Electron Positron Collisions in the Charmonium Region: Results from CLEO-c and BESIII

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April 1, 2012

April APS Meeting
Atlanta

Outline

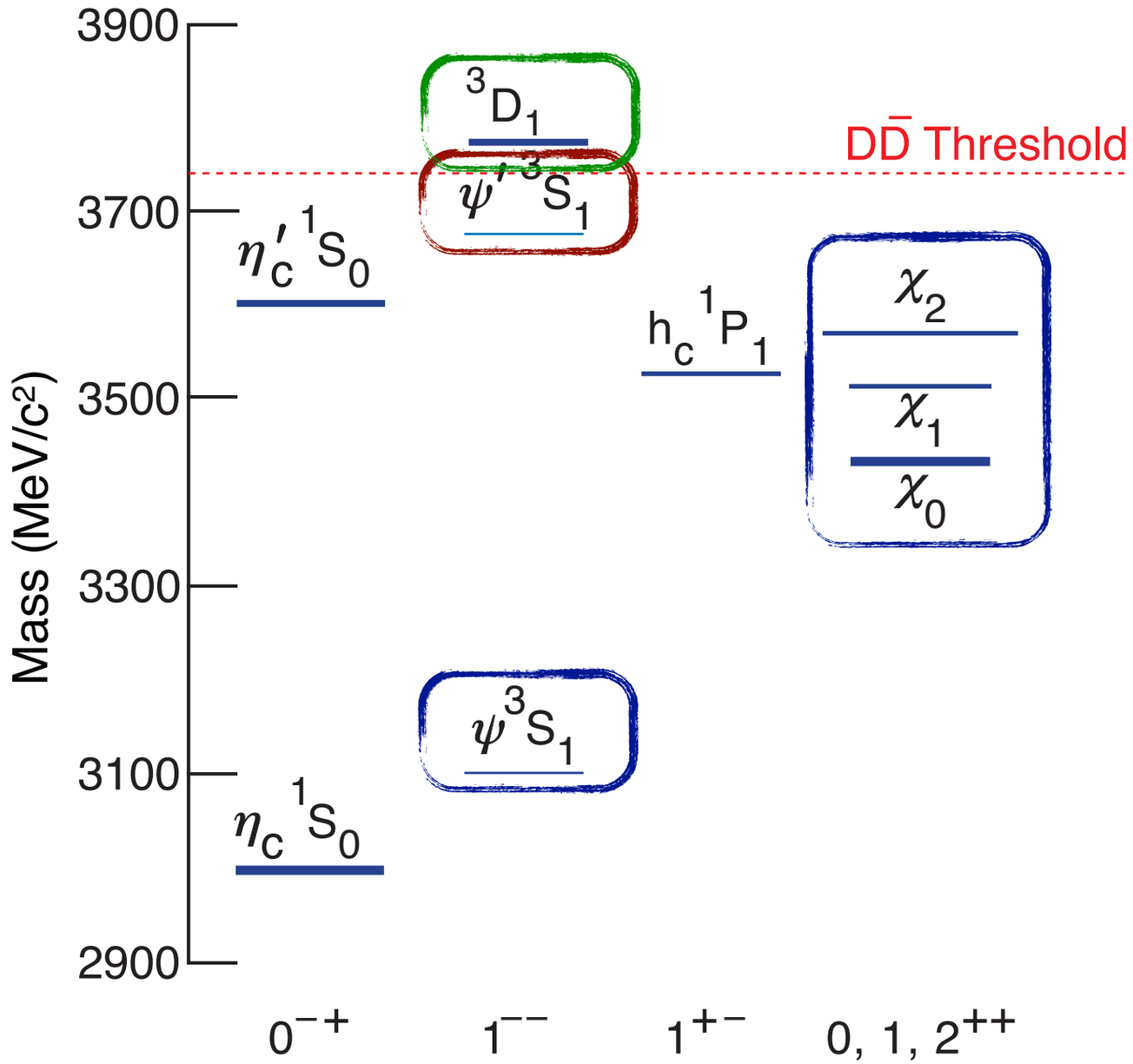
- Broad theme: e^+e^- in the charmonium region provides an opportunity to study QCD with a variety of diverse goals

- Properties of charmonium states, radiative transitions, and decays
  - *a test of QCD in what is thought to be the perturbative regime*
- Decays of charmonium to light hadrons
  - *search for light quark bound states in QCD*
- Hadronic decays of *D* mesons
  - *permits study of light meson states of QCD*
  - *critical input to precision tests of CP violation in the Standard Model*

Only the most recent results will be reported!

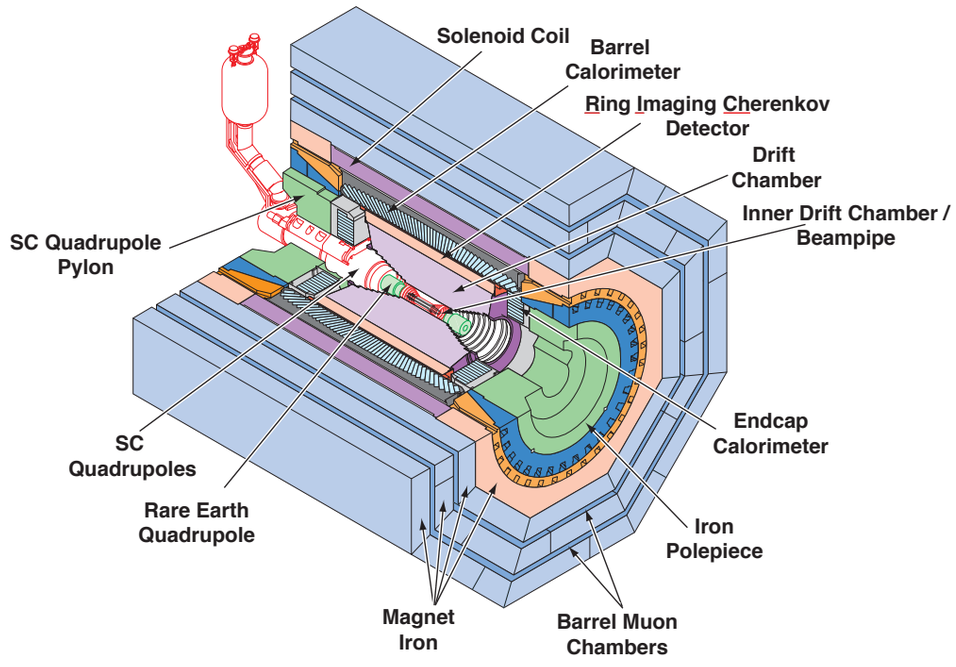
The Charmonium System

- All expected $c\bar{c}$ states below $D\bar{D}$ threshold have been experimentally verified
- The 1^{--} states are easily populated in e^+e^- collisions -- well known and "clean" initial states
- Provides an opportunity to explore the $q\bar{q}$ bound state in heavy quark regime
- Decays of $c\bar{c}$ into light hadrons proceed via "glue-rich" OZI suppressed channels
- Production of quantum correlated $D\bar{D}$ pairs at $\psi(3770)$ provides unique capabilities to measure strong phases

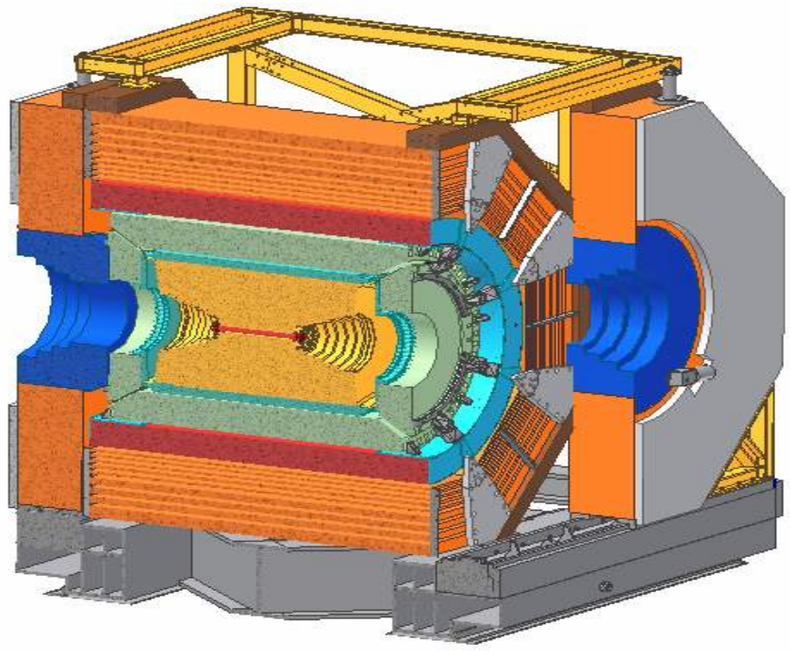


The Detectors

- CLEO-c
  - Cornell Electron Storage Ring (Ithaca, NY)
  - e^+e^- collisions at ψ', ψ(3770), and E_{cm} = 4160 MeV
  - decommissioned in 2008
  - over 100 publications in the charm sector; only a few analyses remaining



- BES III
  - Institute for High Energy Physics (Beijing)
  - successor to BES II
  - world's largest sample of *J*/ψ, ψ', and ψ(3770) decays (and still growing)
  - vibrant current and future program



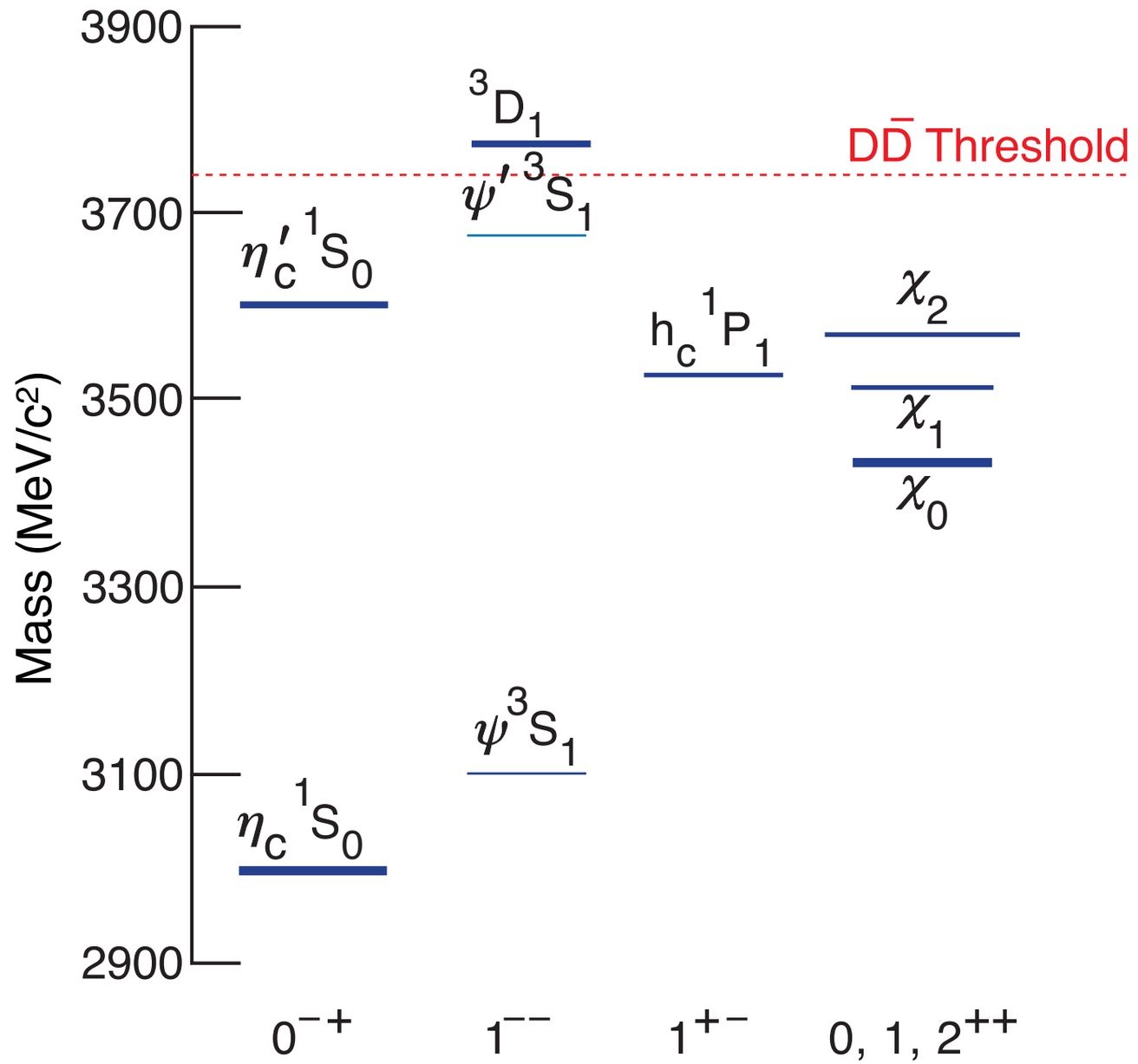
Available (Large*) Data Sets

Energy	Topics	CLEO-c (2008)	BESIII (2011)
J/ψ	light hadron	--	225M decays
ψ'	charmonium, light hadron	26M decays	106M decays
ψ(3770)	*D*	0.8 fb^{-1}	2.9 fb^{-1}
ψ(4040)	charmonium above *DD* threshold	6 pb^{-1}	500 pb^{-1}
E_{cm}=4160 MeV	D_s, charmonium above *DD* threshold	0.6 fb^{-1}	--

**Both have additional data sets for background studies, lineshape scans, etc.*

Charmonium Results

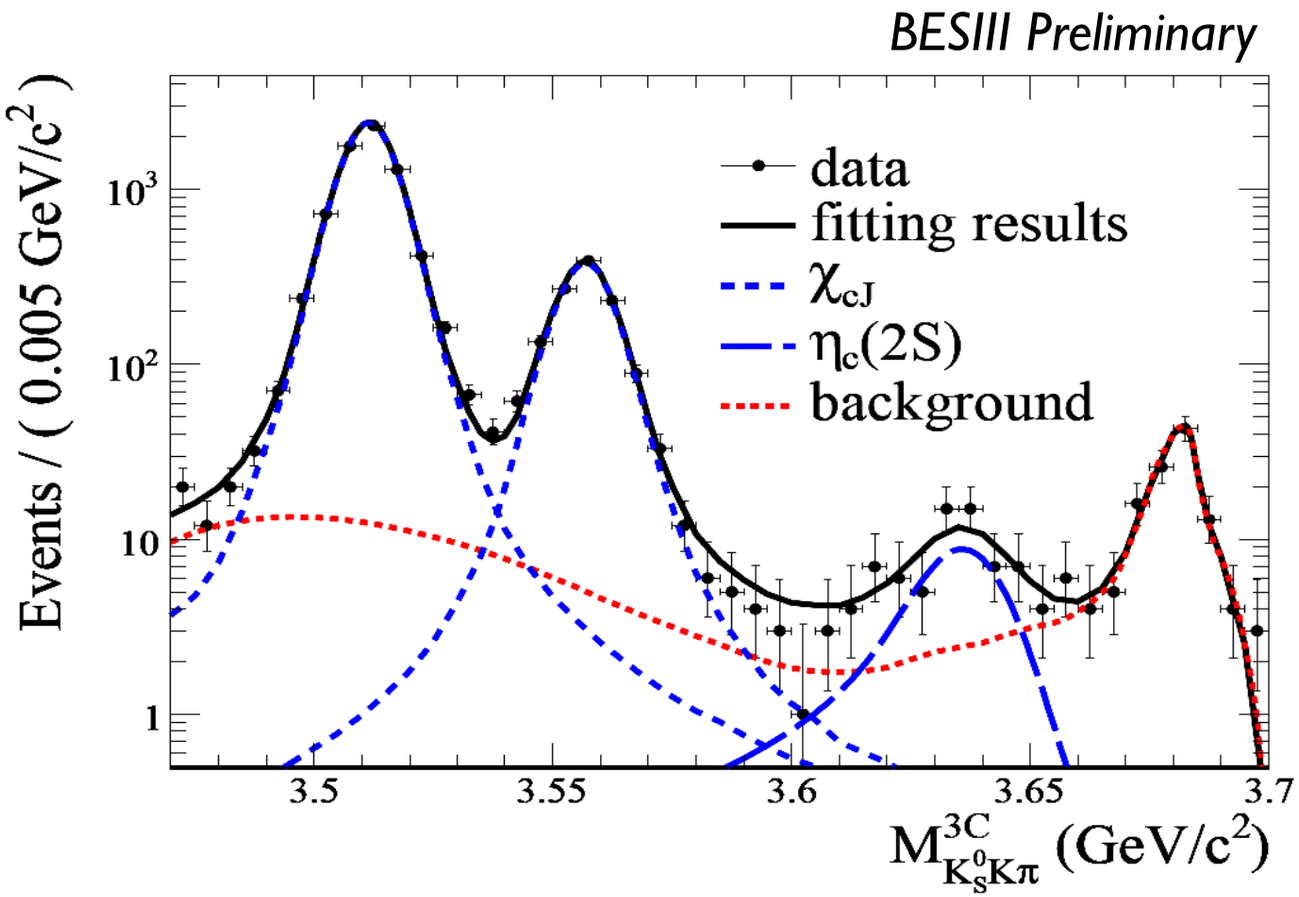
- Bound state of two heavy quarks
- Test perturbative approximations of QCD inspired by positronium-like spectrum
  - radiative transitions
  - hyperfine splittings
- New results:
  - Observation of ψ'→γηc'
  - Magnetic dipole component of ψ'→γχc2
  - Precision $M(\eta_c)$ and $\Gamma(\eta_c)$
  - J/ψ and ψ'→π⁺π⁻π⁰ (no perturbative QCD here!)



First Observation: $\psi' \to \gamma\eta_c'$

- Expect magnetic dipole transition from $\psi' \to \gamma\eta_c'$
  - Search for $K_s K\pi$ decay mode of the η_c'
- $E_\gamma \approx 50$ MeV: high background
  - use data driven technique to determine background
- Signal significance: > 5σ
- Measure:

$$\mathcal{B}(\psi' \to \gamma\eta_c') \times \mathcal{B}(\eta_c' \to K_S K\pi) = (2.98 \pm 0.57 \pm 0.48) \times 10^{-6}$$



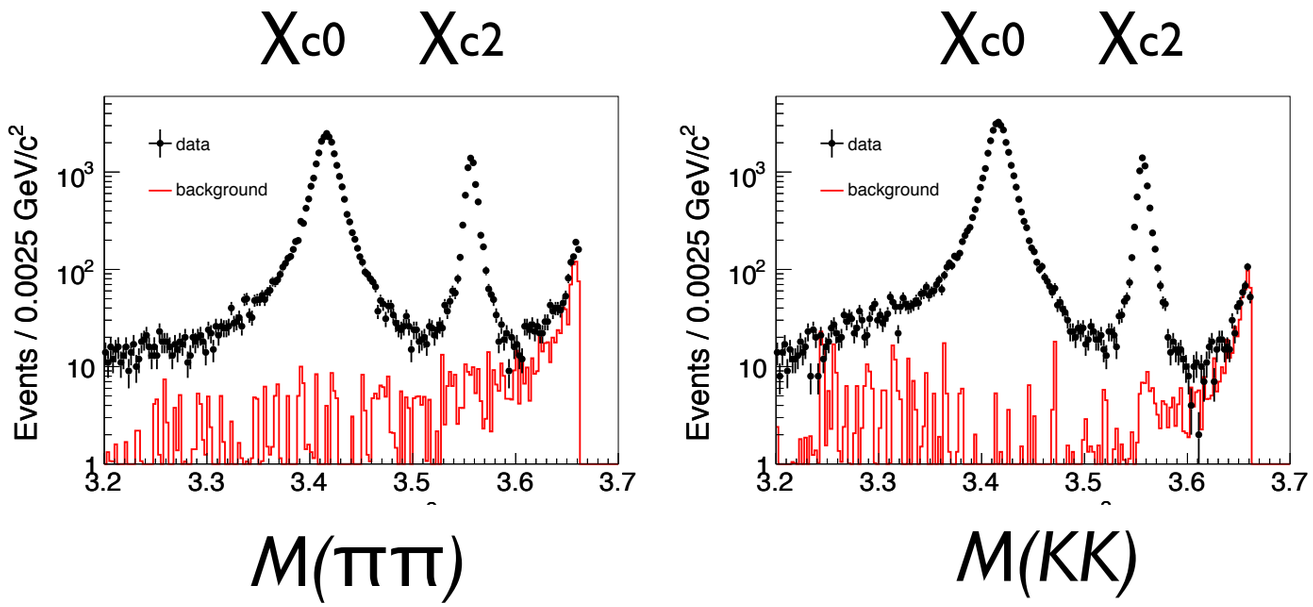
Consistent with potential model predictions: (0.1-6.2)x10^{-4}
[PRL 89, 162002 (2002)]

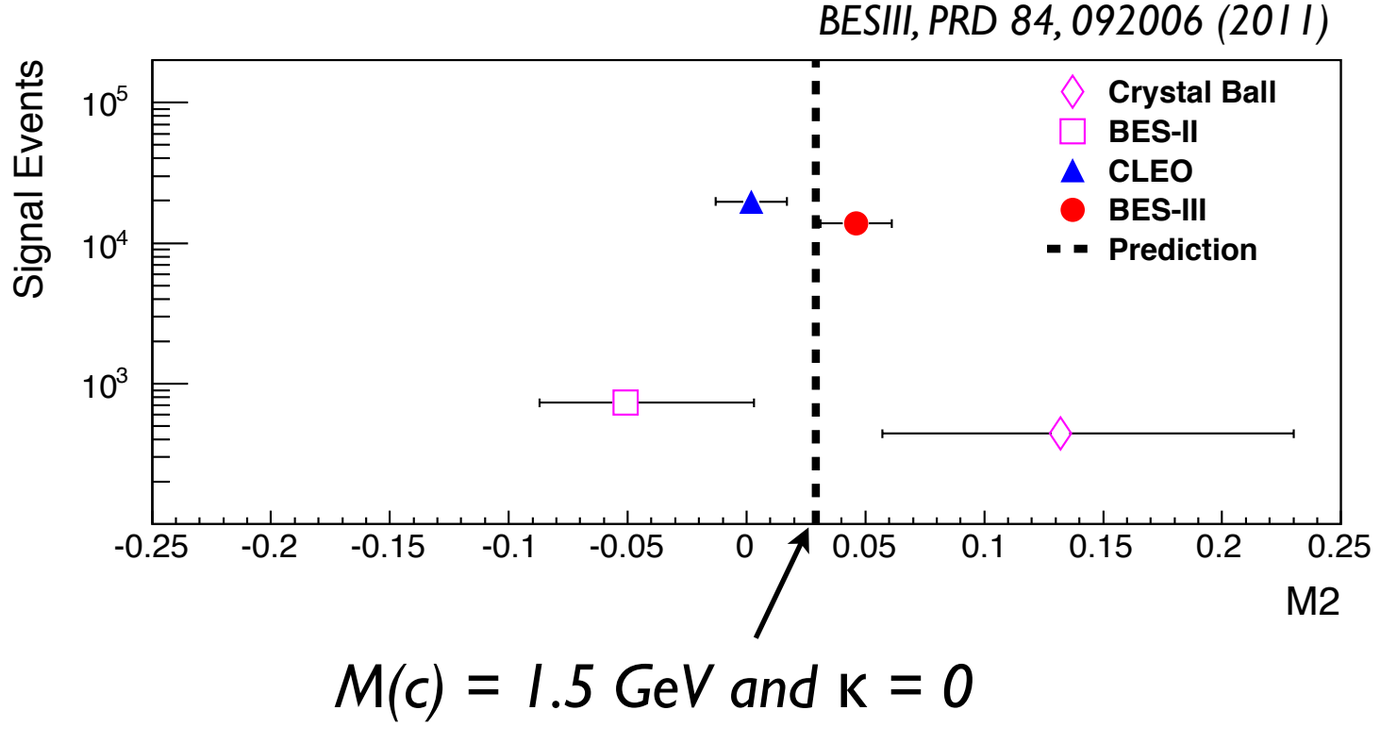
- Combine with BaBar measurement of $B(\eta_c' \to KK\pi)$ to obtain:

$$\mathcal{B}(\psi' \to \gamma\eta_c') = (4.7 \pm 0.9 \pm 3.0) \times 10^{-4}$$

Higher Multipoles in $\psi' \to \gamma\chi_{c2}$

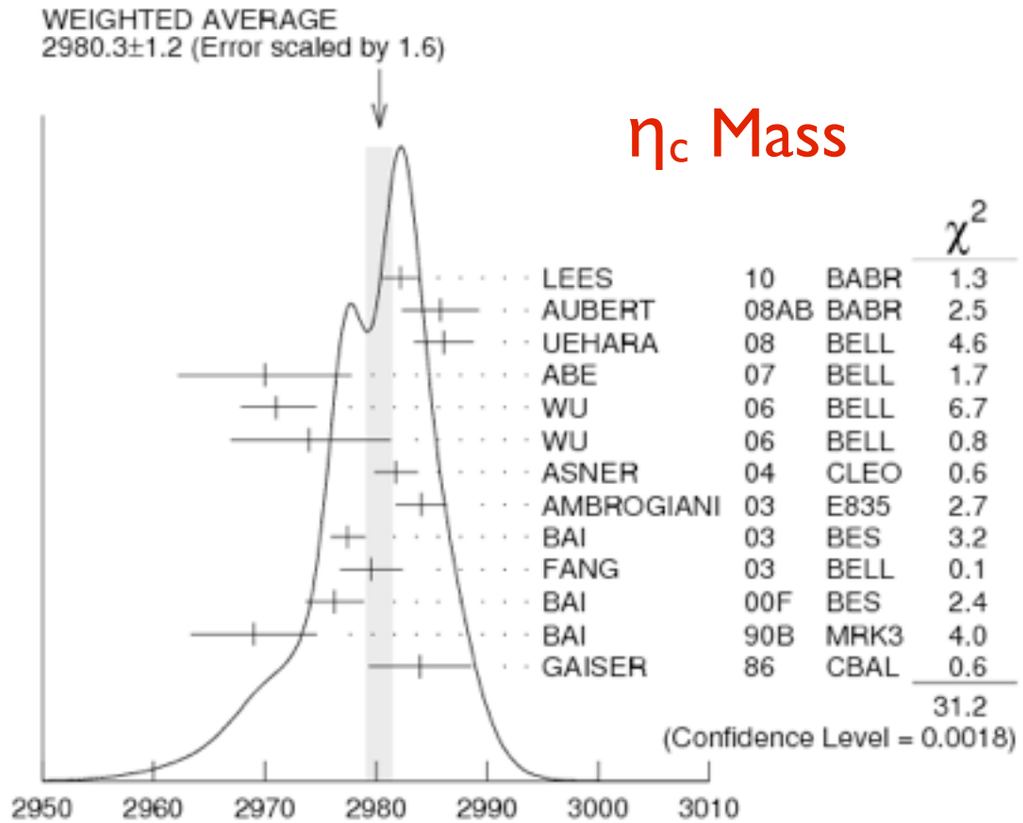
- $\psi' \to \gamma\chi_{c2}$ is dominated by electric dipole (*E1*) transition, but expect some magnetic quadrupole component (*M2*)
- *M2* amplitude provides sensitivity to charm quark anomalous magnetic moment κ
  - expect $M2 = 0.029(1 + \kappa)$
- Use large clean samples of $\chi_{c2} \to \pi\pi$ and $\chi_{c2} \to KK$; χ_{c0} samples used as control since $M2 = 0$
- Extract *M2* using fit to full angular distribution
- Significant signal for *M2* amplitude that is consistent with $\kappa = 0$





Mass and Width of the η_c

- Ground state of cc system, but its properties are not well known
- Error on the measurement of the cc hyperfine splitting: $M(J/\psi) - M(\eta_c)$ is dominated by error on $M(\eta_c)$
  - important experimental input to tests of lattice QCD
- The inconsistency in experimental results may be due to different experimental production mechanisms
  - charmonium radiative decay
  - two-photon fusion or *B* decay
- CLEO discovered distorted η_c lineshape in charmonium radiative decay, but was unable to parametrize the distortion
  [PRL 102, 011801 (2009)]



Mass and Width of the η_c

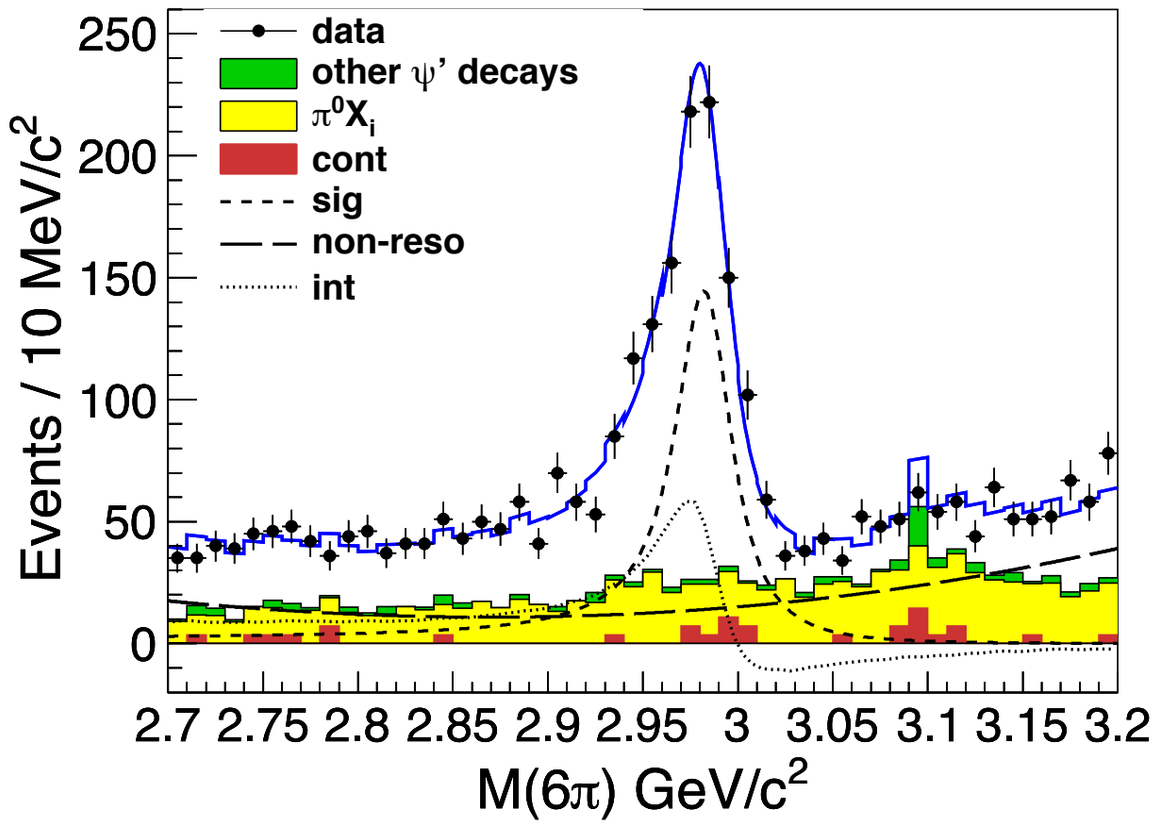
- Perform a simultaneous fit of six different exclusive decay modes of the η_c (two examples at right)
- Parametrize the lineshape asymmetry as an interference between two processes
  - $\psi' \to \gamma\eta_c;\ \eta_c \to X$
  - $\psi' \to \gamma X$
- Final results are the most precise to date:

$$M(\eta_c) = 2984.3 \pm 0.6 \pm 0.6 \text{ MeV}/c^2$$

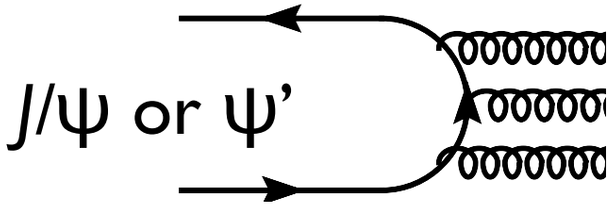
$$\Gamma(\eta_c) = 32.0 \pm 1.2 \pm 1.0 \text{ MeV}$$

- Consistent with B factory results in other production mechanisms and agree with lattice QCD calculations of the charmonium hyperfine splitting

BESIII, arXiv:1111.0398 (to be published in PRL)

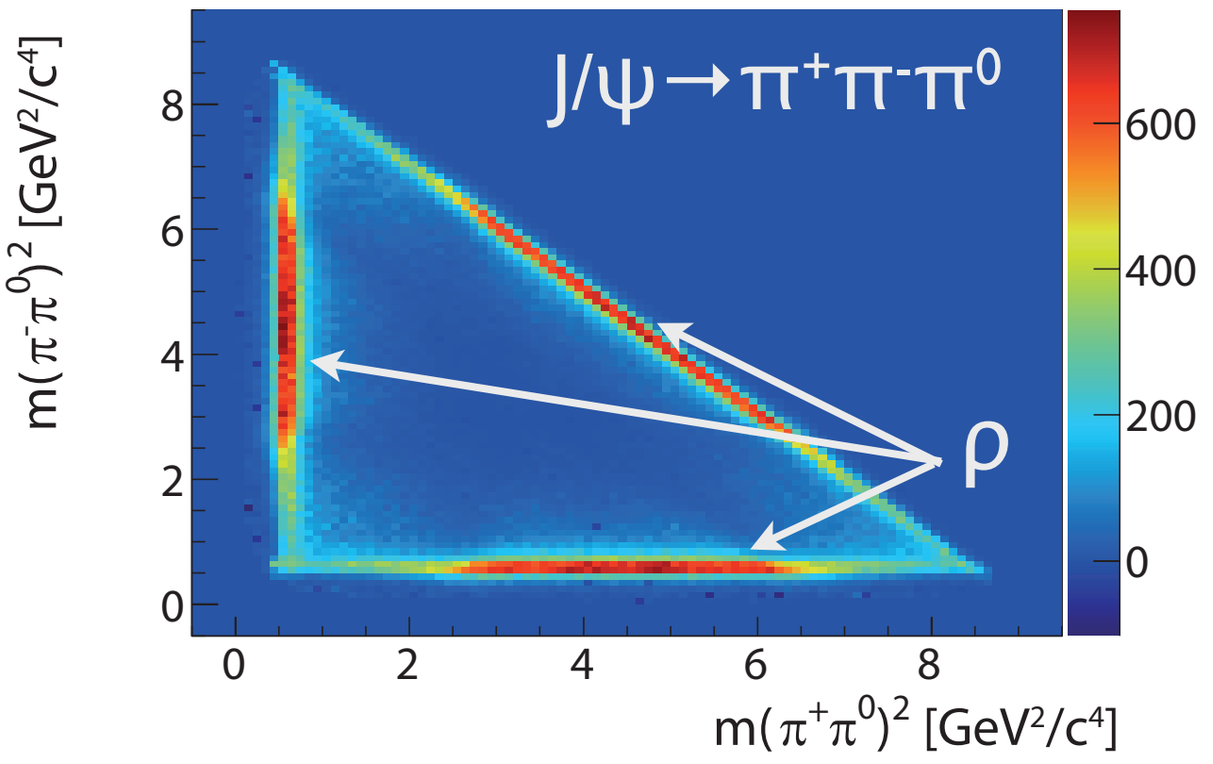


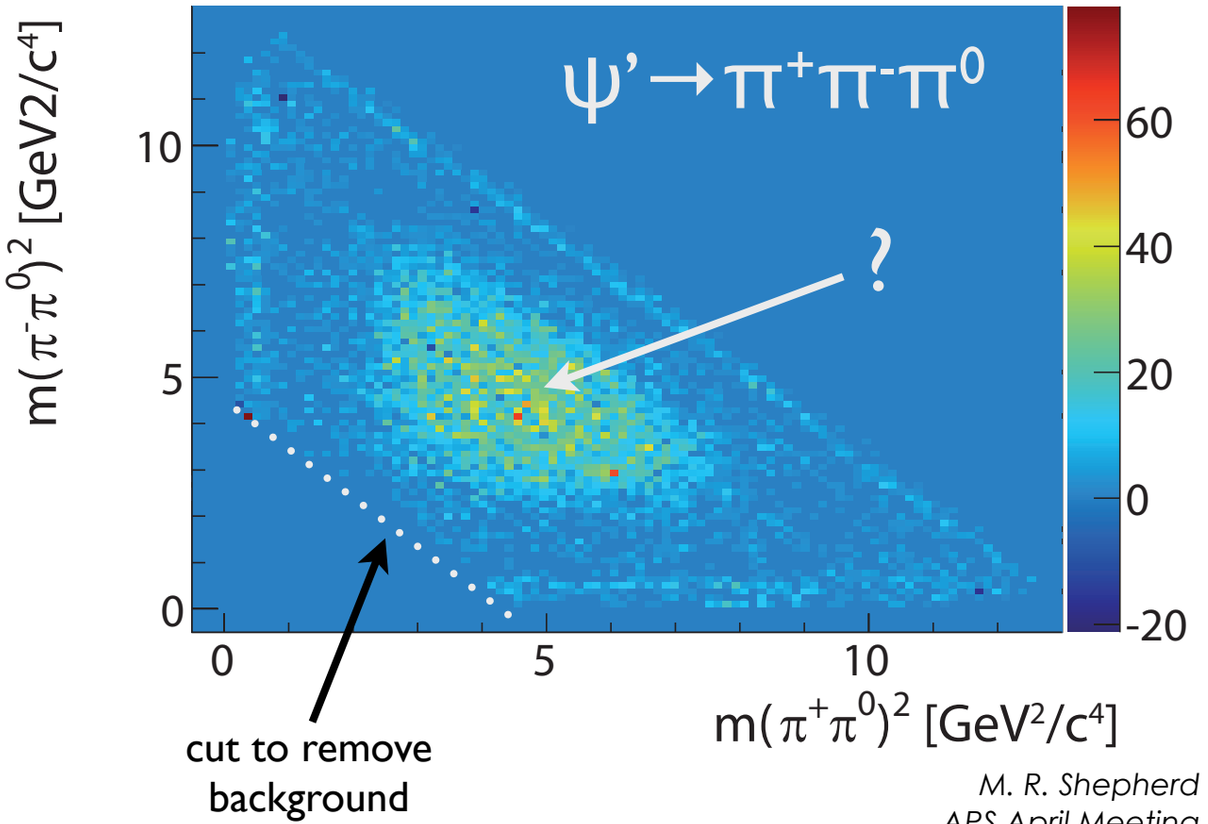
3π Decays of J/ψ and ψ'



- In the perturbative picture both decays should be very similar
  - $c\bar{c}$ annihilation
  - same parent J^{PC}
  - hadronization into 3π at about the same energy scale
- The two Dalitz plots couldn't look any more different!
  - J/ψ is dominated by ρ
  - ψ' is strongly populated by higher mass states absent in J/ψ decay
- Precision measurement of branching ratio

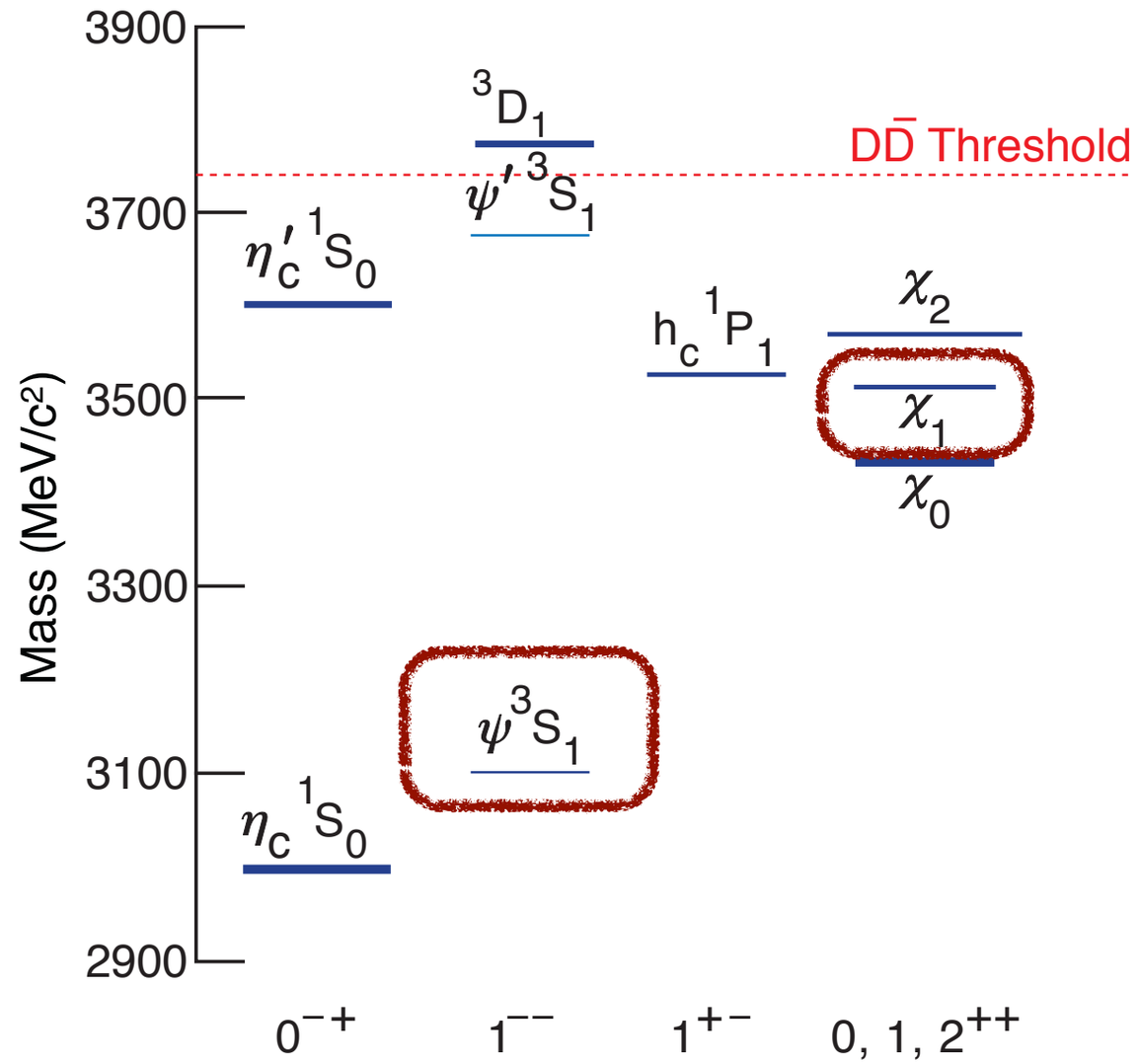
BESIII, arXiv:1202.2048 [to be published in PLB]





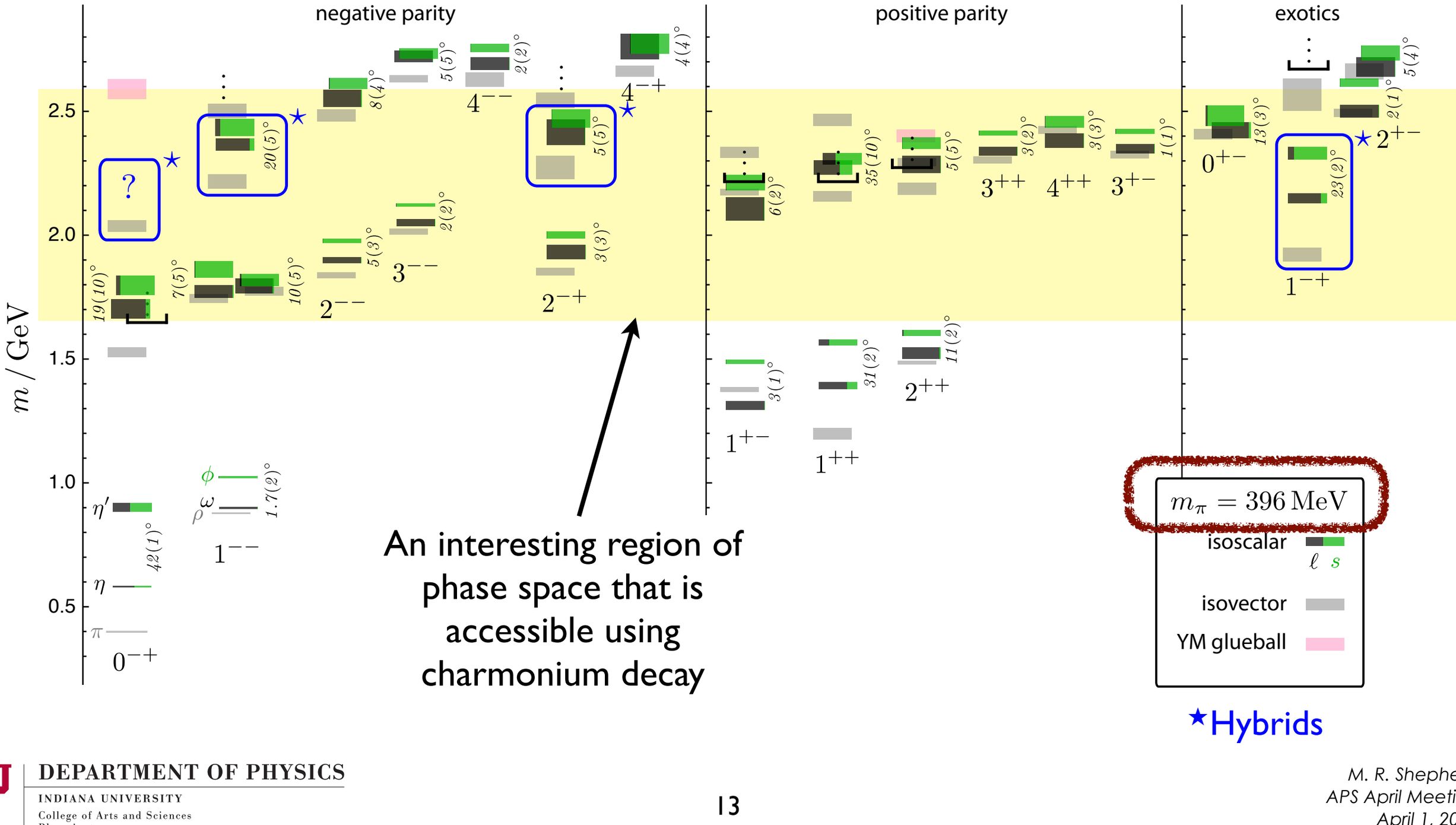
Light Meson Spectroscopy

- Allows opportunity to explore the non-perturbative characteristics of QCD
- Gluons interact with themselves and could form "glueball" or "hybrid" states with constituent glue
  - *Is there any evidence of these states with gluonic degrees of freedom in the spectrum?*
- Production in charmonium is complementary to fixed target mechanisms
  - Initial state is well known, which restricts possible final states
  - glue-rich final state due to OZI-suppressed decays below *DD* threshold
- *Results from both J/Ψ and χ_{c1} decay will be presented; almost any state can be used provided statistics are sufficient*



Unflavored Meson Spectrum from LQCD

J. Dudek
PRD 84, 074023 (2011)



An interesting region of phase space that is accessible using charmonium decay

$J/\psi \to \gamma p\bar{p}$

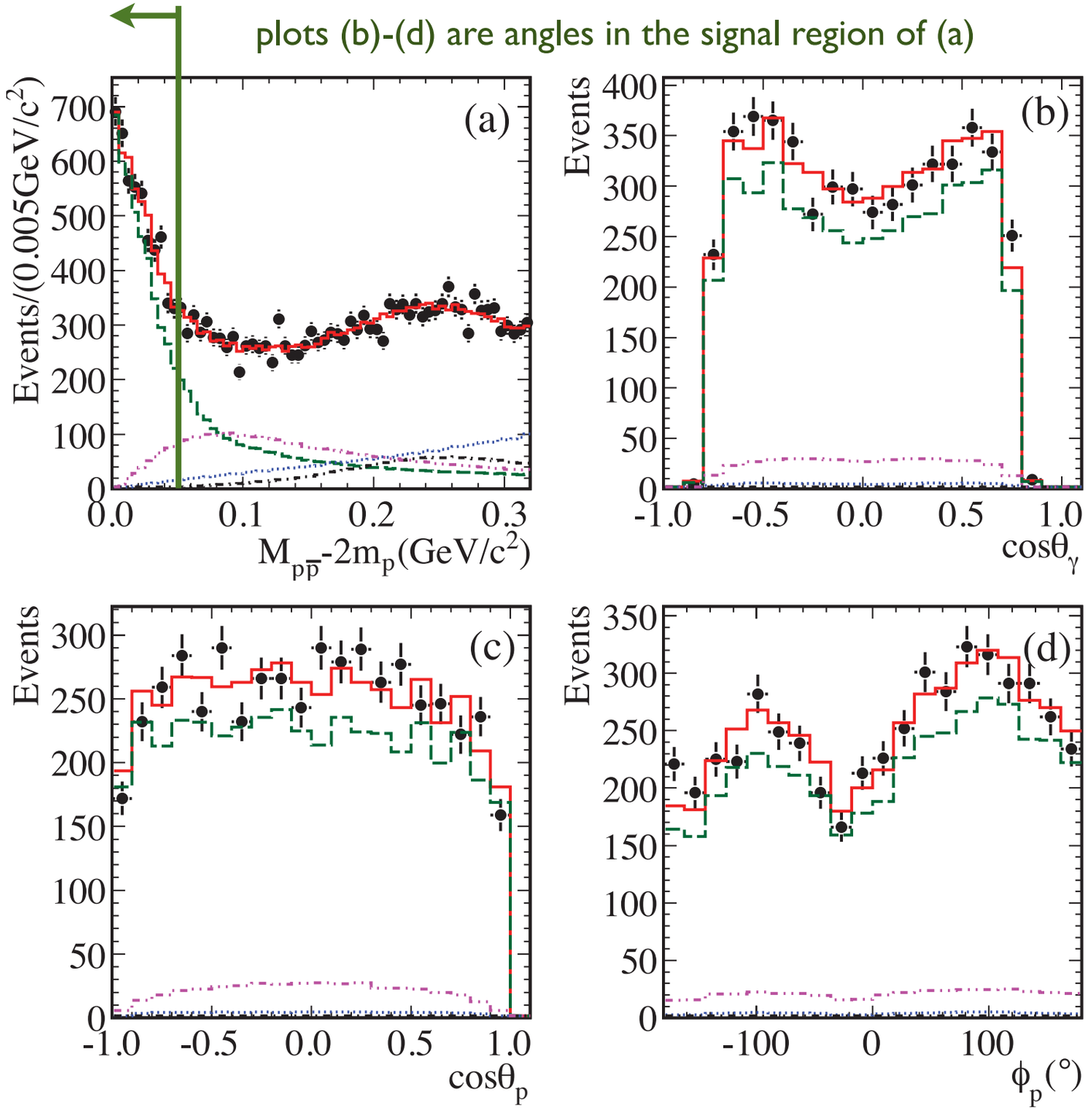
- Threshold enhancement was discovered at BESIII
- Spin-parity analysis is essential for determining place in the spectrum and possible nature
- Also observed in ψ' radiative decay for the first time
- Final results:

$$J^{PC} = 0^{-+}$$

$$M = 1832^{+19}_{-5}\ {}^{+18}_{-17} \pm 19\ \mathrm{MeV}/c^2$$

$$\Gamma < 76\ \mathrm{MeV}$$

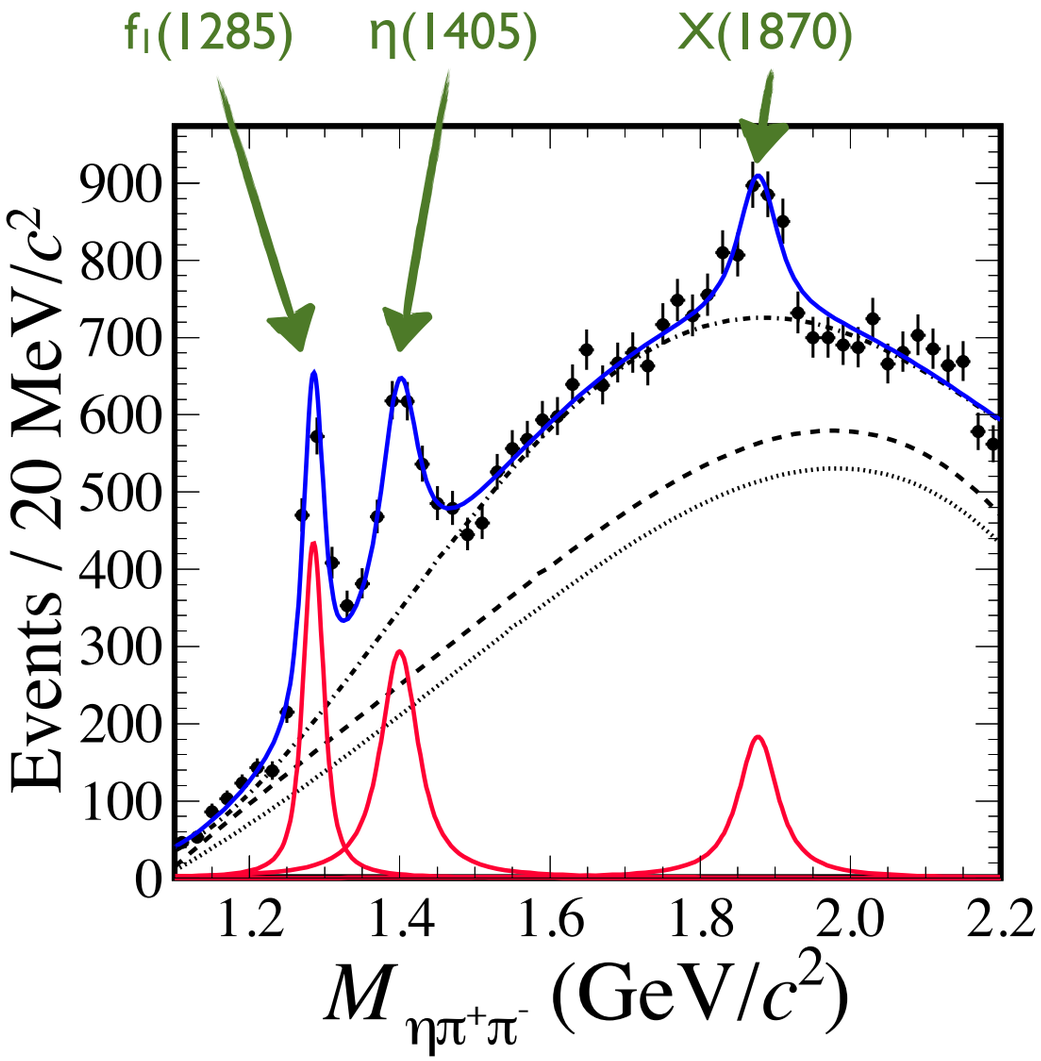
- Nature of this state and its relationship to other states in the region is not clear



BESIII arXiv:1112.09421 (to be published in PRL)

$J/\psi \rightarrow \omega\eta\pi^-\pi^+$

- Study spectrum of $\eta\pi^-\pi^+$ states recoiling against an ω
- Very clear signals for established states $f_1(1285)$ and $\eta(1405)$
  - masses and widths consistent with PDG values
  - no apparent evidence for $\eta(1295)$ reported in other experiments
- New state $X(1870)$ apparent in the spectrum
  - J^P is unknown without further analysis *(C=+)*
  - relation to other X states in this region is not clear (masses and widths somewhat inconsistent)
    - X in $J/\psi \rightarrow \gamma p\bar{p}$ (previous slide)
    - X in $J/\psi \rightarrow \gamma\eta'\pi\pi$ [*BESIII PRL 106, 072002 (2011)*]
- Expect spin-parity analysis in the future



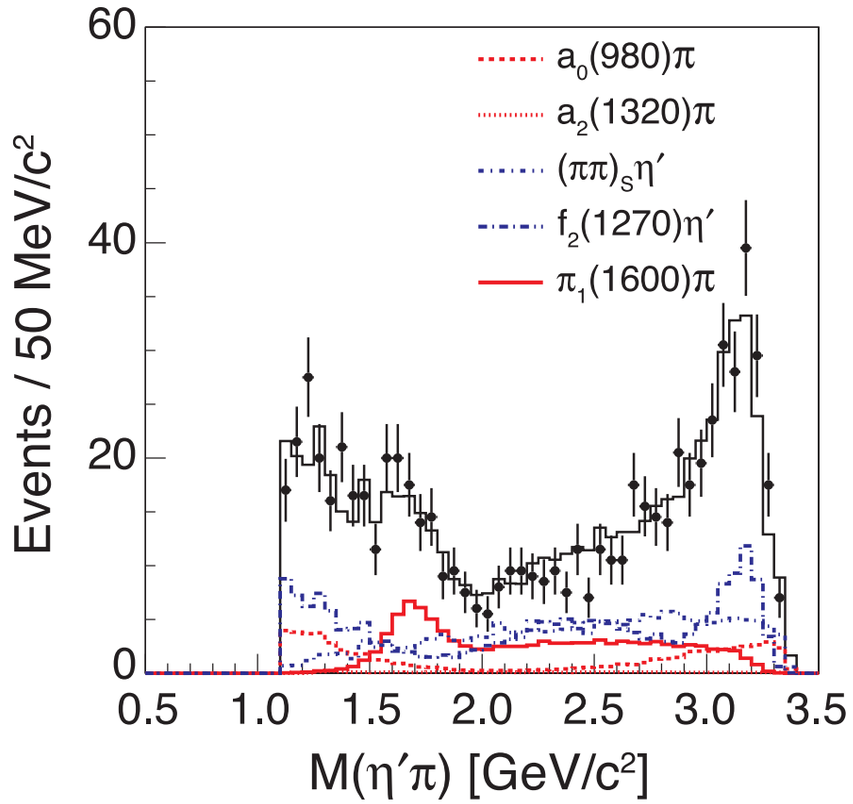
Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}(10^{-4})$
$f_1(1285)$	$1285.1 \pm 1.0^{+1.6}_{-0.3}$	$22.0 \pm 3.1^{+2.0}_{-1.5}$	$1.25 \pm 0.10^{+0.19}_{-0.20}$
$\eta(1405)$	$1399.8 \pm 2.2^{+2.8}_{-0.1}$	$52.8 \pm 7.6^{+0.1}_{-7.6}$	$1.89 \pm 0.21^{+0.21}_{-0.23}$
$X(1870)$	$1877.3 \pm 6.3^{+3.4}_{-7.4}$	$57 \pm 12^{+19}_{-4}$	$1.50 \pm 0.26^{+0.72}_{-0.36}$

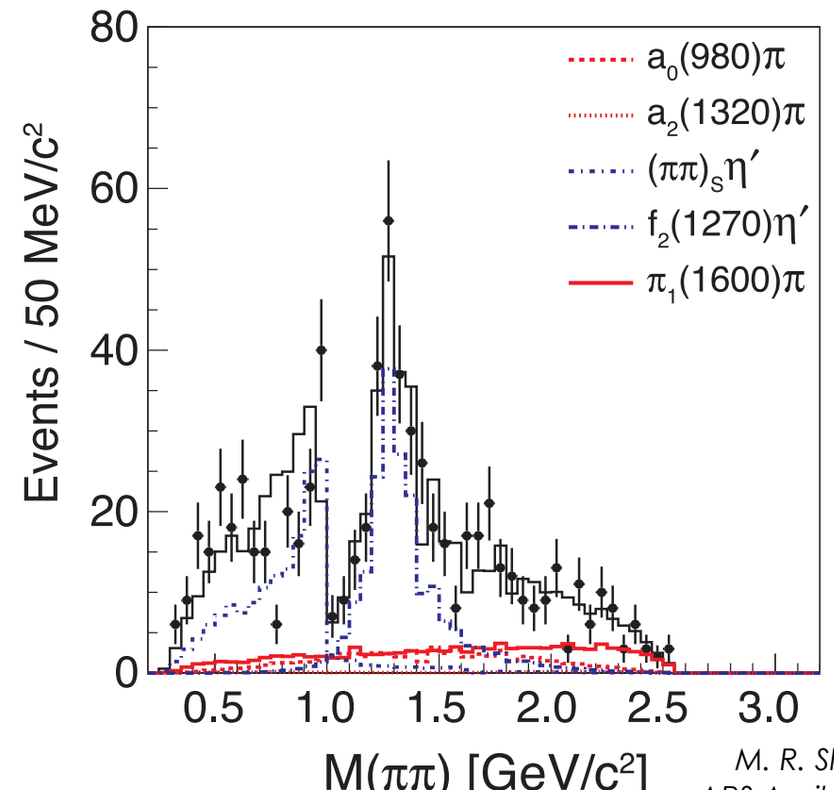
BESIII PRL 107, 182001 (2011)

the plot above is made after requiring $M(\eta\pi) \approx M(a_0)$

$\chi_{c1} \to \eta'\pi\pi$

- The decay $\chi_{c1} \to \eta'\pi\pi$ provides an opportunity to search for $\pi_1 \to \eta'\pi$
- Initial 1^{++} state restricts allowed final state combinations
  - The only allowed $\eta'\pi$ resonance in an S-wave with the second π must have exotic J^{PC}: 1^{-+}
- CLEO results show significant signal in exotic 1^{-+} amplitude that is consistent with previous reports of $\pi_1(1600) \to \eta'\pi$ in pion production
  - *resonant nature, e.g., resonant phase motion is difficult to validate*
  - fit with $\pi_1(1600) \to \eta'\pi$ is $>4\sigma$ better than all other alternative fits pursued
- Exciting opportunity for high-statistics study at BES III! (Now has 10x CLEO data; potential for more in the future.)



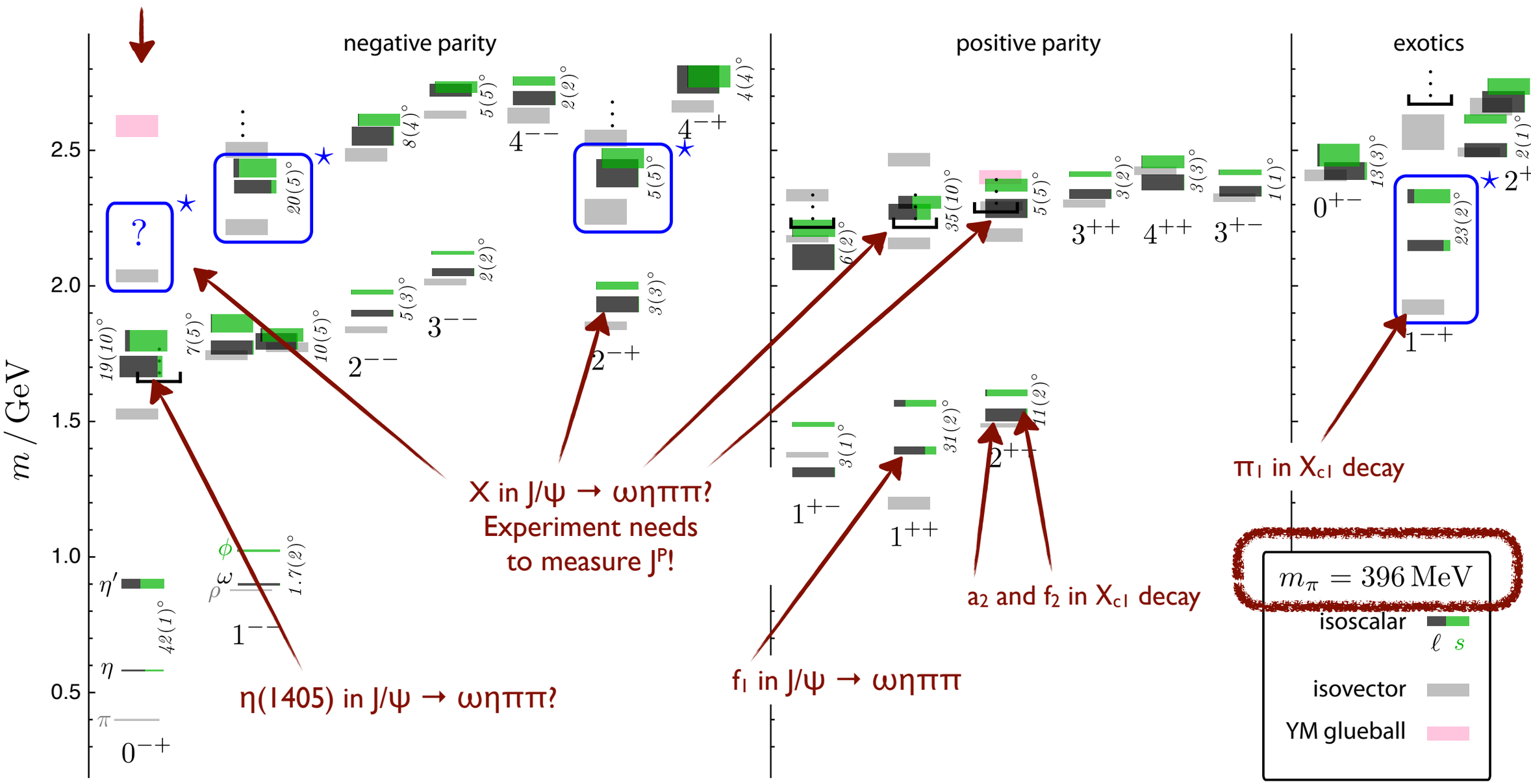


CLEO-c, PRD 84, 112009 (2011)

Previous Slides in the LQCD Context

X in J/ψ → γpp
(no clear assignment,
lattice spectrum is noisy)

J. Dudek
PRD 84, 074023 (2011)



There is clearly much more work to be done on both the theory and experimental fronts, but the prospects for progress are exciting.

$\eta(1405) \to f_0\pi^0$

BESIII, arXiv:1201.2737
[to be published in PRL]

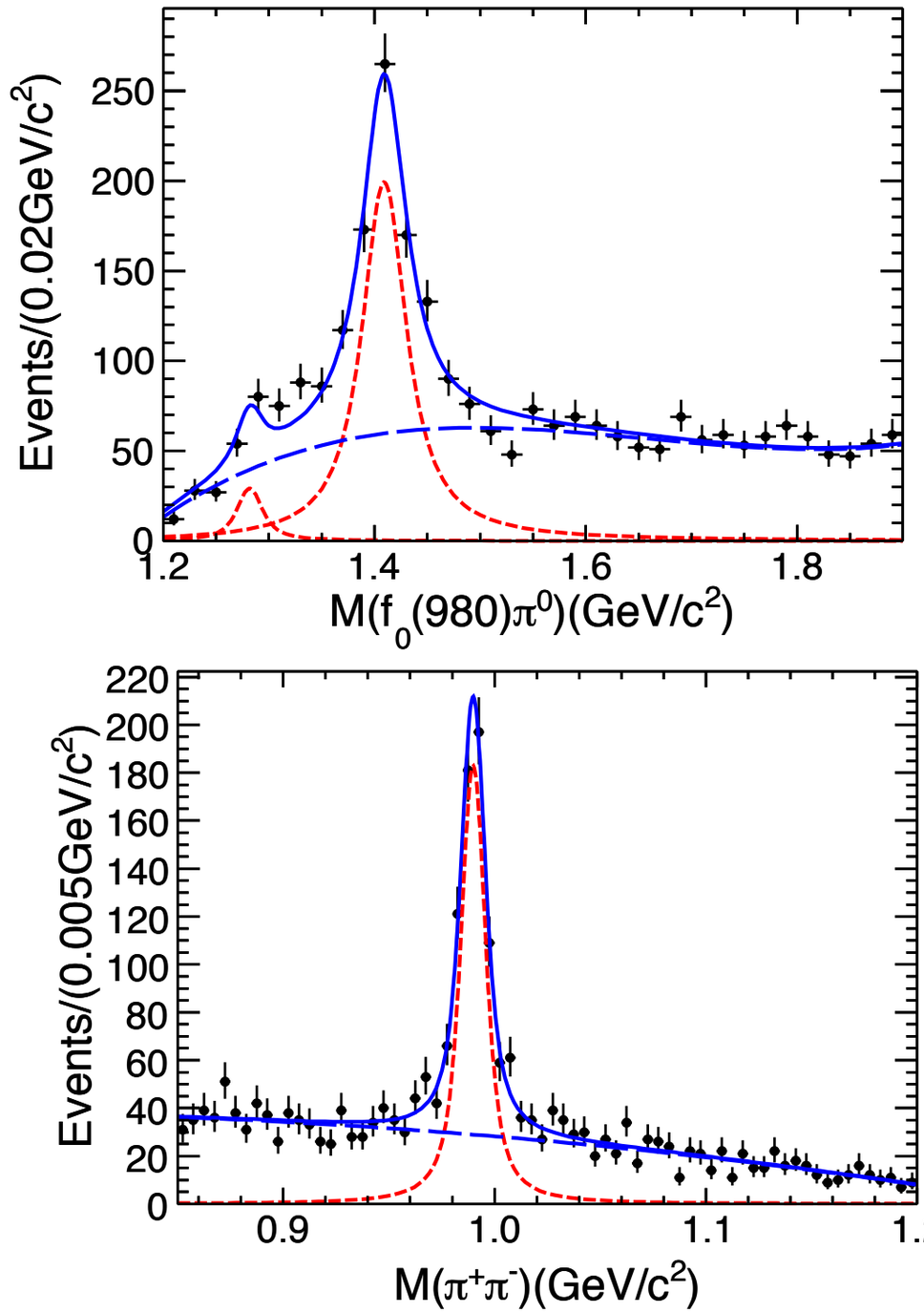
- Explore dynamics of light hadron decays
- $\eta(1405)$ is well-known to decay to $a_0\pi$
- Search for $J/\psi \to \gamma\eta(1405)$; $\eta(1405) \to f_0(980)\pi^0$
  - isospin violating decay of $\eta(1405)$
  - use both $f_0(980) \to \pi^+\pi^-$ and $f_0(980) \to \pi^0\pi^0$
- Two surprising results
  - large isospin violation:

$$\frac{\mathcal{B}(\eta(1405) \to f_0(980)\pi^0)}{\mathcal{B}(\eta(1405) \to a_0(980)\pi^0)} = (17.9 \pm 4.2)\%$$

a_0-f_0 mixing explanation is inconsistent with limits [(BESIII PRD 83, 032003 (2011)]

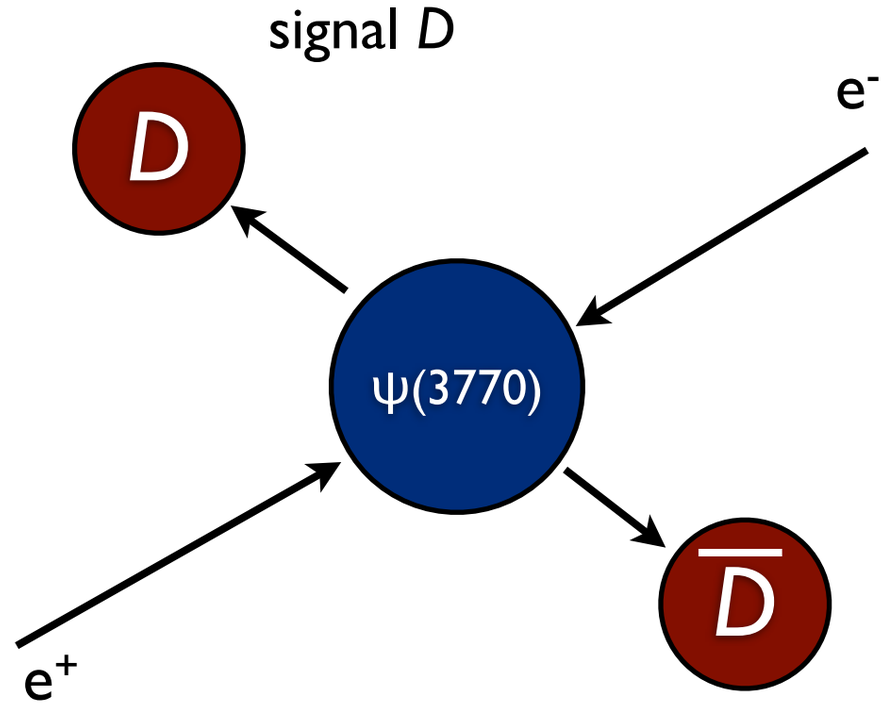
  - very narrow f_0 width (PDG: 40 - 100 MeV) :

$$\Gamma[f_0(980)] < 11.8 \text{ MeV}$$



Open Charm Studies

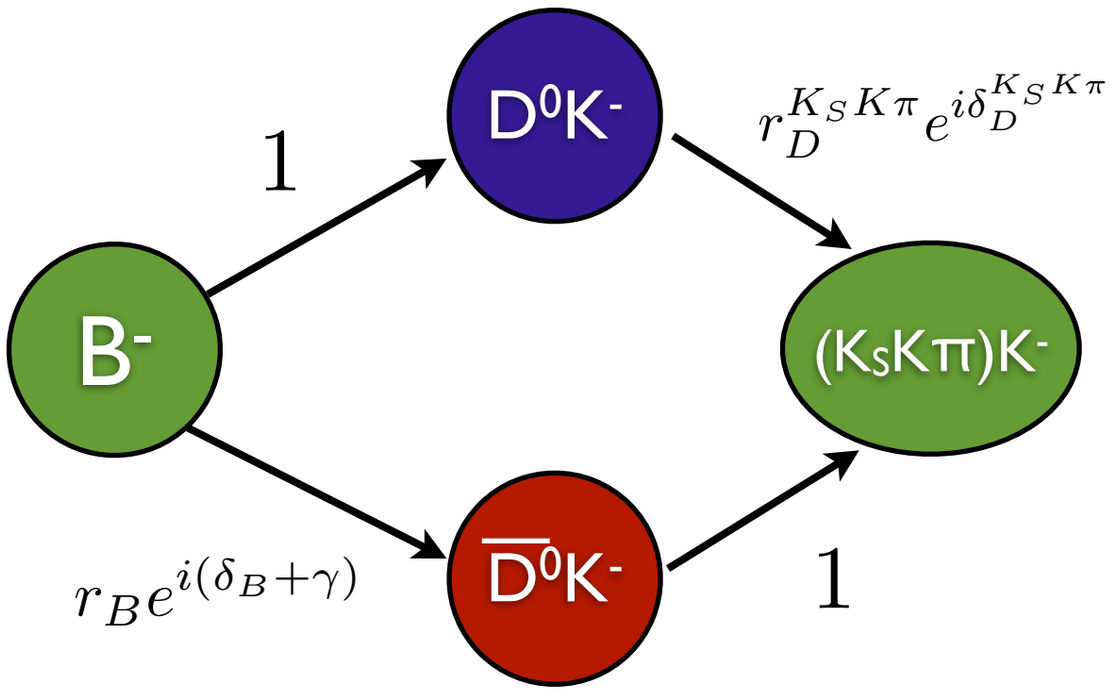
- e^+e^- at ψ(3770) provides large samples of *D* mesons with interesting experimental advantages
  - tagging: reduce backgrounds
  - "quantum coherence"
- Charm decays provide many inputs to precision tests of the SM
  - validation of LQCD calculations of form factors and decay constants
  - absolute *D* hadronic branching fractions for common *D* decays
- *Numerous past results from CLEO on all of the above topics, expect BESIII to soon push these to the next level of precision*

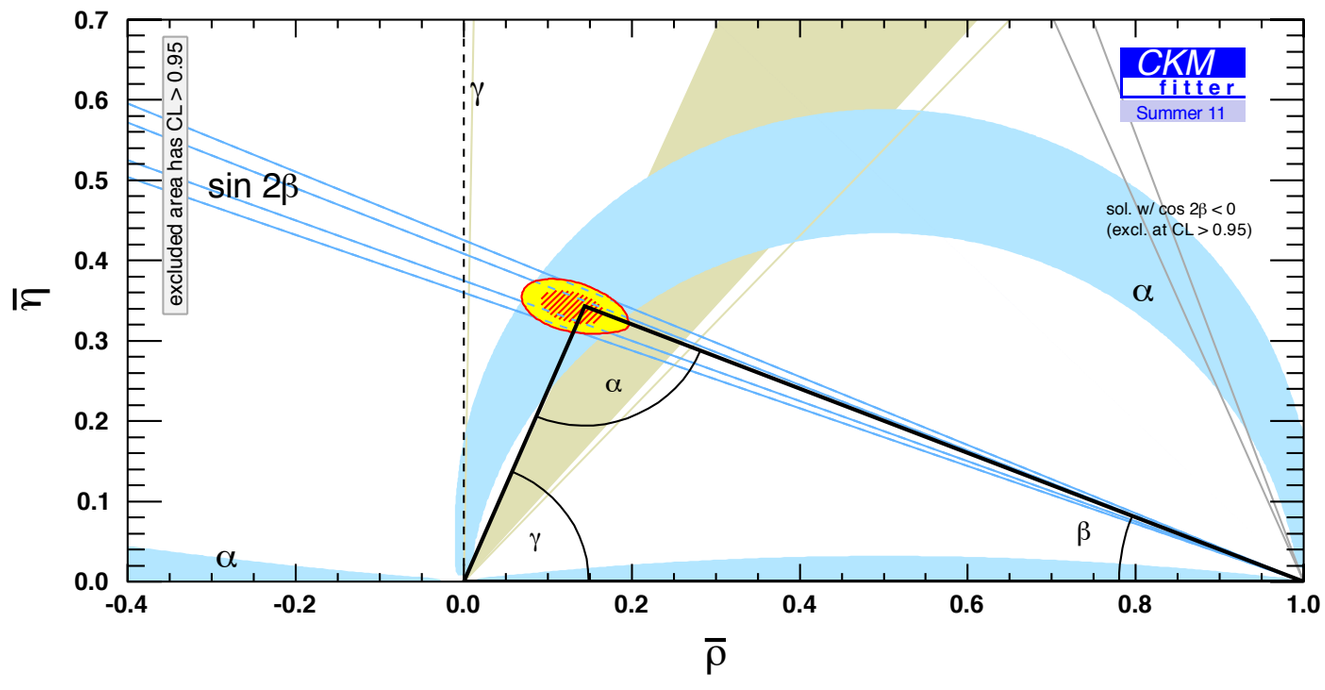


"tag"
(can have definite flavor, CP, or neither)

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|D^0\rangle|\bar{D}^0\rangle - |\bar{D}^0\rangle|D^0\rangle\right)$$

Input to Determination of γ





B Factories Measure CP Asymmetries

$$\Gamma(B^\mp \to D(K^0_S K^\mp \pi^\pm) K^\mp)$$
$$\propto 1 + (r_B r_D^{K^0_S K\pi})^2 + 2 r_B r_D^{K^0_S K\pi} R_{K^0_S K\pi} \cos(\delta_B - \delta_D^{K^0_S K\pi} \mp \gamma)$$

$$\Gamma(B^\mp \to D(K^0_S K^\pm \pi^\mp) K^\mp)$$
$$\propto (r_B)^2 + (r_D^{K^0_S K\pi})^2 + 2 r_B r_D^{K^0_S K\pi} R_{K^0_S K\pi} \cos(\delta_B + \delta_D^{K^0_S K\pi} \mp \gamma)$$

Coherent *DD* Production allows direct measurement of:

$\delta_D^{K_S K\pi}$ $\quad$ $R_{K_S K\pi}$

"coherence factor"

Also need branching ratios for:

r_B $\quad$ $r_D^{K_S K\pi}$

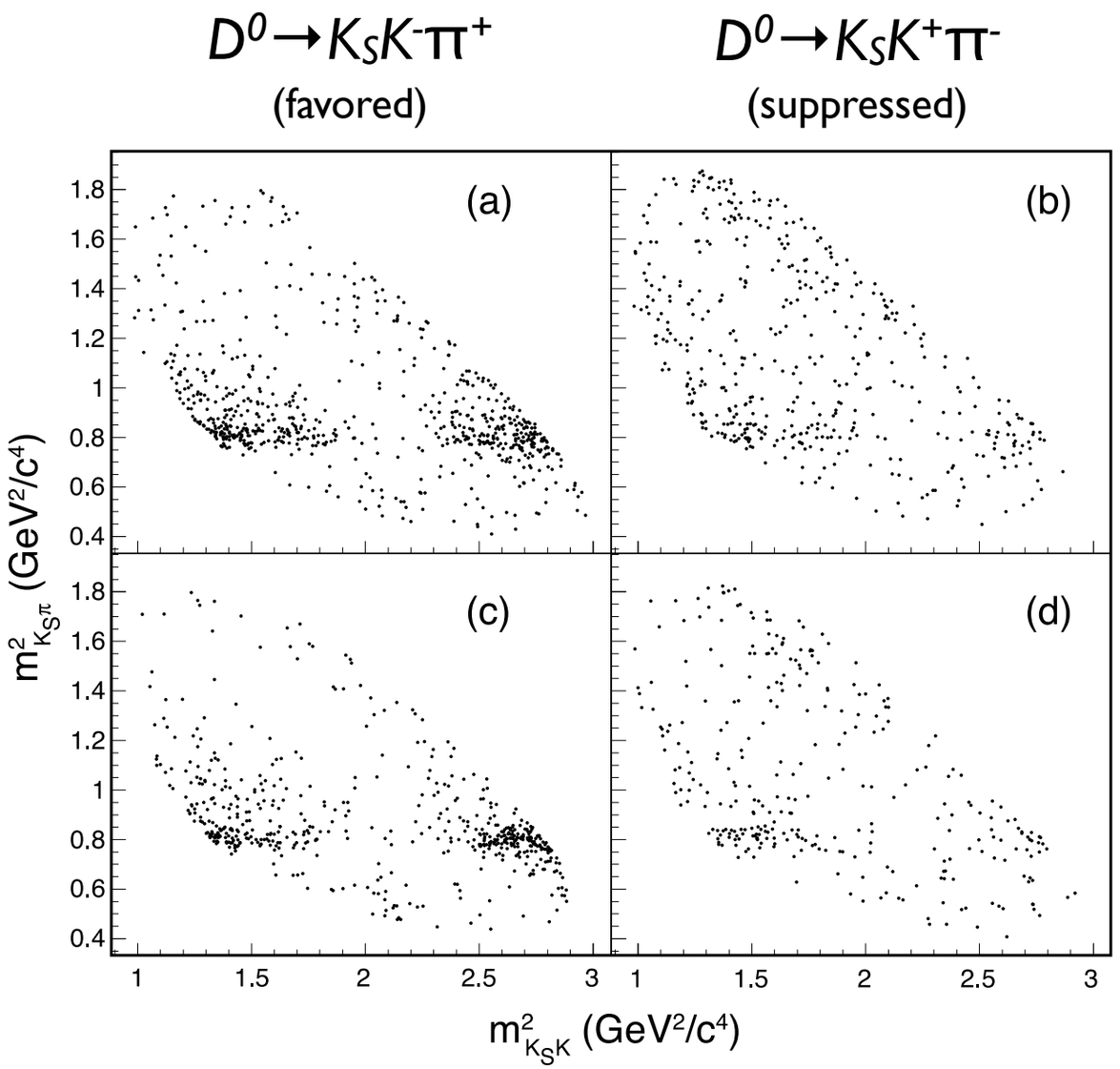
The general approach applies to any common hadronic decay mode of D^0 and $\overline{D}^0$ each have unique values of R, r, and δ

$D^0 \to K_S K^{\mp} \pi^{\pm}$ at CLEO-c and CLEO III

- Multi-faceted analysis strategy uses both CLEO-c and CLEO III ($\Upsilon(4S)$) data
- Flavor tags from CLEO-c and CLEO III (via $D^* \to D\pi$) provide
  - study of amplitudes in both the favored and suppressed decay via fit to the Dalitz plot
  - measurement of the branching ratio of suppressed to favored decay
- Counting signal against different *CP* and flavor tags from CLEO-c provides
  - strong phase difference measurement (strong phase difference of *CP* tags is 0 or π)
  - coherence factor

[D. Atwood and A. Soni, PRD 68, 033003 (2003)]

"flavor tag" samples



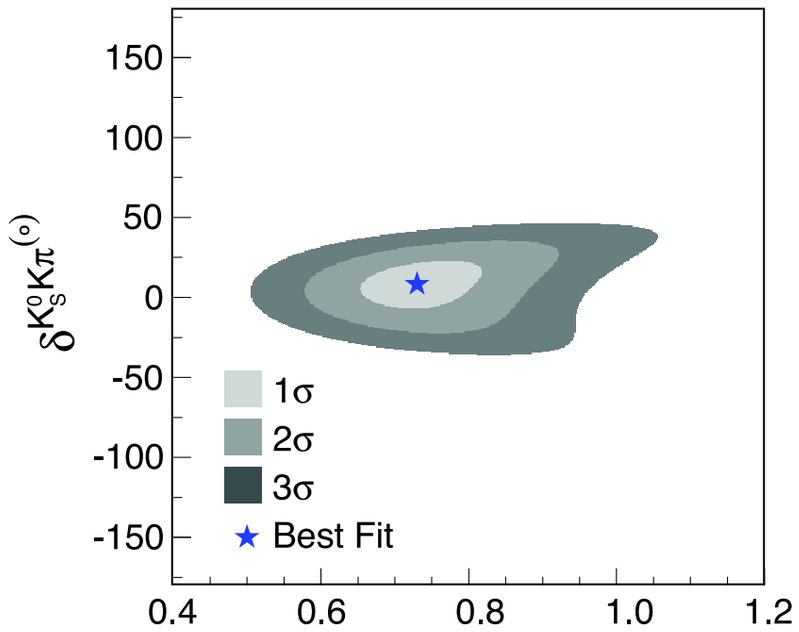
CLEO arXiv:1203.3804 (submitted to PRD)

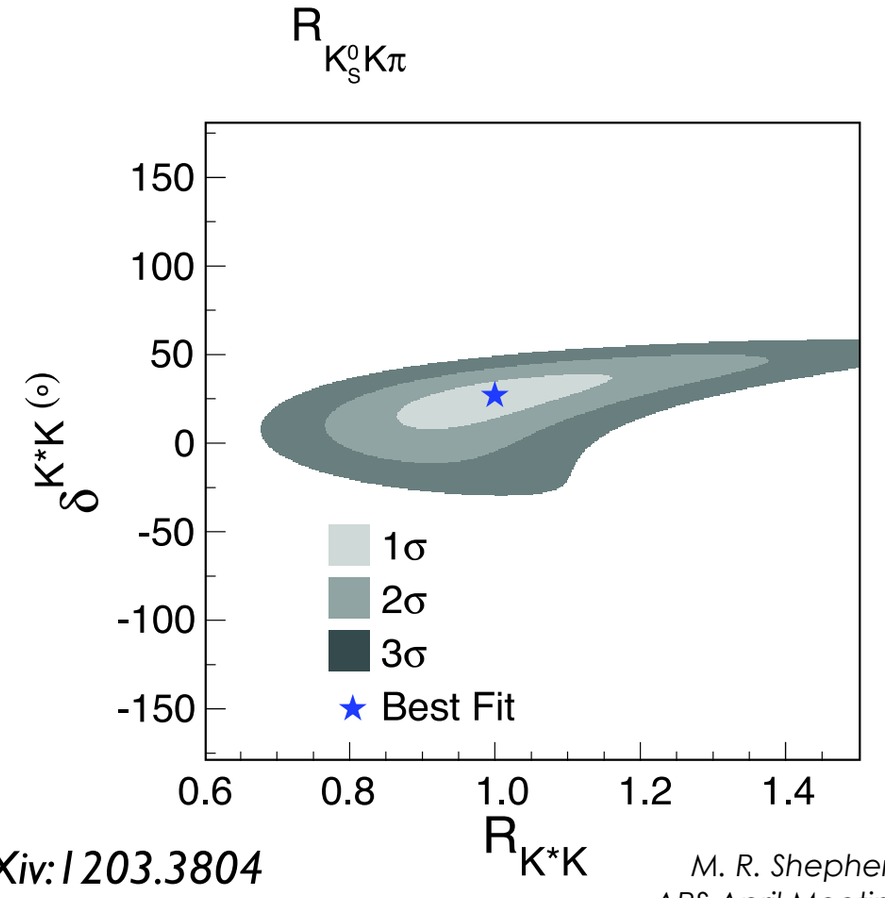
$D^0 \to K_S K^{\mp} \pi^{\pm}$ at CLEO-c and CLEO III

- Amplitude analysis indicates strong presence of $K^*(892)^{\pm}$ in both decays
- Most precise measurement of

$$\frac{\mathcal{B}(D^0 \to K_S K^+ \pi-)}{\mathcal{B}(D^0 \to K_S K^- \pi^+)} = 0.592 \pm 0.044 \pm 0.018$$

- First measurements of coherence factors and strong phase for this decay
  - restricting the kinematic region to the vicinity of the $K^*(892)^{\pm}$ enhances the coherence
- complementary to other measurements by CLEO-c aimed at improving γ extraction
  - $D^0 \to K^-\pi^+\pi^0$ and $D^0 \to K^-\pi^+\pi^+\pi^-$ *[PRD 80, 031105R (2009)]*
  - $D^0 \to K^0 h^+ h^-$ *[PRD 82, 112006 (2010)]*
- Statistics limited -- opportunity for improvement at BESIII





CLEO arXiv:1203.3804 (submitted to PRD)

BESIII Outlook

- The BESIII experiment continues to take data: currently running at the ψ'
- Near term (a year) goals:
  - collect about 700M - 1B ψ': increases current sample by factor of 6-8 and about 30x the CLEO-c sample
  - collect 1B J/ψ decays: increase current sample by factor of 4-5
  - lineshape scan of ψ' and J/ψ: measure EM/strong decay phase differences
  - tau threshold running: precision tau mass measurement
- Longer term (several years) goals under development, some possibilities:
  - dedicated running on *Y(4260)* and/or *Y(4360)*
  - D_s physics
  - *R* measurements
  - ...?
- A diverse future physics program!

Summary

- Studies of the charmonium region provide opportunities to explore QCD in a variety of ways
  - transitions between heavy quark bound states
  - searches for new light meson states
  - dynamics in both light meson and heavy meson decays
  - strong physics inputs to precision tests of the Standard Model
- There is a very active ongoing physics program in this area -- only a subset of the most recent CLEO-c and BESIII results were presented. Some notable omissions:
  - searches for light Higgs in J/ψ radiative decay
    [BESIII, arXiv:1111.2112 (to be published in PRD)]
  - searches for *CP* and *P* violating decays of η, η', and η_c
    [BESIII, Phys. Rev. D 84, 032006 (2011)]
- Expect many more results from the BESIII Collaboration in the future