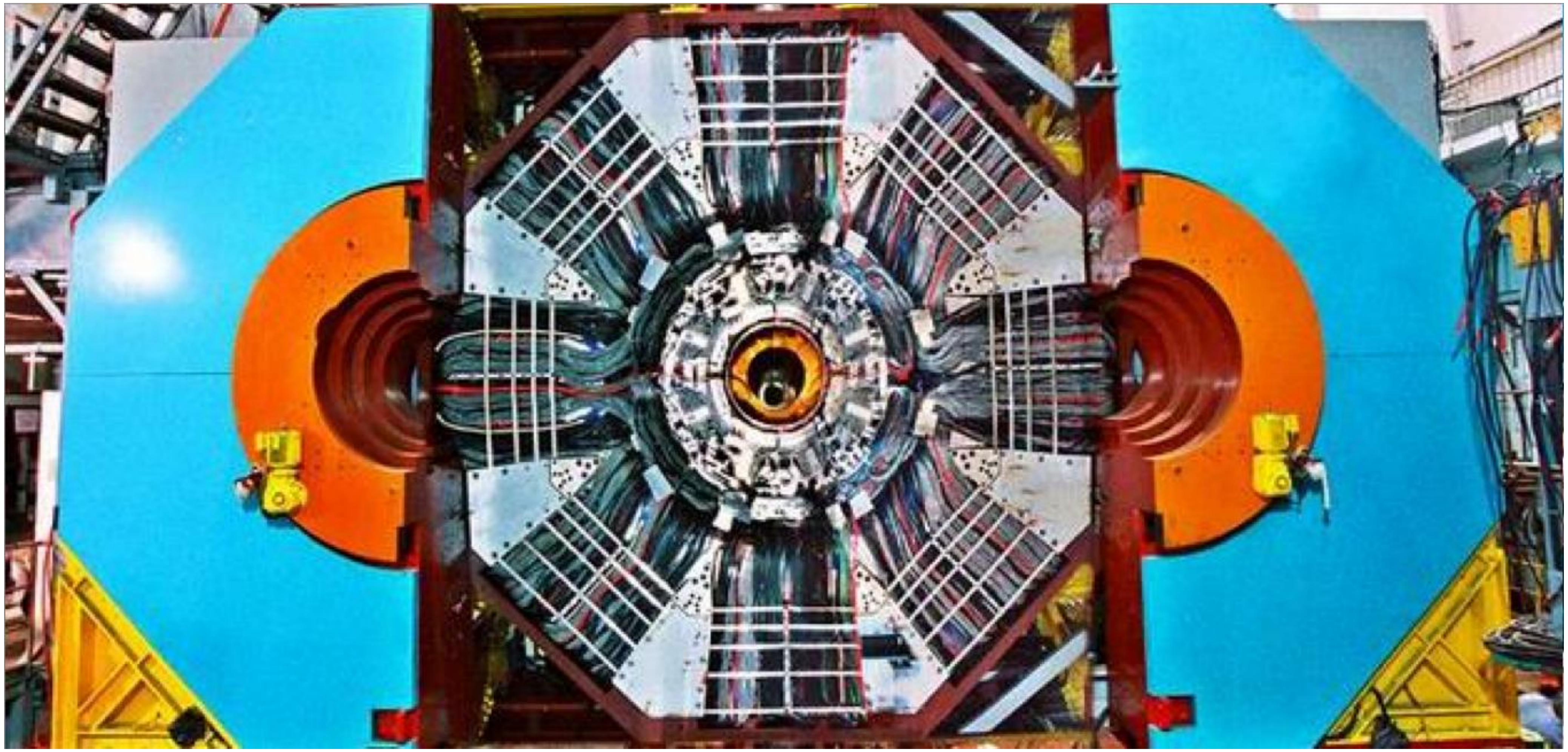


Physics highlights from the BESIII experiment

Xiao-Rui Lyu (吕晓睿)
University of Chinese Academy of Sciences (UCAS), Beijing
(On behalf of the BESIII collaboration)

Flavor and top physics @ 100 TeV workshop
March 4-7 2015, IHEP, Beijing, China

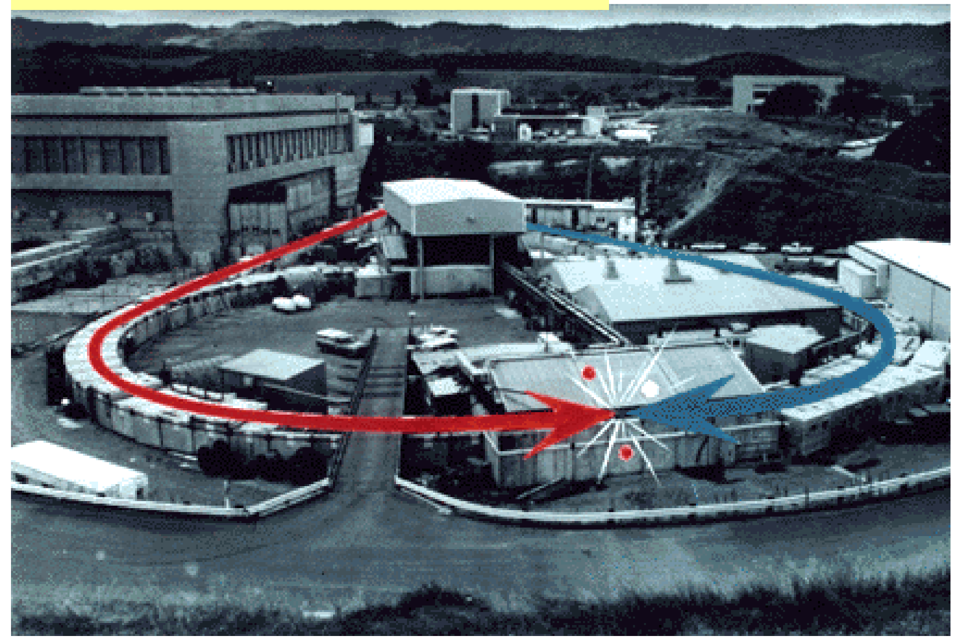
Outline

- **Introduction to the BESIII experiment**
- **Physics highlights (not a complete list)**
  - ✓ **Light hadron spectroscopy:**
    X(18??) states …
  - ✓ **Charmonium(-like) states and exotics:**
    Zc states …
  - ✓ **Charmed hadron:**
    D^+ leptonic decays, $D^0 \to K\pi$ strong phase …
  - ✓ **τ mass measurement**
- **Summary**

Charm from dedicated colliders

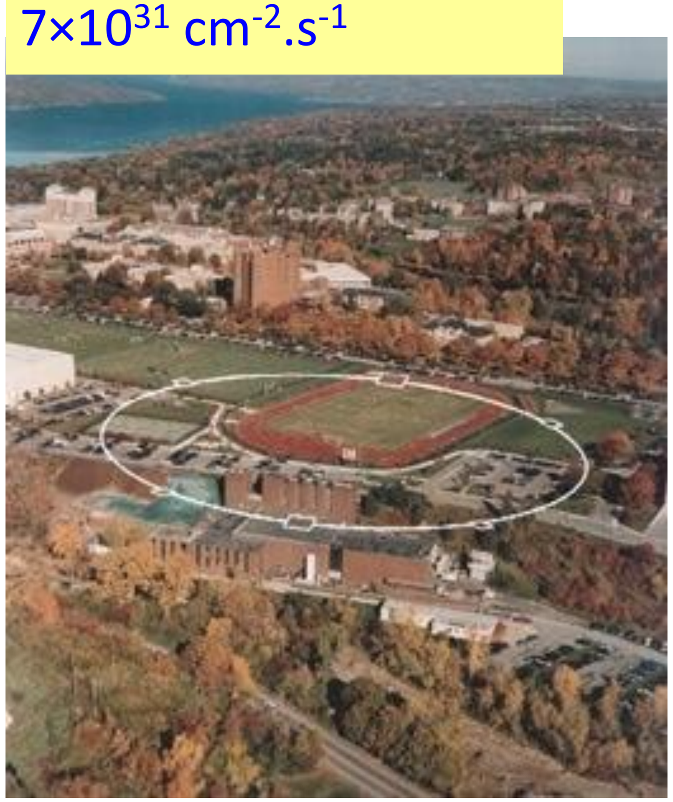
ADONE, FRASCATI '69-'93

SPEAR, SLAC, '72-'90
6×10^{29} cm^{-2}.s^{-1}

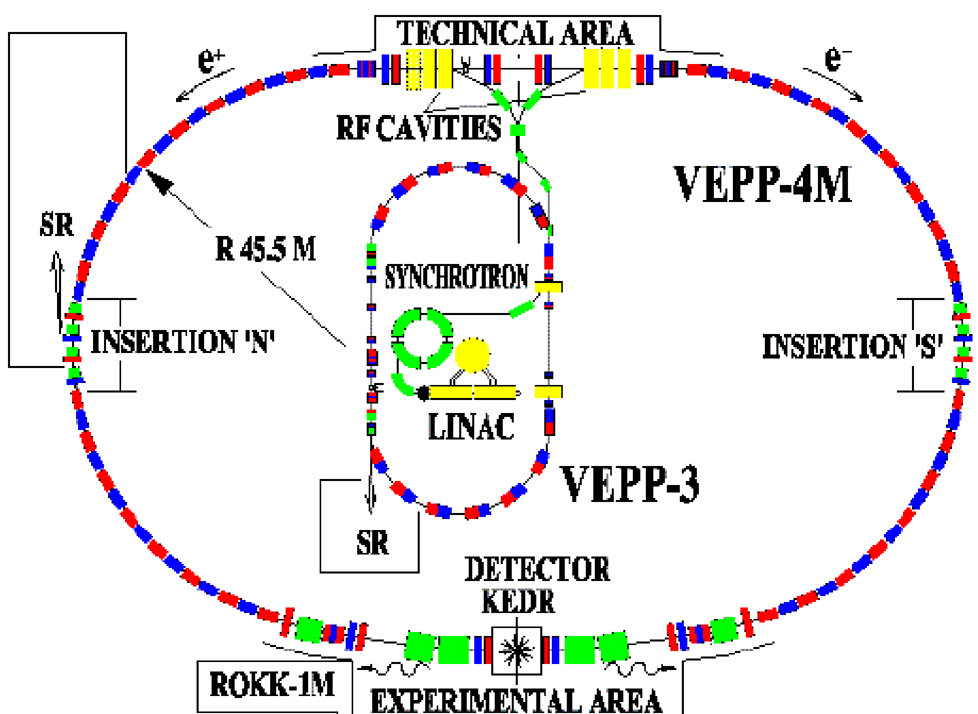


BEPC, IHEP, '90-'04
5×10^{30} cm^{-2}.s^{-1}

CESRc, Cornell, '04-'08
7×10^{31} cm^{-2}.s^{-1}

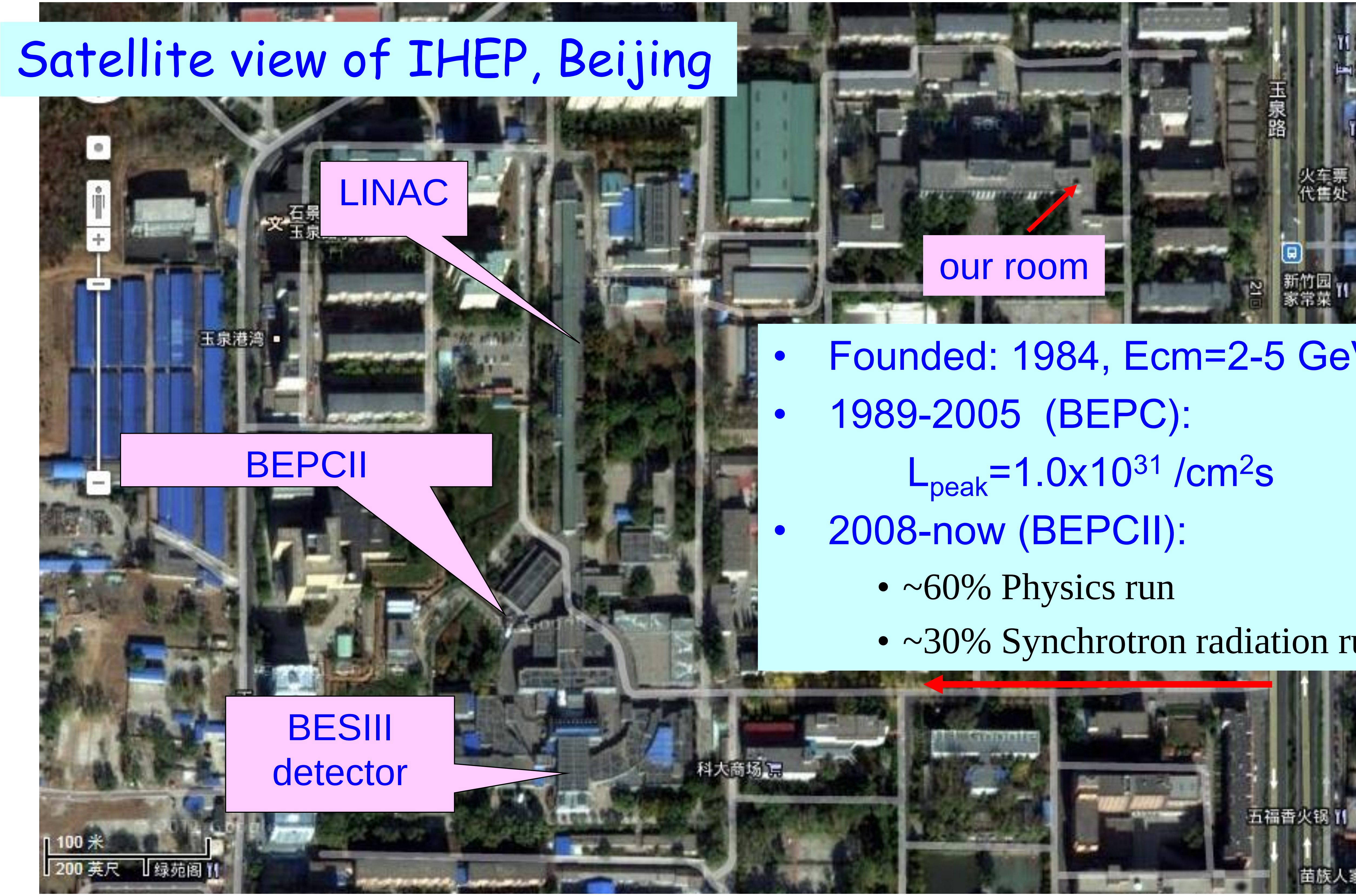


VEPP-4M, Novosibisk, '02-'12
1×10^{30} cm^{-2}.s^{-1}



BEPCII, IHEP, '08-'22(?)
1×10^{33} cm^{-2}.s^{-1}

Beijing Electron Positron Collider II (BEPCII)



- Founded: 1984, Ecm=2-5 GeV
- 1989-2005 (BEPC):
  L_{peak}=1.0x10^{31} /cm^{2}s
- 2008-now (BEPCII):
  - ~60% Physics run
  - ~30% Synchrotron radiation run

The BEPCII Collider

BEMS (beam energy measurement system):
based on Compton backscattering

Beam energy: 1.0 - 2.3 GeV

Peak Luminosity:

achieved: $0.85 \times 10^{33} cm^{-2} s^{-1}$@3770 MeV

Optimum energy: 1.89 GeV

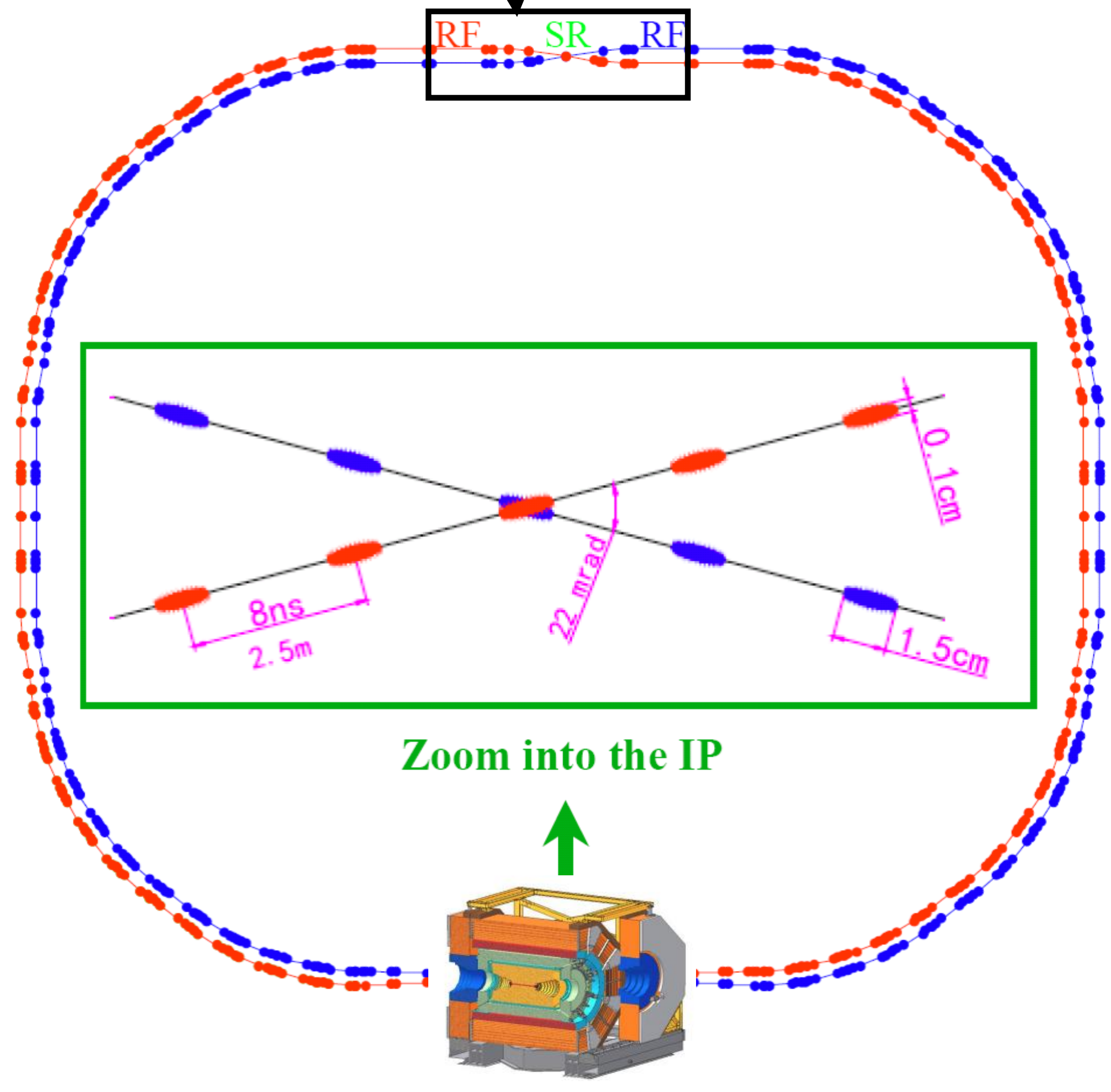
Energy spread: 5.16 $\times 10^{-4}$

No. of bunches: 93

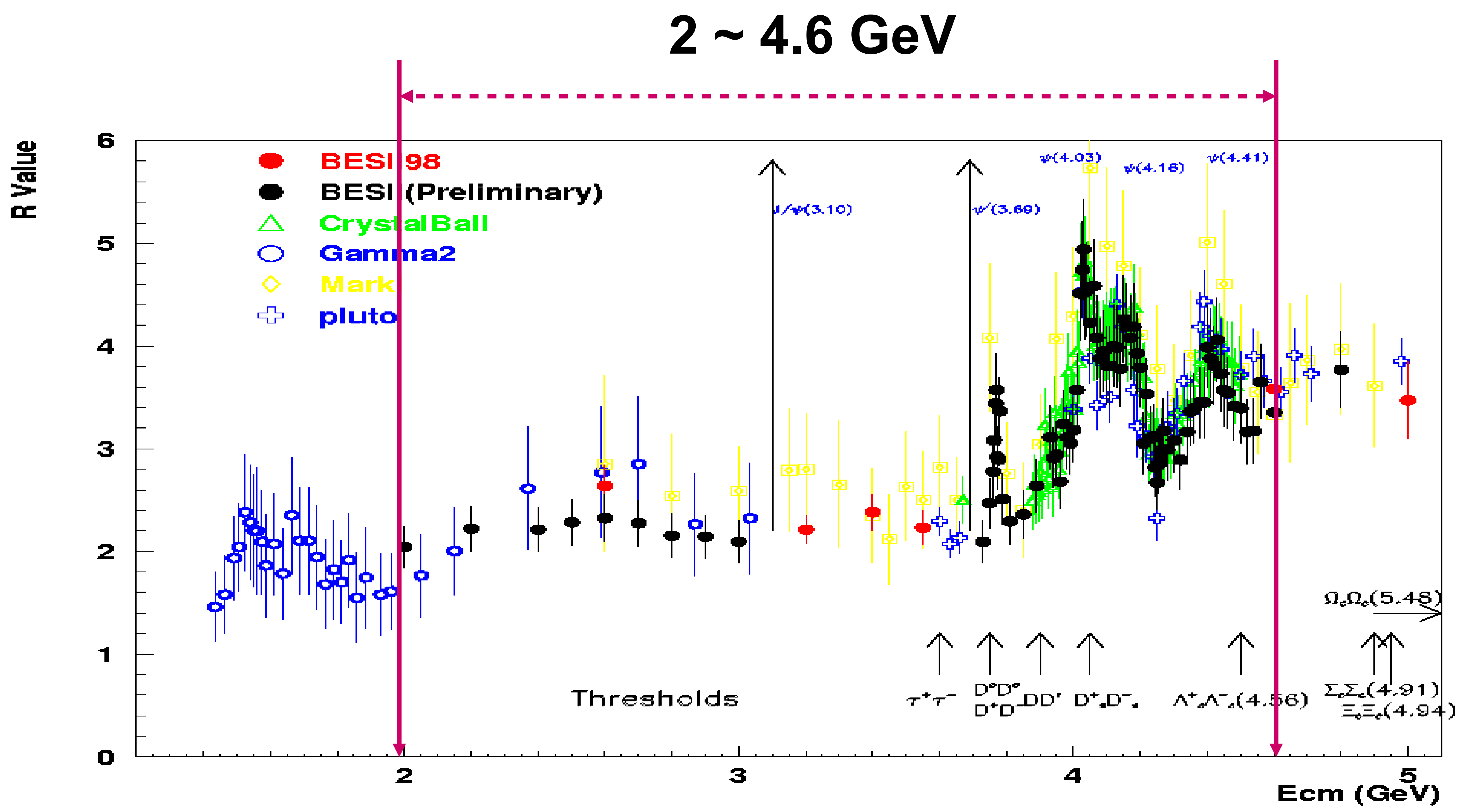
Bunch length: 1.5 cm

Total current: 0.91 A

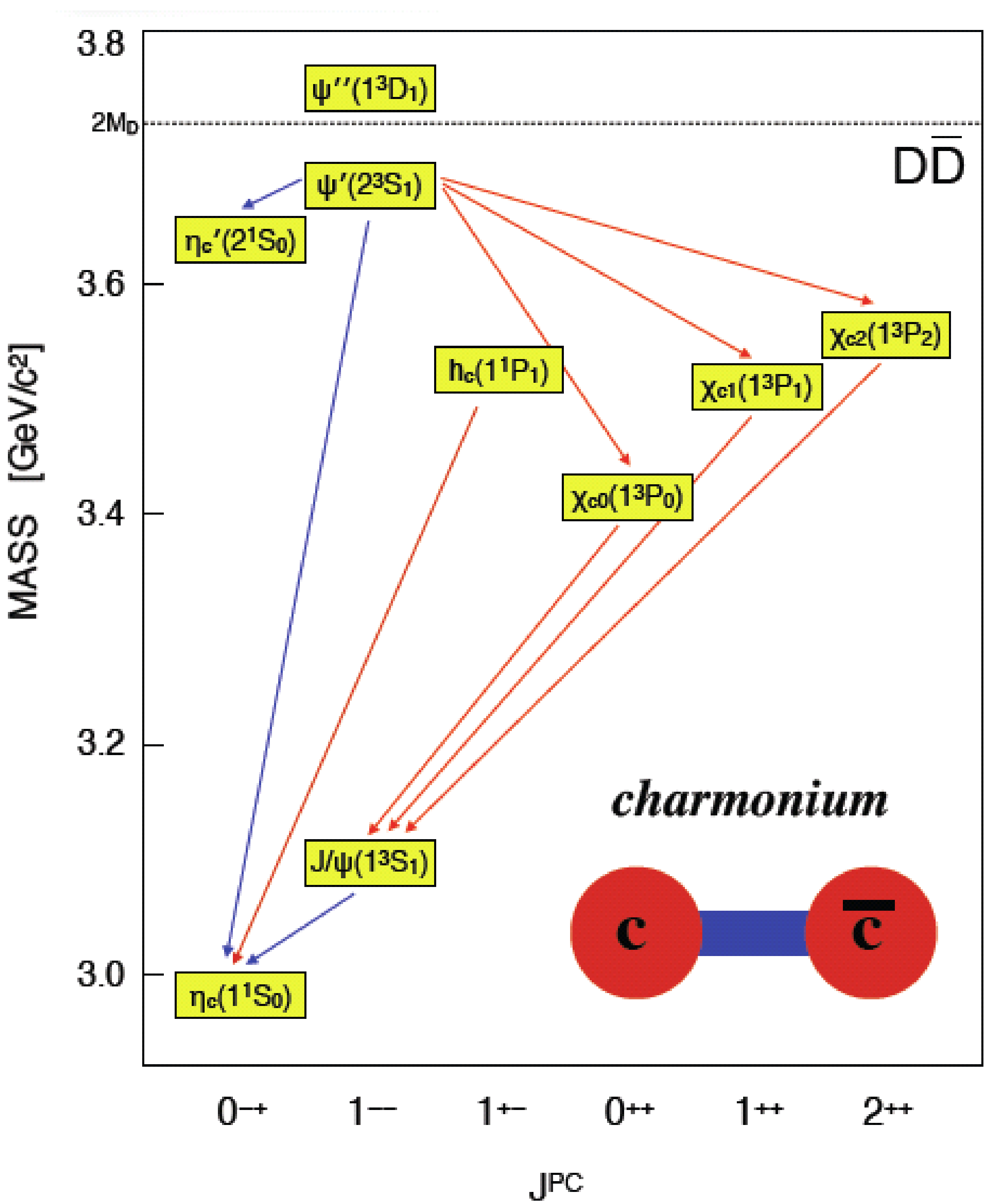
Circumference: 237m



Energies of the BEPCII Collider



BESIII – physics using "charm"



Charmonium physics:
- Spectroscopy
- transitions and decays

Light hadron physics:
- meson & baryon spectroscopy
- glueball & hybrid
- two-photon physics
- e.m. form factors of nucleon

Charm physics:
- (semi)leptonic + hadronic decays
- decay constant, from factors
- CKM matrix: Vcd, Vcs
- D^0-D^0bar mixing and CP violation
- rare/forbidden decays

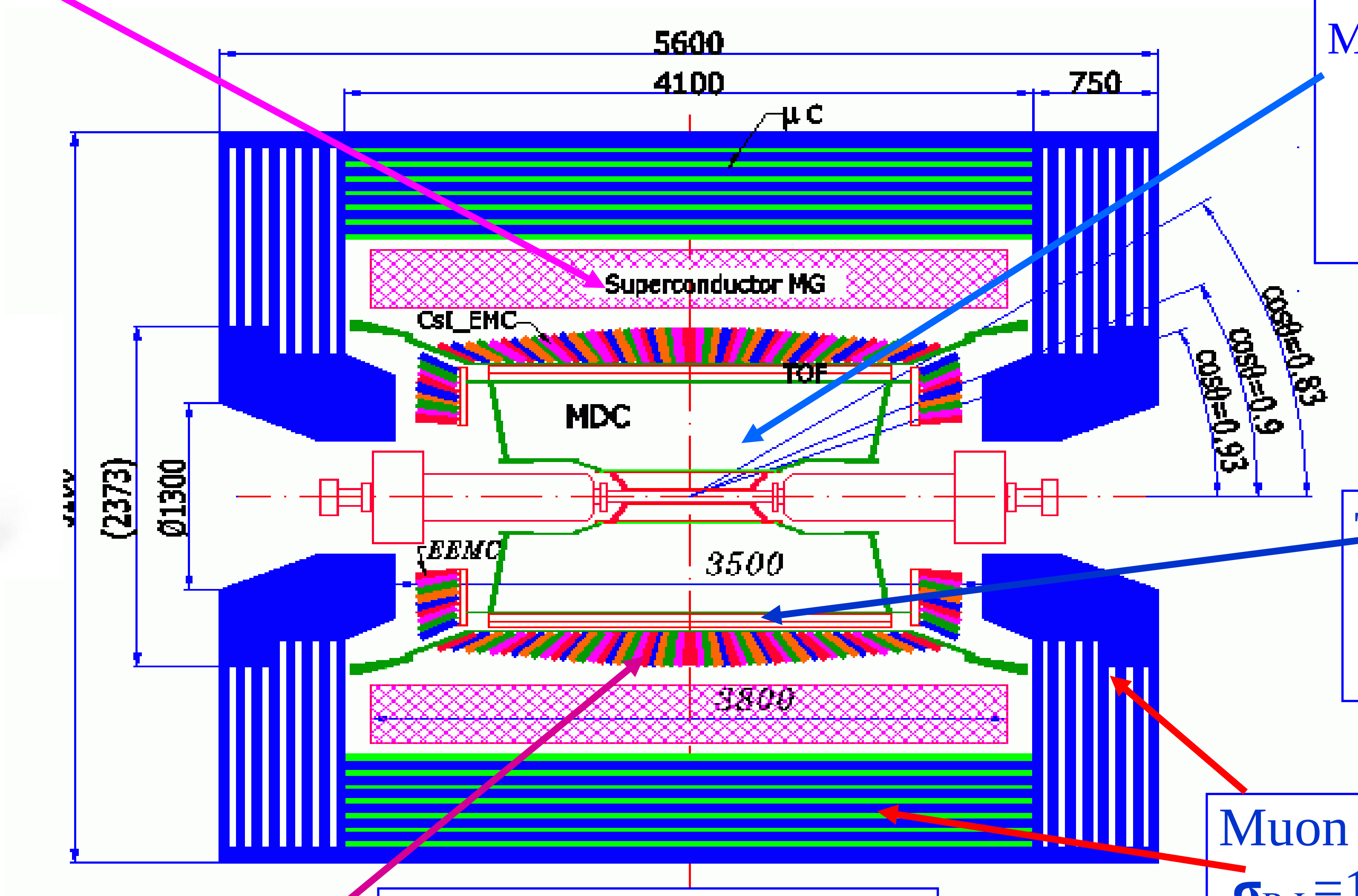
Tau physics:
- Tau decays near threshold
- tau mass scan

…and many more.

NIM A614, 345 (2010)

The BESIII detector

Solenoid Magnet: 1 T Super conducting



MDC: small cell & He gas
σ_{xy}=130 μm
$\delta p/p$ = 0.5% @1GeV
dE/dx=6%

TOF:
σ_T = 90 ps Barrel
110 ps Endcap

Muon ID: 8~9 layer RPC
$\sigma_{R\Phi}$=1.4 cm~1.7 cm

EMCAL: CsI crystal
$\Delta E/E$ = 2.5% @1 GeV
$\sigma_{\varphi,z}$ = 0.5~0.7 cm/√E

Data Acquisition:
Event rate = 3 kHz
Throughput ~ 50 MB/s

Trigger: Tracks & Showers
Pipelined; Latency = 6.4 μs

hermetic spectrometer for neutral and charged particle with excellent resolution, PID, and large coverage.

BESIII Collaboration

US (5)

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

Europe (13)

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

Korea (1)

Seoul Nat. Univ.

Japan (1)

Tokyo Univ.

Pakistan (2)

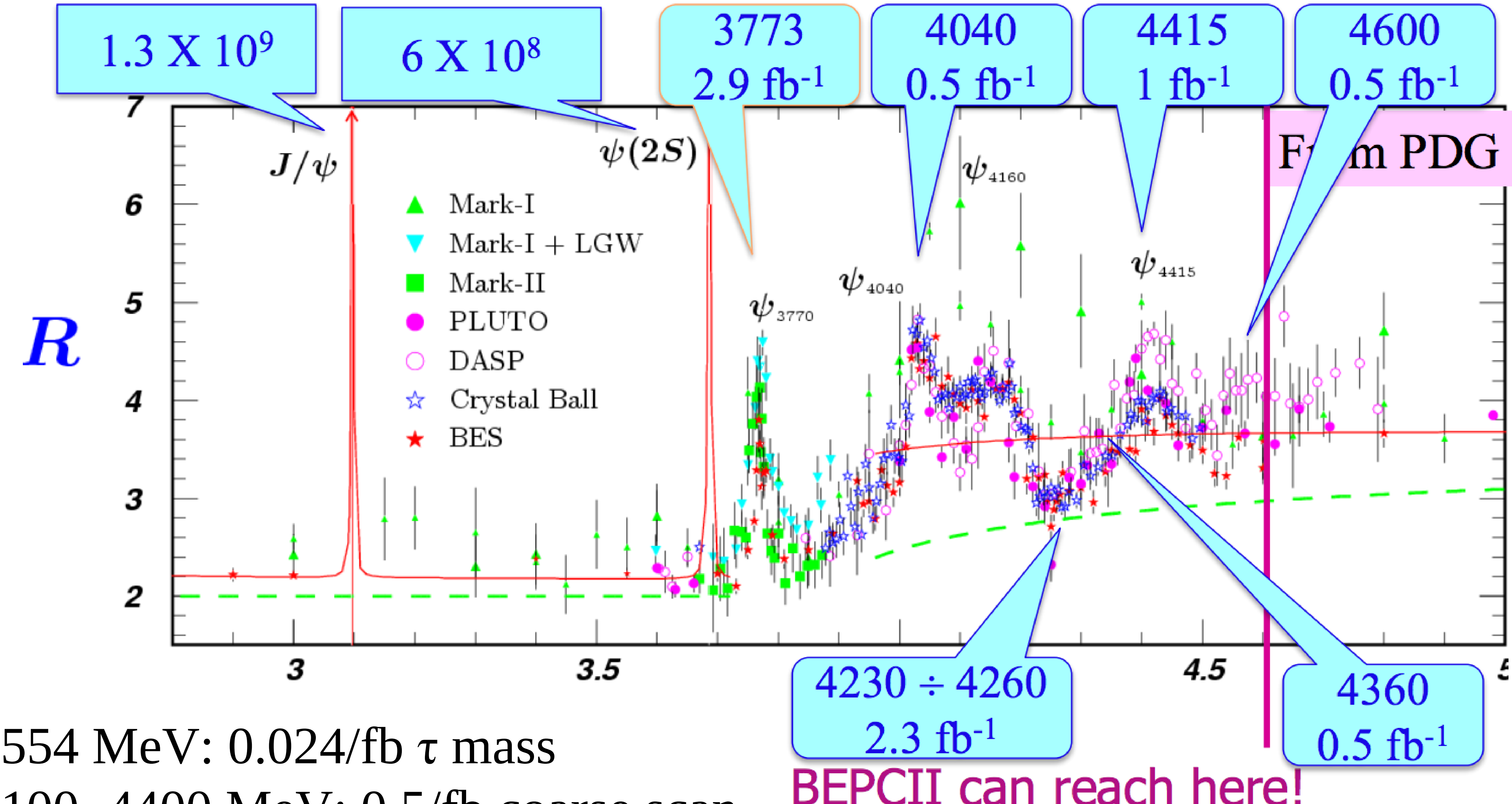
Univ. of Punjab
COMSAT CIIT

China(31)

IHEP, CCAST, GUCAS, 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., Univ. of South China
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.
Beihang Univ., Beijing Petrol Chemical Univ.

~400 members
53 institutions from 11 countries

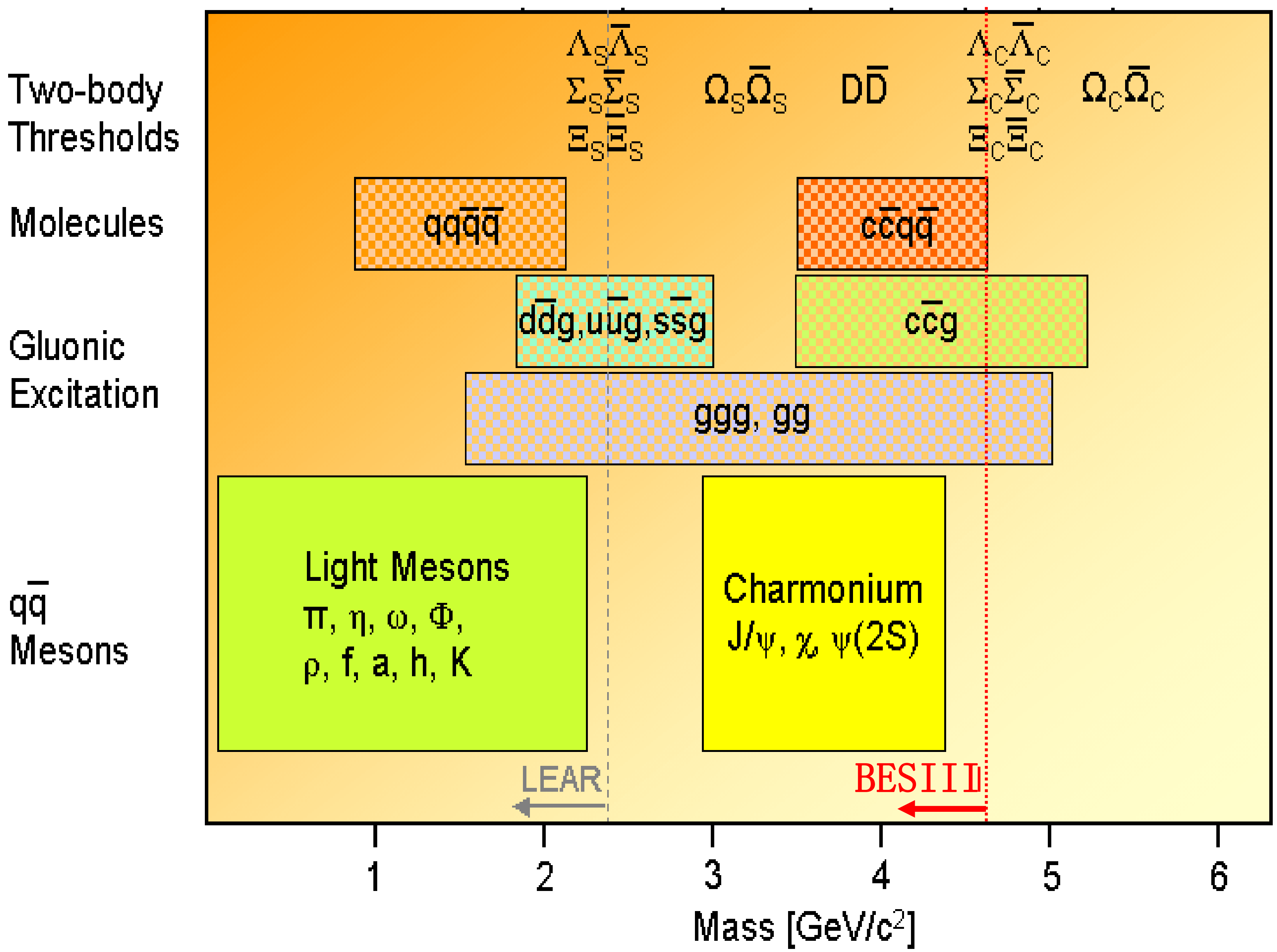
BESIII data samples



- 3554 MeV: 0.024/fb τ mass
- 4100~4400 MeV: 0.5/fb coarse scan
- 3850~4590 MeV: 0.5/fb fine scan
- In 2015, we are doing energy scan at 2000~3000 MeV

Machine luminosity is optimal near ψ" peak

Hadron Landscape



Hadron-physics challenges:

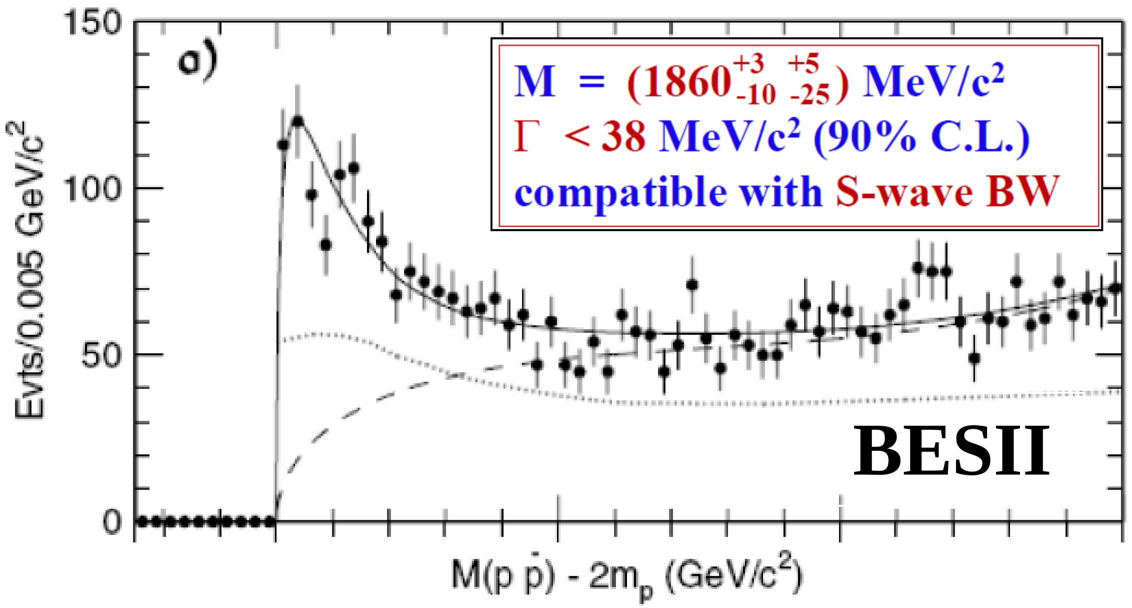
- Understanding of established states: precision spectroscopy
- Nature of exotic states: search and spectroscopy of unexpected states

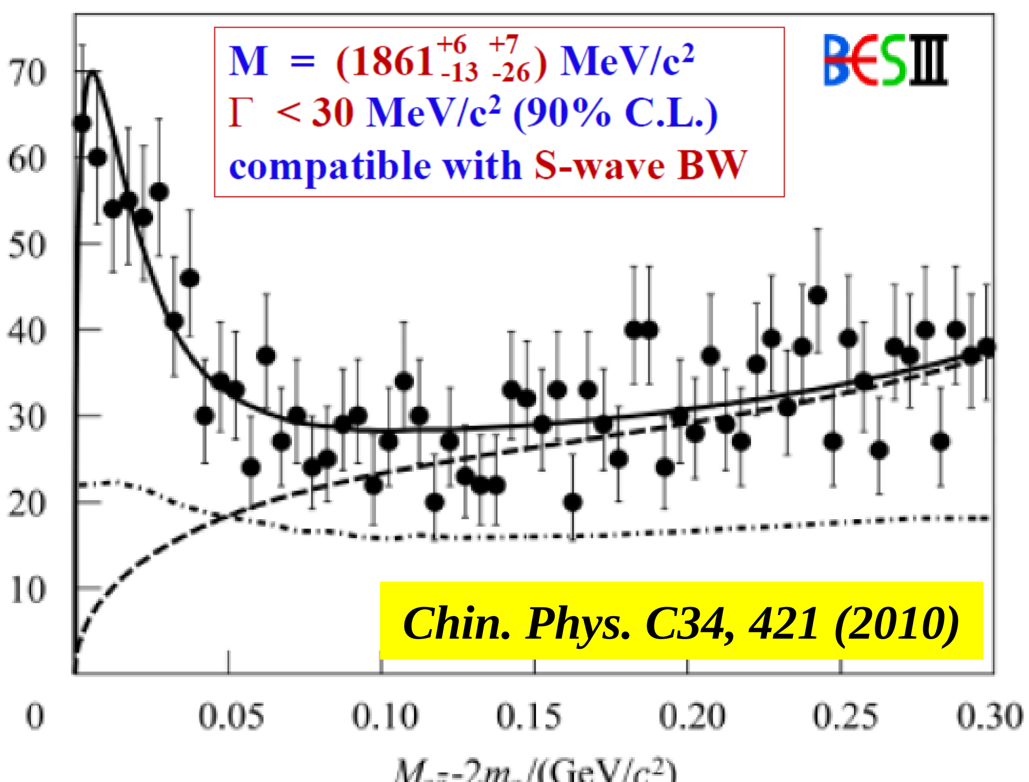
At BESIII, two golden measures to study hadron spectroscopy, *eps*. to search for exotics

- Light hadrons: charmonium radiative decays (act as spin filter)
- Heavy hadrons: direct production, radiative and hadronic transitions

X($p\bar{p}$) observed in J/ψ radiative decays

Firstly observed at BESII



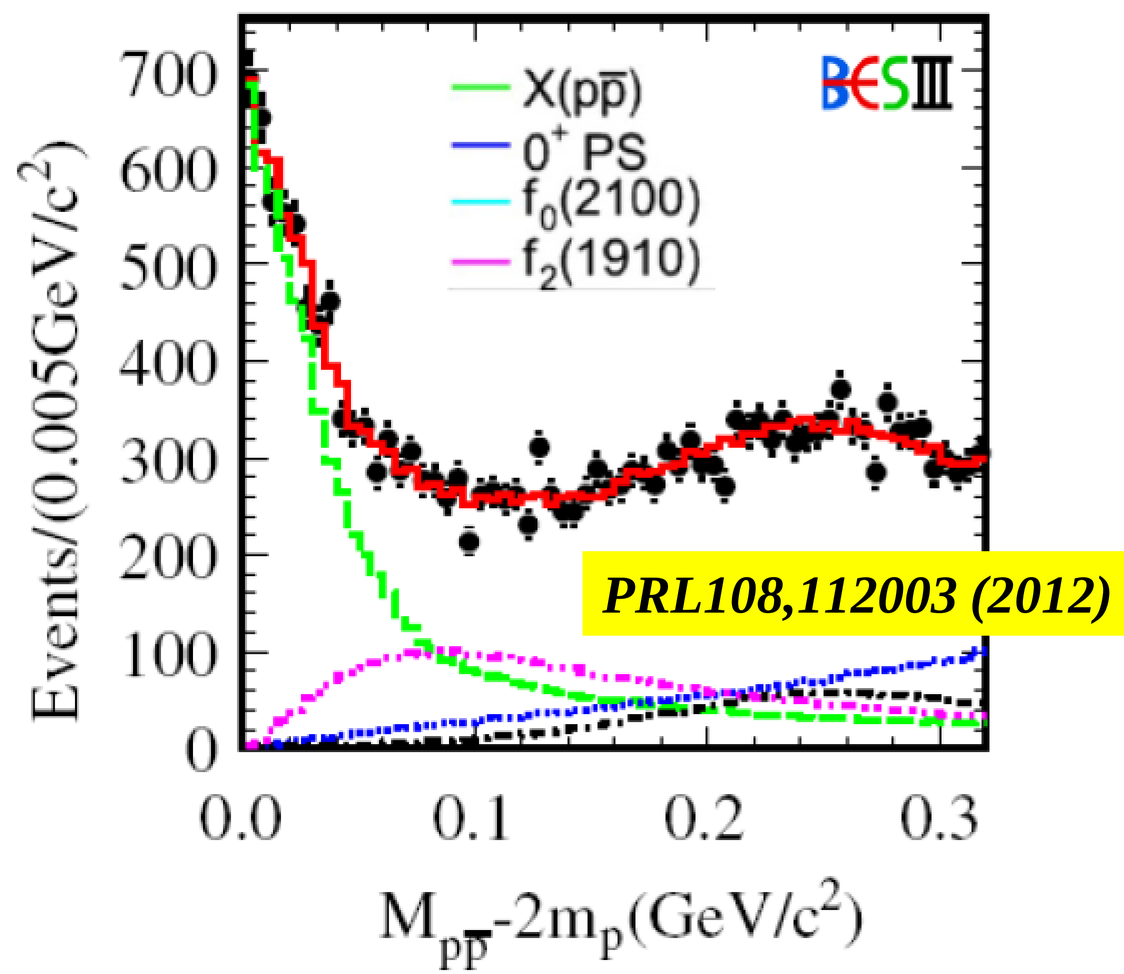


Confirmed in $\psi' \to \pi^+\pi^- J/\psi, J/\psi \to \gamma p\bar{p}$

$J/\psi \to \gamma p\bar{p}$: enhancement at threshold

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

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



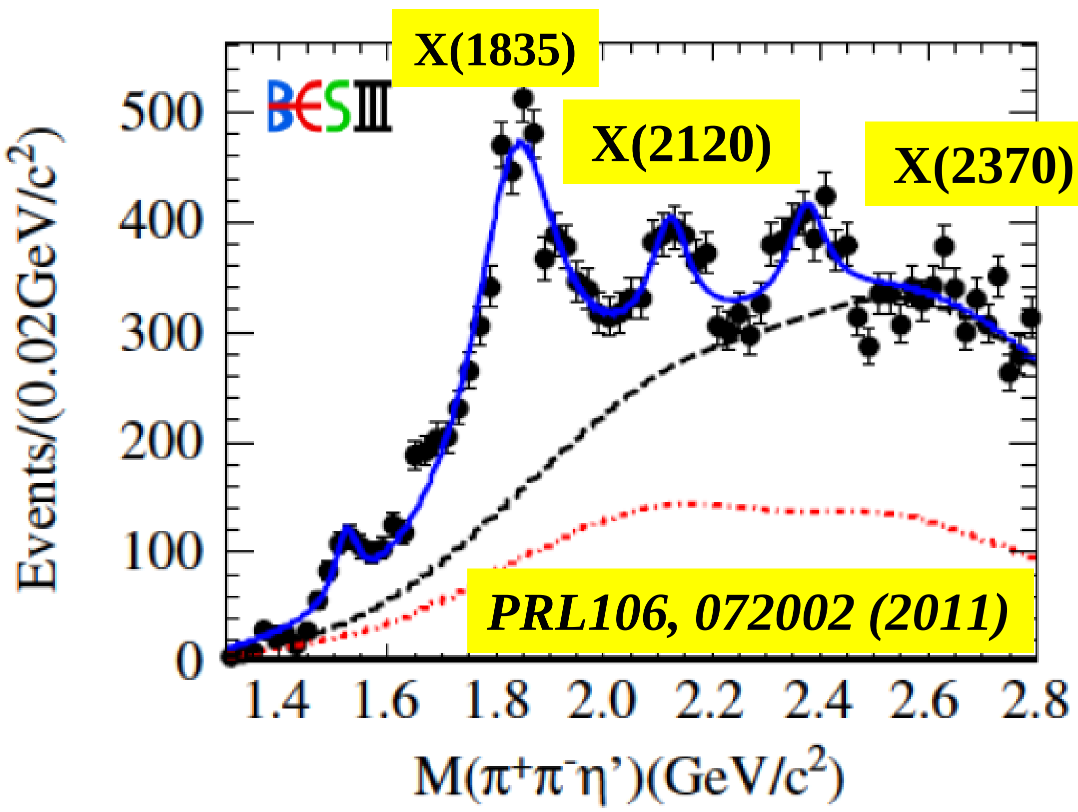
$M = 1832^{+19}_{-5}(stat)^{+18}_{-17}(sys) \pm 19(mod)$ MeV/c^2

$\Gamma < 76$ MeV/c^2

X(1835), X(1840) and X(1870) states

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

- Firstly observed at BESII
- Confirmed at BESIII
- Additional two states found



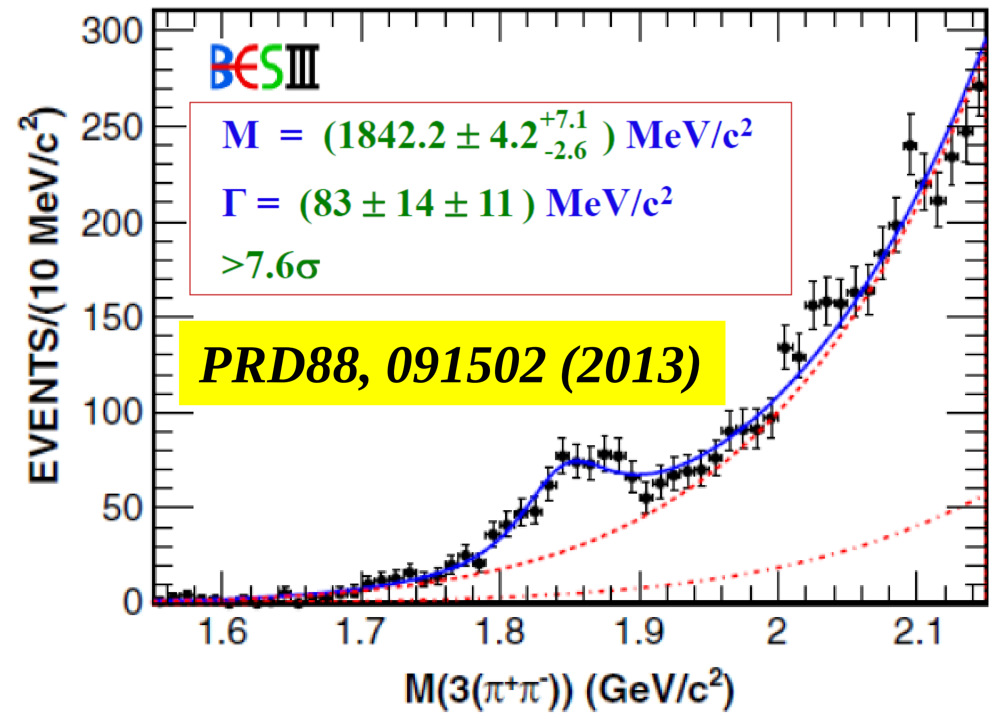
X(1835):

$M = (1836.5 \pm 3.0^{+5.6}_{-2.1})$ MeV/c²

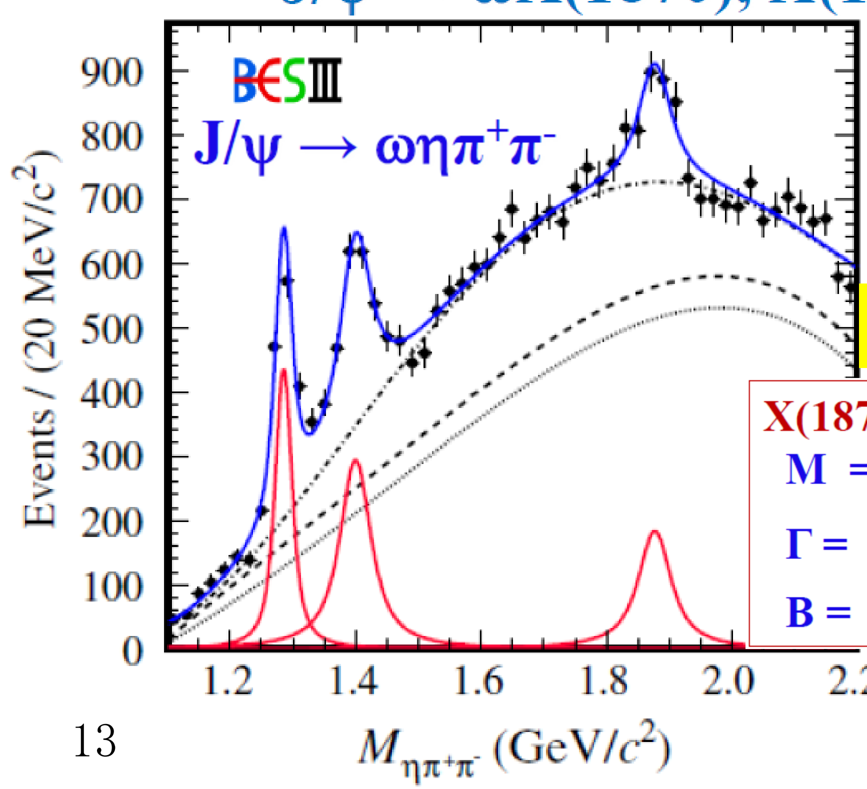
$\Gamma = (190 \pm 9^{+38}_{-36})$ MeV/c²

$>20\sigma$

$J/\psi \rightarrow \gamma X(1840)$, $X(1840) \rightarrow 3(\pi^+\pi^-)$



$J/\psi \rightarrow \omega X(1870)$, $X(1870) \rightarrow a^{\pm}(980)\pi^{\mp}$



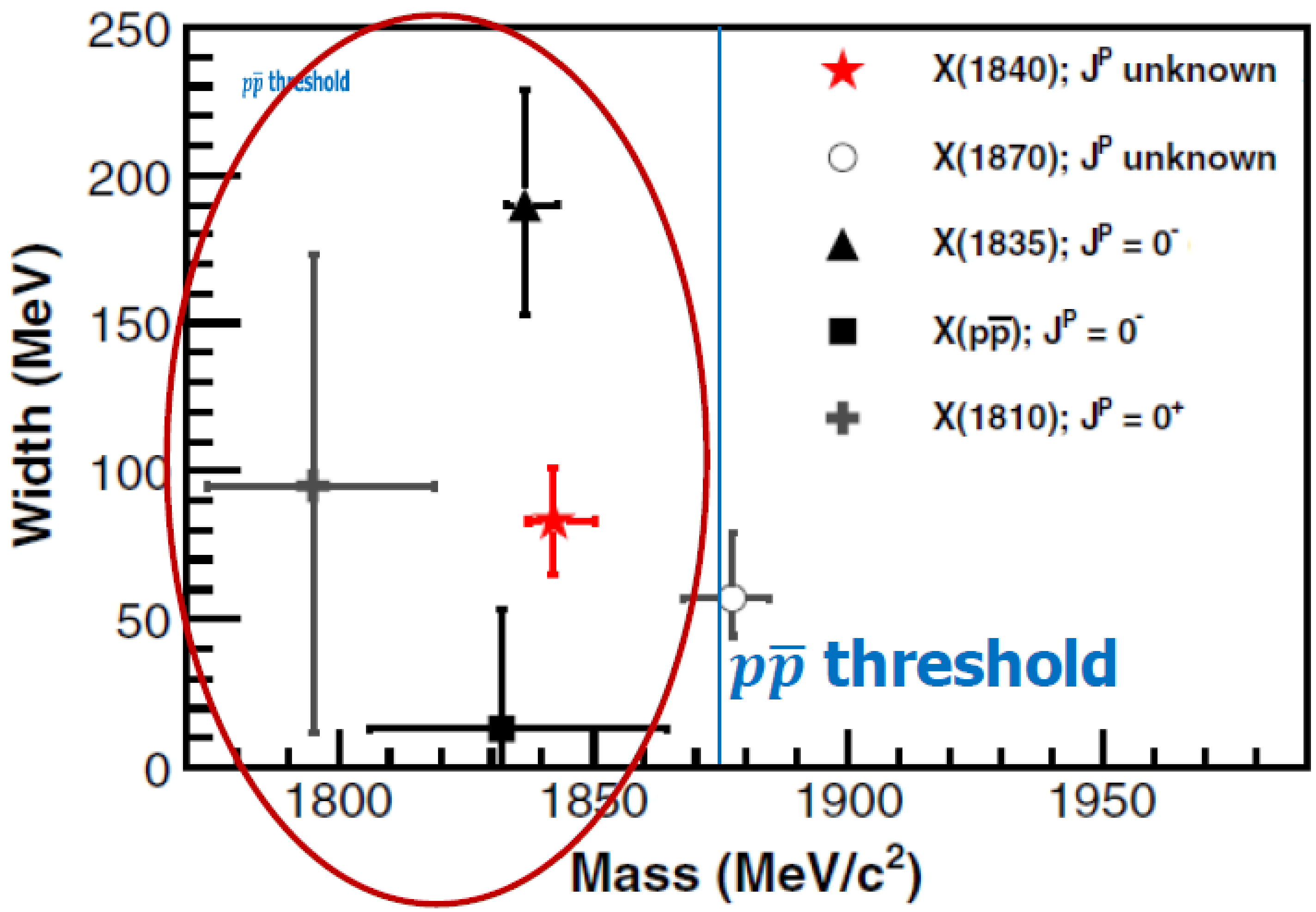
X(1870):

$M = (1877.3 \pm 6.3^{+3.4}_{-7.4})$ MeV/c²

$\Gamma = (57 \pm 12^{+19}_{-4})$ MeV/c²

$B = (1.50 \pm 0.26^{+0.72}_{-0.36}) \cdot 10^{-4}$

Comparisons of the X(18??) states

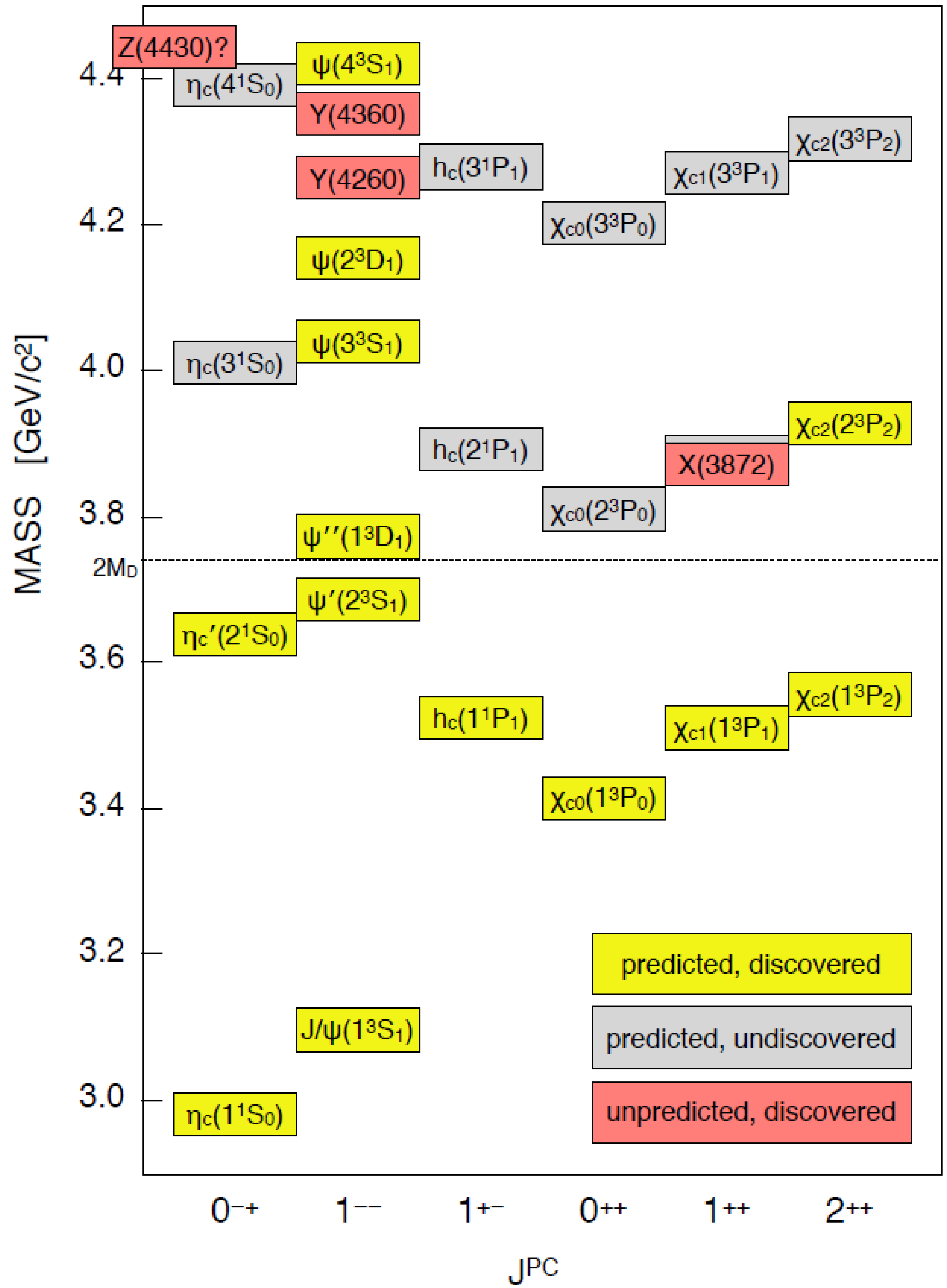


- J/ψ radiative decays
- not found in ψ' radiative decays *PRL108,112003 (2012)*
- non a pure FSI
- PWA is needed

★ **X(1840): $J/\psi \to \gamma 3(\pi^+\pi^-)$ [PRD88, 091502]**
○ **X(1870): $J/\psi \to \omega\eta\pi^+\pi^-$ [PRL107, 182001]**
▲ **X(1835): $J/\psi \to \gamma(\eta\pi^+\pi^-)$ [PRL106, 072002]**
■ **X(1840): $J/\psi \to \gamma(p\bar{p})$ [PRL108, 112003]**
✚ **X(1840): $J/\psi \to \gamma(\omega\phi)$ [PRD87, 032008]**

X(18??):
- **near ($p\bar{p}$) threshold**
- **is a single particle?!?**

Charmonium Spectrum



Hidden-charm region of the spectrum is well understood,

however,

in the open-charm region there are predicted states, but not yet seen...

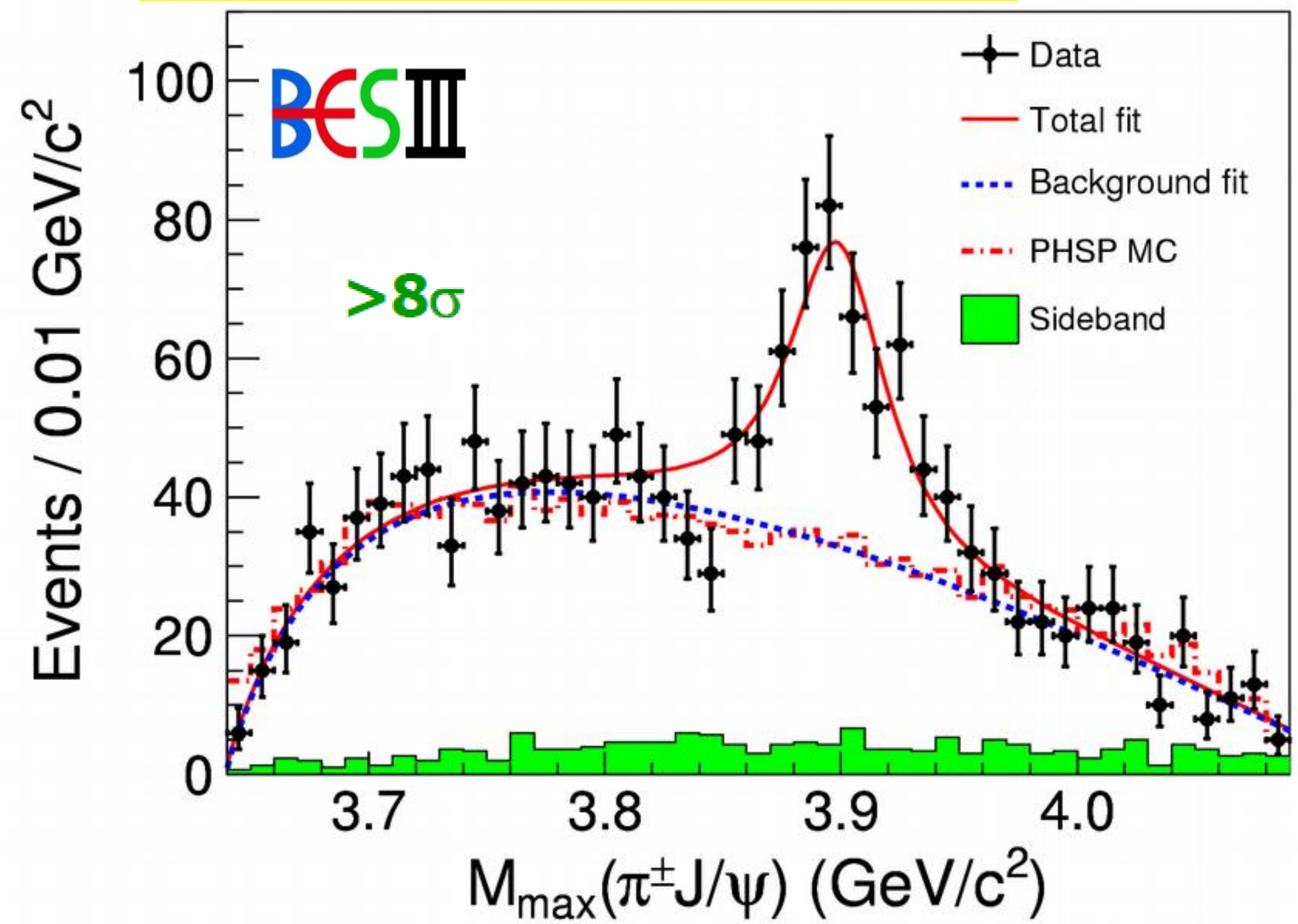
Moreover...

In the last decade there were found not-predicted charmonium-like states with unexpected properties

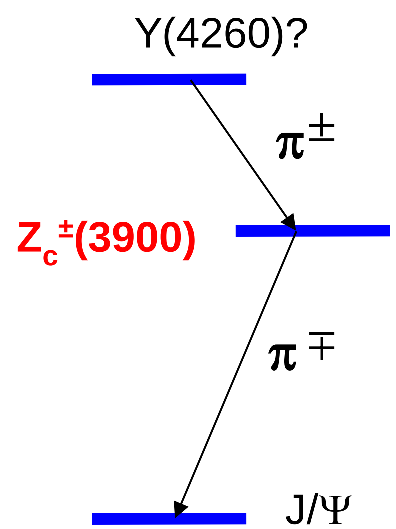
The Zc(3900)$^{\pm}$

[Phys. Rev. Lett. 110, 252001 (2013)]

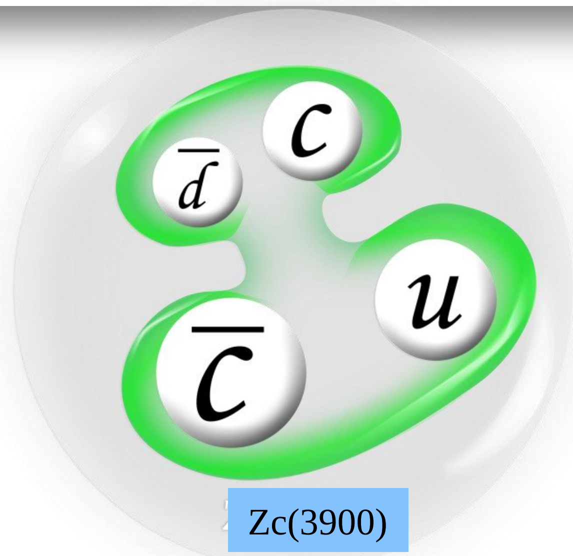
$e^+e^- \rightarrow \pi\, Z_c(3900) \rightarrow \pi^+\pi^- J/\psi$ @ 4.260 GeV



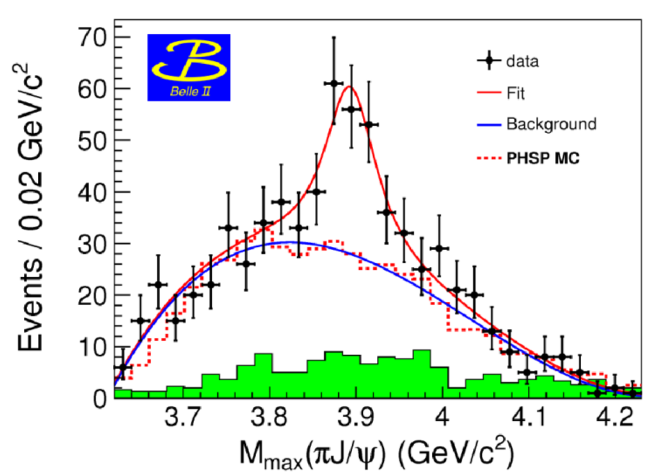
- Fit with S-wave Breit-Wigner
- **M = (3899.0±3.6±4.9) MeV/c^2**
- **Γ = (46±10±20) MeV**



- couples to $c\bar{c}$
- has electric charge
- at least 4-quarks
- what is its nature?



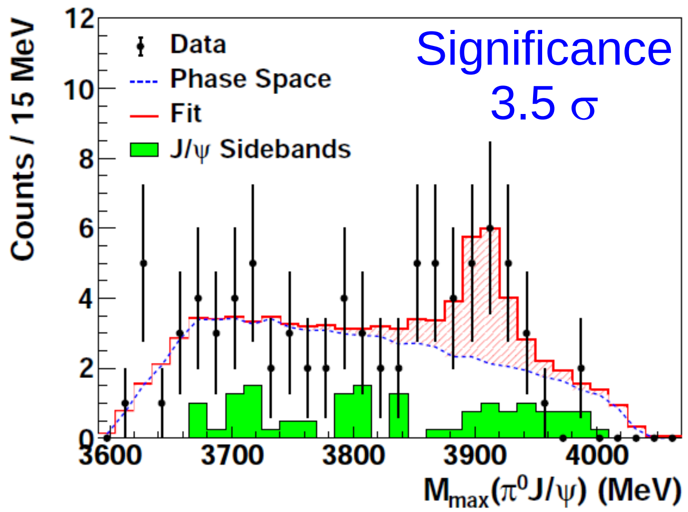
Discovered by BESIII, promptly confirmed by:



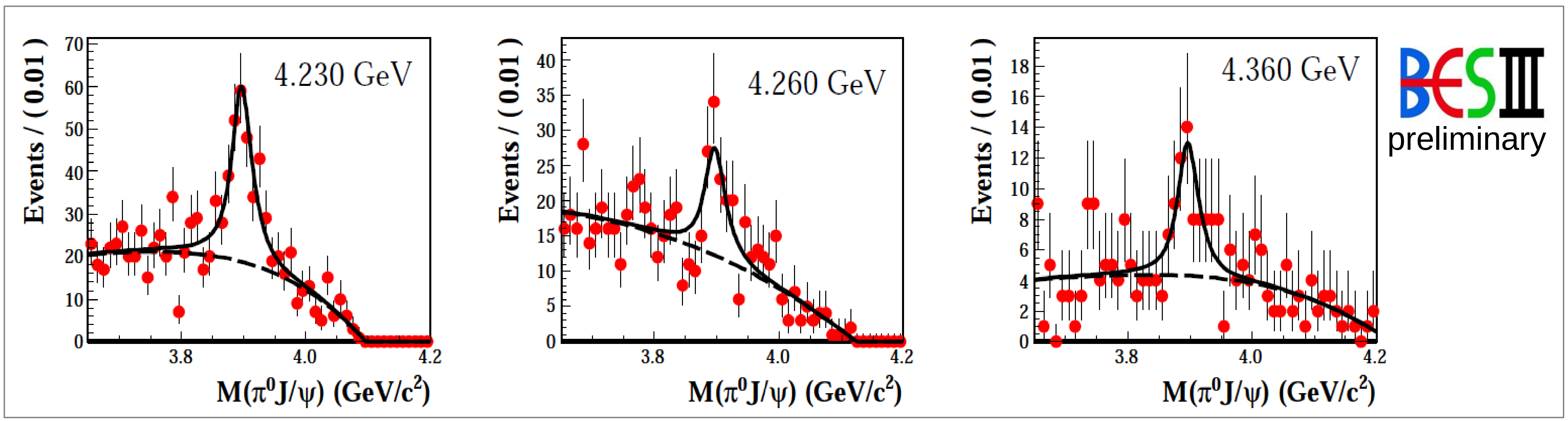
Belle: [Phys. Rev. Lett. 110, 252002 (2013)]
M = 3894.5 ± 6.6 ± 4.5 MeV/c^2
Γ = 63 ± 24 ± 26 MeV

CLEO-c: [Phys. Lett. B 727, 366 (2013)]

The neutral partner Zc(3900)^0



Evidence for $Z_c(3900)^0$
is seen by the CLEO-c
[Phys. Lett. B 727, 366 (2013)]



$e^+e^- \rightarrow \pi^0 Z_c(3900)^0 \rightarrow \pi^0\pi^0 J/\psi$ @ 4.230-4.260 GeV

Structure is seen in $\pi^0 J/\Psi$
(10σ significance):

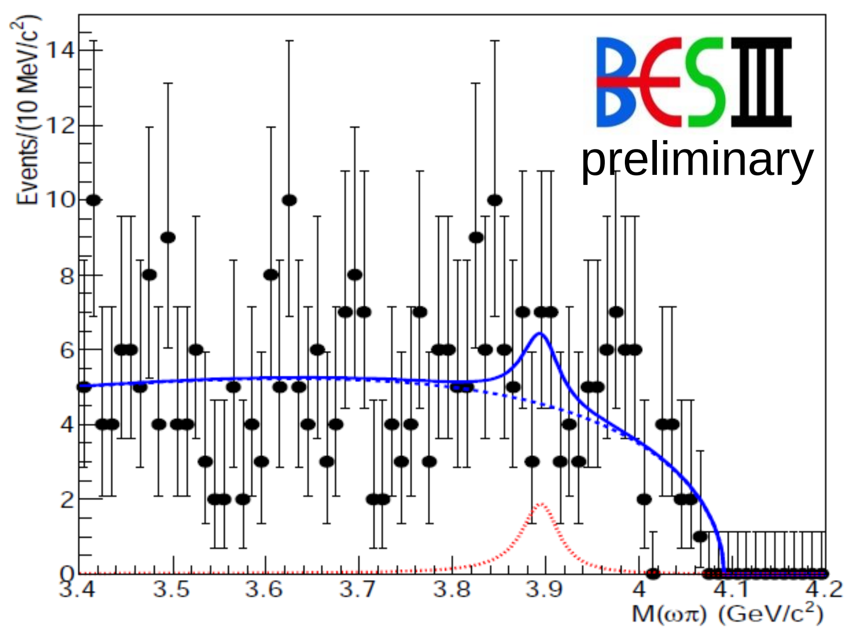
- **M = (3894.0±2.3±2.7) MeV/c^2**
- **Γ = (29±8.2±8.2) MeV**

$Z_c(3900)$ – four-quark isospin triplet?

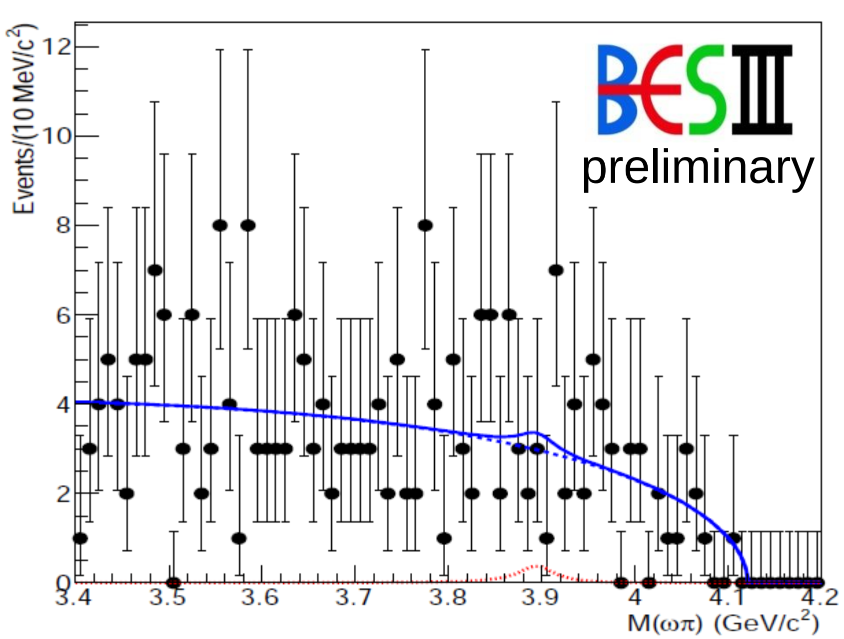
A mystery of the Zc(3900)

$e^+e^- \to \pi^\mp Z_c(3900)^\pm \to \pi^+\pi^-\omega$ @ 4.230-4.260 GeV

$\sqrt{s}$ = 4.23 GeV



$\sqrt{s}$ = 4.26 GeV



There are three important decay modes for charmonium-like states:

- the fall-apart to open charm mesons;
- the cascade to hidden charm mesons;
- decays to light hadrons via intermediate gluons.

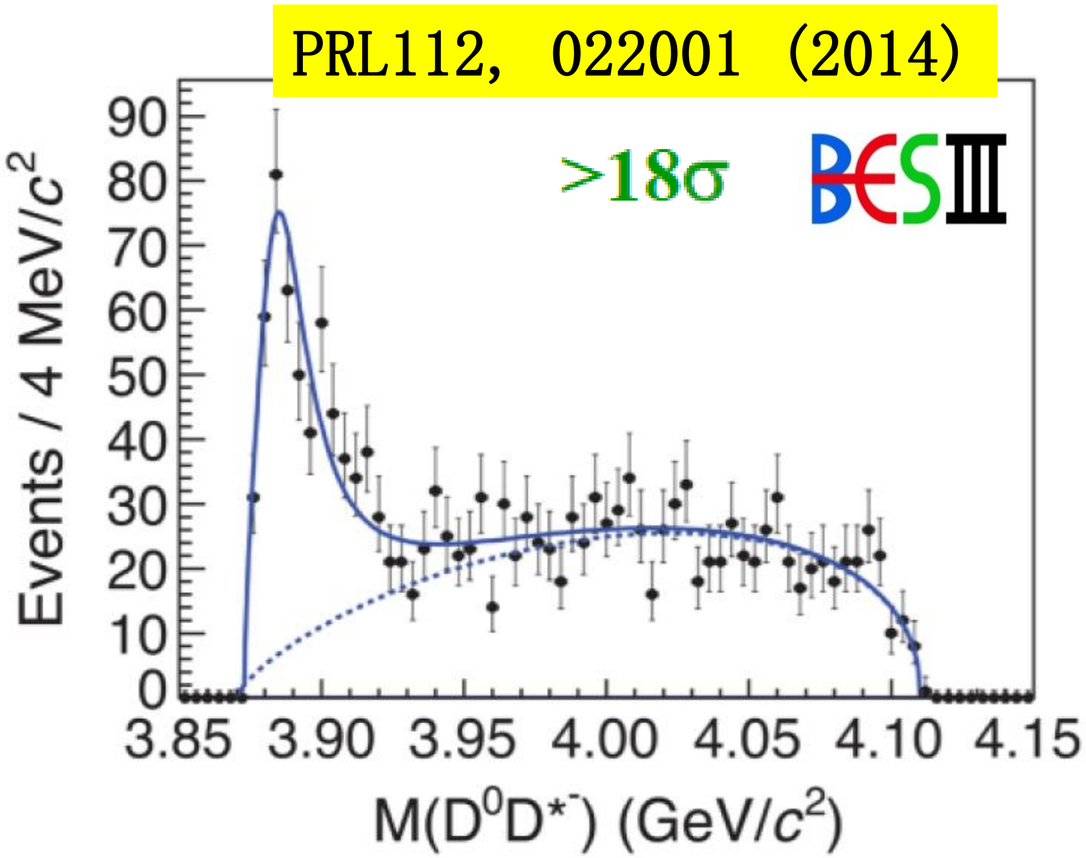
Since **Z_c(3900)** decays to $J/\Psi\pi$, a sizeable annihilation rate could be expected with $\bar{c}c$ in S−wave (as for χ_c)

No significant signal observed:
$\Gamma(Z_c(3900) \to \omega\pi) < 0.2\ \Gamma(Z_c(3900))$

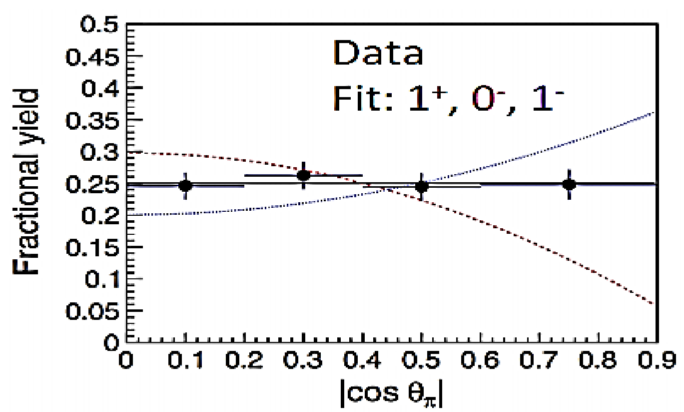
Annihilation to $\bar{c}c$ is suppressed?

The Zc(3885)$^{\pm}$

$e^+e^- \rightarrow \pi Z_c(3885) \rightarrow \pi^- (D\bar{D}^*)^+$+c.c. @ 4.260 GeV



- **M = (3883.9±1.5±4.2) MeV/c^2**
- **Γ = (24.8±3.3±11) MeV**



Fit to angular distribution favors $J^P = 1^+$ over 0^- and 1^-

Single tag method:

- reconstruct π^+ and $D^0 \rightarrow K^-\pi^+$
- infer D^{*-}
- analyze as well $\pi^+ D^- D^{*0}$

Confirmed in a separate analysis @4.23~4.25GeV with double tag method

- **Is found structure** (referred as Z_c(3885)) **different decay mode of the Z_c(3900)?**

Z_c(3900) properties:

- M = (3899.0±3.6±4.9) MeV/c^2
- Γ = (46±10±20) MeV

- Assuming it is, the partial width ratio:

$\Gamma(Z_c \rightarrow DD^*)/\Gamma(Z_c \rightarrow \pi J/\Psi)$ = 6.2±1.1±2.7

Tetraquark model disfavoured ?

Comparison between Zc(3885)$^{\pm}$ and Zc(3900)$^{\pm}$

Single D tag results,
PRL 112, 022001(2014)

	$Z_c(3885) \to D\bar{D}^*$	$Z_c(3900) \to \pi J/\psi$
Mass (MeV/c^2)	$3883.9 \pm 1.5 \pm 4.2$	$3899.0 \pm 3.6 \pm 4.9$
Γ (MeV)	$24.8 \pm 3.3 \pm 11.0$	$46 \pm 10 \pm 20$
$\sigma \times \mathcal{B}$ (pb)	$83.5 \pm 6.6 \pm 22.0$	$13.5 \pm 2.1 \pm 4.8$

- The mass and width are consistent within **2σ!**

- If this is $Z_c(3900)^+$, open charm decays are suppressed, since

$$\frac{\mathcal{B}(Z_c \to D^* \bar{D})}{\mathcal{B}(Z_c \to J/\psi\,\pi)} = 6.2 \pm 1.1 \pm 2.7$$

Compared to e.g.

$$\frac{\mathcal{B}(\psi(4040) \to D^{(*)}\bar{D}^{(*)})}{\mathcal{B}(\psi(4040) \to J/\psi\,\eta)} = 192 \pm 27$$

Different dynamics in Y(4260)-Zc(3900) system!

The Zc(4020)$^{\pm}$

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

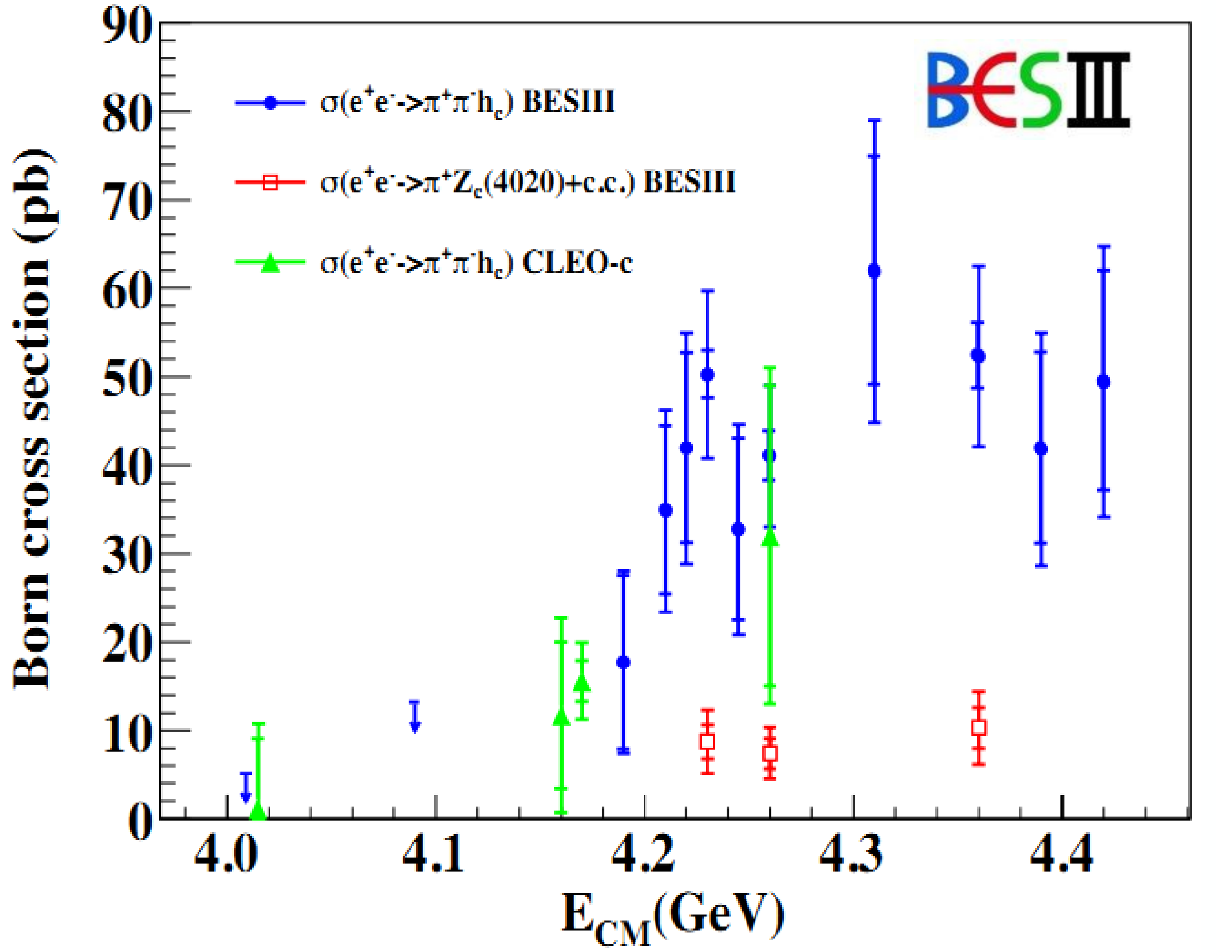
$h_c \to \gamma\eta_c$,
$\eta_c \to$ 16 hadronic decay modes

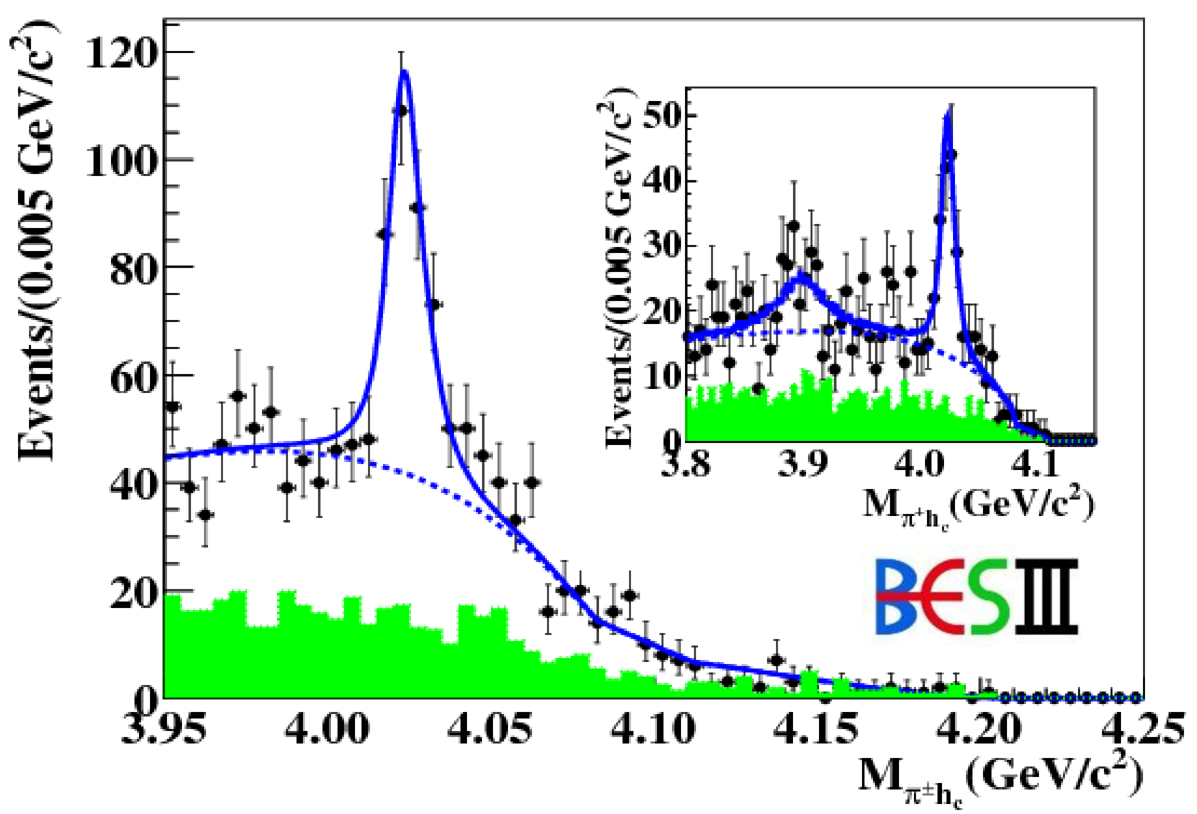
The cross section of $e^+e^- \to \pi^+\pi^- h_c$ is measured, and the shape is not trivial.

A structure, $Z_c(4020)^{\pm}$, is observed.

Mass = 4022.9±0.8 ±2.7 MeV,
Width = 7.9±2.7 ±2.6 MeV

A weak evidence for $Z_c(3900)^{\pm} \to \pi^{\pm} h_c$





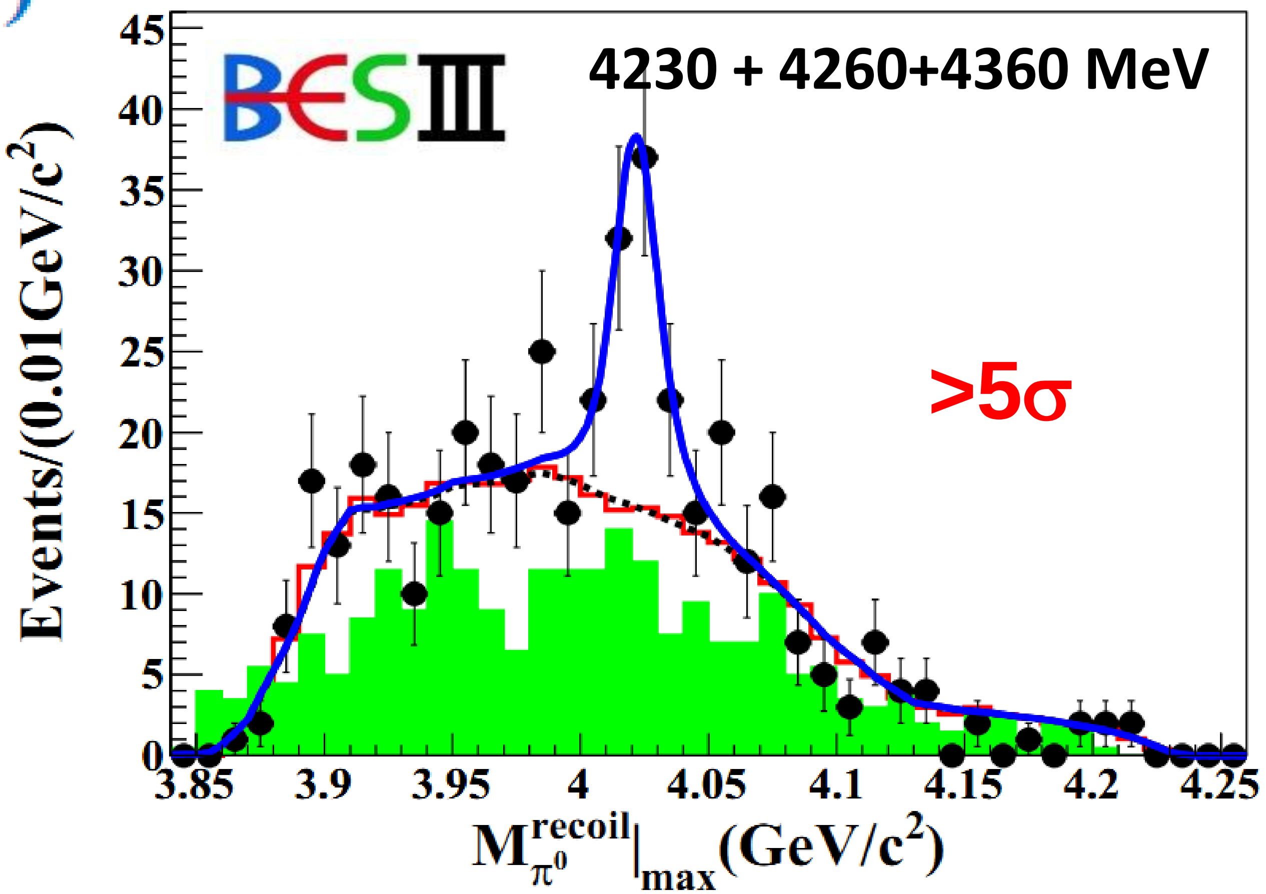
PRL113,212002 (2014)

The Zc(4020)^0

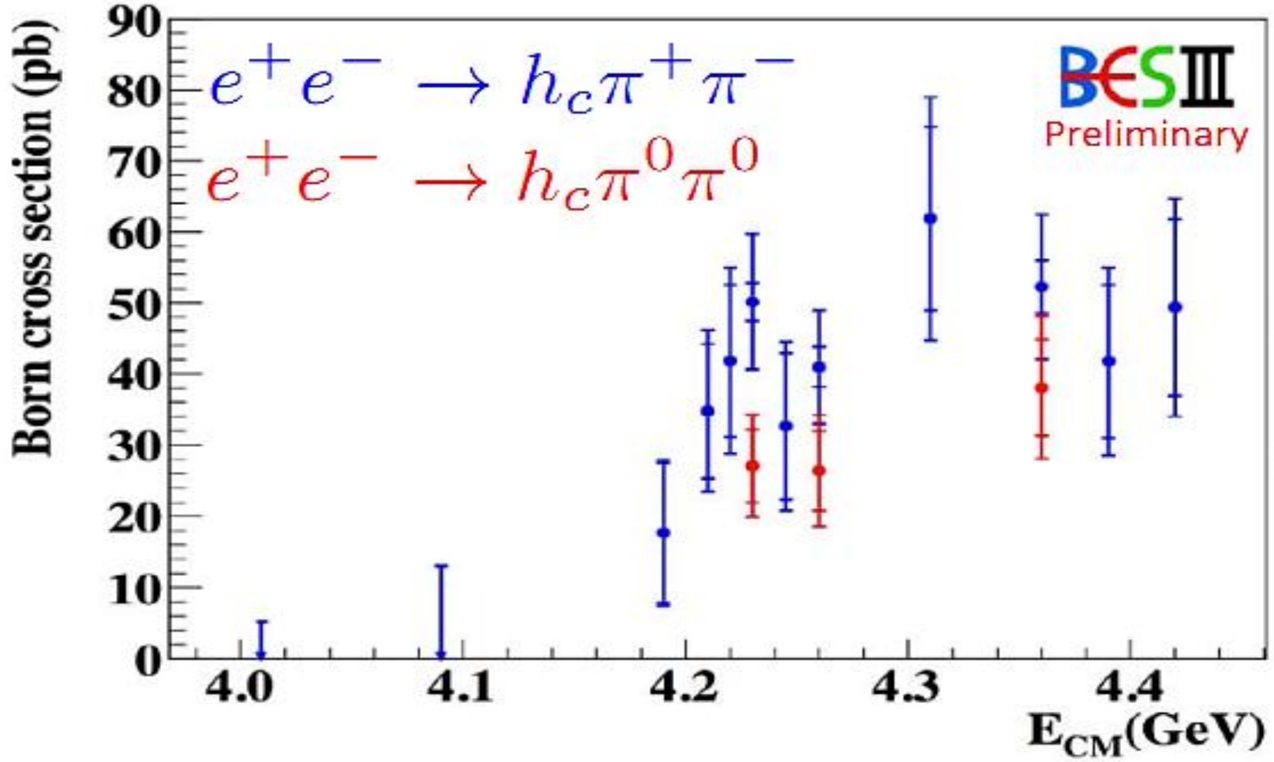
$e^+e^- \to \pi\, Z_c(4020)^0 \to \pi^0\pi^0 h_c(1P)$

A structure on π^0 h_c invariant mass spectrum can be observed:

Mass = 4023.9±2.2 ±3.8 MeV,
Width is fixed to be same as its charged partner.



Another isospin triplet is established!



Cross sections for $e^+e^- \to h_c\pi^+\pi^-$ and $e^+e^- \to h_c\pi^0\pi^0$ are in agreement with isospin conservation

PRL 112, 132001 (2014)

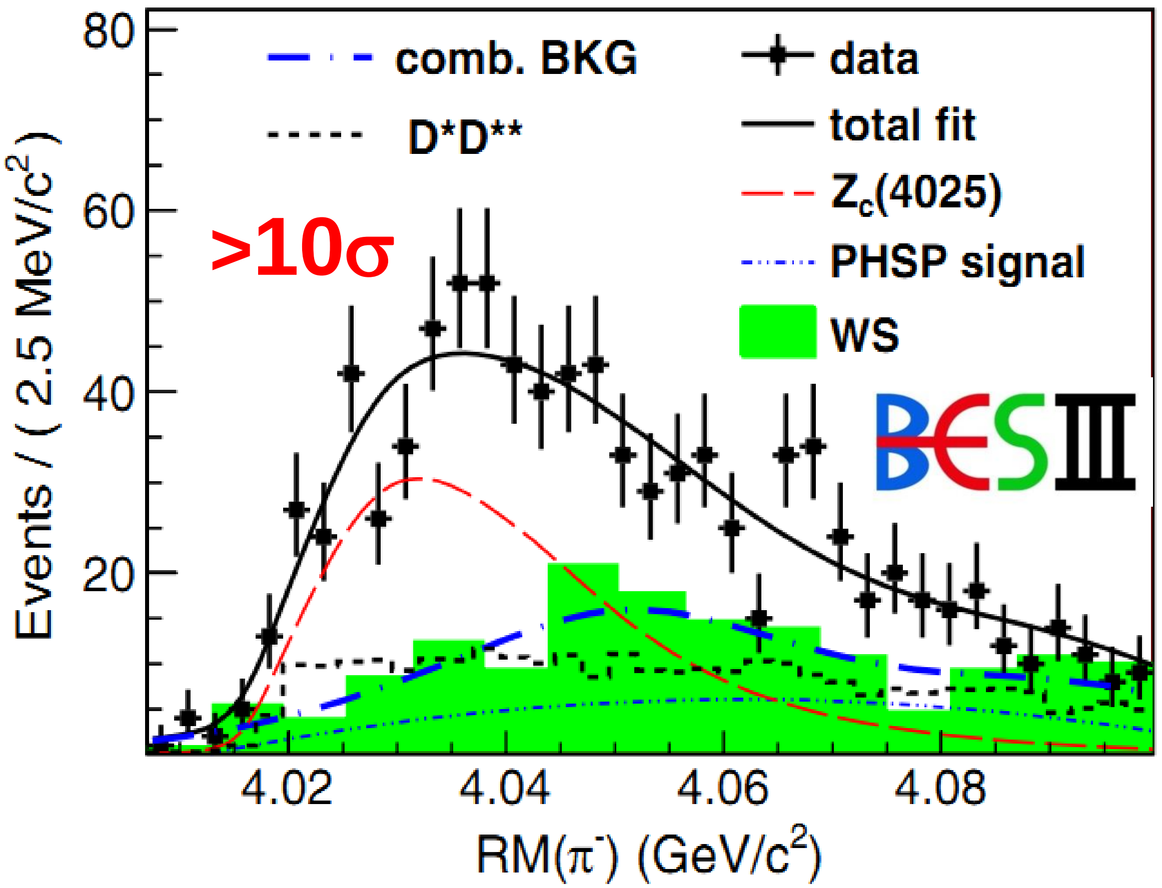
The Zc(4025)$^{\pm}$

4260 MeV

$e^+e^- \to \pi Z_c(4025) \to \pi^- (D^*\bar{D}^*)^+ + c.c.$

Tag a D^+ and a bachelor π^-, reconstruct one π^0 to suppress the background.

A structure, named as **Zc(4025)**, can be observed in the recoil mass of the bachelor π^- .



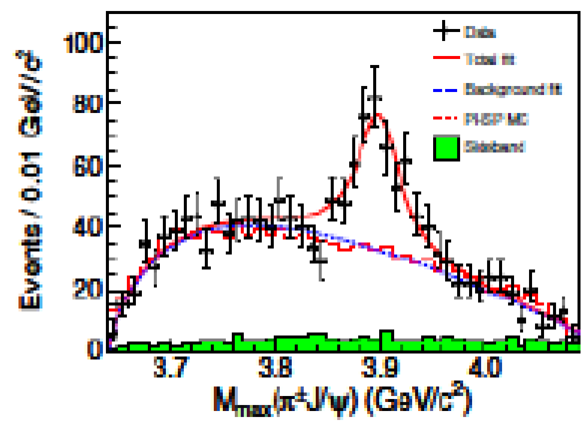
$M(Z_c(4025)) = 4026.3 \pm 2.6 \pm 3.7$ MeV;
$\Gamma(Z_c(4025)) = 24.8 \pm 5.6 \pm 7.7$ MeV

$$\sigma[e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}] = 137 \pm 9 \pm 15 \text{ pb at } 4.26 \text{ GeV}$$

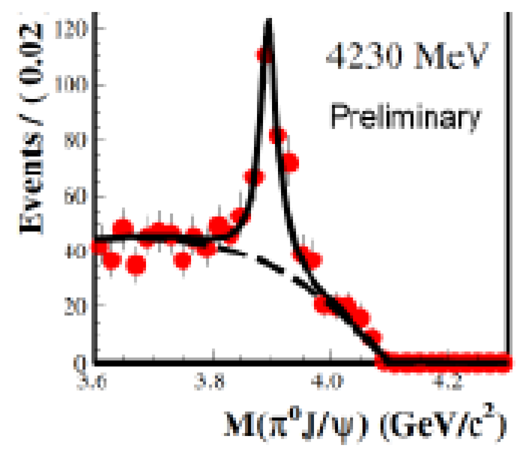
$$\frac{\sigma[e^+e^- \to \pi^{\pm} Z_c(4025)^{\mp} \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}]}{\sigma[e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}]} = 0.65 \pm 0.09 \pm 0.06 \text{ at } 4.26 \text{ GeV}$$

Coupling to $\bar{D}^*D^*$ is much larger than to πh_c if $Z_c(4025)$ and $Z_c(4020)$ are the same state.

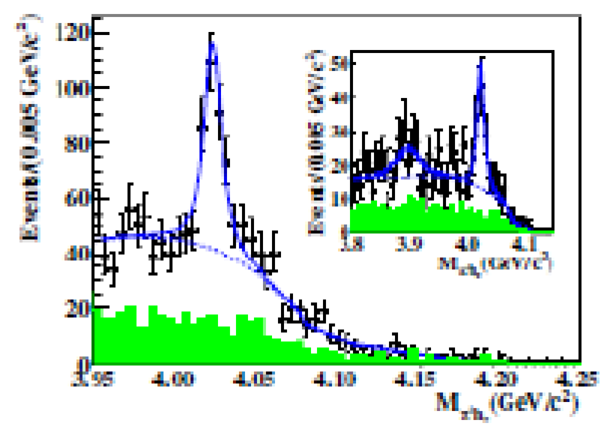
The Zc family at BESIII



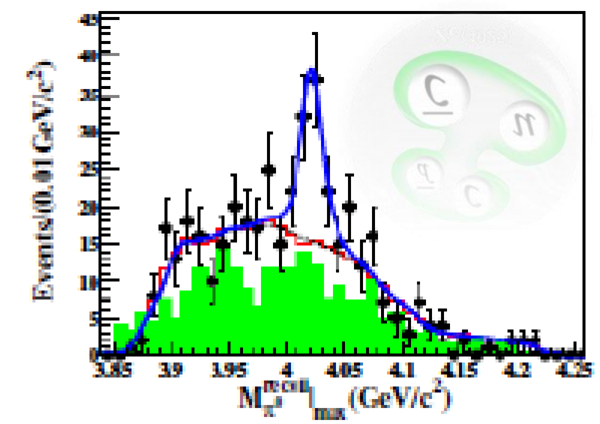
$e^+e^- \to \pi^-\pi^+ J/\psi$



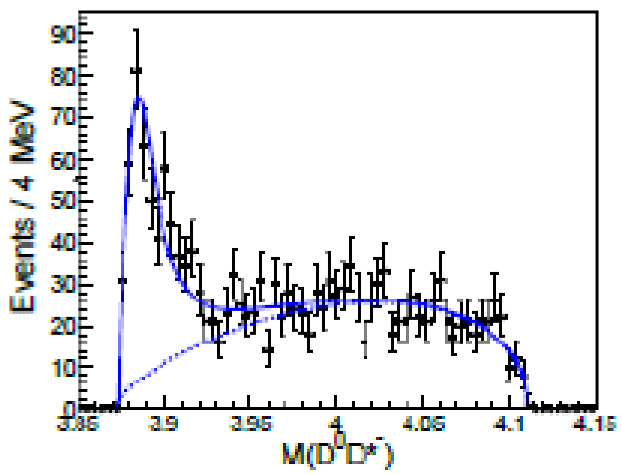
$e^+e^- \to \pi^0\pi^0 J/\psi$



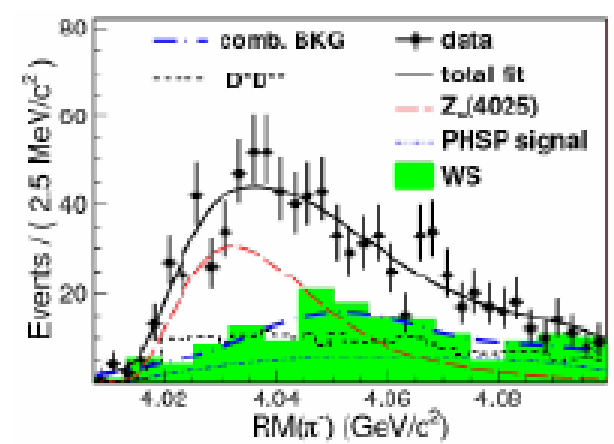
$e^+e^- \to \pi^-\pi^+ h_c$



$e^+e^- \to \pi^0\pi^0 h_c$



$e^+e^- \to \pi^-(D\bar{D}^*)^+$



$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

$Z_c(3900)^+$? **$Z_c(3900)^0$?** **$Z_c(4020)^+$?** **$Z_c(4020)^0$?**

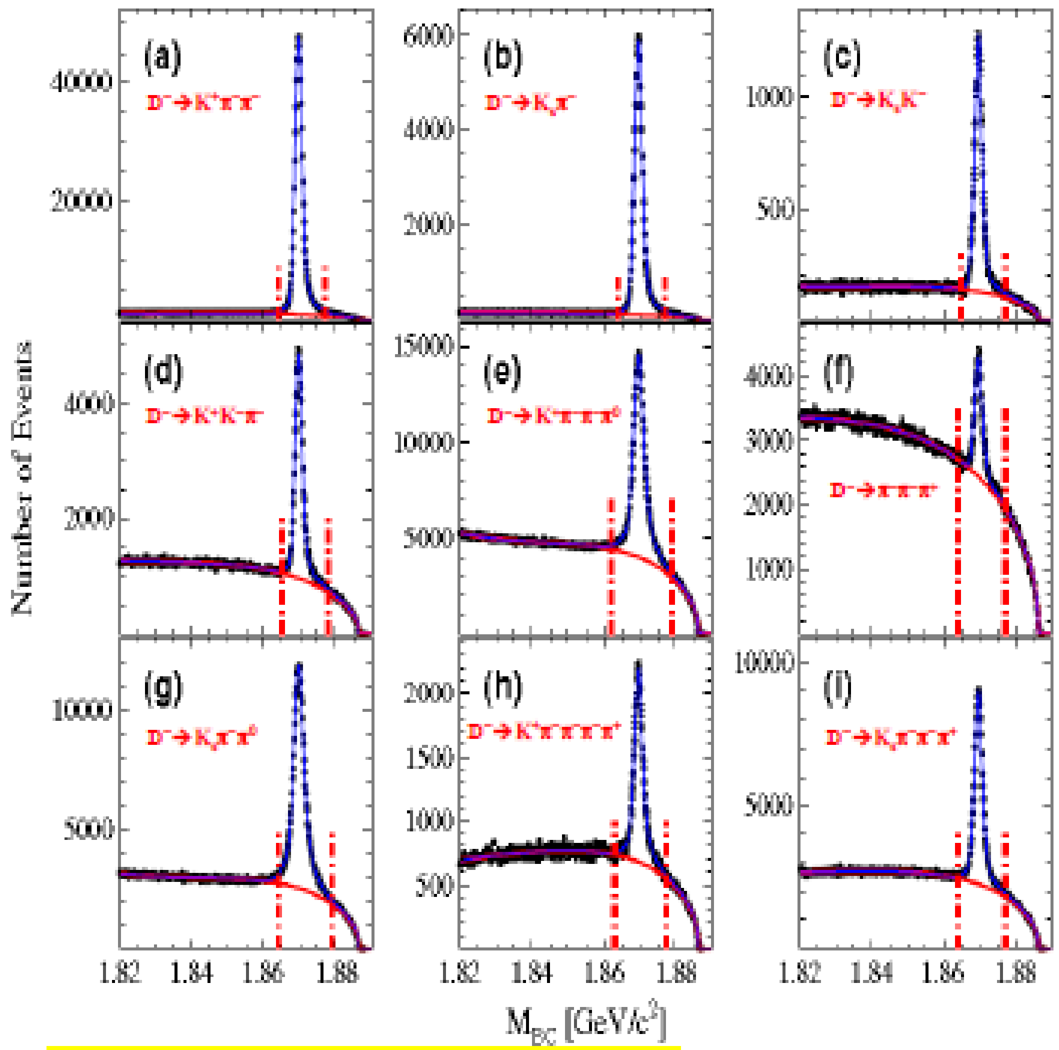
Which is the nature of these states? Isospin triplets?
Different decay channels of the same observed states? Other decay modes?

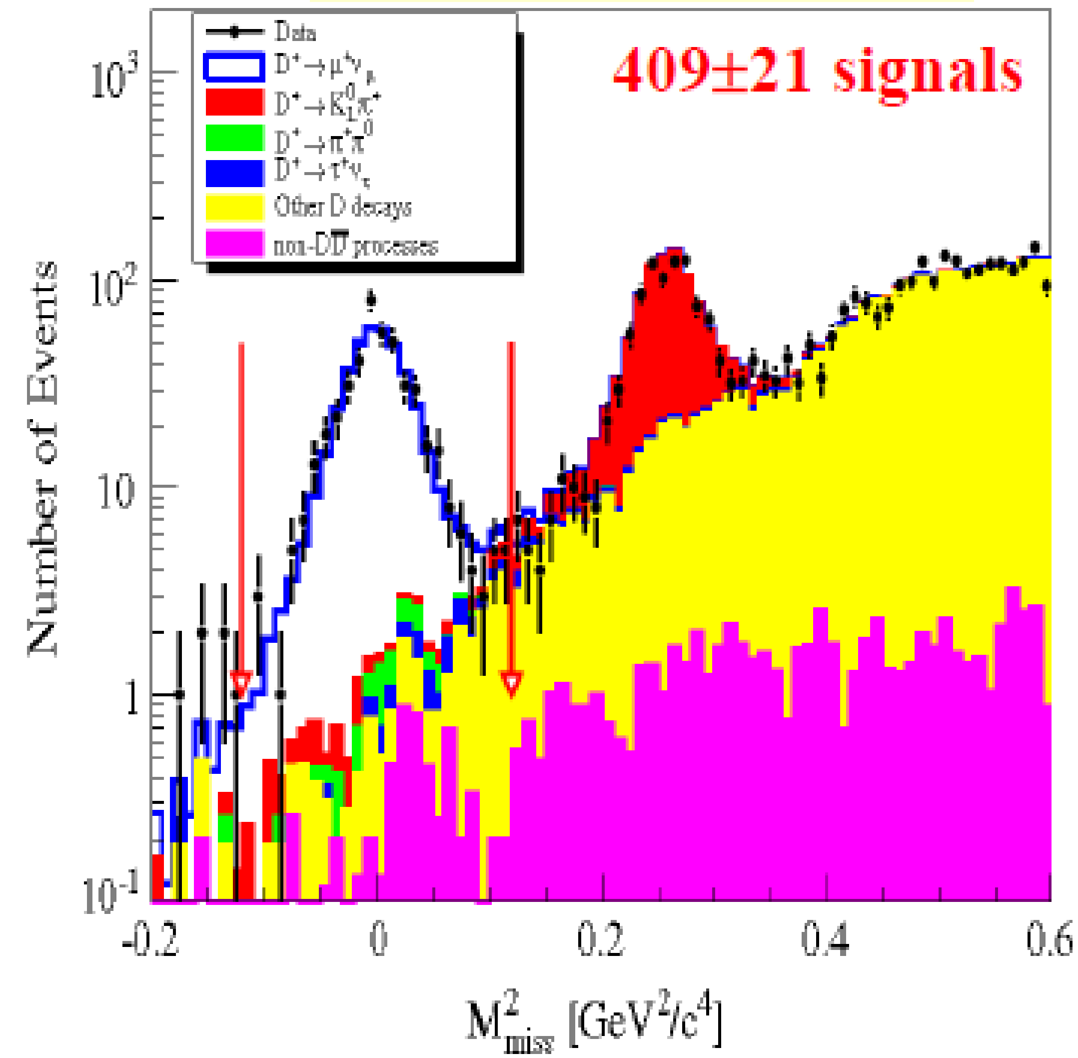
Improved $B[D^+\rightarrow\mu^+\nu]$, f_{D+} and $|V_{cd}|$ at BESIII

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

2.92 fb^{-1} data@ 3.773 GeV

PRD89(2014)051104R





$N_{D^-_{tag}} = (170.31 \pm 0.34) \times 10^4$

$B[D^+\rightarrow\mu^+\nu]=(3.71\pm0.19\pm0.06)\times10^{-4}$

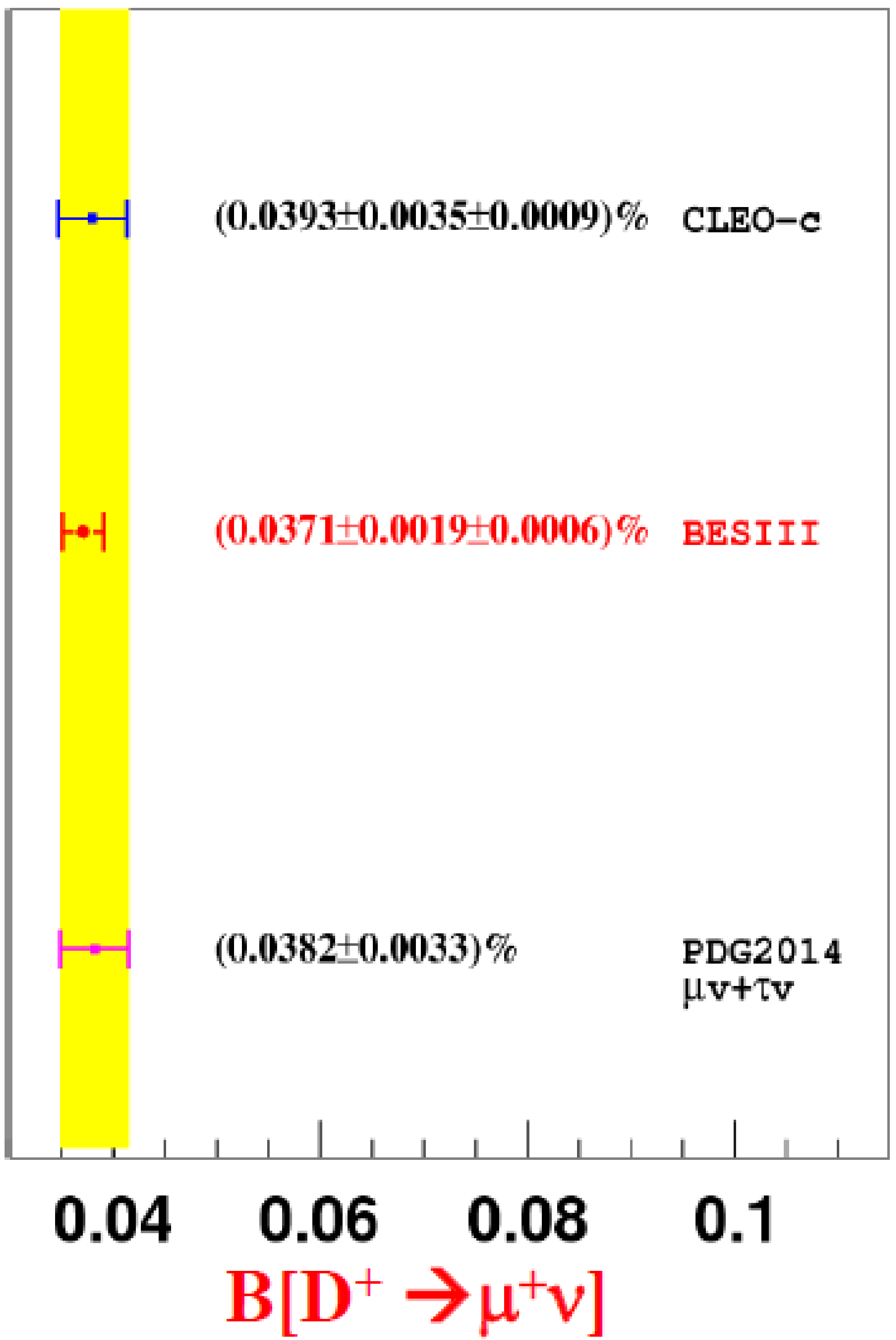
Input t_{D+}, m_{D+}, $m_{\mu+}$ on PDG and $|V_{cd}|$ of CKM-Fitter

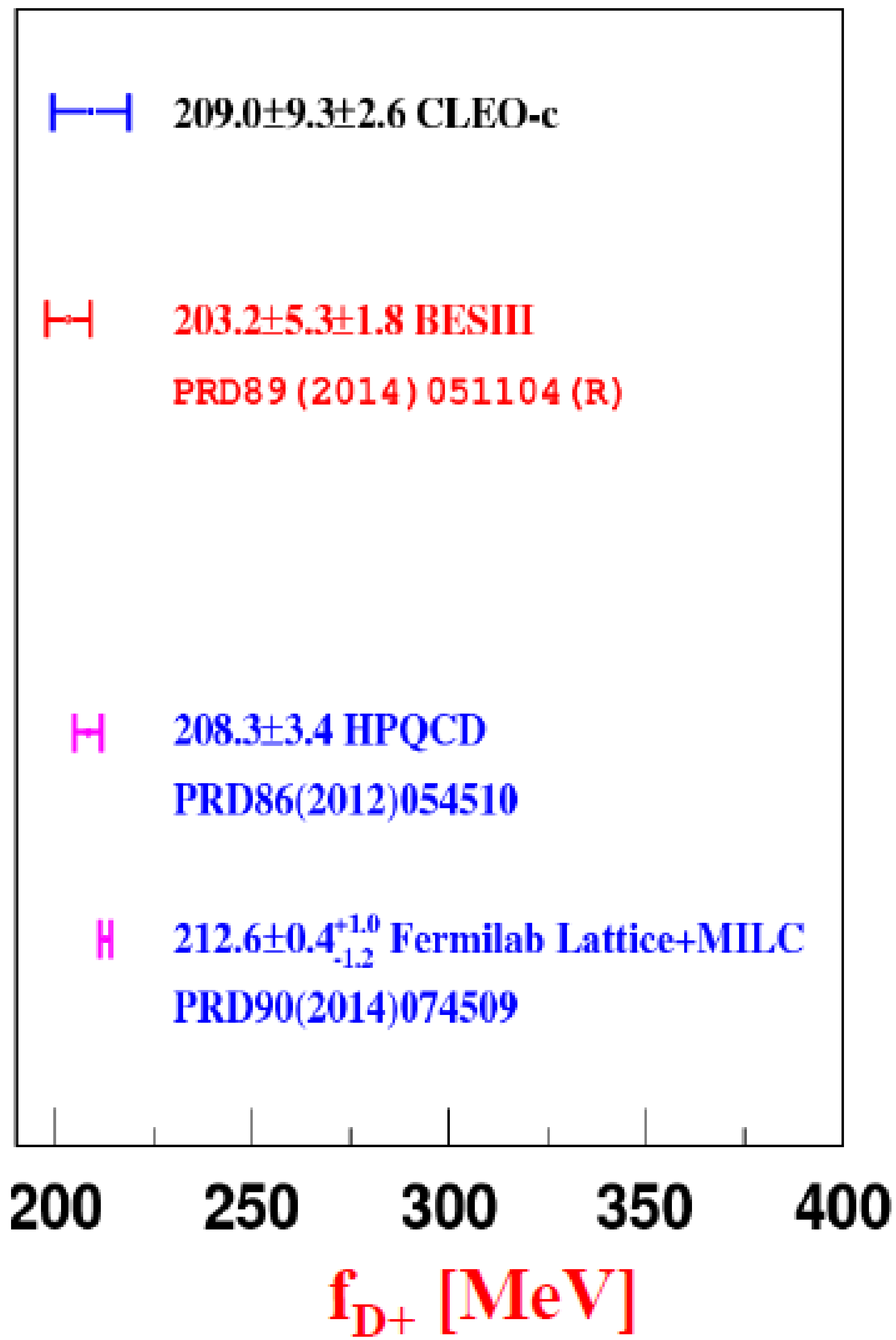
$f_{D+}=(203.2\pm5.3\pm1.8)$ MeV

Input t_{D+}, m_{D+}, $m_{\mu+}$ on PDG and LQCD calculated $f_{D+}=207\pm4$ MeV[PRL100(2008)062002]

$|V_{cd}|=0.2210\pm0.0058\pm0.0047$

Comparisons of $B[D^+ \to \mu^+ \nu_\mu]$ and f_{D^+}





BESIII

PLB734, 227 (2014)

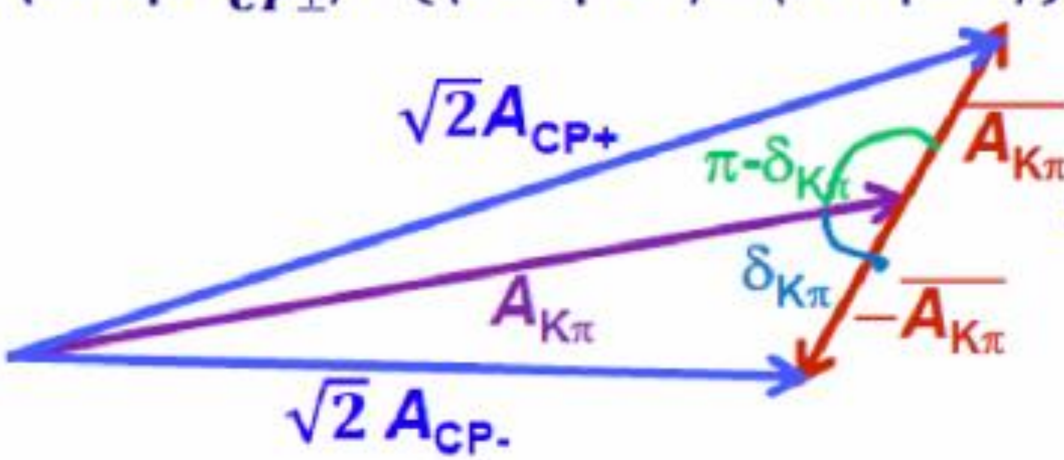
Strong Phase $\delta_{K\pi}$

- ✓ Improving the constraints on the charm mixing parameters is important for testing the SM, such as long-distance effect
- ✓ At charm threshold, strong phase is a unique contribution:
  - to extract the mixing parameter (x,y) from (x′, y′)
  - to (over-)constrain the CKM unitarity triangle, which is crucial for searching for new physics

Strong phase: $\frac{\langle K^-\pi^+|\overline{D}^0\rangle^{DCS}}{\langle K^-\pi^+|D^0\rangle^{CF}} \equiv -r_{K\pi}e^{-i\delta_{K\pi}}$

Quantum correlation → Interference → access strong phase!

$$\langle K\pi|D_{CP\pm}\rangle=(\langle K\pi|D^0\rangle\pm\langle K\pi|\overline{D^0}\rangle)/\sqrt{2} \Rightarrow \sqrt{2}A_{CP\pm}=A_{K\pi}\pm\overline{A}_{K\pi}$$



$$\Rightarrow 2r_{K\pi}\cdot\cos\delta_{K\pi}\approx A_{CP\to K\pi}=\frac{|A_{CP-}|^2-|A_{CP+}|^2}{|A_{CP-}|^2+|A_{CP+}|^2}$$

$$=\frac{Br(D_{CP-}\to K\pi)-Br(D_{CP+}\to K\pi)}{Br(D_{CP-}\to K\pi)+Br(D_{CP+}\to K\pi)}$$

✦ **Measuring $\delta_{K\pi}$ from rate differences if using external $r_{K\pi}$**

BESIII

PLB734, 227 (2014)

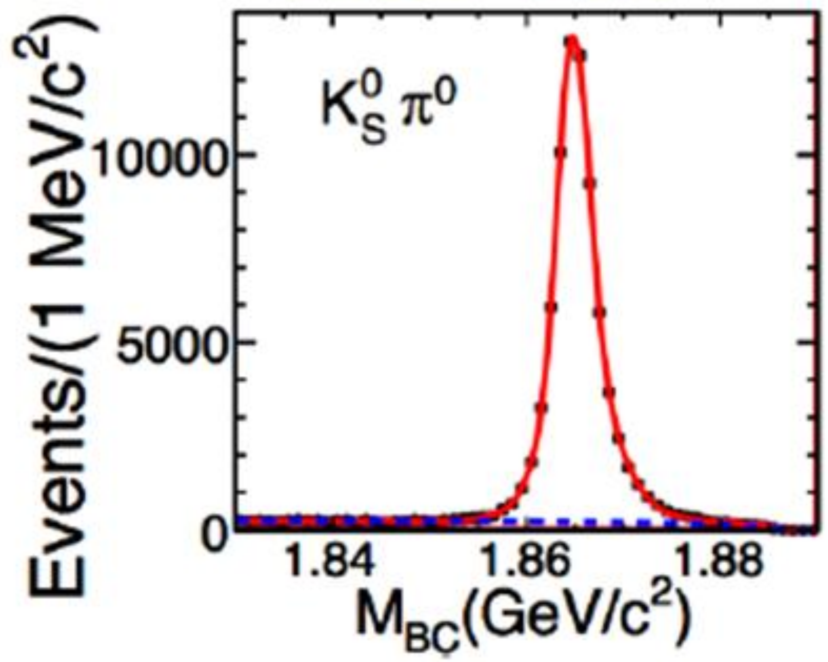
Strong Phase $\delta_{K\pi}$

(BESIII: 2.92 fb^{-1}@3773MeV)

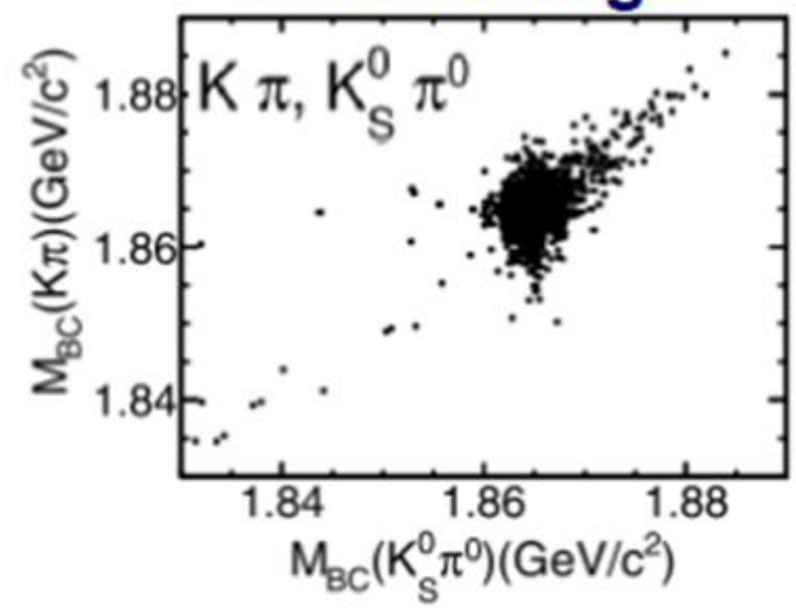
- **Reconstructed modes:**
  - Flavor tags: $K^-\pi^+$, $K^+\pi^-$
  - CP+ tags (5 modes): K^-K^+, $\pi^+\pi^-$, $K_S^0\pi^0\pi^0$, $\pi^0\pi^0$, $\rho^0\pi^0$
  - CP- tags (3 modes): $K_S^0\pi^0$, $K_S^0\eta$, $K_S^0\omega$
- **If we don't ignore the mixing effect**
- $2r_{K\pi}\cos\delta_{K\pi} + y = (1 + R_{WS})\cdot A_{CP\to K\pi}$
  - $R_{WS} \equiv \frac{\Gamma(D^0\to K^+\pi^-)}{\Gamma(D^0\to K^-\pi^+)} = r^2_{K\pi} + r_{K\pi}y' + \frac{(x^2+y^2)}{2}$

with external inputs of $r^2_{K\pi}$, y_{CP} and R_{WS}

Single Tags



Double Tags



BESIII results:

$$\cos\delta_{K\pi} = 1.02 \pm 0.11 \pm 0.06 \pm 0.01$$

CLEO-c results *[Phys. Rev. D 86 (2012) 112001]*

$$\cos\delta_{K\pi} = 0.81^{+0.22+0.07}_{-0.18-0.05}$$

$$\cos\delta_{K\pi} = 1.15^{+0.19+0.00}_{-0.17-0.08} \quad \text{(globalfit)}$$

PRD 90(2014) 012001

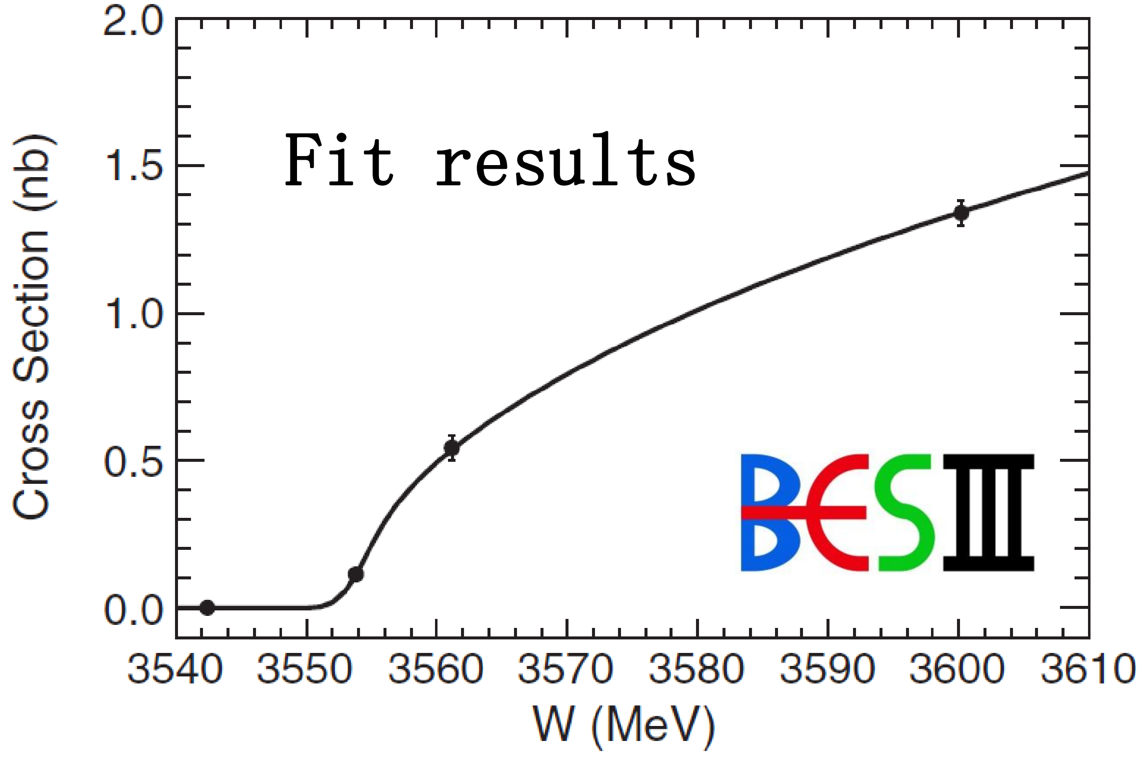
τ mass measurement

- τ mass M_τ is an elementary parameter in SM
- test lepton universality
- compared to M_e and M_μ, M_τ has 3 order of worse precision.

BESIII took threshold scan method and collected dedicated energy scan data for this study

- ☐ **fit to J/ψ and ψ' line shape incorporate with BEMS:** for calibration of beam energy scale and spread
- ☐ **fit to the hadronic cross sections at 4 energy points to measure M_τ (in total ~23/pb):** 13 two-prong τ pair final states are used

Theoretical accuracy of modeling the cross section at the level of 0.1%



τ mass measurement (cont’)

$$m_\tau = (1776.91 \pm 0.12^{+0.10}_{-0.13})\ \mathrm{MeV}/c^2$$

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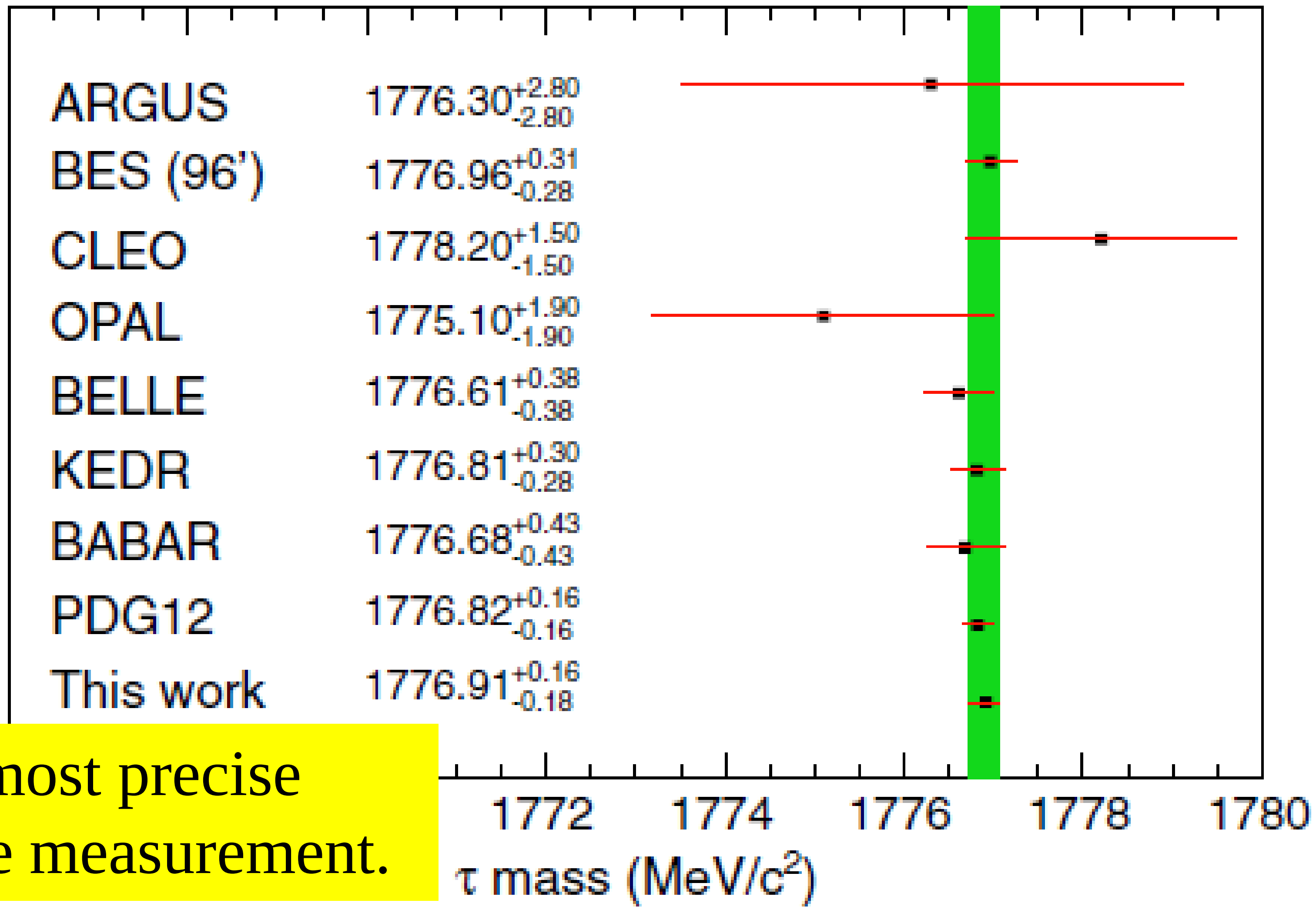

The most precise single measurement.

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = 1.0016 \pm 0.0042$$

Lepton universality can be tested at 0.4%

An updated scan is under discussion:
$23\ pb^{-1} \rightarrow 100\ pb^{-1}$

The last, but not the least

In total 83 publications till now

- PWA of charmonium decays
  - ✓ $J/\psi \to \gamma\eta\eta$ [Phys. Rev. D. 87, 092009 (2013)]
  - ✓ $\psi(2S) \to p\bar{p}\pi^0$, $\psi(2S) \to p\bar{p}\eta$ [PRL 110 ,022001 (2013)]
  - ✓ . . .
- Charmonium(-like) spectroscopy and transitions
  - ✓ $\psi(2S) \to \pi^0 h_c$ [PRL 104, 132002 (2010)]
  - ✓ $\psi(2S) \to \gamma\eta_c(2S) \to \gamma KK\pi$ [PRL 109, 042003 (2012)]
  - ✓ $e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$ [PRL112, 092001 (2014)]
  - ✓ $e^+e^- \to \pi^+\pi^- X(3823)$
  - ✓ . . .
- D semi-leptonic decays: $D \to K^- e^+ \nu$, $\pi^- e^+ \nu$
- $D \to K_s \pi^+ \pi^-$ strong phase
- Λ_c hadronic decay rate
- Hadron pair production cross sections
- Collins fragmentation function
- ...

Summary

Huge statistics:

- J/ψ, ψ' and $\psi(3770)$ peaks
- XYZ studies
- R scans

Near future:

- will continue taking data (possibly) until 2020-22
- collect data at more energy points to complete scans
- higher luminosity expected from BEPCII
- analyze the full data samples
- many PWA to be completed

Stay tuned:

many new exciting results on their way

Thank you!

谢谢！