Recent Results from CLEO-c

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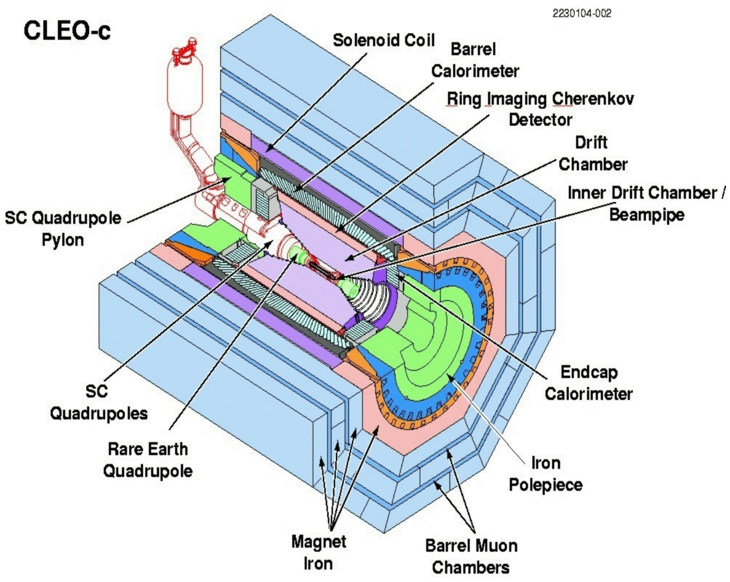
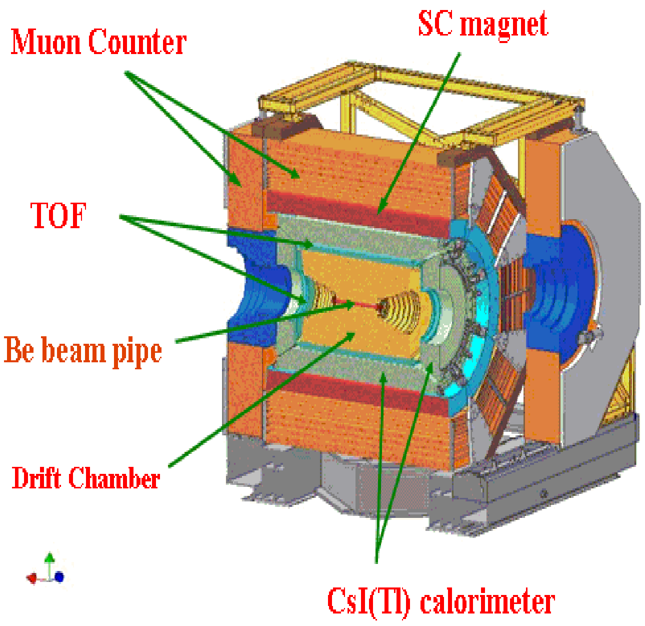
CLEO & BES-III Collaborations





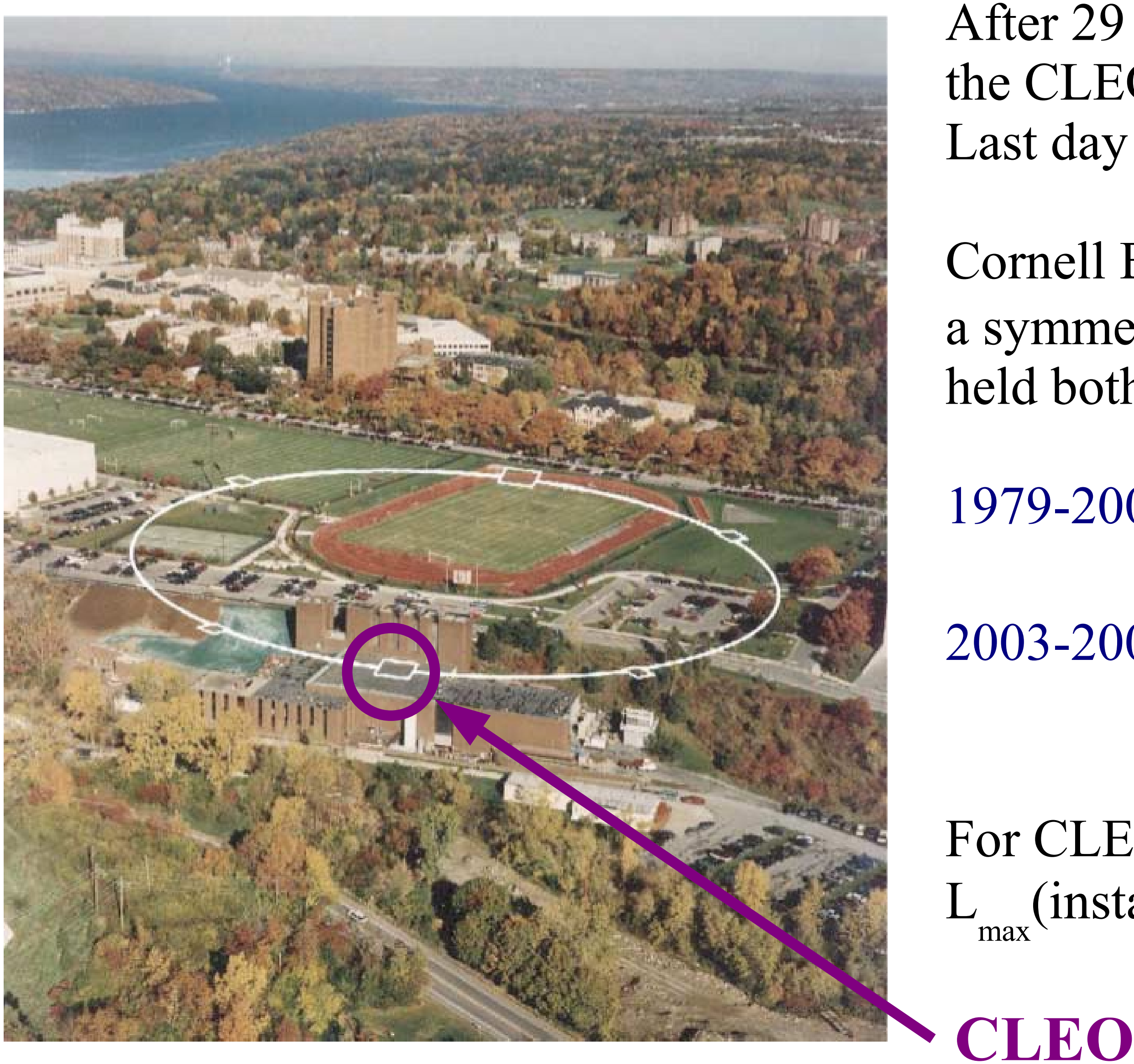
Introduction

The CLEO-c detector has collected
large data samples at the $\psi(2S)$ and $\psi(3770)$
resonances and at $E_{CM} = 4170$ MeV
(peak cross section for $D^*_s D_s$ production)

This talk will discuss recent charmonium and
(semi-)leptonic charm results from
the CLEO-c Collaboration

For recent hadronic charm and bottomonium
results, see Prof. R. A. Briere's seminar next week

The accelerator



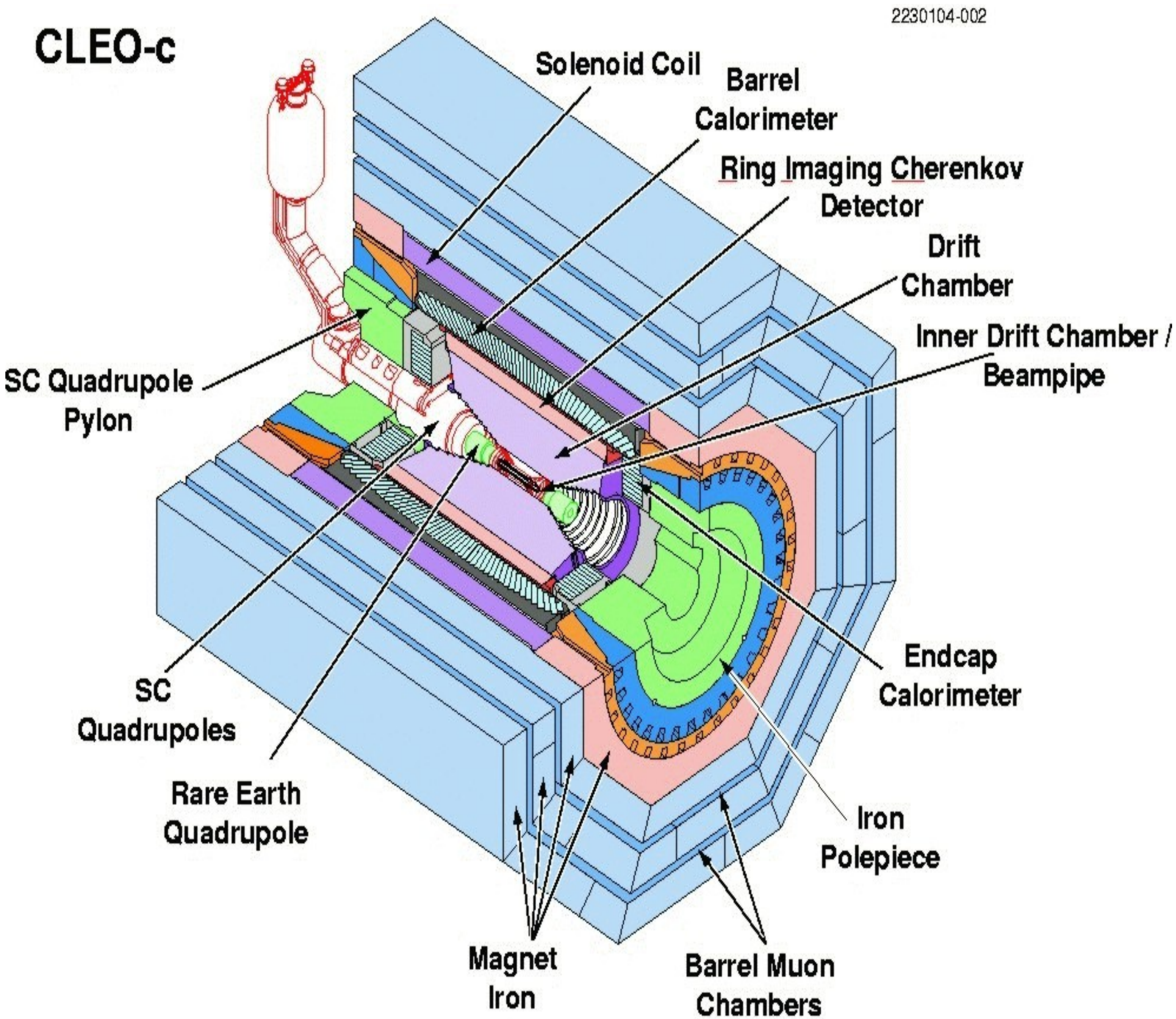
After 29 years of running,
the CLEO program has ended.
Last day was 3 March 2008.

Cornell Electron Storage Ring (CESR),
a symmetric $e^+ e^-$ collider,
held both beams in one ring.

1979-2003: E_{CM} ~ 10 GeV range
(CLEO I, II, II.V, III)
2003-2008: E_{CM} ~ 3-4 GeV range
(CLEO-c)

For CLEO-c running,
L_{max}(instantaneous) ~ $7\text{x}10^{31}$ cm^{-2} s^{-1}

CLEO-c Detector



Covered 93% of solid angle
Operated within 1.0 T B-field

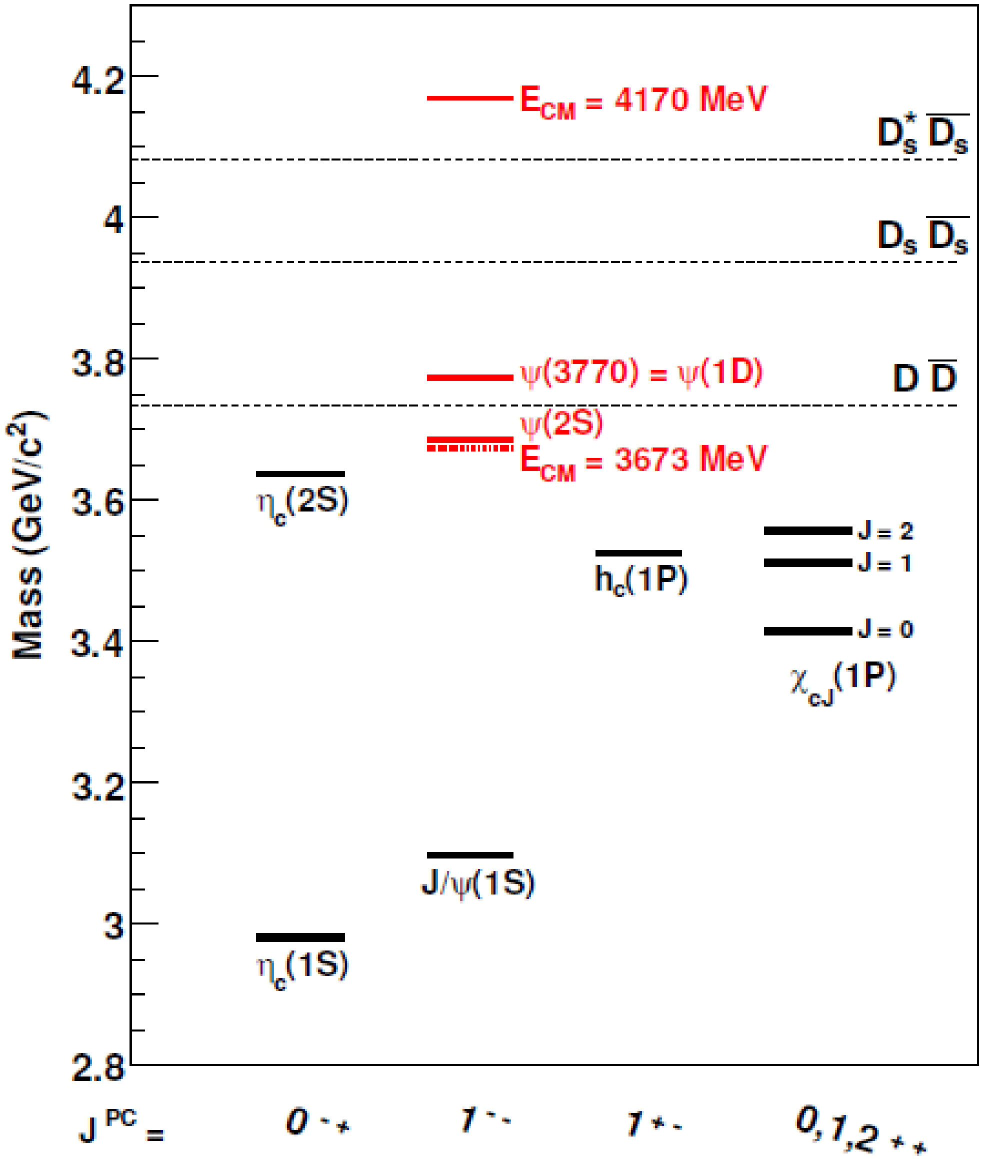
Tracking: $\sigma_p / \mathbf{p} = 0.6\%$ @ 1GeV

Shower Calorimetry:
$\sigma_E / E = 5\ (2.2)\ \%$ @ 0.1 (1) GeV

Charged PID (dE/dx + RICH):
Good K/π separation
for $\mathbf{p} < 2.5$ GeV

Muon Chamber not very useful:
$\mathbf{p}_{min} = 1$ GeV,
$\varepsilon \sim 90\%$ @ $\mathbf{p} > 1.5$ GeV

Data Samples Collected by CLEO-c



Ds Scan: 60 pb^{-1} (2005)

[12 pts; E_{CM} = 3.97 - 4.26 GeV]

E_{CM} = 4.17 GeV: 16 pb^{-1} (from scan)

298 pb^{-1} (2005-06)

+288 pb^{-1} (2007-08)

602 pb^{-1}

ψ(3770): 281 pb^{-1} (2003-05)

+ 537 pb^{-1} (2006-07)

818 pb^{-1}

ψ(2S): 1.47 M (2002-03; CLEO III)

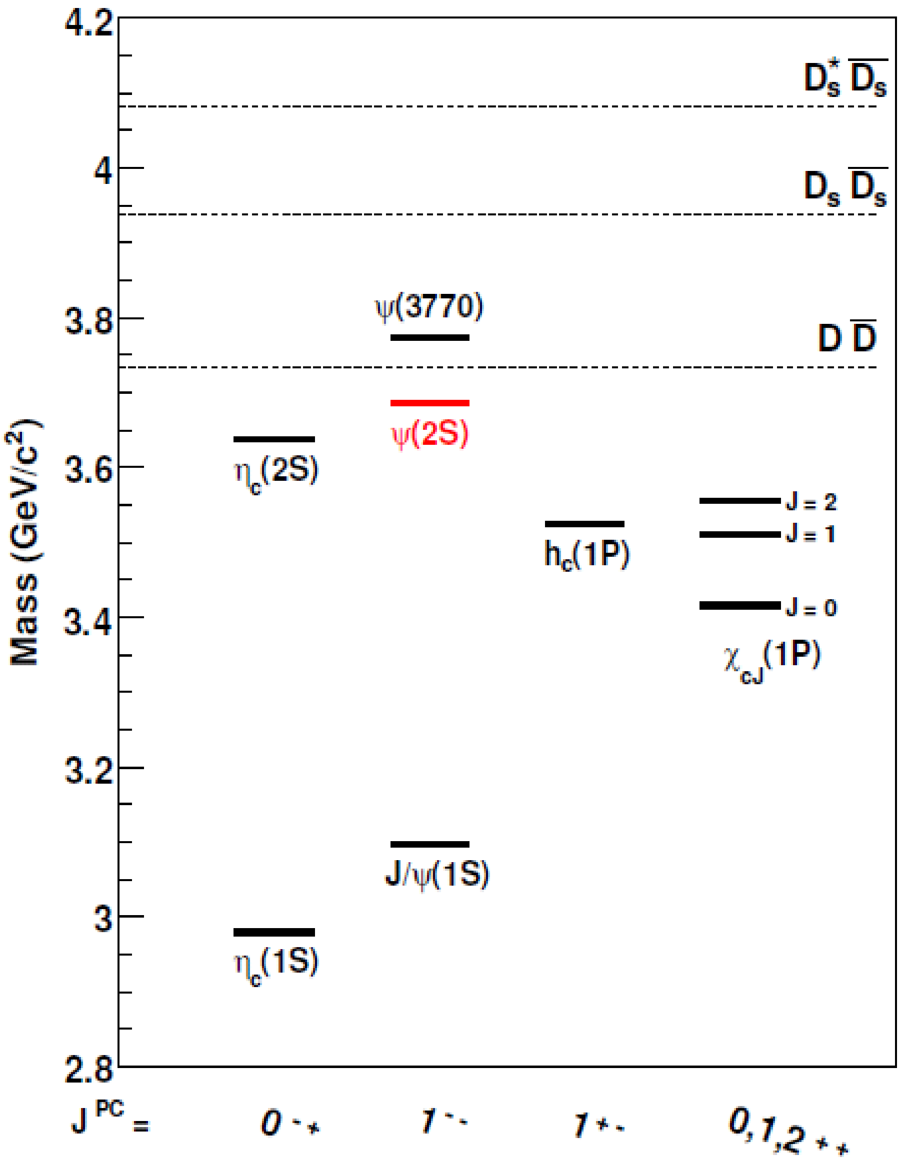
1.44 M (2003)

+ 24.45 M (2006)

27.36 M

E_{CM} = 3.67 GeV: 21 pb^{-1}

Charmonium Spectrum



The first $c\bar{c}$ bound state (J/ψ) was famously observed in 1974.

It would take 30 years to discover all $c\bar{c}$ bound (charmonium) states below $D\bar{D}$ threshold

The last two ($\eta_c(2S)$ and $h_c(1P)$):

2002: $B^+ \rightarrow K^+ \eta_c(2S)$ [Belle]

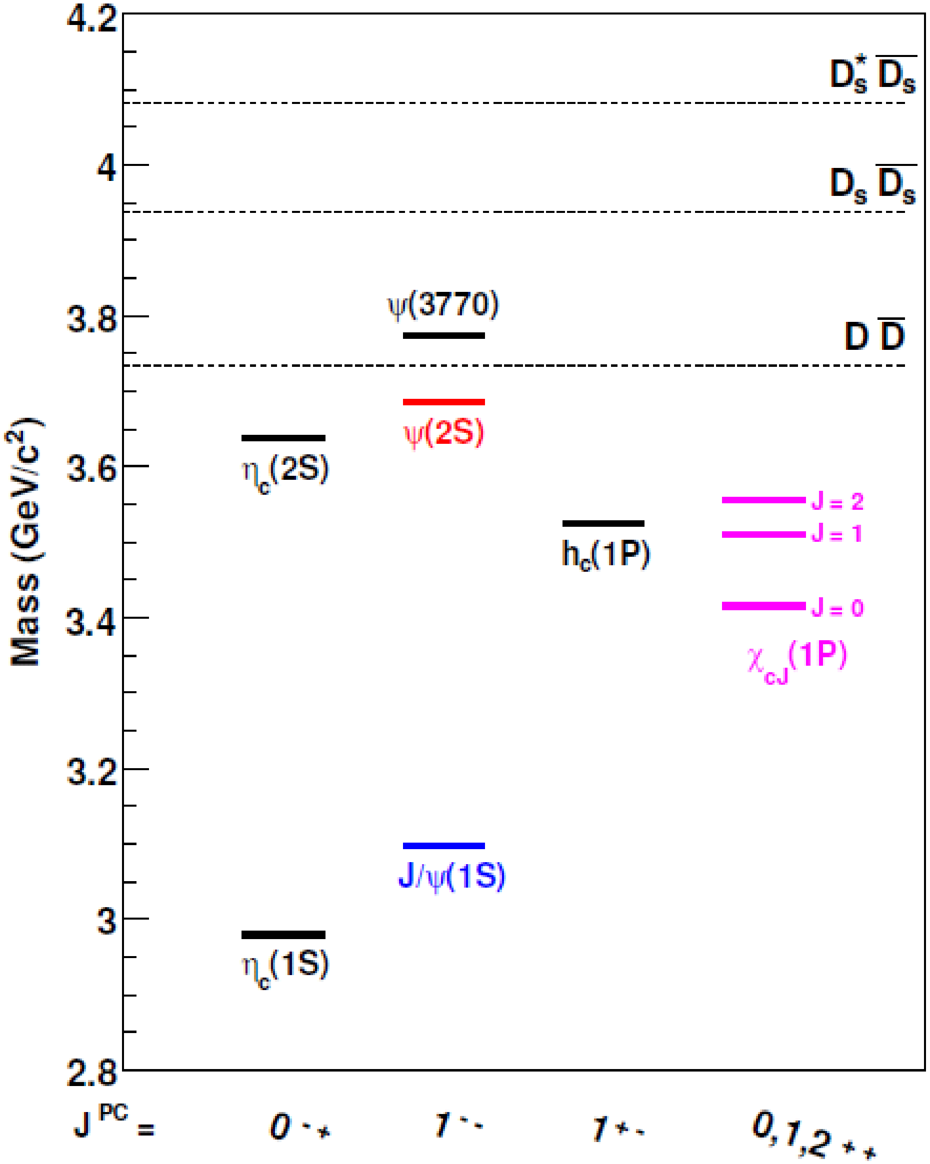
M($\eta_c(2S)$) disagreed w/ Crystal Ball

2004: $p\bar{p} \rightarrow h_c$, $h_c \rightarrow \gamma\, \eta_c(1S)$ [E835]

$\psi(2S) \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma\, \eta_c(1S)$ [CLEO]

Charmonium system is a good laboratory for studying QCD-based models.

$\psi(2S) \to X\ J/\psi$

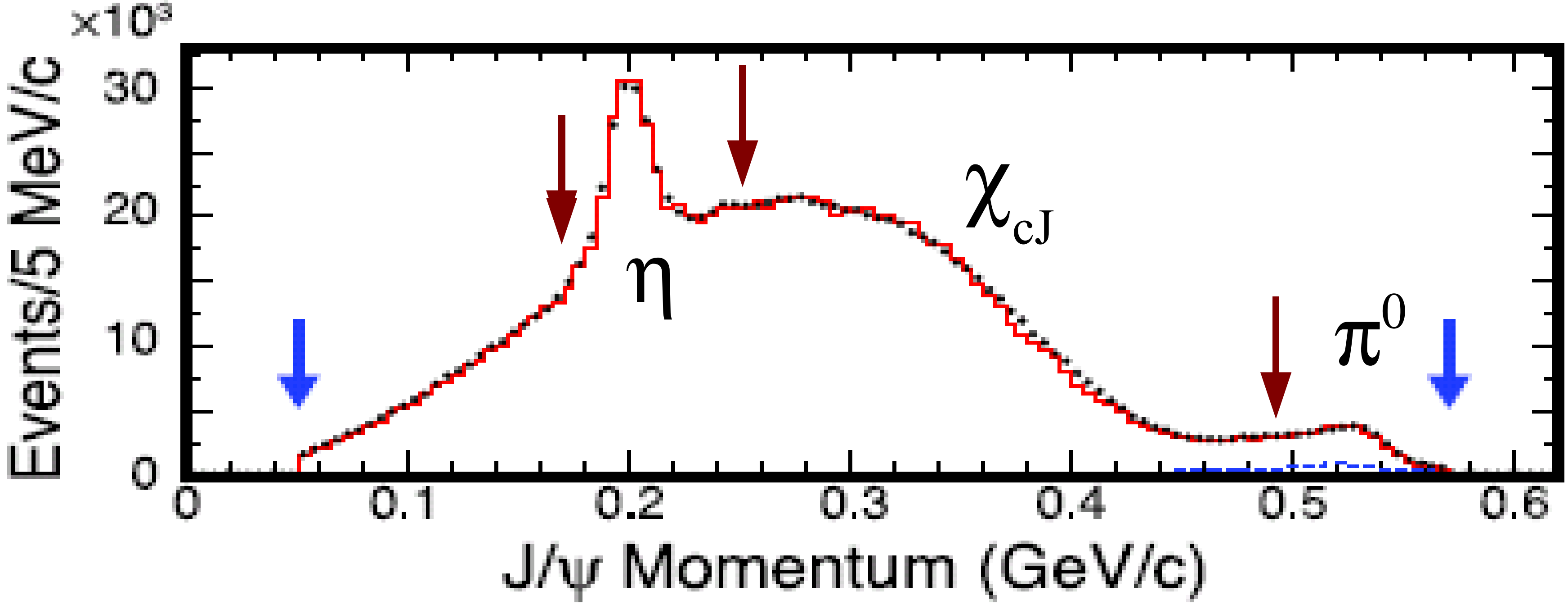


Using N(ψ(2S)) = 27.4 M,

Studied ψ(2S) - to - J/ψ transitions through

* $\pi^+\pi^-$
* $\pi^0\pi^0$
* η
* π^0
* $\gamma\,(\gamma\, J/\psi)\chi_{c0}$
* $\gamma\,(\gamma\, J/\psi)\chi_{c0}$
* $\gamma\,(\gamma\, J/\psi)\chi_{c0}$
* any

$\psi(2S) \to X\ J/\psi$



PRD 78, 011102 (2008)

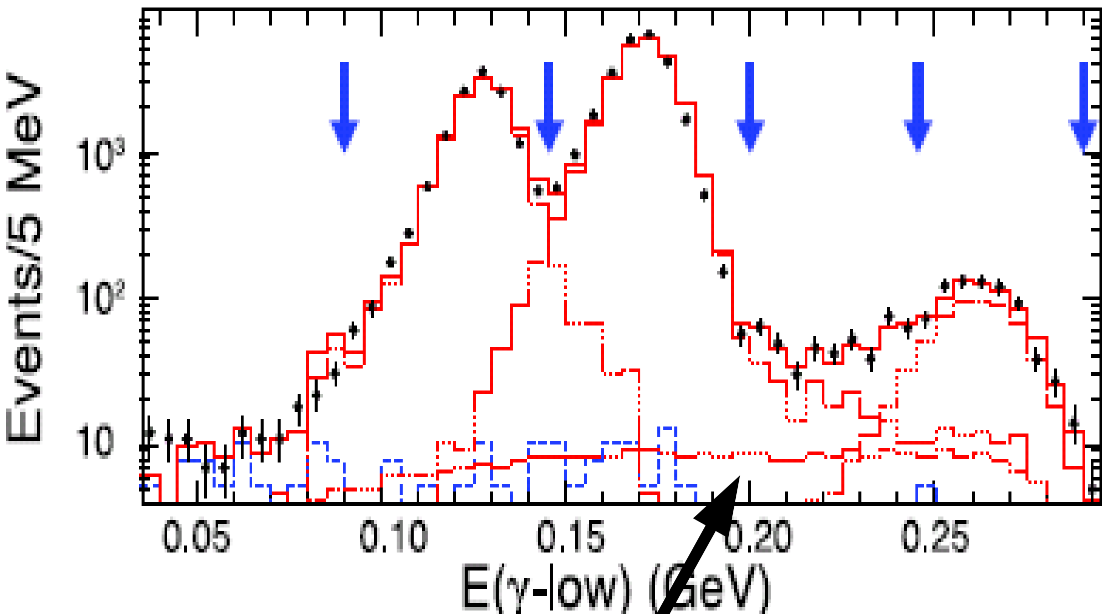
Reconstruct $J/\psi \to \ell^+\ell^-$ ($\ell = e, \mu$)
Mass constrain J/ψ, $\chi^2/\text{dof} < 20$
$\Rightarrow M(\ell^+\ell^-) = [3.03, 3.16]$ GeV

For $J/\psi\ \pi\pi$ ($\pi = \pi^\pm, \pi^0$), require
Recoil $M(\pi\pi) = [3.05, 3.15]$ GeV

For $J/\psi\ \pi^0(\gamma\gamma)$, $\eta(\gamma\gamma, \pi^+\pi^-\pi^0)$,
* Reconstruct π^0, η decays
* Apply $\mathbf{p}_{J/\psi}$ cuts above

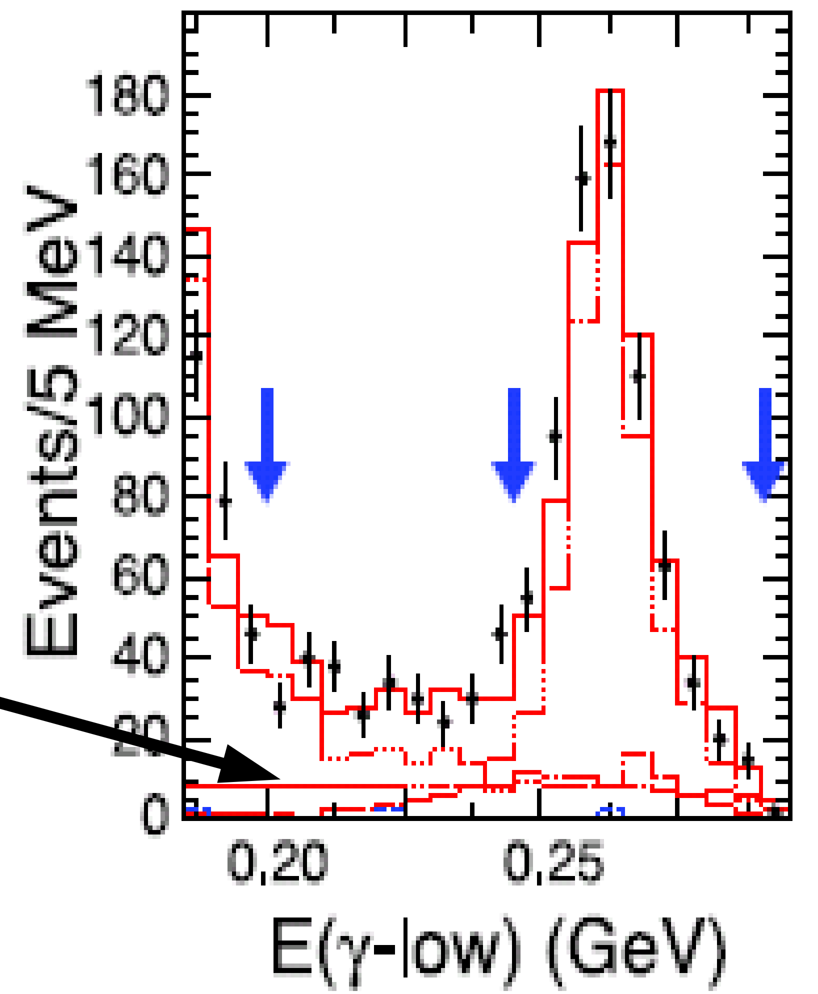
Entire $\mathbf{p}_{J/\psi}$ distribution used
for $\psi(2S) \to$ any + J/ψ

$\psi(2S) \to \gamma\,(\gamma\, J/\psi)\,\chi_{cJ}$



PRD 78, 011102 (2008)

After energy-momentum 4C fit



Non-resonant $\gamma\gamma\, J/\psi$?

$B(\psi(2S) \to (\gamma\gamma)_{nr}\, J/\psi) < 0.1\%$

Interesting what BES-III will see

$\psi(2S) \to X\ J/\psi$

Channels	$\mathcal{B}/\mathcal{B}_{\text{any}}$ (%)	$\mathcal{B}$ (%)
$\pi^+\pi^- J/\psi$	$56.04 \pm 0.09 \pm 0.62$	$35.04 \pm 0.07 \pm 0.77$
$\pi^0\pi^0 J/\psi$	$28.29 \pm 0.12 \pm 0.56$	$17.69 \pm 0.08 \pm 0.53$
$\eta J/\psi$	$5.49 \pm 0.06 \pm 0.09$	$3.43 \pm 0.04 \pm 0.09$
$\pi^0 J/\psi$	$0.213 \pm 0.012 \pm 0.003$	$0.133 \pm 0.008 \pm 0.003$
$\gamma(\gamma J/\psi)_{\chi_{c0}}$	$0.201 \pm 0.011 \pm 0.021$	$0.125 \pm 0.007 \pm 0.013$
$\gamma(\gamma J/\psi)_{\chi_{c1}}$	$5.70 \pm 0.04 \pm 0.15$	$3.56 \pm 0.03 \pm 0.12$
$\gamma(\gamma J/\psi)_{\chi_{c2}}$	$3.12 \pm 0.03 \pm 0.09$	$1.95 \pm 0.02 \pm 0.07$
any $+ J/\psi$	$\equiv 100$	$62.54 \pm 0.16 \pm 1.55$

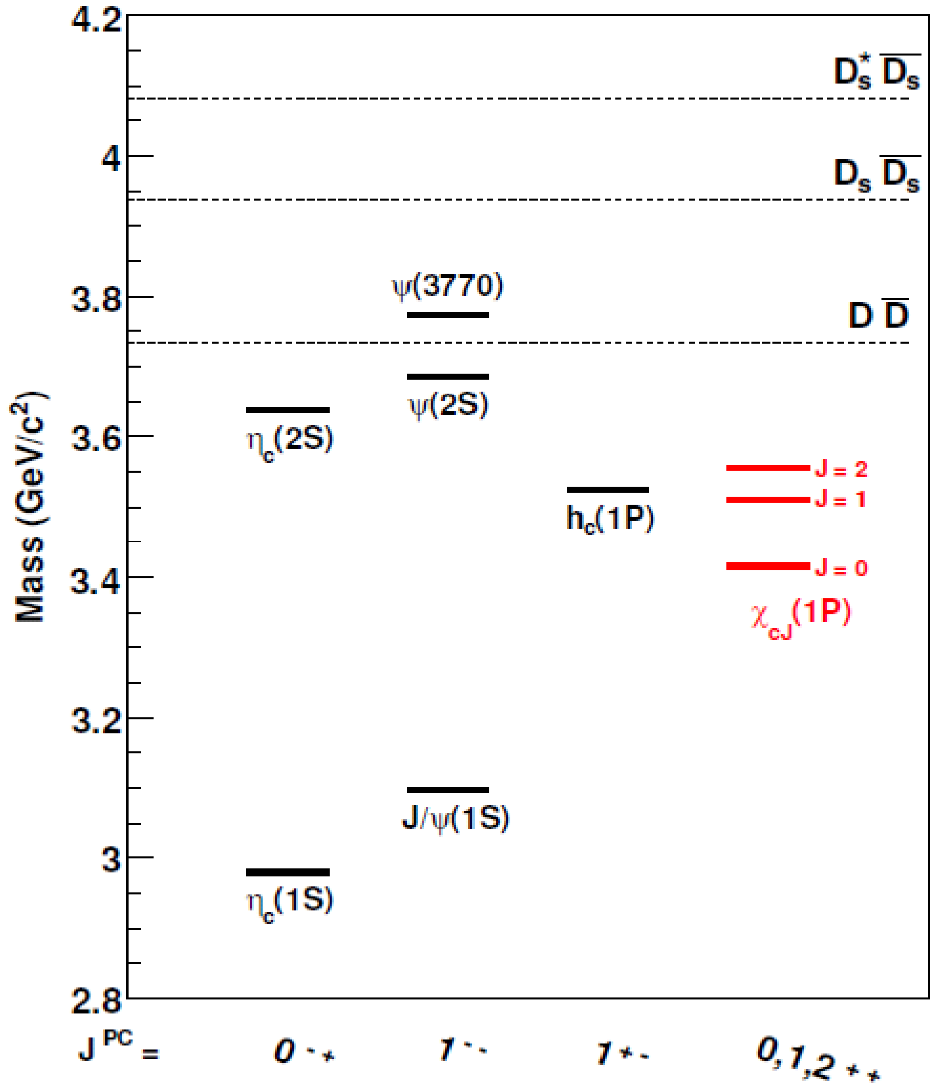
PRD 78, 011102 (2008)

* $(99.05 \pm 0.89)\%$ of all $\psi(2S)$ - to - J/ψ transitions observed in these 7 exclusive modes
* $B(\psi(2S) \to J/\psi\ \pi^0\pi^0)/B(\psi(2S) \to J/\psi\ \pi^+\pi^-) = (50.47 \pm 0.22 \pm 0.11)\%$, consistent with isospin symmetry
* $B(\psi(2S) \to \text{light hadrons}) = (15.4 \pm 1.5)\%$

[after accounting for $\psi(2S) \to \gamma\,\chi_{cJ}, \gamma\,\eta_c(1S), \ell^+\ell^-\ (\ell = e, \mu, \tau)$]

Most precise measurements to date

χ_{cJ} Decays



With $B(\psi(2S) \to \gamma \chi_{cJ}) \sim 9\%$, large $\psi(2S)$ samples are "χ_{cJ} factories"

With $N(\psi(2S)) \sim 27M$,
$N(\chi_{cJ}) \sim$ detect 180k per χ_{cJ}

Results to be presented:

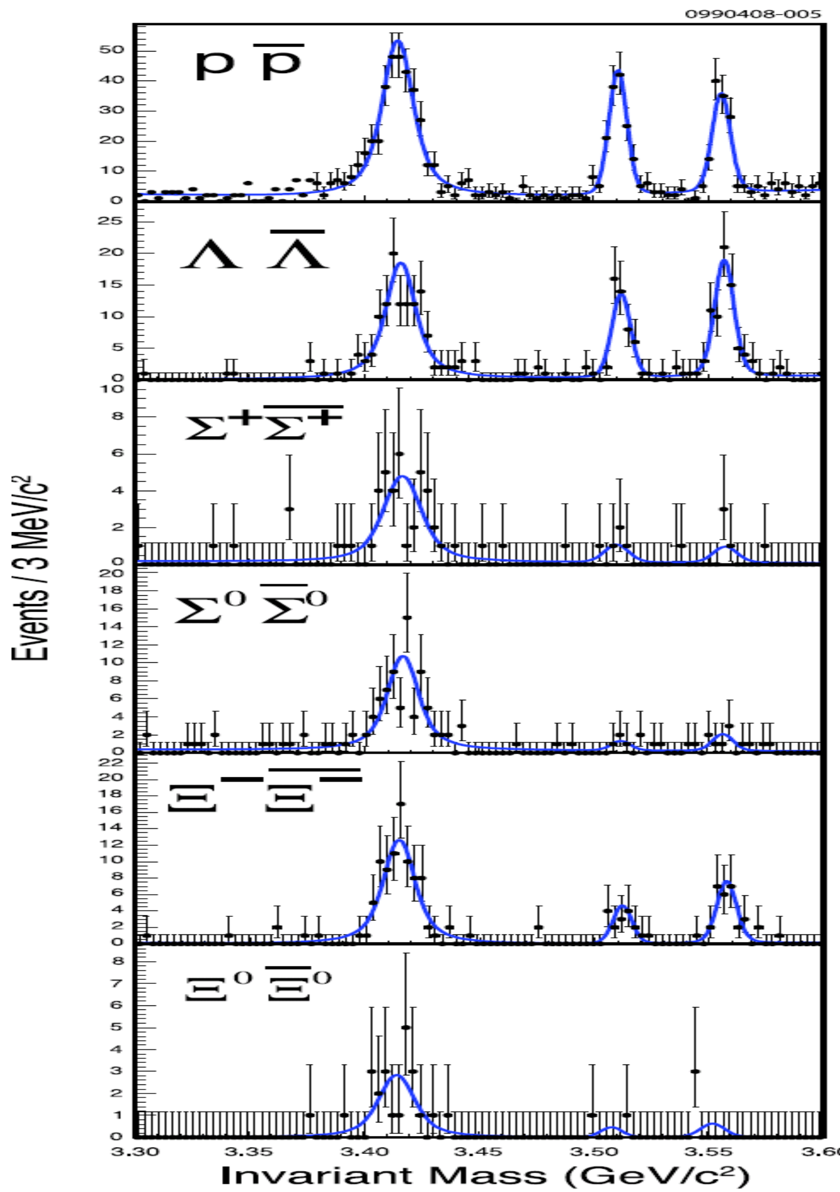
* $\chi_{cJ} \to$ Baryon Antibaryon
* $\chi_{cJ} \to \gamma\gamma$
* $\chi_{cJ} \to \gamma$ Vector

$\chi_{cJ} \to$ Baryon Anti-baryon

Using N(ψ(2S)) = 25.9 M,
studied χ_{cJ} decay into 6 decay modes:

Baryons, besides p, reconstructed in
$\Lambda \to p\, \pi^-$
$\Sigma^+ \to p\, \pi^0$, $\Sigma^0 \to \Lambda\, \gamma$
$\Xi^- \to \Lambda\, \pi^-$, $\Xi^0 \to \Lambda\, \pi^0$
Decays above have displaced vertices

* Kinematically fit baryon decay in-flight,
* Apply mass cuts ~ |3σ|
* 4C energy-momentum fit with
χ_{cJ} transition photon, χ^2/dof < 25/4



PRD 78, 031101 (2008)

$\chi_{cJ} \to$ Baryon Anti-baryon

Mode		χ_{c0}	χ_{c1}	χ_{c2}
$p\bar{p}$	This Work	$25.7 \pm 1.5 \pm 1.5 \pm 1.3$	$9.0 \pm 0.8 \pm 0.4 \pm 0.5$	$7.7 \pm 0.8 \pm 0.4 \pm 0.5$
	PDG	22.5 ± 2.7	7.2 ± 1.3	6.8 ± 0.7
$\Lambda\bar{\Lambda}$	This Work	$33.8 \pm 3.6 \pm 2.2 \pm 1.7$	$11.6 \pm 1.8 \pm 0.7 \pm 0.7$	$17.0 \pm 2.2 \pm 1.1 \pm 1.1$
	PDG	47.0 ± 16.0	26.0 ± 12.0	34.0 ± 17.0
$\Sigma^0\bar{\Sigma}^0$	This Work	$44.1 \pm 5.6 \pm 4.2 \pm 2.2$	< 4.4	< 7.5
	PDG			
$\Sigma^+\overline{\Sigma^+}$	This Work	$32.5 \pm 5.7 \pm 4.0 \pm 1.7$	< 6.5	< 6.7
	PDG			
$\Xi^-\overline{\Xi^-}$	This Work	$51.4 \pm 6.0 \pm 3.9 \pm 2.6$	$8.6 \pm 2.2 \pm 0.6 \pm 0.5$	$14.5 \pm 3.0 \pm 1.2 \pm 0.9$
	PDG	$< 103^a$	< 34	< 37
$\Xi^0\bar{\Xi}^0$	This Work	$33.4 \pm 7.0 \pm 4.5 \pm 1.7$	< 6.0	< 10.6
	PDG			

PRD 78, 031101 (2008)

First observations for $\Sigma^+\Sigma^-$, $\Sigma^0\bar{\Sigma}^0$, $\Xi^-\Xi^+$, $\Xi^0\bar{\Xi}^0$ decay modes

Improved measurements of $p\bar{p}$ & $\Lambda\bar{\Lambda}$

All non-$p\bar{p}$ modes observed, and larger than $p\bar{p}$, in χ_{c0} decays; not true in χ_{c1} and χ_{c2} decays.

$\chi_{c\{0,2\}} \to \gamma\gamma$

Using N(ψ(2S)) = 24.5 M,
first observation of $\chi_{c\{0,2\}} \to \gamma\gamma$
in $\psi(2S) \to \gamma\chi_{c\{0,2\}}$ decays

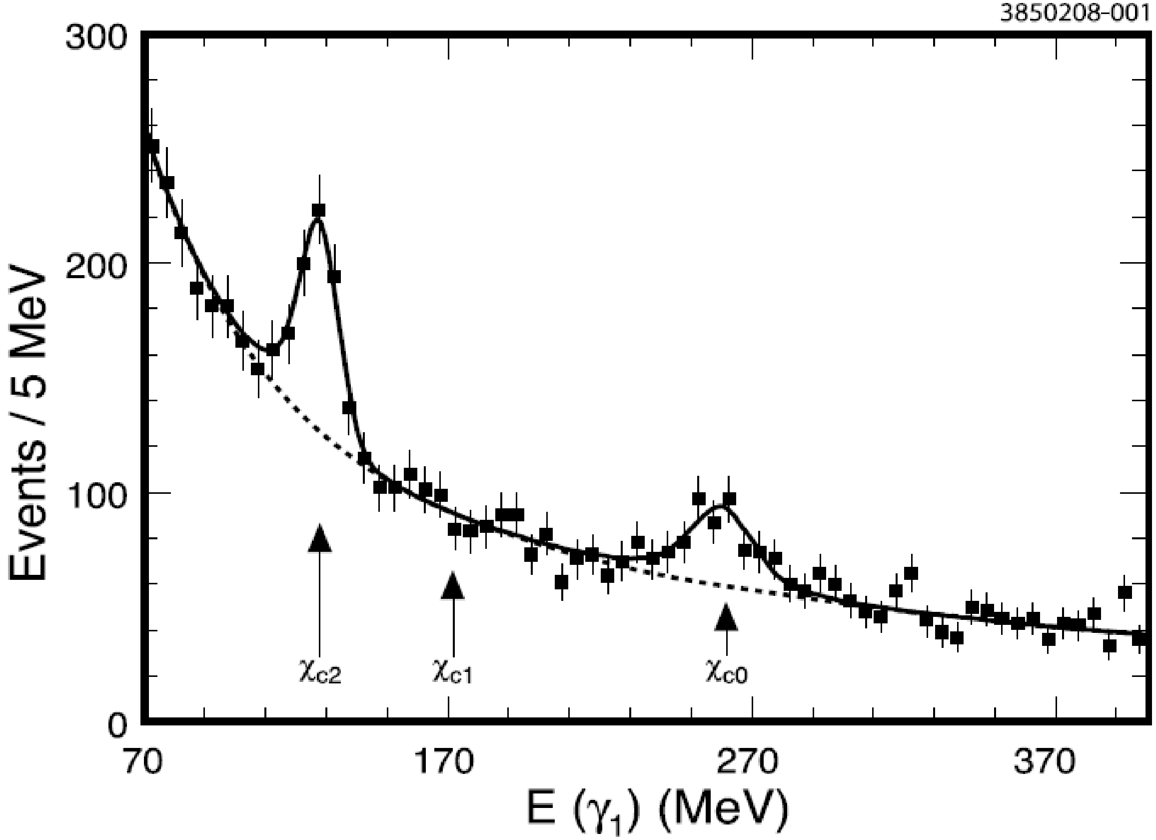
4C fit of 3 candidate γ, χ^2/dof < 6

Bkgd shape determined from study of 281 pb^{-1} ψ(3770) data, agrees with off-resonance data

$\Gamma_{\gamma\gamma}(\chi_{c0})$ = 2.53(37)(11)(24) keV
$\Gamma_{\gamma\gamma}(\chi_{c2})$ = 0.60(6)(3)(5) keV
Consistent with precision from PDG

Forbidden $\chi_{c1} \to \gamma\gamma$: $\Gamma_{\gamma\gamma}(\chi_{c1})$ < 0.03 keV

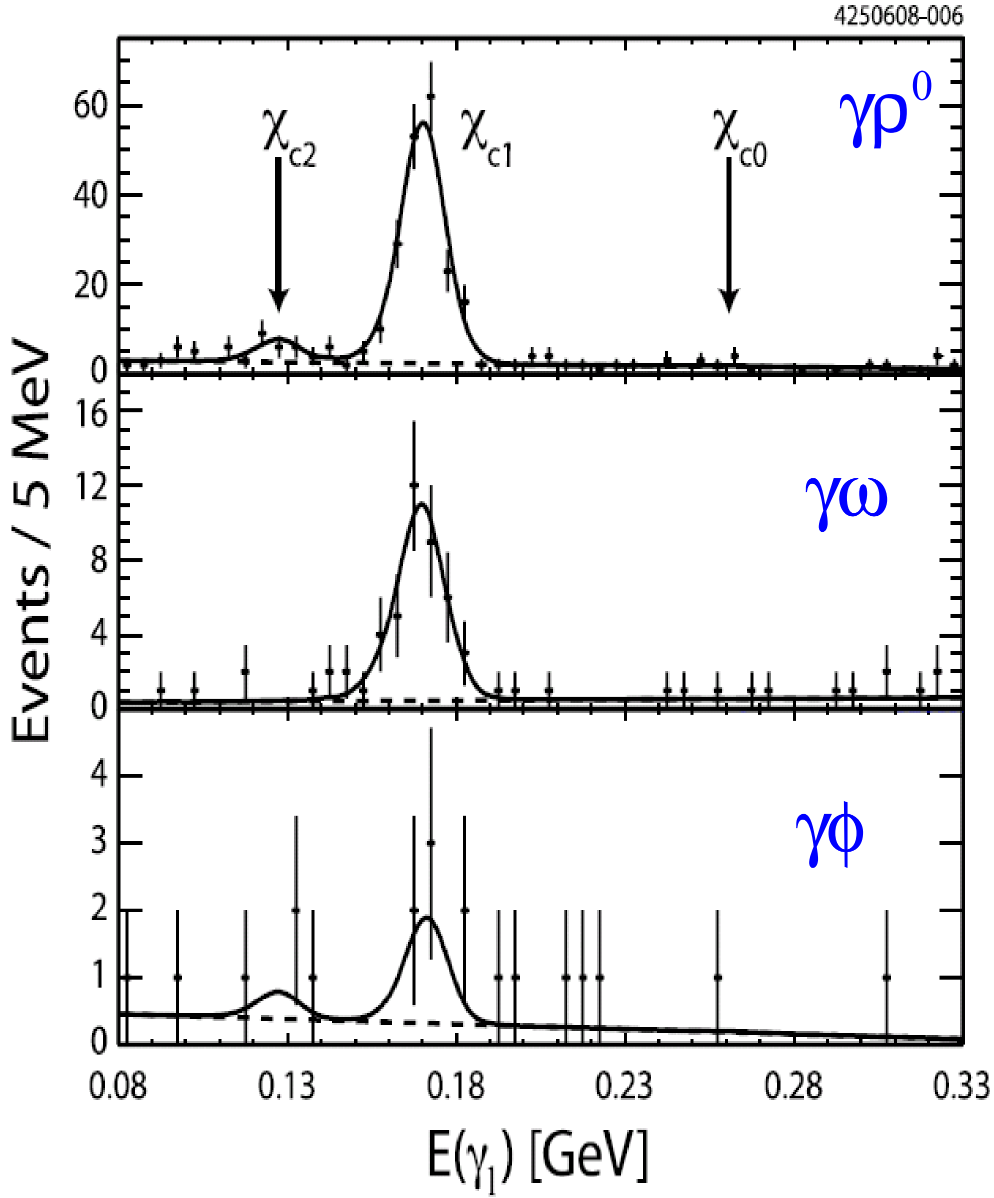
arXiv:0803.2869 [hep-ex], subm to PRL



BES-III can improve on these msmts and search for $\chi_{c1} \to \gamma\gamma^*$ (e^+e^-, $\mu^+\mu^-$)

$\chi_{cJ} \to \gamma V$ ($V = \rho^0, \omega, \phi$)

arXiv:0807.3718 [hep-ex], subm to PRL



One use of $J/\psi \to \gamma X$ is to study P-wave isoscalars (f_J states).

Can use χ_{cJ} states to test theory.

Using $N(\psi(2S)) = 27.4$ M, studied $\psi(2S) \to \gamma \chi_{cJ}, \chi_{cJ} \to \gamma V$

$V = \rho^0\ (\pi^+ \pi^-)$
$\omega\ (\pi^+ \pi^- \pi^0)$
$\phi\ (K^+ K^-)$

4C fit of 2 γ, vector decay; $\chi^2/\mathrm{dof} < 5$
Vetoed $\pi^0, \eta \to \gamma\gamma$ w/ $M(\gamma\gamma)$ cuts

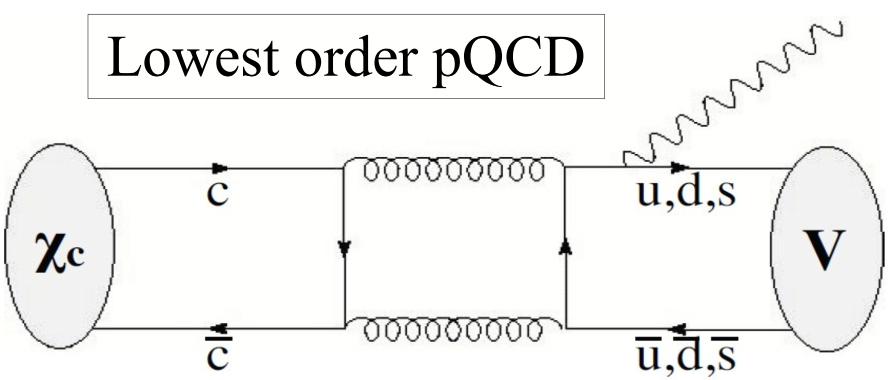
$M(\pi^+ \pi^-)$ within (0.5, 1.1) GeV
$M(\pi^+ \pi^- \pi^0)$ within (0.75, 0.82) GeV
$M(K^+ K^-)$ within (1.01, 1.04) GeV

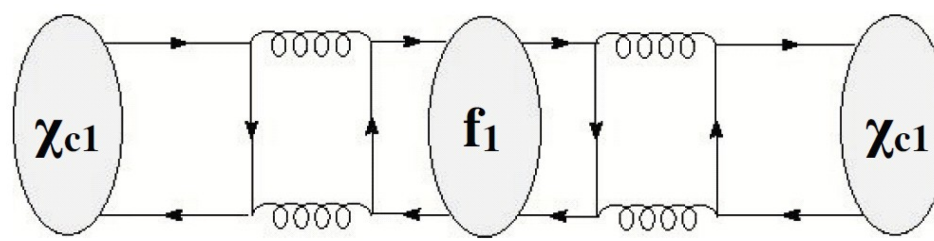
$\chi_{cJ} \rightarrow \gamma V$ ($V = \rho^0, \omega, \phi$)

arXiv:0807.3718 [hep-ex], subm to PRL

Mode	$\mathcal{B} \times 10^6$	U.L. $[10^{-6}]$	pQCD $[10^{-6}]$
$\chi_{c0} \longrightarrow \gamma\rho^0$		< 9.6	1.2
$\chi_{c1} \longrightarrow \gamma\rho^0$	$\boxed{243 \pm 19 \pm 22}$		14
$\chi_{c2} \longrightarrow \gamma\rho^0$	$25 \pm 10^{+8}_{-14}$	< 50	4.4
$\chi_{c0} \longrightarrow \gamma\omega$		< 8.8	0.13
$\chi_{c1} \longrightarrow \gamma\omega$	$\boxed{83 \pm 15 \pm 12}$		1.6
$\chi_{c2} \longrightarrow \gamma\omega$		< 7.0	0.50
$\chi_{c0} \longrightarrow \gamma\phi$		< 6.4	0.46
$\chi_{c1} \longrightarrow \gamma\phi$	$12.8 \pm 7.6 \pm 1.5$	< 26	3.6
$\chi_{c2} \longrightarrow \gamma\phi$		< 13	1.1

Large BFs for $\chi_{c1} \rightarrow \gamma\rho^0, \gamma\omega$; 7.9σ (4.2σ) larger than pQCD predictions





Are these measurements indications of $\chi_{c1} - f_1$ mixing? [Barnes, private comm]

The $1\,^1P_1$ State: h_C

QCD Potential: Coulomb + Confinement

Hyperfine splitting governed by spin-spin interaction of the Coulomb term

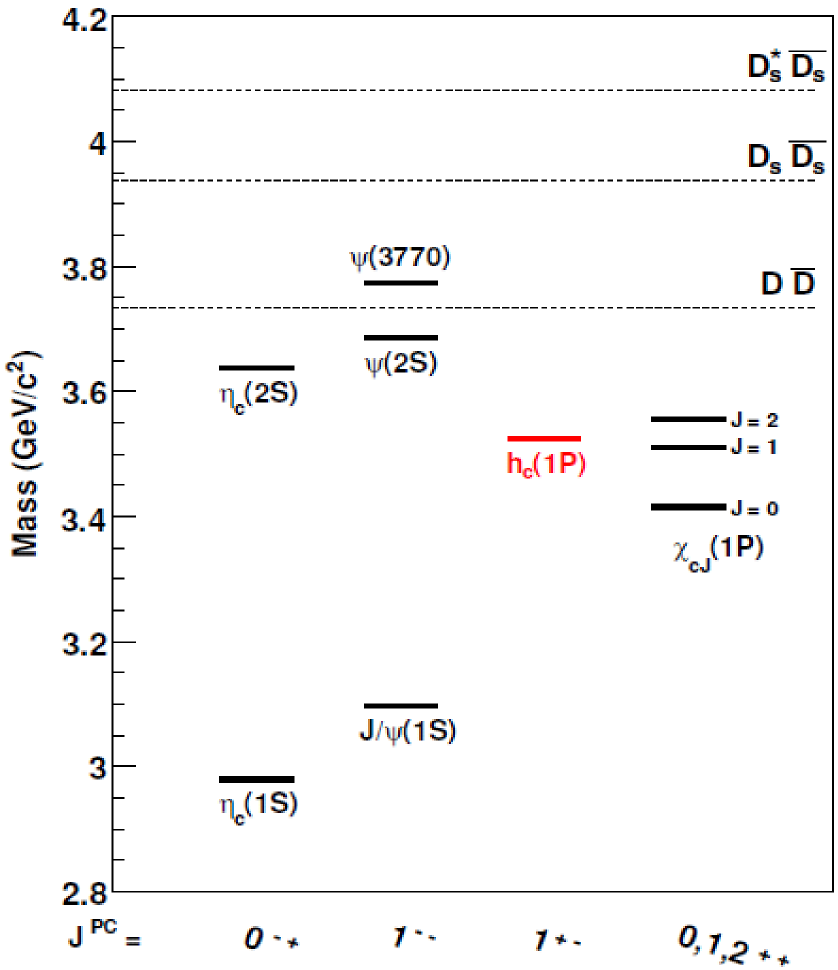
$\Delta M_{hf} = M(^3P) - M(^1P) = 0$

if no extra effects from confinement term

CLEO-c studied h_c in the decay process

$\psi(2S) \to \pi^0 h_c,\ h_c \to \gamma\, \eta_c(1S)$,

look at π^0 recoil, require $E_\gamma = [453,553]$ MeV



Two methods:

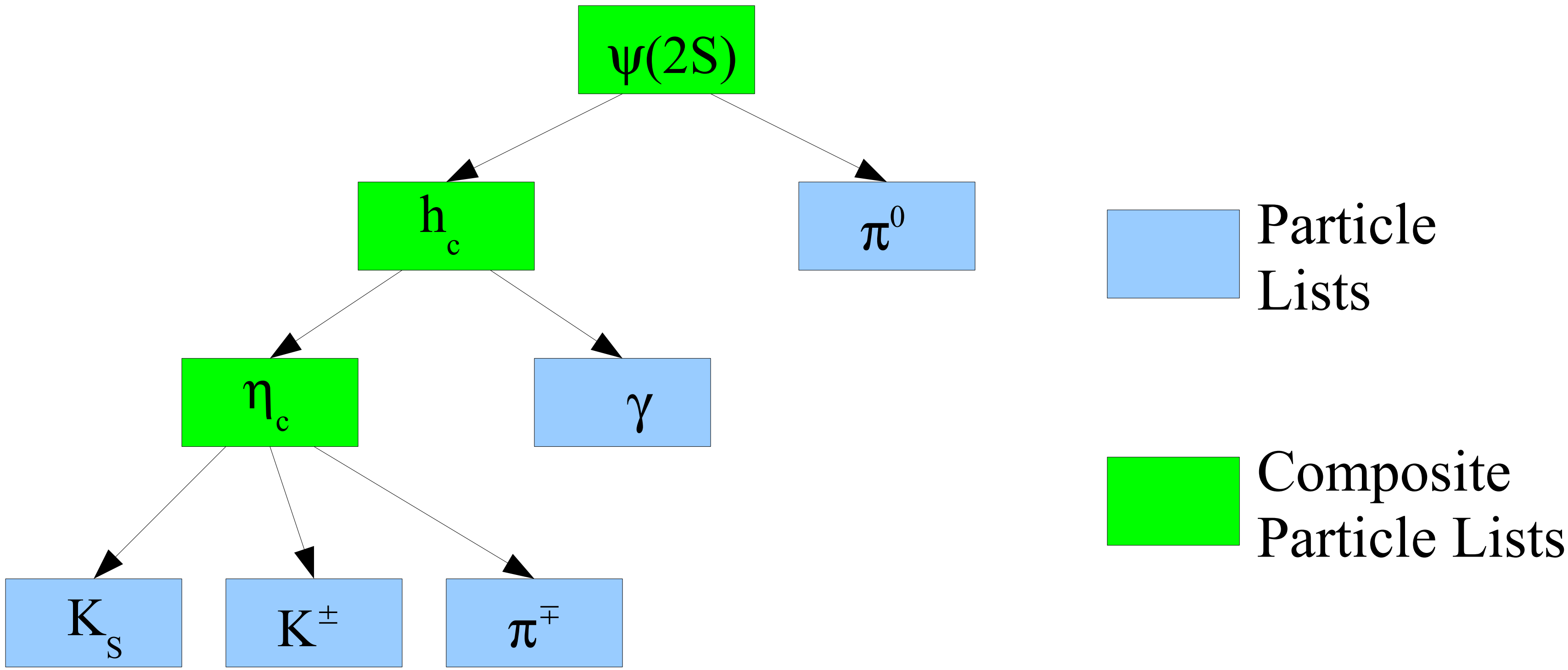
* Inclusive $\eta_c(1S)$

* Reconstruct $\eta_c(1S)$ in 15 decays modes; apply 4C fit, $\chi^2/\mathrm{dof} < 15/4$

(5 new modes: $\eta_c(1S) \to \eta\, K^+ K^-,\ p\bar{p}\pi^0,\ \pi^+\pi^-\pi^0\pi^0,\ p\bar{p}\pi^+\pi^-,\ 2(\pi^+\pi^-)\,\pi^0\pi^0$)

Particle Lists & Combination Engine

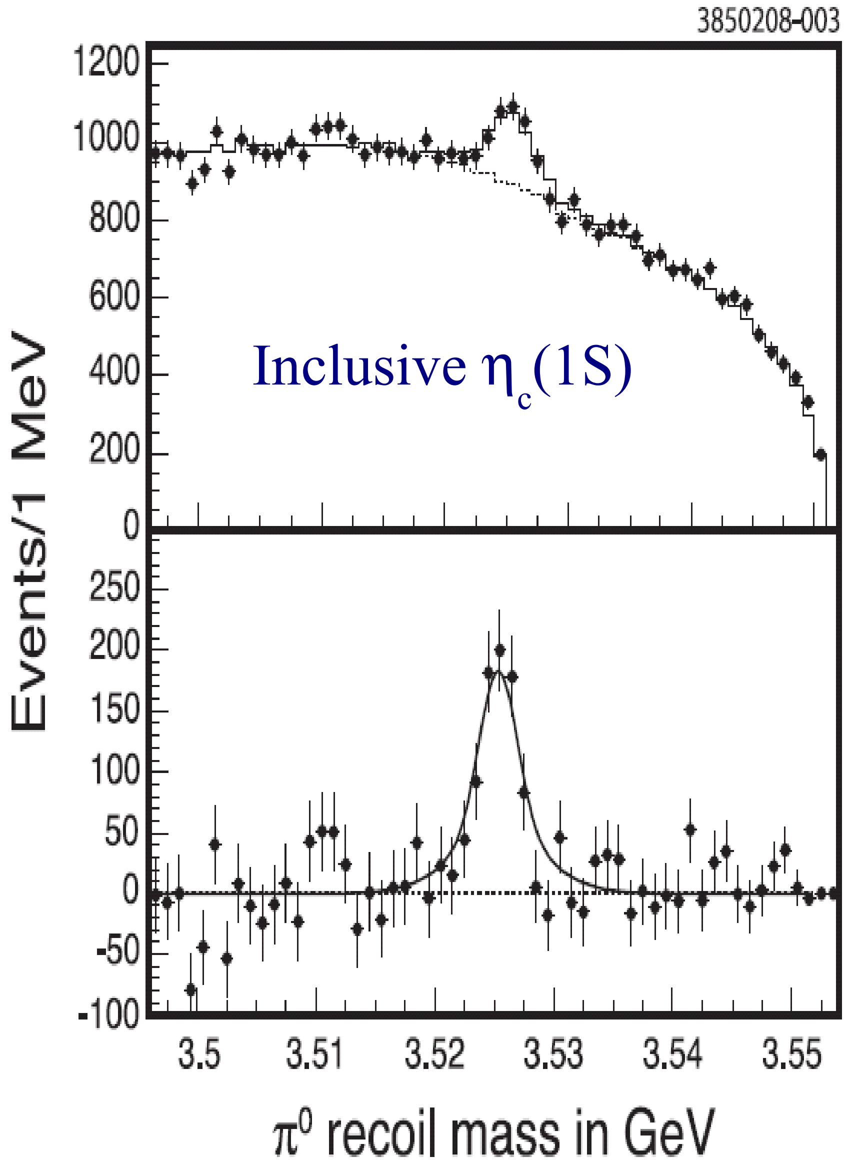
$$\psi(2S) \to \pi^0 h_c,\ h_c \to \gamma\, \eta_c,\ \eta_c \to K_S\, K^{\pm}\, \pi^{\mp}$$

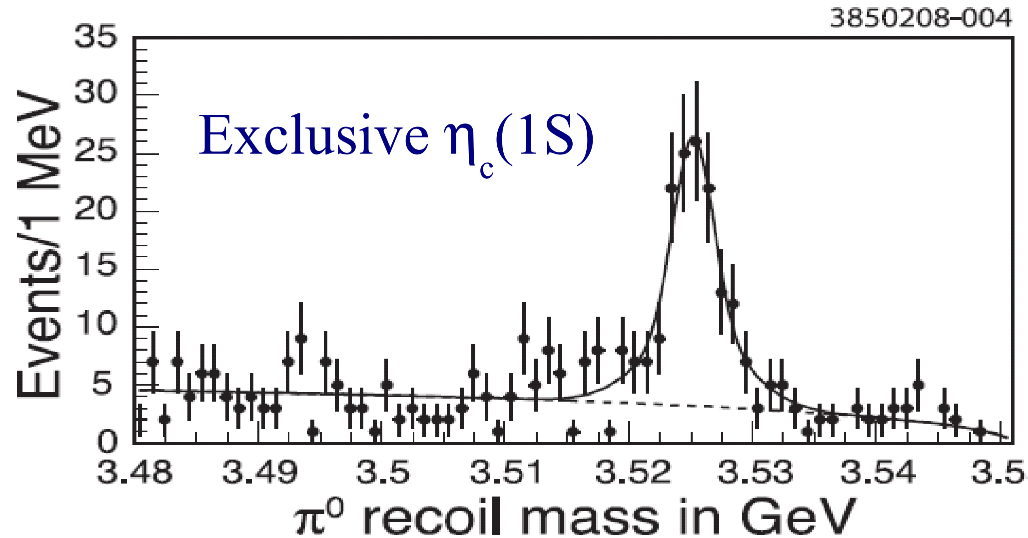


BES-III D Tag Task Force is developing this framework for D Tagging (Jiaheng Zou), will become a general tool for the collaboration

The 1 $^1P_1$ State: h_C

arXiv:0805.4599 [hep-ex], subm to PRL





Both methods have stat significance > 10σ

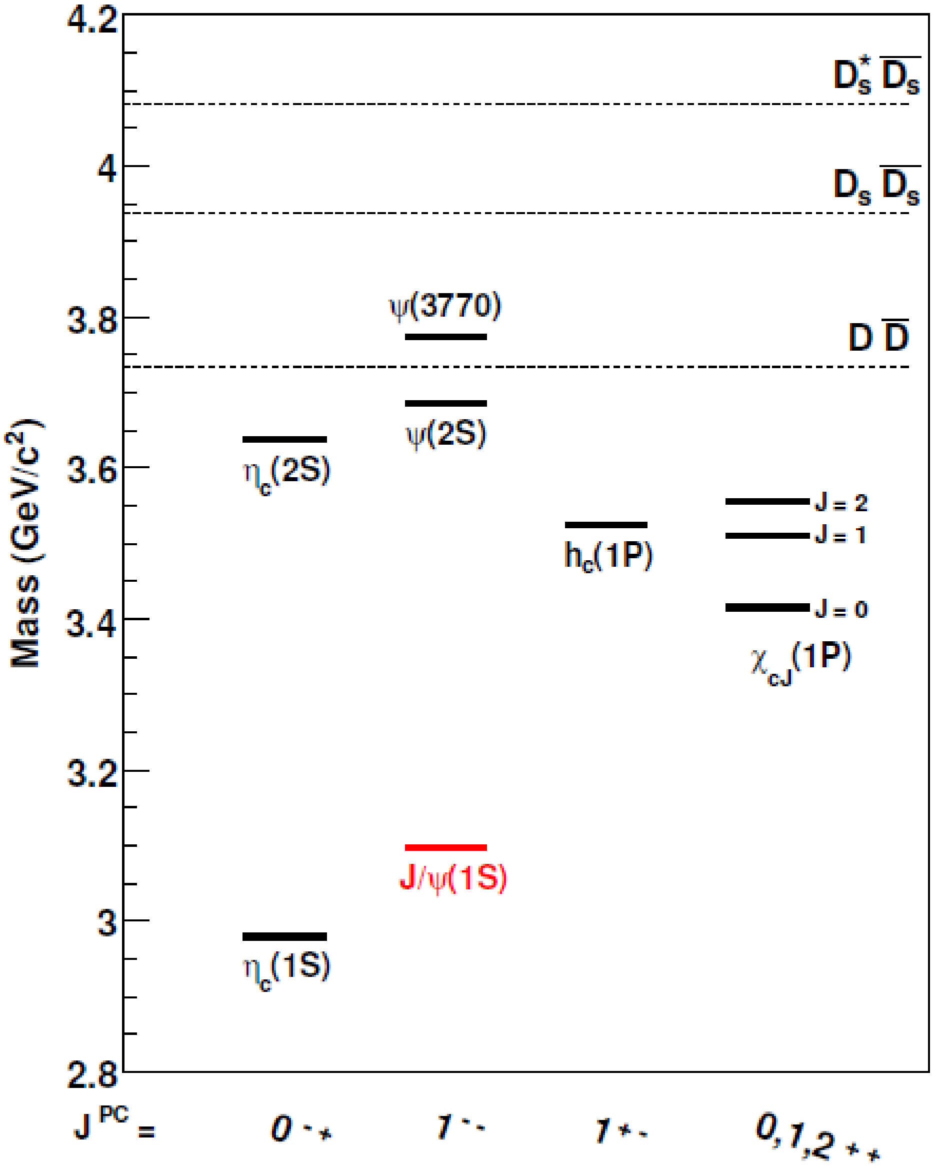
$B(\psi(2S) \to \pi^0 h_c, h_c \to \gamma\, \eta_c(1S))$
$= (4.19 \pm 0.32 \pm 0.45) \times 10^{-4}$

$M(h_c) = 3525.28 \pm 0.19 \pm 0.12$ MeV

$\Delta M_{hf} = +0.02 \pm 0.19 \pm 0.13$ MeV,

where $M(^3P) = \langle M(\chi_{cJ}) \rangle$

J/ψ Decays



With $N(\psi(2S)) \sim 27M$ and $B(\psi(2S) \to \pi^+\pi^- J/\psi) \approx 35\%$,

$N(J/\psi) \sim 950k$

Results to be presented:

* $J/\psi \to 3\gamma$
* $J/\psi \to \gamma\, \eta_c(1S)$

$J/\psi \to 3\gamma$

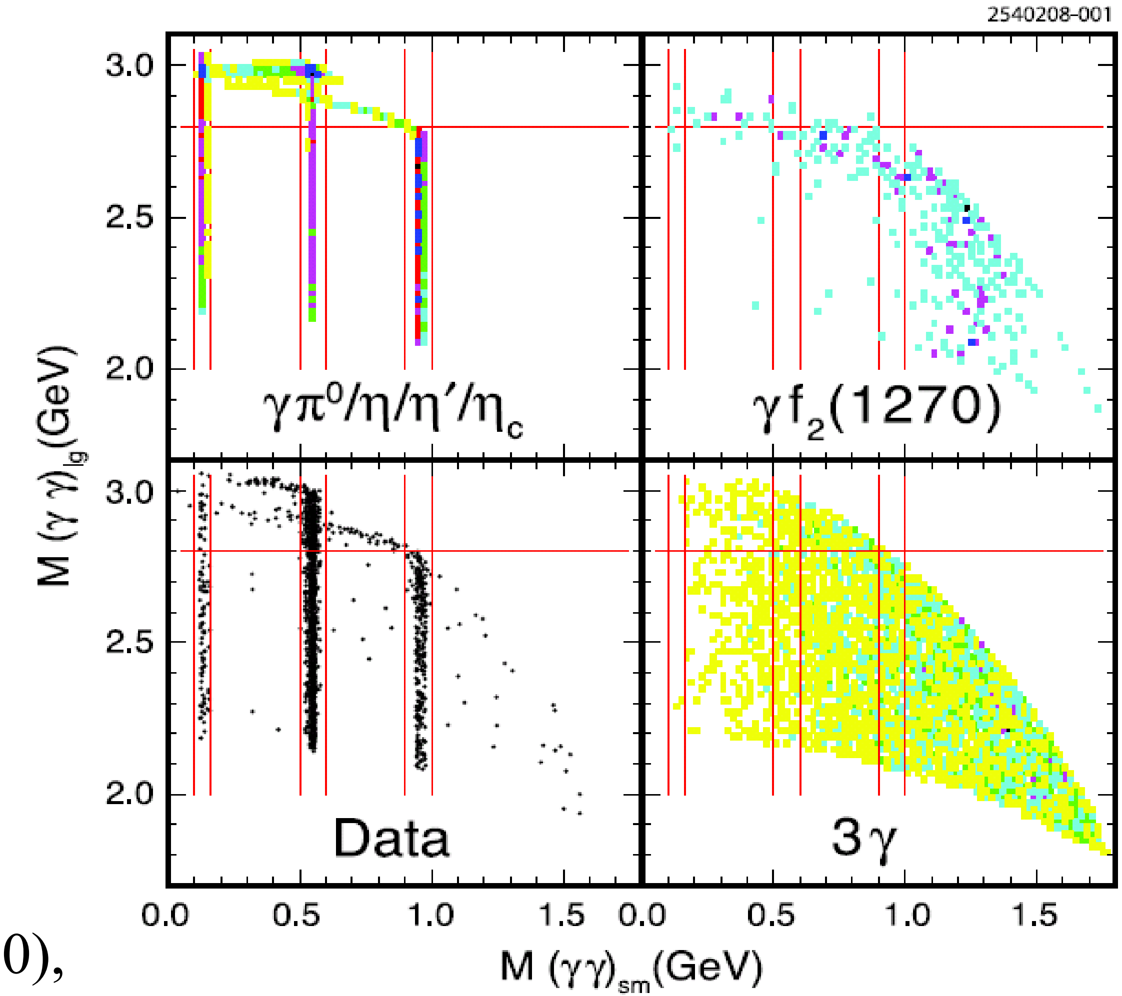
PRL 101, 101801 (2008)

Decay of $J/\psi \to \gamma\gamma\gamma$ probes the strong interaction, esp. in relation to $J/\psi \to \gamma gg$, ggg, & $\ell^+\ell^-$

Studied $J/\psi \to 3\gamma$ produced in $\psi(2S) \to \pi^+\pi^- J/\psi$ decays

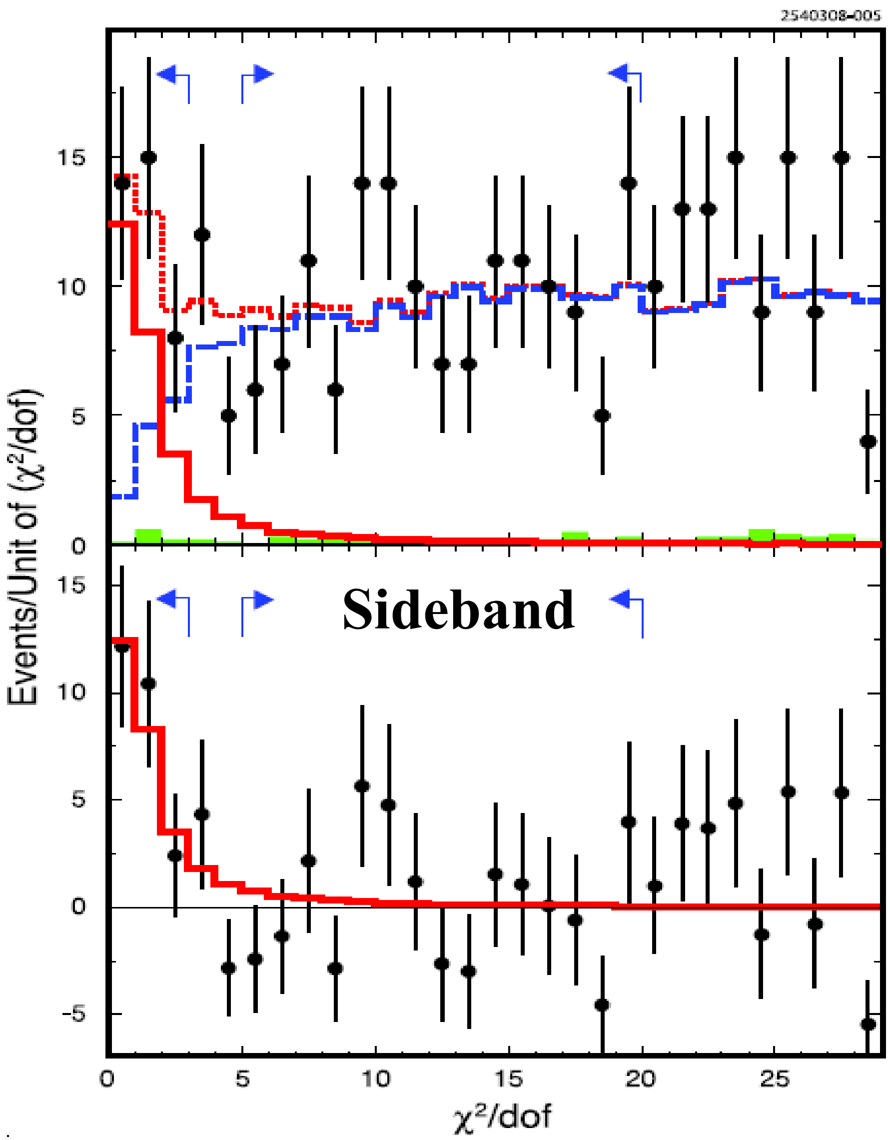
4C fit of 3 γ, $\pi^+\pi^-$ pair; $\chi^2/\mathrm{dof} < 3$

Reject events with $M(\gamma\gamma)$ consistent with π^0, η, η', $\eta_c(1S) \to \gamma\,\gamma$ (see fig)



All other J/ψ decay backgrounds ($\gamma\,\pi^0\pi^0$, $\gamma\,f_0(980)$, $\gamma\,f_2(1270)$, $\gamma\,f_0(1500)$, $\gamma\,f_0(1710)$, $\gamma\,f_0(2020)$, & $\omega\pi^0$) have minima near $\chi^2/\mathrm{dof} = 0$ (next slide)

$J/\psi \to 3\gamma$



Blue: Other background from J/ψ decays
normalization determined by sideband

$B(J/\psi \to 3\gamma) = (1.2 \pm 0.3 \pm 0.2) \times 10^{-5}$

First observation of any meson decaying to 3γ!

From KMRR [PRD 37, 3210 (1988)]:

$B(J/\psi \to 3\gamma) / B(J/\psi \to \ell^+\ell^-) \approx \alpha/14$

$B(J/\psi \to 3\gamma) / B(J/\psi \to \gamma gg) \approx (\alpha/\alpha_s)^2 /3$

$B(J/\psi \to 3\gamma) / B(J/\psi \to ggg) \approx (\alpha/\alpha_s)^3$

and using $B(J/\psi \to \gamma gg) / B(J/\psi \to ggg)$
$= 13.7\%$ [CLEO: 0806.0315 [hep-ex]]

predicts $B(J/\psi \to 3\gamma) = (3.0, 0.9, 1.6) \times 10^{-5}$

$B(J/\psi \to n\gamma) < (5, 9, 15) \times 10^{-5}$ for $n = 2,4,5$

$J/\psi \to \gamma\, \eta_C(1S)$

The M1 transition $J/\psi \to \gamma\, \eta_C(1S)$ has only been measured by one experiment

Crystal Ball (1986): $B(J/\psi \to \gamma\, \eta_C(1S)) = 1.3(4)\%$

Theory predicts larger value. LQCD: B = 2.2(1)(4)% [PRD 73, 074507 (2007)]

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

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

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

For direct M1 (n = n'): $\Gamma(J/\psi \to \gamma\, \eta_C(1S)) \sim E_\gamma^3$

hindered M1 ($n \neq n'$): $\Gamma(\psi(2S) \to \gamma\, \eta_C(1S)) \sim E_\gamma^7$

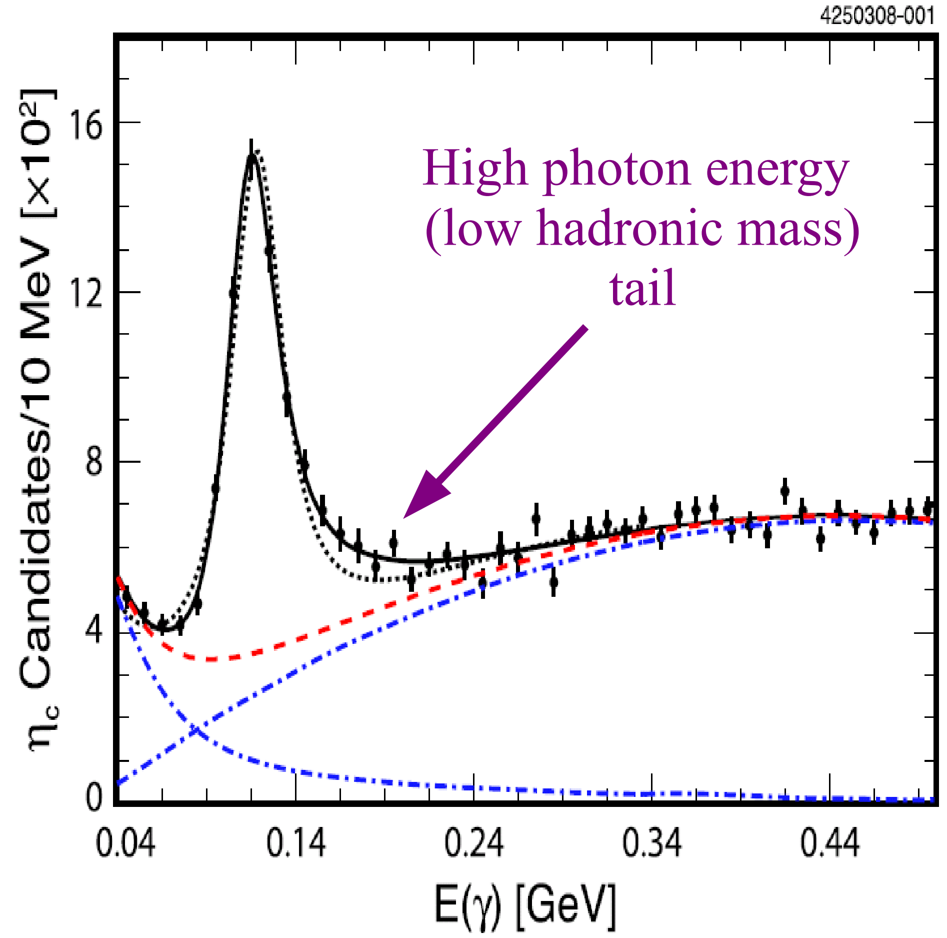
CLEO-c did not measure $J/\psi \to \gamma\, \eta_C(1S)$, measured it wrt $\psi(2S) \to \gamma\, \eta_C(1S)$

$$\mathrm{B}(J/\psi \to \gamma\eta_c(1S)) = \mathrm{B}(\psi(2S) \to \gamma\eta_c(1S))_{\mathrm{incl}} \frac{\mathrm{B}(J/\psi \to \gamma\eta_c(1S))_{\mathrm{excl}}}{\mathrm{B}(\psi(2S) \to \gamma\eta_c(1S))_{\mathrm{excl}}}$$

$J/\psi \to \gamma\, \eta_C(1S)$

arXiv:0805.0252 [hep-ex], subm to PRL

Measured $B(J/\psi \to \gamma\, \eta_C(1S))_{excl}$
in $\psi(2S) \to \pi^+\pi^-\ J/\psi$, $J/\psi \to \gamma\, \eta_C(1S)$,
$\eta_C(1S) \to 12$ excl modes (some new)



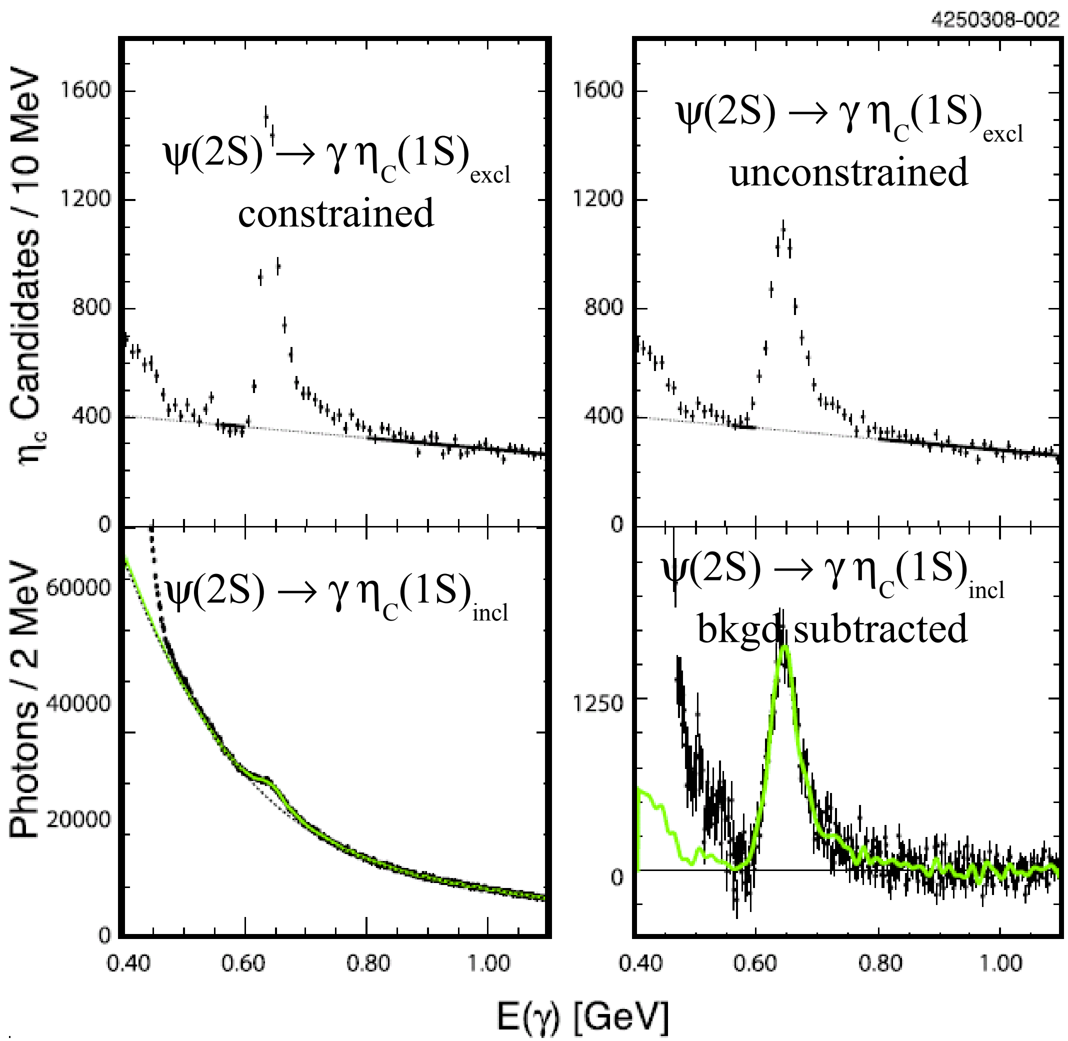
4C fit $\pi^+\pi^- + \gamma + \eta_C(1S)$ decay,
χ^2/dof < 5, fit constrained E_γ (fig)

Resonance not modeled by BW*$E_\gamma^{\ 3}$
[BW: Breit-Wigner]

Used BW*$E_\gamma^{\ 3}$*exp($-E_\gamma^{\ 2}/\beta$)

Cannot determine mass or width with this parameterization

$\psi(2S)$, $J/\psi \to \gamma\, \eta_C(1S)$



Cannot determine mass or width,
need guidance from theory

High energy tail present in $\psi(2S) \to \gamma\, \eta_C(1S)$ decays!

Cannot be modeled with $BW{*}E_\gamma^{\,7}$

Empirical line shape:
signal shape from $\psi(2S) \to \gamma\, \eta_C(1S)_{excl}$
unconstrained E_γ distribution
used for $\psi(2S) \to \gamma\, \eta_C(1S)_{incl}$

$B(\psi(2S) \to \gamma\, \eta_C(1S))_{incl}$
$= 0.432(16)(60)\%$

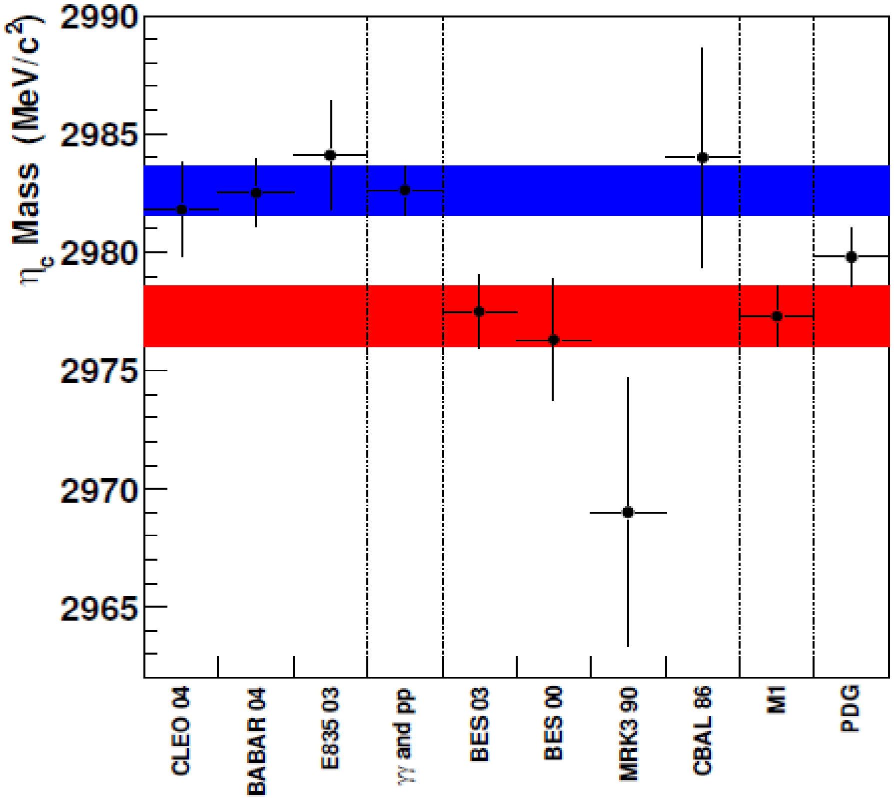
PDG06: $B = 0.26(4)\%$

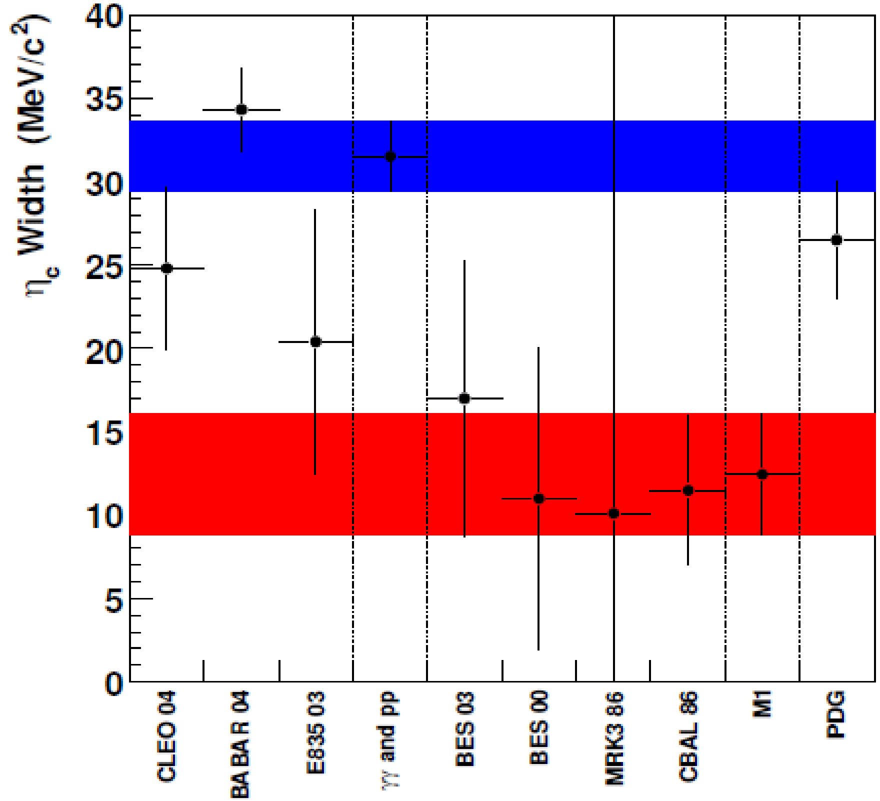
Cut-&-count of exclusive J/ψ & $\psi(2S)$

$B(J/\psi \to \gamma\, \eta_C(1S))_{incl} = 1.98(9)(3)\%$

LQCD: $B = 2.2(1)(4)\%$

$\eta_c(1S)$ Mass and Width



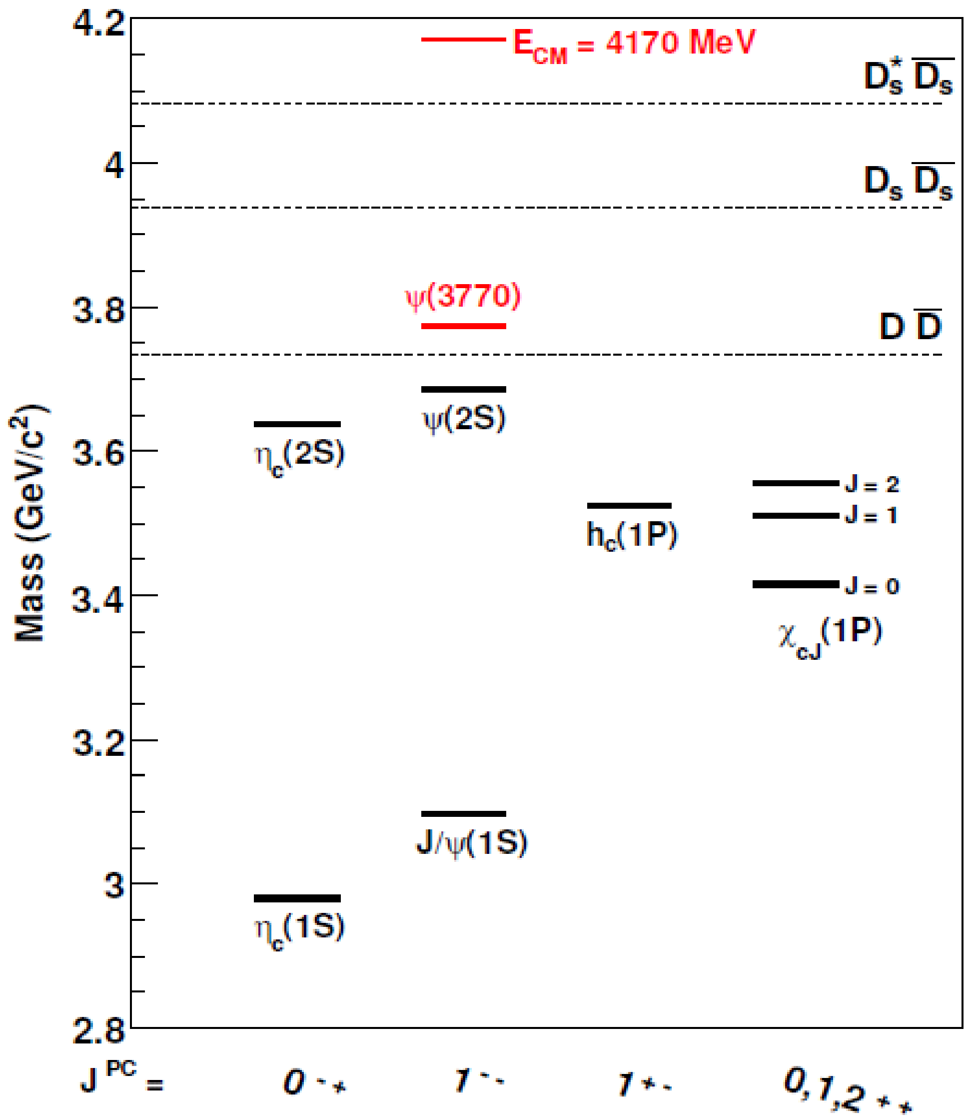


$B^+ \to K^+ \eta_c(1S)$ more consistent with $\gamma\gamma$ and $p\bar{p}$ measurements

Disagreement in M1 transition measurements caused by $\eta_c(1S)$ lineshape?

Important to get input from BES-III

Open Charm: The $D_{(S)}$ Mesons



Precision measurements results

From $\psi(3770)$:

$D \rightarrow K/\pi\, e\, \nu_e$

$D^+ \rightarrow \mu^+ \nu_\mu$

From E_{CM} = 4170 MeV:

$D_S^+ \rightarrow \mu^+ \nu_\mu$

$D_S^+ \rightarrow \tau^+ \nu_\tau$ (two τ decay modes)

* $\tau^+ \rightarrow \pi^+ \nu_\tau$
* $\tau^+ \rightarrow e^+ \nu_e \nu_\tau$

Charm (aka Weak Interaction) Physics

Study of leptonic and
semileptonic charm decays
is an excellent environment to provide
validation and calibration for theory,
especially Lattice QCD (LQCD),
so it can be applied with confidence
to B physics (V_{ub}).

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

A validated theory can be used in
precision measurements of V_{cs} and V_{cd}

Measuring f_D, f_{Ds} in leptonic charm decays
and studying form factors in semileptonic decays
provide very stringent constraints on LQCD

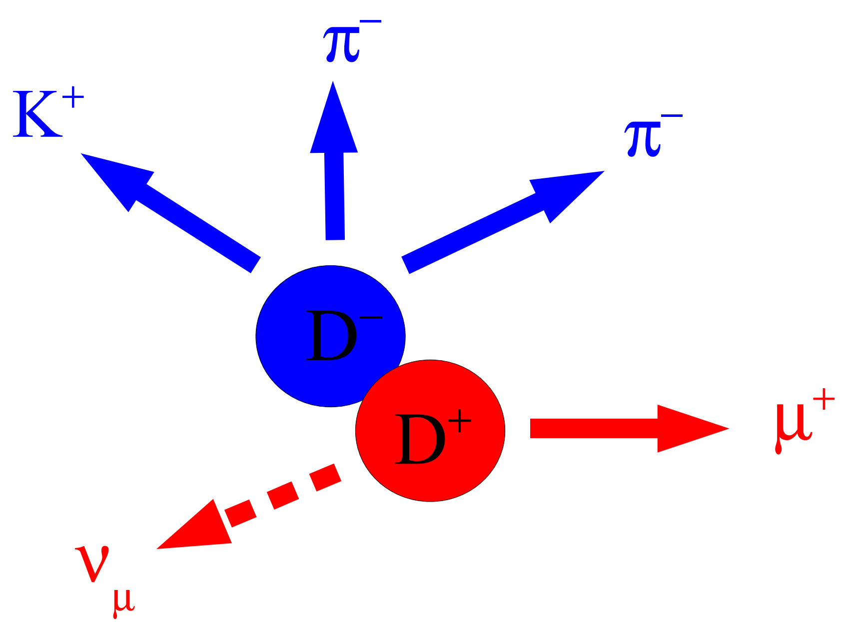
D Tagging

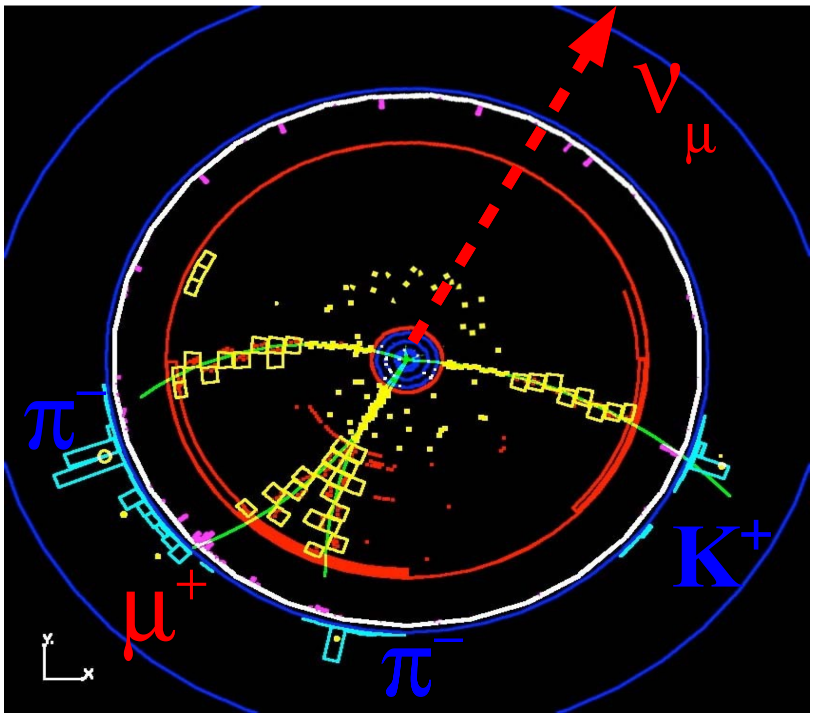
"<u>MARK III Method</u>"

Reconstruct hadronic D decay, reconstruct other side and look for neutrino in missing mass or $U_{miss} = E_{miss} - |\mathbf{P}_{miss}|$,

Allows you to determine absolute branching fractions: $BF = N_{obs} / (\varepsilon N_{tags})$

$e^+e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$



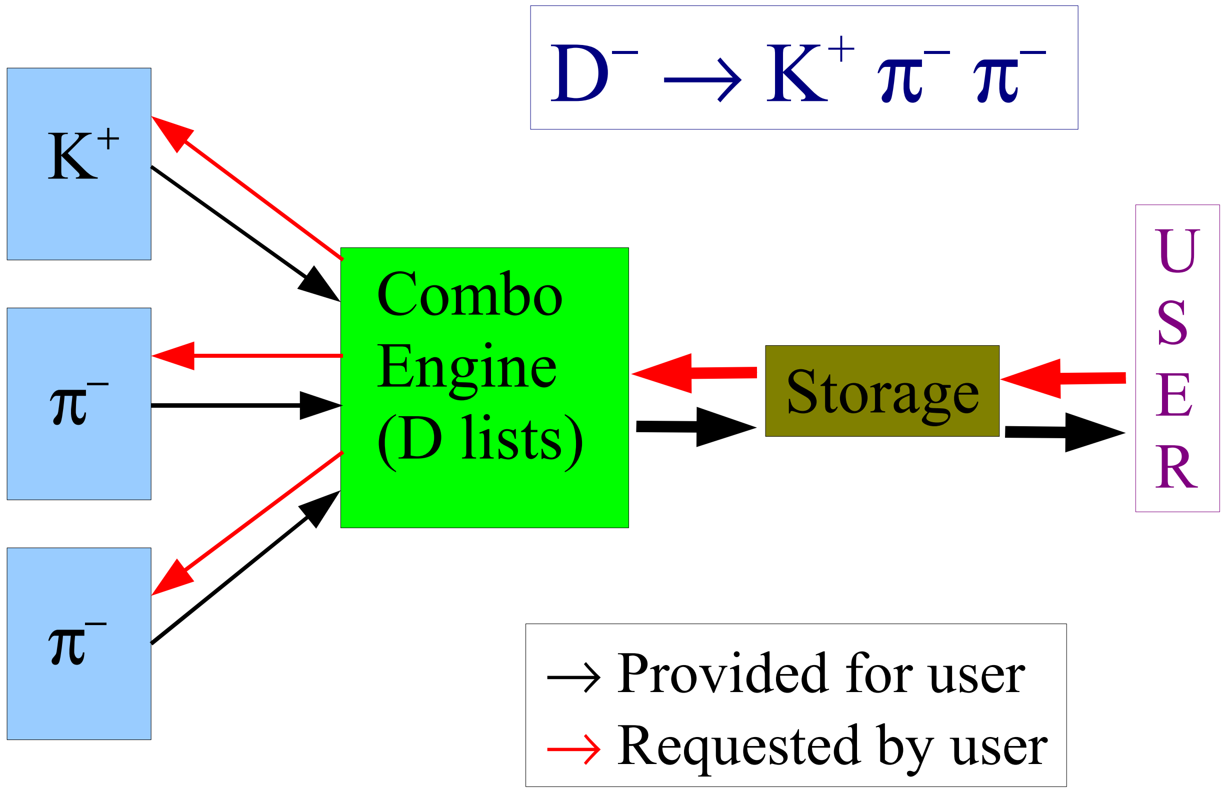


Plan for D Tagging @ BES-III

Allow access to

$\pi^{\pm}$	RecMdcKalTrack RecMdcDedx ...
$K^{\pm}$	RecMdcKalTrack RecMdcDedx ...
π^0	1C Fit Result RecEmcShower (γ_1) RecEmcShower (γ_2)
K_S	Vertex Fit Result RecMdcKalTrack (π^+) RecMdcKalTrack (π^-)

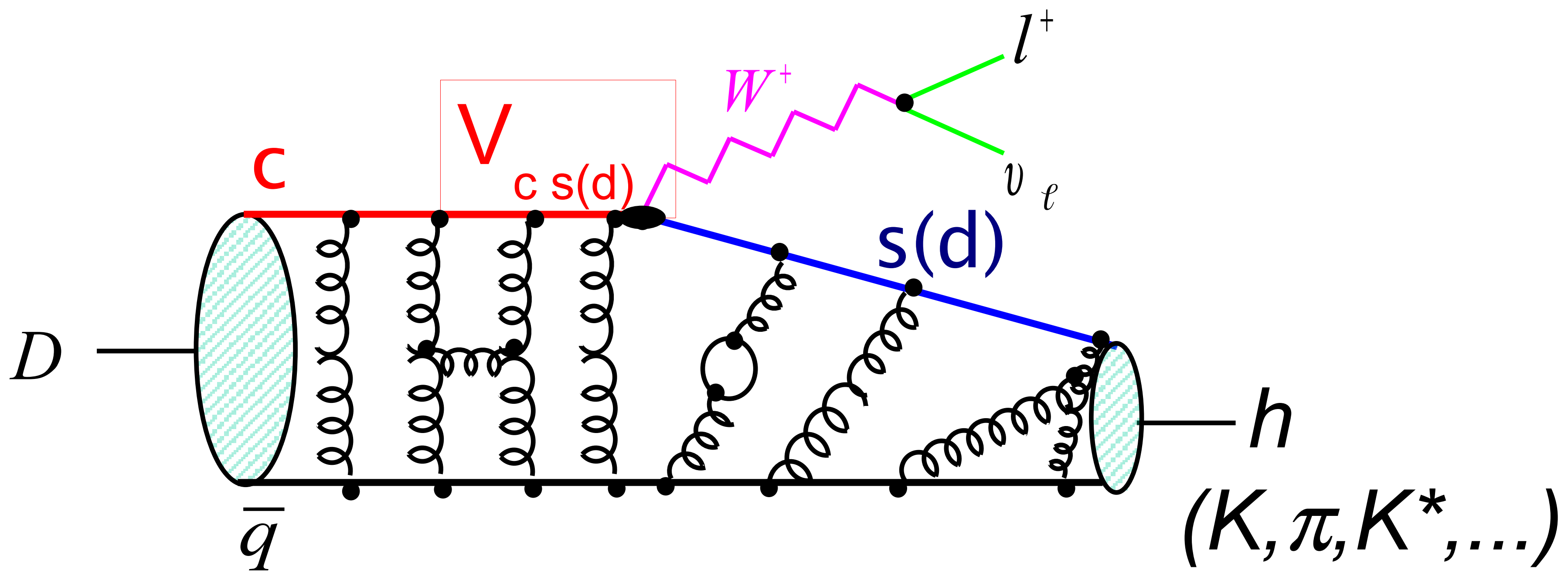
Particle Lists



D Tagging

Work in progress in D Tag Task Force (BES-III Charm Group)

Semileptonic Decays



For pseudoscalars (K,π)

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cq}|^2 p_P^3 |f_+(q^2)|^2$$

Electron ID for semileptonic decays @ CLEO-c

CLEO-c could only make precision measurements of $D \to X\, e\, \nu_e$ decays

[could not identify μ in $D \to X\, \mu\, \nu_\mu$ decays ($\mathbf{p}_{max} \approx 1.2$ GeV in these decays)
because $\mathbf{p} > 1.5$ GeV needed for Muon Chamber]

Electron ID: Likelihood fit using information from RICH, dE/dx,
associated shower energy in EM calorimeter (E_{CC})
and momentum measured in tracking volume [$E_{CC}/\mathbf{p}$]

Criteria: $\mathbf{p} > 200$ MeV, $|\cos\theta| < 0.9$, satisfies Likelihood Fit

Results: $\varepsilon = 71\%$ ($\mathbf{p} = [0.2, 0.3]$ GeV), 95% ($\mathbf{p} = [0.3, 1.0]$ GeV)
K/π-faking-e rate $\approx 0.1\%$ (whole momentum range)

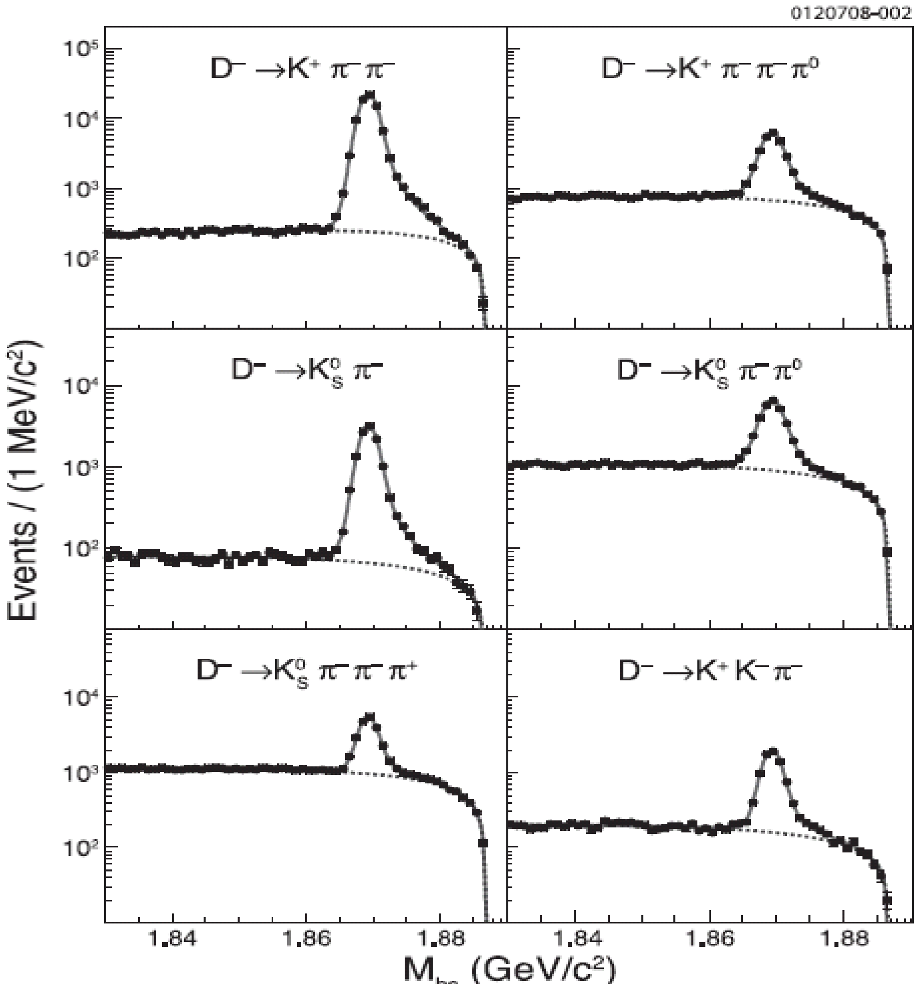
80% of all electrons from D semileptonic decays fall in this range

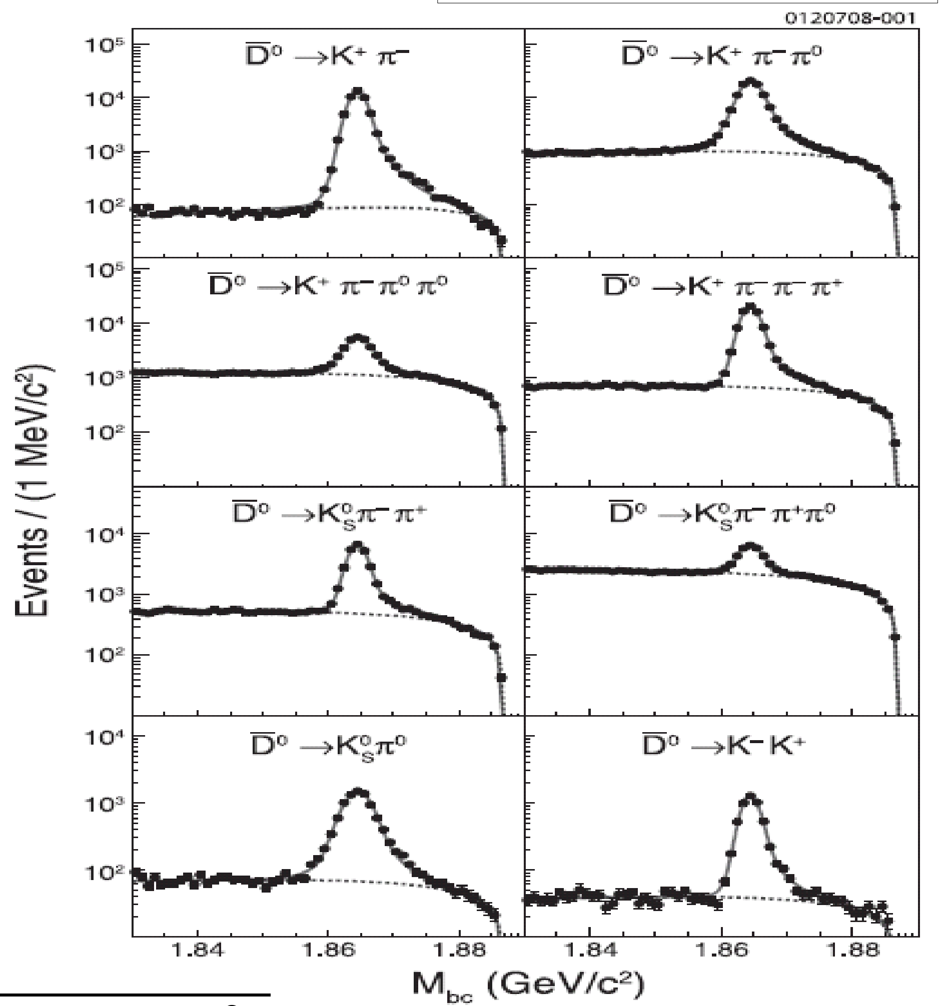
All (semi-)leptonic analyses used this electronID package

Taaging for D → K/π e ν_e

From the 281 pb^{-1} ψ(3770) sample

To be subm to PRD





6 D^- modes: N_{tags} = 163k

$$m_{bc} = \sqrt{(E_{beam}^2 - |\boldsymbol{p}_{D_{tag}}|^2)}$$

8 D^0 modes: N_{tags} = 307k

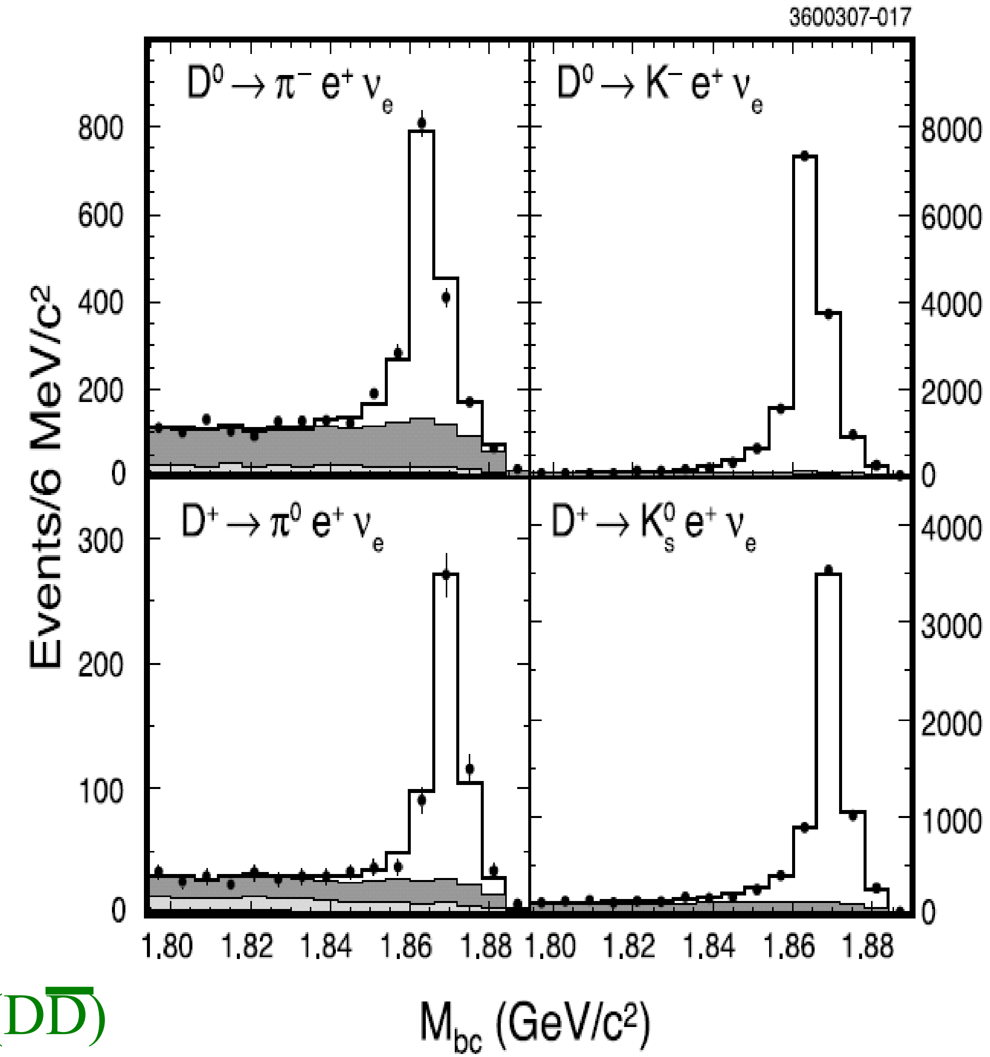
$D \to K/\pi\, e\, \nu_e$ using ν reconstruction (aka Untagged)

PRL 100, 251801 (2008); PRD 77, 112005 (2008)

Also using 281 pb^{-1} $\psi(3770)$ sample, reconstruct entire event and look at missing E and **p** $\Rightarrow \nu$

Improve ν **p** resolution by requiring
$\Delta E = (E_h + E_e + \xi E_\nu) - E_{beam} = 0$

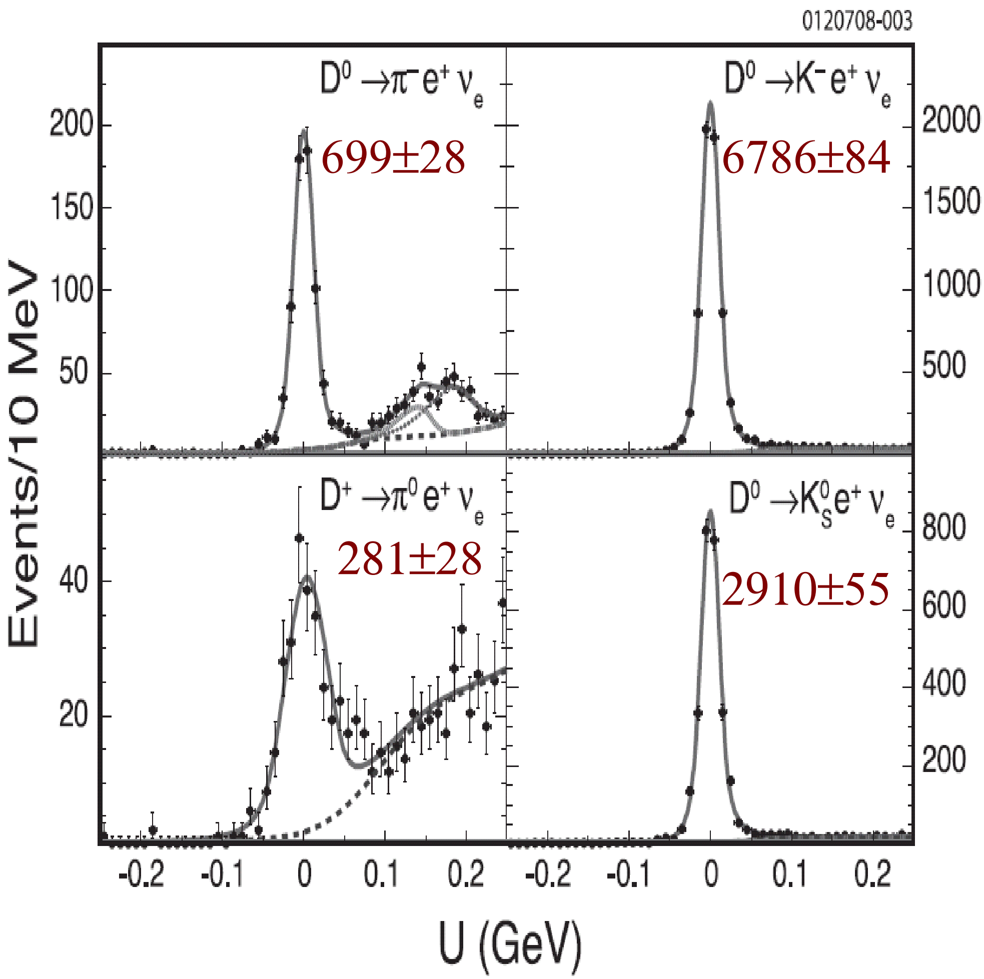
Modifies $M_{bc} = \sqrt{E^2_{beam} - |\mathbf{p}_h + \mathbf{p}_e + \xi \mathbf{p}_\nu|^2}$



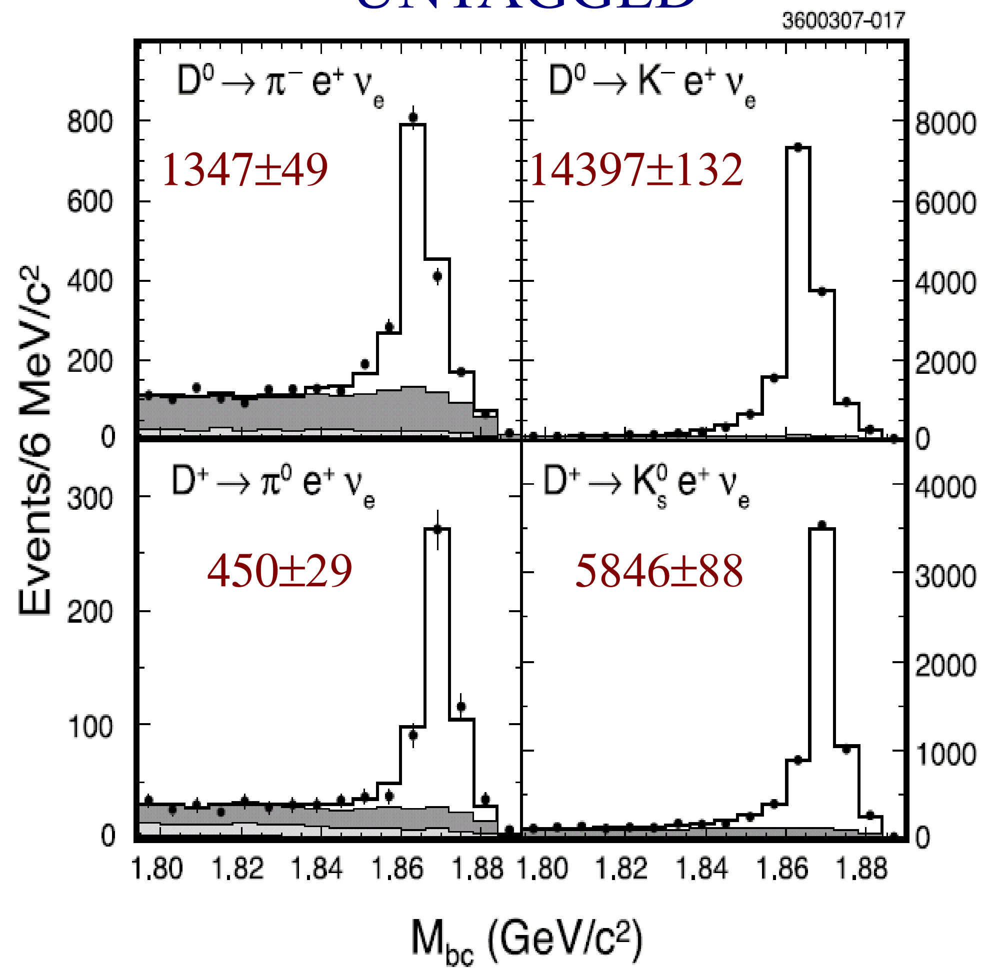
This technique allows you increase the yield by 2.5x, but has larger backgrounds,
Also requires accurate measurement of $N(D\overline{D})$

Signal Yields for D $\rightarrow$ K/π e ν_e

TAGGED



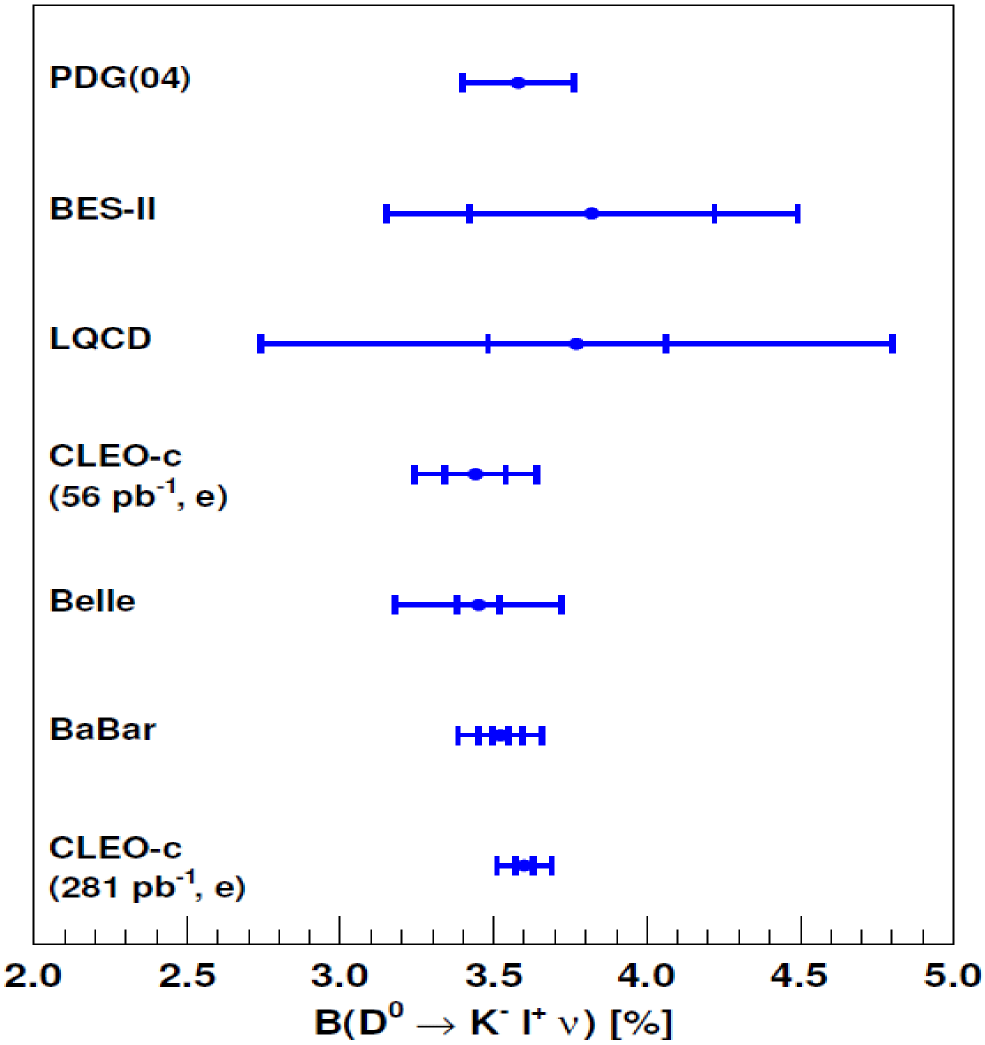
UNTAGGED

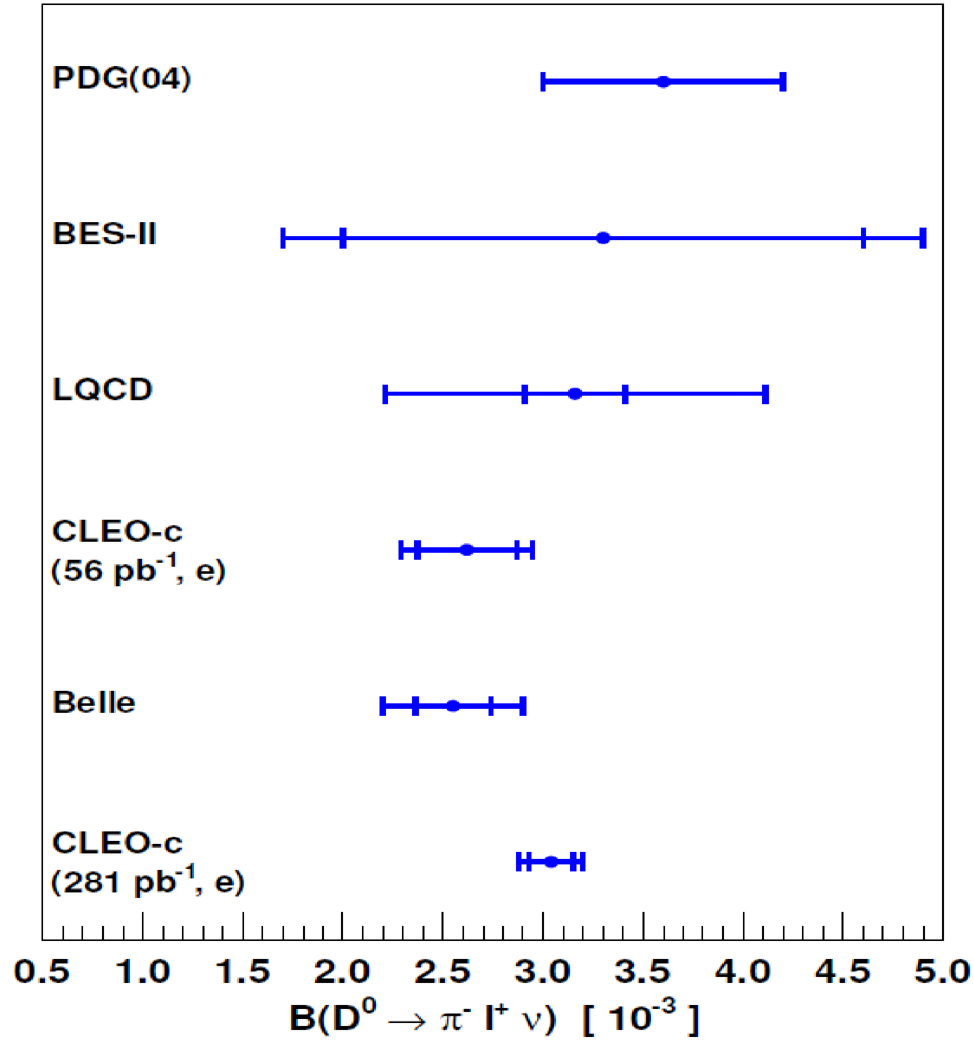


$$U_{miss} = E_{miss} - |\boldsymbol{p}_{miss}|$$

$$M_{bc} = \sqrt{\left(E_{beam}^2 - \left(\boldsymbol{p}_{K(\pi)} + \boldsymbol{p}_e + \xi\, \boldsymbol{p}_{miss}\right)^2\right)}$$

Branching Fractions of $D^0 \to K^- \ell^+ \nu_\ell$





Most precise measurements of branching fractions

$D \to K/\pi\, e\, \nu_e$ Form Factors

Form factor is an analytic function which satisfies the dispersion relation

$$f_+(q^2) = \frac{f_+(0)}{1-\alpha}\frac{1}{1-q^2/m_{\mathrm{pole}}^2} + \sum_{k=1}^{N}\frac{\rho_k}{1-\frac{q^2}{\gamma_k M_{\mathrm{pole}}^2}}$$

$M_{pole} = D_S^{*+}$ (D^{*+}) for $D \to K\,(\pi)\, e\, \nu_e$

Simple mode model

$$f_+(q^2) = \frac{f_+(0)}{(1-\frac{q^2}{M_{\mathrm{pole}}^2})}$$

Fit for $f_+(0)$ and M_{pole}

Modified mode model

$$f_+(q^2) = \frac{f_+(0)}{(1-q^2/M_{\mathrm{pole}}^2)(1-\alpha q^2/M_{\mathrm{pole}}^2)}$$

Fix M_{pole}, fit for $f_+(0)$ and α

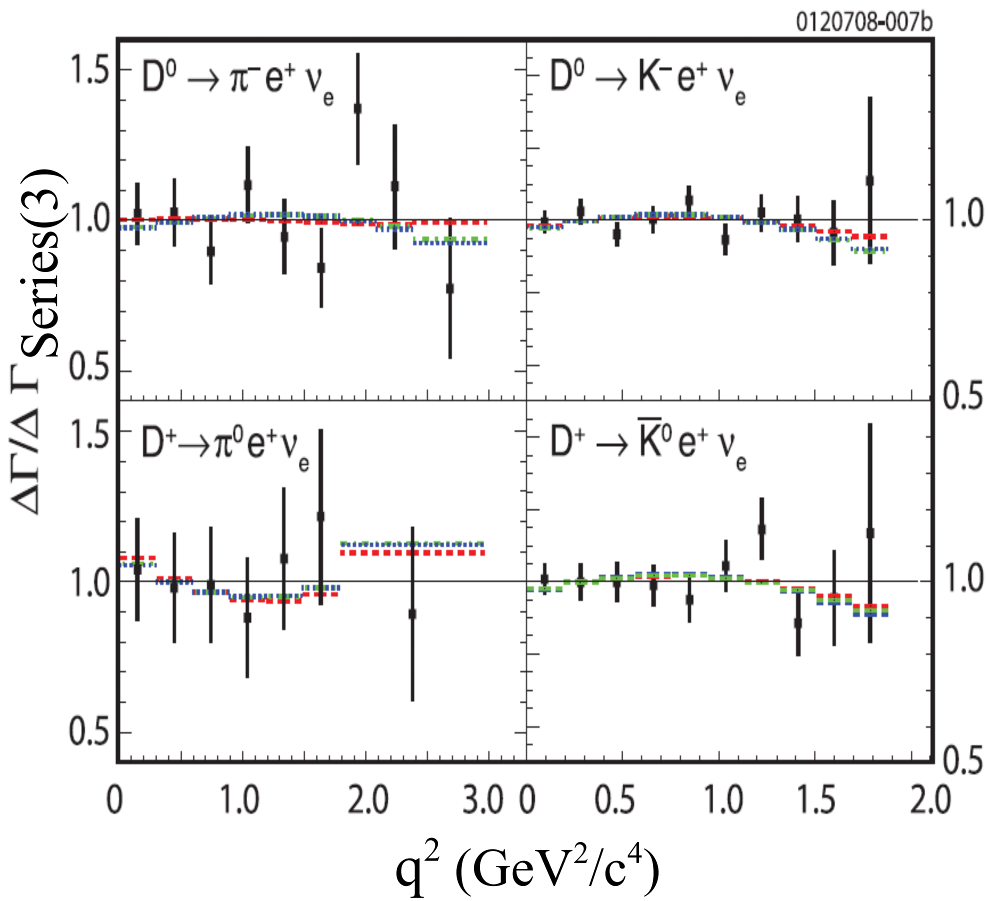
Series Expansion Model

$$f_+(q^2) = \frac{a_0}{P(q^2)\phi(q^2,t_0)}\left(1+\sum_{k=1}^{\infty}a_k(t_0)z(q^2,t^0)^k\right)$$

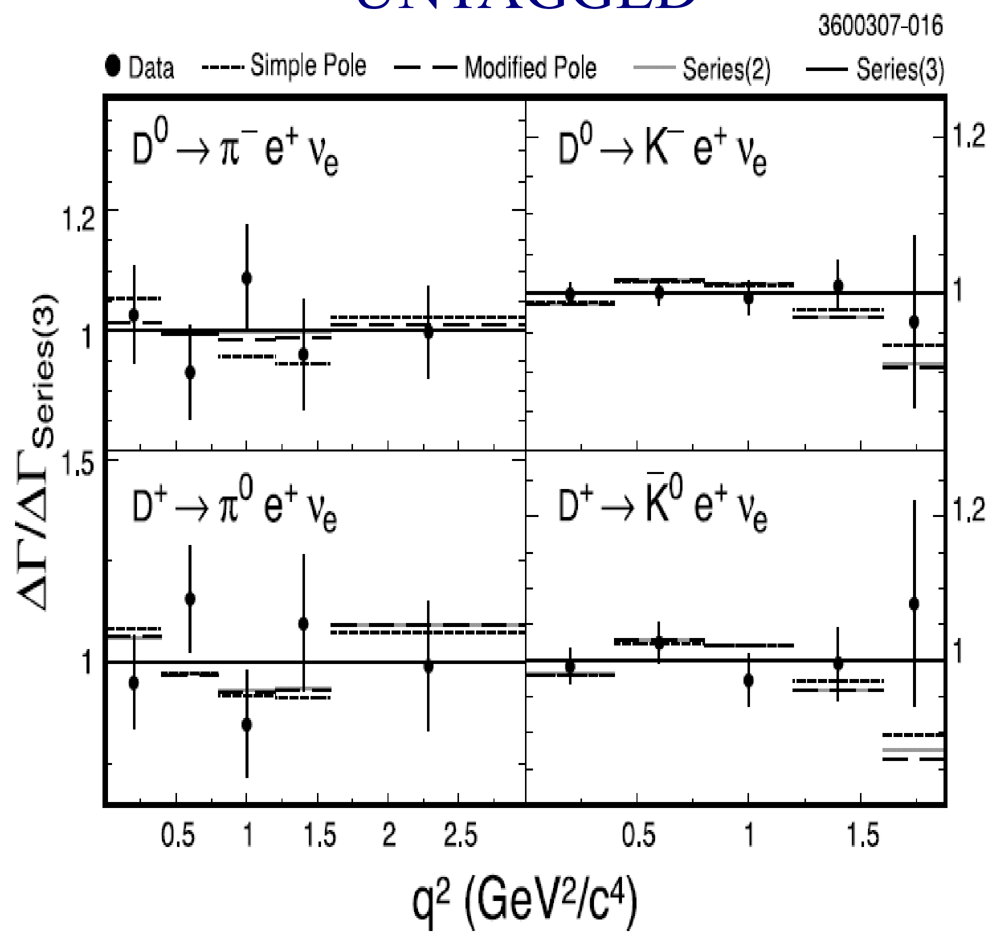
Map q^2 in complex z-space, poles are along real axis, fit for a_i

Fits of q^2 bins

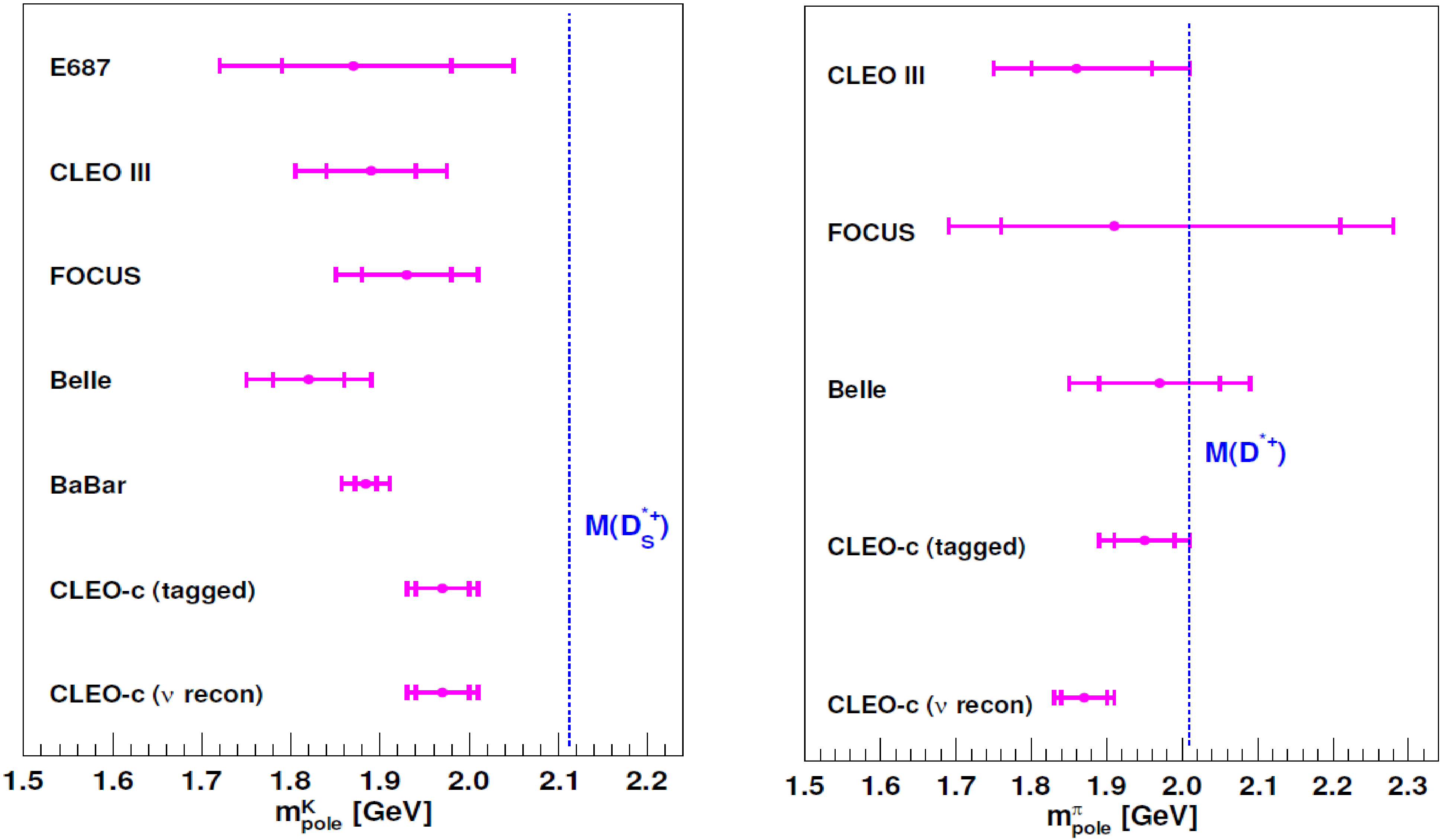
TAGGED



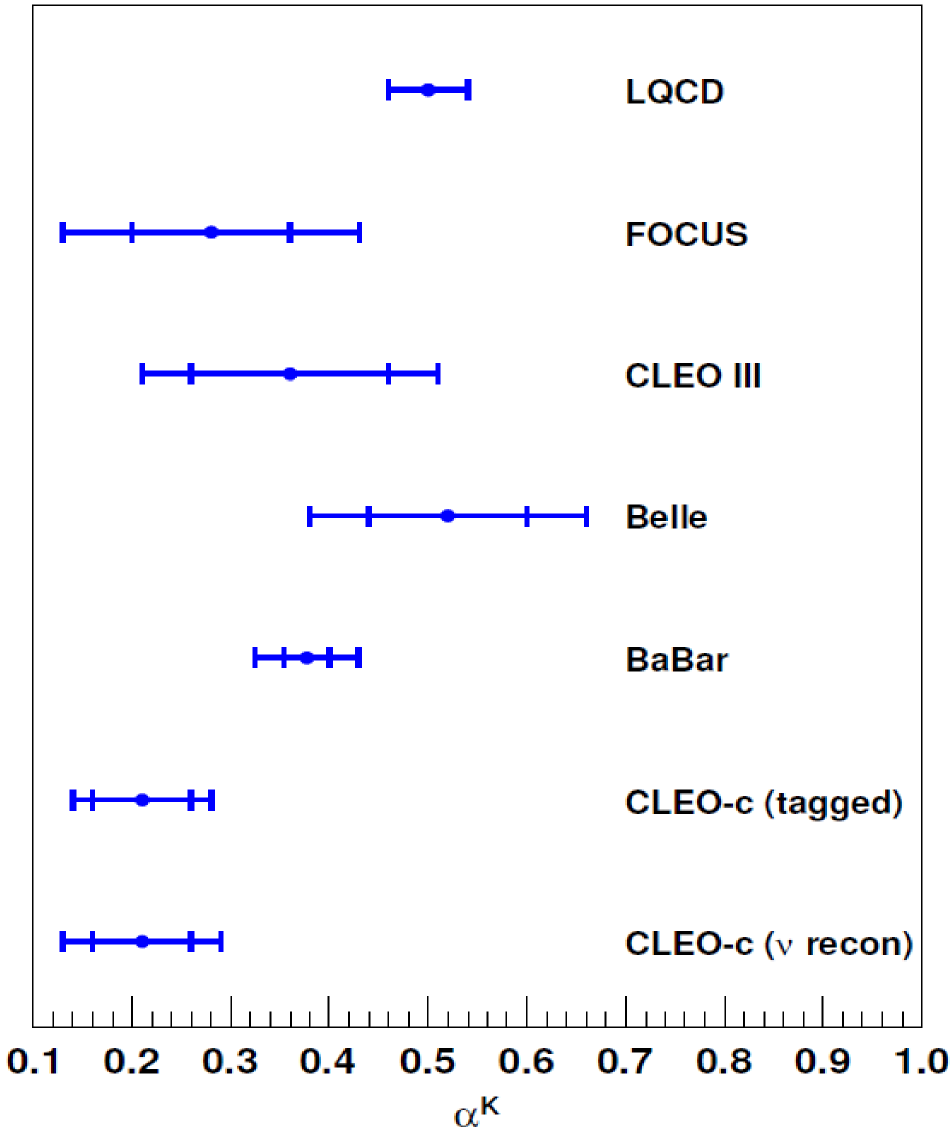
UNTAGGED

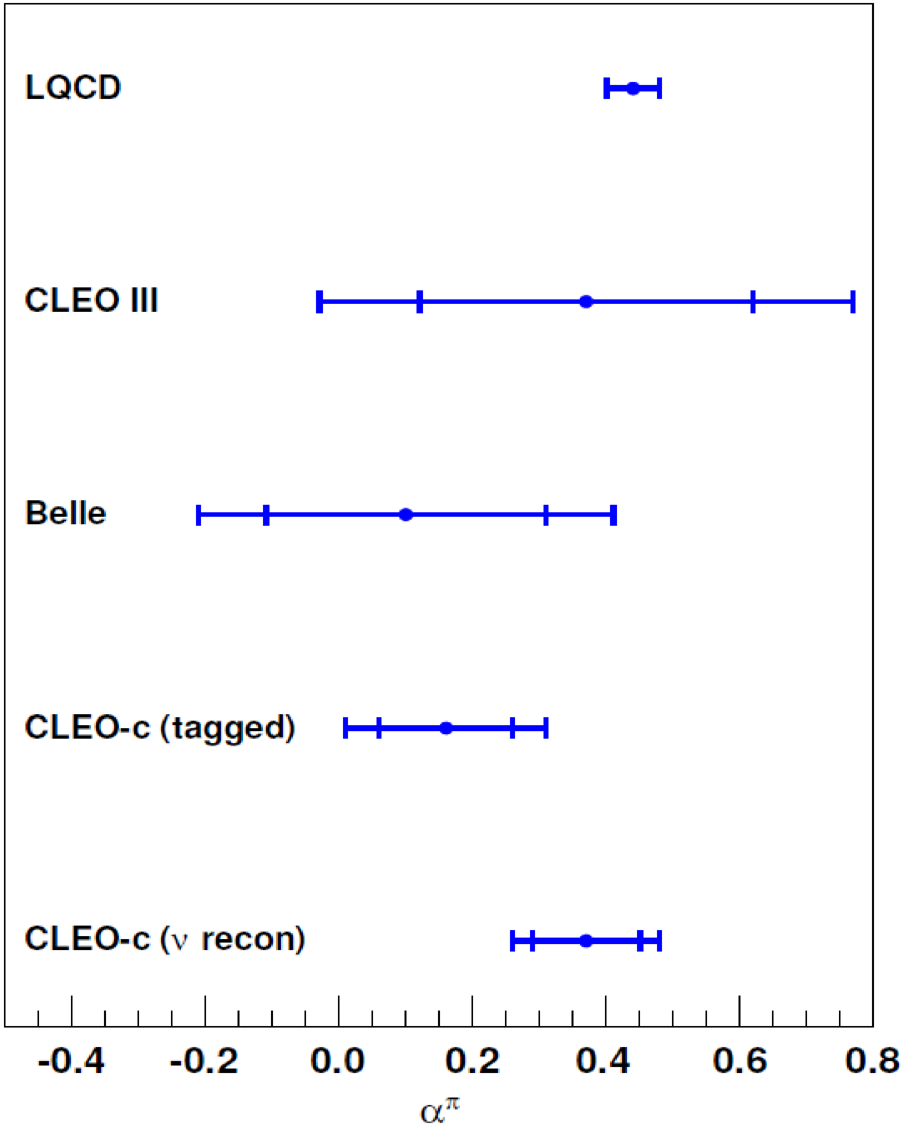


Simple Pole Form Factor Results



Modified Pole Form Factor Results





$D \to K/\pi\, e\, \nu_e$ Results

To be subm to PRD

By averaging the Tagged and Untagged (ν reconstruction) analysis and accounting for correlations, CLEO has determined

$$f^{\pi}_{+}(0)\,|V_{cd}| = 0.143 \pm 0.005 \pm 0.002$$

$$f^{K}_{+}(0)\,|V_{cs}| = 0.744 \pm 0.007 \pm 0.005$$

using the series parameterization form factor model with three parameters from its 281 pb^{-1} sample collected at $\psi(3770)$

Using LQCD: $f^{\pi}_{+}(0) = 0.64(3)(6)$ $f^{K}_{+}(0) = 0.73(3)(7)$

$$|V_{cd}| = 0.223 \pm 0.008 \pm 0.003 \pm 0.023$$

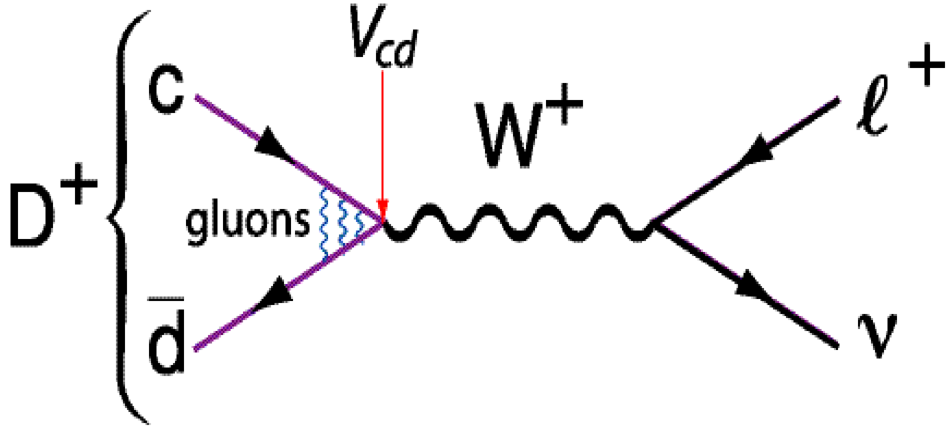
$$|V_{cs}| = 1.019 \pm 0.010 \pm 0.007 \pm 0.106$$

Most precise and robust $|V_{cd}|$ & $|V_{cs}|$ using semileptonic decays

Result using full 818 pb^{-1} $\psi(3770)$ sample still to come

Leptonic Decays

Probability for c and $\bar{d}$ ($\bar{s}$) annihilation is proportional to wave function overlap, related to the decay constant $f_{D(s)}$



$$\Gamma(D^+_{(S)} \to l^+ \nu) = \frac{G_F^2}{8\pi} f^2_{D_{(S)}} m_l^2 M_{D^+_{(S)}} \left(1 - \frac{m_l^2}{M^2_{D^+_{(S)}}}\right)^2 |V_{cd(s)}|^2$$

Decays also test Lepton Universality and search for New Physics

Standard Model (SM) predicts

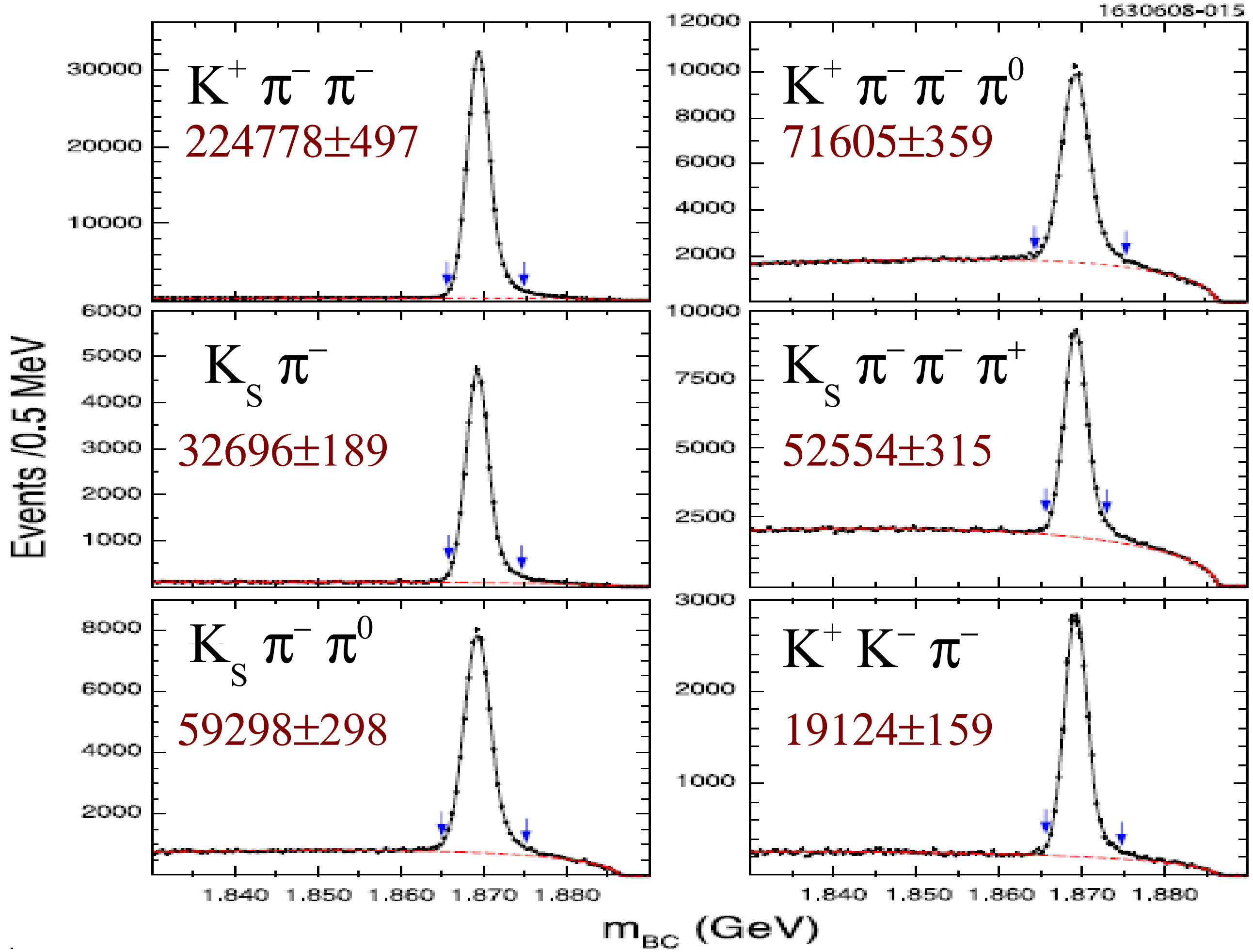
$\Gamma(D^+ \to l^+\nu)$ = $2.35\times10^{-5} : 1 : 2.65$ ($l = e : \mu : \tau$)

$\Gamma(D^+_S \to l^+\nu)$ = $2.35\times10^{-5} : 1 : 9.72$ ($l = e : \mu : \tau$)

Use $|V_{cd\,(s)}|$ to determine $f_{D(s)}$ for comparison with Lattice QCD

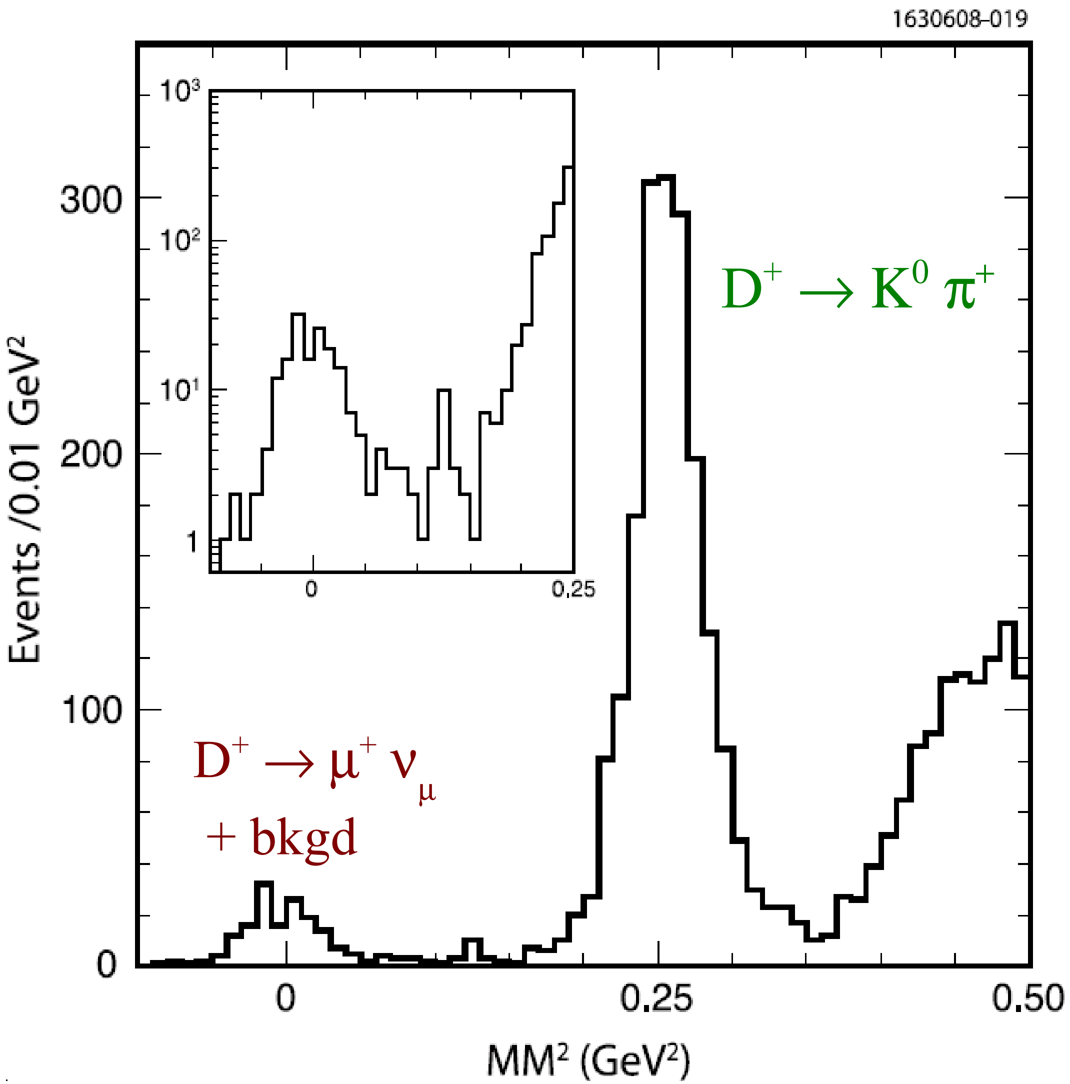
$D^+ \to \mu^+ \nu_\mu$

Full 818 pb^{-1} $\psi(3770)$ sample [arXiv: 0806.2112 [hep-ex], accpt by PRD]



$N_{tags} = 460k$

$D^+ \to \mu^+ \nu_\mu$



$$MM^2 = \left(E_{beam} - E_\mu\right)^2 - \left(\boldsymbol{p}_D + \boldsymbol{p}_\mu\right)^2$$

Require only one track opposite tag
* $|\cos\theta| < 0.90$
* $E_{CC,trk} < 300$ MeV ($\varepsilon = 99\%$ for μ)

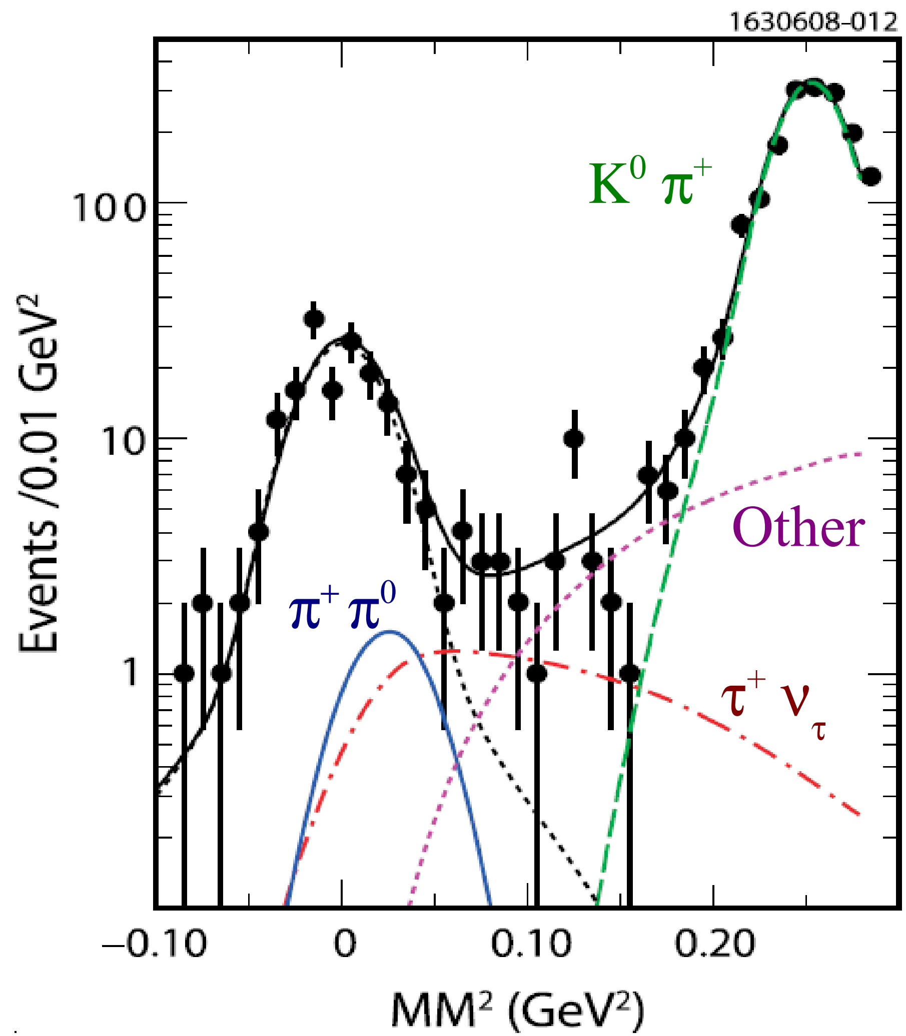
Require maximum energy of unmatched shower $E_{CC} < 250$ MeV

Detection $\varepsilon = 81.8$ %

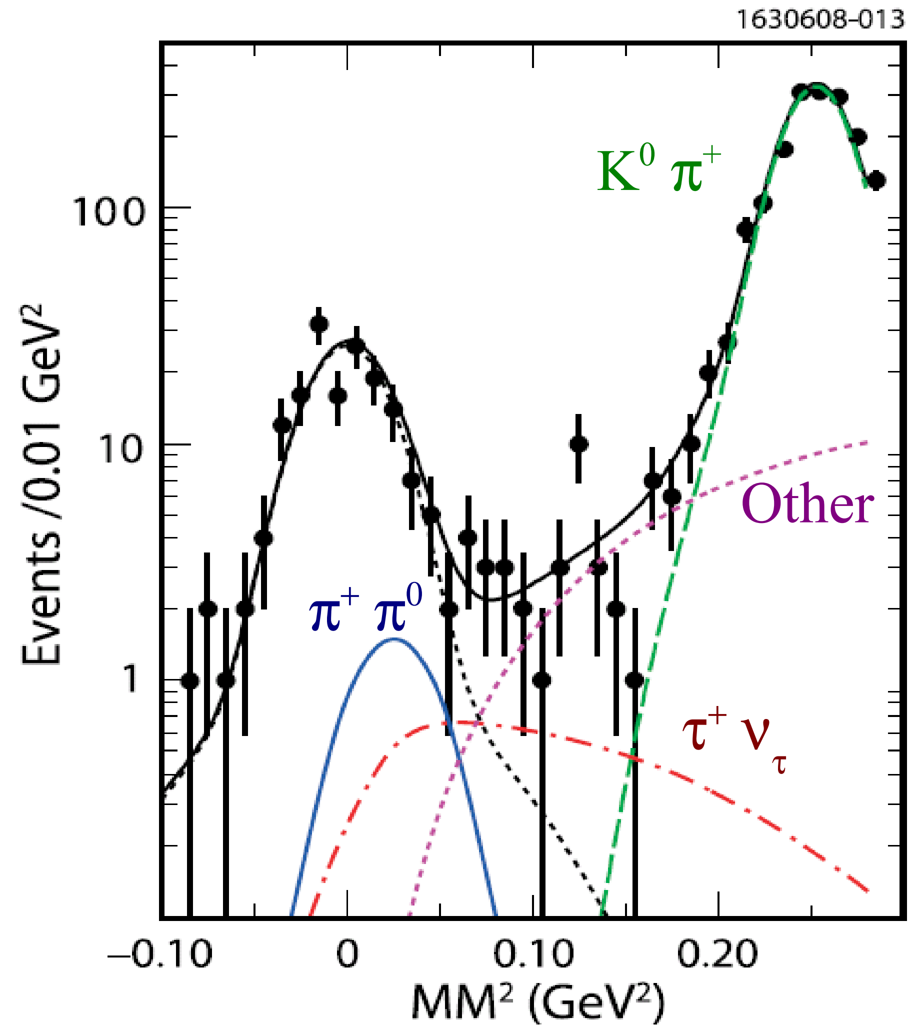
Fit for signal + $D^+ \to \tau^+ (\pi^+ \nu_\tau) \nu_\tau$, $\pi^+ \pi^0$ (fixed), $K^0 \pi^+$ (fixed), other ($\rho^0 \pi^+$, $\pi^0 \mu^+ \nu_\mu$,
$\tau^+ \to \rho^{0+} \nu_\tau$, $\mu^+ \nu_\mu \nu_\tau$;
shape fixed but area free)

Fits shown on next slide

Fits for $D^+ \to \mu^+ \nu_\mu$



$\mu^+ \nu_\mu / \tau^+ \nu_\tau$ fixed to SM



$\mu^+ \nu_\mu / \tau^+ \nu_\tau$ free

$D^+ \to \mu^+ \nu_\mu$

For $\mu^+ \nu_\mu / \tau^+ \nu_\tau$ fixed to SM:

$N(\mu^+ \nu_\mu) = 147.3 \pm 12.0$

$N(\tau^+ \nu_\tau) = 25.8$

$B(D^+ \to \mu^+ \nu_\mu) = 3.82(32)(9) \mathrm{x} 10^{-4}$

$f_D = (205.8 \pm 8.5 \pm 2.5)$ MeV

For $\mu^+ \nu_\mu / \tau^+ \nu_\tau$ free:

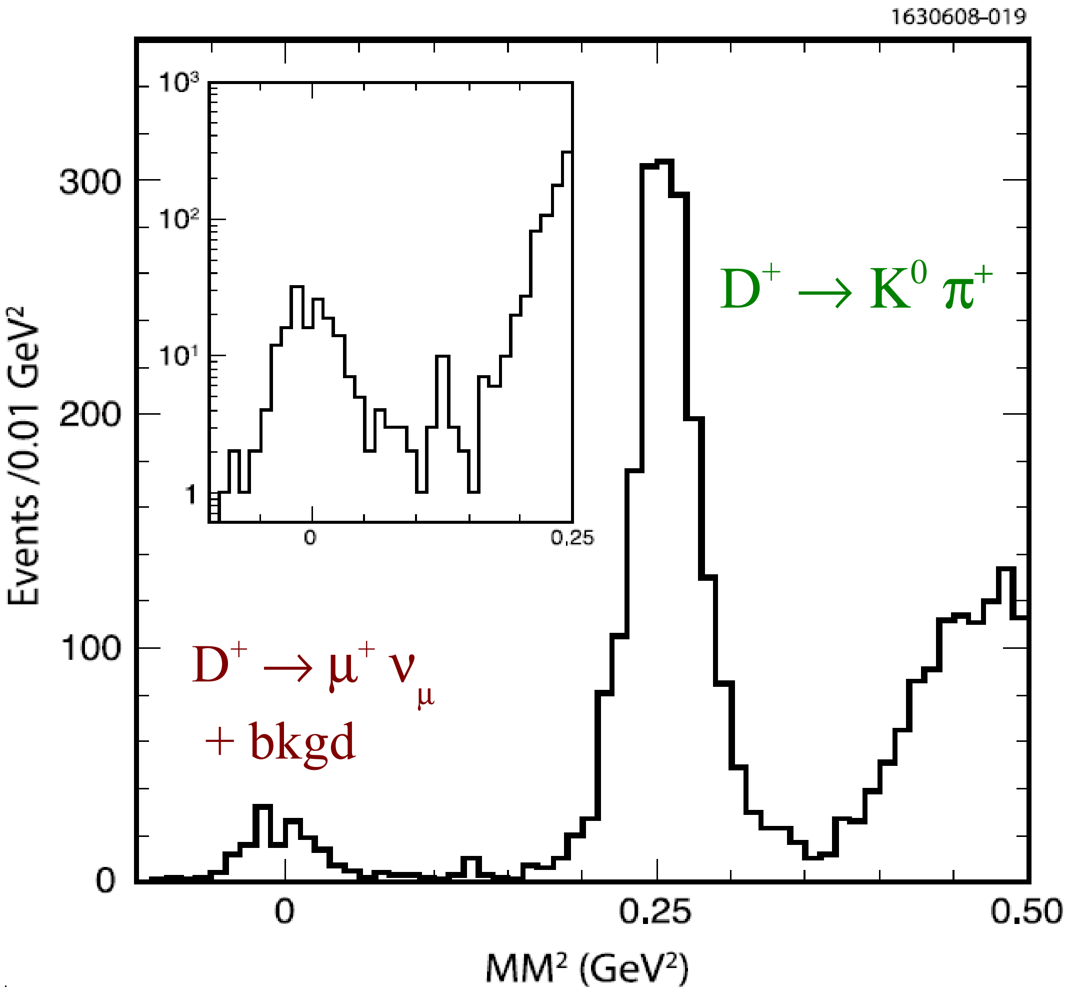
$N(\mu^+ \nu_\mu) = 151.5 \pm 13.5$

$N(\tau^+ \nu_\tau) = 13.5 \pm 15.3$

$B(D^+ \to \mu^+ \nu_\mu) = 3.93(35)(9) \mathrm{x} 10^{-4}$

$f_D = (207.6 \pm 9.3 \pm 2.5)$ MeV

LQCD: $f_D = (207 \pm 4)$ MeV



$$A_{CP} \equiv \frac{\Gamma(D^+ \to \mu^+\nu) - \Gamma(D^- \to \mu^-\bar{\nu})}{\Gamma(D^+ \to \mu^+\nu) + \Gamma(D^- \to \mu^-\bar{\nu})} = 0.08 \pm 0.08$$

$D^+ \rightarrow \tau^+ \nu_\tau$

Fit $E_{CC,trk}$ < 300 MeV and $E_{CC,trk}$ > 300 MeV distributions simutaneously to 55/45 ratio (55% π have $E_{CC,trk}$ < 300 MeV)

$N(\tau^+ \nu_\tau) = 27.8 \pm 16.4$

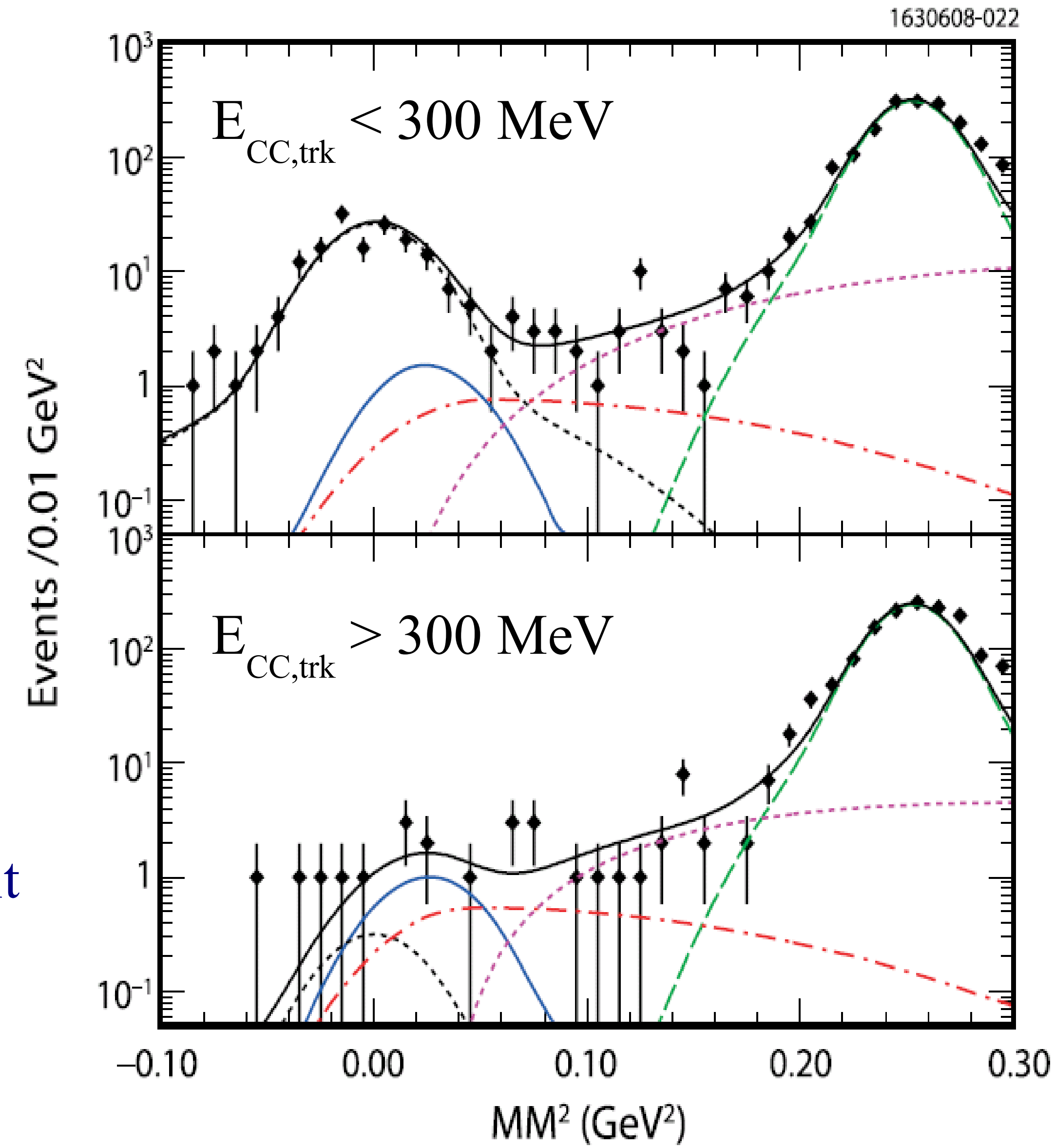
$B(D^+ \rightarrow \tau^+ \nu_\tau) < 0.12\ \%$

$B(D^+ \rightarrow \tau^+ \nu_\tau) = 0.10\ \%$ using SM value $2.65{*}B(D^+ \rightarrow \mu^+ \nu_\mu)$

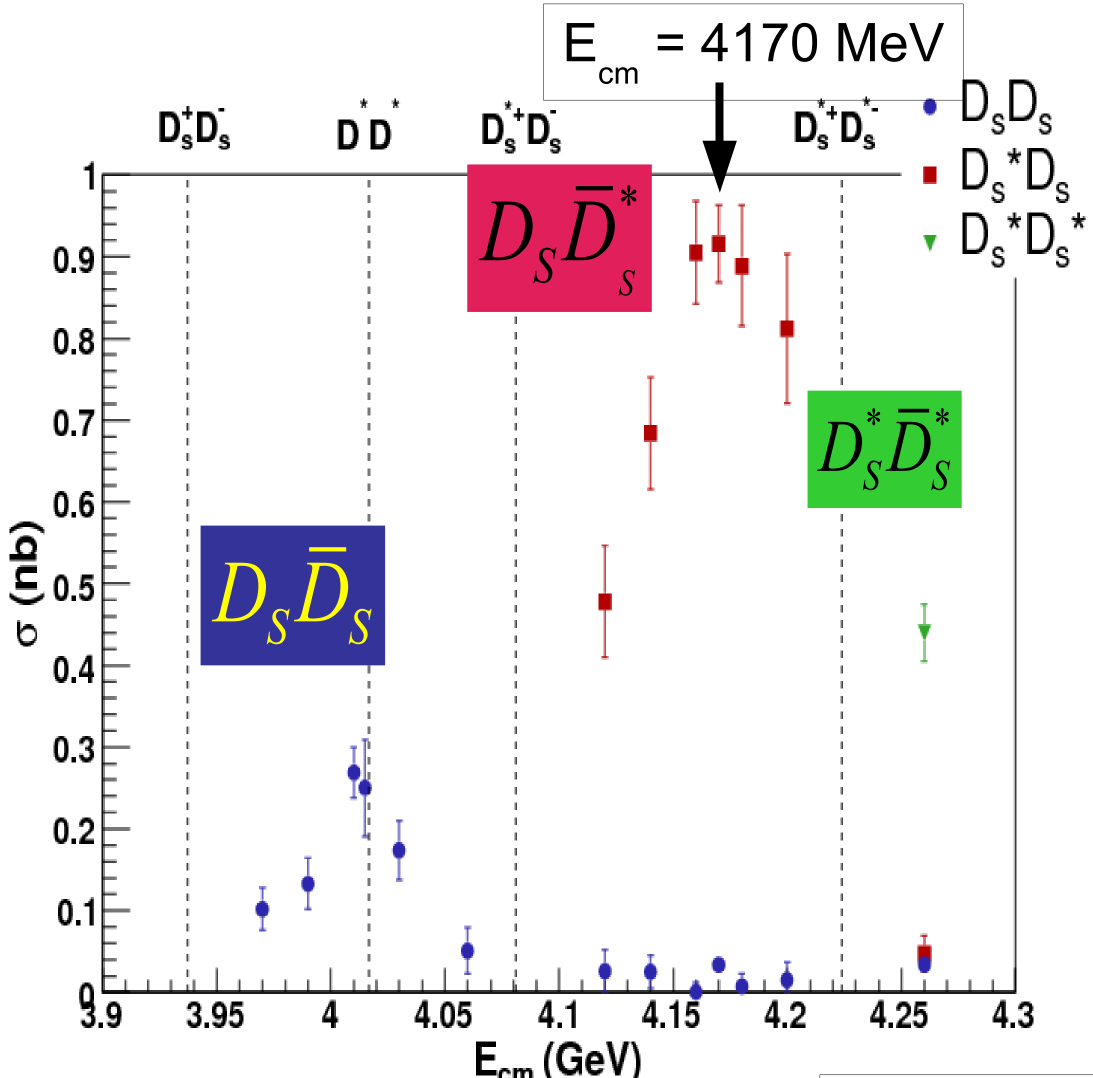
BES-III should be able to observe it

$B(D^+ \rightarrow e^+ \nu_e) < 8.8 \times 10^{-6}$

SM: $B(D^+ \rightarrow e^+ \nu_e) = 9 \times 10^{-9}$



Scanning for Optimal D_s Production



<u>Fall 2005</u>:
Scanned E_{cm} = 3.97 – 4.26 GeV to find optimal D_s production

Optimal E_{cm} = 4170 MeV

Almost all D_s from $e^+e^- \to \bar{D}_S^* D_S$

arXiv:0801.3418 [hep-ex], subm to PRD

Difficulties with D_s D^*_s

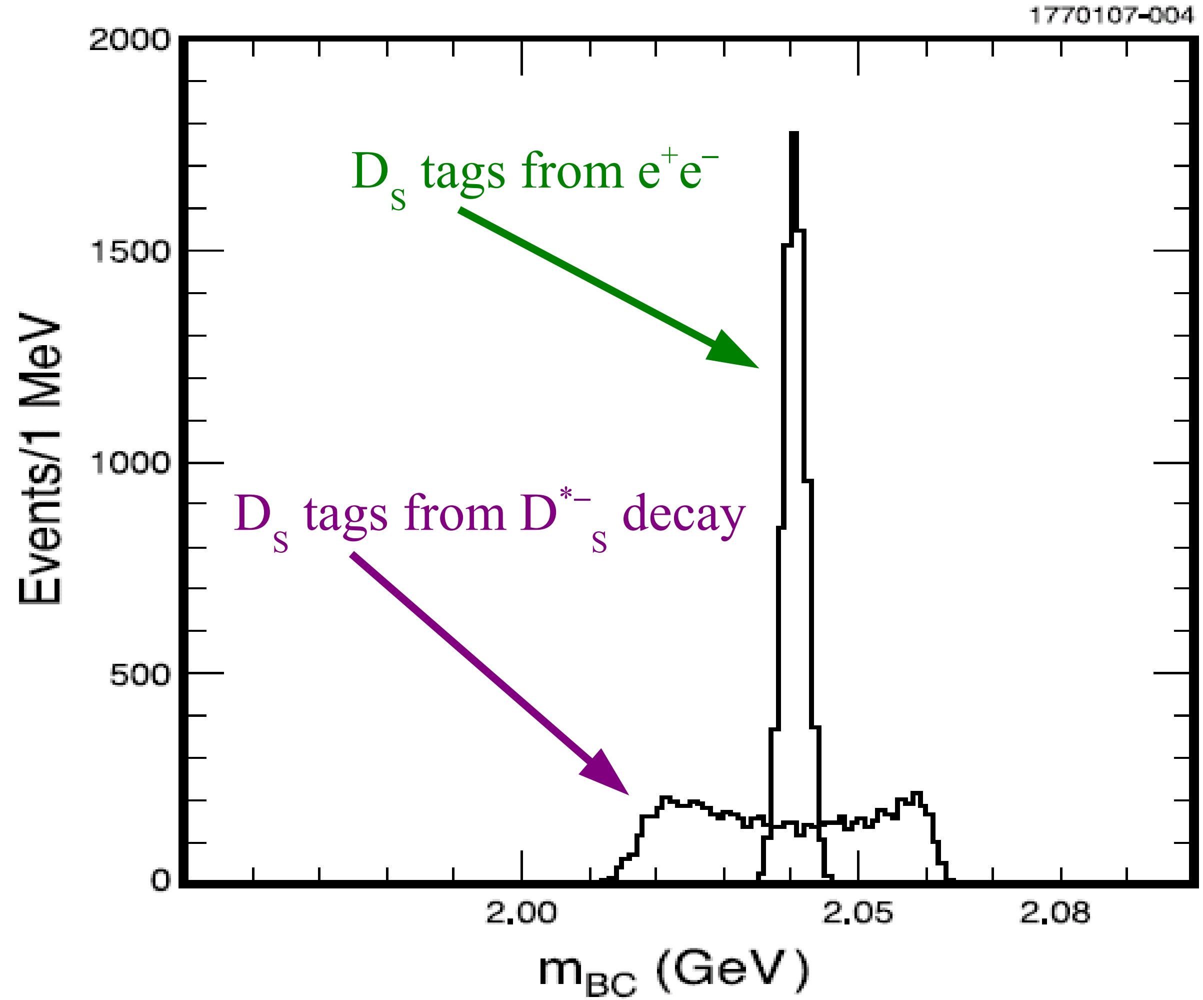
$e^+e^- \to D^+_s D^{*-}_s \to D^+_s (D^-_s \gamma)$

<u>Two Tagging Issues</u>

* γ detection from D^{*-}_s decay
  ($\varepsilon \sim 70\%$ based on ang dist)

* Distorted m_{BC}

CLEO-c:
Use D_s inv mass to select tags ($\sigma_{InvMass} > \sigma_{mBC}$)



Tags for $D^+_s \to \mu^+ \nu_\mu, \tau^+ (\pi^+ \nu_\tau) \nu_\tau$

PRL 99, 071802 (2007); PRD 76, 072002 (2007)

Using 314 pb^{-1} 4170 MeV sample, study $D_s \to \mu^+\nu$, $\tau^+\nu$ decays by studying its recoil against D_s tag and γ ("D_s tag").

8 D_s hadronic decays (tags):

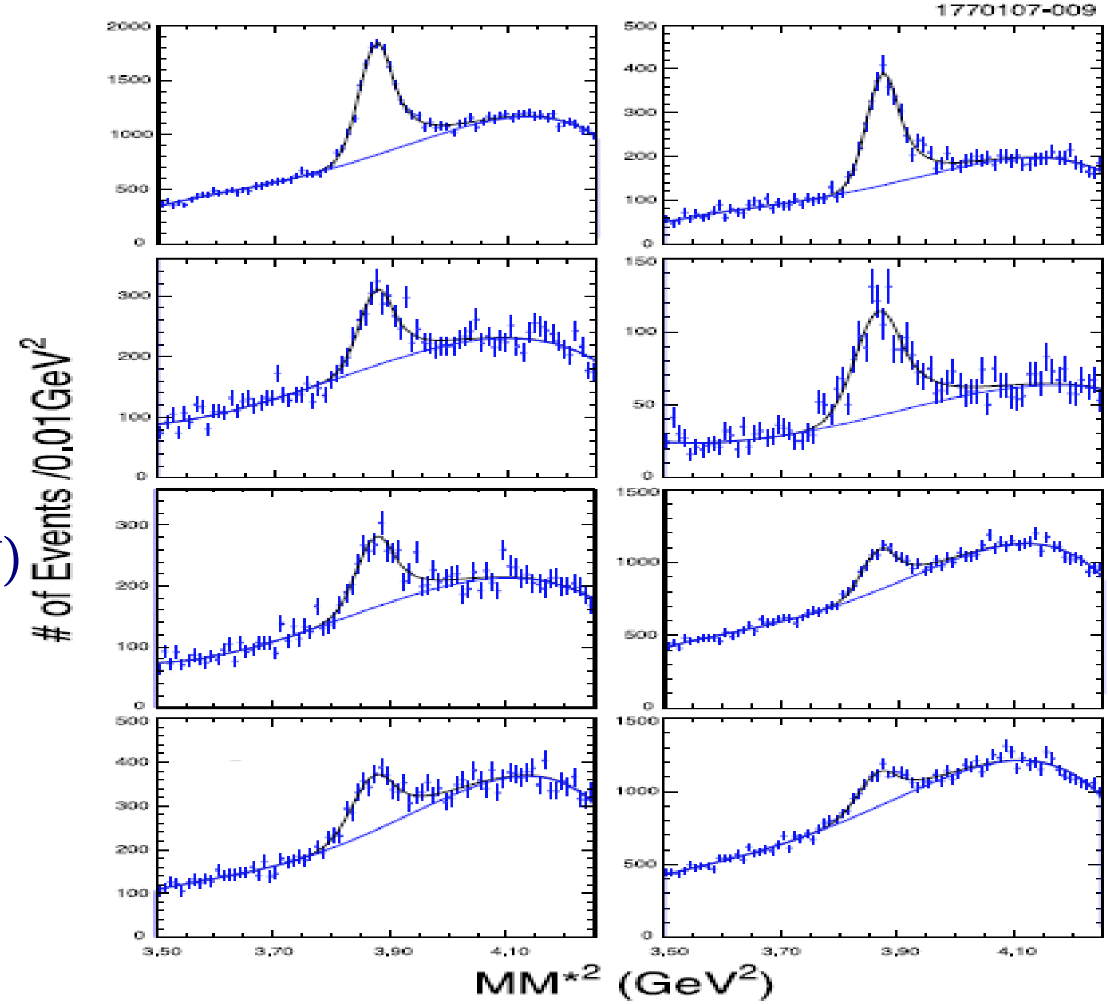
$D_s \to K^+K^-\pi$, K_sK^+, $\pi^+\pi^+\pi^-$

$\to \pi^+\varphi(K^+K^-)$, $K^{*+}(K_s\pi^+)K^0(K^-\pi^+)$

$\to \pi^+\eta(\gamma\gamma)$, $\rho(\pi^+\pi^-)\eta(\gamma\gamma)$

$\to \pi^+\eta'(\pi^+\pi^-\eta(\gamma\gamma))$

31,300 "D_s tags" after MM^{*2} selection



$$MM^{*2} = \left(E_{CM} - E_{D_s} - E_\gamma\right)^2 - \left(\boldsymbol{p}_{D_s} + \boldsymbol{p}_\gamma\right)^2$$

$D^+_s \to \mu^+ \nu_\mu, \tau^+ (\pi^+ \nu_\tau) \nu_\tau$

Three cases

(i) Track has E_{CC} < 300 MeV (μ, π)

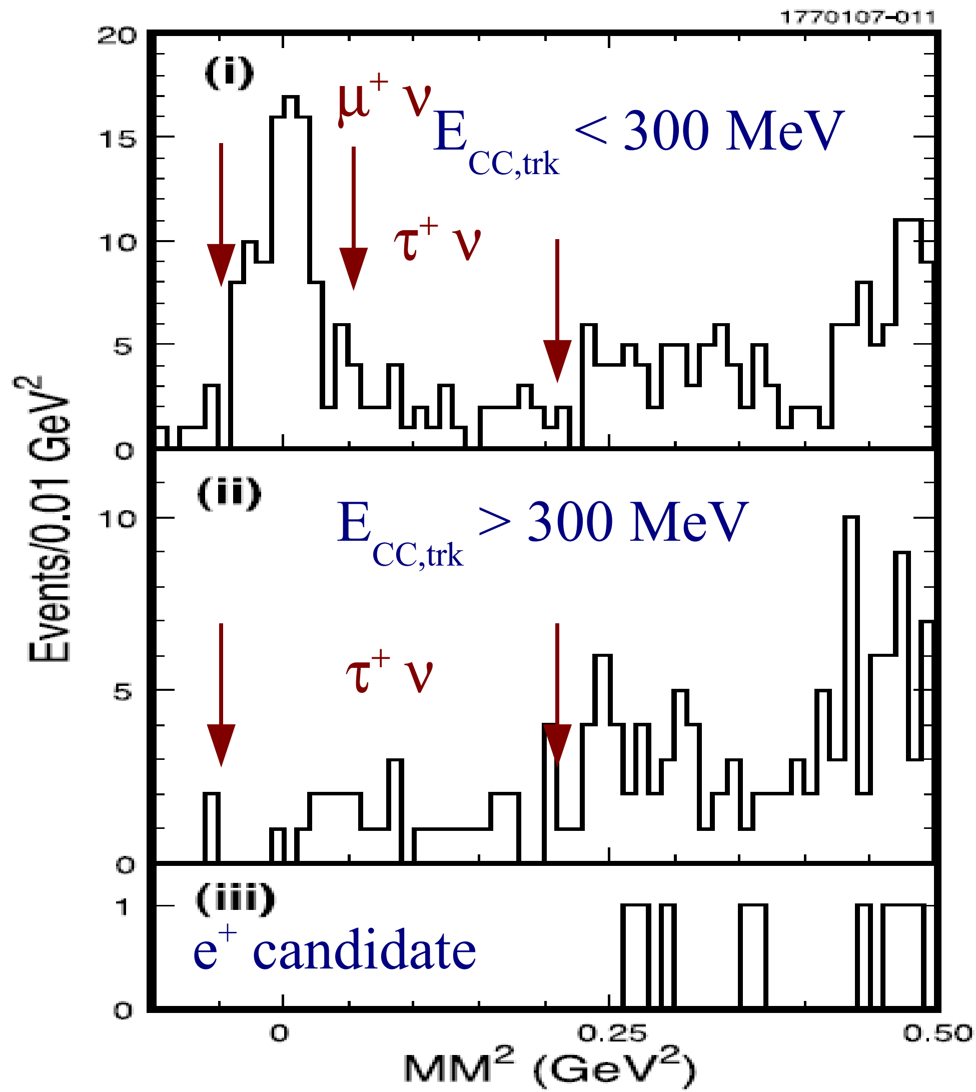
(ii) Track has E_{CC} > 300 MeV (π)

(iii) Track consistent with electron

Cases (i) and (ii) allow for simultaneous study of $D^+_s \to \tau^+\nu, (\pi^+\nu)\, \nu$

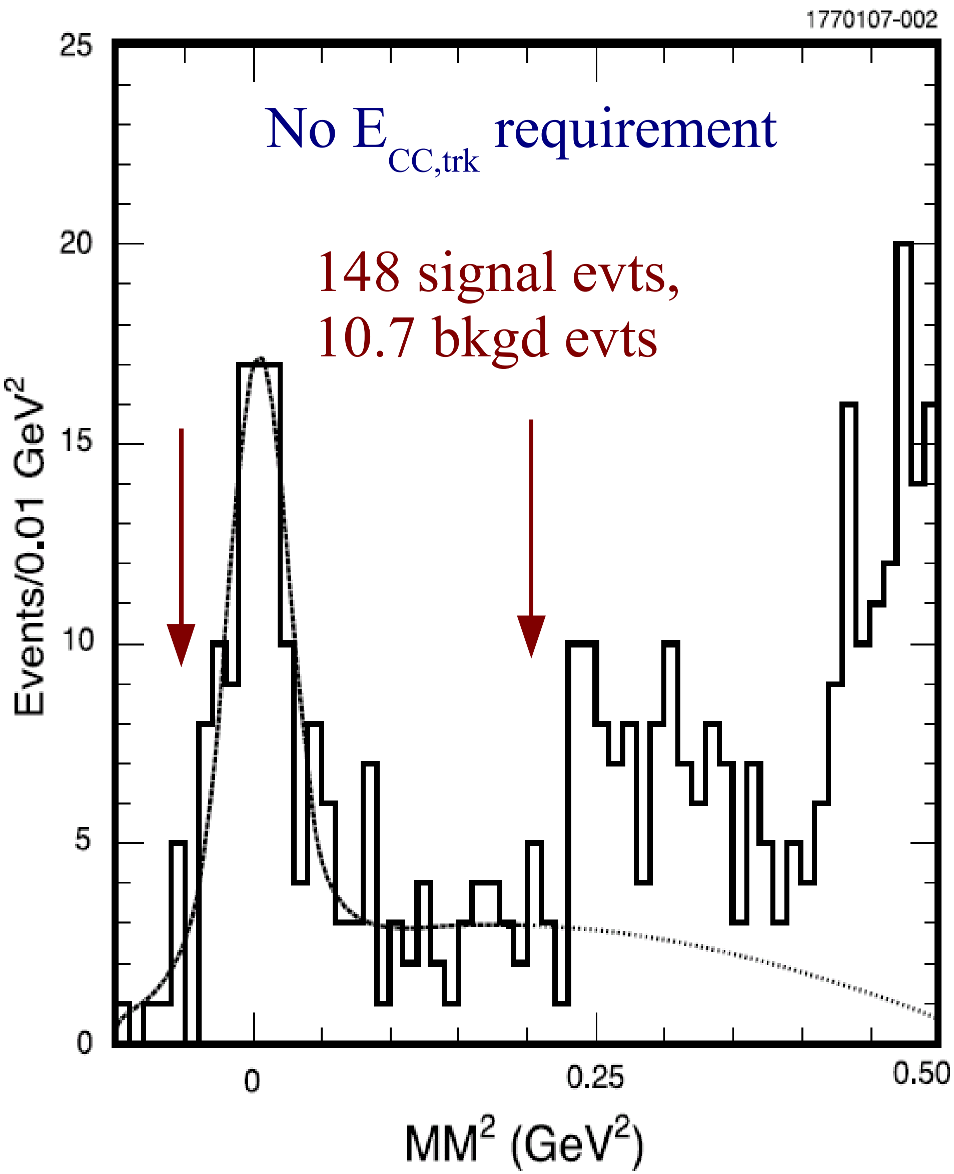
Require maximum energy of unmatched shower E_{CC} < 300 MeV

Look at missing mass squared (MM^2) for enhancements in signal regions



$$MM^2 = \left(E_{CM} - E_{D_s} - E_\gamma - E_\mu\right)^2 - \left(\boldsymbol{p}_{D_s} + \boldsymbol{p}_\gamma + \boldsymbol{p}_\mu\right)^2$$

$D^+_s \to \mu^+ \nu_\mu, \tau^+ (\pi^+ \nu_\tau) \nu_\tau$



$D^+_s \to \mu^+\nu$ [Case (i)]

92 cand, 3.5 bkgd events, use SM for $\tau^+\nu$ yield near $MM^2 = 0$ ($\tau\nu/\mu\nu$ ratio)

$B(D^+_s \to \mu^+\nu) = (0.594 \pm 0.066 \pm 0.031)\%$

$D^+_s \to \tau^+\nu, (\pi^+\nu)\,\nu$ [Case (i) + Case (ii)]

56 signal, 5.5 bkgd events

$B(D^+_s \to \tau^+\nu) = (8.0 \pm 1.3 \pm 0.4)\%$

Using SM $\tau\nu/\mu\nu$ ratio to average (see fig),

$B(D^+_s \to \mu^+\nu) = (0.638 \pm 0.059 \pm 0.033)\%$

$B(D^+_s \to \mu^+\nu) = (0.61 \pm 0.19)\%$ PDG06

$D^+_s \to e^+\nu$ [Case (iii)]

No events in signal region

$B(D^+_s \to e^+\nu) < 1.3 \times 10^{-4}$

Tags for $D^+_s \to \tau^+ (e^+ \nu_e \nu_\tau) \nu_\tau$

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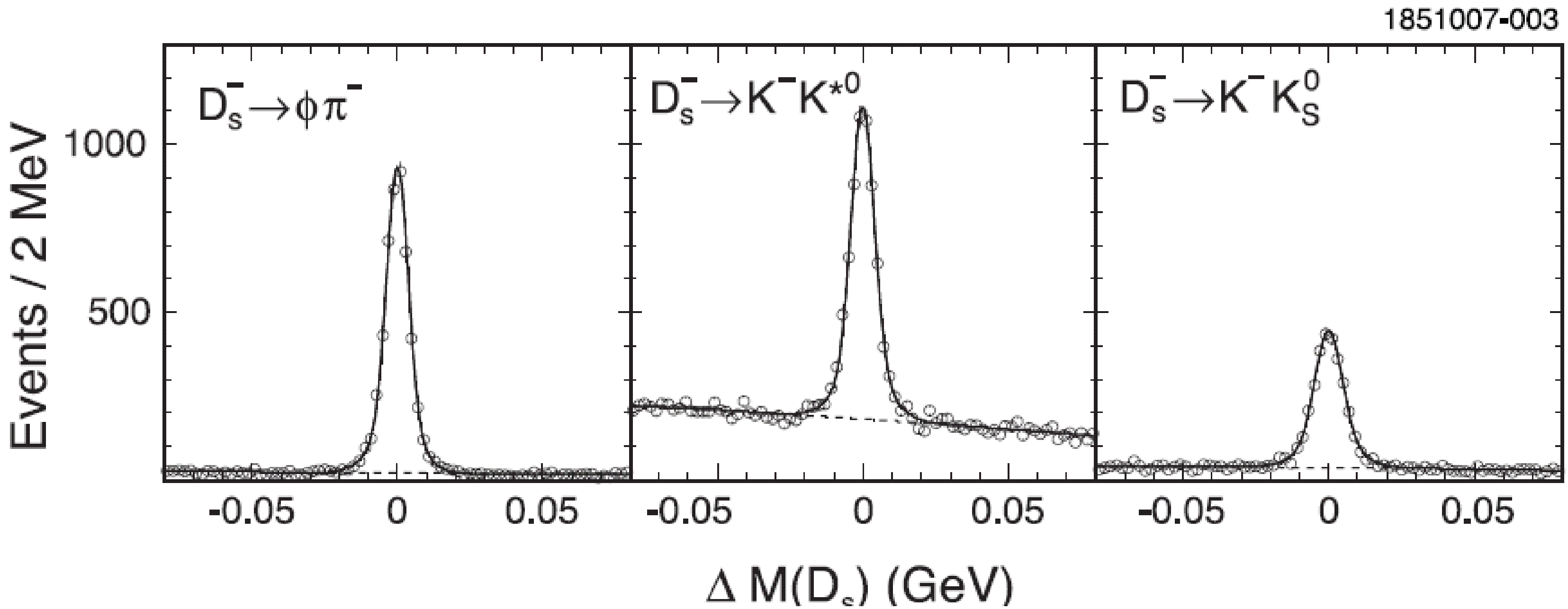
Complementary Analysis

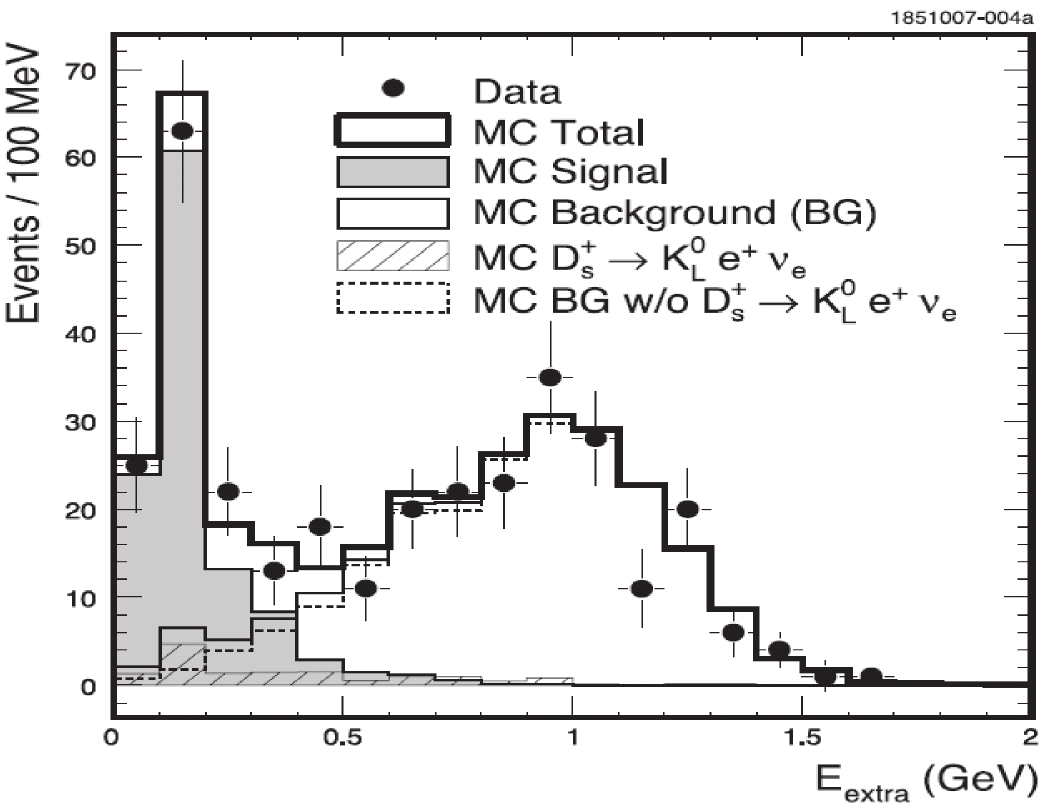
$B(D^+_s \to \tau^+\nu)*B(\tau^+ \to e^+\nu\nu) \sim 1.3\%$,
"large" compared to expected
$B(D^+_s \to Xe^+\nu) \sim 8\%$

Using 298 pb^{-1} 4170 MeV sample and 3 "clean" Ds tag modes

$N_{tags} = 12947 \pm 150$



$D^+_s \to \tau^+ (e^+ \nu_e \nu_\tau) \nu_\tau$



$$\frac{\mathcal{B}(D_s^+ \to \tau^+ \nu_\tau)}{\mathcal{B}(D_s^+ \to \mu^+ \nu_\mu)} = 11.0 \pm 1.4 \pm 0.6$$

Consistent with SM: 9.72

Technique is to find events with
1) an e^+ candidate opposite D^+_s tags
2) Total energy in calorimeter not associated with D^+_s tag or e^+ $(E_{extra}) < 400$ MeV

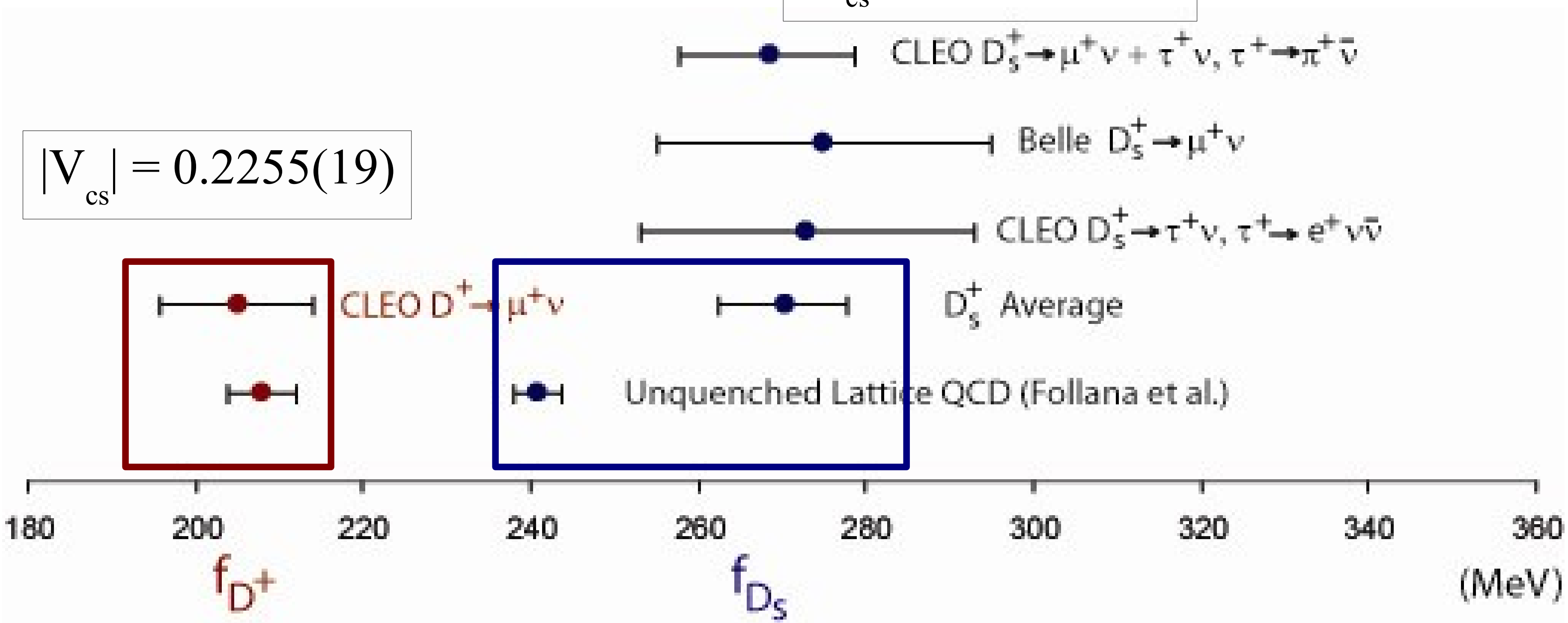
$B(D^+_s \to \tau^+ \nu) = 6.17(71)(34)\%$

Averaged with $D^+_s \to \tau^+ (\pi^+ \nu_\tau) \nu_\tau$,
$B(D^+_s \to \tau^+ \nu) = 6.47(61)(26)\%$
$B(D^+_s \to \tau^+ \nu) = (6.4 \pm 1.5)\%$ PDG06
+ recent msmts from Belle & BaBar

All results to be updated with full 600 pb^{-1} 4170 MeV data

f_D & f_{Ds} (Theory & Experiment)

$|V_{cs}| = 0.97471(18)$



Measurement of f_D agrees well with LQCD, but f_{Ds} does not (3σ diff)

Possible Scenarios: Problem with LQCD?
Signal of New Physics?

Important for BES-III to weigh in on this subject!

Summary

CLEO-c has finished data collection phase,
currently analyzing final samples

Most of the charmonium analyses are finished, some more to come

CLEO-c has made some of the most precise measurements of the D semileptonic form factors and $D_{(S)}$ decay constants:

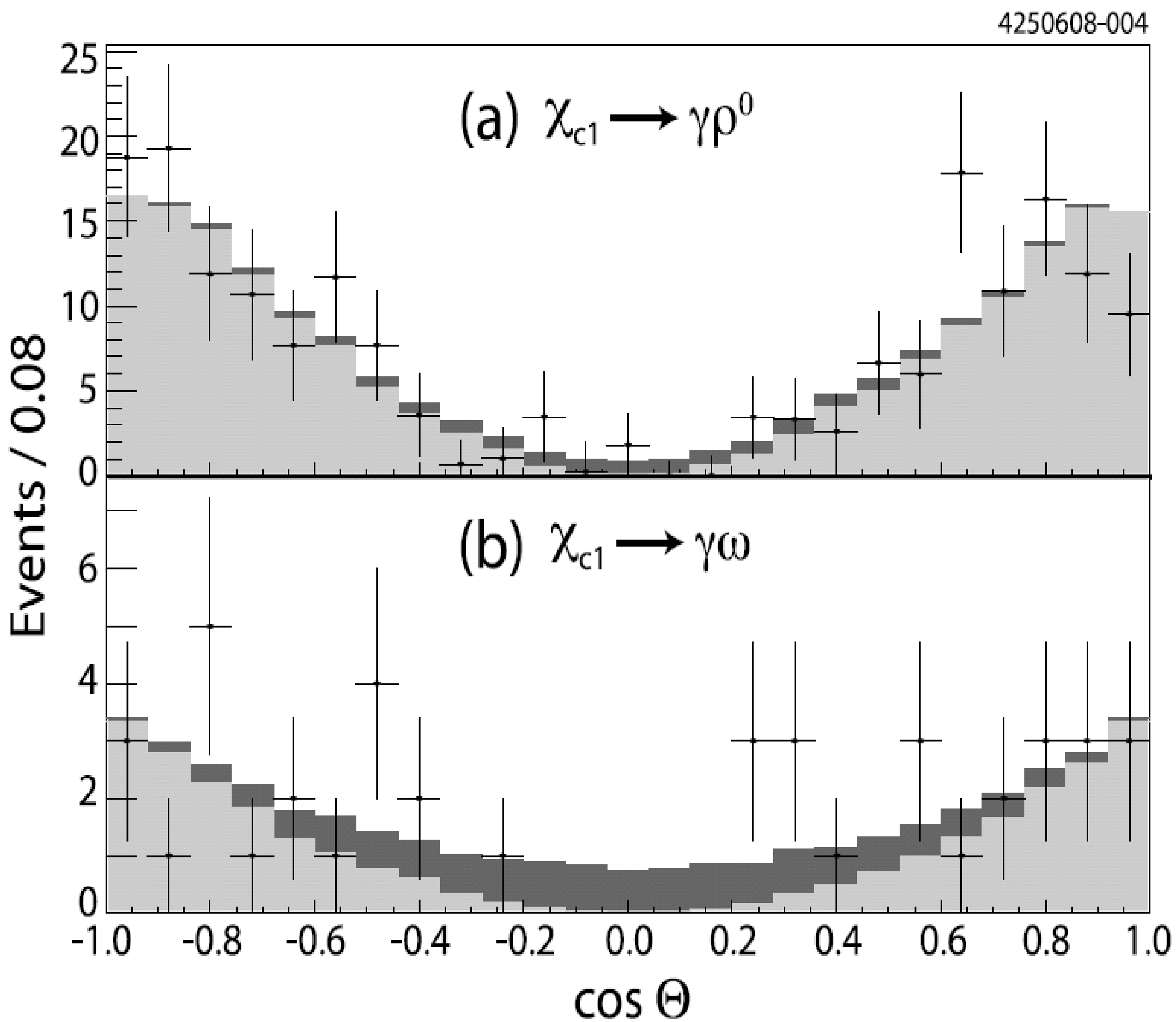
* $D \to K/\pi\, e\, \nu_e$ to be updated with full 818 pb^{-1} $\psi(3770)$ sample
* $D_S \to \mu\, \nu_\mu,\ \tau\, \nu_\tau$ to be updated with full 600 pb^{-1} 4170 MeV sample

BES-III will contribute and exceed all of these results in the near future

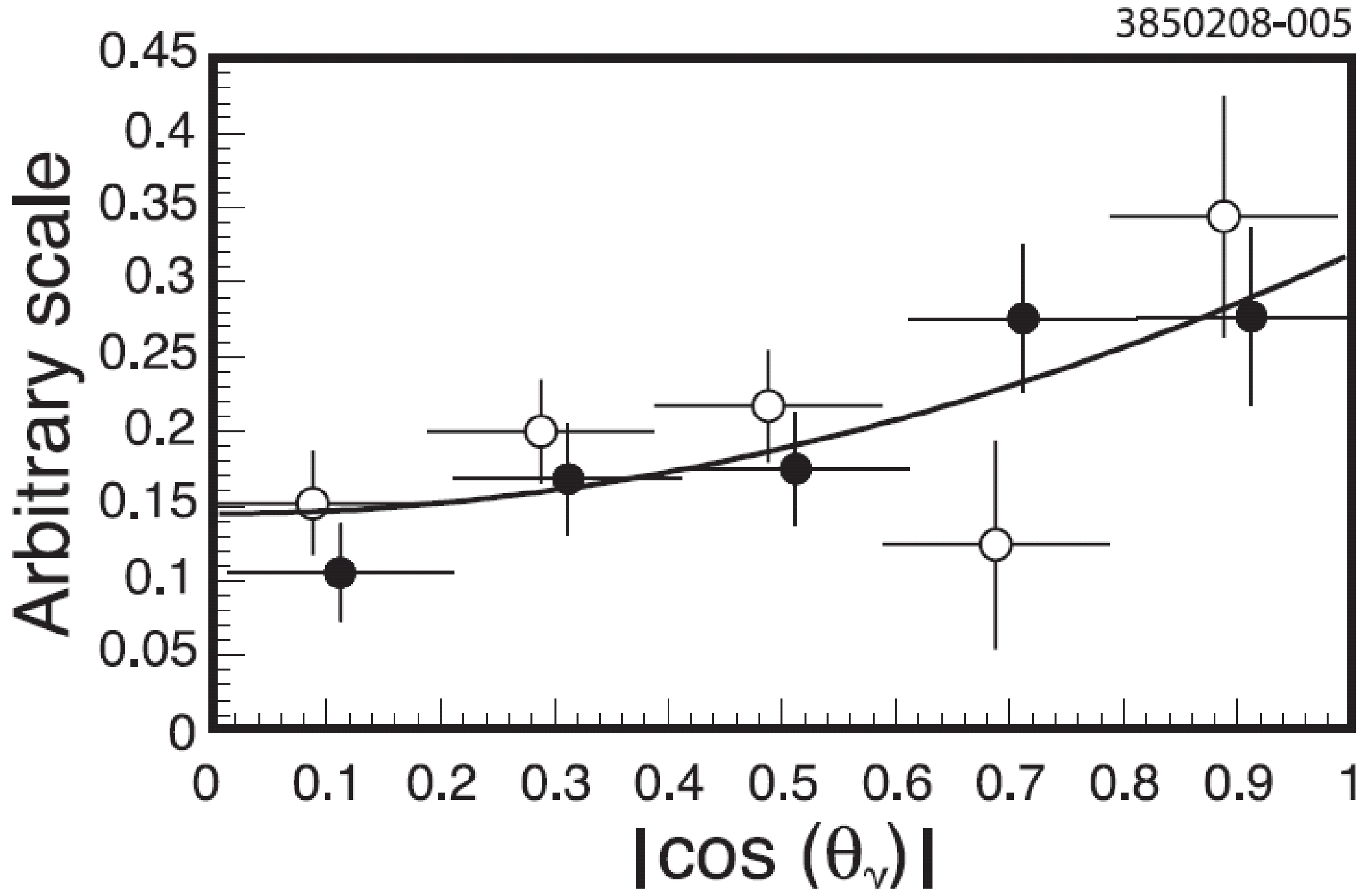
Very exciting time to be part of the BES-III Collaboration!

Backup Slides

$\chi_{c1} \rightarrow \gamma V$ ($V = \rho^0, \omega$) Ang Dist



$h_c \to \gamma\, \eta_c(1S)$ Angular Distribution



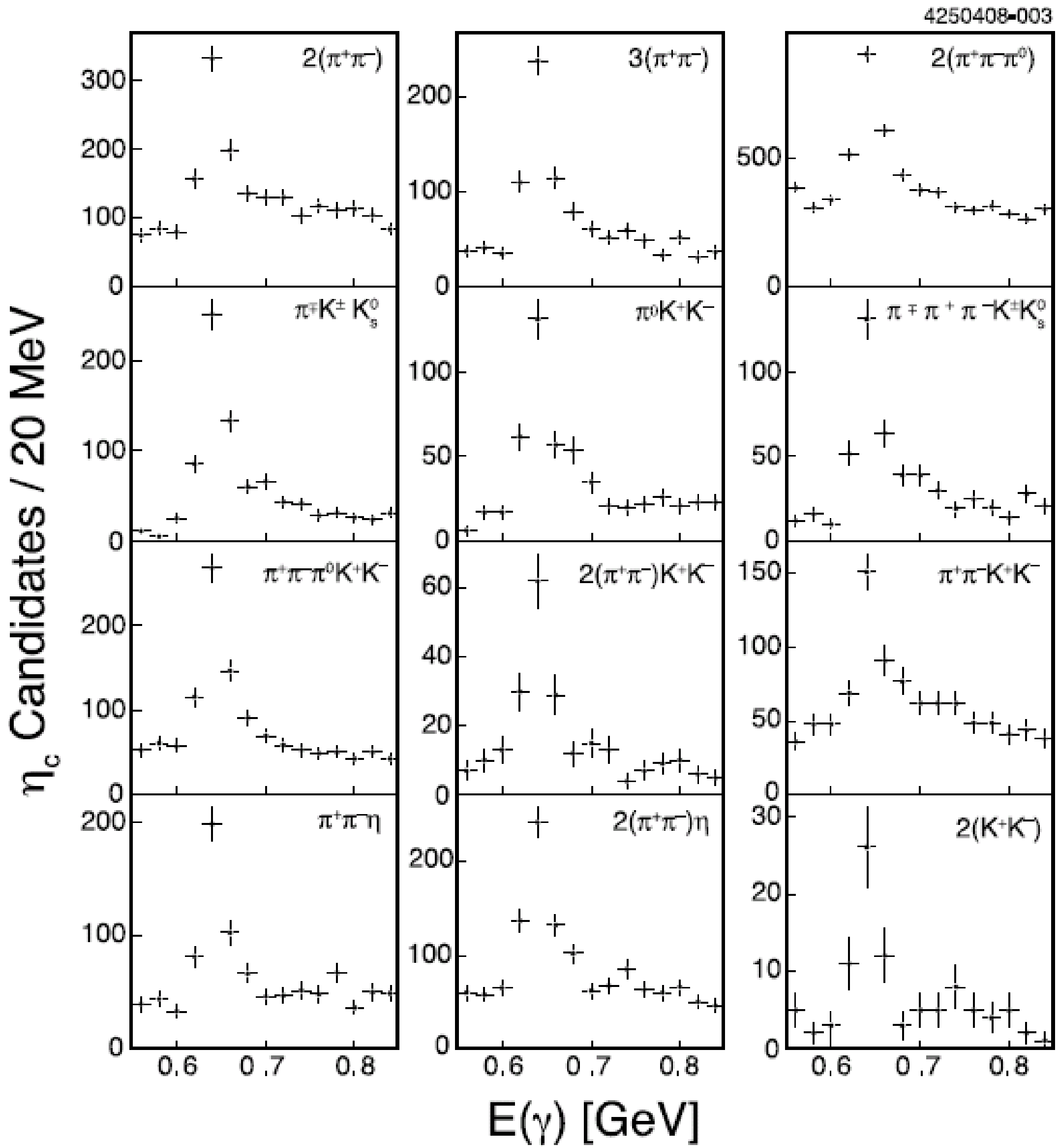
○ Inclusive analysis

● Exclusive analysis

Line: $P(\cos\theta) = 1 + (1.20 \pm 0.53)\cos^2\theta$

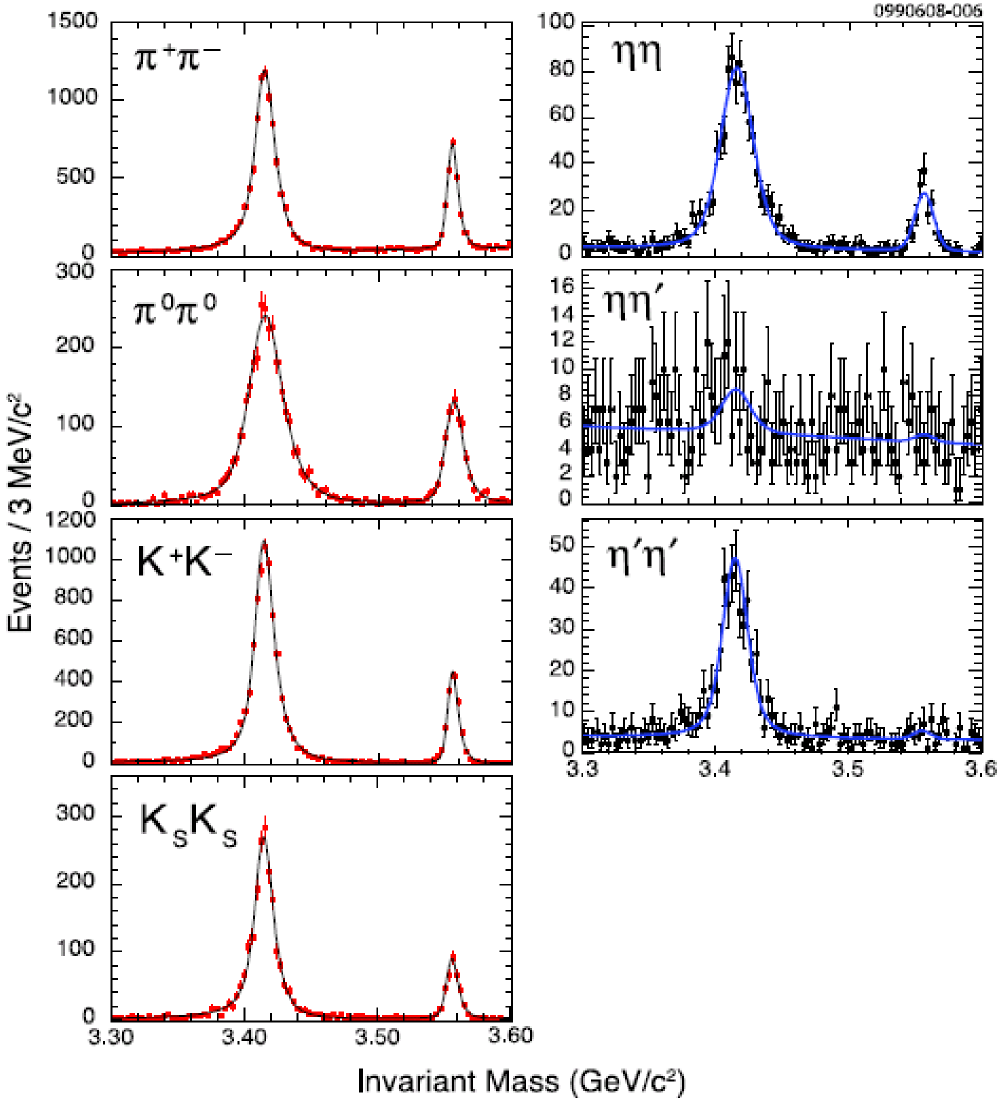
Photon $\cos\theta$ in h_c rest frame

Exclusive η_c modes from $\psi(2S) \to \gamma\,\eta_c$



$\chi_{c\{0,2\}} \rightarrow$ Meson Anti-meson

To be subm to PRD RC

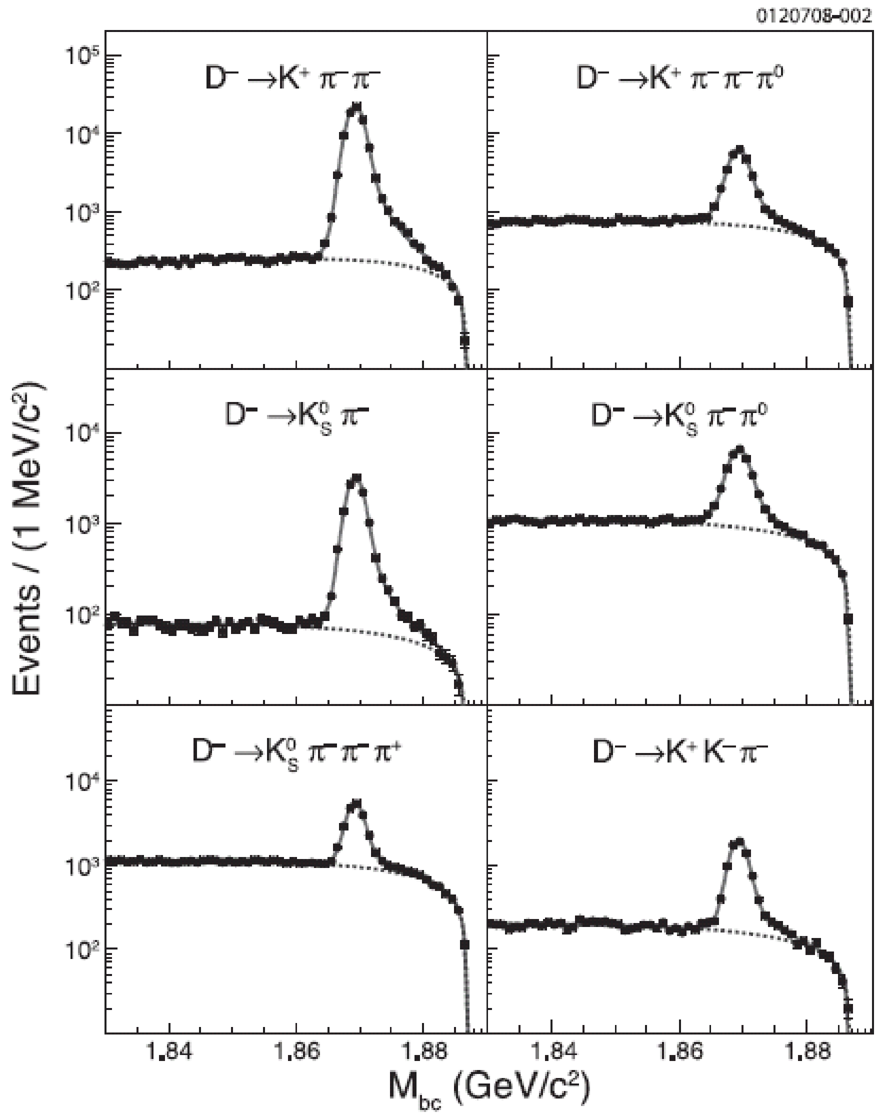


$\chi_{c\{0,2\}} \to$ Meson Anti-meson

To be subm to PRD RC

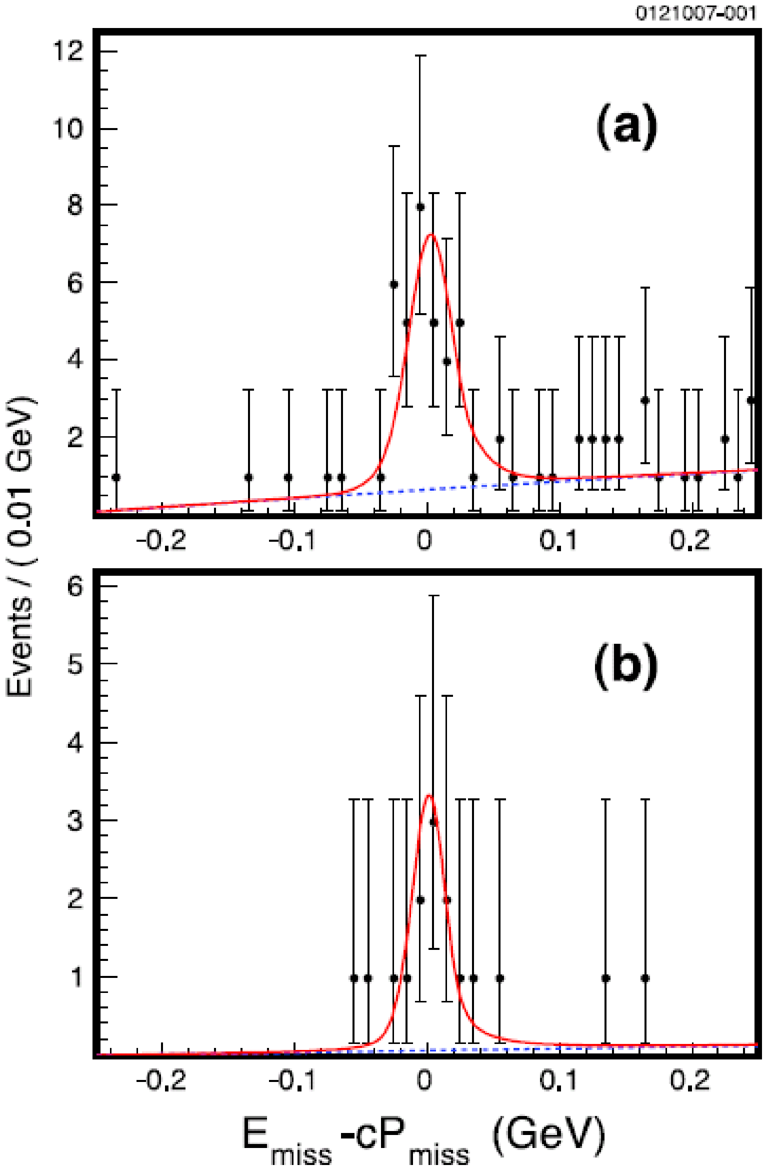
Mode		χ_{c0}	χ_{c2}
$\pi^+\pi^-$	This Work	$6.37 \pm 0.08 \pm 0.29 \pm 0.32$	$1.59 \pm 0.04 \pm 0.07 \pm 0.10$
	PDG [5]	4.87 ± 0.40	1.42 ± 0.16
$\pi^0\pi^0$	This Work	$2.94 \pm 0.07 \pm 0.32 \pm 0.15$	$0.68 \pm 0.03 \pm 0.07 \pm 0.04$
	PDG	$2.43 \pm .20$	0.71 ± 0.08
K^+K^-	This Work	$6.47 \pm 0.08 \pm 0.33 \pm 0.32$	$1.13 \pm 0.03 \pm 0.06 \pm 0.07$
	PDG	5.5 ± 0.6	0.78 ± 0.14
$K^0_S K^0_S$	This Work	$3.49 \pm 0.08 \pm 0.17 \pm 0.17$	$0.53 \pm 0.03 \pm 0.03 \pm 0.03$
	PDG	2.77 ± 0.34	0.68 ± 0.11
$\eta\eta$	This Work	$3.18 \pm 0.13 \pm 0.31 \pm 0.16$	$0.51 \pm 0.05 \pm 0.05 \pm 0.03$
	PDG	2.4 ± 0.4	< 0.5
$\eta\eta'$	This Work	< 0.25	< 0.06
		$(0.16 \pm 0.06 \pm 0.01 \pm 0.01)$	$(0.013 \pm 0.031 \pm 0.001 \pm 0.001)$
	PDG	< 0.5	< 0.26
$\eta'\eta'$	This Work	$2.12 \pm 0.13 \pm 0.18 \pm 0.11$	< 0.10
			$(0.056 \pm 0.032 \pm 0.005 \pm 0.003)$
	PDG	1.7 ± 0.4	< 0.4

$D^+ \to \eta\, e^+ \nu_e$

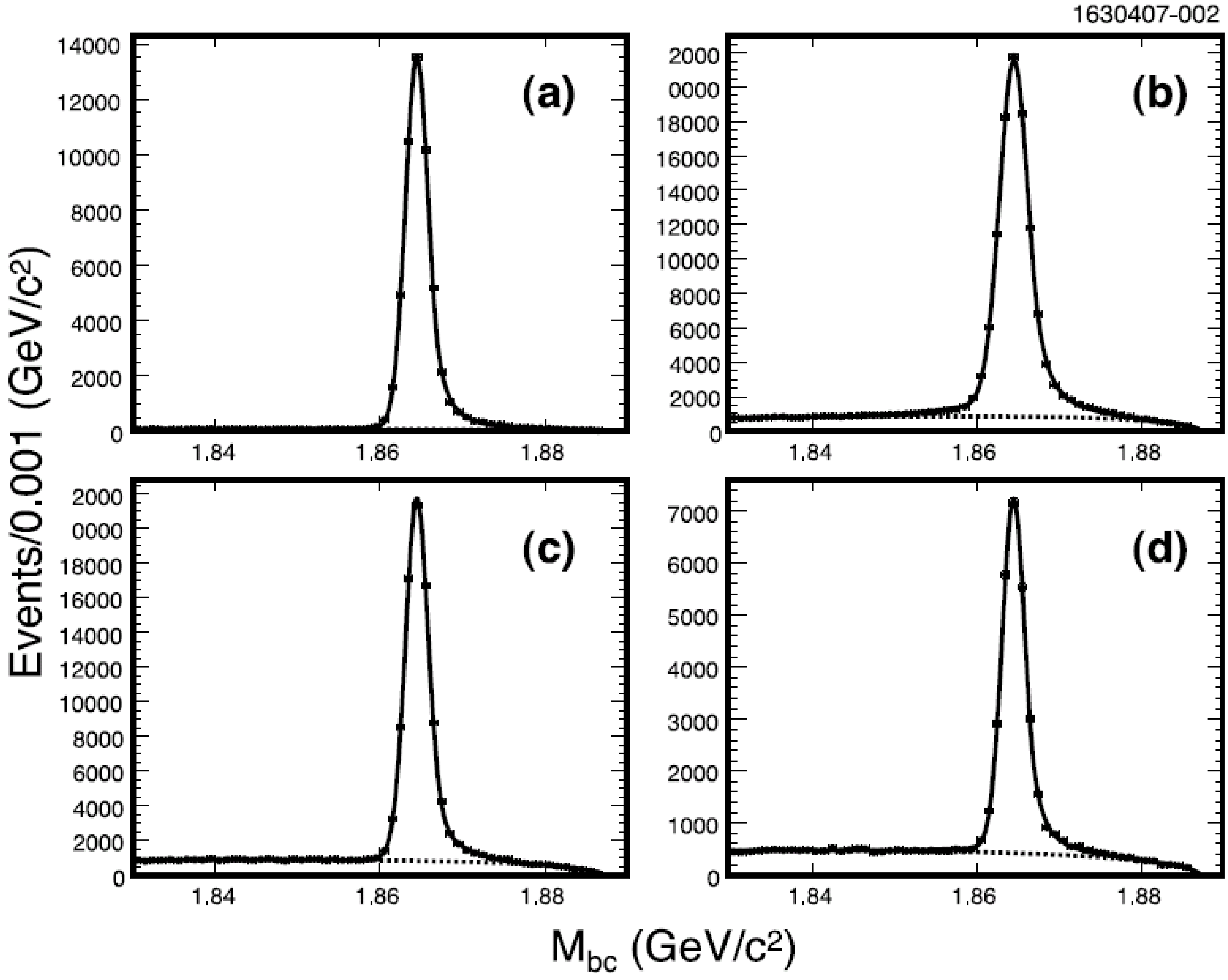

0120708-002
$D^- \to K^+ \pi^- \pi^-$
$D^- \to K^+ \pi^- \pi^- \pi^0$
$D^- \to K^0_S \pi^-$
$D^- \to K^0_S \pi^- \pi^0$
$D^- \to K^0_S \pi^- \pi^- \pi^+$
$D^- \to K^+ K^- \pi^-$
Events / (1 MeV/c^2)
10^2
10^3
10^4
10^5
1.84
1.86
1.88
M_{bc} (GeV/c^2)

$D^+ \to \eta\, e^+ \nu_e$

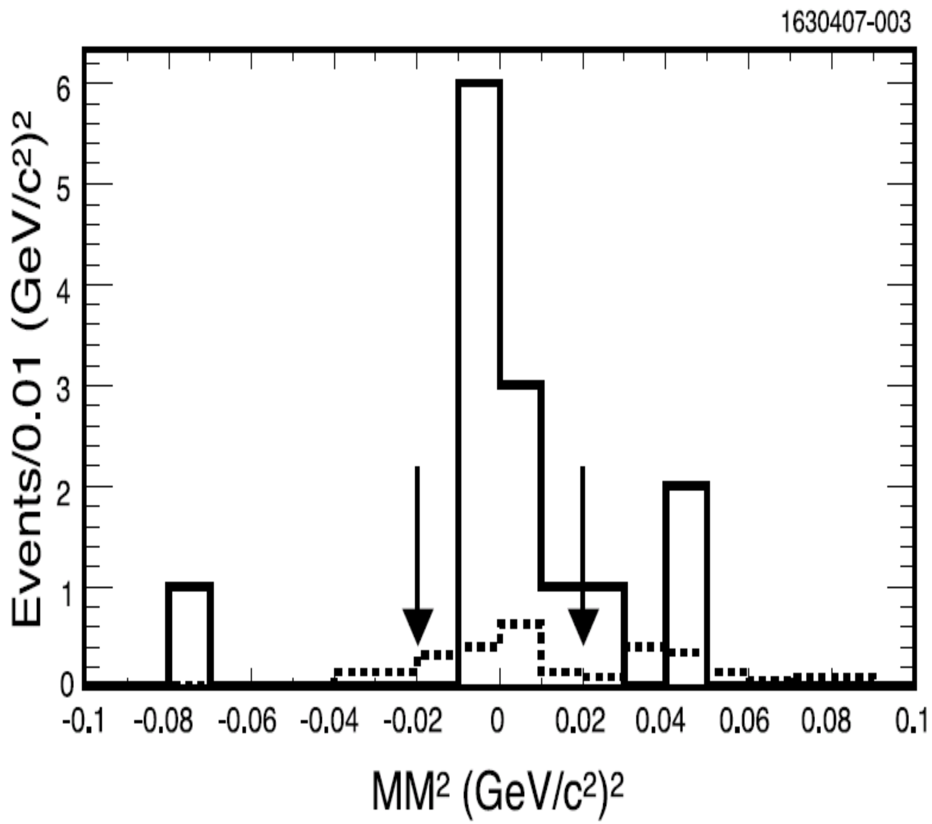
Decay Mode	ϵ (%)	N_{signal} (C.L. interval)	$\mathcal{B}$ or U.L. ($\times 10^{-4}$)	U.L.($\times 10^{-4}$) (PDG)	$\mathcal{B}(\times 10^{-4})$ (ISGW2 [14])	$\mathcal{B}(\times 10^{-4})$ (FK [15])
$D^+ \to \eta(\gamma\gamma)e^+\nu_e$	38.4 ± 0.2	32.6 ± 6.7	$13.2 \pm 2.3 \pm 0.6$			
$D^+ \to \eta(\pi^+\pi^-\pi^0)e^+\nu_e$	26.8 ± 0.2	13.3 ± 4.0	$13.6 \pm 3.7 \pm 0.5$			
$D^+ \to \eta e^+\nu_e$ Combined			$13.3 \pm 2.0 \pm 0.6$	<70	11	10
$D^+ \to \eta'(\pi^+\pi^-\eta \to \pi^+\pi^-\gamma\gamma)e^+\nu_e$	3.38 ± 0.02	(0.00, 2.30)	<4.4			
$D^+ \to \eta'(\pi^+\pi^-\eta \to 2(\pi^+\pi^-)\pi^0)e^+\nu_e$	0.85 ± 0.01	(0.00, 2.30)	<17.3			
$D^+ \to \eta' e^+\nu_e$ Combined	4.23 ± 0.02	(0.00, 2.30)	<3.5	<110	5	1.6
$D^+ \to \phi(K^+K^-)e^+\nu_e$	8.97 ± 0.10	(0.00, 2.30)	<1.6	<209		

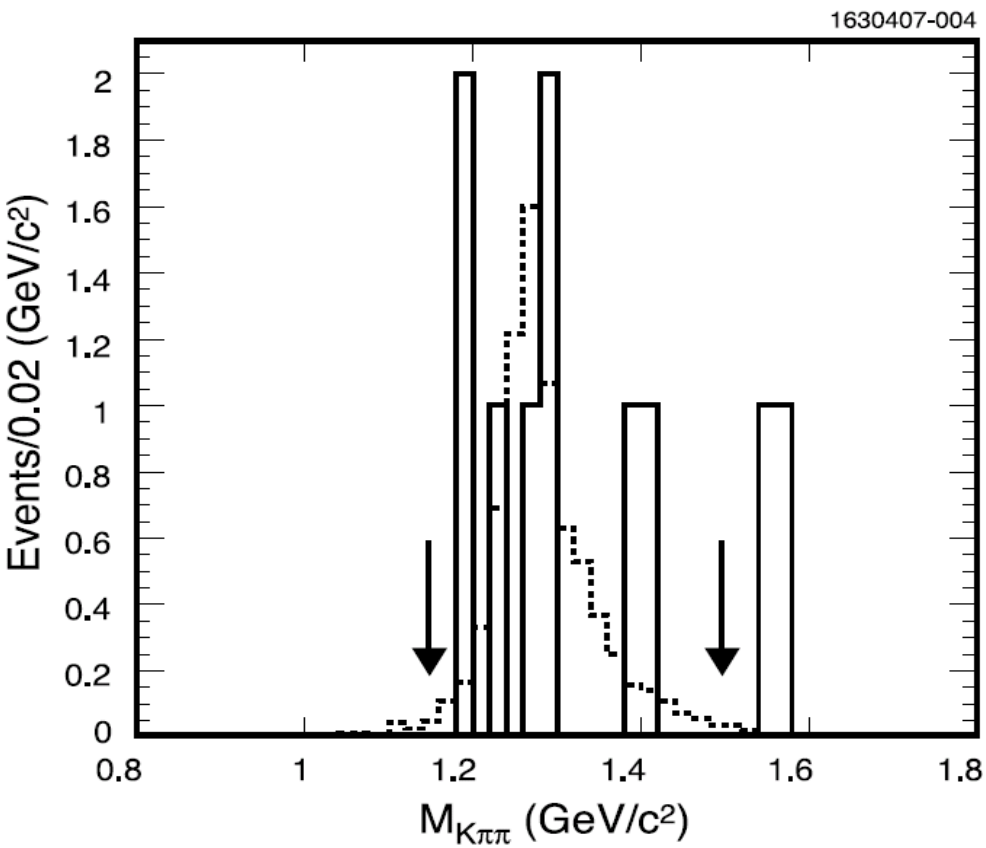


$D^0 \to K^- \pi^+ \pi^- e^+ \nu_e$



$D^0 \to K^- \pi^+ \pi^- e^+ \nu_e$





Signal has significance of 4.0σ

$B(D^0 \to K^- \pi^+ \pi^- e^+ \nu_e) = (2.8\ ^{+1.4}_{-1.1} \pm 0.2) \times 10^{-4}$

Using PDG $B(K_1^-(1270) \to K^- \pi^+ \pi^-)$,

$B(D^0 \to K_1^-(1270)\, e^+ \nu_e) = (7.6\ ^{+4.1}_{-3.0} \pm 0.6 \pm 0.7) \times 10^{-4}$

This gives $D^0 \to K_1^-(1270)\, e^+ \nu_e$ as 2% of total SL width, consistent with ISGW2