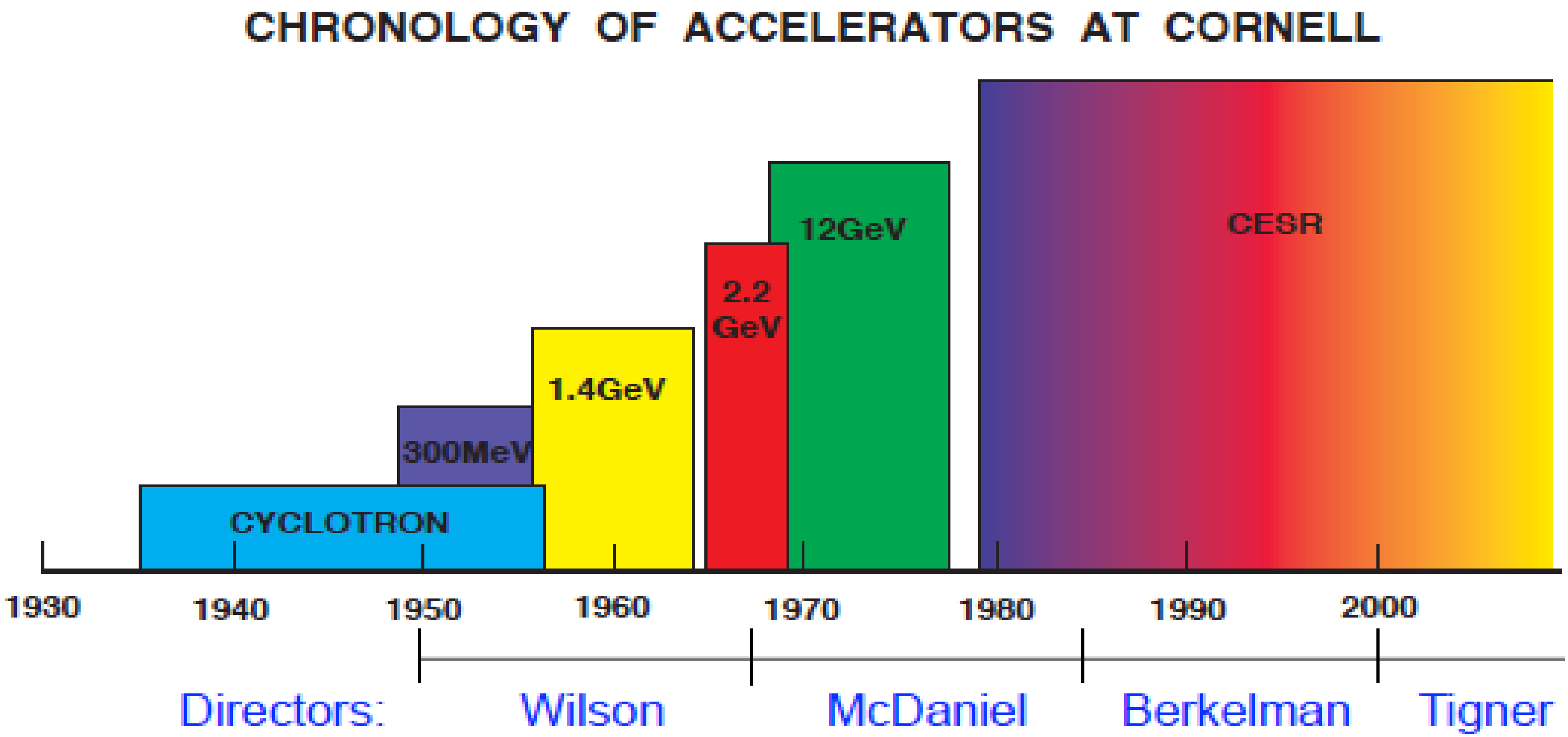
# Two-photon physics @CLEO, retrospective

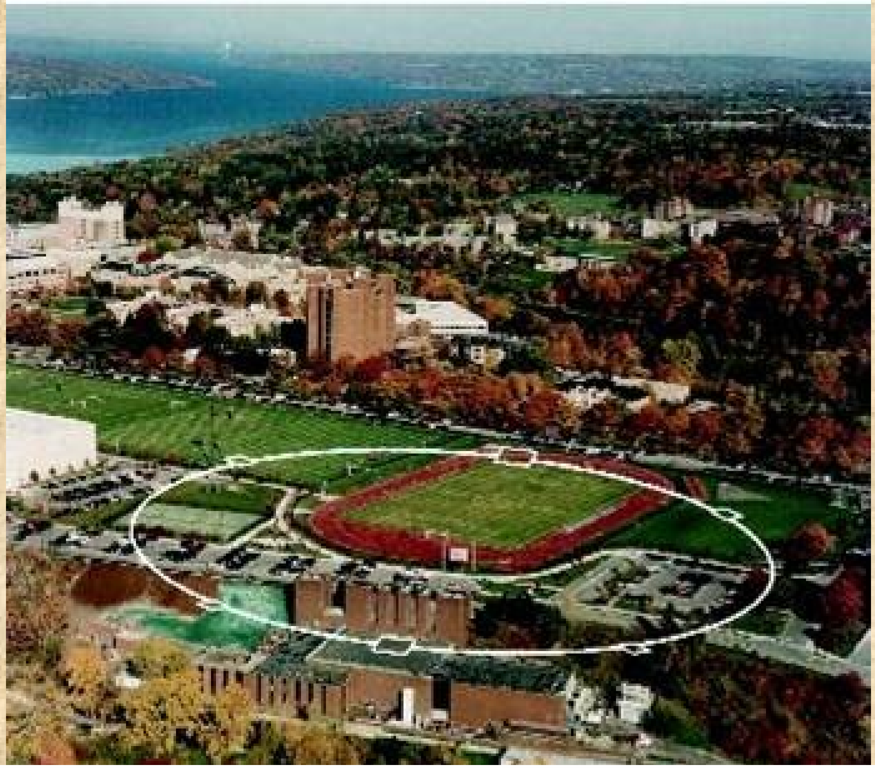
- CLEO overview
  - The salad days, 10' recap
- Two photon physics; reminder of general science
- CLEO $\gamma\gamma \rightarrow X$ program results and reminiscence
  - Thanks to everyone that I shamelessly pilfered slides from, esp. Dave Cassel, Sheldon Stone, Stan Brodsky

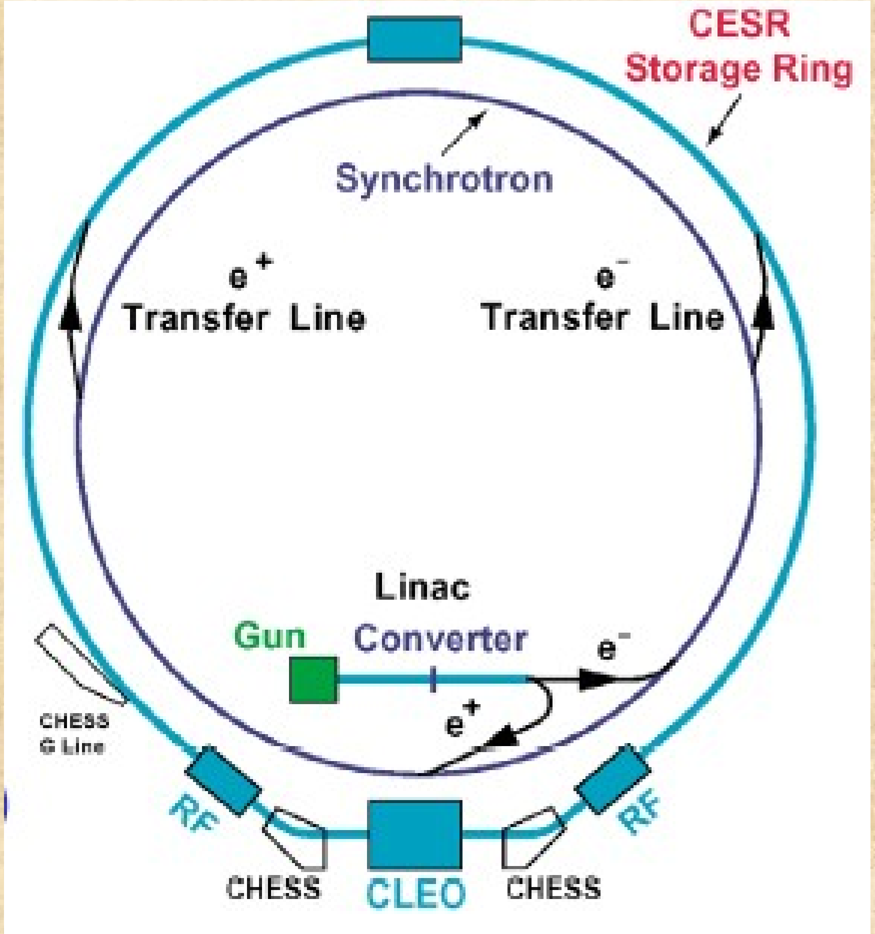
# CESR Prehistory

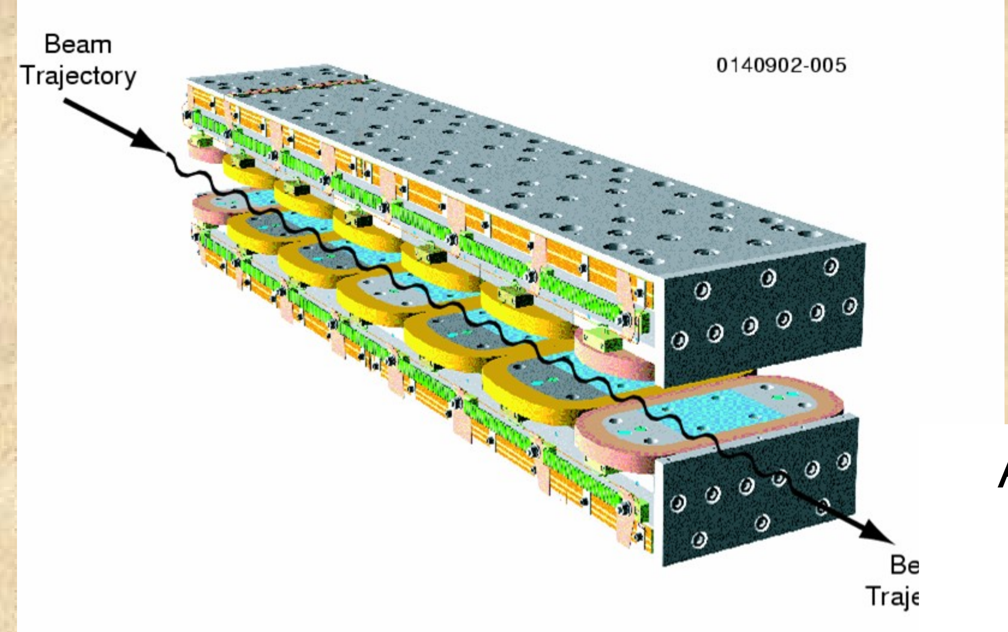
- 1935 -- 1.5 MeV proton cyclotron
- 1949 -- 0.3 GeV electron synchrotron
- 1954 -- 1.2 GeV electron synchrotron
- 1962 -- 2.2 GeV electron synchrotron



# (CESR)






$E_{beam}$ = 1.5 – 5.6 GeV

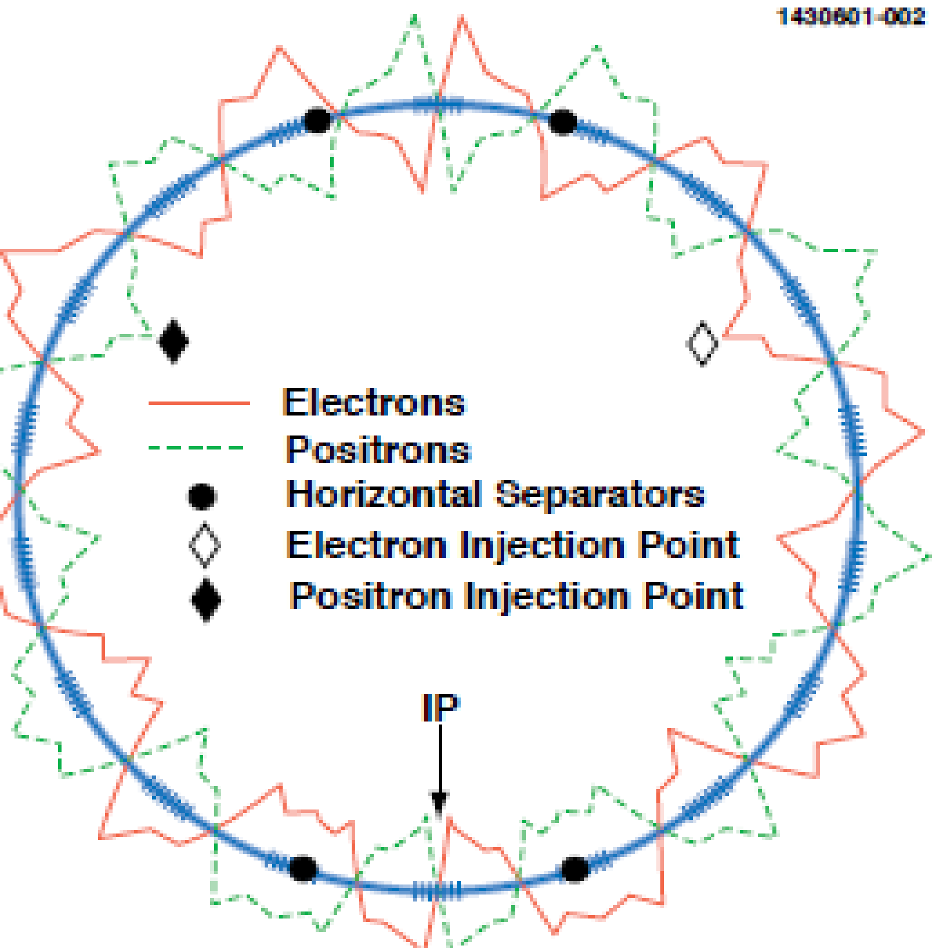
Added 12 superconducting wigglers to CESR for low energy running.

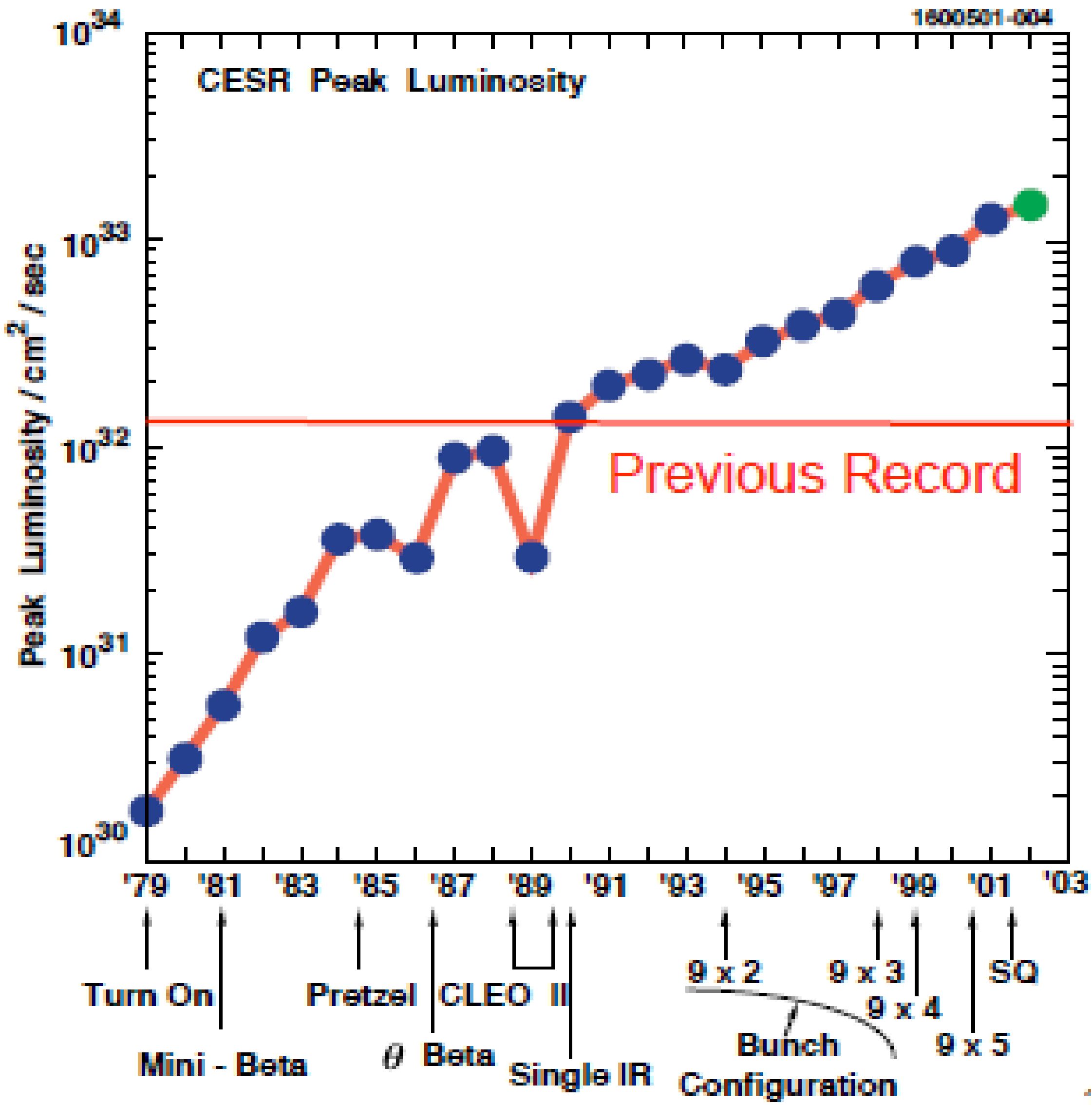
- 1967 – $e^-$ synchrotron
  12 GeV in a 1/2 mile tunnel

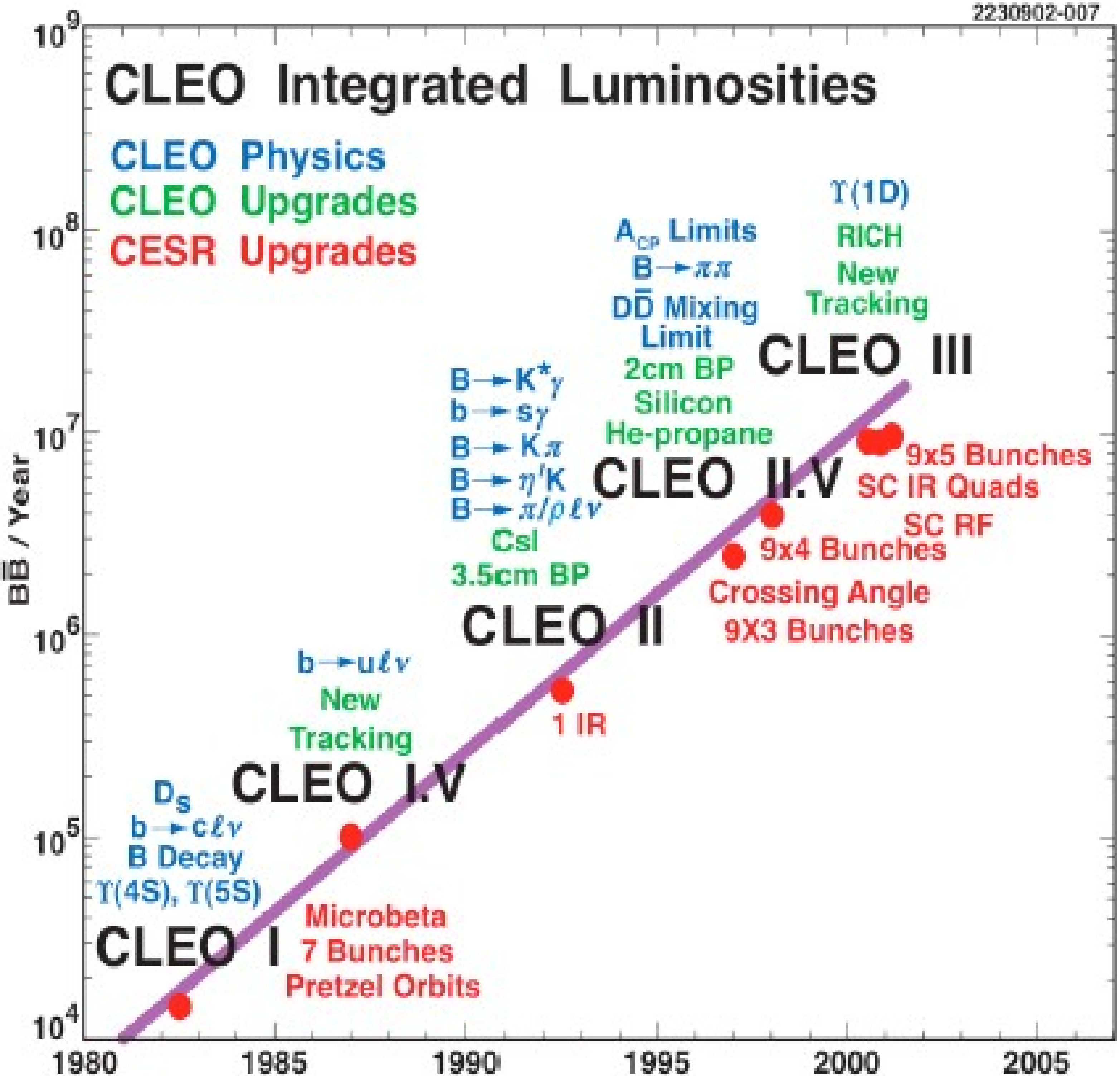
- 1979 – CESR
  Cornell Electron
  Storage Ring
  8+8 GeV $e^+e^-$

# CESR Luminosity Improvements

- Multibunch pretzel orbits
- Superconducting RF cavities
- "μβ" IR focusing
- Single IR (no CUSB)





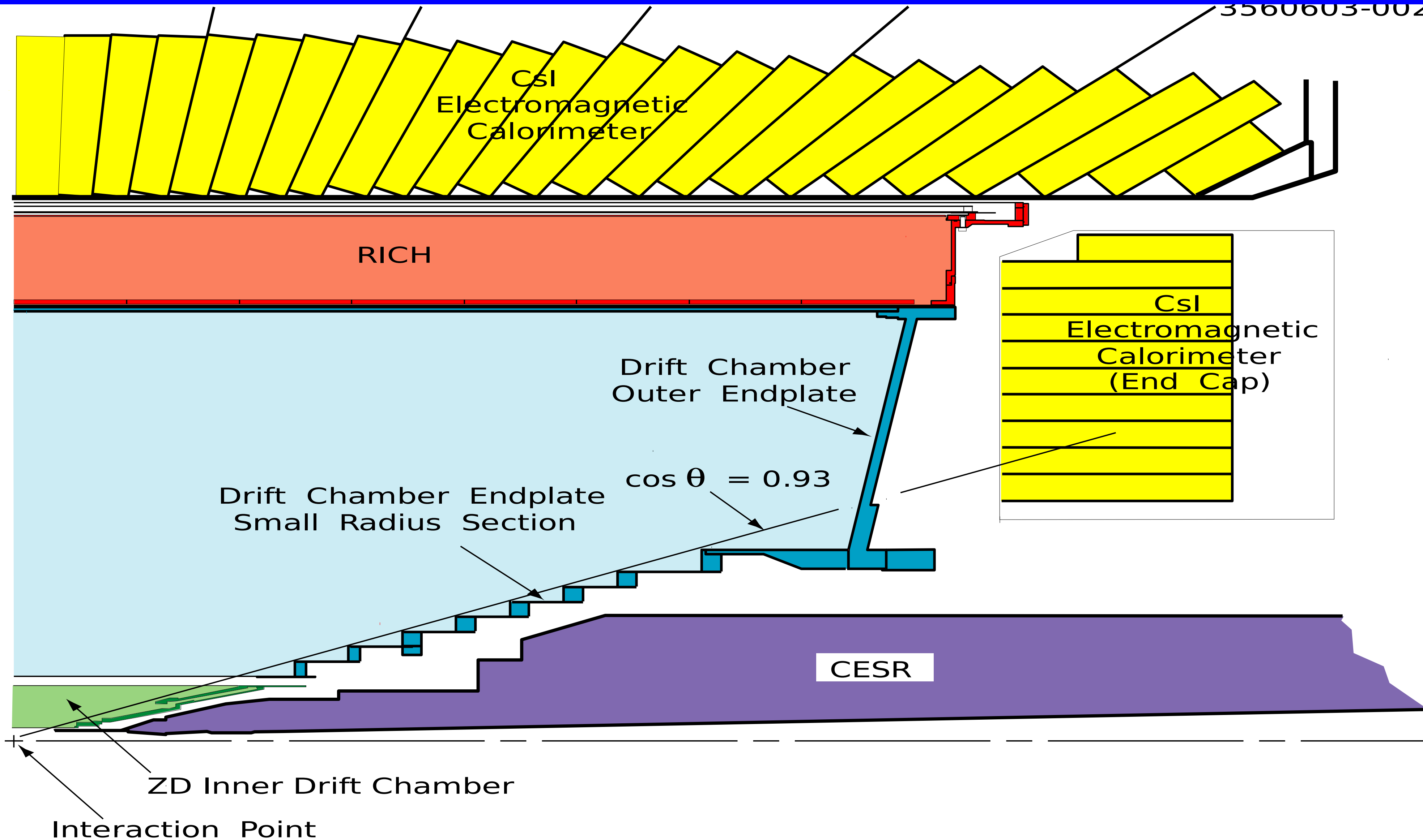

CLEO-c Physics

Observations
- $f_{D^+}$

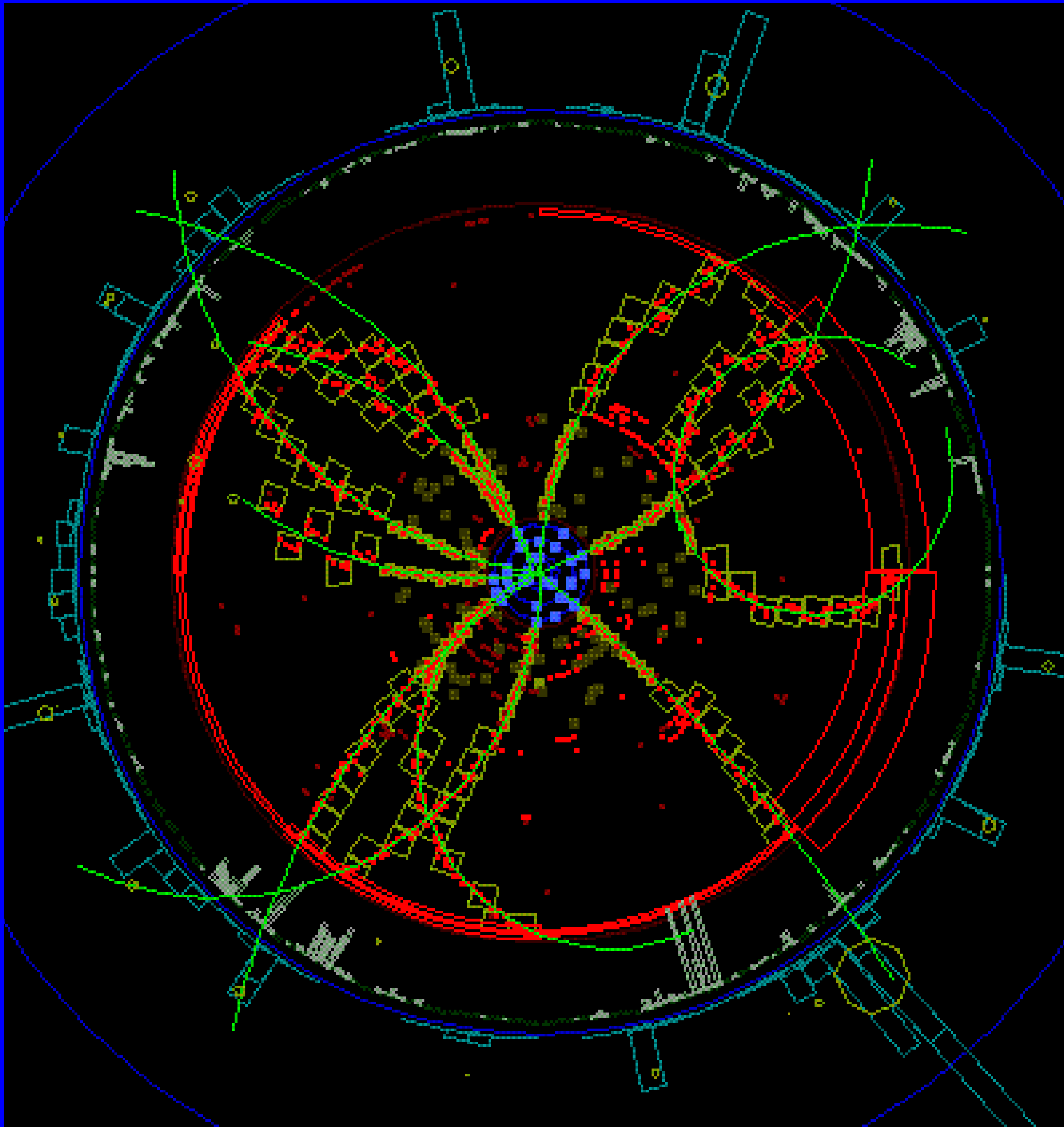
Confirmations
- $h_c(1P)$
- $\eta_c(2S)$
- $\Upsilon(4260)$

Precision
- $f_{D_s}$ & $f_{D^+}$
- $M_{D^0}, M_{\eta}, \& M_{\eta'}$

Absolute $\mathcal{B}$
- $\eta$ & $\eta'$
- $J/\psi \to \gamma\gamma\gamma$
- Hadronic & Semileptonic $D^0, D^+, \& D_s$



3560603-002
CsI
Electromagnetic
Calorimeter
RICH
CsI
Electromagnetic
Calorimeter
(End Cap)
Drift Chamber
Outer Endplate
cos θ = 0.93
Drift Chamber Endplate
Small Radius Section
CESR
ZD Inner Drift Chamber
Interaction Point

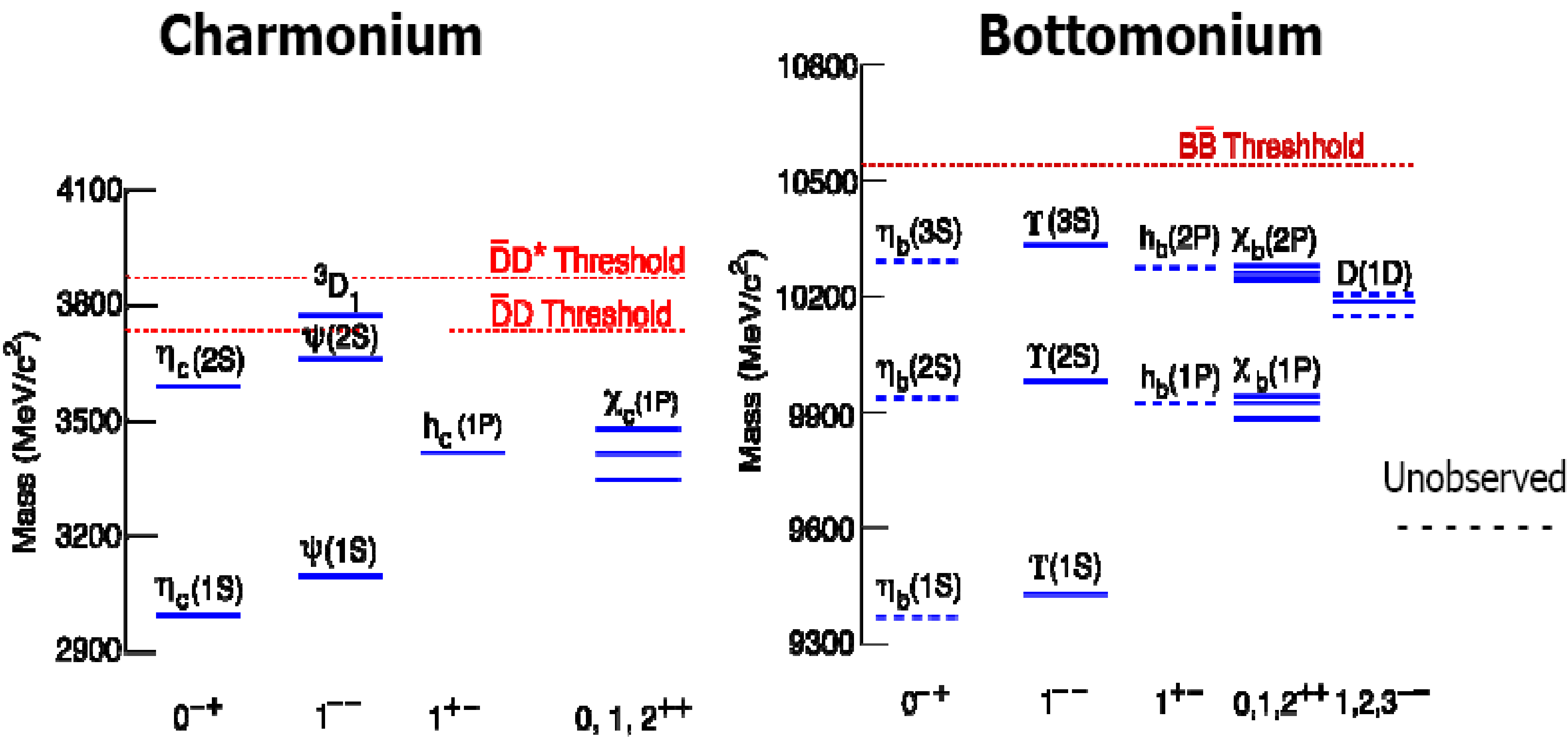


CLEO III
Υ(4S)
Typical
Hadronic
Event

Average:
- 10 tracks
- 10 showers

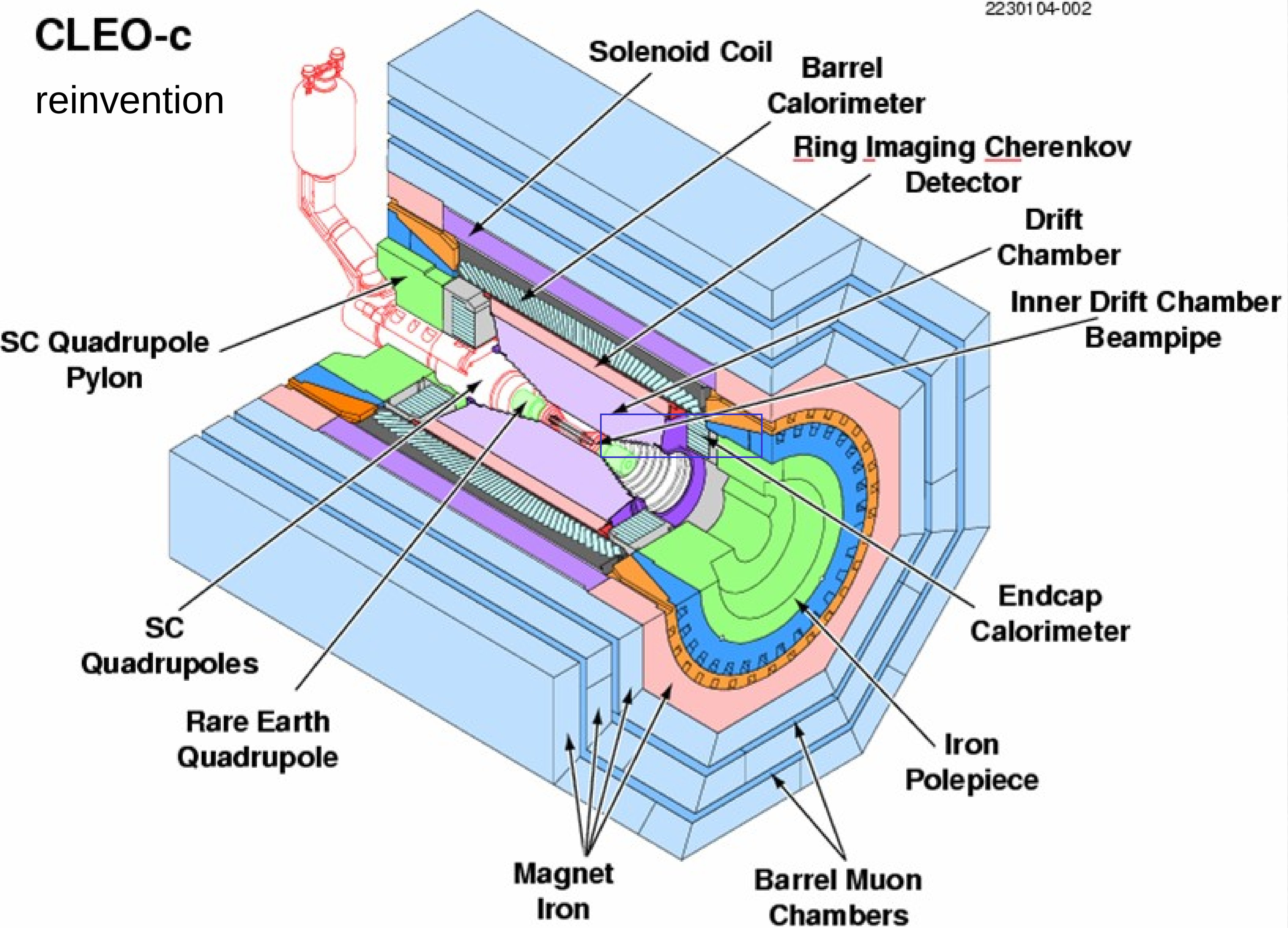
# Mass Levels, Schematically:

Upsilon and ψ provide sources of ggg and ggγ decays!



# CLEO-c

reinvention



**Energy Sample Size**

**Y(5S): 420 /pb**

**Y(4S): 15.5 /fb**

**Y(3S): 1.2 /fb 6M decays**

**Y(2S): 1.2 /fb 9M decays**

**Y(1S): 1.1 /fb 22M decays**

**10.54 GeV: 2 /fb**

**below Y(3S): 10.33 GeV 0.2 /fb**

**below Y(2S): 10.00 GeV 0.4 /fb**

**below Y(1S): 9.43 GeV 0.2 /fb**

**Way below Y(1S): 6.9-8.4 GeV 17 /pb**

Useful for $\gamma\gamma$-fusion studies

**3.97-4.26 GeV 60 /pb includes 13 /pb at 4.26GeV**

**4.17 GeV 586 /pb**

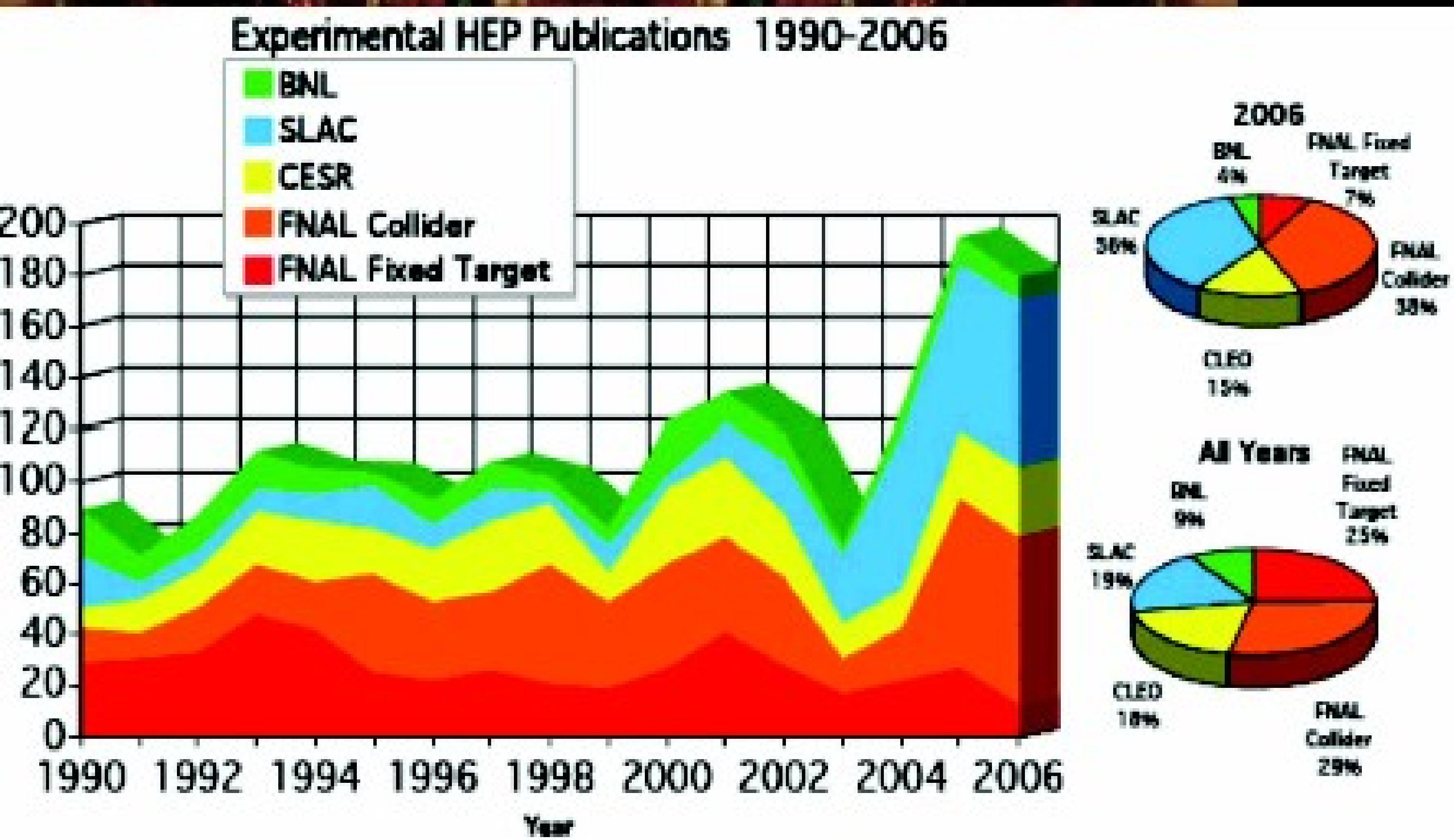
**psi(3770) 818 /pb**

**psi(2S) about 27M decays**

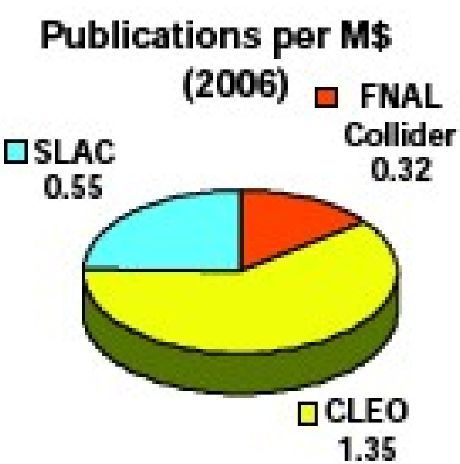
**3.673 GeV 21 /pb**

Direct two-photon decays of $\chi_c$, e.g.

# U.S Experimental Publications




Information compiled by Fermilab




CLEO author list:
~100 – 200 authors

# CLEO, 1973-2013, in excelsio dei

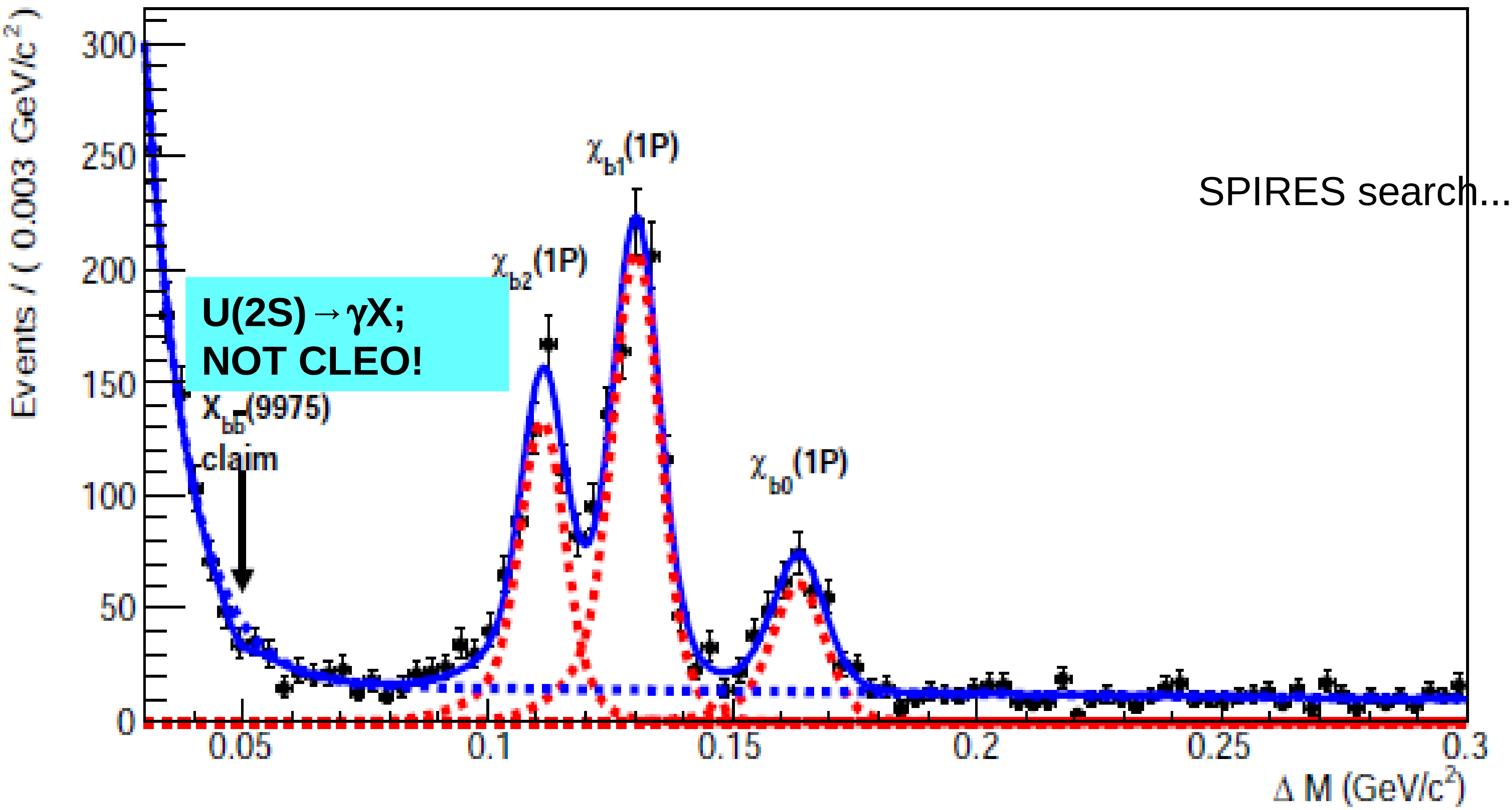


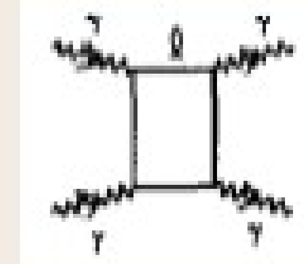

**Figure 1:** $\Delta M$ distributions for $\Upsilon(2S)$ data events that pass the selection criteria applied. Points with error bars are the data, and the blue solid curve is the result of the fit for the signal-plus-background hypothesis, and the blue dashed curve is the background component. The three $\chi_{bJ}(1P)$ components indicated by the red dotted curves are considered here as part of the signal.

# Two-photon physics (not ee→γγ!)

- Fundamental: probes directly EM couplings
  - Ratio of X production in γγ collisions=>high "stickiness"
- N.B., goes both ways γγ→X OR X→γγ

$$\frac{\Gamma_{\gamma\gamma}(\chi_{c2})}{\Gamma_{gg}(\chi_{c2})} = \frac{8\alpha^2}{9\alpha_s^2} \times \left( \frac{1 - \frac{5.33}{\pi}\alpha_s}{1 - \frac{2.2}{\pi}\alpha_s} \right).$$

# Photon-Photon Scattering in QED



**Subthreshold Light-by-Light Scattering**
($s_{\gamma\gamma} \ll 4m_\ell^2$):

$$\sigma(\gamma\gamma \to \gamma\gamma) \sim \frac{\alpha^4 s^3}{m_\ell^8} \text{ from QED box graph.}$$

**Resonant Light-by-Light Scattering**
($s_{\gamma\gamma} = 4m_\ell^2 - 4m\epsilon_n$)

$$\sigma(\gamma\gamma \to [\ell^+\ell^-]_n \to \gamma\gamma) \sim \frac{\Gamma_n^2}{(s-M_n^2)^2+M_n^2\Gamma_n^2}$$

$C = +$ states:
positronium $[e^+e^-]$, true muonium $[\mu^+\mu^-]$, true tauonium $[\tau^+\tau^-]$

**Threshold Domain** Small relative velocity $v$
($s_{\gamma\gamma} \simeq 4m_\ell^2$):

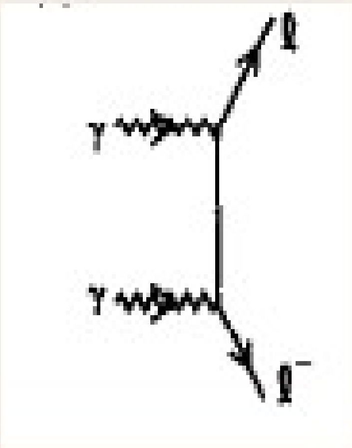
$$\sigma(\gamma\gamma \to \ell^+\ell^-) \sim \frac{\pi\alpha^2 v}{m_\ell^2} \times [1 + \frac{\pi\alpha}{v}]$$

Sommerfeld-Schwinger domain – analytically connected to Bohr spectrum

Bjorken

# Photon-Photon Scattering in QED

Single pair production $(s_{\gamma\gamma} \gg 4m_\ell^2)$:



$$\sigma(\gamma\gamma \to \ell^+\ell^-) \sim \frac{\pi\alpha^2}{s} \log \frac{s}{m_\ell^2}$$

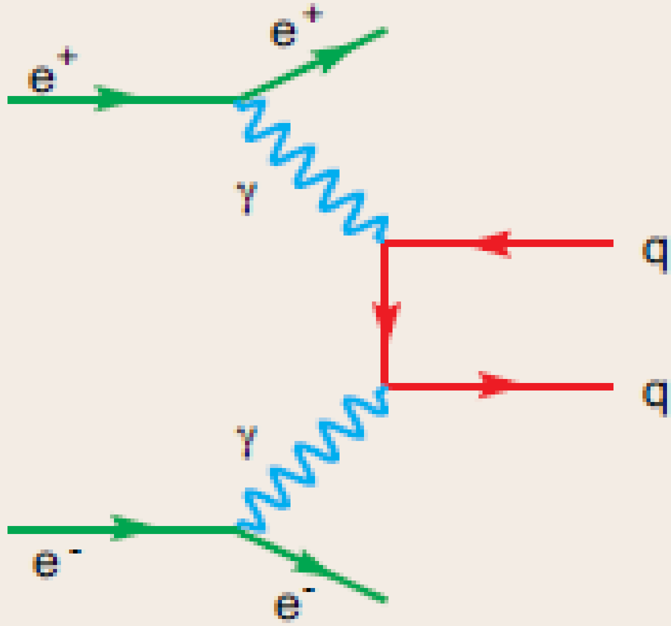
spin-$\frac{1}{2}$ exchange

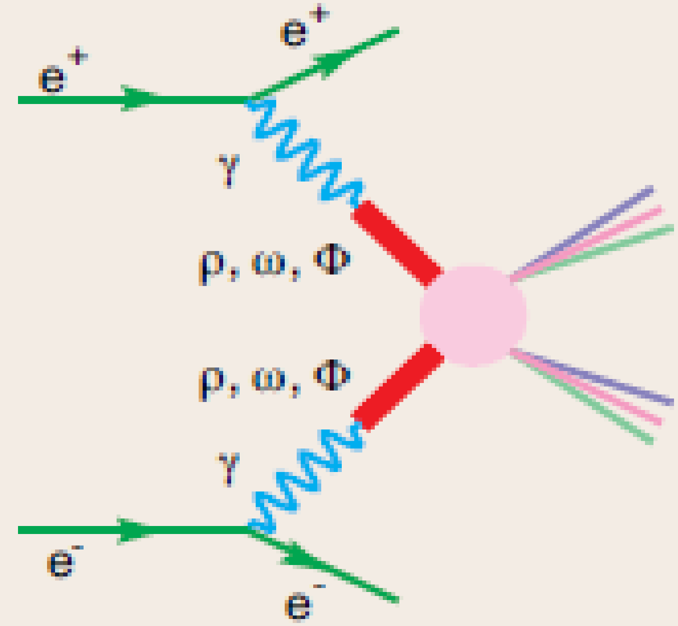
First observed at Novosibirsk, Frascati

Double pair production $(s_{\gamma\gamma} \gg 16m_\ell^2)$:

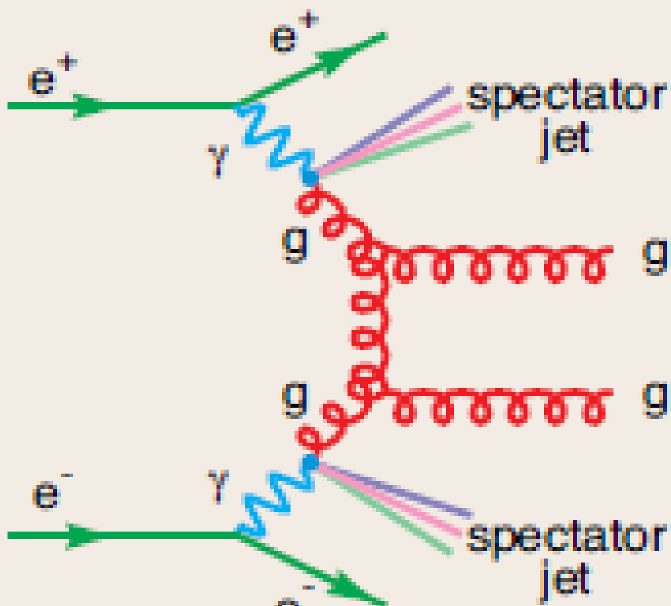

$$\sigma(\gamma\gamma \to \ell^+\ell^-\ell^+\ell^-) \sim \frac{\alpha^4}{m_\ell^2}$$

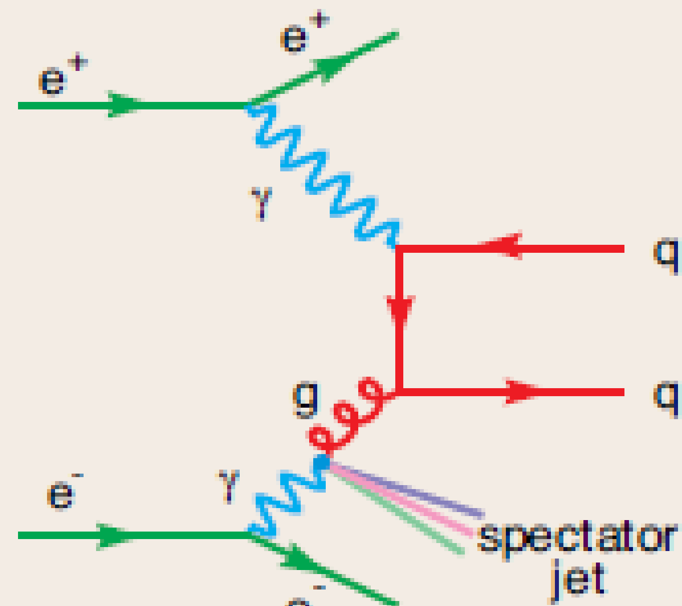
spin-1 exchange






# Contributions to to Total Two-Photon Cross Section



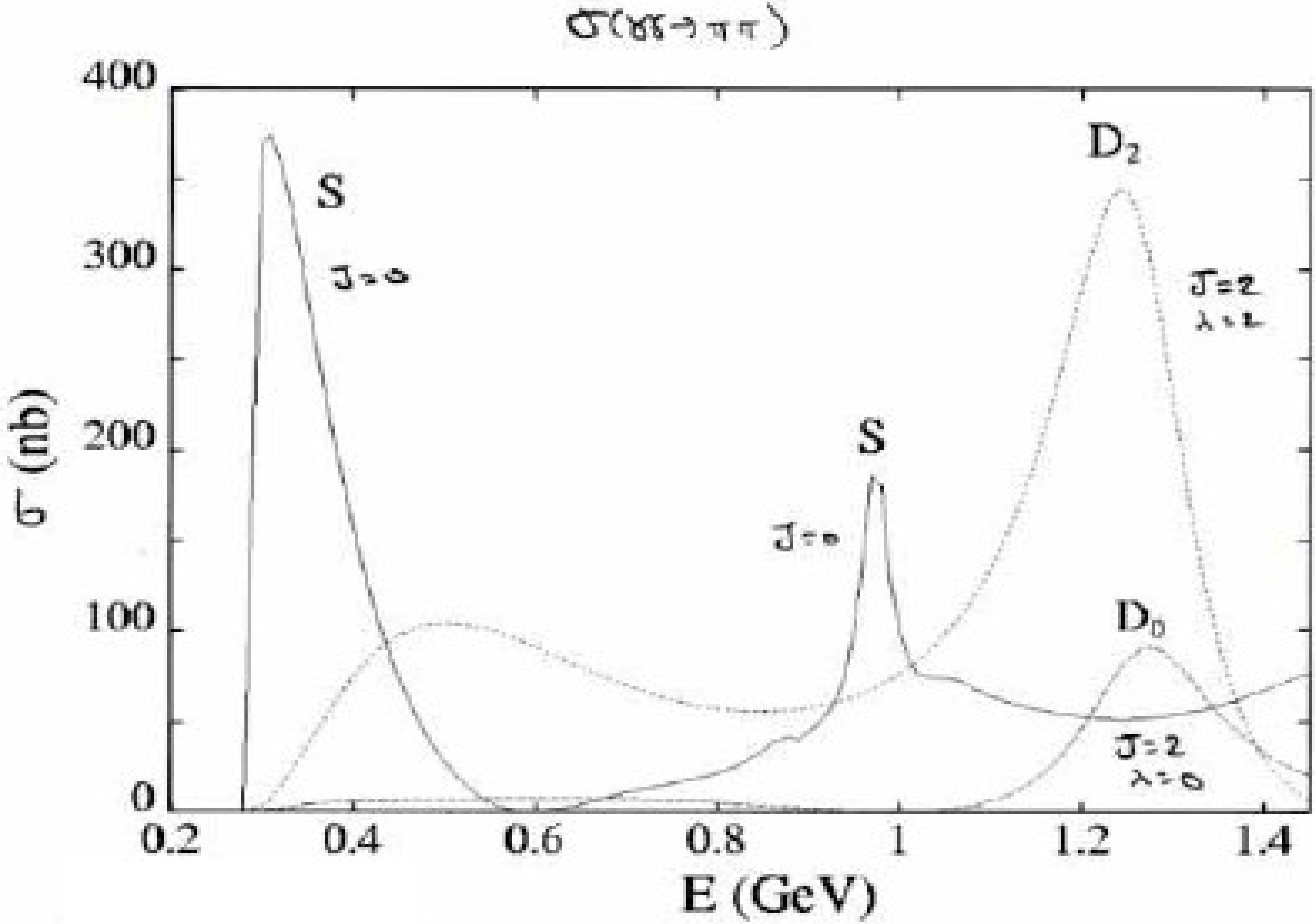


Physics accessed by CLEO in 2-photon collisions:

C=+ resonances
Photon-to-Meson Form Factors
Studies of glueball candidates

No tag
Single tag
Double tag

=> access different regions of phase space/different partial waves

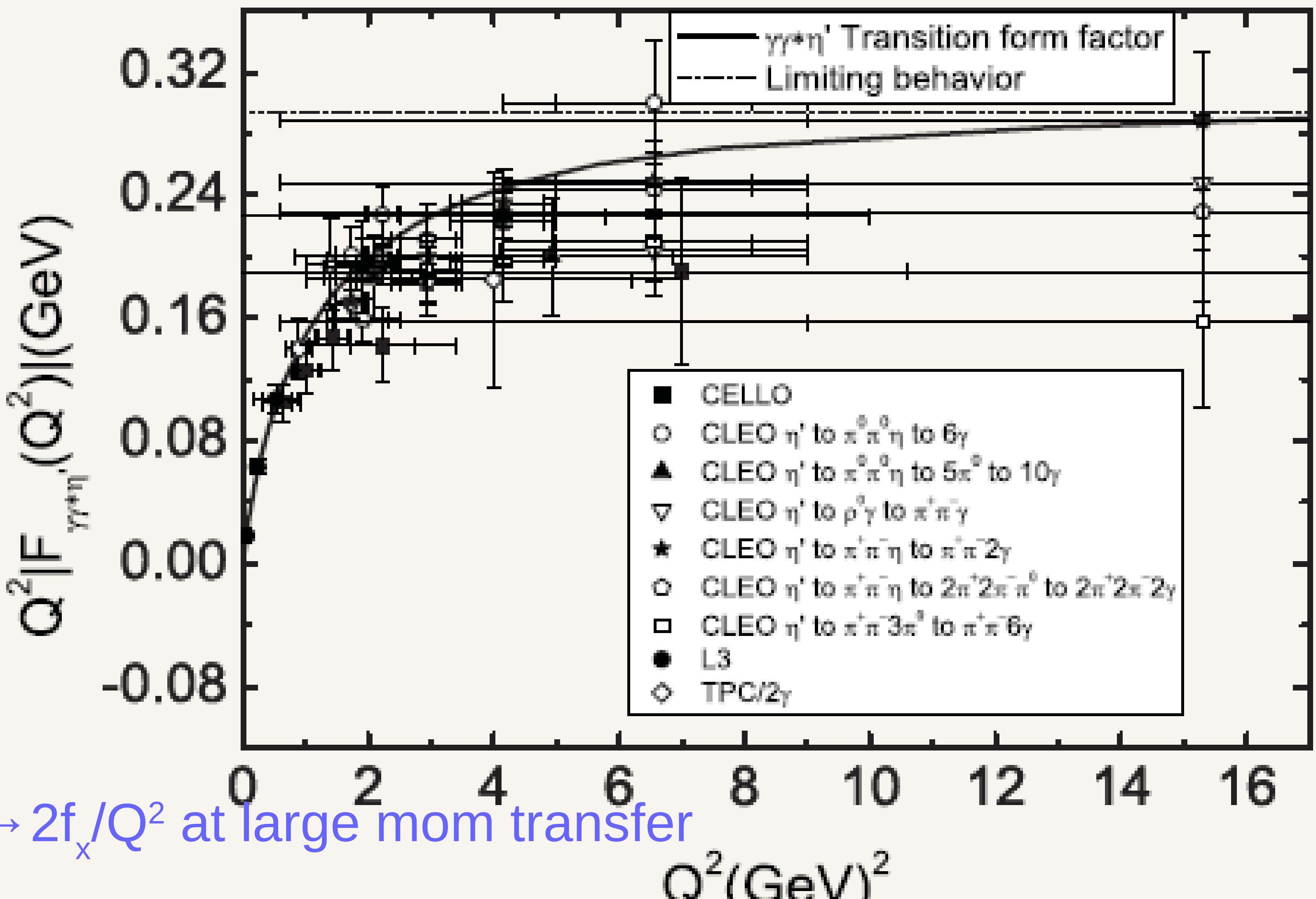



Roglioni, Pennington

# PHOTON-MESON TRANSITION FORM-FACTORS OF LIGHT PSEUDOSCALAR MESONS.

Bo-Wen Xiao　　Bo-Qiang Ma

Phys.Rev.D71:014034,2005




$F_{x\gamma} \to 2f_x/Q^2$ at large mom transfer

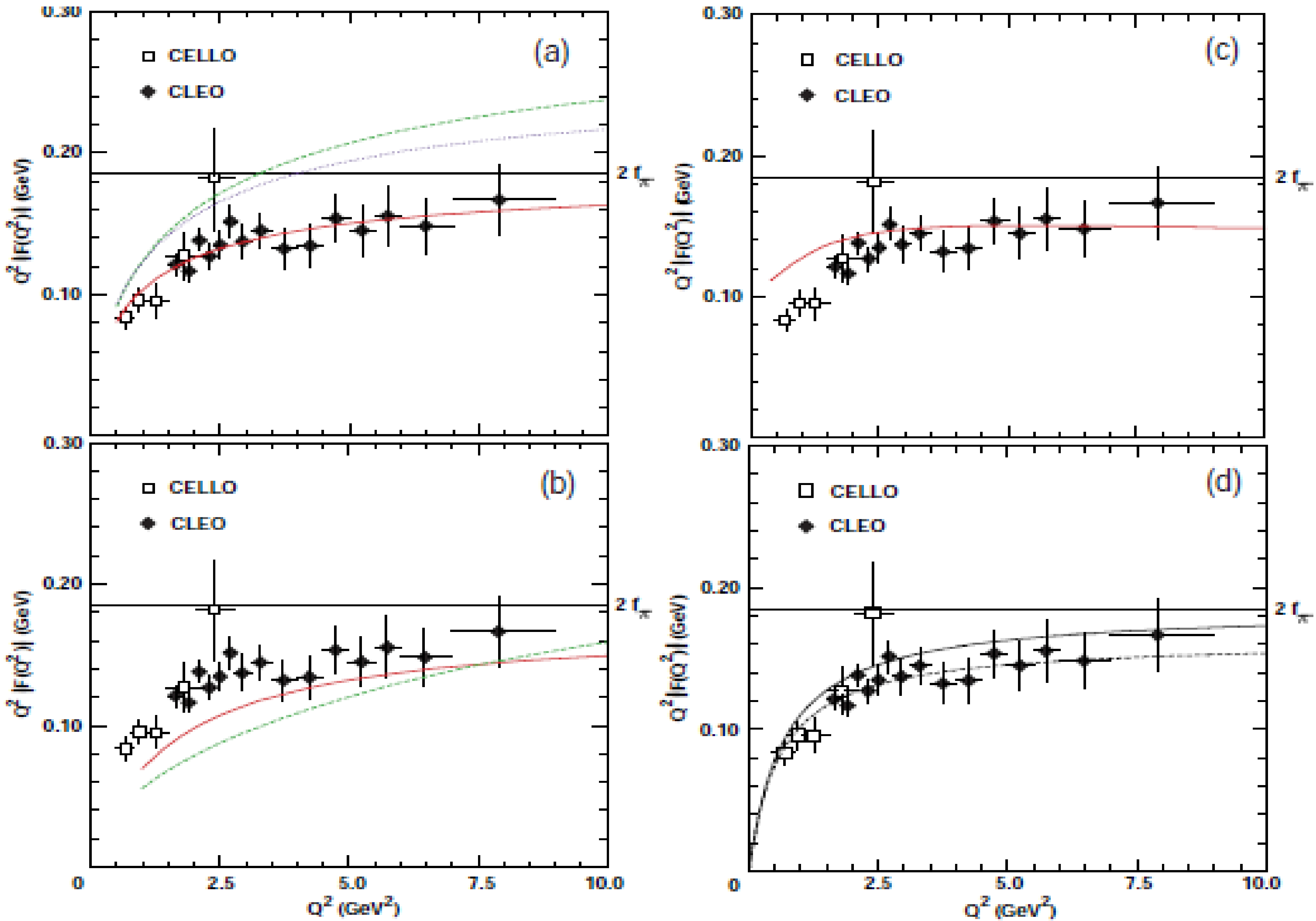



Figure 3: CLEO results on $\gamma^*\gamma \to \pi^0$ production. See the text for more information.

# Two-Photon Exclusive Amplitudes

$$F_M(s)=\frac{16\pi\alpha_s}{3s}\int_0^1 dx\,dy\,\frac{\phi_M^*(x,\tilde{Q}_x)\phi_M^*(y,\tilde{Q}_y)}{x(1-x)y(1-y)}$$

when $\phi_M(x,Q)=\phi_M(1-x,Q)$ is assumed.[7] Thus much of the dependence on $\phi(x,Q)$ can be removed from $\mathscr{M}_{\lambda\lambda'}$ by expressing it in terms of the meson form factor—i.e.,

$$\left.\begin{matrix}\mathscr{M}_{++}\\ \mathscr{M}_{--}\end{matrix}\right\}=16\pi\alpha F_M(s)\left[\frac{\langle(e_1-e_2)^2\rangle}{1-\cos^2\theta_{\rm c.m.}}\right],$$

Lepage, SJB

$$\left.\begin{matrix}\mathscr{M}_{+-}\\ \mathscr{M}_{-+}\end{matrix}\right\}=16\pi\alpha F_M(s)\left[\frac{\langle(e_1-e_2)^2\rangle}{1-\cos^2\theta_{\rm c.m.}}+2\langle e_1e_2\rangle g[\theta_{\rm c.m.};\phi_M]\right],$$

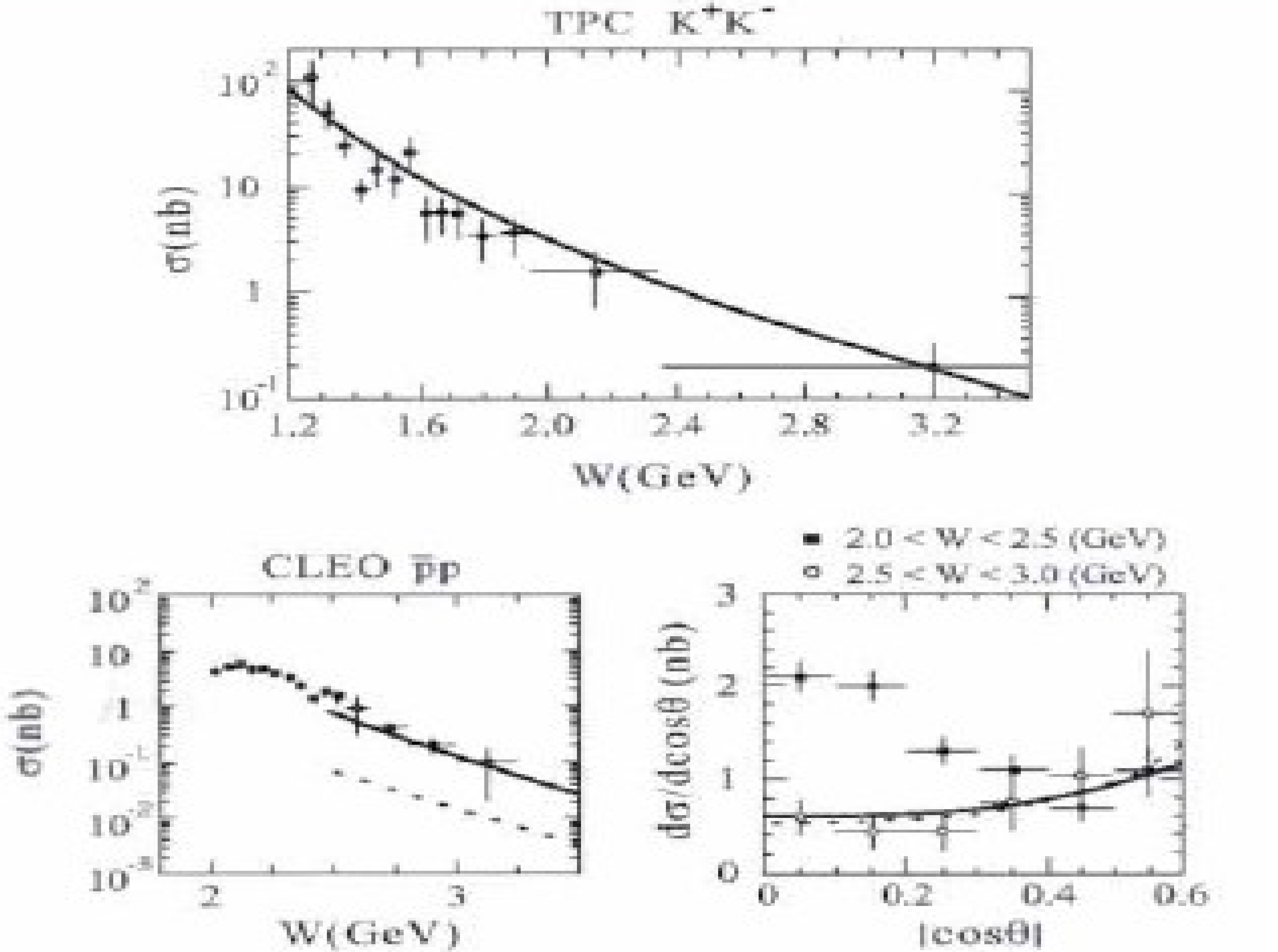
up to corrections of order $\alpha_s$ and $m^2/s$. Now the only dependence on $\phi_M$, and indeed the only unknown quantity, is in the $\theta$-dependent factor

$$g[\theta_{\rm c.m.};\phi_M]=\frac{\displaystyle\int_0^1 dx\,dy\,\frac{\phi_M^*(x,\tilde{Q})\phi_M^*(y,\tilde{Q})}{x(1-x)y(1-y)}\,\frac{a[y(1-y)+x(1-x)]}{a^2-b^2\cos^2\theta_{\rm c.m.}}}{\displaystyle\int_0^1 dx\,dy\,\frac{\phi_M^*(x,\tilde{Q})\phi_M^*(y,\tilde{Q})}{x(1-x)y(1-y)}}.$$

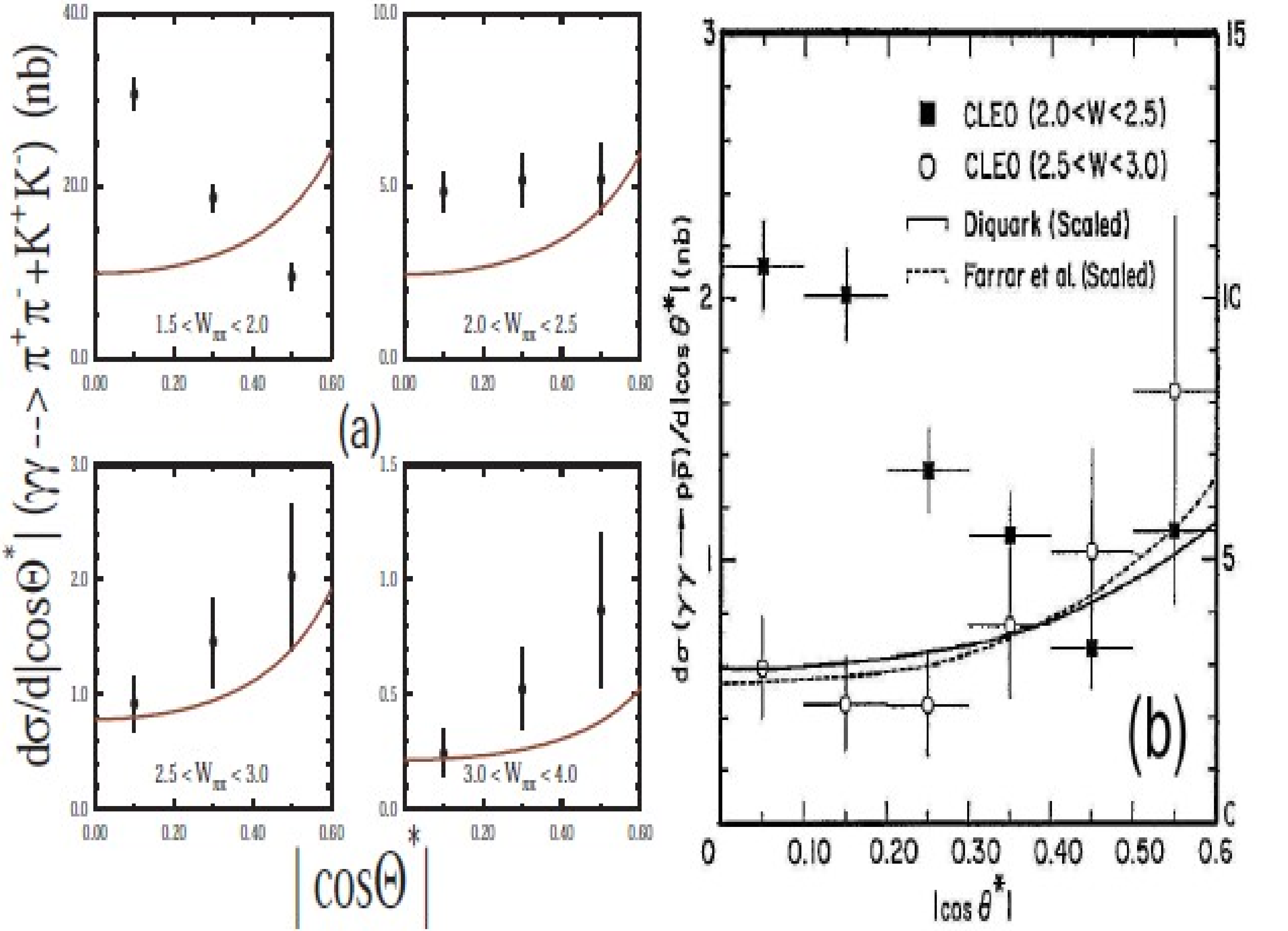
The spin-averaged cross section follows immediately from these expressions

$$\frac{d\sigma}{dt}=\frac{2}{s}\frac{d\sigma}{d\cos\theta_{\rm c.m.}}=\frac{1}{16\pi s^2}\frac{1}{4}\sum_{\lambda\lambda'}|\mathscr{M}_{\lambda\lambda'}|^2$$

$$=16\pi\alpha^2\left|\frac{F_M(s)}{s}\right|^2\left\{\frac{\langle(e_1-e_2)^2\rangle^2}{(1-\cos^2\theta_{\rm c.m.})^2}+\frac{2\langle e_1e_2\rangle\langle(e_1-e_2)^2\rangle}{1-\cos^2\theta_{\rm c.m.}}g[\theta_{\rm c.m.};\phi_M]+2\langle e_1e_2\rangle^2 g^2[\theta_{\rm c.m.};\phi_M]\right\}.$$



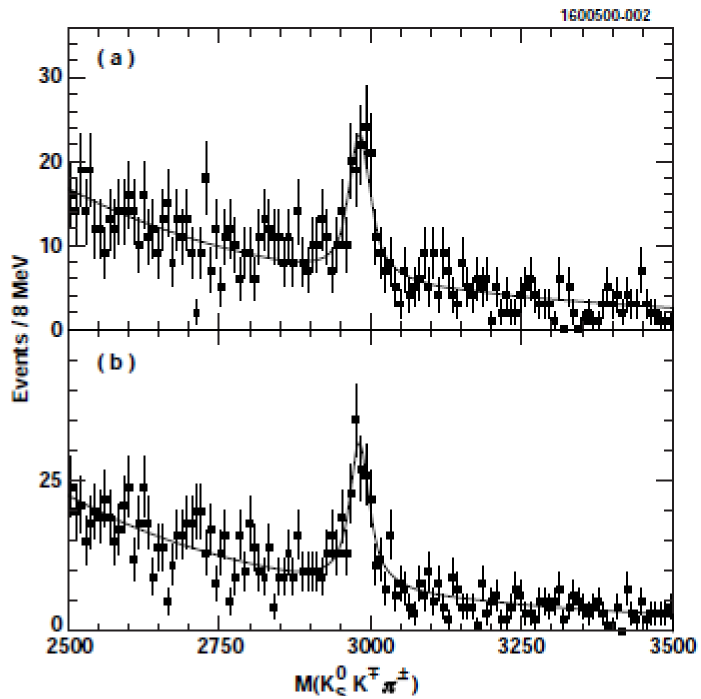
TPC K⁺K⁻
σ(nb)
W(GeV)
CLEO p̄p
σ(nb)
W(GeV)
2.0 < W < 2.5 (GeV)
2.5 < W < 3.0 (GeV)
dσ/dcosθ (nb)
|cosθ|



dσ/d|cosΘ*| (γγ --> π+π-+K+K-) (nb)
1.5 < Wππ < 2.0
2.0 < Wππ < 2.5
2.5 < Wππ < 3.0
3.0 < Wππ < 4.0
(a)
|cosΘ*|
CLEO (2.0<W<2.5)
CLEO (2.5<W<3.0)
Diquark (Scaled)
Farrar et al. (Scaled)
dσ (γγ → pp̄)/d|cos θ*| (nb)
(b)
|cos θ*|

# $\eta_c$ meson in $\gamma\gamma$ collisions (2nd definitive)

Measurements of the Mass, Total Width and Two-photon Partial Width of the $\eta_c$ Meson




Mass, total width and Two-photon width

Using 13.4 $fb^{-1}$ of data collected with the CLEO detector at the Cornell Electron Storage Ring, we have observed 300 events for the two-photon production of ground-state pseudo-scalar charmonium in the decay $\eta_c \to K^0_S K^{\mp}\pi^{\pm}$. We have measured the $\eta_c$ mass to be $(2980.4 \pm 2.3\ (stat) \pm 0.6\ (sys))$ MeV and its full width as $(27.0 \pm 5.8\ (stat) \pm 1.4\ (sys))$ MeV. We have determined the two-photon partial width of the $\eta_c$ meson to be $(7.6 \pm 0.8\ (stat) \pm 0.4\ (sys) \pm 2.3\ (br))$ keV, with the last uncertainty associated with the decay branching

# Obser-vation of $\eta_c'$

CLNS 03/1853
CLEO 03-14

**Observation of $\eta_c'$ Production in $\gamma\gamma$ Fusion at CLEO**


## Abstract

We report on the observation of the $\eta_c'(2^1S_0)$, the radial excitation of $\eta_c(1^1S_0)$ ground state of charmonium, in the two-photon fusion reaction $\gamma\gamma \to \eta_c' \to K_S^0 K^\pm \pi^\mp$ in 13.6 $\text{fb}^{-1}$ of CLEO II/II.V data and 13.1 $\text{fb}^{-1}$ of CLEO III data. We obtain $M(\eta_c')$=3642.9±3.1(stat)±1.5(syst) MeV, and $M(\eta_c)$=2981.8±1.3(stat)±1.5(syst) MeV. The corresponding values of hyperfine splittings between $^1S_0$ and $^3S_1$ states are $\Delta M_{hf}(1S)$=115.1±2.0 MeV, $\Delta M_{hf}(2S)$=43.1±3.4 MeV. Assuming that the $\eta_c$ and $\eta_c'$ have equal branching fractions to $K_S K \pi$, we obtain $\Gamma_{\gamma\gamma}(\eta_c')$=1.3±0.6 keV.


In 1982 the Crystal Ball collaboration reported the observation of a small enhancement at $E_\gamma \approx 91$ MeV in the inclusive photon spectrum from the reaction $e^+e^- \to \psi' \to \gamma X$, and interpreted it as due to $\eta_c'$ with $M(\eta_c')$=3594±5 MeV, $\Gamma(\eta_c')$<8 MeV [1,2]. This observation, which corresponds to a 2S hyperfine splitting $\Delta M_{hf}(2S)=M(\psi') - M(\eta_c')$=92±5 MeV, was in qualitative accord with the well established 1S hyperfine splitting, $\Delta M_{hf}(1S)=M(J/\psi) - M(\eta_c)$=117±2 MeV [2]. However, it was not confirmed, and the listing of the $\eta_c'$ was dropped by the PDG [2] from the meson summary list. The Fermilab experiments E760/E835 [4] failed to identify $\eta_c'$ in the reaction $\bar{p}p \to \eta_c' \to \gamma\gamma$, for $\eta_c'$ mass in the range $M(\eta_c')$=3575–3660 MeV. Similarly, in $e^+e^-$ collisions at $\sqrt{s} \approx 91$ GeV DELPHI [5], and later L3 [6], found no evidence for $\eta_c'$ in the reaction $\gamma\gamma \to hadrons$, in the mass range, 3500–3800 MeV, and concluded that its population in this reaction was less than a third of that of the $\eta_c$. A recent preliminary CLEO measurement [7] of the inclusive photon spectrum from $\psi' \to \gamma X$ has also not found any evidence for the excitation of $\eta_c'$.

The theoretical situation was equally uncertain. The perturbative prediction for the hyperfine splitting of the S states of charmonia is, in the lowest order

$$\Delta M_{hf}(S) = [32\pi\alpha_s/(9m_c^2)]|\Psi(0)|^2 . \qquad (2)$$

Thus, assuming that the strong coupling constant $\alpha_s(2S) = \alpha_s(1S)$,

$$\frac{\Delta M_{hf}(2S)}{\Delta M_{hf}(1S)} = \frac{|\Psi(0)/m_c|^2_{2S}}{|\Psi(0)/m_c|^2_{1S}} = \frac{\Gamma(\psi' \to e^+e^-)}{\Gamma(J/\psi \to e^+e^-)}\frac{M^2(\psi')}{M^2(J/\psi)}$$

since $\Gamma(^3S_1 \to e^+e^-)$ is proportional to $|\Psi(0)|^2/M^2(^3S_1)$. Substituting experimental values [2] yields, $\Delta M_{hf}(2S)$=68±7 MeV. Buchmüller and Tye [8] have pointed out that in order to take approximate account of binding energy, $m_c$ in Eq. (2) can be replaced by $M(^3S_1)/2$, which leads to $\Delta M_{hf}(2S)$=48±5 MeV.

# The Discovery of $\eta_c'(2^1S_0)$

The breakthrough came, of all the places, from the observation of $\eta_c'$ in $B$ decays by Belle. It was followed by its observation in $\gamma\gamma$ fusion at CLEO and BaBar.

| (in MeV) | $M(\eta_c'(2S))$ | $\Gamma(\eta_c'(2S))$ | events (reaction) |
|---|---|---|---|
| Belle(2002) [8] | $3654 \pm 10$ | $< 55$ | $39 \pm 11\ (B \to K(K_S K\pi))$ |
| **CLEO(2004)** [9] | $\mathbf{3642.9 \pm 3.4}$ | $\mathbf{6.3 \pm 14.1}$ | $\mathbf{61 \pm 15\ (\gamma\gamma \to K_S K\pi)}$ |
| BaBar(2004) [10] | $3630.8 \pm 3.5$ | $17.0 \pm 8.7$ | $112 \pm 24\ (\gamma\gamma \to K_S K\pi)$ |
| BaBar(2005) [11] | $3645.0 \pm 5.5$ | $22 \pm 14$ | $121 \pm 27\ (e^+e^- \to J/\psi(c\bar{c}))$ |
| Belle(2005)* [12] | $3636 \pm 9$ | | $311 \pm 42\ (e^+e^- \to J/\psi(c\bar{c}))$ |

*Both $\eta_c$ and $\chi_{c0}$ masses in this measurement were obtained $\sim 10$ MeV lower than their known values. With apologi
I have therefore arbitrarily increased the $\eta_c'$ mass reported by Belle by 10 MeV in the above table.

- New measurements are being made, but $M(\eta_c')$ is still not firmly anchored. The present weighte average is $M(\eta_c') = 3638.7 \pm 2.0$ MeV.
- This leads to the hyperfine splitting
  **$\Delta M_{hf}(2S) = 3686.1 - 3638.7 = 47.4 \pm 2.0$ MeV.**
  Recall that, **$\Delta M_{hf}(1S) = 3097 - 2980 = 117 \pm 1$ MeV.**
  Explaining this large difference is a challenge for theorists.

TABLE IV: Compilation of experimental results for two-photon partial widths of $\chi_{c0}$ and $\chi_{c2}$.

| Experiment [Ref.] | Measured | $\Gamma_{\gamma\gamma}(\chi_{c0})$ keV* | $\Gamma_{\gamma\gamma}(\chi_{c2})$ keV* | $\mathcal{R}$ |
|---|---|---|---|---|
| E760(1993) [12] | $\mathcal{B}(\bar{p}p \to \chi_{c2}) \times \mathcal{B}_{\gamma\gamma}$ | - | 0.47±0.12±0.07 | - |
| E835(2000) [13] | $\mathcal{B}(\bar{p}p \to \chi_{cJ}) \times \mathcal{B}_{\gamma\gamma}$ | 2.01±1.03±0.24 | 0.39±0.07±0.03 | 0.20±0.11±0.03 |
| E835(2004) [14] | $\mathcal{B}(\bar{p}p \to \chi_{c0}) \times \mathcal{B}_{\gamma\gamma}$ | 3.3±0.6±0.5 | - | - |
| OPAL(1998) [24] | $\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{c2} \to \gamma J/\psi)$ | - | 1.19±0.32±0.26 | - |
| L3(1999) [25] | $\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{c2} \to \gamma J/\psi)$ | - | 0.69±0.27±0.11 | - |
| CLEO(1994) [26] | $\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{c2} \to \gamma J/\psi)$ | - | 0.74±0.21±0.18 | - |
| CLEO(2001) [27] | $\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{cJ} \to \gamma J/\psi)$ | 3.09±0.54±0.44 | 0.51±0.14±0.09 | 0.17±0.06±0.04 |
| CLEO(2006) [28] | $\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{c2} \to \gamma J/\psi)$ | - | 0.55±0.06±0.05 | - |
| Belle(2002) [29] | $\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{c2} \to \gamma J/\psi)$ | - | 0.56±0.05±0.05 | - |
| Belle(2007) [30] | $\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{cJ} \to K^0_S K^0_S)$ | 2.53±0.23±0.40 | 0.46±0.08±0.09 | 0.18±0.03±0.04 |
| Belle(2007) [31]** | $\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{cJ} \to 4\pi)$ | 1.84±0.15±0.27 | 0.40±0.04±0.07 | 0.22±0.03±0.05 |
| | $\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{cJ} \to 2\pi 2K)$ | 2.07±0.20±0.40 | 0.44±0.04±0.16 | 0.21±0.03±0.09 |
| | $\Gamma_{\gamma\gamma} \times \mathcal{B}(\chi_{cJ} \to 4K)$ | 2.88±0.47±0.53 | 0.62±0.12±0.12 | 0.21±0.05±0.06 |
| This measurement | $\mathcal{B}(\psi(2S) \to \gamma\chi_{cJ}) \times \mathcal{B}_{\gamma\gamma}$ | 2.53±0.37±0.26 | 0.60±0.06±0.06 | 0.24±0.04±0.03 |
| **Averages** (weighted by total errors) | | 2.31±0.10±0.12 | 0.51±0.02±0.02 | 0.20±0.01±0.02 |

# Or, from direct $\gamma\gamma$ production (CLEOc):

## Two–Photon Width of $\chi_{c2}$

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(CLEO Collaboration)

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The two–photon width of $\chi_{c2}$ ($^3P_2$) state of charmonium has been measured using 14.4 fb$^{-1}$ of $e^+e^-$ data taken at $\sqrt{s} = 9.46 - 11.30$ GeV with the CLEO III detector. The $\gamma\gamma$–fusion reaction studied is $e^+e^- \to e^+e^-\gamma\gamma$, $\gamma\gamma \to \chi_{c2} \to \gamma J/\psi \to \gamma e^+e^-(\mu^+\mu^-)$. We measure $\Gamma_{\gamma\gamma}(\chi_{c2})\mathcal{B}(\chi_{c2} \to \gamma J/\psi)\mathcal{B}(J/\psi \to e^+e^- + \mu^+\mu^-) = 13.2 \pm 1.4(\text{stat}) \pm 1.1(\text{syst})$ eV, and obtain $\Gamma_{\gamma\gamma}(\chi_{c2}) = 559 \pm 57(\text{stat}) \pm 48(\text{syst}) \pm 36(\text{br})$ eV. This result is in excellent agreement with the result of $\gamma\gamma$–fusion measurement by Belle and is consistent with that of the $\bar{p}p \to \chi_{c2} \to \gamma\gamma$ measurement, when they are both reevaluated using the recent CLEO result for the radiative decay $\chi_{c2} \to \gamma J/\psi$.

CLNS 01-1732
CLEO 01-08

# Experimental Investigation of the Two-photon Widths of the $\chi_{c0}$ and the $\chi_{c2}$ Mesons

CLEO Collaboration

(June 11, 2015)

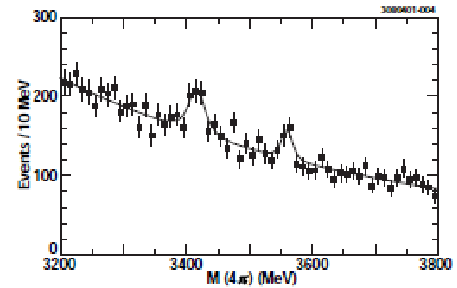



FIG. 1. The $\pi^+\pi^-\pi^+\pi^-$ invariant mass (data point with errors). The solid line is the fit with a $\chi^2$/d.o.f. = 44/54.

## Abstract

Using 12.7 fb$^{-1}$ of data collected with the CLEO detector at CESR, we observed two-photon production of the $c\bar{c}$ states $\chi_{c0}$ and $\chi_{c2}$ in their decay to $\pi^+\pi^-\pi^+\pi^-$. We measured $\Gamma_{\gamma\gamma}(\chi_c) \times \mathcal{B}(\chi_c \to \pi^+\pi^-\pi^+\pi^-)$ to be 75 $\pm$ 13 (stat) $\pm$ 8 (syst) eV for the $\chi_{c0}$ and 6.4 $\pm$ 1.8 (stat) $\pm$ 0.8 (syst) eV for the $\chi_{c2}$, implying $\Gamma_{\gamma\gamma}(\chi_{c0}) = 3.76 \pm 0.65(\text{stat}) \pm 0.41(\text{syst}) \pm 1.69(\text{br})$ keV and $\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.53 \pm 0.15(\text{stat}) \pm 0.06(\text{syst}) \pm 0.22(\text{br})$ keV. Also, cancelation of dominant experimental and theoretical uncertainties permits a precise comparison of $\Gamma_{\gamma\gamma}(\chi_{c0})/\Gamma_{\gamma\gamma}(\chi_{c2})$, evaluated to be $7.4 \pm 2.4(\text{stat}) \pm 0.5(\text{syst}) \pm 0.9(\text{br})$, with QCD-based predictions.

The two-photon width of a $\chi_c$ meson can be determined from a measurement of its two-photon cross section. The ratio of the two-photon width to the two-gluon width of a $\chi_c$ meson can be calculated in PQCD with reduced uncertainties due to cancelation of charmed quark mass factors, non-perturbative factors, and wave function dependence. In next-to-leading order (NLO) PQCD one obtains the following relationships [1] :

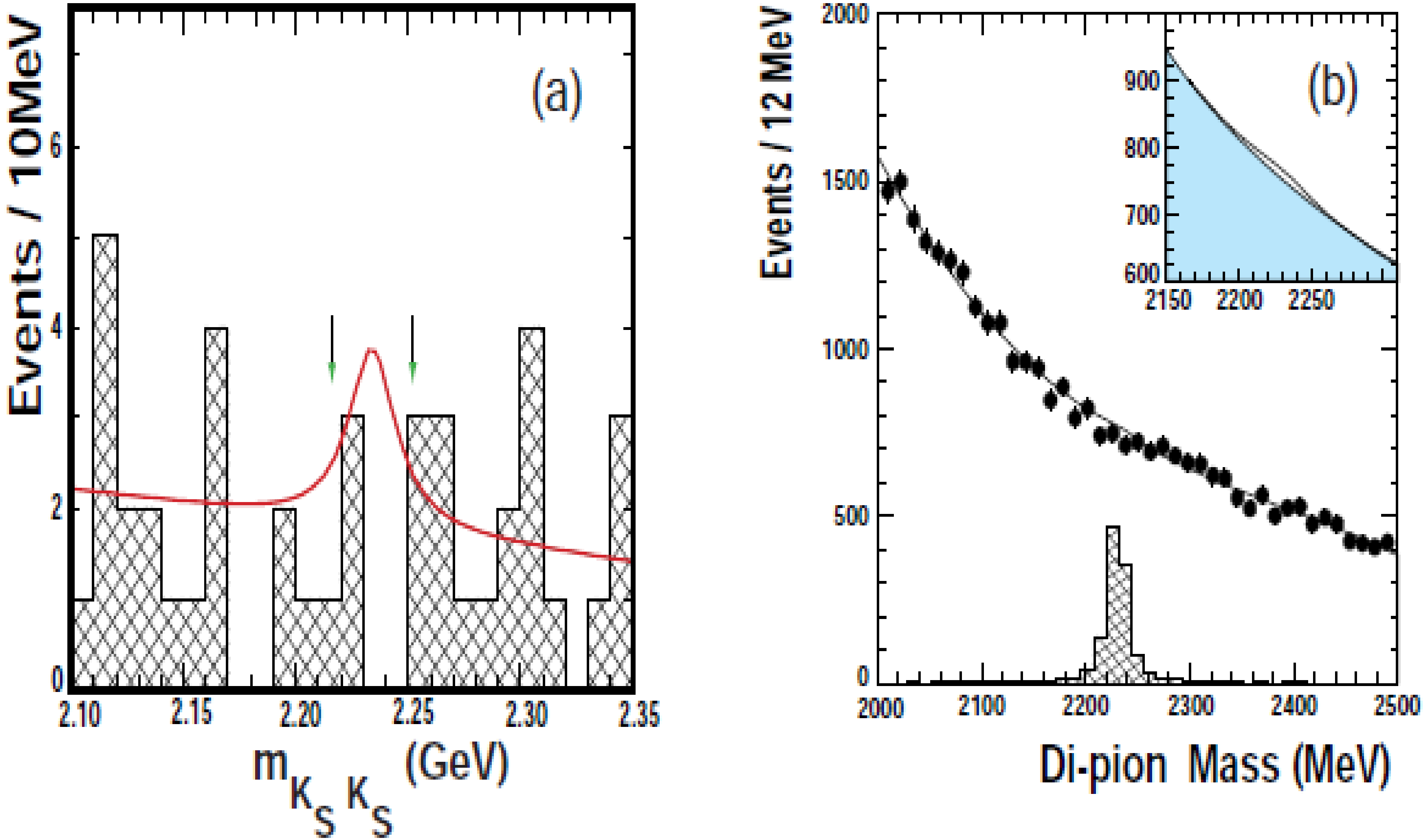
$$\frac{\Gamma_{\gamma\gamma}(\chi_{c0})}{\Gamma_{gg}(\chi_{c0})} = \frac{8\alpha^2}{9\alpha_s^2}\frac{(1+0.18\alpha_s/\pi)}{(1+9.5\alpha_s/\pi)}, \tag{1}$$

$$\frac{\Gamma_{\gamma\gamma}(\chi_{c2})}{\Gamma_{gg}(\chi_{c2})} = \frac{8\alpha^2}{9\alpha_s^2}\frac{(1-5.3\alpha_s/\pi)}{(1-2.2\alpha_s/\pi)}. \tag{2}$$

The width of the $\chi_{c0}$ meson can be assumed to be dominated by its two-gluon component, so $\Gamma_{gg}(\chi_{c0}) \approx \Gamma_{tot}(\chi_{c0}) = 14.9^{+2.6}_{-2.3}$ MeV [2]. Using a value of the strong coupling constant $\alpha_s = 0.28$ [1], one obtains the NLO PQCD prediction $\Gamma_{\gamma\gamma}(\chi_{c0}) = 5.0 \pm 0.8$ keV. Due to the uncertainty in the charm mass scale, we also calculate the NLO PQCD prediction at $\alpha_s = 0.35$ and find $\Gamma_{\gamma\gamma}(\chi_{c0}) = 2.9 \pm 0.5$ keV. A measurement reported in a thesis gave $\Gamma_{\gamma\gamma}(\chi_{c0}) = 4.0 \pm 2.8$ keV [3]. The E835 collaboration reported an upper limit of $\Gamma_{\gamma\gamma}(\chi_{c0}) \leq$ 3.47 keV (95% C.L.) [4].

# Things we didn't find (glueball candidates)

- LEP's $\eta_c(1440)$ ($KK\pi$)
- $f_J(2220) \rightarrow MM$
  - (BES $J/\psi \rightarrow \gamma f_J(2220)$)


(a)
Events / 10MeV
0
2
4
6
2.10
2.15
2.20
2.25
2.30
2.35
$m_{K_S K_S}$ (GeV)
(b)
Events / 12 MeV
0
500
1000
1500
2000
2000
2100
2200
2300
2400
2500
600
700
800
900
2150
2200
2250
Di-pion Mass (MeV)

# Summary

- Despite the richness of the basic physics accessed, $\gamma\gamma$-physics has a Hennie Youngman complex (or Groucho Marx complex [or Rodney Dangerfield complex]) at B-factories.
- Nevertheless, two-photon couplings formed the basis of roughly one CLEO publication per year during the salad days.
- Still huge data samples waiting to be mined (esp. Belle-II!!)