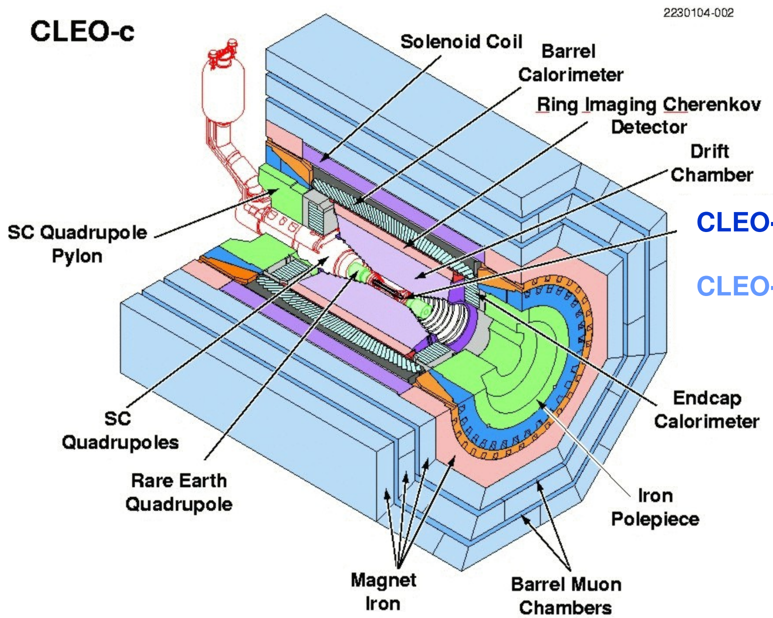
Recent Results from CLEO

(selected topics among the most recent results)

Tomasz Skwarnicki

After 29 years CLEO program comes to an end



CLEO-III: Silicon Vertex Detector; B=1.5T
CLEO-c: Inner Drift Chamber; B=1.0T

- CLEO-I (1979-89)
- CLEO-II (1989-95)
  - CsI calorimeter
- CLEO-II.V (1995-99)
  - Silicon Vertex Detector
- CLEO-III (2000-03)
  - RICH Particle ID
  - New IR & tracking: Silicon, Drift Chamber
- CLEO-c (2003-08)
  - Silicon replaced by ZD inner drift chamber

CESR-b (~10.6 GeV): L=1.2 10^{33} $cm^{-2}s^{-1}$
CESR-c (~4.0 GeV): L=0.7 10^{32} $cm^{-2}s^{-1}$

Last data taken: Run # 234607 Start: 07:38:06 End: 08:00:19 Date: 3/3/2008

CLEO-III/CLEO-c data samples

Detector	Energy GeV or $Q\bar{Q}$ resonance (targeted $Q\bar{q}$ meson)	Luminosity fb^{-1}	Narrow resonance statistics
CLEO-III	11.227-11.383	0.71	
	Υ(5S) (B_s)	0.42	
	Υ(4S) (B) + cont	6.2 + 2.2	
	Υ(3S) + cont	1.2 + 0.2	6M
	Υ(2S) + cont	1.2 + 0.4	9M
	Υ(1S) + cont	1.1 + 0.2	22M
	6.9 – 8.4	0.02	
CLEO-c	4.17 (D_s)	0.614	
	3.97-4.26	0.06	
	ψ(3770) (D)	0.818	
	ψ(2S)	0.054	27M
	3.673	0.021	

Search for light CP-odd Higgs

- SM Higgs

$$\hat{H}_{SM} = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \Rightarrow$$

Longitudinal components of W^+, W^-, Z^0

CP-even h^0

  - Electroweak symmetry breaking
  - Direct searches at LEP2: $e^+e^- \to Z^0 h^0, h^0 \to b\bar{b}$ $m(h^0)>114$ GeV
  - Precision EW measurements: $m(h^0)=89^{+38}_{-28}$ GeV
- MSSM
  - Fixes hierarchy problem (stabilizes h^0 mass, $m(h^0) << M_{Planck}$ natural)

$$\hat{H}_{up} = \begin{pmatrix} \varphi^+_{up} \\ \varphi^0_{up} \end{pmatrix} \quad \hat{H}_{dn} = \begin{pmatrix} \varphi^0_{dn} \\ \varphi^-_{dn} \end{pmatrix} \Rightarrow$$

L.c. of W^+, W^-, Z^0 H^+, H^- CP-even h^0, H^0 CP-odd A^0

  - h^0 SM-like. The LEP2 lower limit applies. h^0, H^0 heavy.
  - $m(A^0)> m(h^0)$. A^0 heavy.
  - Coupling of A^0 to down(up-)type fermions $\propto m_f \tan\beta$ ($m_f / \tan\beta$)
  - Theoretically expect h^0 to be light: $m(h^0)<100$ GeV
  - μ-problem: $\mu \hat{H}_{up} \hat{H}_{dn}$ why $\mu << M_{Planck}$?

Search for light CP-odd Higgs

- NMSSM
  - Fixes μ-problem: $\lambda \hat{S}\widehat{H}_{up}\widehat{H}_{dn}, \quad \mu_{eff} = \lambda\langle \hat{S} \rangle$ (μ << M_{Planck} natural)

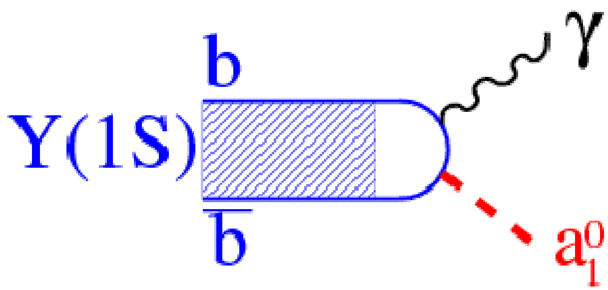
$$\widehat{H}_{up} = \begin{pmatrix} \varphi^{+}_{up} \\ \varphi^{0}_{up} \end{pmatrix} \quad \widehat{H}_{dn} = \begin{pmatrix} \varphi^{0}_{dn} \\ \varphi^{-}_{dn} \end{pmatrix} \quad \hat{S} = \left(\varphi^{0}_{s}\right) \Rightarrow$$

L.c. of W^+, W^-, Z^0

	CP-even	CP-odd
H^+, H^-	h^0, H^0, h_s^0	A^0, a_s^0

  - Lightest CP-odd Higgs is a mixture: $$a_1^0 = A^0 \cos\theta_A - a_s^0 \sin\theta_A$$
  - $m(a_1^0) < m(h^0)$ possible
  - If $m(a_1^0) < 2\, m_b$ then $a_1^0 \not\to b\bar{b}$ and $B(h^0 \to b\bar{b}) << B(h^0 \to a_1^0 a_1^0)$ i.e. both $h^0 \& a_1^0$ evade the LEP2 lower mass limit based on $b\bar{b}$ final state:
    - Relieves "tension" between the direct LEP2 limit and precision EW measurements
    - Relieves "tension" between the direct LEP2 limit and SUSY preference for light h^0
    - Scenario advocated by Dermisek,Gunion,McElrath [PRD76,051105(R),2007]
  - Coupling of a_1^0 to down(up)-type fermions $\propto$ $m_f \cos\theta_A \tan\beta$ ($m_f \cos\theta_A / \tan\beta$); $\cos\theta_A$ decreases with $\tan\beta$

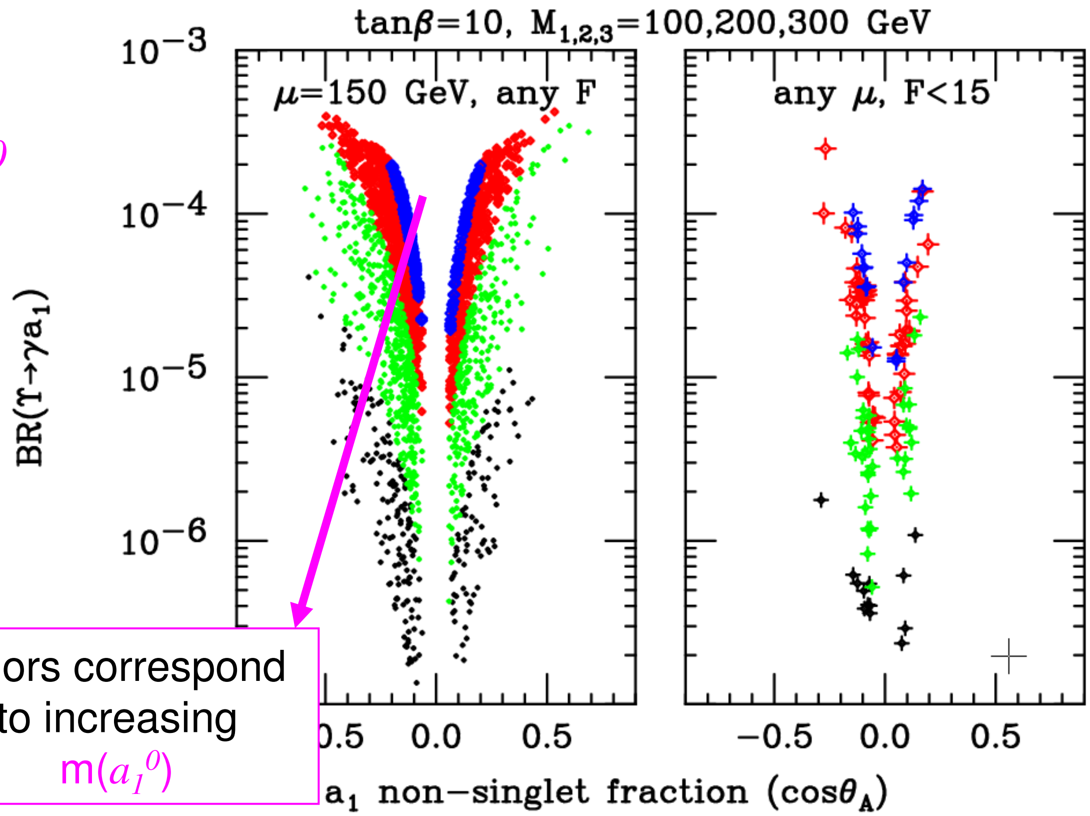
Search for light CP-odd Higgs



$$\frac{B(\Upsilon(1S)\to\gamma a_1^0)}{B(\Upsilon(1S)\to\mu^+\mu^-)} = \frac{G_F m_b^2}{\sqrt{2}\pi\alpha} g_d^2 \left\{1-\left(\frac{m(a_1^0)}{m(\Upsilon(1S))}\right)^2\right\}$$

$$g_d^2 \propto \cos^2\theta_A \tan^2\beta$$

- Good place to produce a_1^0 with mass $m(a_1^0) < 2\, m_b$:
  - Favored over lighter mesons by:
    - m_f dependence of the coupling
    - tanβ dependence of the coupling (compared to charmonium)
    - phase-space

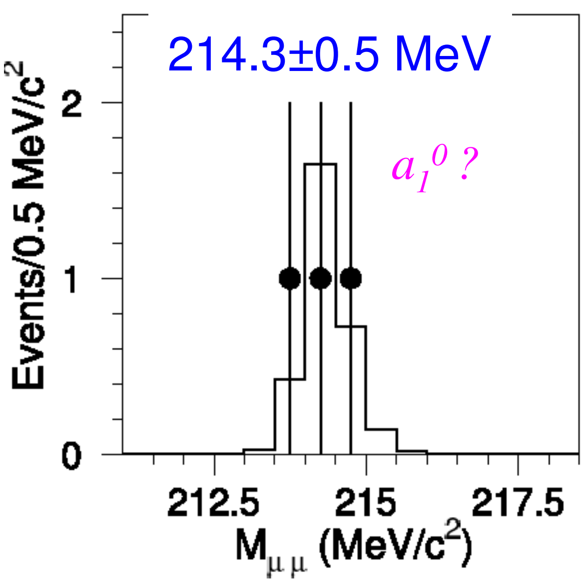


Dermisek,Gunion,McElrath [PRD76,051105(R),2007]

Search for light CP-odd Higgs

Using 21.5M $\Upsilon(1S)$ decays

- We have searched for $\Upsilon(1S) \to \gamma\, a_1^0$, $a_1^0 \to \tau^+\tau^-$ ($a_1^0 \to \mu^+\mu^-$ for $m(a_1^0) < 2\, m_\tau$)
  - $B(a_1^0 \to \tau^+\tau^-)$
    - completely dominates for large $\tan\beta$ (and $m(a_1^0) > 2m_\tau$)
    - must compete with $B(a_1^0 \to c\bar{c})$ for small $\tan\beta$
  - $B(a_1^0 \to \mu^+\mu^-)$
    - large below $s\bar{s}$ threshold (~1 GeV)
    - ~100% for $m(a_1^0)$ slightly above $2m_\mu$



3 $\Sigma^+ \to p\mu^+\mu^-$ events observed by HyperCP PRL 94, 021801 (2005)

He, Tandean, Valencia suggested it could be a a_1^0 PRL 98, 081802 (2007):

Fair amount of fine-tuning to reconcile with the limits from $K \to \pi\mu^+\mu^-$

$g_d \sim O(1)$

$\to$ *observable* $B(\Upsilon(1S) \to \gamma\, a_1^0)$ [Mangano,Nason Mod.Phys.Lett.A22,1373 (2007)]

Search for light CP-odd Higgs

2 oppositely charged tracks + at least 1 photon

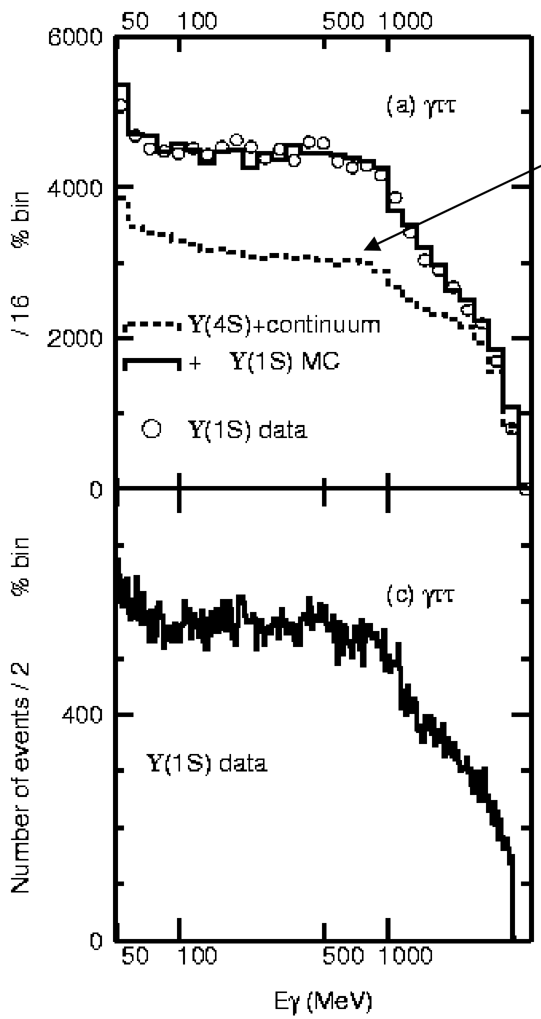
$\gamma\tau^+\tau^-$

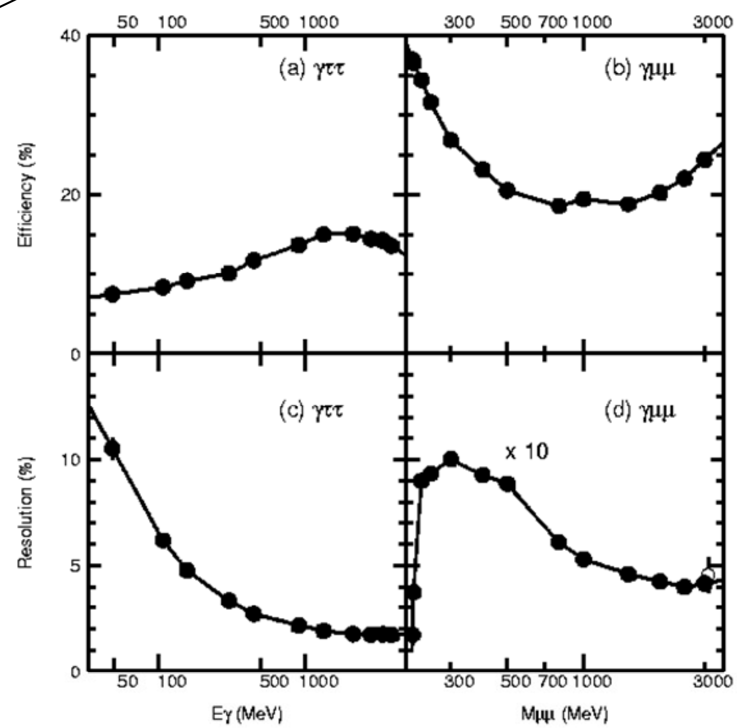
At least one μ or e (no ee)
2 < missing energy < 7 GeV

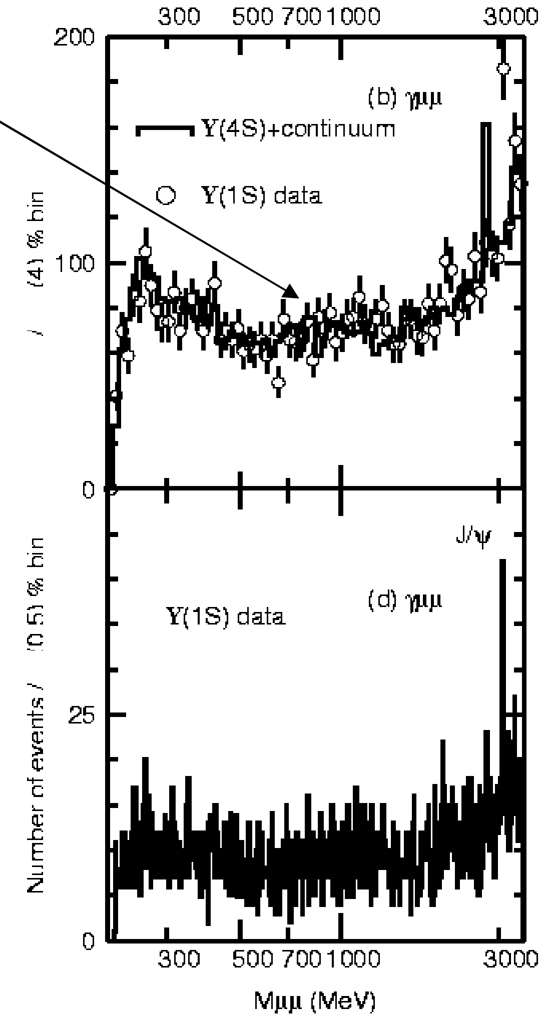
$\gamma\mu^+\mu^-$

Two μ's
No missing energy

Continuum background dominates



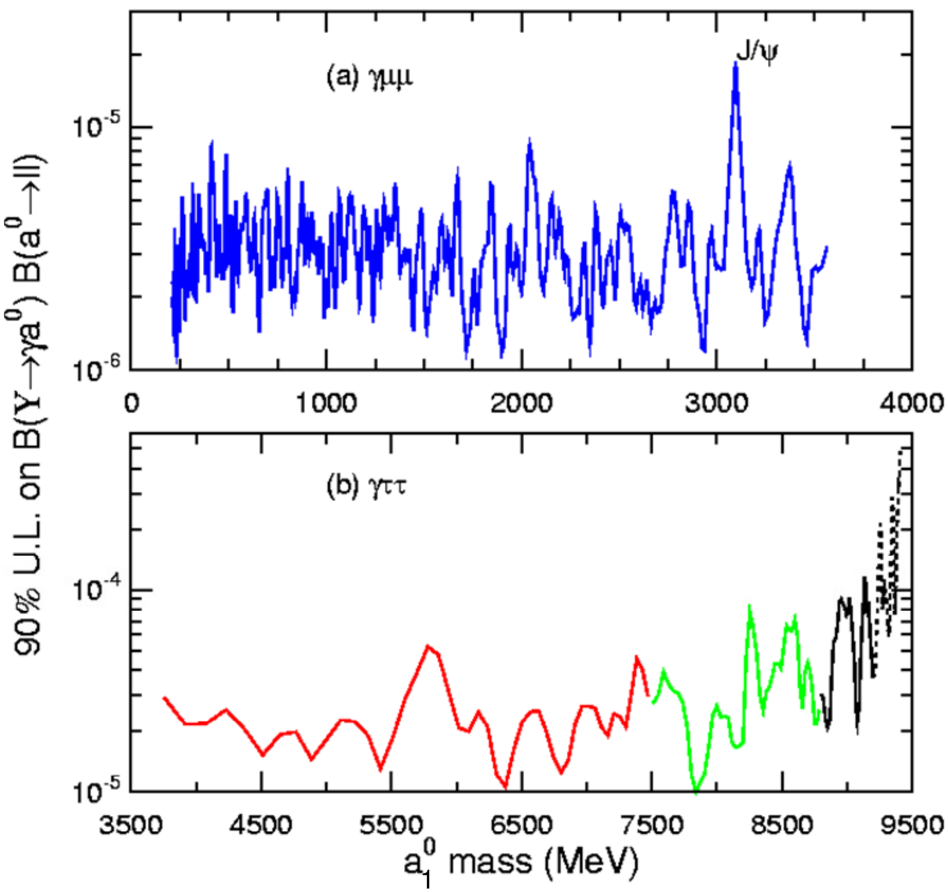


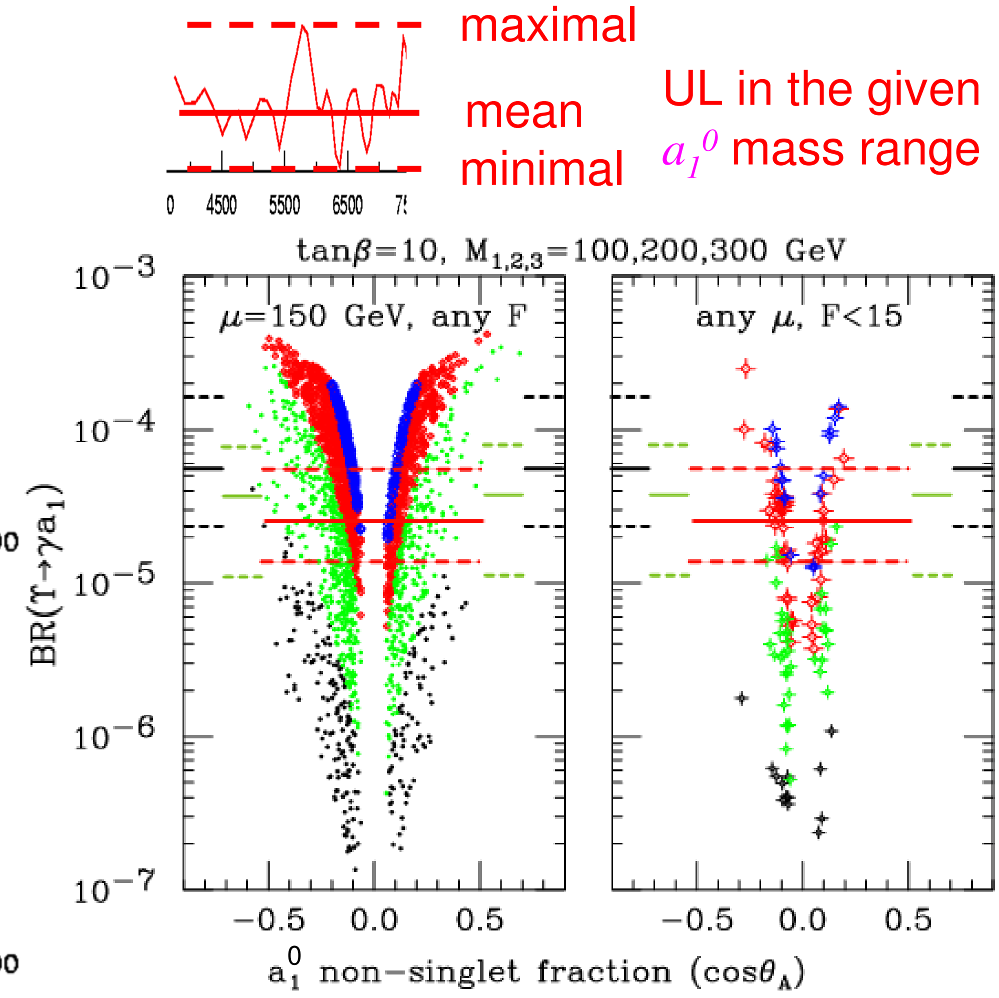


- No significant peaks found except for ISR J/ψ

Search for light CP-odd Higgs

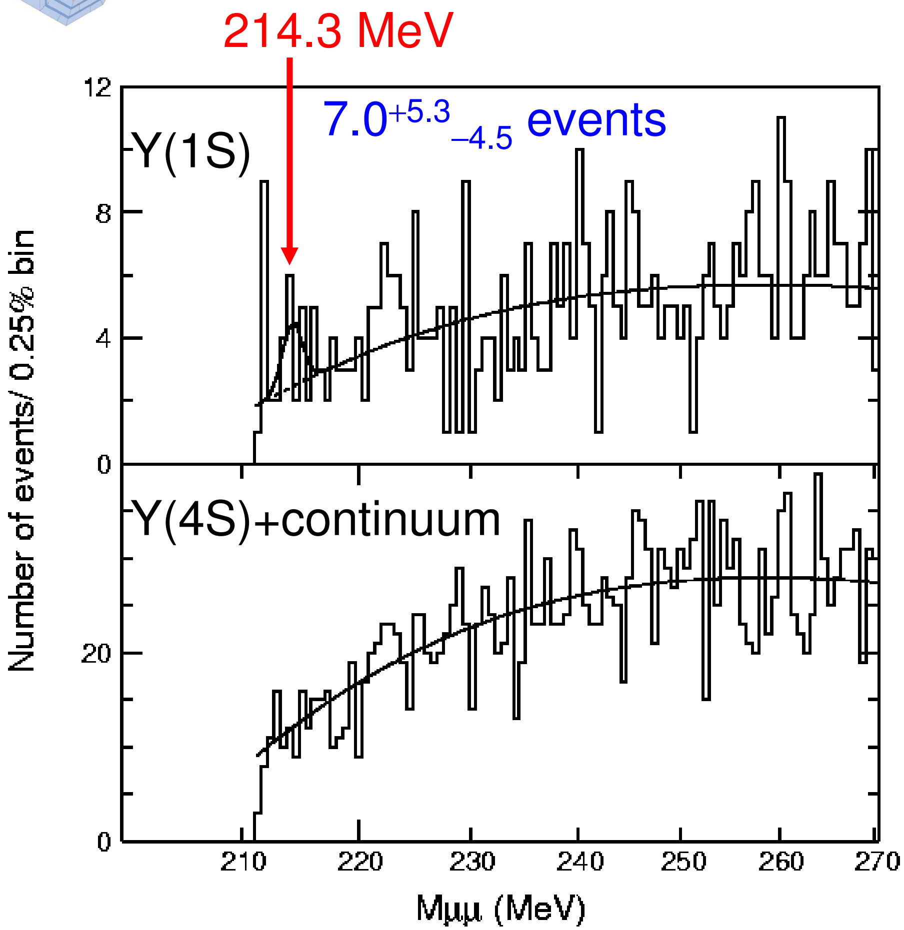
CLEO-III Preliminary!





- Our $\gamma\tau^+\tau^-$ limits significantly constrain NMSSM models

Search for light CP-odd Higgs



For $m(a_1^0)$ =214.3 MeV

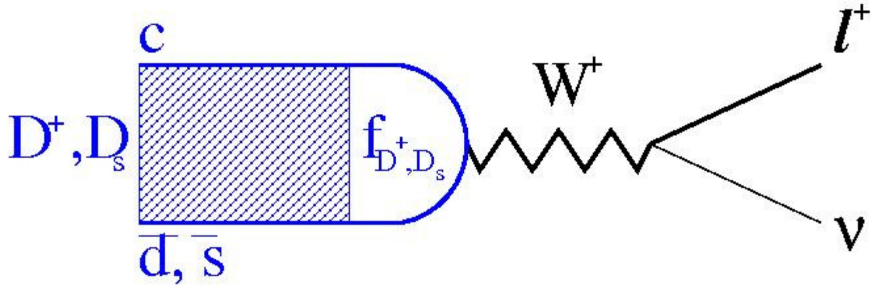
$$B(\Upsilon(1S) \to \gamma a_1^0) B(a_1^0 \to \mu^+\mu^-) < 2.3 \cdot 10^{-6}$$
$$(at\ 90\%\ C.L.)$$

$g_d^2 < 0.026$

vs $g_d^2 = 0.12$ used in the He, Tandean, Valencia paper explaining the HyperCP events with the a_1^0 hypothesis

- Our $\gamma\mu^+\mu^-$ limit makes a_1^0 interpretation of the HyperCP events difficult

D, D_s decay constants



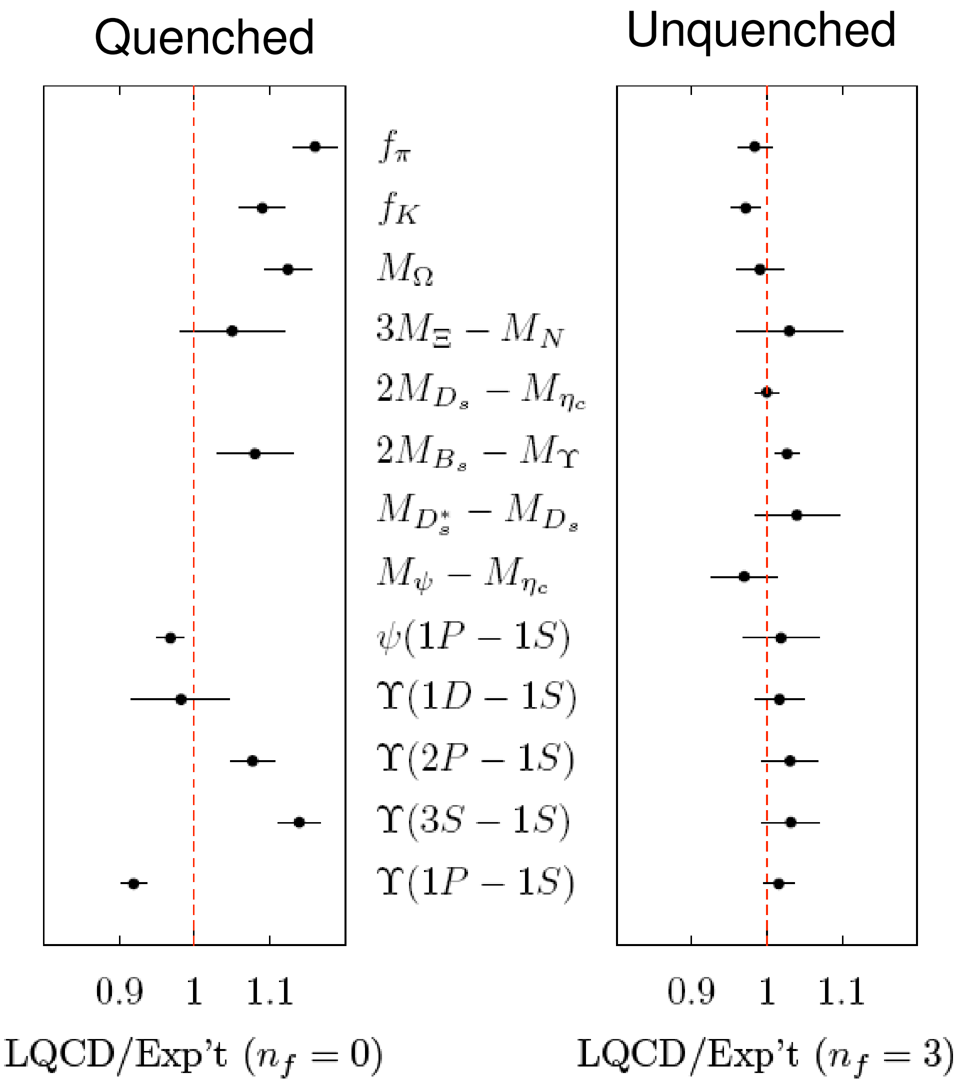
$$\Gamma(D_q^+ \to \ell^+\nu) = \frac{1}{8\pi} G_F^2 f_{D_q}^2 m_\ell^2 M_{D_q} \left(1 - \frac{m_\ell^2}{M_{D_q}^2}\right) |V_{cq}|^2$$

Helicity suppression of $D^+,D_s^+ \to e^+\nu$

Phase space suppression of $D^+ \to \tau^+\nu$

- Take $V_{cd} = V_{us}$=0.2256, determine $f_{D,Ds}$ and compare to lattice QCD calculations:
  - "Calibration point" for lattice QCD calculations needed for B,Bs studies
  - Test of S.M. on f_D/f_{Ds}

Unquenched lattice QCD

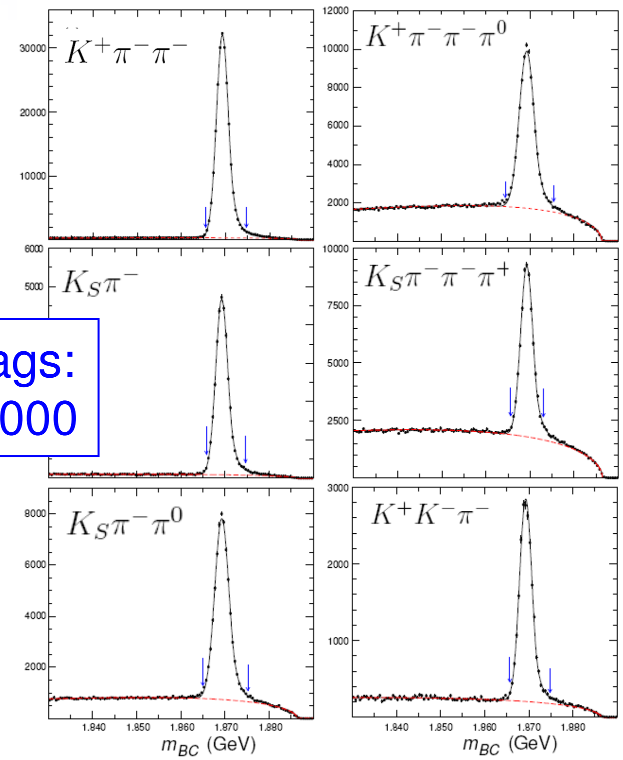


- Precision of a few % possible with unquenched calculations
- New predictions of f_{D^+} = 207±4 MeV f_{Ds} = 241±3 MeV by Follana et al HPQCD & UKQCD collaborations (PRL **100,** 062002 (2008))

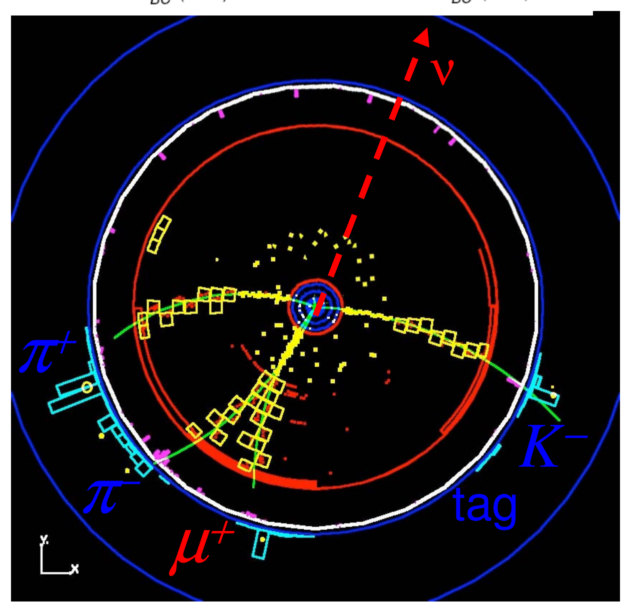
$D^+ \to \mu^+\nu$ with tagging technique

- $e^+e^- \to \psi(3770) \to D^+D^-$
  - No fragmentation particles produced
- Reconstruct one D (tag) in several clean hadronic decay modes:
  - Cut on $\Delta E = E_D - E_{beam}$
  - Fit $M_{bc} = \sqrt{E_{beam}^2 - \mathbf{p}_D^2}$ to determine N_{tag}
  - The tag determines momentum of the other D: $\mathbf{p}_{D\ signal} = -\mathbf{p}_{D\ tag}$
- Find subsample of events with only one additional oppositely charged track within $|\cos\theta|<0.9$ and no additional photons >250 MeV (to veto $D^+ \to \pi^+\pi^o$)
- Charged track must deposit only minimum ionization in calorimeter [< 300 MeV] (can't use muon system at these low momenta)
- Compute Missing-Mass². If close to zero then almost certainly we have a $\mu^+\nu$ decay.

$$M_\nu^2 = MM^2 = (E_{beam} - E_\mu)^2 - (\vec{p}_{D\ signal} - \vec{p}_\mu)^2$$

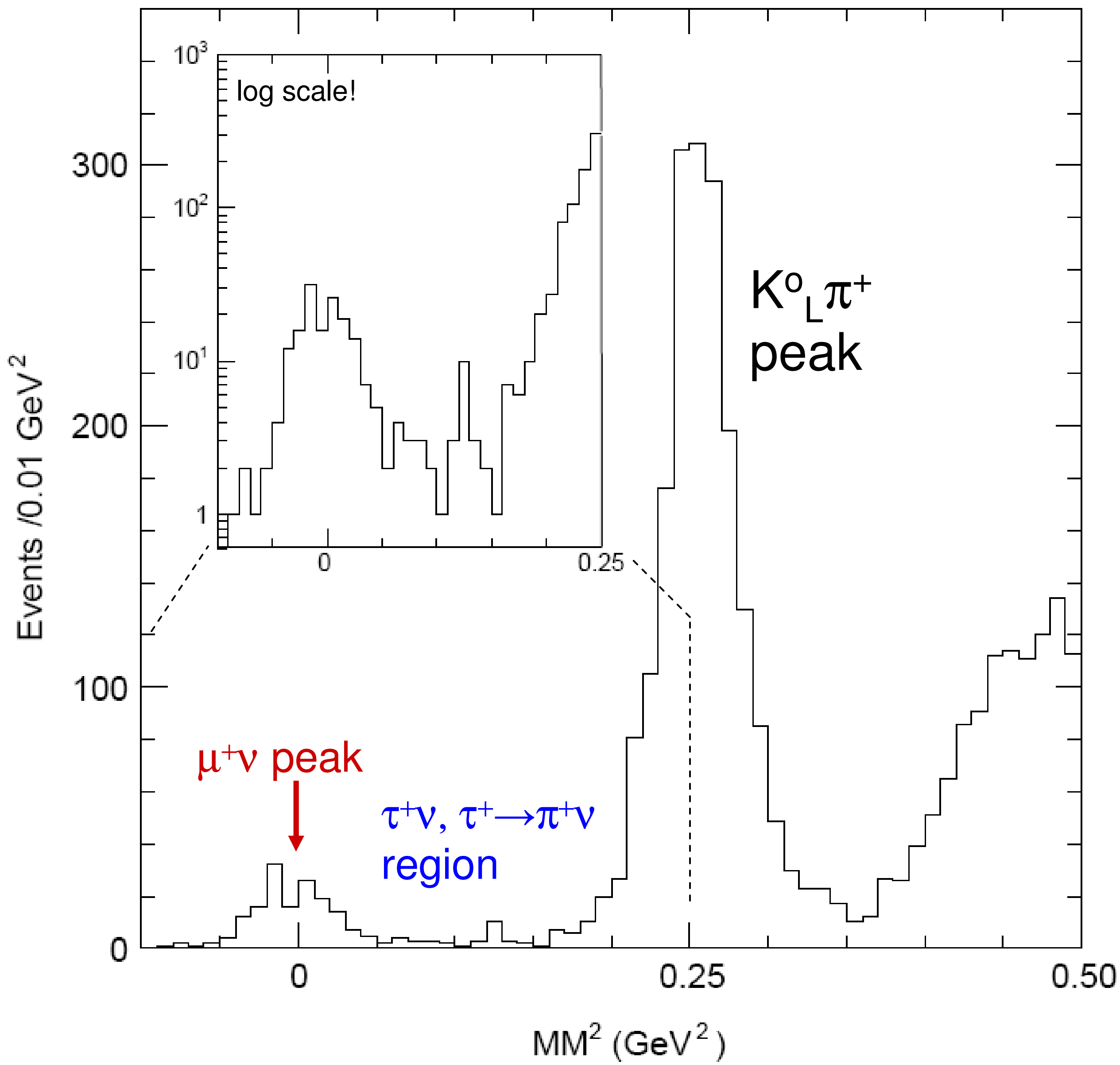


D⁺ tags: 460,000



$D^+ \to \mu^+\nu$ signal

818 pb^{-1} of $\psi(3770)$ data
Entire CLEO-c sample.

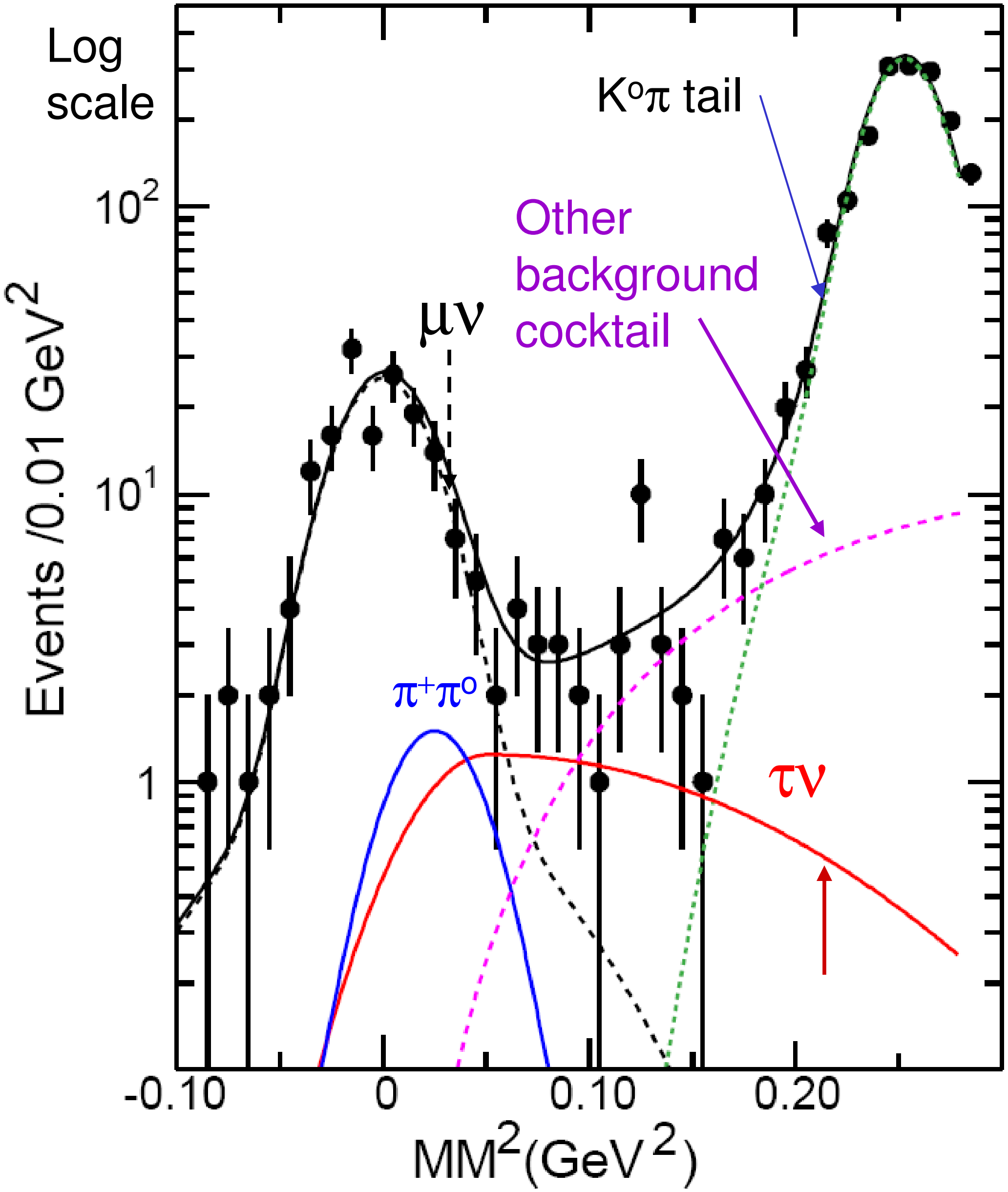


- Very good signal/bkg ratio thanks to the threshold kinematics

$D^+ \to \mu^+\nu$ fit

- $\tau^+\nu/\mu^+\nu$ **fixed** to SM ratio
  - 149.7±12.0 $\mu\nu$ events
  - 28.5 $\tau\nu$
  - $B(D^+\to\mu^+\nu)=$ $(3.86\pm0.32\pm0.09)\times10^{-4}$
  - $f_{D^+}=(207\pm8.5\pm2.5)$ MeV
- $\tau^+\nu/\mu^+\nu$ is allowed to **float**
  - 153.9±13.5 $\mu\nu$
  - 13.5±15.3 $\tau\nu$
  - $B(D^+\to\mu^+\nu)=$ $(3.96\pm0.35\pm0.10)\times10^{-4}$
  - $f_{D^+}=(208.5\pm9.3\pm2.5)$ MeV

CLEO-c Preliminary!



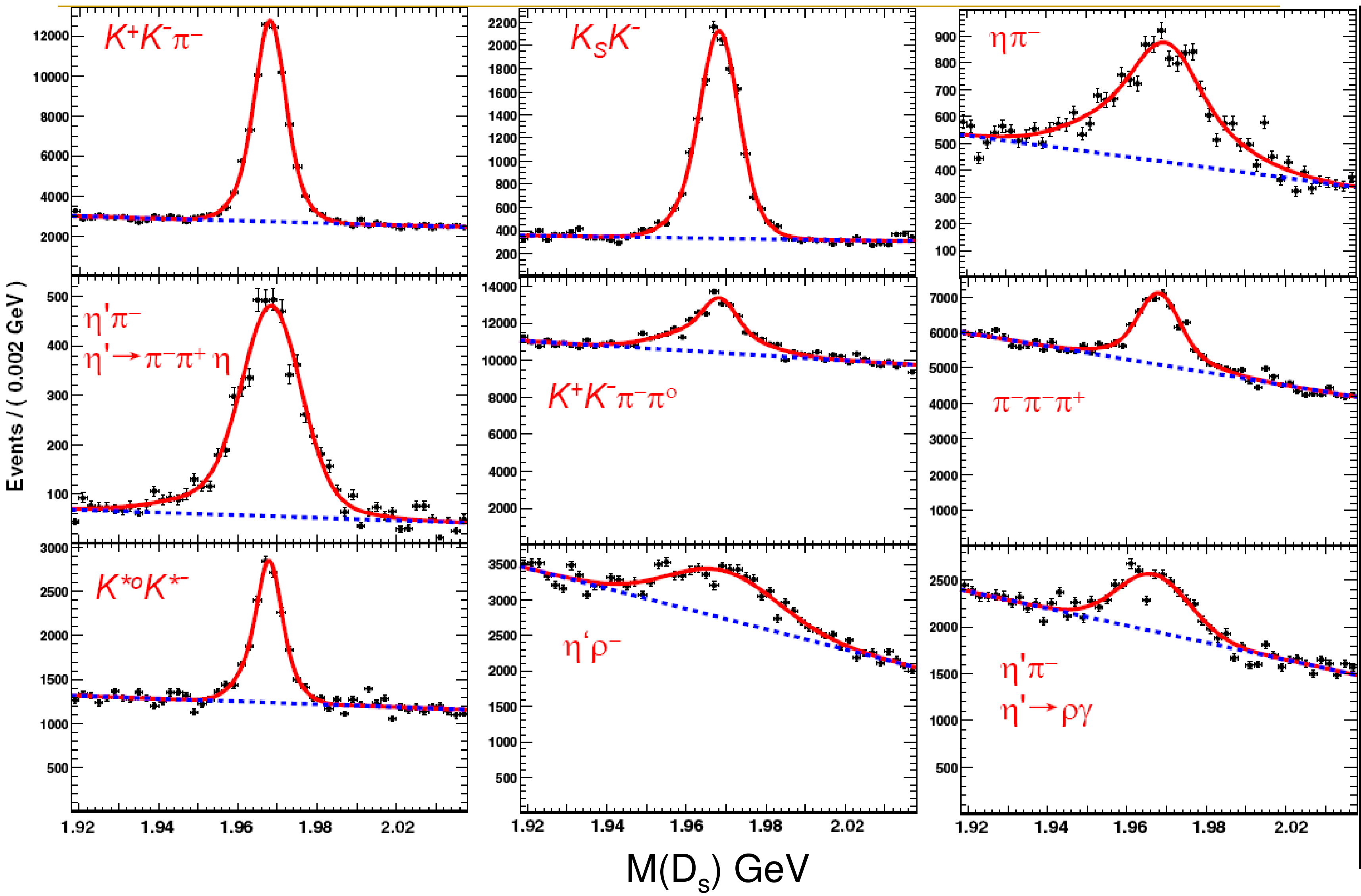
$D_s^+ \to \mu^+\nu$

424 pb^{-1} at E_{CM}=4170 MeV

$e^+e^- \to D_s D_s^*$

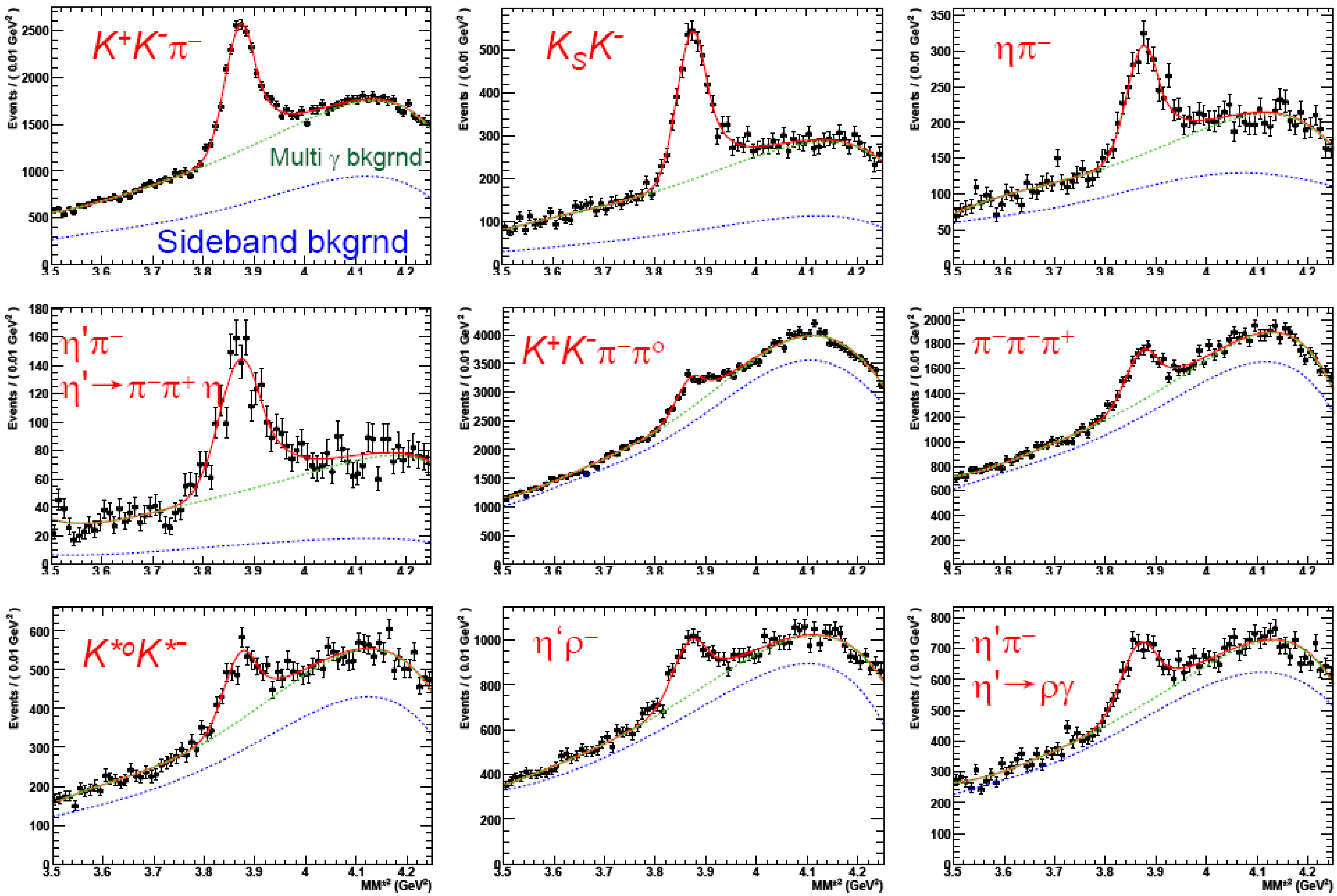
2/3 of full CLEO-c sample

- Reconstruction of tagging D_s^-



$D_s^+ \to \mu^+\nu$

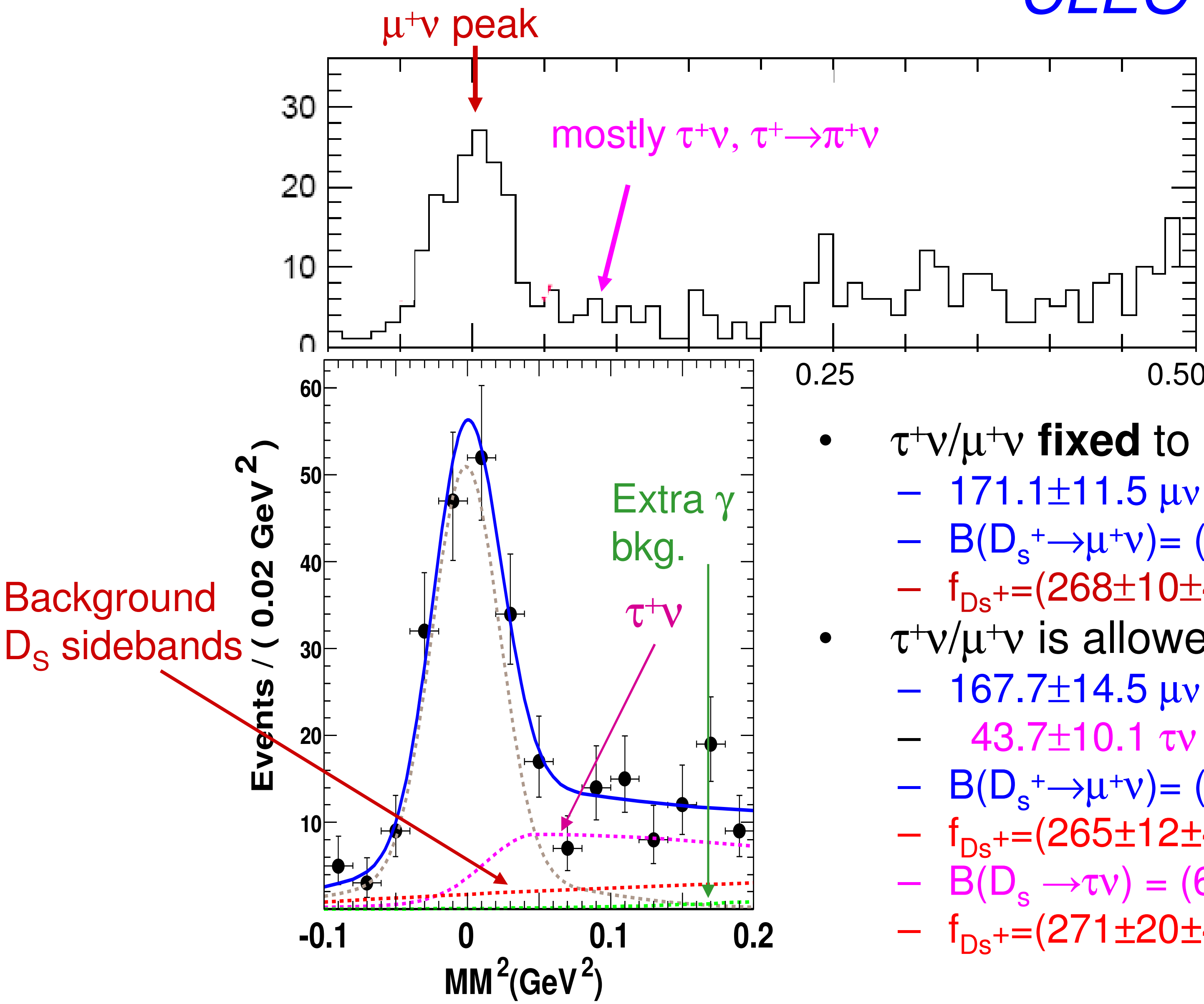
- Counting tagged D_s^+ events in $e^+e^- \to D_sD_s^*$: 30,848±695



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

$D_s^+ \to \mu^+\nu$ & $D_s^+ \to \tau^+\nu$

CLEO-c Preliminary!

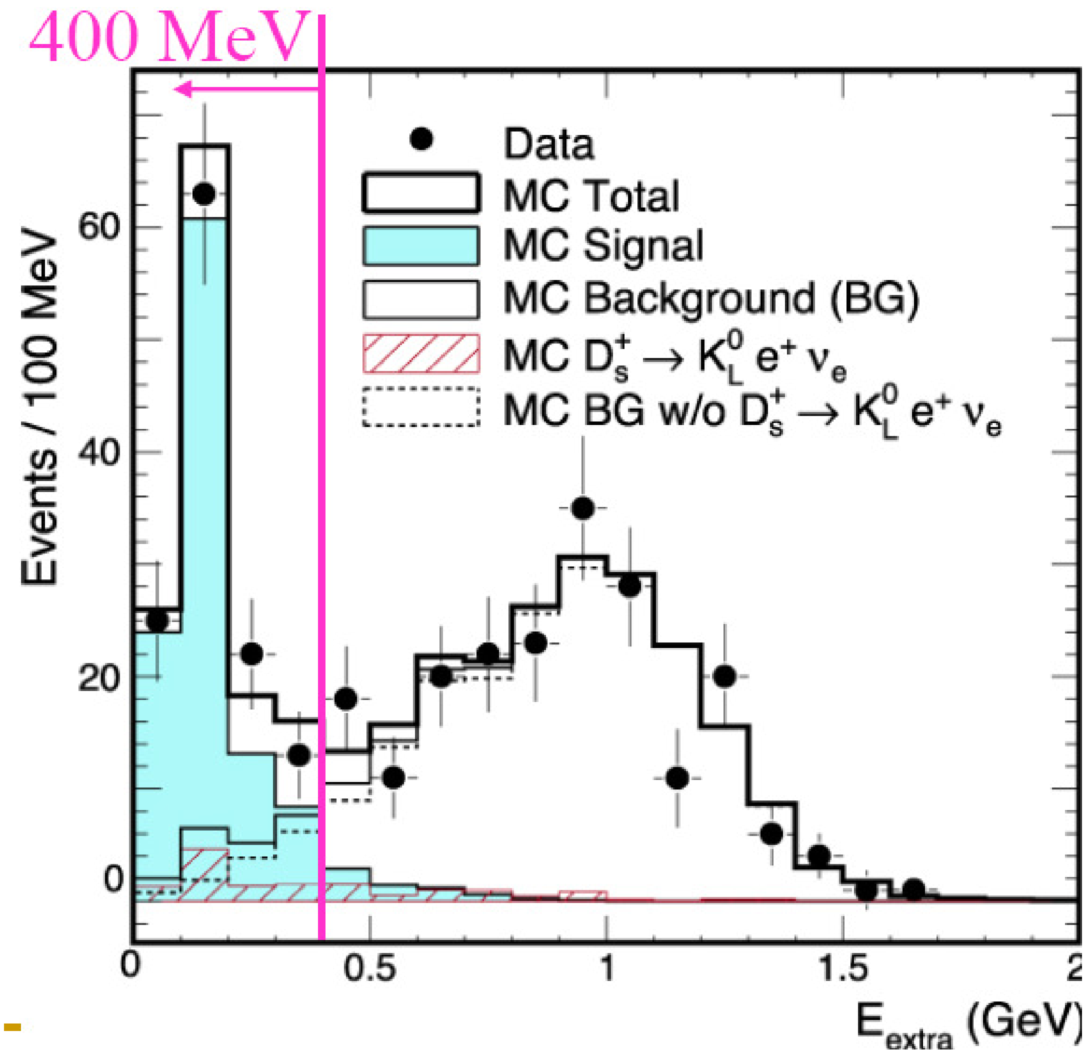


- $\tau^+\nu/\mu^+\nu$ **fixed** to SM ratio
  - 171.1±11.5 $\mu\nu$
  - $B(D_s^+\to\mu^+\nu)$= (6.13±0.44±0.20)x10^{-3}
  - f_{Ds^+}=(268±10±4) MeV
- $\tau^+\nu/\mu^+\nu$ is allowed to **float**
  - 167.7±14.5 $\mu\nu$
  - 43.7±10.1 $\tau\nu$ (significant! $\tau\to\pi^+\nu$)
  - $B(D_s^+\to\mu^+\nu)$= (6.00±0.54±0.20)x10^{-3}
  - f_{Ds^+}=(265±12±4) MeV
  - $B(D_s\to\tau\nu)$ = (61±9±2)x10^{-3}
  - f_{Ds^+}=(271±20±4) MeV

$D_s^+ \to \tau^+\nu$, $\tau^+ \to e^+\nu\nu$

316 pb^{-1} at E_{CM}=4170 MeV

- No $D_s^+ \to e^+\nu$ because of helicity suppression
- MM technique not very useful with 3 neutrinos
- Select events with a tag, electron and then look at extra energy in the calorimeter (includes ~150 MeV γ from $D_s^* \to \gamma D_s$)
- $B(D_S^+ \to \tau^+\nu)$= $(6.17 \pm 0.71 \pm 0.36) \times 10^{-2}$
- f_{Ds^+}=(273±16±8) MeV



CLEO-c f_{D_s} results

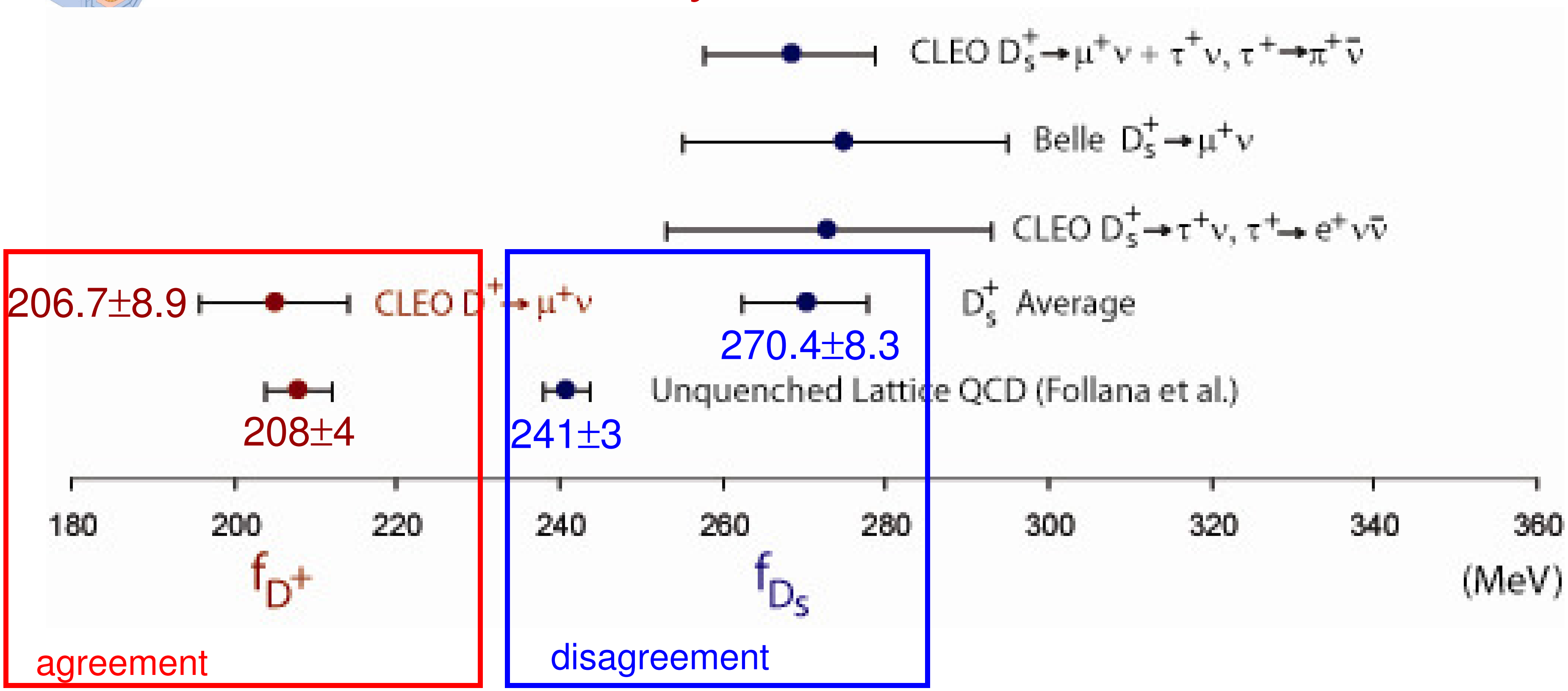
$\Gamma(D_s^+ \to \tau^+\nu)/\Gamma(D_s^+ \to \mu^+\nu)$ = 10.3±1.1

vs SM(lepton universality)=9.7

Mode	B(%)	f_{D_s} (MeV)
(1) $\mu\nu+\tau\nu$ (fix at SM ratio)	$B^{eff}(D_s \to \mu\nu)$ = 0.613±0.044±0.020	268±10±4
(2) $\mu\nu$ only	$B(D_s \to \mu\nu)$ = 0.600±0.054±0.020	265±12±4
(3) $\tau\nu$, $\tau\to\pi\nu$	$B(D_s \to \tau\nu)$ = 6.1±0.9±0.2	271±20±4
(4) $\tau\nu$, $\tau\to e\nu\nu$	$B(D_s \to \tau\nu)$ = 6.17±0.71±0.36	273±16±8
CLEO-c Average of (1) & (4)		269.4±8.2±3.9

Preliminary !

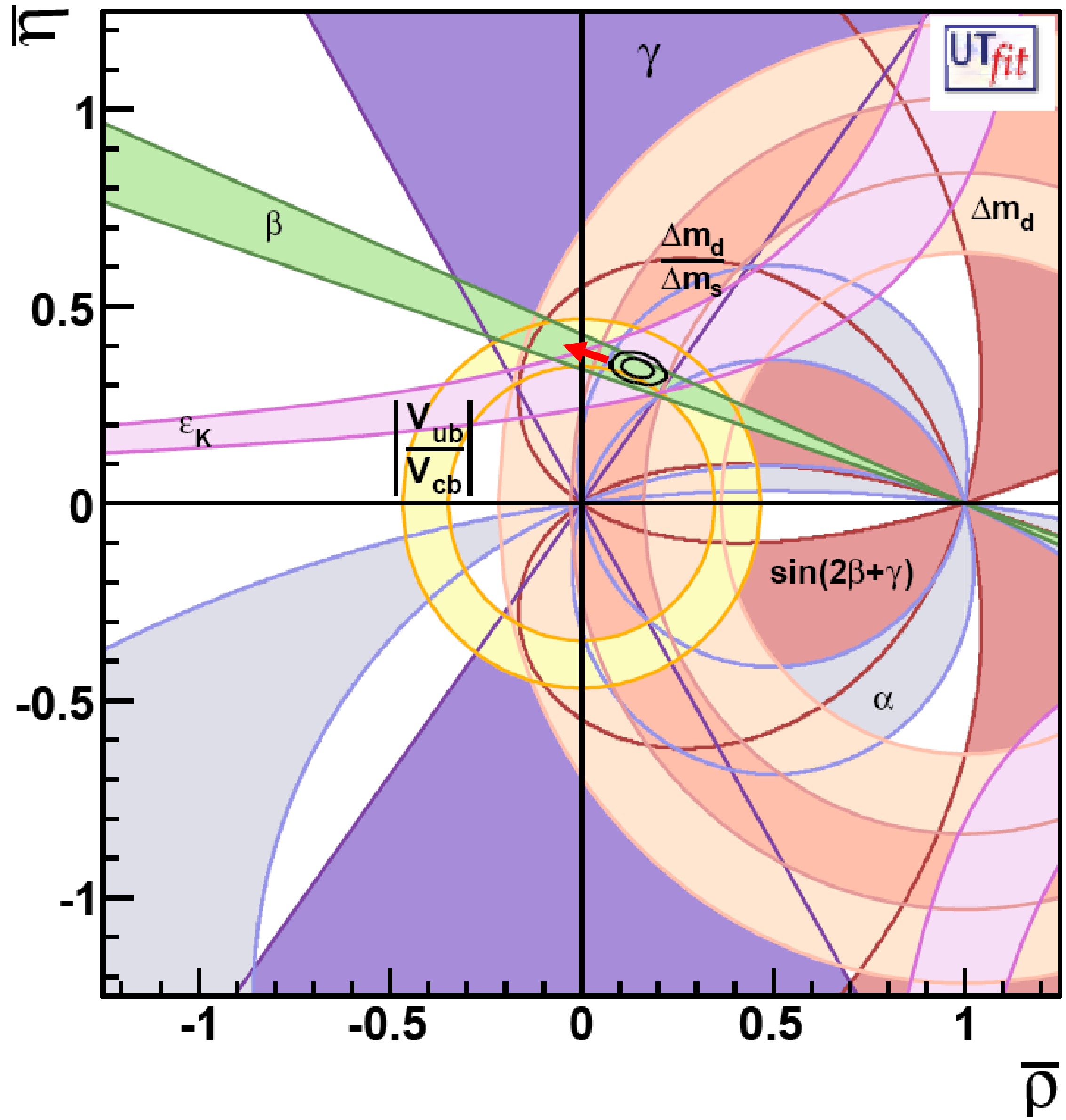
Conclusions on Decay Constants



- We are in close agreement with the Follana et al calculation for f_{D^+}. This gives credence to their calculations.
- The disagreement with f_{Ds} is 3.3σ

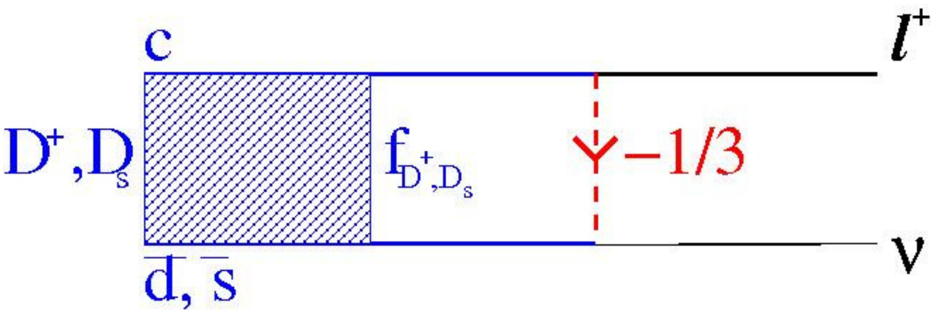
Can we trust lattice QCD calculations?

- If theoretical predictions of f_{D_s}/f_{D^+} do not agree with the data, why should we believe f_{B_s}/f_B from theory? What does this do to the CKM fits?

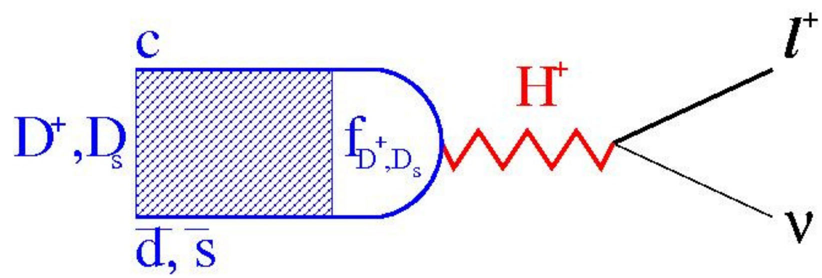


If we can trust lattice QCD calculations…

- New Physics possibilities:
  - Dobrescu, Kronfeld, arXiv:0803.0512



A scalar lepto-quark with electric charge of -1/3



A charged Higgs from Two Higgs doublets model in which one doublet gives masses to u,c quarks and charged leptons, and the other doublet gives masses to down type quarks and top

  - Kundu, Nandi, arXiv:0803.1898

Supersymmetry with R-parity violating couplings

M1 Transitions in Charmonium

- Theory:

$$\Gamma(i \xrightarrow{\mathrm{M1}} f + \gamma) = \frac{4\alpha e_Q^2}{3m_Q^2}(2J_f + 1)k^3[\mathcal{M}_{if}|]^2$$

$$\mathcal{M}_{if} = \int r^2 dr\, R_{n_i \mathrm{L}_i}(r) j_0(\frac{rk}{2}) R_{n_f \mathrm{L}_f}(r)$$

$j_0 = 1 - (kr)^2/24 + \ldots$, so in NR limit

$$k = 0: \quad \mathcal{M}_{if} = 1 \quad n_i = n_f; L_i = L_f \qquad \text{“direct”}$$
$$= 0 \quad \text{otherwise} \qquad \text{“hindered”}$$

$$\Gamma(J/\psi \to \eta_c \gamma) = \frac{16}{3}\alpha e_c^2 \frac{k_\gamma^3}{M_{J/\psi}^2}(1 + \kappa_c)[1 + o(v^2)] \qquad \text{(direct)}$$

LQCD 2.0±0.1±0.4 keV Dudek, Edwards, Richards PRD,73,074507(2007)
Not much different than the naïve calculation

- Experiment:

$B(J/\psi \to \eta_c \gamma) = (1.3 \pm 0.4)\%$ Gaiser *et al.* (Crystal Ball), PRD 34, 711 (1986)
$\Gamma(J/\psi \to \eta_c \gamma) = B(J/\psi \to \eta_c \gamma) \times \Gamma_{tot} = (1.2 \pm 0.3)$ keV
Significantly smaller than theoretically predicted!

CLEO-c method

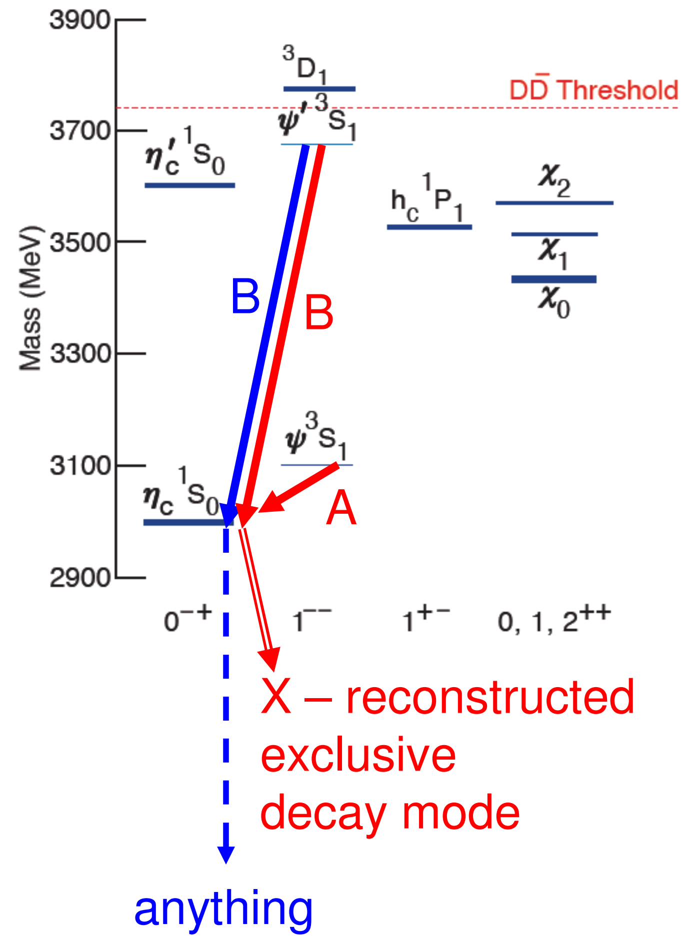
CLEO arXiv:0805.0252 [hep-ex]

- $B(J/\psi \to \gamma \eta_c)$ 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.

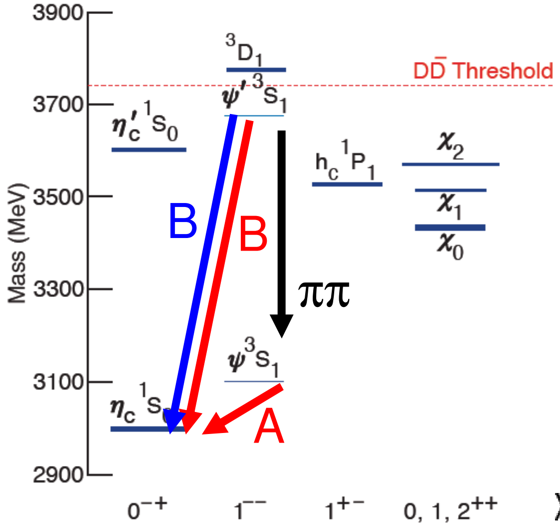
Use exclusive reconstruction of a large number of possible final states X (suppresses the backgrounds). Take the ratio to cancel unknown $B(\eta_c \to X)$

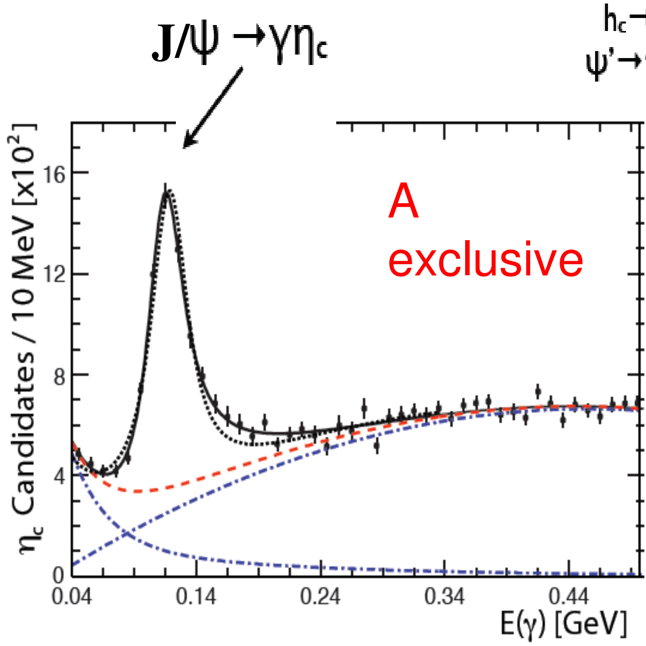


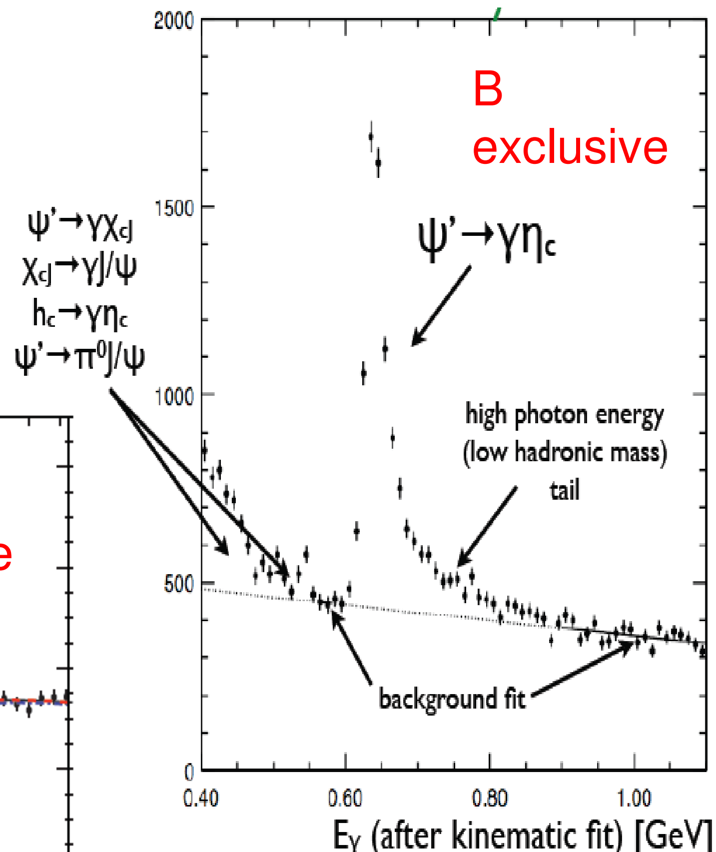
CLEO-c M1 transitions to η_c

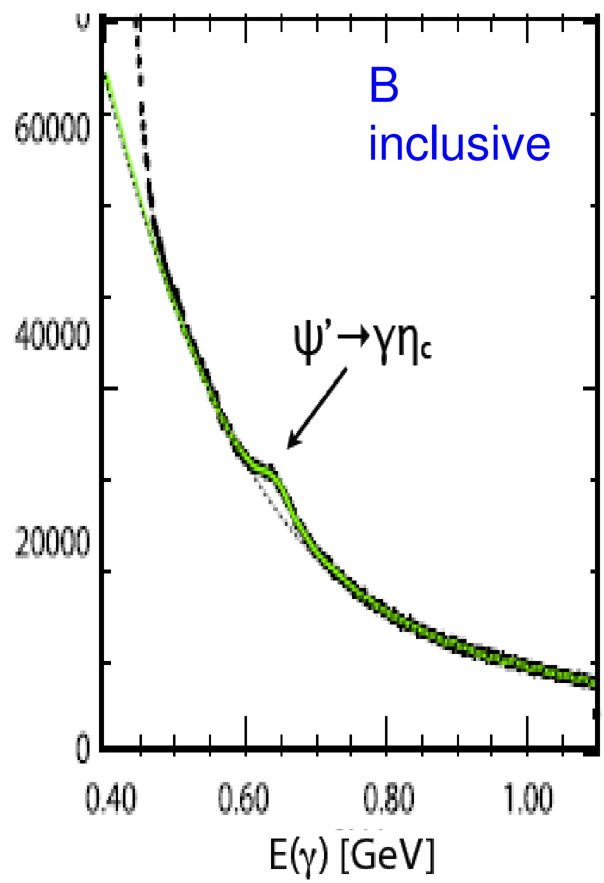
25M $\psi(2S)$ decays

- In exclusive approach use 13 signal-rich η_c decay modes (some new)
  - Kinematic fitting of events to improve energy resolution
- Non-trivial line-shape in the hindered transition:
  - count signal events above bkg in exclusive sample
  - use exclusive signal shape to fit inclusive spectrum







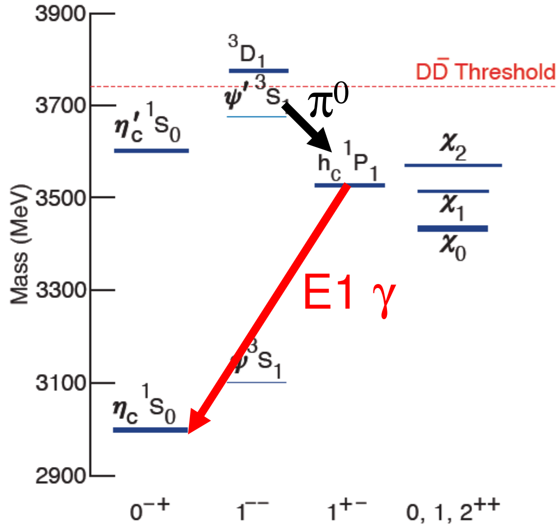


CLEO-c M1 transitions to η_c

Branching Ratio	CLEO-c	PDG 2006
$B(\psi(2S) \rightarrow \gamma\eta_c)$	$(4.32 \pm 0.16 \pm 0.60) \times 10^{-3}$	$(2.6 \pm 0.4) \times 10^{-3}$
$B(J/\psi \rightarrow \gamma\eta_c)$	$(1.98 \pm 0.09 \pm 0.30) \times 10^{-2}$	$(1.3 \pm 0.4) \times 10^{-2}$

- The hindered M1 rate $B(\psi(2S)\rightarrow\gamma\eta_c)$:
  - Previous measurements low since they neglected the high energy tail in the signal shape.
  - Theoretical predictions difficult because of the suppressed character of the matrix element.
- The direct M1 rate $B(J/\psi\rightarrow\gamma\eta_c)$:
  - Measured via exclusive event reconstruction. Significantly higher than previously measured by Crystal Ball from inclusive photons.
  - Agrees well with the theoretical expectations. Mystery solved.

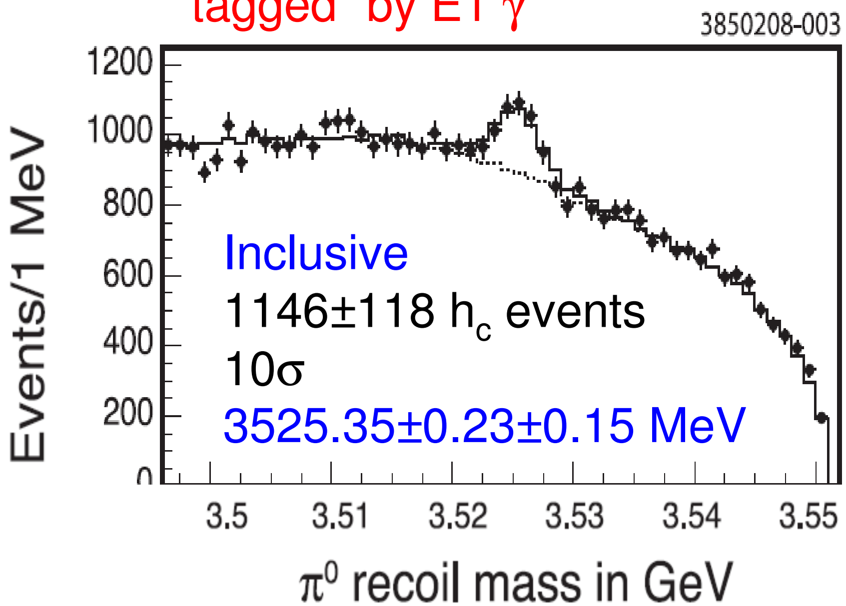
New improved determination of h_c mass



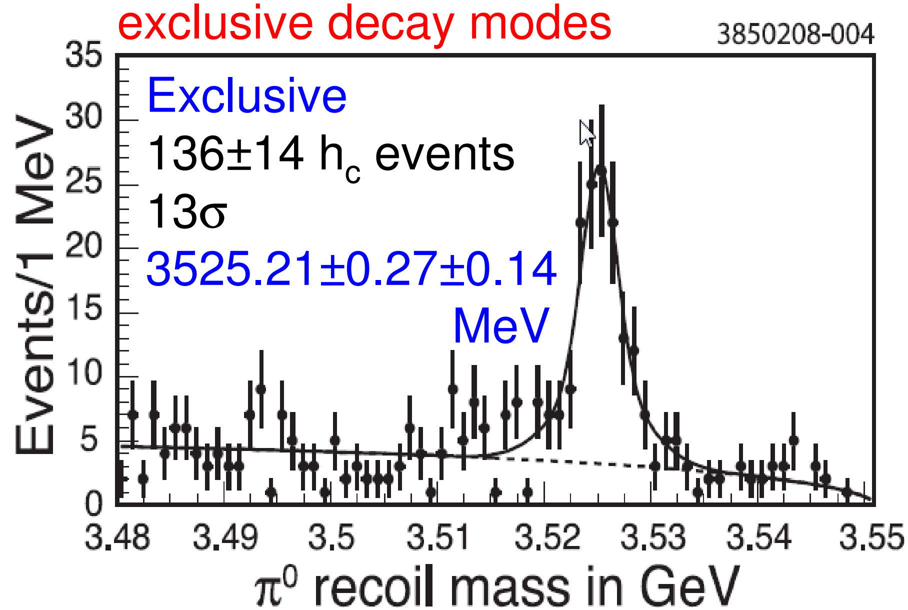
CLEO-c arXiv:0805.4599 [hep-ex]

- A factor of ~6 larger statistics than in the initial publication

"tagged" by E1 γ



η_c reconstructed in one of 15 exclusive decay modes



New improved determination of h_c mass

- Averaging inclusive and exclusive results:
  - CLEO-c: $m(h_c(1^1P_1))$ $=3525.28\pm0.19\pm0.12$ MeV
  - vs. spin-averaged $m(\chi_c(1^3P_J))$ $=3525.30\pm0.11$ MeV
- Thus, hyperfine mass splitting of 1P states is $0.02\pm0.19\pm0.13$ MeV
  - vs. hyperfine splitting of 1S states of 115 MeV
  - consistent with naïve theoretical prejudice that spin-spin interactions are only short-range and, therefore, not present in 1P states
  - surprisingly small given that corrections to the naïve expectation may be several MeV (see J. M. Richard, Proc. 15th Int. Workshop, DIS 2007 (Munich), Ed. G. Grindhammer and K. Sachs, DESY-PROC-2007-01, p. 849.)

Other recent quarkonium measurements

- Measurement of $B(\chi_{c0,2}\to\gamma\gamma)=(2.4\pm0.3\pm0.2)\text{x}10^{-4}$, $(3.1\pm0.3\pm0.2)\text{x}10^{-4}$ arXiv:0803.2869 [hep-ex]
- First measurement of $B(J/\psi\to\gamma\gamma\gamma)=(1.2\pm0.3\pm0.2)\text{x}10^{-5}$ arXiv:0806.0671 [hep-ex]
- Measurements of $B(J/\psi\to\gamma gg)/B(J/\psi\to ggg)=$ $=0.137\pm0.001\pm0.016$ arXiv:0806.0315 [hep-ex]
- Update on $B(\psi(2S)\to X\ J/\psi)$, $X=\pi^+\pi^-,\pi^0\pi^0,\eta,\pi^0,\gamma\gamma$ via χ_{cJ} arXiv:0804.4432 [hep-ex]
- First measurement of $B(\Upsilon(2S)\to\eta\Upsilon(1S))=(2.1\pm0.6\pm0.5)\text{x}10^{-5}$ (preliminary)
- Improved measurements of $B(\Upsilon(2S)\to X\Upsilon(1S))$, $X=\pi^+\pi^-,\pi^0\pi^0$ (preliminary)

Summary

- Search for light CP-odd Higgs in radiative decays of Υ(1S):
  - No evidence found
  - Limits in $\gamma\tau\tau$ channel 2 orders of magnitude more stringent than previously available.
  - Limit on $\gamma\mu\mu$ for $M(\mu\mu)$=214.3 MeV makes the Higgs interpretation of HyperCP events unlikely
  - Both provide new constraints on NMSSM
- Decay constants of f_D,f_{Ds}:
  - Disagreement with HPQCD lattice QCD calculations on f_{Ds}
  - New physics or problems with HPQCD lattice calculations?
- Measurement of M1 transition rates in charmonium:
  - Significantly different than previously determined
  - Now good agreement with the theory
- Precision measurement of h_c mass:
  - Hyperfine splitting in 1P state very small
- Many other results which I did not have time to describe