CLEO Results on Charmonium and Charm

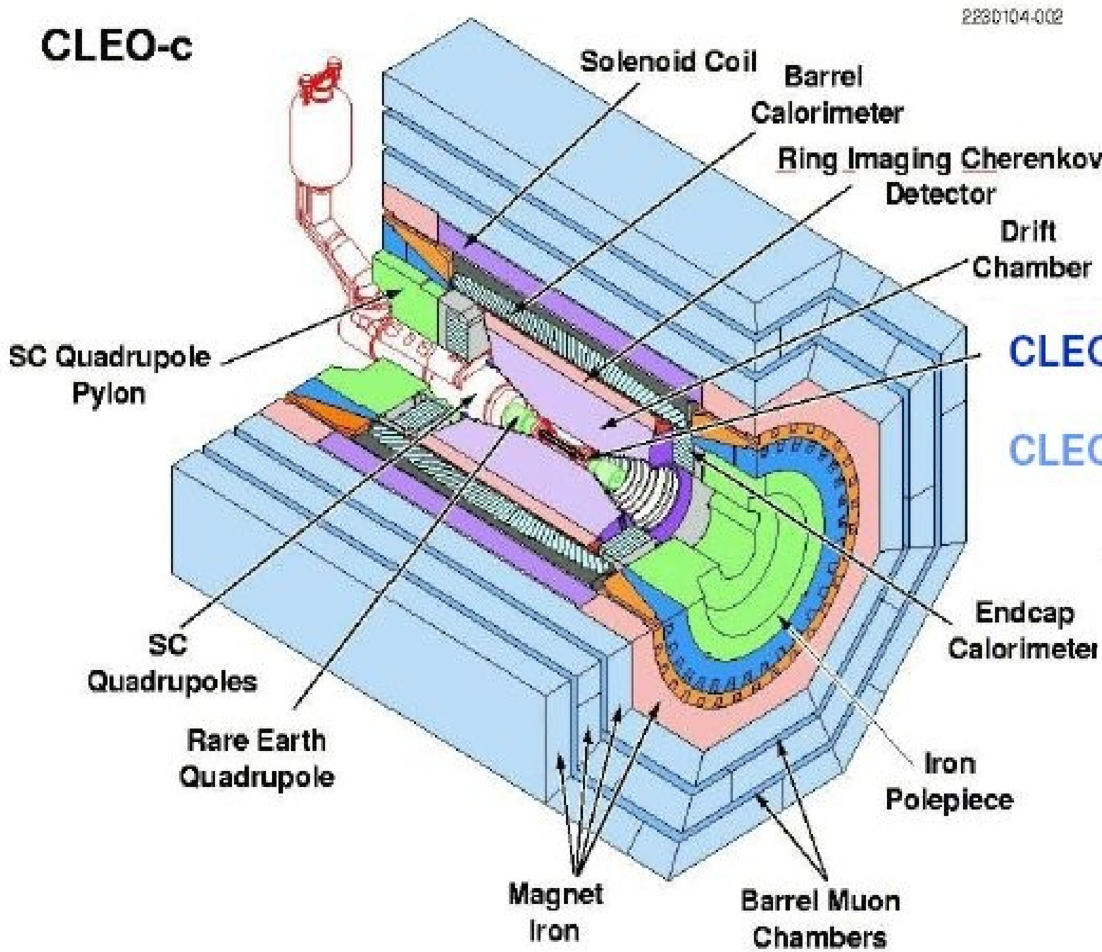
Helmut Vogel (for the CLEO Collaboration)
Carnegie Mellon University QCD08 Montpellier, France

Charmonium: First observation of $J/\psi \to 3\gamma$
Exclusive decays of χ_{cJ}
Properties of η_c and h_c

Light systems: $\psi(2S) \to \eta\, J/\psi$: η BF's and $M(\eta)$
$\psi(2S) \to \pi^+\pi^-\, J/\psi$, $J/\psi \to \gamma\,\eta'$: $M(\eta')$

Open Charm: f_D and f_{Ds} (a puzzle?)
Discovery of $D_s \to p\,\bar{n}$

Detector and Data Samples



CLEO-III: Silicon Vertex Detector; B=1.5T

CLEO-c: Inner Drift Chamber; B=1.0T

Detector	Energy GeV or QQ resonance (targeted $q\bar{q}$ meson)	Luminosity fb^{-1}	Narrow resonance statistics
CLEO-III	11.227-11.383	0.71	
	$\Upsilon(5S)$ (B_s)	0.42	
	$\Upsilon(4S)$ (B) + cont	6.2 + 2.2	
	$\Upsilon(3S)$ + cont	1.2 + 0.2	6M
	$\Upsilon(2S)$ + cont	1.2 + 0.4	9M
	$\Upsilon(1S)$ + cont	1.1 + 0.2	22M
	6.9 – 8.4	0.02	
CLEO-c	4.17 (D_s)	0.586	
	3.97-4.26	0.06	
	$\psi(3770)$ (D)	0.818	
	$\psi(2S)$	0.054	27M
	3.673	0.021	

$B(\psi(2S) \to \pi^+\pi^- J/\psi = 32\%$ ($\varepsilon \approx 75\%$)

$B(\psi(2S) \to \gamma\, \chi_{cJ}$ $\approx 9\%$ for each J=0,1,2

Clean, tagged, abundant J/ψ, χ_{cJ} data!

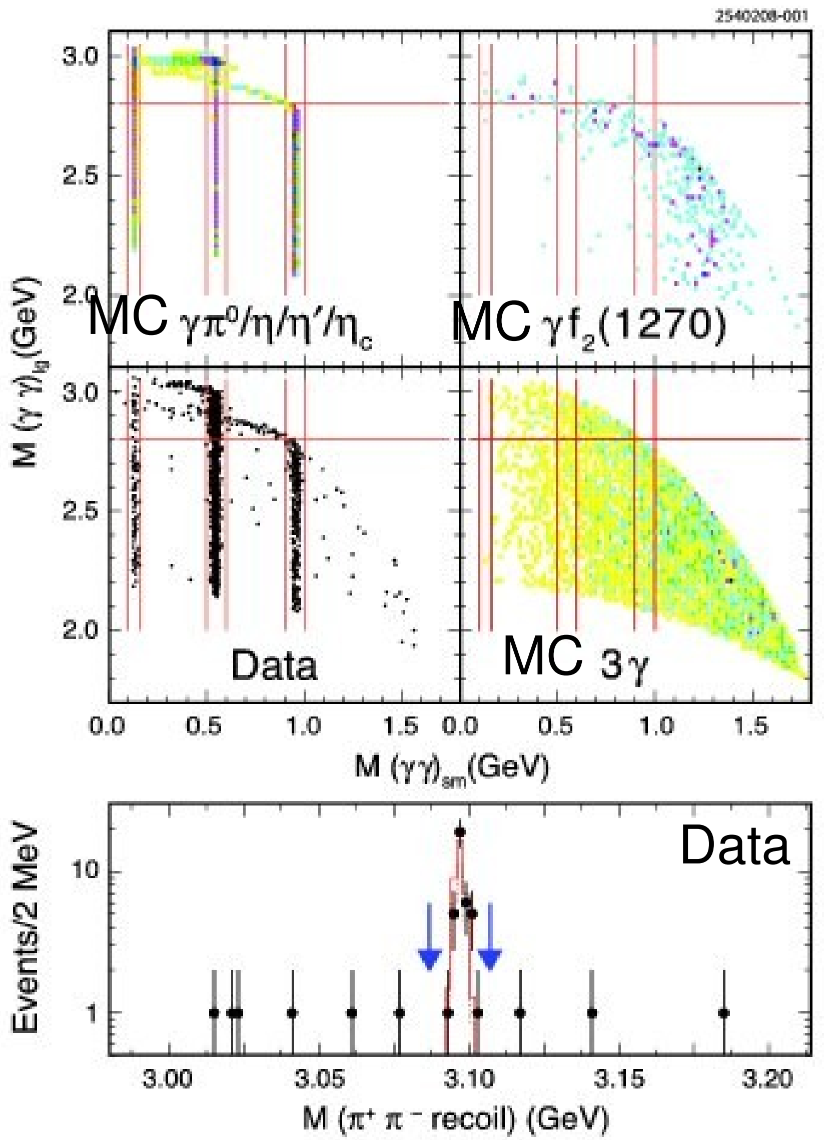
$J/\psi \rightarrow 3\gamma$

Tag via $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$
(eliminates QED background!)

Veto resonances π^0, η, η', η_c

Main remaining background:
$J/\psi \rightarrow \gamma\, \pi^0\pi^0$

Tagging gives very clean J/ψ sample!



$J/\psi \rightarrow 3\gamma$

Perform kinematic fit;

Signal peaks at low χ^2/dof

Background rises away from zero

(and is independent of $\pi^0\pi^0$ substructure!)

Result (arXiv:0806.0671[hep-ex]):

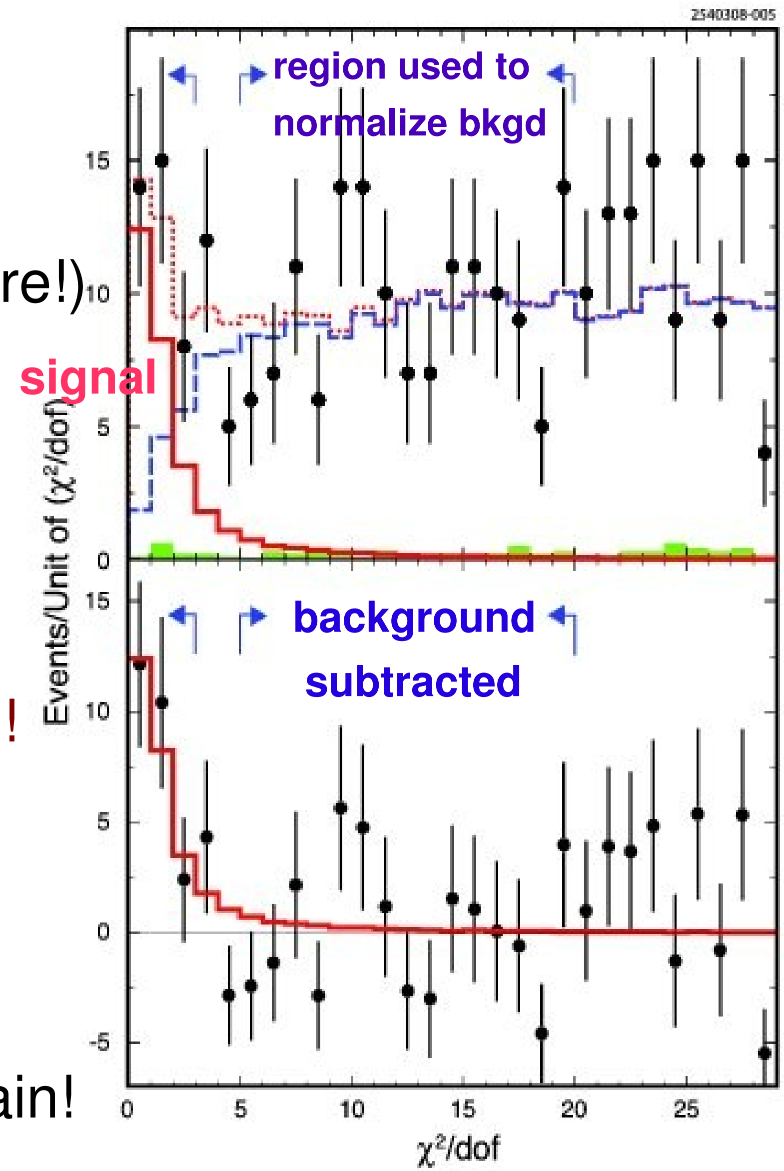
B = (1.2 ± 0.3 ± 0.2) x 10^{-5} (6σ)

First observed 3γ decay of any hadron!

Theory: QED: $B(3\gamma)/B(3g) \approx (\alpha/\alpha_s)^3$

and $B(3\gamma)$ $(\alpha/14)B_{\mu\mu} \approx 3 \times 10^{-5}$

But QCD corrections difficult & uncertain!



Exclusive Decays of χ_{cJ}

$\psi(2S)$ is a χ_{cJ} factory:

$B(\psi(2S) \to \gamma\,\chi_{cJ}) \approx$ 8-10 %

for each of J=0,1,2 (>2M each)

Can probe exclusive decays

down to BR$\approx 10^{-4}$

Gluonic environment in χ_{cJ} decay

differs from J/ψ, $\psi(2S)$ decay

Studied 14 exclusive decay modes

(13 hadronic + $\gamma\gamma$)

$\chi_{cJ} \to$ 2 hadrons: color octet contribution?

$\chi_{cJ} \to \gamma\gamma$

"pure" QED? Relativistic & rad' corrections!

wide range of predictions and measurements for rate

$\chi_{cJ} \to \eta(') \, \eta(')$

single-OZI vs double-OZI

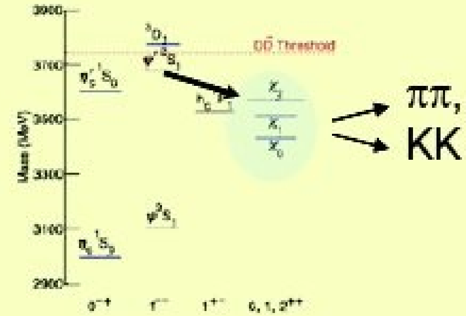
$\chi_{cJ} \to$ baryon antibaryon

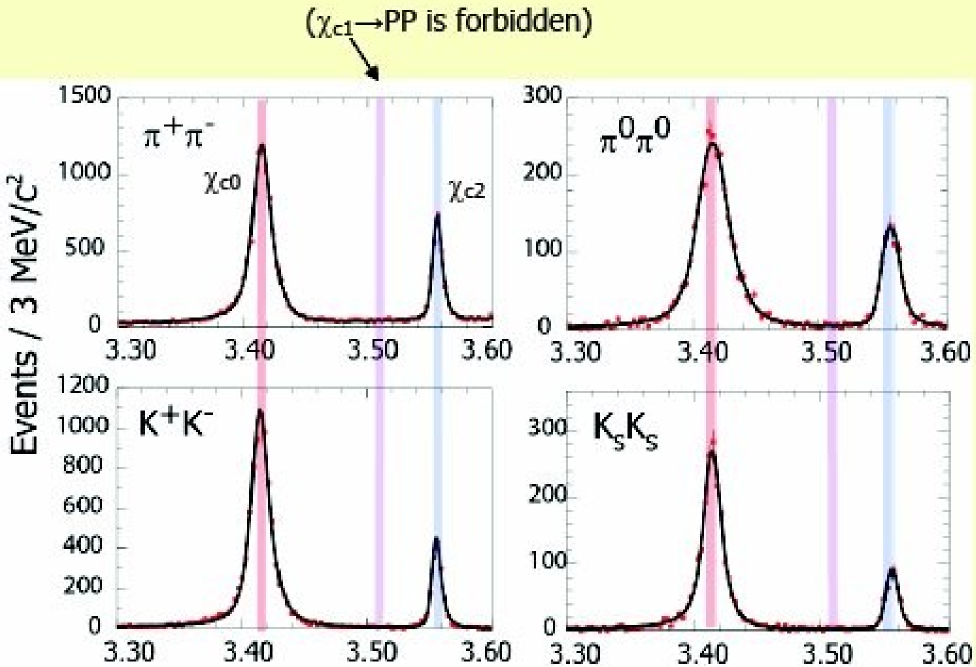
puzzling relative production rates

$\chi_{cJ} \to$ multi-hadrons

resonant substructure, isospin relations, etc.

$\chi_{cJ} \rightarrow M\bar{M}$, M=$\pi$,K





Previous measurements had uncertainties of 10% or larger

Clean signals seen in CLEO data

CLEO uncertainties <=10%

Ratios:

Belle PLB 651, 15 (2007)

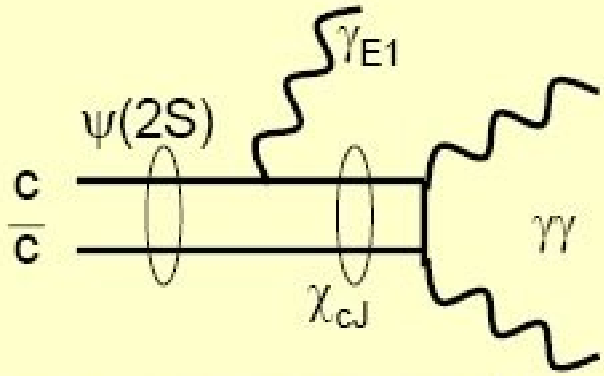
	χ_{c0}	χ_{c2}
K_sK_s/K^+K^-	0.54±0.03 Belle: 0.49±0.11	0.47±0.05 Belle: 0.70±0.24
$\pi^0\pi^0/\pi^+\pi^-$	0.46±0.05	0.43±0.13
$K_sK_s/\pi^+\pi^-$	0.55±0.03 Belle: 0.46±0.11	0.33±0.03 Belle: 0.40±0.12

CLEO improves upon precision, is consistent with Belle and with isospin counting expectations,

$K_sK_s : K^+K^- = 1:2$

$\pi^0\pi^0 : \pi^+\pi^- = 1:2$

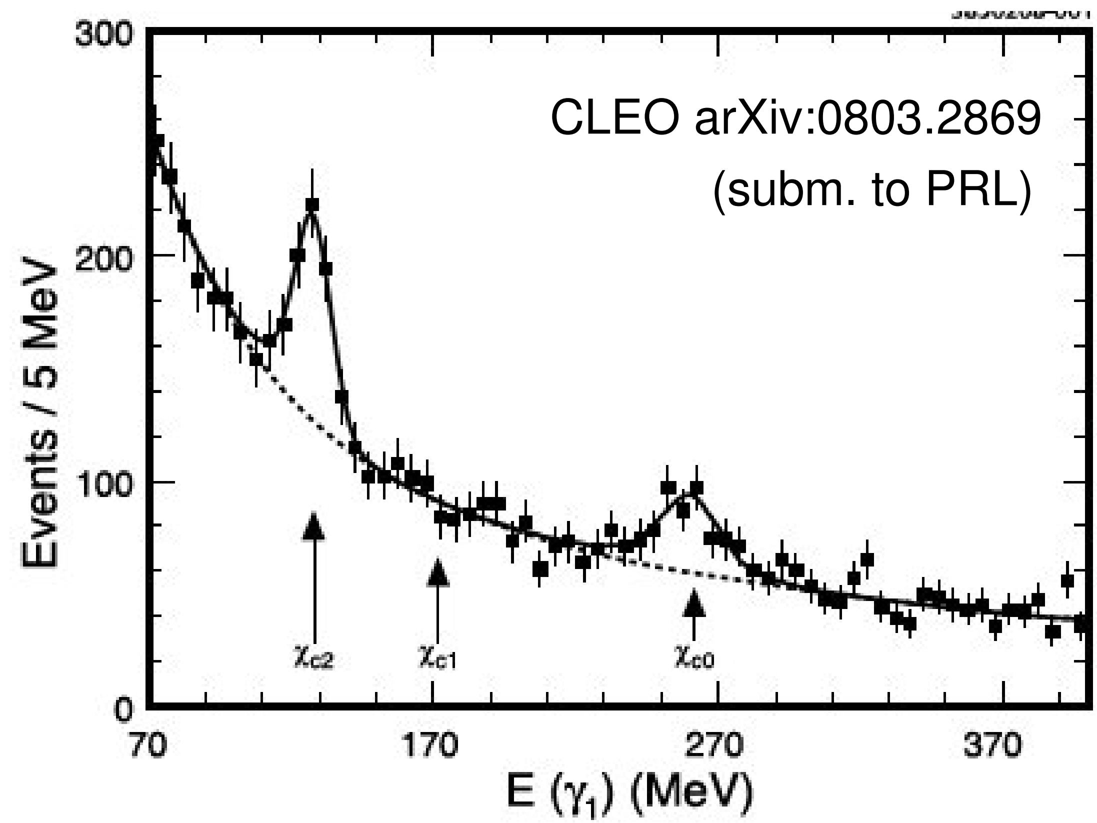
$\chi_{cJ} \rightarrow \gamma\gamma$



$\chi_{cJ} \rightarrow \gamma\gamma$ is pure QED in first approximation

Decay rates $\Rightarrow$ relativistic and radiative corrections (significant in the charmonium system!)

$\Gamma(\chi \rightarrow \gamma\gamma)$ measurements range from 2-4keV, with smallest error 0.6keV



Result: **$\Gamma_{\gamma\gamma}$(J=2) = (0.60±0.06±0.03±0.05) keV**

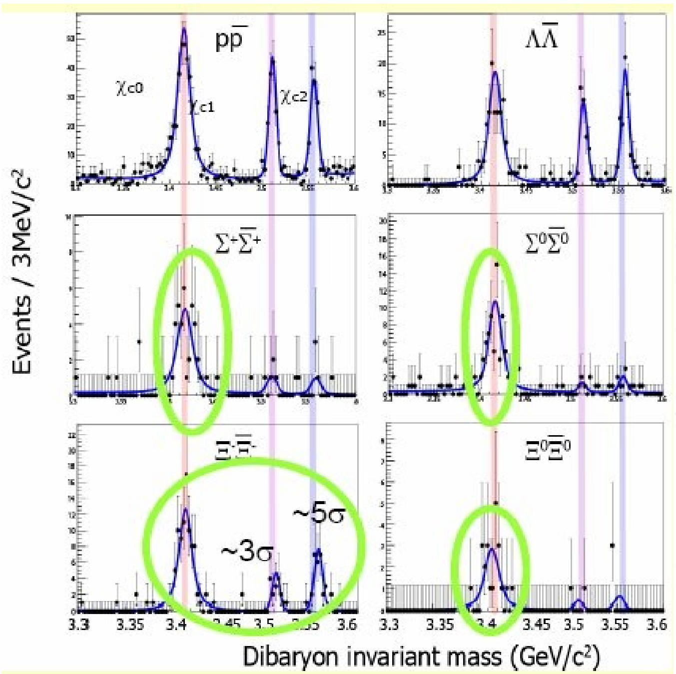
$\Gamma_{\gamma\gamma}$(J=0) = (2.53±0.37±0.11±0.24) keV

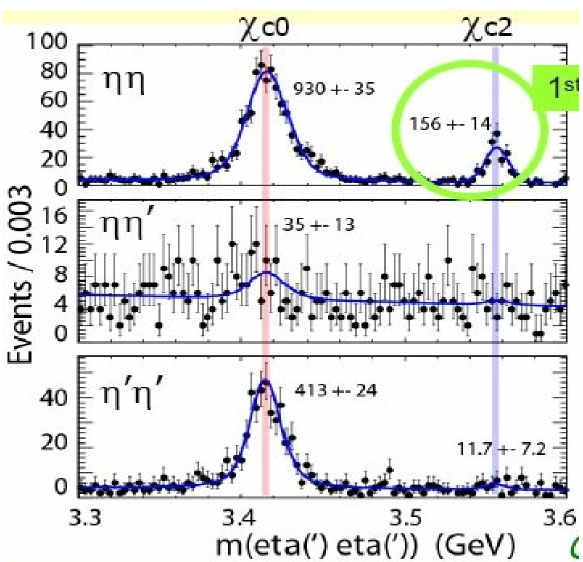
Important quantity is $R = \Gamma_{\gamma\gamma}(J=2)/\Gamma_{\gamma\gamma}(J=0)$

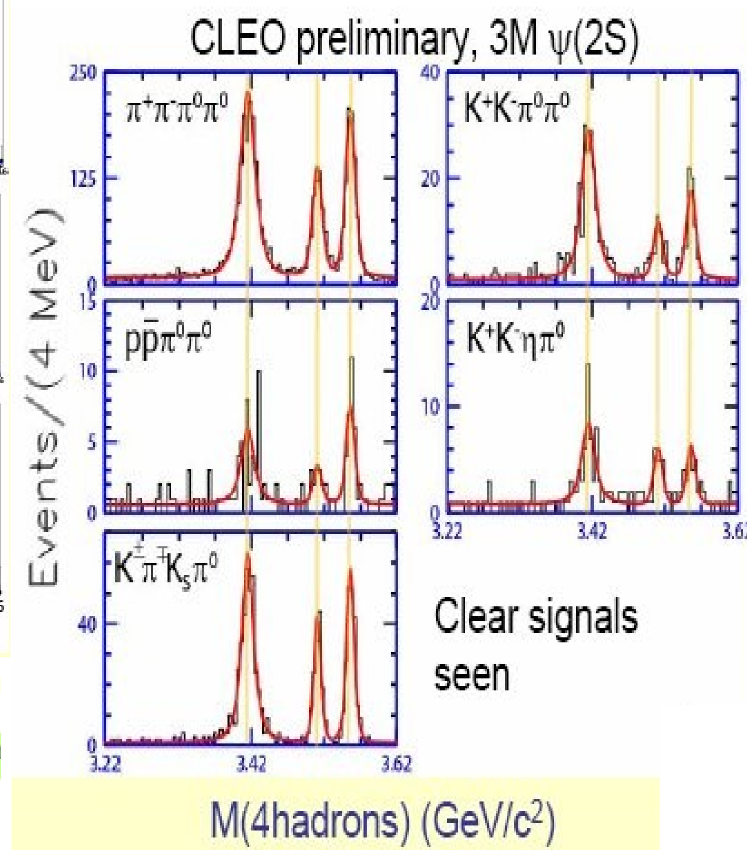
(cancellations in pQCD), $R_{th}=(4/15)(1-1.76\alpha_s)$

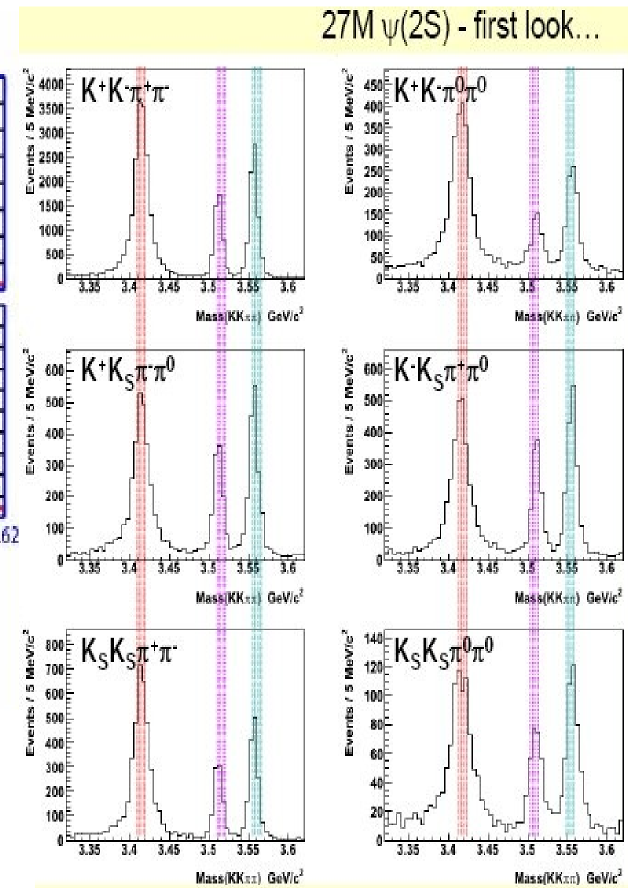
$R_{th}(\alpha_s=0.32)=0.12$, *vs.* R_{exp}(world avg)=0.20±0.02

Picture book of more exclusive χ_{cJ} decays



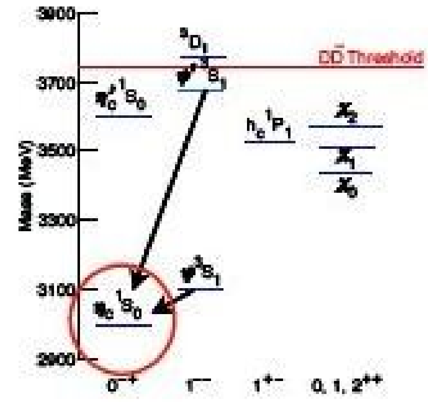


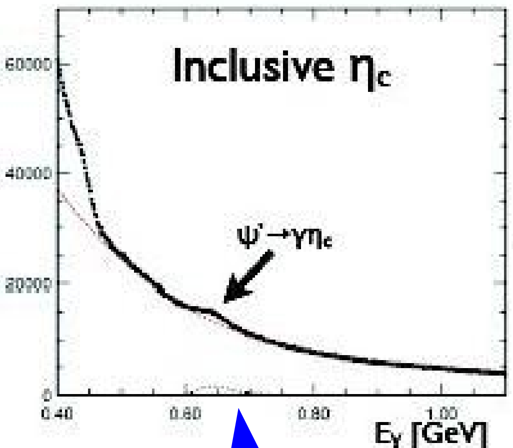




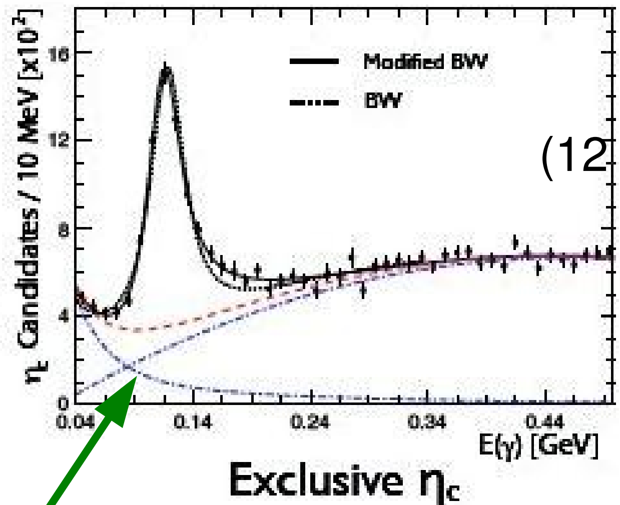
All CLEO. Many are First Observations, or more precise than previous world averages!

$J/\psi, \psi' \rightarrow \gamma\eta_c$





X



(12 modes)

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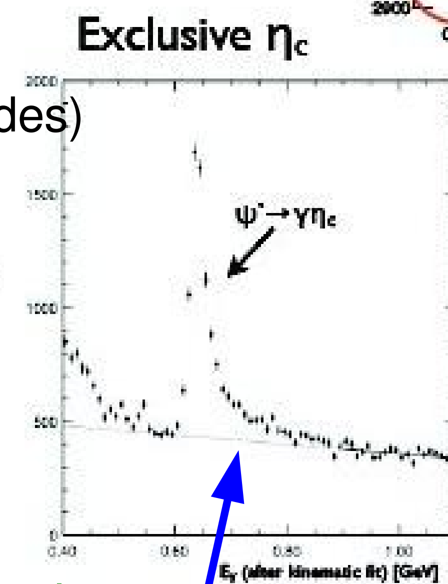


$=B(J/\psi \rightarrow \gamma\eta_c)$

$J/\psi \rightarrow \gamma\,\eta_c$: DIRECT M1 transition

Inclusive rate measurement difficult:

low γ energy, unknown bkgd shape.

Use exclusive event reconstruction.

$\psi(2S) \rightarrow \gamma\,\eta_c$: HINDERED M1 transition

Must take into account the high-energy tail in the signal shape.

We do both inclusive analysis (counting!) and exclusive event reconstruction.

$J/\psi, \psi' \rightarrow \gamma \eta_c$

Results: CLEO arXiv: 0805.0252
(submitted to PRL)

$B(\psi(2S) \rightarrow \gamma\, \eta_c) = (4.32 \pm 0.16 \pm 0.60) \times 10^{-3}$

PDG06: $(2.6 \pm 0.4) \times 10^{-3}$

Theory: difficult: M.E. suppressed in HINDERED M1

$(J/\psi \rightarrow \gamma\, \eta_c)/(\psi(2S) \rightarrow \gamma\, \eta_c) = 4.59 \pm 0.23 \pm 0.64$

$B(J/\psi \rightarrow \gamma\, \eta_c) = (1.98 \pm 0.09 \pm 0.30)\%$

PDG06: $(1.3 \pm 0.4)\% \rightarrow \Gamma_{\gamma \eta c} = (1.2 + 0.3)$ keV

Theory (LQCD, Dudek et al., 2007): $\Gamma_{\gamma \eta c} = (2.0 \pm 0.1 \pm 0.4)$ keV

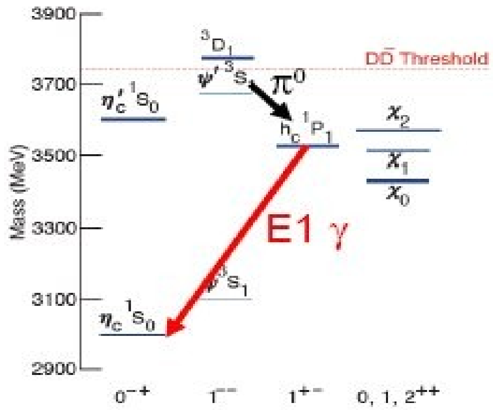
(Now good agreement -- discrepancy resolved!)

As “byproduct”, can calculate

$B(\eta_c \rightarrow \gamma\gamma) = (0.6^{+1.3}_{-0.5} \pm 0.1) \times 10^{-4}$ ($< 3 \times 10^{-4}$ at 90%CL),

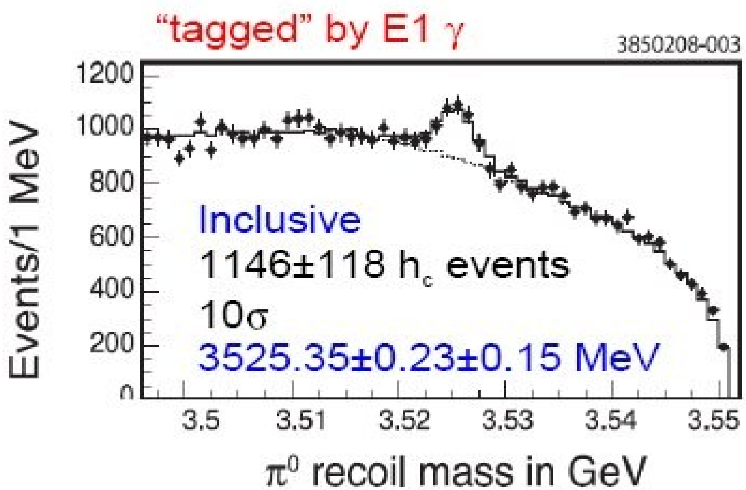
consistent with PDG.

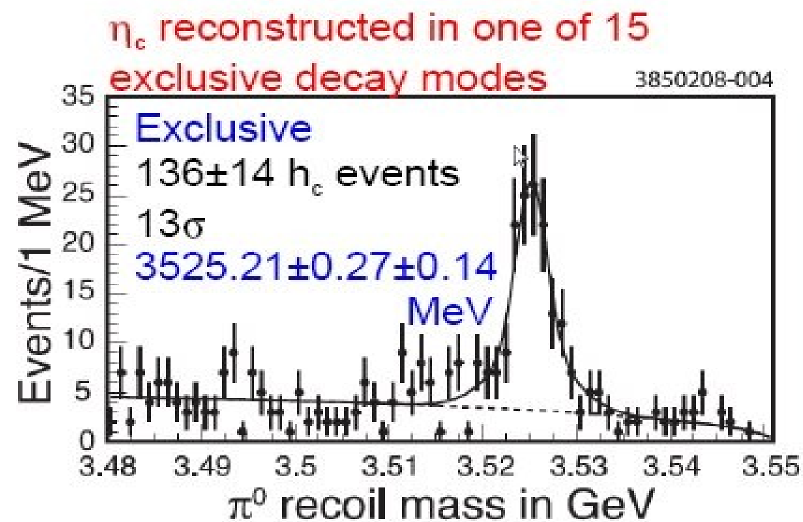
h_c Mass: New, updated measurement



CLEO-c arXiv:0805.4599 [hep-ex]

- A factor of ~9 larger statistics than in the initial publication





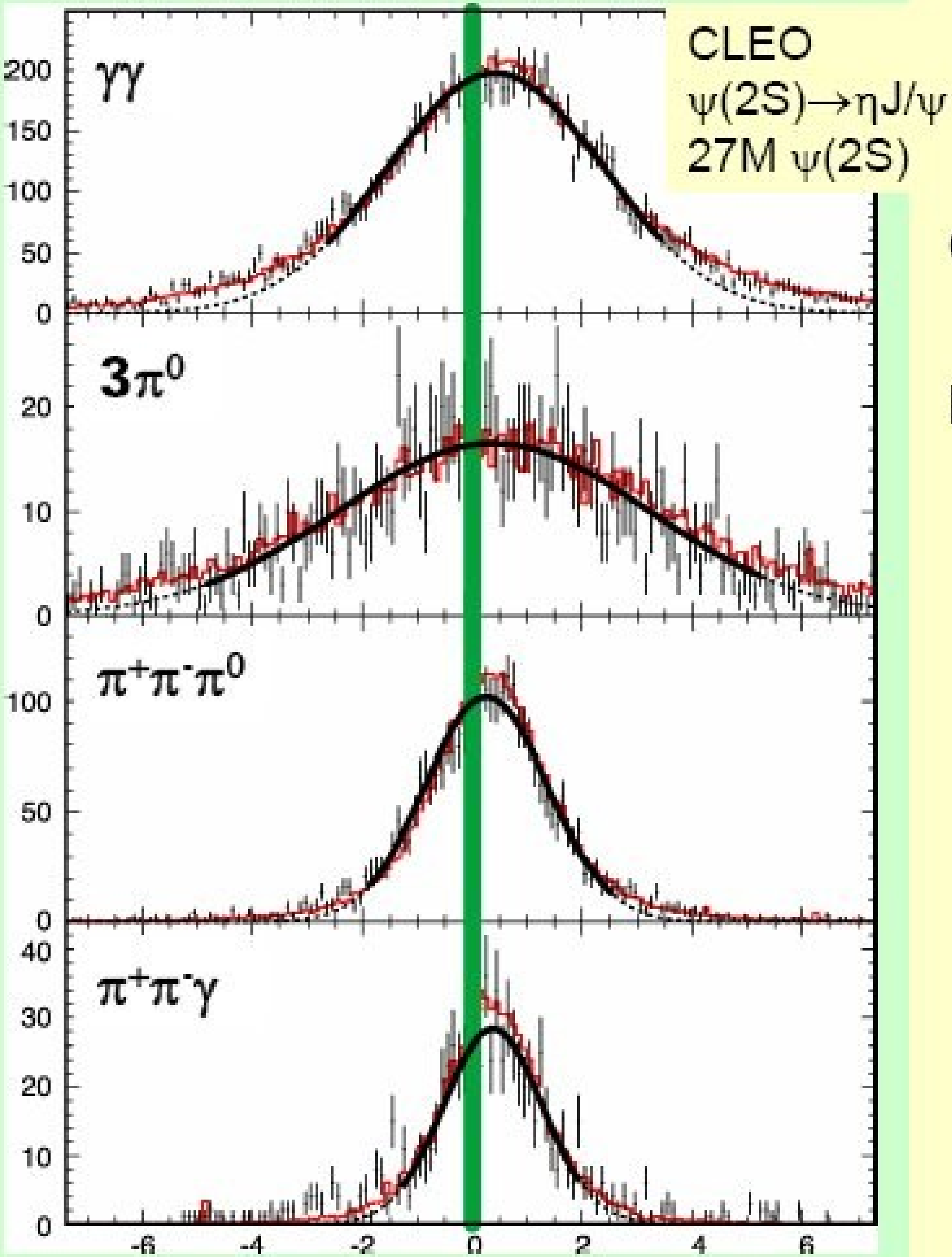
Result: **$M(h_c)$=(3525.28±0.19±0.12) MeV**

cf. $\langle M(\chi_{cJ})\rangle$=(3525.30±0.11) MeV (PDG)

→ **HF splitting of 1P states is negligibly small!**

η Mass

Invariant mass of η decay products:



M(CLEO) – M(PDG06) (MeV)

16k fully reconstructed events

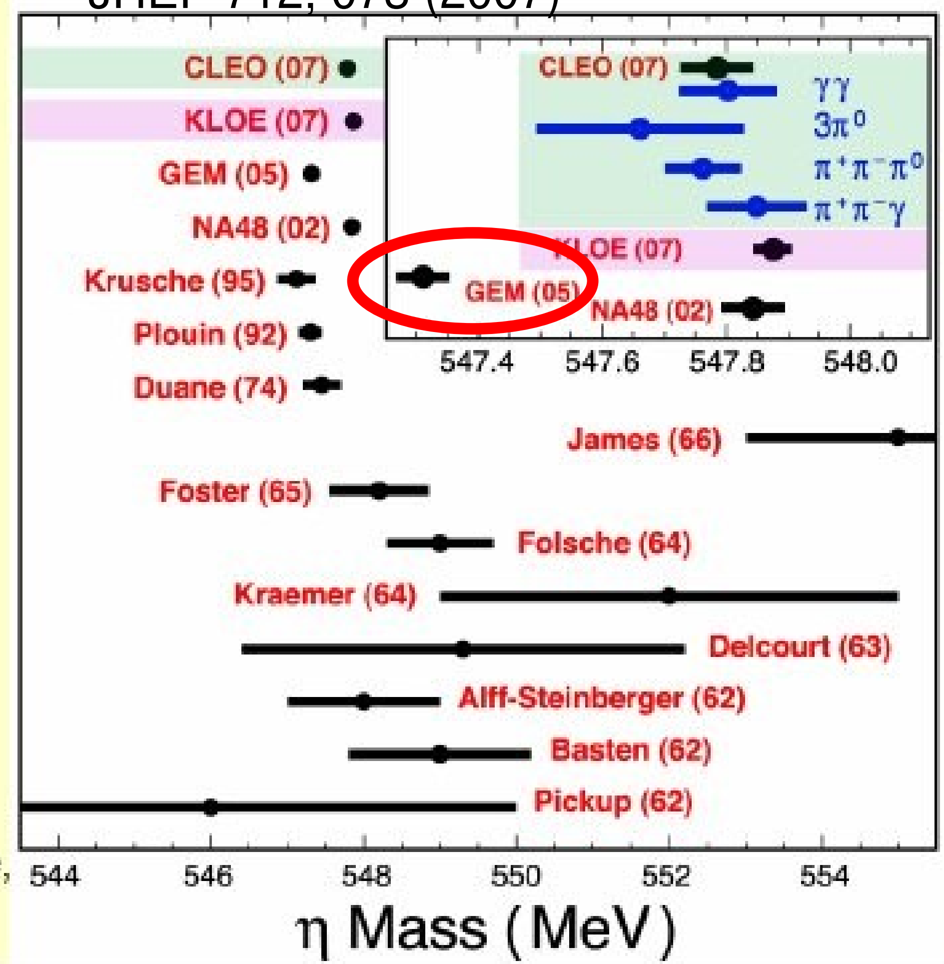
CLEO: $M(\eta) = 547.785 \pm 0.017 \pm 0.057$ MeV

PRL 99, 122002 (2007) (arXiv:0707.1810)

KLOE: $M(\eta) = 547.874 \pm 0.007 \pm 0.029$ MeV

arXiv:0707.4616 (LP07 contribution)

JHEP 712, 073 (2007)

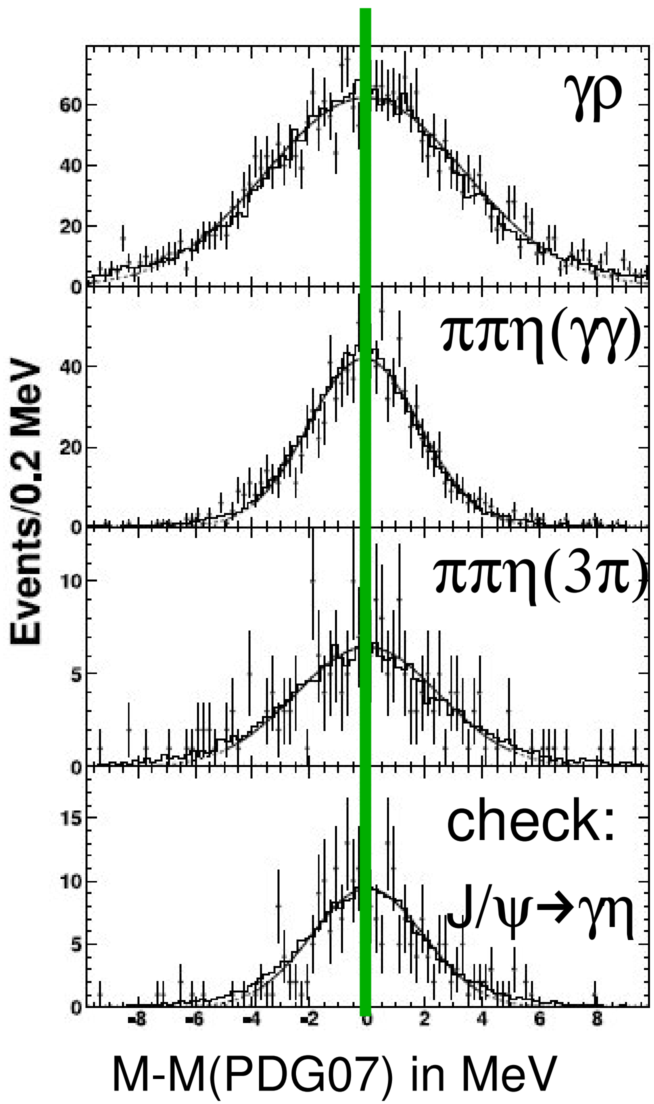


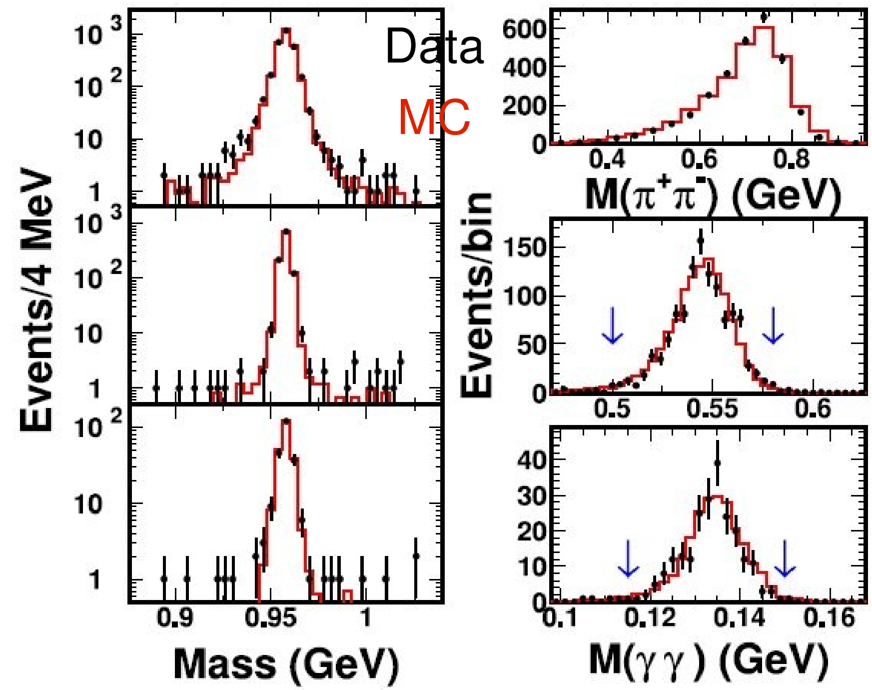
lahlke,

η' Mass

Use **ψ(2S) → $\pi^+\pi^-$ J/ψ, J/ψ → γ η'**

Similar technique as in η mass measurement





Result:

(CLEO arXiv:0806.2344, subm' to PRL)

M(η')=(957.793±0.054±0.036) MeV

consistent with and substantially more precise than previous world average

Implication for the pseudoscalar η-η' mixing angle:

ϕ_P=(41.461±0.008)^0 (Jones & Scadron 1979)

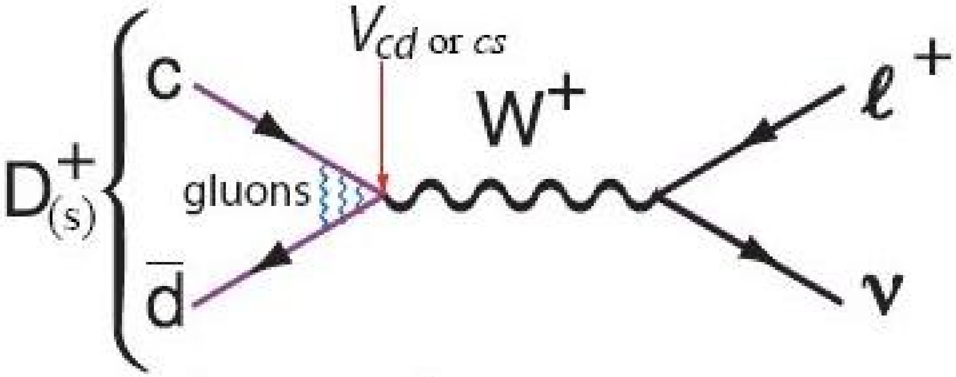
Agrees with ϕ_P from BFs: flavor symm' breaking small?

$$\tan^2\phi_P = \frac{(M_{\eta'}^2 - 2M_K^2 + M_\pi^2)(M_\eta^2 - M_\pi^2)}{(2M_K^2 - M_\pi^2 - M_\eta^2)(M_{\eta'}^2 - M_\pi^2)}$$

Charm: Decay Constants f_D and f_{Ds}

c and $\bar{q}$ can annihilate, probability is proportional to wave function overlap

Feynman diagram in Standard Model :



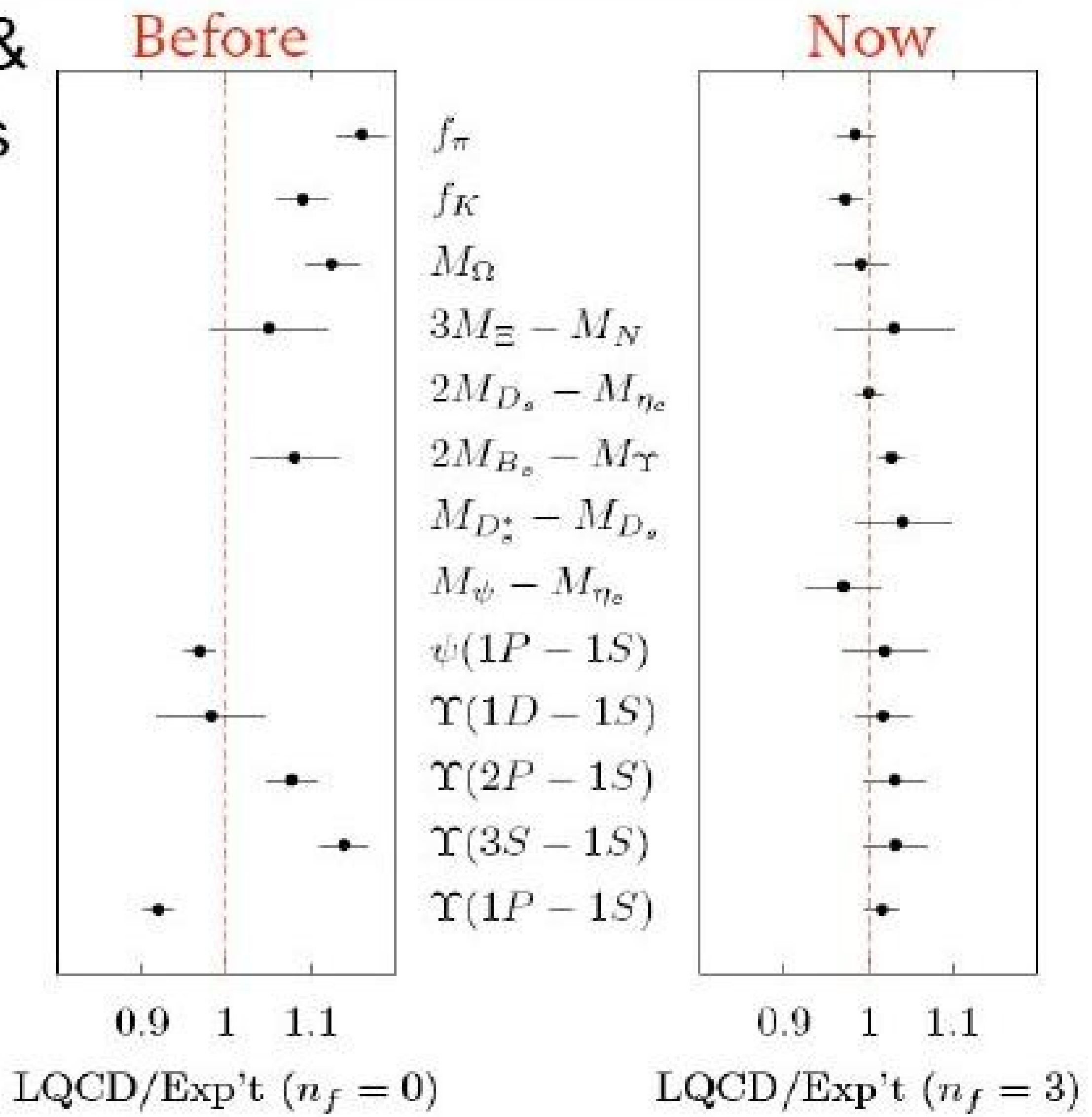
In general for all pseudoscalars:

$$\Gamma(P^+ \to \ell^+ \nu) = \frac{1}{8\pi} G_F^2 f_P^2 m_\ell^2 M_P \left(1 - \frac{m_\ell^2}{M_P^2}\right)^2 |V_{Qq}|^2$$

Calculate, or measure if V_{Qq} is known, here take $V_{cd}=V_{us}=0.2256$

f_D & f_{Ds}: New LQCD Calculations

- Follana et al HPQCD & UKQCD collaborations (PRL **100**, 062002 (2008)) New predictions of
  f_{D^+}= 207±4 MeV
  f_{Ds} = 241±3 MeV
- Older unquenched from FNAL+MILC +HPQCD are:
  f_{D^+}= 201±3 ±17 MeV
  f_{Ds} = 249±3 ±16 MeV
  (Aubin et al., PRL 95, 122002 (2005))



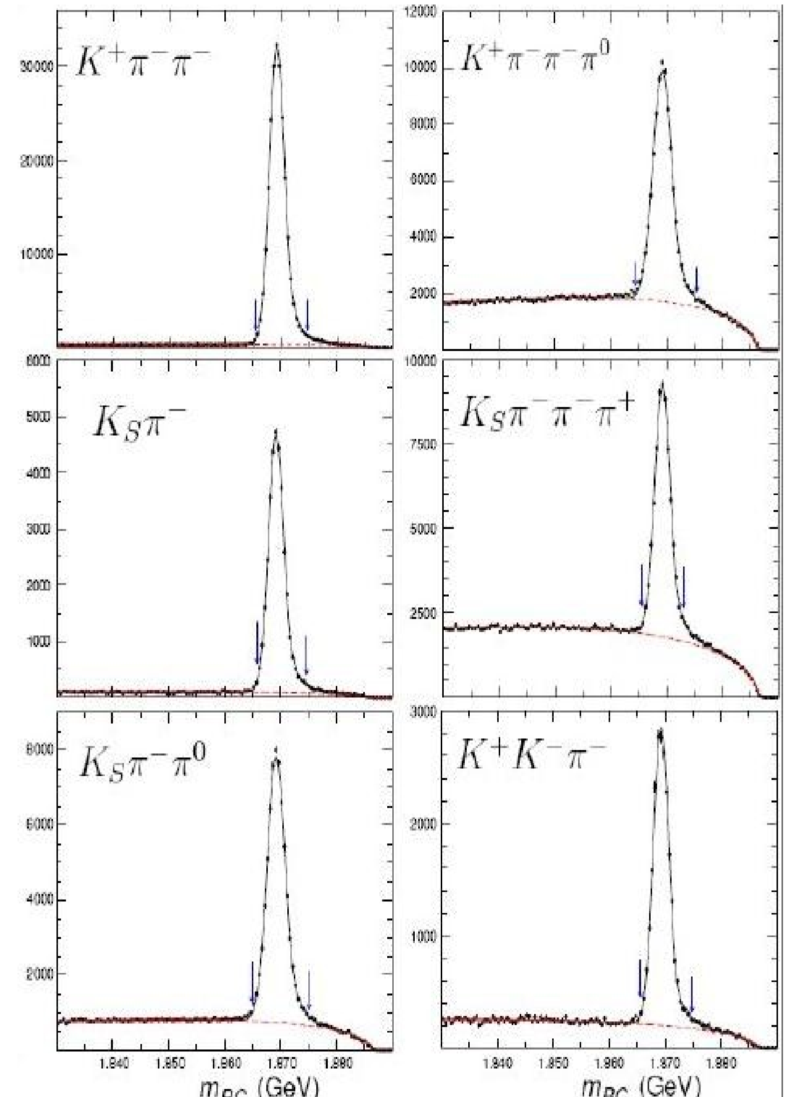
Basic Technique for $D^+ \rightarrow \mu^+ \nu$

CLEO-c, 818/pb

- Fully reconstruct a D^-, and count total # of tags
- Seek events with only one additional oppositely charged track within $|\cos\theta|<0.9$ & no additional photons > 250 MeV (to veto $D^+ \rightarrow \pi^+\pi^o$)
- Charged track must deposit only minimum energy (from ionization) in calorimeter < 300 MeV
- Compute MM^2. If close to zero then almost certainly we have a $\mu^+\nu$ decay.

$$MM^2 = (E_{D^+} - E_{\ell^+})^2 - (\vec{p}_{D^+} - \vec{p}_{\ell^+})^2$$

We know $E_{D^+} = E_{beam}$, $\mathbf{p}_{D^+} = -\mathbf{p}_{D^-}$



$D^+ \rightarrow \mu^+\nu$ Signal & Fit

$\tau\nu/\mu\nu$ **fixed** to SM ratio:

-- $B(D^+ \rightarrow \mu^+\nu) = (3.82 \pm 0.32 \pm 0.09) \times 10^{-4}$

-- **f_{D^+} = (205.8±8.5±2.5) MeV**

$\tau\nu/\mu\nu$ ratio allowed to **float**:

-- $B(D^+ \rightarrow \mu^+\nu) = (3.93 \pm 0.35 \pm 0.09) \times 10^{-4}$

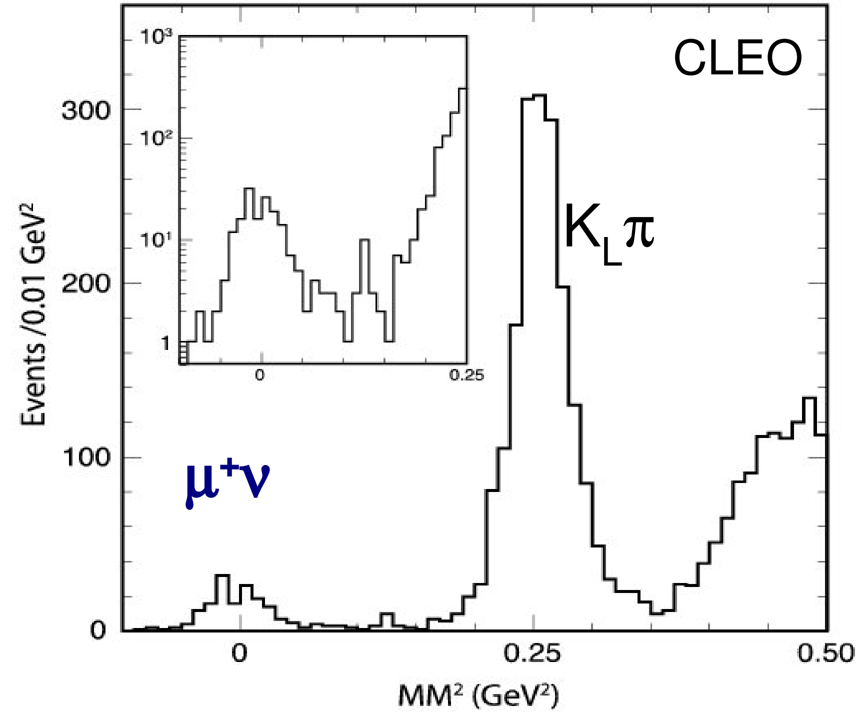
-- **f_{D^+} = (207.6±9.3±2.5) MeV**

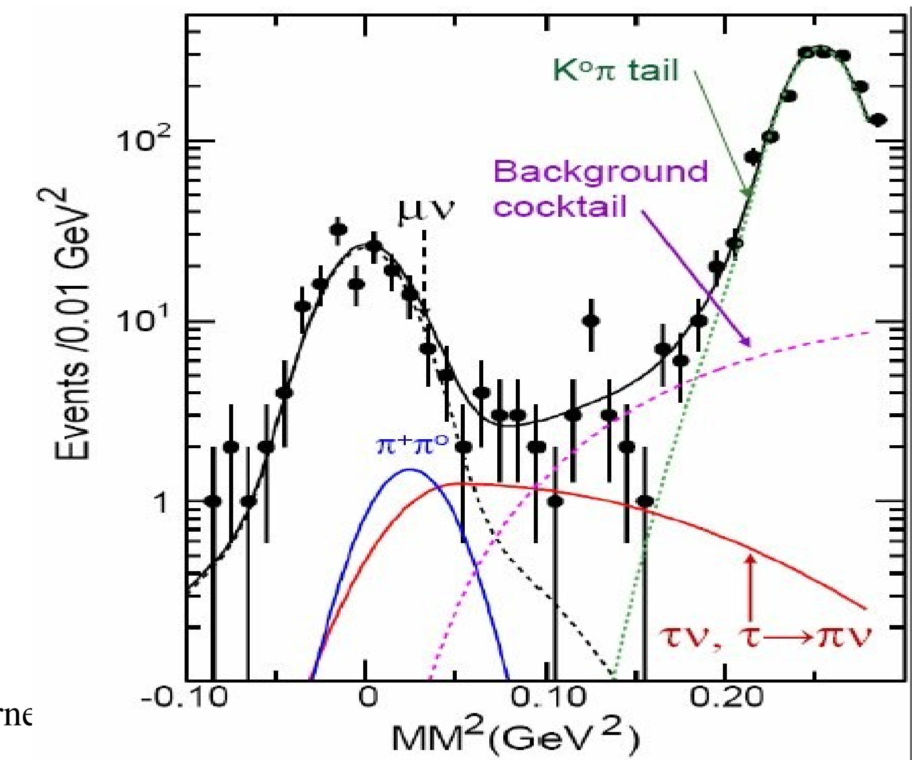
(arXiv:0806.2112, subm' to PRD)

Theory (Follana et al.):

-- **f_{D^+}= (208±4) MeV**

Excellent agreement!





f_{D_s}: use $e^+e^- \to D_s D_s^*$ at 4170 MeV

- Reconstruct D_S^-, similar invariant mass distributions as for absolute $\mathcal{B}$ analysis
- Find the γ from the D_S^* & compute MM^2 from D_S^- & γ

$$MM^{*2}=(E_{CM}-E_{D^-}-E_\gamma)^2-(-\vec{p}_{D^-}-\vec{p}_\gamma)^2$$

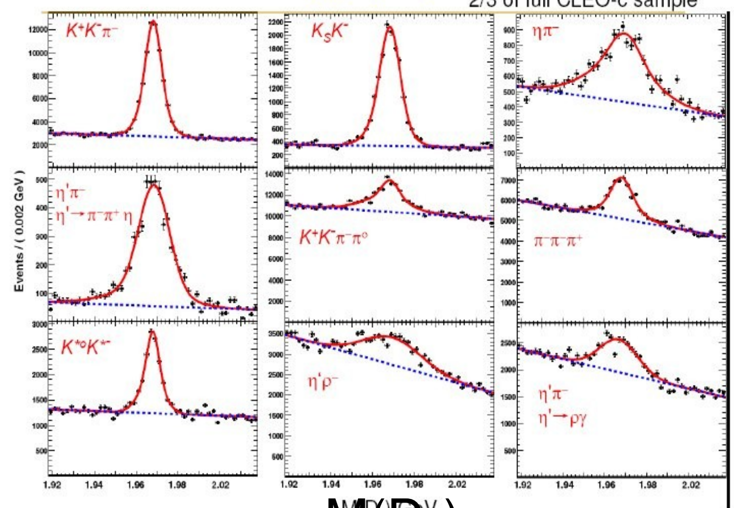
- Select combinations consistent with a missing D_S^+ & count the number
- Find MM^2 from candidate muons in the tag sample, where

$$MM^2=(E_{CM}-E_{D^-}-E_\gamma-E_\mu)^2-(-\vec{p}_{D^-}-\vec{p}_\gamma-\vec{p}_\mu)^2$$

For further details, cf. S.Stone (CLEO), arXiv:0806.3921, and talk at FPCP08)

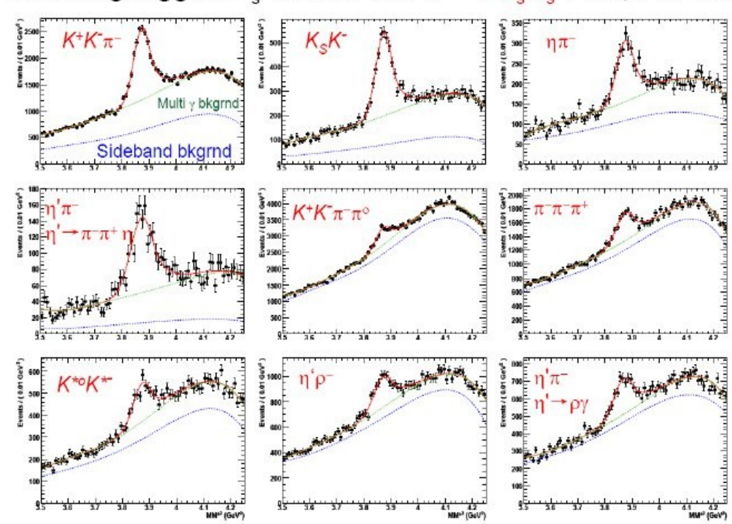
- Reconstruction of tagging D_s^-

$e^+e^- \to D_sD_s^*$
2/3 of full CLEO-c sample



M(D_s)

Counting tagged D_s^+ events in $e^+e^- \to D_sD_s^*$: 30,848±695



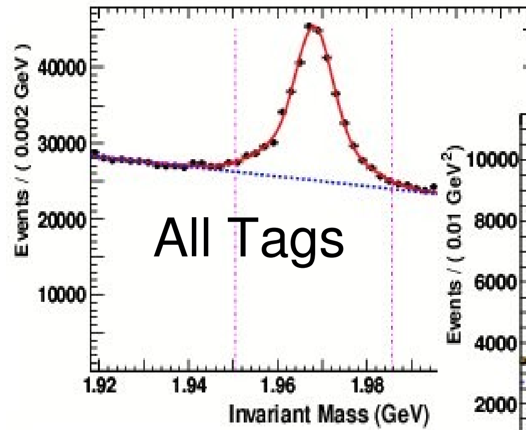
MM^{*2}

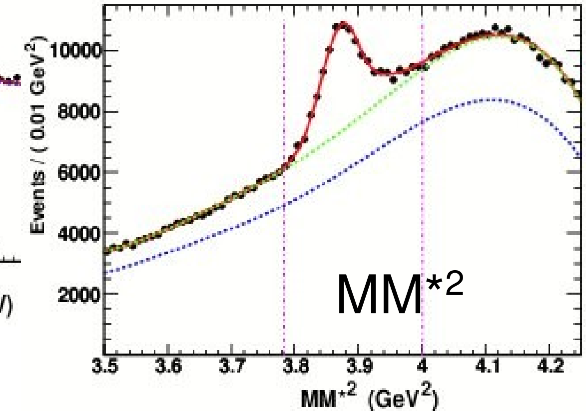
$D_s^+ \to \mu^+\nu, \tau^+\nu$ Signal & Fit (CLEO PRELIMINARY!)

arXiv:0806.3921

$\tau\nu/\mu\nu$ fixed to SM ratio. Average the result with that from $D_s \to \tau(e\nu\nu)\,\nu$ analysis (PRL 100, 161801 (2008):

-- $f_{D_s^+}$ = **(267.9±8.2±3.9) MeV**



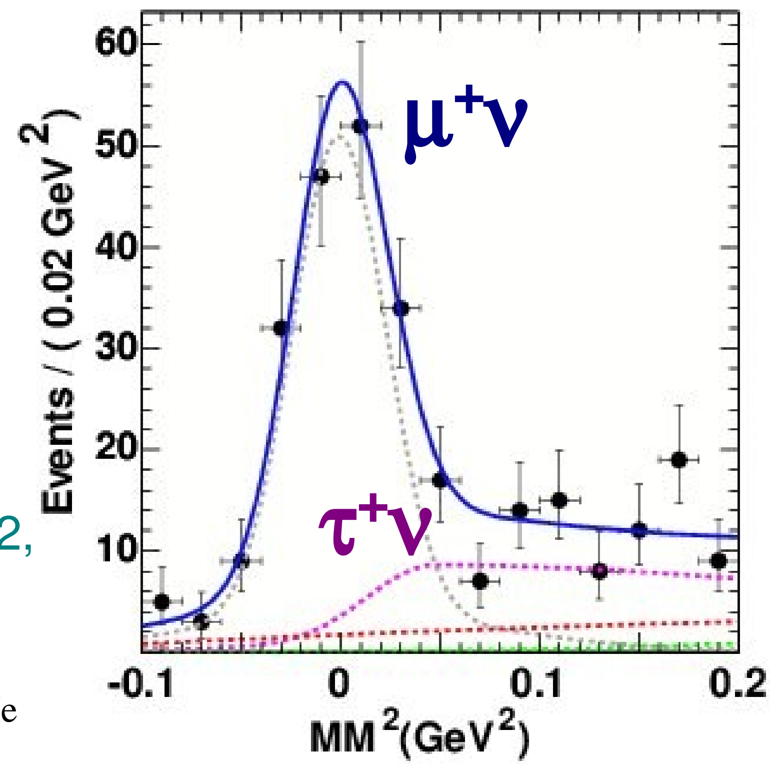


Agrees with Belle: (269.6±8.3) MeV, arXiv:0709.1340 but disagrees with Follana et al.: **(241±3) MeV**, by 3.2σ!

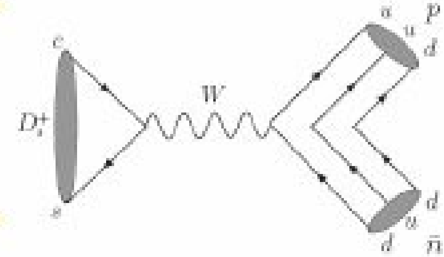
Are the calculations reliable?

If not then what about f_B , f_{Bs} , CKM fits?

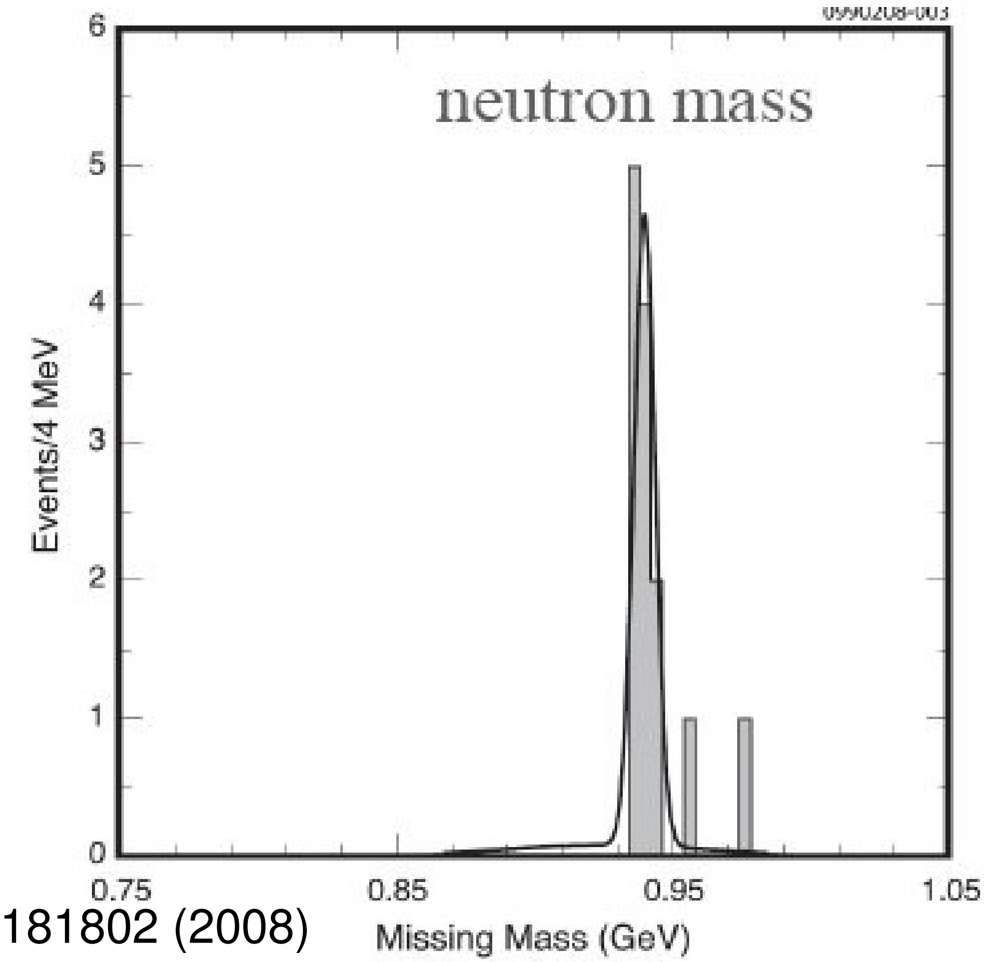
If yes then are we seeing New Physics (leptoquarks, charged Higgs, R-parity violating SUSY,...)? cf. Dobrescu & Kronfeld, arXiv:0803.0512, or Kundu & Nandi, arXiv:0803.1898



Discovery of $D_S^+ \to p\bar{n}$



- Use same technique as for $\mu^+\nu$, but plot MM from an identified proton
- No background
- First example of a charm meson decaying into baryons



arXiv:0803.1118v2 [hep-ex]

PRL 100, 181802 (2008)

$$B(D_s^+ \to p\bar{n}) = (1.30 \pm 0.36^{+0.12}_{-0.16})\ x10^{-3}$$

- Consequences for understanding W annihilation dynamics

see Chen, Cheng & Hsiao arXiv:0803.2910v3 [hep-ph]

Summary

Charmonium is an excellent testing ground for QCD:

-- Spectroscopy: η_c, h_c

-- Can "dial" gluonic environments: $\psi(2S)$, J/ψ, χ_{cJ}

-- Production of lighter systems ($\pi^+\pi^-$ tagging is wonderful!)

Decay constants: f_D in excellent agreement with LQCD,

f_{Ds} in 3.2σ disagreement with LQCD.

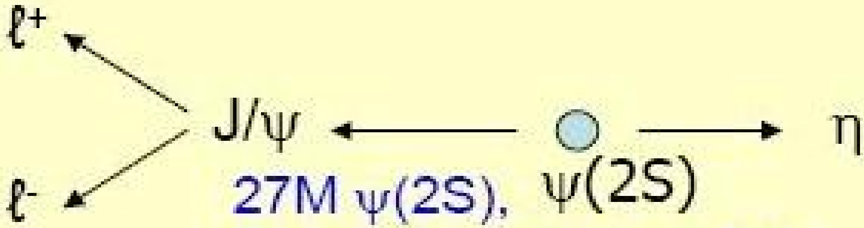
Who is to blame – exp't, theory, or NP ?

First Observations & Discovery: $J/\psi \to 3\gamma$, $D_s \to p\,n$

CLEO-c is laying good groundwork for BES III

Backup Slides

η branching fractions



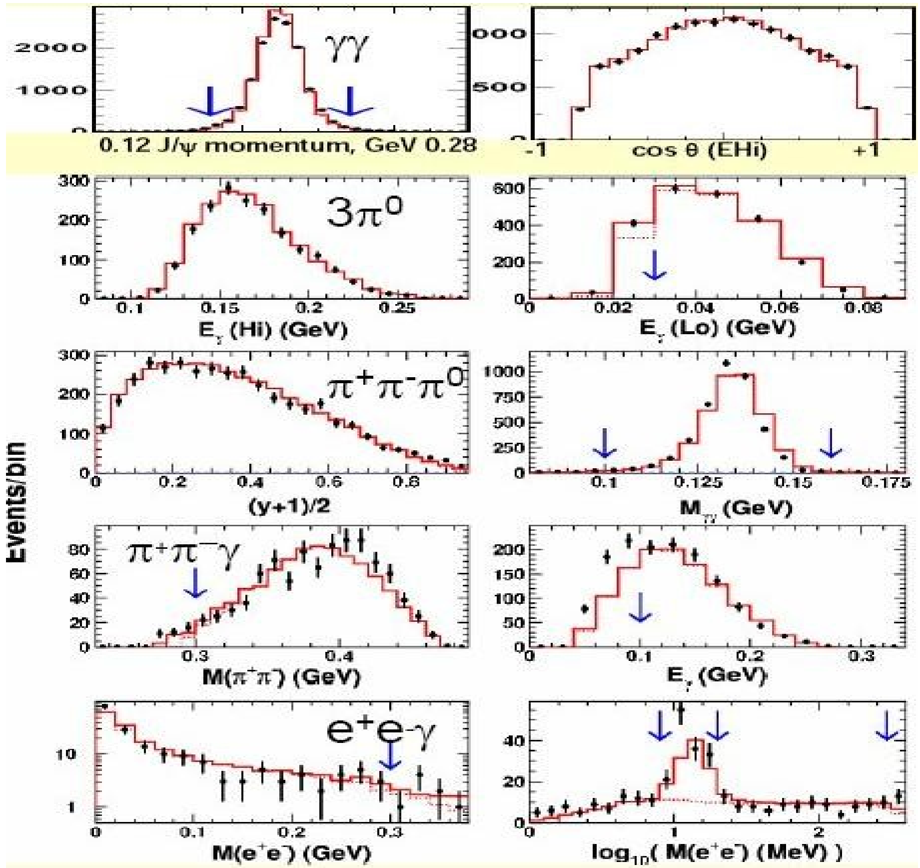
27M ψ(2S),
$B(\psi(2S)\to\eta J/\psi)$ = 3.1%,
$B(J/\psi\to l^+l^-)$ = 12%,

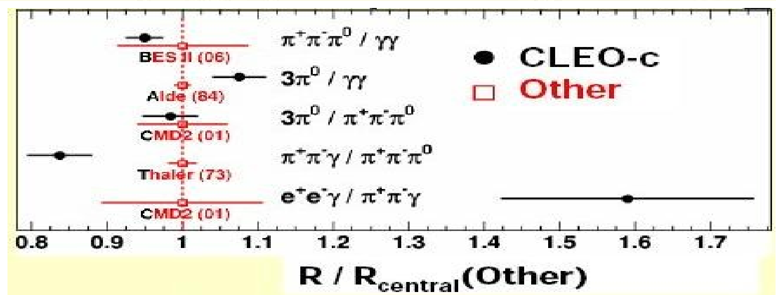
Fully reconstruct five final states:
$\gamma\gamma$ + $3\pi^0$ + $\pi^+\pi^-\pi^0$ + $\pi^+\pi^-\gamma$ + $e^+e^-\gamma$
38.5 34.0 22.6 4.0 0.9%

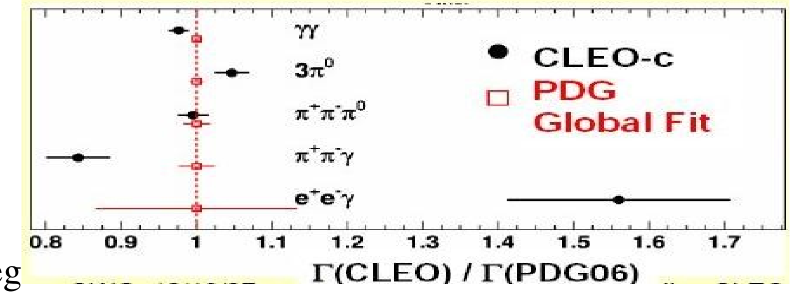
Follow PDG procedure: sum of the above five modes is ~ 100%
⇒ build absolute Br's from ratios

$\pi^+\pi^-\gamma$ and $e^+e^-\gamma$: 3σ deviation

CLEO, PRL 99, 122001 (2007) or arXiv:0707.1601







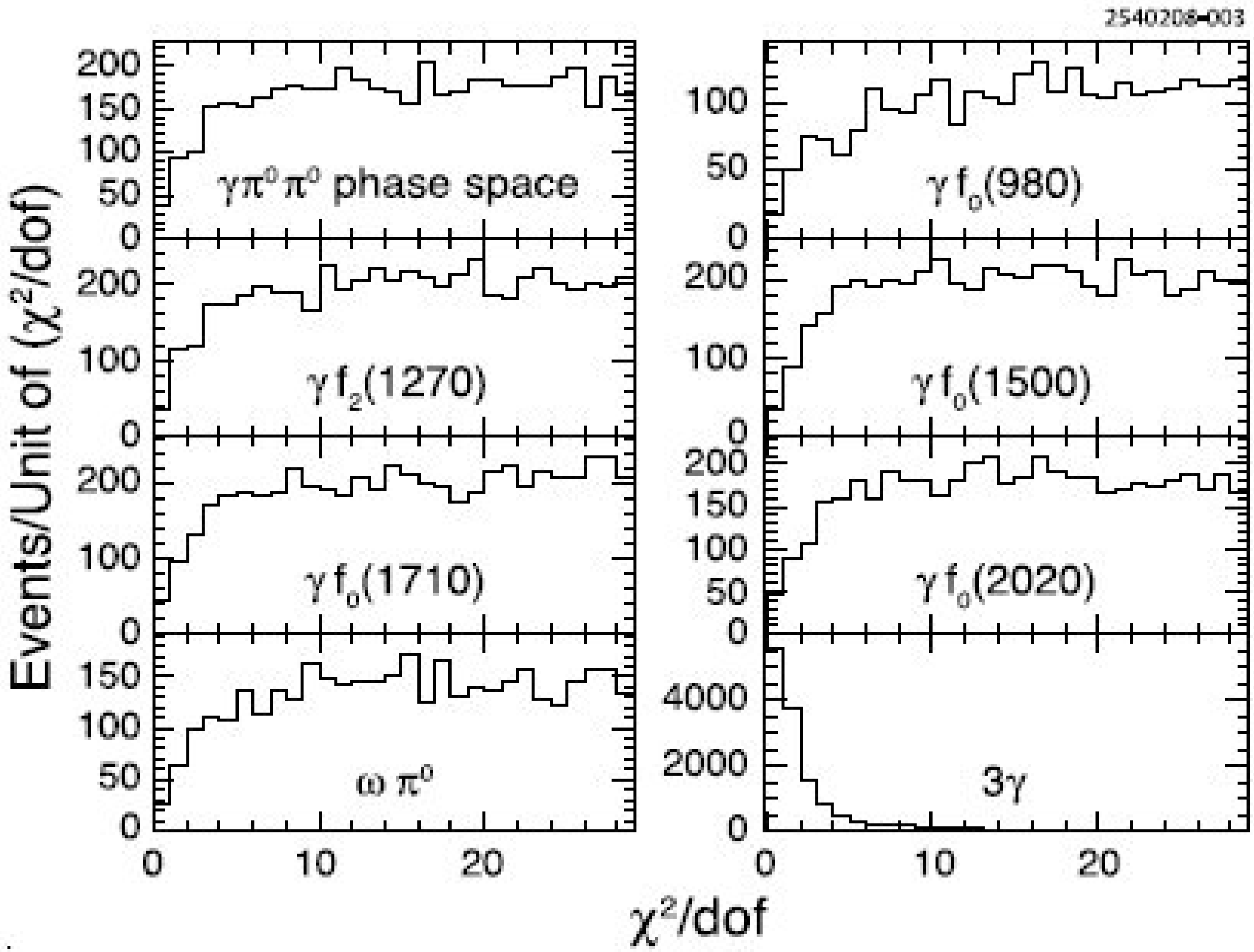


FIG. 3: The distribution of χ^2/d.o.f. for $J/\psi \to 3\gamma$ (lower right) and several sources of $\gamma\pi^0\pi^0$ background.

CLEO-c method

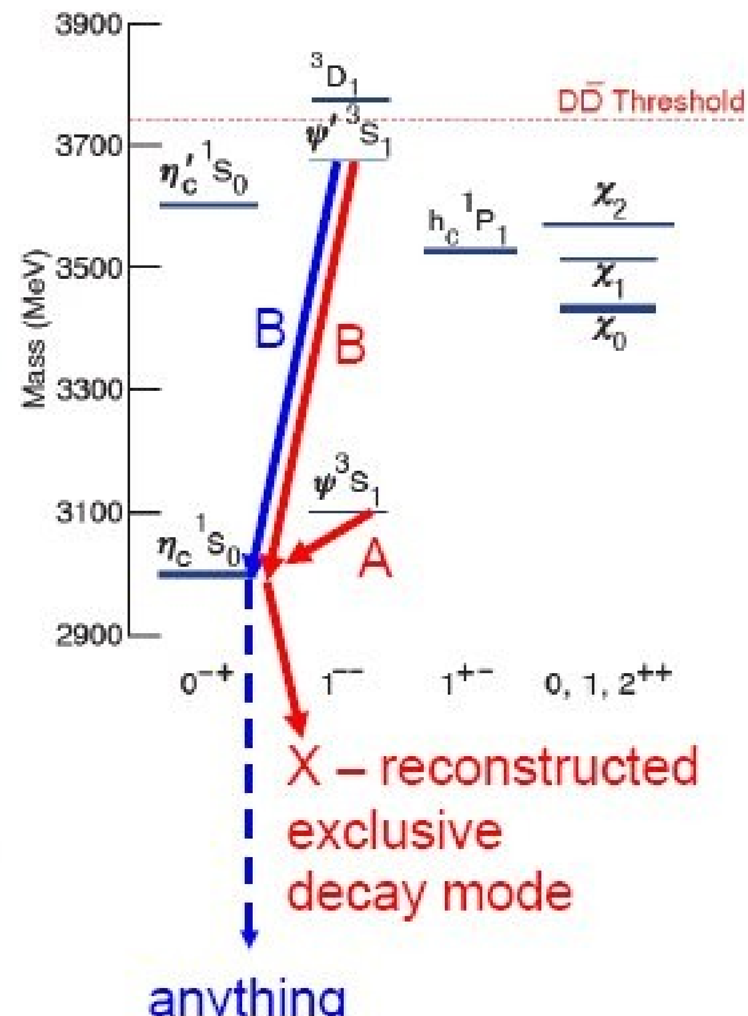
CLEO arXiv:0805.0252 [hep-ex]

- $B(J/\psi \to \gamma\eta_c)$ difficult to measure from inclusive photon spectrum since η_c is broad (25 MeV) and the photon is relatively soft (large background of unknown shape)
- CLEO-c method:

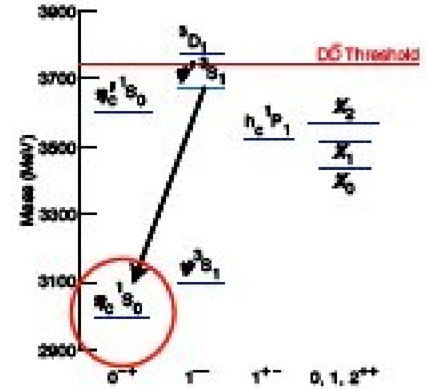
$$B(J/\psi \to \gamma\eta_c) = \underbrace{B(\psi' \to \gamma\eta_c)}_{B} \times \underbrace{\frac{B(J/\psi \to \gamma\eta_c) \times B(\eta_c \to X)}{B(\psi' \to \gamma\eta_c) \times B(\eta_c \to X)}}_{A\,/\,B}$$

Measure from inclusive photon spectrum. The photon is hard, thus backgrounds are under control.

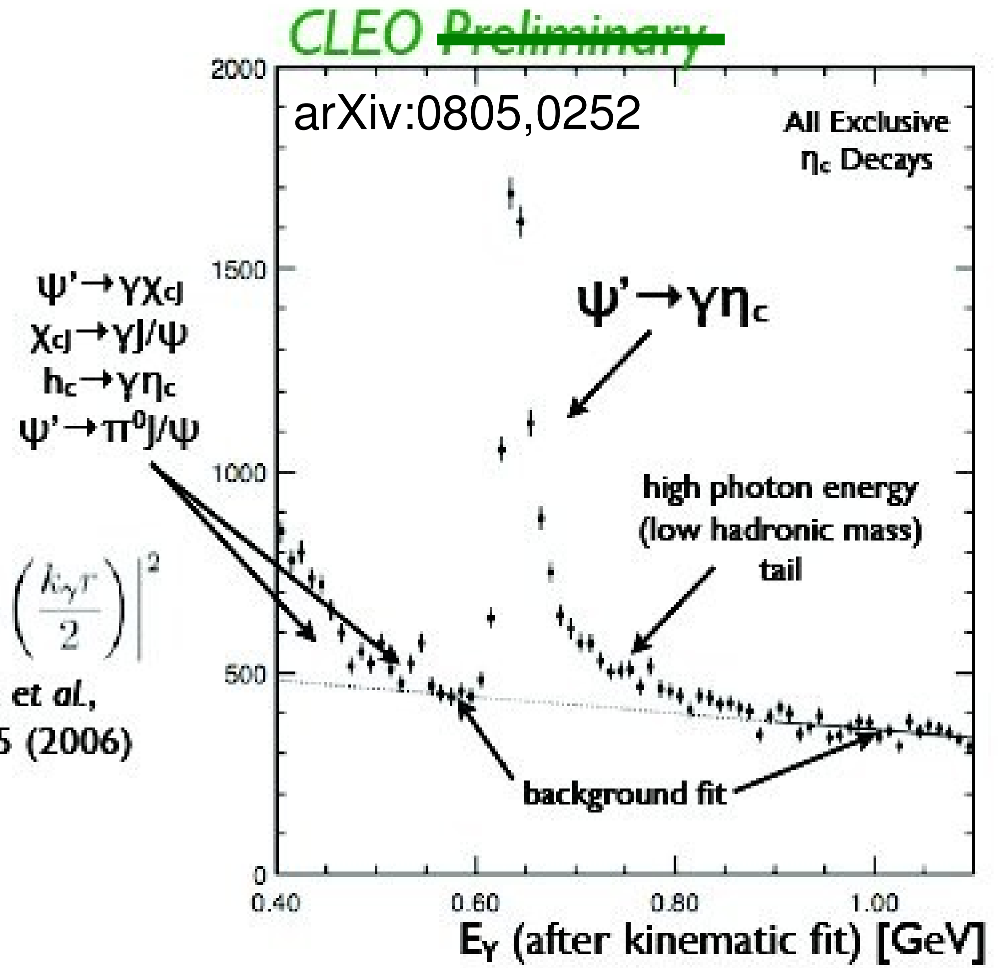
Use exclusive reconstruction of a large number of possible final states X (suppresses the backgrounds). Take the ratio to cancel unknown $B(\eta_c \to X)$



$\psi' \to \gamma\eta_c$



- Tag η_c decay using 13 signal-rich decay modes (some new)
- Perform full event kinematic fit to sharpen photon resolution
- The η_c line shape in hindered M1 transitions is nontrivial and cannot be easily fit by a Breit-Wigner (even when energy-dependent phase space and matrix element terms are included)



$$\Gamma_{n^3S_1 \to n'^1S_0\gamma} = \frac{4}{3}\,\alpha\, e_Q^2\, \frac{k_\gamma^3}{m^2} \left| \int_0^\infty dr\, r^2\, R_{n'0}(r)\, R_{n0}(r)\, j_0\left(\frac{k_\gamma r}{2}\right) \right|^2$$

$$j_0(k_\gamma r/2) = 1 - (k_\gamma r)^2/24 + \ldots .$$

c.f.: Brambilla *et al.*, PRD 73, 054005 (2006)

$\Gamma(\psi' \to \gamma\eta_c)\ [n \neq n'] \propto E_\gamma^7$

$\Gamma(J/\psi \to \gamma\eta_c)\ [n = n'] \propto E_\gamma^3$