From Studies of Light Mesons to Charmonium

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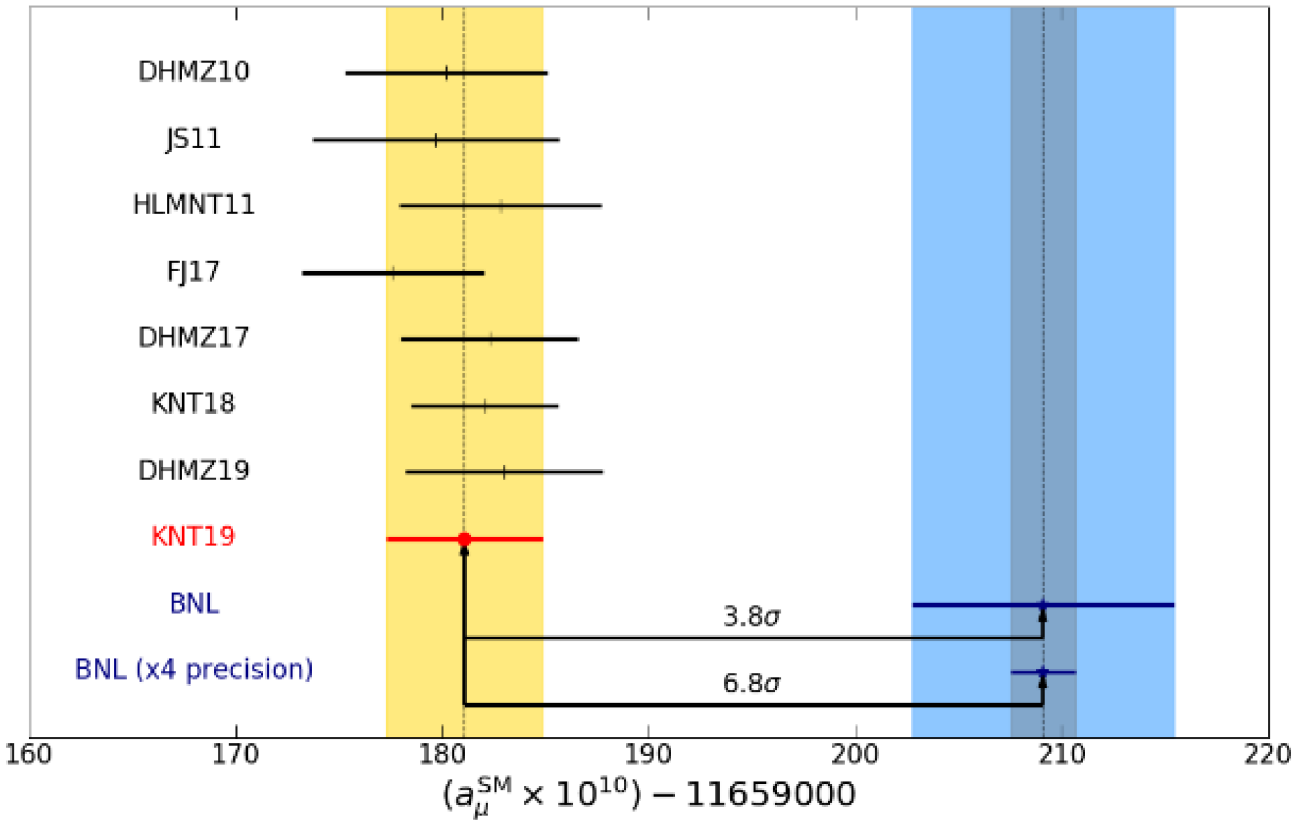
Outline

Low-Energy Physics from Initial-State Radiation (ISR)

What Can We Learn from Low-Energy e^+e^- Cross Sections?

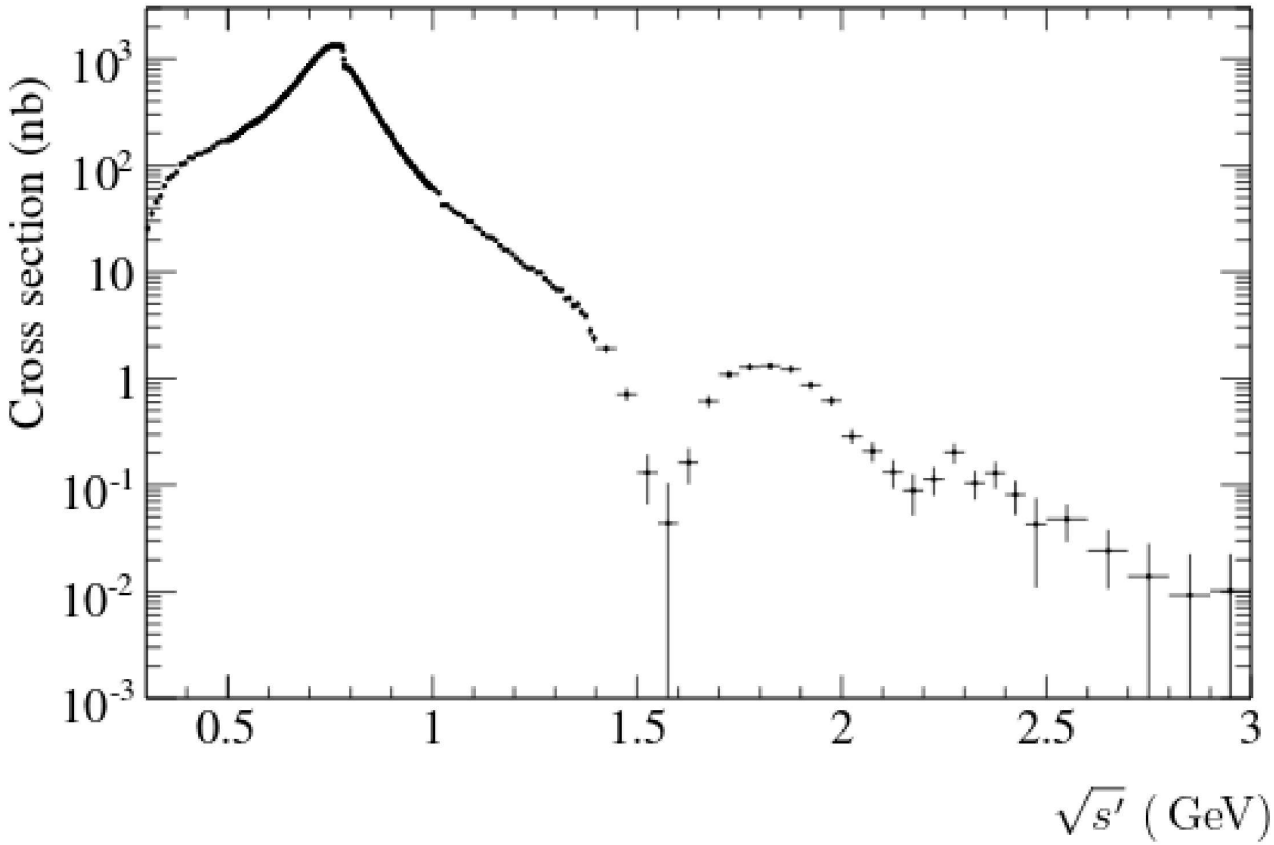
1. Detailed study of exclusive processes $e^+e^- \to (2-7)h, h = \pi, K, \eta, p, \ldots$
   - Test of models and input to theory (ChPT, Vector Dominance, QCD, ...)
   - Properties of vector mesons $(\rho', \omega', \phi', \ldots)$
   - Search for exotic states (tetraquarks, hybrids, glueballs)
   - Test of CVC relations between e^+e^- and τ-lepton
   - Interactions of light (u, d, s) quarks
2. High-precision determination of $R = \sigma(e^+e^- \to \text{ hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ at low energies and fundamental quantitites
   - $(g_\mu - 2)/2$
   - $\alpha(M_Z^2)$
   - QCD sum rules (α_s, quark and gluon condensates)

Current Status of a_μ



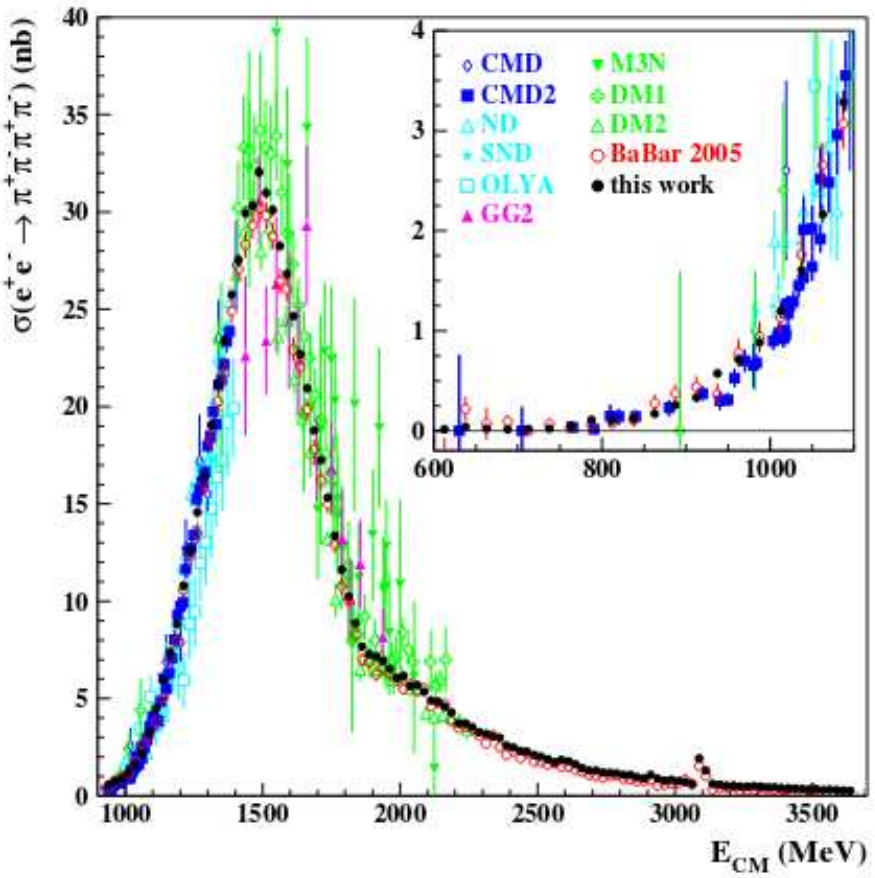
A. Keshavarzi, D. Nomura, Th. Teubner, arXiv:1911.00367

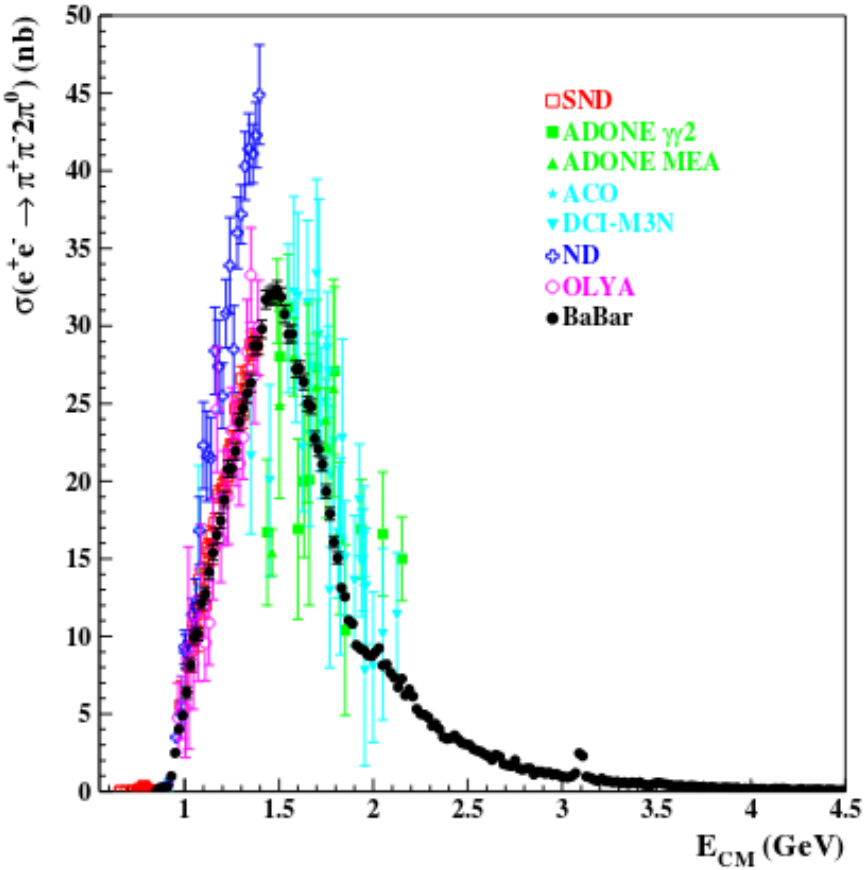
$e^+e^- \to \pi^+\pi^-$ at BaBar



J.P.Lees et al., Phys.Rev. D86, 032013 (2012)

Production of Four Pions at BaBar

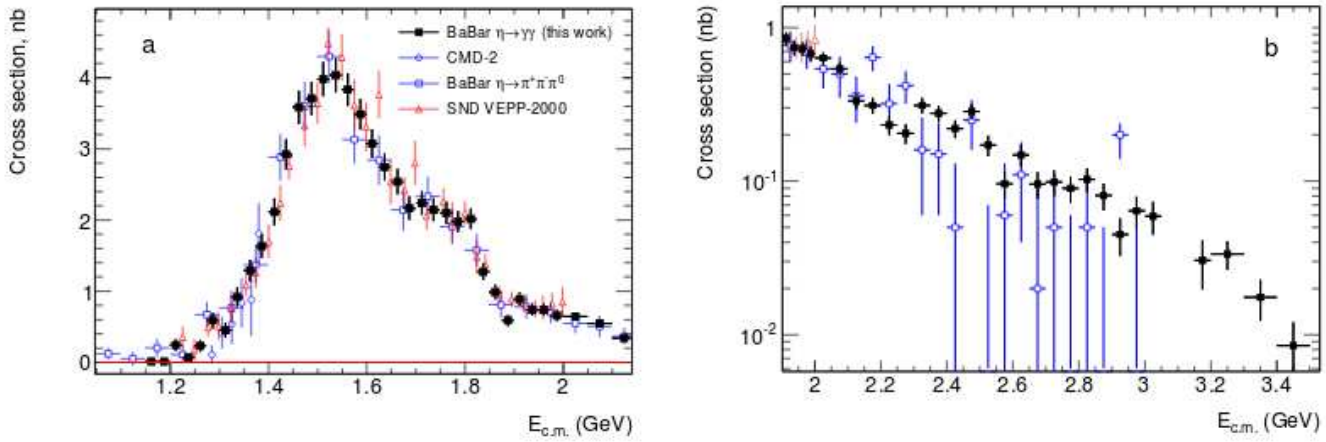




$2\pi^+2\pi^-$ J.P.Lees et al., Phys.Rev. D85, 112009 (2012)

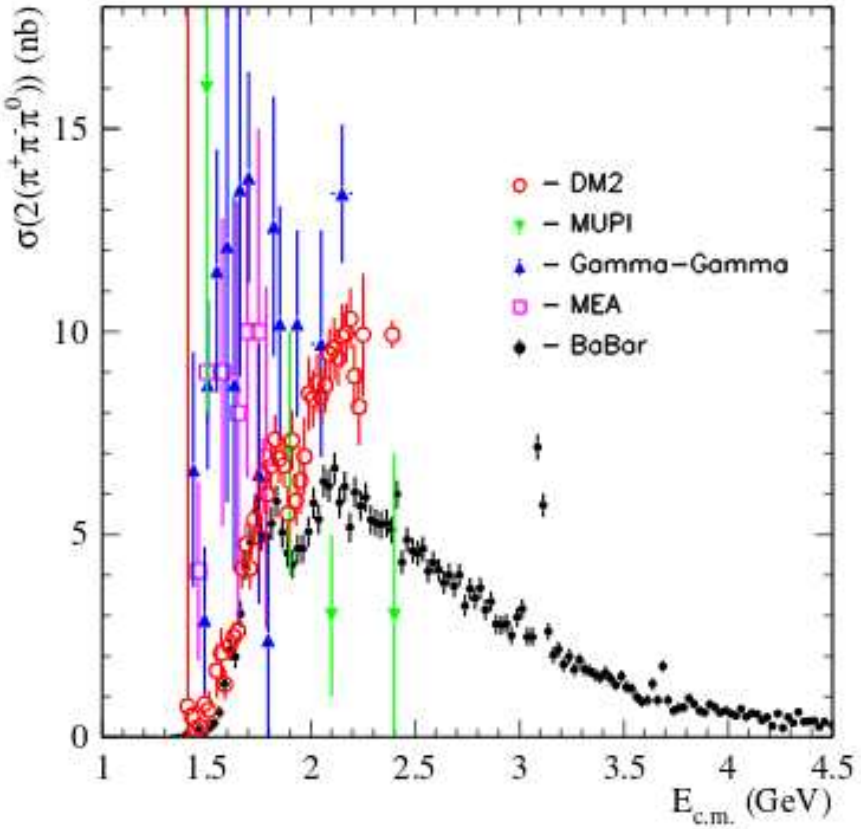
$\pi^+\pi^-2\pi^0$ J.P.Lees et al., Phys.Rev. D96, 092009 (2017)

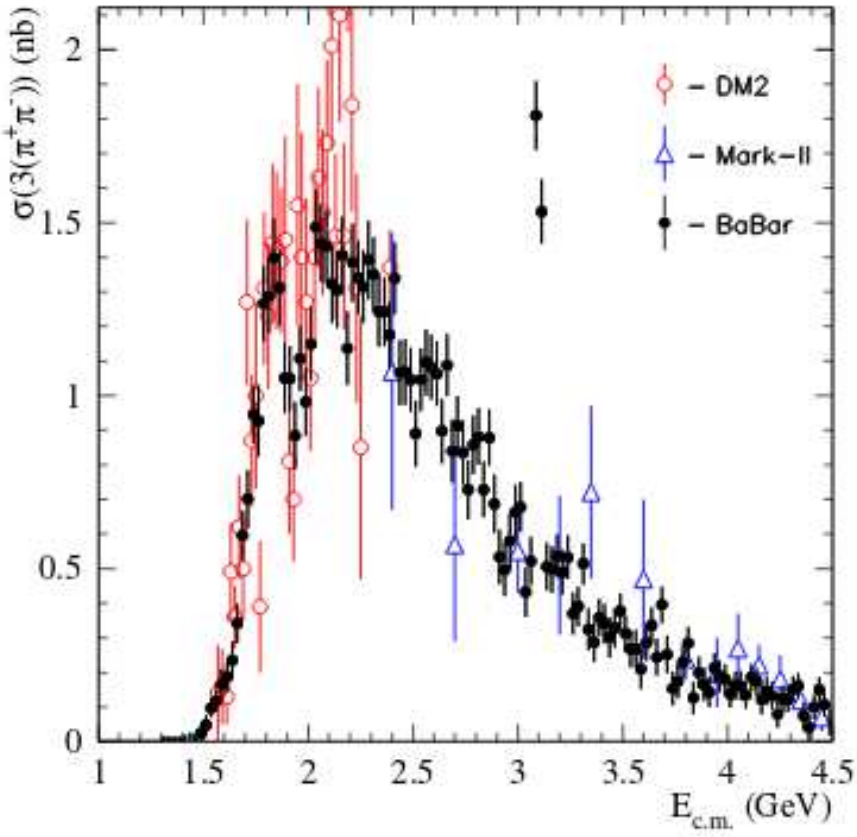
$e^+e^- \to \eta\pi^+\pi^-$ at BaBar



J.P.Lees et al., Phys.Rev. D86, 032013 (2012)

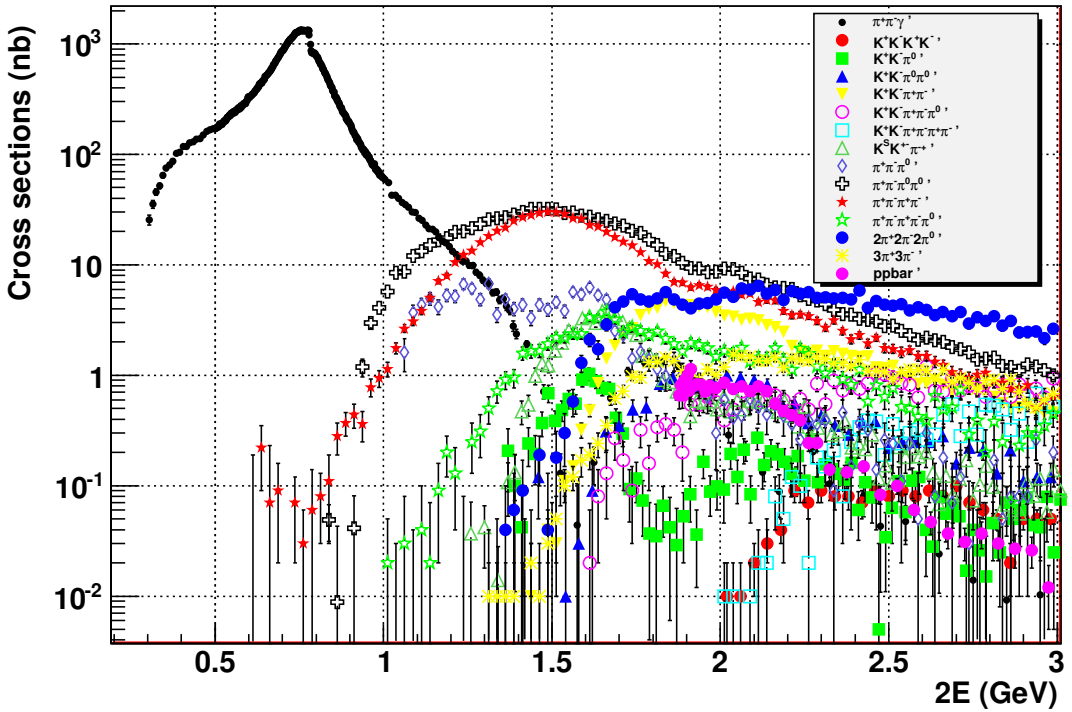
Production of Six Pions at BaBar





$2\pi^+2\pi^-2\pi^0$, $3\pi^+3\pi^-$ B. Aubert et al., Phys.Rev. D73, 052003 (2006)

Current Status of Exclusive Measurements with ISR



BaBar studied the energy range $\sqrt{s} < 3$ GeV, also BESIII

BelleII will contribute with $\times 100$ statistics and $\sqrt{s} < 5$ GeV

Conclusions on Cross Section Measurements

BaBar collected large statistics below 2 GeV with ISR,
precision is much smaller from 2 to 3 GeV

Direct scans at BESIII already gave a few million events on tape

CMD-3 and SND at VEPP-2000 plan to collect about 0.5fb^{-1} from 1 to 2 GeV

Measurements of exclusive cross sections and joint analysis of
the data of BESIII and VEPP-2000 provide excellent input for
developing new models of low-energy strong interactions

Light Mesons

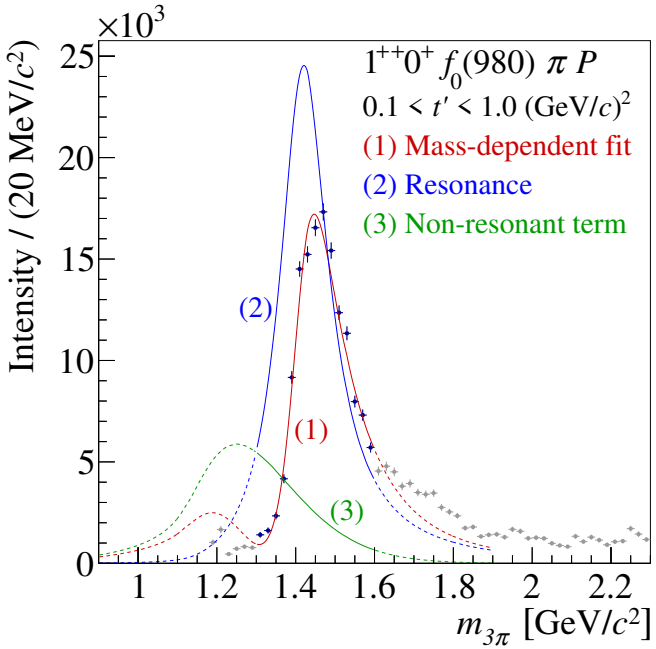
Light Mesons – $a_1(1260)$

$a_1(1260)$ $I^G(J^{PC}) = 1^-(1^{++})$ Observed in hadronic reactions, e^+e^-, τ

$M = 1230 \pm 40$ MeV $\quad \Gamma = 250 - -600$ MeV

Decay modes: 3π ($\rho\pi$ ($S/D-$wave), $f_0\pi$, $f_2\pi$), $K\bar{K}\pi$

Light Mesons – $a_1(1420)$



COMPASS discovered a new light meson, $a_1(1420)$, $I^G(J^{PC}) = 1^-(1^{++})$

$M = 1414^{+15}_{-13}$ MeV, $\Gamma = 153^{+\ 8}_{-23}$ MeV

Decays into $f_0(980)\pi$ only, suggests exotic nature?

C. Adolph et al., Phys. Rev. Lett. 115, 082001 (2015)

$a_1(1640)$

$a_1(1640)$ $I^G(J^{PC}) = 1^-(1^{++})$ Observed in hadronic reactions

$M = 1655 \pm 16$ MeV $\Gamma = 254 \pm 40$ MeV

Decay modes: 3π, $\omega\pi\pi$, $f_1(1285)$

New coupled-channel analysis of the τ decays needed

Light Mesons – $\pi(1300)$

$\pi(1300)$ $I^G(J^{PC}) = 1^-(0^{-+})$ Observed in hadronic reactions

$M = 1300 \pm 100$ MeV $\Gamma = 200 - -400$ MeV

Decay modes: $\rho\pi$, $\pi(\pi\pi)_{\mathrm{S-wave}}$

$\Gamma(\pi(\pi\pi)_{\mathrm{S-wave}})/\Gamma(\rho\pi)$:
2.2 ± 0.4 in $p\bar{p}$ at Obelix, but
< 0.15 in $p\bar{p}$ at Crystal Barrel

Light Mesons – $f_0(1370)$, $f_0(1500)$

State	$f_0(1370)$	$f_0(1500)$
$I^G(J^{PC})$	$0^+(0^{++})$	$0^+(0^{++})$
Mass, MeV	1200-1500	1506 ± 6
Width, MeV	300-500	112 ± 9
Decay	$\pi\pi$??	34.5 ± 2.2
fractions, %	4π ??	48.9 ± 3.3
	$K\bar{K}$??	8.5 ± 1.0
	$\eta\eta$??	6.0 ± 0.9

Two many scalars!

Light Mesons – $X(1835)$

$X(1835)$ – Different quantum numbers

Mass: 1825 – 1910 MeV Width from very small to 270 MeV

Decay modes: $p\bar{p}$, $\eta'\pi^+\pi^-$, $K^0_S K^0_S \eta$, $\gamma\phi(1020)$, $3(\pi^+\pi^-)$

A combination of various states near $N\bar{N}$ threshold,
account of strong interactions is necessary

Light Mesons – $\phi(2170)$, $\rho(2200)$

State	$\phi(2170)$	$\rho(2200)$
$I^G(J^{PC})$	$0^-(1^{--})$	$1^+(1^{--})$
Mass, MeV	2080–2240	2070–2250
Width, MeV	60–190	100–400
Decays	$\phi\pi\pi$ $\phi\pi\pi$ $\phi\eta$	$\pi^+\pi^-$ K^+K^-, $K^0_SK^0_L$ $p\bar{p}$ $\omega\pi^0$ $\eta'(958)\pi^+\pi^-$

Light Mesons – Conclusions

Many interesting problems

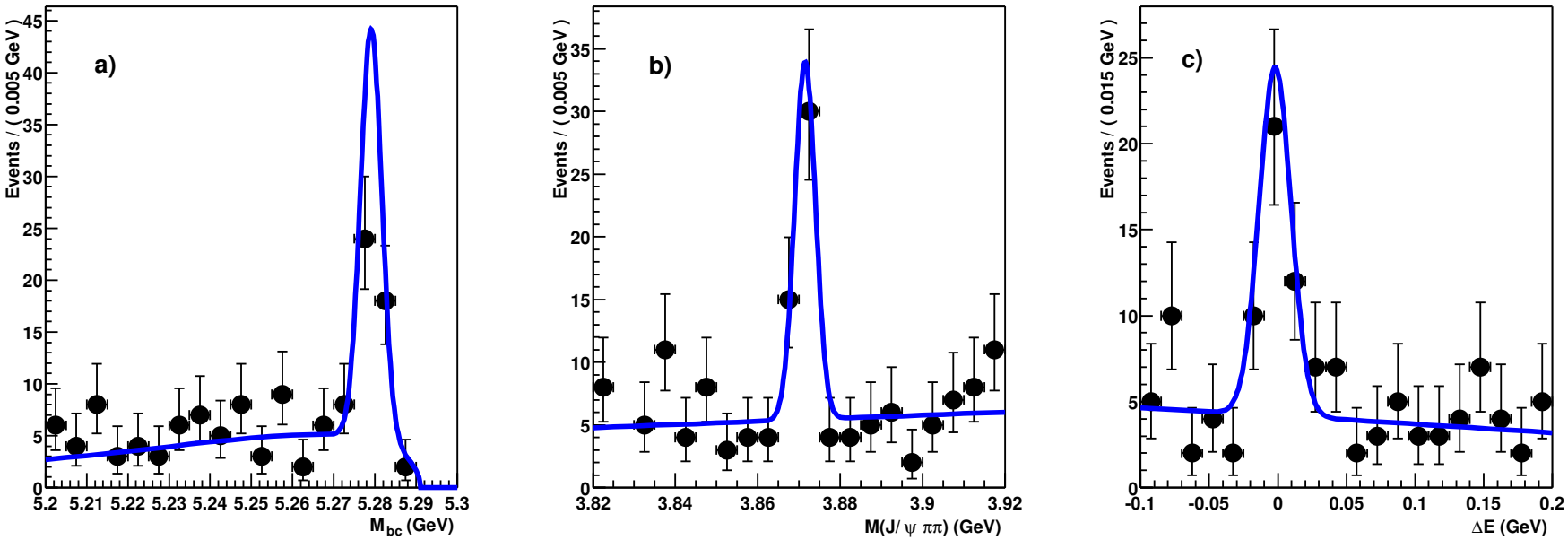
in the light meson sector

awaiting solution and

promising for low-energy QCD

Charmonium Spectroscopy

Discovery of $X(3872)$



Belle – S.-K. Choi et al., PRL 91 (2003) 262001; 152M $B\bar{B}$ pairs; 1699 cites!

A 10.3σ $J/\psi\pi^+\pi^-$ state with $M = (3872.0 \pm 0.6 \pm 0.5)$ MeV and $\Gamma < 2.3$ MeV

Confirmed by CDF and D0 in $p\bar{p}$ and BaBar in B decays

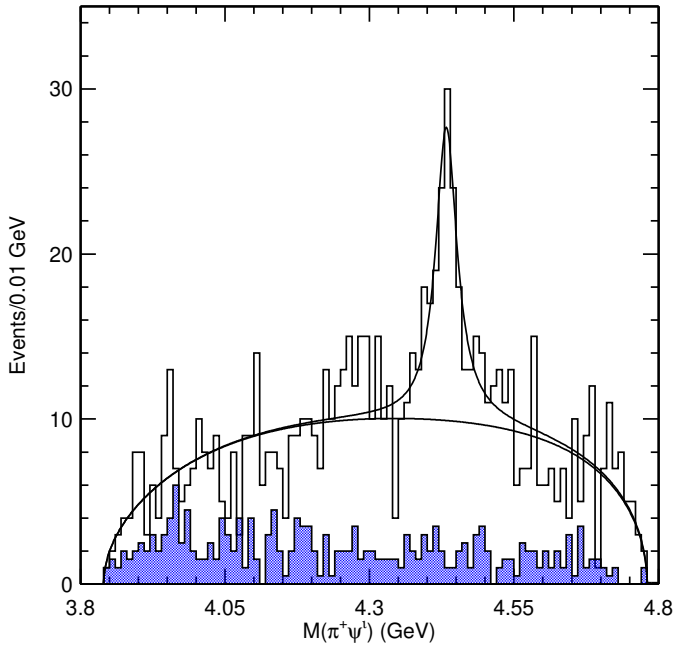
Seen and extensively studied at LHC

What do we know about $X(3872)$?

- $M_{\pi^+\pi^-} \approx M_\rho$ (violates isospin)
- Decays to $J/\psi\gamma,\ \psi(2S)\gamma \Rightarrow C = +1$
- $\mathcal{B}(\psi(2S)\gamma)/\mathcal{B}(J/\psi\gamma) = 2.46 \pm 0.64 \pm 0.29$
- Spin-parity analysis $\Rightarrow J^{PC} = 1^{++}, 2^{-+}$, finally $J^{PC} = 1^{++}$
- Doesn't decay to $\chi_{c1}\gamma,\ D\bar{D},\ \gamma\gamma,\ e^+e^-$
- No charged partner, not an isovector
- Belle (BaBar) observed decays to $D^0\bar{D}^0\pi^0 (D^0\bar{D}^{*0})$ with mass 3875 MeV, marginally OK with one state or could be two states, the rate much larger than that of $J/\psi\pi^+\pi^-$, many models suggested, but ...
- CDF: $M = 3871.61 \pm 0.16 \pm 0.19$ MeV Most precise!
  0.19 ± 0.43 MeV below the $D^0\bar{D}^{*0}$ threshold, no 2 states, $\Delta M < 3.6$ MeV at 95%CL

Charged States – I

S.-K. Choi et al., Phys. Rev. Lett. 100 (2008) 142001 saw the very first charged $c\bar{c}$-like state, $B \to K\ Z(4430)^{\pm}(\psi(2S)\pi^{\pm})$, with 657M $B\bar{B}$ pairs (605 fb^{-1}), 629 cites!!



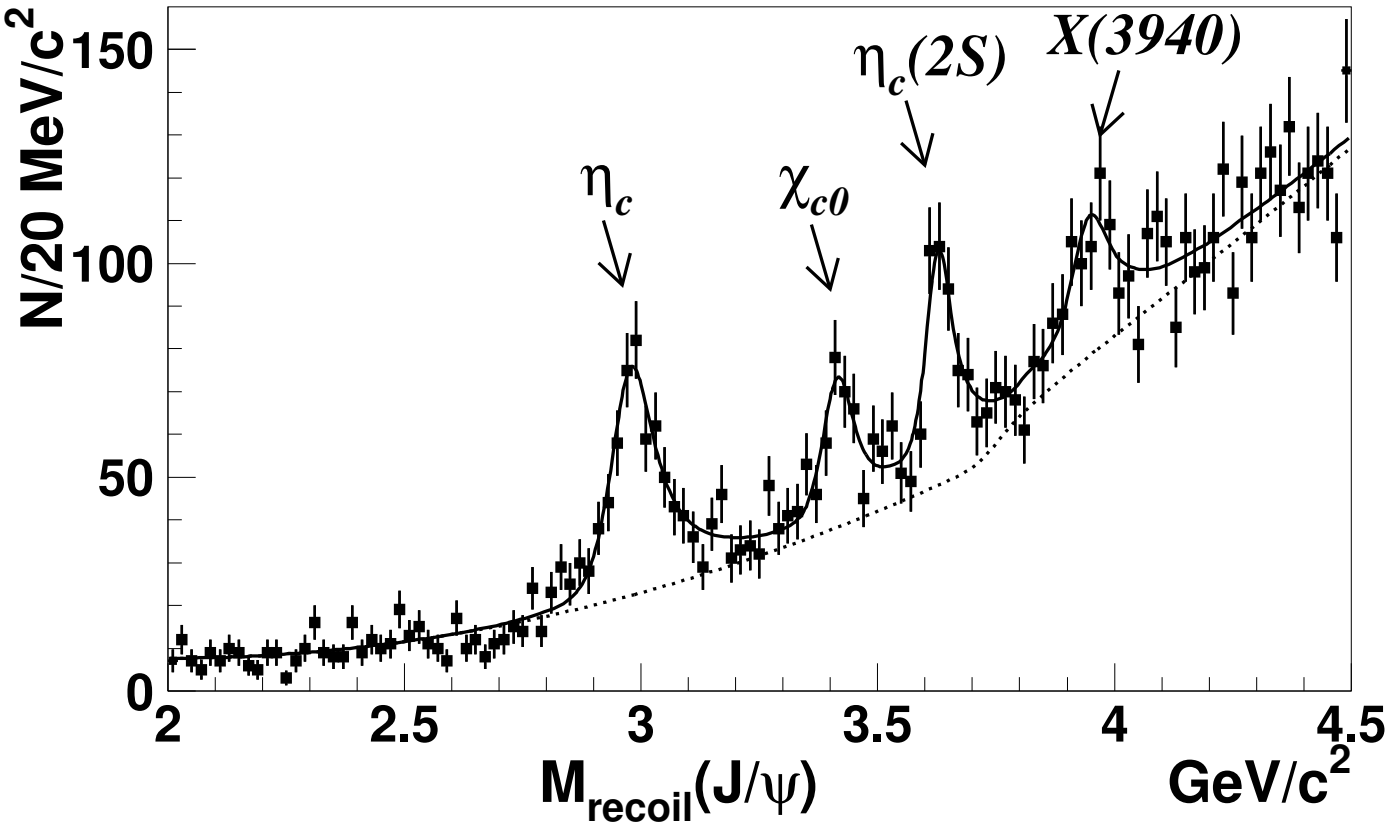
Confirmed by Dalitz plot analysis in R. Mizuk et al., Phys. Rev. D80 (2009) 031104

Amplitude analysis by LHCb, R. Aaij et al., Phys. Rev. Lett. 112 (2014) 222002

Charged States – II

State	$I^G(J^{PC})$	M/Γ, MeV	Decays
$Z_c(3900)$	$1^+(1^{+-})$	3887/28	$J/\psi,\ D\bar{D}^*$
$X(4020)$	$1^+(?^{?-})$	4024/13	$h_c(1P)\pi,\ D^*\bar{D}^*$
$X(4050)$	$1^-(?^{?+})$	4051/24	$\chi_{c1}(1P)\pi$
$X(4055)$	$1^+(?^{?-})$	4054/45	$\psi(2S)\pi$
$Z_c(4200)$	$1^+(1^{+-})$	4196/370	J/ψ
$R_{c0}(4240)$	$1^+(0^{--})$	4239/220	$\psi(2S)\pi$
$X(4250)$	$1^-(?^{?+})$	4248/177	$\chi_{c1}(1P)\pi$
$Z_c(4430)$	$1^+(1^{+-})$	4478/181	$\psi(2S)\pi,\ J/\psi\pi$

Double Charmonium at Belle



K. Abe et al., PRL 98, 082001 (2007); Belle – 357 fb^{-1}

A new state $X(3940)$ observed in the recoil to J/ψ,

M=$3942^{+7}_{-6} \pm 6$ MeV, $\Gamma = 37^{+26}_{-15} \pm 8$ MeV

Conclusions on $c\bar{c}$ States

- A lot of new information/states from BESIII and LHCb
- Charged charmonia well established
- 38 states listed by PDG in 2019
- Their nature is sometimes unclear:
  molecules, tetraquarks, hadrocharmonia, hybrids, ...
- In the new PDG Naming scheme $X(3872)$ is now called $\chi_{c1}(3872)$,
  is it indeed a mixture of the $D^0\overline{D}^{*0}$ molecule and $c\bar{c}$?