Physics with e^+e^- at Low Energy

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Outline

1. Physics of light quarks (u, d, s)
2. Physics of τ lepton and c, b quarks

Physics of τ lepton and c, b quarks

Outline

1. τ lepton
2. Charmonium
3. Bottomonium
4. Conclusions

General about τ

- τ lepton is one of the six fundamental leptons
- As the heaviest lepton, it may decay into both leptons and hadrons:
  PDG-2016 lists 244 different τ decay modes
- We can study all interactions allowed in the Standard Model
  and search for effects of New Physics
  usually enhanced due to large m_τ
- It is a very clean laboratory with no hadrons
  in the initial and only a few in the final state
- τ leptons are important at LHC
- Serious progress is related to the B-factories

τ Lepton Factories

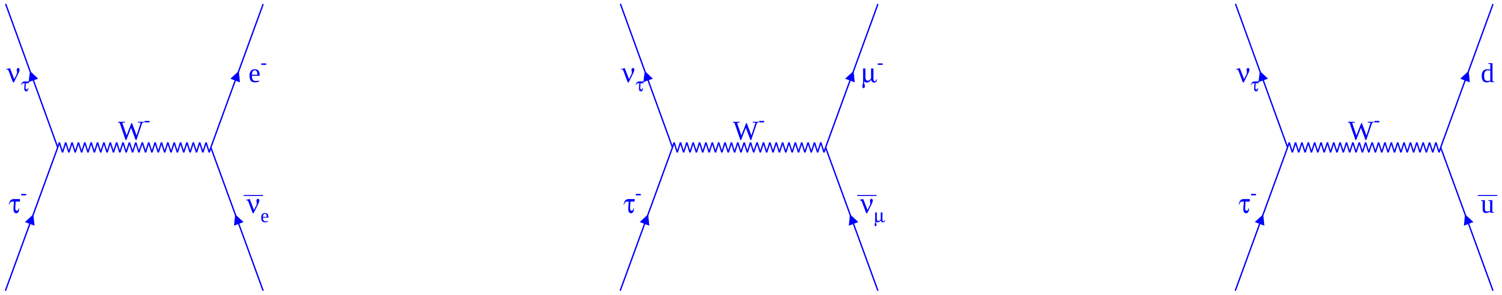
Group	$\int L\ dt$, fb^{-1}	$N_{\tau\tau}$, 10^6
LEP (Z-peak)	0.34	0.33
CLEO (10.6 GeV)	13.8	12.6
BaBar (10.6 GeV)	534	492
Belle (10.6 GeV)	854	782
$c-\tau$ (4.2 GeV)	10	32
SuperB	50k	45k

BaBar ($\sim$ 530 fb^{-1}) and Belle ($\sim$ 1000 fb^{-1}) collected together about 1.5 ab^{-1}

At the $\Upsilon(4S)$ the cross section of $e^+e^- \to \tau^+\tau^-$ is 0.92 nb

B is also a τ factory producing $0.9 \cdot 10^6$ $\tau^+\tau^-$ pairs per each fb^{-1}!!

How Large Is $\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)$?



$R_\tau = \frac{\Gamma(\tau^- \to \text{hadrons})}{\Gamma(\tau^- \to e^-\bar{\nu}_e\nu_\tau)}$, in the asymptotic limit $(m_\tau \to \infty)$ $R_\tau = N_c = 3$,

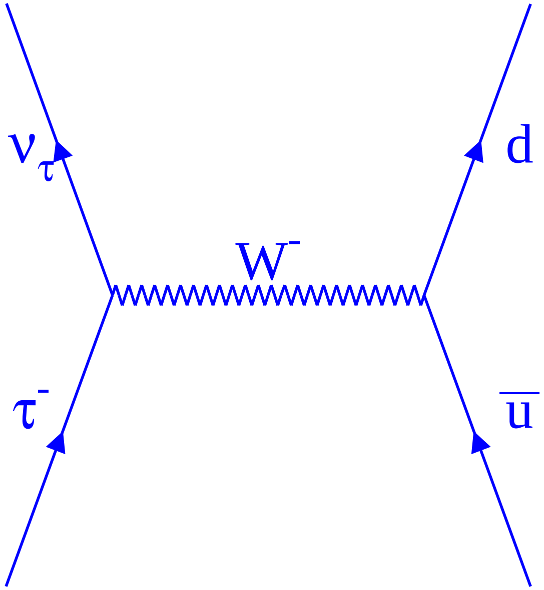
QCD and EW $(\alpha_s(m_\tau) \sim 0.33)$:

$$R_\tau = 3.058[1 + \frac{\alpha_s(m_\tau)}{\pi} + 5.2{\frac{\alpha_s(m_\tau)}{\pi}}^2 + 26.4{\frac{\alpha_s(m_\tau)}{\pi}}^3 + \ldots + n.p.t.]$$

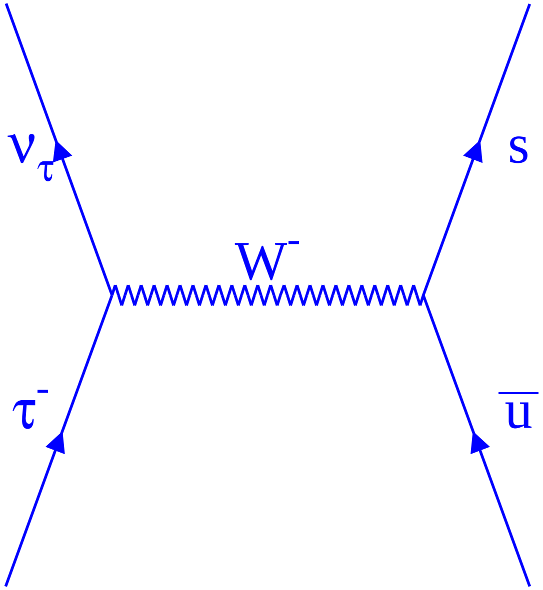
Decay mode	$\mathcal{B}$, % (w/out QCD)	$\mathcal{B}$, % (QCD)	$\mathcal{B}$, % (Exper.)
$e^-\bar{\nu}_e\nu_\tau$	20	17.6	17.82 ± 0.04
$\mu^-\bar{\nu}_e\nu_\tau$	20	17.6	17.39 ± 0.04
Hadrons + ν_τ	60	64.8	~ 65

τ Hadronic Decays in Standard Model

Cabibbo-allowed



Cabibbo-suppressed

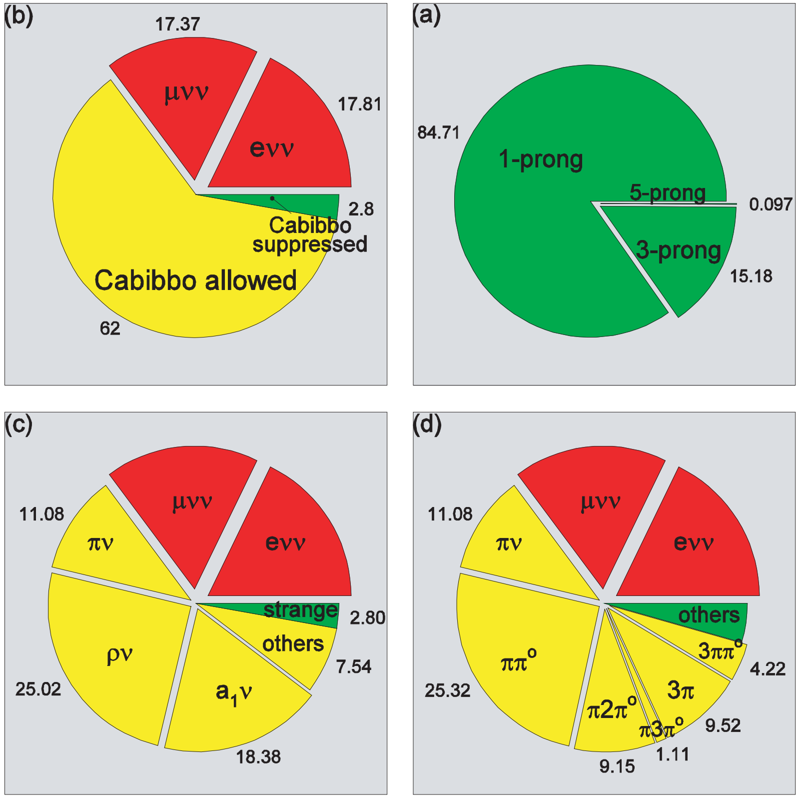


$\mathcal{B}$ of Cabibbo-allowed decays $\propto cos^2\theta_C$, for Cabibbo-suppressed $\propto sin^2\theta_C$.

$cos\theta_C \approx |V_{ud}| = 0.97425 \pm 0.00022$, Suppression $\propto\ cos^2\theta_C/sin^2\theta_C\ \approx 18$.

Each Wud (Wus) vertex includes the m.e. $V_{ud(us)}$

A Zoo of τ decays

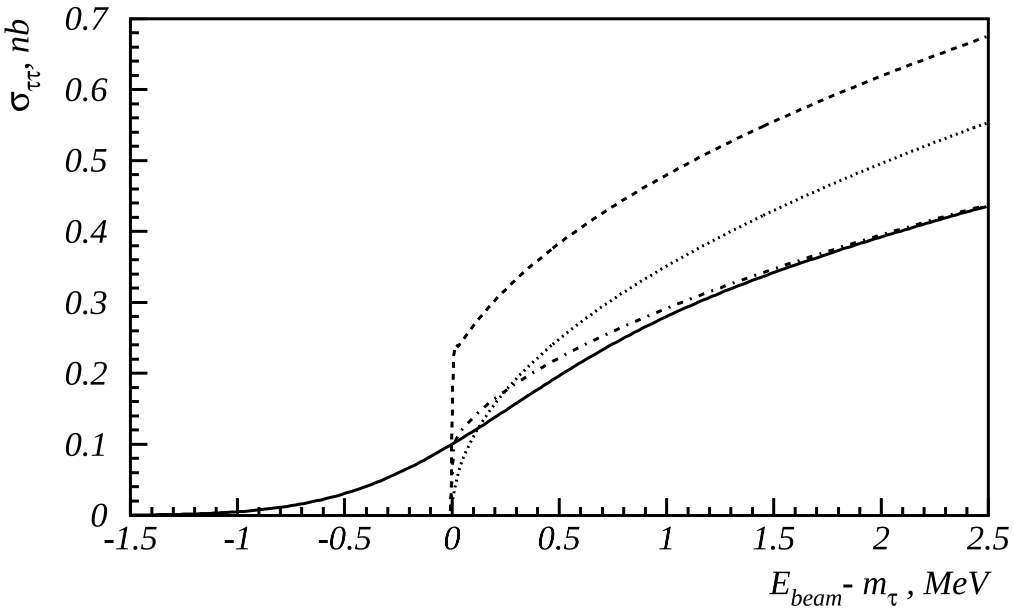


1 track	3 tracks	5 tracks
$(84.58 \pm 0.06)\%$	$(15.21 \pm 0.06)\%$	$(9.9 \pm 0.4) \times 10^{-4}$

Mass of the τ Lepton

- Lepton masses are fundamental parameters of SM and should be precisely measured
- m_τ is important for tests of lepton universality and $\mathcal{B}$
- $\Gamma = \frac{g_\tau^2 g_l^2 m_\tau^5}{192\pi^3} f(m_l^2/m_\tau^2)(1 + \frac{3m_\tau^2}{5m_W^2})(1 + \frac{\alpha(m_\tau)}{2\pi}[25/4 - \pi^2])$, $f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 lnx,\ \alpha^{-1}(m_\tau) = 133.3$
- Today m_τ is known to $8 \cdot 10^{-5}$ while e to $2 \cdot 10^{-8}$ and μ to $3 \cdot 10^{-8}$
- Two methods of m_τ measurement – threshold and pseudomass

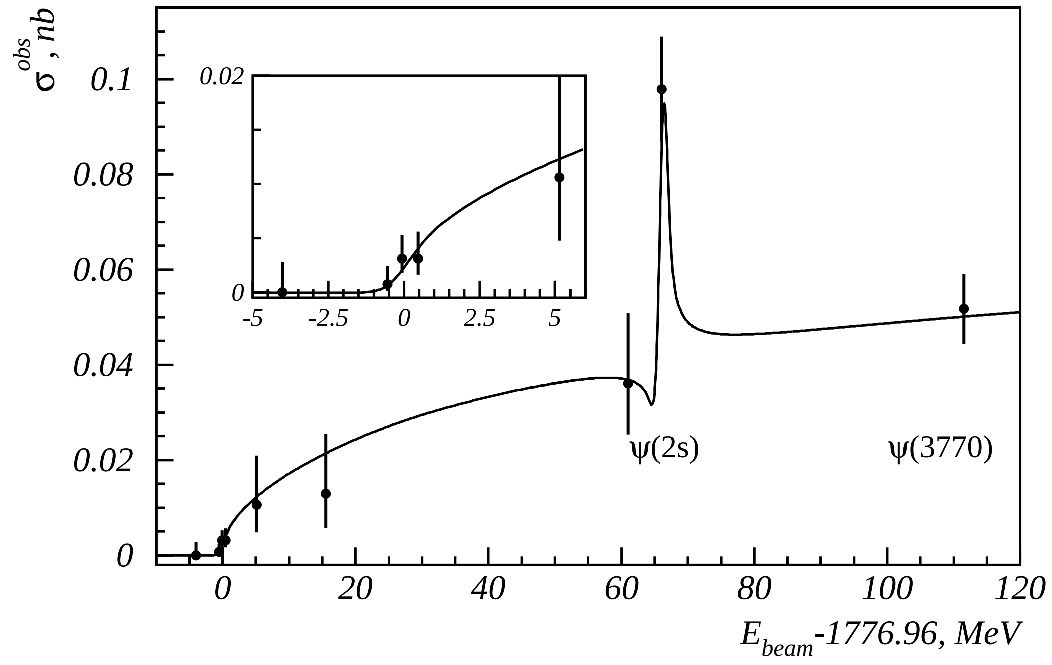
$\sigma(e^+e^- \to \tau^+\tau^-)$ Near Threshold



$$\sigma(e^+e^- \to \tau^+\tau^-) \;=\; \frac{4\pi\alpha^2}{3s}\sqrt{1 \;-\; 4m_\tau^2/s}\;(1 \;+\; 2m_\tau^2/s)$$

Dotted – Born, dashed – Coulomb, FSR and VP,
dash-dotted – ISR, solid – beam energy spead

m_τ at KEDR: Observed $\sigma(e^+e^- \to \tau^+\tau^-)$



$\int Ldt = 6.7\ \mathrm{pb}^{-1}$, 81 events selected

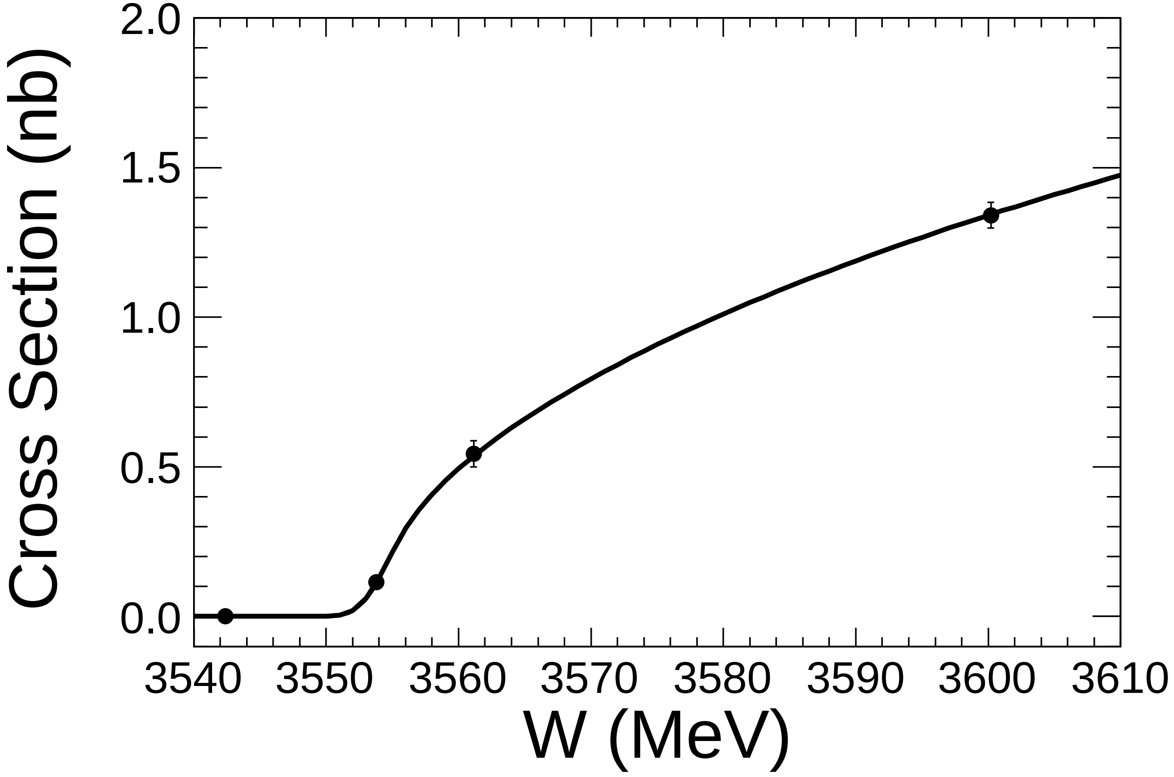
$m_\tau = (1776.81^{+0.25}_{-0.23} \pm 0.15)\ \mathrm{MeV}/c^2$

V.V. Anashin et al., JETP Lett. 85, 347 (2007)

m_τ at BESIII – General

- BINP installed the BSLP system to measure E_{beam}
- BESIII collected 24 pb^{-1} at 4 energies
- 1171 events of τ decay selected
- $m_\tau = 1776.91 \pm 0.12^{+0.10}_{-0.13}$ MeV
- $(g_\tau/g_\mu)^2 = 1.0016 \pm 0.0042$
- M. Ablikim et al., Phys. Rev. D90, 012001 (2014)

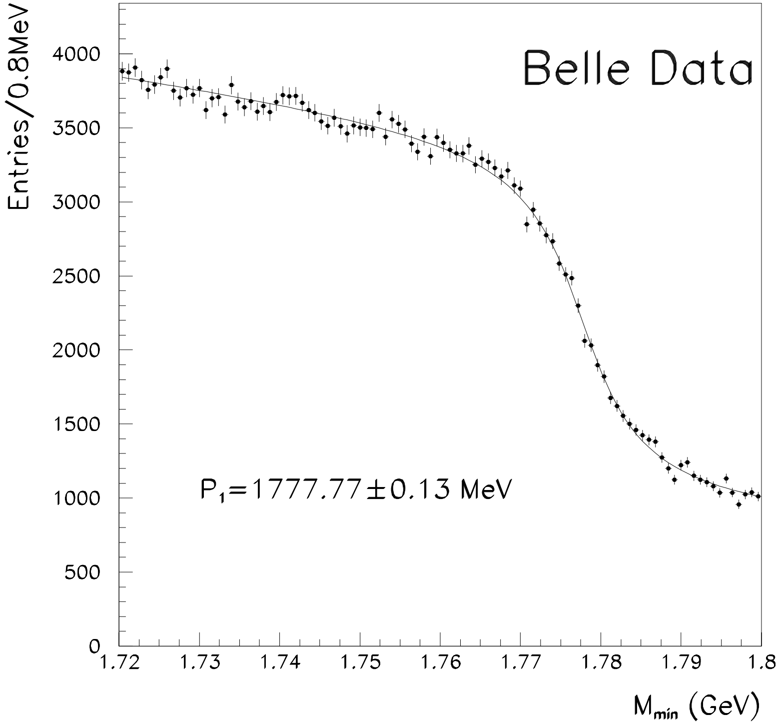
m_τ at BESIII – Cross Section



m_τ at Belle: Pseudomass

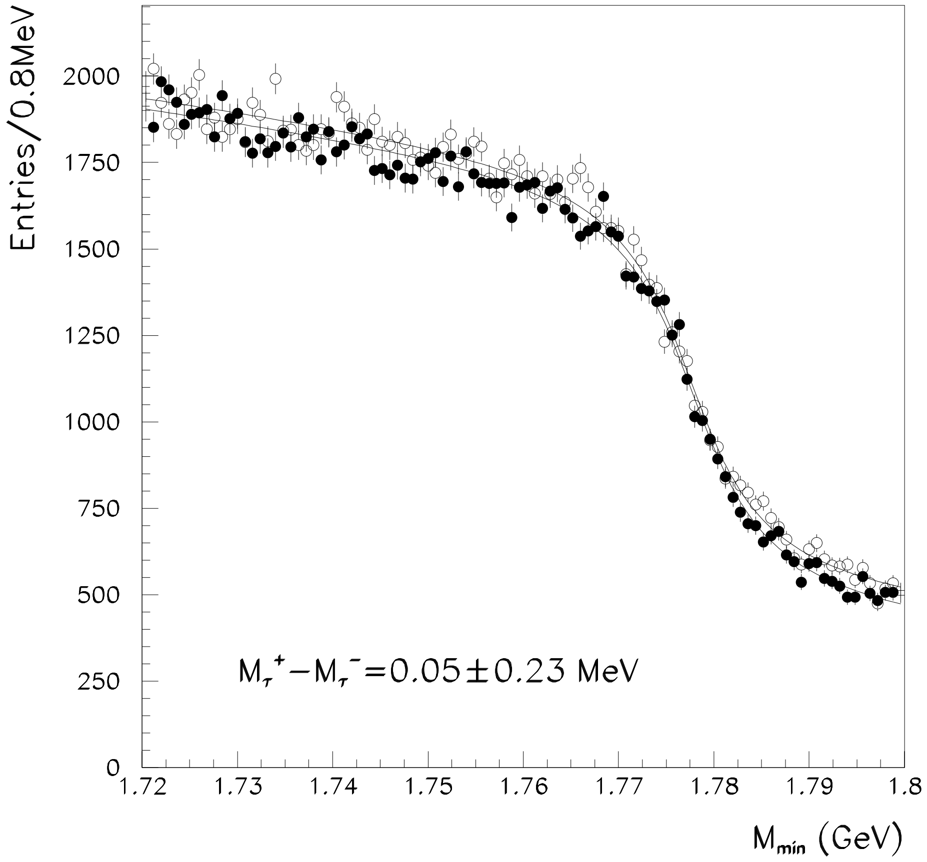
- 414 fb^{-1} or 370×10^6 $\tau^+\tau^-$ pairs
- $\sim 5.8 \cdot 10^5$ events $\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$
- Pseudomass method
- $p_\tau = p_X + p_\nu \Rightarrow m_X^2 + m_\nu^2 + 2(E_X E_\nu - |\vec{p}_X||\vec{p}_\nu| cos\theta)$
- $m_\nu = 0,\ |\vec{p}_\nu| = E_\nu = E_\tau - E_X$
  $m_\tau^2 = m_X^2 + 2(E_\tau - E_X)(E_X - |\vec{p}_X| cos\theta)$
  $m_\tau^2 \geq m_{\mathrm{min}}^2 = m_X^2 + 2(E_{\mathrm{beam}} - E_X)(E_X - |\vec{p}_X|).$
- $f(m_{\mathrm{min}}) \sim (a_1 + a_2 m_{\mathrm{min}}) \tan^{-1}(m_{\mathrm{min}} - a_3)/a_4 + a_5 + a_6 m_{\mathrm{min}}$

m_τ at Belle: Data



From $\sim 5.8 \cdot 10^5$ $\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$ events $m_\tau = (1776.61 \pm 0.13 \pm 0.35)$ MeV

CPT Test from m_{τ^+} vs. m_{τ^-} – I



CPT Test from m_{τ^+} vs. m_{τ^-} – II

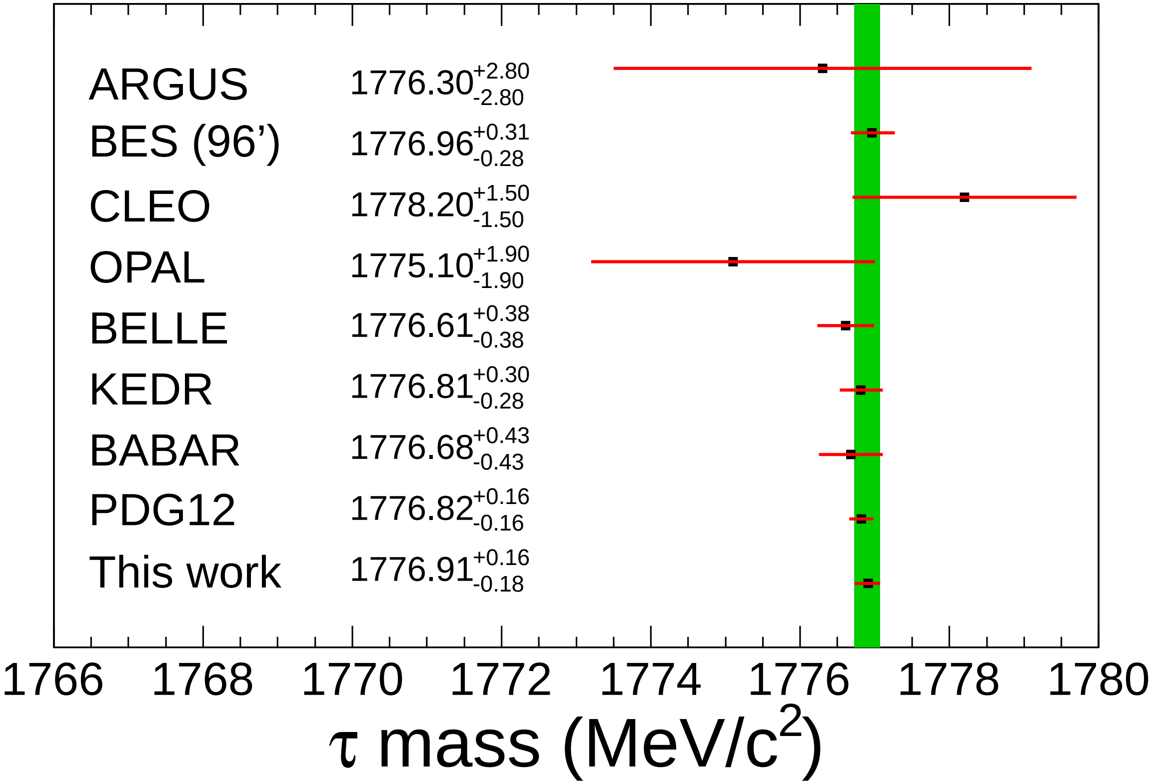
$$\Delta m = m_{\tau^+} - m_{\tau^-}$$

Group	OPAL, 2000	Belle, 2007	BaBar, 2008
$N_{\tau^+\tau^-}, 10^6$	0.16	370	389
$\Delta m/m_\tau, 10^{-4}$	0.0 ± 18.0	0.3 ± 1.5	-3.5 ± 1.3
$\Delta m/m_\tau, 10^{-4}$ $90\% CL$	< 30.0	$< 2.8 \times 10^{-4}$	$-5.6 < \ldots < -1.4$

Belle: K. Abe et al., Phys. Rev. Lett. 99, 011801 (2007)

BaBar: B. Aubert et al.,Phys. Rev. D80, 092005 (2009)

m_τ Measurements – Summary



Masses of Charged Leptons

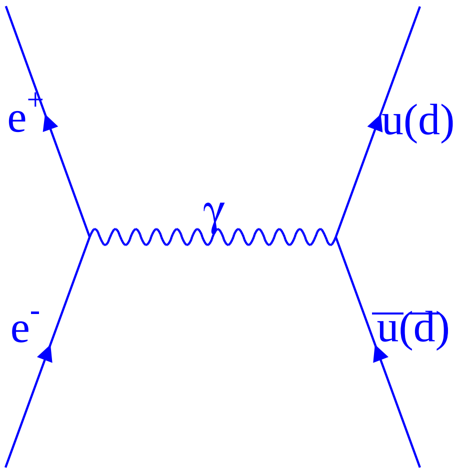
- Masses of fundamental leptons should be measured precisely

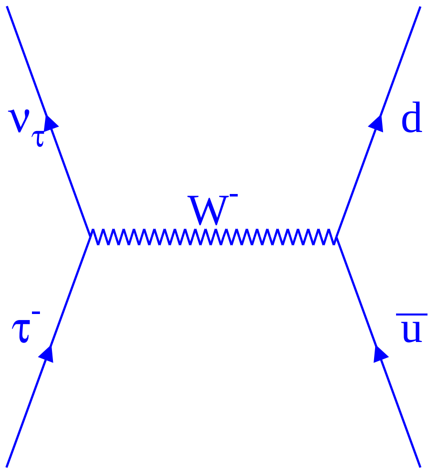
Particle	Mass, MeV	σ_m/m
$\boldsymbol{e}$	$\mathbf{0.5109989461 \pm 0.0000000031}$	$\mathbf{6.1 \cdot 10^{-9}}$
$\boldsymbol{\mu}$	$\mathbf{105.6583745 \pm 0.0000024}$	$\mathbf{2.3 \cdot 10^{-8}}$
$\boldsymbol{\tau}$	$\mathbf{1776.86 \pm 0.12}$	$\mathbf{6.8 \cdot 10^{-5}}$

- Mass enters tests of leptonic universality as m_τ^5
- Koide formula:

$$\frac{(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2}{(m_e + m_\mu + m_\tau)} = 1.4999973^{+0.0000395}_{-0.0000304}$$

CVC: $e^+e^- \to V^0 \quad \tau^- \to \nu_\tau V^-$





Allowed $I^GJ^P = 1^+1^-$: $V^- = \pi^-\pi^0, (4\pi)^-, \omega\pi^-, \eta\pi^-\pi^0, K^-K^0, (6\pi)^-$, $\mathcal{B}(V^-\nu_\tau) \sim 32\%$

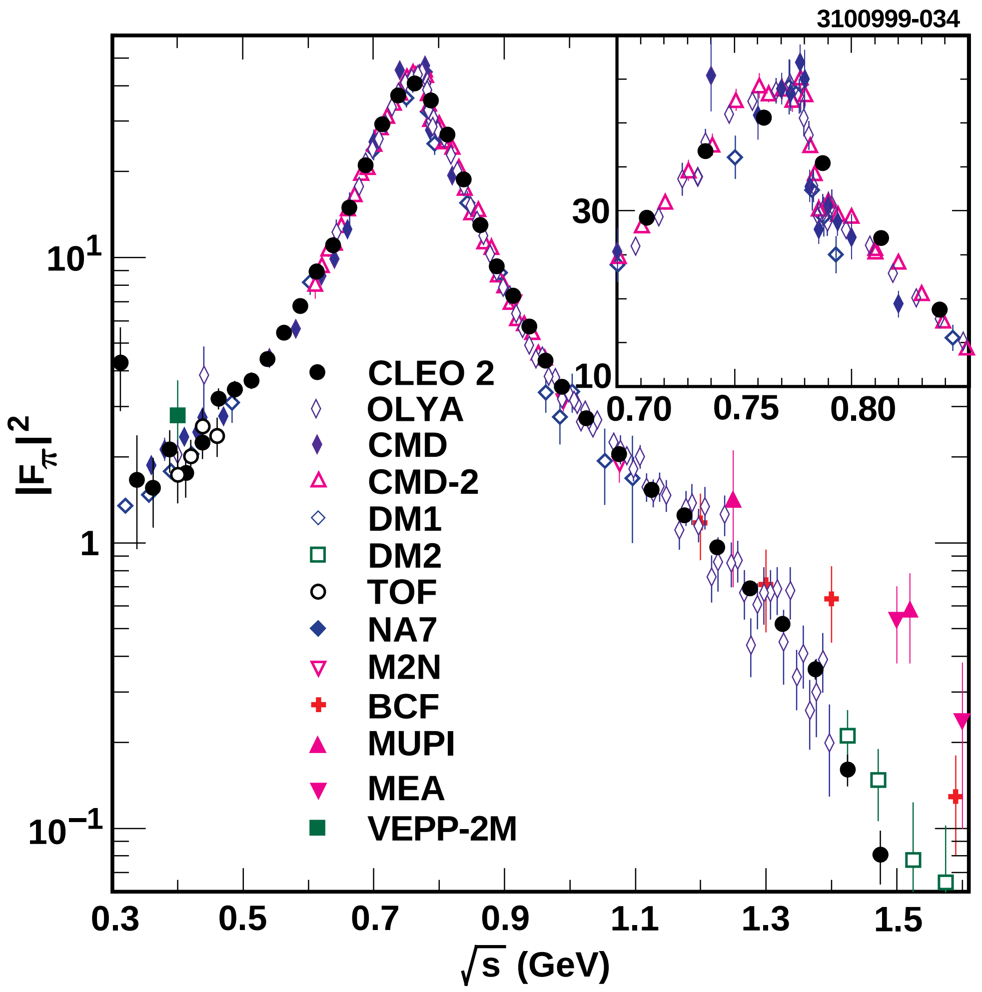
First CVC tests: fair agreement of $\mathcal{B}_\tau$ from e^+e^- with τ data (N.Kawamoto, A.Sanda, 1978; F.Gilman, D.Miller, 1978; SE, V.Ivanchenko, 1991, 1997).

Some Basic Formulae

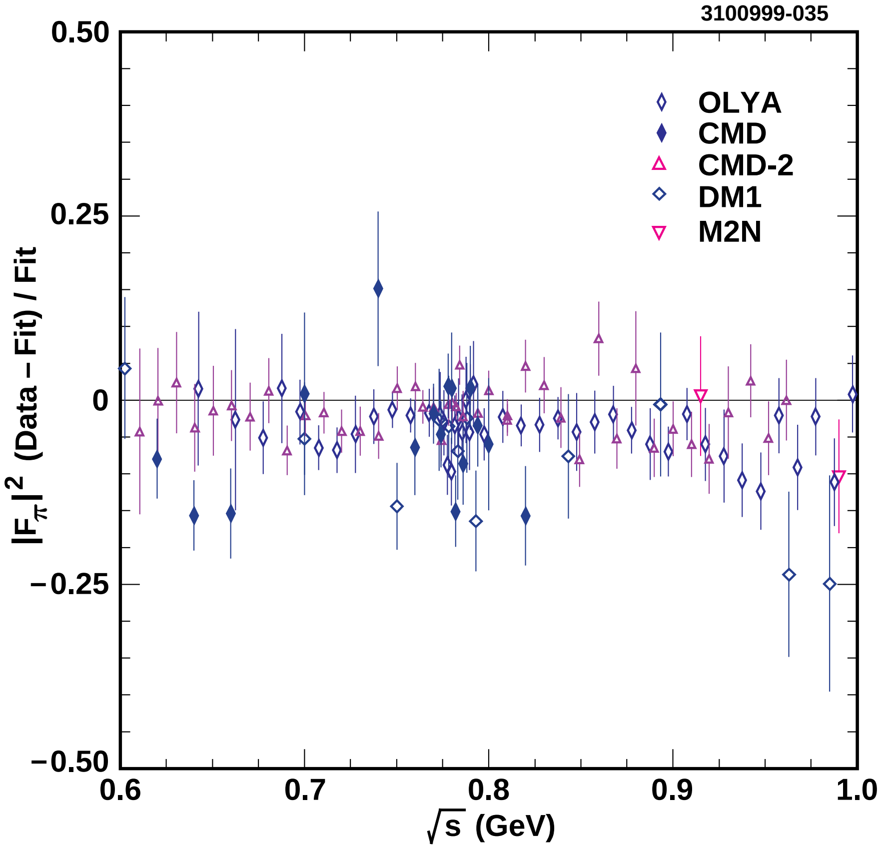
$$\frac{d\Gamma}{dq^2} = \frac{G_F |V_{ud}|^2 S_{EW}}{32\pi^2 m_\tau^3} (m_\tau^2 - q^2)^2 (m_\tau^2 + 2q^2) v_1(q^2),$$

$$v_1(q^2) = \frac{q^2 \sigma^{I=1}_{e^+e^-}(q^2)}{4\pi\alpha^2}$$

CLEO: CVC Test in $\tau^- \to \pi^- \pi^0 \nu_\tau$ – I



CLEO: CVC Test in $\tau^- \to \pi^-\pi^0\nu_\tau$ – II

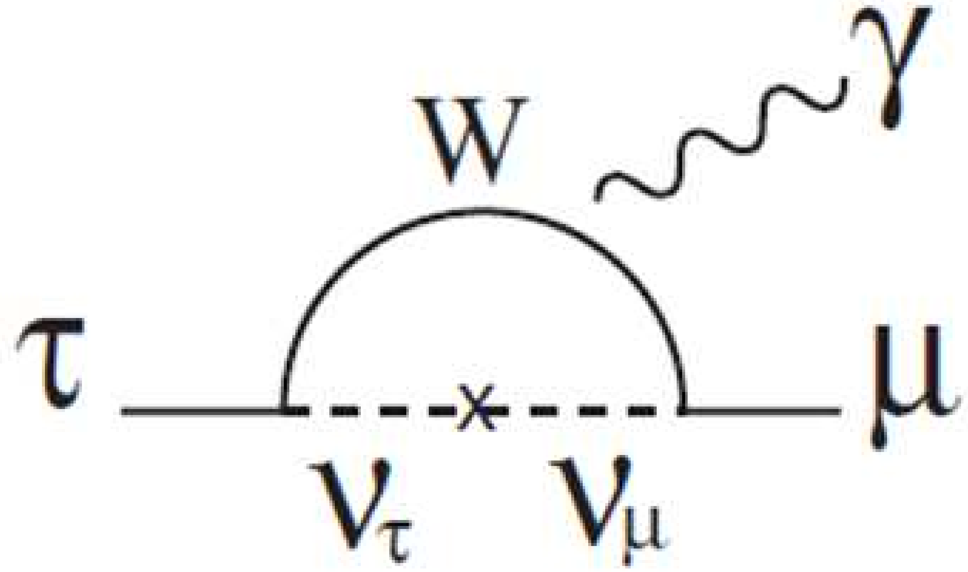


Most of the e^+e^- points are below τ

Searches for New Physics (NP) in the Lepton Sector – I

In Standard Model (SM) Lepton Flavor Violation (LFV) is strongly suppressed:

$$\mathcal{B}(\tau^- \to \mu^- \gamma) \sim \mathcal{O}(10^{-54})$$



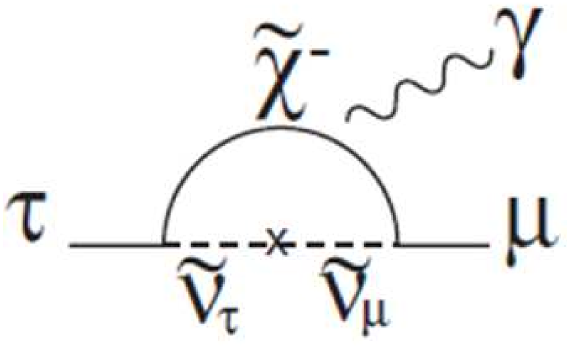
Effects of NP may enhance this probability

Searches for New Physics (NP) in the Lepton Sector – II

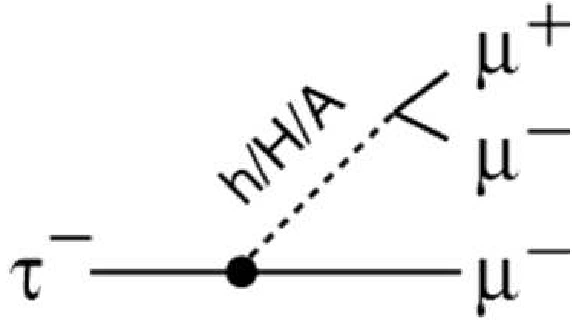
Neutrino oscillations, in particular $\nu_\mu \to \nu_\tau$ oscillations with a big mixing angle $\Rightarrow$ searches for large $\mu - \tau$ LFV, e.g., $\tau^- \to \mu^- \gamma$

In schemes with inverted hierarchy $\tau - e$ is also possible, e.g., $\tau^- \to e^- \gamma$

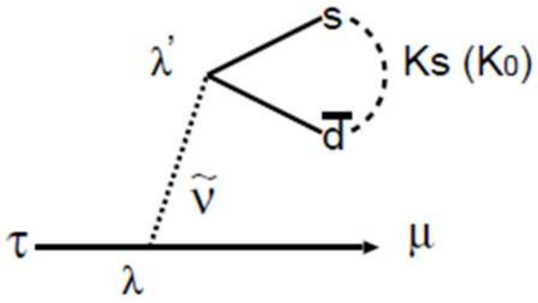
Many models consider SM extensions with enhanced LFV:
predicted $\mathcal{B}(\tau^- \to \mu^- \gamma)$ reach $10^{-8} - 10^{-7}$



SUSY



Higgs mediation



R-parity violation

Searches for New Physics (NP) in the Lepton Sector – III

For a muon, two LFV decays only are possible: $\mu^- \to e^-\gamma$ and $\mu^- \to e^-e^+e^-$

τ lepton is heavy ⇒ A lot of decays possible!

It can decay to leptons only:

$\tau^- \to \mu^-\gamma$, $\tau^- \to e^-\gamma$,

$\tau^- \to \mu^-\mu^+\mu^-,\ \mu^-e^+e^-,\ \mu^-\mu^+e^-,\ \mu^-\mu^-e^+,\ \mu^+e^-e^-,\ e^+e^-e^-$

or to a mixture of leptons and hadrons:

$e^-h^0,\ \mu^-h^0,\ h = \pi,\ \eta,\ \eta',\ \rho,\ \omega,\ \phi,\ K^*(892),\ \ldots$

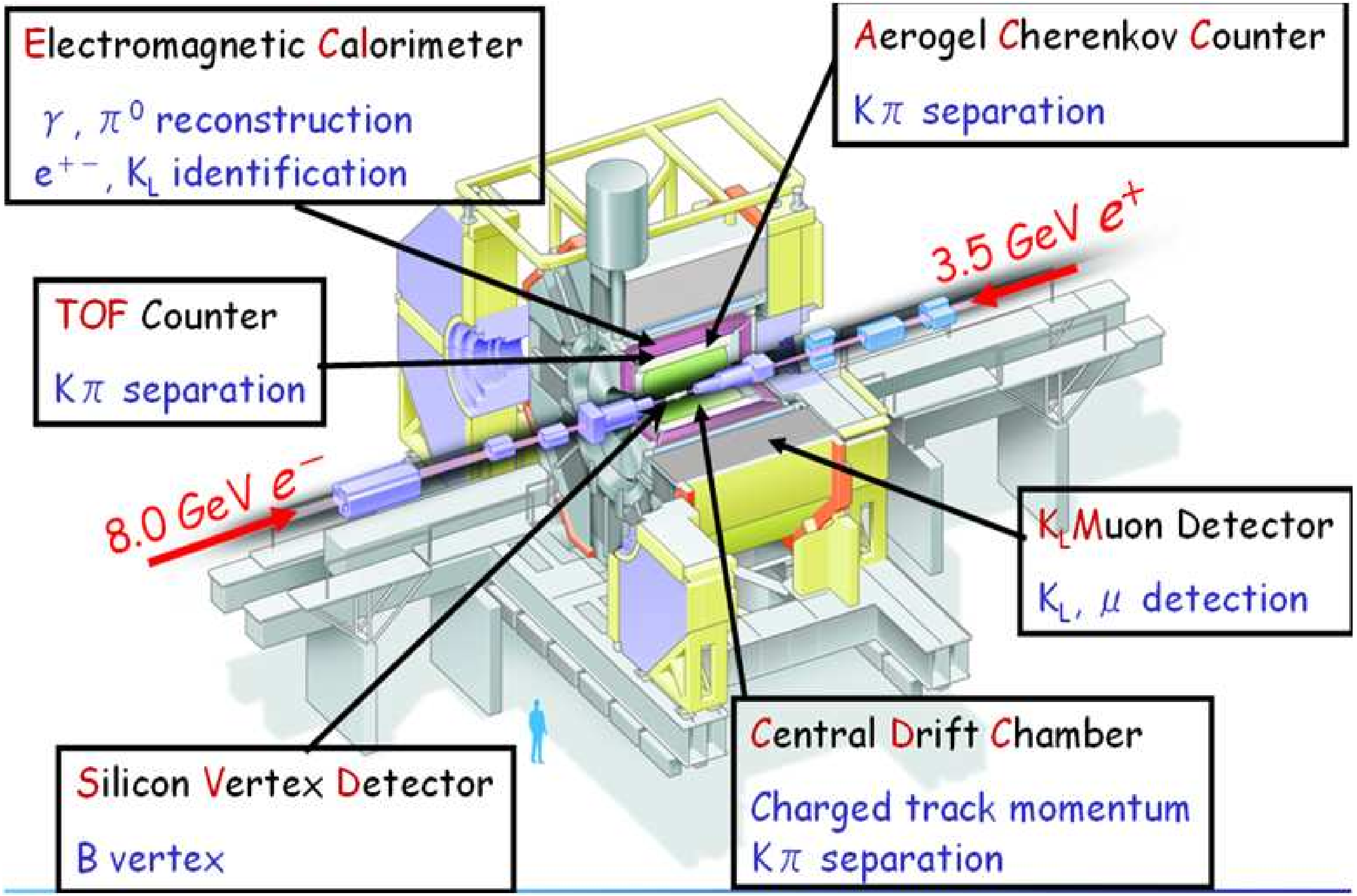
or to final states with baryons:

$\overline{p}\gamma,\ \overline{p}\mu^+\mu^-,\ p\mu^-\mu^-,\ \overline{p}h^0,\ \Lambda\pi^-,\ \ldots$

There have also been searches for l^-a^0, where a^0 is a light boson

In total, 61 various LFV modes have been searched for

Belle Detector



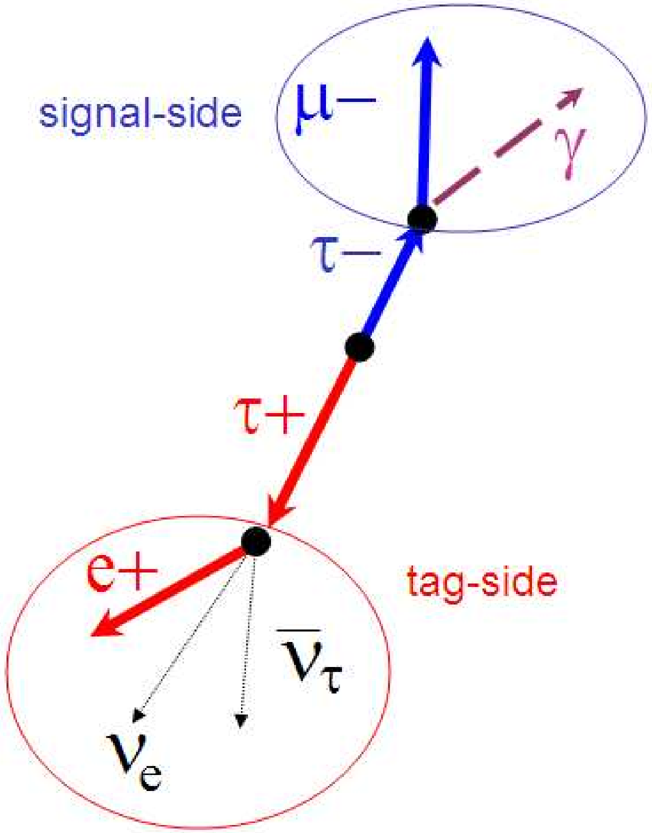
KEKB achieved a luminosity of $2.1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Belle collected ~ 1 ab^{-1} or $\sim 10^9$ $\tau^+\tau^-$ events

How Do We Search for LFV τ Decays?

- At $\Upsilon(4S)$ (10.58 GeV) $\sigma(e^+e^- \to \tau^+\tau^-) = 0.92$ nb $\Rightarrow$ 100 fb^{-1} provides $N_{\tau\tau} = 92 \times 10^6$.
- We divide the event space by the plane perpendicular to the thrust axis into two hemispheres – "tag" side , in which some ordinary τ decay (usually 1-prong modes are selected) is observed and "signal" side , in which we try to completely reconstruct a neutrinoless LFV τ decay.
- Decays we are searching for are very rare ($\mathcal{P} < 10^{-7}$) $\Rightarrow$ mostly background (BG) is detected in the "signal" side. We apply various kinematical, topological and PID cuts to suppress BG.
- We compare various distributions in data (the sidebands) with MC to be sure that we completely understand BG (blind analysis)
- We calculate the branching ratio or place an upper limit: $\mathcal{B} = N_{\rm sig}/2N_{\tau\tau}\epsilon$, $N_{\rm sig}$ – signal yield, ϵ – acceptance

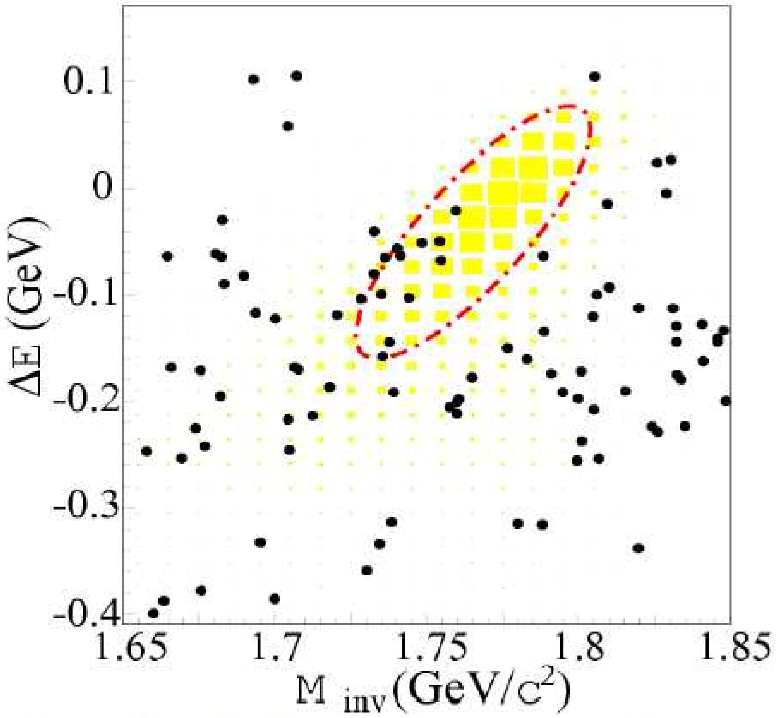
Search for $\tau \to \mu\gamma$ – I



$$m_{\rm inv} = \sqrt{E^2_{\mu\gamma} - p^2_{\mu\gamma}} \qquad \Delta E = E^{\rm CM}_{\mu\gamma} - E^{\rm CM}_{\rm beam}$$

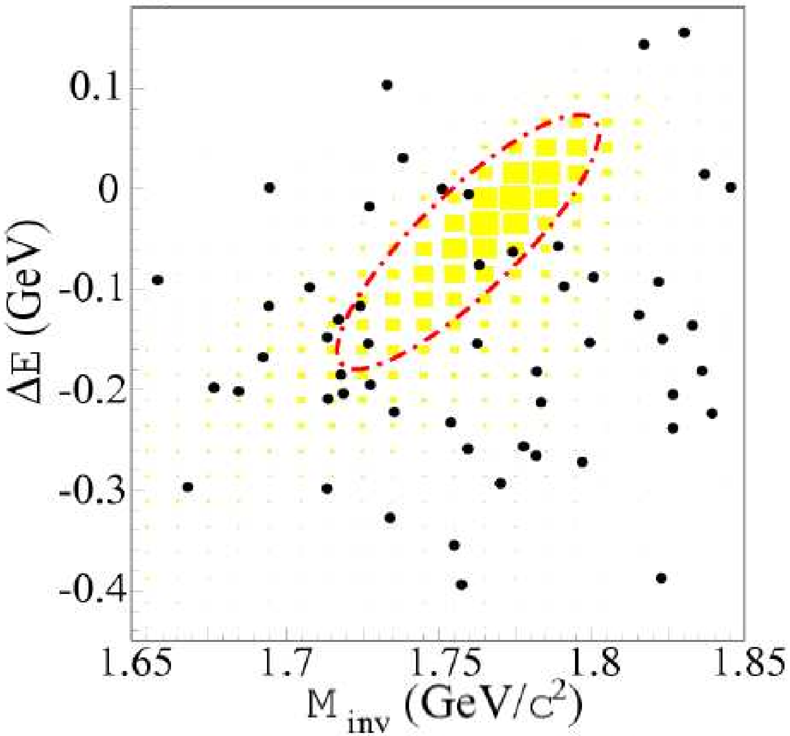
Search for $\tau \to \mu\gamma$ – II

$\tau \to \mu\gamma$



– Br<4.5x10^{-8} at 90%C.L.

$\tau \to e\gamma$



– Br<1.2x10^{-7} at 90%C.L.

Efficiencies: 5.1% for $\mu^-\gamma$ and 3.0% for $e^-\gamma$

K. Hayasaka et al., Phys. Lett. B666 (2008) 16

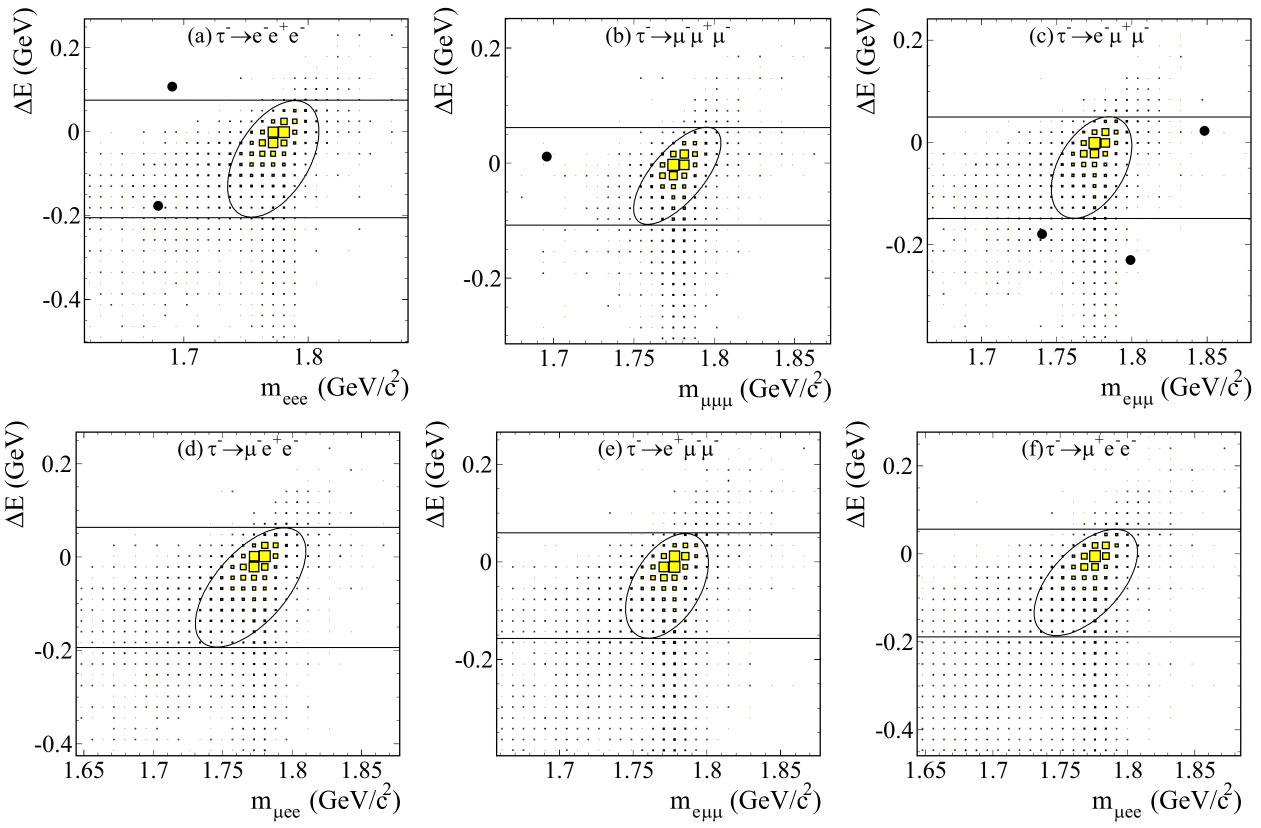
$\tau^- \to l^- \gamma$

τ^-	Belle		BaBar		CLEO	
mode	$\mathcal{B}, 10^{-8}$	$\int Ldt$,fb^{-1}	$\mathcal{B}, 10^{-8}$	$\int Ldt$,fb^{-1}	$\mathcal{B}, 10^{-8}$	$\int Ldt$,fb^{-1}
$\mu^-\gamma$	4.5	535	4.4	515.5	110	13.8
$e^-\gamma$	12	535	3.3	515.5	270	4.68

Belle K. Hayasaka et al., Phys. Lett. B666 (2008) 16

BaBar B. Aubert et al., Phys. Rev. Lett. 104 (2010) 021802

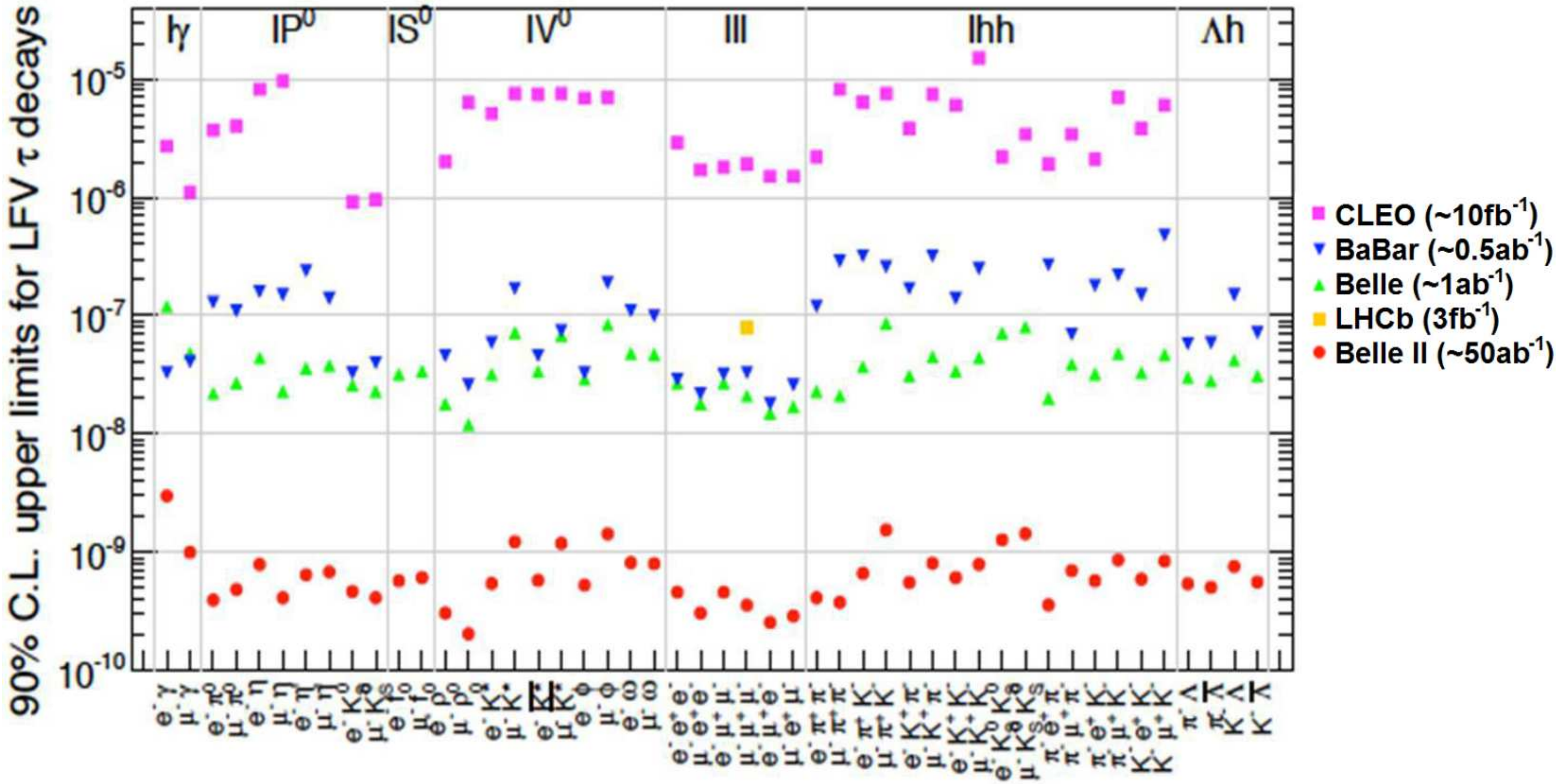
τ decays to Three Leptons



Efficiencies: (6.0-11.5)%, UL for $\mathcal{B}$: $(1.5\text{-}2.7)\times 10^{-8}$

K. Hayasaka et al., Phys. Lett. B687 (2010) 139

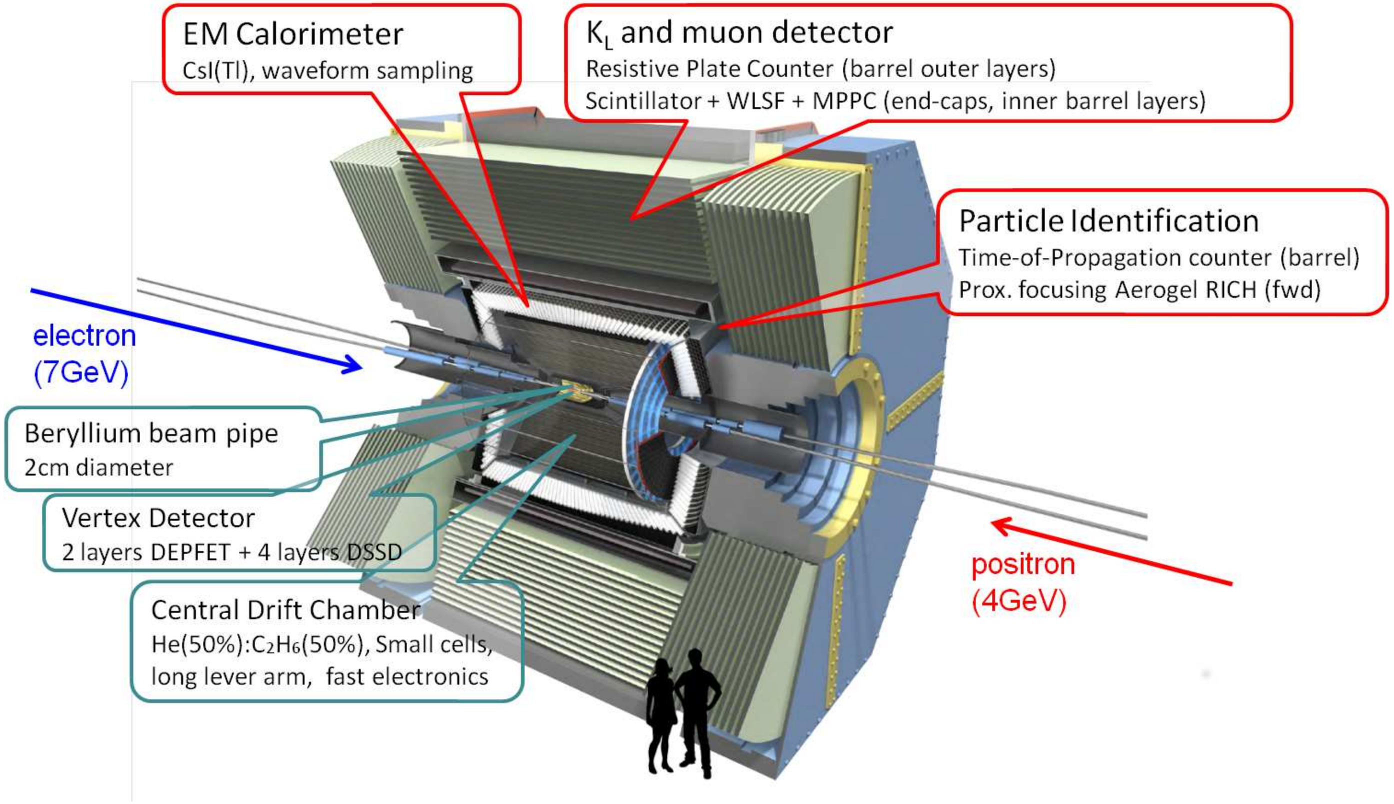
Current Upper Limits on LFV τ Decays



Progress of LFV Studies – $\tau^- \to \mu^-\gamma$

Group	Date	$\mathcal{L}$, fb^{-1}	$N_{\tau\tau}$, 10^6	$B_{\rm UL}^{90}$
MARK II	1982	0.017	0.048	5.5×10^{-4}
ARGUS	1992	0.387	0.374	3.4×10^{-5}
DELPHI	1995	0.07	0.081	6.2×10^{-5}
CLEO	2000	13.8	12.6	1.1×10^{-6}
Belle	2004	86.3	78.5	3.1×10^{-7}
BaBar	2005	232.2	207	6.8×10^{-8}
Belle	2006	535	477	4.5×10^{-8}
BaBar	2010	515.5	481.5	4.4×10^{-8}
BaBar & Belle	2006	767.2	684	1.6×10^{-8}

BelleII Experiment – I

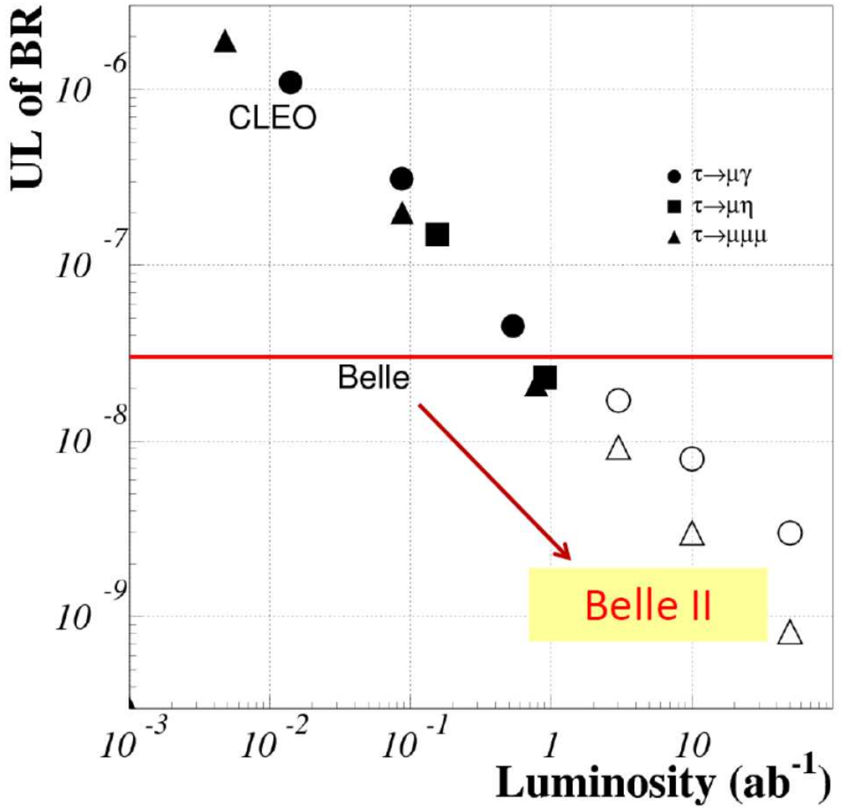


The design luminosity of the upgraded KEKB is $8 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

BelleII will start data taking in 2018 with a goal of 50 ab^{-1}

Prospects for the Future

- With 5×10^{10} $\tau^+\tau^-$ and $\epsilon \sim 3\%$: $\mathcal{B} < 10^{-9}$ for $N_{\rm ev} = 0$
- Background suppression needed (PID, higher ϵ, better $\Delta E_\gamma / E_\gamma$)
- $\tau \to l\gamma, \mu\eta(\gamma\gamma), l\rho$: BG $\neq 0$, $\mathcal{B} \propto 1/\sqrt{N}$
- $\tau \to lll, \mu\eta(\pi^+\pi^-\pi^0), \Lambda\pi$: BG $= 0$, $\mathcal{B} \propto 1/N$



Conclusions on τ Physics

- The largest data sample was collected by Belle: $\sim 10^9$ $\tau^+\tau^-$ events allowing to reach $\mathcal{O}(10^{-8})$ sensitivity in $\mathcal{B}$ measurements
- There is very good progress in mass and lifetime measurements, lepton universality is in good shape
- Interesting physics with hadronic decays: CVC tests, decays with kaons, searches for second class currents
- In total, 61 decay modes have been searched for LFV;
  the strongest limit achieved is $\mathcal{B}(\tau^- \to \mu^- \rho^0) < 1.2 \times 10^{-8}$ at 90%CL
- With $\int Ldt = 50$ ab^{-1} BelleII will collect $\sim 5 \times 10^{10}$ $\tau^+\tau^-$ events reaching a sensitivity of $\mathcal{O}(10^{-9}) - \mathcal{O}(10^{-10})$
- τ decays have good potential for searches of New Physics

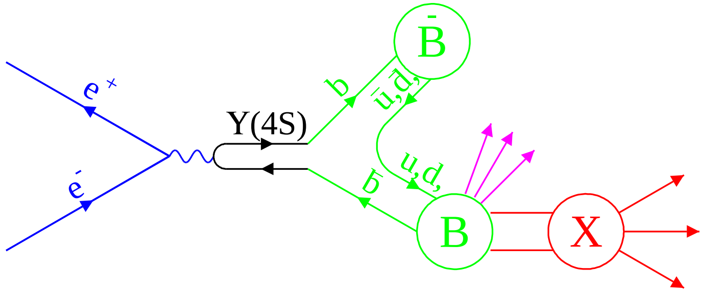
Charm Production in e^+e^- Collisions

- $\sigma(e^+e^- \to c\bar{c}X)$ at 10.58 GeV is about 1 nb ⇒ B-factory is also a charm factory producing $\sim 10^6$ charm pairs per each fb^{-1}!!
- BaBar ($\sim$ 530 fb^{-1}) and Belle ($\sim$ 1020 fb^{-1}) collected about 1.5 ab^{-1} or 1.5×10^9 $c\bar{c}$ pairs
- CLEOc at Cornell ran at charm threshold with $\mathcal{L} \sim 10^{32}$ cm^{-2} s^{-1} and BES3 is now running in Beijing with $\mathcal{L} \sim 10^{33}$ cm^{-2} s^{-1}
- In future copious sources of charm at PANDA and SuperB, plus a dream of a Super-τ-c-factory (10^{35} cm^{-2} s^{-1})

Particle Production at B Factories

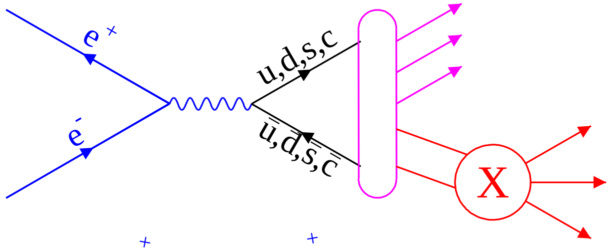
Production from B-decay

(broad D^{**}, D_{sJ}, $X(3872)$, $Y(3940)$)



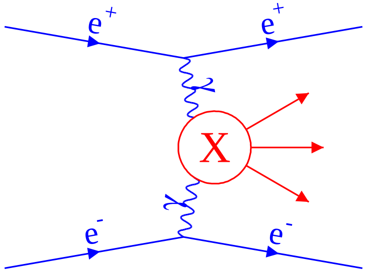
Production from continuum

(D_{sJ}, $\eta_c(2S)$, $X(3940)$, $\Sigma(2800)$)



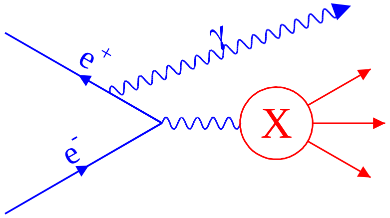
Two-photon production

($\eta_c(2S)$, $\chi_{c2}(2P)$, $Y(4350)$)



Initial state radiation

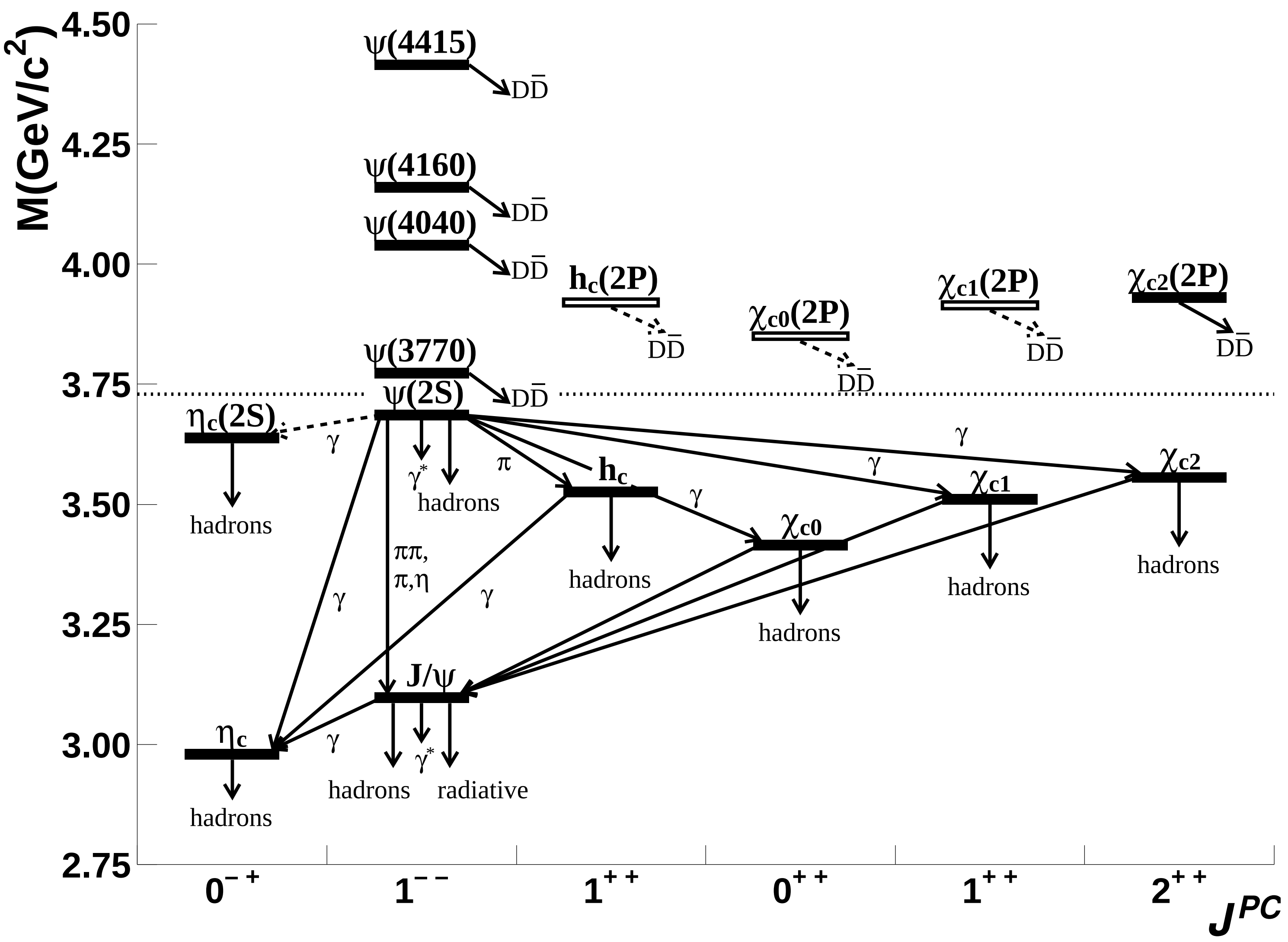
($Y(4260)$, $Y(4360)$, $X(4630)$, $Y(4660)$)



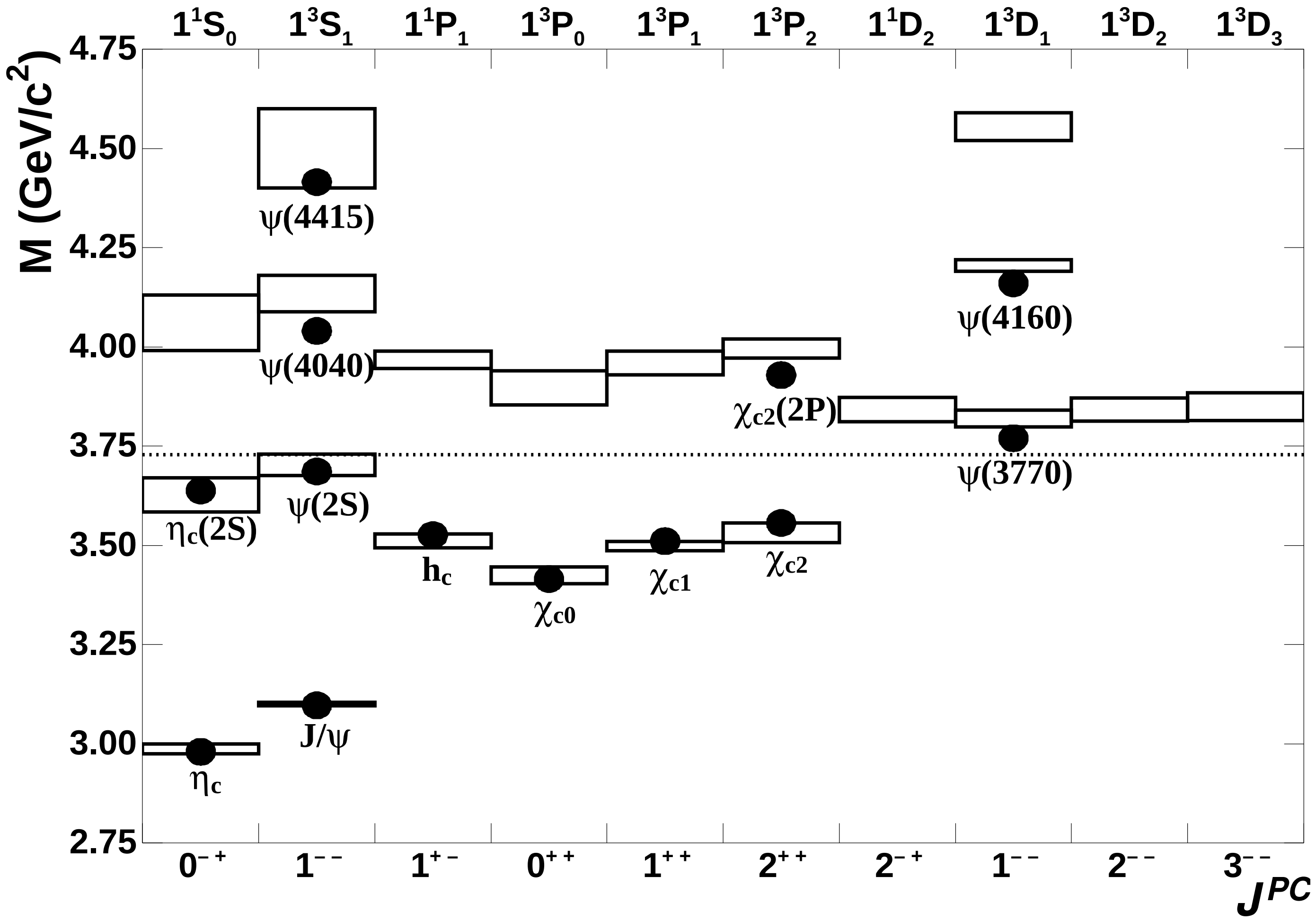
Charmonia – General Picture

- Ten $c\bar{c}$ were found in 1974-1980:
  J/ψ, $\eta_c(1S)$, $\chi_{c0}(1P)$, $\chi_{c1}(1P)$, $\chi_{c2}(1P)$, $\psi(2S)$ below and
  $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$ above the open charm threshold
- With $\eta_c(2S)$ (in 2002) and $h_c(1P)$ (in 2005)
  the $c\bar{c}$ system seemed completely understood,
  but many new $c\bar{c}$-like states decaying to $c\bar{c}X$
  rather than to open charm unexpectedly were found.
  For some of them there is no place in the $c\bar{c}$ spectrum.

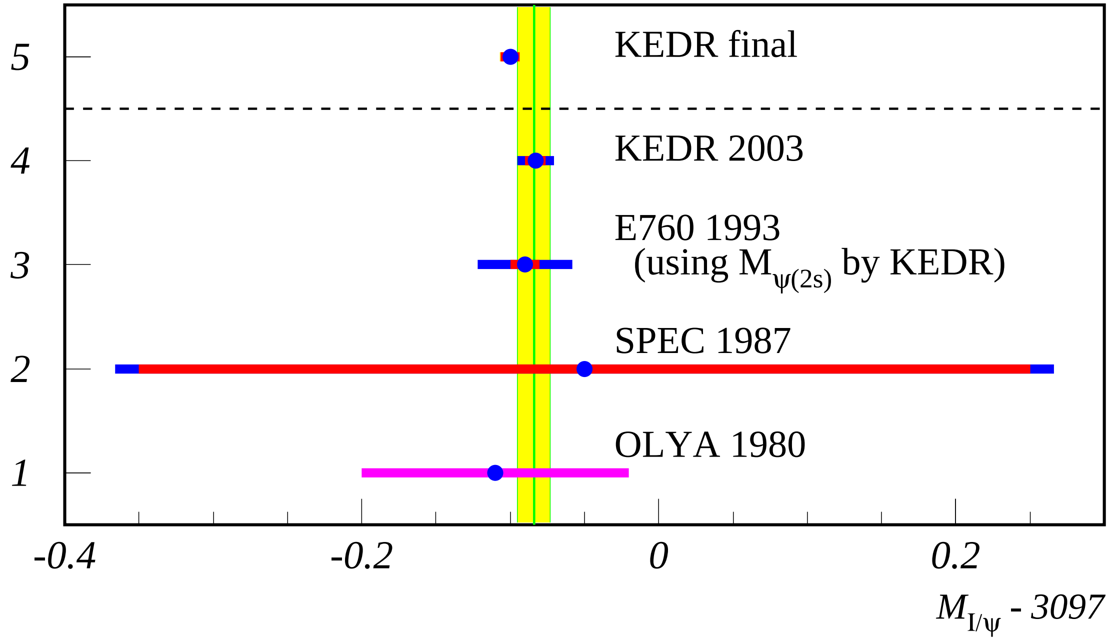
The Charmonium System



Predictions of Potential Model



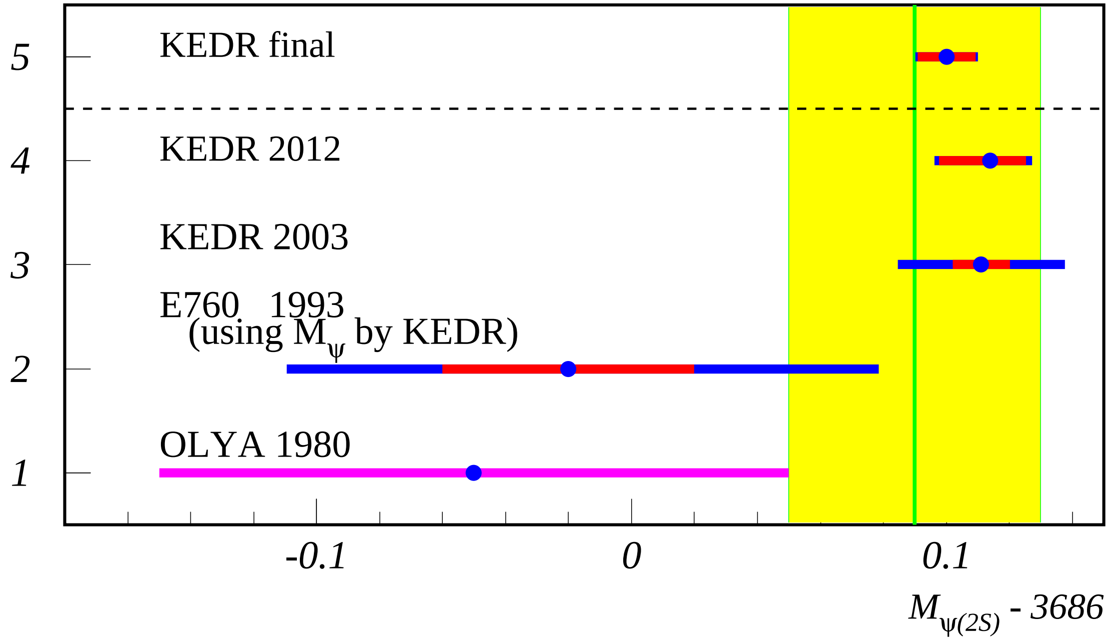
J/ψ Mass Measurement at KEDR



Based on 6 scans and $7 \cdot 10^5$ multihadronic events

V.V. Anashin et al., Phys. Lett. B 479 (2015) 50

$\psi(2S)$ Mass Measurement at KEDR



Based on 7 scans and $2 \cdot 10^5$ multihadronic events

V.V. Anashin et al., Phys. Lett. B 479 (2015) 50

What Do We Know about J/ψ Excitations?

- Four broad ψ-like structures known since 30 years –
  $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$ found
  in the measurements of $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$
- Even main properties $(M,\ \Gamma,\ \Gamma_{ee})$ from DASP/MARK I data known badly
- Difficulties are due to opening thresholds, common decay channels $(D^{(*)}_{(s)}\bar{D}^{(*)}_{(s)})$
- Recently BES made a model-dependent coupled-channel analysis
  M. Ablikim et al., PLB 660, 315 (2008)
- Exclusive studies and determination of decay mechanisms will be helpful

Parameters of Higher Charmonia

Parameter	Source	$\psi(3770)$	$\psi(4040)$	$\psi(4160)$	$\psi(4415)$
M, MeV	PDG,2004	3769.9 ± 22.5	4040 ± 10	4159 ± 20	4415 ± 6
	BES,2007	3771.4 ± 1.8	4038.5 ± 4.6	4191.6 ± 6.0	4415.2 ± 7.5
Γ, MeV	PDG,2004	23.6 ± 2.7	52 ± 10	78 ± 20	43 ± 15
	BES,2007	25.4 ± 6.5	81.2 ± 14.4	72.7 ± 15.1	73.3 ± 21.2
Γ_{ee}, keV	PDG,2004	0.26 ± 0.04	0.75 ± 0.15	0.77 ± 0.23	0.47 ± 0.10
	BES,2007	0.18 ± 0.04	0.81 ± 0.20	0.50 ± 0.27	0.37 ± 0.14

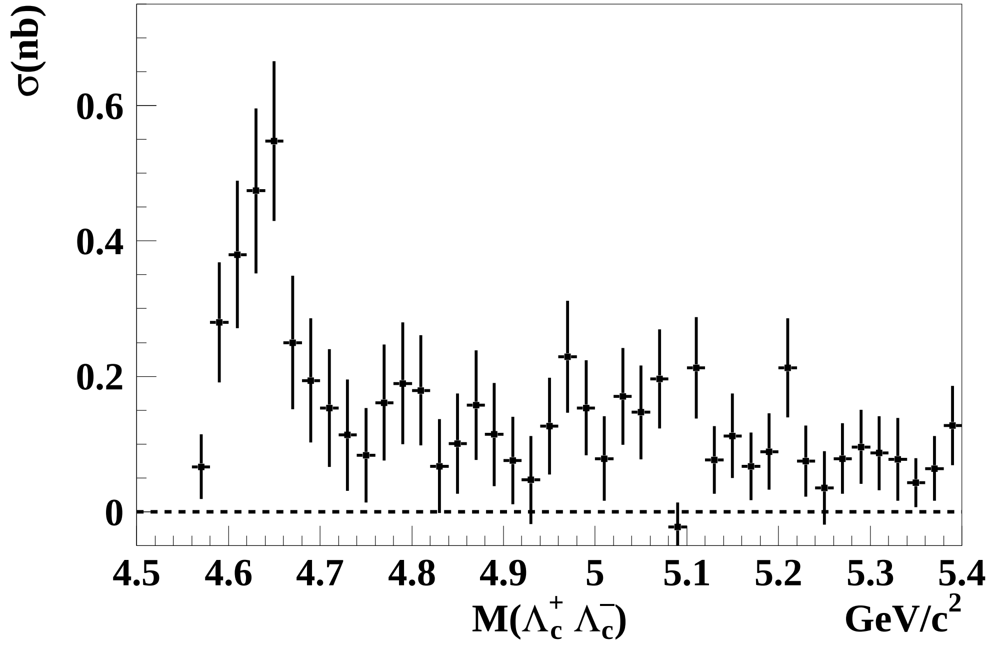
BES parameterizes R as a smooth u, d, s background
plus a coherent sum of the four ψ states,
each an incoherent sum of two-body $D_1 D_2$ states,
a more realistic model needed

It is important to study specific decay modes of the vector ψ's

$e^+e^- \to \Lambda_c^+\Lambda_c^-$ via ISR

Many modes with open charm studied using ISR:

$D\bar{D},\ D\bar{D}^*,\ D^*\bar{D}^*,\ D\bar{D}\pi,\ \ldots$

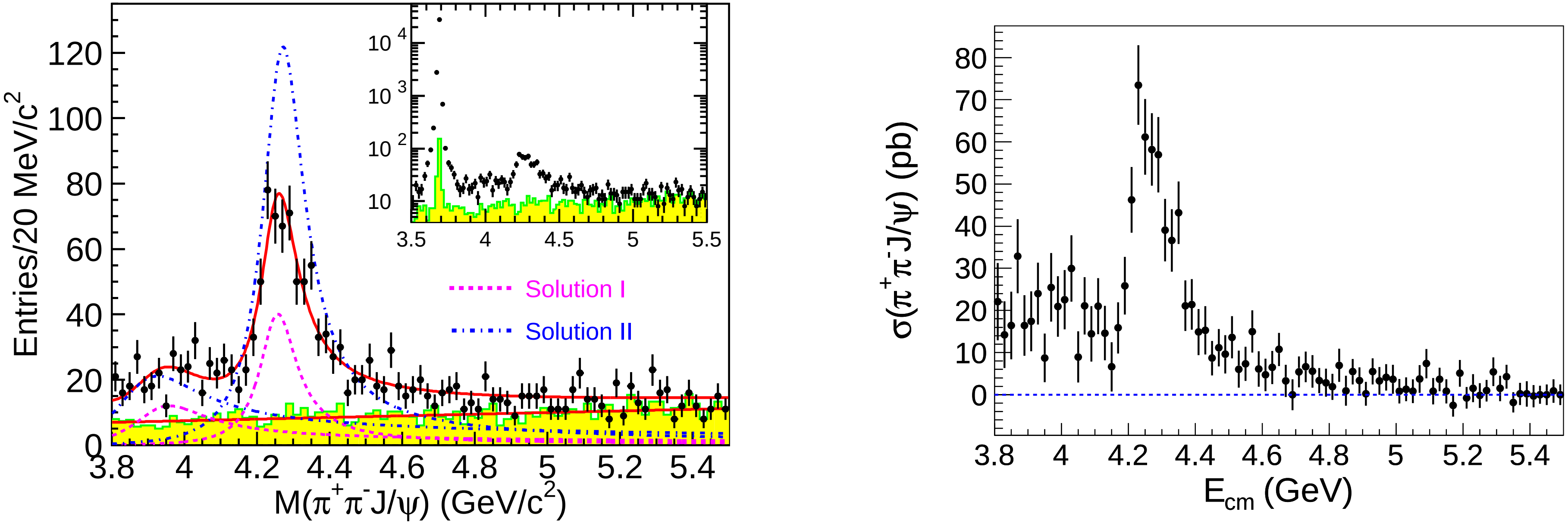


G. Pakhlova et al., PRL 101, 172001 (2008); Belle – 695 fb^{-1}

142^{+32}_{-28} events $(\sim 8.2\sigma)$ $M = 4634^{+8+5}_{-7-8}$ MeV $\Gamma = 92^{+40+10}_{-24-21}$ MeV

Study of $e^+e^- \to \pi^+\pi^- J/\psi$ at Belle

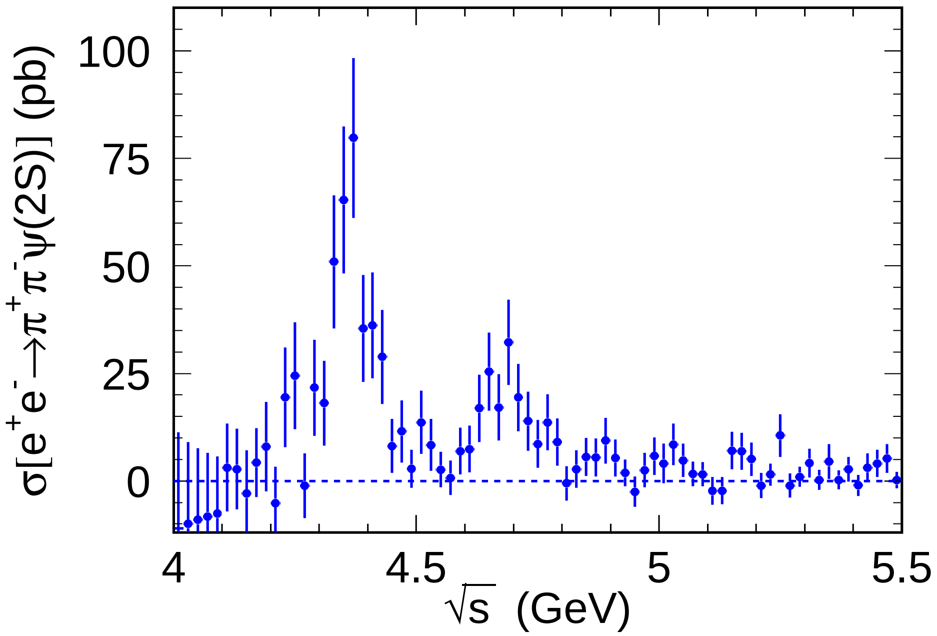
With 967 fb^{-1} Belle confirms $Y(4260) \to J/\psi\pi^+\pi^-$ discovered with ISR by BaBar in B. Aubert et al., Phys. Rev. Lett. 95 (2005) 142001 and sees $Y(3990)$



Z.Q. Liu et al., Phys. Rev. Lett. 110 (2013) 222002

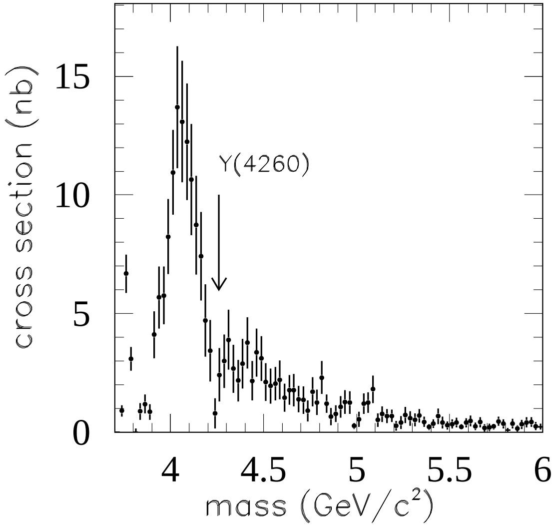
Study of $e^+e^- \to \pi^+\pi^-\psi(2S)$ at Belle

With 980 fb^{-1} Belle confirms $Y(4360) \to \psi(2S)\pi^+\pi^-$ discovered with ISR by BaBar in B. Aubert et al., Phys. Rev. Lett. 98 (2007) 212001 and $Y(4660)$ first seen by Belle in X.L.Wang et al., Phys. Rev. Lett. 99 (2007) 142002



X.L. Wang et al., Phys. Rev. D 91 (2015) 112007

$Y(4260)$ and Sum of Cross Sections of $e^+e^- \to D\bar{D},\ D^*\bar{D},\ D^*\bar{D}^*$



BaBar – 384 fb^{-1} B. Aubert et al., Phys. Rev. D 79, 092001 (2009)

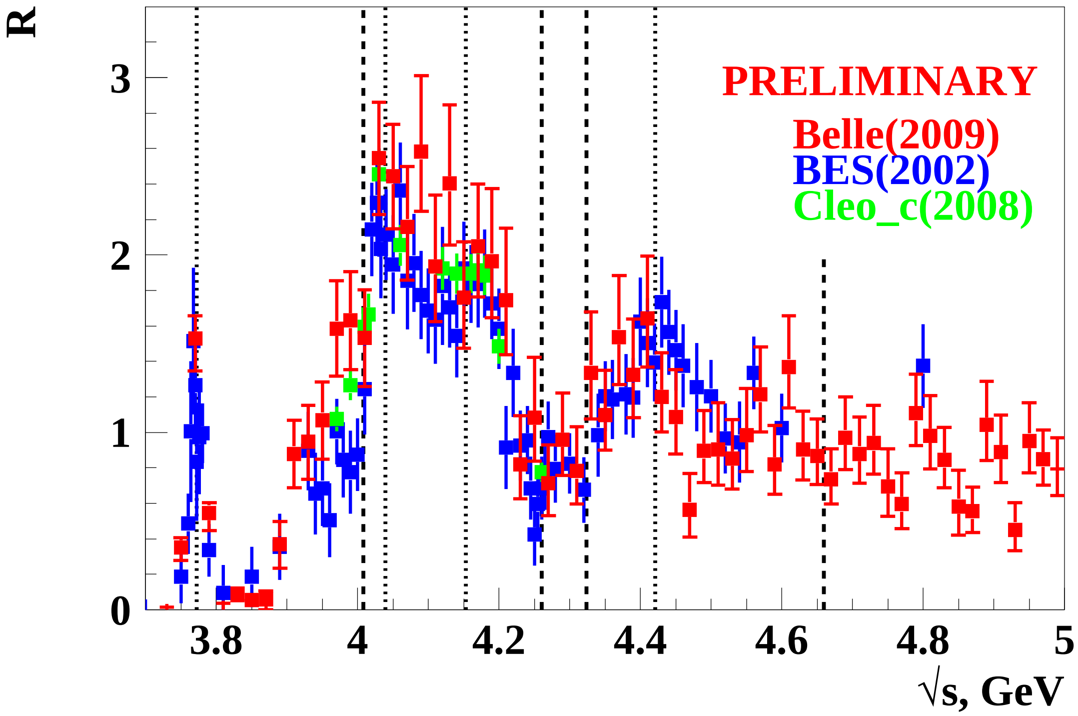
A dip just at the $Y(4260)$

The $Y(4260)$ is unlikely $4^3S_1(\psi(4S))$, which is assigned to the $\psi(4415)$,

for the unaccounted $\psi(3^3D_1)$ the predicted mass is 4500 MeV

The lowest $c\bar{c}$ hybrid is predicted at $\approx$ 4200 MeV

Total Exclusive Cross Section via ISR



Exclusive modes seem to saturate R

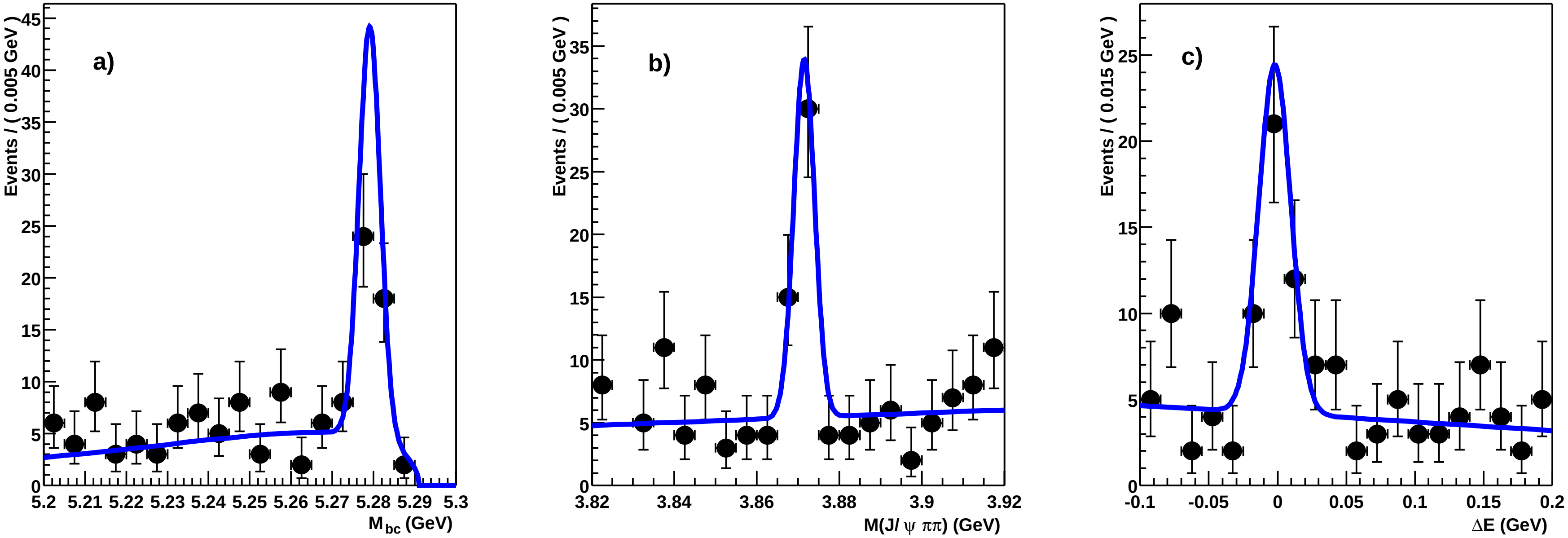
after subtracting the contribution of light $(u,\ d,\ s)$ quarks.

Small room only left for states with $D_s^{(*)}$ and charmed baryons

Summary on 1^{--} States

- Four well-known excitations of the J/ψ are confirmed in exclusive channels; first steps to disentangle decay mechanisms made. Larger data samples and additional decay modes needed to perform fits in the coupled-channel model to determine their parameters.
- New vector states observed ($Y(4260)$, $Y(4360)$, $Y(4630)$, $Y(4660)$). Although well above open charm threshold, they decay to $J/\psi(\psi(2S))\pi^+\pi^-$. Energy dependence of cross sections may be affected by coupled-channel and rescattering ($D^{(*)}\bar{D}^{(*)}$) effects
- The $Y(3990)$ state of Belle is not confirmed by BaBar, but is not ruled out by them
- Are the $\psi(2S)\pi^+\pi^-$ state at 4660 MeV and $\Lambda_c^+\Lambda_c^-$ state at 4630 MeV the same?
- Interpretation is not straightforward and needs theory input.

Discovery of $X(3872)$



Belle – S.-K. Choi et al., PRL 91 (2003) 262001; 152M $B\bar{B}$ pairs; 1080 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

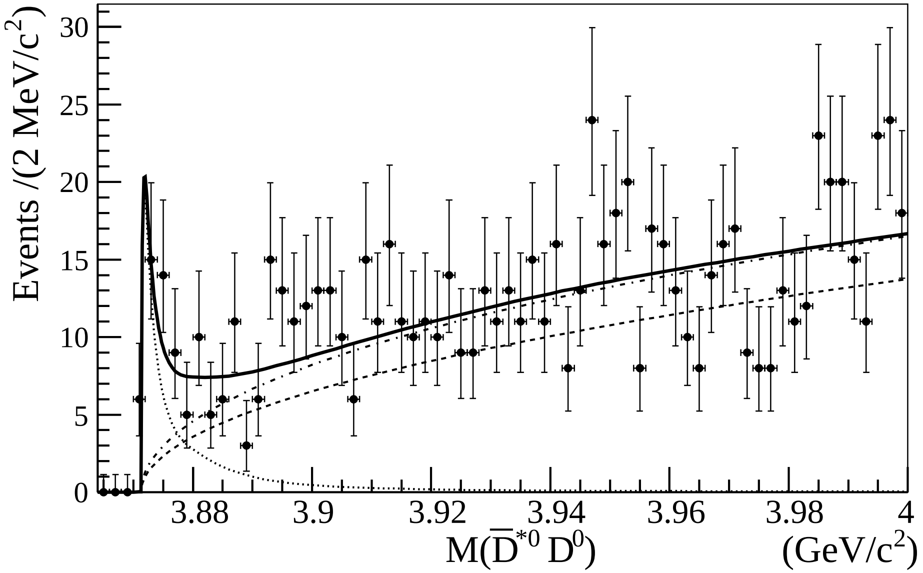
Confirmed by CDF and D0 in $p\bar{p}$ and BaBar in B decays

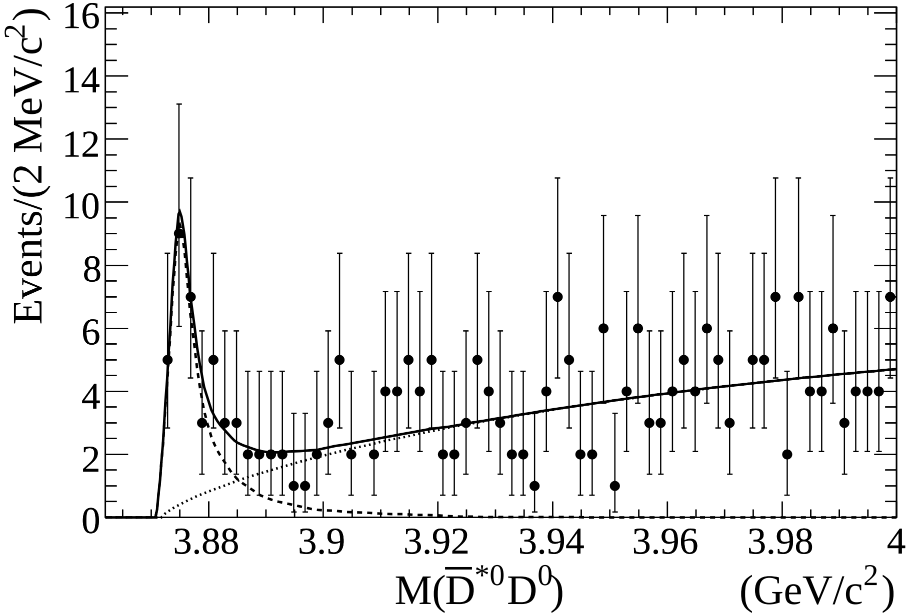
Seen and extensively studied at LHC

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

Study of $B \to X(3872)(D^{*0}\bar{D}^0)K$





Belle – $657 \cdot 10^6$ $B\bar{B}$ pairs;
T. Aushev et al., Phys. Rev. D 81 (2010) 031103.

BaBar – $383 \cdot 10^6$ $B\bar{B}$ pairs;
B.Aubert et al., PRD 77 (2008) 011102

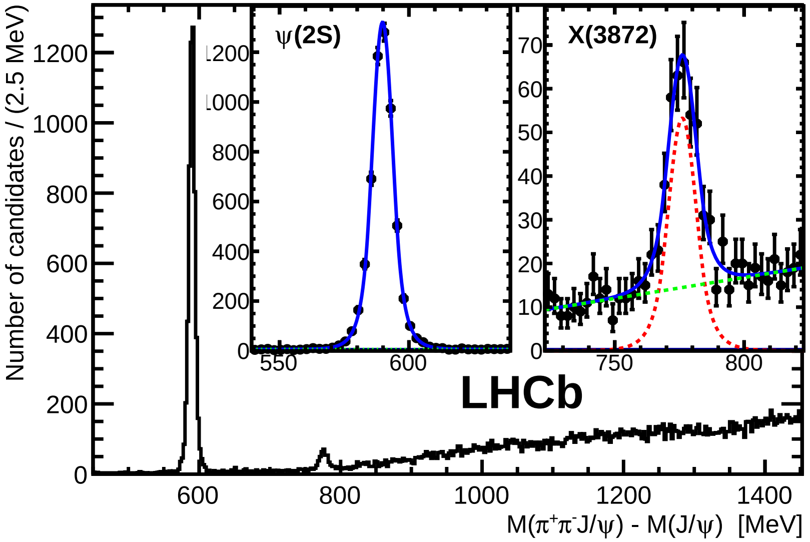
New M, Γ from Belle consistent with $J/\psi\pi^+\pi^-$, mass 2.3σ lower than in BaBar:

$$M = 3872.9^{+0.6+0.4}_{-0.4-0.5} \text{ MeV}$$

compared to the world-average $M_{J/\psi\pi\pi} = 3871.69 \pm 0.17$ MeV

Determination of X(3872) Quantum Numbers – I

A study of $B^+ \to X(3872)K^+,\ X(3872) \to J/\psi\pi^+\pi^-,\ J/\psi \to \mu^+\mu^-$ produced in pp at $\sqrt{s} = 7$ TeV with $\int Ldt = 1\ \mathrm{fb}^{-1}$

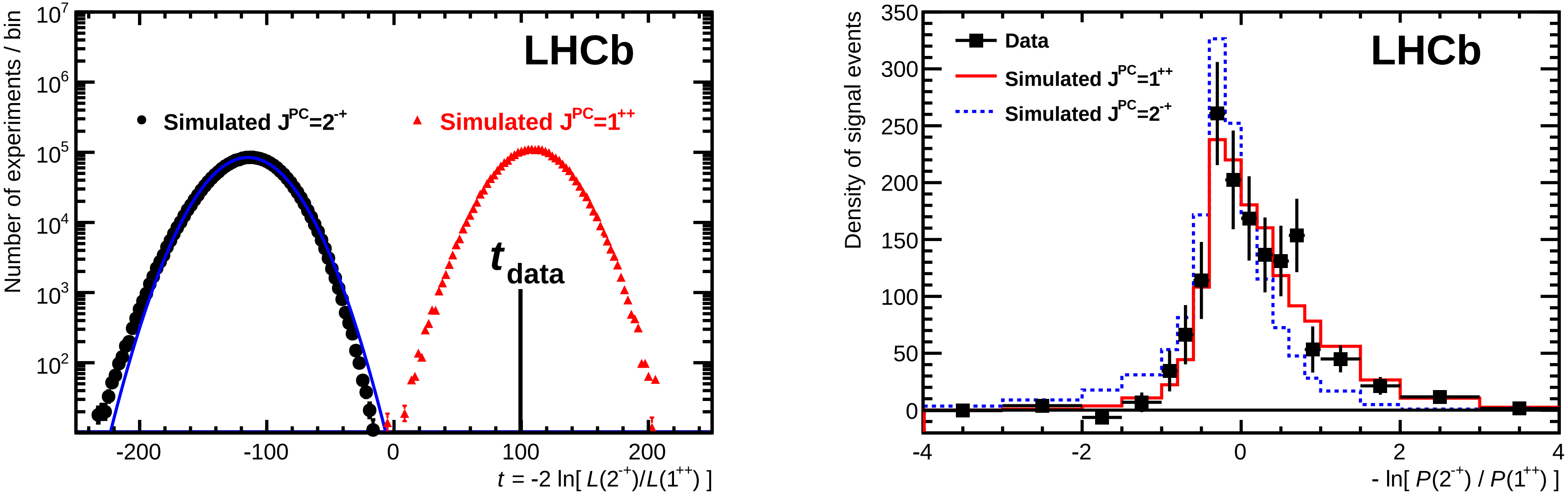


About 38000 B candidates selected in $M(J/\psi\pi^+\pi^-K^+)$ in a $\pm 2\sigma$ range, a fit yields 5642 ± 76 $\psi(2S)$ events and 313 ± 26 $X(3872)$ (68% purity)

R. Aaij et al., Phys. Rev. Lett. 110 (2013) 222001

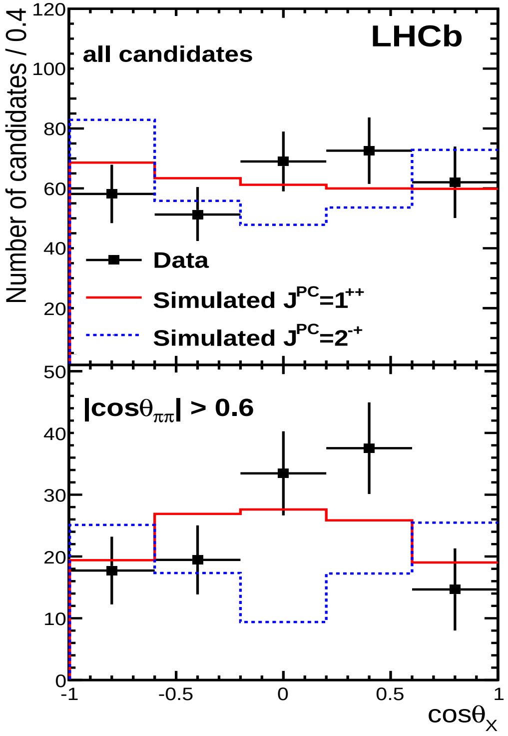
Determination of X(3872) Quantum Numbers – II

Analysis in $5D$ angular space $\Omega \equiv (\cos\theta_X, \cos\theta_{\pi\pi}, \Delta\phi_{X,\pi\pi}, \cos\theta_{J/\psi}, \Delta\phi_{X,J/\psi})$



The 2^{-+} hypothesis is rejected with 8.4σ significance

Determination of X(3872) Quantum Numbers – III



- Projections onto five $1D$ and ten $2D$ binned distr. are all consistent with 1^{++}
- Correlations between $\cos\theta_X$ and $\cos\theta_{\pi\pi}$ increase the separation btw. 1^{++} and 2^{-+}

1^{++} rules out $X(3872)$ as a conventional $\eta_{c2}(1^1D_2)$ state,

$\chi_{c1}(2^3P_1)$ $c\bar{c}$ disfavored by $X(3872)$ mass,

Possible exotics: $D^{*0}\bar{D}^0$ molecule, 4-q state, $c\bar{c}$-molecule mixture

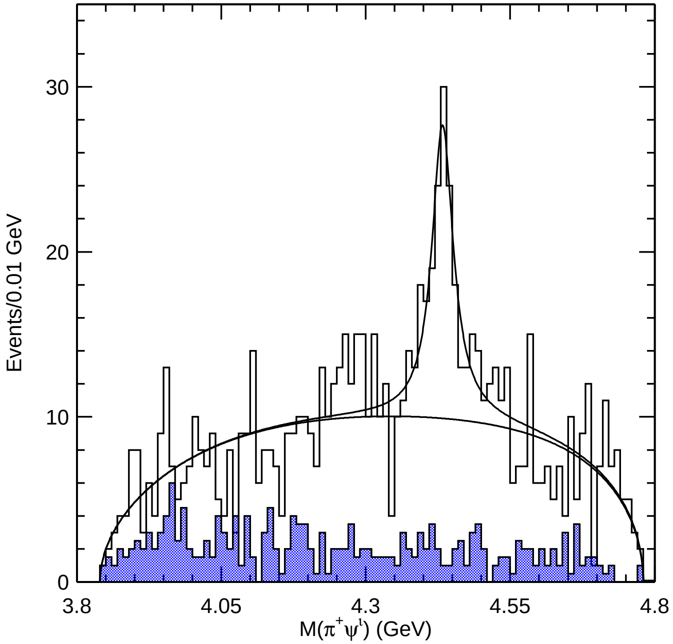
Summary on the $X(3872)$

- $J^{PC} = 1^{++}$ proved by LHCb
- $\chi_{c1}(2P)(1^{++})$ is not very likely considering the decay pattern, mass and observation of $Z(3930) = \chi_{c2}(2P)$
- Possible interpretations (in arbitrary order):

  1. an S-wave $D^0\bar{D}^{*0}$ molecule (loosely bound $[c\bar{q}][\bar{c}q]$)
  2. tetraquarks (tightly bound $[cq][\bar{c}\bar{q}]$)
  3. hybrids ($q\bar{q}$-gluon)
  4. threshold effect (cusp)
  5. a $D^0\bar{D}^{*0}$ molecule mixed with $c\bar{c}$
  6. hadrocharmonium – $c\bar{c}$ ($J/\psi, \ \ldots$) in the excited light-hadron matter

Observation of the $Z(4430)^{\pm}$ by Belle – I

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



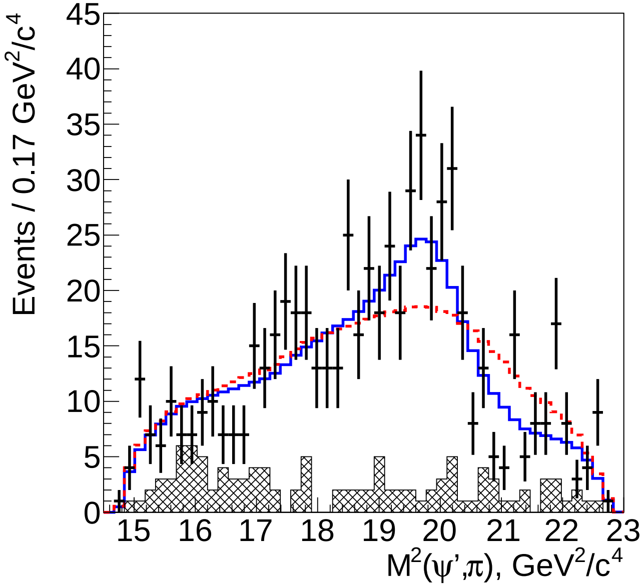
Confirmed by Dalitz plot analysis in R. Mizuk et al., Phys. Rev. D80 (2009) 031104

Not seen by BaBar with 413 fb^{1}, B. Aubert et al., Phys. Rev. D79 (2009) 112001

Observation of the $Z(4430)^{\pm}$ by Belle – II

Confirmed with full amplitude analysis and 772M $B\bar{B}$ pairs

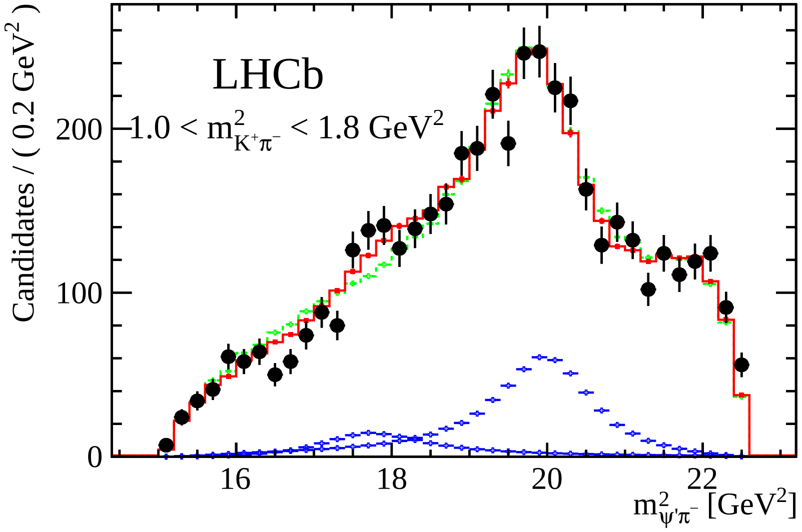
$J^P = 1^+$ is favored over the $0^-,\ 1^-,\ 2^-,\ 2^+$ $(3.4\sigma,\ 3.7\sigma,\ 4.7\sigma,\ 5.1\sigma)$



K. Chilikin et al., Phys. Rev. D88 (2013) 074026

Confirmation of the $Z(4430)^{\pm}$ by LHCb

LHCb confirms it, $J^P = 1^+$, with ×10 $B\bar{B}$ pairs



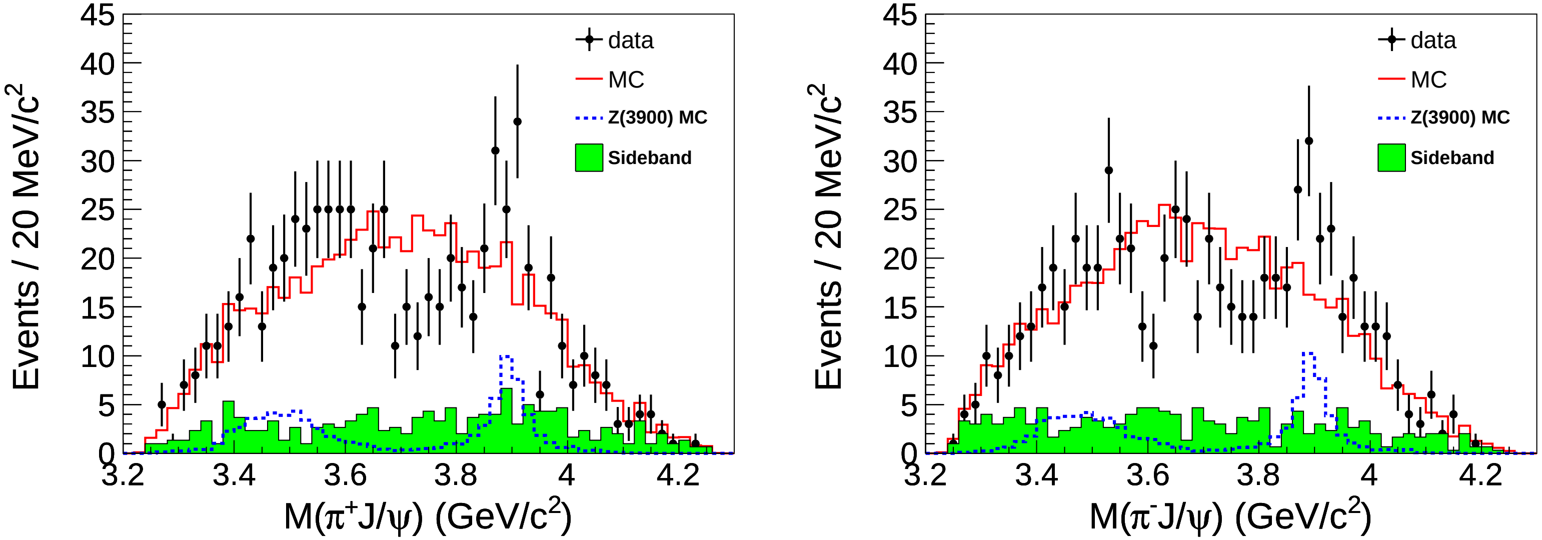
R. Aaij et al., Phys. Rev. Lett. 112 (2014) 074026

Observation of the Charged $J/\psi\pi^{\pm}$ State – I

From analysis of the $J/\psi\pi^{\pm}$ mass in $Y(4260) \to J/\psi\pi^{+}\pi^{-}$
both BESIII and Belle find a charged structure –$Z_c(3900)^{\pm}$

Group	BES	Belle
$\int \mathcal{L}dt$, fb^{-1}	0.525	967
Mass, MeV	$3899.0 \pm 3.6 \pm 4.9$	$3894.5 \pm 6.6 \pm 4.5$
Width, MeV	$46 \pm 10 \pm 20$	$63 \pm 24 \pm 26$
R, %	$21.5 \pm 3.3 \pm 7.5$	29.0 ± 8.9
Events	307 ± 48	159 ± 50
Ref.	PRL 110 (2013) 252001	PRL 110 (2013) 252002

Observation of the Charged $J/\psi\pi^\pm$ State – II

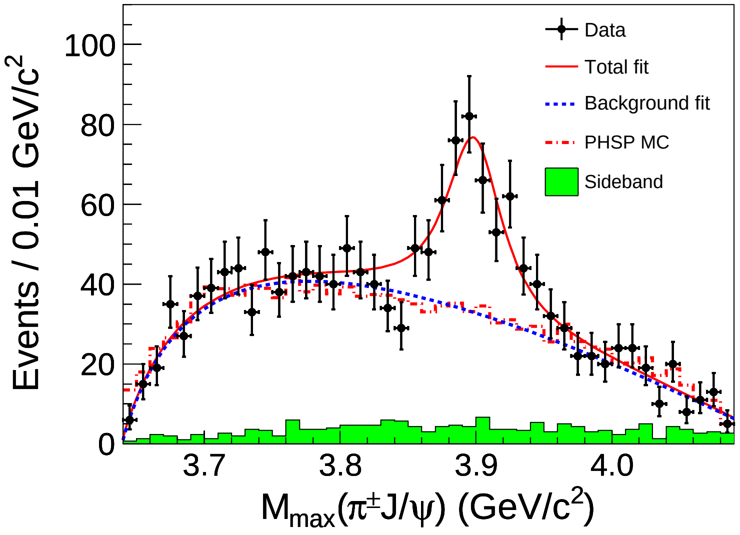


Observed in both $J/\psi\pi^+$ and $J/\psi\pi^-$

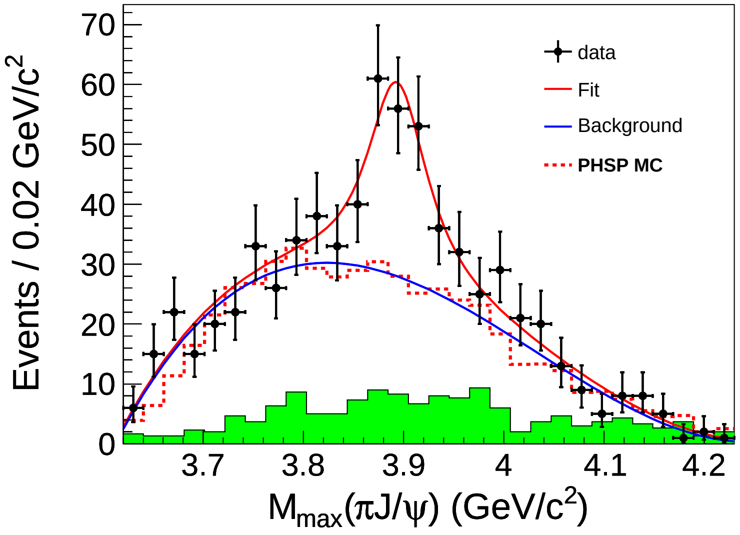
BES: M. Ablikim et al., Phys. Rev. Lett. 110 (2013) 252001

Belle: Z.Q. Liu et al., Phys. Rev. Lett. 110 (2013) 252002

Observation of the Charged $J/\psi\pi^{\pm}$ – III



BES



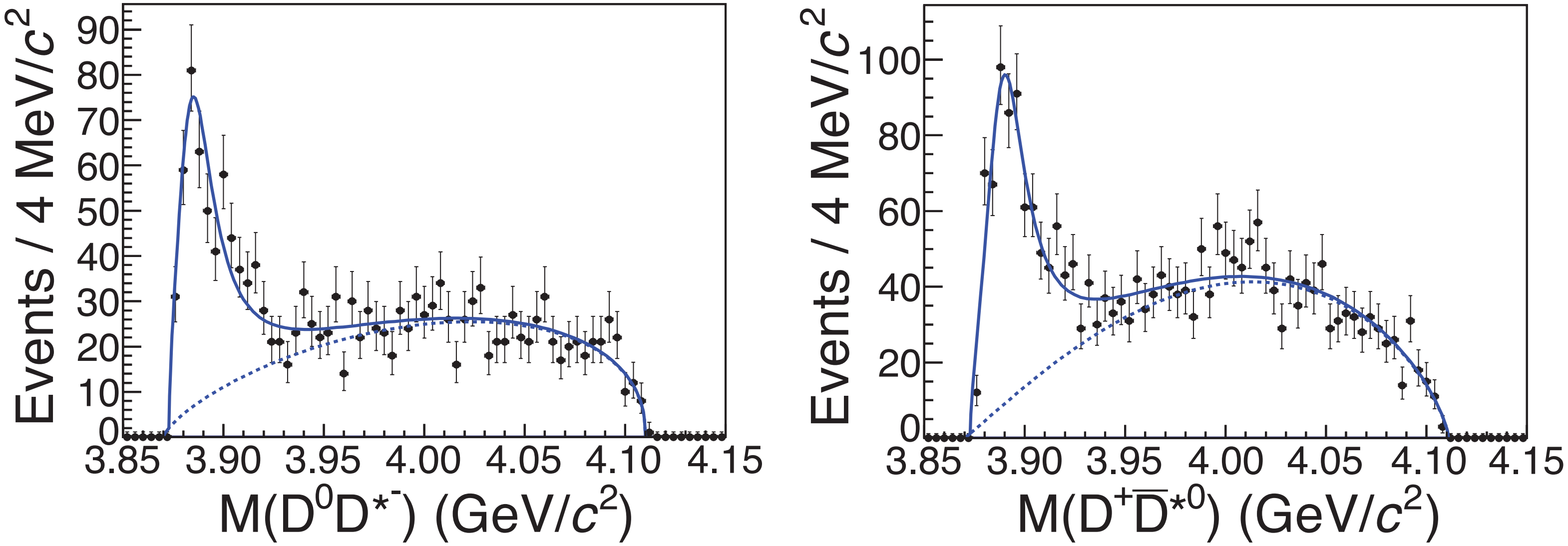
Belle

BES: M. Ablikim et al., Phys. Rev. Lett. 110 (2013) 252001

Belle: Z.Q. Liu et al., Phys. Rev. Lett. 110 (2013) 252002

Observation of $Z_c(3900)^\pm$ in $(D\bar{D}^*)^\pm$ at BESIII

A $J^P = 1^+$ structure in $(D\bar{D}^*)^\pm$ with mass (width) 2σ (1σ) below the $J/\psi\pi$

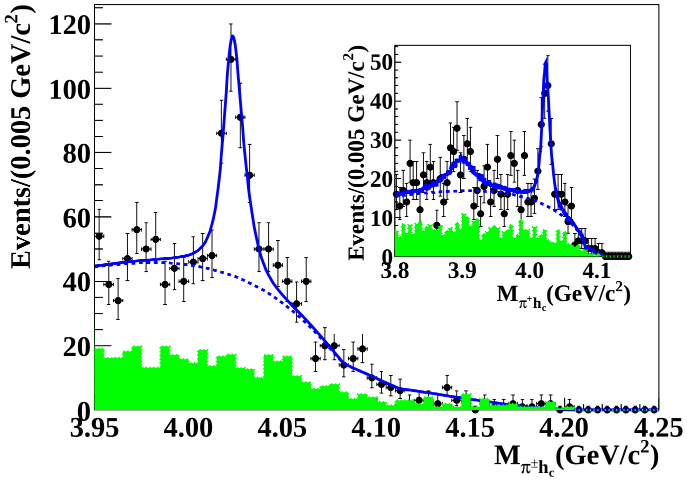


$$\Gamma(D\bar{D}^*)/\Gamma(J/\psi\pi) = 6.2 \pm 1.1 \pm 2.7$$

M. Ablikim et al., Phys. Rev. Lett. 112 (2014) 022001

Observation of $Z_c(4020)^{\pm}$ in $e^+e^- \to h_c\pi^+\pi^-$

In $e^+e^- \to h_c\pi^+\pi^-$ a charged structure in $h_c\pi^{\pm}$ seen with mass $4022.9 \pm 0.8 \pm 2.7$ MeV and width $7.9 \pm 2.7 \pm 2.6$ MeV



M. Ablikim et al., Phys. Rev. Lett. 111 (2013) 242001

Also observed by BES3: in $D^*\bar{D}^*$, neutral partners for both modes

New Charmonium(like) States – I

State	J^{PC}	Process
$\eta_c(2S, 3639)$	0^{-+}	$B \to K(K_S K \pi)$
$\psi(3820)$	2^{--}	$B \to \chi_{c1}\gamma K$
$X(3872)$	1^{++}	$B \to K(J/\psi\pi^+\pi^-)$
$X(3915)$	$0/2^{?+}$	$B \to K(J/\psi\omega)$
$\chi_{c2}(2P, 3927)$	2^{++}	$\gamma\gamma \to D\bar{D}$
$X(3940)$	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$
$Y(3990)$	1^{--}	$e^+e^- \to \gamma(J/\psi\pi^+\pi^-)$
$Y(4140)$	$?^{?+}$	$B \to K(J/\psi\phi)$
$X(4160)$	$?^{?+}$	$e^+e^- \to J/\psi(D^*\bar{D}^*)$
$Y(4260)$	1^{--}	$e^+e^- \to \gamma(J/\psi\pi^+\pi^-)$
$X(4350)$	$0/2^{++}$	$\gamma\gamma \to J/\psi\phi$

New Charmonium(like) States – II

State	J^{PC}	Process
$Y(4140)$	$?^{?+}$	$B \to K(J/\psi\phi)$
$X(4160)$	$?^{?+}$	$e^+e^- \to J/\psi(D^*\bar{D}^*)$
$Z_2(4250)^+$	$?$	$B \to K(\chi_{c1}(1P)\pi^+)$
$Y(4260)$	1^{--}	$e^+e^- \to \gamma(J/\psi\pi^+\pi^-)$
$X(4350)$	$0/2^{++}$	$\gamma\gamma \to J/\psi\phi$
$Y(4360)$	1^{--}	$e^+e^- \to \gamma(\psi(2S)\pi^+\pi^-)$
$Z(4430)^+$	$?$	$B \to K(\psi(2S)\pi^+)$
$Y(4630)$	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$
$Y(4660)$	1^{--}	$e^+e^- \to \gamma(\psi(2S)\pi^+\pi^-)$

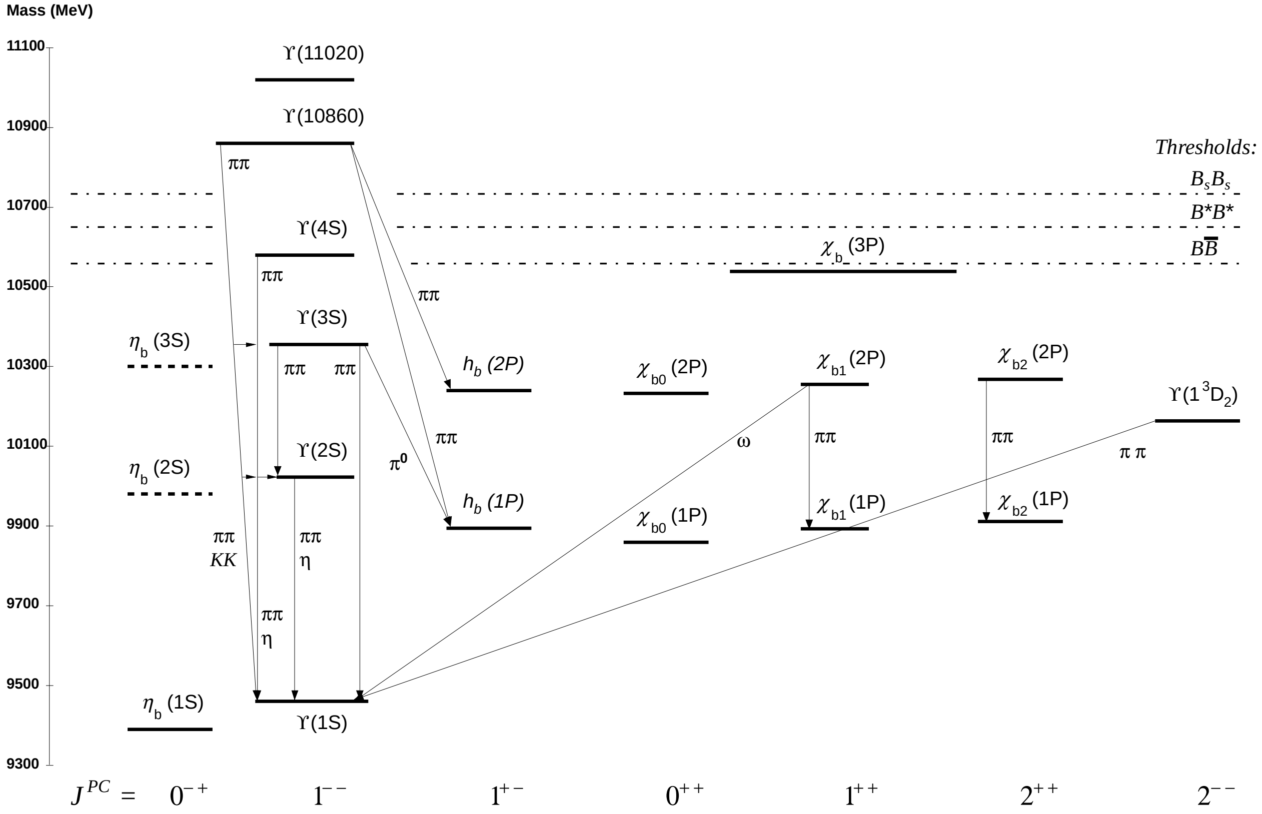
Conclusions on Charmonium

- Various $c\bar{c}$ states have been discovered or remeasured
  high statistics measurements and sophisticated analysis
- There are too many 1^{--} states
- Many states do not fit the expected pattern of $c\bar{c}$
- Many exotic structures found not fitting the quark model,
  they decay into both hidden ($c\bar{c}\pi$) and open charm ($D^{(*)}\bar{D}^{(*)}$) states
- A lot of work for BESIII, BelleII and LHC experiments in the future

Bottomonium – Some History

- Until recently most of the info on bottomonium came from CLEO and CUSB at CESR (80-ies and 90-ies) as well as from ARGUS and Crystal Ball at DESY
- These works followed the discovery of the $\Upsilon(1S)$ at Fermilab in 1977, so by mid-90-ies we knew three narrow and three broad $\Upsilon(nS)$'s plus six $\chi_{bJ}(1P)$ and $\chi_{bJ}(2P)$ states
- Then for a long time CLEO had a monopoly improving precision, which was broken by BaBar and Belle during last 5 years
- In particular, Belle collected $\sim$146 fb^{-1} from 10.63 to 11.05 GeV, two orders of magnitude larger than before
- An important addition to Standard Model tests, providing a lot of information on strong interactions and new (exotic) hadrons

Bottomonium Levels

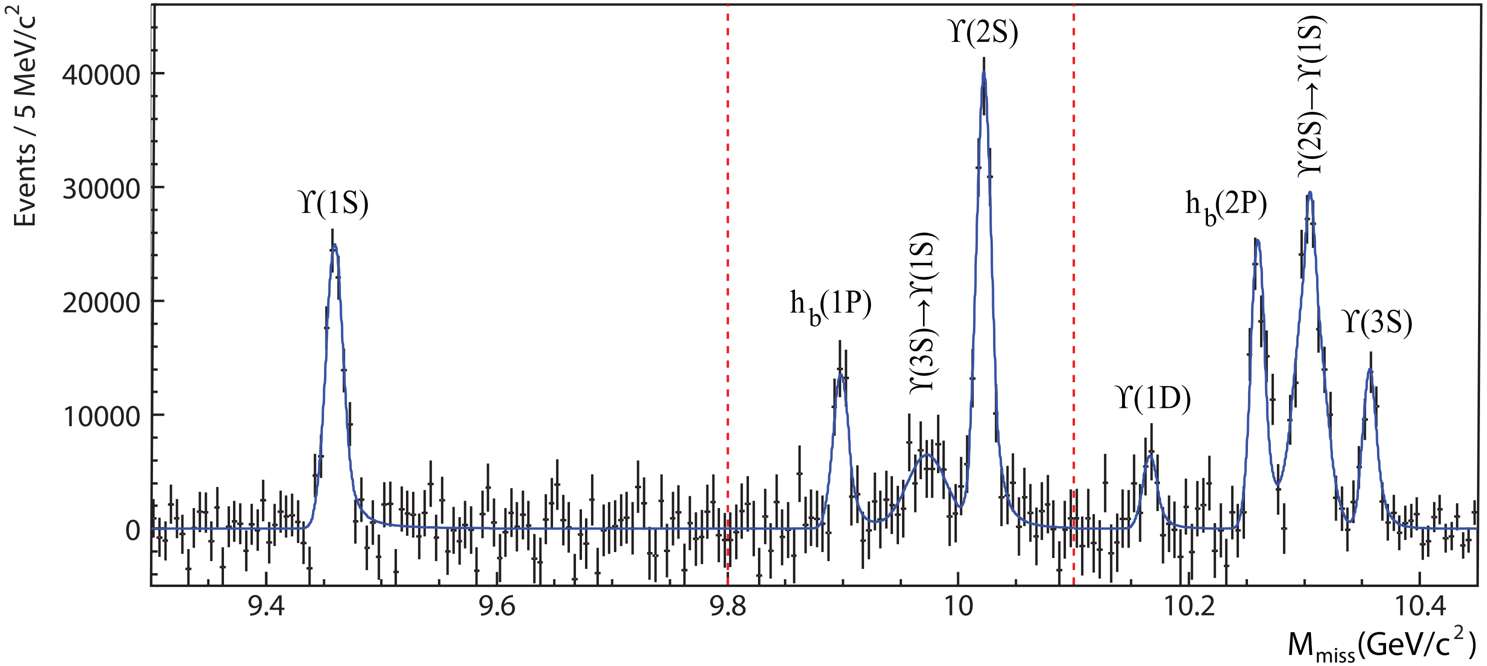


K.A. Olive et al. (Particle Data Group), Chin. Phys. C38, 090001 (2014)

Summary of Recent Findings

- First observation of $h_b(1P)$ and $h_b(2P)$
  I. Adachi et el., Phys. Rev. Lett. 108, 032001 (2012)
- Reliable observation of $\eta_b(1S)$ and first evidence for $\eta_b(2S)$
  R. Mizuk et el., Phys. Rev. Lett. 109, 232002 (2012)
- Discovery of charged states $Z_b(10610)$ and $Z_b(10650)$
  A. Bondar et el., Phys. Rev. Lett. 108, 122001 (2012)
- Discovery of the neutral state $Z_b(10610)$
  P. Krokovny et al., Phys. Rev. D88, 052015 (2013)
- Amplitude analysis of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ and quantum numbers of Z_b
  A. Garmash et al., Phys. Rev. D91, 072003 (2015)

Observation of $h_b(1P)$ and $h_b(2P)$ at Belle



Missing mass distribution clearly shows
a variety of states with different J^P

New Measurement of the $h_b(1P)$ and $\eta_b(1S)$ from $\Upsilon(4S) \to \eta h_b(1P)$

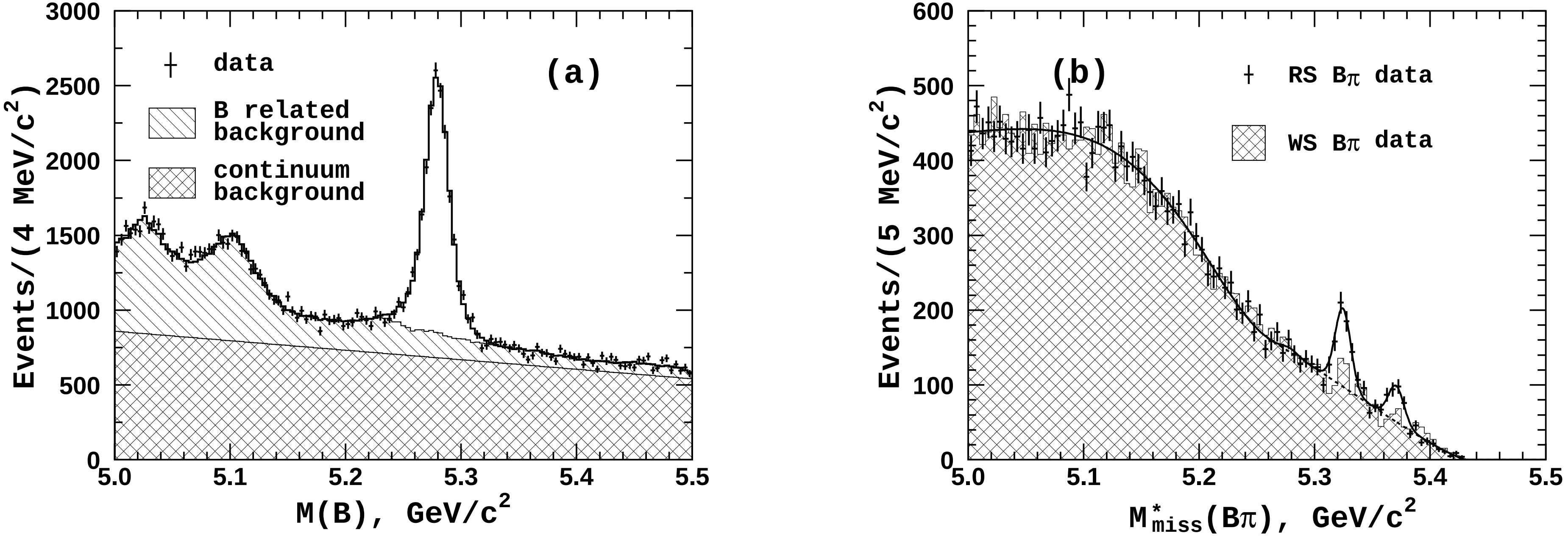
Observable	Value
$\mathcal{B}[\Upsilon(4S) \to \eta h_b(1P)]$	$(2.18 \pm 0.11 \pm 0.18) \times 10^{-3}$
$\mathcal{B}[h_b(1P) \to \gamma \eta_b(1S)]$	$(56 \pm 8 \pm 4)\%$
$M_{h_b(1P)}$	$(9899.3 \pm 0.4 \pm 1.0)$ MeV/c^2
$M_{\eta_b(1S)} - M_{h_b(1P)}$	$(-498.6 \pm 1.7 \pm 1.2)$ MeV/c^2
$\Gamma_{\eta_b(1S)}$	$(8^{+6}_{-5} \pm 5)$ MeV/c^2
$M_{\eta_b(1S)}$	$(9400.7 \pm 1.7 \pm 1.6)$ MeV/c^2
$\Delta M_{\mathrm{HF}}(1S)$	$(+59.6 \pm 1.7 \pm 1.6)$ MeV/c^2
$\Delta M_{\mathrm{HF}}(1P)$	$(+0.6 \pm 0.4 \pm 1.0)$ MeV/c^2

U. Tamponi et al., Phys. Rev. Lett. 115, 142001 (2015)

Observation of $Z_b(10610)$ and $Z_b(10650)$ Decaying to B Mesons – I

Belle: $e^+e^- \to B\bar{B}\pi^\pm, B\bar{B}^*\pi^\pm + c.c., B^*\bar{B}^*\pi^\pm$ with 121.4 fb^{-1} at 10.866 GeV

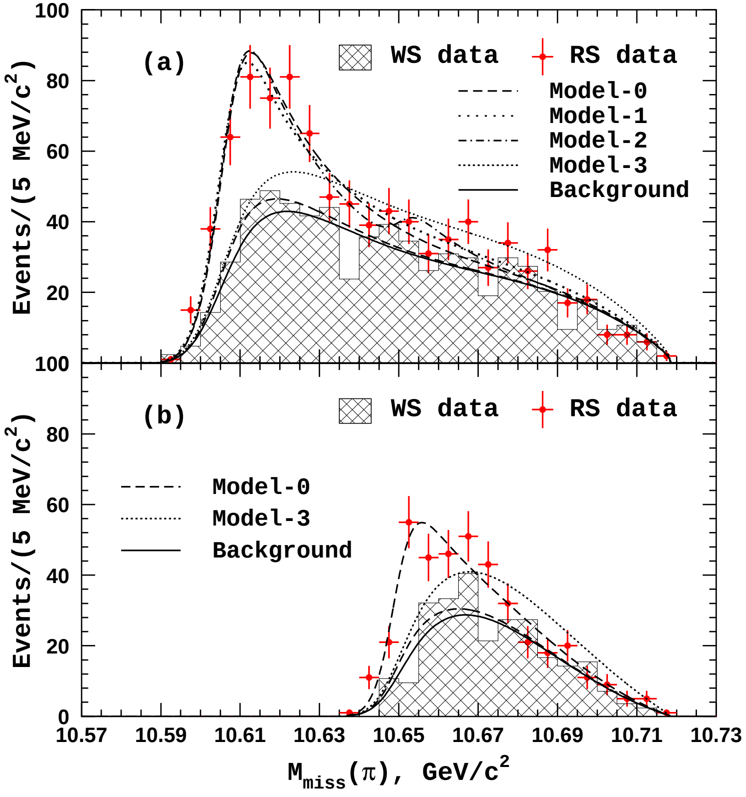
$$M_{\rm miss}(B\pi) = \sqrt{(\sqrt{s} - E_{B\pi})^2 - P^2_{B\pi}}$$



12263 ± 168 fully reconstructed B mesons

A. Garmash et al., Phys. Rev. Lett. 116, 212001 (2016)

Observation of $Z_b(10610)$ and $Z_b(10650)$ Decaying to B Mesons – II



$13 \pm 25\ B\bar{B}\pi$ events

$357 \pm 30\ B^*\bar{B}\pi$ events

$161 \pm 21\ B^*\bar{B}^*\pi$ events

$M_{\rm miss}(\pi) = \sqrt{(\sqrt{s} - E_\pi)^2 - P_\pi^2}$

A. Garmash et al., Phys. Rev. Lett. 116, 212001 (2016)

Observation of $Z_b(10610)$ and $Z_b(10650)$ Decaying to B Mesons – III

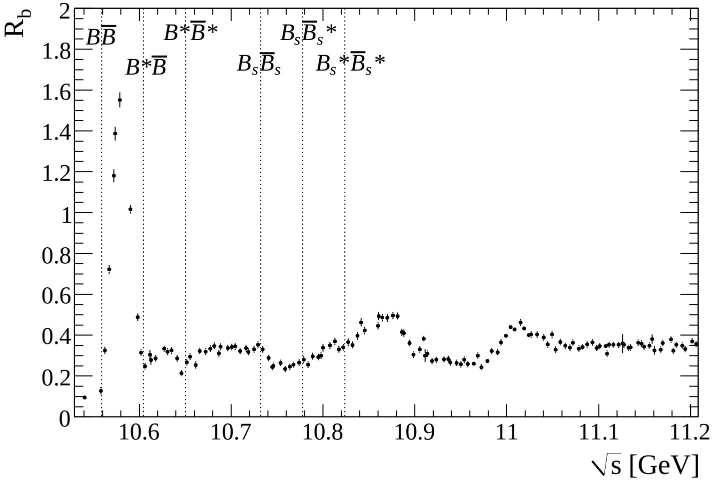
Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	$0.54^{+0.16+0.11}_{-0.13-0.08}$	$0.17^{+0.07+0.03}_{-0.06-0.02}$
$\Upsilon(2S)\pi^+$	$3.62^{+0.76+0.79}_{-0.59-0.53}$	$1.39^{+0.48+0.34}_{-0.38-0.23}$
$\Upsilon(3S)\pi^+$	$2.15^{+0.55+0.60}_{-0.42-0.43}$	$1.63^{+0.53+0.39}_{-0.42-0.28}$
$h_b(1P)\pi^+$	$3.45^{+0.87+0.86}_{-0.71-0.63}$	$8.41^{+2.43+1.49}_{-2.12-1.06}$
$h_b(2P)\pi^+$	$4.67^{+1.24+1.18}_{-1.00-0.89}$	$14.7^{+3.2+2.8}_{-2.8-2.3}$
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	$85.6^{+1.5+1.5}_{-2.0-2.1}$	–
$B^{*+}\bar{B}^{*0}$	–	$73.7^{+3.4+2.7}_{-4.4-3.5}$

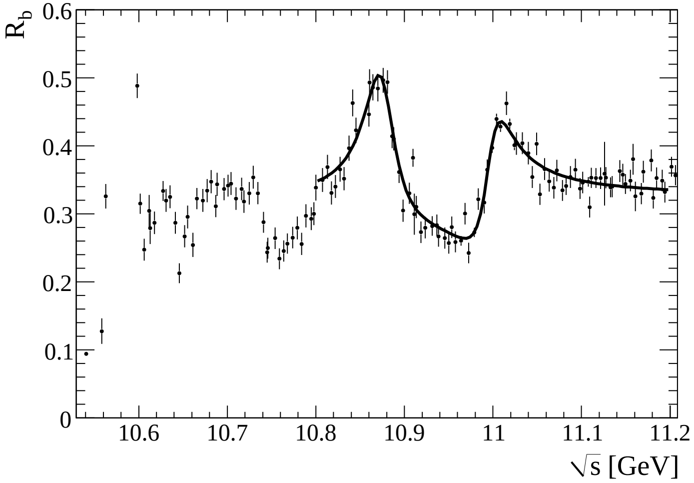
A. Garmash et al., Phys. Rev. Lett. 116, 212001 (2016)

Puzzles of $\Upsilon(10860)$ and $\Upsilon(11020)$

- The rate for $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ (n=1,2,3) at $\Upsilon(10860)$ is $\sim$ 100 times that for $\Upsilon(nS) \to \Upsilon(1S)\pi^+\pi^-$ (n=2,3,4)
  K.-F.Chen et al. (Belle), Phys.Rev.Lett. 100, 112001 (2008)
- Rates to $h_b(mP)\pi^+\pi^-$ (m=1,2) are of the same order as to $\Upsilon(nS)\pi^+\pi^-$ despite a b-quark spin flip
  I.Adachi et al., Phys.Rev.Lett. 108, 032001 (2012)
- The peak of $R_{\Upsilon(nS)\pi\pi} \equiv \sigma(\Upsilon(nS)\pi^+\pi^-)/\sigma^0_{\mu\mu}$ near $\Upsilon(10860)$ occurs at 9 ± 4 MeV higher than that of $R_b \equiv \sigma(b\bar{b})/\sigma^0_{\mu\mu}$
  K.-F.Chen et al., Phys.Rev. D82, 091106 (2010)
- Is there another peaking structure at 10.9 GeV suggested by data of Belle and BaBar?
  A.Ali et al., Phys. Lett. B684, 28 (2010), Phys. Rev. Lett. 104, 162001 (2010)
- $R'_{b,i} = R_{b,i} - \Sigma\sigma_{\rm ISR,i}/\sigma^0_{\mu^+\mu^-,i}$

BaBar High-Energy Scan





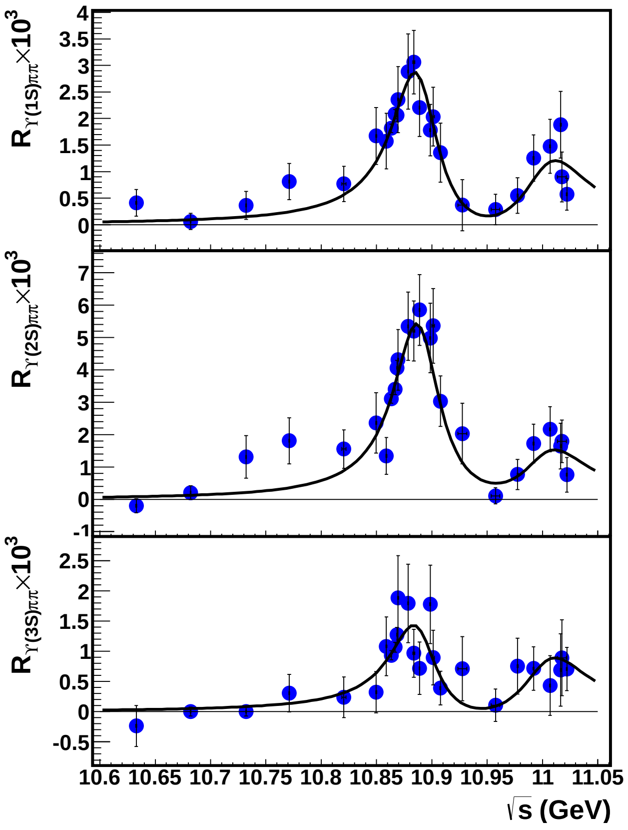
$3.3\ \text{fb}^{-1}$ from 10.54 to 11.20 GeV + $0.6\ \text{fb}^{-1}$ from 10.96 to 11.10 GeV

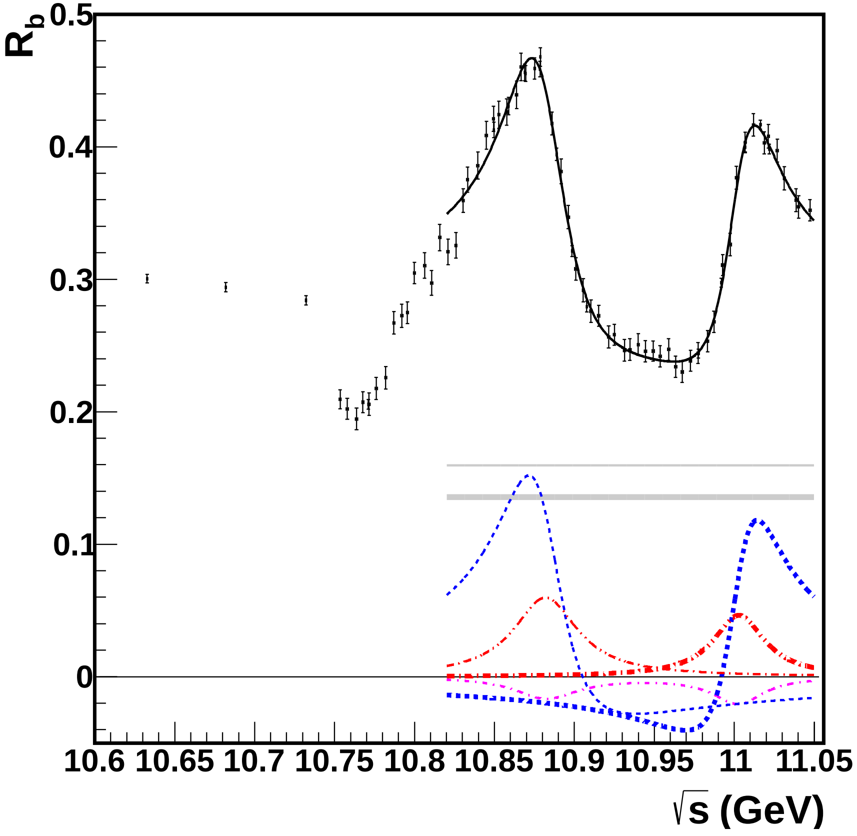
Parameters of the $\Upsilon(5S, 6S)$ are sensitive to the $\sigma(s)$ shape

Clear structures at opening thresholds, a plateau near $B_s^* \bar{B}_s^*$

B. Aubert et al., Phys. Rev. Lett. 102, 012001 (2009)

Belle High-Energy Scans – I





About 146 fb^{-1} from 10.63 to 11.05 GeV, 35 times more than at BaBar

D. Santel et al., Phys. Rev. D93, 011101 (2016)

Belle High-Energy Scans – II

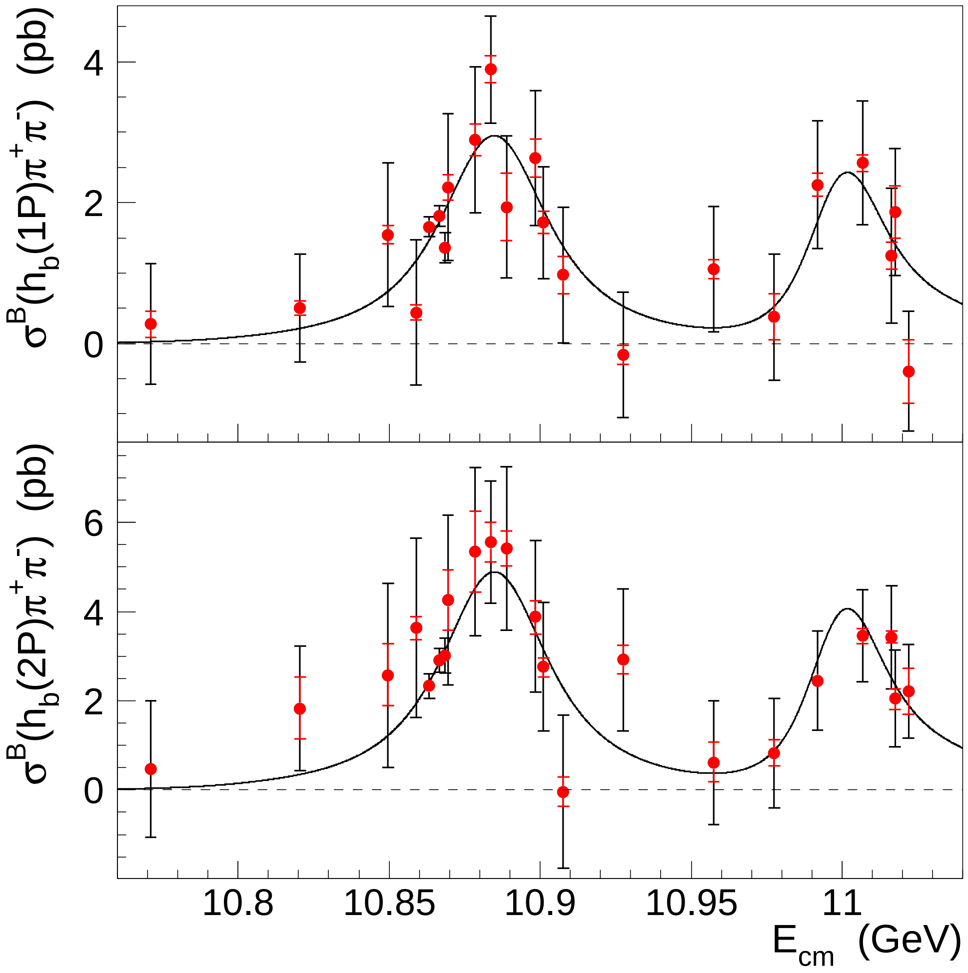
	$M_{5\mathrm{S}}$ (MeV)	$\Gamma_{5\mathrm{S}}$ (MeV)	$M_{6\mathrm{S}}$ (MeV)	$\Gamma_{6\mathrm{S}}$ (MeV)
R_b'	$10881.8^{+1.0}_{-1.1} \pm 1.2$	$48.5^{+1.9\ +2.0}_{-1.8\ -2.8}$	$11003.0 \pm 1.1\ ^{+0.9}_{-1.0}$	$39.3^{+1.7\ +1.3}_{-1.6\ -2.4}$
$R_{\Upsilon\pi\pi}$	$10891.1 \pm 3.2^{+0.6}_{-1.7}$	$53.7^{+7.1\ +1.3}_{-5.6\ -5.4}$	$10987.5^{+6.4\ +9.0}_{-2.5\ -2.1}$	$61^{+9\ \ +2}_{-19\ -20}$

- M and Γ from R_b' and $R_{\Upsilon\pi\pi}$ are consistent, but the fitted $\mathcal{A}$'s are not and validity of flat continuum for R_b' is doubtful; interference effects
- $\Upsilon\pi\pi$ spectra have little or no nonresonant component, so it makes sense to quote resonance parameters from $R_{\Upsilon\pi\pi}$
- First hadronic transitions $\Upsilon(6S) \to \Upsilon(nS)\pi^+\pi^-$ are observed
- No peaking structure at 10.9 GeV in the R_b' observed, $\Gamma_{ee} < 9$ eV at 90%CL

D. Santel et al., Phys. Rev. D93, 011101 (2016)

Belle High-Energy Scans – III

Belle used $\sim 140\ \mathrm{fb}^{-1}$ from 10.77 to 11.02 GeV to study $e^+e^- \to h_b(nP)\pi^+\pi^-$



Belle High-Energy Scans – IV

Parameter	$h_b\pi\pi$	$\Upsilon\pi\pi$
M_{5S}, MeV	$10884.7^{+3.6+8.9}_{-3.4-1.0}$	$10891.1 \pm 3.2^{+0.6}_{-1.7}$
Γ_{5S}, MeV	$40.6^{+12.7+\ 1.1}_{-8.0-19.1}$	$53.7^{+7.1+1.3}_{-5.6-5.4}$
M_{6S}, MeV	$10999.0^{+7.3+16.9}_{-7.8-\ 1.0}$	$10987.5^{+6.4+9.0}_{-2.5-2.1}$
Γ_{6S}, MeV	$27^{+27+\ 5}_{-11-12}$	$61^{+\ 9+\ 2}_{-19-20}$

- Results in $h_b\pi\pi$ and $\Upsilon\pi\pi$ modes are consistent
- There is no non-resonant component in $h_b\pi\pi$
- $\Upsilon(11020) \to h_b\pi^+\pi^-$ transitions proceed via $Z_b(10610)$ and/or $Z_b(10650)$

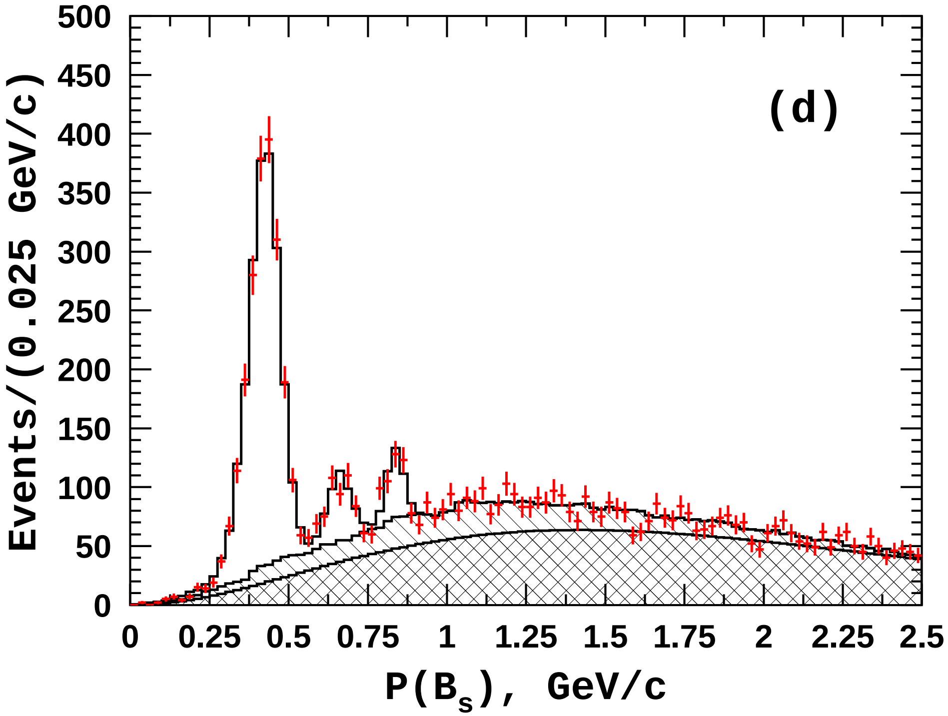
A.Abdessalam et al., Phys.Rev.Lett. 117 (2016) 142001

Study of $e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)}$ from 10.77 to 11.05 GeV – I

121.4 fb^{-1} near the $\Upsilon(10860)$ peak

2283 ± 63 events from a fit to the $M(B_s)$ distribution

$B_s^*\bar{B}_s^*$, $B_s\bar{B}_s^* + c.c.$, $B_s\bar{B}_s$ expected to peak at 0.43, 0.63, 0.83 GeV/c



K. Kinoshita, talk at ICHEP-16, preliminary

Study of $e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)}$ from 10.77 to 11.05 GeV – II

	$B_s^*\bar{B}_s^*$	$B_s\bar{B}_s^* + \bar{B}_sB_s^*$	$B_s\bar{B}_s$
N_{events}	1824 ± 51	223 ± 27	168 ± 24
Belle	7	$0.856 \pm 0.106 \pm 0.053$	$0.645 \pm 0.094 \pm 0.033$
PDG	7	0.537 ± 0.152	0.199 ± 0.199
HQSS	7	4	1

Heavy Quark Spin Symmetry (HQSS) Approximation considered by

A. De Rujula, H. Georgi and S.L. Glashow, Phys. Rev. Lett. 38 (1977) 317

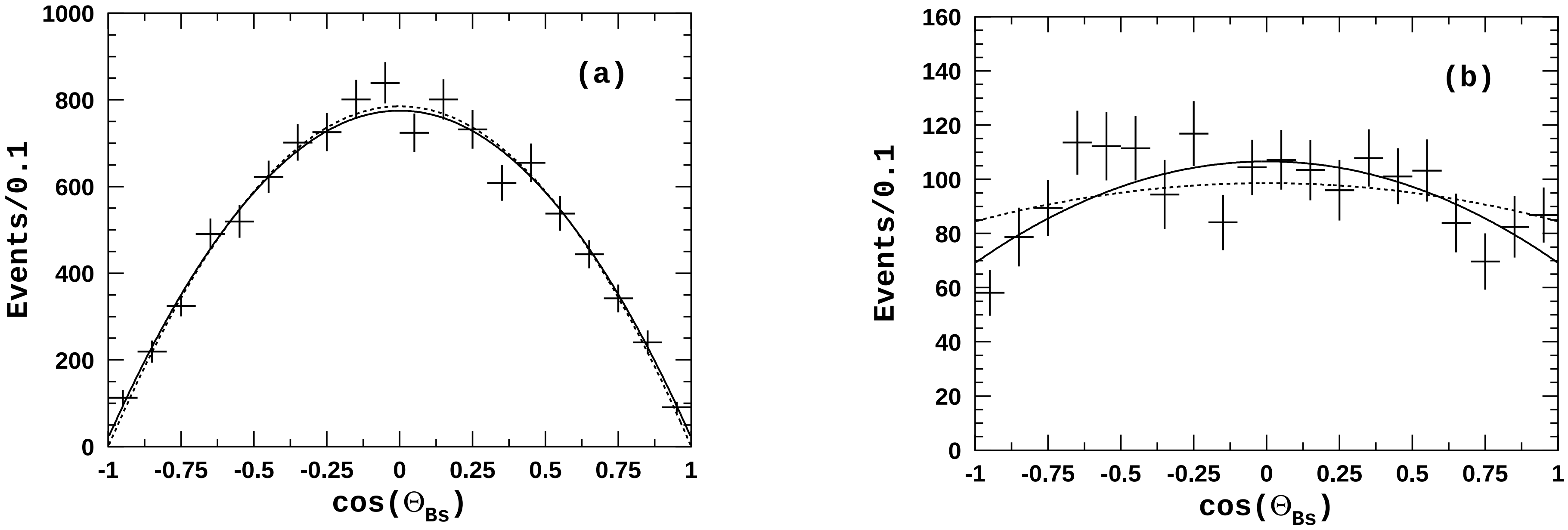
is strongly broken near threshold of open flavor for both $c\bar{c}$ and $b\bar{b}$ states

M. Voloshin, Phys. Rev. D 85 (2012) 034024 argues that

strong HQSS breaking near threshold is due to mixing of quarkonium-like states

with pairs of heavy mesons, should be also seen in angular distributions

Study of $e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)}$ from 10.77 to 11.05 GeV – III



MC with $a_2 = 0$ Data

For $e^+e^- \to B_s^*\bar{B}_s^*$ $\quad d\sigma/dcos\theta \sim a_0^2(1-cos^2\theta) + a_2^2(7-cos^2\theta)/10$

In HQSS $a_0^2 : a_2^2 = 1:20$ or $r = a_0^2/(a_0^2+a_2^2) = 1:21 = 0.048$

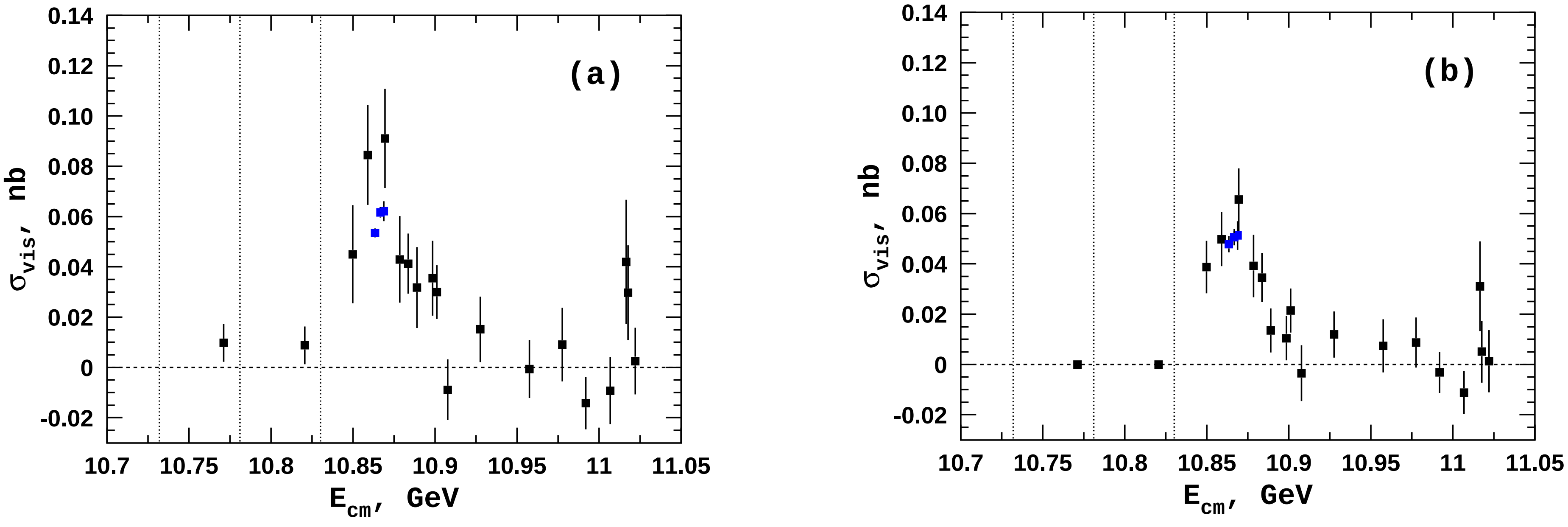
From a fit Belle obtains $r = 0.175 \pm 0.057 \pm 0.020$

or 2.6σ significance for the $S=0$ component

Study of $e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)}$ from 10.77 to 11.05 GeV – IV

121.4 fb^{-1} near the $\Upsilon(10860)$ (grouped into three points)
and 16.4 fb^{-1} from 10.77 to 11.02 GeV

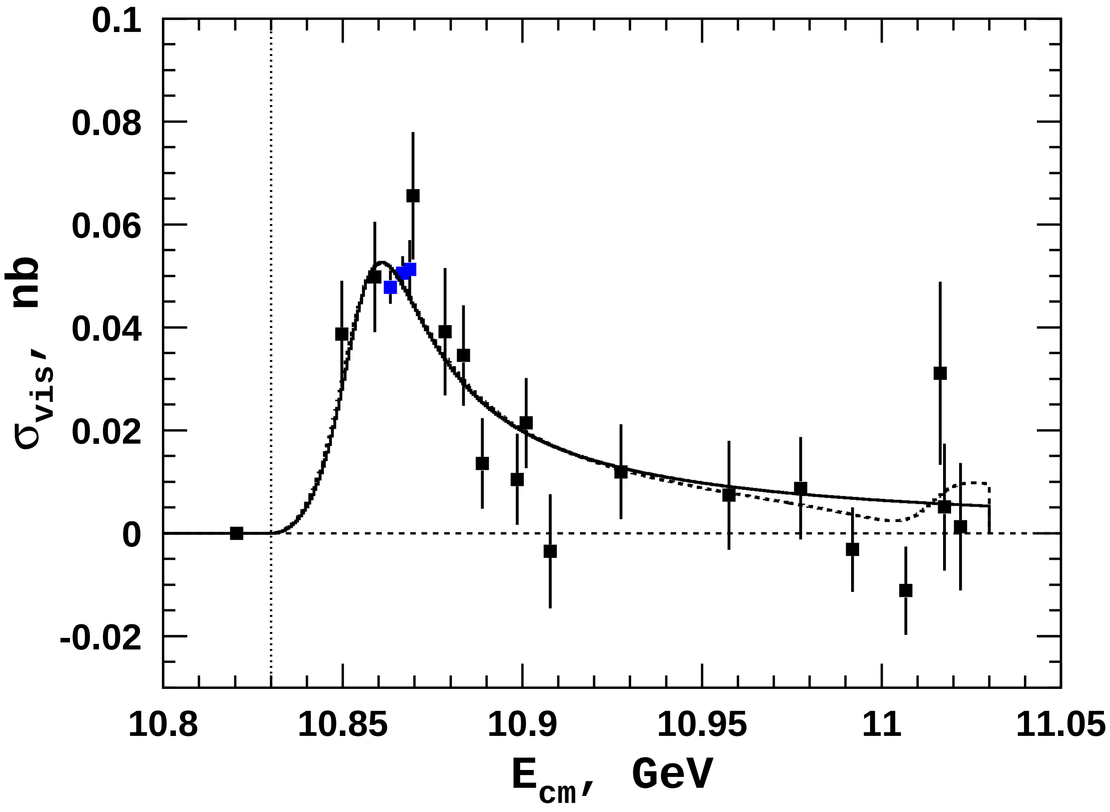
Prominent signals in $M(B_s)$ at three points with large luminosity



$e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)}$ $e^+e^- \to B_s^{*}\bar{B}_s^{*}$

Study of $e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)}$ from 10.77 to 11.05 GeV – V

For $e^+e^- \to B_s^*\bar{B}_s^*$ separate analysis with tighter conditions



K. Kinoshita, talk at ICHEP-16, preliminary

Study of $e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)}$ from 10.77 to 11.05 GeV – VI

$$\sigma \sim (P/P_0)|F_{BW}(s, M_5, \Gamma_5) + aF_{BW}(s, M_6, \Gamma_6)\exp^{i\phi}|^2$$

Parameter	$\Upsilon(10860)$	$\Upsilon(10860)$+$\Upsilon(11020)$
M_5, MeV	10869.1 ± 5.3	10870.8 ± 5.8
Γ_5, MeV	59 ± 22	65 ± 23
M_6, MeV	–	11013.0 ± 8.9
Γ_6, MeV	–	27
a_6	–	0.121 ± 0.072
ϕ/π	–	1.38 ± 0.43
χ^2/ndf	20.9/17	18.5/14

Parameters of $\Upsilon(10860)$ are close to these in $\Upsilon(nS)(h_b(mP))\pi^+\pi^-$ final states

No significant signal of $\Upsilon(11020) \to B_s^*\bar{B}_s^*$

Conclusions and Future

- Various $b\bar{b}$ states have been discovered/remeasured due to new energy domains, high statistics measurements and sophisticated analysis
- Higher $M_{\eta_b(1S)}$ confirmed, smaller tension with theory for $\Delta M_{\mathrm{HF}}(1S)$
- Exotic states (two Z_b's) not fitting the quark model exist, they decay into both hidden ($\Upsilon\pi,\ h_b\pi$) and open beauty ($B^*\bar{B}^*, B\bar{B}^* + c.c.$) states
- Not yet discovered bottomonium analogues of $c\bar{c}$ states likely, the question of analogies with charmonium is of great interest
- $\Upsilon(10860)$ and $\Upsilon(11020)$ decay to $\Upsilon(nS)\pi\pi$ and $h_b(1P)\pi\pi$
- New decay modes of $\Upsilon(10860) \to B_s^{(*)}\bar{B}_s^{(*)}$, no signal at $\Upsilon(11020)$
  $B_s^*\bar{B}_s^* : B_s\bar{B}_s^* + c.c. : B_s\bar{B}_s = 7 : 0.856 \pm 0.119 : 0.645 \pm 0.100$
  Strong breaking of HQSS
- A lot of work for BelleII and LHC experiments in the future