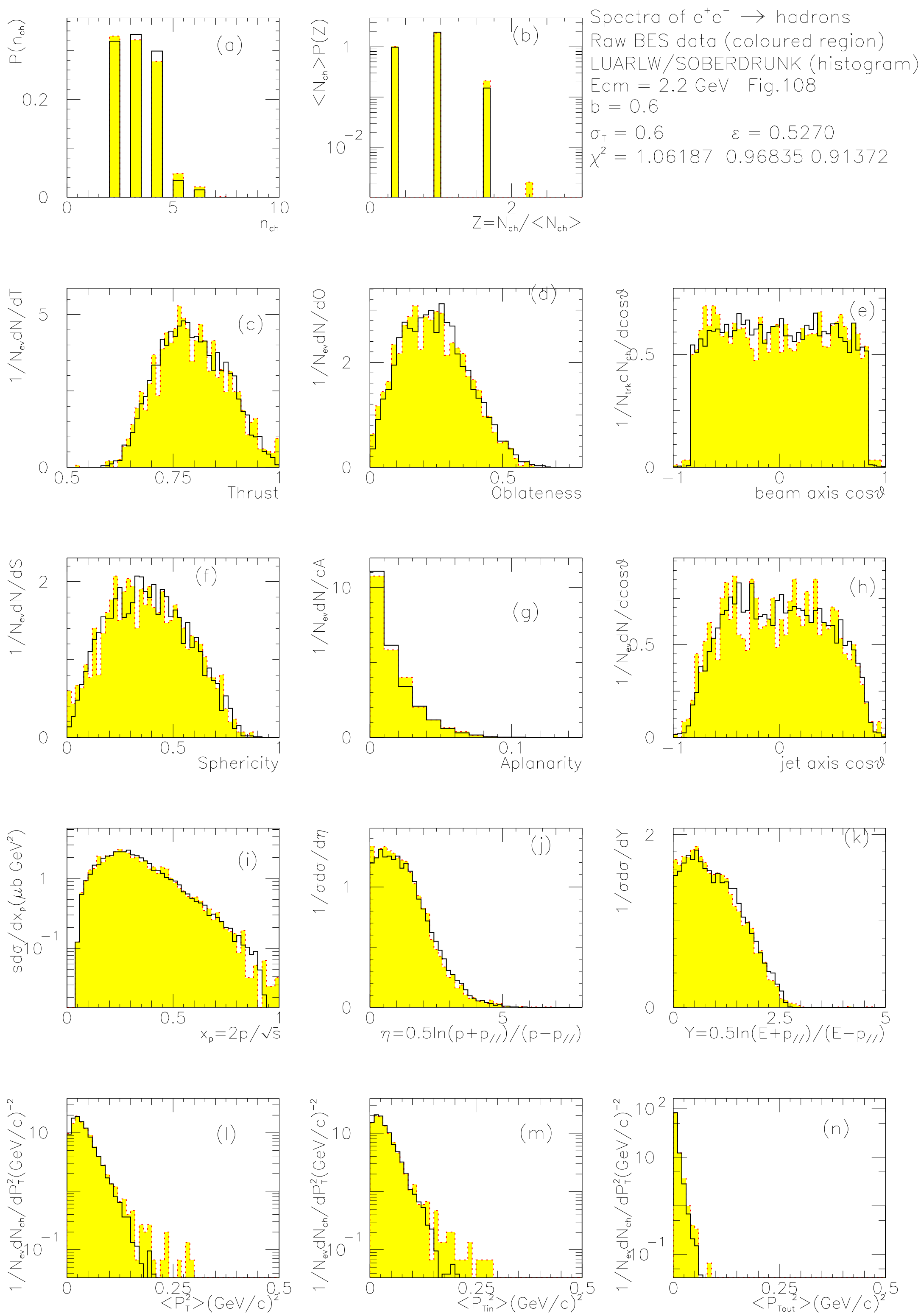
- Differences between methods range from 0.3 to 2.3 %. Included in systematic errors.
- Varied order of polynomial. Included in event selection systematic error.



Hadron Efficiency

Lund group and BES have worked to develop LUARLW:

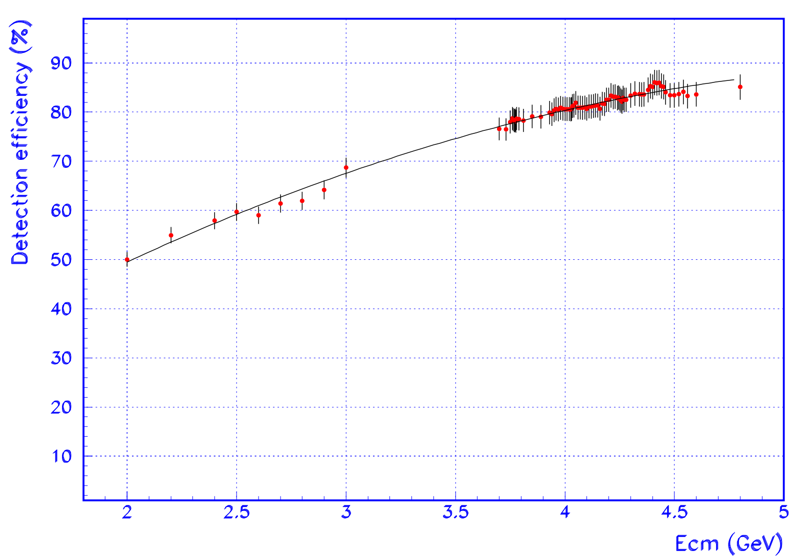
- New generator based on Area Law. Especially important to describe low energy region (≤ 3 GeV).
- Removes high energy approximation in string approximation in JETSET.
- Final state generation is exclusive.
- Above 3.77 GeV, Eichten Model used for charmed meson production.
- Parameters especially tuned to fit the data in the BES energy region.
- Uncertainty in parameters (tuning) included in systematic error.
- Tuned both locally and globally. Difference into systematic error.
- Varied D fractions. Difference in systematic error.

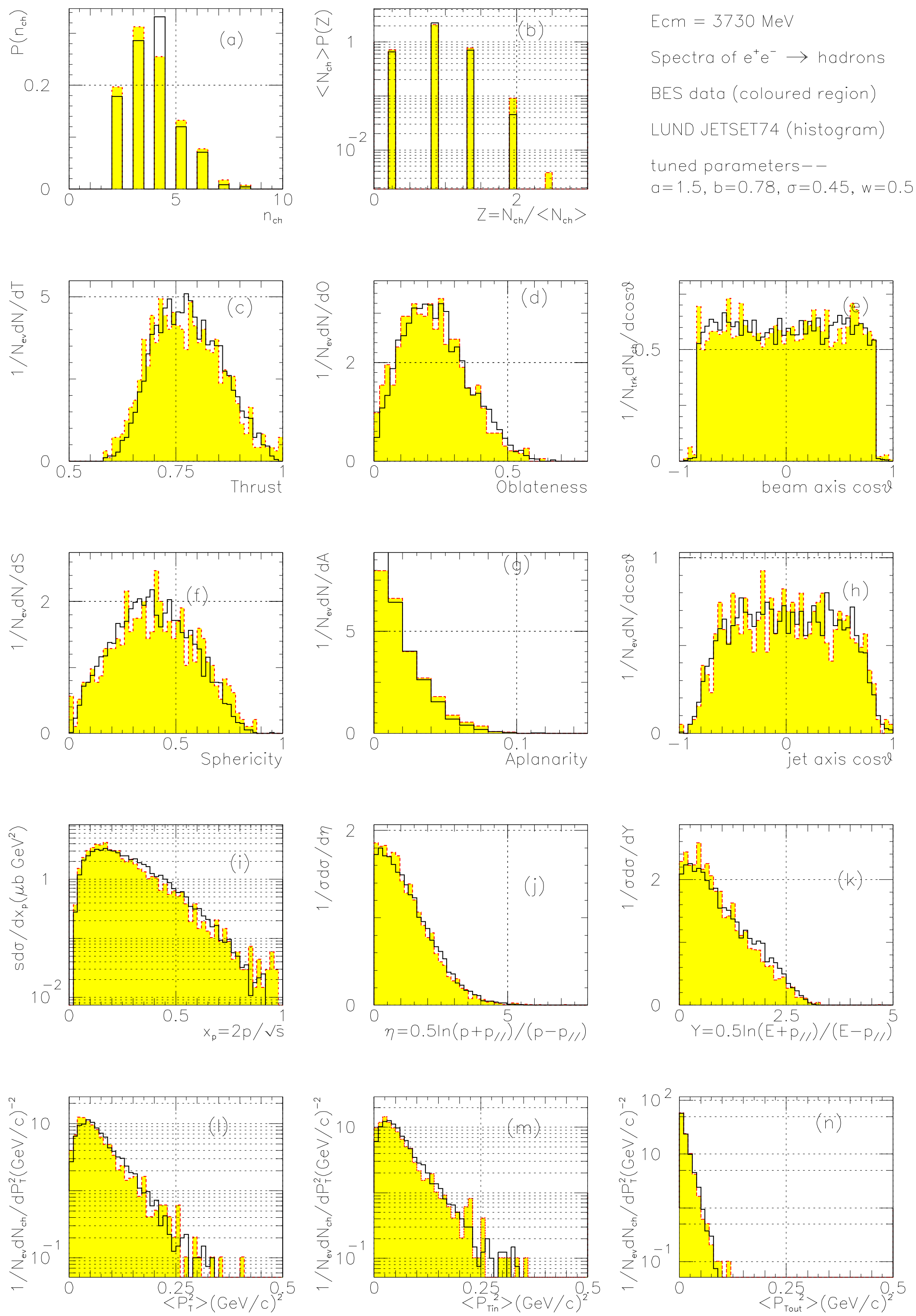

Spectra of e⁺e⁻ → hadrons
Raw BES data (coloured region)
LUARLW/SOBERDRUNK (histogram)
Ecm = 2.2 GeV Fig.108
b = 0.6
σ_T = 0.6 ε = 0.5270
χ² = 1.06187 0.96835 0.91372
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)
(m)
(n)
Thrust
Oblateness
beam axis cosϑ
Sphericity
Aplanarity
jet axis cosϑ

- ϵ_{had} above 3 GeV are also determined using Lund model: LUND - JETSET74 generator.
  - $E_{cm} > 4$ GeV, default parameters
  - $E_{cm} \leq 4$ GeV, tuned parameters
- Difference with LUARLW is about 1 % at most points but is up to 3 or 4 % at a few points. Included in systematic error.

E_{cm} (GeV)	3.0	4.6	4.8
ϵ JETSET	0.6733	0.8628	0.8796
ϵ Area Law	0.6969	0.8757	0.8664
diff (%)	3.5	1.5	1.5

- Overall systematic error about 3 %.

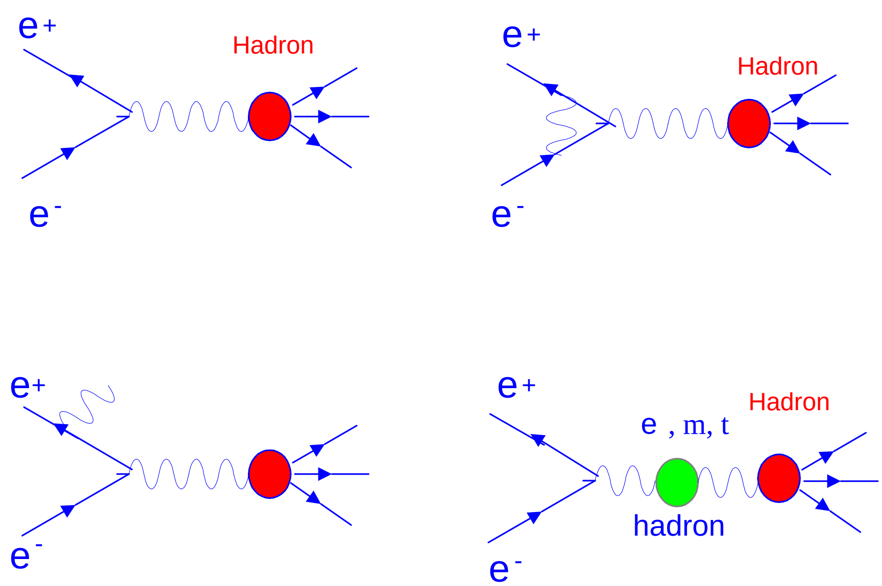



Ecm = 3730 MeV
Spectra of e⁺e⁻ → hadrons
BES data (coloured region)
LUND JETSET74 (histogram)
tuned parameters--
a=1.5, b=0.78, σ=0.45, w=0.5
(a) P(n_ch) n_ch
(b) <N_ch>P(Z) Z=N_ch/<N_ch>
(c) 1/N_ev dN/dT Thrust
(d) 1/N_ev dN/dO Oblateness
(e) 1/N_trk dN_ch/dcosϑ beam axis cosϑ
(f) 1/N_ev dN/dS Sphericity
(g) 1/N_ev dN/dA Aplanarity
(h) 1/N_ev dN/dcosϑ jet axis cosϑ
(i) sdσ/dx_p(μb GeV²) x_p=2p/√s
(j) 1/σ dσ/dη η=0.5ln(p+p//)/(p−p//)
(k) 1/σ dσ/dY Y=0.5ln(E+p//)/(E−p//)
(l) 1/N_ev dN_ch/dP_T²(GeV/c)⁻² <P_T²>(GeV/c)²
(m) 1/N_ev dN_ch/dP_T²(GeV/c)⁻² <P_Tin²>(GeV/c)²
(n) 1/N_ev dN_ch/dP_T²(GeV/c)⁻² <P_Tout²>(GeV/c)²

Radiative Corrections: $(1+\delta)$

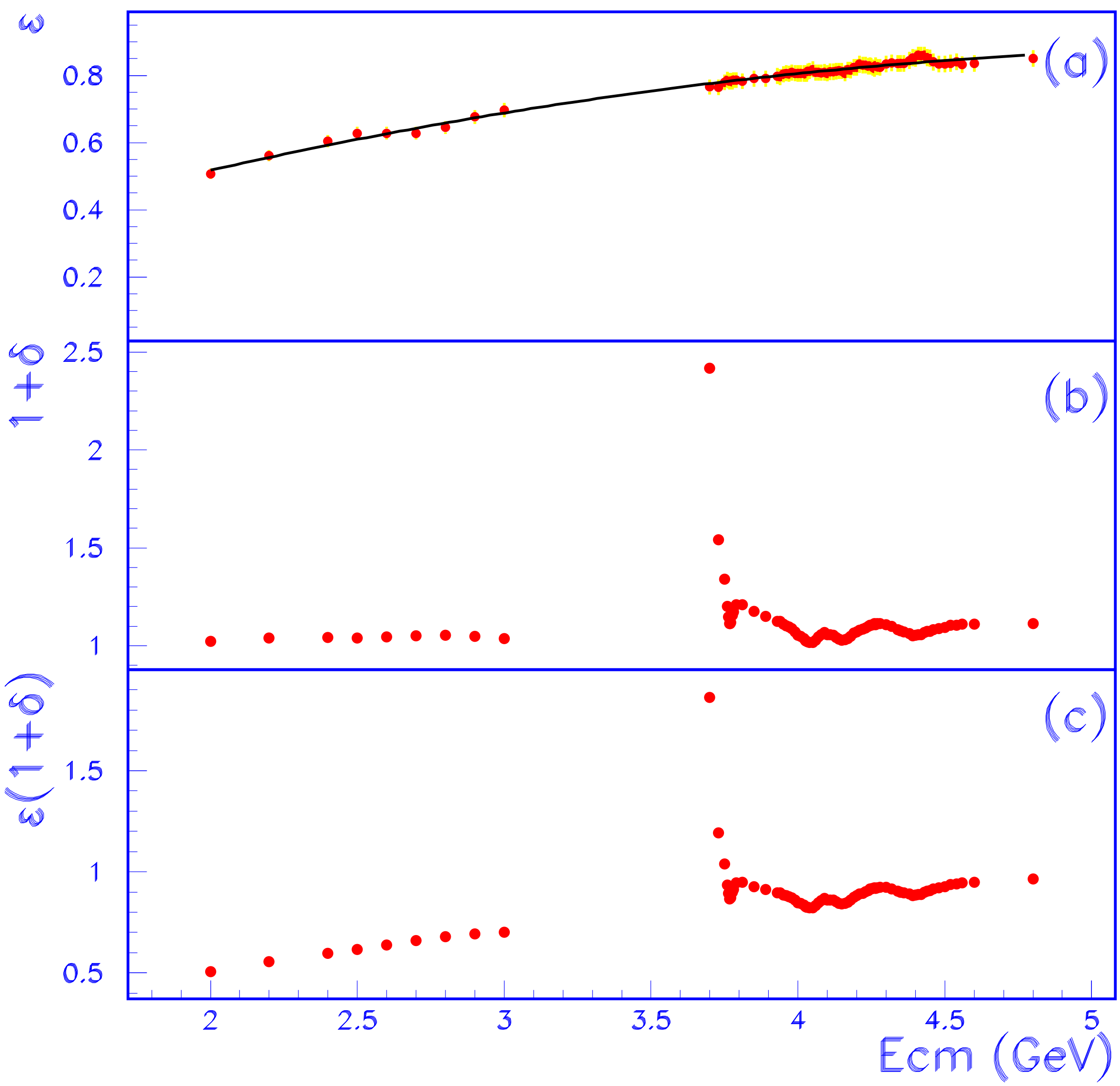
Remove high order effects from σ_{had}^{obs}

$$\sigma_{had}^{obs} = \sigma_{had}^{o} \cdot \epsilon_{had} \cdot (1+\delta)$$



- Applied methods of:
  - Berends and Kleiss
    Nucl. Phys. **B178**, 141 (1981)
  - Bonneau and Martin
    Nucl. Phys. B **27**, 387 (1971).
  - Kuraev and Fadin
    Sov. J. Nucl. Phys. **41**, 3 (1985)
  - Osterheld *et al.*
    SLAC-PUB-4160, 1990. (T/E)

- all agree within 1% in continuum region; 1-3 % in resonance region.
- Use Osterheld method and include differences in systematic error.



Luminosity Measurement

Integrated luminosity:

$$L = \frac{N_{obs}}{\sigma \epsilon \epsilon_{trg}}$$

Used: $\gamma\gamma$, Bhabha, and dimu events

Results consistent

Systematic error: cut variations, background uncertainties, cross section uncertainty, and efficiency uncertainty.

Trigger Efficiency

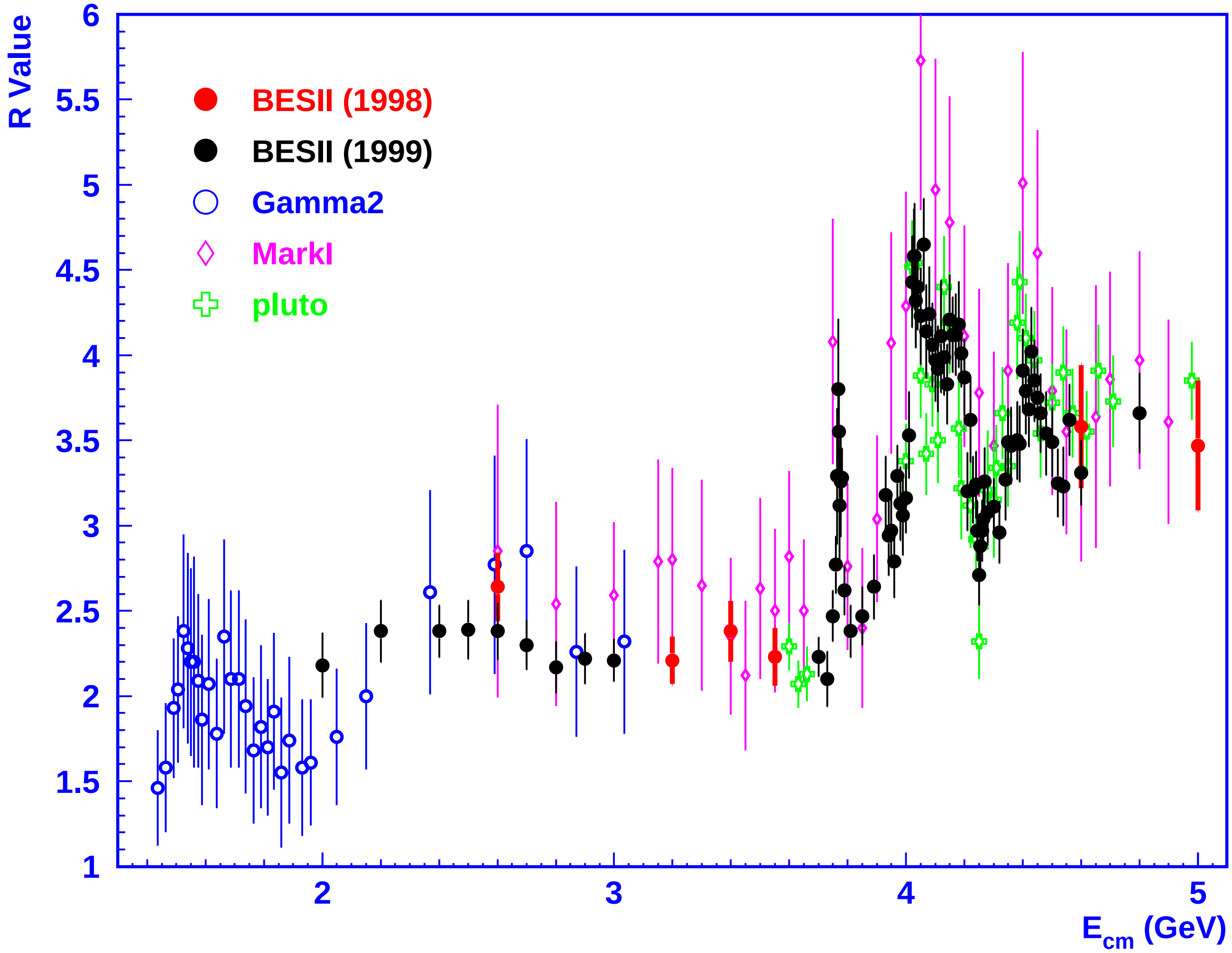
Measured by comparing different trigger configurations in runs at J/ψ.

$$\epsilon_{\text{Bhabha}} = 99.96\%$$
$$\epsilon_{\mu\mu} = 99.33\%$$
$$\epsilon_{\mu\mu} = 99.76\%$$

Error = 0.5 %

BES Results

- 1998 results published: **J.Z. Bai** *et al.*, **Phys. Rev. Lett.84, 594 (1999).**
- 1999 results submitted to PRL: **J.Z. Bai** *et al.*, **hep-ex/0102003**



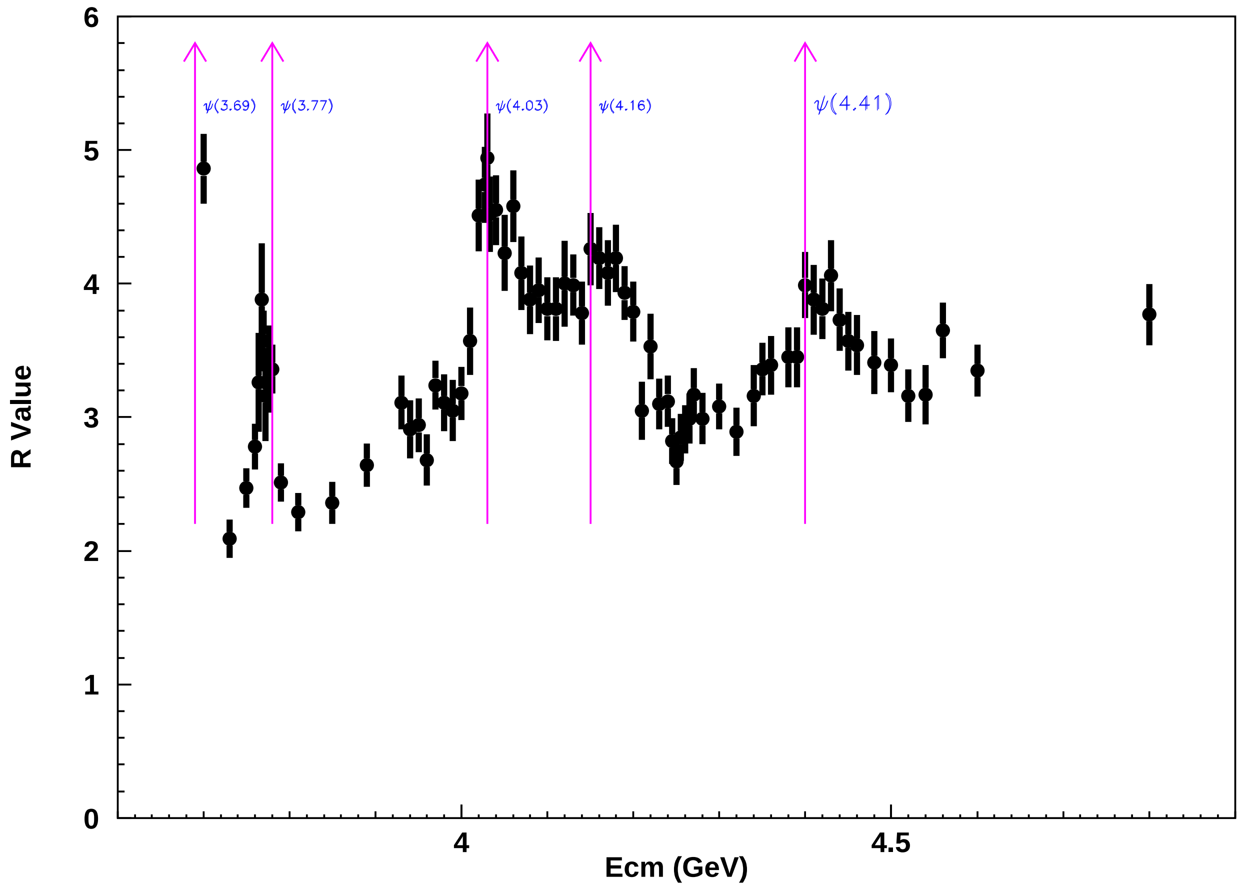
- Values at a few typical energy points.

E_{cm}(GeV)	$N_{\rm had}$	$N_{ll}+N_{\gamma\gamma}$	L($\rm nb^{-1}$)	$\epsilon_{\rm had}$ (%)	$1+\delta$
2.0	1155.4	19.5	47.3	49.50	1.024
3.0	2055.4	24.3	135.9	67.55	1.038
4.0	768.7	58.0	48.9	80.34	1.055
5.0	1215.3	93.6	84.4	86.79	1.113

- Systematic uncertainties are between 6 and 10 % and are about half of the previous uncertainties. Average 6.6 %.

- Systematic errors at 3.0 GeV.

Source	Error (%)
N_{had}	3.3
L	2.3
$1+\delta$	1.3
ϵ_{had}	2.7
Sys.	5.0
Stat.	2.5
Total	**5.6**



6
5
4
3
2
1
0
R Value
4
4.5
Ecm (GeV)
ψ(3.69)
ψ(3.77)
ψ(4.03)
ψ(4.16)
ψ(4.41)

New CLEO Measurement

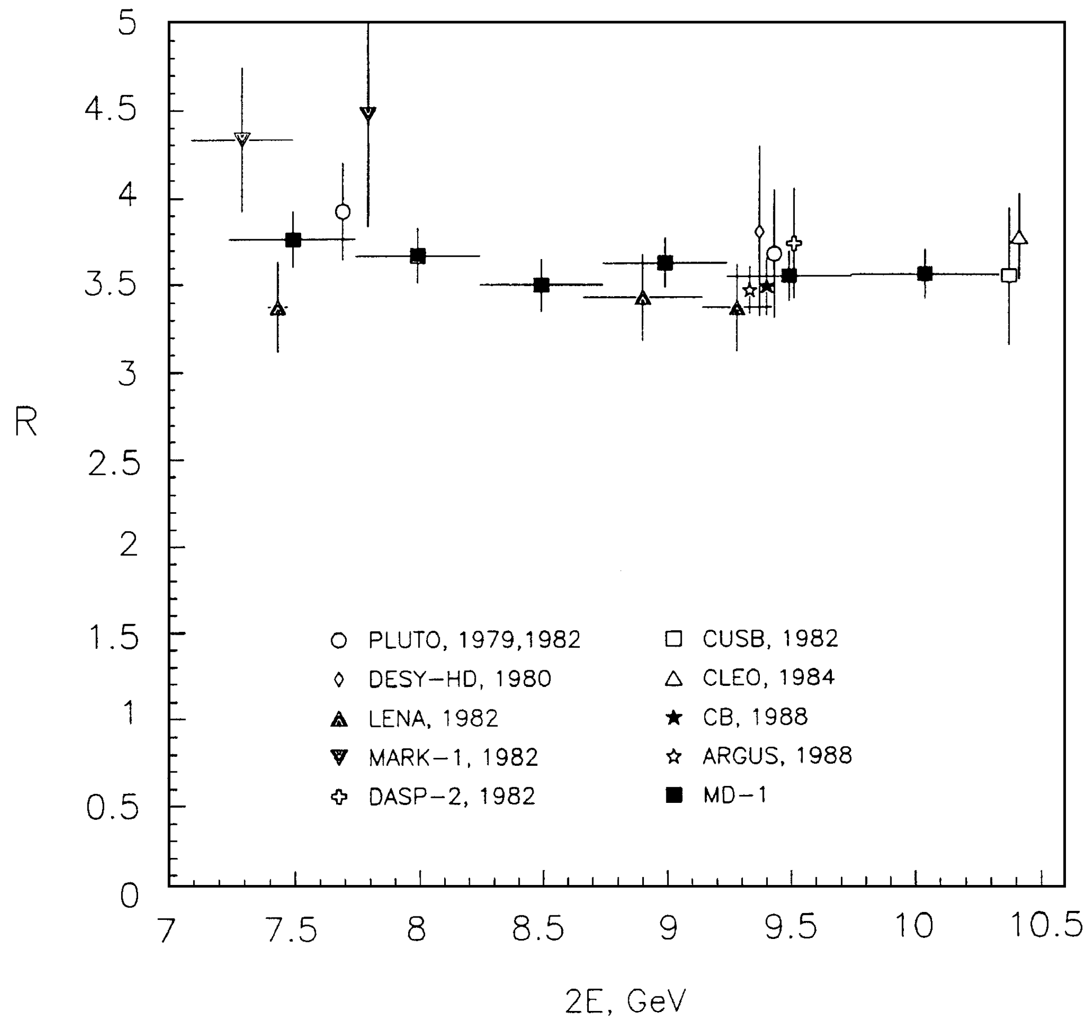
R. Ammar *et al.* , CLEO Collab., Phys. Rev. D57, 1350 (1998).

Measured R at $E_{cm} = 10.52$ GeV. Just below $\Upsilon(4S)$

$$R = 3.56 \pm 0.01 \pm 0.07 \qquad (2\%)$$

Very precise - error similar to error of all previous results in this region combined.

$$\bar{R} = 3.579 \pm 0.066 \qquad (1.8\%)$$



A. E. Blinov *et al.* , Z. Phys. C 70, 31 (1996).

Why errors much smaller than BES?

- better solid angle coverage and detection efficiency.
- better detector.
- higher luminosity: (1.521 ± 0.015) fb^{-1}
- more events: 4 M

Source	BES Error (%) (3 GeV)	CLEO Error (%)
N_{had}	3.3	–
Backgd./Ev. Modeling	–	0.7
L	2.3	1.0
$1+\delta$	1.3	–
ϵ_{had}	3.0	–
$\epsilon_{had} \times (1+\delta)$	–	1.0
Sys.	5.2	1.8
Stat.	2.5	0.3
Total	5.8	2.0

With a much bigger sample, both statistical and systematic errors are reduced.

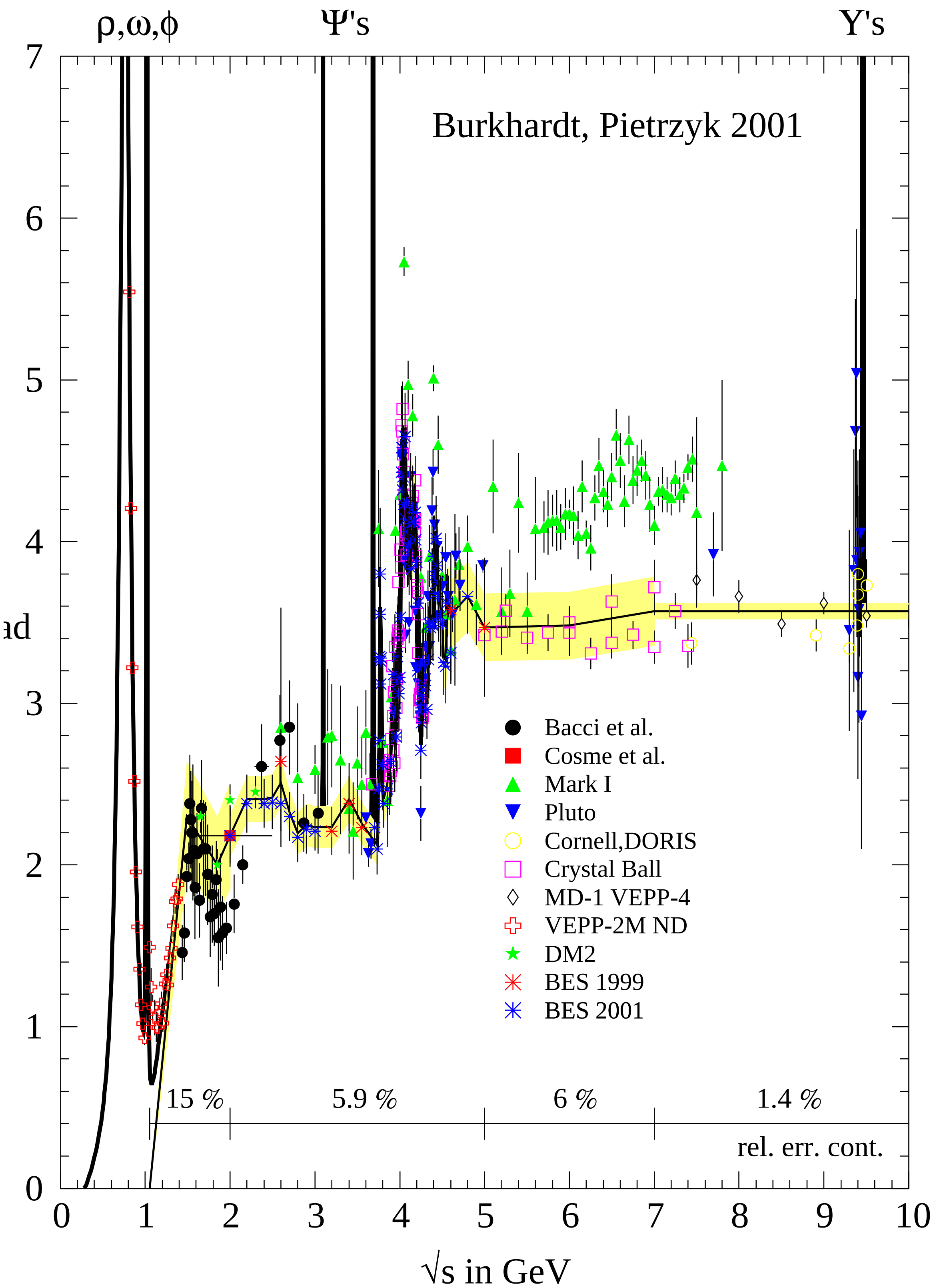
Current Status

- Burkhardt and Pietrzyk have an updated analysis with CMD-2, CLEO, BES, and 3rd order QCD for $E_{cm} > 12$ GeV.
  (H. Burkhardt and B. Pietrzyk, accepted by Phys. Lett. B, LAPP-EXP 2001-03 (Feb. 2001).)

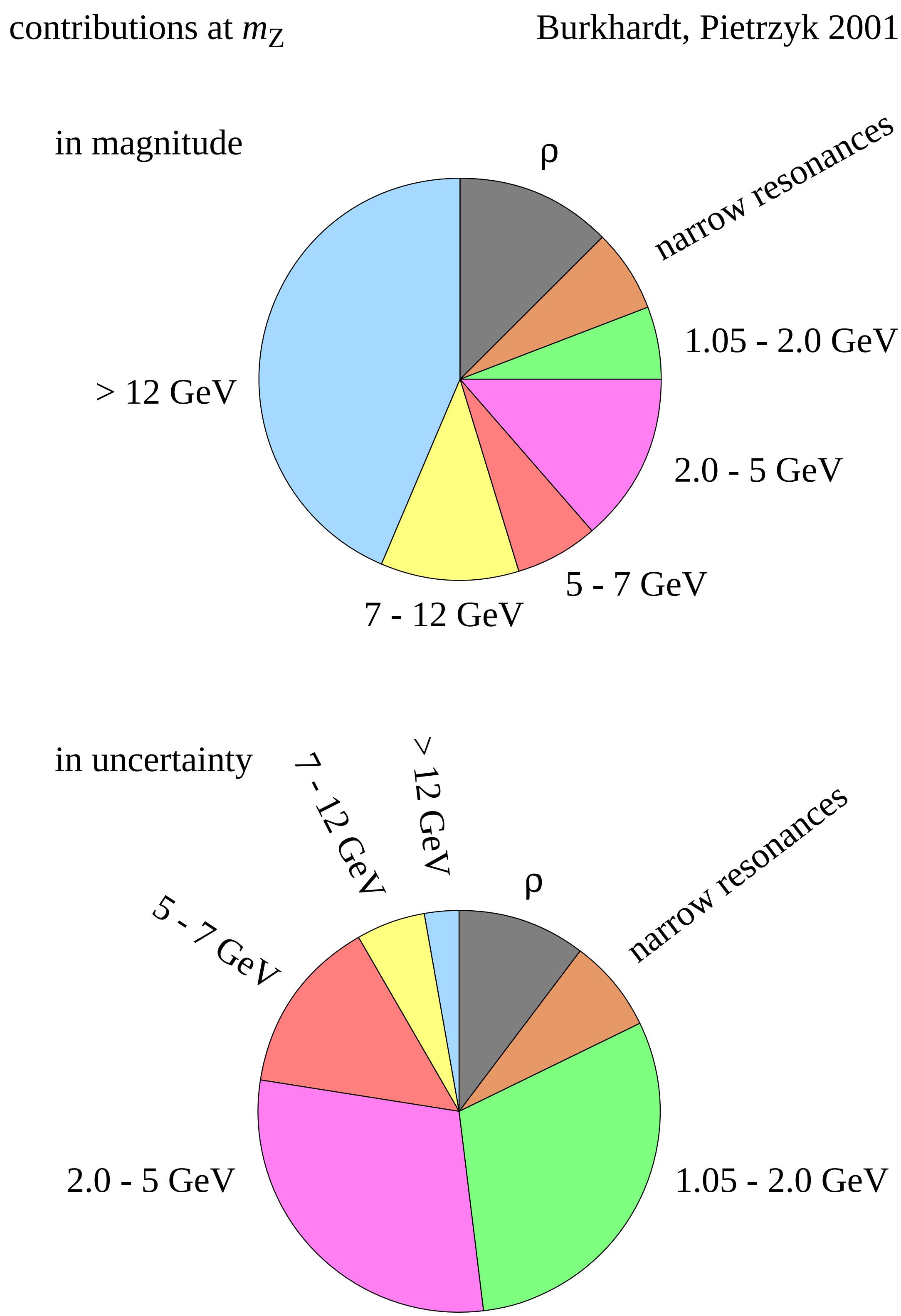
  $\alpha^{-1}(M_Z^2) = 128.936 \pm 0.046$
  $\Delta\alpha_{\rm had}^{(5)} = 0.02761 \pm 0.00036$

  Previously:

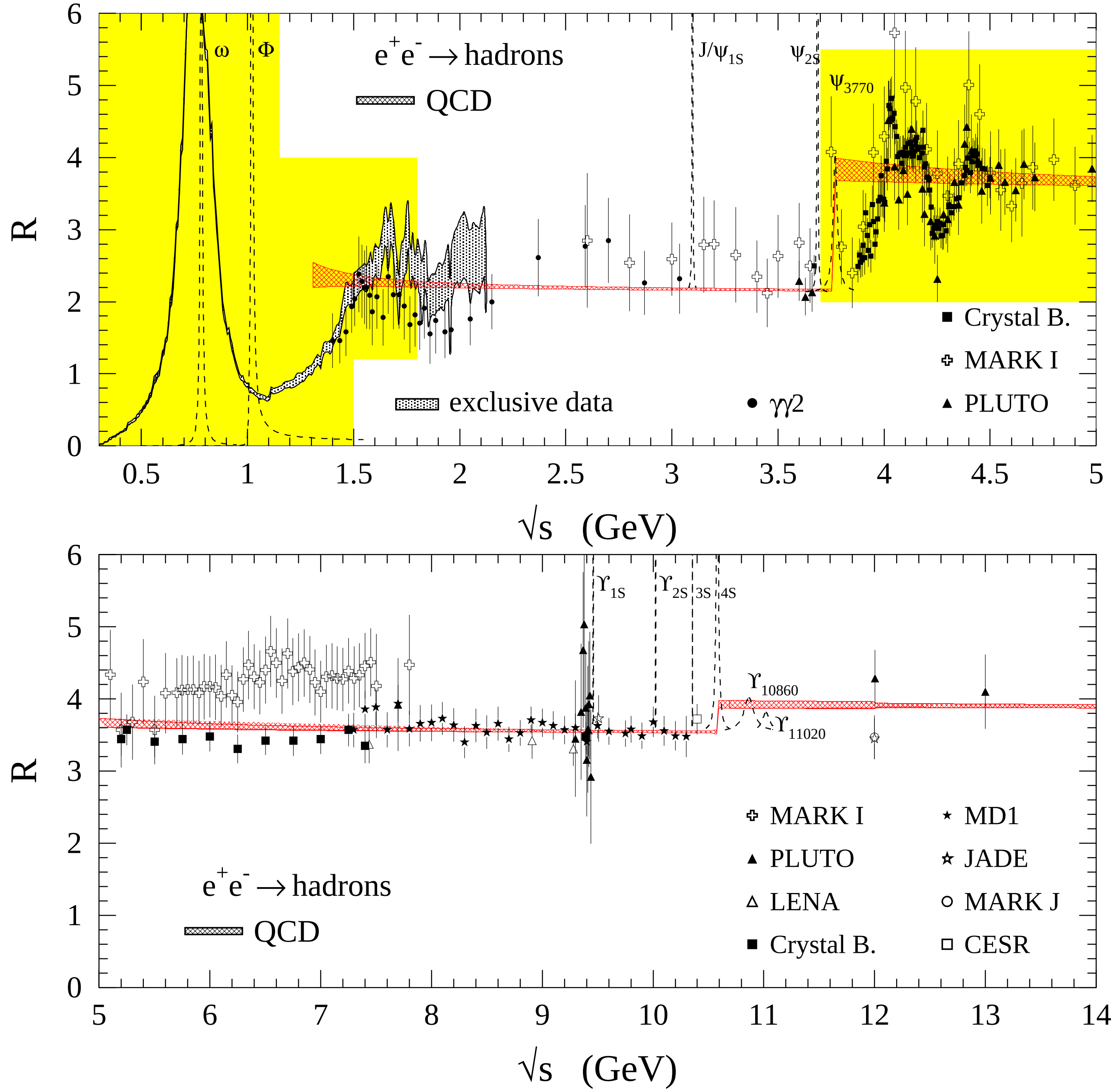
  $\alpha^{-1}(M_Z^2) = 127.938 \pm 0.027$ (PDG2000)

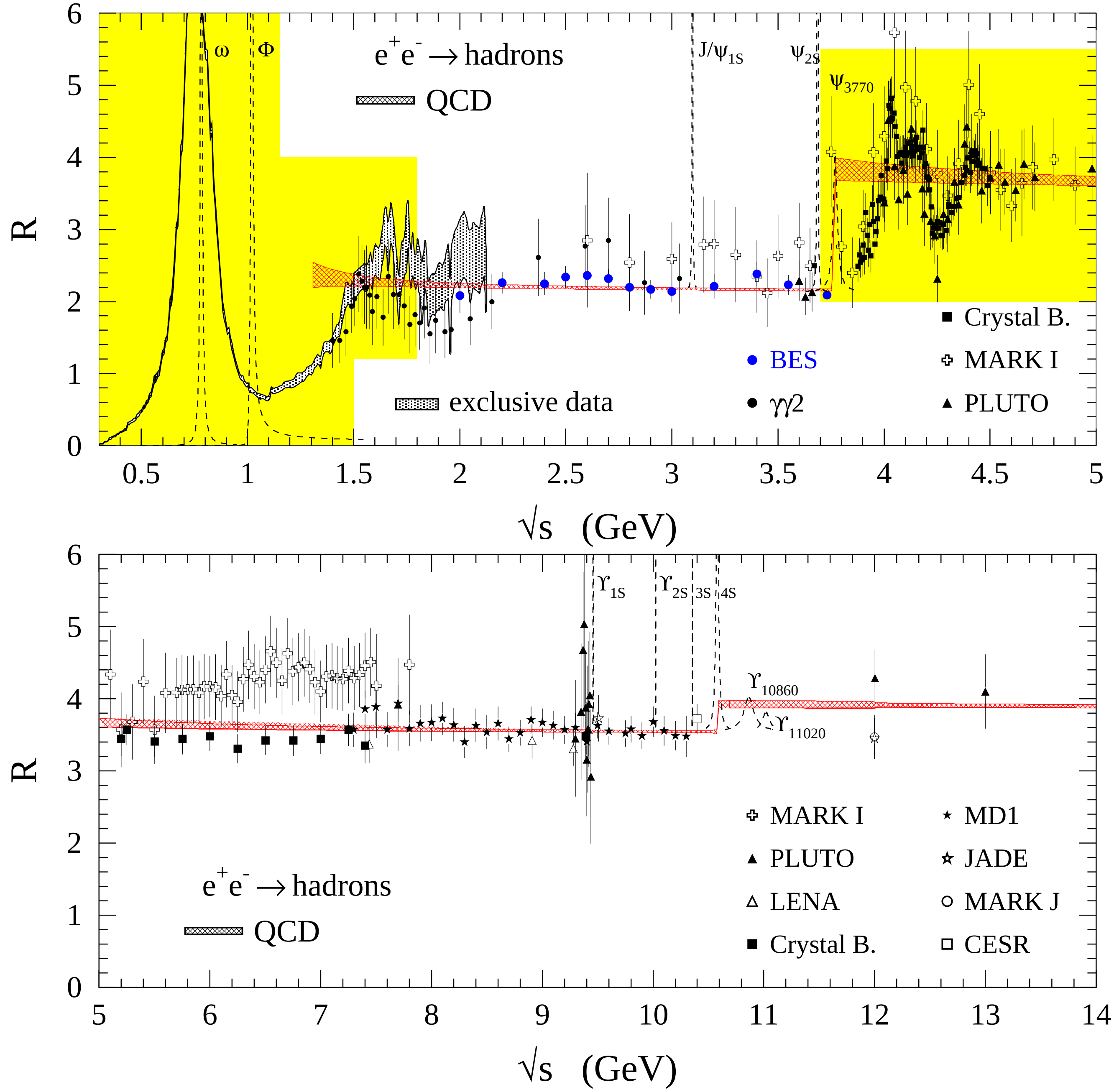


ρ,ω,φ
Ψ's
Υ's
Burkhardt, Pietrzyk 2001
ad
Bacci et al.
Cosme et al.
Mark I
Pluto
Cornell,DORIS
Crystal Ball
MD-1 VEPP-4
VEPP-2M ND
DM2
BES 1999
BES 2001
15 %
5.9 %
6 %
1.4 %
rel. err. cont.
√s in GeV


contributions at m_Z
Burkhardt, Pietrzyk 2001
in magnitude
ρ
narrow resonances
1.05 - 2.0 GeV
2.0 - 5 GeV
5 - 7 GeV
7 - 12 GeV
> 12 GeV
in uncertainty
7 - 12 GeV
> 12 GeV
ρ
narrow resonances
5 - 7 GeV
2.0 - 5 GeV
1.05 - 2.0 GeV

- Experimental R-values below 5 GeV confirm QCD calculation (M. Davier and A. Hoecker, Phys. Lett. B419, 419 (1998).)





e+e- → hadrons
QCD
exclusive data
ω
Φ
J/ψ1S
ψ2S
ψ3770
BES
γγ2
Crystal B.
MARK I
PLUTO
R
√s (GeV)
ϒ1S
ϒ2S
3S
4S
ϒ10860
ϒ11020
MARK I
PLUTO
LENA
Crystal B.
MD1
JADE
MARK J
CESR

Future R Measurements?

- Need to improve 1 - 2 GeV cm region. Important for both a_μ and $\alpha(M_Z^2)$
  - KLOE
  - PEP-N
- Also 2 - 5 GeV.
  - BES in 2001?
  - PEP-N
  - CLEO-C
  - ISR Events at Belle and BaBar? T. Benninger, X.C. Lou, and W. M. Dunwoodie, "Physics with ISR EVENTS at B Factory Experiments"
- Next 5 - 7 GeV region.
  - CLEO-C
  - ISR Events at Belle and BaBar

What is needed to improve precision?

- High luminosity $\rightarrow$ large sample
- Good solid angle coverage
- Excellent detector
- Radiative correction better than 1 %
- More effort on event generator (LUARLW)
- Large sample for tuning generator
- Measure exclusive channels at low energy. Need good PID

Energy reach of PEP-N?

Suggestion: Extend energy range to above $\psi(2S)$

- Above threshold for $\tau\tau$ production.
- Can study decays of η_c and χ_c states.
- Study $\psi(2S)$ hadronic decays.

Study $\rho\pi$ puzzle

- Compare J/ψ and $\psi(2S)$ decays.

World's largest sample: $\sim$4 M events (BES)

Summary

- Improved R-value precision very important because of a_μ and $\alpha(m_Z^2)$.
- BES measurements are a major improvement.
- Many interesting possibilities for future improvements.