B Factories: Status and Prospects

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Outline

1. Introduction
2. CP Violation and CKM Matrix
3. Quarkonium Spectroscopy
4. Initial-State Radiation
5. τ-lepton Physics
6. Conclusions

Introduction

A Bit of History

- The idea to construct an asymmetric e^+e^- collider running at the $\Upsilon(4S)$ appeared in eighties
- PEP-II at SLAC (BaBar) ran in 1999-2008, 3.1 GeV $(e^+)\times$ 9 GeV (e^-), $\mathcal{L}_{\rm peak} = 1 \times 10^{34}$ cm^{-2} s^{-1} and collected 0.5 ab^{-1}
- KEKB at KEK (Belle) ran in 1999-2010, 3.5 GeV $(e^+)\times$ 8 GeV (e^-), $\mathcal{L}_{\rm peak} = 2.1 \times 10^{34}$ cm^{-2} s^{-1} and collected 1 ab^{-1}
- The physical goal – CP violation in the B-meson system – was reached by both Belle and BaBar in 2001
- Most of the luminosity was collected at the $\Upsilon(4S)$, but both Belle and BaBar also ran above/below the $\Upsilon(4S)$: narrow $\Upsilon(1,2,3S)$, continuum, 10.6-11.02 GeV

Integrated Luminosity at Belle

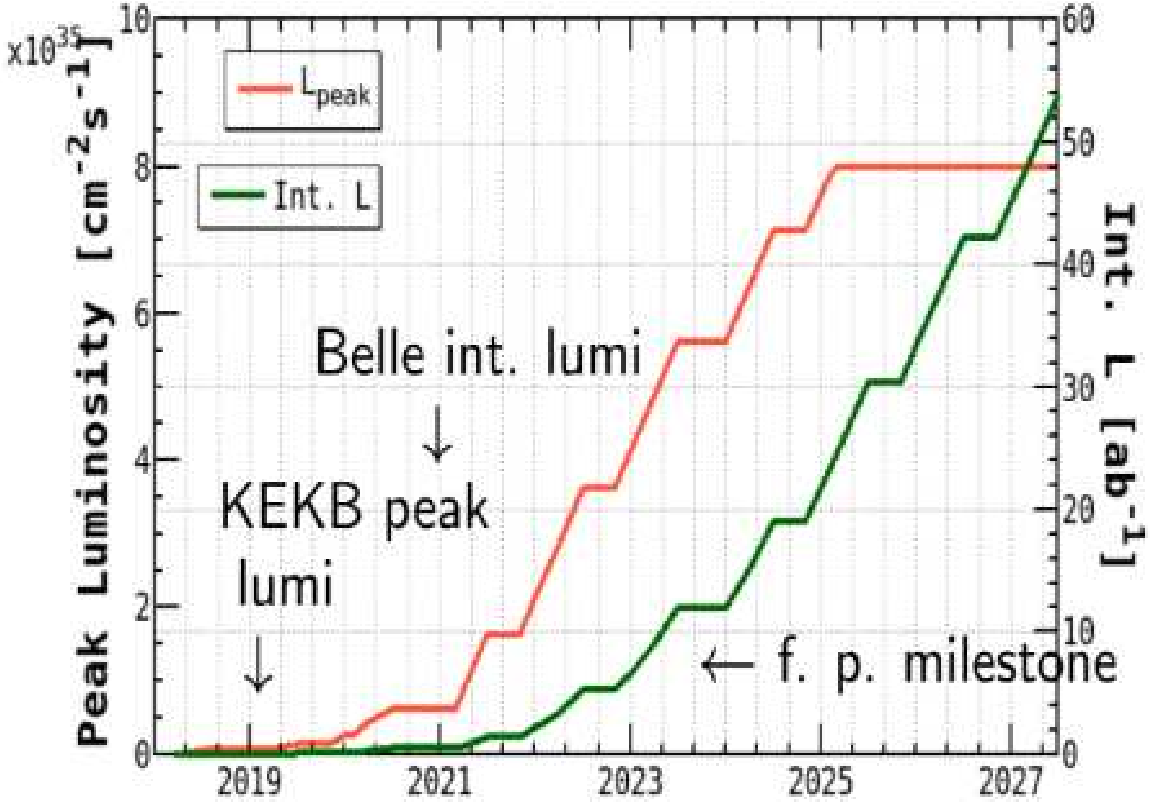
Table 1. Summary of the luminosity integrated by Belle, broken down by CM energy.

Resonance	On-peak luminosity (fb^{-1})	Off-peak luminosity (fb^{-1})	Number of resonances
$\Upsilon(1S)$	5.7	1.8	102×10^6
$\Upsilon(2S)$	24.9	1.7	158×10^6
$\Upsilon(3S)$	2.9	0.25	11×10^6
$\Upsilon(4S)$ SVD1	140.0	15.6	152×10^6 $B\bar{B}$
$\Upsilon(4S)$ SVD2	571.0	73.8	620×10^6 $B\bar{B}$
$\Upsilon(5S)$	121.4	1.7	7.1×10^6 $B_s\bar{B}_s$
Scan		27.6	

J. Brodzicka et al., PTEP 2012, 04D001(2012)

Belle collected $\times$ 35 luminosity than BaBar above the $\Upsilon(4S)$

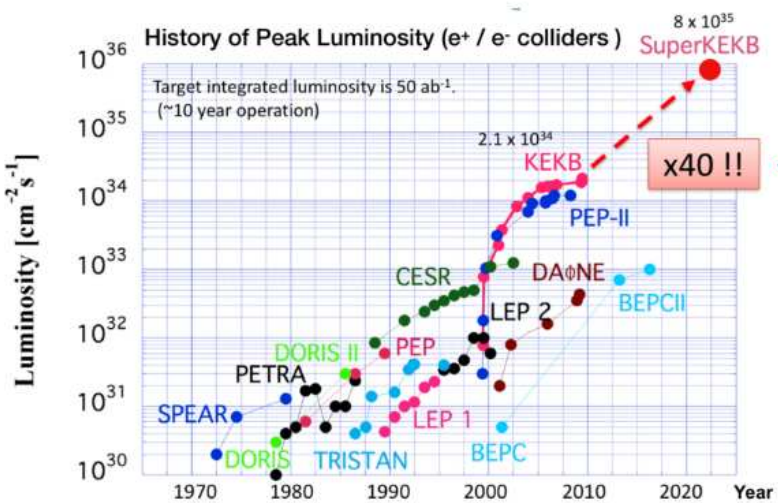
Luminosity

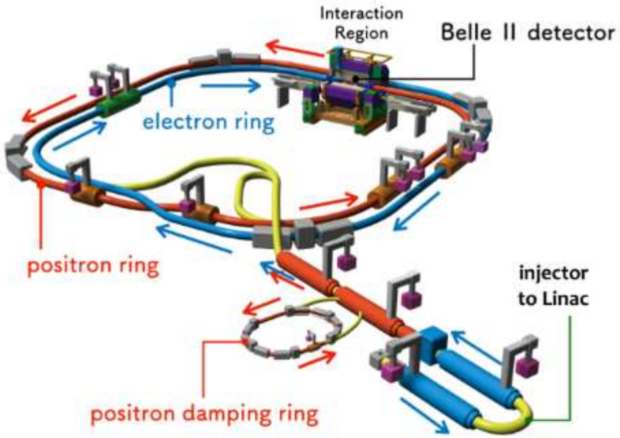


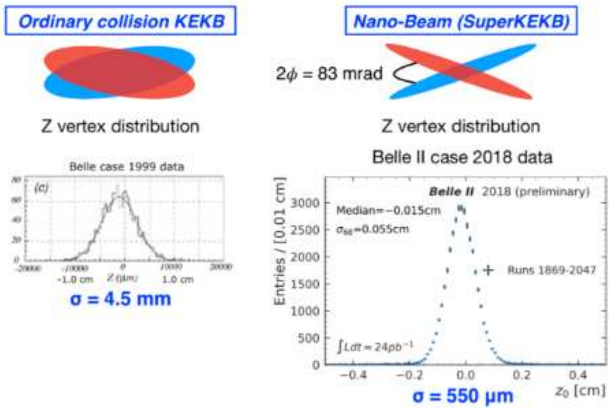
The goal of BelleII is to have a peak luminosity of 8×10^{35} cm^{-2} s^{-1} and collect an integrated luminosity of 50 ab^{-1} in about 10 years

From KEKB to SuperKEKB

Upgrade of KEKB accelerator to SuperKEKB







$$e^- \xrightarrow{7\text{ GeV}} (\star) \xleftarrow{4\text{ GeV}} e^+$$

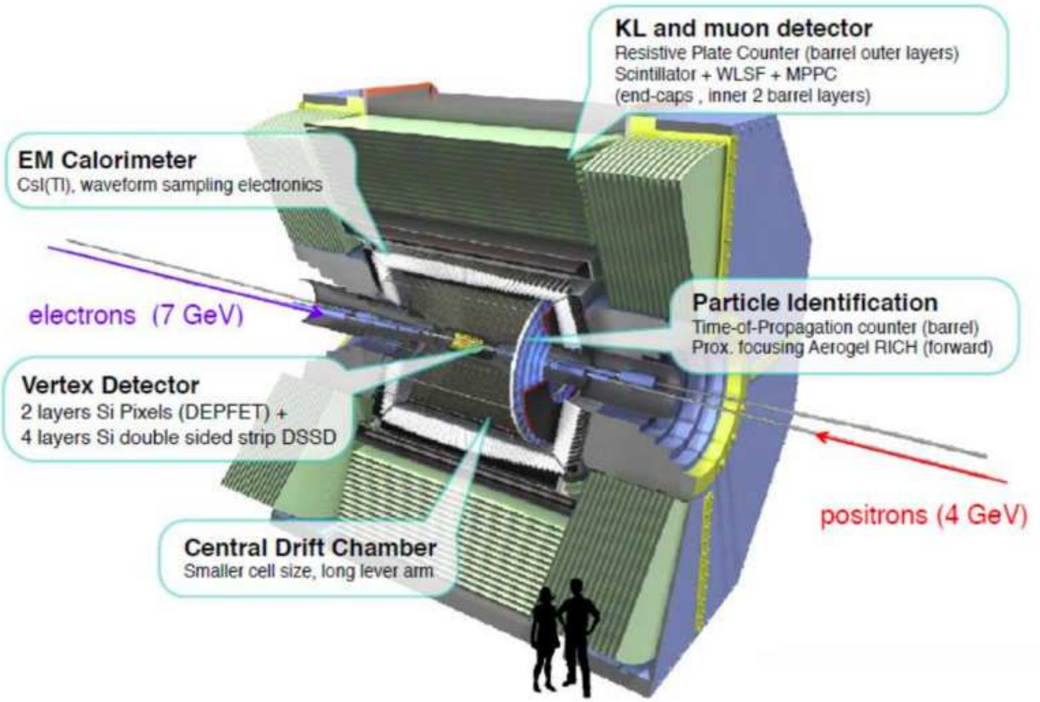
$$\mathcal{L} = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_{\mathcal{L}}}{R_{\xi_y}}\right)$$

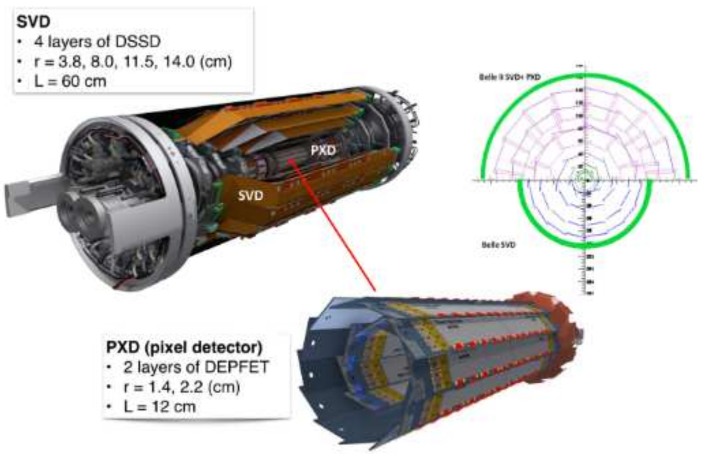
- Doubling the beam current
- Reducing the beam size by factor 20 at IP

From Belle to BelleII

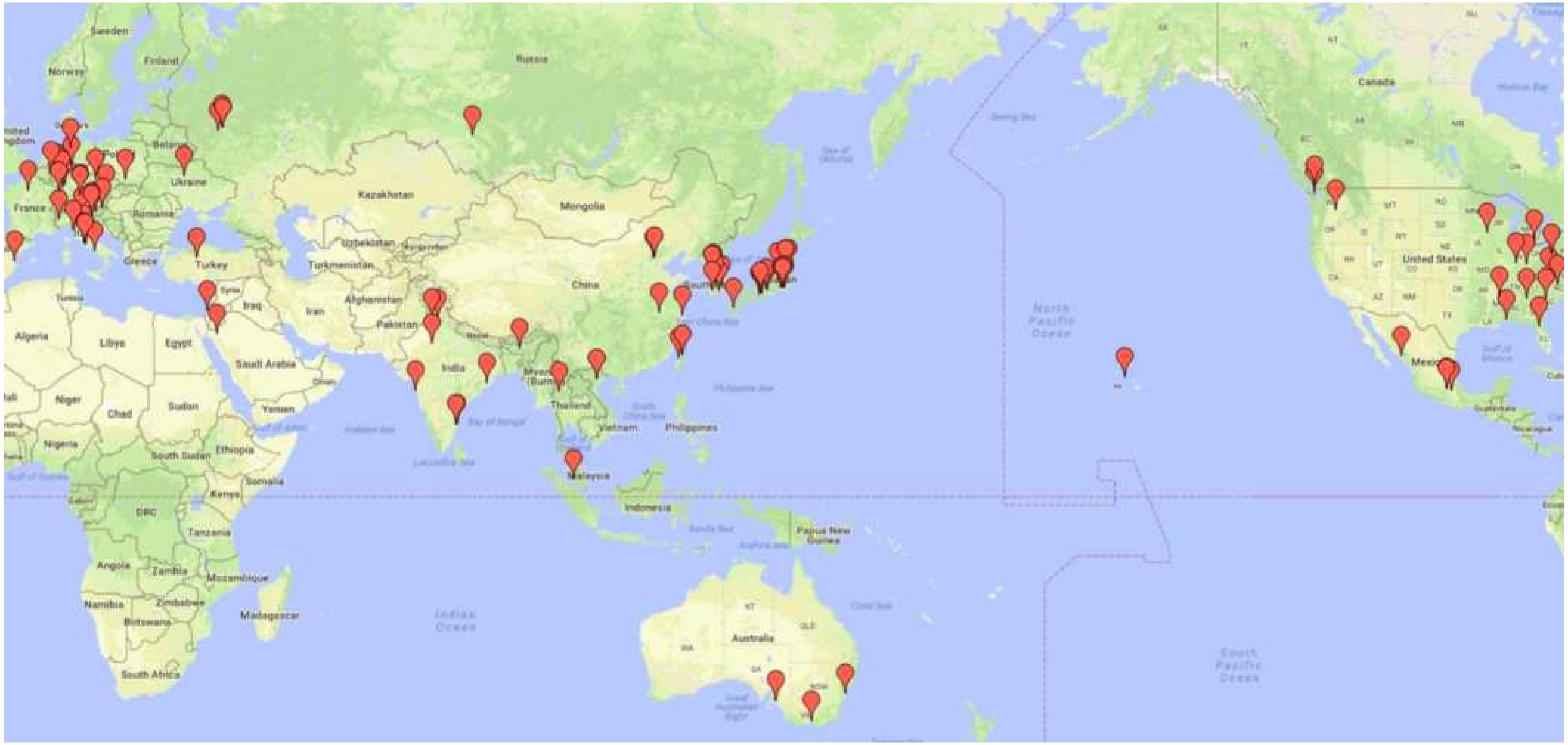
Upgrade from Belle detector to Belle II

- Higher luminosity → higher occupancy & background level
- Upgrade of all Belle detector subsystems was done





BelleII Collaboration

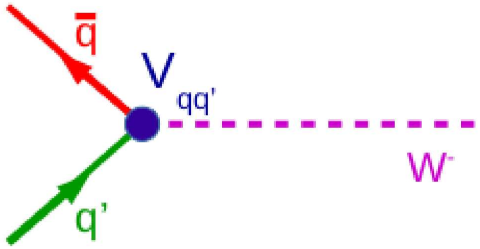


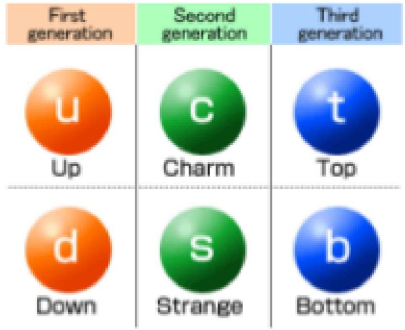
About 1000 physicists from 26 countries

CP Violation and CKM Matrix

The CKM Matrix – I

- The coupling of the quarks via the charged weak current





$q = +\frac{2}{3}$

$q = -\frac{1}{3}$

is described by the Cabibbo-Kobayashi-Maskawa matrix:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

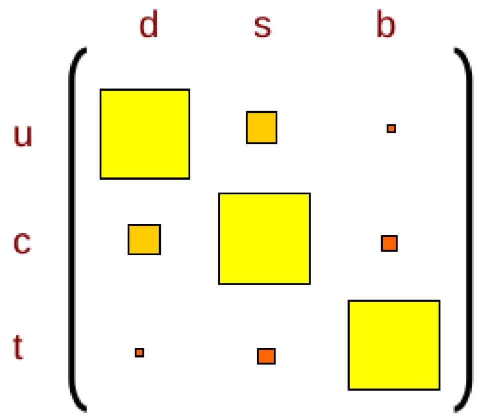
- The CKM Matrix is a 3x3 complex matrix;
- The condition that the Matrix must be unitarity and the freedom to redefine the complex phase of five out of six quark fields, reduces the number of degrees of freedom to 4 (not predicted by the Theory).

The CKM Matrix – II

- The CKM Matrix can be parameterized as:

$$V_{CKM} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Wolfenstein parameterization
λ: expansion parameter, aka sine of Cabibbo angle,
$\lambda \sim 0.22$



- Strong hierarchical structure: the coupling between quarks of different generations is suppressed;
- There can be a weak phase, affecting only the smallest elements of the Matrix, at first order;
- This weak phase is the origin of all CP Violating phenomena we have observed so far in the quark sector.

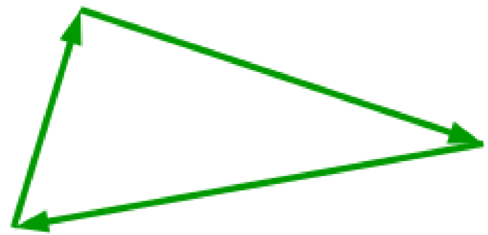
The CKM Unitarity Triangle – I

Six (only three are independent) of the unitarity conditions of the CKM Matrix define triangles on the complex plane:

$$V_{CKM}V_{CKM}^{\dagger} = \mathbb{1}$$

1) $V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$

$O(\lambda^3)$ $O(\lambda^3)$ $O(\lambda^3)$



2) $V_{us}V_{ub}^{*} + V_{cs}V_{cb}^{*} + V_{ts}V_{tb}^{*} = 0$

$O(\lambda^4)$ $O(\lambda^2)$ $O(\lambda^2)$

3) $V_{ud}V_{us}^{*} + V_{cd}V_{cs}^{*} + V_{td}V_{ts}^{*} = 0$

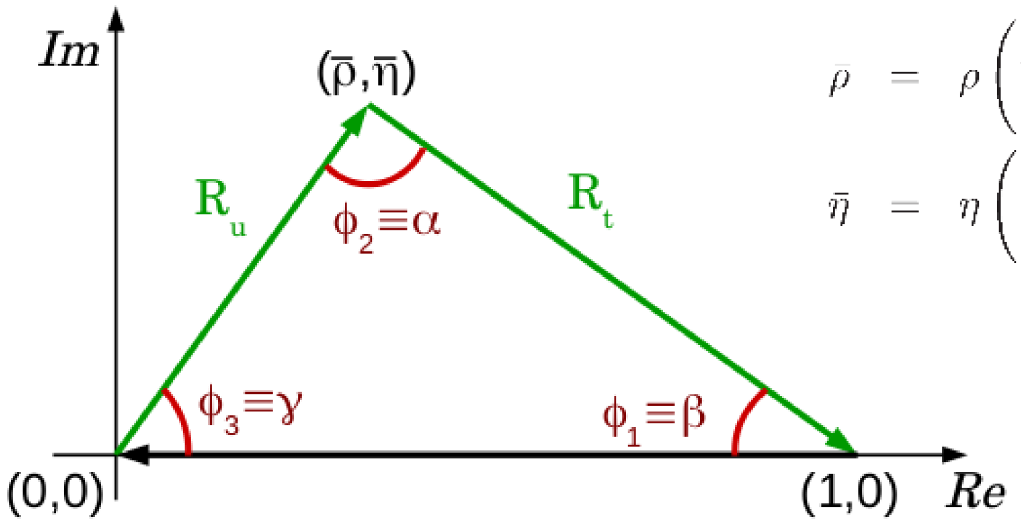
$O(\lambda)$ $O(\lambda)$ $O(\lambda^5)$

The CKM Unitarity Triangle – II

- Dividing 1) by $V_{cd}V^*_{cb}$, we obtain:

$$\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}} + 1 + \frac{V_{td}V^*_{tb}}{V_{cd}V^*_{cb}} = 0$$

which defines the "standard" CKM Unitarity Triangle:



$$\bar\rho = \rho\left(1 - \frac{\lambda^2}{2} + \mathcal{O}(\lambda^4)\right)$$

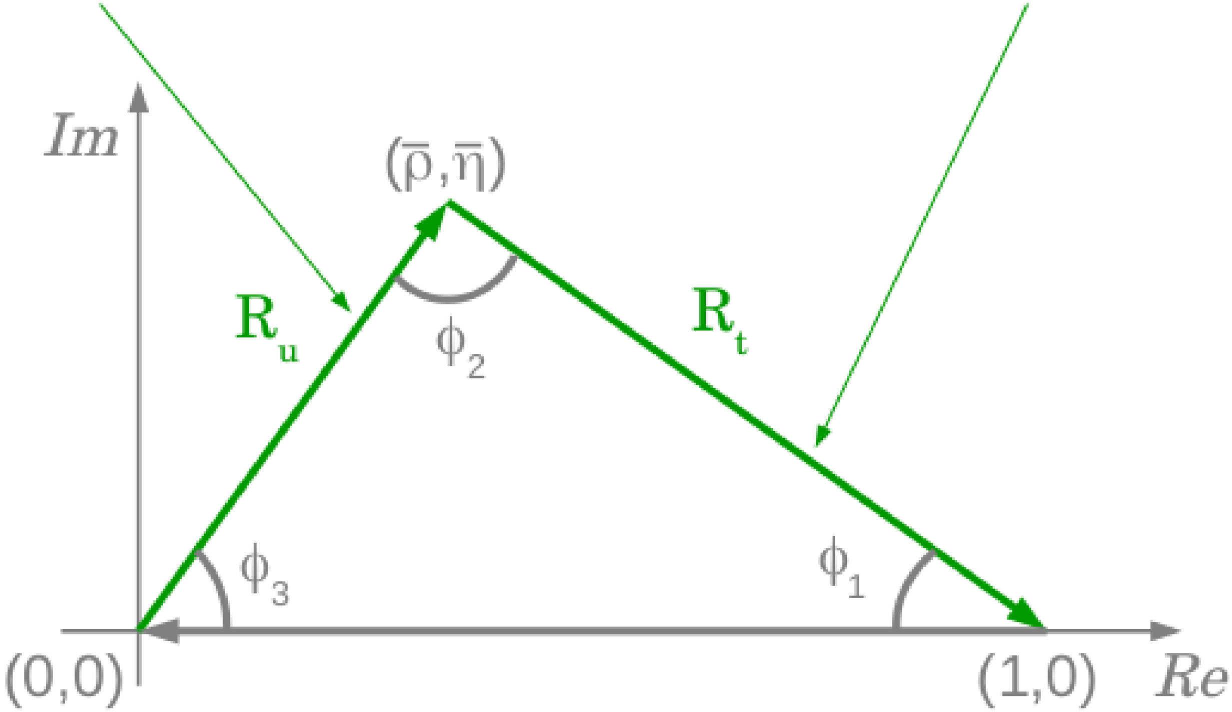
$$\bar\eta = \eta\left(1 - \frac{\lambda^2}{2} + \mathcal{O}(\lambda^4)\right)$$

- We can (over)constrain the position of the apex $(\bar\rho, \bar\eta)$, by performing independent measurements of the magnitude of the sides R_u and R_t, and of the angles ϕ_1, ϕ_2, and ϕ_3.

Determination of the UT Sides

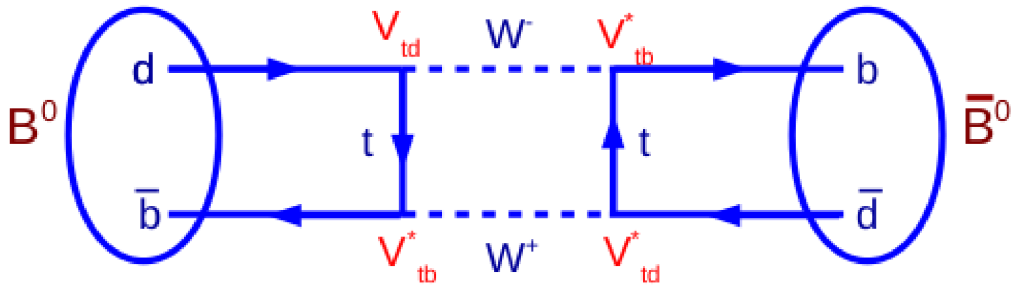
$$R_u \equiv \left| \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right|$$

$$R_t \equiv \left| \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} \right|$$

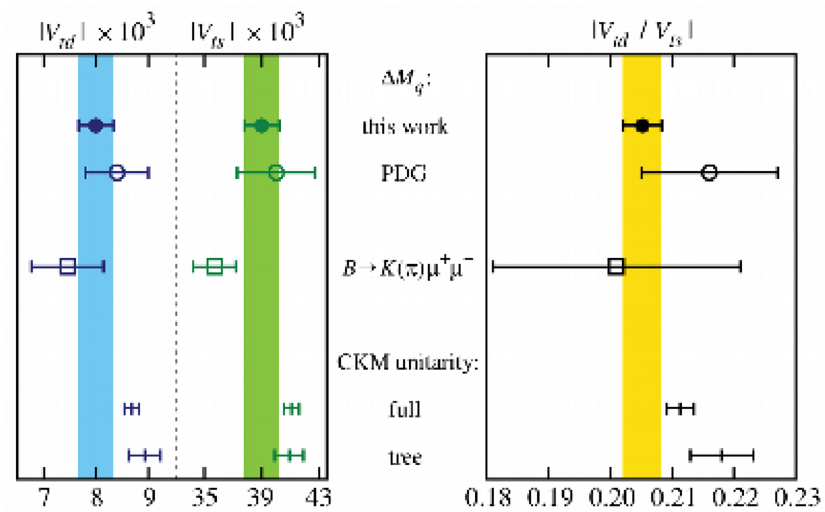


Sides: R_t

$$R_t \equiv \left| \frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*} \right|$$



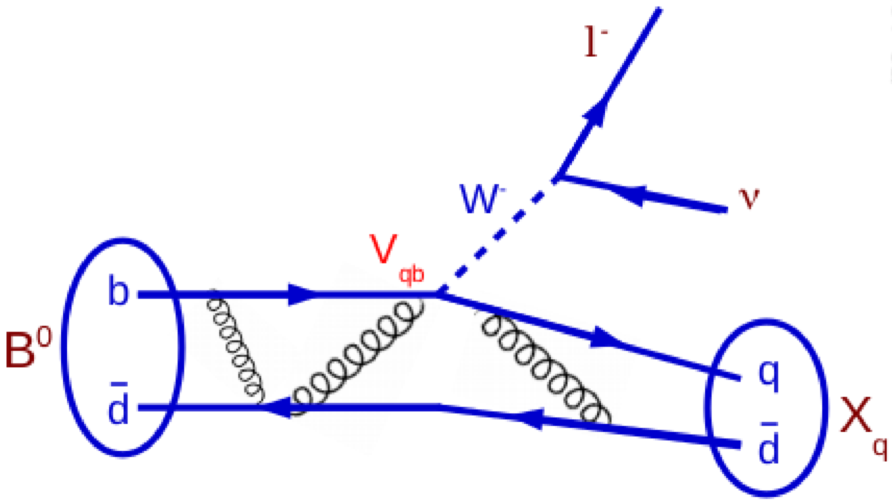
- R_t mostly comes from the $B\bar{B}$ oscillation frequencies $\Delta m_d / \Delta m_s$ (systematics cancel in the ratio);
- The experimental measurements are close to being systematics dominated, the focus is on Lattice QCD, which computes the relevant hadronic quantities;
- Some tension with the CKM fit!

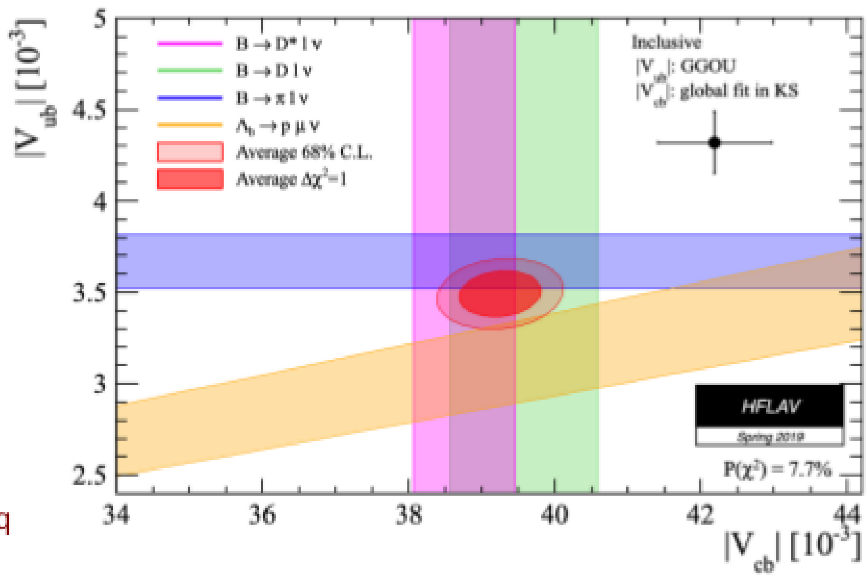


Sides: R_u

$$R_u \equiv \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right|$$

- The precision on R_u is dominated by V_{ub} and V_{cb};
- Experimentally, these parameters are measured from semileptonic decays of B mesons (hadrons);
- Tree level transitions: fundamental inputs for the CKM fit!





Determination of the Angles – I

Detector	$N(B\overline{B}), 10^6$	$\sin 2\phi_1$	Cit.
BaBar	32	$0.59 \pm 0.14 \pm 0.05$	906
Belle	31.3	$0.99 \pm 0.14 \pm 0.06$	971

BaBar: B. Aubert et al., Phys.Rev.Lett. 87, 091801 (2001)

Belle: K. Abe et al., Phys.Rev.Lett. 87, 091802 (2001)

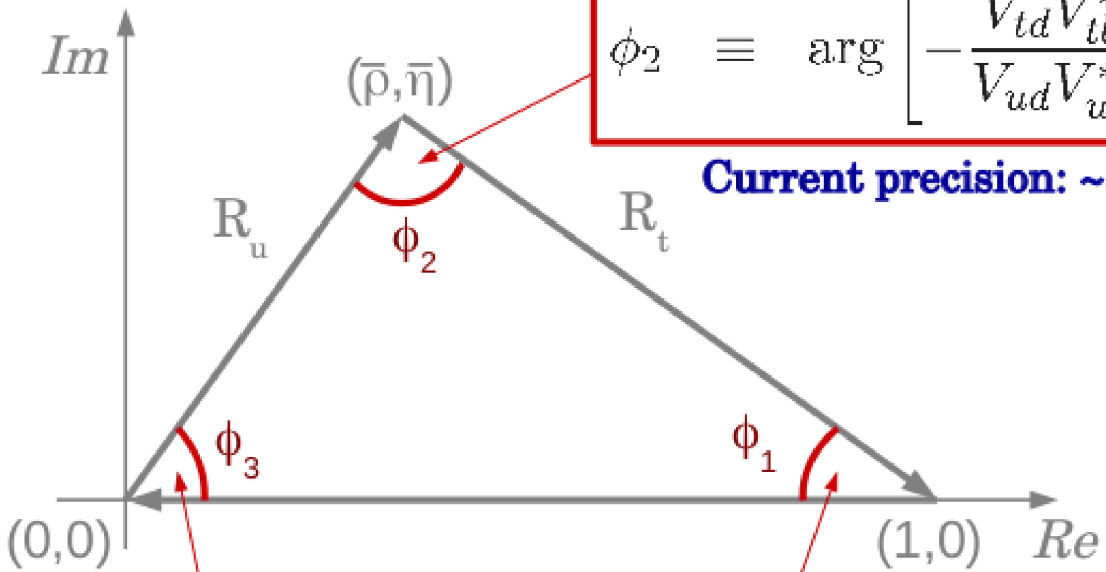
Determination of the Angles – II

alternative nomenclature:

$\phi_1 = \beta$

$\phi_2 = \alpha$

$\phi_3 = \gamma$



$$\phi_2 \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$$

Current precision: ~5°

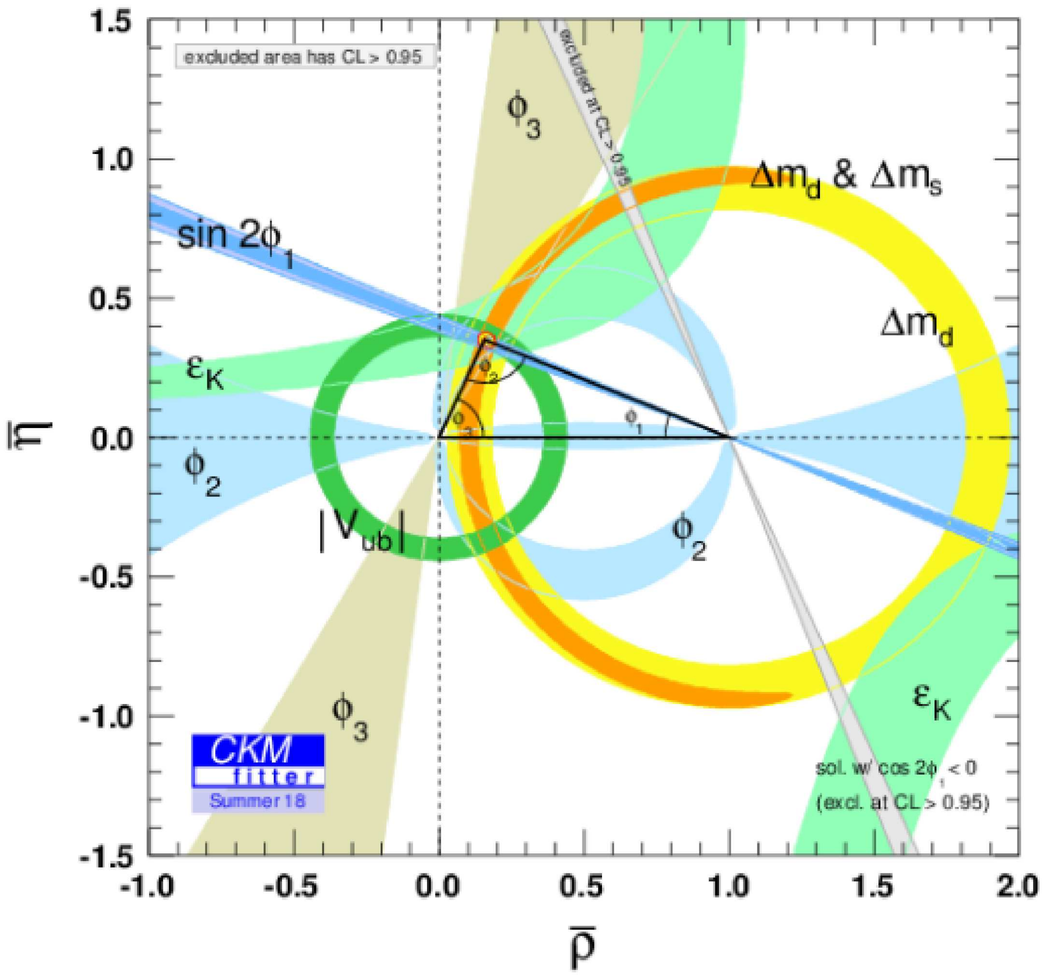
$$\phi_3 \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

Current precision: ~5°

$$\phi_1 \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

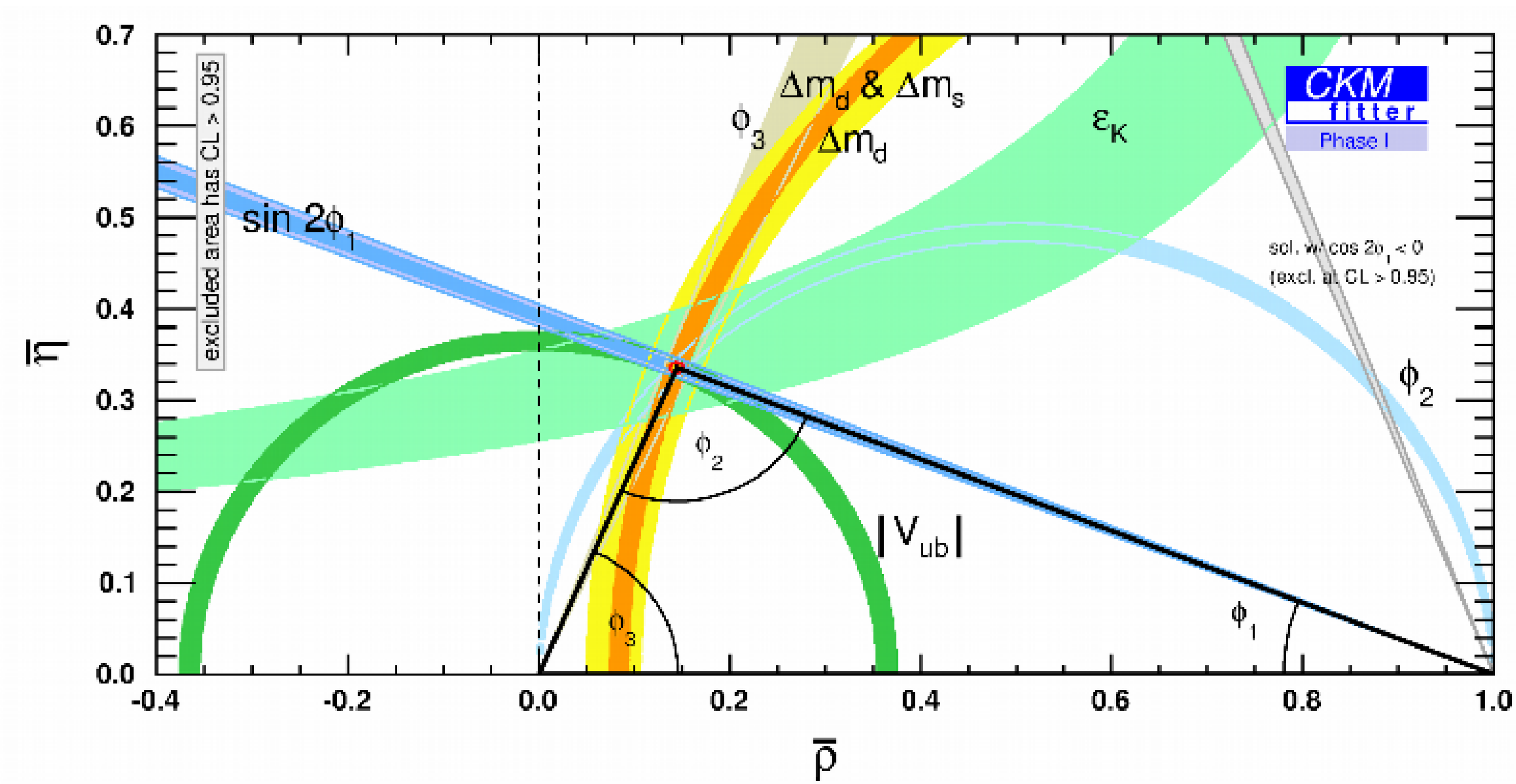
Current precision: ~0.7°

CKM UT: Today


excluded area has CL > 0.95
excluded at CL > 0.95
ϕ_3
Δm_d & Δm_s
sin $2\phi_1$
Δm_d
ε_K
ϕ_2
$|V_{ub}|$
ϕ_2
ϕ_3
ε_K
sol. w/ cos $2\phi_1 < 0$
(excl. at CL > 0.95)
CKM fitter
Summer 18
$\bar{\eta}$
$\bar{\rho}$
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0

CKM UT: Outlook

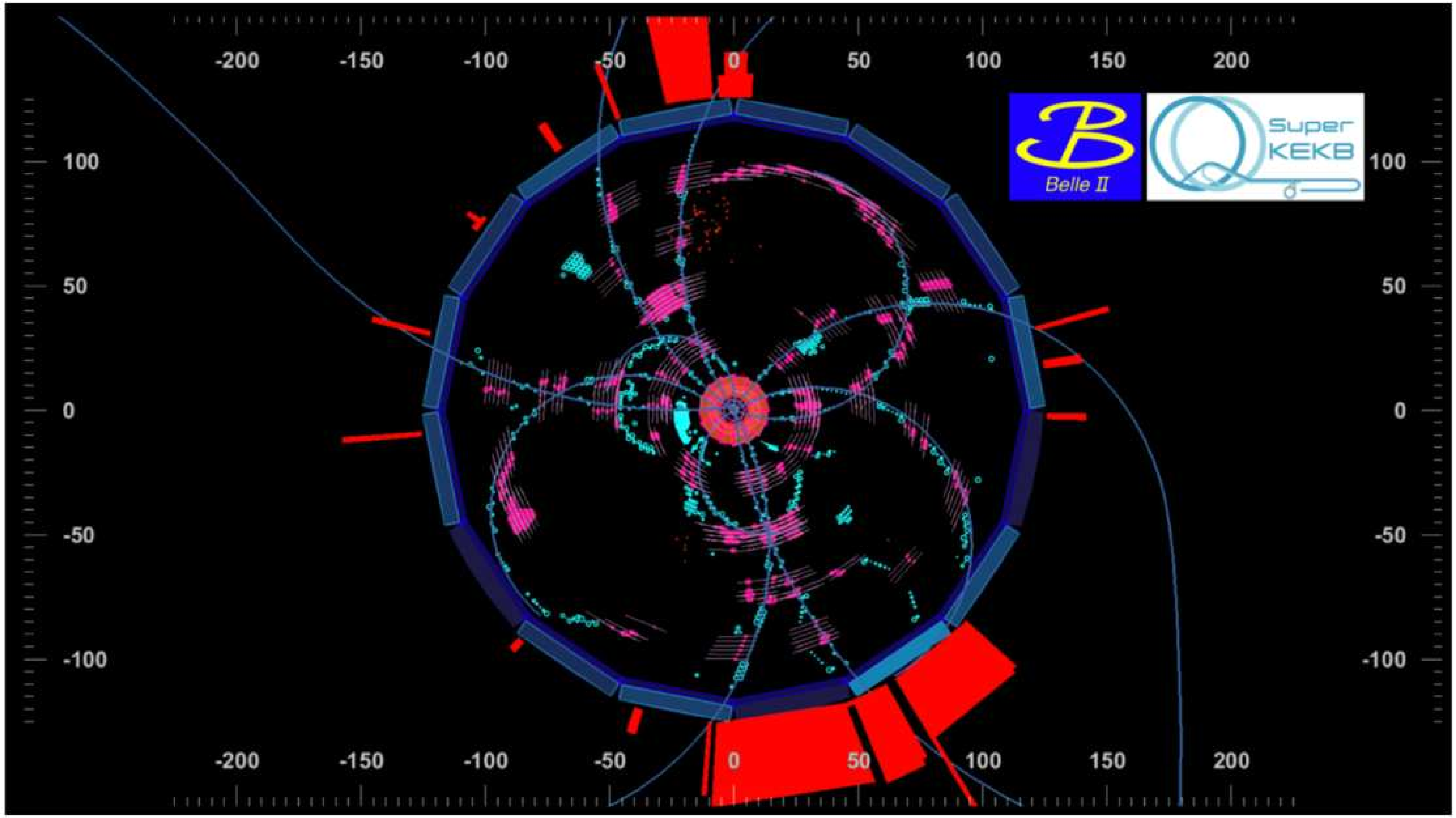
CKM Unitarity Triangle ~8 years from now:



Assumptions: Belle II 50 ab^{-1}, LHCb 23 fb^{-1}

BelleII – A B-decay Event

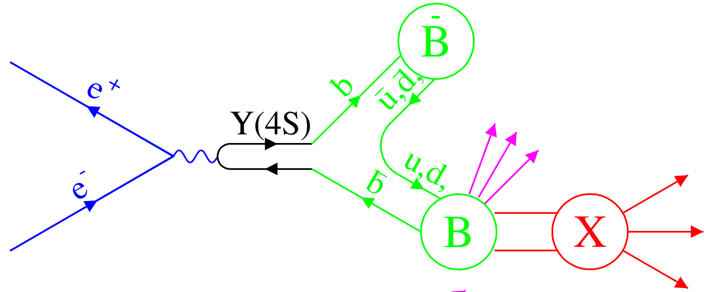
First B-like event in the Belle II Phase 3 run



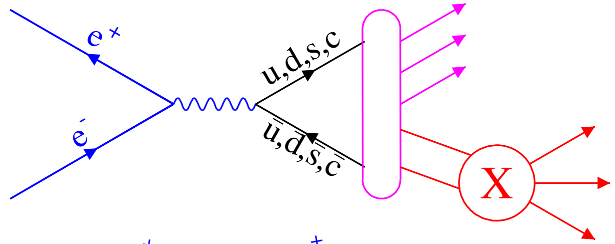
Charmonium Spectroscopy

Particle Production at e^+e^- Factories

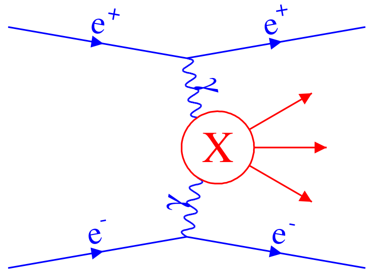
Production from B-decay
(broad D^{**}, D_{sJ}, $\chi_{c1}(3872)$)



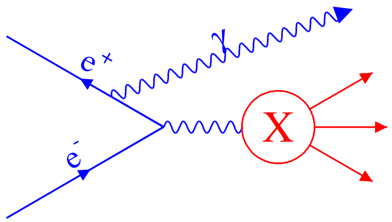
Production from continuum
(D_{sJ}, $\eta_c(2S)$, $X(3940)$, $\Sigma(2800)$)



Two-photon production
($\eta_c(2S)$, $\chi_{c2}(2P)$, $X(4350)$)



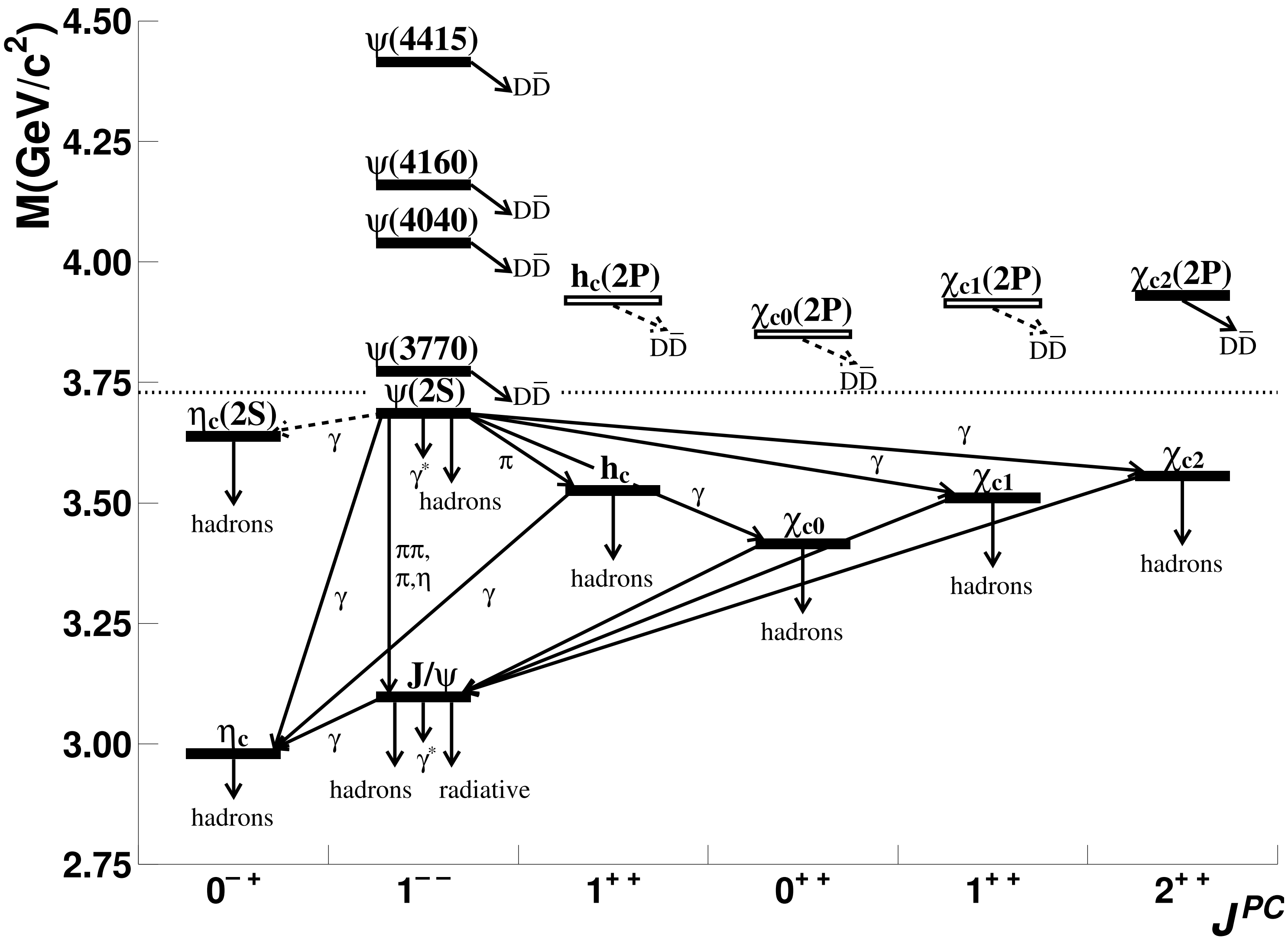
Initial-state radiation
($\psi(4260)$, $\psi(4360)$, $\psi(4660)$)



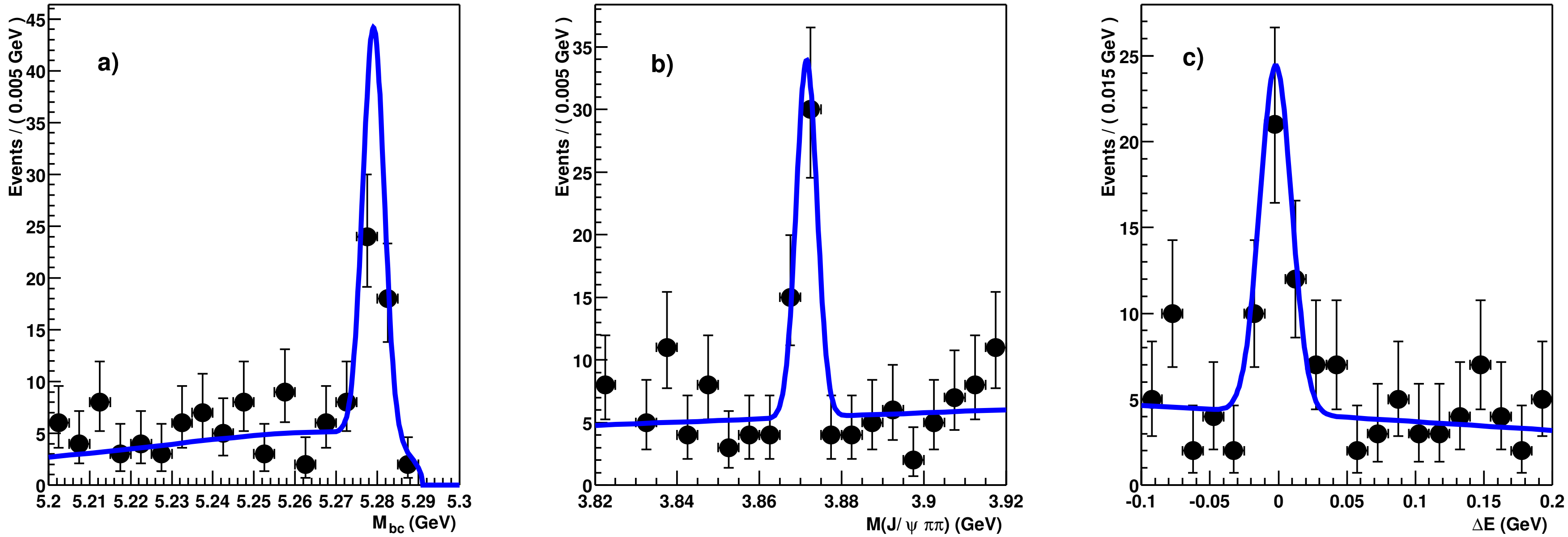
Charmonium – General Picture

- 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
- After 2003 more than 20 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.
- More than 30 different states listed by PDG in 2017
- E.Fermi: If I could remember the names of
  all these particles, I'd be a botanist

The Charmonium System



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

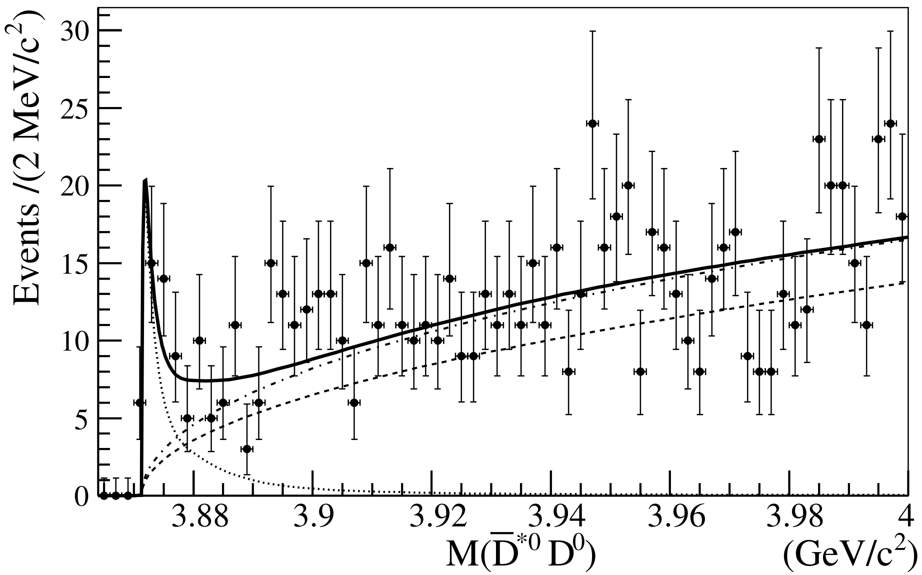
Confirmed by CDF and D0 in $p\bar{p}$ and BaBar in B decays

Seen and extensively studied at LHC

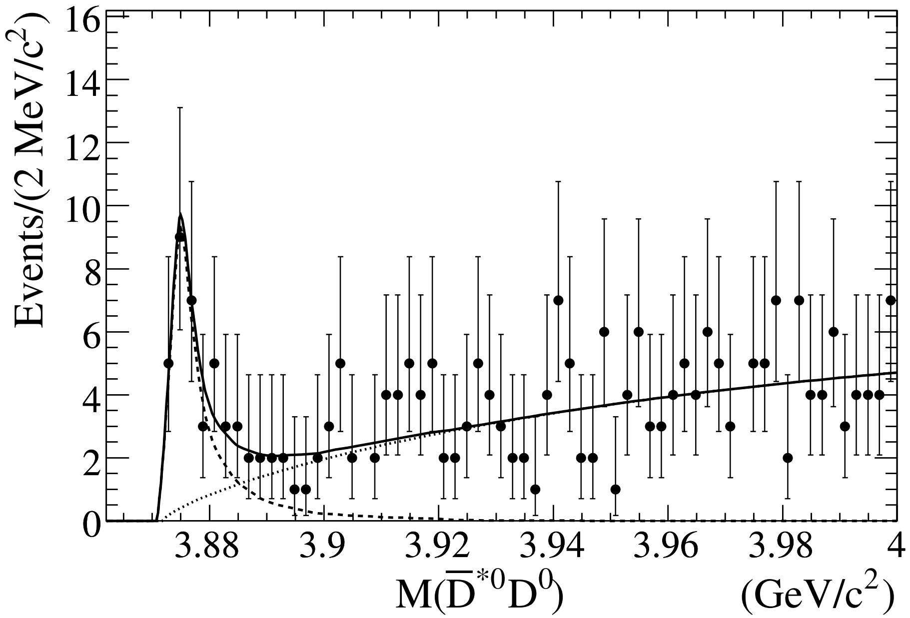
What do we know about $X(3872)$?

- $M_{\pi^+\pi^-} \approx M_\rho$ (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

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.



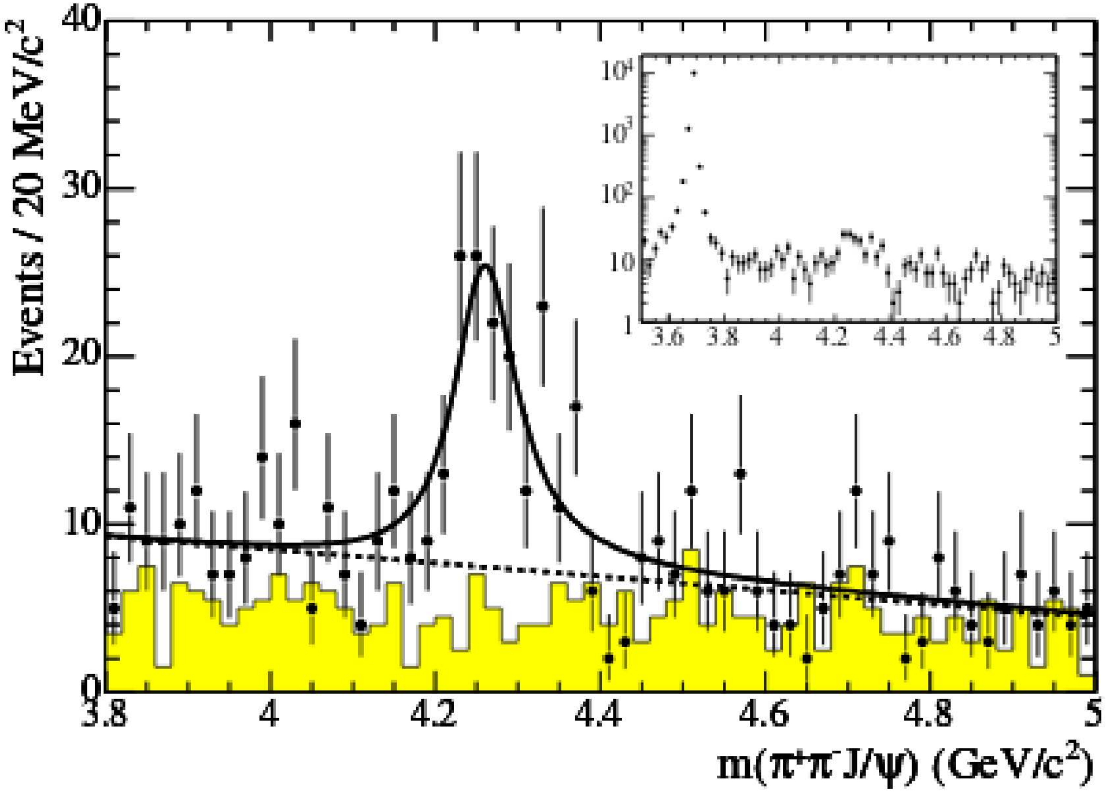
BaBar – $383 \cdot 10^6$ $B\bar{B}$ pairs;
B.Aubert et al., PRD 77 (2008) 011102

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

Discovery of $Y(4260)$

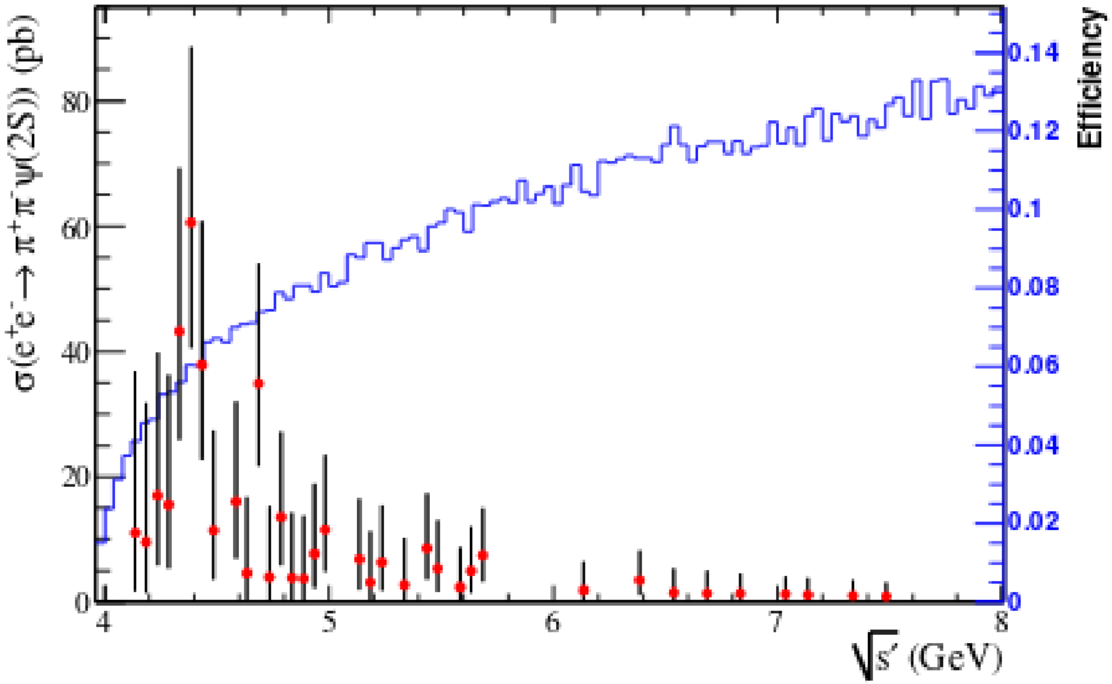


BaBar studied $e^+e^- \to J/\psi\pi^+\pi^-\gamma_{\rm ISR}$ and found an excess

125 ± 23 events, $M = 4259 \pm 8^{+2}_{-6}$ MeV, $\Gamma = 88 \pm 23^{+6}_{-4}$ MeV

B. Aubert et al., Phys.Rev.Lett. 95, 151804 (2005), 820 cites!

Discovery of $Y(4360)$

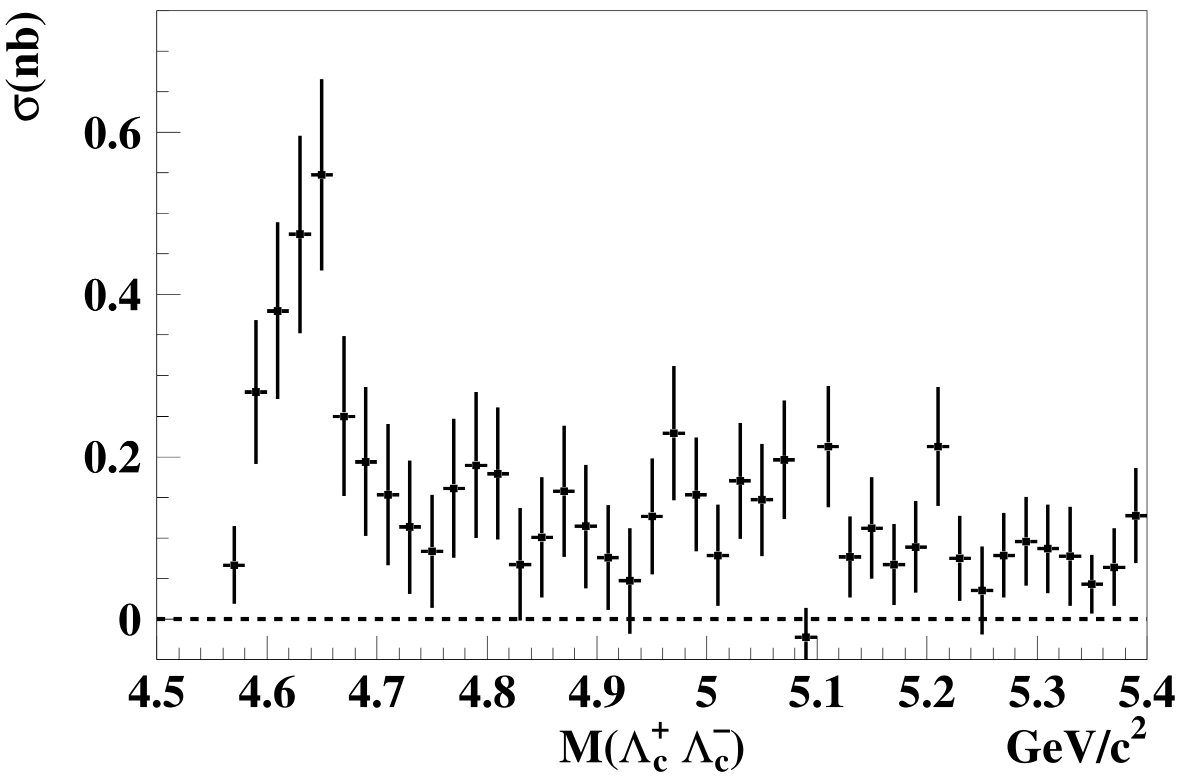


BaBar studied $e^+e^- \to \psi(2S)\pi^+\pi^-\gamma_{\rm ISR}$ and found an excess

125 ± 23 events, $M = 4324 \pm 24$ MeV, $\Gamma = 172 \pm 33$ MeV

B. Aubert et al., Phys.Rev.Lett. 98, 212001 (2007), 345 cites!

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



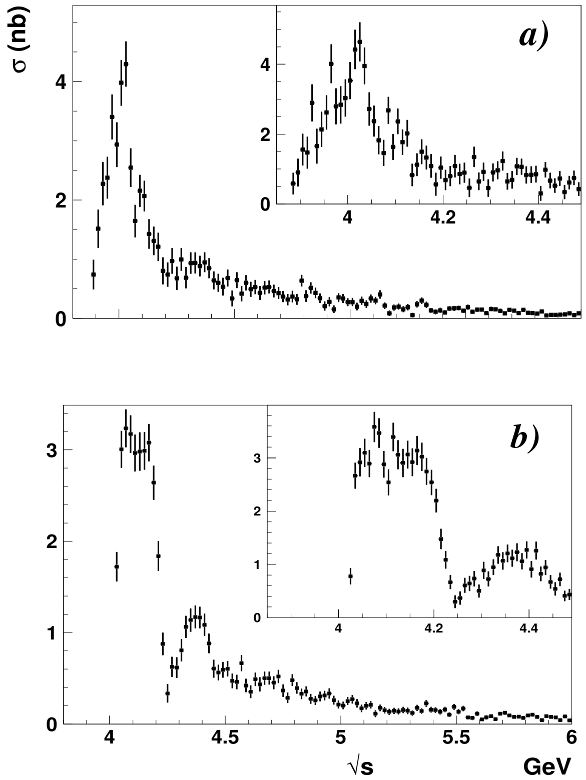
142^{+32}_{-28} events $(\sim 8.2\sigma)$ $M = 4634^{+8+5}_{-7-8}$ MeV $\Gamma = 92^{+40+10}_{-24-21}$ MeV

Was also confirmed in the $\psi(2S)\pi^+\pi^-$ final state

G. Pakhlova et al., PRL 101 (2008) 172001; Belle – 695 fb^{-1}, 207 cites

$e^+e^- \to D^{(*)}\bar{D}^{(*)}$ at Belle with ISR

Belle studied $e^+e^- \to D^{(*)}\bar{D}^{(*)}(\gamma)$ with 951 fb^{-1} up to 6 GeV



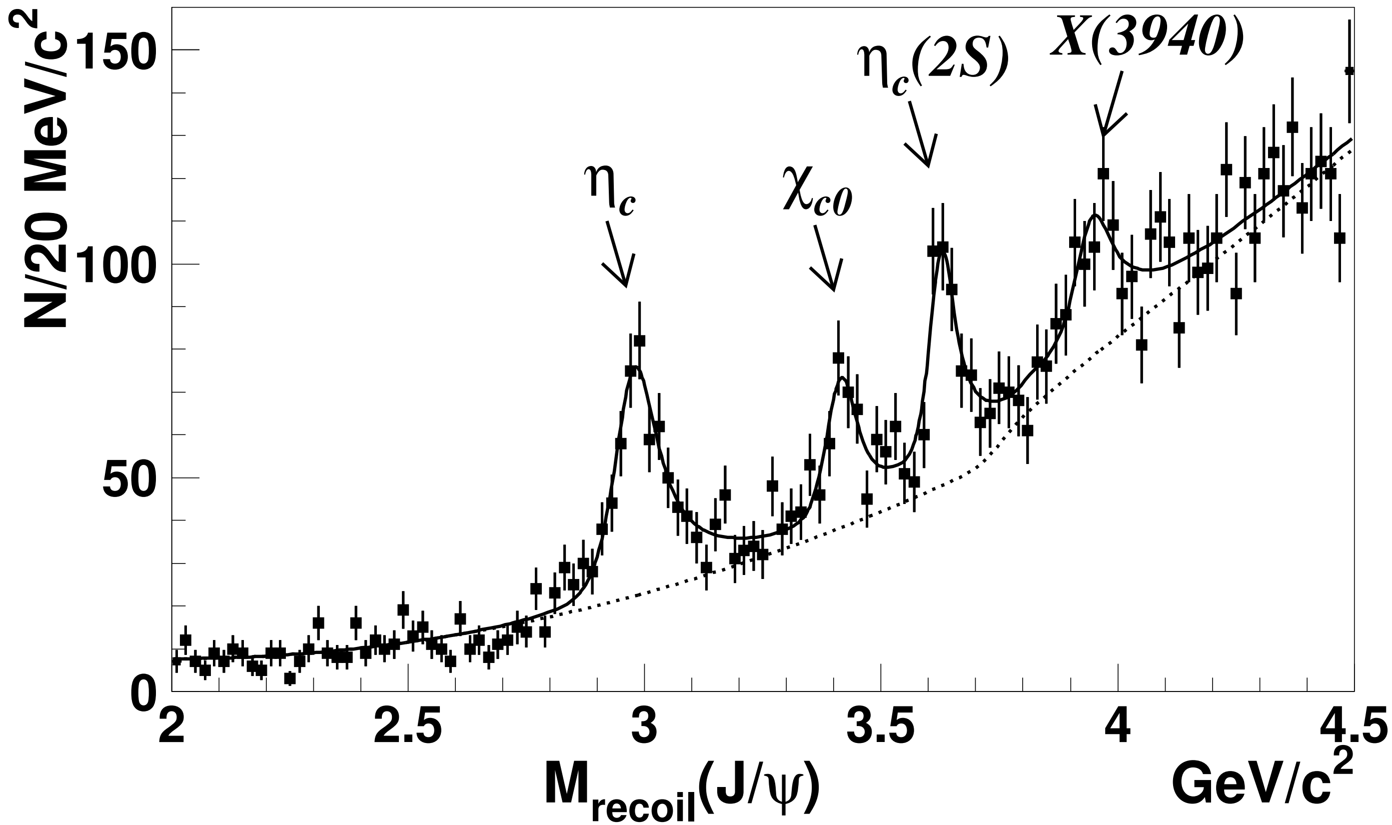
a) $e^+e^- \to D^+D^{*-}$ + c.c, b) $e^+e^- \to D^{*+}D^{*-}$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$ seen

V. Zhukova et al., Phys.Rev. D97, 012002 (2018)

Summary on 1^{--} States

- Four well-known broad 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 ($\psi(4260)$, $\psi(4360)$, $\psi(4660)$).
  Although well above open charm threshold, they decay to $J/\psi(\psi(2S))\pi^+\pi^-$.
  Energy dependence of cross sections may be affected by interference, coupled-channel and rescattering ($D^{(*)}\bar{D}^{(*)}$) effects
- The $\psi(3990)$ state of Belle is not confirmed by BaBar and BESIII, but is not ruled out by them
- The $\psi(2S)\pi^+\pi^-$ state at 4660 MeV and the $\Lambda_c^+\Lambda_c^-$ state at 4630 MeV are probably the same
- Interpretation is not straightforward and needs theory input.

Double Charmonium at Belle



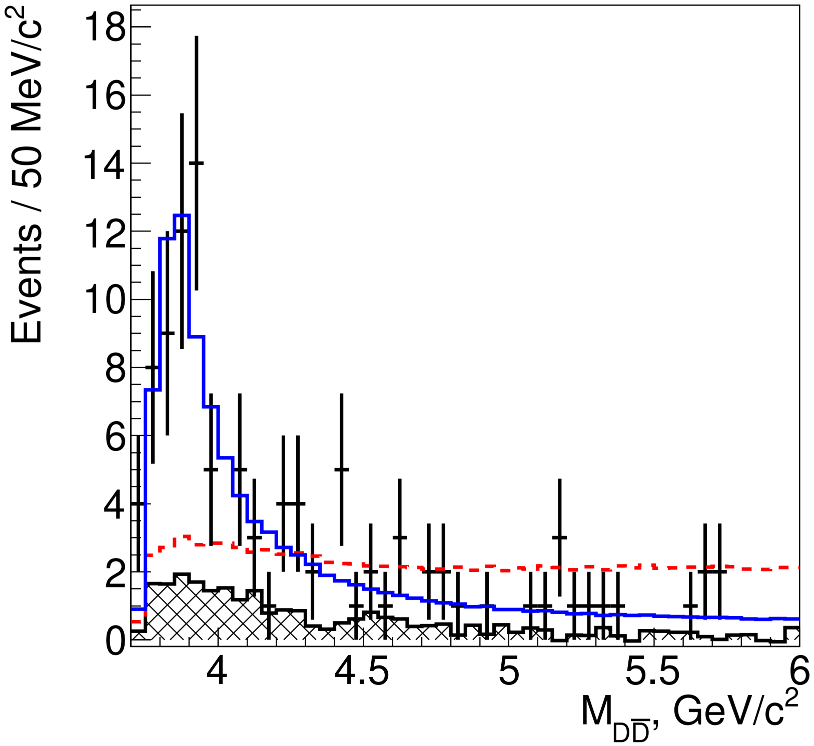
K. Abe et al., PRL 98, 082001 (2007); Belle – 357 fb^{-1}

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

Alternative Candidate for $\chi_{c0}(2P)$ at Belle

Belle studied $e^+e^- \to J/\psi D\bar{D}$ with 980 fb^{-1}

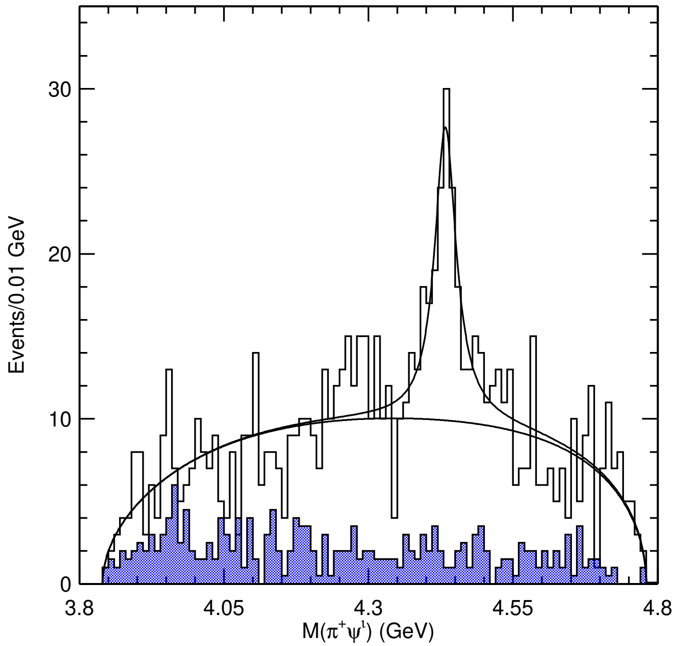


The 0^{++} state with $M = 3862^{+48}_{-35}$ MeV, $\Gamma = 201^{+177}_{-106}$ MeV with 6.5σ sign. found

K. Chilikin et al., Phys. Rev. D95 (2017) 112003

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



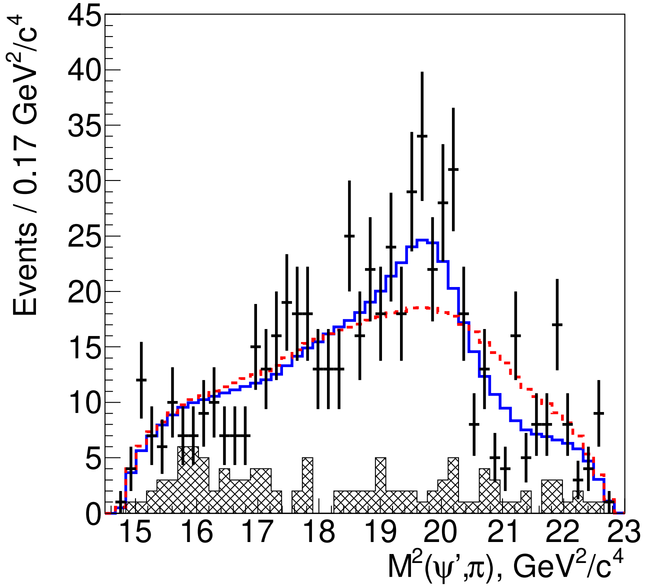
Confirmed by Dalitz plot analysis in R. Mizuk et al., Phys. Rev. D80 (2009) 031104

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

Conclusions on $c\overline{c}$ States

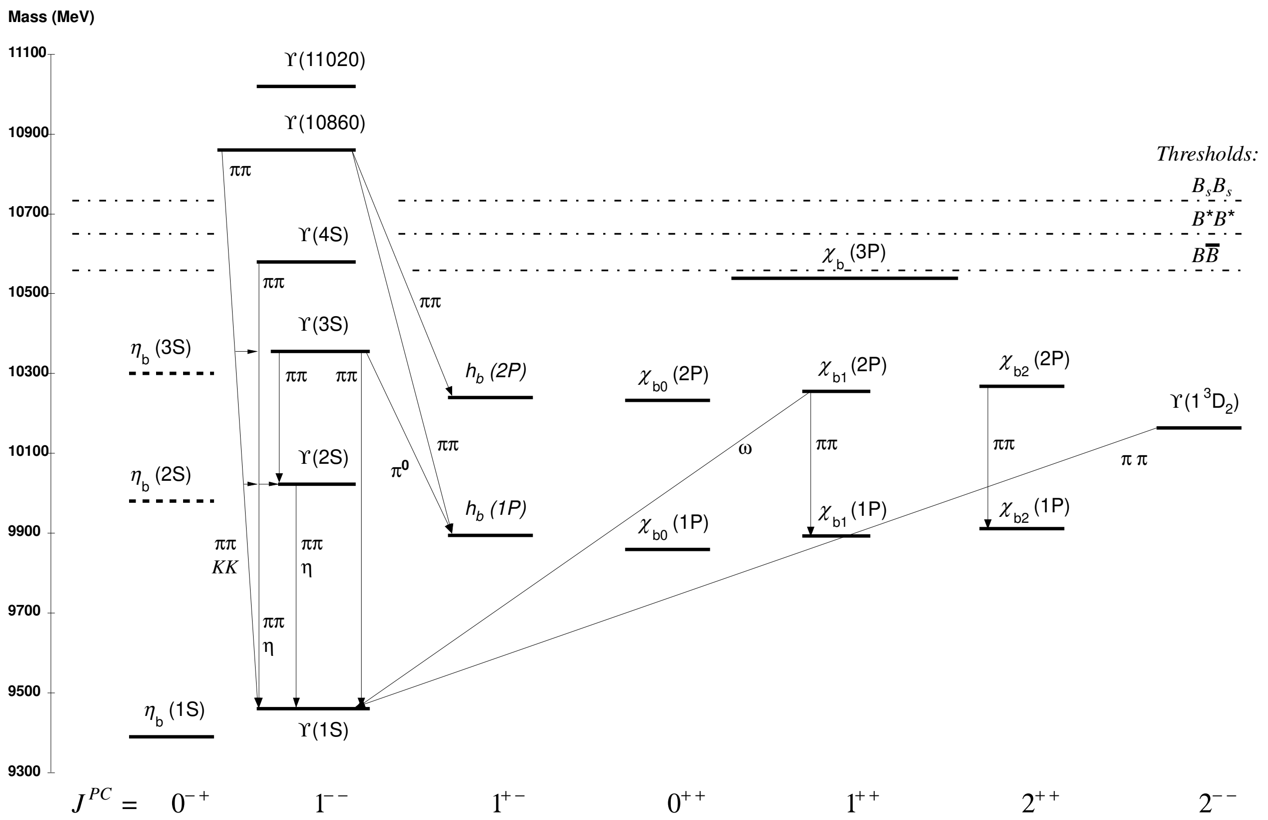
- A lot of new information/states from BESIII and LHCb
- Charged charmonia well established
- 38 states listed by PDG in 2019
- Their nature is sometimes unclear:
  molecules, tetraquarks, hadrocharmonia, hybrids, ...
- In the new PDG Naming scheme $X(3872)$ is now called $\chi_{c1}(3872)$,
  is it indeed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

Bottomonium Spectroscopy

Introduction – 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

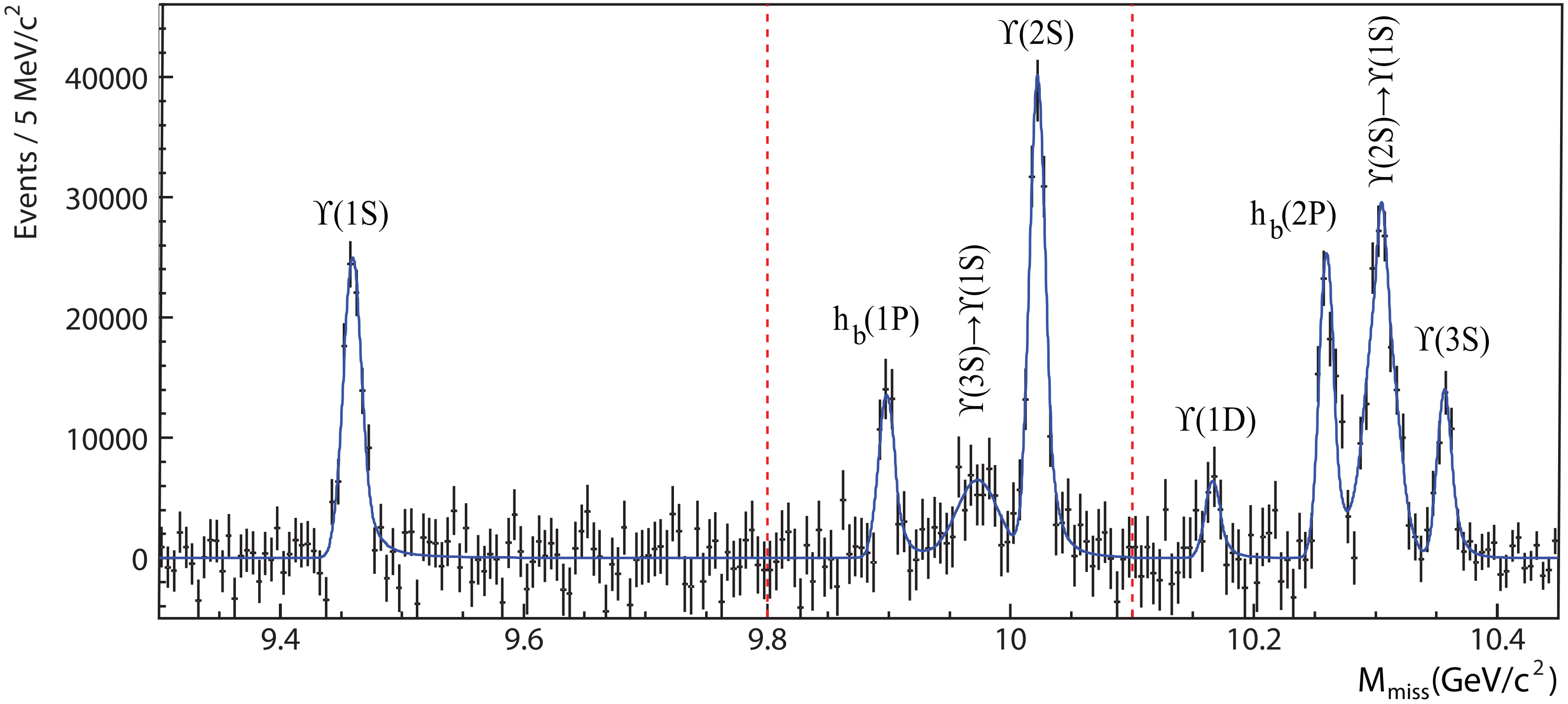


K.A. Olive et al. (Particle Data Group), Chin. Phys. C38, 090001 (2014)

Summary of Recent Findings

- First observation of $h_b(1P)$ and $h_b(2P)$
  I. Adachi et el., Phys. Rev. Lett. 108, 032001 (2012), 185 citations
- Reliable observation of $\eta_b(1S)$ and first evidence for $\eta_b(2S)$
  R. Mizuk et el., Phys. Rev. Lett. 109, 232002 (2012), 95 cit.
- Discovery of charged states $Z_b(10610)$ and $Z_b(10650)$
  A. Bondar et el., Phys. Rev. Lett. 108, 122001 (2012), 515 cit.
- Discovery of the neutral state $Z_b(10610)$, 72 cit.
  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), 69 cit.

Strength of the Recoil Mass Method



More About Bottomonium

- $\Upsilon(4S)$, $\Upsilon(10860)$, $\Upsilon(11020)$ have properties unexpected for pure $b\bar{b}$ bound states: much higher rate of transitions to lower bottomonia with emission of light hadrons, strong violation of HQSS
- Possible explanation – hadron loops, presence of $B_{(s)}^{(*)}\overline{B}_{(s)}^{(*)}$; in this approach $\Upsilon(10860), \Upsilon(11020)$ are $\Upsilon(5S)$ and $\Upsilon(6S)$ "dressed" by hadrons
- In the region of the $\Upsilon(4S,\ 5S,\ 6S)$ states the $\Upsilon(3D,\ 4D)$ are also predicted. In addition, exotic states are possible here
- Various final states have been studied in the $b\bar{b}$ region: $\Upsilon(nS)\pi^+\pi^-$, $h_b(nP)\pi^+\pi^-$, $\chi_{bJ}(1P)\pi^+\pi^-\pi^0$, $B_s^{(*)}\overline{B}_s^{(*)}$
- Electromagnetic quarkonium production is a good lab to test NRQCD predictions for the cross sections of radiative processes

A new structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ – I

Analysis is based on about 200 fb^{-1} collected at 28 c.m.energy points

Energy, MeV	Points	Luminosity, fb^{-1}
10520	1	60
10630-11020	21	20
$\Upsilon(10860)$ peak	6	121

$E_{\rm c.m.}$ calibration was performed with $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$

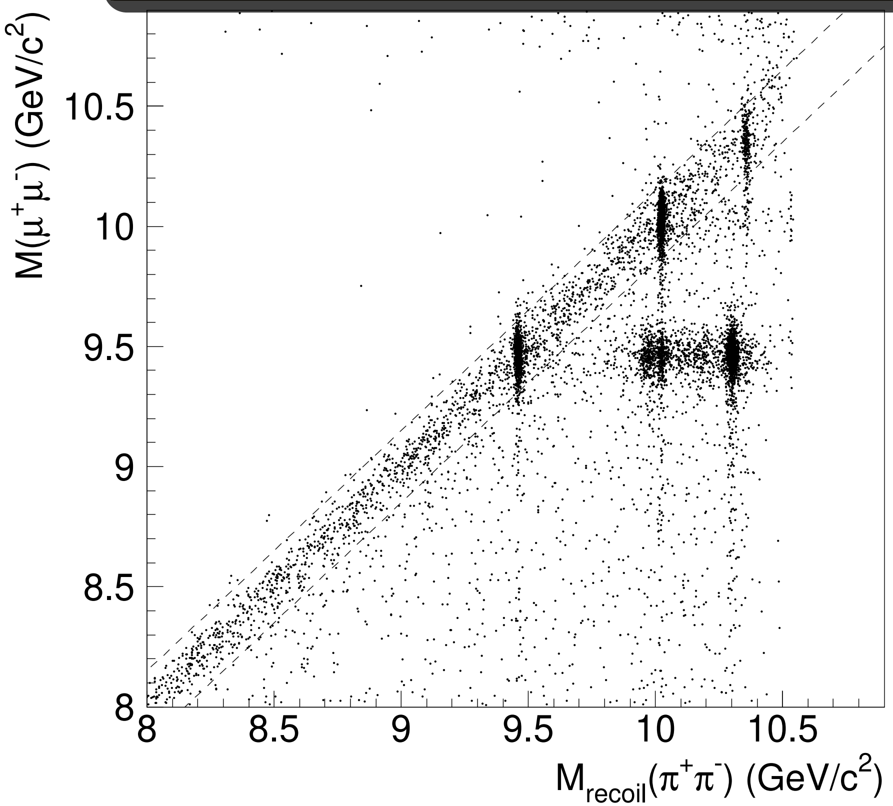
Events of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ are selected, $\Upsilon(nS) \to e^+e^-$, $\mu^+\mu^-$, n=1,2,3

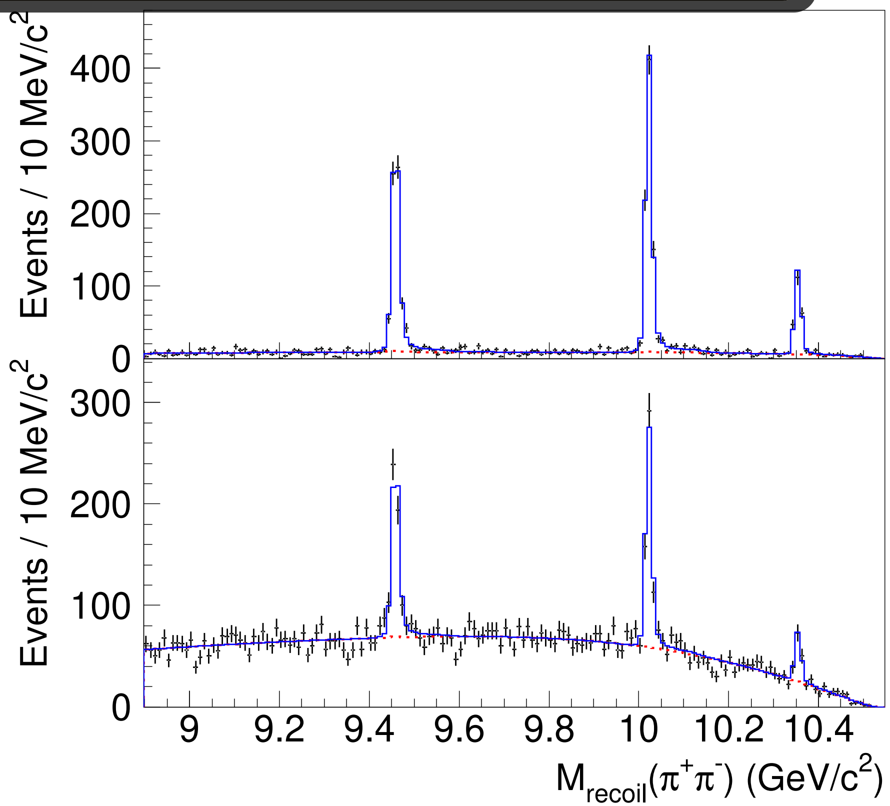
A special variable for selection and BG suppression is the recoil mass:

$$M_{\rm recoil}(\pi^+\pi^-) = \sqrt{(E_{\rm c.m.} - E_{\pi^+\pi^-})^2 - p^2_{\pi^+\pi^-}}$$

R. Mizuk et al., JHEP 1910, 220 (2019)

A new structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ – II



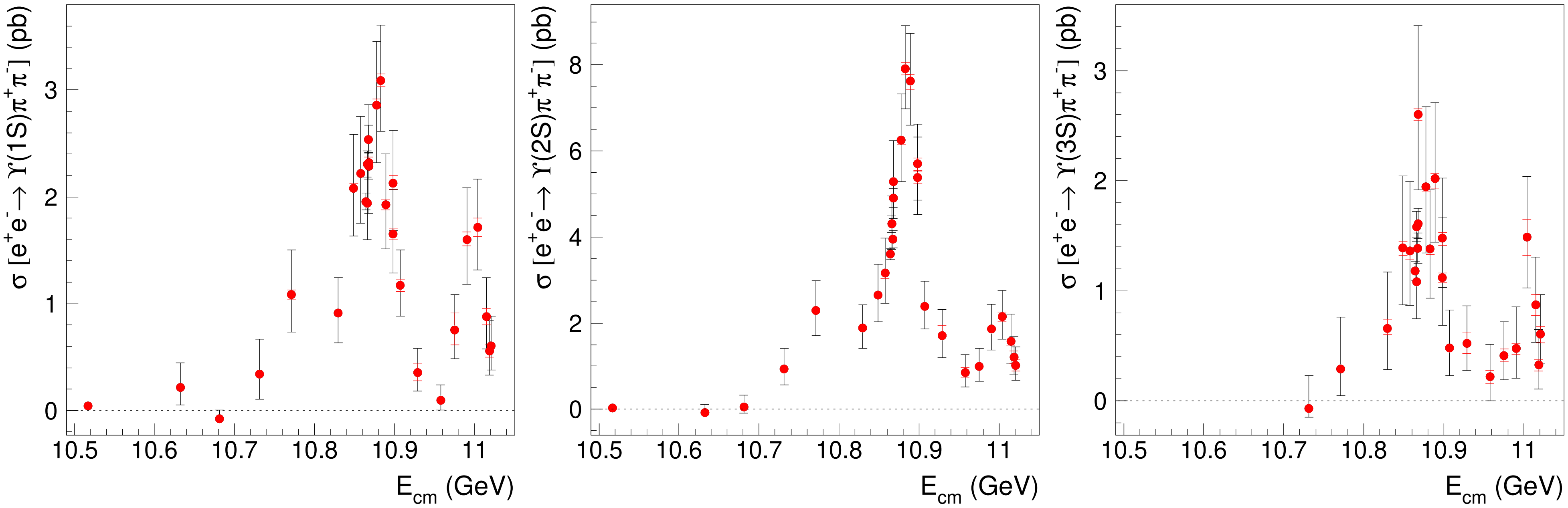


The fully reconstructed events (diagonal): $|M_{\rm recoil}(\pi^+\pi^-) - M(l^+l^-)| <$150 MeV.

Two populated regions below the diagonal are due to transitions from the $\Upsilon(10860)$ to the $\Upsilon(2S, 3S)$ via ISR and light mesons

R. Mizuk et al., JHEP 1910, 220 (2019)

A new structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ – III

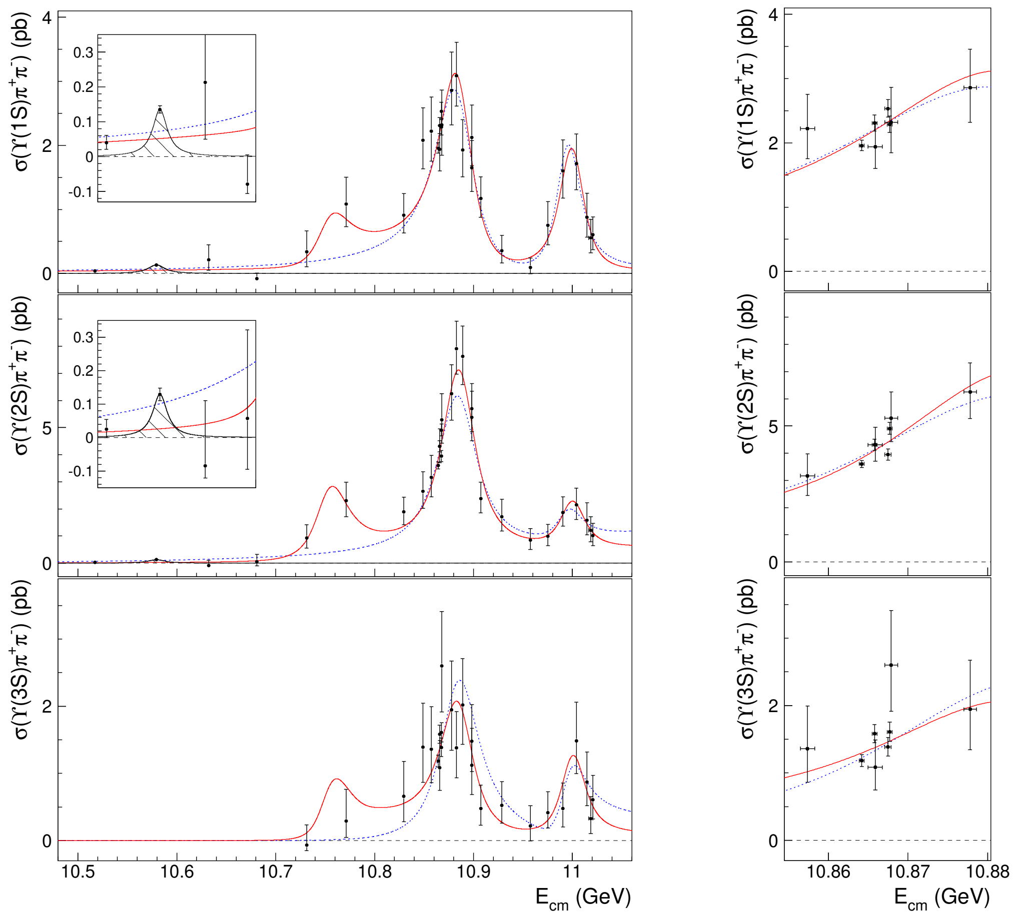


From the $M_{\rm recoil}(\pi^+\pi^-)$ fit the Born cross sections are obtained.

Clear $\Upsilon(10860)$ and $\Upsilon(11020)$ peaks are seen, also a structure at 10.75 GeV

R. Mizuk et al., JHEP 1910, 220 (2019)

A new structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ – IV



The fit of the $\sigma(\Upsilon(nS))$ and $M_{\rm recoil}(\pi^+\pi^-)$ includes the $\Upsilon(10860)$, $\Upsilon(11020)$, the new structure and the $\Upsilon(2S, 3S)$ tails

R. Mizuk et al., JHEP 1910, 220 (2019)

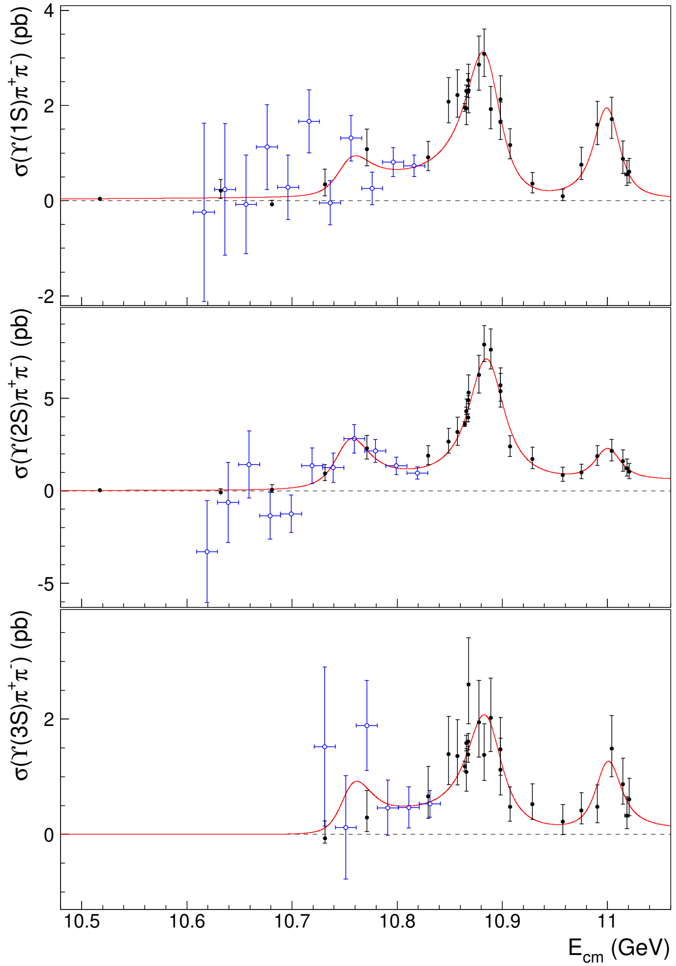
A new structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ – V

Measured masses and widths

State	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M, MeV	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0\,+1.0}_{-4.5\,-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ, MeV	$36.6^{+4.5\,+0.5}_{-3.9\,-1.1}$	$23.8^{+8.0\,+0.7}_{-6.8\,-1.8}$	$35.5^{+17.6\,+3.9}_{-11.3\,-3.3}$

R. Mizuk et al., JHEP 1910, 220 (2019)

A new structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ – VI



Energy dependence of $\sigma(\Upsilon(nS))$ with visualized ISR

R. Mizuk et al., JHEP 1910, 220 (2019)

Conclusions and Future of Bottomonium Studies

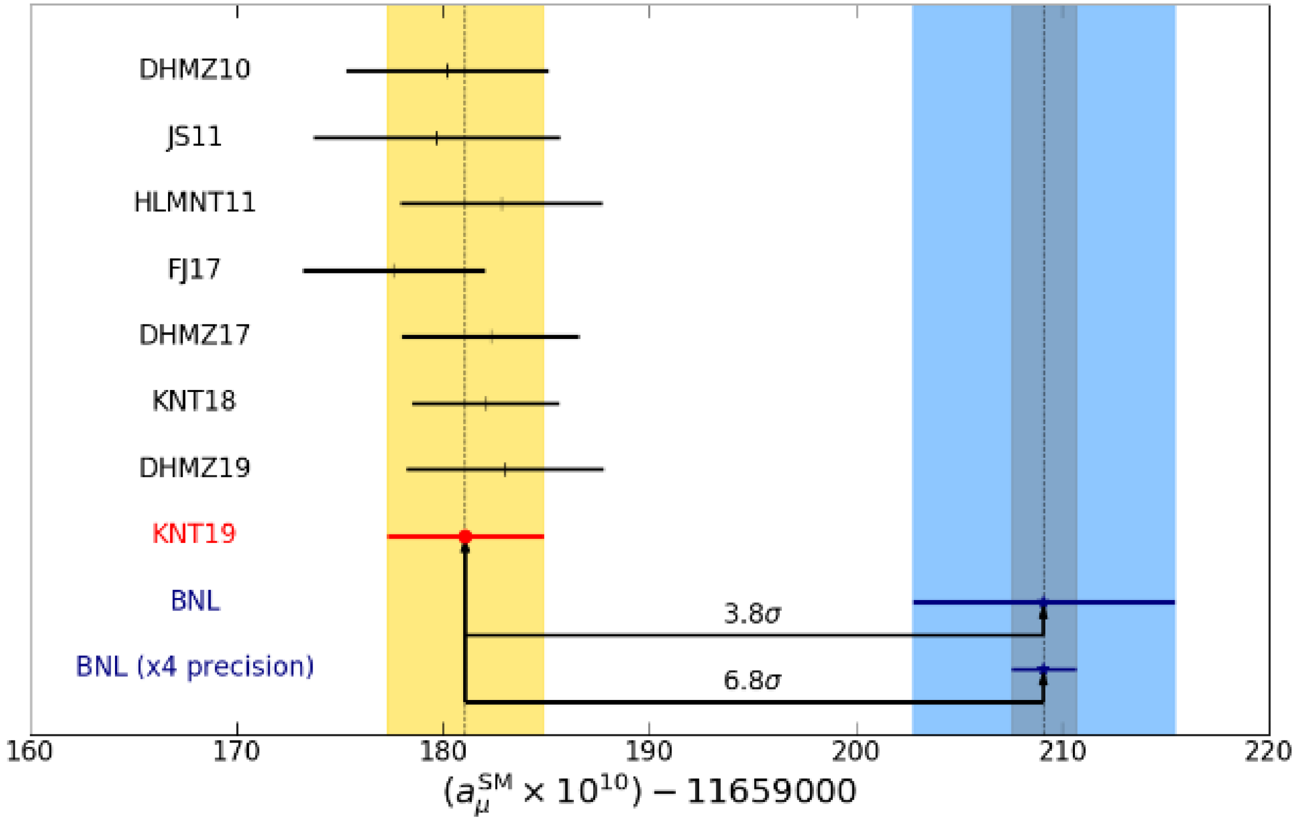
- Various $b\bar{b}$ states have been discovered/remeasured due to new energy domains, high statistics measurements and sophisticated analysis
- Higher $M_{\eta_b(1S)}$ confirmed, smaller tension with theory for $\Delta M_{\mathrm{HF}}(1S)$
- Exotic states (two Z_b's) not fitting the quark model exist, 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

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

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

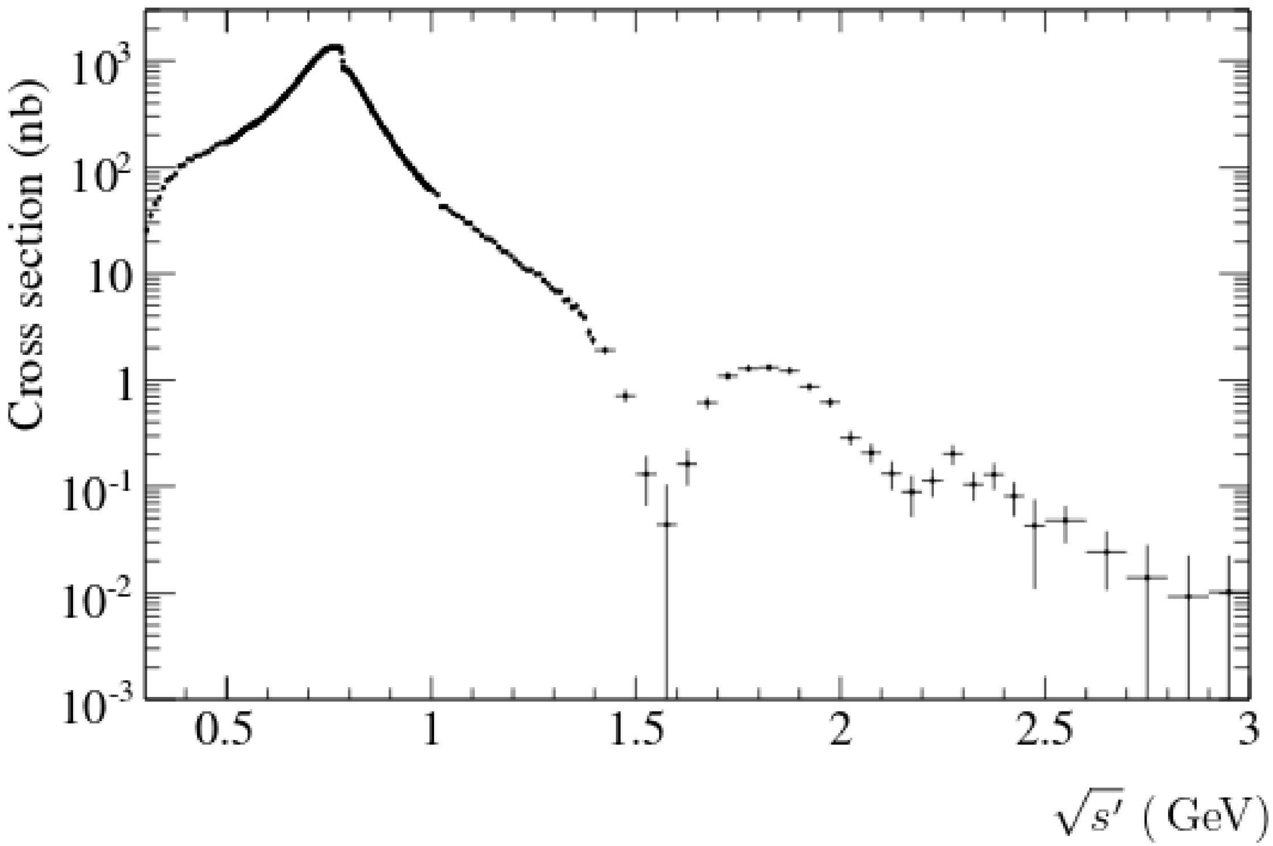
1. Detailed study of exclusive processes $e^+e^- \to (2-7)h, h = \pi, K, \eta, p, \ldots$
   - Test of models and input to theory (ChPT, Vector Dominance, QCD, . . .)
   - Properties of vector mesons $(\rho', \omega', \phi', \ldots)$
   - Search for exotic states (tetraquarks, hybrids, glueballs)
   - 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



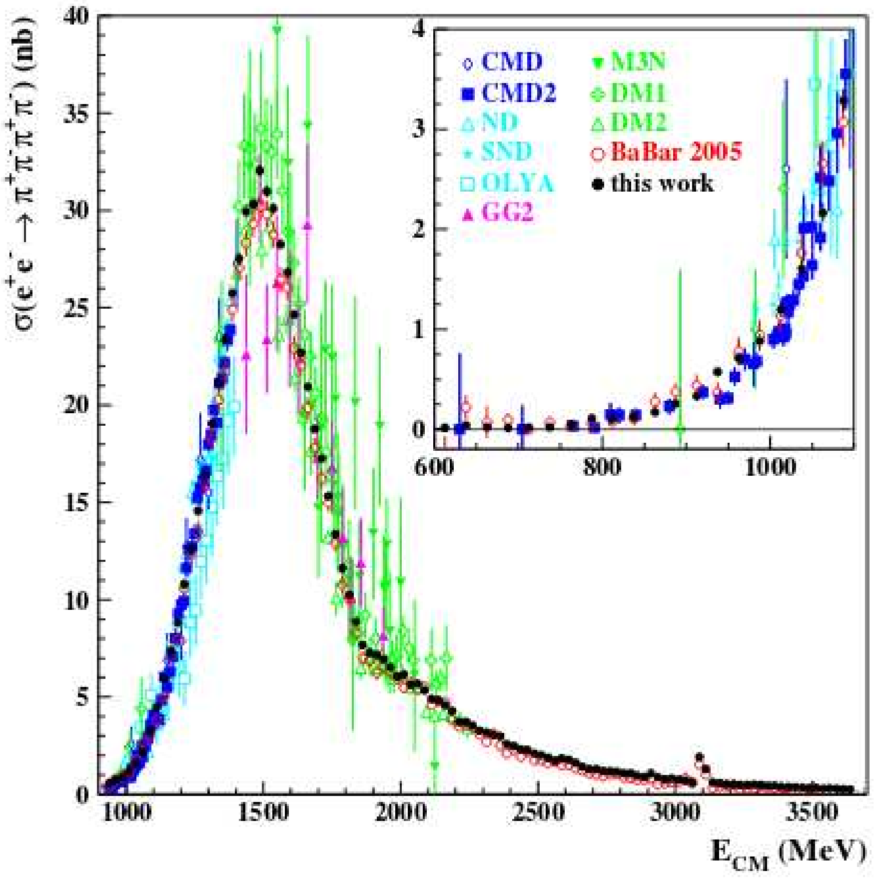
A. Keshavarzi, D. Nomura, Th. Teubner, arXiv:1911.00367

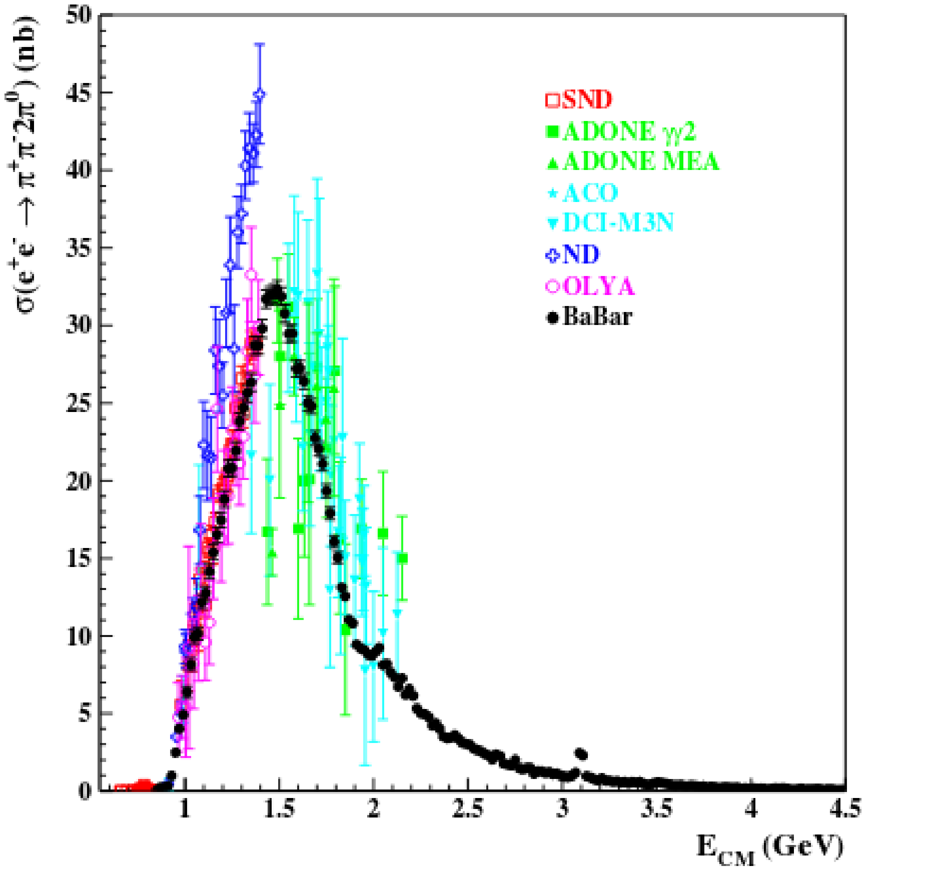
$e^+e^- \to \pi^+\pi^-$ at BaBar



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

Production of Four Pions at BaBar

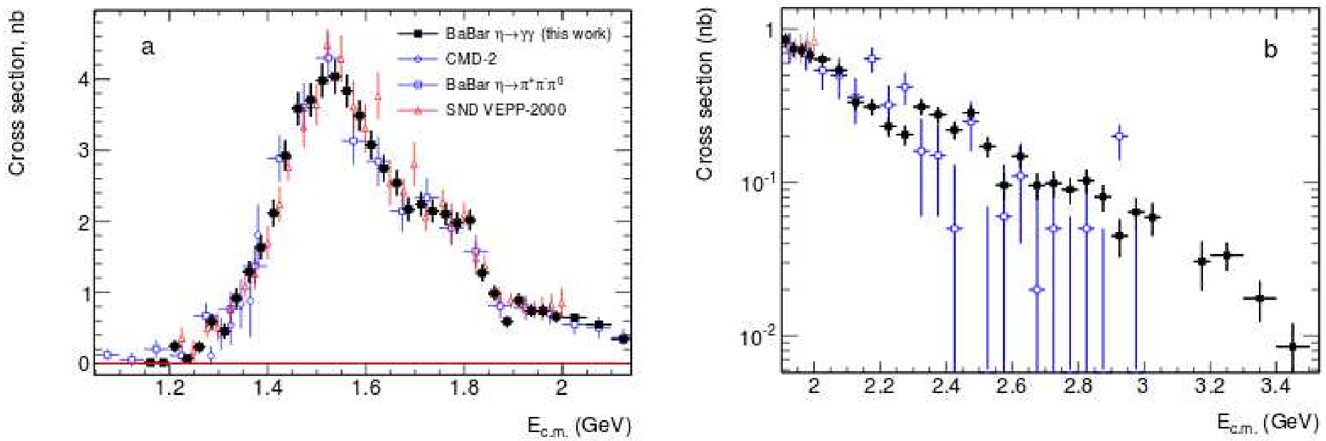




$2\pi^+2\pi^-$ J.P.Lees et al., Phys.Rev. D85, 112009 (2012)

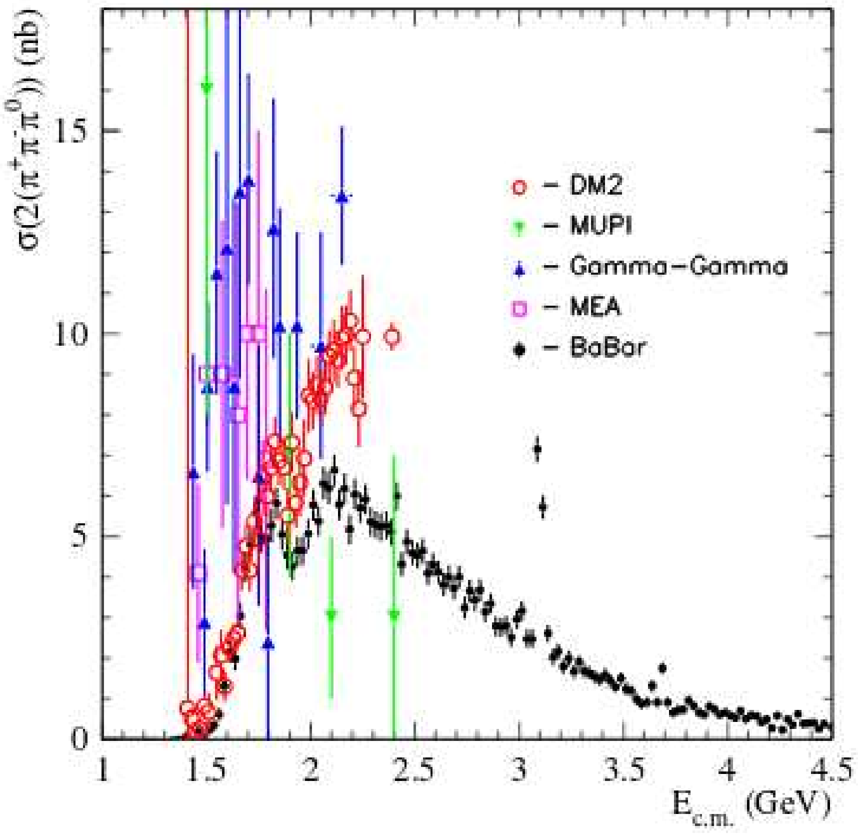
$\pi^+\pi^-2\pi^0$ J.P.Lees et al., Phys.Rev. D96, 092009 (2017)

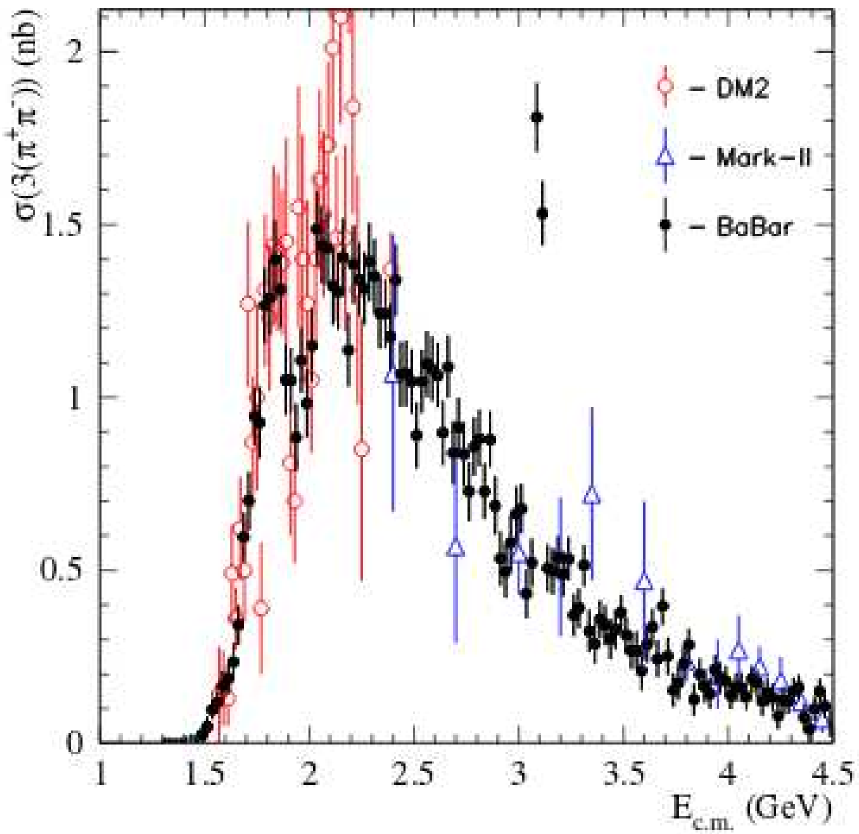
$e^+e^- \to \eta\pi^+\pi^-$ at BaBar



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

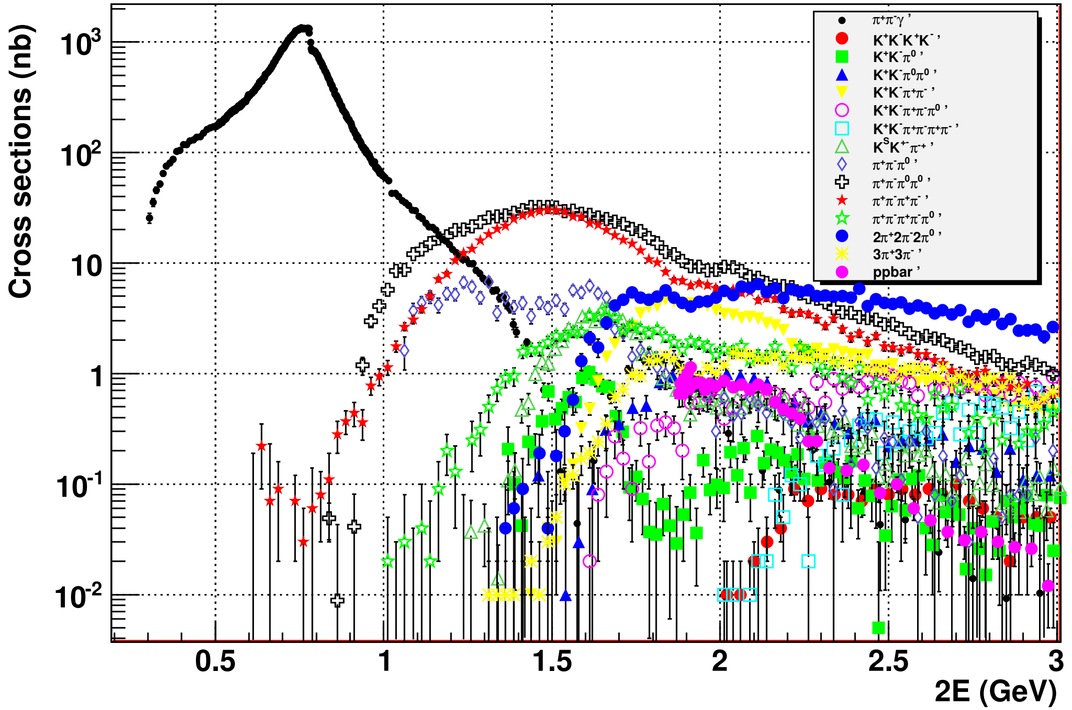
Production of Six Pions at BaBar





$2\pi^+2\pi^-2\pi^0,\ 3\pi^+3\pi^-$ 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

τ-lepton Physics

τ lepton Studies

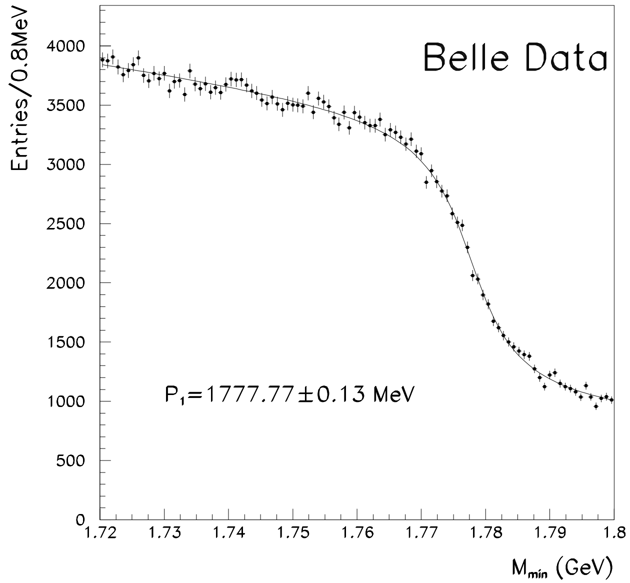
- A pure laboratory to test Standard Model
- All three basic interactions are probed:
  electromagnetic production in $e^+e^- \to \tau^+\tau^-$, weak decay,
  strong form factors in hadronic decays
- Low decay multiplicity $\Rightarrow$ smaller combinatorial BG
- Each hadronic decay is saturated by a single resonance:
  $2\pi,\ 4\pi,\ \eta\pi\pi - \rho + \rho' + \ldots$, $3\pi - a_1(1260) + a_1'$ etc.
- No hadrons in the initial, the only hadronic system in the final state
- At $\Upsilon(4S)$ $\sigma(e^+e^- \to \tau^+\tau^-)$ $\approx$0.9 nb, so 1 ab^{-1} gives $\approx 10^9$ $\tau^+\tau^-$ pairs
- BelleII will collect a data sample
  three orders of magnitude higher than CLEO

τ-lepton Mass at Belle – I

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

K. Belous et al., Phys.Rev.Lett. 99, 011801 (2007)

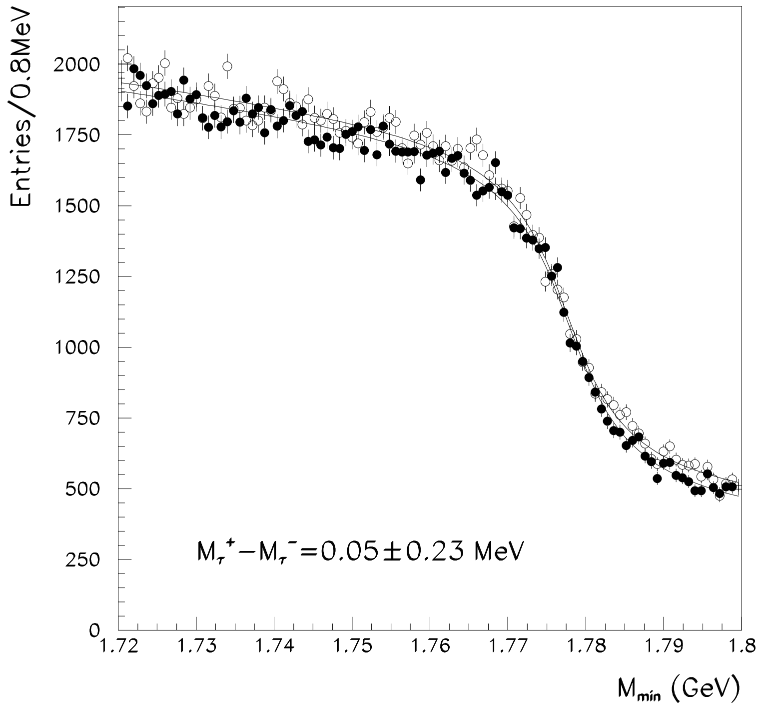
τ-lepton Mass at Belle – II



$$M_\tau = (1776.61 \pm 0.13 \pm 0.35)\ \mathrm{MeV}$$

K. Belous et al., Phys.Rev.Lett. 99, 011801 (2007)

CPT test from comparison of M_{τ^+} and M_{τ^-} – I



Belle: $M_{\tau^+} - M_{\tau^-} = 0.05 \pm 0.23 \pm 0.14$ MeV

K. Belous et al., Phys.Rev.Lett. 99, 011801 (2007)

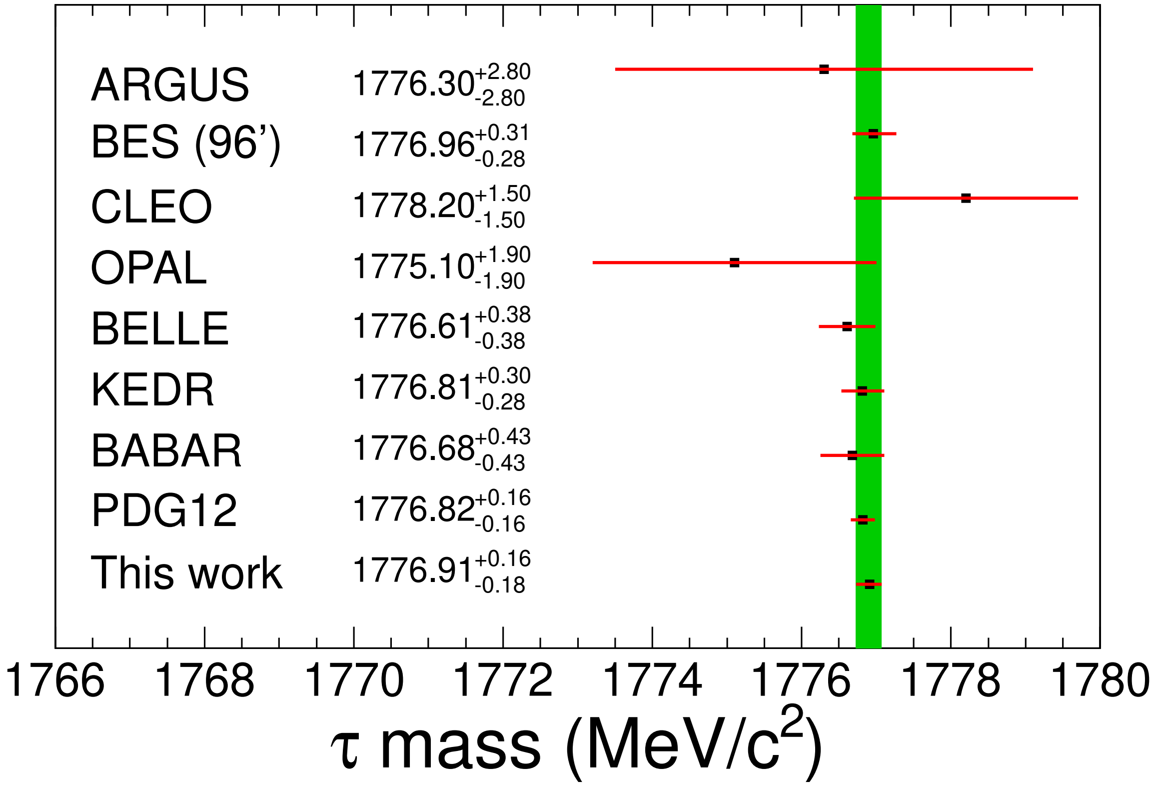
CPT test from comparison of M_{τ^+} and M_{τ^-} – II

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

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	$< 2.8 \times 10^{-4}$	$-5.6 < \ldots < -1.4$

K. Belous et al., Phys.Rev.Lett. 99, 011801 (2007)

m_τ after BESIII Measurement



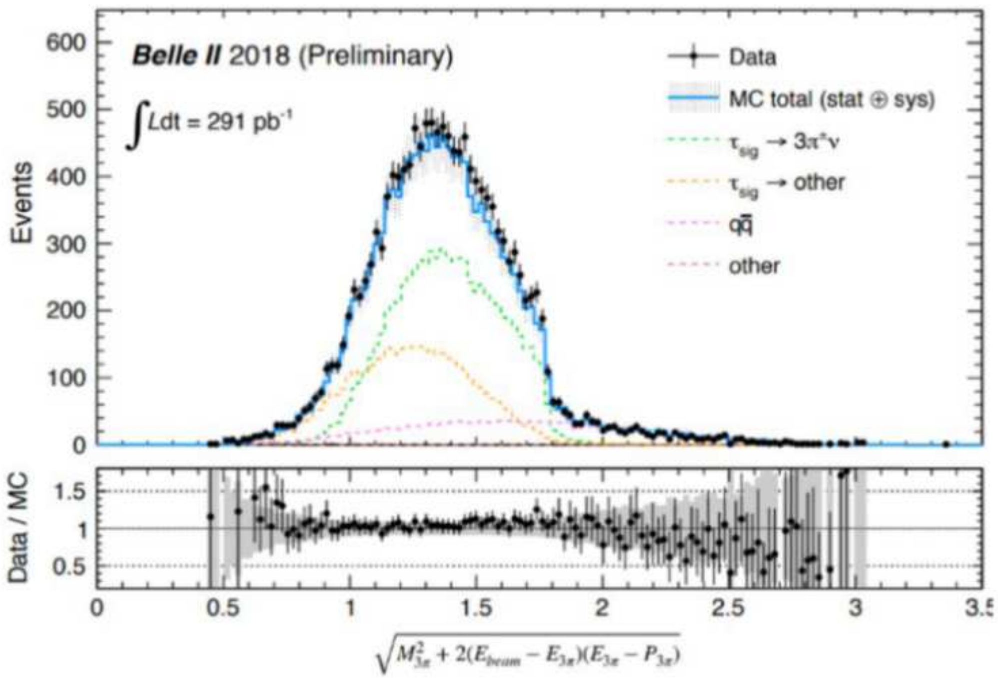
BESIII: M. Ablikim et al., Phys.Rev. D90, 012001 (2014)

PDG19: $m_\tau = (1776.86 \pm 0.12)$ MeV

First Analysis with τ Leptons

τ reconstruction (Phase 2 data)

τ → 3 π ν Pseudo-Mass

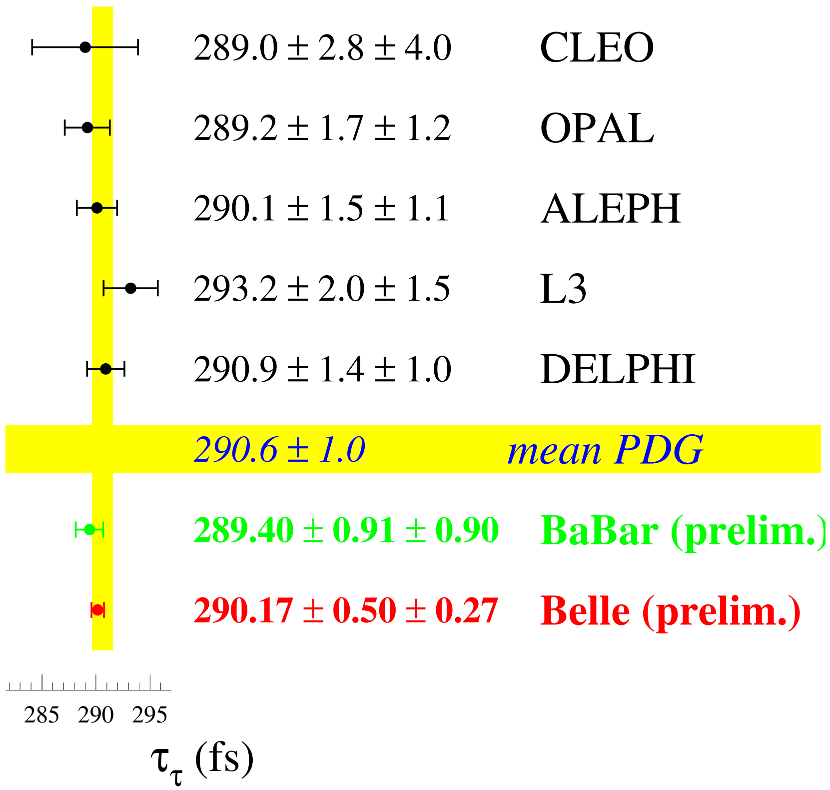


Preliminary τ mass measurement:

$m_\tau = (1776.4 \pm 4.8(\mathrm{stat}))\ \mathrm{MeV}/c^2$

consistent with previous results

Measurement of τ_τ at Belle



$$\tau_\tau = (290.17 \pm 0.50(\text{stat.}) \pm 0.33(\text{syst.})) \times 10^{-15}\ \text{s} \Rightarrow (290.3 \pm 0.5) \times 10^{-15}\ \text{s}$$

$$|\tau_{\tau^+} - \tau_{\tau^-}|/\tau_{\text{average}} < 7.0 \times 10^{-3} \text{ at } 90\% \text{ CL}$$

K. Belous et al., Phys.Rev.Lett. 112, 031801 (2014)

Test of Lepton Universality in Leptonic Decays – I

$$\Gamma(L \to l\nu_L\bar{\nu}_l) = \frac{G_L^2 \; m_L^5}{192\pi^3} F_{\rm cor}(m_L, m_l)$$

$$F_{\rm cor}(m_L, m_l) = f(m_l^2/m_L^2) \; F_{\rm W} \; F_{\rm rad}$$

$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 ln x$$

$$F_{\rm W} = 1 + \frac{3}{5}\frac{m_l^2}{m_W^2}$$

$$F_{\rm rad} = 1 + \frac{\alpha(m_L)}{2\pi}\left(\frac{25}{4} - \pi^2\right)$$

Test of Lepton Universality in Leptonic Decays – II

$$\mathcal{B}(\tau \to f) = \Gamma(\tau \to f)/\Gamma(\tau \to all) \Rightarrow$$

$$\Gamma(\tau \to e\nu_\tau\bar{\nu}_e) = \mathcal{B}(\tau \to e\nu_\tau\bar{\nu}_e)/t_\tau$$

$$\left(\frac{G_{\tau\to e\nu_\tau\bar{\nu}_e}}{G_{\mu\to e\nu_\mu\bar{\nu}_e}}\right)^2 = \left(\frac{m_\mu}{m_\tau}\right)^5\left(\frac{t_\mu}{t_\tau}\right)\mathcal{B}(\tau \to e\nu_\tau\bar{\nu}_e)\frac{F_{\rm cor}(m_\mu,m_e)}{F_{\rm cor}(m_\tau,m_e)}$$

$\sqrt{s}$	0	m_μ	m_τ	m_W
$\alpha(\sqrt{s})^{-1}$	137.036	136	133.3	128

Correction	μ	τ
$f(m_e^2/m_L^2)$	0.9998	1.0000
$F_{\rm W}(m_L)$	1.0000	1.0003
$F_{\rm rad}(m_L)$	0.9958	0.9957
Total	0.99558	0.99597

Test of Lepton Universality in Leptonic Decays – III

r	t_τ, fs	$\mathcal{B}(\tau \to e\nu_\tau\bar{\nu}_e)$, %	m_τ, MeV	Comments
0.9405 **$\pm$0.0249**	**305.6 $\pm$ 6.0** **$\pm$0.0185**	**17.93 $\pm$ 0.26** **$\pm$0.0136**	$\mathbf{1784.1^{+2.7}_{-3.6}}$ $\mathbf{^{+0.0095}_{-0.0071}}$	**PDG, 1992** $\mathbf{-2.4\sigma}$
0.9999 **$\pm$0.0069**	**291.0 $\pm$ 1.5** **$\pm$0.0052**	**17.83 $\pm$ 0.08** **$\pm$0.0045**	$\mathbf{1777.0^{+0.30}_{-0.27}}$ **$\pm$0.0008**	**PDG, 1996** $\mathbf{-0.01\sigma}$
1.0020 **$\pm$0.0051**	**290.6 $\pm$ 1.1** **$\pm$0.0038**	**17.84 $\pm$ 0.06** **$\pm$0.0034**	$\mathbf{1776.99^{+0.29}_{-0.26}}$ **$\pm$0.0008**	**PDG, 2004** $\mathbf{+0.4\sigma}$

Currently (from leptonic decays):

$$\frac{g_\tau}{g_\mu} = 1.0010 \pm 0.0015$$

$$\frac{g_\tau}{g_e} = 1.0029 \pm 0.0015$$

$$\frac{g_\mu}{g_e} = 1.0019 \pm 0.0014$$

Test of Lepton Universality in Hadronic Decays

$$(\frac{g_\tau}{g_\mu})^2 = \frac{\mathcal{B}(\tau^- \to h^- \nu_\tau)}{\mathcal{B}(h^- \to \mu^- \bar{\nu}_\mu)} \frac{2 m_h m_\mu^2 \tau_h}{m_\tau^3 (1 + \delta R_{\tau/h})} \frac{(1 - m_\mu^2/m_h^2)^2}{(1 - m_h^2/m_\tau^2)^2} \frac{\tau_h}{\tau_\tau}$$

$h = \pi,\ K, \quad \delta R_{\tau/\pi} = (0.16 \pm 0.14)\%, \quad \delta R_{\tau/K} = (0.90 \pm 0.22)\%$

$(\frac{g_\tau}{g_\mu})_\pi = 0.9961 \pm 0.0027, \qquad (\frac{g_\tau}{g_\mu})_K = 0.9860 \pm 0.0070$

$(\frac{g_\tau}{g_\mu})_{\tau+\pi+K} = 1.0000 \pm 0.0014$

The situation with W leptonic decays is less satisfactory:

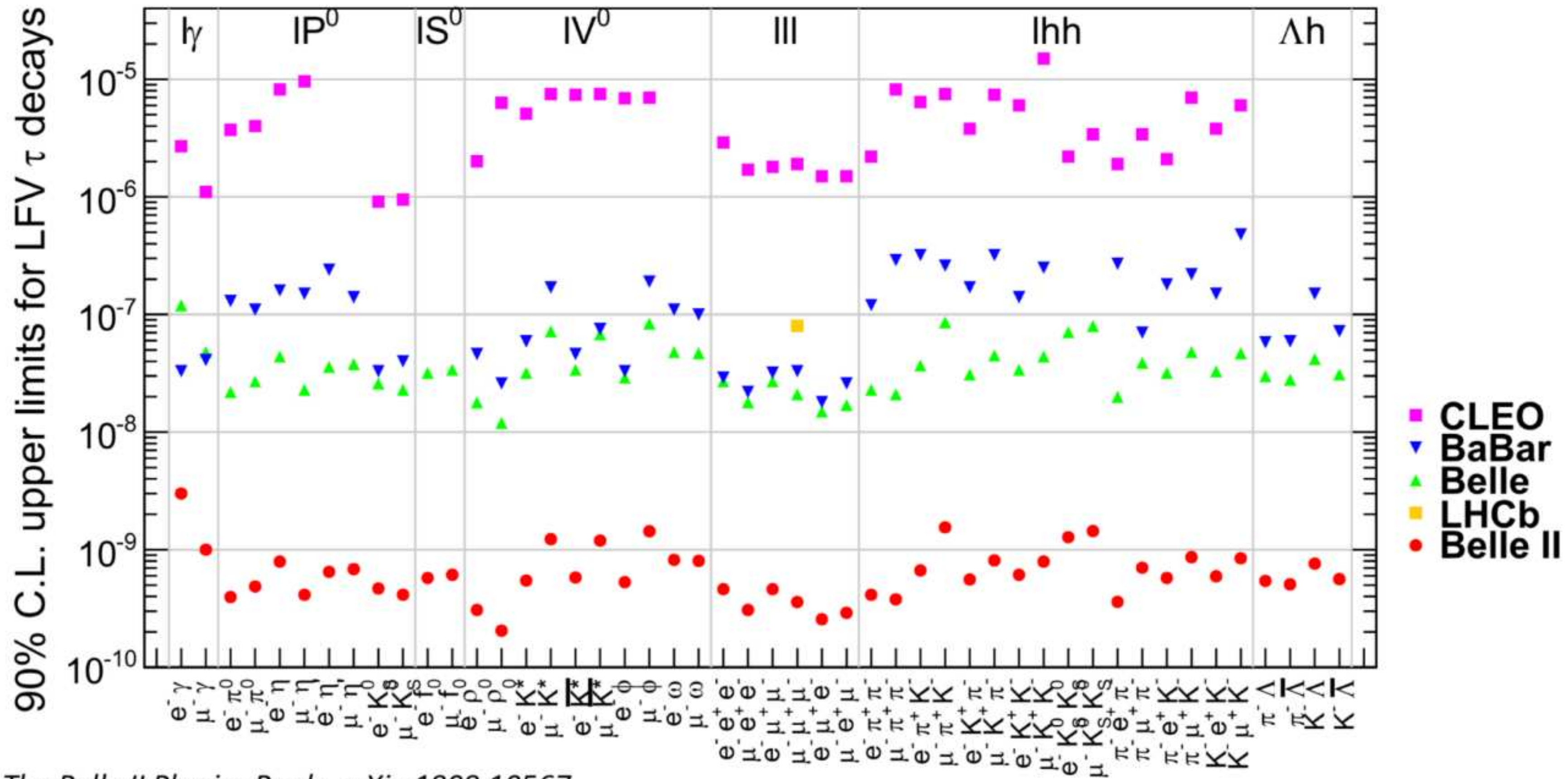
$\mathcal{B}(W^+ \to \mu^+ \nu_\mu)/\mathcal{B}(W^+ \to e^+ \nu_e) = 0.997 \pm 0.010$

$\mathcal{B}(W^+ \to \tau^+ \nu_\tau)/\mathcal{B}(W^+ \to e^+ \nu_e) = 1.036 \pm 0.014$

$\mathcal{B}(W^+ \to \tau^+ \nu_\tau)/\mathcal{B}(W^+ \to \mu^+ \nu_\mu) = 1.039 \pm 0.013$

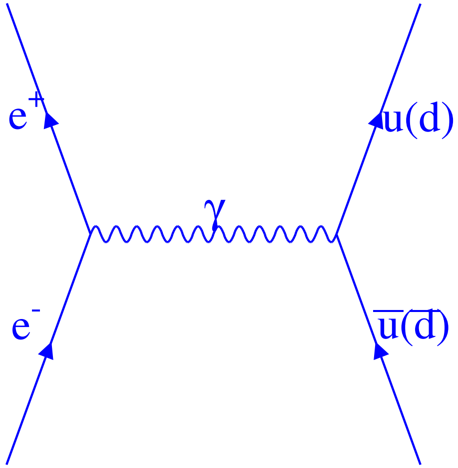
Lepton Flavor Violation (LFV)

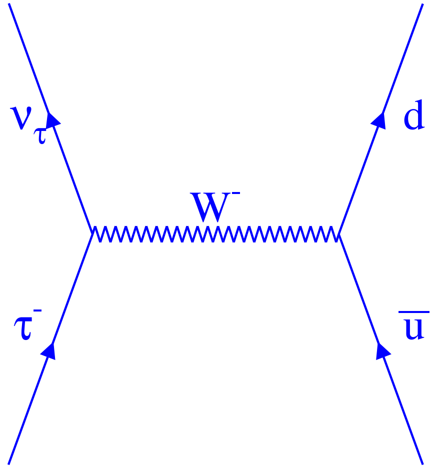
Upper limits for LFV τ decays at B factories



The Belle II Physics Book arXiv:1808.10567

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





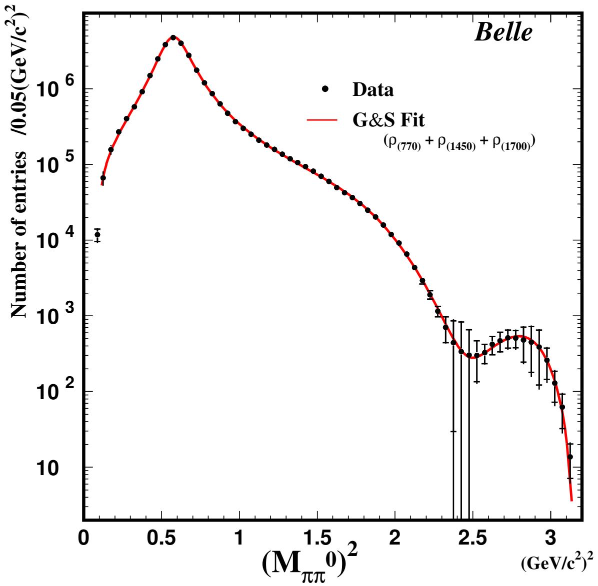
Allowed quantum numbers $I^G J^P = 1^+ 1^-$:

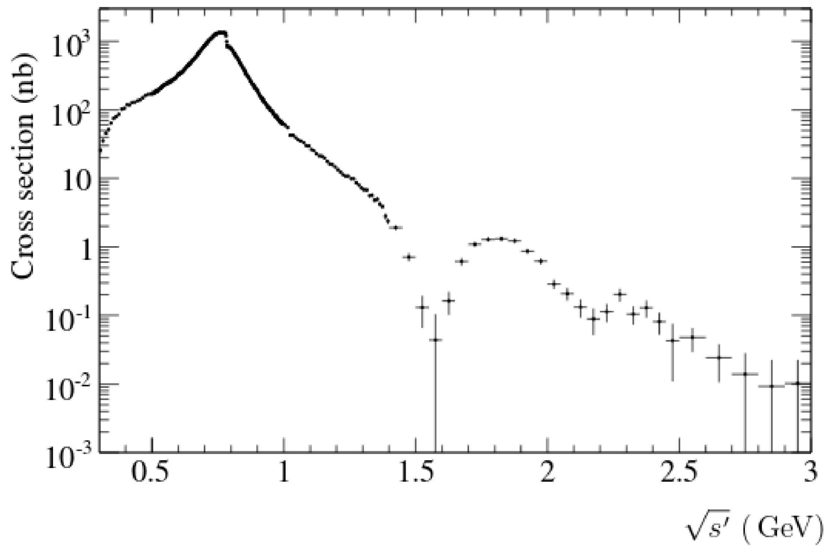
$V^- = \pi^-\pi^0, (4\pi)^-, \omega\pi^-, \eta\pi^-\pi^0, K^-K^0, (6\pi)^-,$

Total branching $\mathcal{B}(V^-\nu_\tau) \sim 32\%$

First CVC tests: good agreement of $\mathcal{B}_\tau$ from e^+e^- with τ data

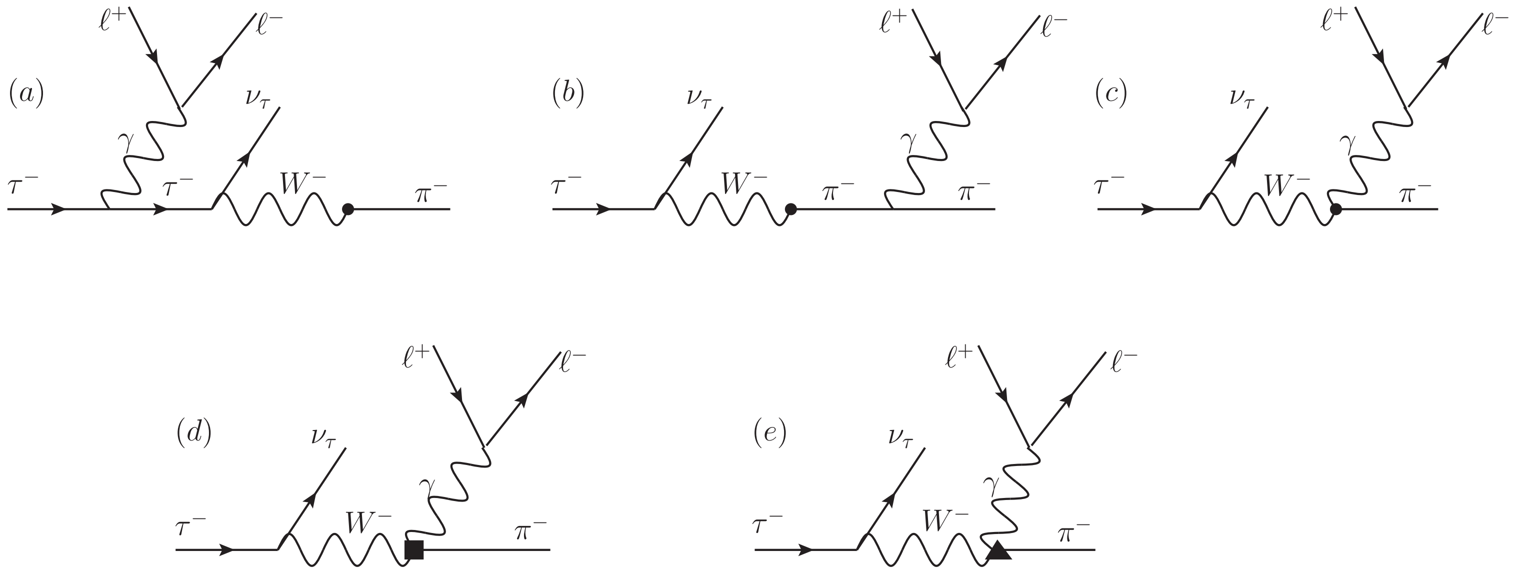
$e^+e^- \to \pi^+\pi^-$ and $\tau^- \to \pi^-\pi^0\nu_\tau$





In both e^+e^- annihilation and τ decays $\rho(770)$, $\rho(1450)$ and $\rho(1700)$ seen, detailed comparison indicates importance of $SU(2)$ breaking effects

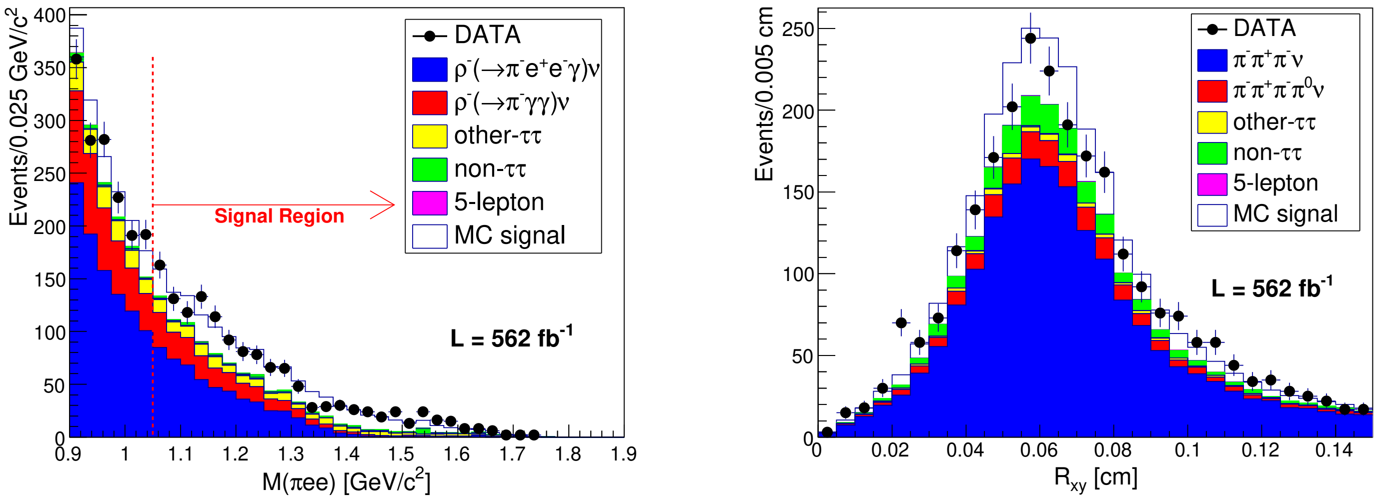
Observation of $\tau^- \to \pi^- \nu_\tau e^+ e^-$ at Belle – I



Diagrams a,b,c are structure independent, d,e – structure dependent.

Y. Jin et al., Phys. Rev. D100, 071101 (2019)

Observation of $\tau^- \to \pi^- \nu_\tau \mu^+ \mu^-$ at Belle – II



Decay	$\tau^- \to \pi^- \nu_\tau e^+ e^-$	$\tau^- \to \pi^- \nu_\tau \mu^+ \mu^-$
$N_{\rm ev}$ $(N_{\rm bg})$	1365 (954 ± 45)	2578 (2244 ± 109)
$\mathcal{B}, 10^{-5}$	A $1.46 \pm 0.13 \pm 0.21$ V $3.01 \pm 0.27 \pm 0.43$	< 1.14 90% CL
Sign., σ	7.0	2.8

Y. Jin et al., Phys. Rev. D100, 071101 (2019)

Conclusions

- BelleII reached the peak luminosity of 1.05×10^{34} cm^{-2} s^{-1}
- Last week first 10 fb^{-1} were collected
- Very rich physics in tests of the Standard Model
- Will we move to better understanding QCD?
- Unprecedental possibilities in searches for New Physics