Обзор эксперимента BESIII

Нефедов Юрий
(for the BESIII collaboration)

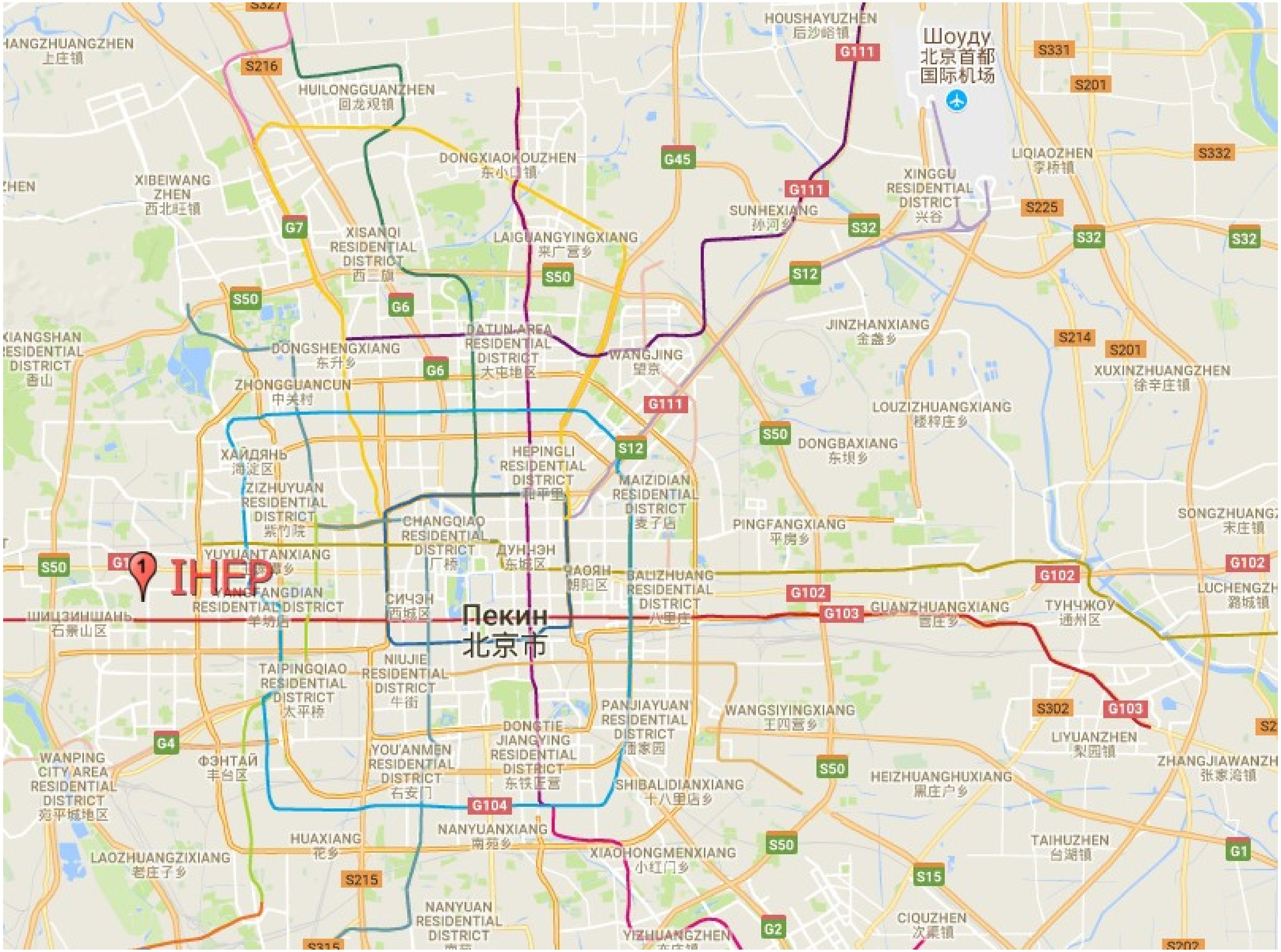
ОИЯИ Дубна

Сессия-конференция СЯФ ОФН РАН

Новосибирск 2020

BEPCII/BESIII @ IHEP (Beijing)

Location of IHEP in Beijing



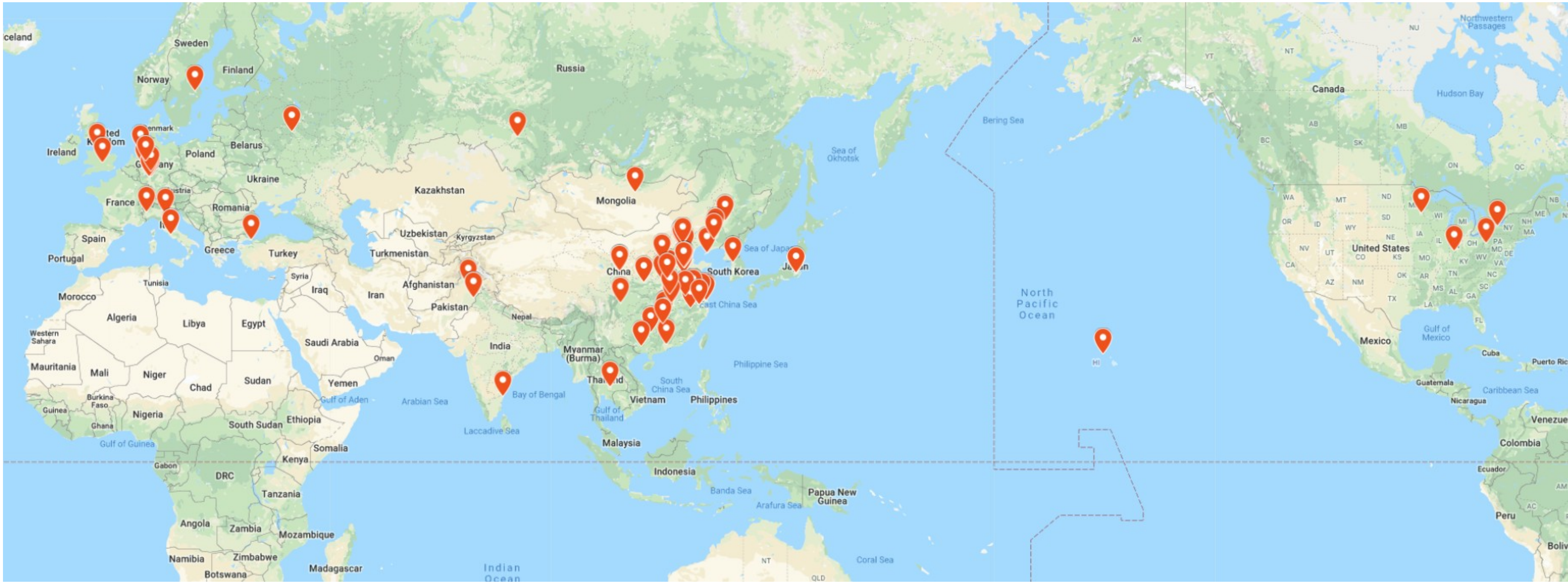
History

- BES: 1989 – 1993 (BEPC)
- BESII: 1998 – 2004 (BEPC)
- BESIII: 2008 –… (BEPCII)

BES = BEijing Spectrometer

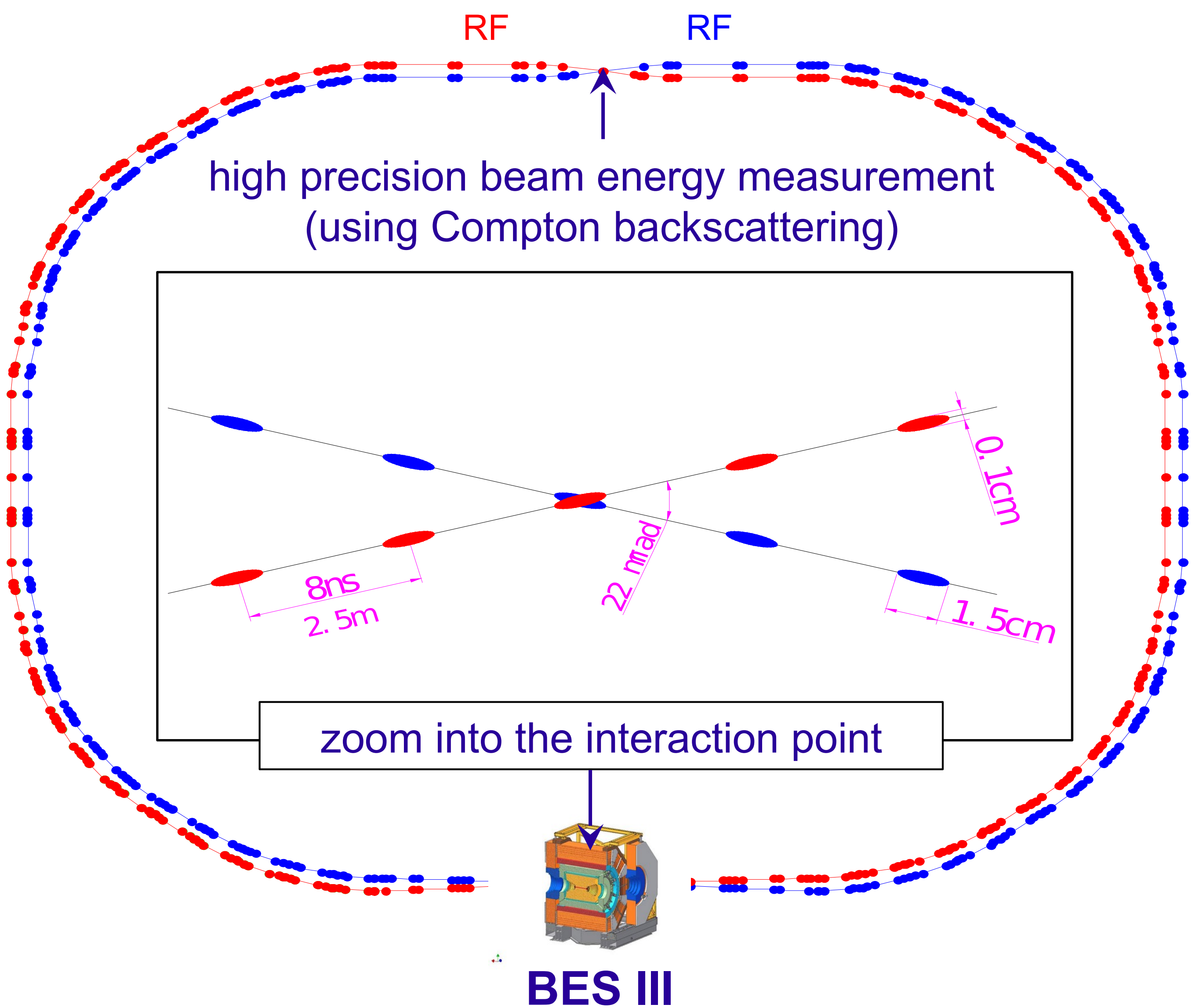
BEPC = Beijing Electron-Positron Collider

The BESIII Collaboration



- 14 countries, almost 500 members
- 43 institutions from China, 8 others in Asia
  16 Europe (inc. Dubna & Novosibirsk), 5 USA

Beijing Electron Positron Collider (BEPCII)

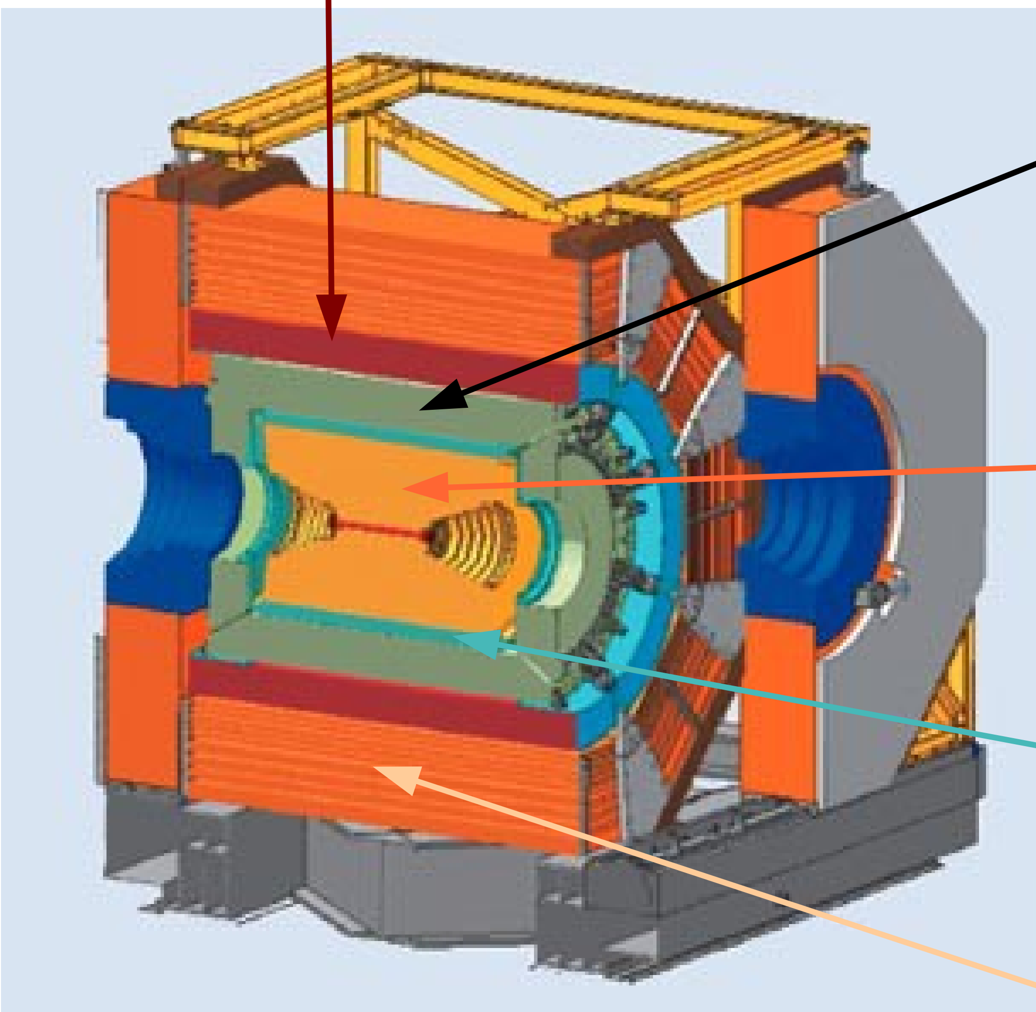


- Double-ring
- Large crossing angle
- Beam energy:
  1.0 - 2.3 GeV → **2.45 GeV**
- Design luminosity:
  1×10^{33} /cm^2 s
  @ψ(3770)
- Achieved luminosity:
  $L_{peak} = 1.0 \times 10^{33}$ /cm^2 s
- Beam energy measurement:
  5×10^{-5}

BESIII detector

NIM A614, 345 (2010)

Super conducting magnet: 1 T



Acceptance:93% of 4π

EMC: CsI cristal
- Energy resolution: **2.5% @1GeV**
- Spatial resolution: **6mm**

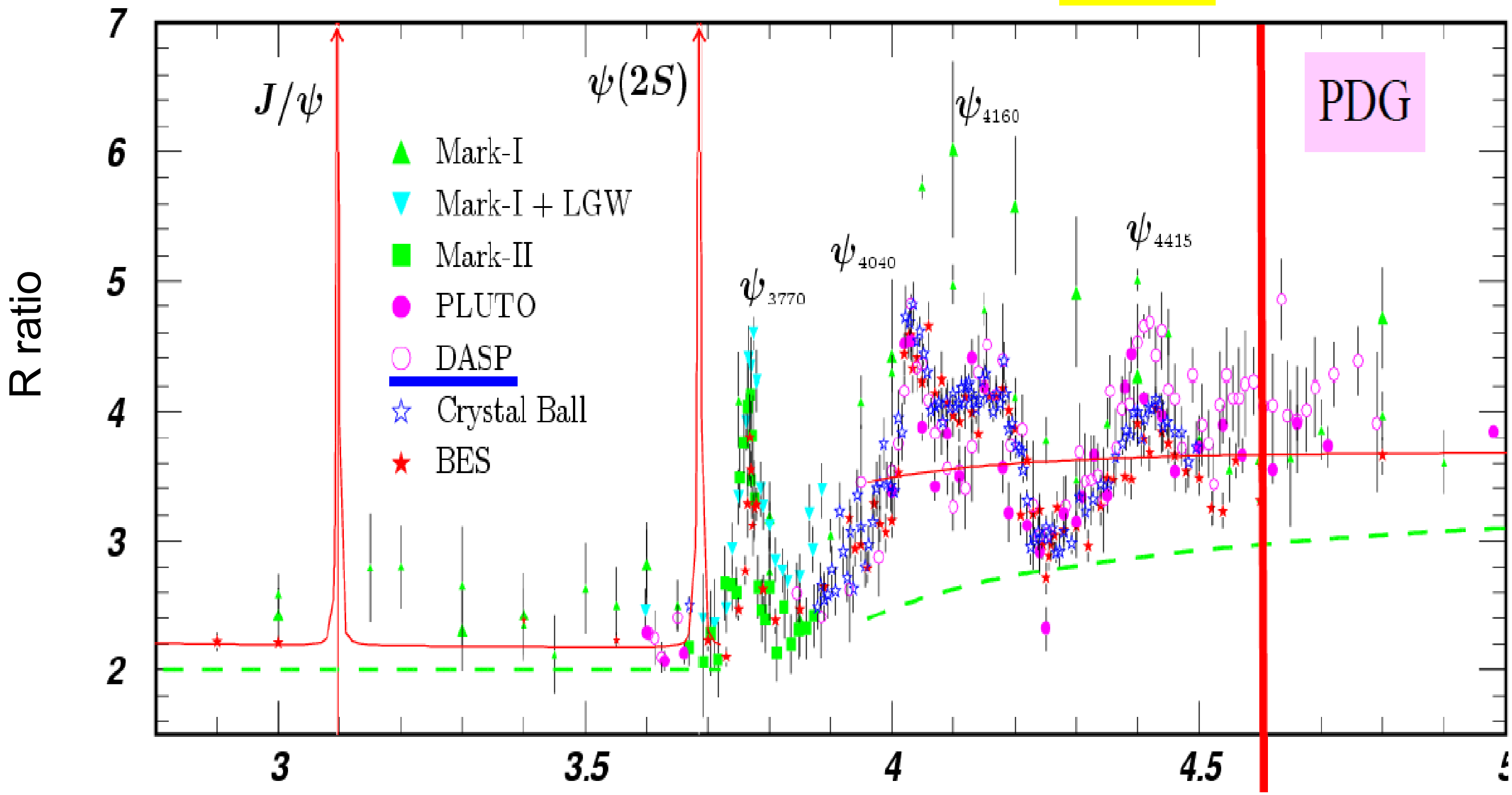
MDC:
- Spatial resolution: **σ_{xy}= 120μm**
- Momentum resolution:**0.5% @ 1GeV**
- **dE/dx** resolution: 6%

TOF:
Time resolution: **100ps** (barrel)
110ps (endcaps)

Muon ID:
9 layers RPC, 8 for endcaps

BESIII data

J/ψ	ψ′	ψ′′	4040	4180	4230 +4260	4360	4420	4600
10×10^9	0.5×10^9	$2.9fb^{-1}$	$0.5fb^{-1}$	$3.0fb^{-1}$	$1.9fb^{-1}$	$0.5fb^{-1}$	$1.0fb^{-1}$	$0.6fb^{-1}$



XYZ
16points
[4130,4440]
$7.7fb^{-1}$

130 points for R-scan, $1.3fb^{-1}$

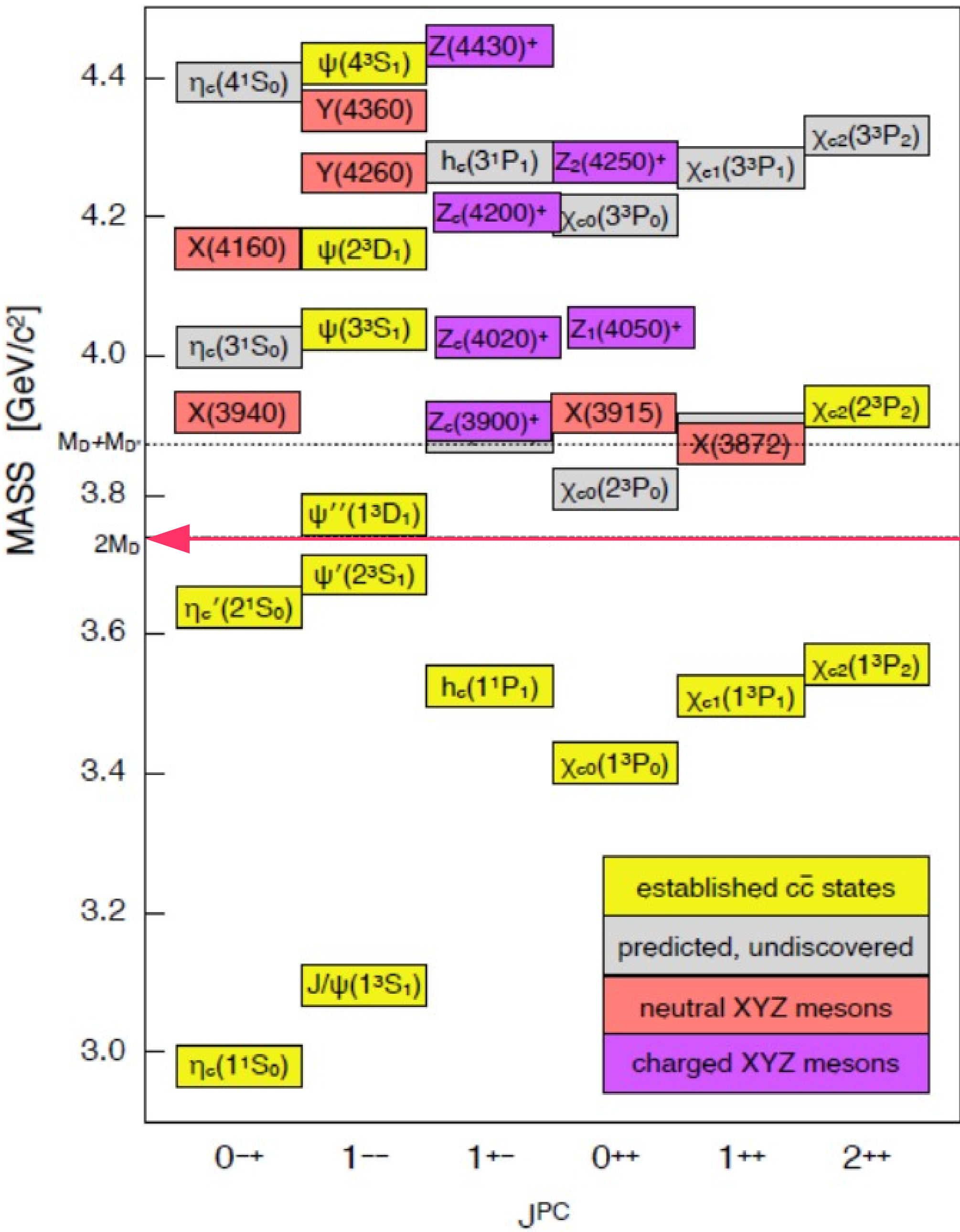
World largest samples of J/ψ, ψ(2S), ψ(3770), ψ(4040), ψ(4180), Y(4260), …

BESIII physics program

- Charmonium physics
- Charmed hadrons
- Exotic states
- Light hadron spectroscopy
- Tau lepton physics
- R-scan (inclusive hadron yield)
- Baryon form-factors
- Searches for new physics

XYZ particles

Charmonium and XYZ states



- "Y" – neutral, $J^{PC} = 1^{--}$
- "X" – neutral, $J^{PC} \,!\!= 1^{--}$
- "Z" – charged

$D\bar{D}$ threshold (~3.73GeV)

$$n^{(2S+1)}L_J$$

n radial quantum number

S total spin of c & cbar

L orbital angular momentum

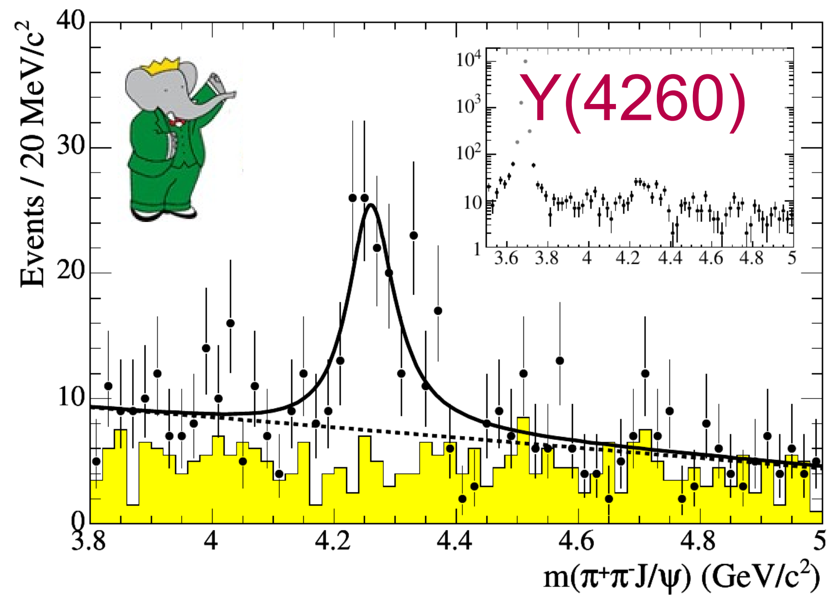
L = 0, 1, 2 ... correspond to S, P, D, …

$J = S + L$

$P = (-1)^{L+1}$ parity

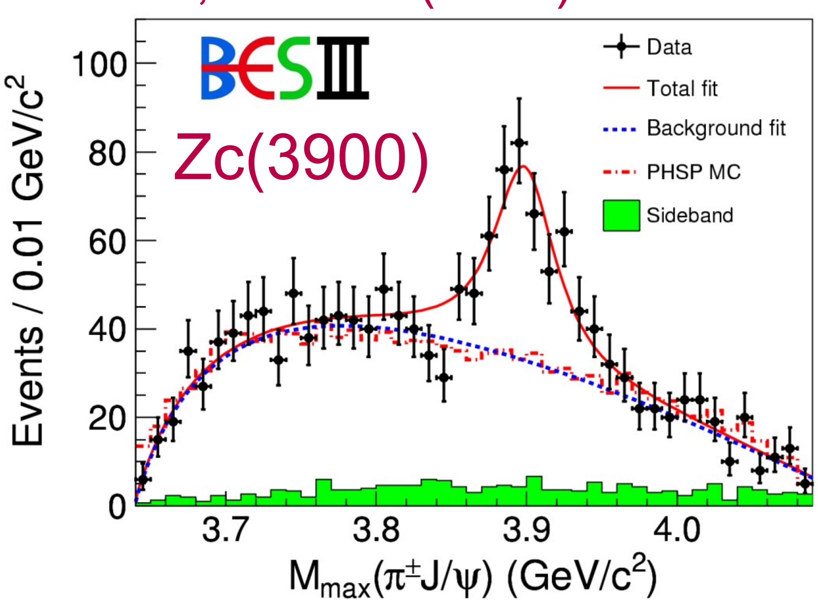
$C = (-1)^{L+S}$ charge conj.

Most famous X,Y,Z states

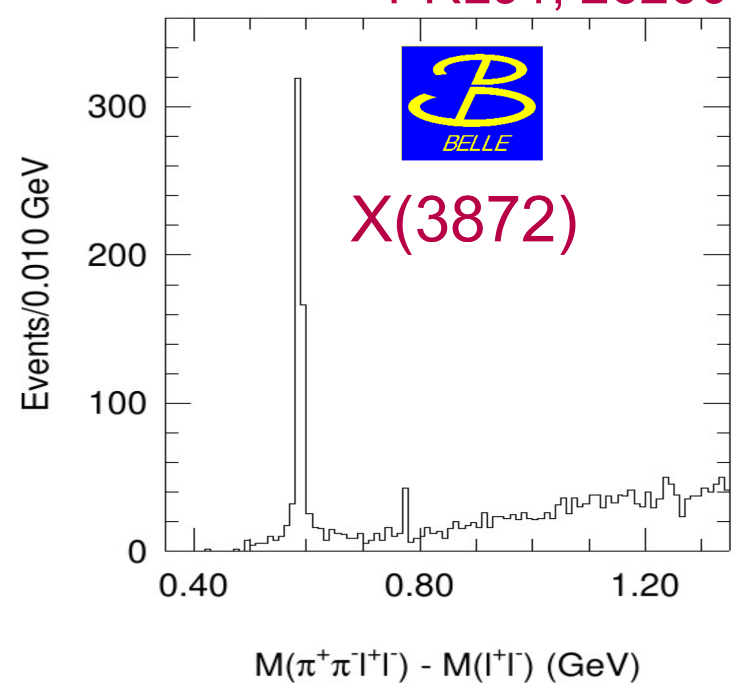


PRL95, 142001 (2005)

PRL110, 252001 (2013)

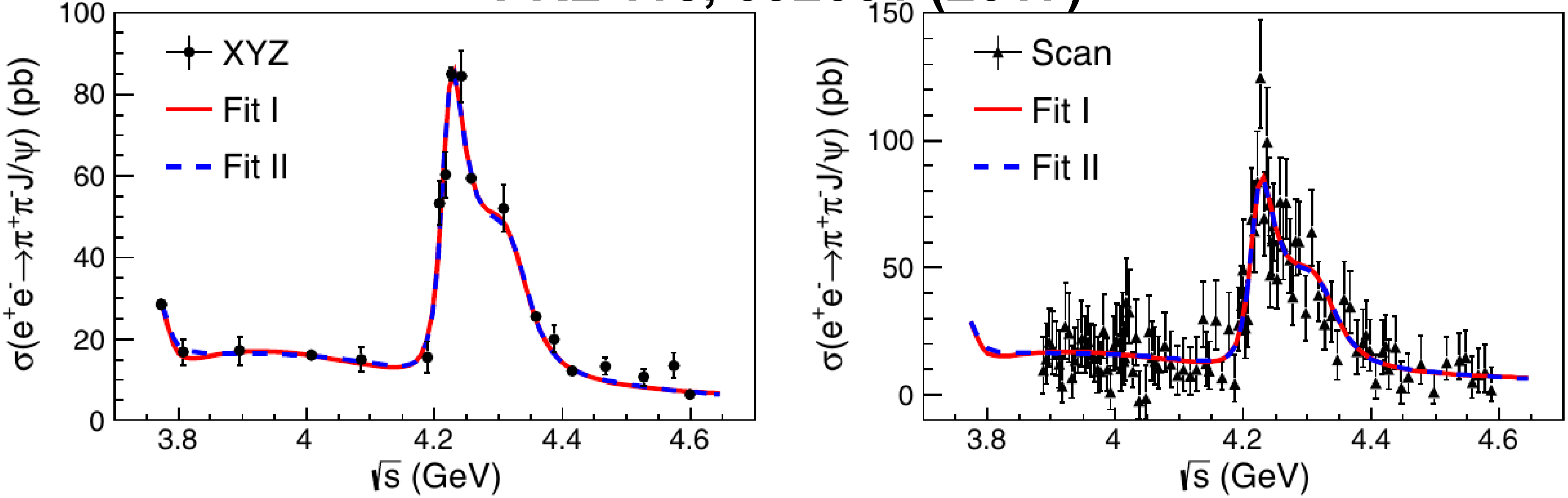


PRL91, 262001 (2003)



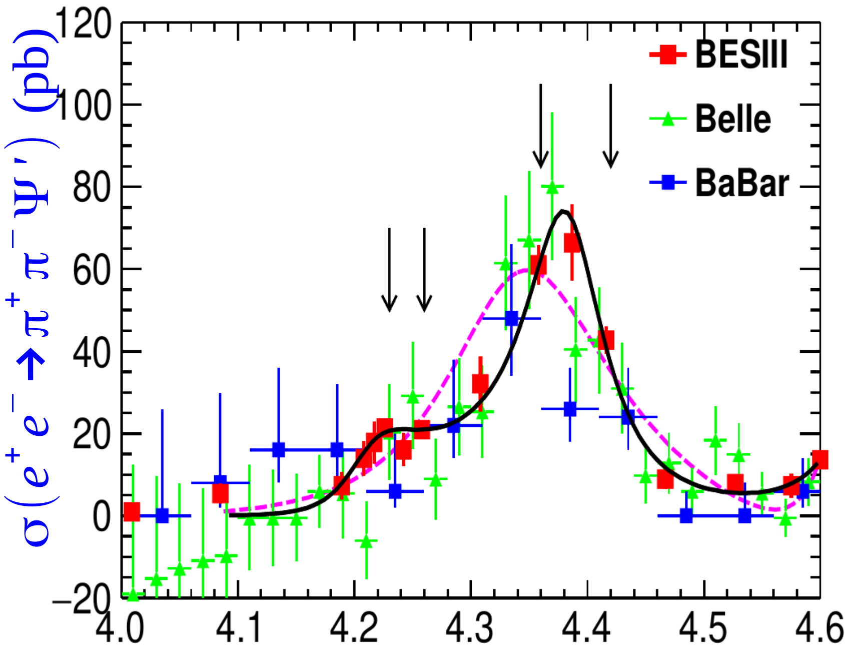
Y(4260)?: $\sigma\left(e^{+}e^{-} \rightarrow \pi^{+}\pi^{-} J/\Psi\right)$

PRL 118, 092001 (2017)



- Most precise cross section measurement to data from BESIII
- Two resonant structures are observed:
  - M = 4222.0±3.1±1.4 MeV; Γ = 44.1±4.3±2.0 MeV
  - M = 4320.0±10.4±7 MeV; Γ = 101.4±25±10 MeV
- Y(4320): first observation in $ee \rightarrow \pi\pi J/\Psi$ (signif.>7.6 σ)

Y(4220): more observations



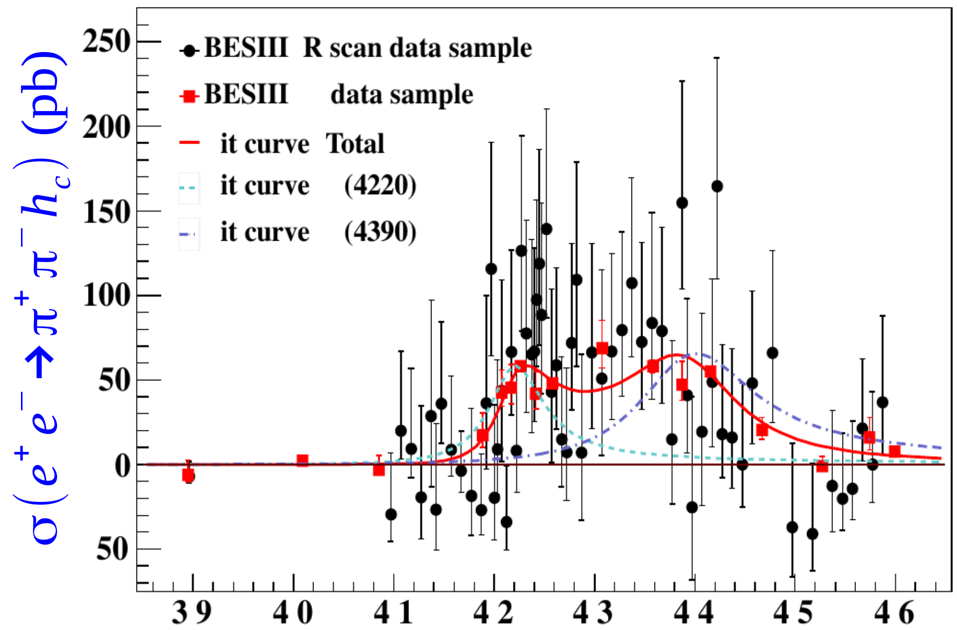
PRD96, 032004 (2017)

$e^+e^- \to \pi^+\pi^-\Psi(3686)$

M = 4209.5±7.4±1.4 MeV

Γ = 80.1±24.6±2.9 MeV

Significance 5.8σ



PRL118, 092002 (2017)

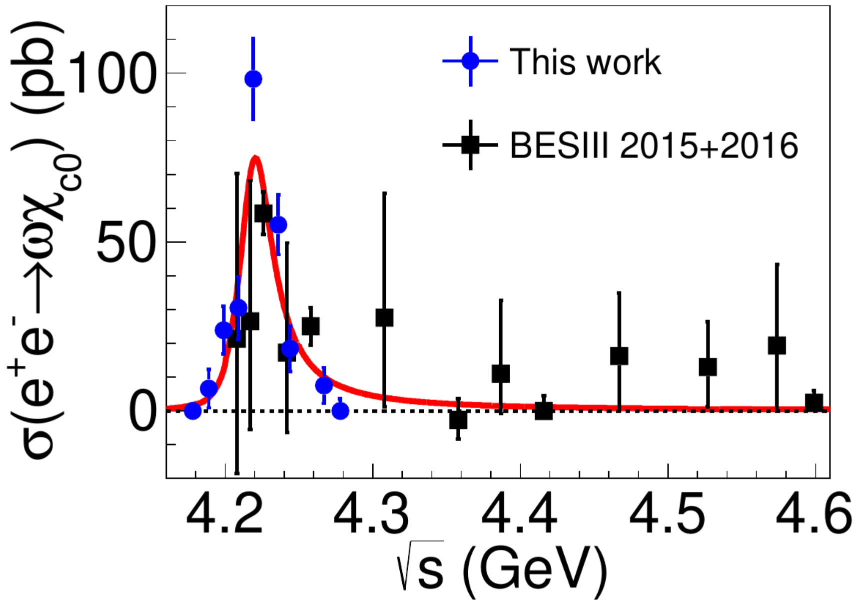
$e^+e^- \to \pi^+\pi^- h_c$

M = 4218.4±5.5±0.9 MeV

Γ = 66±12±0.4 MeV

Significance > 10σ

Y(4220): more observations

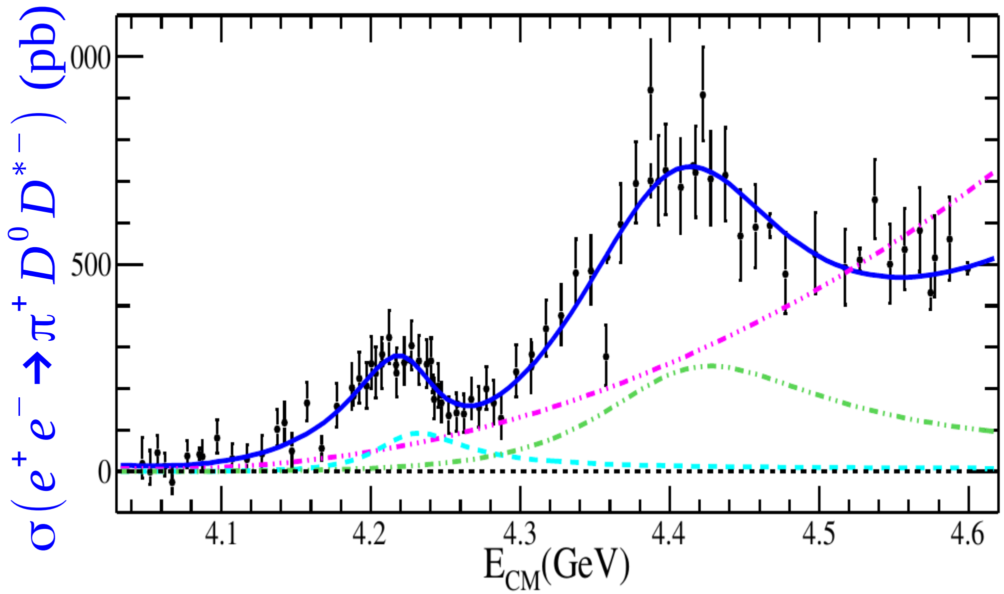


PRD99, 091003 (2019)

$e^+e^- \to \omega\,\chi_{c0}$

M = 4218.5±1.6±4.0 MeV

Γ = 28.3±3.9±1.6 MeV



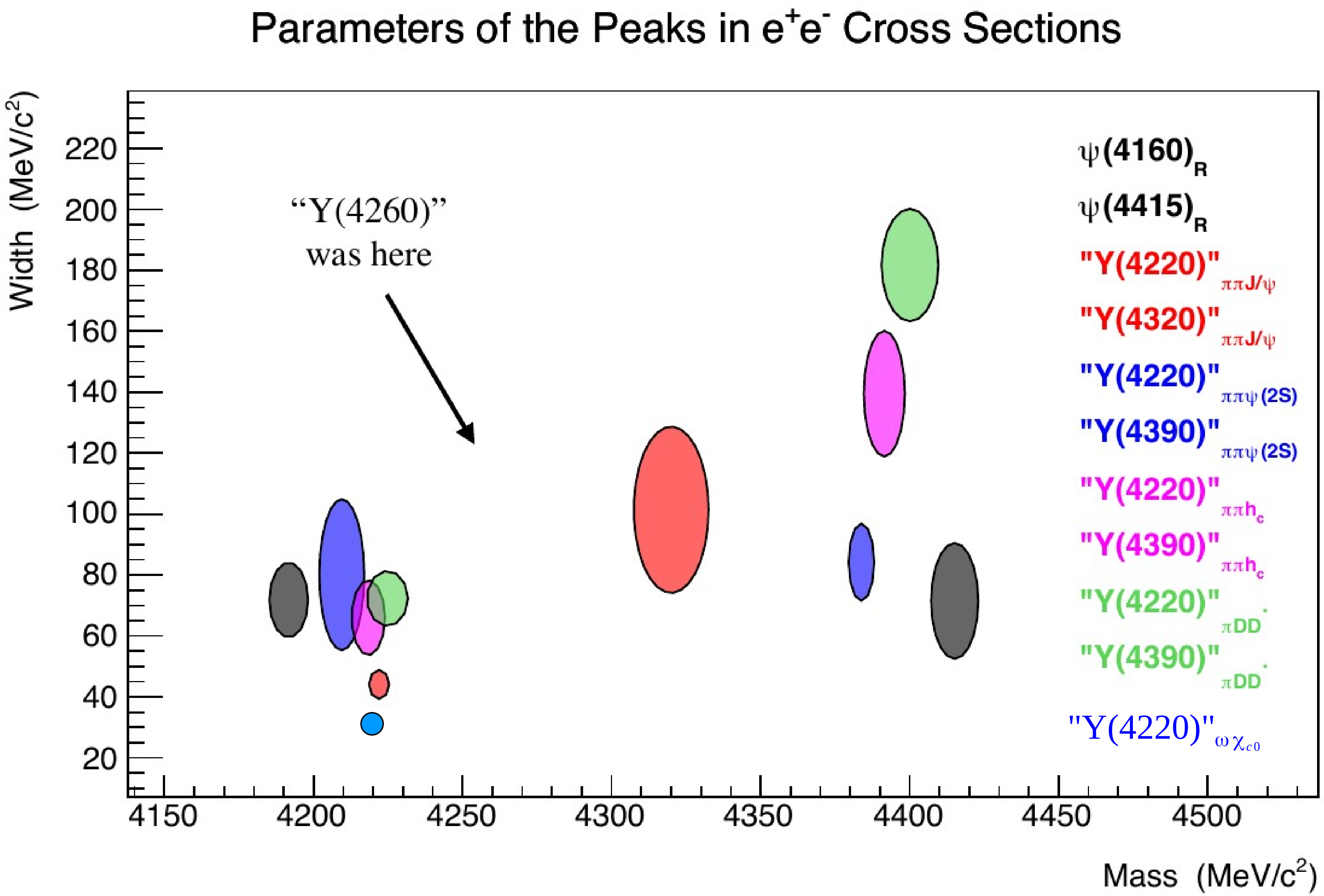
PRL122, 102002 (2019)

$e^+e^- \to \pi^+ D^0 D^{*-}$

M = 4228.6±4.1±6.3 MeV

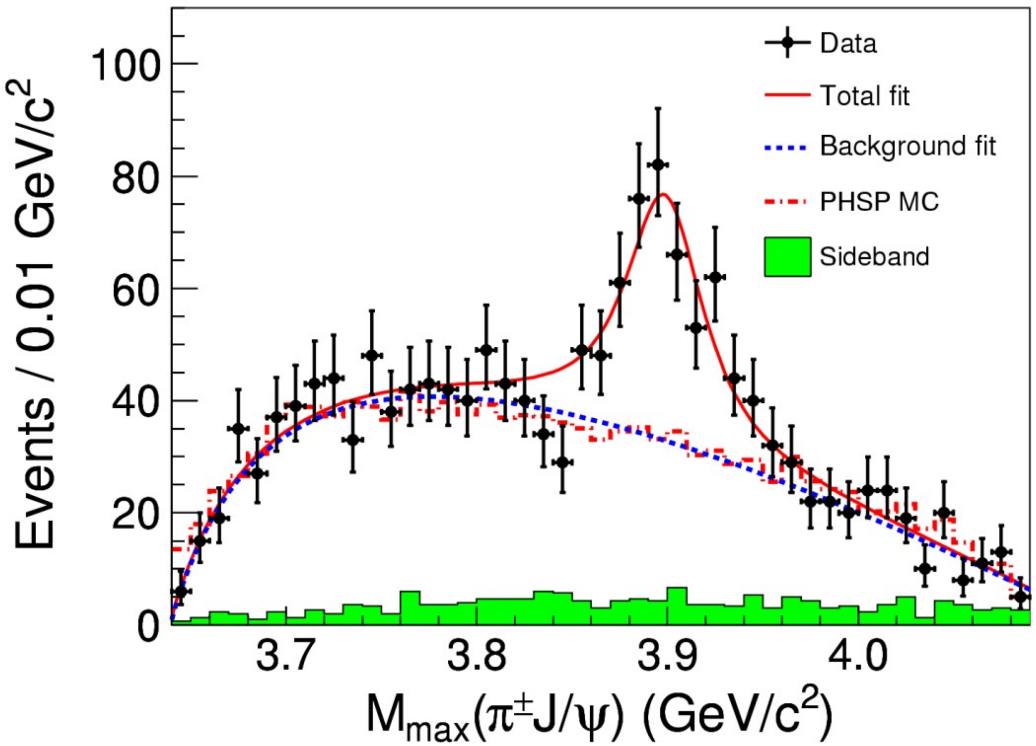
Γ = 77.0±6.8±6.3 MeV

Y summary



Parameters of the Peaks in e+e- Cross Sections
Width (MeV/c2)
220
200
180
160
140
120
100
80
60
40
20
4150
4200
4250
4300
4350
4400
4450
4500
Mass (MeV/c2)
"Y(4260)" was here
ψ(4160)R
ψ(4415)R
"Y(4220)"ππJ/ψ
"Y(4320)"ππJ/ψ
"Y(4220)"ππψ(2S)
"Y(4390)"ππψ(2S)
"Y(4220)"ππhc
"Y(4390)"ππhc
"Y(4220)"πDD*
"Y(4390)"πDD*
"Y(4220)"ωχc0

Discovery of the $Z_c^{\pm}(3900)$



PRL 110, 252001 (2013)

$e^+e^- \rightarrow \pi^+\pi^- J/\Psi$ at 4260 MeV

M = 3899.0±3.6±4.9 MeV

Γ = 46±10±20 MeV

Fraction=(21.5±3.3±7.5)%

Significance > 8σ

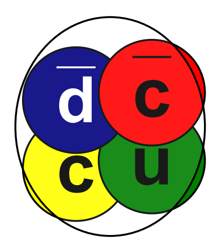
✔ Couples to $c\bar{c}$ and has charge

What is it?

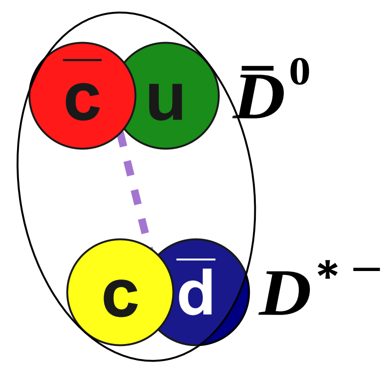
✗ A tetraquarks state?

✗ A $\bar{D}D^*$ molecule?

✗ ...



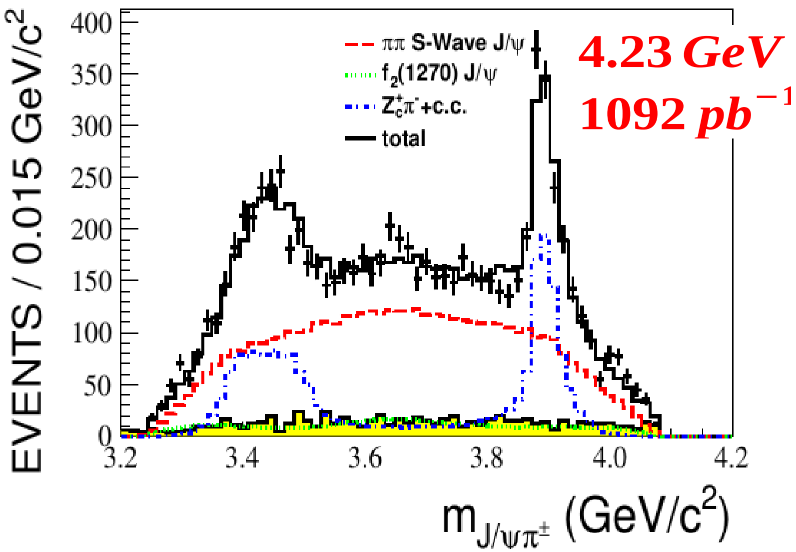
tetraquark

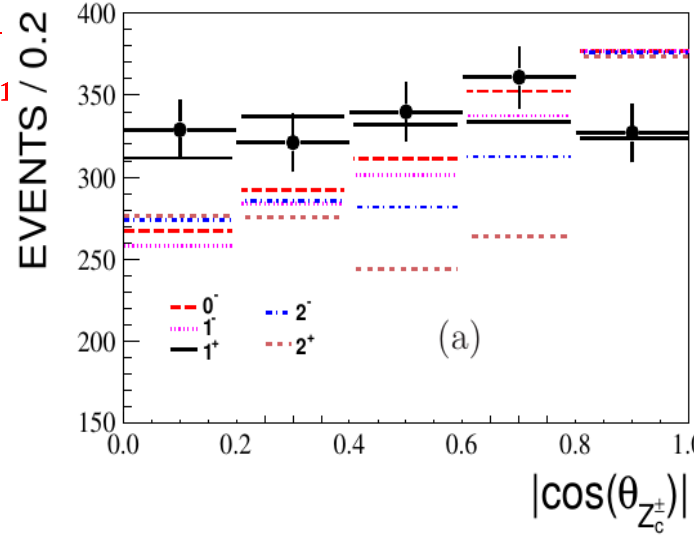


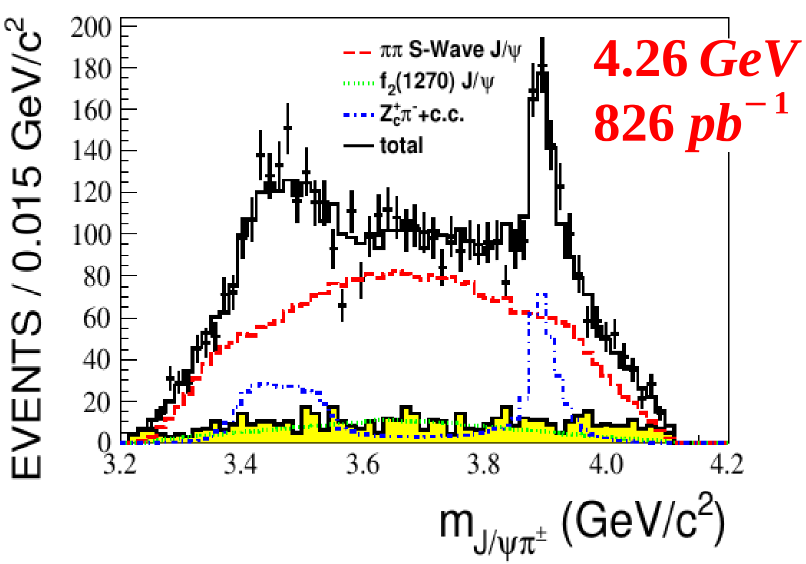
$\bar{D}D^*$ molecule

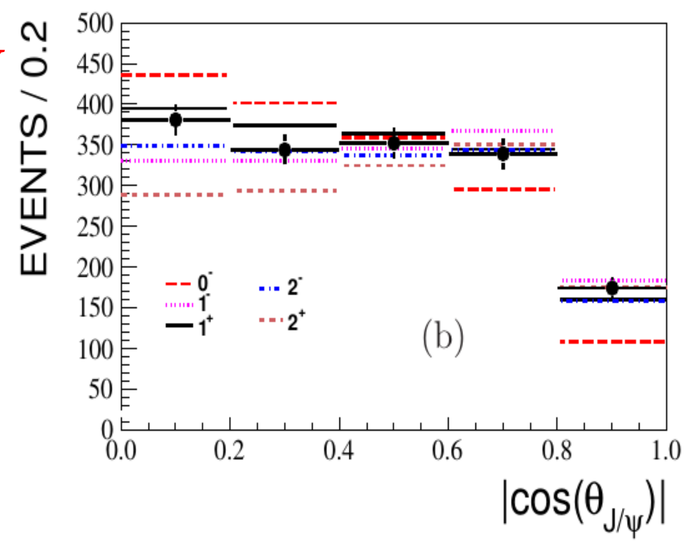
PWA fit of $Z_c^{\pm}(3900)$

PRL 119, 072001 (2017) $e^+e^- \rightarrow \pi^+\pi^- J/\Psi$





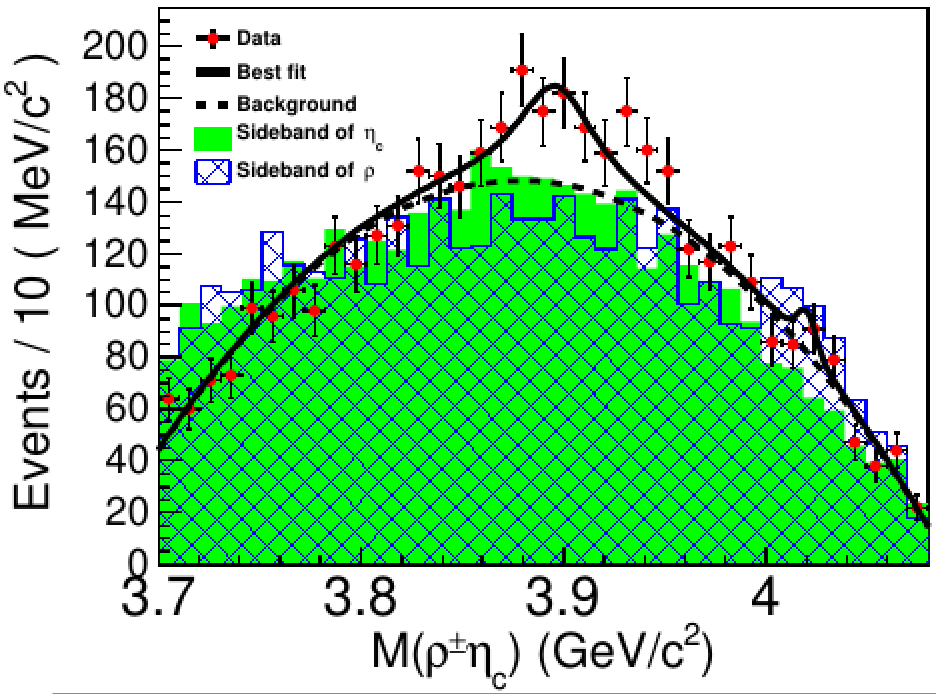


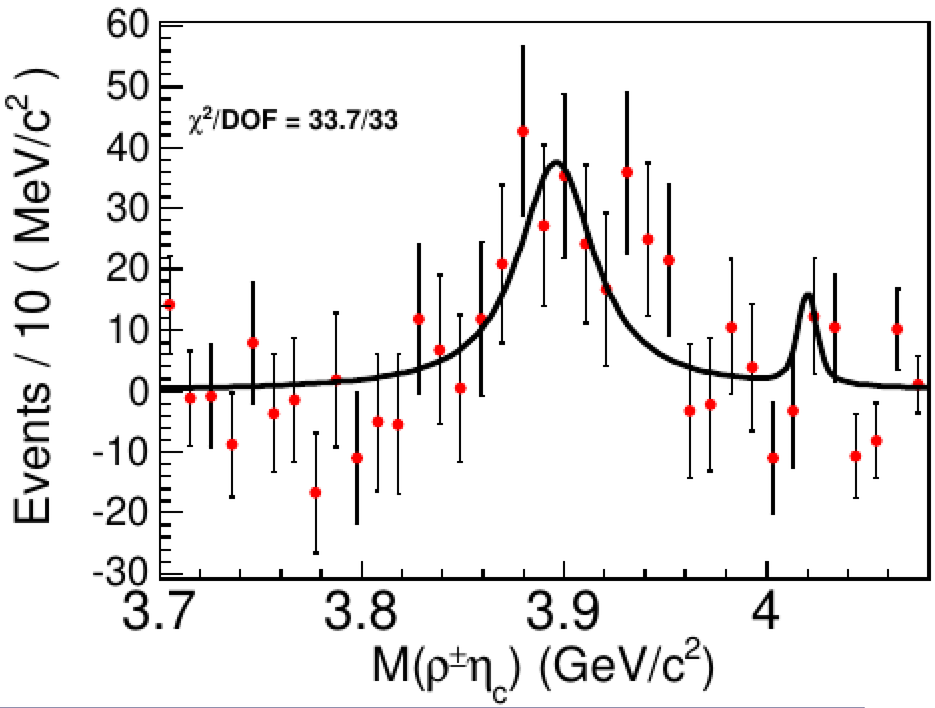


- **JP=1^+ preferred over 0^-, 1^-, 2^-, 2^+ by at least 7σ**
- **Significant contr. of ππ S-wave: $\sigma, f_0(980), f_0(1370)$ contribution**
- **ππ S-wave increases as Ecm increases**

Evidance for $Z_c(3900)^{\mp} \to \rho^{\mp}\,\eta_c$

PR D100, 111102 (2019)



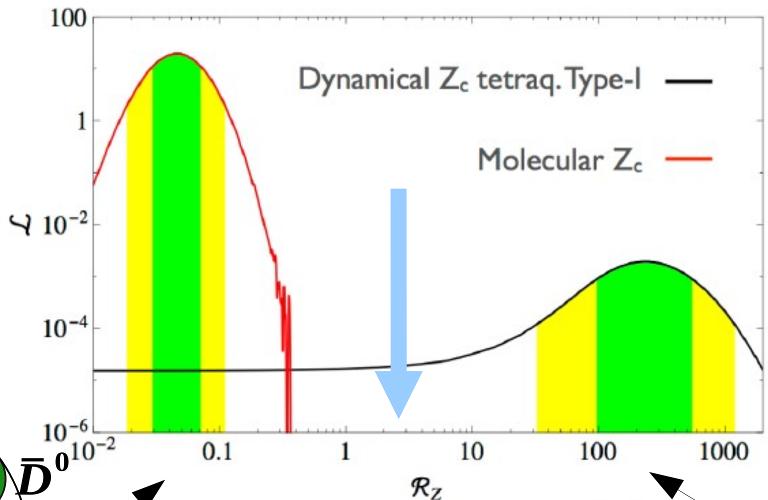


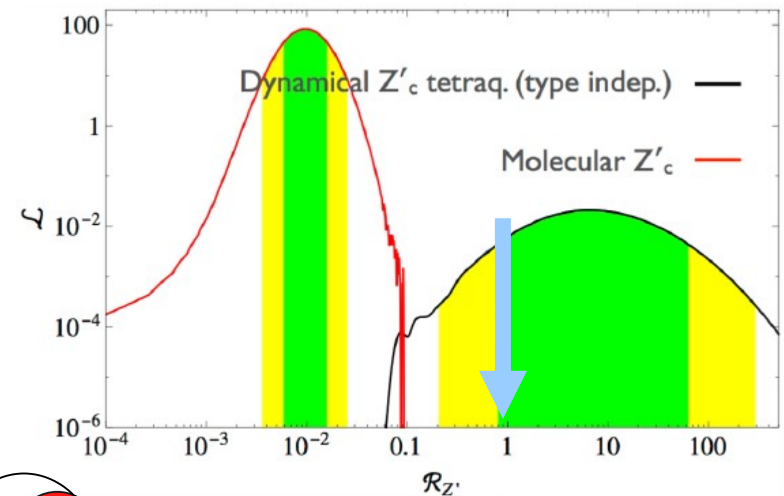
- $e^+e^- \to \pi^{\pm} Z_c(3900)^{\mp} \to \pi^{\pm}(\rho^{\mp}\,\eta_c)$ at $E_{cm} = 4.23\,GeV$

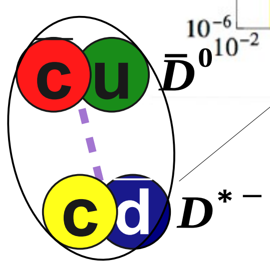
  $\eta_c \to 9$ hadronic decays

- $Z_c(3900) \to \rho\,\eta_c$ with significance $3.9\,\sigma$ (insluding systematics)
- hint for $Z_c(4020)$

Theory: A.Esposito et.al., Phys. Lett. B 746, 194 (2015)
discrimination between different multi-quark schemes

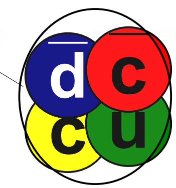






$\bar{D}D^*$ molecule

$$R_z = \frac{Br(Z_c \to \rho\eta_c)}{Br(Z_c \to \pi J/\psi)}$$



tetraquark

$$R_{Z'} = \frac{Br(Z'_c \to \rho\eta_c)}{Br(Z'_c \to \pi h_c)}$$

$$\sigma\left(e^+e^- \to \pi^\pm Z_c^\mp \to \pi^\pm(\rho^\mp\eta_c)\right) = 48 \pm 11 \pm 11\ pb \quad @\,4.23\,GeV$$

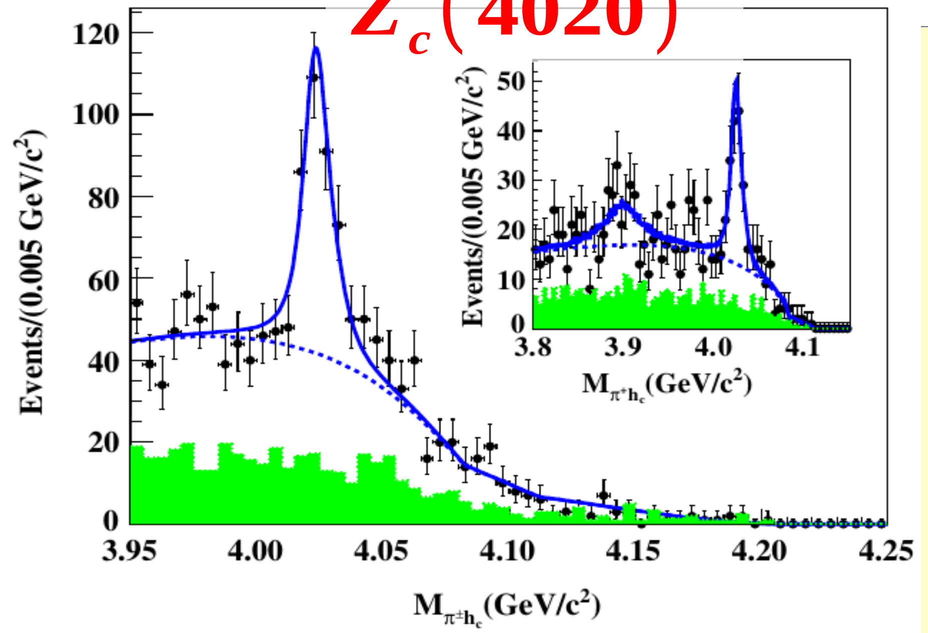
	BESIII results [Phys.Rev.D100.111102]			models predictions		
	$\sqrt{s} = 4.226$ GeV	$\sqrt{s} = 4.258$ GeV	$\sqrt{s} = 4.358$ GeV	Type-I	Type-II	Molecule
$R_{Z_c(3900)}$	2.2 ± 0.9	< 5.6	...	230^{+330}_{-140}	$0.27^{+0.40}_{-0.17}$	$0.046^{+0.025}_{-0.017}$
$R_{Z_c(4020)}$	< 1.6	< 0.9	< 1.4	$6.6^{+56.8}_{-5.8}$		$0.010^{+0.006}_{-0.004}$

Z_c properties summary

$Z_c(3900)$

- ✔ $I^G=1^+$
- ✔ $J^{PC}=1^{+-}$
- ✔ Decay modes:
  - ➢ $\pi^+ J/\Psi$
  - ➢ $D\bar{D}^*$
  - ➢ $\rho\,\eta_c$ $(3.9\,\sigma)$
  - ➢ $\pi\, h_c$ $(2.1\,\sigma)$
  - ➢ not to light hadrons

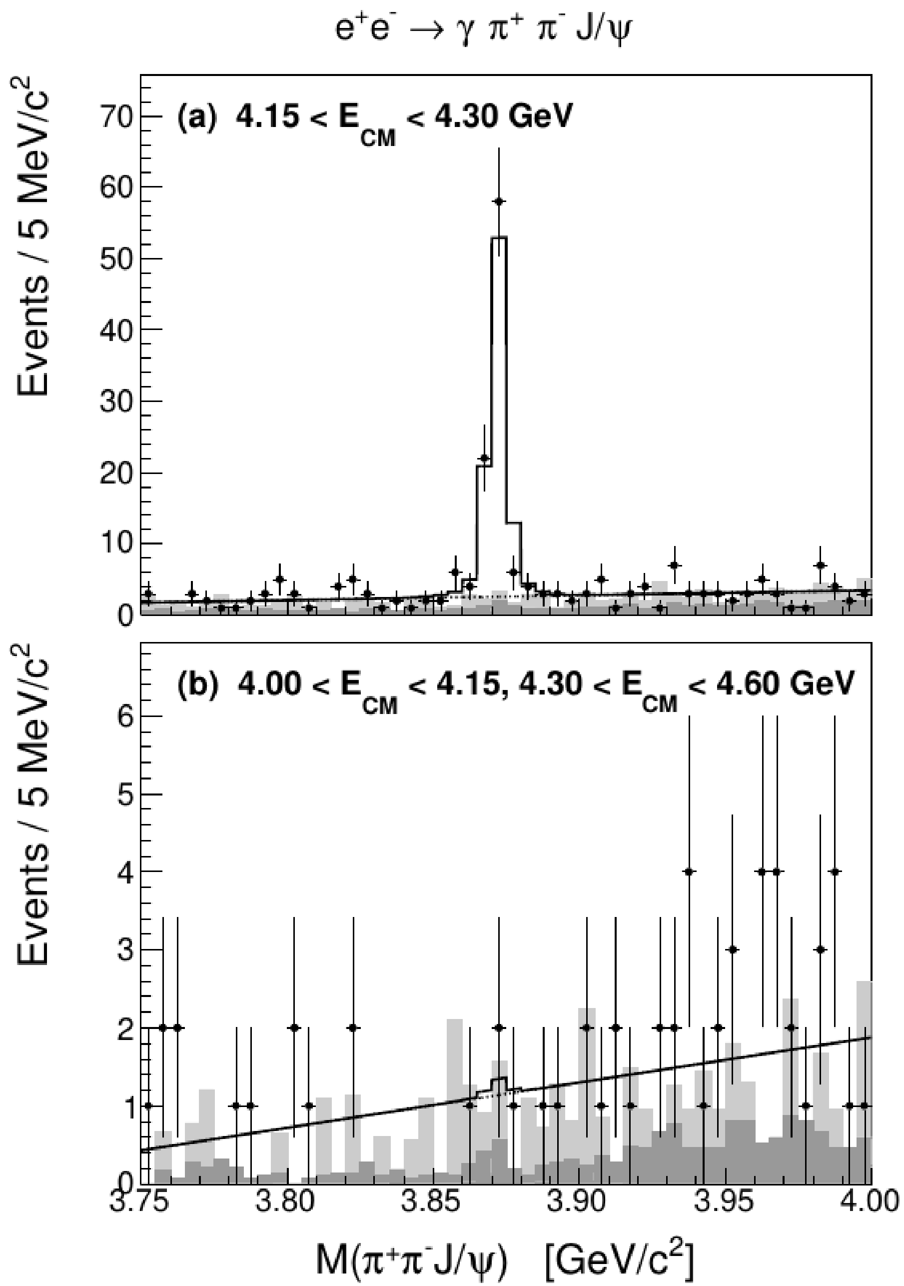
$Z_c(4020)^{\pm}$



- ✔ $I^G=1^+$ $J^{PC}=?^{??}$
- ✔ $M = 4022.9 \pm 0.8 \pm 2.7$ MeV
  $\Gamma = 7.9 \pm 2.7 \pm 2.6$ MeV
- ✔ Decay modes:
  - ➢ $\pi\, h_c$ and $D^* \bar{D}^*$
  - ➢ possibly to $\pi\Psi(3686)$

PRL 111, 242001 (2013)

X(3872) related to Y(4220) ?



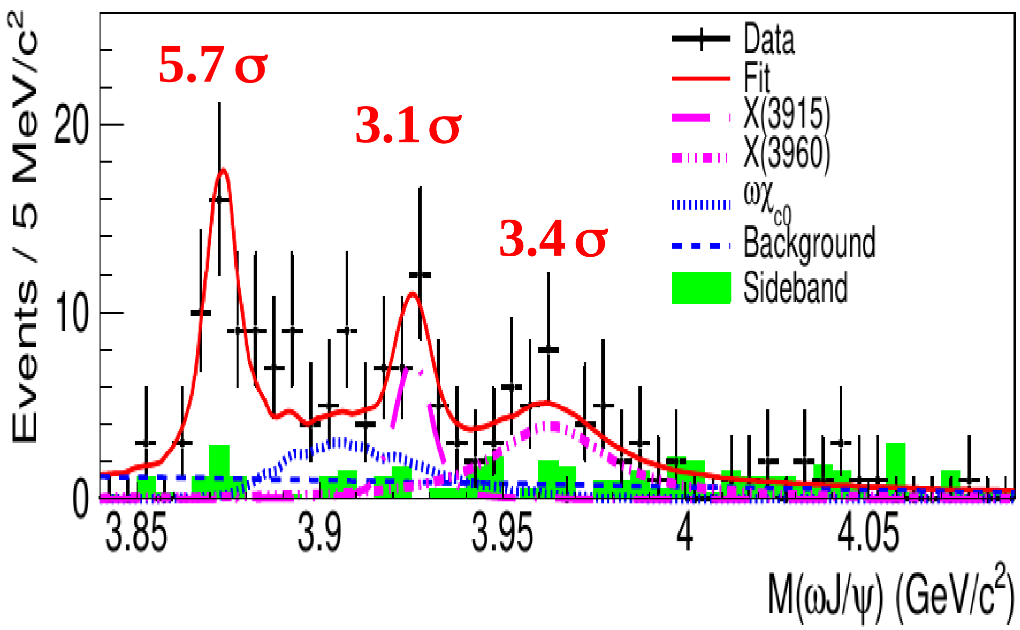
PRL 122, 202001 (2019)

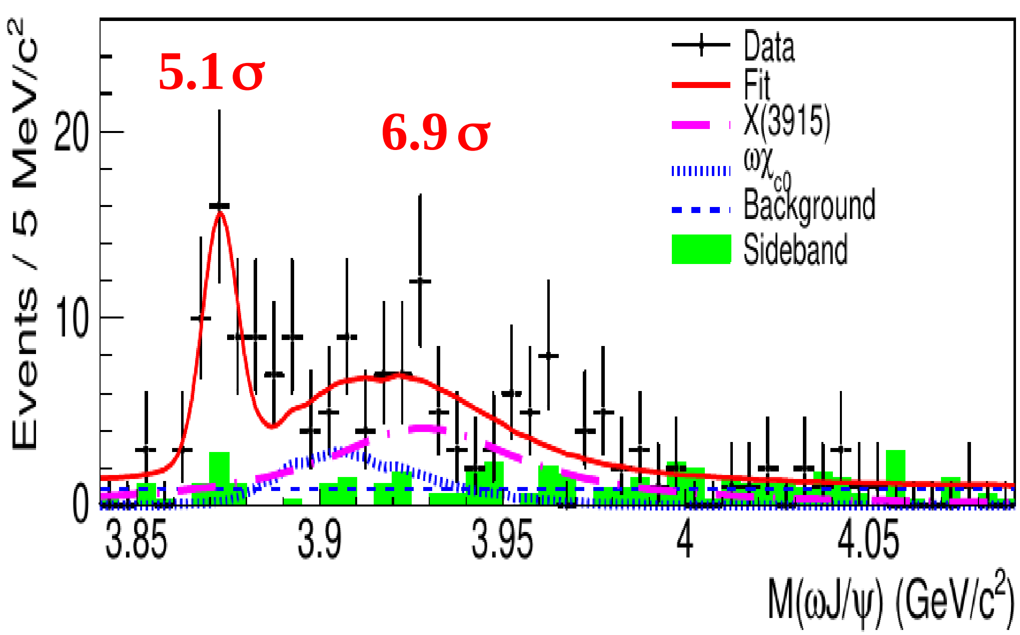
$X(3872) \to \pi^+ \pi^- J/\Psi$

- Clear signal X(3872) in Y(4220) region
- No X(3872) outside

(Light hist: sideband of J/Ψ
Dark hist: peaking J/Ψ
background from MC)

$X(3872) \to \omega J/\Psi$





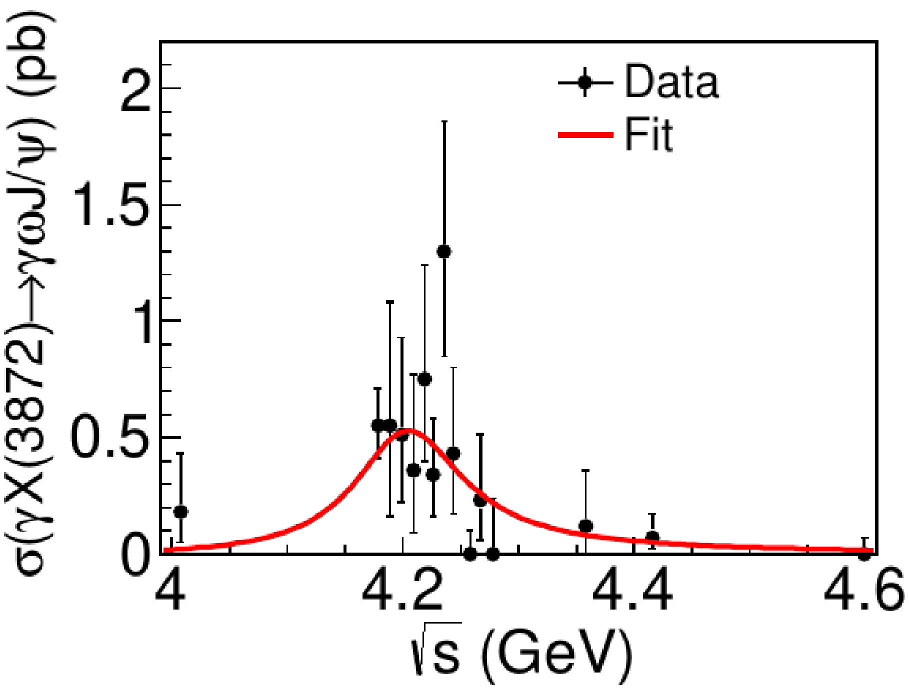
PRL 122, 232002 (2019)

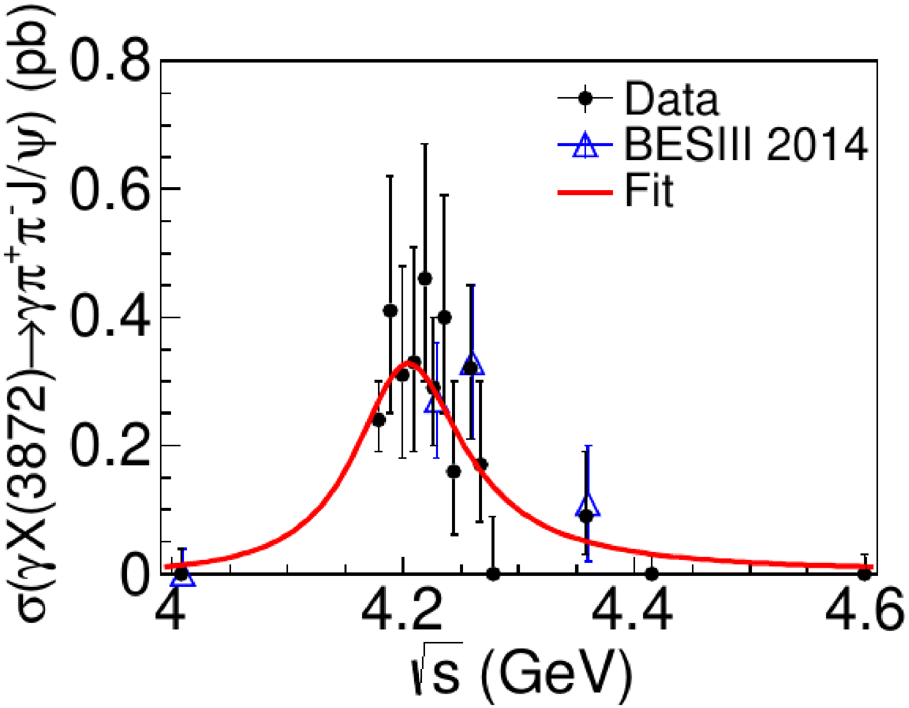
$e^+e^- \to \gamma X \to \gamma \omega J/\Psi$

- At least one additional resonance except X(3872)
- Hard to distinguish the two hypotheses since only 2.5σ difference

	Mass	Width
$X(3872)$	$3873.3 \pm 1.1\ (3872.8 \pm 1.2)$	$1.2\ (1.2)$
$X(3915)$	$3926.4 \pm 2.2\ (3932.6 \pm 8.7)$	$3.8 \pm 7.5\ (59.7 \pm 15.5)$
$X(3960)$	3963.7 ± 5.5	33.3 ± 34.2

Simultaneous Fit





$X(3872) \rightarrow \omega J/\Psi$ and $\pi^+\pi^- J/\Psi$

$\mathrm{M(Y(4200))} = 4200.6^{+7.9}_{-13.3} \pm 3.0$ MeV

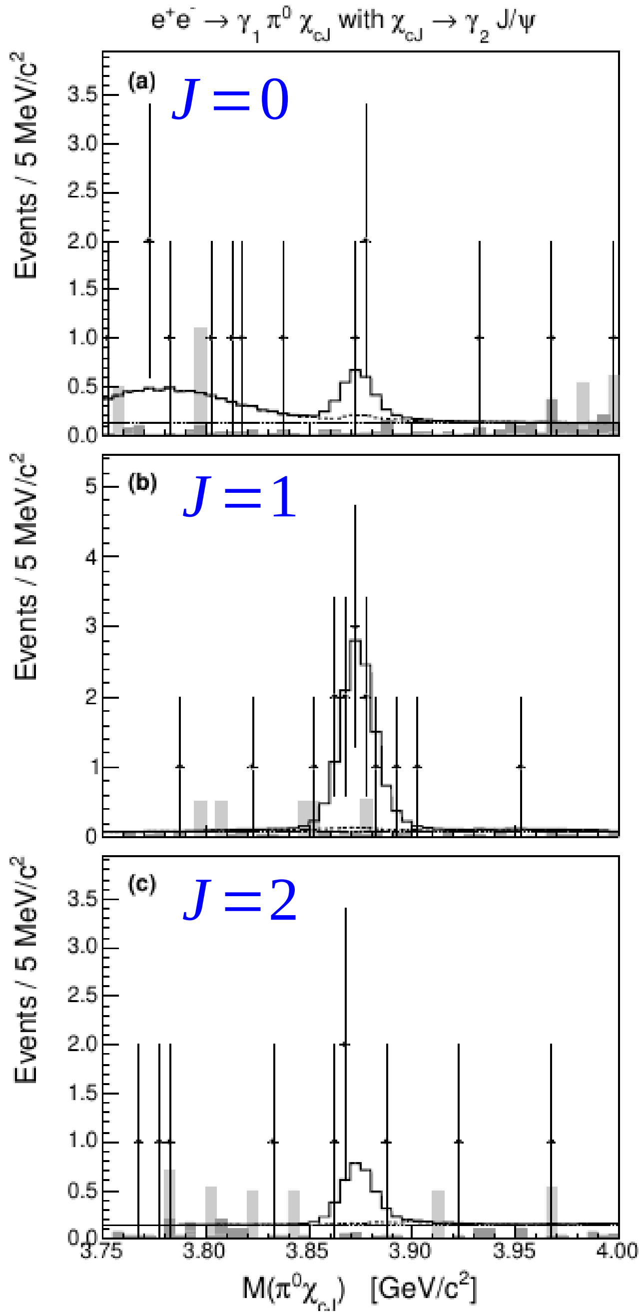
$\Gamma(\mathrm{Y(4200)}) = 115^{+38}_{-26} \pm 12$ MeV

PRL 122, 232002 (2019)

Is it Y(4220) ?

$$\frac{B(X(3872) \rightarrow \omega J/\Psi)}{B(X(3872) \rightarrow \pi^+\pi^- J/\Psi)} = 1.6^{+0.4}_{-0.3} \pm 0.2$$

$X(3872) \to \pi^0 \chi_{cJ}$



PRL 122, 202001 (2019)

$$e^+e^- \to \gamma X(3872), X(3872) \to \pi^0 \chi_{cJ}$$

$$\chi_{cJ} \to \gamma J/\Psi, J/\Psi \to l^+ l^-$$

- First obserfation of $X(3872) \to \pi^0 \chi_{c1}(1P)$
- Significance 5.2σ

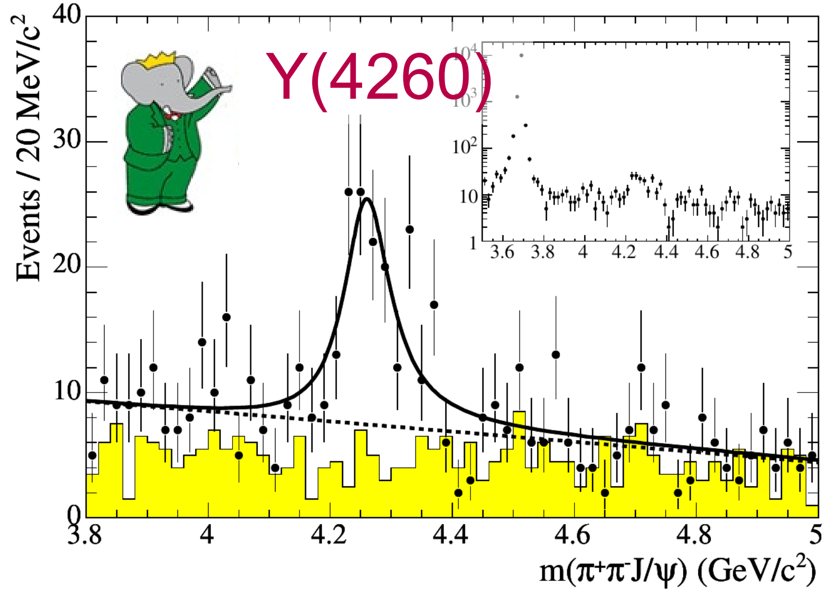
$$R(J) = \frac{B(X(3872) \to \pi^0 \chi_{cJ})}{B(X(3872) \to \pi^+ \pi^- J/\Psi)}$$

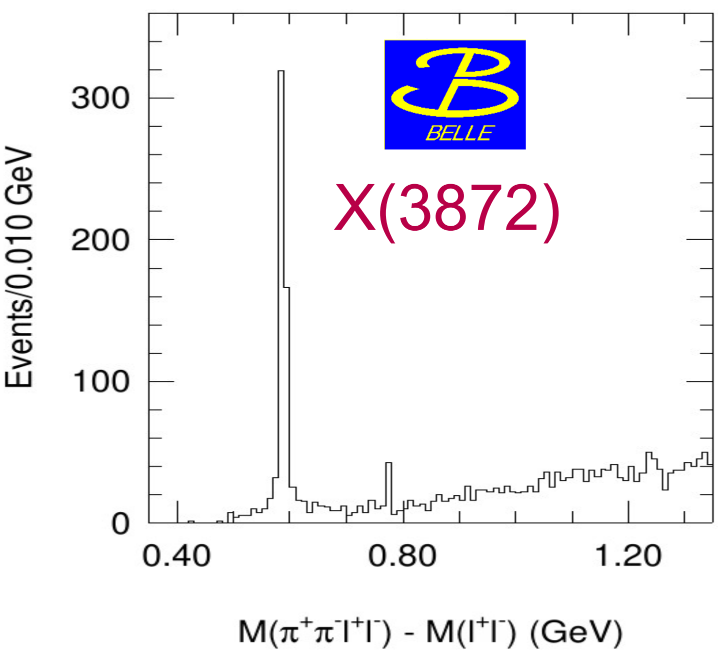
R(J=0) < 19 (90%CL)

R(J=1) $= 0.88^{+0.33}_{-0.27} \pm 0.10$

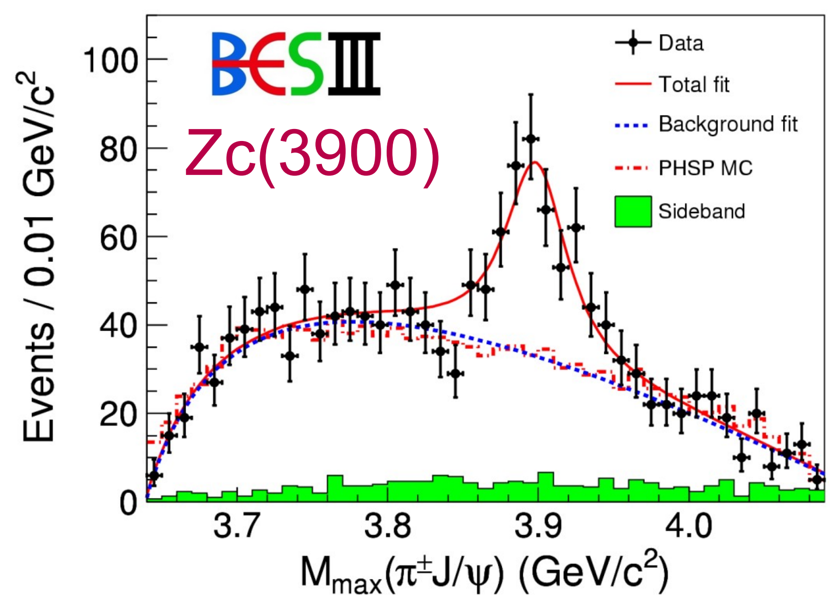
R(J=2) < 1.1 (90%CL)

X,Y,Z are correlated!





?

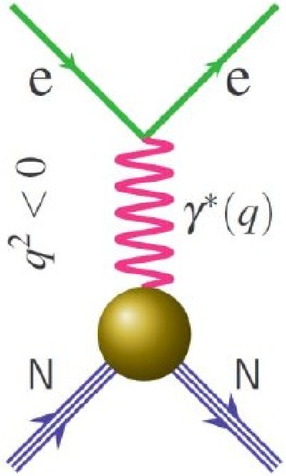


Nucleon (and baryon) form-factors

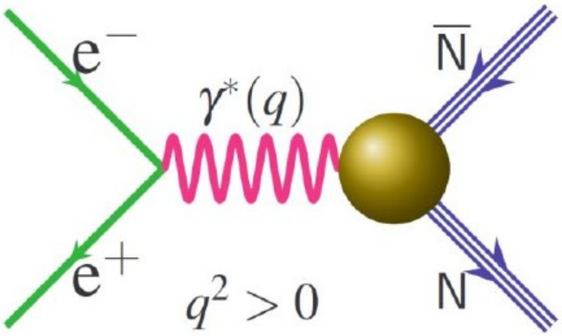
Electromagnetic Form Factors

- Fundamental properties (internal structure) of nucleon:
  - related to Born cross section
  - represent charge distribution in momentum space
- Can be measured:
  - elastic scattering eN: space-like, real FF
  - e^+e^- – annihilation: time-like, complex FF

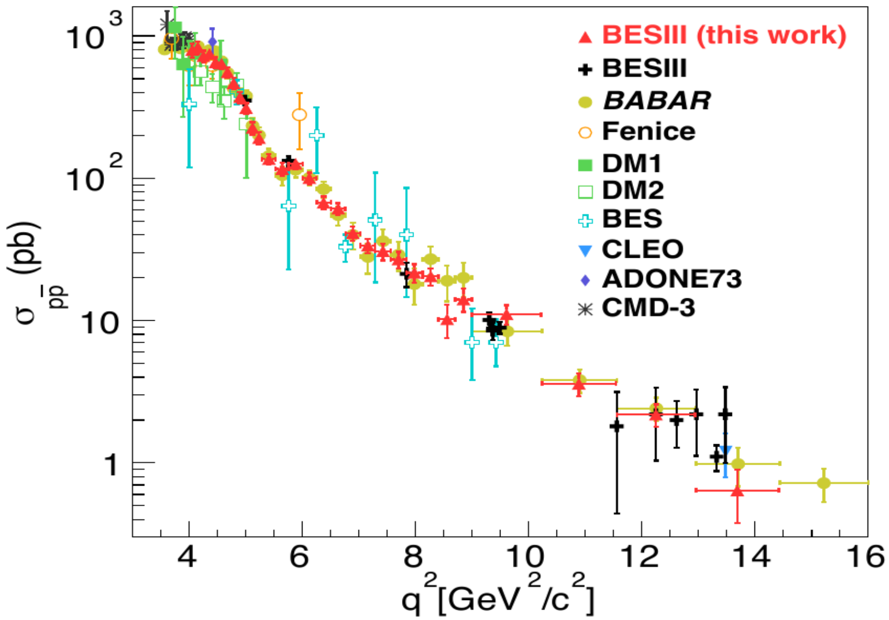
$e N \rightarrow e N$

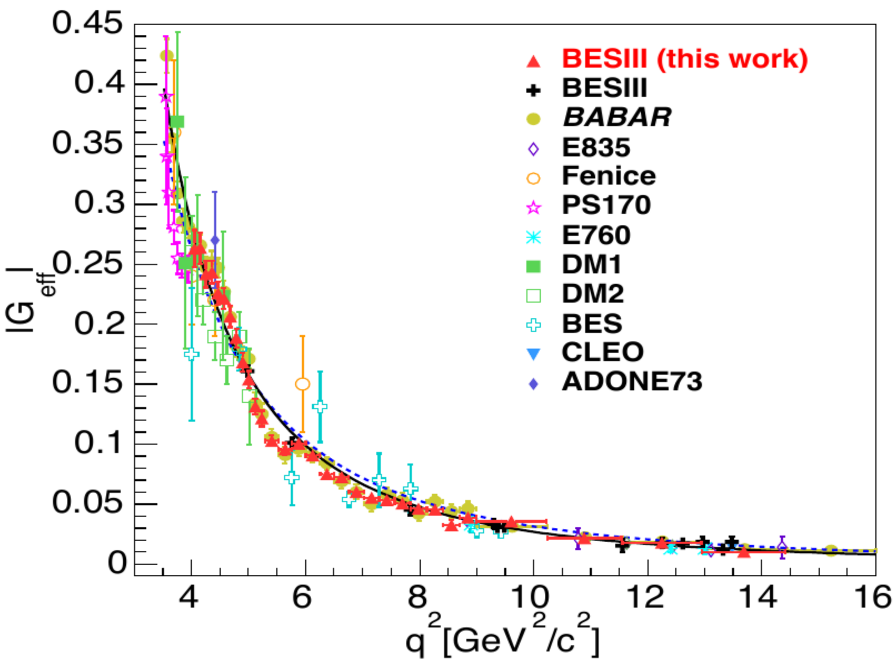


$e^+ e^- \rightarrow N \bar{N}, \Lambda \bar{\Lambda}, \Lambda_c \bar{\Lambda}_c$



Proton Form Factors I



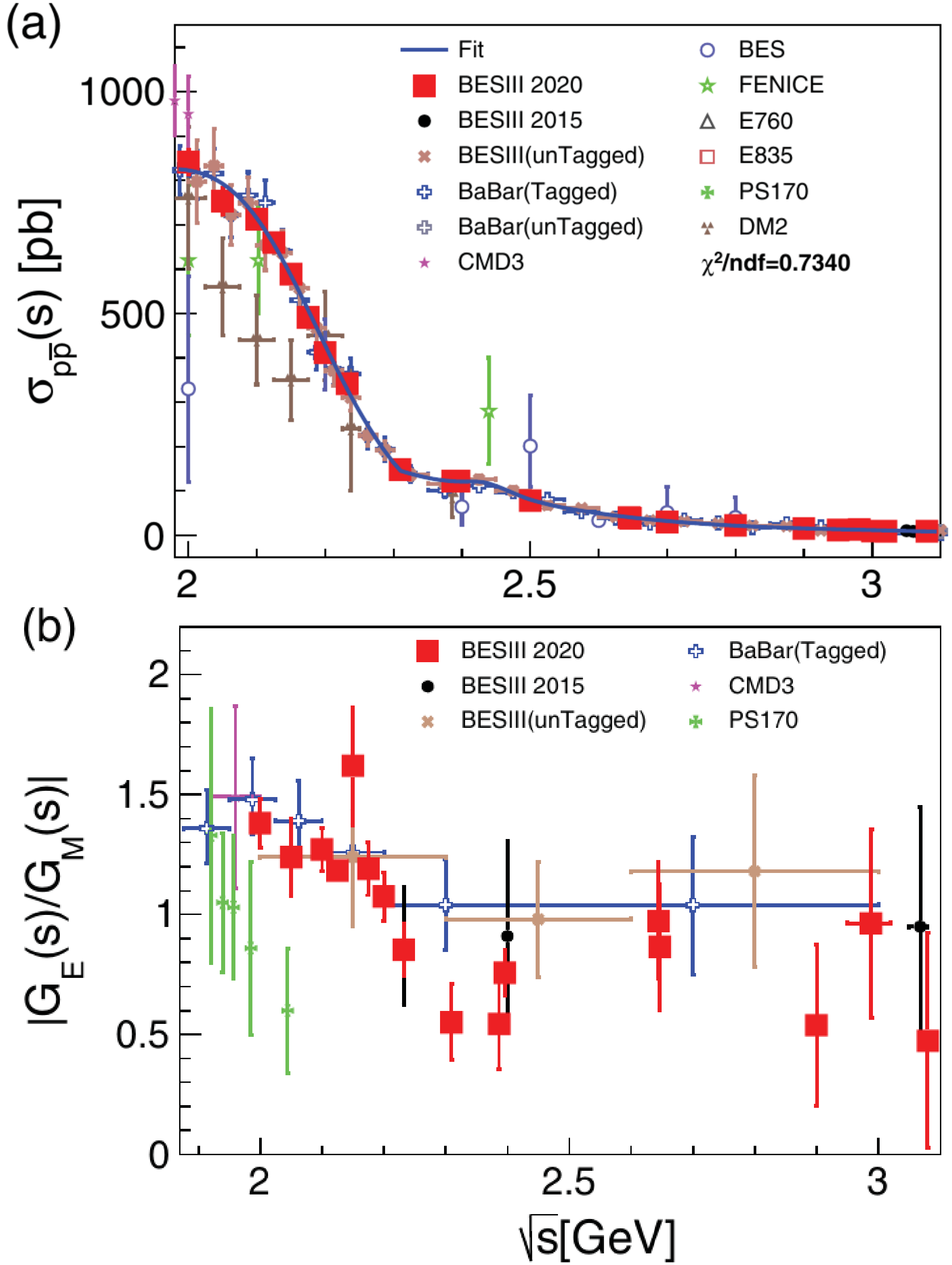


ISR: $e^+e^- \to \gamma p \bar{p}$

PR D99, 092002 (2019)

- Cross section: $\sigma(e^+e^- \to p\bar{p}) \sim$
$$|G_M|^2(1+\cos^2\theta_p) + \frac{4m_p^2}{s}|G_E|^2\sin^2\theta_p$$
- Most experiments assume
$$|G_M| = |G_E| = |G_{Eff}|$$
- Proton FF ratio:
$$R = |G_E/G_M|$$

Proton Form Factors II

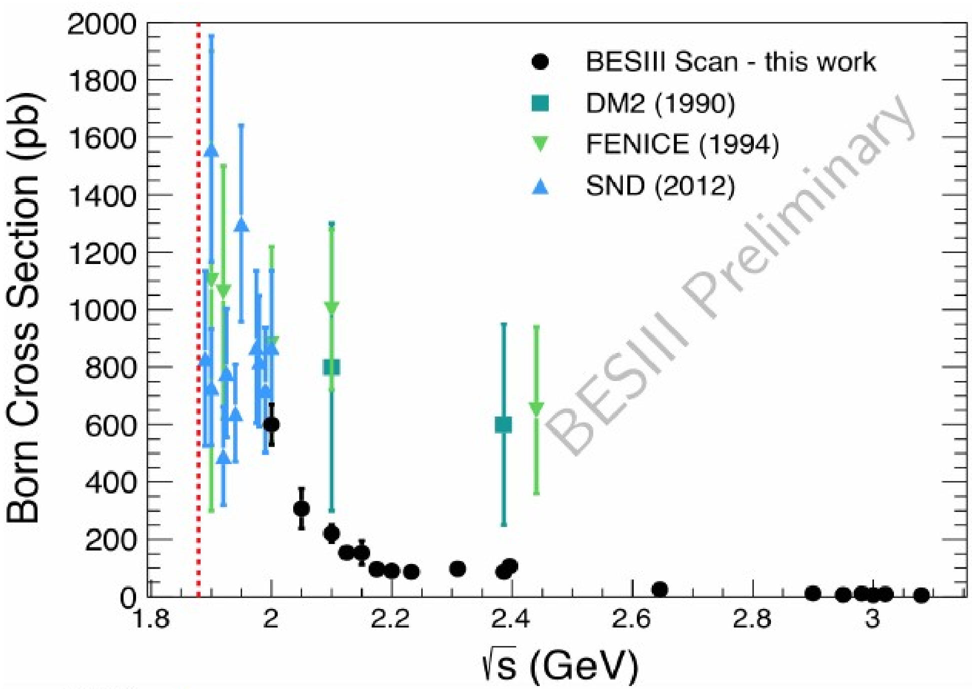


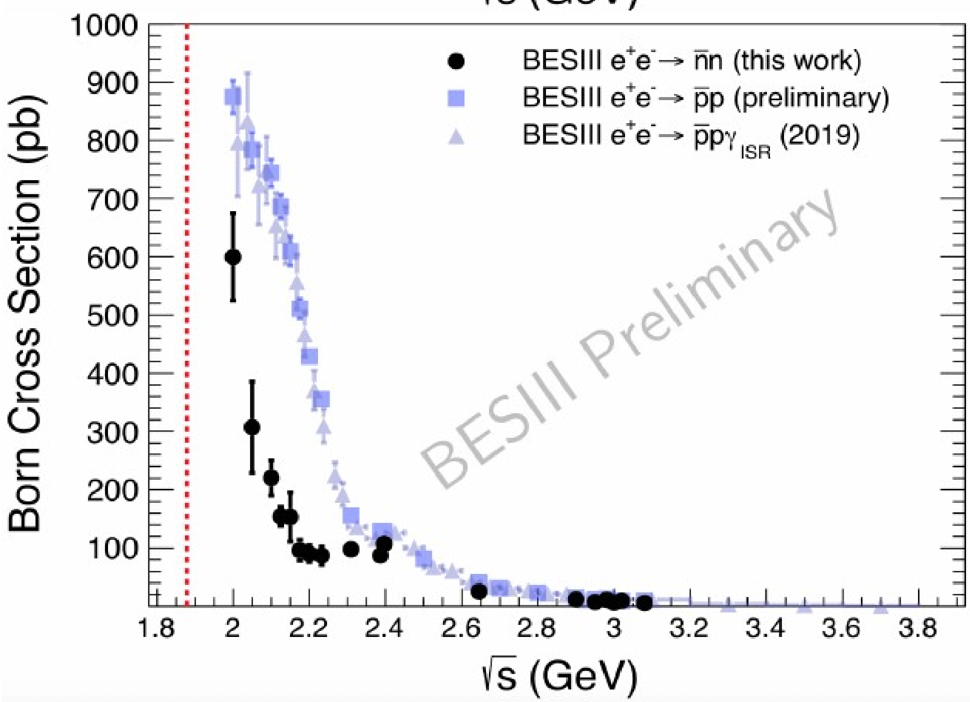
PRL 124, 042001 (2020)

[2.00, 3.08] GeV $e^+e^- \to p\bar{p}$

- unprecedented accuracy for the time-like region
- $|G_E/G_M|$ and $|G_M|$ are determined with accuracy comparable to the space-like region

Neutron Form Factors



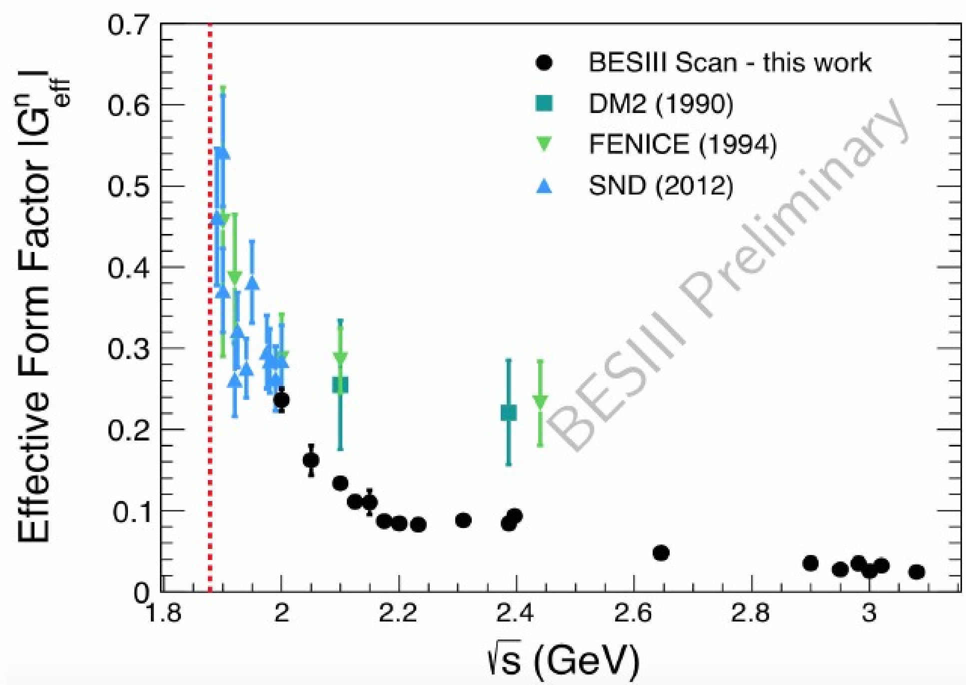


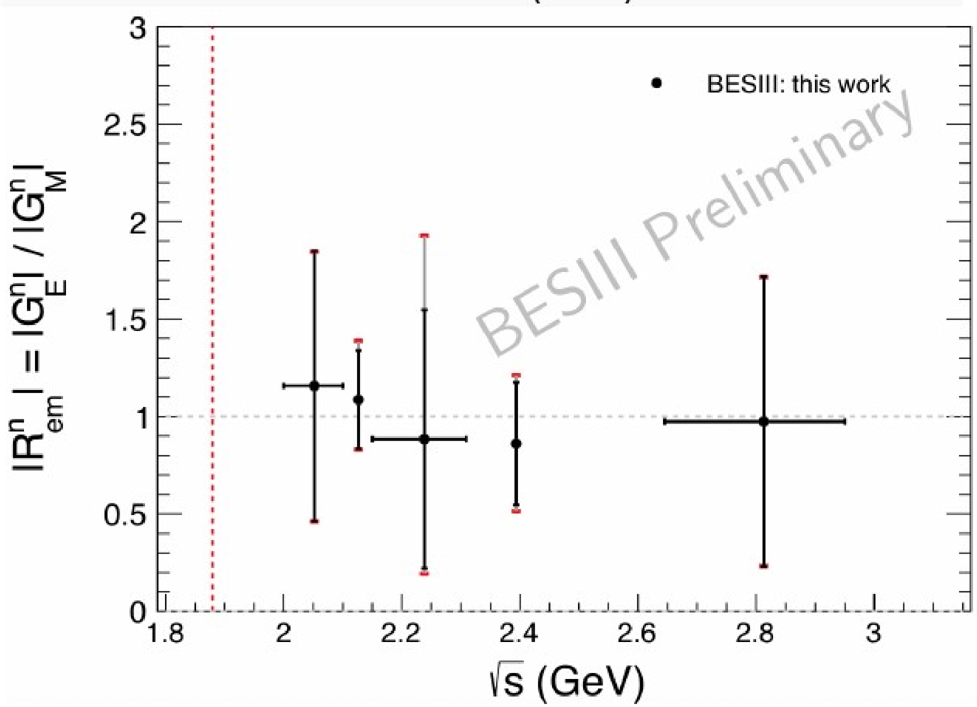
[2.00, 3.08] GeV $e^+e^- \rightarrow n\bar{n}$

BESIII Preliminary!

- The Born cross sections are determined in a wide range of $\sqrt{s}$ with unprecedented precision
- $\sigma_{Born}(n\bar{n})$ and $\sigma_{Born}(p\bar{p})$ are roughly similar at $\sqrt{s} > 2.4$ GeV

Neutron Form Factors



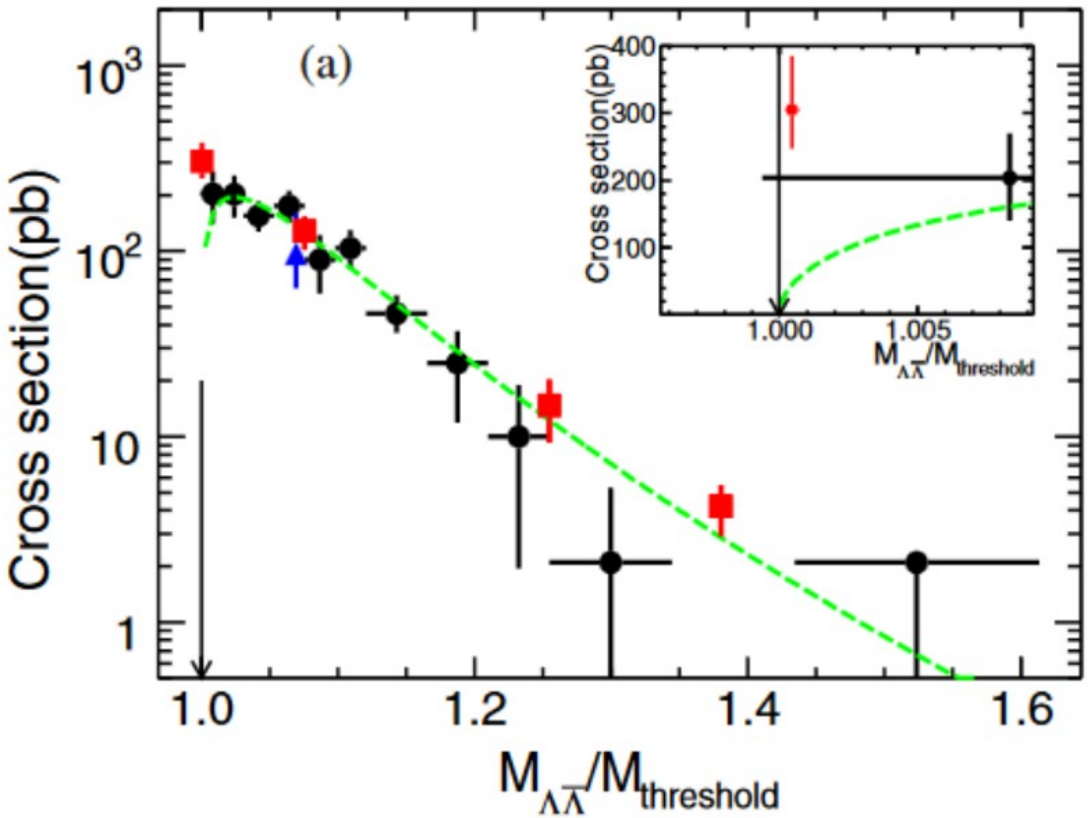


[2.00, 3.08] GeV $e^+e^- \rightarrow n\bar{n}$

BESIII Preliminary!

- $|G_E/G_M|$ and $|G_M|$ have been determined for the first time in the time-like region
- the statistical errors are dominated

Λ Form Factors



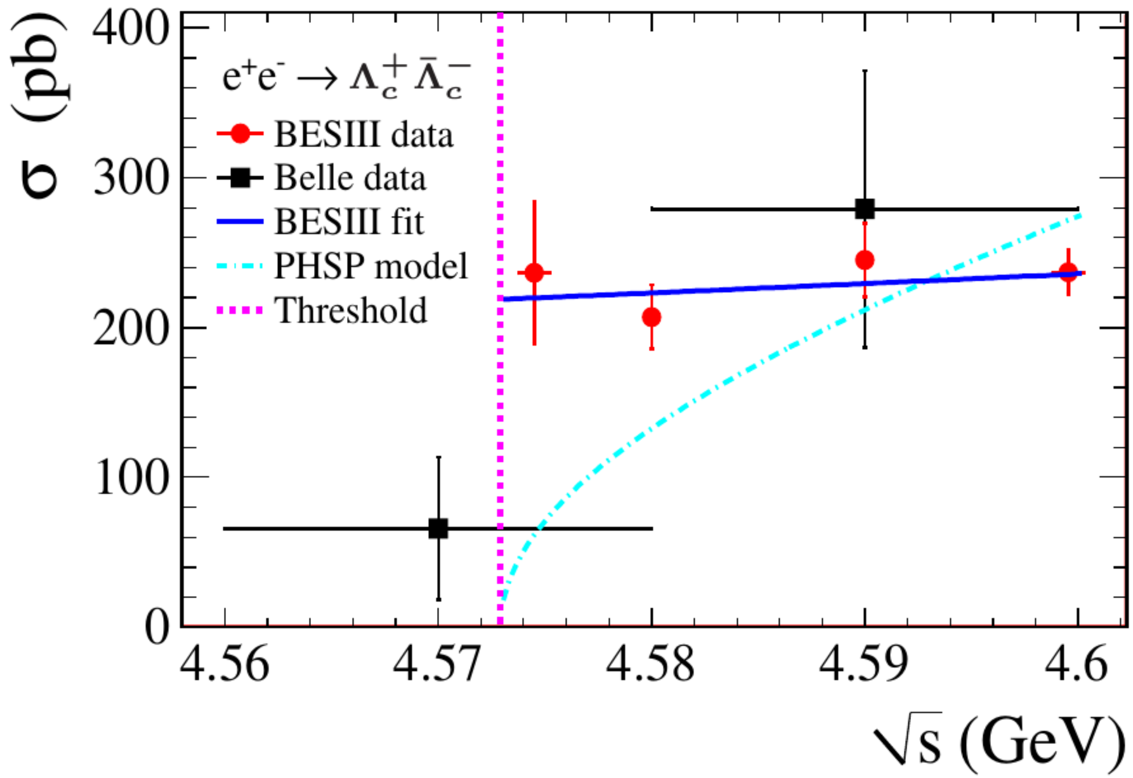
$e^+e^- \rightarrow \Lambda\bar{\Lambda}$

PR D97, 032013 (2018)
PRL 123, 122003 (2019)

- BESIII
- BaBar
- DM2
- pQCD fit

- At BESIII it is possible to measure cross-section down to the threshold energy (1 MeV above)
- BESIII observes a threshold enhancement

Λ_c Form Factors near threshold



$e^+e^- \to \Lambda_c \bar{\Lambda}_c$

PRL 120, 132001 (2018)

- Ecm = 4574.5; 4580.0; 4590.0; 4599.5 MeV
- A flat cross-section down to the threshold
- $|G_E/G_M|$ is measured for the first time for Λ_C:

$G_E = 1.14 \pm 0.14 \pm 0.07$ $G_M = 1.23 \pm 0.05 \pm 0.03$

Summary

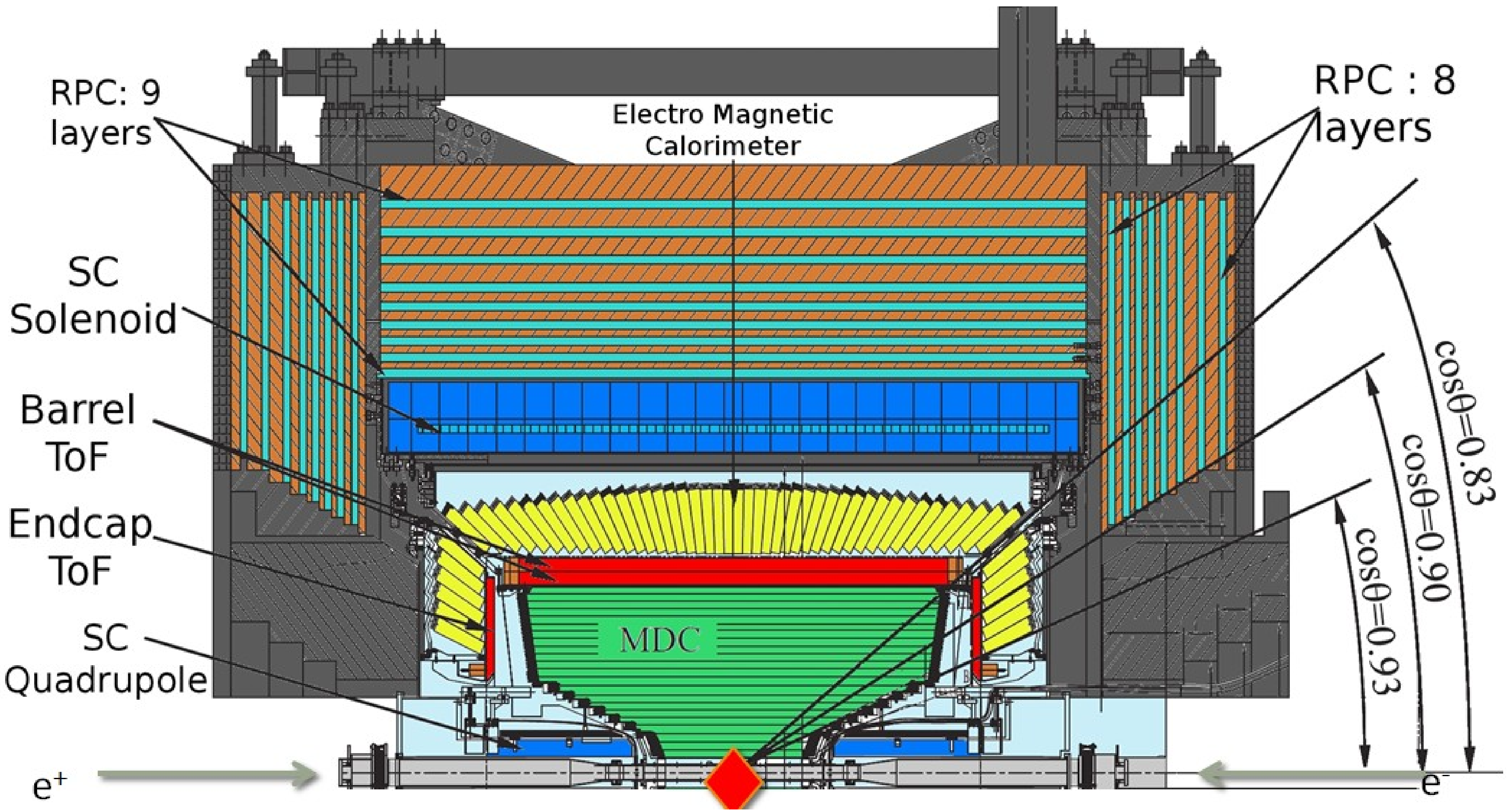
- With its excellent detector and huge statistics, BESIII is now the world leader in the energy domain of charm and charmonium
- Many intriguing and puzzling results obtained in spectroscopy of XYZ states
- The BESIII experiment provides an excellent opportunity to measure the nucleon/baryon form-factors
- BEPCII beam energy is upgraded from 2.3 to 2.45 GeV; top-up injection increases luminosity by 30%; BESIII inner detector upgrade in progress
- BESIII will continue data taking for another 5-10 years – expect even more results!

Backup

The BESIII Collaboration

BESIII detector

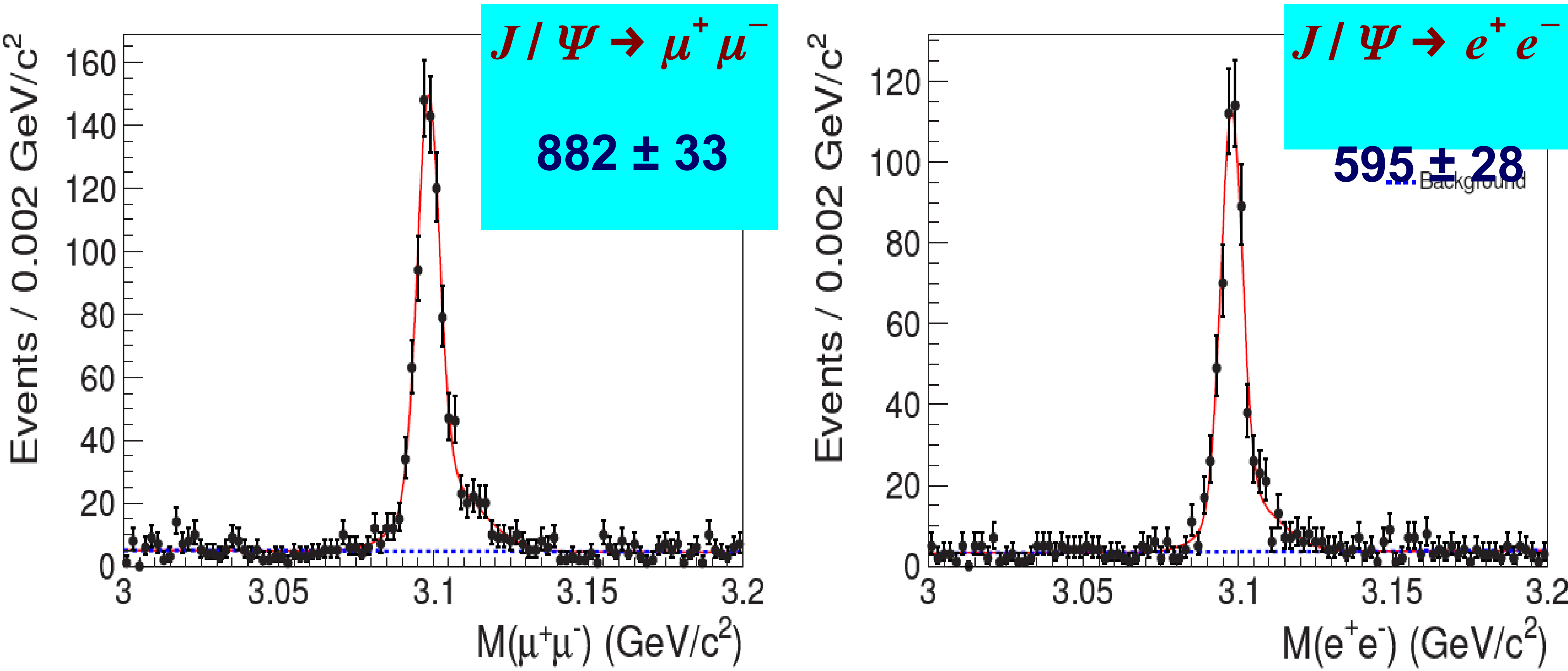
NIM A614, 345(2010)



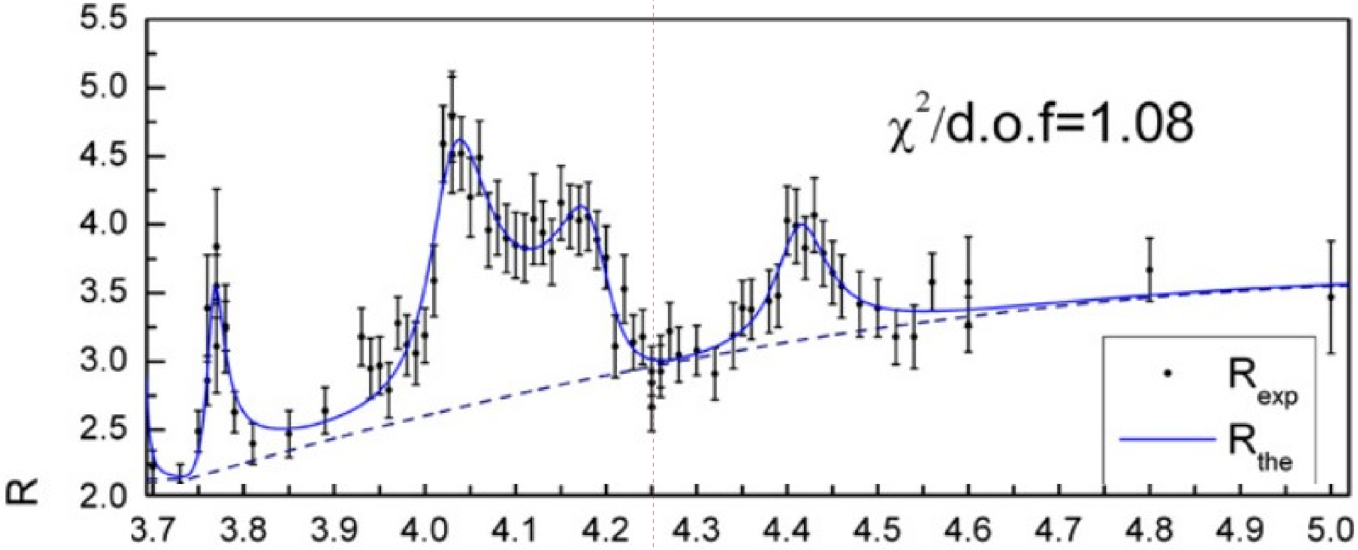
Acceptance:93% of 4π

$e^+e^- \to Y(4260) \to \pi^+\pi^- J/\psi$

BES-III: PRL110, 252001



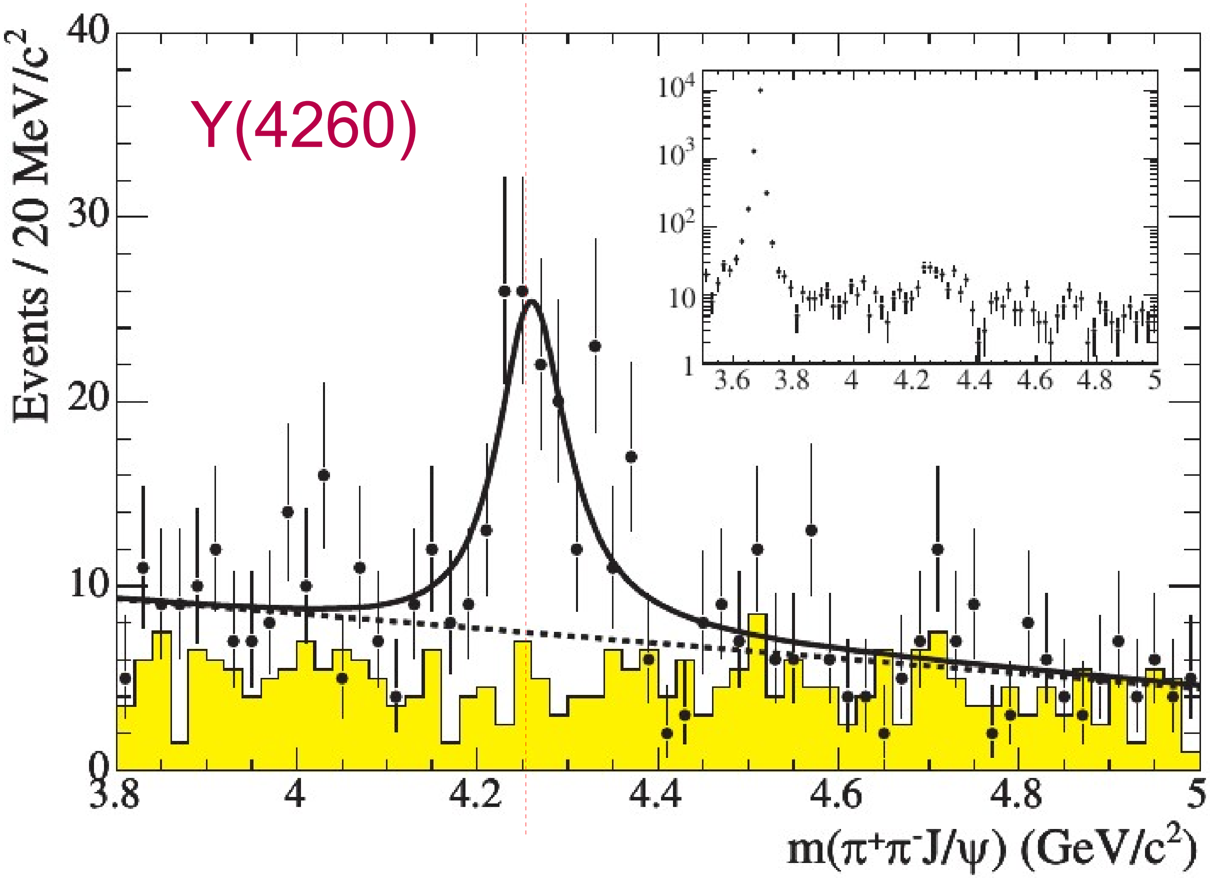
- Lum = 525 pb^{-1}
- J/ψ clearly identified in dilepton decay modes



BESII

PLB 660, 315 (2008)

$e^+e^- \rightarrow$ hadrons

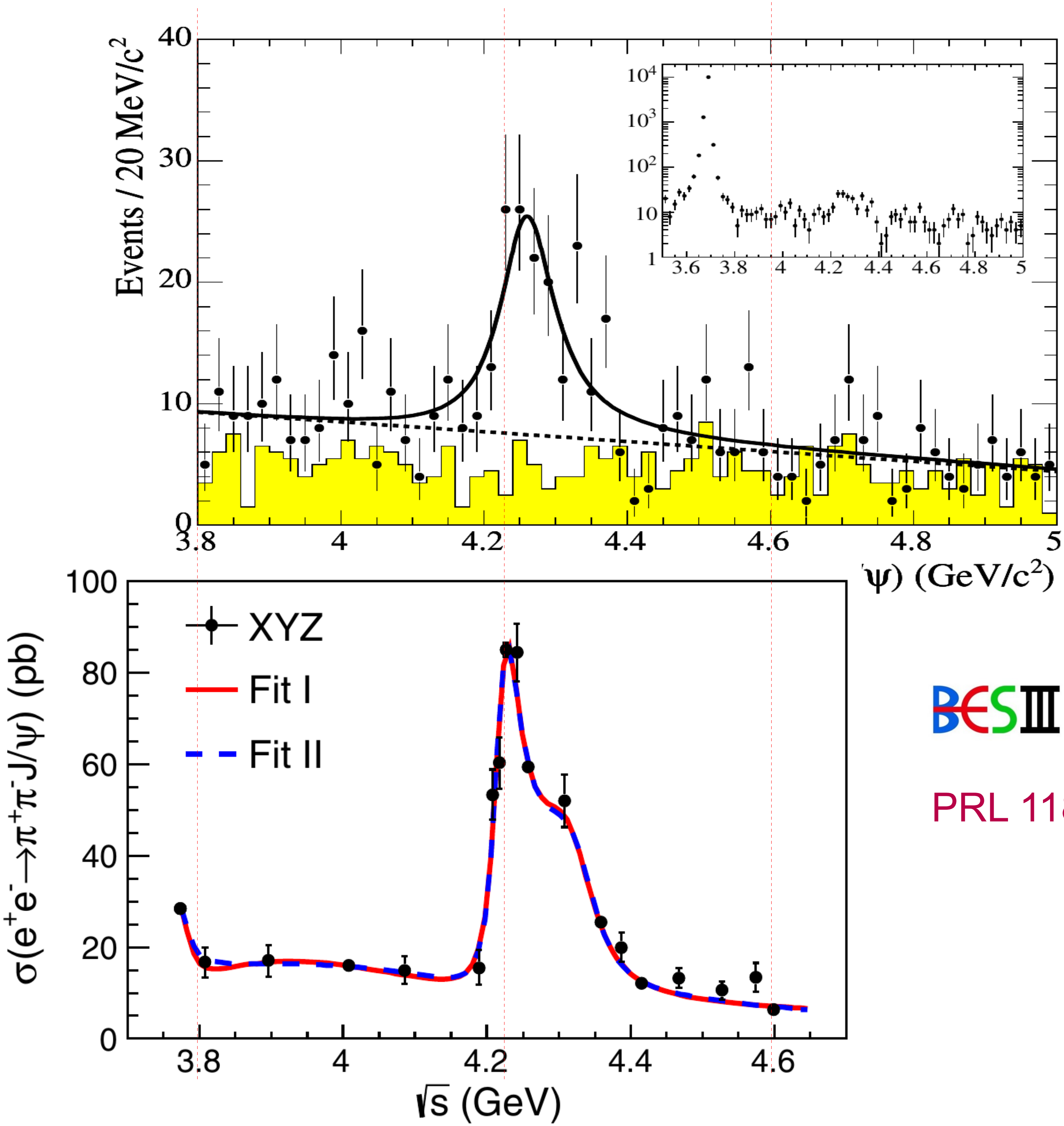


BaBar

PRL 95, 142001 (2005)

$e^+e^- \rightarrow \pi^+\pi^- J/\Psi$

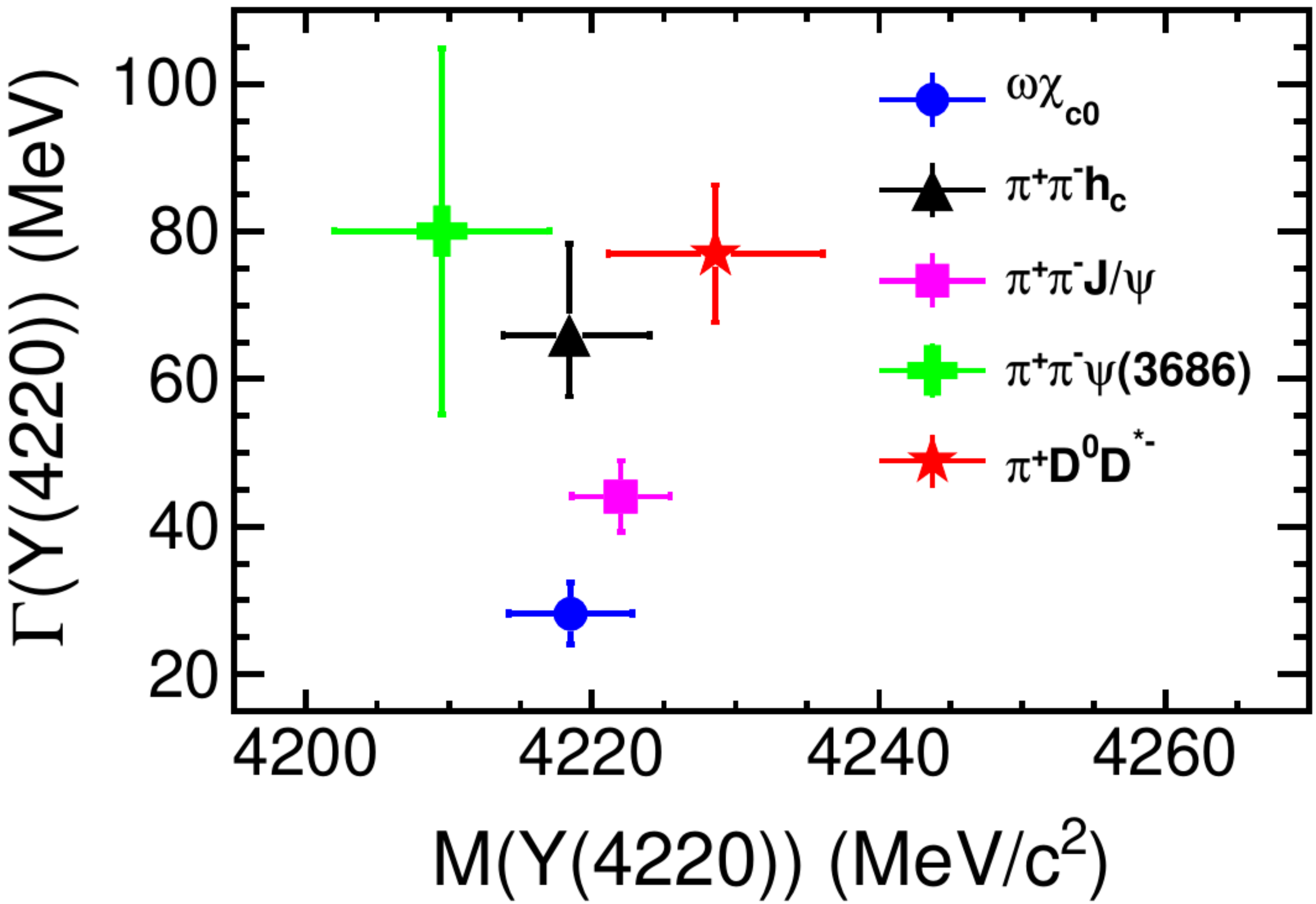
Y(4260)



PRL 95, 142001 (2005)

PRL 118, 092001 (2017)

Y(4220) summary

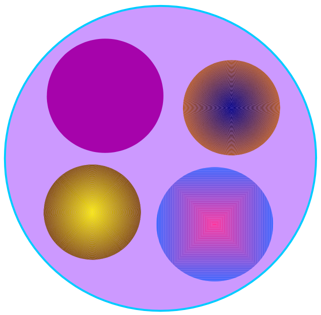


Z_c – заряженные чармоний-подобные мезоны

- BES-3: $e^+e^- \to \pi^{\pm} Z_c^{\mp}$ (also check $\pi^0 Z_c^0$)

  $Z_c^{\pm} \to \pi^{\pm}\left(J/\Psi \text{ or } h_c \text{ or } \Psi' \text{ or } D^* D^{(*)}\right)$

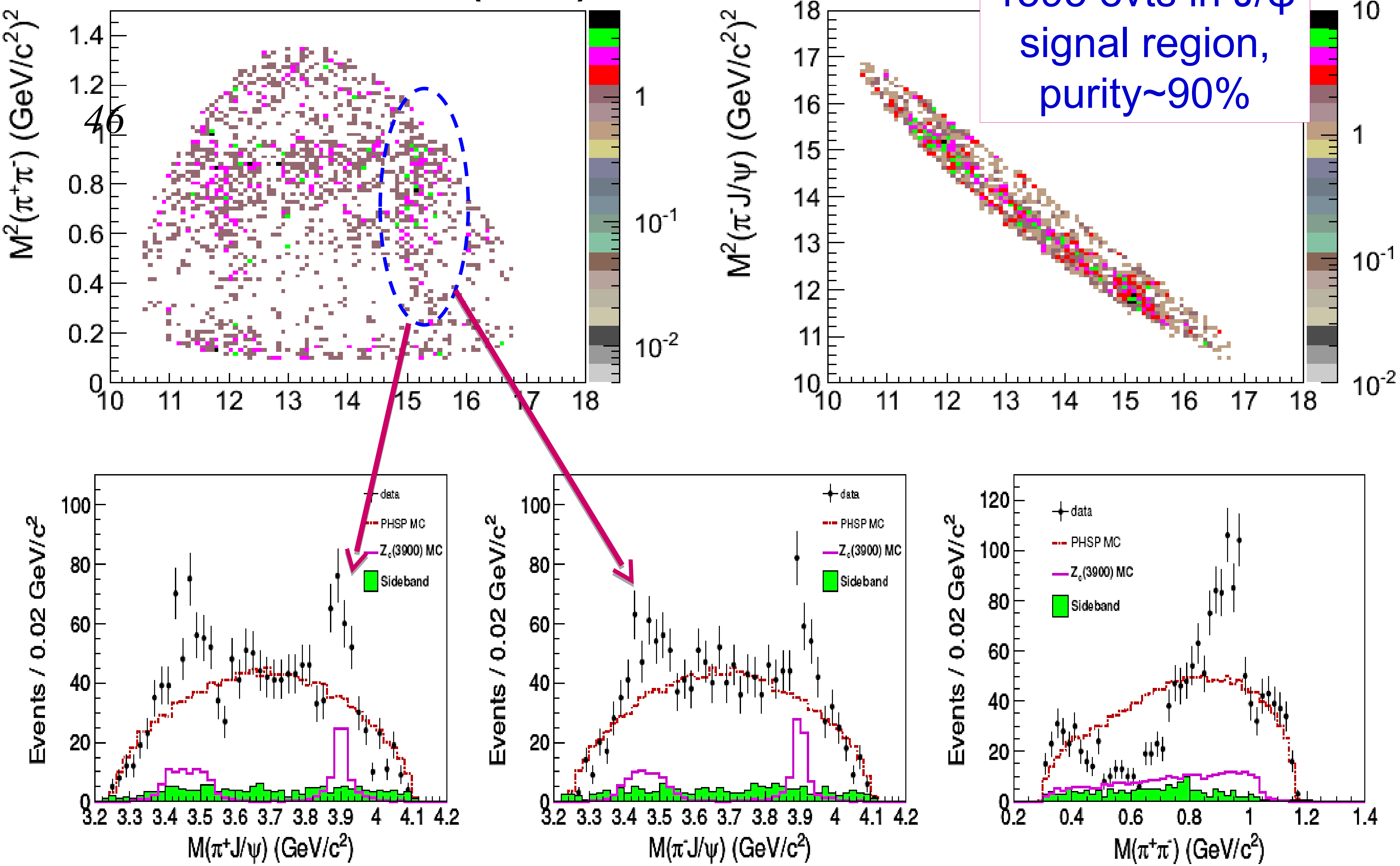
- Хорошая сигнатура события:
  – распад на одно из известных состояний чармония
  – имеет заряд $\Rightarrow$ Nquark ≥ 4



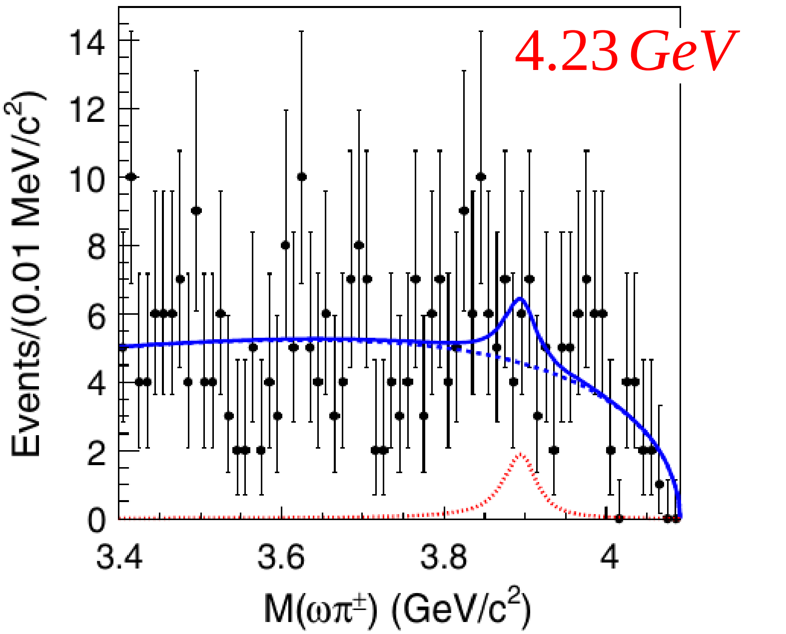
$e^+e^- \to \pi^+\pi^- J/\psi$ @ Ecm=4260 MeV

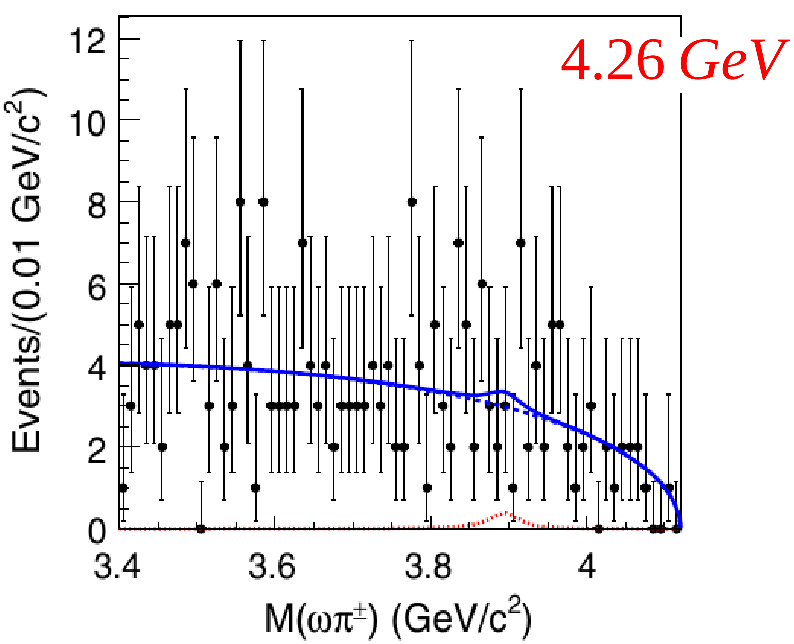
PRL 110, 252001 (2013)

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



Поиск $e^+e^- \to \pi^\pm Z_c^\mp(3900) \to \pi^\pm(\omega\pi^\mp)$





PR D92, 032009 (2015)

- Выполнен поиск распада $Z_c^\pm \to \omega\pi^\pm$
- Значимого сигнала нет
- Пределы (90% CL) на Борновское сечение $\sigma(e^+e^- \to \pi^\pm Z_c^\mp \to \pi^\pm\omega\pi^\mp)$

  < 0.26 pb для Ecm = 4.23 GeV

  < 0.18 pb для Ecm = 4.26 Gev

Summary on Zc decay modes

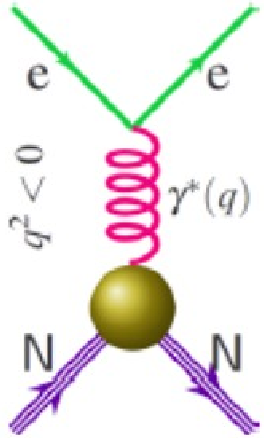
Zc	Decay	Mass (MeV/c^2)	Width (Mev)	J^P
$Z_c^+(3900)$	$\pi^+ J/\Psi$	$3899.0\pm3.6\pm4.9$	$46\pm10\pm20$	1^+
$Z_c^0(3900)$	$\pi^0 J/\Psi$	$3894.8\pm2.3\pm3.2$	$29.6\pm8.2\pm8.2$	
$Z_c^+(3885)$	$(DD^*)^+$	$3883.9\pm1.5\pm4.2$	$24.8\pm3.3\pm11.0$	1^+
$Z_c^0(3885)$	$(DD^*)^0$	$3885.7^{+4.3}_{-5.7}\pm8.4$	$35^{+11}_{-12}\pm15$	
$Z_c^+(4020)$	$\pi^+ h_c$	$4022.9\pm0.8\pm2.7$	$7.9\pm2.7\pm2.6$	
$Z_c^0(4020)$	$\pi^0 h_c$	$4023.8\pm2.2\pm3.8$		
$Z_c^+(4025)$	$(D^*D^*)^+$	$4026.3\pm2.6\pm3.7$	$24.8\pm5.6\pm7.7$	
$Z_c^0(4025)$	$(D^*D^*)^0$	$4025.5^{+2.0}_{-4.7}\pm3.1$	$23.0\pm6.0\pm1.0$	

- Strong evidence for $Zc(3900) \rightarrow \rho^{\pm}\eta_c$

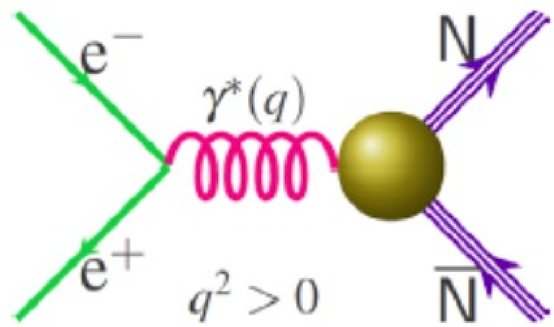
Electromagnetic Form Factors

$eN \to eN$

Space-like: FF real



$e^+e^- \leftrightarrow N\bar{N}, \Lambda\bar{\Lambda}, \ldots$



Time-like: FF complex

Vector current, **two form factors** (F_1 and F_2)

$$\Gamma_\mu = e\bar{u}(p')[F_1(q^2)\gamma_\mu + \frac{\kappa}{2M_N}F_2(q^2)i\sigma_{\mu\nu}q^\nu]u(p)e^{iqx}$$

Dirac	**Pauli**
$F_1^p(q^2=0)=1$	$F_2^p(q^2)=1$
$F_1^n(q^2=0)=0$	$F_2^n(q^2)=1$

Sachs

$$G_E = F_1 + \frac{\kappa q^2}{4M^2}F_2 \qquad G_M = F_1 + \kappa F_2$$

$$G_E(4M_p^2) = G_M(4M_p^2)$$

Baryon-pair production near threshold

- The Born cross section for $e^+e^- \to \gamma^* \to B\bar{B}$, can be expressed in terms of electromagnetic form factor G_E and G_M:

$$\sigma_{B\bar{B}}(m) = \frac{4\pi\alpha^2 C\beta}{3m^2}\left[|G_M(m)|^2 + \frac{1}{2\tau}|G_E(m)|^2\right]$$

$\alpha = \frac{1}{137}$ is fine structure constant, $\beta = \sqrt{1 - 4m_B^2/m^2}$ is the velocity, $\tau = m^2/4m_B^2$

- The Coulomb factor $C = \begin{cases} \frac{\pi\alpha}{\beta}\frac{1}{1-\exp(-\frac{\pi\alpha}{\beta})} & \text{for a charged } B\bar{B} \text{ pair} \\ 1 & \text{for a neutral } B\bar{B} \text{ pair} \end{cases}$

- For the neutral pair production, the cross section should be 0 at threshold, and is expected to increase with the velocity near the threshold.