Perspectives and Challenges on:

Spectroscopy and decays of charmonia below DD threshold

Charmonium yields: B factories vs dedicated factories

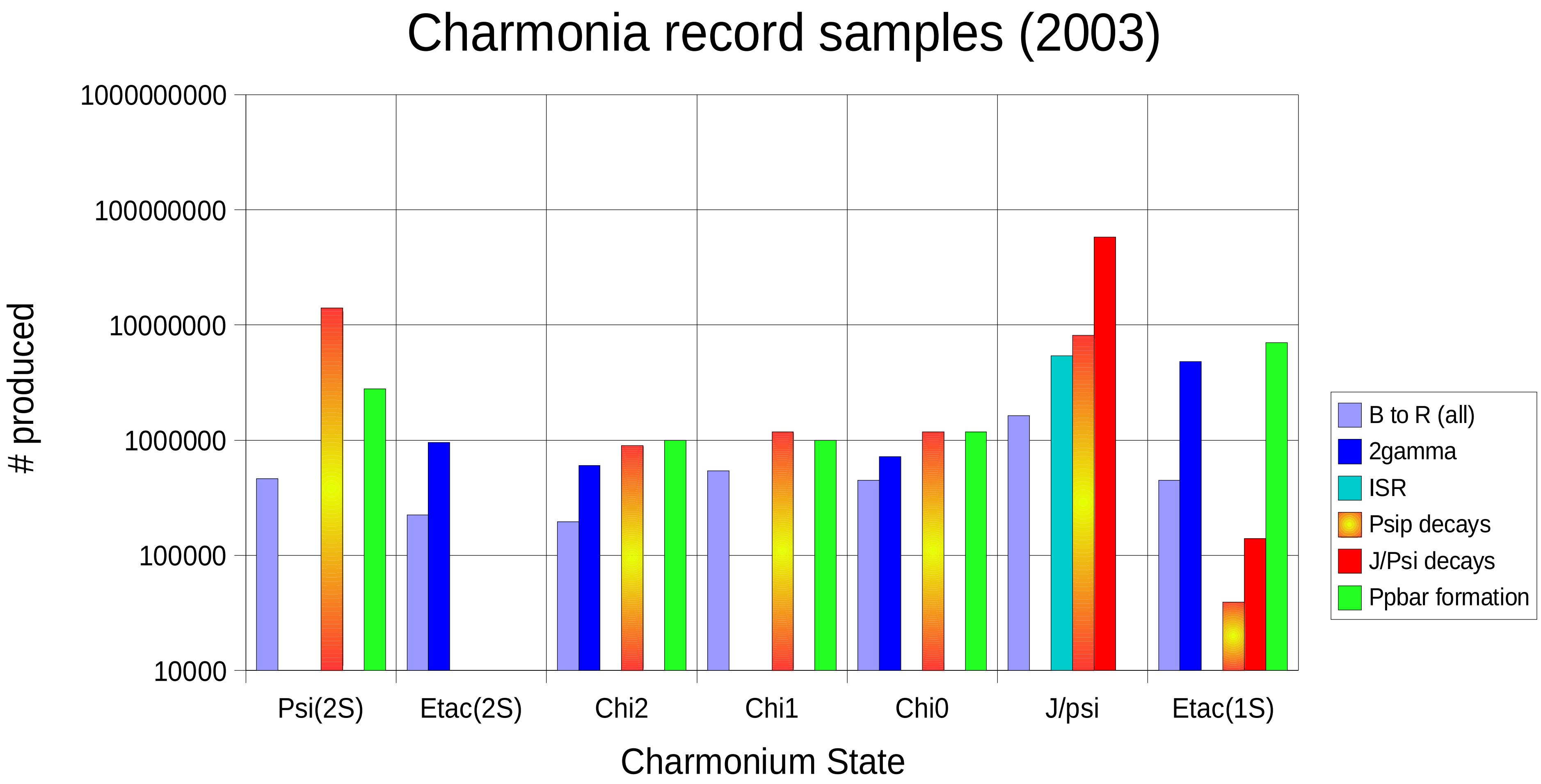
Precision studies on QCD with charmonia

Unresolved issues: searches , puzzles

Technical problems, possible solutions

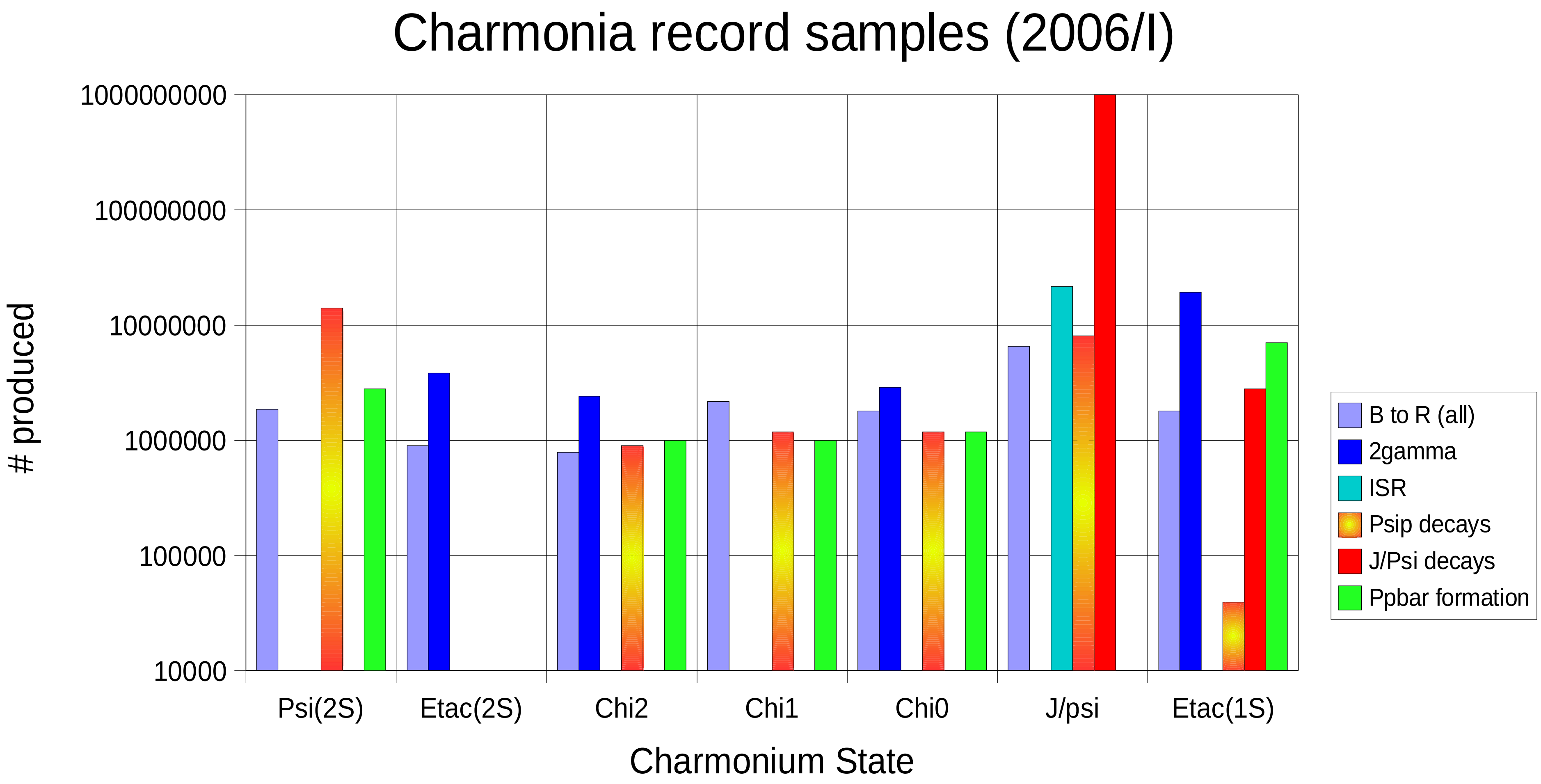
A wishlist

Roberto Mussa , INFN Torino
Joint CLEO-c/BES||| Workshop, Beijing, Jan.13-15, 2004



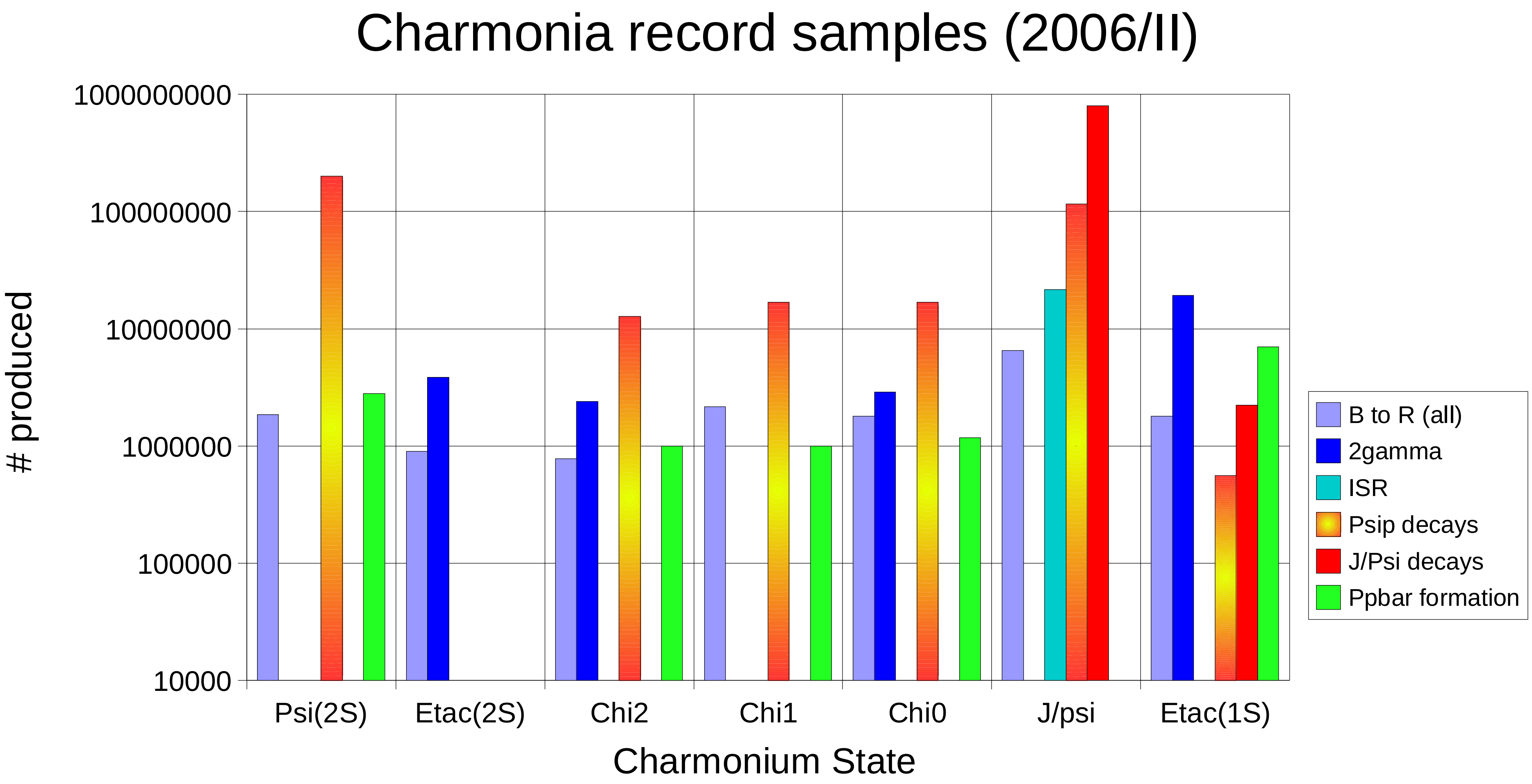
Here we plot the number of charmonia produced in:

- Asymmetric B-factory: Babar | Belle, with 150 fb-1
- τ-charm factory : BES, with 58 M J/ψ and 14 M ψ(2s)
- p$\bar{p}$ charmonium factory: E835



Here we plot the number of charmonia produced in:

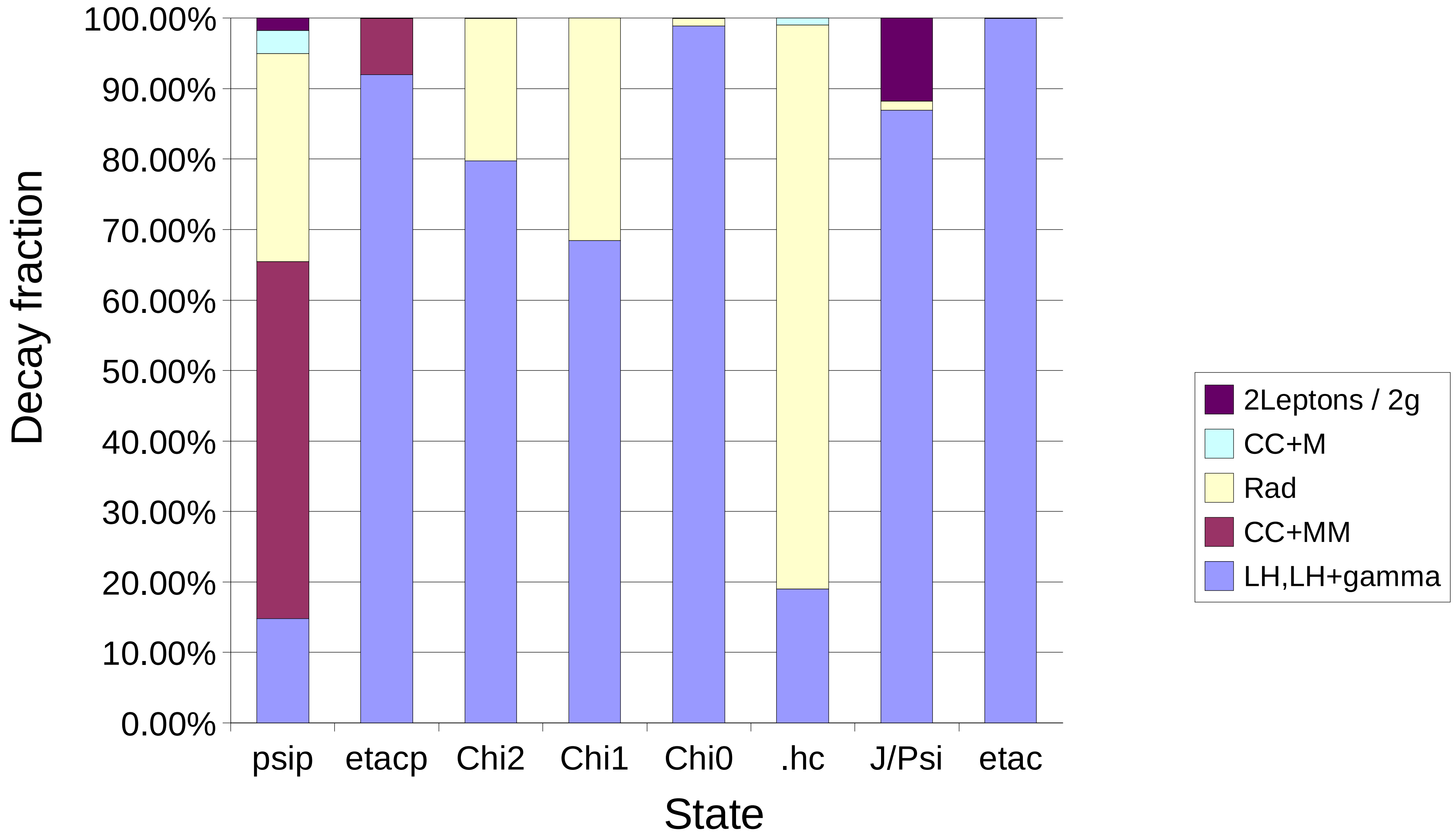
- Asymmetric B-factory: Babar | Belle, with 500 fb-1
- τ-charm factory : CLEO-c, with 1G J/ψ and BES, 14 M ψ(2s)
- $p\bar{p}$ charmonium factory: E835



Here we plot the number of charmonia produced in:

- Asymmetric B-factory: Babar | Belle, with 600 fb-1
- τ-charm factory : CLEO-c, with 0.8G J/ψ and 200 M ψ(2s)
- $p\bar{p}$ charmonium factory: E835

Charmonium decays



The road to precision charmonium physics

- Solid Roots: a group of reactions known with very good accuracy: 1-3% , as a figure of merit.
- When statistics is rich, focus on systematics:
  - Crosschecks between experiments are crucial
  - Angular distributions provide inner crosschecks
  - Global fits accounting for correlations between measurements
  - Interference with continuum must be under control
- When statistics is poor: focus on backgrounds:
  - Feeddown calculations
  - MonteCarlo tools
  - Blind analysis , whenever is possible

The goal of precision charmonium physics

- To provide a robust and consistent ideal laboratory to study the interplay between perturbative and non-perturbative aspects of QCD, exploiting :

(on the experimental side)

- The huge increase in available data on this system which we are experiencing in this decade
- The large variety of techniques which allow access to these states
- The clear experimental signature of charmonia

(on the theoretical side)

- The progress in computational techniques of Lattice QCD
- The robust EFT formalization of NRQCD (and derivations), which try to decouple hard and soft scales from the non perturbative regime.

A multifold approach: the (Heavy) Quarkonium Working Group

A joint experimental & theoretical working group to define priorities , unify language, develop common analysis tools and maximize the amount of information than can be extracted from the wealth of new data.

- Spectroscopy
- Precision SM measurements
- Decays
- Quarkonium at finite T
- Production
- New Physics Opportunities

QWG1, CERN, November 2002
QWG2, FNAL, September 2003

Visit our web site at www.qwg.to.infn.it

CHARMONIUM RADIATIVE TRANSITIONS

- are the main road to access non vector states from e+e- machines.

- are an ideal arena to study relativistic corrections on charmonium wavefunctions

- Should be ideal tools to measure both β_c and μ_c

CHARMONIUM RADIATIVE TRANSITIONS

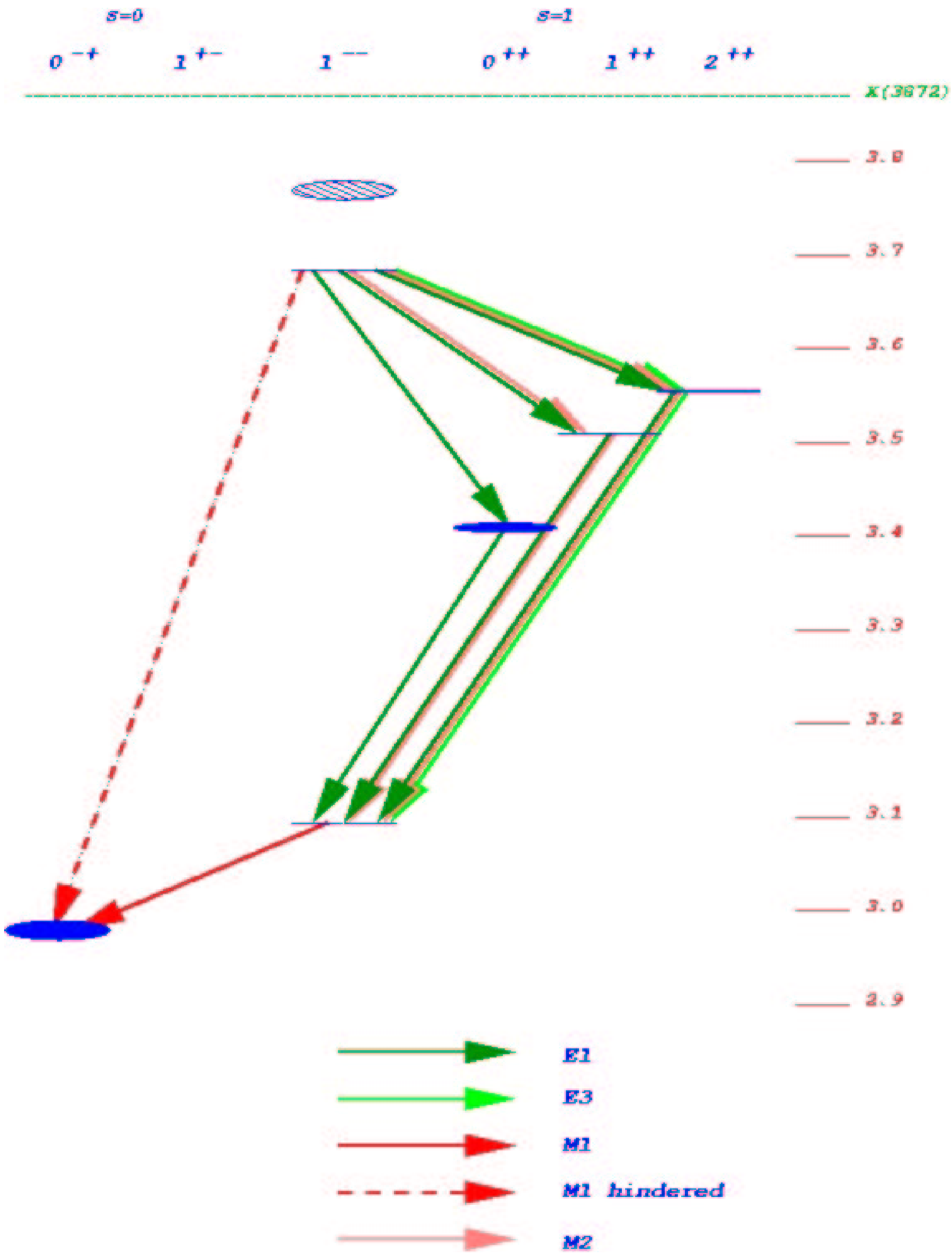
- are the main road to access non vector states from e+e- machines.

- are an ideal arena to study relativistic corrections on charmonium wavefunctions

- Should be ideal tools to measure both β_c and μ_c

We have:

- The good old ones (8+4 parameters to measure)....



CHARMONIUM
RADIATIVE TRANSITIONS

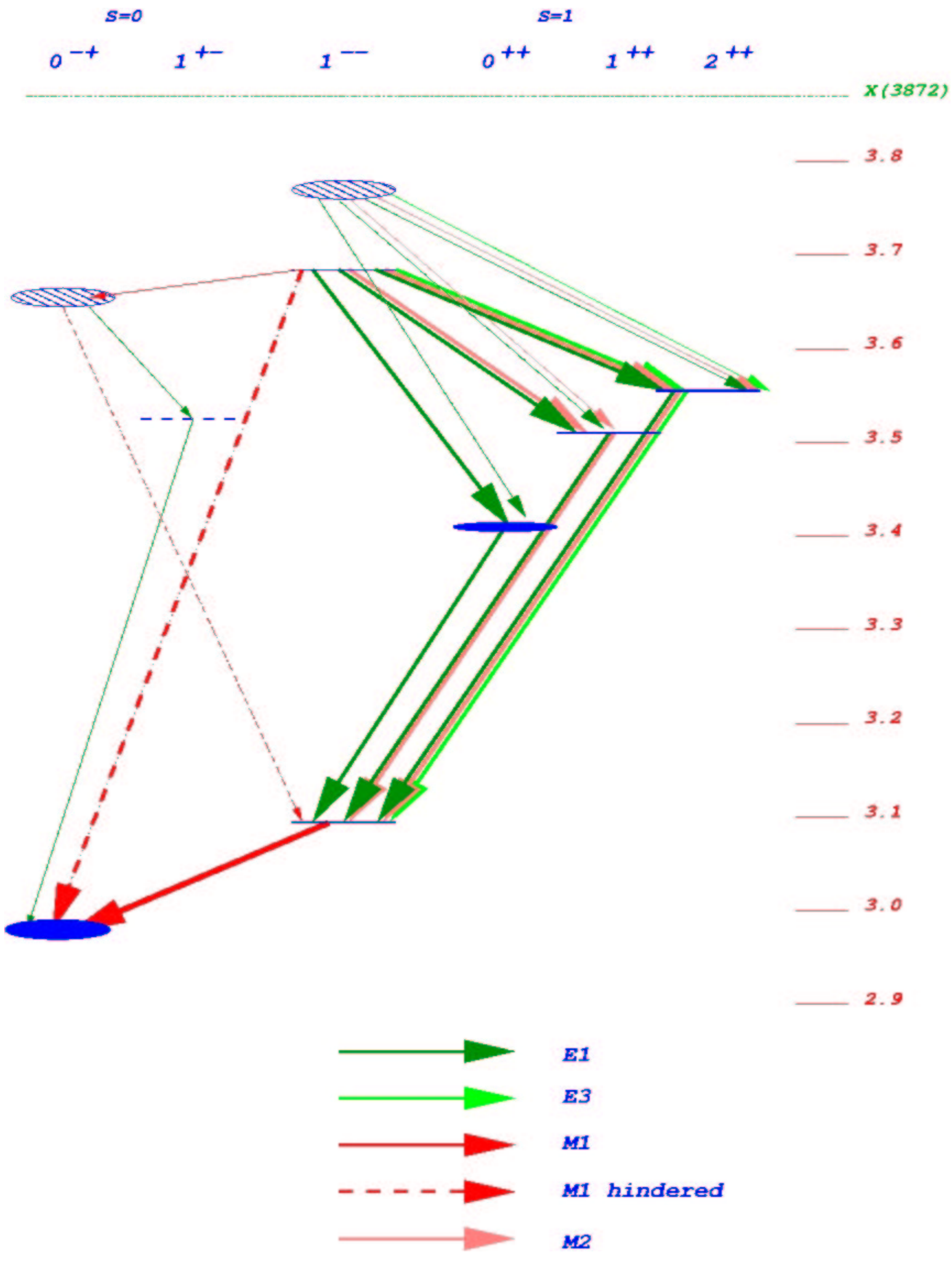
- are the main road to access non vector states from e+e- machines.

- are an ideal arena to study relativistic corrections on charmonium wavefunctions

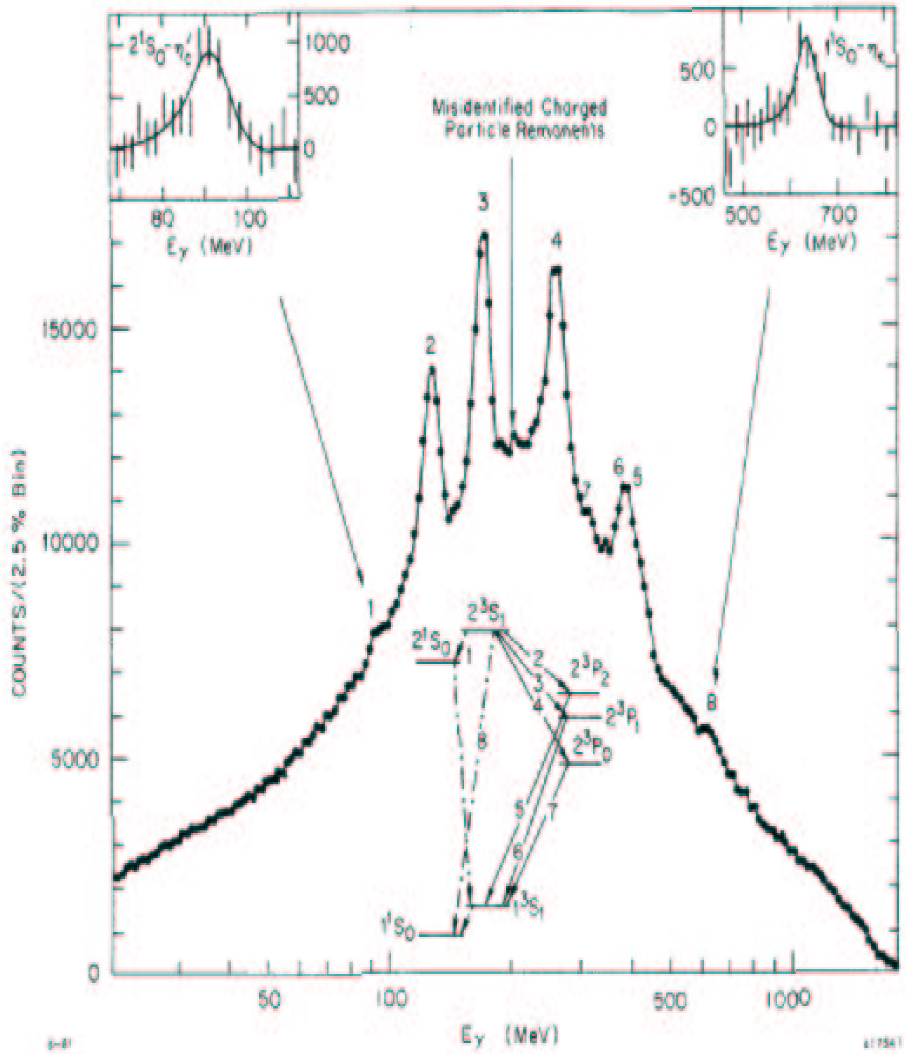
- Should be ideal tools to measure both β_c and μ_c

We have:

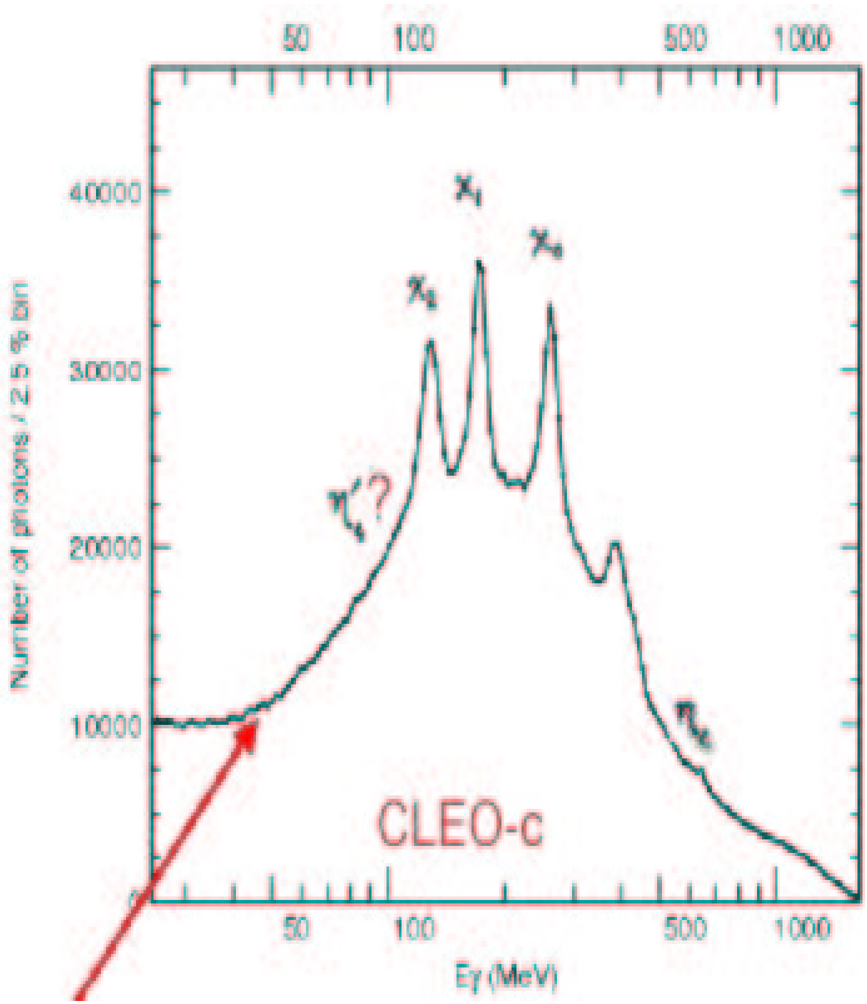
- The good old ones (8+4 parameters to measure)....
- ... and tough new ones (7+3 other parameters)



Inclusive photon data spectrum



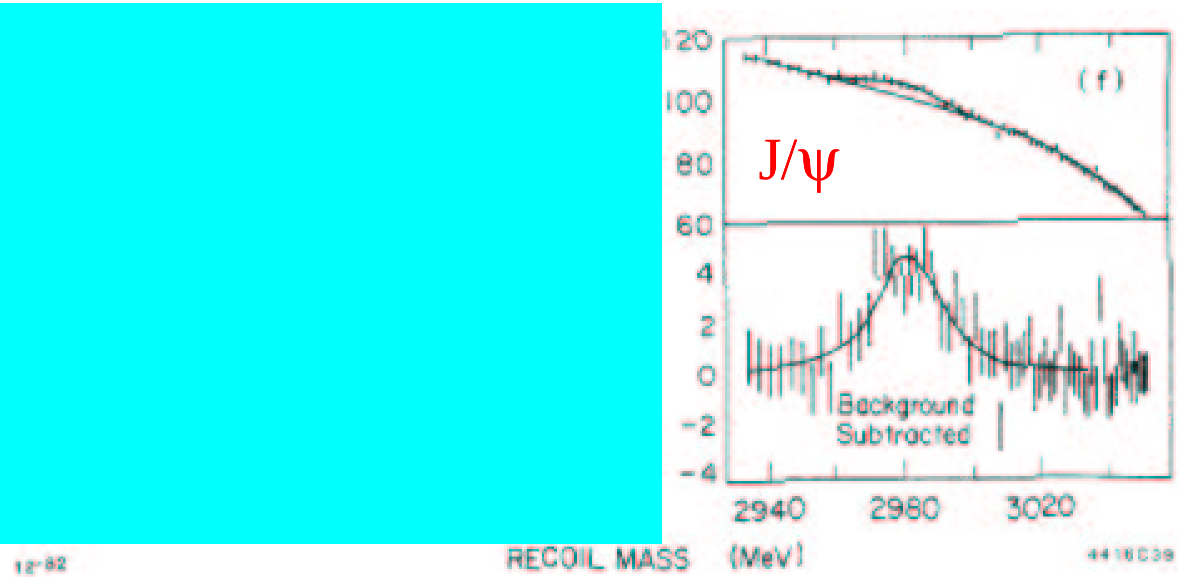
Crystal Ball 1982 : 1.8 M ψ(2s)



η_c(2s) seen at B-factories

CLEO-c 2002 : 1.5 M ψ(2s)

Inclusive photon data spectrum : M1 peaks



Crystal Ball 1982 :

1.8 M $\psi(2s)$, 2.2M J/ψ

$BR(J/\psi \rightarrow \gamma\eta_c) = 1.3 \pm 0.3\%$

$BR(\psi(2s) \rightarrow \gamma\eta_c) = 0.28 \pm 0.06\%$

Small Direct M1: large relativistic corrections, or large negative anomalous magnetic moment ?

CLEO-c 2002 :

1.5 M $\psi(2s)$

- Statistic errors on M1 BR's are *already* the dominant systematic on $BR(B \rightarrow K\eta_c)$

New results from CLEO-c shape the future problems

E1 and M1 transitions from ψ(2S)

BR(ψ(2S) → γ η_c(1S)) in %

	Hindered M1 line
)	$J = 0$
± 0.87	0.278 ± 0.033 ± 0.049
± 0.8	0.28 ± 0.06
.8	0.28 ± 0.06
.13	0.99 ± 0.30

	Hindered M1 line
0	$J = 0$
± 0.27 ± 1.31	641.5 ± 2.4 ± 3.3
0.03	639.00 ± 0.28
11 0.0050	1.0039 ± 0.064

(H.Muramatsu @ QWG2)

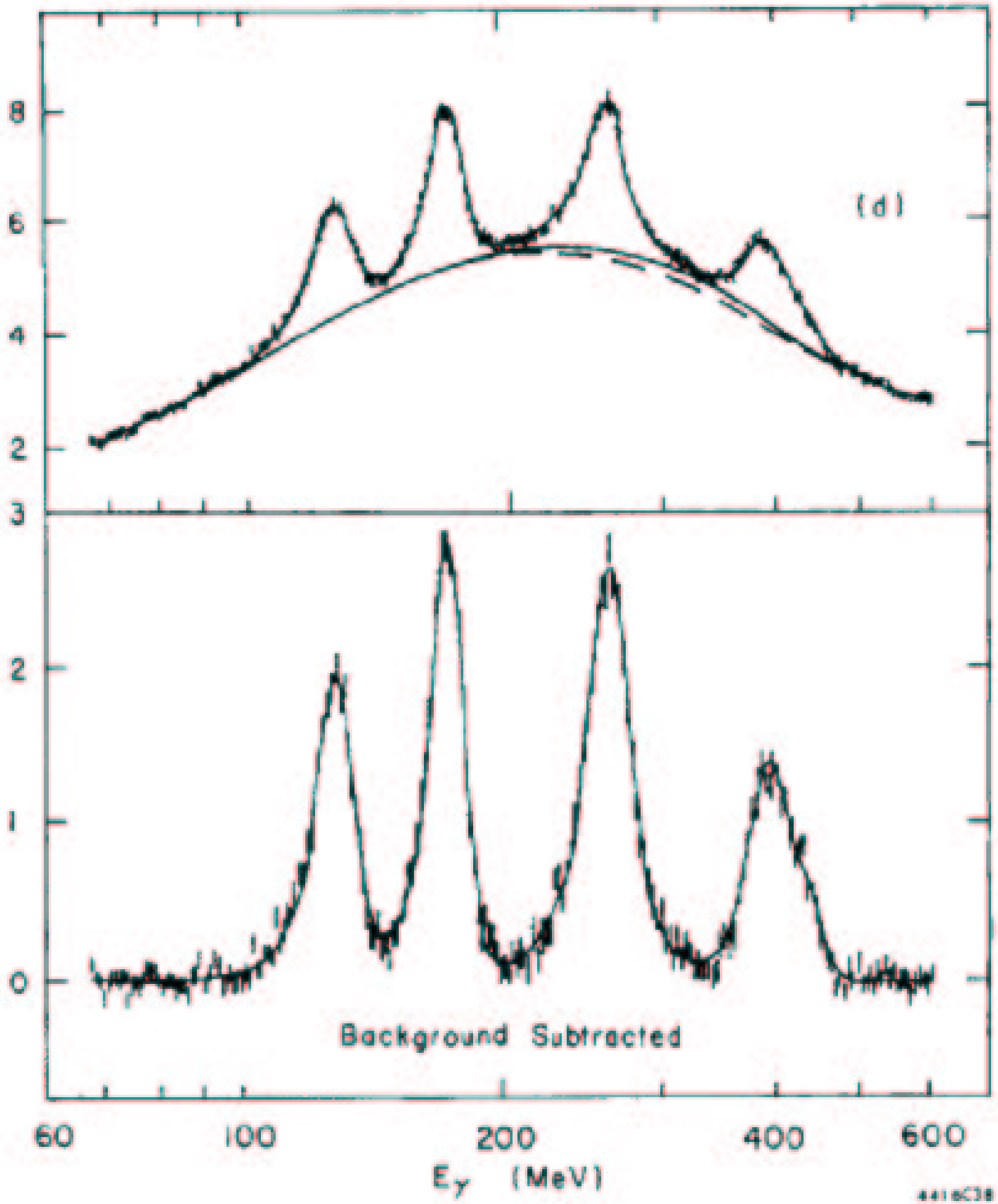
- 200 M ψ(2s) decays needed to reach 1% stat errors on hindered M1.
- Syst errors on the 640 MeV hindered M1 photon (Eγ and BR) should be manageable to reduce.
- before CLEO-c J/ψ run (2006), *assuming you will take ~20 M ψ(2s) for calibrations*, statistical error may go to 3% on BR, and 0.6 MeV on mass.
- CLEO-c has good chances to pin down η_c mass+width before 2006.
- Cross checks:
  - γ inclusive vs
  - X_i inclusive

$$BR(J/\psi \to \gamma\eta_c) = \frac{BR(J/\psi \to \gamma\eta_c \to \gamma X_i)}{BR(\psi' \to \gamma\eta_c \to \gamma X_i)} \times BR(\psi' \to \gamma\eta_c)_{CLEO}$$

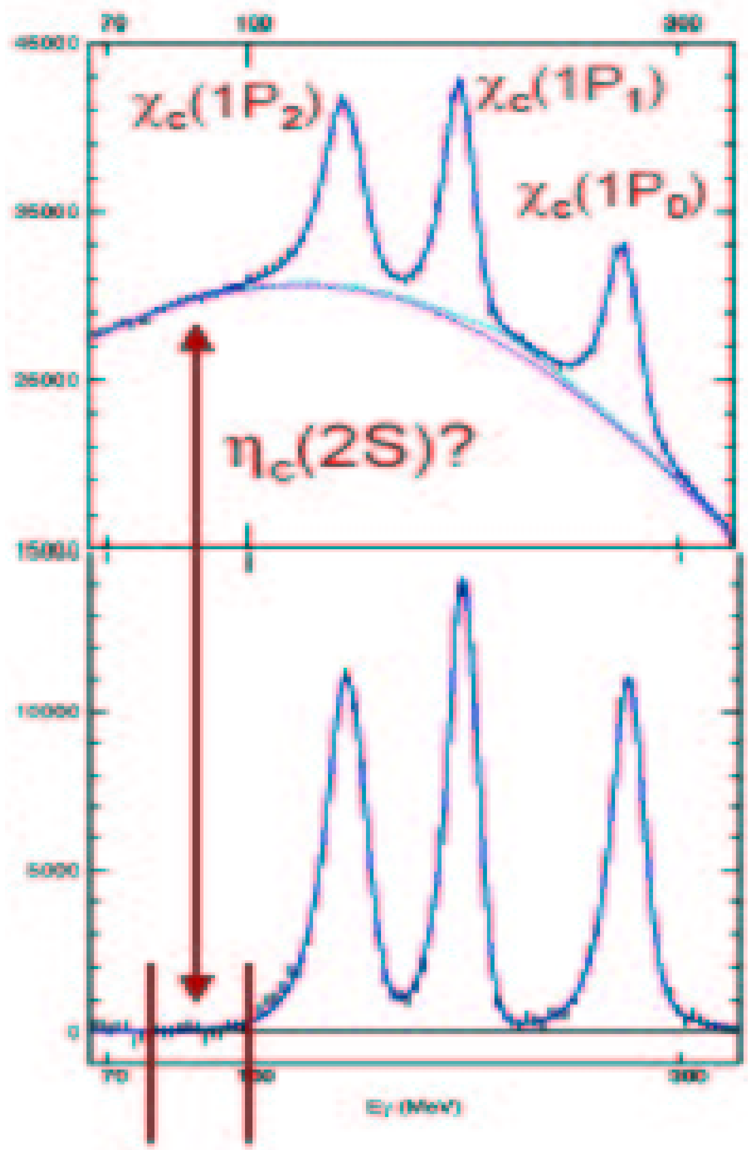
before 2006 — 10%

3%

Inclusive photon data spectrum : E1 peaks

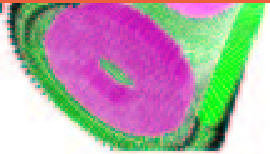


Crystal Ball 1982 : 1.8 M ψ(2s)



CLEO-c 2002 : 1.5 M ψ(2s)

New results from CLEO-c : E1's consistent?



E1 and M1 transitions from ψ(2S)

Preliminary

$BR(\psi(2S) \to \gamma \chi_c(1P_J))$ in % | $BR(\psi(2S) \to \gamma \eta_c(1S))$ in %

	E1 lines			Hindered M1 line
	$J=2$	$J=1$	$J=0$	$J=0$
CLEO	$9.75 \pm 0.14 \pm 1.17$	$9.64 \pm 0.11 \pm 0.69$	$9.83 \pm 0.13 \pm 0.87$	$0.278 \pm 0.033 \pm 0.049$
C.Ball	$8.0 \pm 0.5 \pm 0.7$	$9.0 \pm 0.5 \pm 0.7$	$9.9 \pm 0.5 \pm 0.8$	0.28 ± 0.06
PDG	7.8 ± 0.8	8.7 ± 0.8	9.3 ± 0.8	0.28 ± 0.06
ratio	1.25 ± 0.20	1.11 ± 0.13	1.06 ± 0.13	0.99 ± 0.30

$E\gamma$ in MeV

	E1 lines			Hindered M1 line
	$J=2$	$J=1$	$J=0$	$J=0$
CLEO	$128.00 \pm 0.08 \pm 0.09 \pm 0.64$	$172.05 \pm 0.08 \pm 0.16 \pm 0.86$	$261.99 \pm 0.14 \pm 0.27 \pm 1.31$	$641.5 \pm 2.4 \pm 3.3$
PDG	127.50 ± 0.01	171.27 ± 0.01	260.72 ± 0.03	639.00 ± 0.28
ratio	$1.0039 \pm 0.0009 \pm 0.0050$	$1.0046 \pm 0.0010 \pm 0.0050$	$1.0049 \pm 0.0011 \pm 0.0050$	1.0039 ± 0.064

Other errors ↗ ↖ Calibration errors

(from H.Muramatsu talk at QWG2)

Focus on systematic errors: did we reach the limit for this technique?

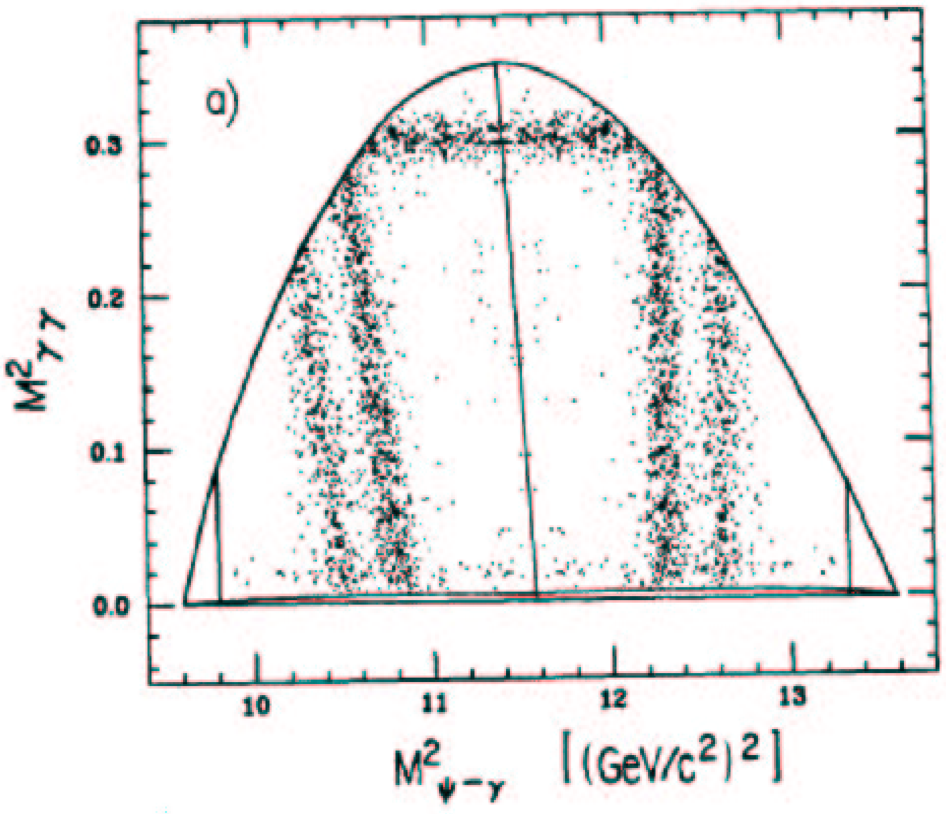
The errors on $BR(\psi' \to \gamma\chi_c)$ are dominant systematic in $BR(B \to \chi_c + any)$

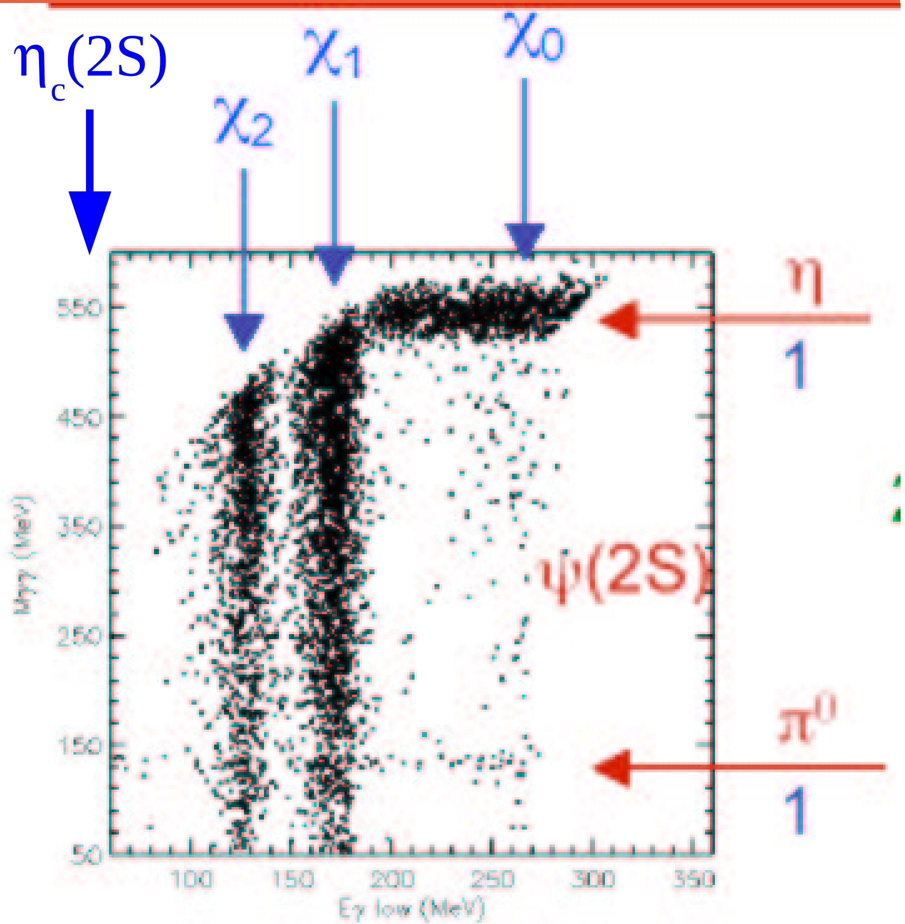
Internal checks are possible:

- the product $BR(\psi' \to \gamma\chi_c)*BR(\chi_c \to \psi\gamma)$ can be measured with inclusive photon spectra AND with exclusive ($\psi\gamma\gamma$) events.
- the study of angular distributions in exclusive events (NOT only $\psi\gamma\gamma$).

Note : CLEO-c and C.Ball samples are comparable: gain in stat errors due to independent measures on M and Γ of χ_c,η_c states.

$\psi' \to \gamma\chi \to \gamma\gamma J/\psi$ event samples





CRYSTAL BALL - 1982

- 1979-80 Data sample: 830 k $\psi(2s)$
- Analyses: Dalitz plot , Angular Distributions
- *The full data sample (1M extra $\psi(2s)$ in 81) was never analyzed!*

CLEOc - present

- 2002 Data sample: 1.5M $\psi(2s)$
- 2003: 2x ?

$\psi' \to \gamma\chi_c \to \gamma\gamma J/\psi$ at E835

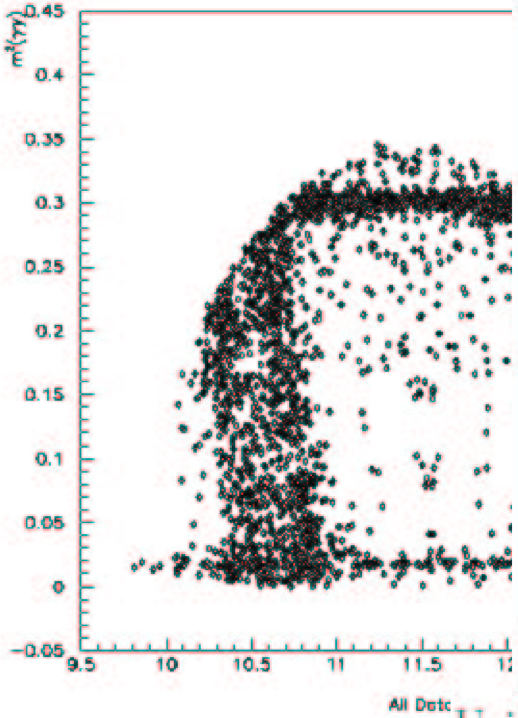


Figure 2: Dalitz Plot for $\psi' \to J/\psi\gamma$

Decay Mode	$\frac{\mathcal{B}(mode)}{\mathcal{B}(J/\psi X)}$ (%)		
	E760 $\approx$ 2400 ev	E835-I $\approx$ 13800 ev	E835-II (PREL) $\approx$ 31500 ev
e^+e^-	$1.44 \pm 0.08 \pm 0.02$	$1.28 \pm 0.03 \pm 0.02$	$1.21 \pm 0.06 \pm 0.02$
$J/\psi\pi^+\pi^-$	49.6 ± 3.7	-	51.8 ± 2.7
$J/\psi\pi^0\pi^0$	32.3 ± 3.3	$32.8 \pm 1.3 \pm 0.8$	29.9 ± 3.3
$J/\psi\eta$	6.1 ± 1.5	7.2 ± 0.9	5.3 ± 0.8
		E835-I and E835-II VERY PRELIMINARY	
$J/\psi\eta$		5.6 ± 0.5	
$\chi_0\gamma \to J/\psi\gamma\gamma$		0.23 ± 0.08	
$\chi_1\gamma \to J/\psi\gamma\gamma$		5.40 ± 0.38	
$\chi_2\gamma \to J/\psi\gamma\gamma$		3.30 ± 0.28	
$J/\psi\pi^0$		0.41 ± 0.09	
$\sum J/\psi X$ excl. modes		99 ± 3	

Using $\mathcal{B}(\psi' \to J/\psi X) = 0.579 \pm 0.019$ (PDG03 web update)

Channel	$\mathcal{B}(mode)$(%) E835 (preliminary)	$\mathcal{B}(mode)$(%) Crystal Ball (exclusive)	$\mathcal{B}(mode)$(%) Crystal Ball (inclusive)
$J/\psi\eta$	3.24 ± 0.29	2.55 ± 0.29	-
$J/\psi\pi^o$	0.24 ± 0.05	0.11 ± 0.03	-
$\chi_2\gamma \to J/\psi\gamma\gamma$	1.91 ± 0.16	1.47 ± 0.14	0.99 ± 0.13
$\chi_1\gamma \to J/\psi\gamma\gamma$	3.13 ± 0.22	2.78 ± 0.30	2.56 ± 0.23
$\chi_0\gamma \to J/\psi\gamma\gamma$	0.13 ± 0.05	0.069 ± 0.019	-

- E835/96+00:
- 2 M ψ'
- Only e+e- mode
- Dalitz plot analysis

Access to higher multipoles

- When $J_i \otimes J_f \neq 0$, higher multipoles can be measured, through the interference terms in angular distributions:
  - e.g.: $d\Gamma(\Omega)/d\Omega = |E1|^2 f_{E1}(\Omega) + E1{*}M2\, f_{12}(\Omega) + E1{*}E3\, f_{13}(\Omega) + \ldots$
- Measurements exist for the processes:
  - From $p\bar{p} \rightarrow \chi_{c1,2} \rightarrow \gamma J/\psi \rightarrow \gamma e^+e^-$
    - *R704: C.Baglin et al., Phys.Lett. B195,85 (1987)*
    - *E760: T.Armstrong et al., Phys.Rev. D48,3037 (1993)*
    - *E835: M.Ambrogiani et. al.,Phys.Rev. D65,52002 (2002)*
  - From $e^+e^- \rightarrow \psi' \rightarrow \gamma\chi_{c1,2} \rightarrow \gamma\gamma J/\psi \rightarrow \gamma\gamma e^+e^-$
    - *Crystal Ball: M.Oreglia et al., Phys.Rev.D25,2259(1982).*

➡ Angular distributions allow also to study the helicity structure of the $\psi, \psi', \chi_{c2} \rightarrow p\bar{p}$ decays

Radiative Multipolarities: definitions and more

Fractional multipole amplitudes:

- Electric Dipole

$$a_{E1} \equiv a_1 = \frac{E1}{\sqrt{E1^2 + M2^2 + E3^2}}$$

Dominant term. Naïvely $E1 \propto \langle \chi | \mathbf{r} | \psi \rangle$.

Anomalous magnetic moment correction on radiative width:

$$\delta E1 \propto \kappa_c \langle \chi | \mathbf{S} \times \mathbf{r} | \psi \rangle \Rightarrow \delta\Gamma/\Gamma = (J(J+1)-4)\kappa_c E_\gamma/(8m_c)$$

- Magnetic Quadrupole

$$a_{M2} \equiv a_2 = \frac{M2}{\sqrt{E1^2 + M2^2 + E3^2}}$$

Proportional to total magnetic moment: $M2 \propto (1+\kappa_c) \langle \chi | \mathbf{Sr}_{ij} | \psi \rangle$,

where $\mathbf{Sr}_{ij}$ *is an irreductible rank 2 tensor with zero trace:*

$$\mathbf{Sr}_{ij} = \{\mathbf{S}_i, \mathbf{r}_j\} - 2/3\,\delta_{ij}(\mathbf{S} \cdot \mathbf{r})$$

- Electric Octupole (χ_{c2} only)

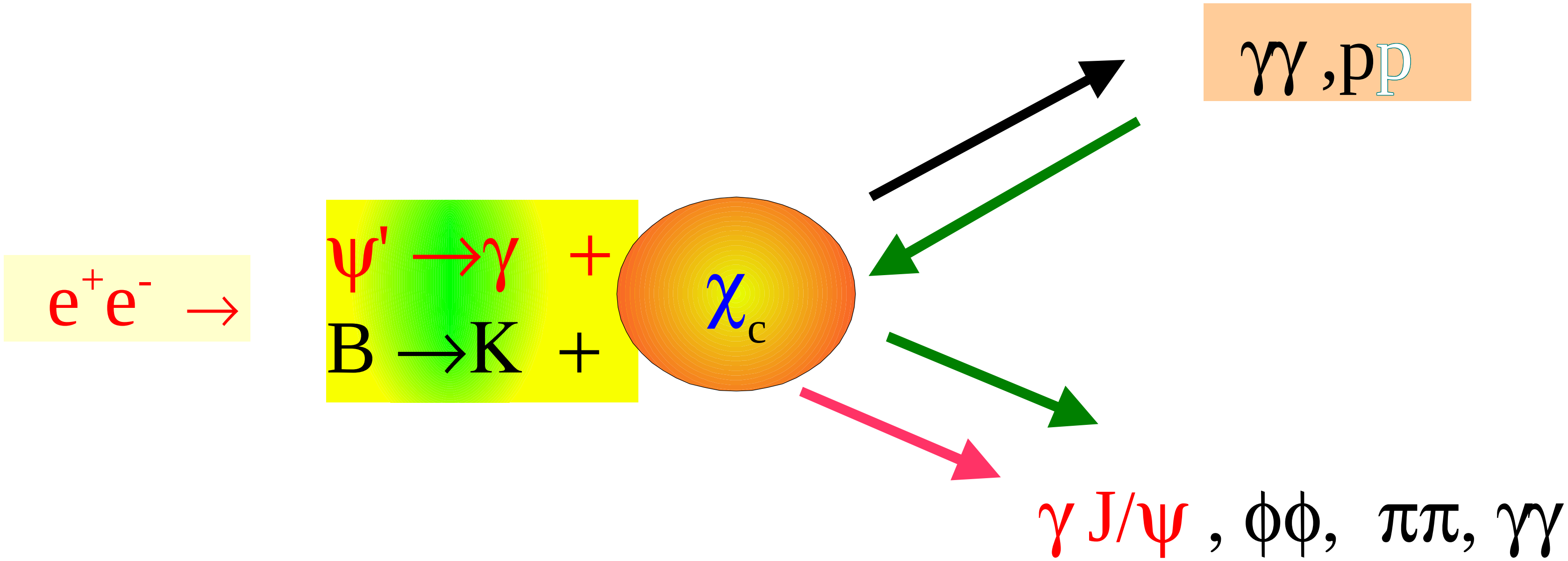
$$a_{E3} \equiv a_3 = \frac{E3}{\sqrt{E1^2 + M2^2 + E3^2}}$$

If the single quark radiation hypothesis is correct, this is proportional to the D wave admixture in ψ *or* ψ'.

The E3 amplitude needs very large statistics to be accessed.

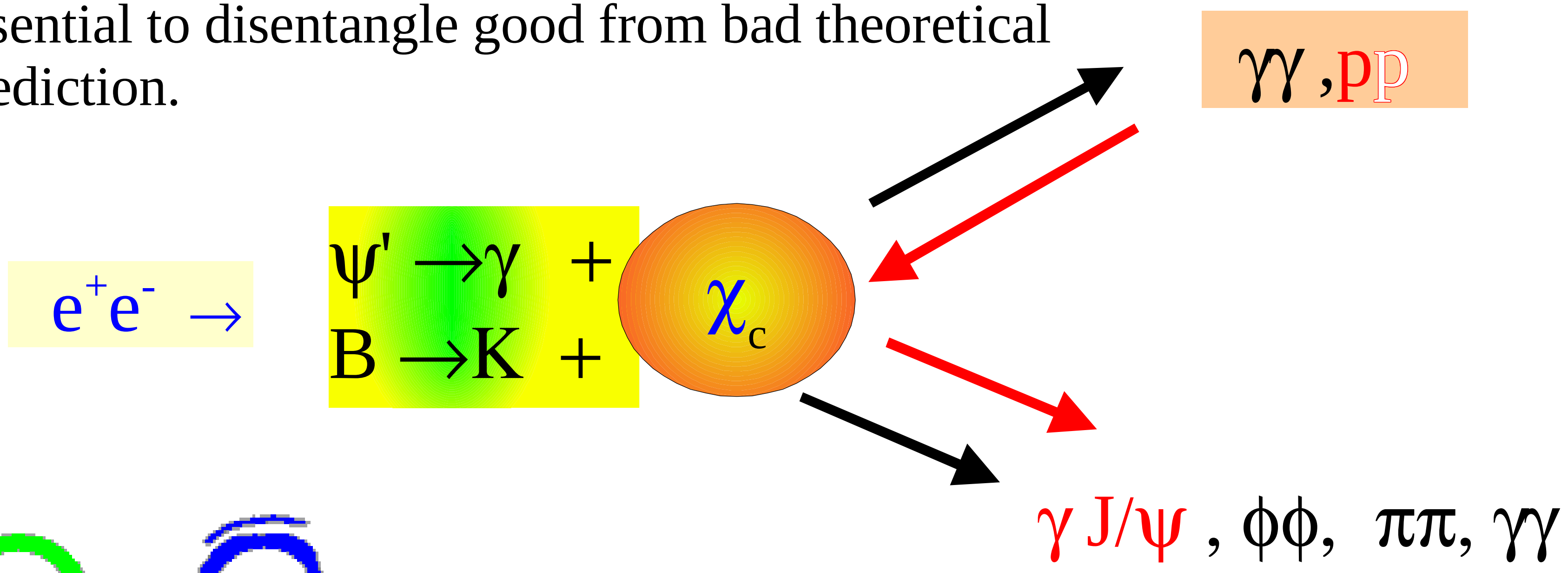
Complementarity between formation and production experiments

Non vector charmonia can be accessed via γγ fusion (also from e+e-), or directly formed from p$\bar{p}$ annihilations, where helicity selection rule does not hold and all quantum numbers can be reached.

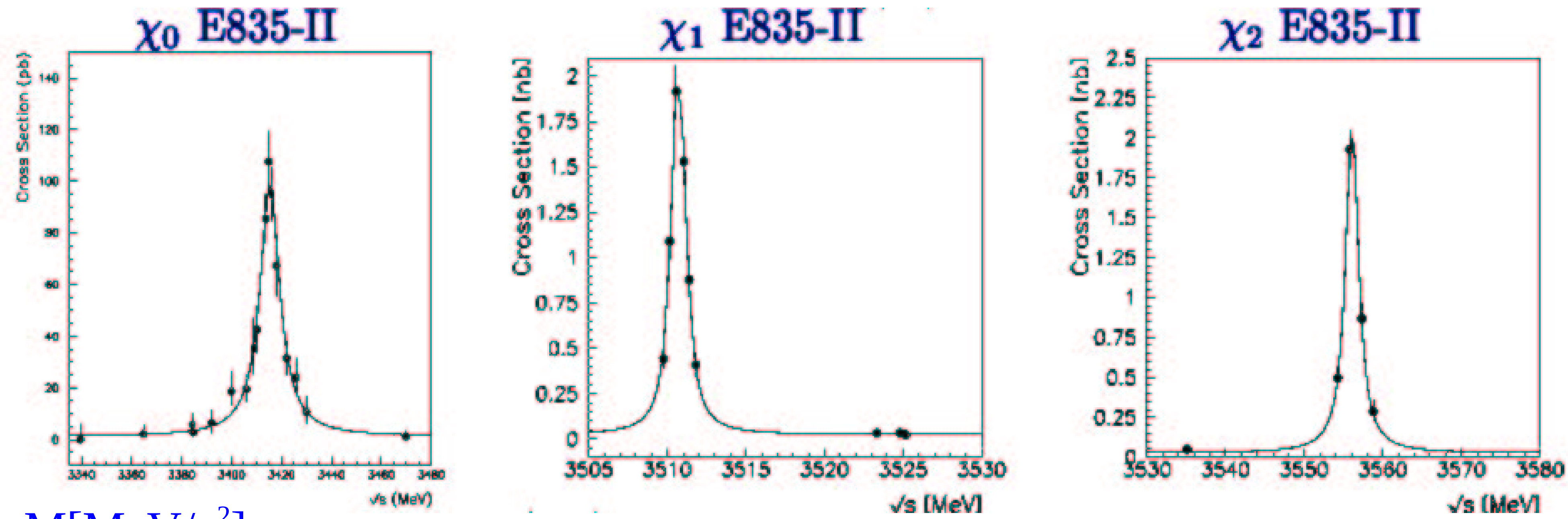


Redundancy between measurements is fundamental

Most experiments measure products, ratios , or other combinations of quantities relevant to theory.
It's important to work together among experiments to avoid unwanted correlations.
Global Fits to set of theoretical predictions are essential to disentangle good from bad theoretical prediction.



E760/E835: Widths and masses of χ_{cJ} from $p\bar{p} \rightarrow \chi_{cJ} \rightarrow \gamma + J/\psi$



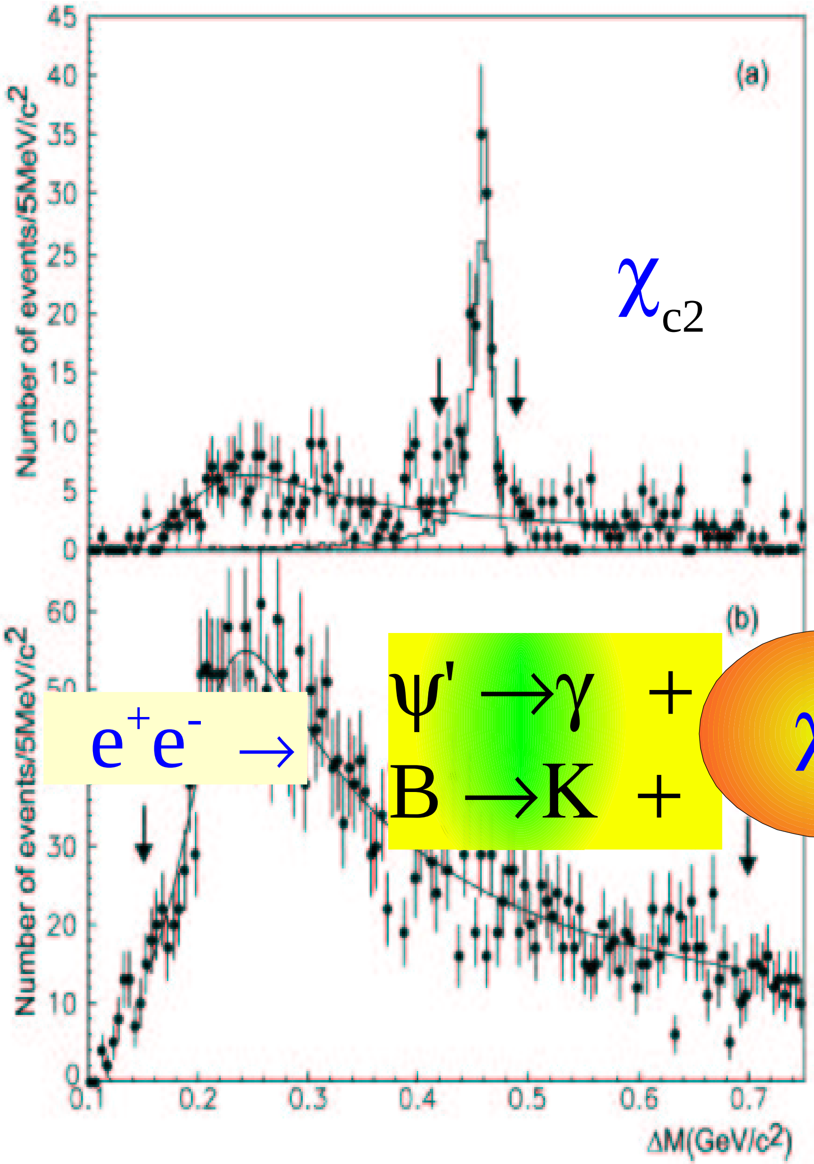
	χ_{c0}	χ_{c1}	χ_{c2}
M[MeV/c^2]	3415.6 ± 0.4	3510.67 ± 0.06	3556.21 ± 0.09
Γ_{tot}[MeV]	**9.7 ± 1.0**	**0.87 ± 0.07**	**1.94 ± 0.14**
$B(\chi_{cJ} \rightarrow \gamma J/\psi) * B(\chi_{cJ} \rightarrow p\bar{p})$ / $\Gamma(\chi_{cJ} \rightarrow \gamma J/\psi) * B(\chi_{cJ} \rightarrow p\bar{p})$ [eV]	$(27.9 \pm 2.7 \pm 0.7) * 10^{-7}$	$19.7 \pm 0.7 \pm 0.5$	$26.8 \pm 1.9 \pm 0.8$

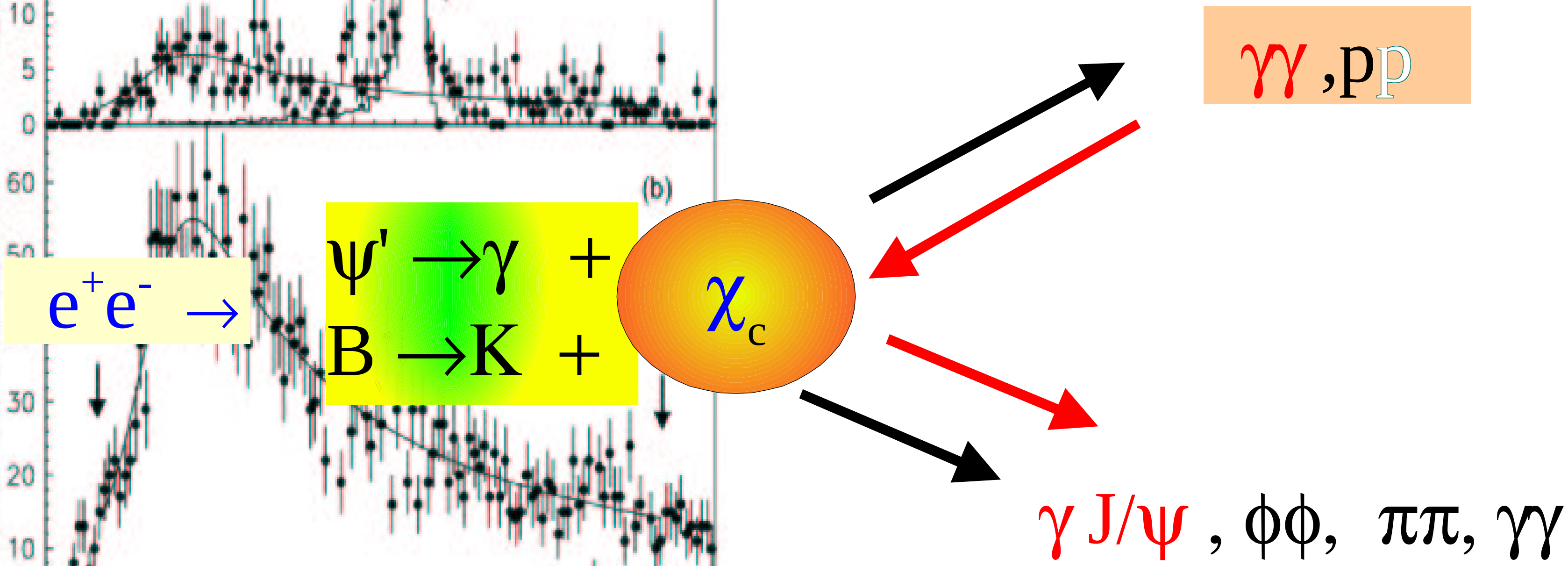
$\Gamma(\chi_{c0} \rightarrow LH) \simeq \Gamma_{tot}(\chi_{c0})$

$\Gamma(\chi_{c1,2} \rightarrow LH) = \Gamma(\chi_{c1,2}) - \Gamma(\chi_{c1,2} \rightarrow \gamma J/\psi)$

Belle's measurement in $\gamma\gamma$ to $\gamma\ J/\psi$

BELLE, Phys.Lett.B540(2002),33
from 32 fb^{-1}



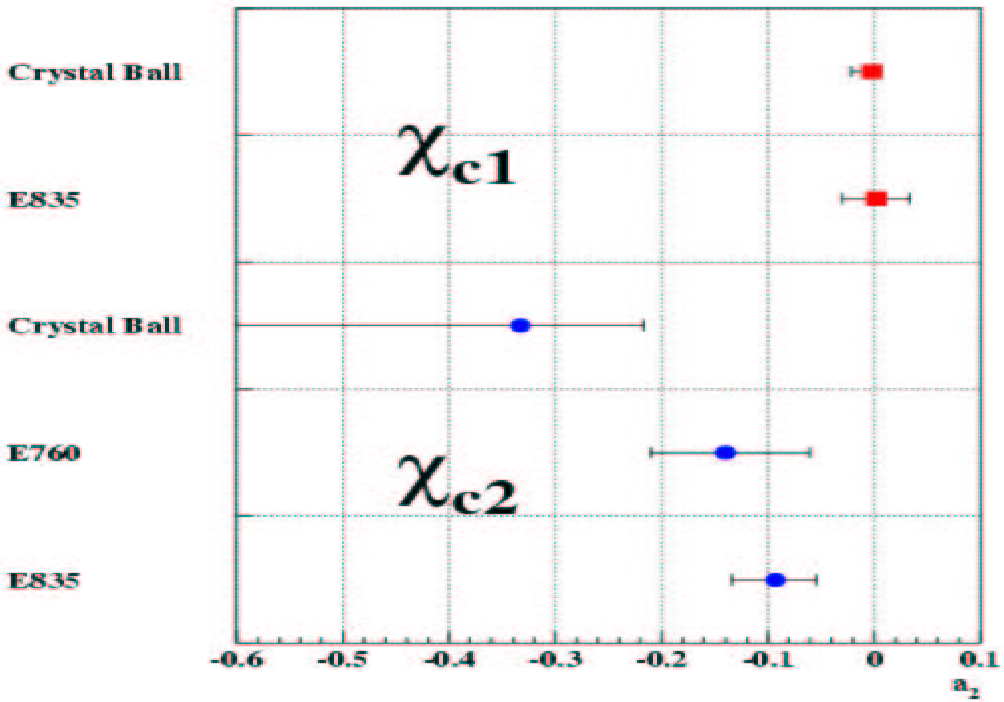


BR($\chi_{c2} \rightarrow \gamma\ J/\psi$) : 13.5±1.1% (PDG2000) to 18.7±2.0% (2002) to 20.2±1.8%(2003)

Radiative widths: comparison with theory

- The current results (*PDG2003*) are compared with these theory predictions:
  - ref.A: Fayyazuddin and Mobarek, Phys.Rev.D48, 1220(1983)
  - ref.B:Gupta et al., Phys.Rev.D39, 974 (1989)
  - ref.C:Resag and Munz, Nucl.Phys. A590,735 (1995)
  - ref.D:McClary and Byers, Phys.Rev. D28,1692 (1985)
- The errors on P->S widths include the syst errors on BR(S->P)

Transition	*Rad.Width (keV)*	*Error*	re
PSIP to CHI2	*19*	*16%*	
PSIP to CHI1	*23*	*15%*	
PSIP to CHI0	*20*	*20%*	
CHI2 to JPSI	*374*	*17%*	
CHI1 to JPSI	*281*	*19%*	
CHI0 to JPSI	*119*	*23%*	
PSIP to ETAC	***0.78***	***24%***	
JPSI to ETAC	***1.13***	***31%***	
	M2/E1 Ratio	*Error*	
PSIP to CHI2	8%	5%	
PSIP to CHI1	13%	9%	
CHI2 to JPSI	-9%	4%	
CHI1 to JPSI	0%	2%	



Radiative BR's to singlet states

$\psi(2s) \rightarrow \gamma\eta_c(2s)$

- M1 transition: $\Gamma \sim E^3_\gamma$. Expect BR~10^{-3}.
- Almost impossible from single photon spectrum (1/100 of the χ_{c2} events, resonance 10 MeV wide, 10^4 background γ's per 2% E bin in 1.5 M triggers)
- With 1G$\psi(2s)$, expect :
  - ~10000 KKπ (ideal for mass+width measurement also)
  - ~1000 $p\bar{p}$ (waiting for Panda)
  - ~100 $\gamma\gamma$ (to exploit B-factory measurements).

$\eta_c(2s) \rightarrow \gamma\,\psi(1s)$: M1 hindered, η_c broad

$\eta_c(2s) \rightarrow \gamma\, h_c(1P)$: E1 but small E_γ

- Good targets for Panda ($\gamma\,\psi$, $\gamma\pi\,\psi$)

$h_c(1P) \rightarrow \gamma\eta_c(1s)$: 1Gψ(2s) may yield 400-4k $\psi(2s) \rightarrow \pi\gamma\,(KK\pi)$, but this measures only BR($\psi(2s) \rightarrow \pi h_c$)*BR($h_c(1P) \rightarrow \gamma\eta_c(1s)$).

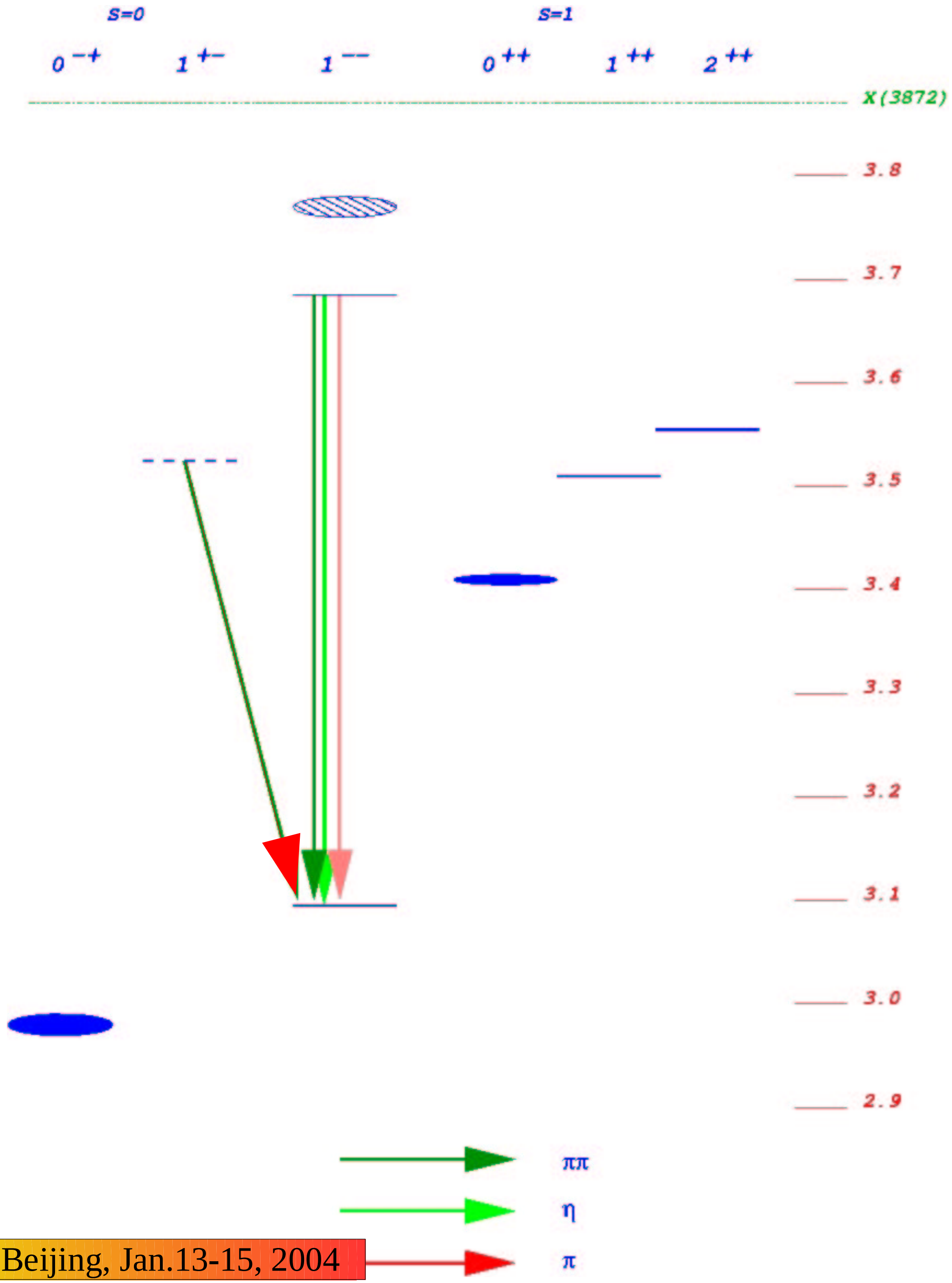
CHARMONIUM HADRONIC TRANSITIONS

OZI disconnected processes to light mesons.

Powerful to test:

QCD sum rules
HQ expansion

Seen so far:



CHARMONIUM HADRONIC TRANSITIONS

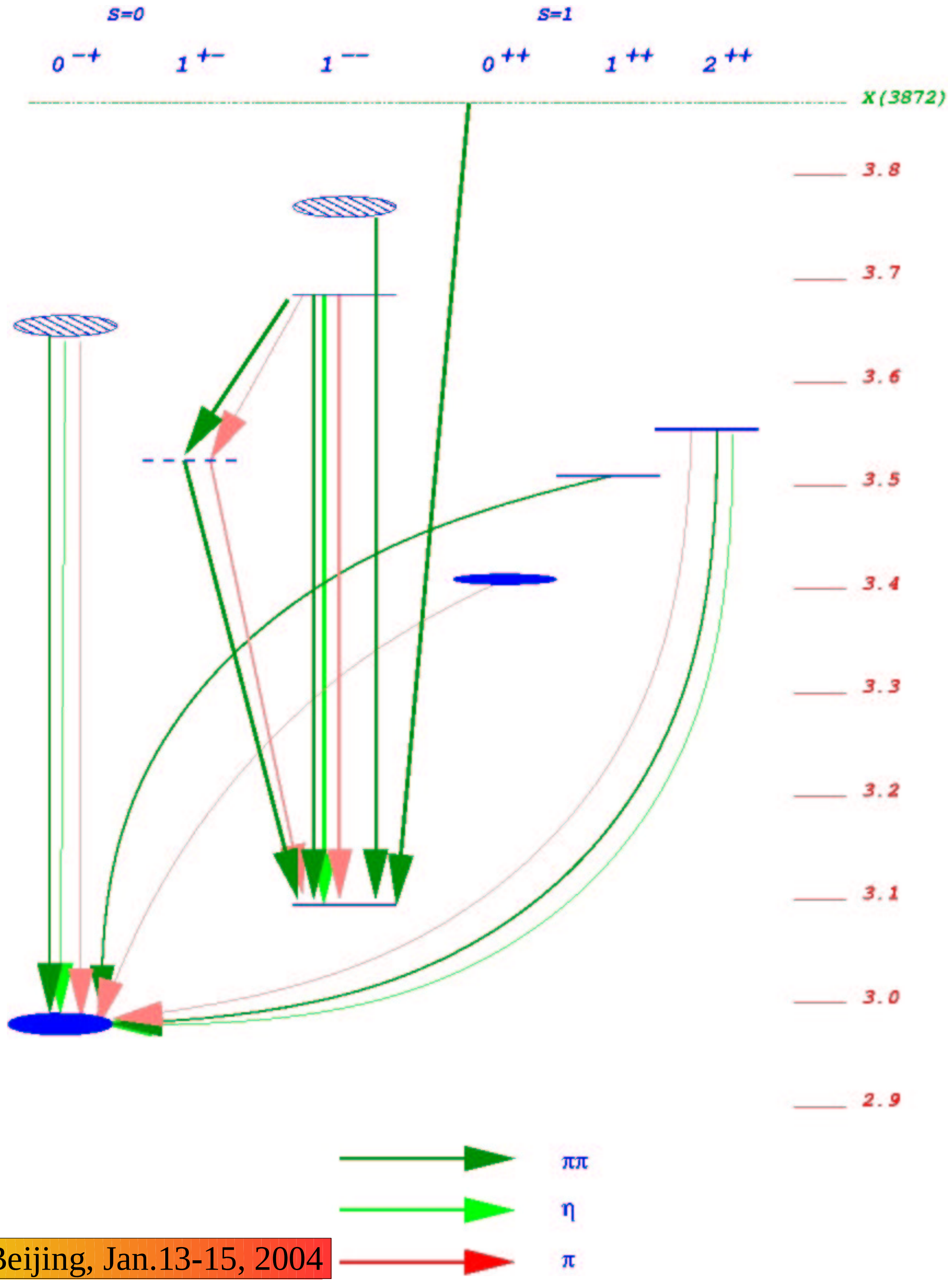
OZI disconnected processes to light mesons.

Powerful to test:

QCD sum rules
HQ expansion

Seen so far ... are just the tip of an iceberg.

Search for rare ones



$c\bar{c} \to c\bar{c}\,\pi\pi$

$\psi' \to J/\psi\, \pi^+ \pi^-$: L=0,2; $l_{\pi\pi}$=0,2

is the best studied. Issues : Dipion mass distribution,
D wave content in dipion. Expect results from BES 15 M data sample.

$\psi' \to J/\psi\, \pi^o \pi^o$: L=0,2; $l_{\pi\pi}$=0,2

Isospin conservation implies BR($J/\psi\, \pi^+ \pi^-$)/ BR($J/\psi\, \pi^o \pi^o$) =2
E835/00 analysis almost complete. Preliminary: Ratio = 0.58±0.07
Excellent item for CLEO-c and BES-III in perspective.
Isospin violation (violates C!) can show up in anomalous BR, differences in dipion mass, angular distributions.
Good place for checks and searches: continuum , $h_c\, \pi^o \to J/\psi\, \pi^o \pi^o$

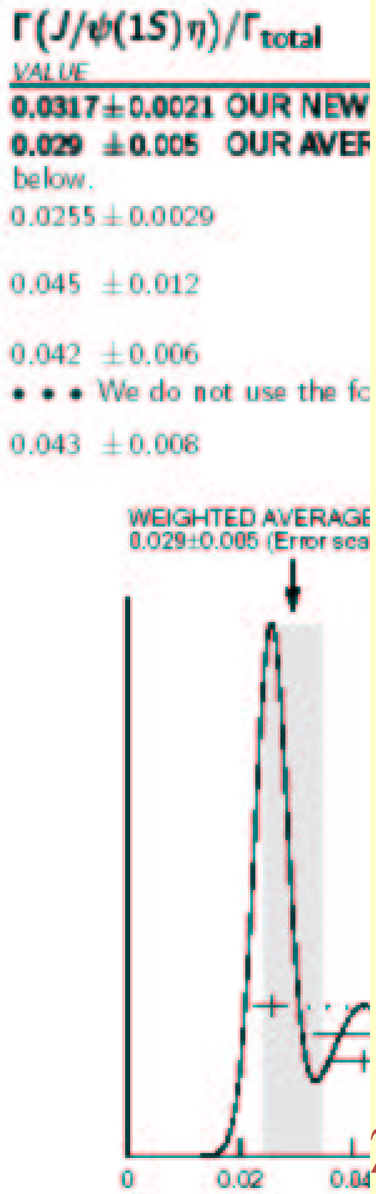
$\eta_c(2S) \to \eta_c(1S)\, \pi\pi$: L=0,2; $l_{\pi\pi}$=0,2

Expect results soon , from B-factories..
Voloshin (hep/ph-0206240): BR=5-10%

$h_c \to J/\psi\, \pi\pi$, $\chi_{c1} \to \eta_c\, \pi\pi$ (L=1; $l_{\pi\pi}$=0) ; $\chi_{c2} \to \eta_c\, \pi\pi$ (L=1; $l_{\pi\pi}$=2)

Expect suppression. Large samples needed. [$D_{sJ}(2457) \to D\, \pi\pi$]

$c\bar{c} \to c\bar{c}\,\eta$



$\psi' \to J/\psi\,\eta$: L=1; p_η = 193 MeV

- Last measured by C.Ball (1980).
- Inconsistent with previous ones

- Preliminary result by E835: BR=3.24±0.29%

- Systematic errors from $J/\psi\pi^0\pi^0$ feeddown?

(E835 MC includes newer BES data)

- Current samples:

  BES: 14M*3%*23%*11.8% = ~12k ($\pi^+\pi^-\pi^0$) rec.evts

  CLEO-c: 1.5M*3%*94%11.8% = ~5k ($3\pi+\gamma\gamma$) rec.evts

→ If systematic effects are understood... already close to 1%

- Related to prediction on $\Upsilon(2S) \to \Upsilon(1S)\eta$

$\chi_{c2} \to \eta_c\,\eta$ (L=2; p_η = 158 MeV). What suppression to expect?

$c\bar{c} \rightarrow c\bar{c}\,\pi$ (1)

$\psi' \rightarrow J/\psi\, \pi^0$: L=1, I=1

- PDG: BR=0.096±0.023%
  (30 evts from C.Ball + Mark II)
- Preliminary result by E835:
  BR=0.24±0.05%
- Interference with continuum?
- Current samples:
  CLEO-c: 1.5M*0.1%*11.8% ≥180
  ($\gamma\gamma\psi$) rec.evts

➔ Here we need ~200 M $\psi(2s)$ to get to 1% level

$\psi' \rightarrow h_c \pi^0$, L=0, I=1

- Gateway to h_c? Godfrey:BR: ~0.05%
- Inclusive π^0 spectrum: feed-down from $\psi' \rightarrow \chi_{c1,2}\gamma$
- Low π^0 momentum (~60-80 MeV γ's)

$h_c \to \psi\pi^0$ (L=0, I=1)

$c\bar{c} \to c\bar{c}\,\pi$ (2)

- E760 : observed h_c at M=3526.2 MeV/c^2

  $(1.7\pm0.4)*10\text{-}7 < BR(h_c \to \psi\pi^0)BR(h_c \to p\bar{p}) < (2.3\pm0.6)*10\text{-}7$

  if Γ=1 MeV   if Γ=0.5 MeV

- E835 sensitivity: $BR(h_c \to \psi\pi^0)\,BR(h_c \to p\bar{p}) \sim 10^{-7}$

  (for M = $M_{E760}\pm1$ MeV) $BR(h_c \to \gamma\eta_c)\,BR(h_c \to p\bar{p}) \sim 10^{-5}$

- Exclusive searches:
  - $\eta_c\gamma\pi^0$ Dalitz Plot : ~ 20 k evts/1G ψ' (all $Kk\pi$ modes)
  - $\psi\pi^0\pi^0$ Dalitz Plot : ~ 60 evts / 1G ψ' (e+e-, $\mu+\mu-$) [Interference?]
  - $p\bar{p}\,\pi^0$: ~ 10 evts / 1G ψ'

- Competitive search by B-factories (feed-down from $\chi_{c1,2} \to \gamma J/\psi$)

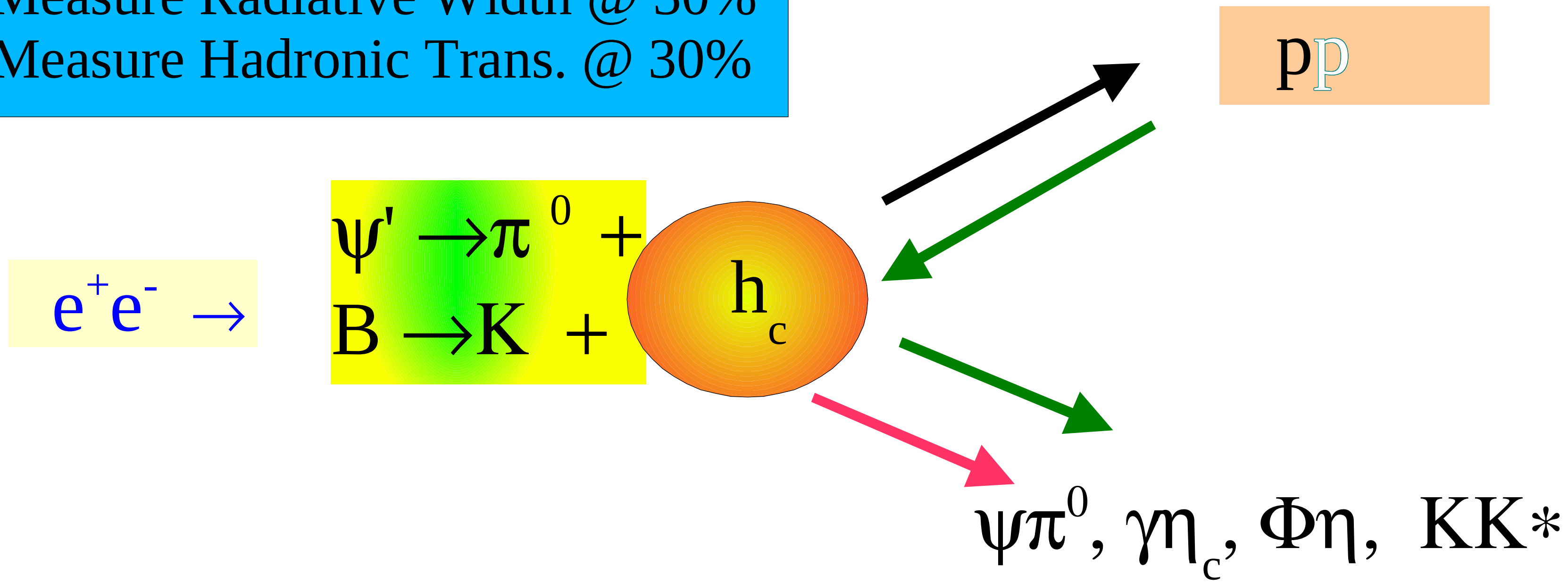
  If $BR(B \to h_c K) \sim BR(B \to \chi_{c0} K) \sim 0.05\%$

  Comparable yields but worse resolution , and more background

h_c studies: long range planning

Task List

- Find/confirm the state
- Measure hf splitting @ 10%
- Measure Total width @ 10%
- Measure Radiative Width @ 30%
- Measure Hadronic Trans. @ 30%



Summary 1: Milestones at 20 M $\psi(2s)$

- M1 transitions at 3%
- Total Width of η_c with 10% precision
- BR($\psi \rightarrow$ ee) @ 0.5% (now: 1.6%)
- BR($\psi' \rightarrow$ ee) @ 1.5% (now: 7%)
- BR($\psi\pi\pi$), neutral and charged.
- Angular Distributions $\psi\pi\pi$, neutral and charged.
- Tests of Isospin violation in $\psi\pi\pi$.
- Search for hc outside E760 range.
- BR($\psi\eta$) @ 1% level
- Total Width of χ_{c0} with 5% precision?
- Inclusive BR($\psi' \rightarrow \gamma\chi$) @ 3%
- Angular Distributions $\psi\gamma\gamma$. M2/E1
-

Summary 2: Milestones at 200 M $\psi(2s)$

- M1 transitions to $\eta_c(1s)$ @1%
- M1 transitions to $\eta_c(2s)$ @3% (KKπ)
- Mass + Width measurement of $\eta_c(2s)$
- Search for $\eta_c\pi\pi$ from χ_{c1}
- Search for h_c inside E760 range.
- BR($\psi\pi$) @ 1% level
- BR($\psi' \rightarrow \gamma\chi$) , BR($\chi \rightarrow \gamma\,\psi$)@ 1%
- Angular Distributions $\psi\gamma\gamma$. M2/E1 AND E3/M1
-

Exclusive 2 body transitions

Test $SU(3)_{flavor}*SU(2)_{spin}$ simmetry
with all Nℕ quantum numbers.

4 out of 8 states have 2 independent helicity amplitudes. Total: 12 measurements per nucleon octet state.

NRQCD predictions :Wong reference, Kroll
Diquark model: Anselmino et al.
V states: the ρπ puzzle is still unresolved, and its solution will surely give us deep insights on the quarkonium dynamics, as well as on the annihililation process.

Analogous puzzles may show up between η(2s) and η(1s), or comparing rates to LH, between P wave states.

A full systematic analysis of ππ,ρρ,ϕϕ,ωω,ηη, ... as well as
ηϕ,ηω,ηη', ... (I=0) or πη,πω,πϕ,ρϕ,... (I=1) can be fruitful only with
large samples of ψ decays.

Inclusive decays to MM':
A search for narrow peaks in recoil mass distributions from tagged c decays has a large discovery potential on light quarkonia. (e.g.:χ_{c1} to π+X can spot 1^{-+} oddballs)

Spare slides

Searches for inclusive η_c evidence in $\psi(2s)$ decays

Known production mechanisms :

$\psi(2s) \rightarrow \gamma\eta_c$ (0.3%)

$\psi(2s) \rightarrow \pi\pi\psi \rightarrow \pi\pi+\gamma\eta_c$ (0.6%)

$\psi(2s) \rightarrow \gamma\gamma\,\psi \rightarrow \gamma\gamma+\gamma\eta_c$ (0.1%)

Alternative production mechanisms :

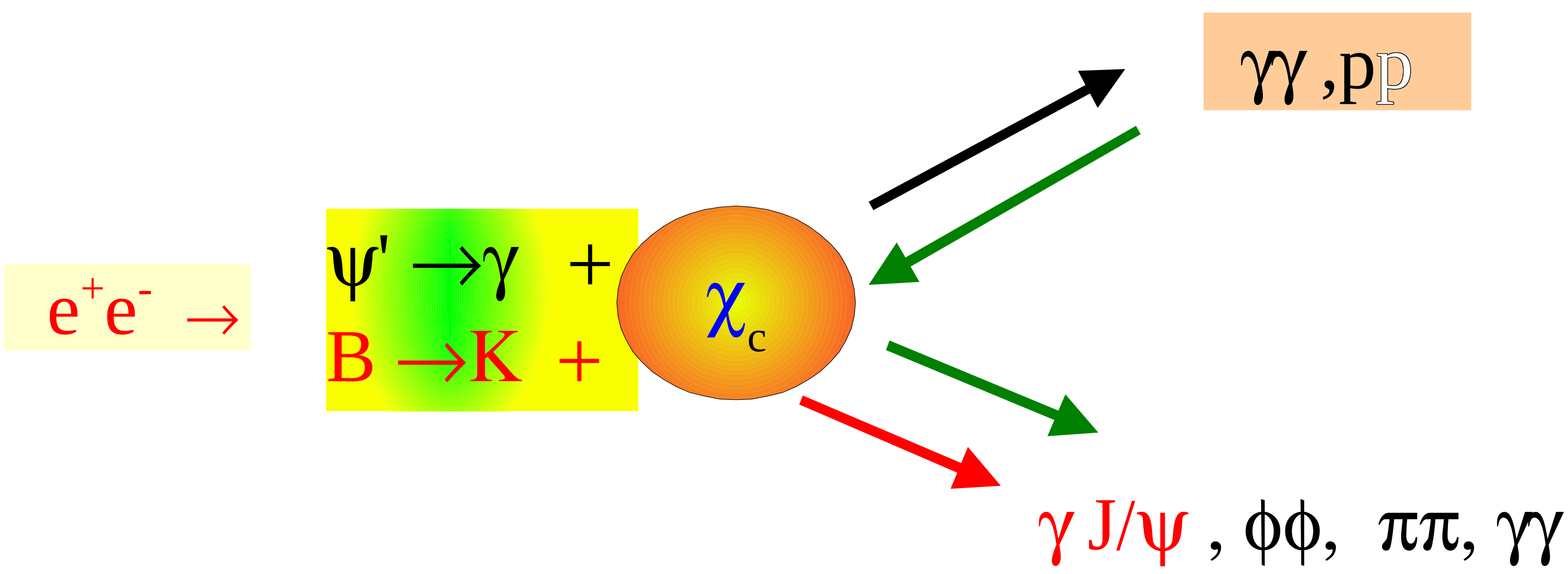
$\psi(2s) \rightarrow \gamma\chi \rightarrow \gamma\,\pi\eta_c$ (J=0,2 - I=1)

$\psi(2s) \rightarrow \gamma\chi \rightarrow \gamma\,\pi\pi\eta_c$ (J=1,2)

$\psi(2s) \rightarrow \gamma\chi \rightarrow \gamma\,\eta\eta_c$ (J=2 - Q=20-30 MeV)

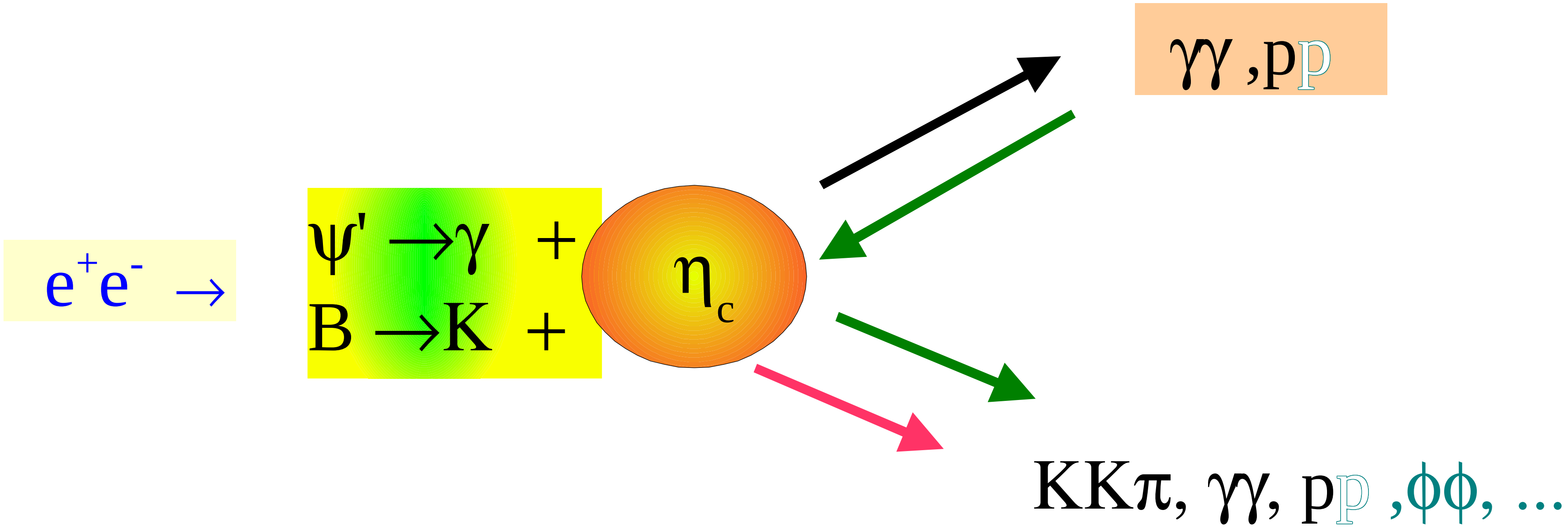
$\psi(2s) \rightarrow \pi h_c \rightarrow \pi\,\gamma\,\eta_c$

Complementarity between formation and production experiments



Complementarity between formation and production experiments

Non vector charmonia can be accessed via $\gamma\gamma$ fusion (also from e+e-), or directly formed from $p\bar{p}$ annihilations, where helicity selection rule does not hold and all quantum numbers can be reached.

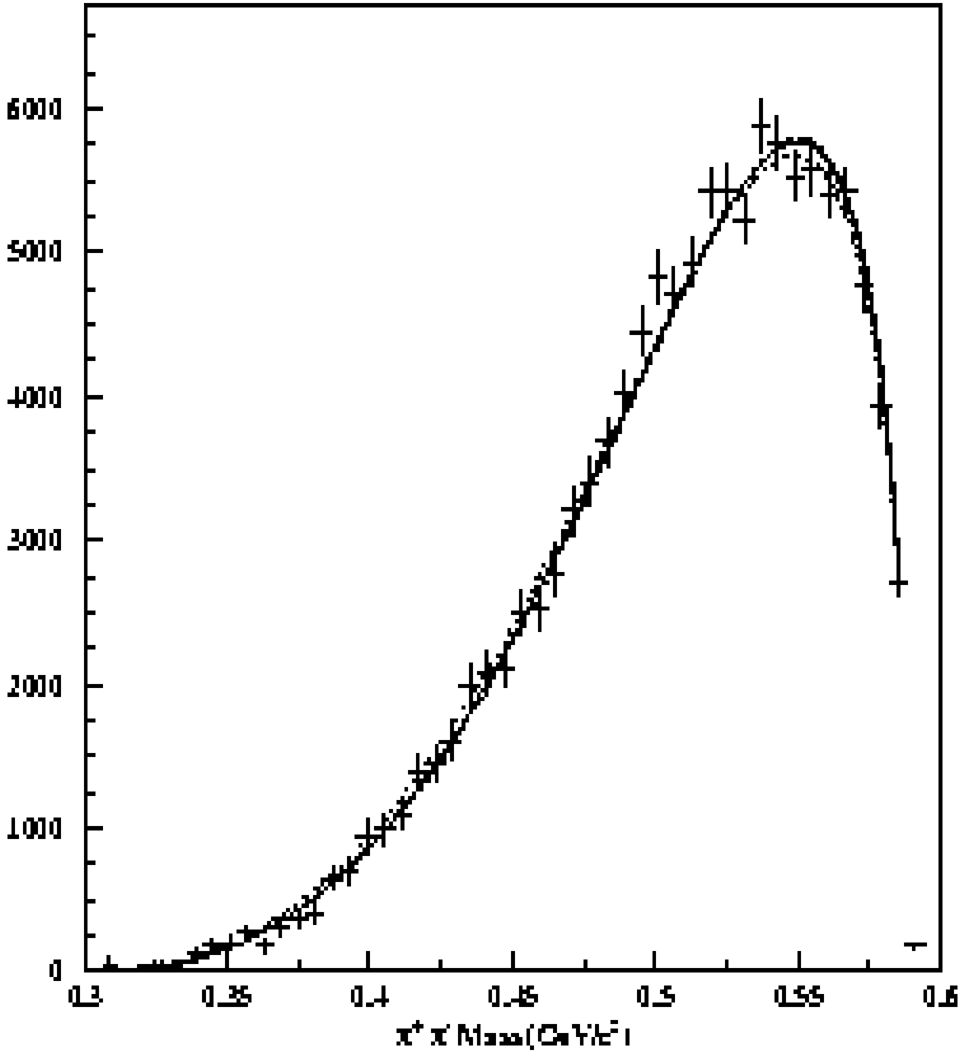


Yields at BES-III

Tot Ψ' produced	1.00E+09	Frac error
$\psi' \to \gamma\chi_2$	7.80E+07	0.01%
$\to \gamma\psi \to \gamma e^+e^-$	6.24E+05	0.13%
$\to p\bar{p}$	7.80E+03	1.13%
$\psi' \to \gamma\chi_1$	8.70E+07	0.01%
$\to \gamma\psi \to \gamma e^+e^-$	1.41E+06	0.08%
$\to p\bar{p}$	8.70E+03	1.07%
$\psi' \to \gamma\chi_0$	9.70E+07	0.01%
$\to \gamma\psi \to \gamma e^+e^-$	3.80E+04	0.51%
$\to p\bar{p}$	3.88E+04	0.51%
$\psi' \to \gamma\eta_c$	2.80E+06	0.06%
$\to p\bar{p}$	3.36E+03	1.73%
$\to \gamma\gamma$	8.40E+02	3.45%

$\psi' \to J/\psi\, \pi^+ \pi^-$

- BES results in
  Bai et al,Phys.Rev.D62(2000)032002
- From a 3.8M ψ' sample.
- $M_{\pi\pi}$ peaked at high values.
- S wave between ψ and $\pi\pi$
- D wave content in the dipion: ~18%



An example

A high statistics (~fb^{-1})sample at Ψ' will allow a precise measurement of the ratio:

$$\Xi = \frac{BR(\chi_c \to \gamma J/\psi)}{BR(\chi_c \to p\bar{p})} \propto \frac{N(\psi' \to \gamma \chi_c \to \gamma J/\psi)}{N(\psi' \to \gamma \chi_c \to p\bar{p})}$$

with *little systematic dependence* on other processes.

The radiative width will be extracted from:

$$\Gamma(\chi_c \to \gamma J/\psi) = \sqrt{\{\Gamma(\chi_c \to \gamma J/\psi) * \Gamma(\chi_c \to p\bar{p})\}_{E835} * \Xi_{CLEO-C}}$$

The stat error is then given by:

where

$$\frac{\delta \Gamma_{rad}}{\Gamma_{rad}} = \frac{1}{2}\left\{\frac{\delta \Pi}{\Pi} \oplus \frac{\delta \Xi}{\Xi}\right\}$$

$$\Pi = \{\Gamma(\chi_c \to \gamma J/\psi) * \Gamma(\chi_c \to p\bar{p})\}_{E835}$$

Exclusive decays to MM'

V states: the $\rho\pi$ puzzle is still unresolved, and its solution will surely give us deep insights on the quarkonium dynamics, as well as on the annihililation process.

Analogous puzzles may show up between $\eta(2s)$ and $\eta(1s)$, or cpmparing rates to LH between P wave states.

A full systematic analysis of $\pi\pi,\rho\rho,\phi\phi,\omega\omega,\eta\eta$, ... as well as $\eta\phi,\eta\omega,\eta\eta'$, ... (I=0) or $\pi\eta,\pi\omega,\pi\phi,\rho\phi$,... (I=1) can be fruitful only with large samples y decays.

Inclusive decays to MM':

A search for narrow peaks in recoil mass distributions from tagged c decays has a large discovery potential on light quarkonia. (e.g.:χ_{c1} to π+X can spot 1-+ oddballs)

Selection Rules and Naming Schemes

- C-Parity conservation implies C_f=-C_i:
  - Forbids $h_c \to \gamma J/\psi, \chi_c \to \gamma \eta_c$
- Parity Flip and Electric/Magnetic multipoles
  - P_f=-P_i: E1,M2,E3,M4,...
    - $e.g.: \chi_c \to \gamma J/\psi, h_c \to \gamma \eta_c$
  - P_f=P_i: M1,E2,M3,E4,...
    - $e.g.: J/\psi \to \gamma \eta_c$

Radiative widths: experimental overview

- All current values are obtained combining e^+e^- and $p\bar{p}$ data as follows:

$$\Gamma_{rad}(\Psi_i \rightarrow \gamma \Psi_f) = \Gamma_{tot}(\Psi_i) * BR(\Psi_i \rightarrow \gamma \Psi_f)$$

- The fractional error is given by: $$\frac{\delta \Gamma_{tot}}{\Gamma_{tot}} \oplus \frac{\delta BR}{BR} = \frac{\delta \Gamma_{rad}}{\Gamma_{rad}}$$
- The refitted values (*C.Patrignani,hep-ex/0104003*) are summarized below:

Transition	Rad.Width (keV)					Error
PSIP to CHI2	19	11%	⊕	12%	=	16%
PSIP to CHI1	23	11%	⊕	10%	=	15%
PSIP to CHI0	20	11%	⊕	17%	=	20%
CHI2 to JPSI	374	9%	⊕	6%	=	11%
CHI1 to JPSI	281	16%	⊕	5%	=	17%
CHI0 to JPSI	119	10%	⊕	15%	=	18%
PSIP to ETAC	**0.78**	**11%**	⊕	**21%**	**=**	**24%**
JPSI to ETAC	**1.13**	**6%**	⊕	**31%**	**=**	**31%**