Overview of BESIII Experiment

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(On behalf of BESIII Collaboration)

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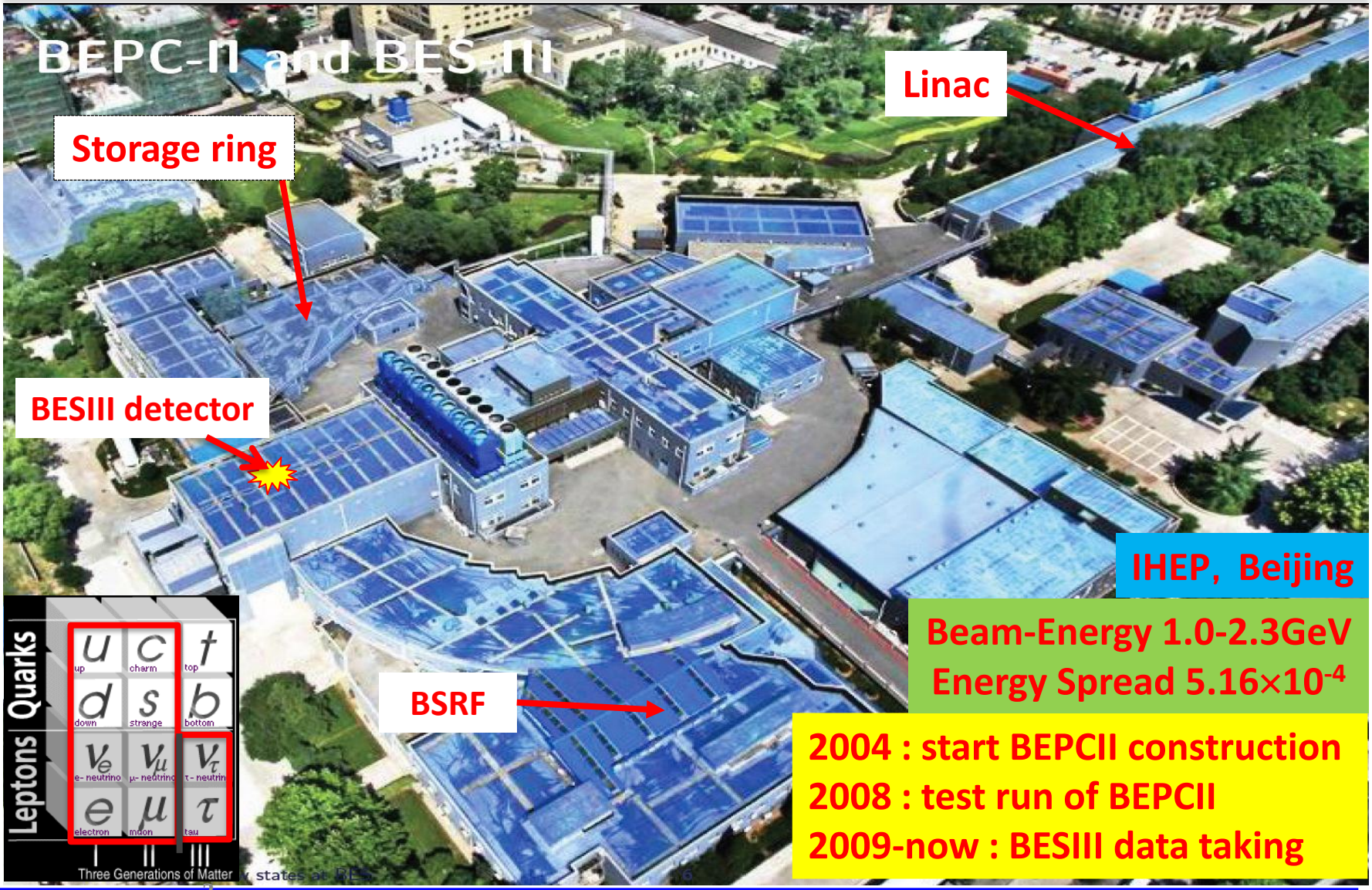
Outline

- Status of BEPCII/BESIII and Data
- Selected Results from BESIII
  - Charmonium (XYZ) Spectroscopy
  - Charmonium Physics
  - Light Hadron Spectroscopy
  - Charm Decays
- Summary & outlook

Beijing Electron Positron Collider II



IHEP, Beijing

Beam-Energy 1.0-2.3GeV

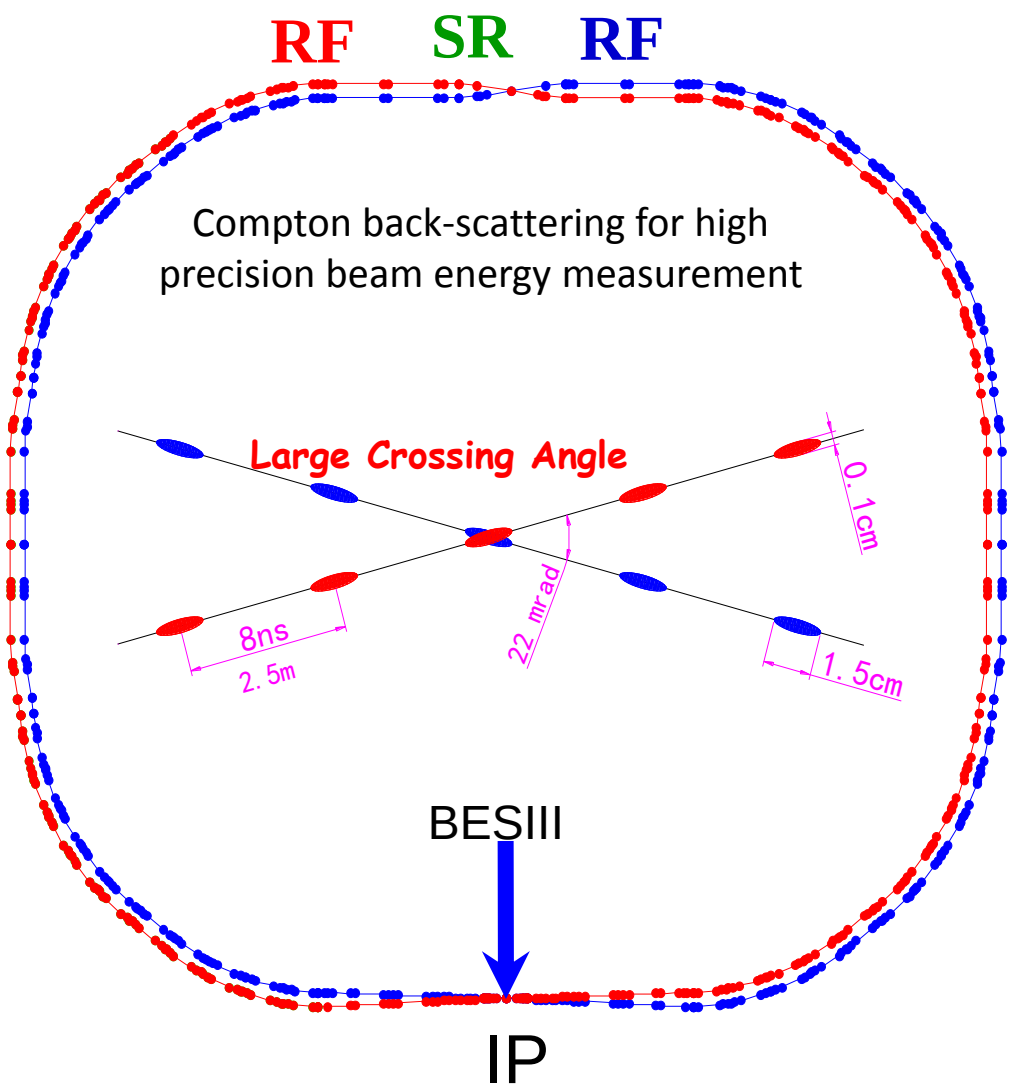
Energy Spread 5.16×10^{-4}

2004 : start BEPCII construction

2008 : test run of BEPCII

2009-now : BESIII data taking

BEPCII Storage Rings



- **Beam energy :** 1.0-2.3 GeV
- **Energy spread:** 5.16×10^{-4}
- **Optimum energy:** 1.89 GeV
- **Luminosity:** 1×10^{33} $cm^{-2}s^{-1}$
- **No. of bunches :** 93
- **Bunch length:** 1.5 cm
- **Total current :** 0.91 A
- **SR mode :** 0.25A@2.5Ge

Achieved Luminosity
$0.7\times10^{33}cm^{-2}s^{-1}$@3770MeV

BESIII Detector

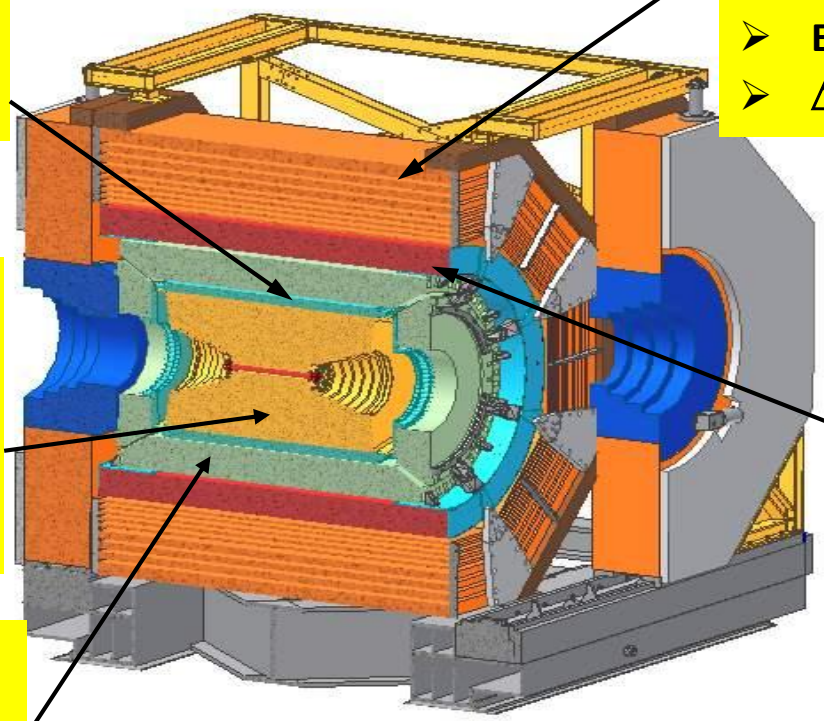
Drift Chamber (MDC)

- Small cell, 43 layer
- Gas He/C_3H_8=40/60
- σ_P/P=0.5%(1GeV)
- $\sigma_{dE/dx}$= 6%

NIM A614(2010), 345

Muon Counter

- Resistive Plate Chamber
- Barrel: 9 layers
- Endcaps: 8 layers
- $\Delta R\Phi$=1.4 cm~1.7 cm



Time Of Flight (TOF)

- Plastic Scintillator
- σ_T (Barrel) : 90 ps
- σ_T (Endcap) : 110 ps
- Endcap upgrading ……

Super-conduct

magnet (1.0 Tesla)

RO channels: 10^4
Cost: 200 M RMB

EM Calorimeter

- CSI(Tl) : L=28cm (15 X_0)
- Energy Range : 0.02-2GeV
- $\sigma_E/\sqrt{E}(^0/_0)$ = 2.5 % (1 GeV)
- $\sigma_{z,\phi}$(cm) = 0.5 - 0.7 cm/$\sqrt{E}$

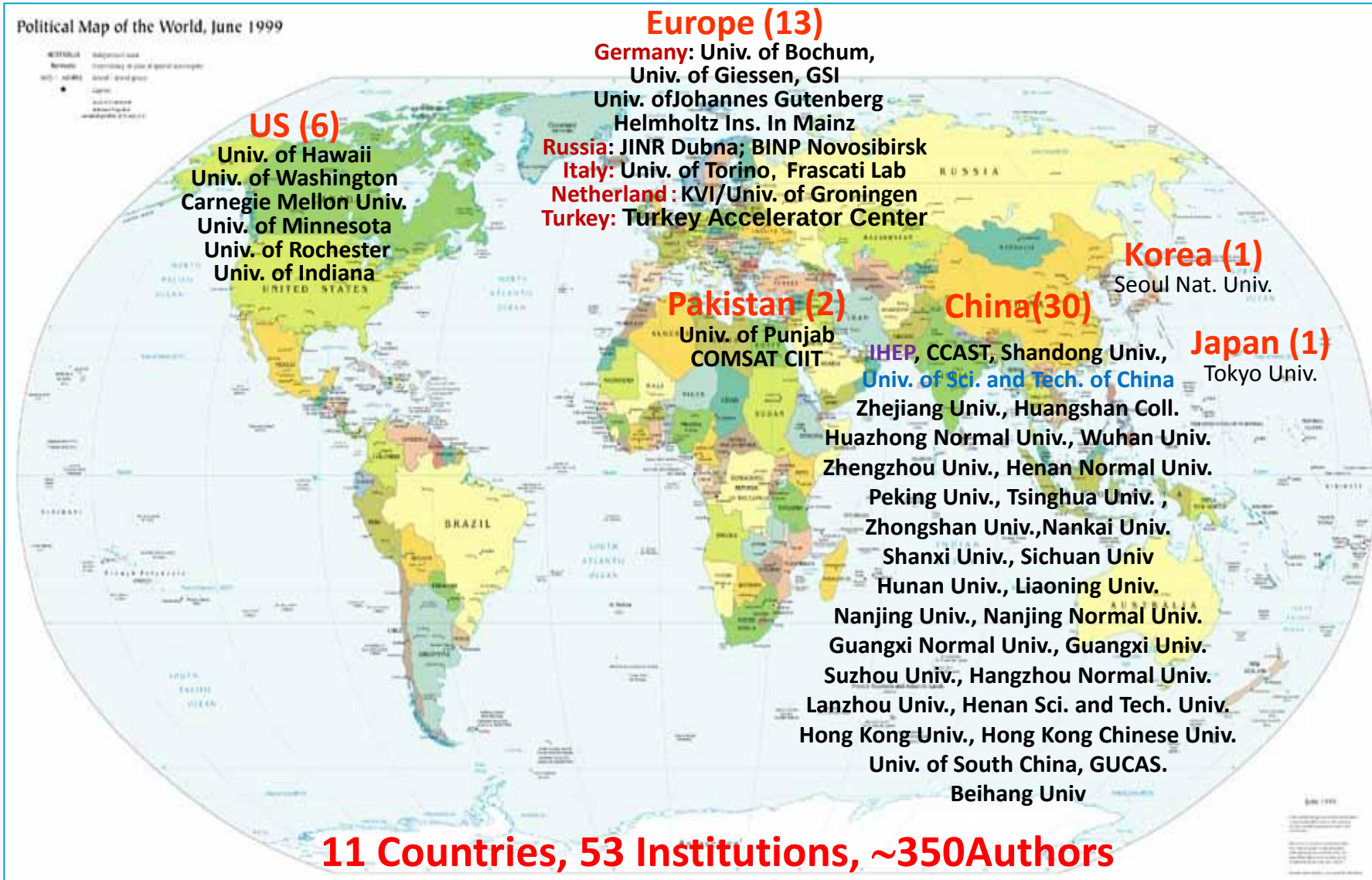
Data acquisition

- Event rate : 4 kHz
- Data size : 50 MB/s

"Grid" computing

- CPU: 3200 cores
- Storage: 2.2 pB

BESIII Collaboration



Europe (13)

Germany: Univ. of Bochum,
Univ. of Giessen, GSI
Univ. ofJohannes Gutenberg
Helmholtz Ins. In Mainz
Russia: JINR Dubna; BINP Novosibirsk
Italy: Univ. of Torino, Frascati Lab
Netherland : KVI/Univ. of Groningen
Turkey: Turkey Accelerator Center

US (6)

Univ. of Hawaii
Univ. of Washington
Carnegie Mellon Univ.
Univ. of Minnesota
Univ. of Rochester
Univ. of Indiana

Korea (1)

Seoul Nat. Univ.

Pakistan (2)

Univ. of Punjab
COMSAT CIIT

China(30)

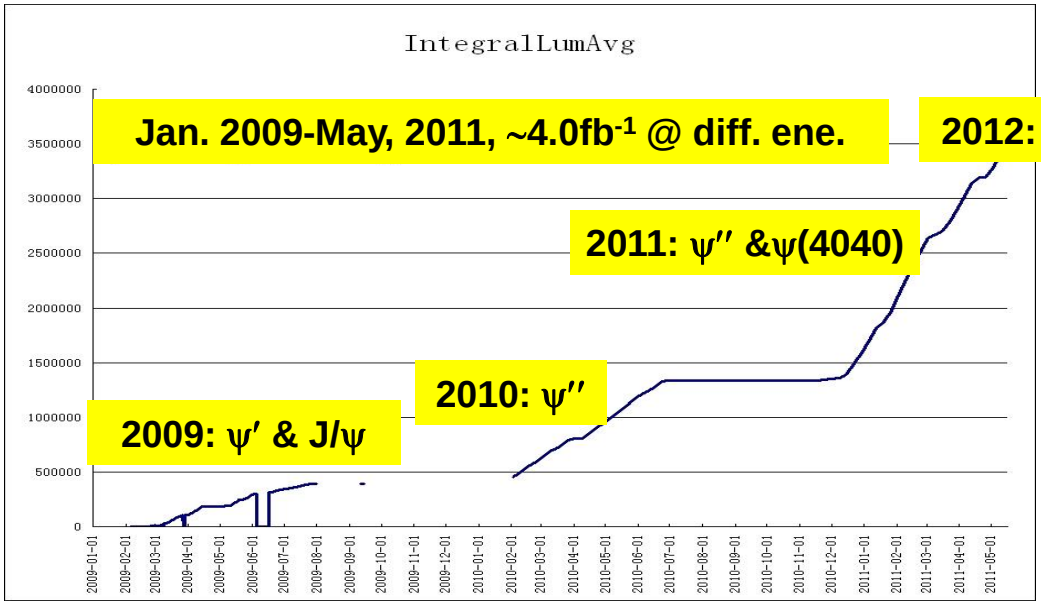
IHEP, CCAST, Shandong Univ.,
Univ. of Sci. and Tech. of China
Zhejiang Univ., Huangshan Coll.
Huazhong Normal Univ., Wuhan Univ.
Zhengzhou Univ., Henan Normal Univ.
Peking Univ., Tsinghua Univ. ,
Zhongshan Univ.,Nankai Univ.
Shanxi Univ., Sichuan Univ
Hunan Univ., Liaoning Univ.
Nanjing Univ., Nanjing Normal Univ.
Guangxi Normal Univ., Guangxi Univ.
Suzhou Univ., Hangzhou Normal Univ.
Lanzhou Univ., Henan Sci. and Tech. Univ.
Hong Kong Univ., Hong Kong Chinese Univ.
Univ. of South China, GUCAS.
Beihang Univ

Japan (1)

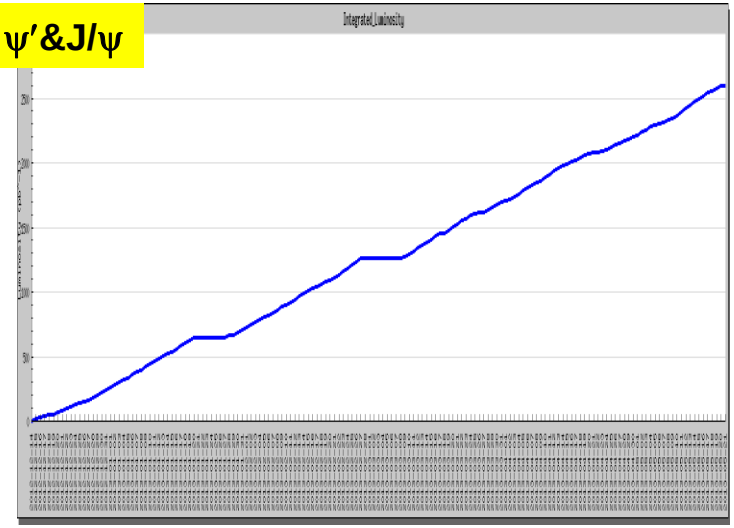
Tokyo Univ.

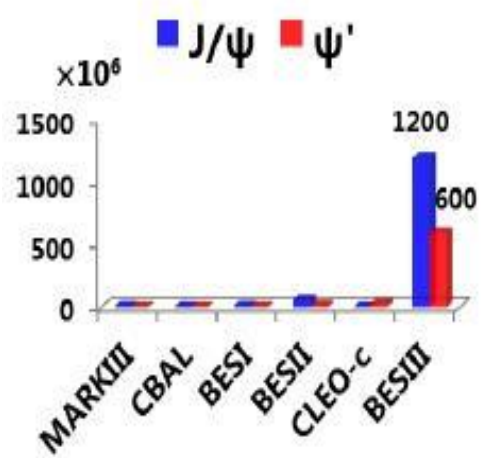
11 Countries, 53 Institutions, ~350Authors

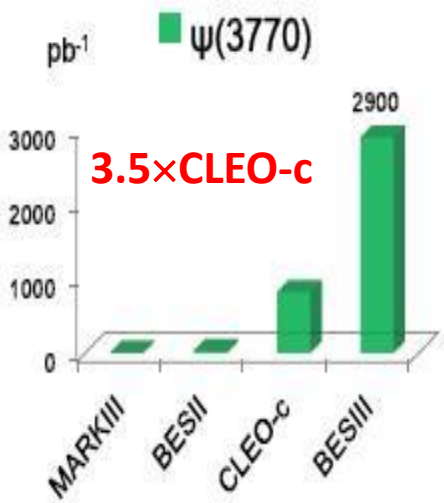
BESIII Commissioning



3.4fb^{-1} XYZ data (25pb^{-1}/day)





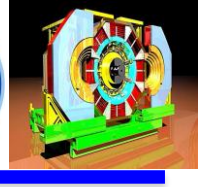


- 12pb^{-1} @ 2.23, 2.4, 2.8, 3.4
- 25pb^{-1} @ τ mass Scan

Have collected World's largest threshold producted sample of J/ψ, ψ′, ψ′′ and XYZ data!!!

Plan to take R measurement data & High mass resonances data

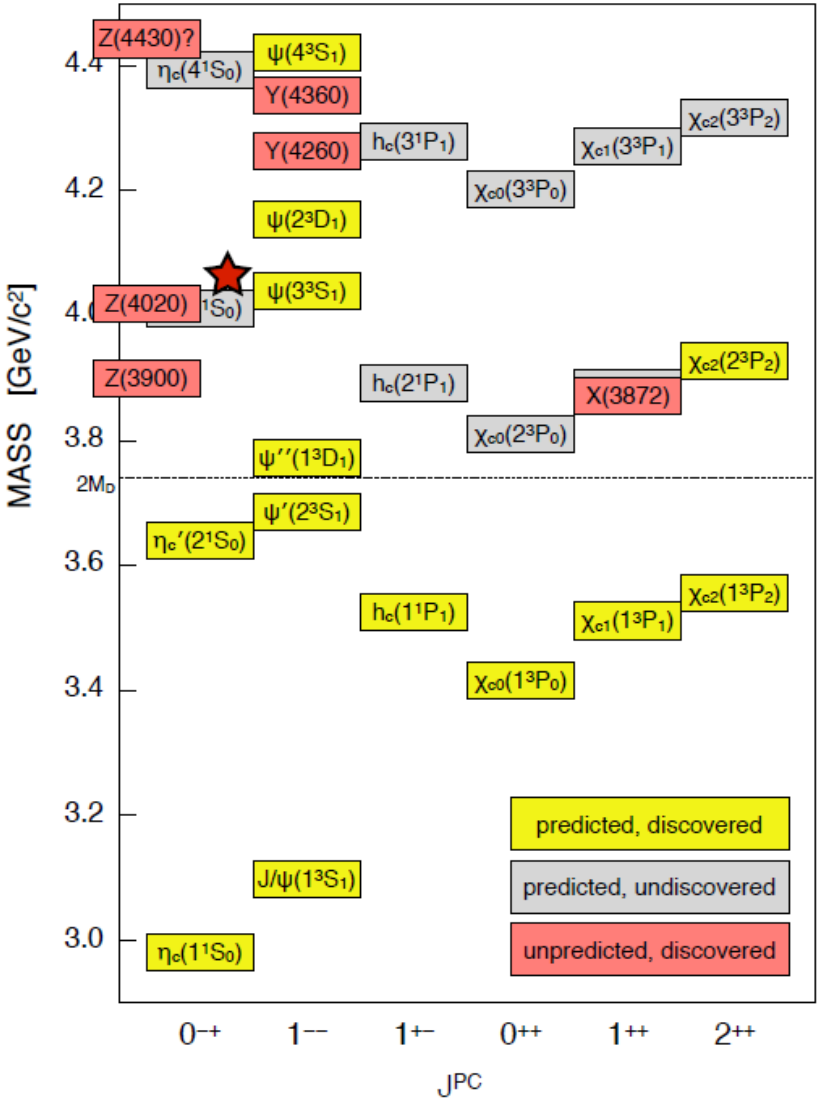
Physics Programs @ BESIII

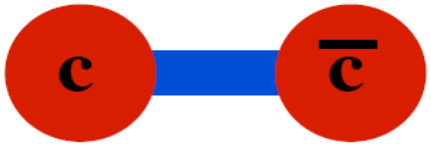


- ***Light hardron physics***
  - meson & baryon spectroscopy
  - threshold effects
  - multiquark states
  - glueballs & hybrids
  - two-photon physics
  - form-factors
- ***Charmonium physics:***
  - precision spectroscopy
  - transitions and decays
- ***QCD & τ-physics:***
  - precision R-measurement
  - τ mass / τ decays
- ***Charm physics:***
  - (semi-)leptonic form factors
  - f_D & f_{Ds} decay constants.
  - CKM matrix: V_{cd} , V_{cs}
  - D^0-D^0 mixing and CPV
  - strong phases
- ***XYZ meson physics:***
  - XYZ new states
  - XYZ properties
- ***SM Test & New Physics Searches :***
  - η&η'decay physics
  - Light dark matter, LFV ……
  - Rare decay

XYZ

Charmonium Spectroscopy





- **Below open charm threshold :**
  - All are observed.
- **Above open charm threshold :**
  - Many expected states are not observed.
  - Many unexpected charmonium-like states are observed.

Z(4430)
Z(4250)
Z(4050)
Z(3900)
Z(4020)
Z(4025)

X(3872)
X(3915)
X(4160)
X(4350)

XYZ(3940)

Y(4008)
Y(4140)
Y(4260)
Y(4360)
Y(4660)

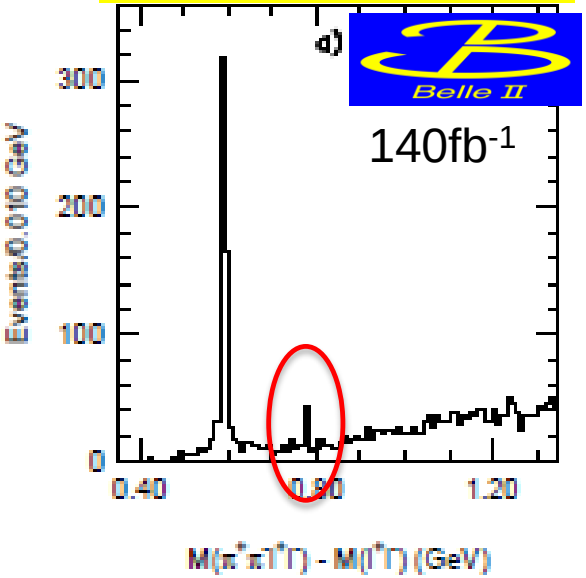
Not all charmonia, What are they?

Hybrid? Tetraquark? Molecule?

X(3872) State

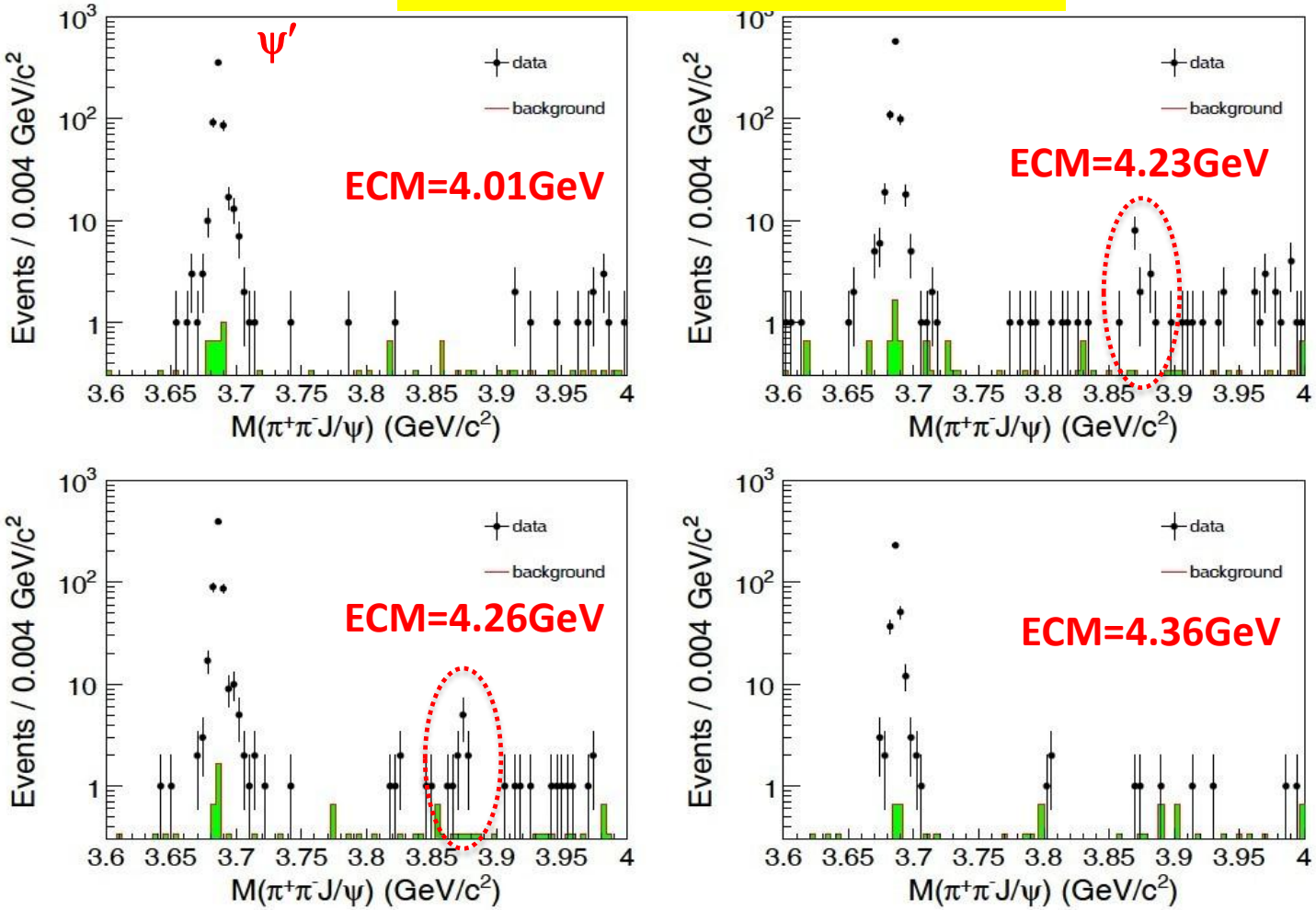
- **First observed** : $B^{\pm}\to k^{\pm}\pi^{+}\pi^{-}J/\psi$ by Belle
- **Mass** : close to $D^0\bar{D}^{*0}$ threshold
- **Width** : very narrow (<1.2MeV)
- **J^{PC}** :
  - 1^{++} [CDF (PRL98, 132002); LHCb (EPJC72, 1972)]
- **Production** :
  - B meson decay – KX similar to $c\bar{c}$, K*X smaller than $c\bar{c}$
  - $p\bar{p}$/pp collision – rate similar to charmonia
  - $Y(4260)\to\gamma X(3872)$ [BESIII, next slides]
- **Decay** :
  - Open charm ~50%, charmonium ~ O(%)
- **Nature (Very likely exotic)** :
  - Loosely $D^0\bar{D}^{*0}$ bound state (Like deuteron)?
  - Mixture of excited χ_{c1} and $D^0\bar{D}^{*0}$ bound state?
  - Many other possibilities (if it is not χ_{c1}', where is χ_{c1}'?)

PRL 91 (2003) 262001



$e^+e^- \to \gamma X(3872) \to \pi^+\pi^- J/\psi$

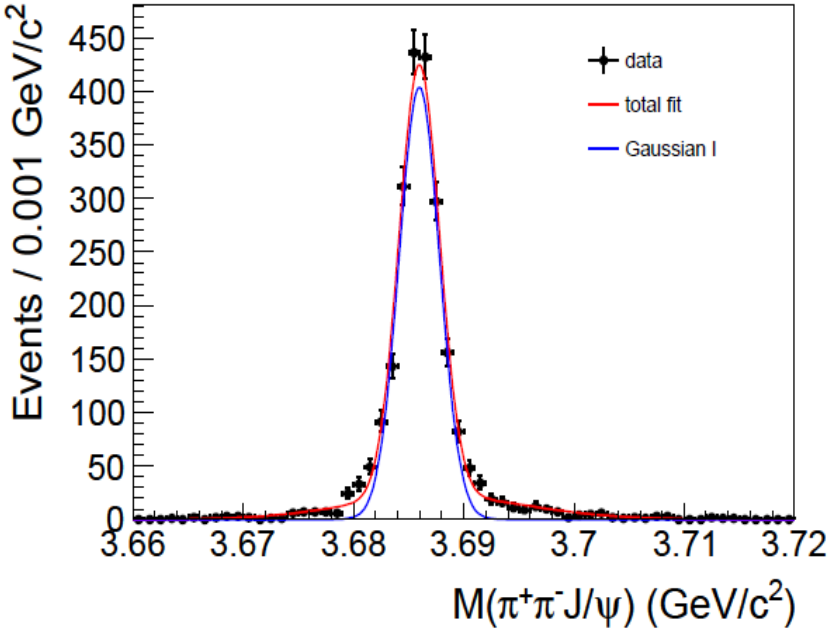
arXiv:1310.4101, Submitted o PRL

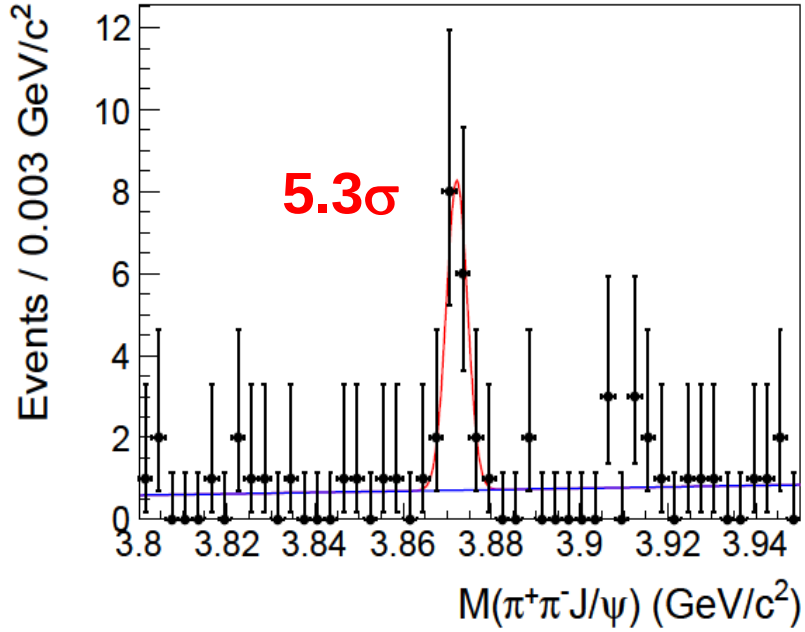


Clear ISR ψ′ signal for data validation; X(3872) signal at around 4.23-4.26GeV

$e^+e^- \to \gamma X(3872) \to \pi^+\pi^- J/\psi$

arXiv:1310.4101, Submitted o PRL





- **ISR ψ′ signal is used for rate, mass, and resolution calibration.**
  - **N(ψ′)=1242; Mass = 3685.96±0.05MeV/c²; σ=1.84±0.06MeV**
- **X(3872) signal**
  - **N(X(3872))=15.0±3.9**
  - **M(X(3872))=3872.1±0.8±0.3MeV/c² [PDG : 3871.68±0.17MeV/c²]**

$e^+e^- \to \gamma X(3872) \to \pi^+\pi^- J/\psi$

arXiv:1310.4101, Submitted o PRL

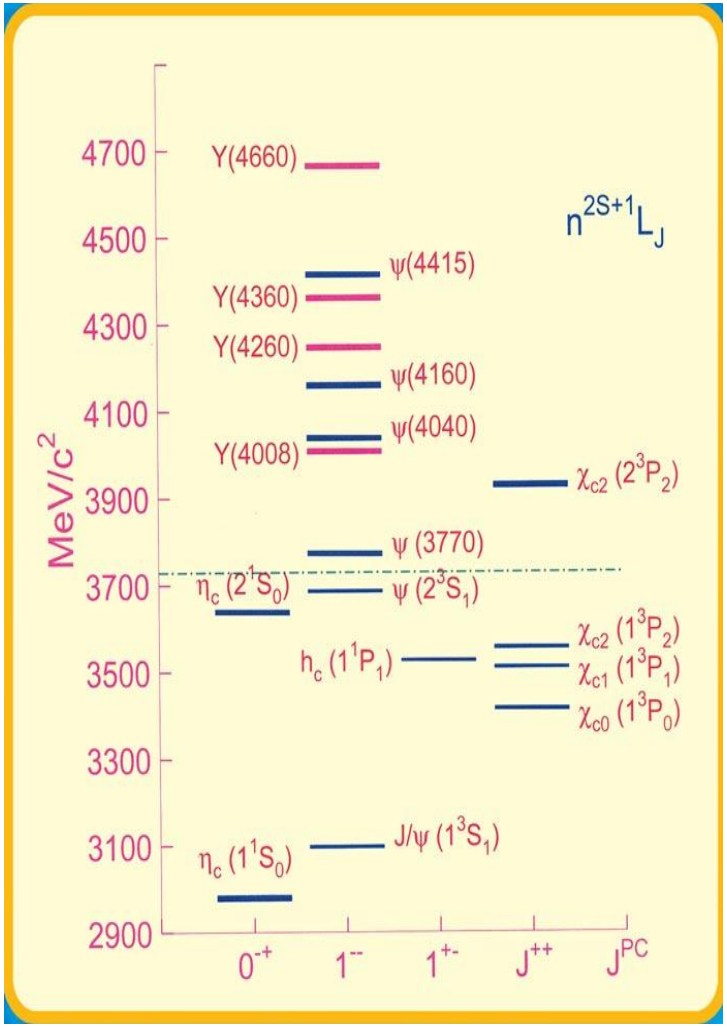
$\sqrt{s}$ (GeV)	$\sigma^B[e^+e^- \to \gamma X(3872)] \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ (pb)
4.009	< 0.13 at 90% C.L.
4.230	$0.32 \pm 0.15 \pm 0.02$
4.260	$0.35 \pm 0.12 \pm 0.02$
4.360	< 0.39 at 90% C.L.

It seems X(3872) is from Y(4260) decays. At 4.26 GeV,
$\sigma^B(e^+e^- \to \pi^+\pi^- J/\psi) = (62.9 \pm 1.9 \pm 3.7)$ pb,

$$\frac{\sigma[e^+e^- \to \gamma X(3872)] \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} = (5.6 \pm 2.0) \times 10^{-3}$$

If we take $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) \sim 5\%$, (>2.6% in PDG)
$\frac{\sigma(e^+e^- \to \gamma X(3872))}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} \sim 11.2\%$ Large transition ratio !

The Y States



Mainly from B factory via ISR

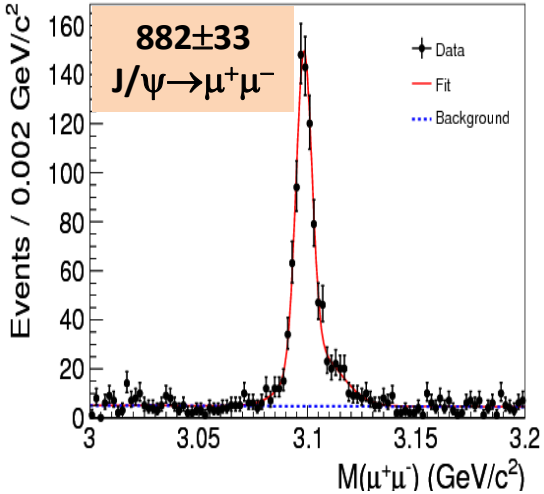
- Y(4008) : $e^+e^- \to \gamma\pi^+\pi^- J/\psi$ [Belle, not BaBar]
- Y(4260) : $e^+e^- \to \gamma\pi^+\pi^- J/\psi$ [BaBar, Belle, CLEO]
- Y(4360) : $e^+e^- \to \gamma\pi^+\pi^- \psi(2S)$ [BaBar, Belle]
- Y(4460) : $e^+e^- \to \gamma\pi^+\pi^- \psi(2S)$ [BaBar, Belle]

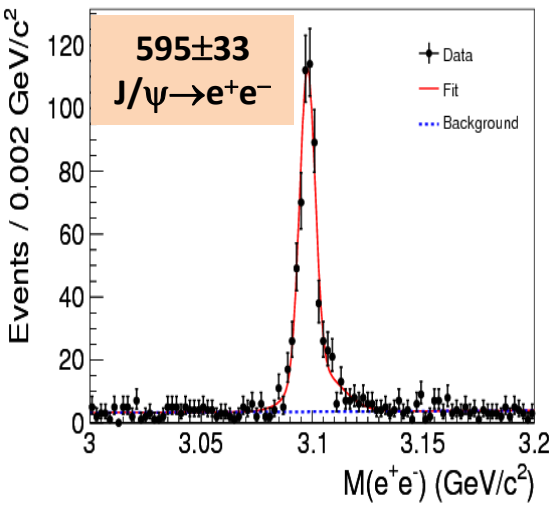
BESIII : directly from e^+e^- collision

What are the Y states?

- Hybrids are expected in this region
- Molucular states?
- Threshold effect/FSI can not rule out
- ……

$e^+e^- \to \pi^+\pi^- J/\psi$ @4.26GeV



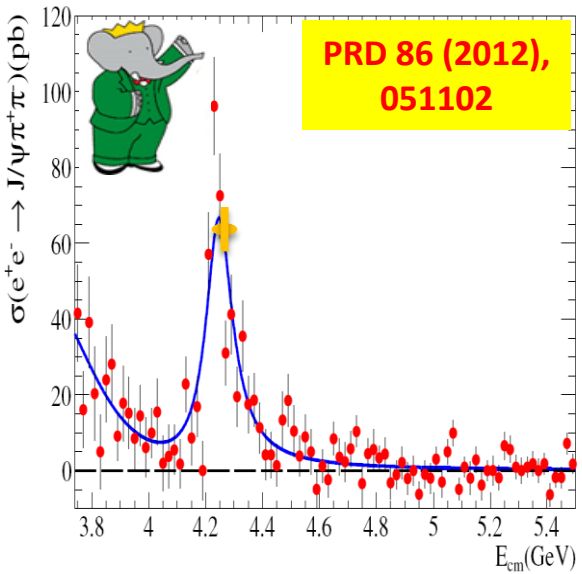


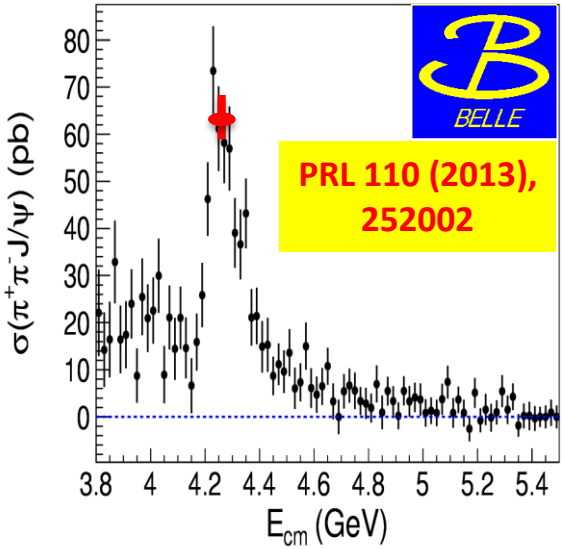
PRL110 (2013), 252001

- Select 4 charged tracks and reconstruct J/ψ with lepton pair
- Very clean sample, very high efficiency (~45%)

$\sigma(e^+e^- \to \pi^+\pi^- J/\psi) = (62.9 \pm 1.9 \pm 3.7)$pb

Agree with Babar& Belle, best precision!

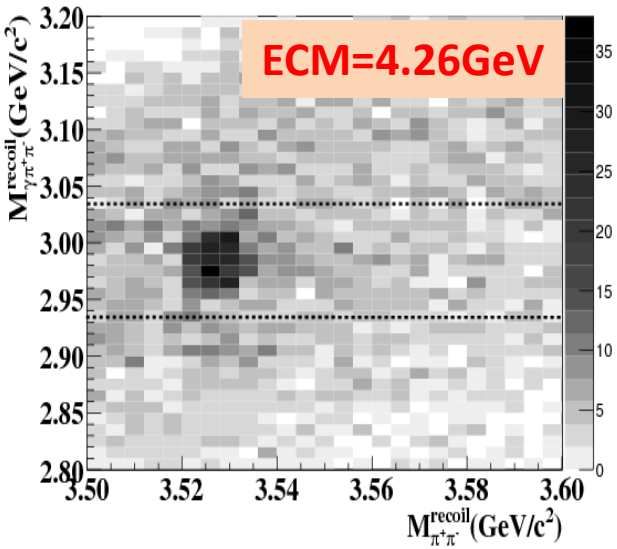


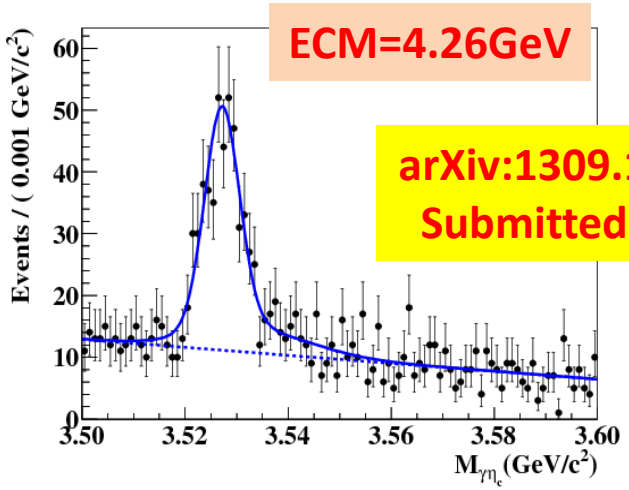


measuring Xsec at more energy points, and will take more data!

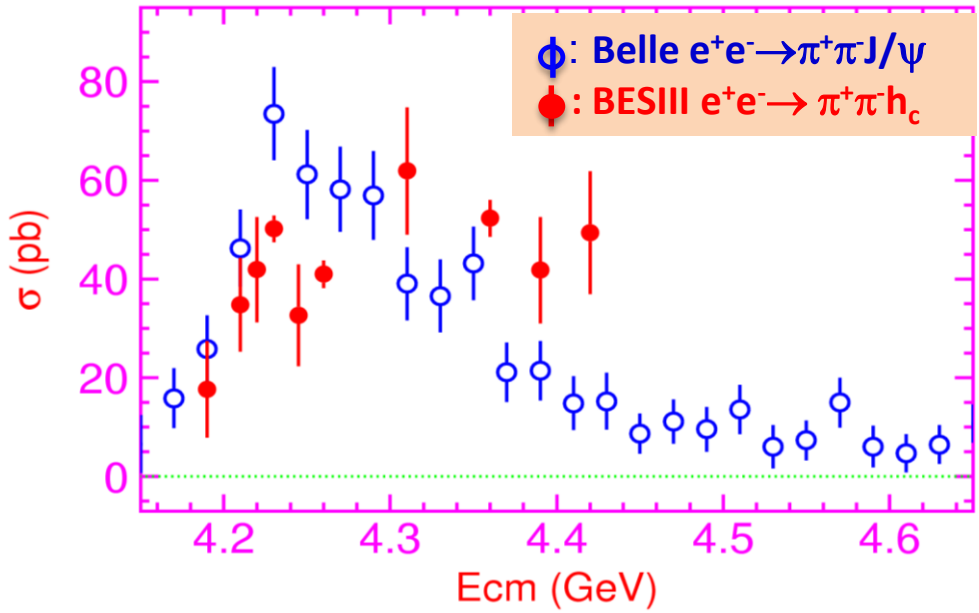
$e^+e^- \to \pi^+\pi^- h_c(1P)$

$h_c \to \gamma\eta_c$, $\eta_c \to$ hadrons (16 decay modes, ~35% of the h_c decays)





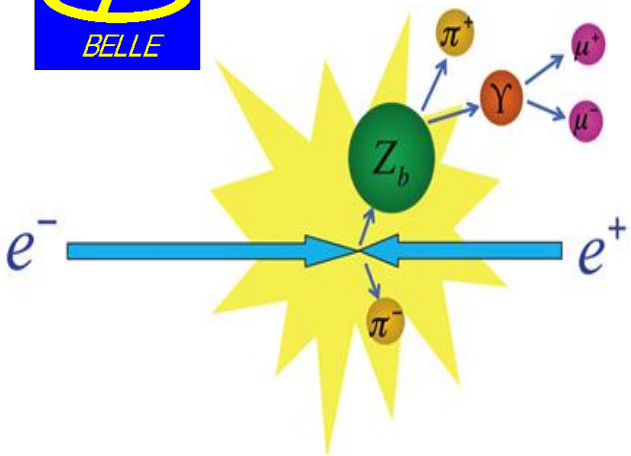
arXiv:1309.1896, Submitted PRL

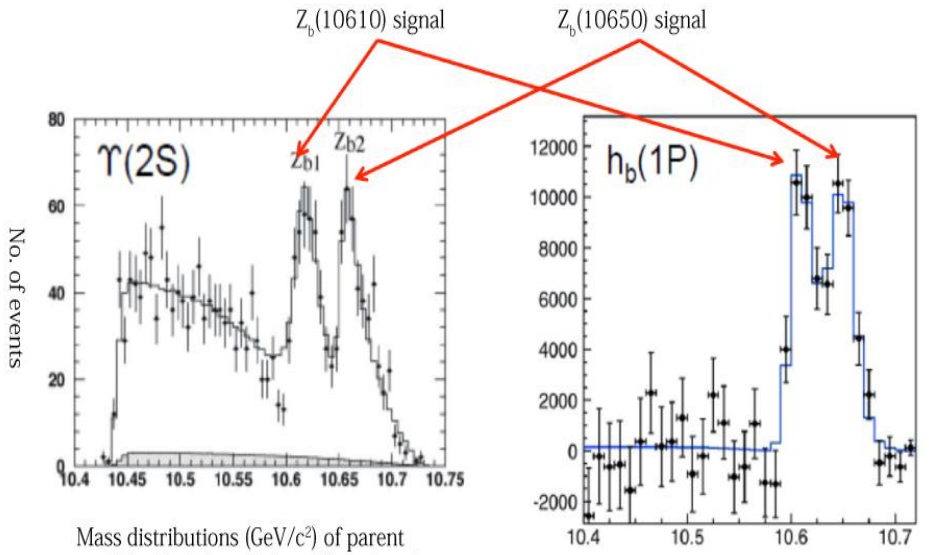


- $\sigma(e^+e^- \to \pi^+\pi^- h_c) \sim \sigma(e^+e^- \to \pi^+\pi^- J/\psi)$, but different line shape
- Local Maximum ~4.23GeV, Hint for a vector $c\bar{c}$ hybrid? [PRD 78, 056003, 094504]
- Broad structure ~4.4GeV, more data at high energies to complete the line shape

Z_c : Charged charmomium-like States

Z_b in B factory

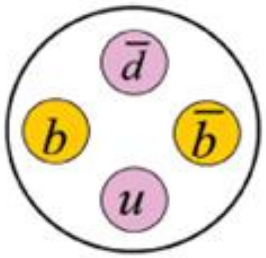




Mass distributions (GeV/c²) of parent particles that decay into an Υ and a pi meson.

Mass distribution (GeV/c²) of parent particles that decay into an hb and a pi meson.

New discovery at Belle:
Exotic mesons containing bottom quarks
→ At least four quarks must be contained

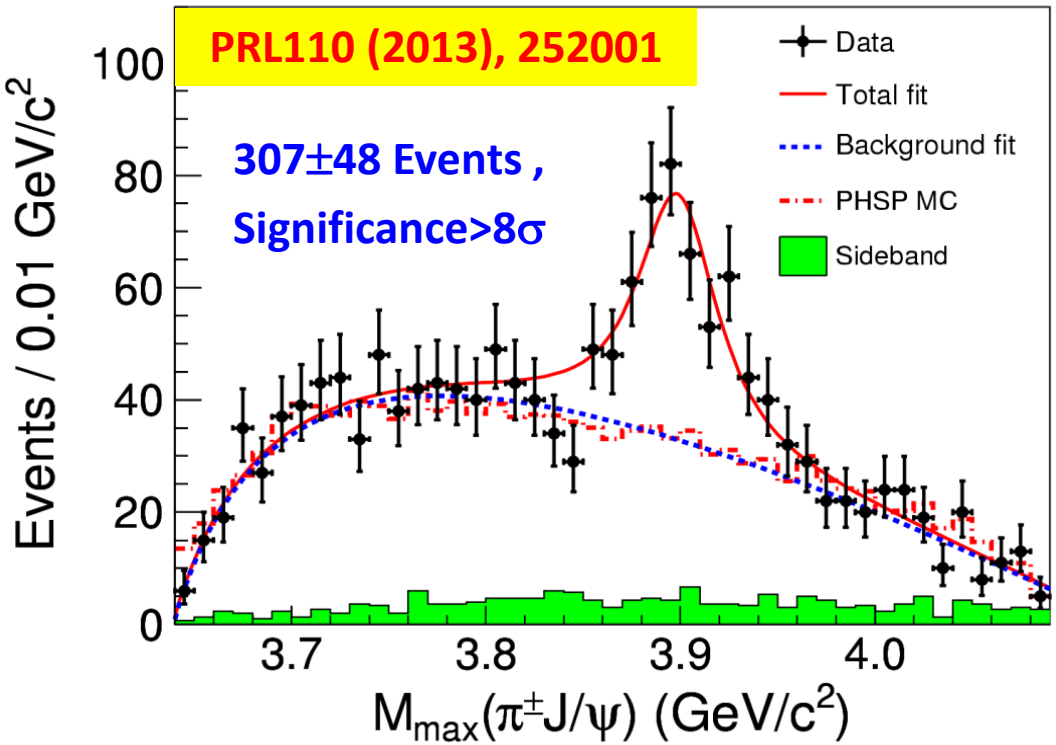


Z_b(10610) and Z_b(10650)

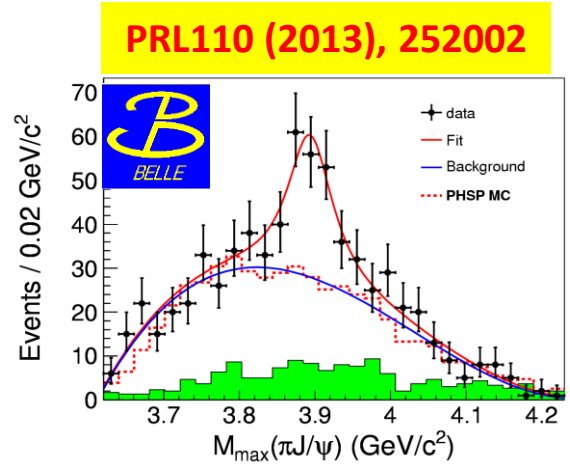
PRL 108 (2012) 122001

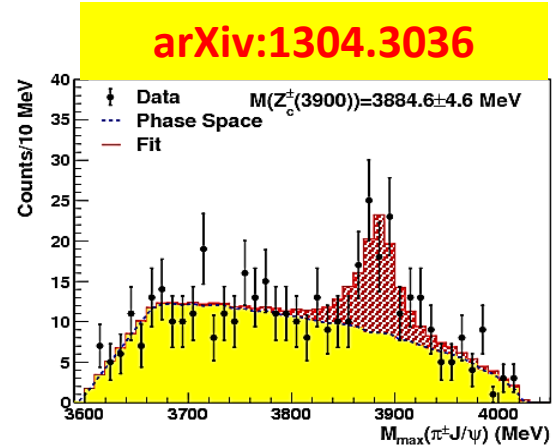
By analogy, similar substructure with charm quarks pair?

$Z_c(3900)$: $e^+e^- \to \pi^+\pi^- J/\psi$ @4.26GeV



1595 Evts in J/ψ signal region, purity ~90%





- **1D fit to extract resonance parameters**

  S-wave B-W with phase space factor & efficiency corr.
- **$M=(3899.0\pm3.6\pm4.9)$MeV/c², $\Gamma=(46\pm10\pm20)$MeV**
- **Conformed by Bell and with CLEOc data**

$Z_c(3885)$: $e^+e^- \to \pi^+(D\bar{D}^*)^-$ @4.26GeV

Partial Reconstruct

- Reconstruct D0/D+;
- Reconstruct "bachelor" $\pi^\pm$
- Require D* in he missing mass
- Looking at the recoil side of $\pi^\pm$

- Fit with rel. Breit Wigner (S-Wave).
- Bkg modeled with smooth function
- D^0D^{*-} and $D^+\bar{D}^{*0}$ give compatible results:

— M = (3883.9 ± 1.5 ± 4.2) MeV/c^2

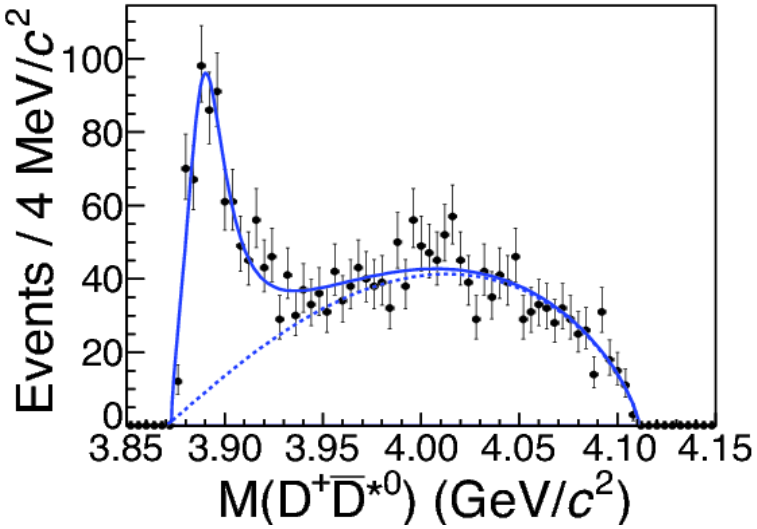
— Γ = (24.8 ± 3.3 ± 11.0) MeV

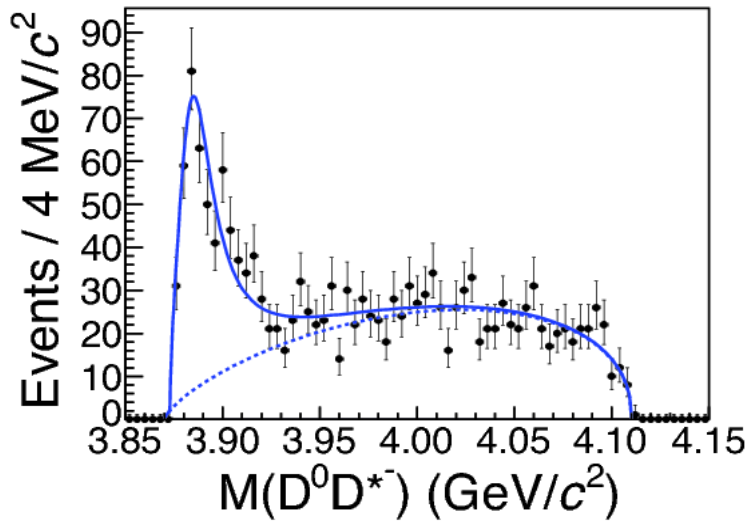
— $\sigma\times$Br= (83.5 ± 6.6 ± 22.0) pb

Are $Z_c(3885)$ and $Z_c(3900)$ same states?

$\frac{\Gamma(Z_c(3885)\to D\bar{D}^*)}{\Gamma(Z_c(3900)\to\pi J/\psi)} = 6.2 \pm 1.1 \pm 2.7$ Large non-DD coupling

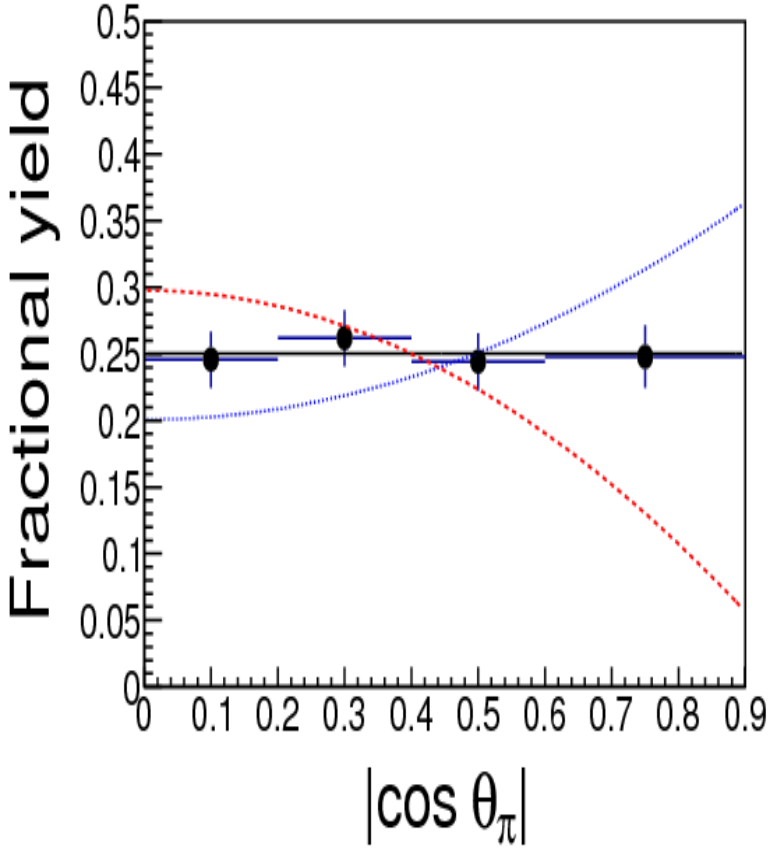
arXiv:1310.1163, Submitted PRL





Quantum number of $Z_c(3885)$

$\cos\theta_\pi$ – angle between bachelor pion and beam axis in CMS

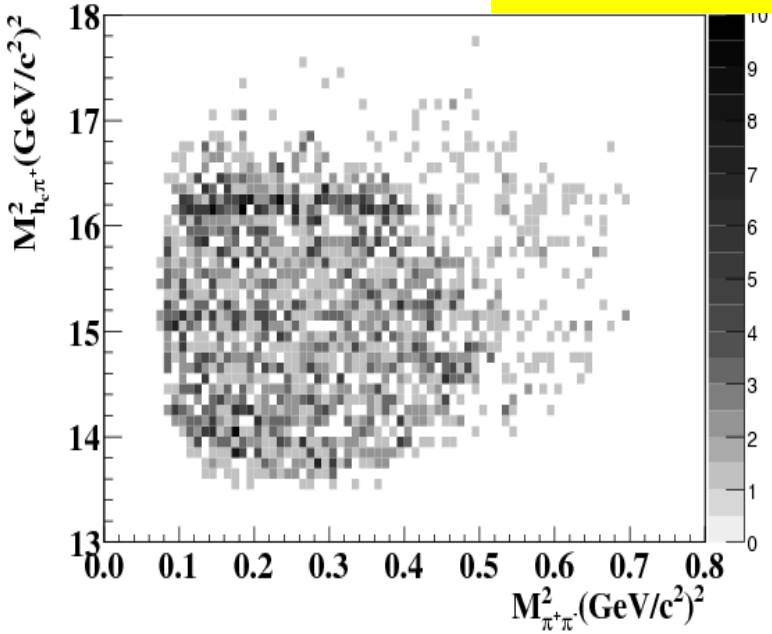


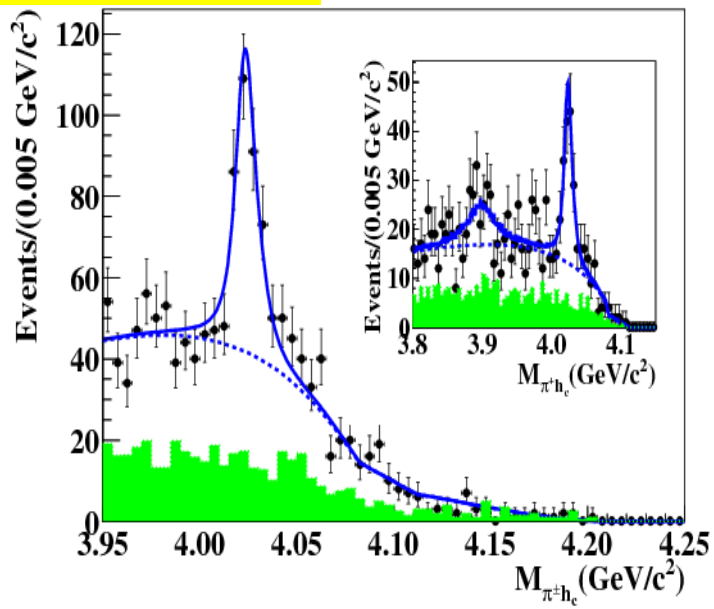
- 0^+ : excluded by parity conservation
- 0^- : P-wave, with $J_z=\pm1 \propto \sin^2\theta_\pi$
- 1^- : P-wave, $\propto 1+\cos^2\theta_\pi$
- 1^+ : S/D-wave, Assume D wave small near threshold, flat distribution in $\cos\theta_\pi$

Clearly favor $J^P=1^+$ assumption

$Z_c(4020)$: $e^+e^- \to \pi^+\pi^- h_c(1P)$

arXiv:1309.1896, Submitted PRL





- Obvious structure around 4.02GeV/c^2
- Simultaneously fit to

  4.23/4.26/4.36GeV data (2.4fb^{-1})
- M= (4022.9 ± 0.8 ± 2.7) MeV/c2
- Γ = (7.9 ± 2.7 ± 2.6) MeV

- σ = 8.7 ± 1.9 ± 2.8 ± 1.4 pb @ 4230

  7.4 ± 1.7 ± 2.1 ± 1.2 pb @ 4260

  10.3 ± 2.3 ± 3.1 ± 1.6 pb @ 4360

Significance $Z_c(4020) \sim 8.9\sigma$

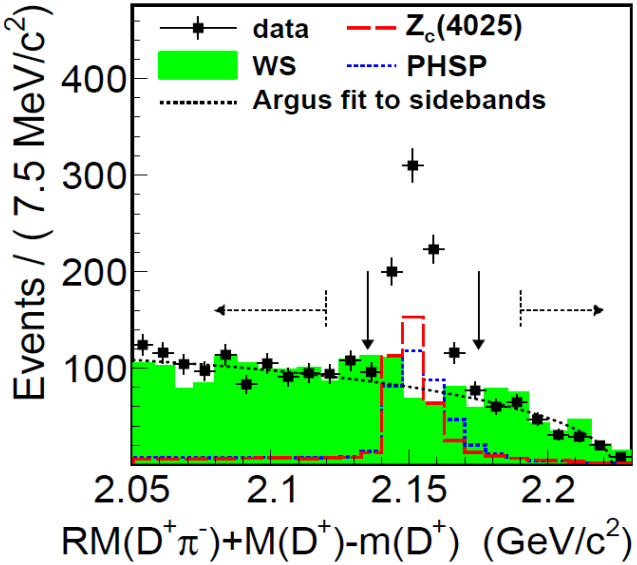
Significance $Z_c(3900) \sim 2.1\sigma$

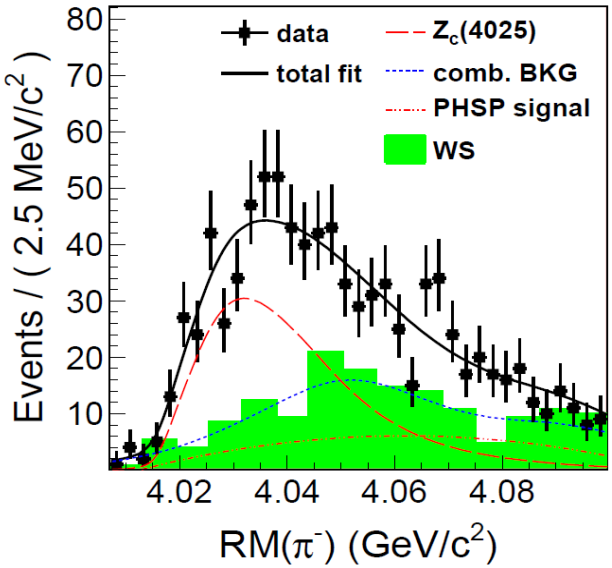
$Z_c(4025)$: $e^+e^- \to \pi^-(D^*\bar{D}^*)^+$ @4.26GeV

arXiv:1308.2760, Submitted PRL

Partial reconstruction technique

Reconstruct π^-, D^+ and one π^0 from $D^{*+} \to D^+\pi^0$ or $D^{*0} \to D^0\pi^0$





Fit to $\pi^\pm$ recoil mass yields :

- **M = (4026 ± 2.6 ± 3.7) MeV/c^2**
- **Γ = (24.8 ± 5.6 ± 7.2) MeV**
- **401±47 Events, Significance : >10σ**

$$\sigma(e^+e^- \to \pi^\pm(D^*\bar{D}^*)^\mp) = (137 \pm 9 \pm 15)\ \text{pb}$$

$$R = \frac{\sigma\ (e^+e^- \to \pi^\pm Z_c^\mp(4025) \to \pi^\pm(D^*\bar{D}^*)^\mp)}{\sigma\ (e^+e^- \to \pi^\pm(D^*\bar{D}^*)^\mp)} = (65 \pm 9 \pm 6)\%$$

Summary of Z_c

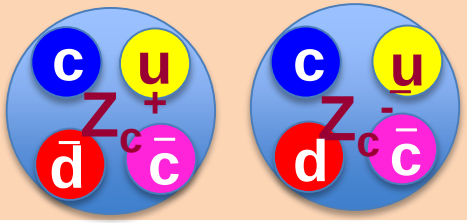
Channel	Mass [MeV/c^2]	Width [MeV]
$J/\psi\,\pi^+$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$
$(D\bar{D}^*)^+$	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$
$h_c\pi^+$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$
$(D^*\bar{D}^*)^+$	$4026.3 \pm 2.6 \pm 3.7$	$24. \pm 5.6 \pm 7.7$

DD* mass threshold (3875MeV)

D*D* mass threshold (4017MeV)

Signature of exotic states

- $c\bar{c}$
- has electric charge
- $\Rightarrow$ At least 4-quarks Clearly

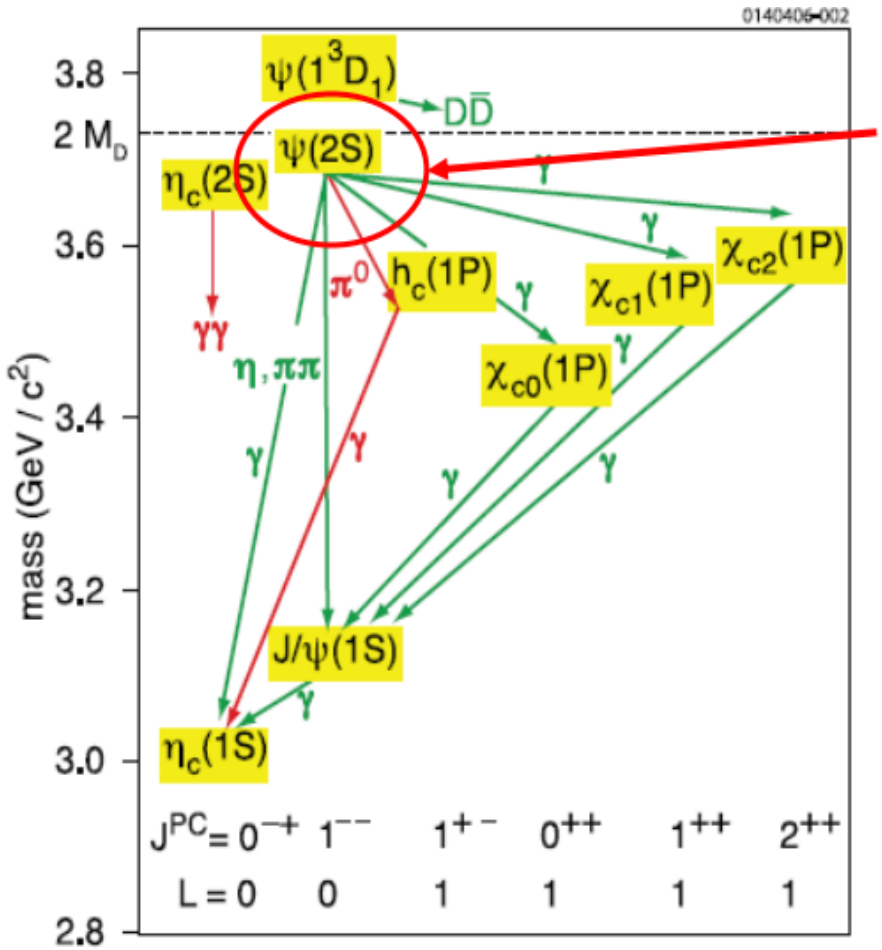


Nature of these states?

- Tetraquark? L. Maiani, A. Ali et al
- Hadronic molecule? U.-G Meissner et al
- Hadro-charmonium? M. B. Voloshin
- Meson loop? Q. Zhao et al
- ISPE model? X. Liu et al
- ……

Charmonium states

Spin singlet states : $\eta_c(1S)$, $\eta_c(2S)$, $h_c(^1p_1)$



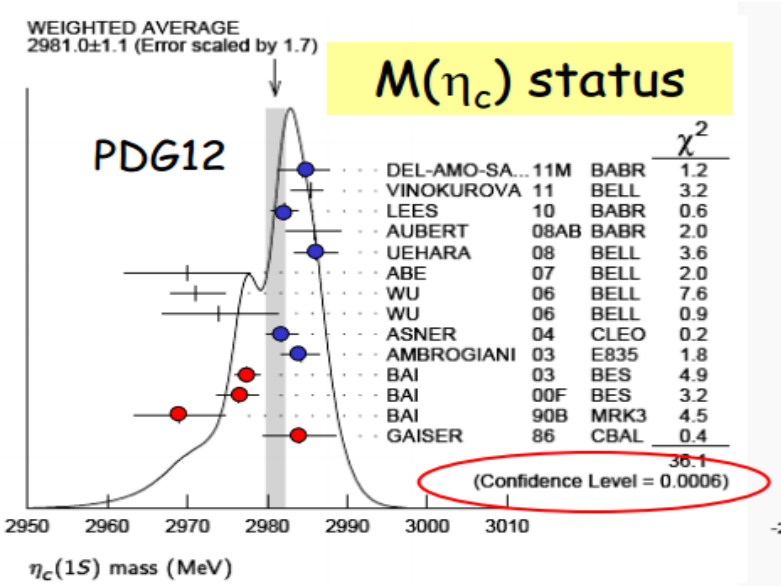
BESIII: 106 M Ψ' events. Will be used for following analyses.

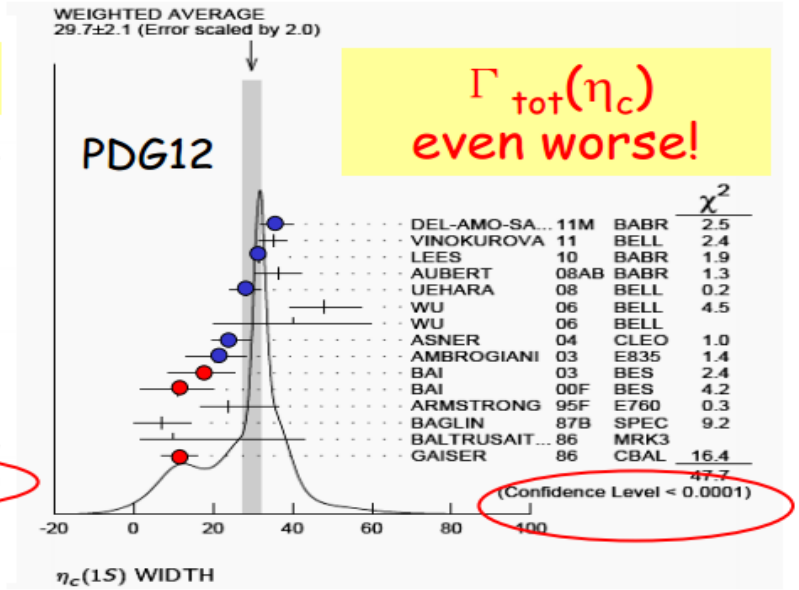
$\eta_c(1S)$: $\psi(2S) \to \gamma\, \eta_c(1S)$

- S-wave spin-singlet ground state [MARKII, PRL 45 (1980), 1146].
- The mass and width are not well know

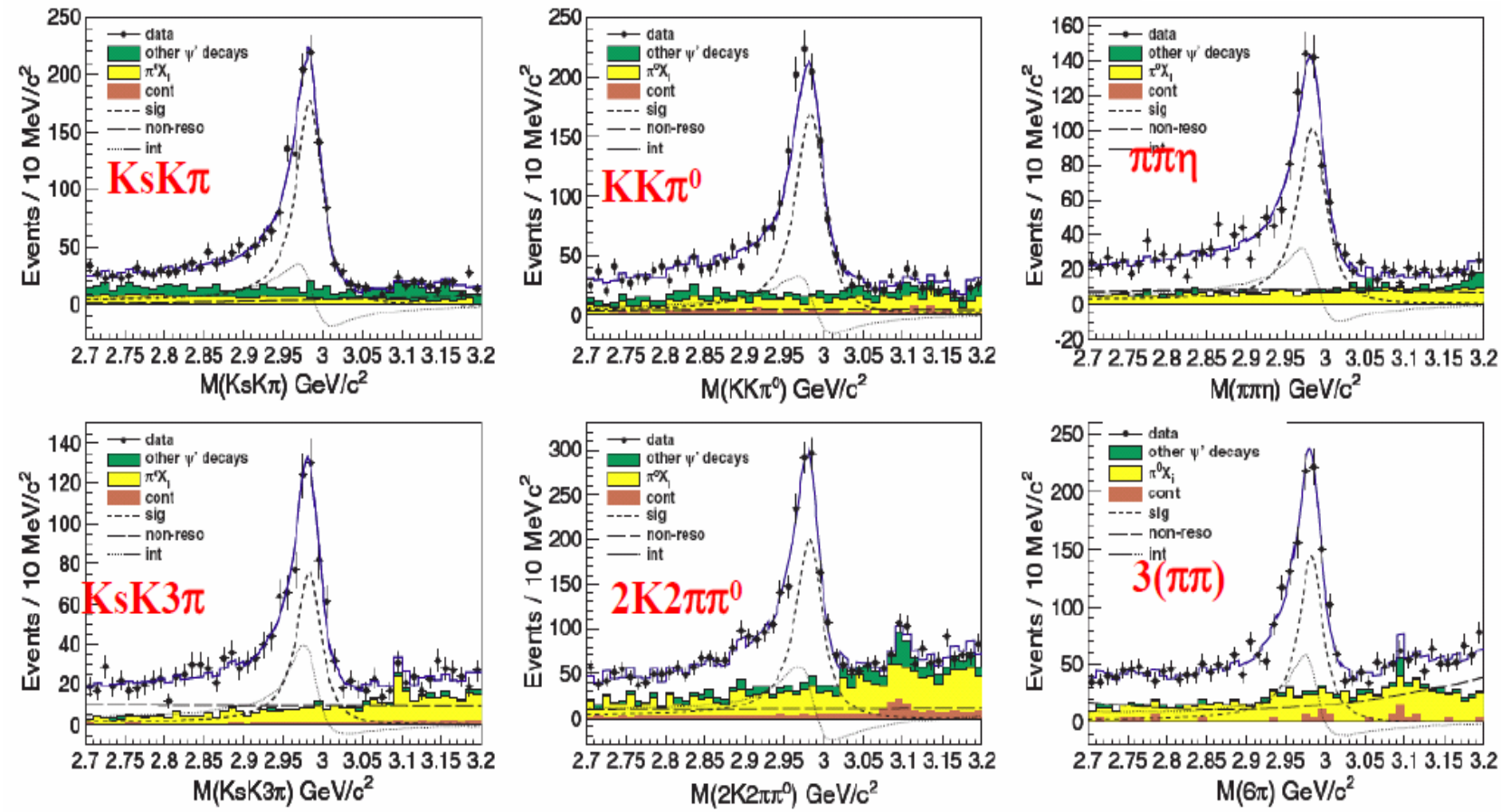
  J/ψ radiative transition : M ~ 2978.0 MeV/c^2, G ~ 10 MeV

  $\gamma\gamma/p\bar{p}$/B decay : M = 2983.1 ± 1.0 MeV/c^2, G = 31.3 ± 1.9 MeV
- $c\bar{c}$ hyperfine splitting M(J/ψ)-M(η_c(1S)) is the important input to test LQCD, but is dominated by error on M(η_c(1S))
- CLEOc found the distortion of η_c line shape in ψ(2S) decays.





$\eta_c(1S)$: $\psi(2S)\to\gamma\,\eta_c(1S)$

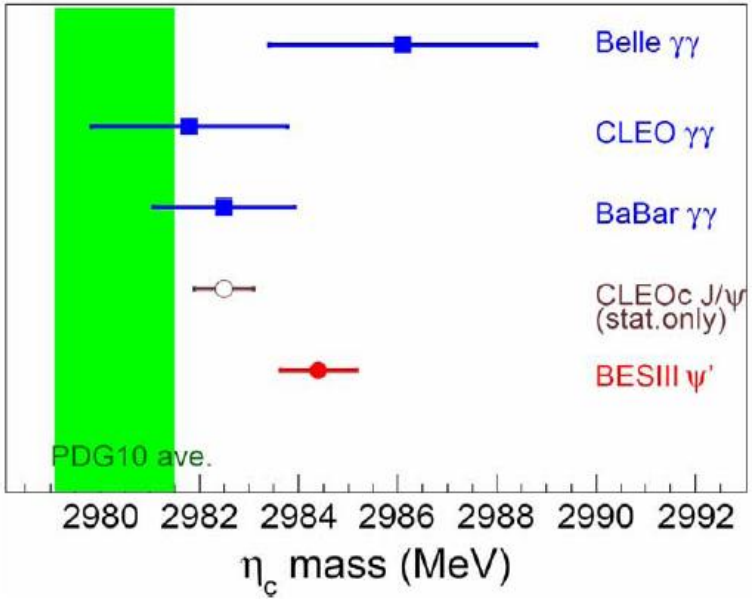


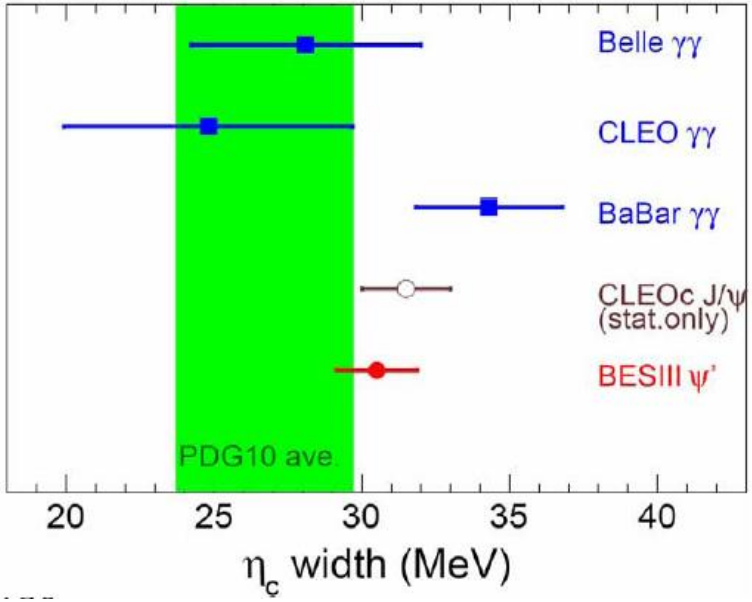
- Studied from $\psi(2S)\to\gamma\eta_c$, with 6 η_c decay models
- Simultaneous fit with distorted lineshape with significant interference (15σ) between η_c and non-η_c decays

$M = 2984.3 \pm 0.6 \pm 0.6$ MeV
$\Gamma = 32.0 \pm 1.2 \pm 1.0$ MeV

PRL108 (2012), 222002

$\eta_c(1S)$: $\psi(2S) \to \gamma\, \eta_c(1S)$

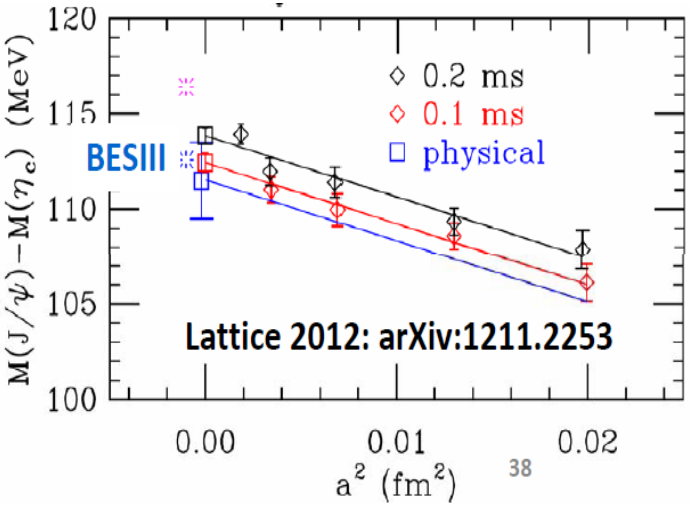




- **BESIII is the most precise measurement**
- **Consistent well with γγ and $p\bar{p}$ production.**
- **Hyperfine splitting :**

  $\Delta M_{hf}(1S)_{ccbar} = 112.6 \pm 0.8$ MeV/c^2
- **Good agreement with LQCD calculations:**

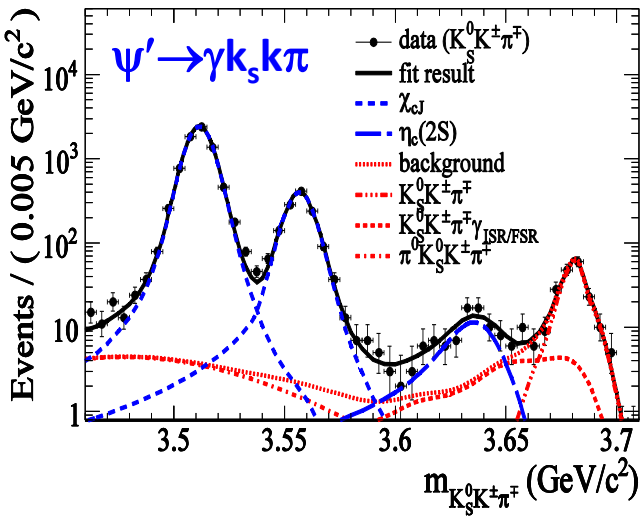
  108 ~ 117 MeV/c^2

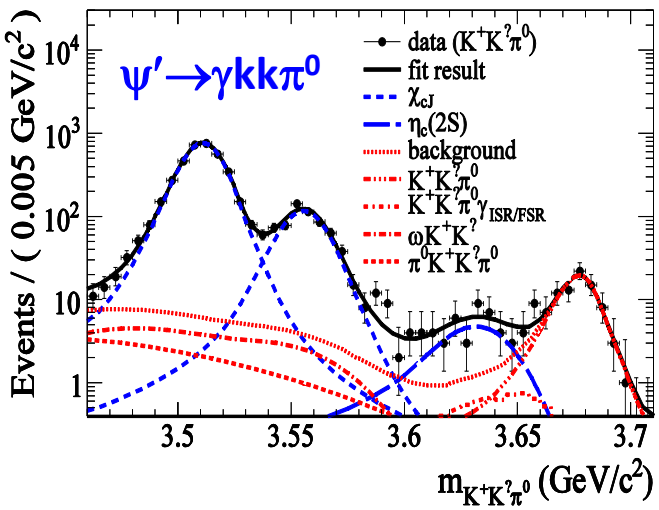


$\eta_c(2S)$: $\psi(2S)\to\gamma\,\eta_c(2S)$

- First "observation" by Crystal Ball in 1982 (M=3592MeV, $\psi(2S)\to\gamma X$), not confirmed
- First observed by Belle in $B^{\pm}\to K^{\pm}\,\eta_c(2S)$, $\eta_c(2S)\to KsK\pi$
- PDG2012 : All from B-factory/CLEO

Experiment challenge : search for photons with 48MeV





- Observed signal in $K_sK\pi$, found evidence in $KK\pi^0$
- Simultaneous fit of $\eta_c(2S)$ and χ_{cJ} signals
  - M = (3637.6 ± 2.9 ± 1.6) MeV/c², Γ = (16.9 ± 6.4 ± 4.8) MeV
  - Statistical significance 11σ, 127 ± 18 events

PRL109 (2012), 042003

$\eta_c(2S)$: $\psi(2S)\to\gamma\,\eta_c(2S)$

BESIII : $Br(\psi(2S)\to\gamma\eta_c(2S)\to\gamma KK\pi) = (1.30 \pm 0.20 \pm 0.30)\times10^{-5}$

[PRL 109 (2012), 042003]

BaBar : $Br(\eta_c(2S)\to KK\pi) = (1.9 \pm 0.4 \pm 1.1)\%$

[PRD 78 012006 (2008)]

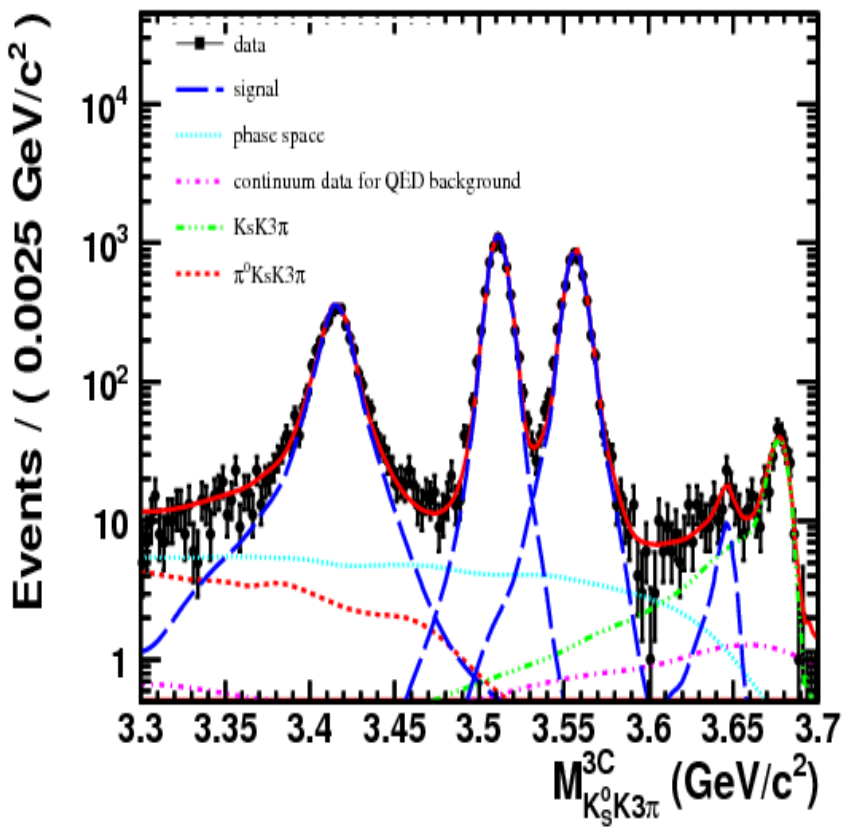
First measured $Br(\psi(2S)\to\gamma\eta_c(2S)) = (6.8 \pm 1.1 \pm 4.5)\times 10^{-4}$

Potential model $(0.1\text{-}6.2)\times10^{-4}$;

CLEOc : $< 7.6\times 10^{-4}$ [PRD 81, 052002]

$\eta_c(2S)$: $\psi(2S)\to\gamma\,\eta_c(2S)$

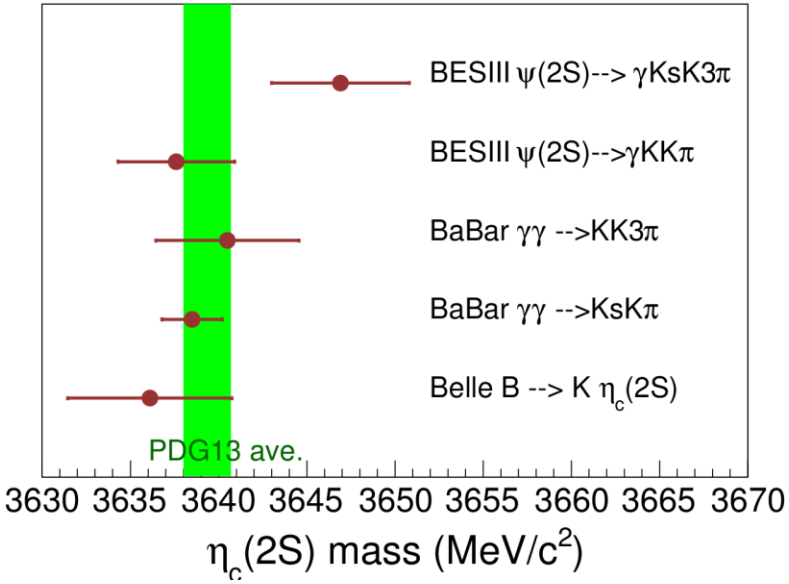
$\psi(2S)\to\gamma\,\eta_c(2S)\to\gamma K_s K3\pi$

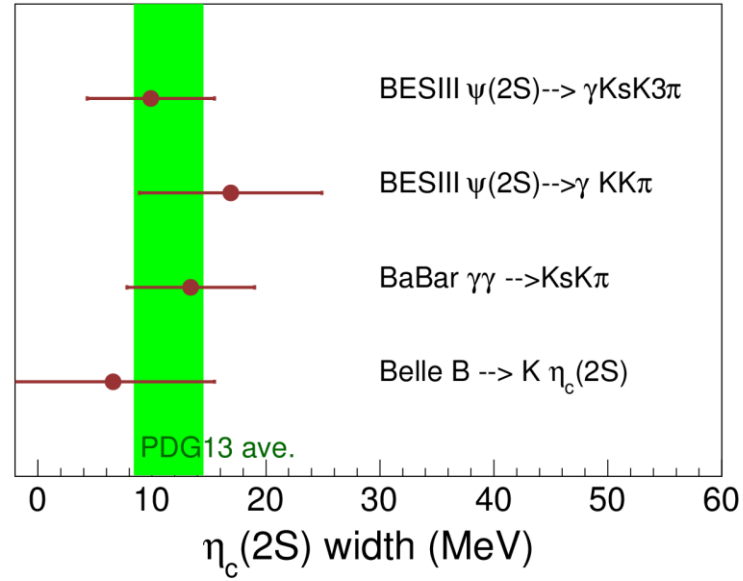


- Evidence significance 4.2σ
- $M = (3646.9 \pm 1.6 \pm 3.6)$ MeV/c^2
- $\Gamma = (9.2 \pm 4.8 \pm 2.9)$ MeV
- $Br(\psi(2S)\to\gamma\,\eta_c(2S)\to\gamma K_s K3\pi) = (7.03 \pm 2.10 \pm 0.70)\times 10^{-6}$

PRD 87 (2013), 052005

$\eta_c(2S)$: $\psi(2S) \to \gamma\, \eta_c(2S)$





Hyperfine splitting : $\Delta M_{hf}(2S) = 46.7 \pm 1.3$ MeV/c^2 (PDG2012)

LQCD calculation : $\Delta M_{hf}(2S) = 57.9 \pm 2.0$ MeV/c^2 (arXiv:1209.5790)

BESIII will be able to improve mass and width precision with more data!

$h_c(^1P_1)$: $\psi(2S)\to\pi^0 h_c$

- **Spin singlet P-wave (S=0, L=1), its mass is important to learn about hyperfine interaction of P-wave states.**
- **Potential model : if non-vanishing P-wave spin-spin interaction**

  $\Delta M_{hf}(1P) = M(^1P_1) - \langle M(^3P_J)\rangle = M(^1P_1) - [\, M(c_{c0}) + 3M(c_{c1}) + 5M(c_{c2})\,]/9 \sim 0$
- **Theoretical predictions :**

— $B(\psi(2S)\to\pi^0 h_c) = (0.4\text{-}1.3)\times10^{-3}$, $B(h_c\to\gamma\eta_c) = 41\%$ (NRQCD)

$B(h_c\to\gamma\eta_c) = 88\%$ (PQCD) [PRD65 (2002), 094024]

— $B(h_c\to\gamma\eta_c) = 38\%$ [Godfrey and Rosner, PRD66 (2002), 014012]

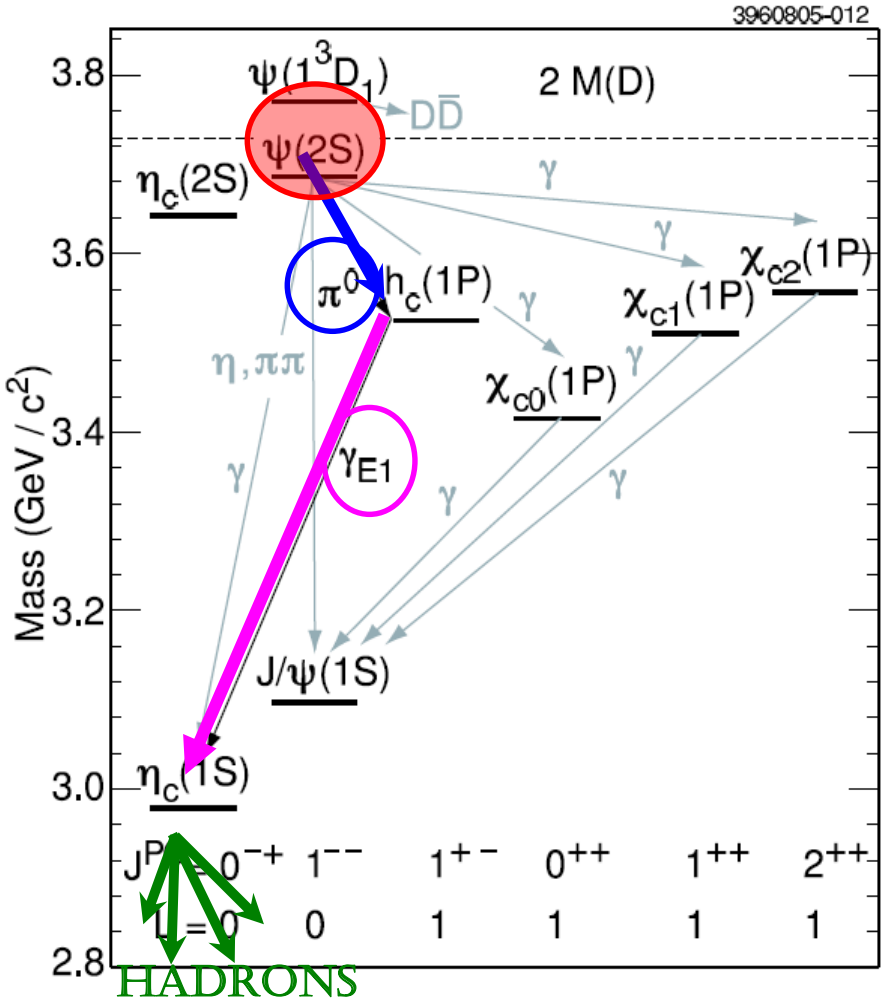
- **Experiment measurement :**

— First reported by E760 in decay $pp\to h_c\to J/\psi\pi^0$, not confirmed

— Evidence found by E835 in $pp\to h_c\to\gamma\eta_c$ in 2005 [PRD72, 032001]

— Observed by CLEO in $\psi(2S)\to\pi^0 h_c$, $h_c\to\gamma\eta_c$ [PRL95 (2005), 102003]

$h_c(^1P_1)$: $\psi(2S)\to\pi^0 h_c$



"inclusive"

only detect the π^0

(compute $M(h_c)$ from kinematic)

Rate $\propto B(\psi(2S)\to\pi^0 h_c)$

"E1 tagged"

detect the π^0 & γ

Rate $\propto B(\psi(2S)\to\pi^0 h_c)\times B(h_c\to\gamma\eta_c)$

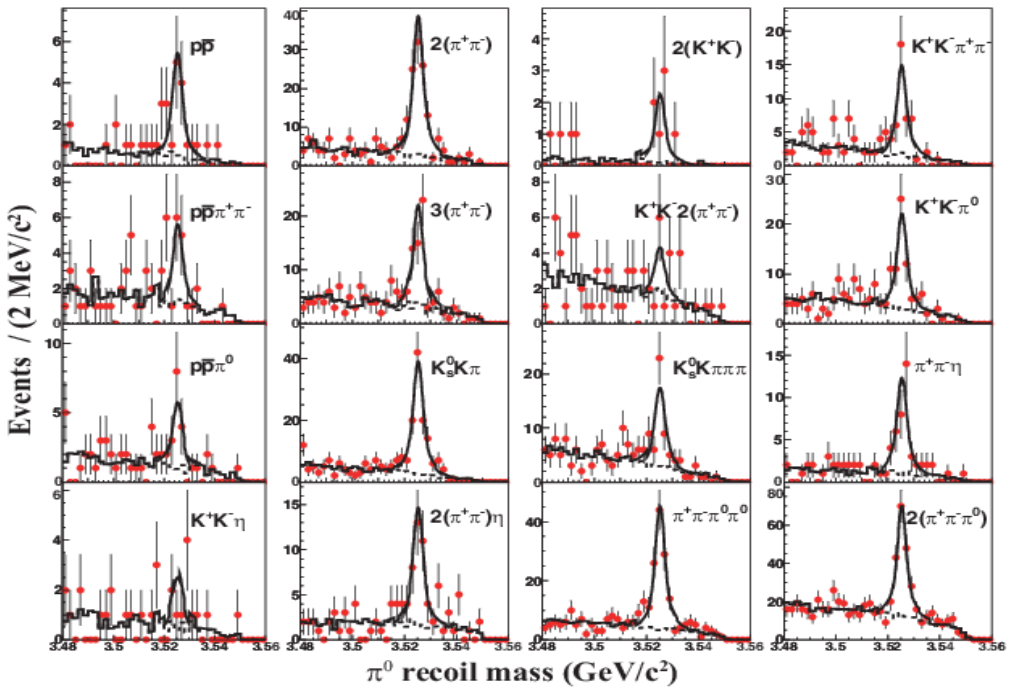
"exclusive"

detect the π^0, γ & $\eta_c\to X_i$ decays

Rate $\propto B(\psi(2S)\to\pi^0 h_c)\times B(h_c\to\gamma\eta_c)$

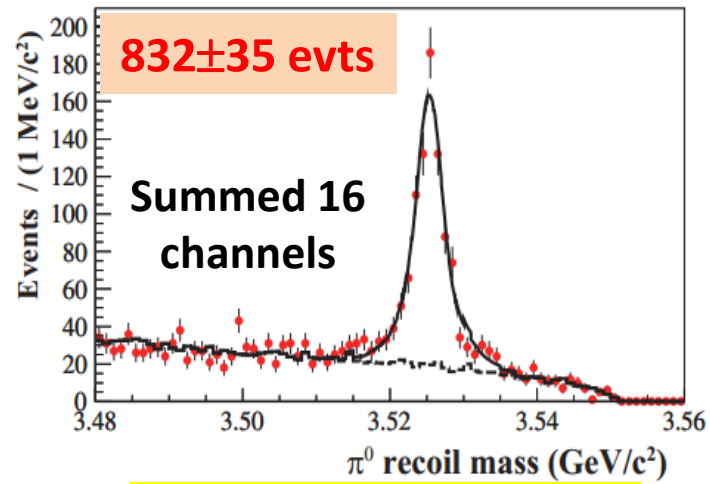
$\times B(\eta_c\to X\ i\ )$

$h_c(^1P_1)$: $\psi(2S)\to\pi^0 h_c$ ($h_c\to\gamma\eta_c$)



16 hadronic decays

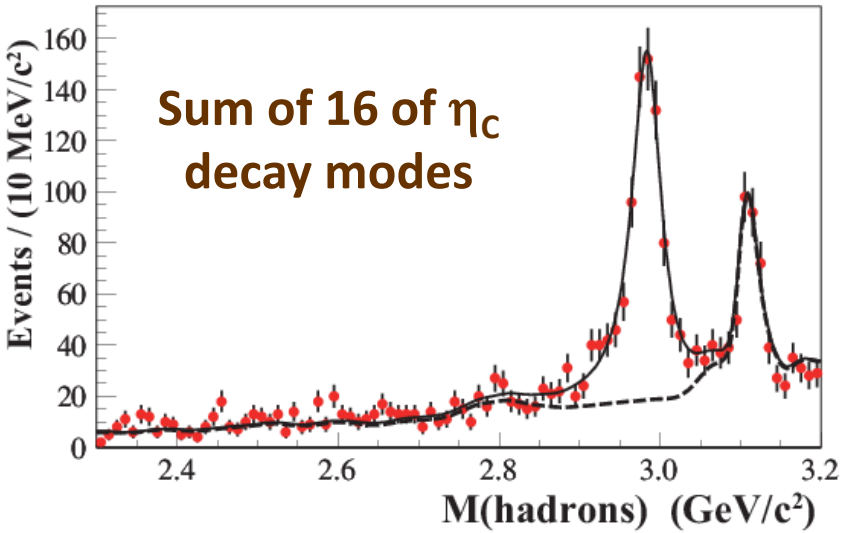
(~40% η_c decays)

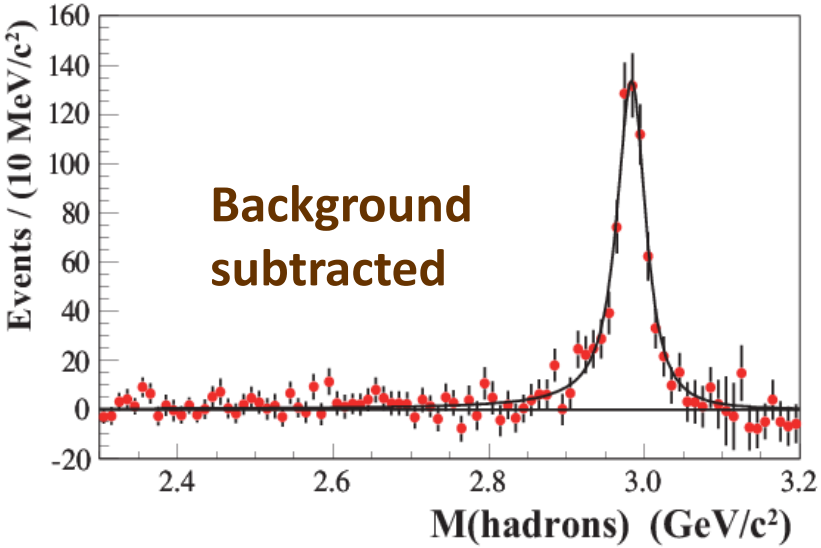


PRD 86 (2012), 092009

(MeV)	BESIII Exclusive [PRD 86, 092009]	BESIII Inclusive [PRL 104, 132002]	CLEO [PRL 101, 182003]
Mass	$3525.31 \pm 0.11 \pm 0.14$	$3525.40 \pm 0.13 \pm 0.18$	$3525.21 \pm 0.27 \pm 0.14$
Width	$0.70 \pm 0.28 \pm 0.22$	$0.73 \pm 0.45 \pm 0.28$	--
$\Delta M_{hf}(1P)$	$-0.01 \pm 0.11 \pm 0.15$	$0.10 \pm 0.13 \pm 0.18$	$0.08 \pm 0.18 \pm 0.12$

$\eta_c(1S)$: $h_c \to \gamma\eta_c$





η_c lineshape in $h_c \to \gamma\eta_c$ is not as distorted as in $\psi(2S) \to \gamma\eta_c$ decays :

- **the non-resonant interfering background is smaller than $\psi(2S) \to \gamma\eta_c$**
- **will be best suited to determine η_c resonance parameters**

(MeV)	$h_c \to \gamma\eta_c$	$\psi(2S) \to \gamma\eta_c$
Mass	$2984.49 \pm 1.16 \pm 0.52$	$2984.3 \pm 0.6 \pm 0.6$
Width	$36.4 \pm 3.2 \pm 1.7$	$32.0 \pm 1.2 \pm 1.0$

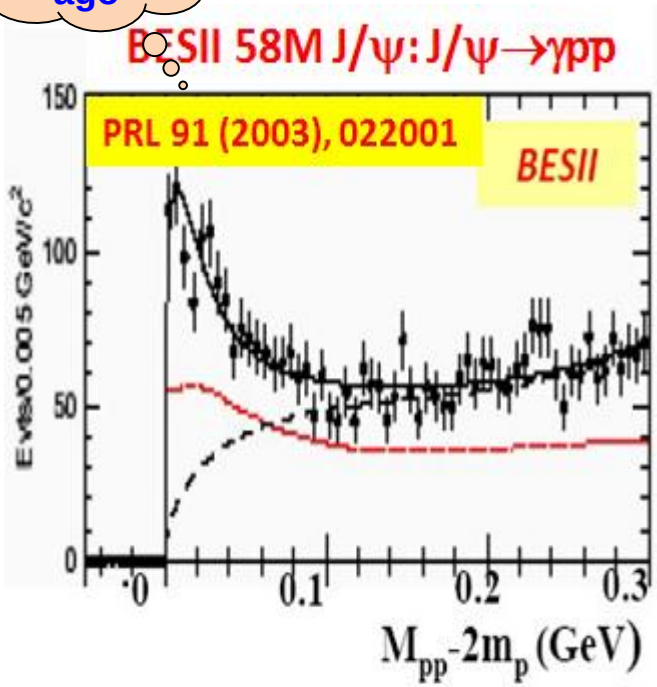
Consistent with those from $\psi(2S) \to \gamma\eta_c$, statistic errors are dominated, need more statistics.

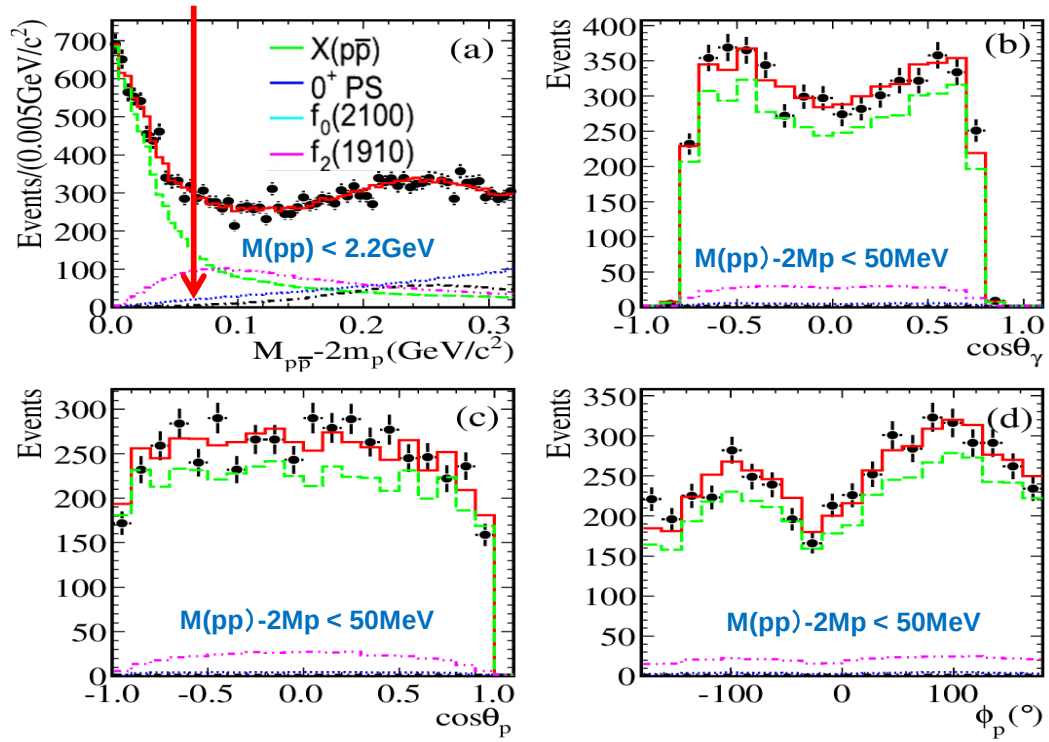
PRD 86 (2012), 092009

Light Hadron Spectroscopy

PWA of $J/\psi \to \gamma p\bar{p}$ ($m_{p\bar{p}}$<2.2GeV)

10 years ago





- **The fit with BW and S-wave FSI (I=0) factor can well describe $p\bar{p}$ threshold structure.**
- **Better than that w/o FSI effect (7.1σ), BESIII Results:**

— $J^{PC} = 0^{-+}$, >6.8σ better than other J^{PC} assignments.

— $M = 1832^{+19}_{-5}(stat)^{+18}_{-17}(syst) \pm 19(model)$ MeV/c²

— $\Gamma = 13 \pm 39(stat)^{+10}_{-13}(syst) \pm 4(model)$ MeV/c² or Γ < 76MeV/c² @ 90 C.L.

— $Br(J/\psi \to \gamma X(p\bar{p})) \times Br(X(p\bar{p}) \to p\bar{p}) = (9.0^{+0.4}_{-1.1}(stat)^{+1.5}_{-5.0}(syst) \pm 2.3(model)) \times 10^{-5}$

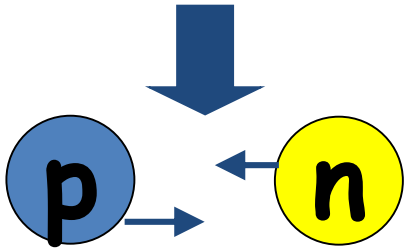
PRL 108 (2012), 112003

A $p\bar{p}$ bound state (baryonium)?

- **Many theoretical Interpretation :**
  - Normal meson, multi-quark, glueball ….
  - Final state interaction (FSI)
  - $p\bar{p}$ bound state?

deuteron

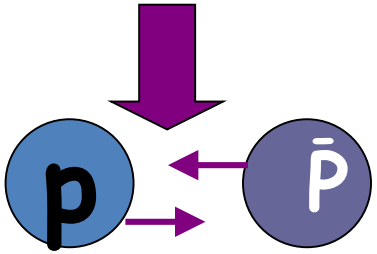
attractive nuclear force



loosely bound 3-q &
3-q color singlets
with $M_d=2m_p-\varepsilon$

Baryonium

attractive force?



loosely bound 3-q &
3-$\bar{q}$ color singlets
with $M_b=2m_p-\delta$?

A $p\bar{p}$ bound state (baryonium)?

Fermi & Yang in 1949
(7 years before p discovery)

If NN potential is attractive, they could bind to form π-like states.

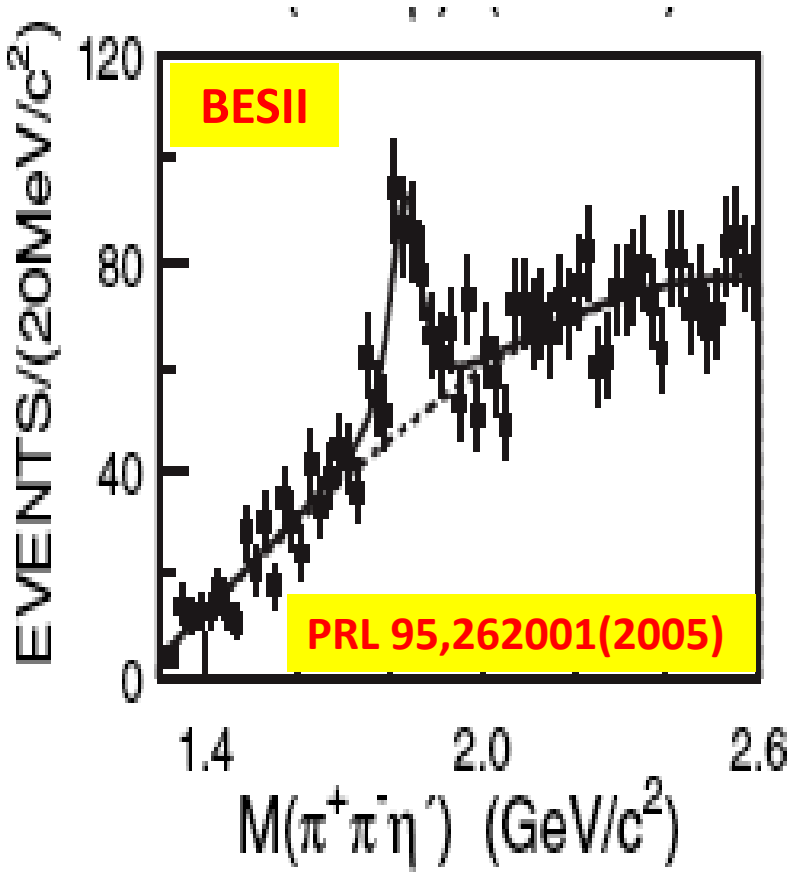
THE
PHYSICAL REVIEW
A journal of experimental and theoretical physics established by E. L. Nichols in 1893
SECOND SERIES, VOL. 76, NO. 12 DECEMBER 15, 1949

Are Mesons Elementary Particles?

E. FERMI AND C. N. YANG*
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received August 24, 1949)

The hypothesis that π-mesons may be composite particles formed by the association of a nucleon with an anti-nucleon is discussed. From an extremely crude discussion of the model it appears that such a meson would have in most respects properties similar to those of the meson of the Yukawa theory.

X(1835) in $J/\psi \to \gamma\pi^+\pi^-\eta'$

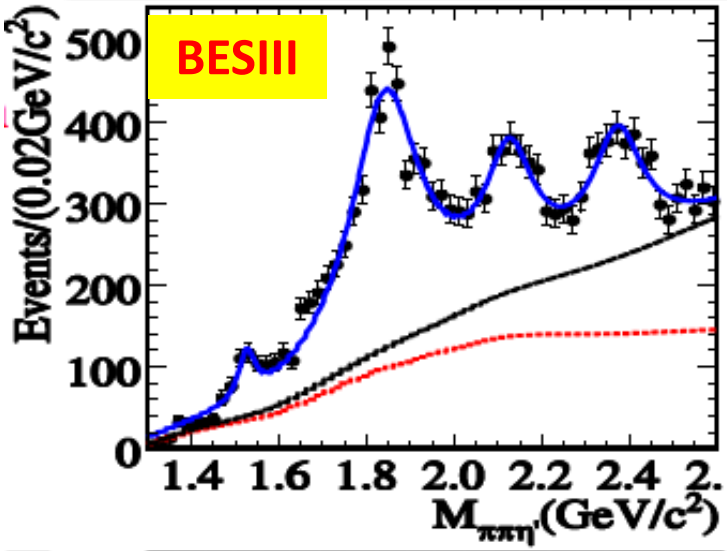


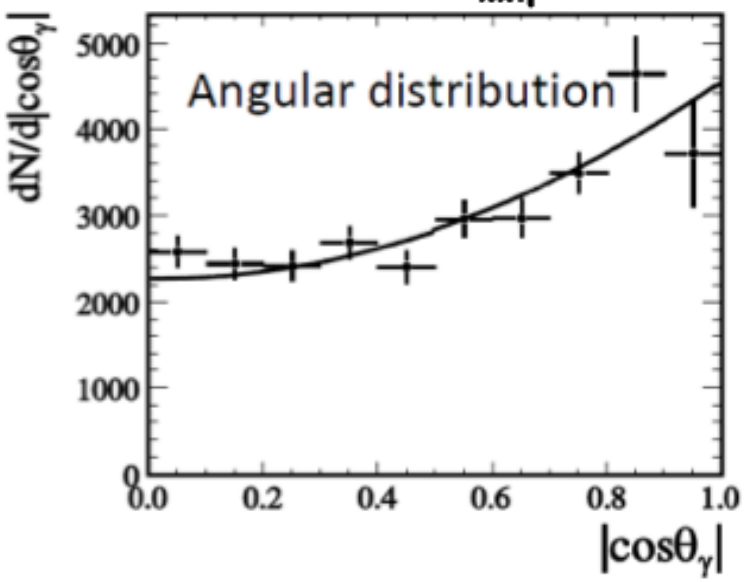
BESIII $p\bar{p}$ PWA
$1832^{+19}_{-5}{}^{+18}_{-17} \pm 19 MeV/c^2$

- **BESII Results :**
  - $M=1833.7\pm6.1(stat)\pm2.7(syst)\ MeV/c^2$
  - $\Gamma=67.7\pm20.3(stat)\pm7.7(syst)\ MeV/c^2$
  - $B(J/\psi\to\gamma X(1835))B(X(1835)\to\pi^+\pi^-\eta')$ $=(2.2\pm0.4(stat)\pm0.4(syst))\times10^{-4}$
  - Statistical Significance 7.7σ
- **Many Theoretical interpretations:**
  - $p\bar{p}$ bound state
  - η excitation
  - ....

Are X($p\bar{p}$) and X(1835) from the same source ?

X(1835) in $J/\psi \to \gamma\pi^+\pi^-\eta'$





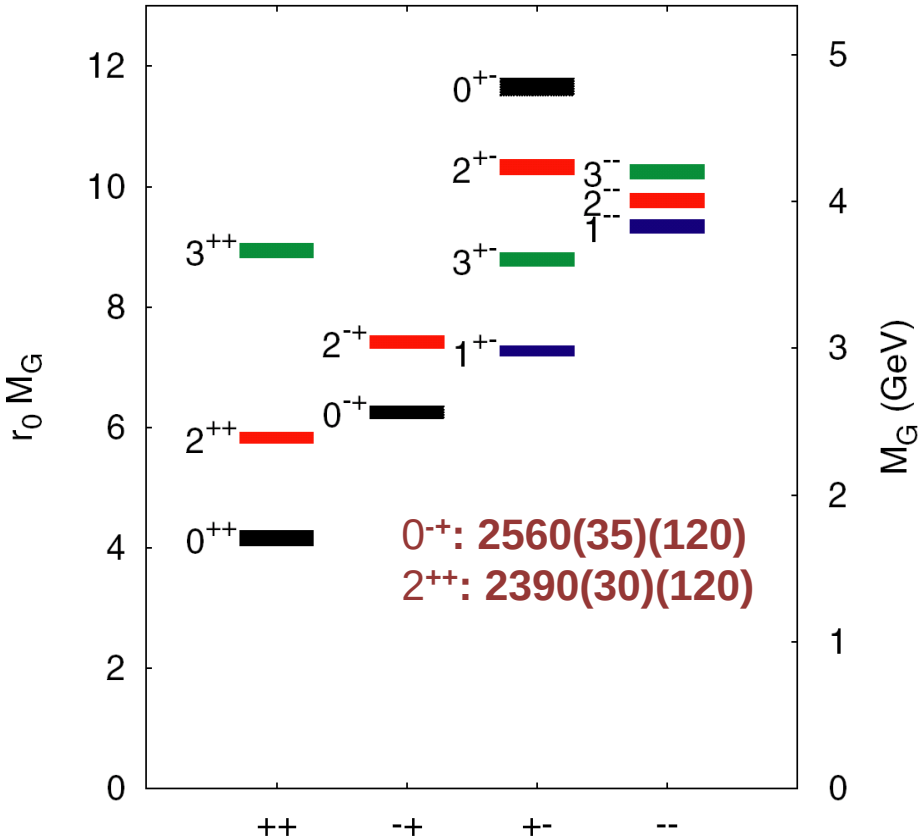
PRL 106, 072002 (2011)

resonance	M(MeV/c^2)	Γ(MeV/c^2)	significance
X(1835)	1836.5 ± 3.0	190.1 ± 9.0	$>> 20\sigma$
X(2120)	2122.4 ± 6.7	84 ± 16	$> 7.2\sigma$
X(2370)	2376.3 ± 8.7	83 ± 17	$> 6.4\sigma$

- **BESIII Results:**
  - **$B(J/\psi \to \gamma X(1835)) \times B(X(1835) \to \pi^+\pi^-\eta')$ =**
    $(2.87 \pm 0.09(stat)^{+0.49}_{-0.52}(syst)) \times 10^{-4}$
  - **The polar angle of the photon is consistent with expectation for a pseudoscalar.**
  - **Two more structures are observed.**

What are the two new structures?

PRD73 (2006), 014516 Y.Chen et al

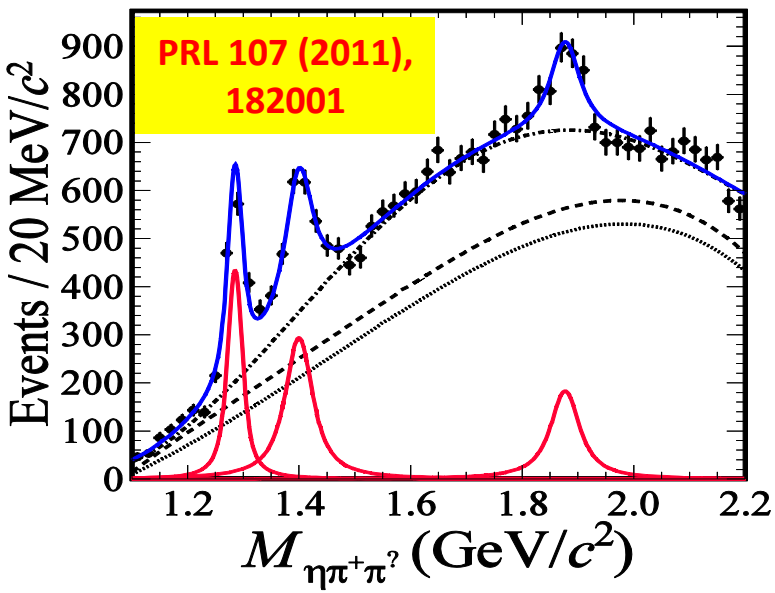


PRD82 (2010), 074026, PRD83 (2011), 114007 more…

- **First distinct narrow structures observed above 2 GeV (Γ<100MeV)**
  - LQCD predicts that the lowest–lying pseudoscalar glueball: around 2.3GeV
  - $J/\psi \to \gamma\eta'\pi^+\pi^-$ is a good channel for finding 0^{-+} glueballs.
- **X(2120)/X(2370) possibilities:**
  - Pseudoscalar & tensor glueballs?
  - η/η' excited states?
- **PWA is needed, interference among the resonances needs to be considered**
- **More processes to search these status are necessary.**

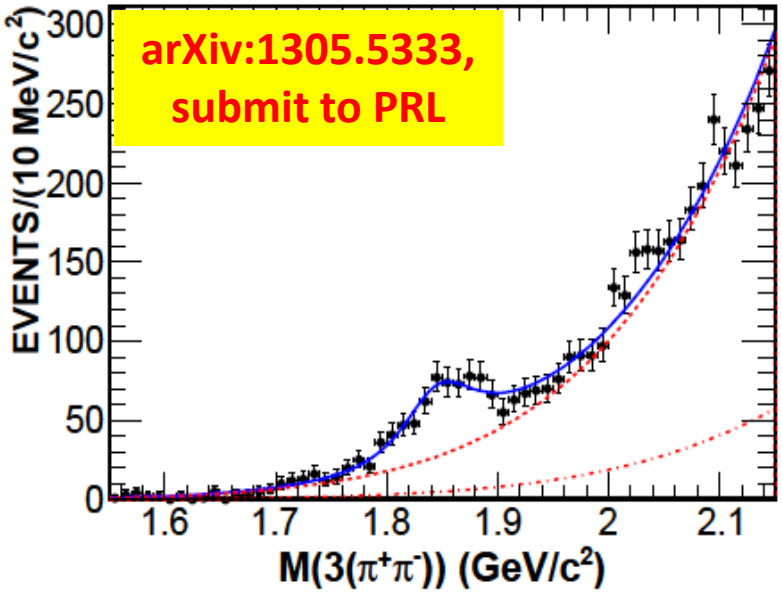
Others new observations

X(1870) in $J/\psi \to \omega\pi^+\pi^-\eta$



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

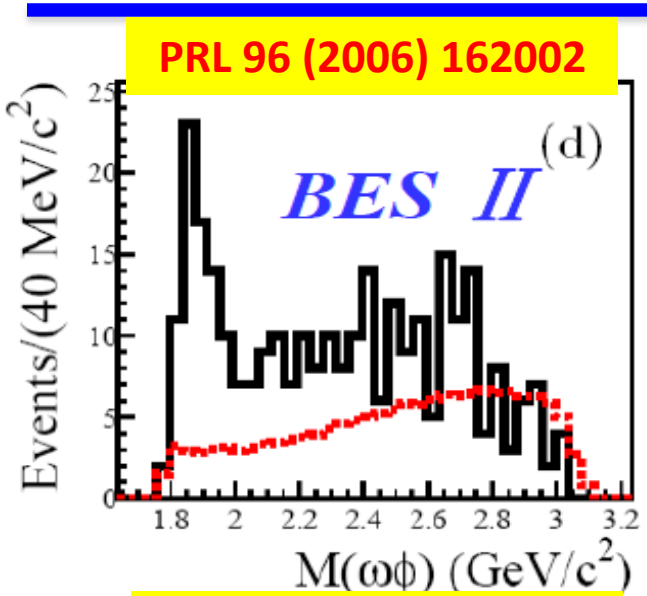
X(1840) in $J/\psi \to \gamma 3(\pi^+\pi^-)$

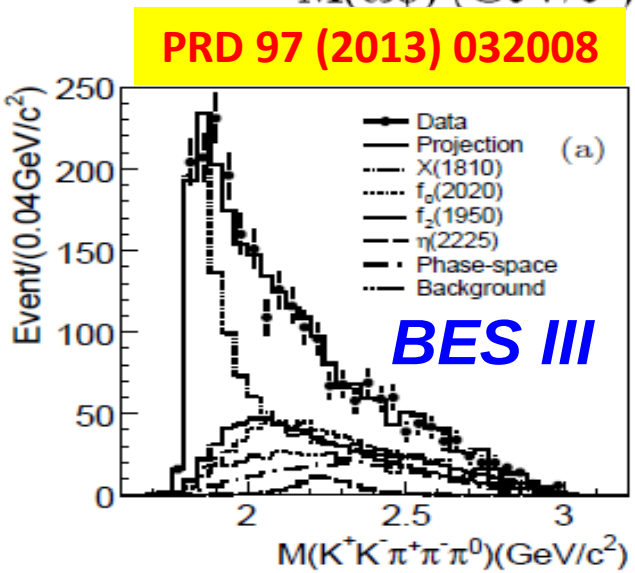


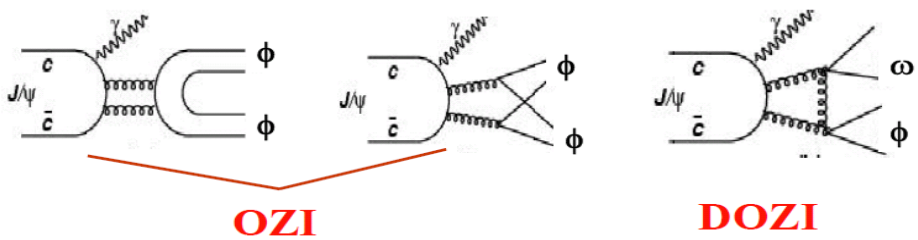
- **A structure is observed.**
  - **M = 1842.2 ± 4.2 + 7.1 - 2.6MeV/c²**
  - **Γ = 83 ± 14 ± 11MeV**
- **No structure observed above 2.0 GeV**

New structures or an existing states? Need more study! (J^{PC}, relationship between different observations)

Threshold Enhancement in $J/\psi \to \gamma\omega\phi$





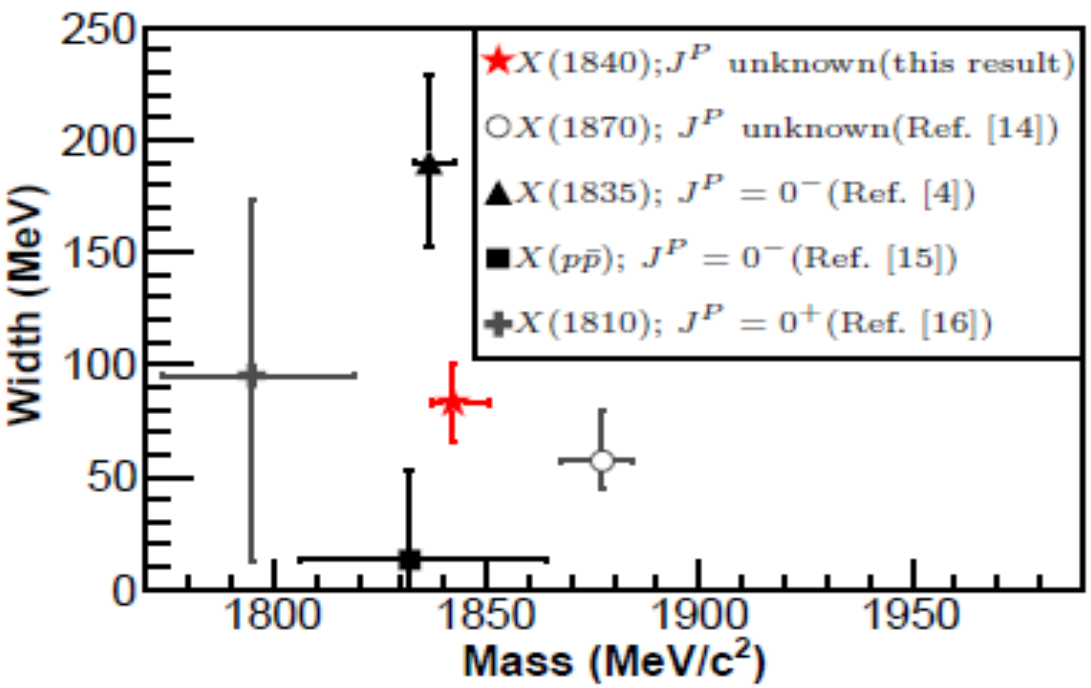


$J/\psi \to \gamma\phi\phi, \phi \to K^+K^-$

$J/\psi \to \gamma\omega\phi$

- First observed in the 58M J/ψ in BESII
- Confirmed and improved measurement with 225M J/ψ in BESIII.
  - $J^{PC} = 0^{++}$,
  - $M = 1795 \pm 7^{+23}_{-5}$ MeV/c², $\Gamma = 95 \pm 10^{+78}_{-34}$ MeV
- DOZI suppressed, but large branching ratio.
  - $Br(J/\psi \to \gamma X \to \gamma\omega\phi) = (2.00 \pm 0.08^{+1.38}_{-1.00}) \times 10^{-4}$
  - ~1/2 $Br(J/\psi \to \gamma\phi\phi)$
- Exotic states, $f_0(1710)$, FSI .....?
- More channels searchs....

X(18xx) new particles



J^{PC} = ?

X(1840): $J/\psi \to \gamma 3(\pi^+\pi^-)$

X(1870): $J/\psi \to \omega\, \eta\pi^+\pi^-$

$J^P = 0^-$

X(1835): $J/\psi \to \gamma 3(\pi^+\pi^-)$

X($p\bar{p}$) : $J/\psi \to \gamma\ p\ \bar{p}$

$J^P = 0^+$

X(1810): $J/\psi \to \gamma\omega\phi$

Are $J^P = 0^-$ same particles?

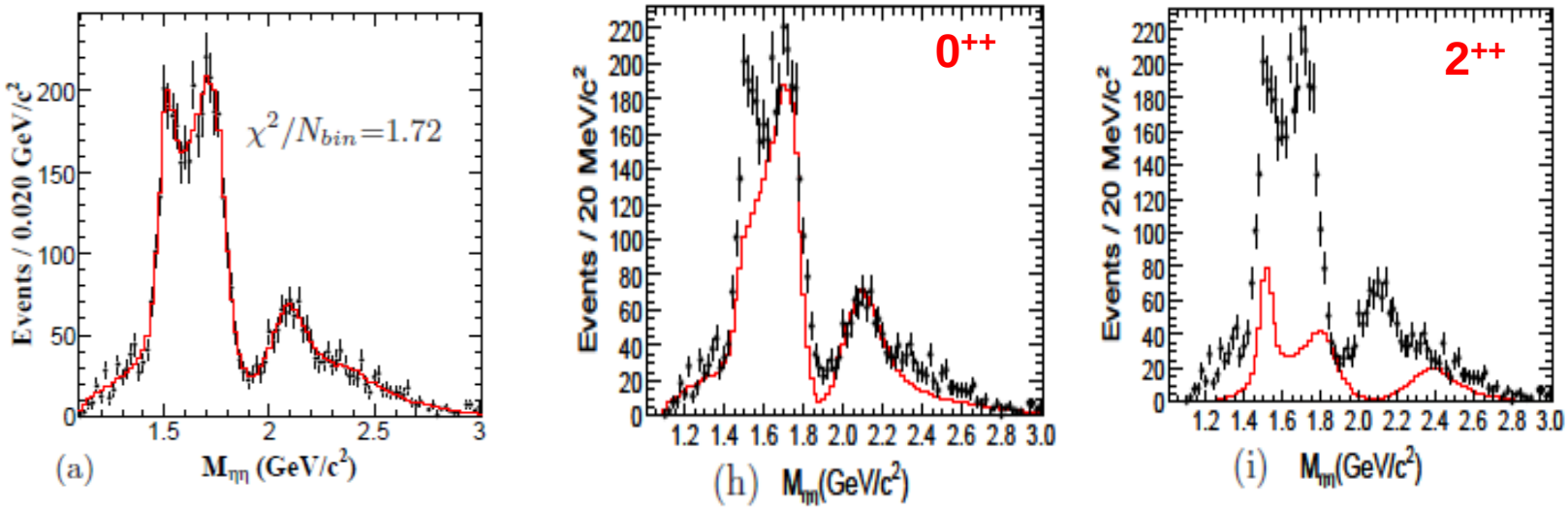
PWA, more data, more decay/produce channels are needed!

PWA of J/ψ→γηη

- Glueball searches is the directly test of QCD.

PRD 87 (2013), 092009

- Radiative J/ψ decay is a gluon-rich process and is regarded as one of most promising hunting grounds for glueballs.
- Glueball is flavor blindness : $\Gamma(G\to\pi\pi : KK : \eta\eta : \eta\eta' : \eta'\eta') = 3 : 4 : 1 : 0 : 1$



Resonance	Mass(MeV/c^2)	Width(MeV/c^2)	$\mathcal{B}(J/\psi\to\gamma X\to\gamma\eta\eta)$	Significance
$f_0(1500)$	1468^{+14+23}_{-15-74}	$136^{+41+28}_{-26-100}$	$(1.65^{+0.26+0.51}_{-0.31-1.40})\times10^{-5}$	8.2 σ
$f_0(1710)$	$1759\pm6^{+14}_{-25}$	$172\pm10^{+32}_{-16}$	$(2.35^{+0.13+1.24}_{-0.11-0.74})\times10^{-4}$	25.0 σ
$f_0(2100)$	$2081\pm13^{+24}_{-36}$	273^{+27+70}_{-24-23}	$(1.13^{+0.09+0.64}_{-0.10-0.28})\times10^{-4}$	13.9 σ
$f_2'(1525)$	$1513\pm5^{+4}_{-10}$	75^{+12+16}_{-10-8}	$(3.42^{+0.43+1.37}_{-0.51-1.30})\times10^{-5}$	11.0 σ
$f_2(1810)$	1822^{+29+66}_{-24-57}	$229^{+52+88}_{-42-155}$	$(5.40^{+0.60+3.42}_{-0.67-2.35})\times10^{-5}$	6.4 σ
$f_2(2340)$	$2362^{+31+140}_{-30-63}$	$334^{+62+165}_{-54-100}$	$(5.60^{+0.62+2.37}_{-0.65-2.07})\times10^{-5}$	7.6 σ

- The scalar contribution are mainly from $f_0(1500)$, $f_0(1710)$ and $f_0(2100)$.
- No evident contribution from $f_0(1370)$ and $f_0(1790)$.
- The tensor components are dominantly from $f_2(1525)$, $f_2(1810)$ and $f_2(2340)$.

Decay rate of glueball from LQCD

Pure scalar-glueball rate in J/ψ radiative decays

$BR(J/\psi \to \gamma G(0^{++})) = 3.8(9) \times 10^{-3}$

Γ_{157}	$\gamma f_0(1710) \to \gamma K\overline{K}$	$(8.5\ ^{+1.2}_{-0.9}) \times 10^{-4}$	S=1.2
Γ_{158}	$\gamma f_0(1710) \to \gamma\pi\pi$	$(4.0 \pm 1.0) \times 10^{-4}$	
Γ_{159}	$\gamma f_0(1710) \to \gamma\omega\omega$	$(3.1 \pm 1.0) \times 10^{-4}$	
	$\gamma f_0(1710) \to \gamma\eta\eta$	$(2.35^{+0.13+1.24}_{-0.11-0.74}) \times 10^{-4}$	

L. C. Gui et al. PRL 110 (2013), 021601

Suggest $f_0(1710)$ to have the large scalar-glue components

Pure Tensor-glueball rate in J/ψ radiative decays

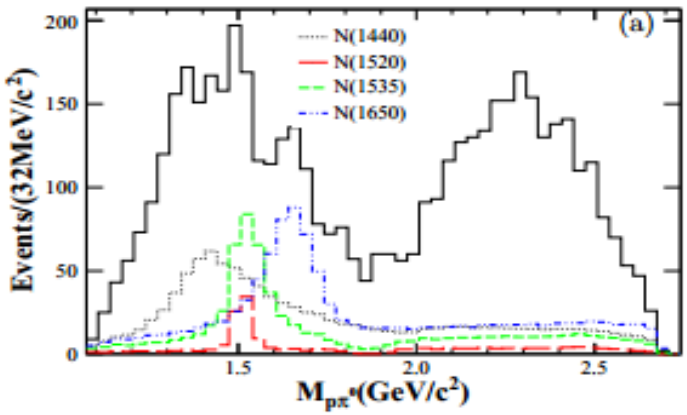
$BR(J/\psi \to \gamma G(2^{++})) = 1.1(2) \times 10^{-2}$

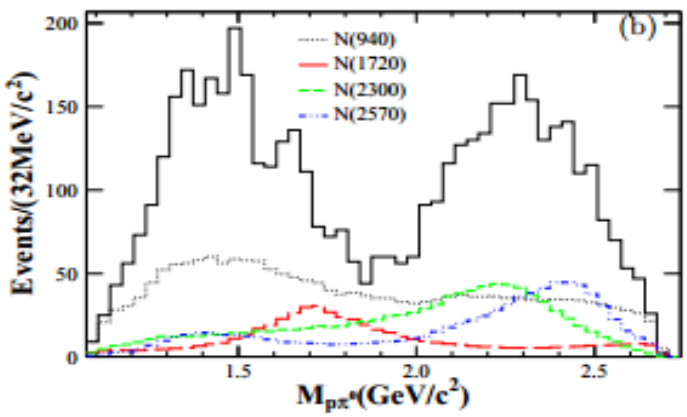
Large decay rate is predicted

Y. B. Yang et al. PRL 111 (2013), 091601

Need More experimental information

N* Resonance in $\psi(2S) \to p\bar{p}\pi^0$





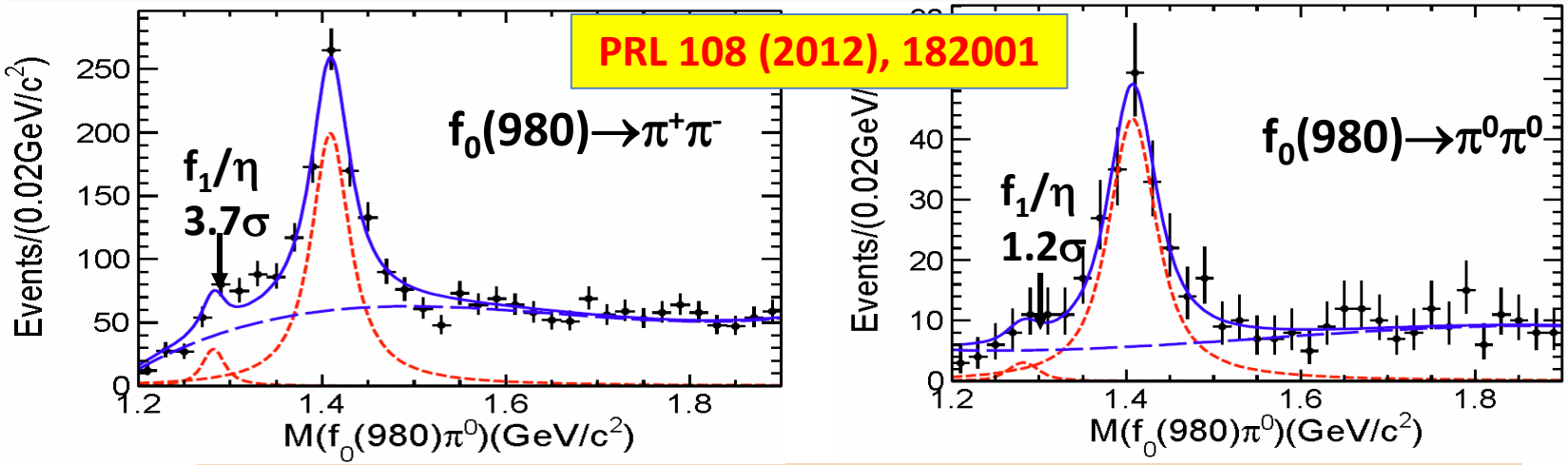
- **2-body decay :**
  - $\psi(2S) \to X\pi^0$, $X \to p\bar{p}$
  - $\psi(2S) \to p\bar{N}^*$, $\bar{N}^* \to \bar{p}\pi^0$
- **Isospin conservation**
  - Δ is suppressed
- **Best solution :**

PRL 110 (2013), 022001

Resonance	N	ϵ(%)	B.F.($\times 10^{-5}$)
$N(940)$	$1870^{+90+487}_{-90-327}$	27.5 ± 0.4	$6.42^{+0.20+1.78}_{-0.20-1.28}$
$N(1440)$	$1060^{+90+459}_{-90-227}$	27.9 ± 0.4	$3.58^{+0.25+1.59}_{-0.25-0.84}$
$N(1520)$	190^{+14+64}_{-14-48}	28.0 ± 0.4	$0.64^{+0.05+0.22}_{-0.05-0.17}$
$N(1535)$	$673^{+45+263}_{-45-256}$	25.8 ± 0.4	$2.47^{+0.28+0.99}_{-0.28-0.97}$
$N(1650)$	$1080^{+77+382}_{-77-467}$	27.2 ± 0.4	$3.76^{+0.28+1.37}_{-0.28-1.66}$
$N(1720)$	$510^{+27+50}_{-27-197}$	26.9 ± 0.4	$1.79^{+0.10+0.24}_{-0.10-0.71}$
$N(2300)$	$948^{+68+394}_{-68-213}$	34.2 ± 0.4	$2.62^{+0.28+1.12}_{-0.28-0.64}$
$N(2570)$	$795^{+45+127}_{-45-83}$	35.3 ± 0.4	$2.13^{+0.08+0.40}_{-0.08-0.30}$
Total	4515 ± 93	25.8 ± 0.4	$16.5 \pm 0.3 \pm 1.5$

Two new excited baryon $N^*(2300)[1/2^+]$, $N^*(2570)[5/2^-]$ are observed

$\eta(1405)$ in $J/\psi \to \gamma f_0(980)\pi^0$



First observed: $\eta(1405) \to f_0(980)\pi^0$ (Large isospin breaking)

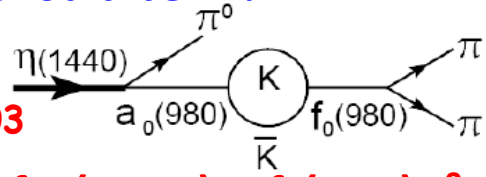
- **Helicity analysis indicates the peak is from $\eta(1405)$, not from $f_1(1420)$**
- **Large Isospin-violating decay rate:**

$$\frac{BR(\eta(1405) \to f_0(980)\pi^0 \to \pi^+\pi^-\pi^0)}{BR(\eta(1405) \to a_0(980)\pi^0 \to \pi^0\pi^0\eta)} \approx (17.9 \pm 4.2)\%$$

- **In general, magnitude of isospin violation in strong decay should be <1%.**

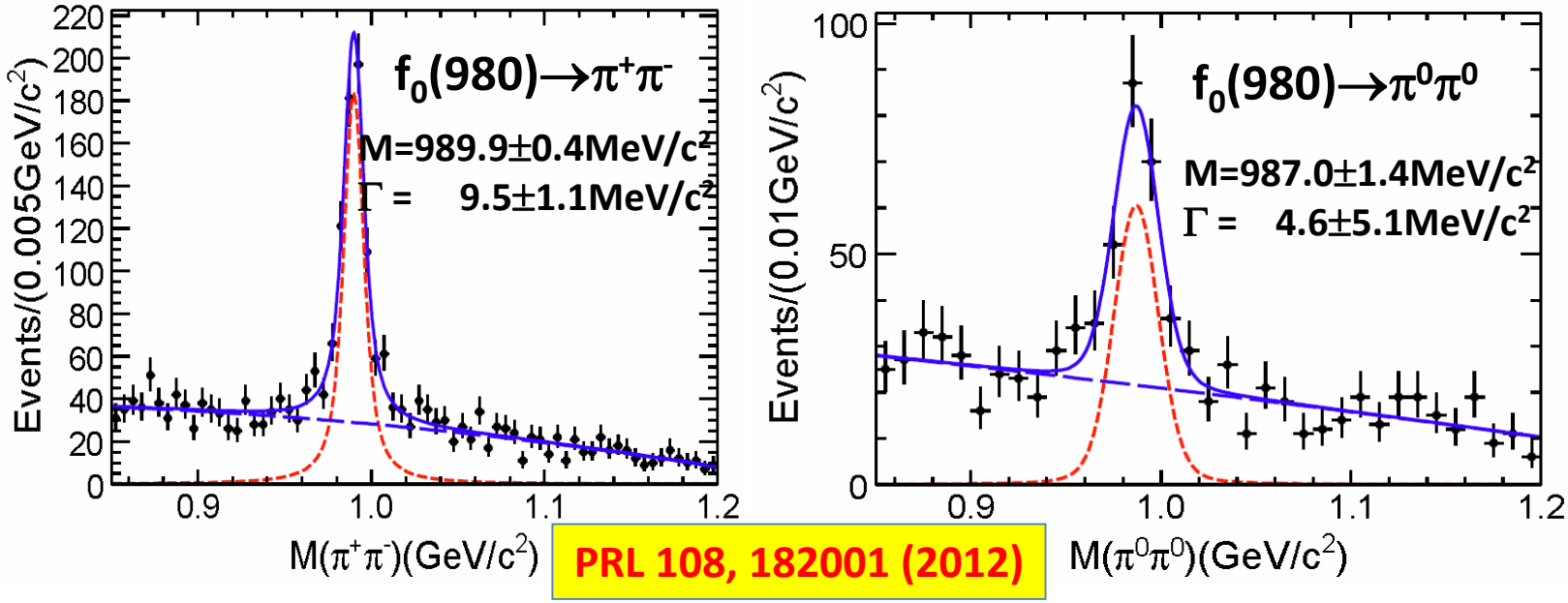
$$\xi_{af} = \frac{Br(\chi_{c1} \to f_0(980)\pi^0 \to \pi^+\pi^-\pi^0)}{Br(\chi_{c1} \to a_0(980)\pi^0 \to \eta\pi^0\pi^0)} < 1\%(90\% C.L.)$$

PRD, 83(2100)032003



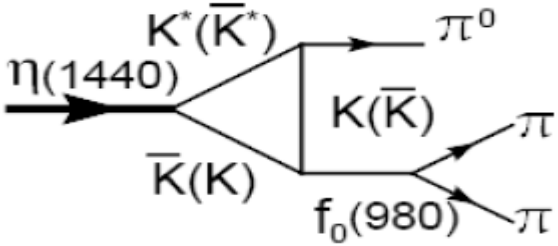
a_0-f_0 mixing alone can not explain the branching ratio of $\eta(1405) \to f_0(980)\pi^0$

Anomalous line shape of $f_0(980)$



PRL 108, 182001 (2012)

- **Surprising result:**
  - Very narrow $f_0(980)$ width: <11.8MeV/c²@90 % C.L.
  - The world average (PDG 2010: 40-100 MeV/c²)

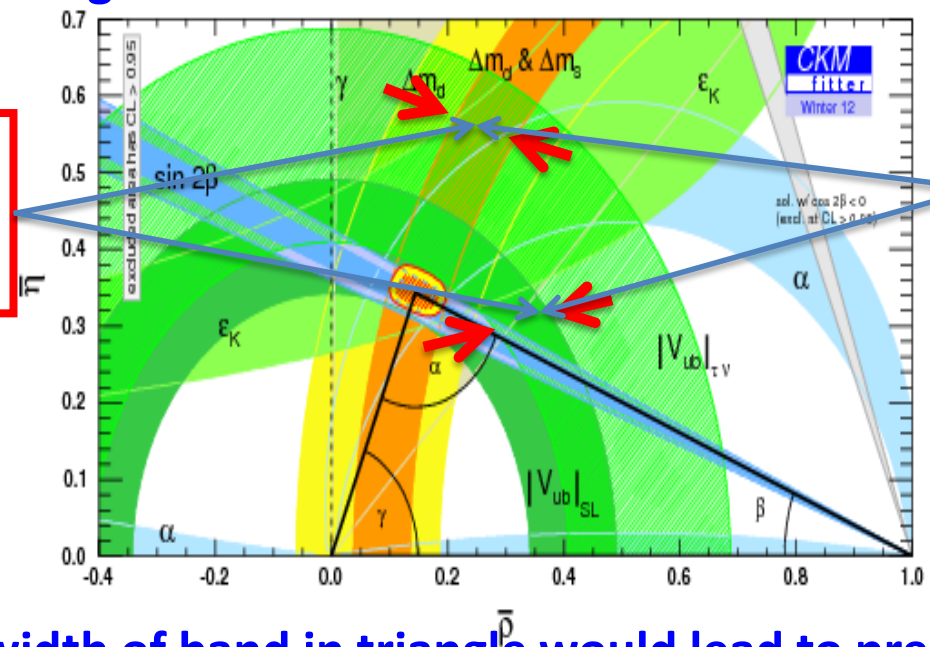


A possible explanation is KK^* loop, Triangle Singularity (TS)
(J.J. Wu et al, PRL 108 (2012), 081803)

Charm Physics

- D leptonic decays is the window on weak and strong physics, and play an important role in understanding of the SM of the particles.
- Weak decay is theoretically clean, and the strong interaction can test Lattice QCD and over-constrain CKM.
- Unitary triangle

The widths of bands are dominated by the error of f_B and f_{Bs} from LQCD.

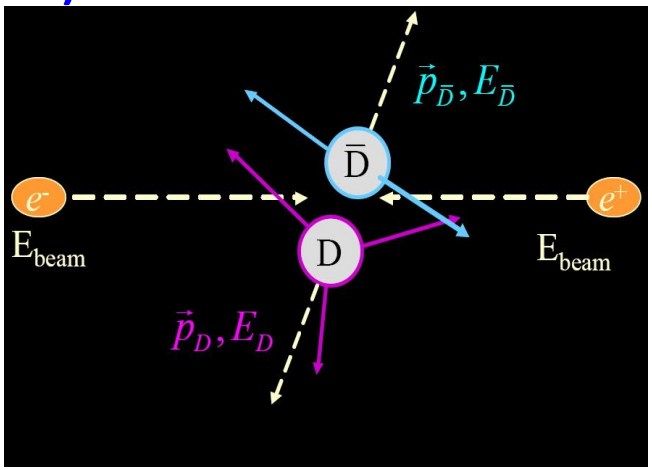


The widths of bands will be reduced if LQCD pass the test with measured f_D and f_{Ds}.

- Reduce width of band in triangle would lead to precisely test SM and search for new physics beyond the SM.

Charm Physics @BESII

- **Charm pair is produced at mass threshold ψ(3770)**
- **Advantage :**
  - Clean environment.
  - Known initial energy and quantum numbers (quantum correlated for $D^0\bar{D}^0$ pair)
  - Both D and $\bar{D}$ fully reconstructed.



- **Double-tag technique, absolute measurement**
  - Reconstruct D first, search for signal $\bar{D}$ on the other side
  - Two variables ΔE & M_{BC}
  - Fully reconstruct about 15% of D decays.

$$\Delta E = E_D - E_{\text{Beam}}$$
$$M_{\text{BC}} = \sqrt{E_{\text{Beam}}^2 - p_D^2}$$

- **Nine D^+ tag and four D^0 modes :**

$K^+\pi^-\pi^-$ $K^0\pi^-$ K^0K^- $K^+K^-\pi^-$ $K^+\pi^-\pi^-\pi^0$

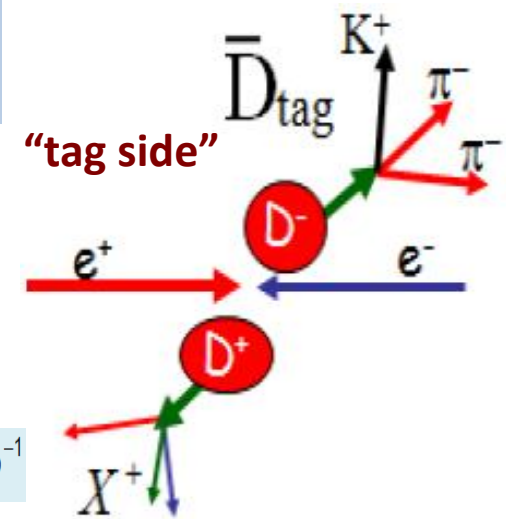
$\pi^+\pi^-\pi^-$ $K^0\pi^-\pi^0$ $K^+\pi^-\pi^-\pi^-\pi^+$ $K^0\pi^-\pi^-\pi^+$

$K^-\pi^+$ $K^-\pi^+\pi^0$

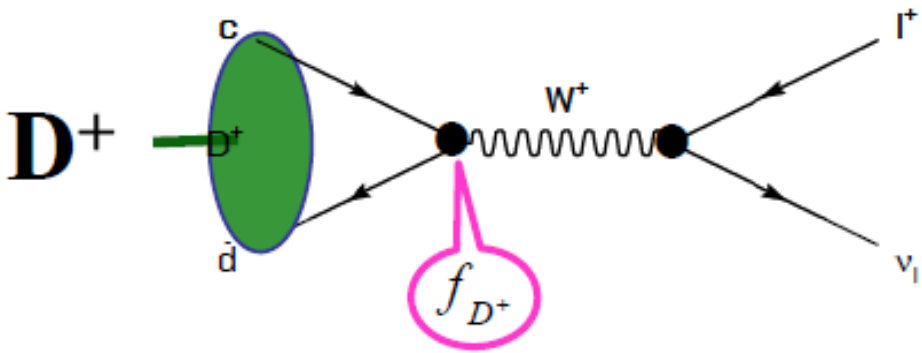
$K^-\pi^+\pi^0\pi^0$ $K^-\pi^+\pi^+\pi^-$

$$N_{D^-}^{\text{tag}} = (1.566 \pm 0.002) \times 10^6 \text{ in } 2.9 \text{ fb}^{-1}$$

$$N_{D^-}^{\text{tag}} = (0.774 \pm 0.001) \times 10^6 \text{ in } 0.92 \text{ fb}^{-1}$$



Leptonic Decay

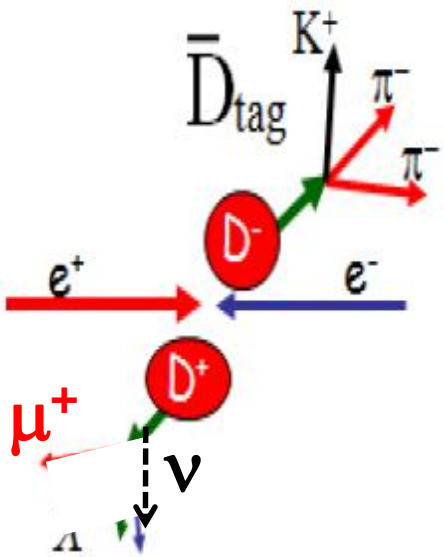


from CKM fitter

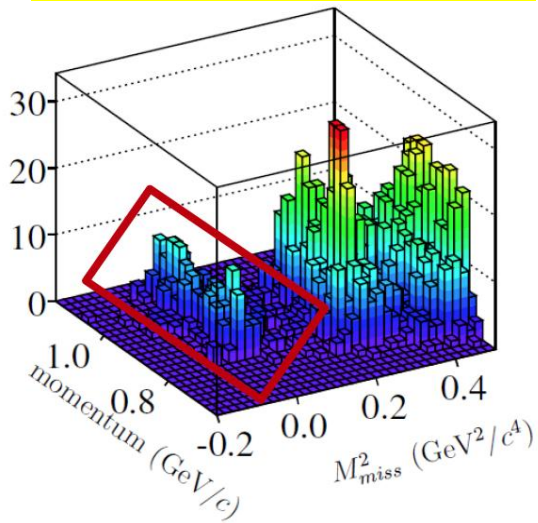
$$\Gamma_{SM}(D^+_{(s)} \to l^+\nu) = \frac{G_F^2}{8\pi} m_l^2 m_{D_{(s)}} \left(1 - \frac{m_l^2}{m_{D_{(s)}}^2}\right)^2 |V_{cd(s)}|^2 f_{D^+_{(s)}}$$

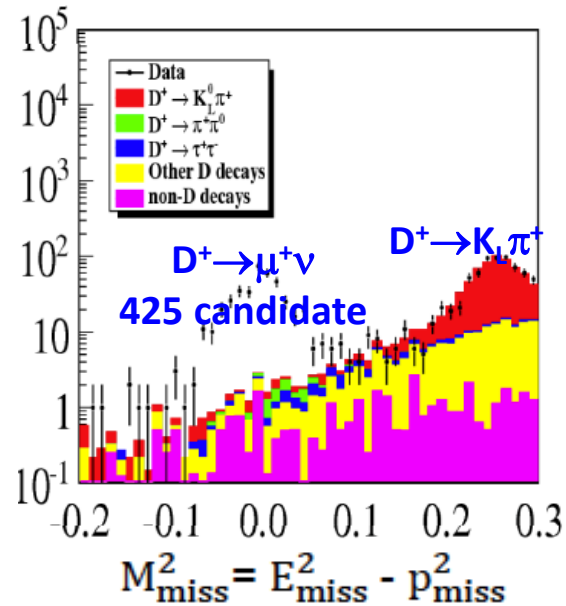
- Decay constant f_D incorporates the strong interaction effects (Wave function at the origin).
- Use charm leptonic decay to validate theory (LQCD) and apply to B mixing, which requires f_B.
- Multiple test with charm : f_D, f_{Ds} and f_D/f_{Ds}.
- Sensitivity to new physics (charged Higgs contribution …..)

Leptonic decay $D^+ \to \mu^+ \nu$



Preliminary results





Results: $N(D^+ \to \mu\nu) = 377.3 \pm 20.6 \pm 2.6$

$BF(D^+ \to \mu\nu) = (3.74 \pm 0.21 \pm 0.06) \times 10^{-4}$

CLEOc : $(3.82 \pm 0.32 \pm 0.09) \times 10^{-2}$

$$\Gamma(D^+ \to l^+ \upsilon_l) = \frac{G_F^2 f_{D^+}^2}{8\pi} |V_{cd}|^2 m_l^2 m_{D^+} (1 - \frac{m_l^2}{m_{D^+}^2})^2$$

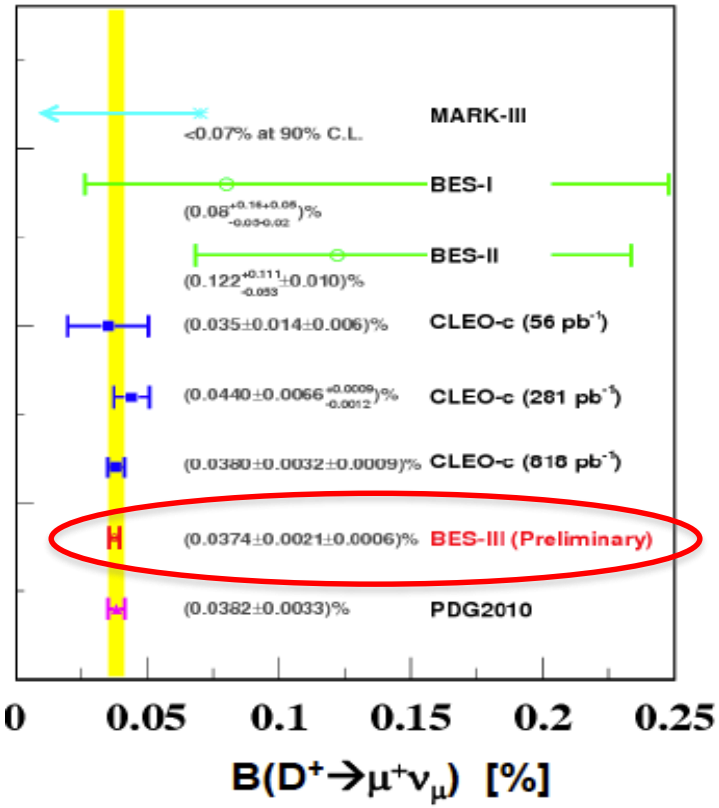
$f_{D+} = (203.91 \pm 5.72 \pm 1.97)$ MeV/c^2

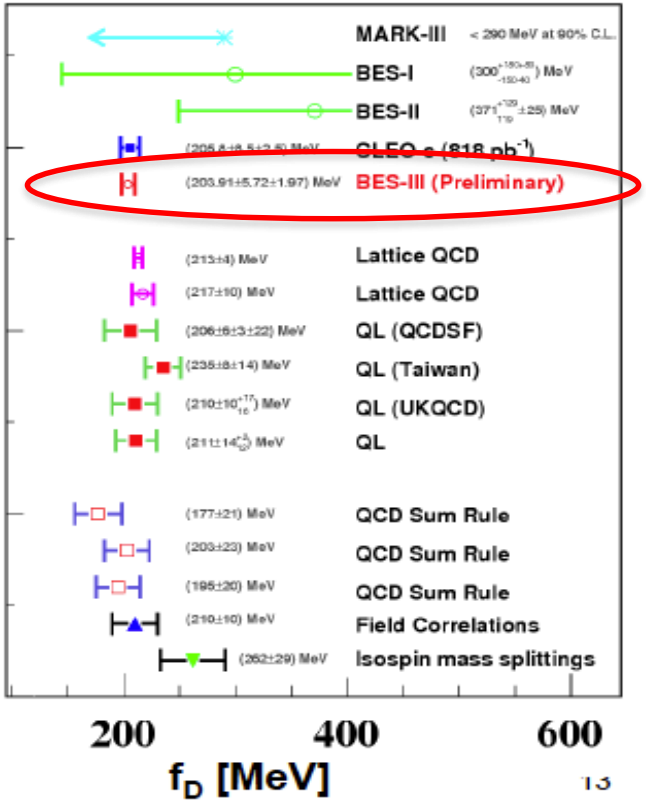
$|V_{cd}| = (0.222 \pm 0.006 \pm 0.005)$

$f_{D+} = (207 \pm 4)$ MeV/c^2 LQCD

$|V_{cd}| = (0.2252 \pm 0.007)$ CKM Fitter

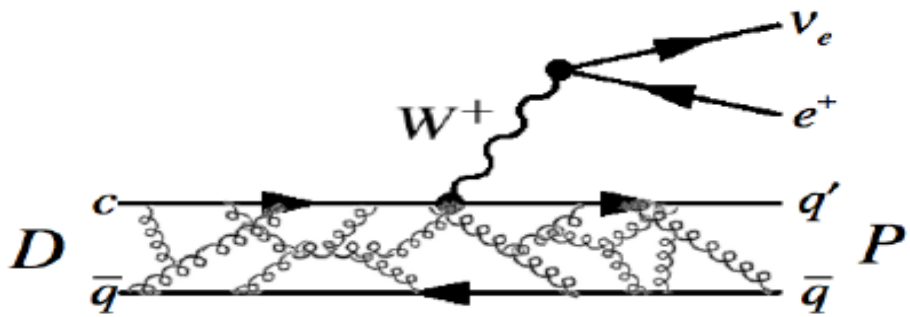
Preliminary results of $D^+ \to \mu^+ \nu$





- The most precise measurement is provided by BESIII
- The error is still dominated by statistics, needing more data taken at 3773 MeV to reduce it.

Semi-leptonic Decays



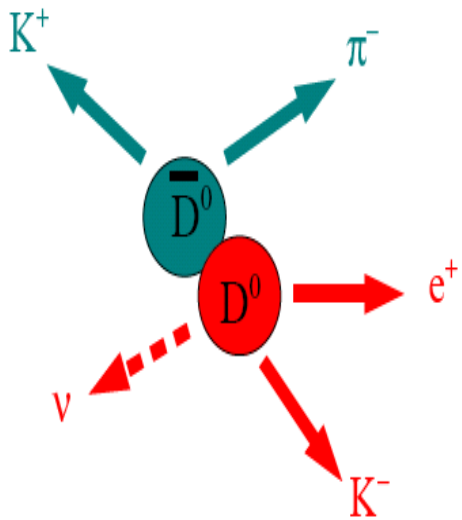
$$\frac{d\Gamma\left(D \to K(\pi) e\nu\right)}{dq^2} = \frac{G_F^2 \left|V_{cs(d)}\right|^2 P_{K(\pi)}^3}{24\pi^3} \left|f_+\left(q^2\right)\right|^2$$

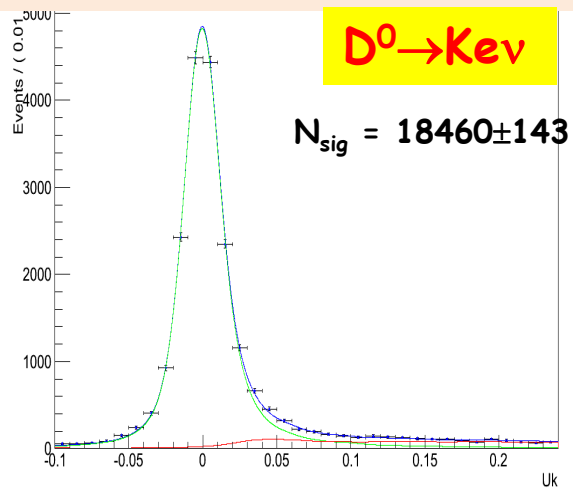
q2 – the invariant mass square of the lepton-neutrino system

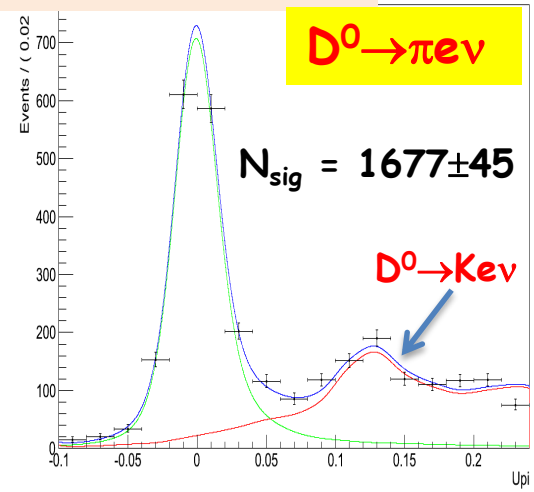
- Use strong interaction theory (LQCD) for form factor, extract CKM.
- Use other measurements and unitarity for CKM and test theory.
- Theoretical uncertainties can be reduce in determination of $|V_{ub}|$ if form factor calculation can be validated with Charm.
- Multiple tests available, semi-leptonic D decays to pseudoscalar mesons are cleanest.

Semi-leptonic Decays $D^0 \to K/\pi\, e\nu$

4 tag modes, 0.92 fb^{-1} data @3.773 (BESIII preliminary)





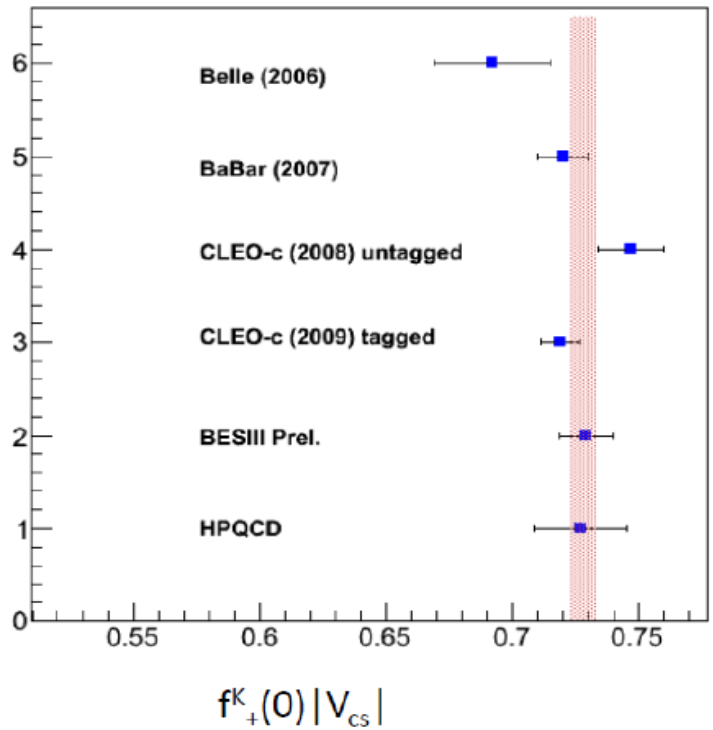


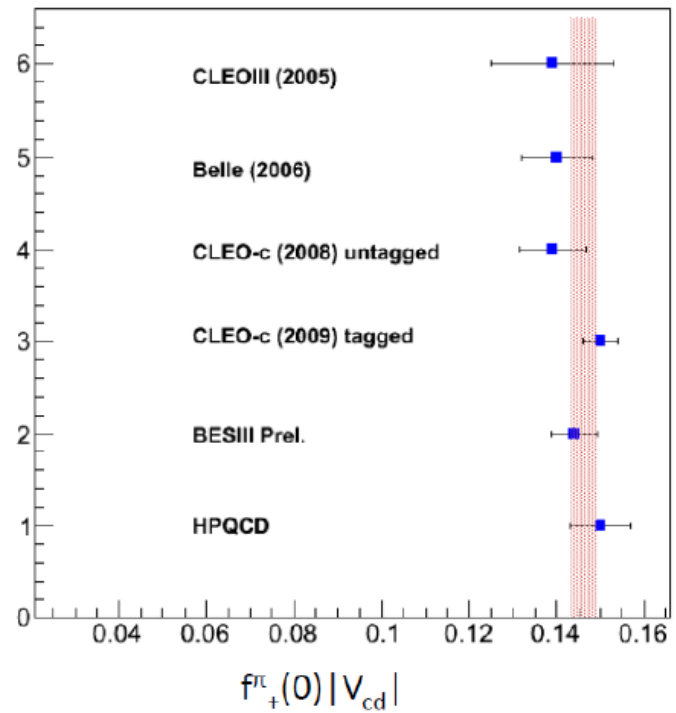
Mode	measured branching fraction(%)	PDG	CLEOc
$\bar{D}^0 \to K^+ e^- \bar{\nu}$	3.542 ±0.030±0.067	3.55 ±0.04	3.50 ±0.03 ±0.04
$\bar{D}^0 \to \pi^+ e^- \bar{\nu}$	0.288 ±0.008±0.005	0.289 ±0.008	0.288 ±0.008±0.003

- **Systematics are preliminary**
- **Will improve with full data set 2.9/fb in the near future.**
- **Good consistency with CLEO-c, statistical precision is comparable with only 1/3 data analyzed.**

Semi-leptonic Decays $D^0 \to K/\pi\, e\nu$

Preliminary results

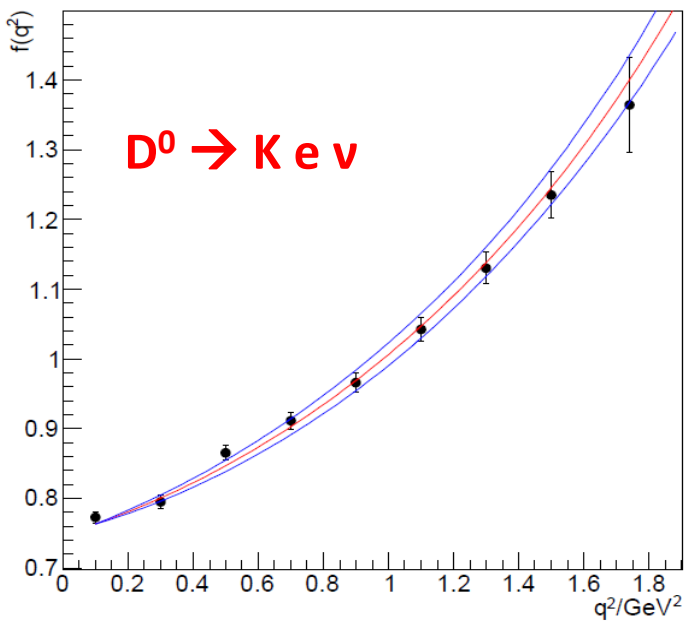


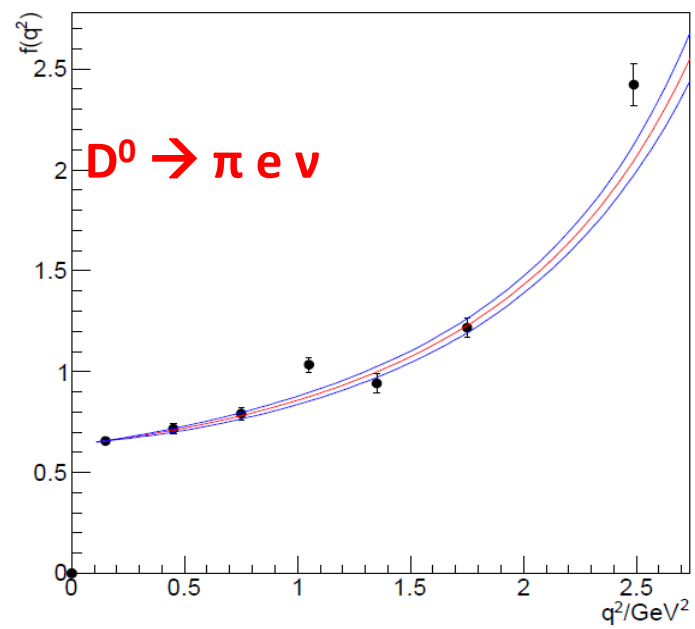


- Number are from HFAG2012 report (arXiv:1207.1158).
- Error bar of BESIII preliminary results Will shrink with full data.
- BESIII results from D^0 only, CLEO-c use both D^0 and D^+

Semi-leptonic Decays $D^0 \to K/\pi\, e\nu$

- Points: data with stat. error only
- Curves: from Fermilab-MILC within one stat. error, preliminary, arXiv:1111.5471 (XXIX International Symposium on Lattice Field Theory);
- Other theoretical work: HPQCD, arXiv:1111.0225
- Comparing shape only here ($f_+(0)$ not known)

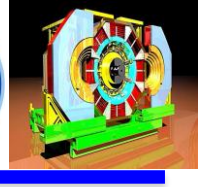




BESIII Preliminary

NP Search
&
SM Test

NP Search & SM Test



η and η' decays are the prefect lab to

- Test symmetries and symmetry breaking in QCD at low energies
- Search for new physics beyond the SM

"η/η' physics at BESIII" J. Phys. G: Nucl. Part. Phys. 36 085009 (2009)

Published results

- Matrix element for $\eta' \to \pi^+\pi^-\eta$ — Phys. Rev. D83 (2011), 012003
- Search for CP violation $\eta/\eta' \to \pi^+\pi^-\pi^0\pi^0$ — Phys. Rev. D83 (2011), 032006
- BF measurement of $\eta' \to \pi^+\pi^-\pi^0/\eta' \to \pi^0\pi^0\pi^0$ — Phys. Rev. Lett 108 (2011), 182001
- BF measurement of $\eta' \to \pi^+\pi^-e^+e^-,/\pi^+\pi^-\mu^+\mu^-$ — Phys. Rev. D87 (2013), 092001
- Search for η/η' invisible decays — Phys. Rev. D87 (2013), 012009
- Search for η/η' weak decays — Phys. Rev. D87 (2013), 032006

On going analysis at BESIII

- Observation of $\eta' \to \pi^+\pi^-\pi^+\pi^-$
- Observation of $\eta' \to \gamma\gamma\pi^0$
- Observation of $\eta' \to \gamma\, e^+e^-/\ \pi^0\, e^+e^-$ ……

Others searches

- Search for LFV decay $J/\psi \to e\mu$ — Phys. Rev. D87 (2013) 112007
- Search for J/ψ invisible decay
- Search for FCNC decay $D_0 \to \gamma\gamma$ ……

Tentative data-taking plan

- R scan data : 3.8 ~ 4.6 GeV (108 energy points)
- 500pb^{-1} @ 4415MeV peak for XYZ and higher charmonium searches in E1/M1 and hadronic transitions
- Data @ 4.62GeV for Λ_c baryon (absolute BR measurement)
- More data (5fb^{-1}) @4.170 GeV for D_s physics
- More data (10fb^{-1}) @3.77 GeV for D physics

Red : year 2013-2014, approved by the collaboration

Black : future plans, need be approved in the Collaboration

Summary

- **BEPCII is operating near design luminosity (0.7×10^{33} @ 3.73GeV) &BESIII is performing successfully**

— **World largest data threshold produced samples J/ψ, ψ', ψ(3770), ψ(4040)**

— **Large samples of Y(4260), Y(4360) etc. are produced directly**

- **Some selected results have been shown :**

— **XYZ physics :**

$Y(4260)\to\gamma X(3872)$; $e^+e^-\to\pi^+\pi^-J/\psi(h_c)$; $Z_c(3900)/Z_c(3885)/Z_c'(4020)/Z_c'(4025)$

— **Charmonium physics :**

$\psi(2S)\to\gamma\eta_c(1S)$; $\psi(2S)\to\gamma\eta_c(2S)\to KK\pi/K_sK\pi\pi\pi$; $\psi(2S)\to\pi^0h_c\to\gamma\eta_c(1S)$

— **Light hadron physics**

New X(18xx) particle; Scalar meson; new excited baryons; Isospin Violating

— **Charm physics**

Leptonic decay; Semileptonic decay; (strong phase; Y_{CP})

— **New physics search and SM test**

BESIII is in her golden age, expect many more results soon !!!!

Thanks !

Backup

Search for $D_0 \to \gamma\gamma$

- Flavor Changing Neutral Current (FCNC) ($c \to u+\gamma$) is forbidden at tree level.

- Charm meson FCNC including two effects :

— Long distance effect : $c \to uV(V=\rho,\omega,\phi)$, non-perturbative calculated, large errors, Dominated.

— Short distance effect : non-perturbative calculated, interested, test SM.

- Within SM :

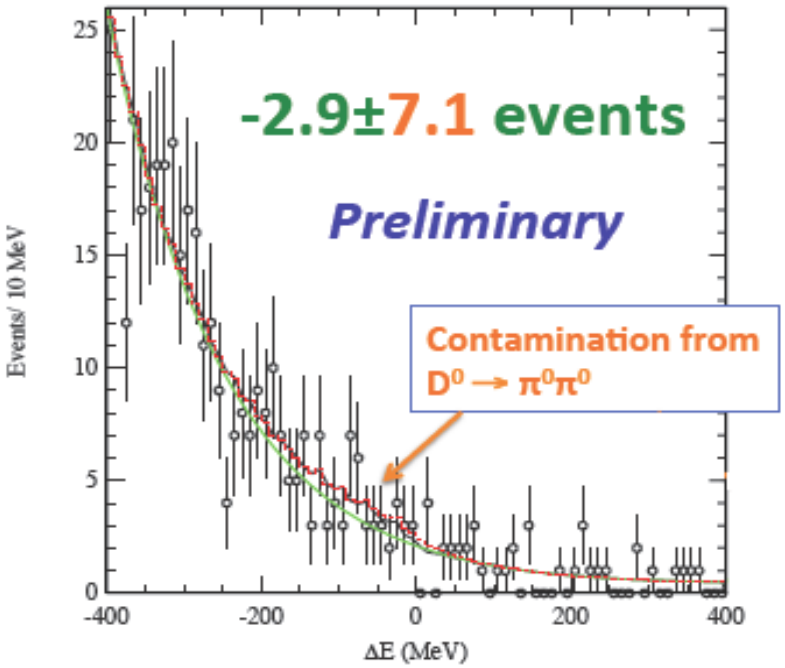
— Short distance : $Br(D_0 \to \gamma\gamma) \sim 10^{-11}$

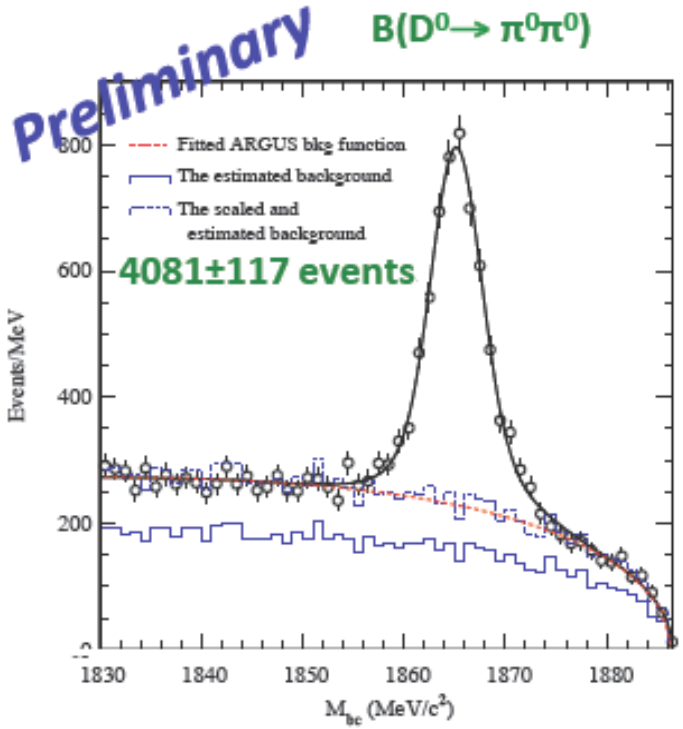
— Long distance : $Br(D_0 \to \gamma\gamma) \sim 10^{-8}$ (PRD 64, 074008)

- Beyond SM – minimal super-symmetric (MSSM) predicts the rate could be enhanced by a factor of 100 by exchanging gluino :

— $Br(D_0 \to \gamma\gamma) \sim 10^{-8}$ (PLB 500, 304)

Search for $D_0 \to \gamma\gamma$





$B(D^0 \to \gamma\gamma)/B(D^0 \to \pi^0\pi^0) < 5.8 \times 10^{-3}$@90%C.L.

Experiments	BESIII	BABAR	CLEOc	PDG11
$B^{up}(D^0 \to \gamma\gamma)$ [$\times 10^{-6}$]	<4.6	<2.2	<8.63	<27

Search for LFV in $J/\psi \to e\mu$

- With finite neutrino masses included, Lepton Flavor Violation (LFV) is allowed, but the smallness of the mass leads to the predicted branching fraction well beyond current experimental sensitivity.
- However, there are various theoretical models such as SUSY may enhance LFV effects up to a detectable level.
- Any detection of a LFV decay indicates the existence of new physics.
- The LFV decay have been searched in lepton (μ/τ) decay, pseudoscalar meson (k/π) decay and vector meson ($\phi, J/\psi, \Upsilon$) decay.

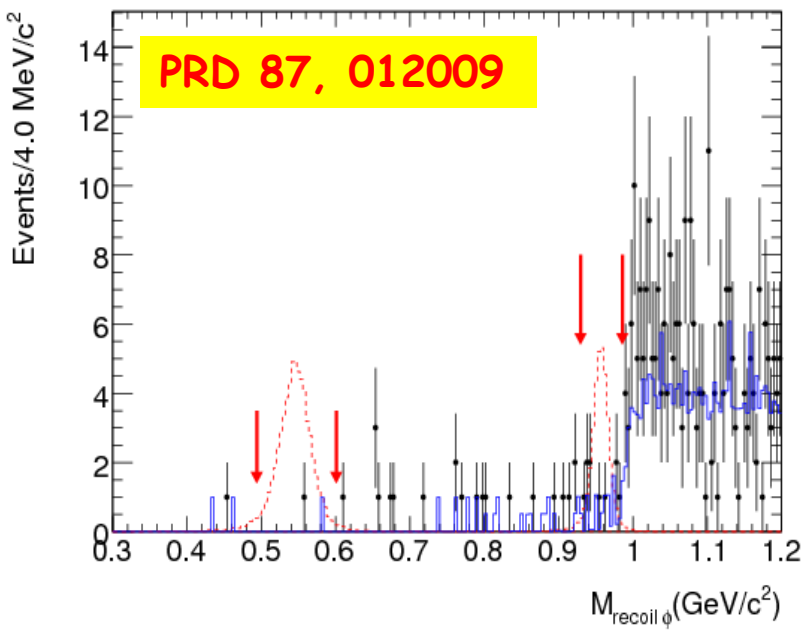
$Br(J/\psi \to e\mu) < 1.5\times10^{-7}$ (90% C.L.) (BESIII 225M J/ψ)

Literature:

		$Br(\phi \to \mu^+e^-) < 2.0\times10^{-6}$
		$Br(J/\psi \to \mu e) < 1.1\times10^{-6}$
$Br(\mu^+ \to \gamma e^+) < 2.4\times10^{-12}$	$Br(K_L^0 \to \mu^+e^-) < 4.7\times10^{-12}$	$Br(J/\psi \to e\tau) < 8.3\times10^{-6}$
$Br(\tau^+ \to \gamma e^+) < 3.3\times10^{-8}$	$Br(\pi^0 \to \mu^+e^-) < 3.8\times10^{-10}$	$Br(J/\psi \to \mu\tau) < 2.0\times10^{-6}$

Search for η/η' invisible in $J/\psi \to \phi\eta/\eta'$

- η/η' decay play special role in low energy scale QCD theory.
- Invisible and radiative decays offer a window for new physics beyond the SM.
- The observation of the invisible final states provide information for light dark matter states χ, spin-0 axions, and light spin-1 U bosons.
- Huge J/ψ sample, large branching fraction of $J/\psi \to (\gamma/\phi)\eta/\eta'$ and narrow intermediate meson width provide clean, large η/η' sample.



$Br(\eta' \to invisible)/Br(\eta' \to \gamma\gamma) < 2.39 \times 10^{-2}$
$Br(\eta \to invisible)/Br(\eta \to \gamma\gamma) < 2.58 \times 10^{-4}$

$Br(\eta' \to invisible) < 5.21 \times 10^{-4}$@90%C.L.
$Br(\eta \to invisible) < 1.01 \times 10^{-4}$@90%C.L.
Improved PDG Value

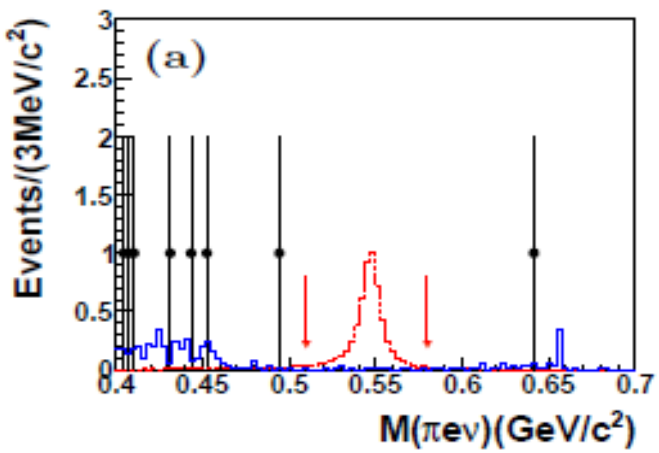
PDG : $Br(\eta' \to invisible) < 9 \times 10^{-4}$@90%C.L
$Br(\eta \to invisible) < 6 \times 10^{-4}$@90%C.L.

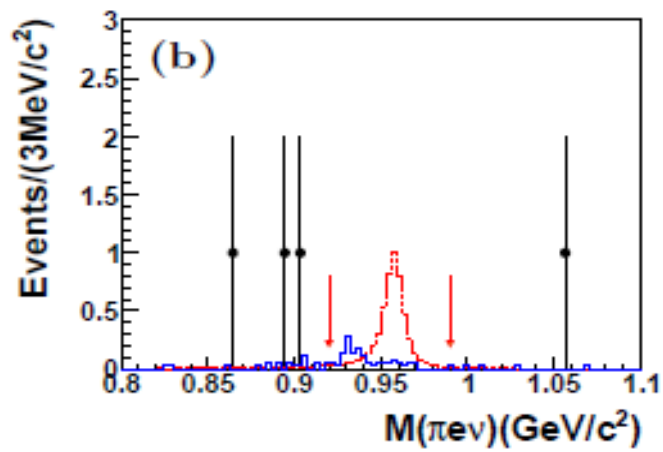
Theory : $Br(\eta' \to \chi\chi) \sim 8.1 \times 10^{-7}$
$Br(\eta \to \chi\chi) \sim 7.4 \times 10^{-5}$
B. McElrath, PRD 72, 103508 (2005)

η/η' weak decay in $J/\psi \to \phi\eta/\eta'$

- The rates of quarkonium weak decays are expected to be tiny in SM ($Br(\eta\to\pi l\nu)\sim 2.6\times10^{-13}$)
- The $Br(\eta/\eta'\to\pi l\nu)$ is expected at level of $10^{-8}\sim10^{-9}$ by considering scalar or vector type interaction.
- Search for η/η' weak decay will provide information on the new physics beyond the SM.

225M J/ψ , $\eta/\eta'\to\pi^+e^-\nu_e$ PRD 87, 032006, (2013)





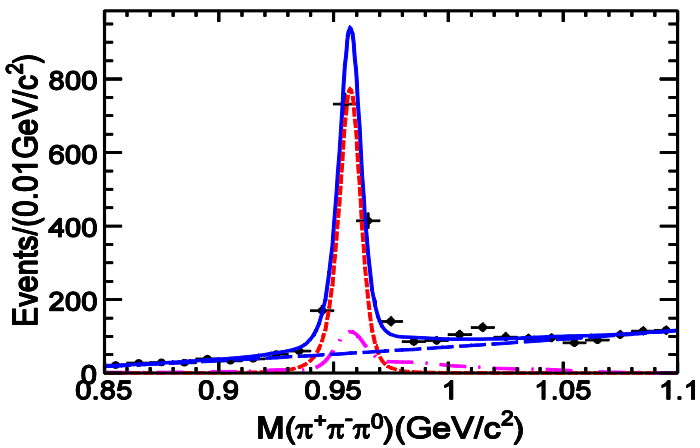
$Br(\eta\to\pi^+e^-\nu_e)/Br(\eta\to\pi^+\pi^-\pi^0) < 7.3\times10^{-4}$
$Br(\eta'\to\pi^+e^-\nu_e)/Br(\eta'\to\pi^+\pi^-\eta) < 7.3\times10^{-4}$

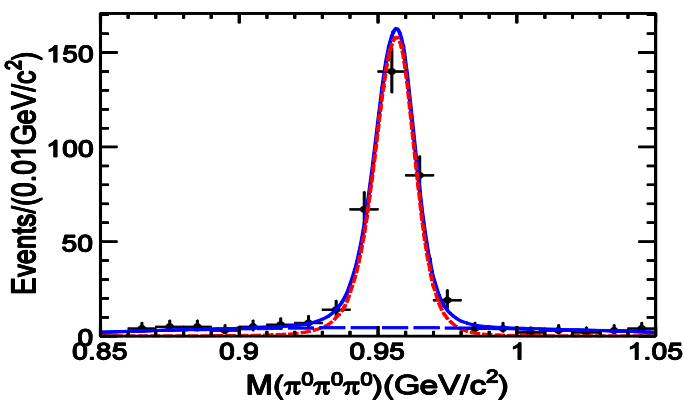
$\Rightarrow$

$Br(\eta\to\pi^+e^-\nu_e) < 1.7\times10^{-4}$ @90% C. L.
$Br(\eta'\to\pi^+e^-\nu_e) < 2.2\times10^{-4}$ @90% C. L.

η' three-pion decay in $J/\psi \to \gamma\eta'$

- The three-pion decays of the η' can probe isospin breaking.
- The decay branching ratio are related to the strange quark mass and SU(3) breaking.





$Br(\eta' \to \pi^+\pi^-\pi^0) = (3.83 \pm 0.15 \pm 0.39) \times 10^{-3}$
$Br(\eta' \to \pi^0\pi^0\pi^0) = (3.56 \pm 0.22 \pm 0.34) \times 10^{-3}$

PDG: $Br(\eta' \to \pi^+\pi^-\pi^0) = (3.6^{+1.1}_{-0.9}) \times 10^{-3}$
$Br(\eta' \to \pi^0\pi^0\pi^0) = (1.68 \pm 0.22) \times 10^{-3}$

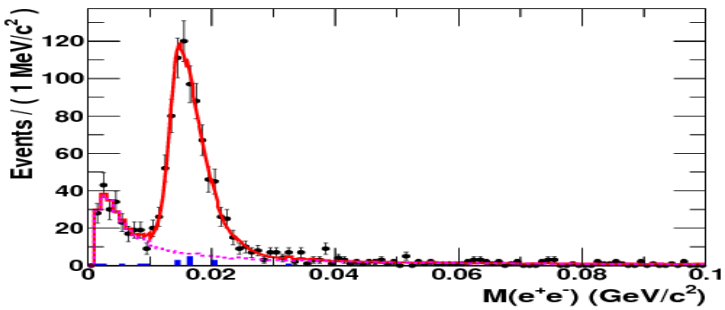
$Br(\eta' \to \pi^+\pi^-\pi^0)/Br(\eta' \to \pi^+\pi^-\pi^0) = (8.87 \pm 0.98) \times 10^{-3}$
$Br(\eta' \to \pi^0\pi^0\pi^0)/Br(\eta' \to \pi^+\pi^-\eta) = (16.41 \pm 1.94) \times 10^{-3}$

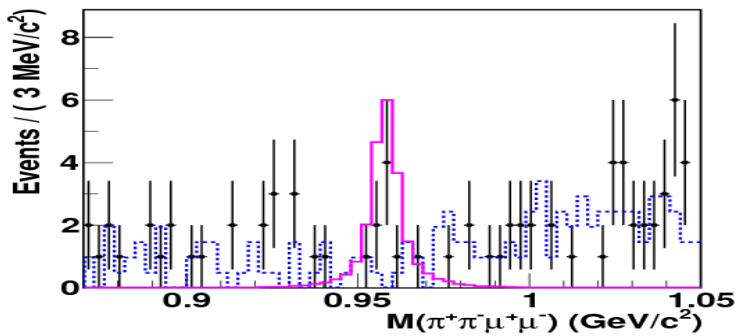
Theory : $Br(\eta' \to \pi^+\pi^-\pi^0)/Br(\eta' \to \pi^+\pi^-\pi^0) = 3.90\%$
$Br(\eta' \to \pi^0\pi^0\pi^0)/Br(\eta' \to \pi^+\pi^-\eta) = 0.73\%$
B. Borasoy et. al PLB 643, 41, 2006

More than 4 standard deviations away from both π^0-η mixing prediction and the chiral unitary framework prediction.

$\eta' \to \pi^+\pi^-\ell^+\ell^-$ in $J/\psi \to \gamma\eta'$

- $\eta' \to \pi^+\pi^-e^+e^-$ have been discussed based on the Vector Meson Dominance model and Chiral Perturbation Theory.
- $\eta' \to \pi^+\pi^-e^+e^-$ is expected to proceed via virtual photon intermediate state, $\eta' \to \pi^+\pi^-\gamma^* \to \pi^+\pi^-e^+e^-$, and provides a more stringent test of theories.
- The e^+e^- mass spectrum is expected to be a peak with a long tail just above $2m_e$. While a dominant ρ^0 contribution in $M_{\pi+\pi-}$.





BESIII Results

$Br(\eta' \to \pi^+\pi^-e^+e^-) = (2.11 \pm 0.12 \pm 0.15) \times 10^{-3}$

$Br(\eta' \to \pi^+\pi^-\mu^+\mu^-) < 2.9 \times 10^{-5}$ @ 90% C. L.

Effective Meson theory

(PRC 61, 0305206, 2000)

$Br(\eta' \to \pi^+\pi^-e^+e^-) = 1.8 \times 10^{-3}$

$Br(\eta' \to \pi^+\pi^-\mu^+\mu^-) = 2.9 \times 10^{-5}$

Chiral Unitary

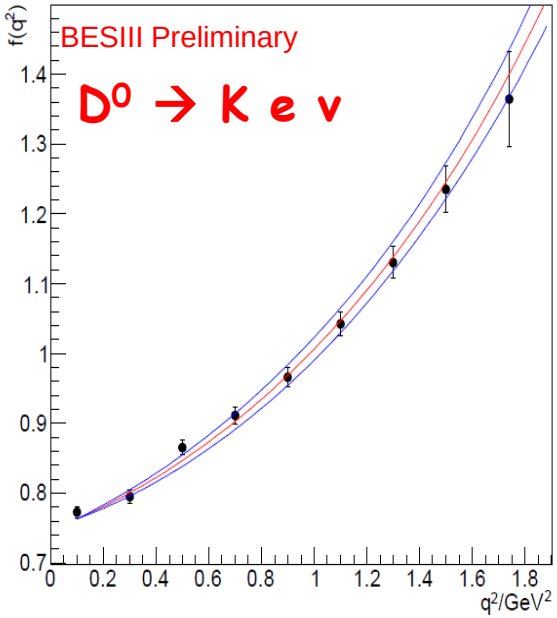
(EPJA 33, 95 (2007))

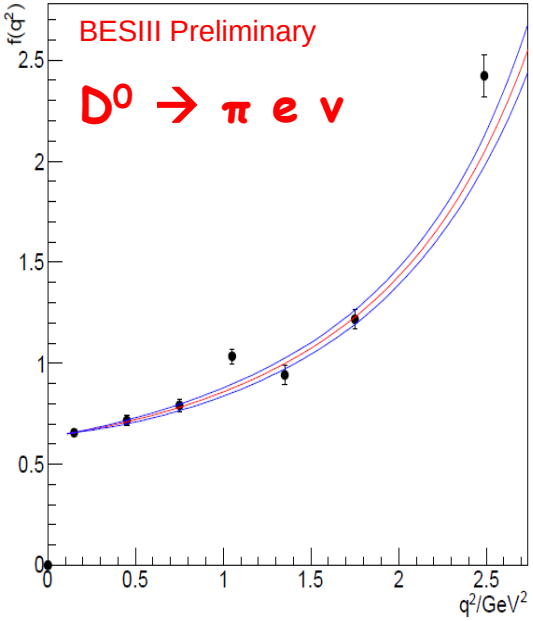
$Br(\eta' \to \pi^+\pi^-e^+e^-) = 2.13^{+0.19}_{-0.32} \times 10^{-3}$

$Br(\eta' \to \pi^+\pi^-\mu^+\mu^-) = 1.57^{+0.96}_{-0.75} \times 10^{-5}$

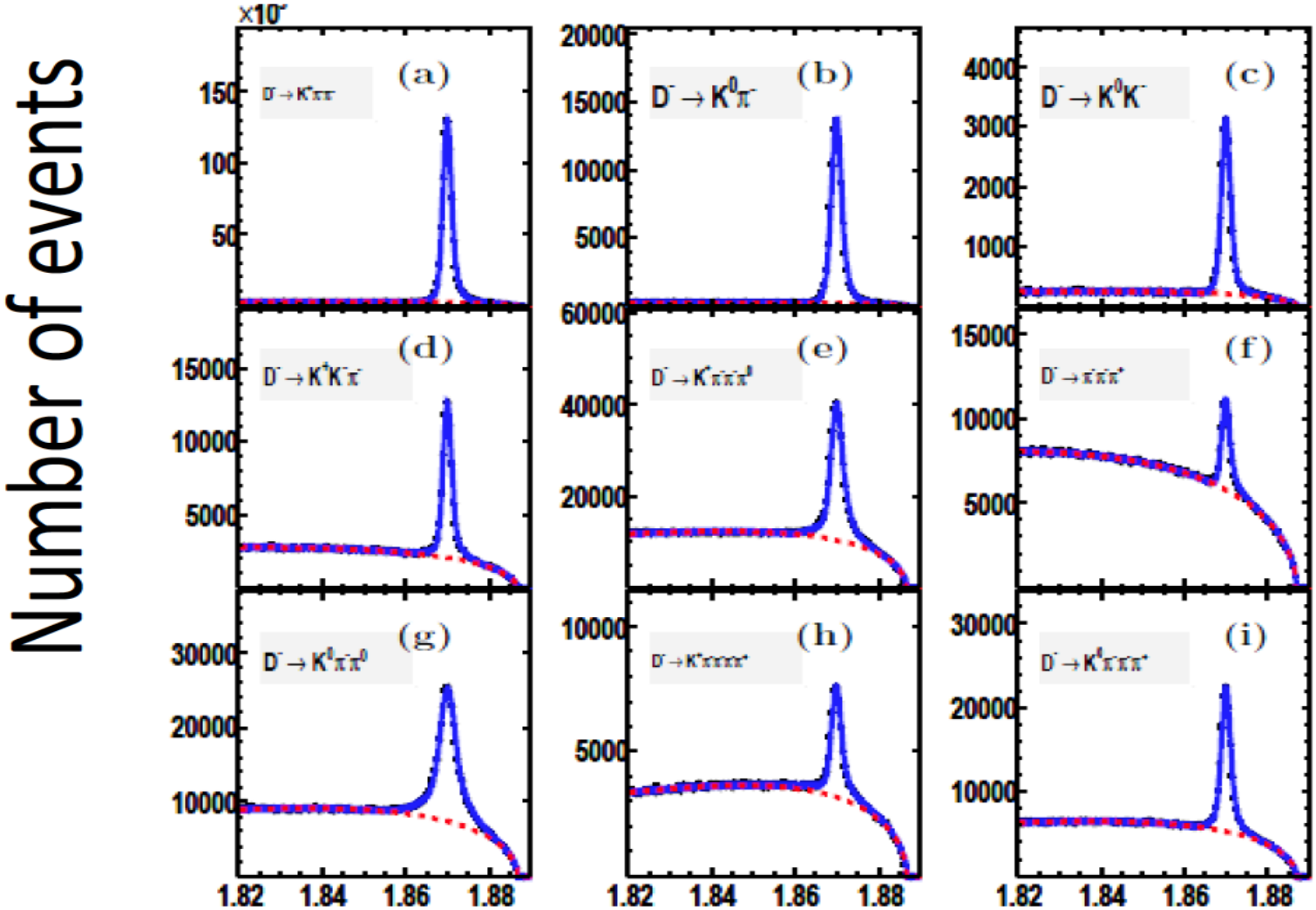
$f(q^2)$ Results

- Points: data with stat. error only
- Curves: from Fermilab-MILC within one stat. error, preliminary, **arXiv:1111.5471** (XXIX International Symposium on Lattice Field Theory);
- Other theoretical work: HPQCD, arXiv:1111.0225
- Comparing shape only here ($f_+(0)$ not known)





D tag modes



Is the X(1835) from the same source of X($p\bar{p}$)?

- The mass of X($p\bar{p}$) is consistent with X(1835)

- The width of X($p\bar{p}$) is much narrower.

  Possible reasons:

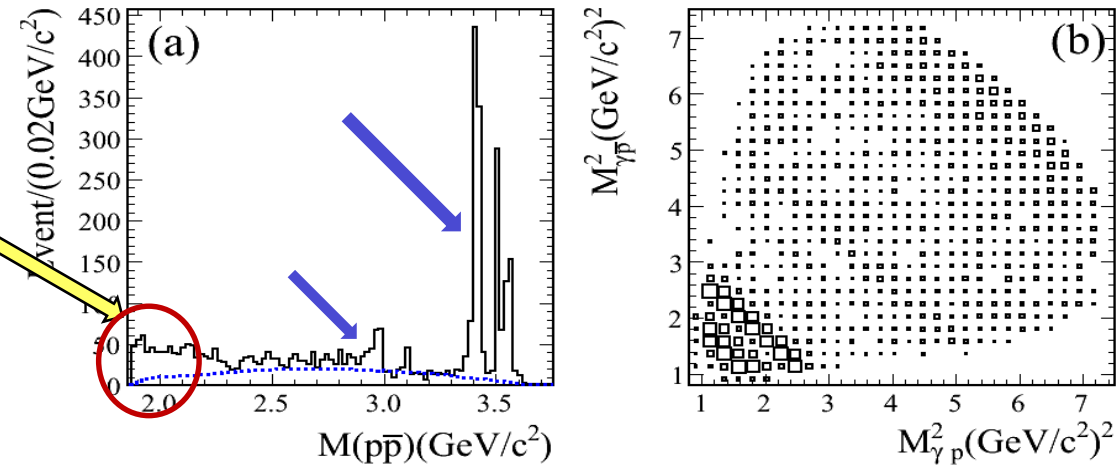
  – X($p\bar{p}$) and X(1835) come from different sources

  – Interference effect in J/ψ->γππη' process should not be ignored in the determination of the X(1835) mass and width

  – There may be more than one resonance in the mass peak around 1.83GeV in J/ψ->γππη' decays.

$M_{p\bar{p}}$ threshold structure of @ BESIII

Obviously different line shape of $p\bar{p}$ mass spectrum near threshold from that in J/ψ decays



PWA results:

- Significance of $X(p\bar{p})$ is > 6.9σ.
- The production ratio R:

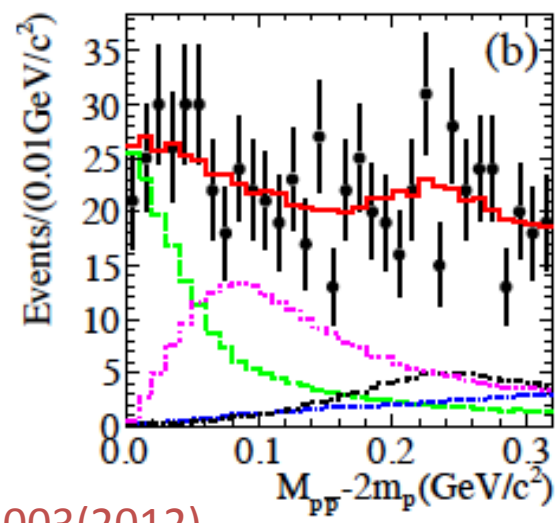
first measurement

$$R = \frac{B(\psi' \to \gamma X(p\bar{p}))}{B(J/\psi \to \gamma X(p\bar{p}))}$$

$$= (5.08^{+0.71}_{-0.45}(\text{stat})^{+0.67}_{-3.58}(\text{syst}) \pm 0.12(\text{mod}))\%$$

- It is suppressed compared with "12% rule".

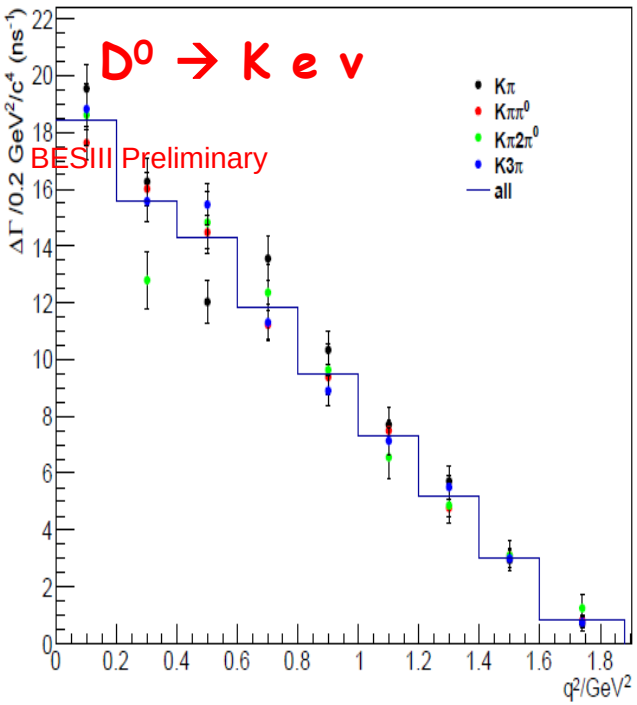
PWA Projection:

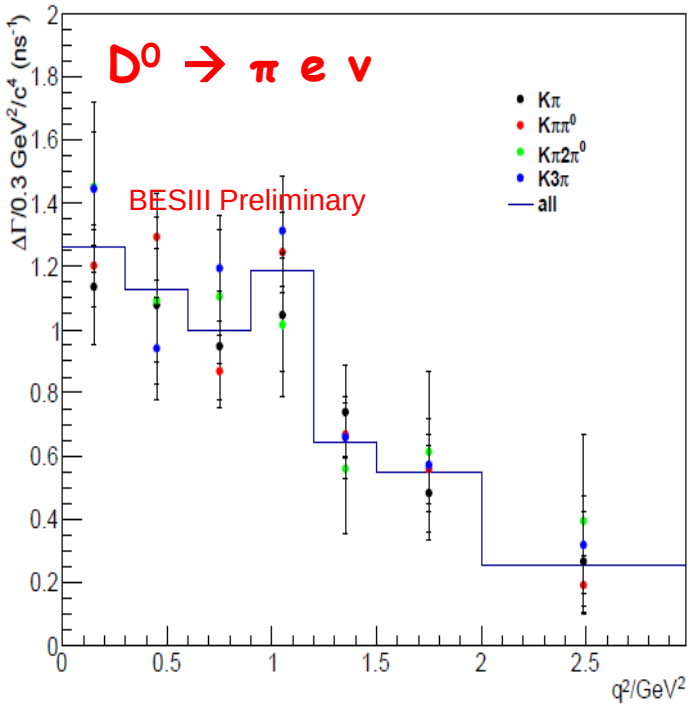


PRL 108,112003(2012)

Semi lepton decays : Partial Decay Rates Results

- Measured in each q^2 bin, by fitting U distribution
- Compare results from each tag mode





Form Factor Fits

BESIII Preliminar

Simple pole model:

$$f_+(q^2) = \frac{f_+(0)}{1 - q^2/m^2_{pole}}$$

Modified pole model:
Beciirevic and Kaidalov PLB 478, 417 (2000)

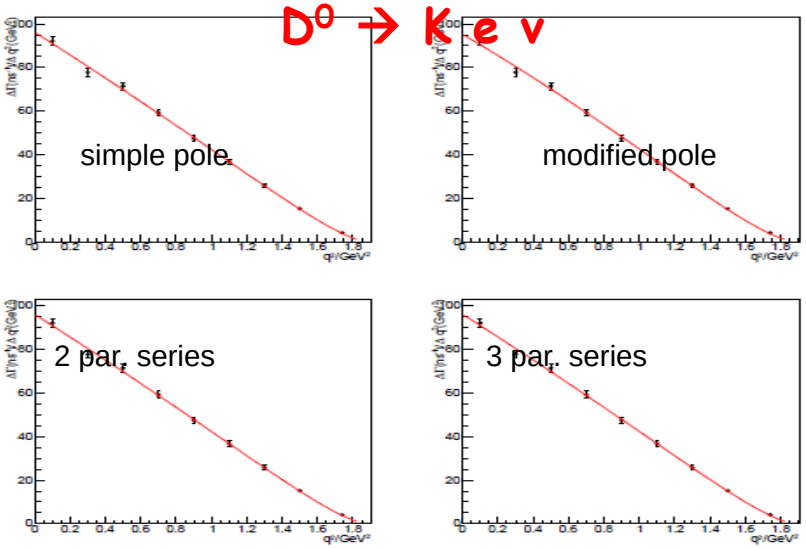
$$f_+(q^2) = \frac{f_+(0)}{\left(1 - \frac{q^2}{m^2_{pole}}\right)\left(1 - \alpha\frac{q^2}{m^2_{pole}}\right)}$$

Series expansion:
Becher and Hill PLB 633, 61 (2006)

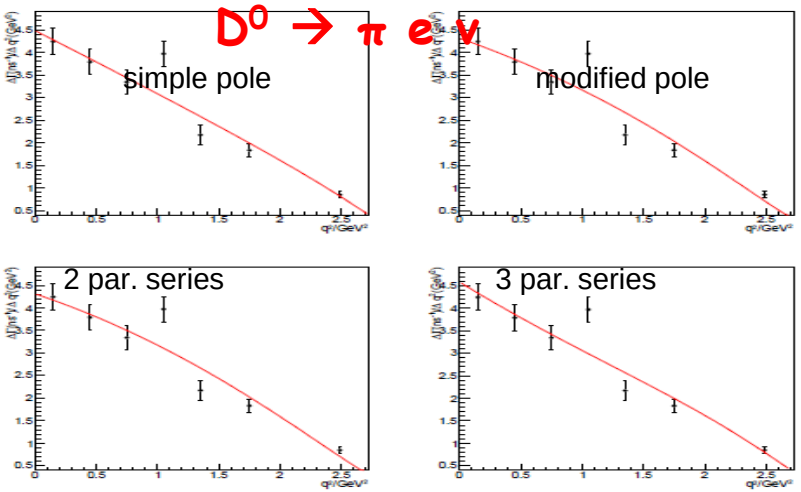
$$f_+(q^2) = \frac{1}{P(q^2)\,\phi(q^2,t_0)} \sum_{k=0}^{\infty} a_k(t_0)\,\left[z(q^2,t_0)\right]^k$$

Could fit: $f_+(0)$, $r_1 = a_2/a_1$, $r_2 = a_3/a_1$

$D^0 \to K e \nu$



$D^0 \to \pi e \nu$



Form Factor Results

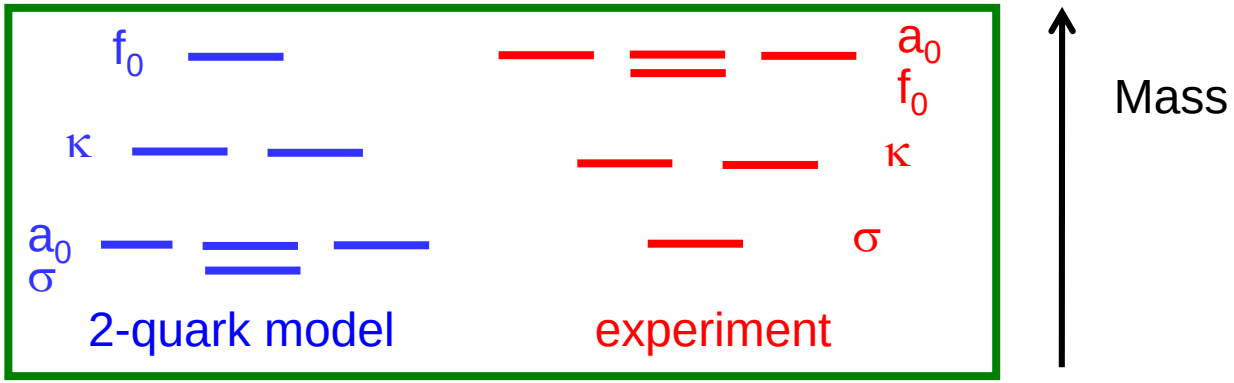
BESIII Preliminary

Simple Pole	$f_+(0)\lvert V_{cd(s)}\rvert$	m_{pole}	
$D^0 \to Ke\nu$	$0.729 \pm 0.005 \pm 0.007$	$1.943 \pm 0.025 \pm 0.003$	
$D^0 \to \pi e\nu$	$0.142 \pm 0.003 \pm 0.001$	$1.876 \pm 0.023 \pm 0.004$	
Modified Pole	$f_+(0)\lvert V_{cd(s)}\rvert$	α	
$D^0 \to Ke\nu$	$0.725 \pm 0.006 \pm 0.007$	$0.265 \pm 0.045 \pm 0.006$	
$D^0 \to \pi e\nu$	$0.140 \pm 0.003 \pm 0.002$	$0.315 \pm 0.071 \pm 0.012$	
2 par. series	$f_+(0)\lvert V_{cd(s)}\rvert$	r_1	
$D^0 \to Ke\nu$	$0.726 \pm 0.006 \pm 0.007$	$-2.034 \pm 0.196 \pm 0.022$	
$D^0 \to \pi e\nu$	$0.140 \pm 0.004 \pm 0.002$	$-2.117 \pm 0.163 \pm 0.027$	
3 par. series	$f_+(0)\lvert V_{cd(s)}\rvert$	r_1	r_2
$D^0 \to Ke\nu$	$0.729 \pm 0.008 \pm 0.007$	$-2.179 \pm 0.355 \pm 0.053$	$4.539 \pm 8.927 \pm 1.103$
$D^0 \to \pi e\nu$	$0.144 \pm 0.005 \pm 0.002$	$-2.728 \pm 0.482 \pm 0.076$	$4.194 \pm 3.122 \pm 0.448$

Light Scalar Meson

Problems :

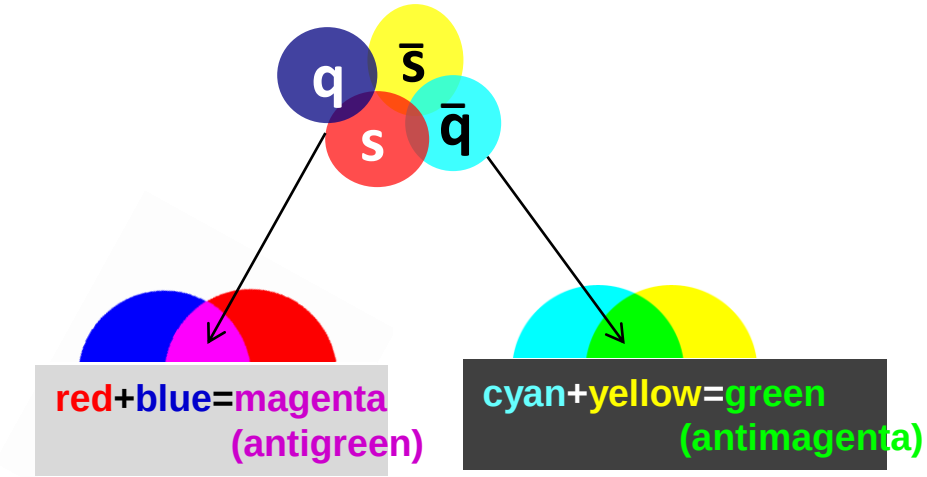
- Inverted mass spectrum.



- In qqbar meson monets, the 1=1 state (here the $a_0(980)$) has not s-quarks
- $M(f_0(980))\sim M(a_0(980))$ ⟹ "ideal" mixing & small s-quark content in $f_0(980)$.
- But strong $a_0(980)$ & $f_0(980)$ coupling to Kkbar indicate strong OZI rule violations.
- No "light" $J^P=1^+$ and 2^{++} partner nonet in the same mass region.

If not qqbr, then what

tightly bound diquark-diantiquark

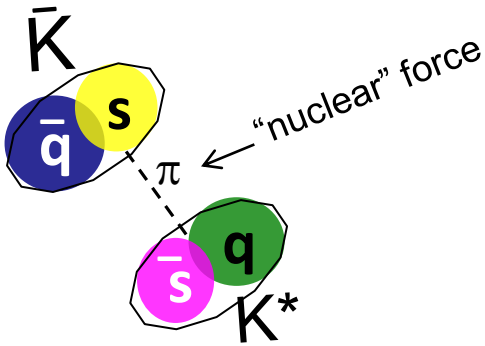


A colored diquark is like a antiquark

A colored diantiquark is like a quark

R.L.Jaffe PRD 15, 267 (1977)

loosely bound meson-antimeson "molecule"

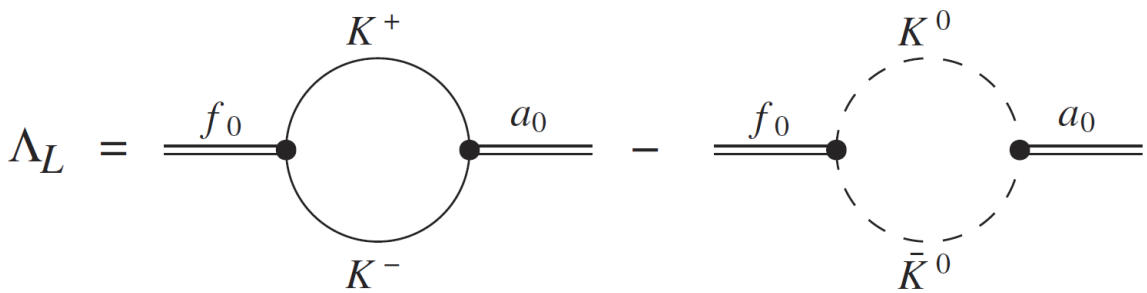


J.D.Weinstein & N.Isgur PRD 27, 588 (1983)

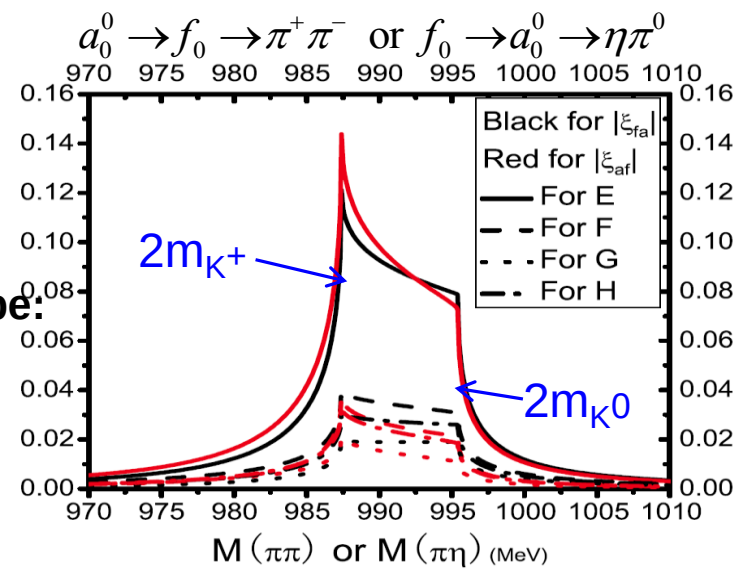
$a_0(980)$-$f_0(980)$ mixing

isospin violation enhanced by K^0 – K^+ mass difference

C. Hanhart, B. Kubis, and J. R. Pelaez, Phys. Rev. D **76**, 074028 (2007)



$2m_{K^+}$ = 987.4 MeV $2m_{K^0}$ = 995.2 MeV



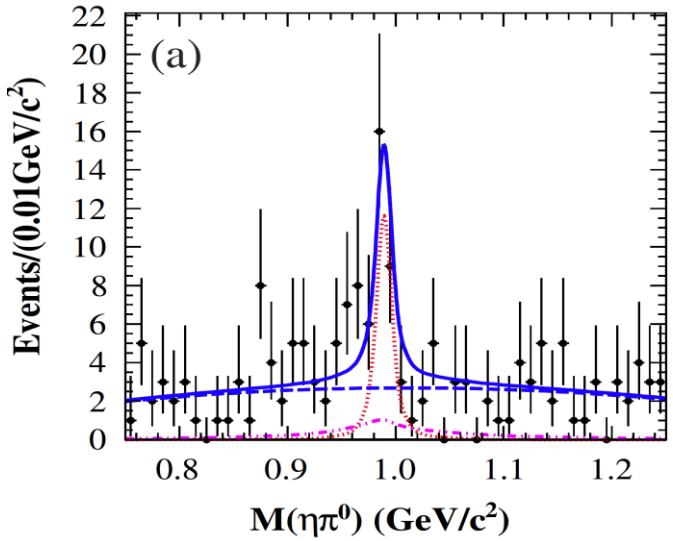
expect a narrow line shape:
$G \approx 2(m_{K^0}-m_{K^+})=7.8$ MeV

PDG2010:
M_{f_0}= 980 ± 10 MeV
Γ_{f_0}= 40 ~ 100 MeV

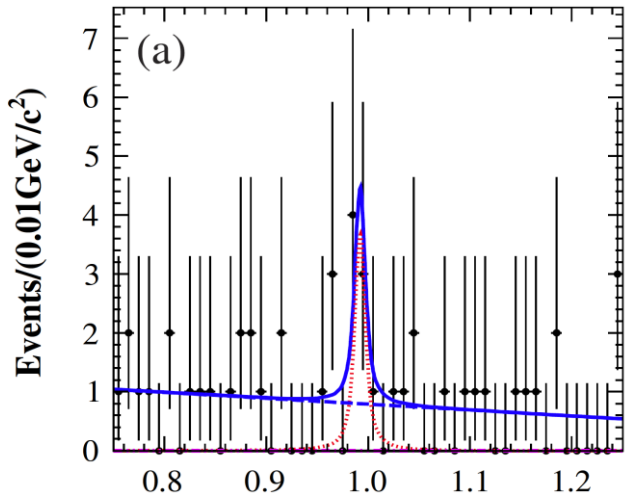
M_{a_0}= 980 ± 20 MeV
Γ_{a_0}= 50 ~ 100 MeV

BESIII $a_0(980)$-$f_0(980)$ mixing

$J/\psi \to \phi f_0 \to \varphi a_0^0 \to K^+K^-\eta\pi^0$

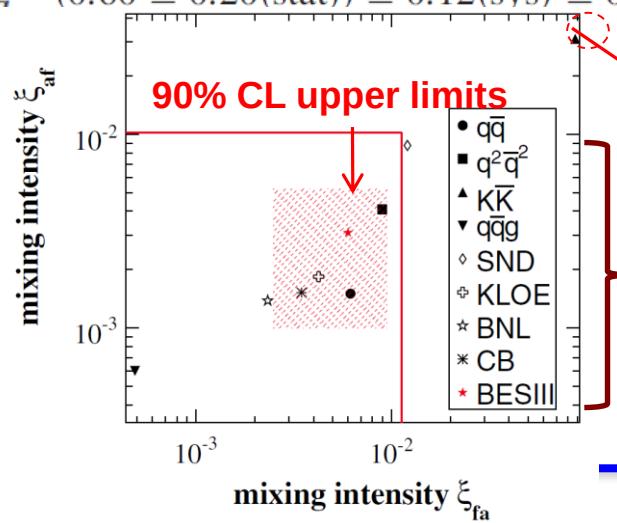


$\psi' \to \gamma\chi_{c1} \to \gamma\pi^0 a_0^0 \to \gamma\pi^0 f_0 \to \gamma\pi^0\pi^+\pi^-$



$\xi_{fa} = (0.60 \pm 0.20(\text{stat})) \pm 0.12(\text{sys}) \pm 0.26(\text{para})\%$

$\xi_{af} = (0.31 \pm 0.16(\text{stat}) \pm 0.14(\text{sys}) \pm 0.03(\text{para}))\%$



KK molecule model

different models & parameterizations

BESIII PRD 83, 032003 (2011)

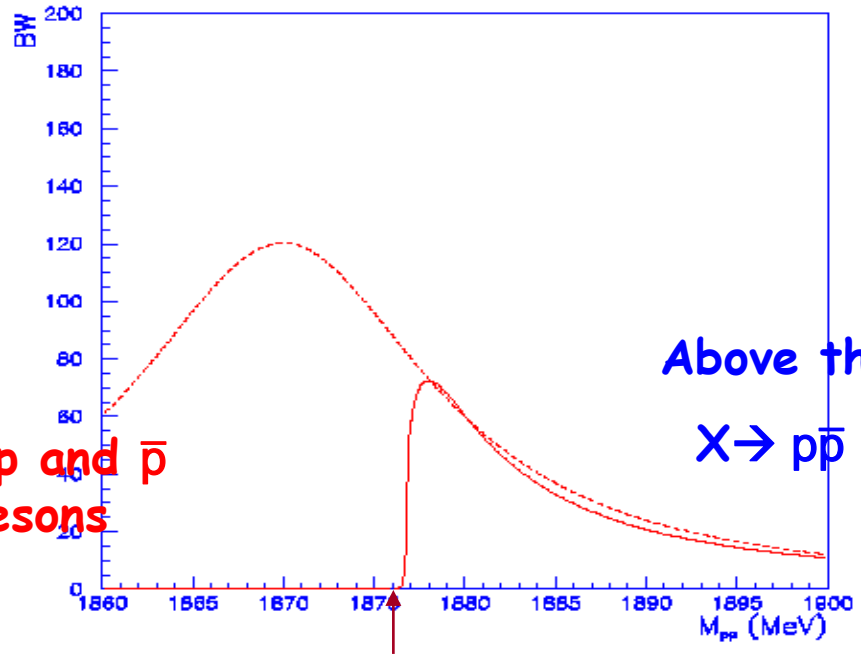
A $p\bar{p}$ bound state (baryonium)?

If baryonium :

— Above-threshold : $X \rightarrow p\bar{p}$ ~100%

— Below-threshold : annihilate to mesons

— I=0, $J^{PC}=0^{-+}$, decay to $\pi^+\pi^-\eta'$ is common



below-threshold: p and $\bar{p}$ annihilate to mesons

Above threshold:

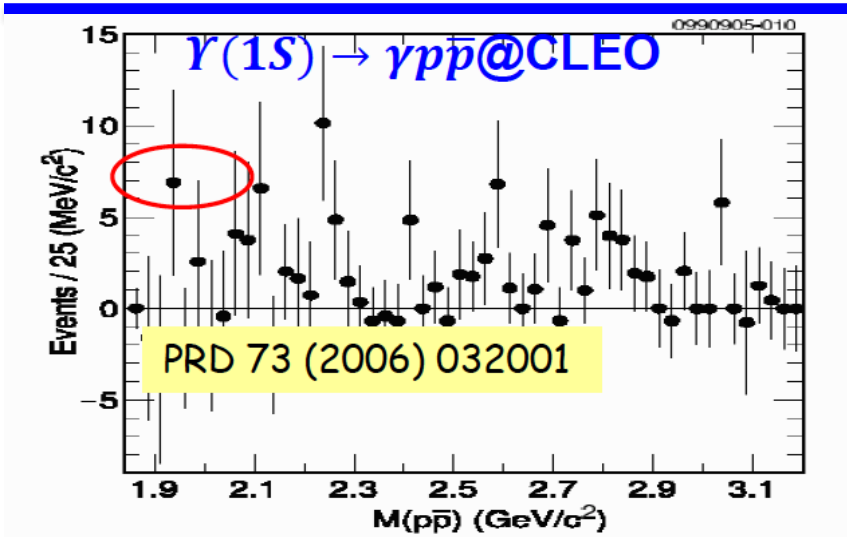
$X \rightarrow p\bar{p}$ ~100%

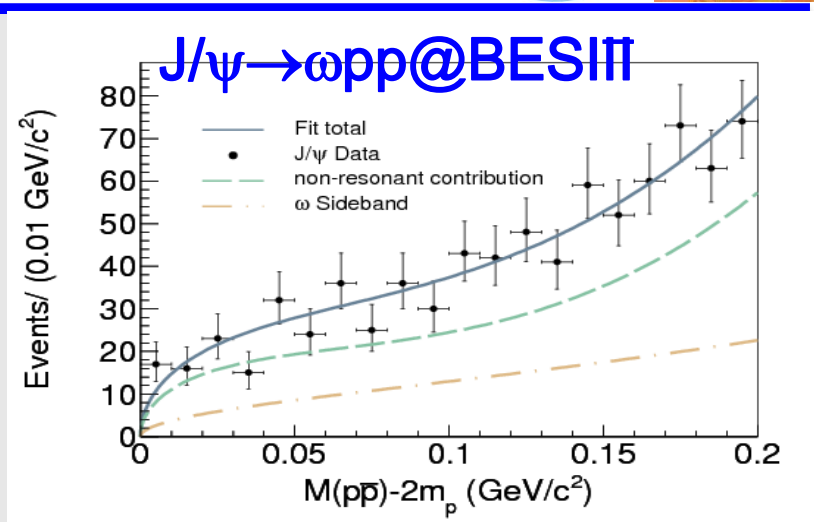
$m_p + m_p$

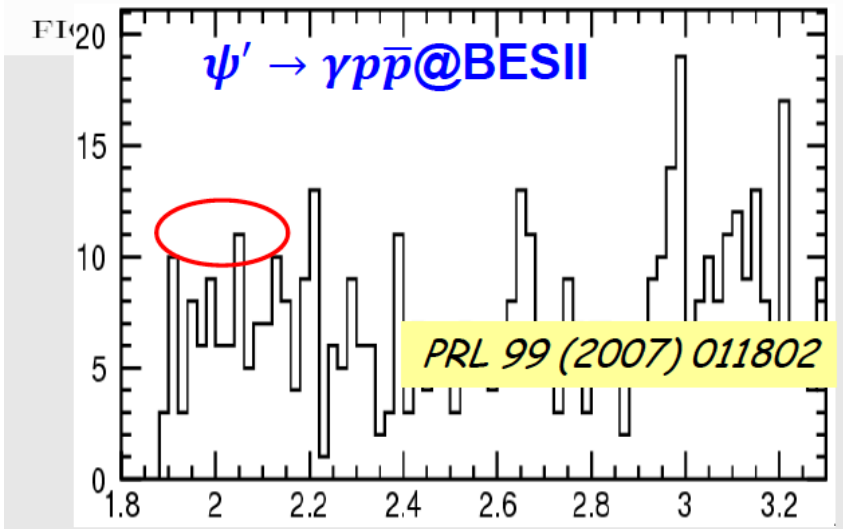
Phys. Rev. C 72, 015208 (2005) G.J. Ding and M.L.Yan

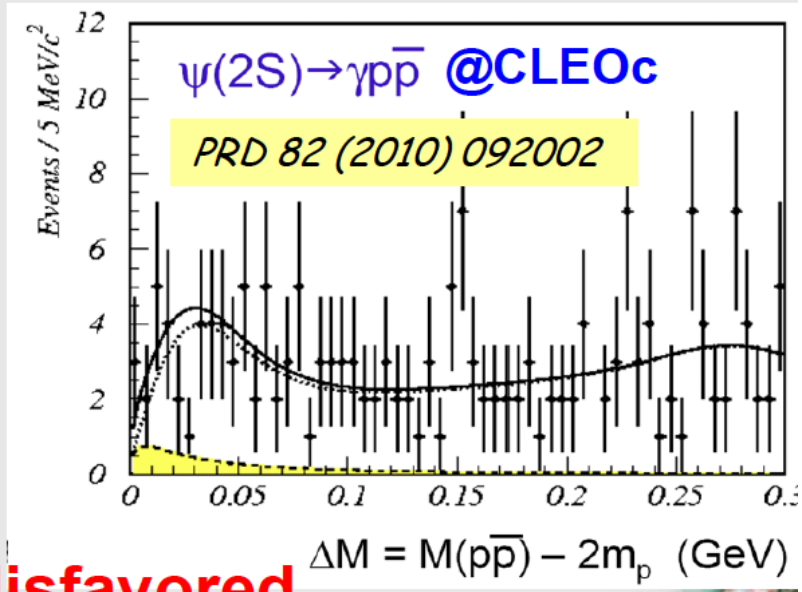
Comm. Theor. Phys. 42, 844 (2004) C.S. Gao and S.L. Zhu

Some non-Observation



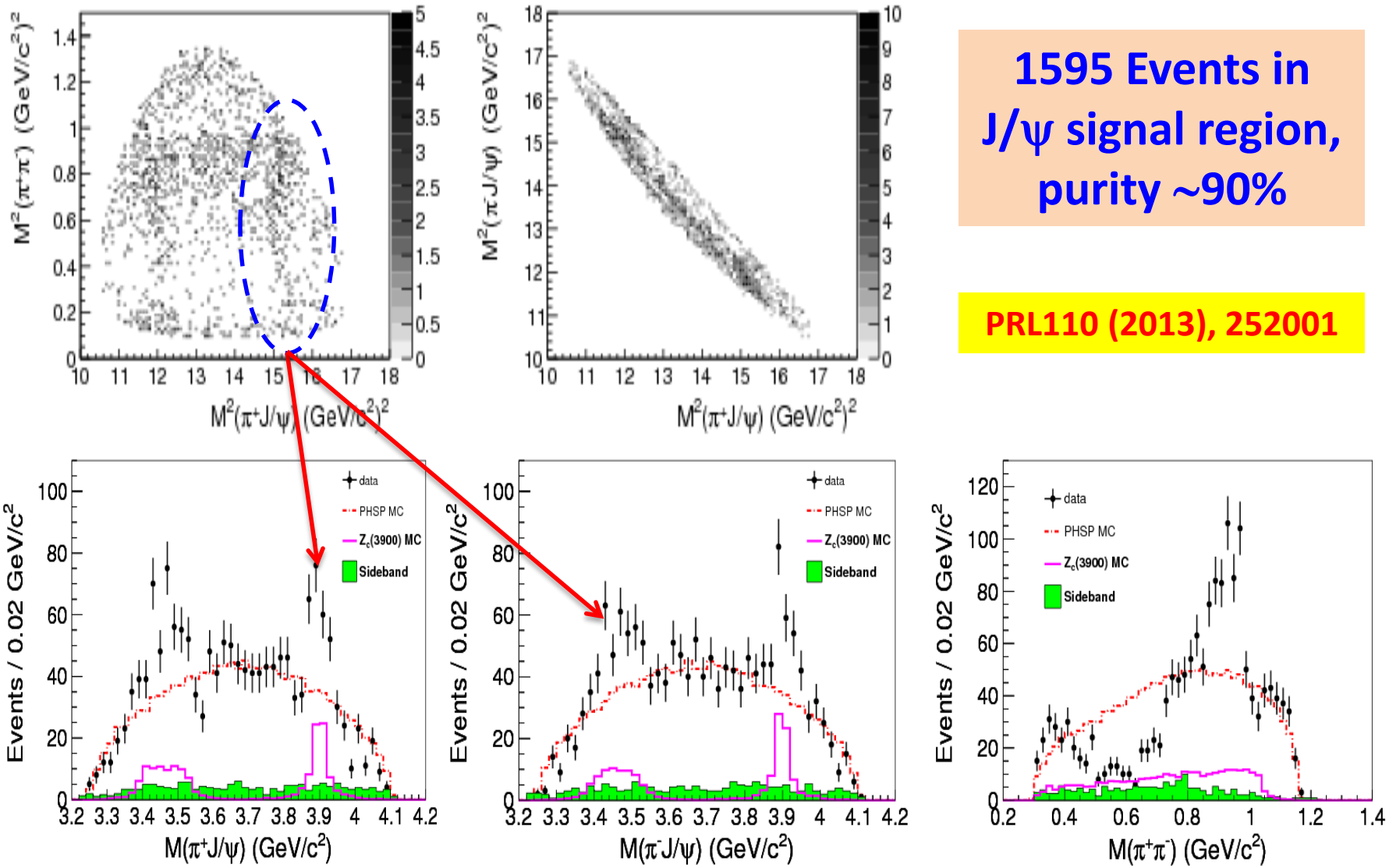






Pure FSI interpretation is disfavored

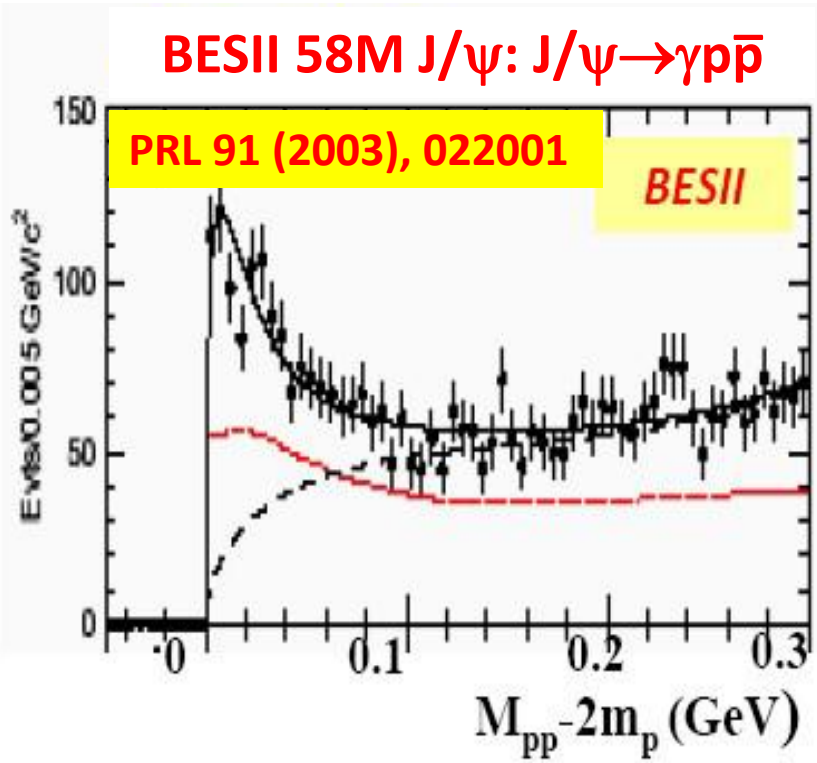
$Z_c(3900)$: $e^+e^- \to \pi^+\pi^- J/\psi$ @4.26GeV

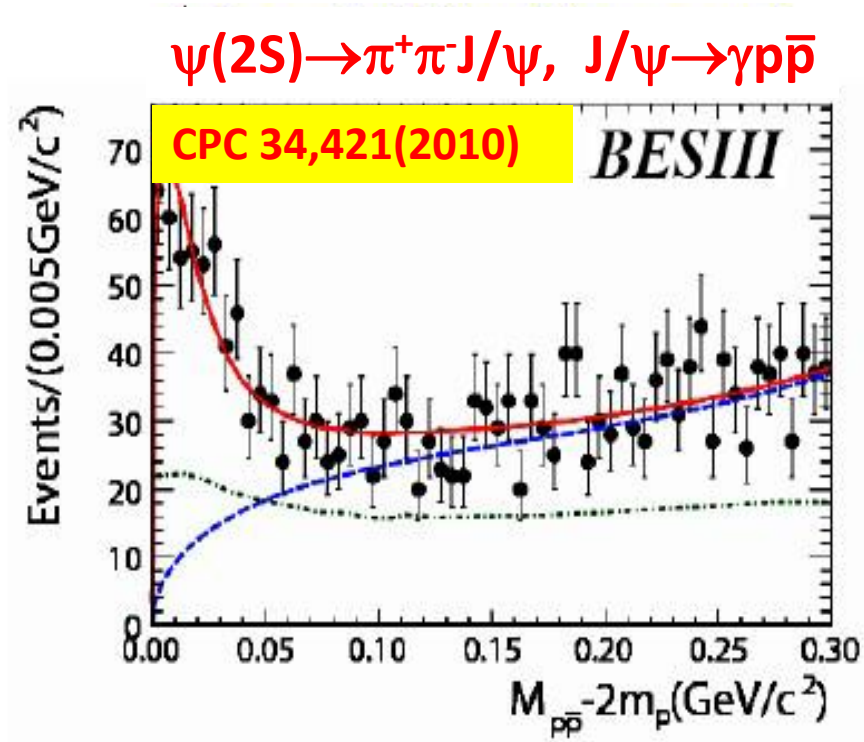


1595 Events in J/ψ signal region, purity ~90%

PRL110 (2013), 252001

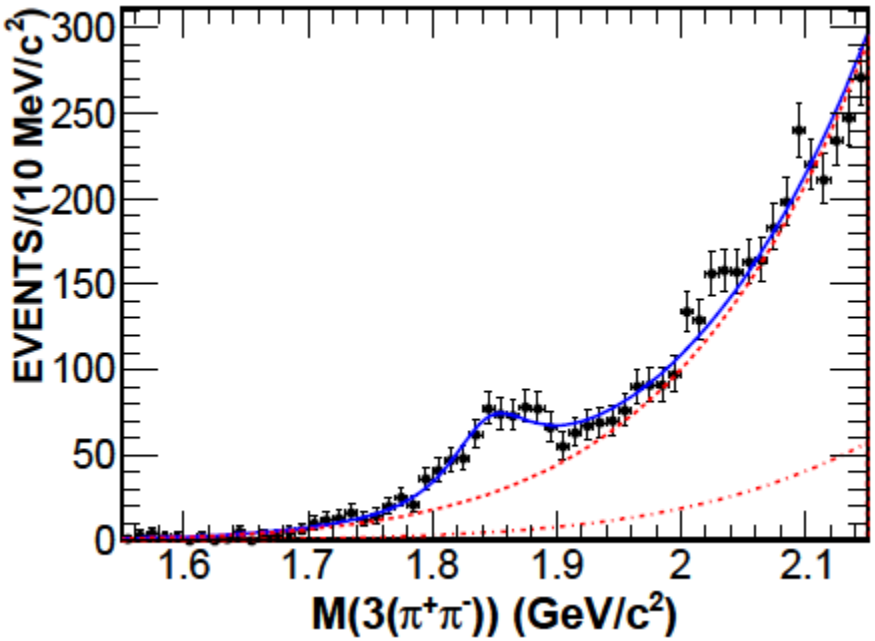
$p\bar{p}$ Threshold Enhancement





- **Observed at BESII:**
  - $M = 1860_{-10-25}^{+3+5}$ MeV/c^2
  - $\Gamma < 38$ MeV/c^2 (90% C.L.)
  - Agree with spin zero expectation
- **Confirmed at BESIII in 2010:**
  - $M = 1859_{-13-26}^{+6+6}$ MeV/c^2
  - $\Gamma < 30$ MeV/c^2 (90% C.L.)

X(1840) in $J/\psi \to \gamma 3(\pi^+\pi^-)$



arXiv:1305.5333, submit to PRL

- A structure is observed.
  - $M = 1842.2 \pm 4.2 + 7.1 - 2.6 MeV/c^2$
  - $\Gamma = 83 \pm 14 \pm 11 MeV$
- No obviously structure observed above 2.0 GeV/c^2

- The Mass is in agreement with those of X(1835) and X($p\bar{p}$)
- but width do not ….
- The production ratio :

— $Br(J/\psi \to \gamma X(1840)) \times Br(X(1840) \to 3(\pi+\pi-)) = (2.44 \pm 0.36^{+0.60}_{-0.74}) \times 10^{-5}$

A new structure or an existing state? Need more study!
(J^{pc}, relationship between different observations)