復旦大學
FUDAN UNIVERSITY

Recent results from Belle

Tao Luo (Fudan University)
On Behalf of the Belle Collaboration

June 8 - 10, 2018

Seventh Workshop on Theory, Phenomenology and Experiments in Flavour Physics and the future of BSM physics, Capri Island, Italy

Outline

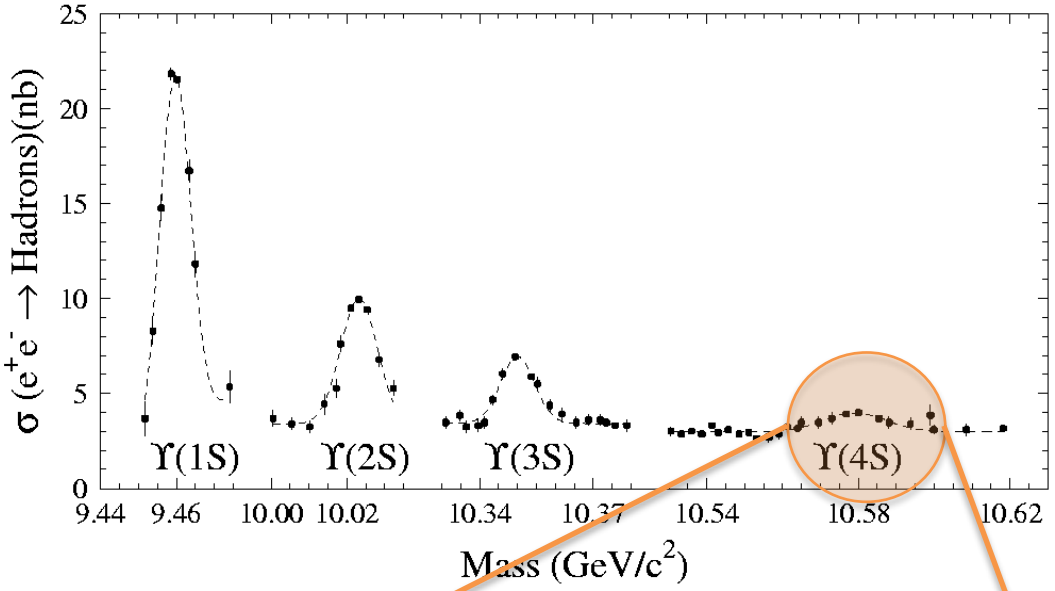
- The KEKB accelerator
- The Belle detector
- Overview of recent Belle results
- Summary

The B Factories

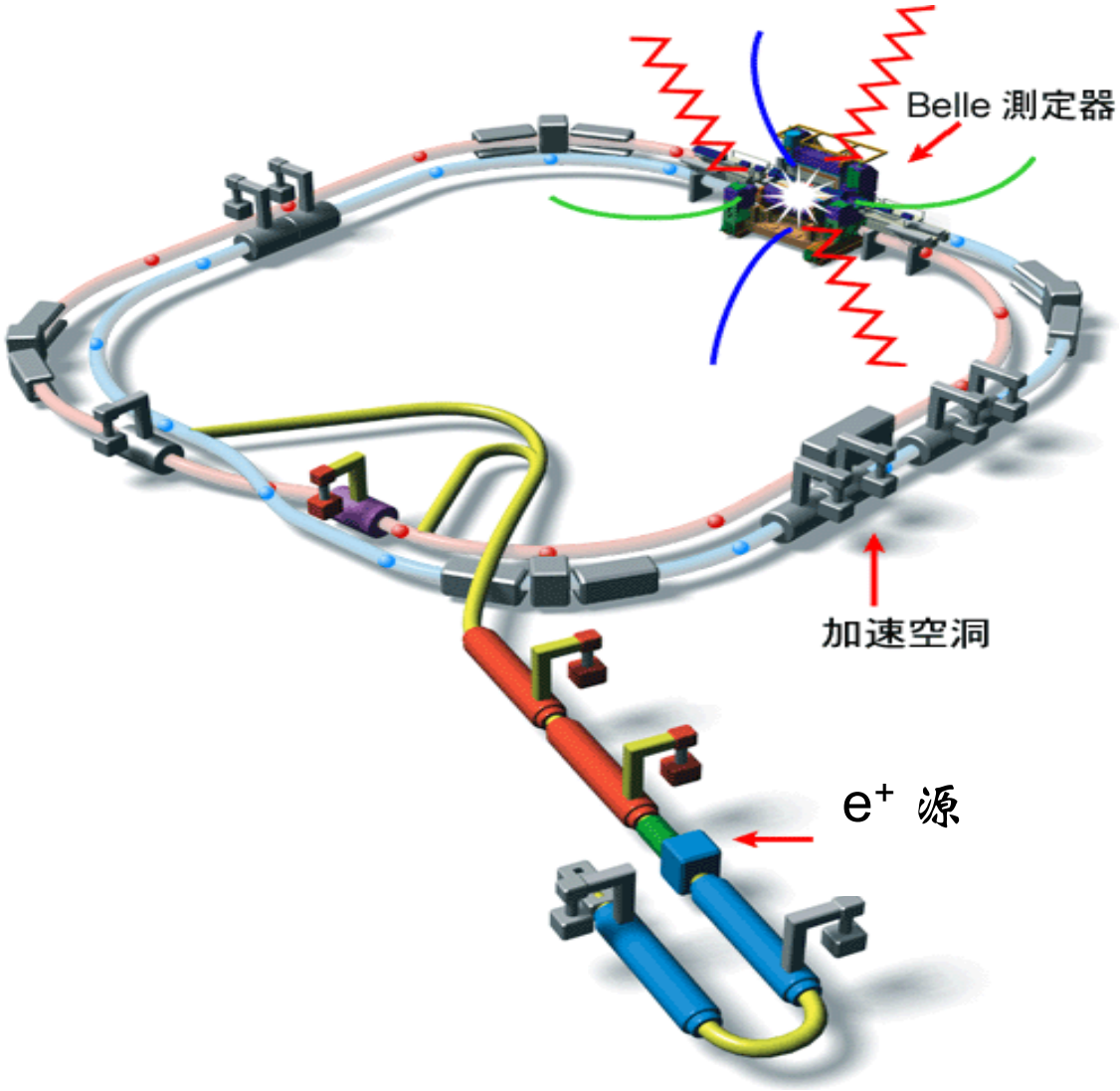
- Belle at KEKB

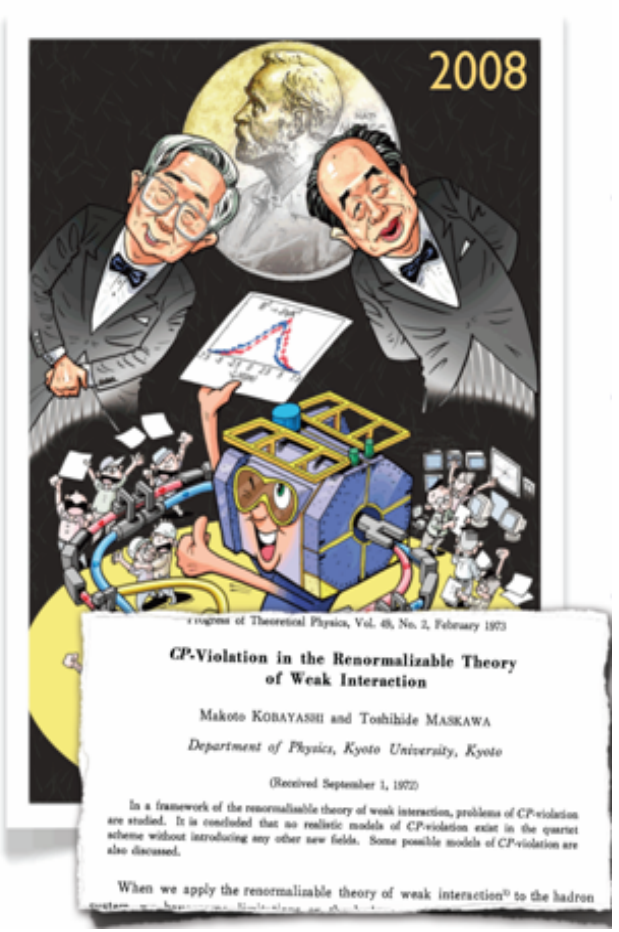
  BABAR at PEP-II

- Very high luminosity:
  - ✓ ~2x10^{34}/cm^2/s (Belle)(twice the design value)
- Asymmetric beams:
  - ✓ 8GeV e$^-$/3.5 GeV e$^+$ (Belle)
    - → Boosted BB pairs
      - (→ time dep. CPV)

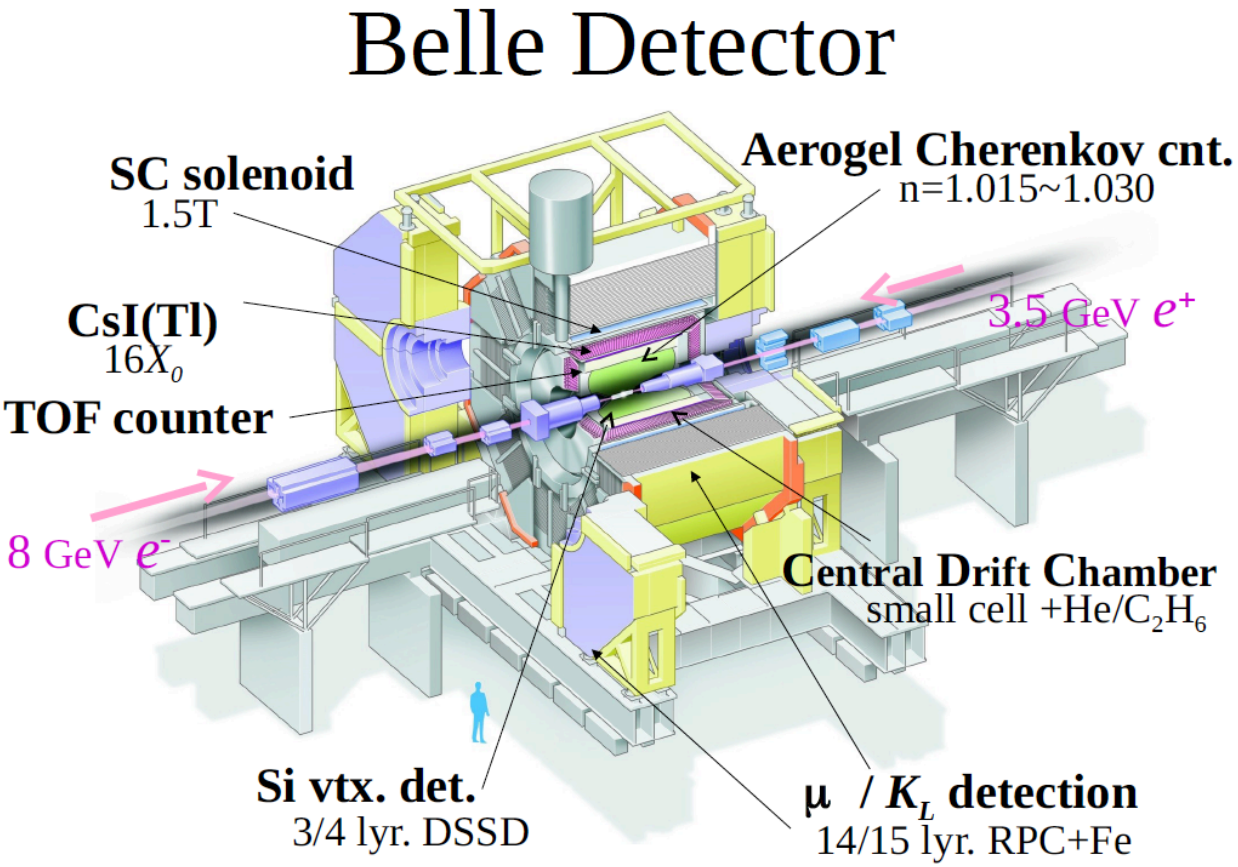


The KEKB accelerator





The Belle experiment



- Data set on Belle
  - ✓ $\Upsilon(4S)$: 711 fb^{-1}, 772 × 10^6 $B\bar{B}$ pairs.
  - ✓ All energies: 980 fb^{-1}.

Overview of recent Belle results

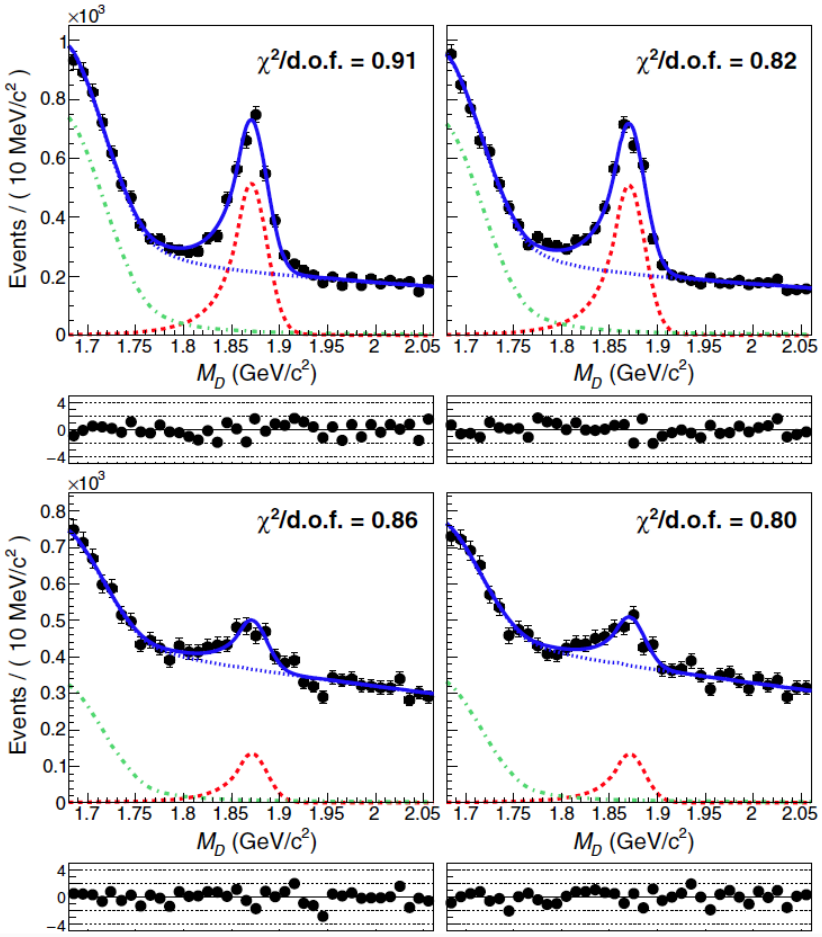
- Belle results from 2018 are included into this talk. There are following categories by physics subject:
  - ✓ CP violation.
  - ✓ Standard model tests.
  - ✓ Spectroscopy.
  - ✓ Transitions between quarkonium states.
  - ✓ Initial state radiation processes.
  - ✓ τ physics.
  - ✓ $\gamma\gamma$ processes.
  - ✓ Branching fraction and cross section measurements.

復旦大學
FUDAN UNIVERSITY

CP violation

CP violation in $D^+ \to \pi^+\pi^0$

PRD 97, 011101



The D mass for $p^*_{D^*} > 2.95$ GeV/c (top), $2.50 < p^*_{D^*} < 2.95$ GeV/c (bottom), D^+ (left), D^- (right)

- The raw asymmetry

$$A_{\rm raw}^{K\pi} = A_{CP}^{K\pi} + A_{FB} + A_{\varepsilon}^{\pi^\pm},$$

where $A_{CP}^{K\pi}$ is the CP asymmetry of $D^+ \to K_S^0\pi^+$;

- The difference in the raw asymmetries

$$\Delta A_{\rm raw} \equiv A_{\rm raw}^{\pi\pi} - A_{\rm raw}^{K\pi} = A_{CP}^{\pi\pi} - A_{CP}^{K\pi},$$

$$A_{CP}^{\pi\pi} = A_{CP}^{K\pi} + \Delta A_{\rm raw}.$$

- Measured results:

$$\Delta A_{\rm raw} = (+2.67 \pm 1.24 \pm 0.20)\%,$$

$$A_{CP}(D^+ \to \pi^+\pi^0) = (+2.31 \pm 1.24 \pm 0.23)\%.$$

Consistent with SM, null asymmetry!

Time-dependent CPV in $B^0 \to K^0_S \eta\gamma$

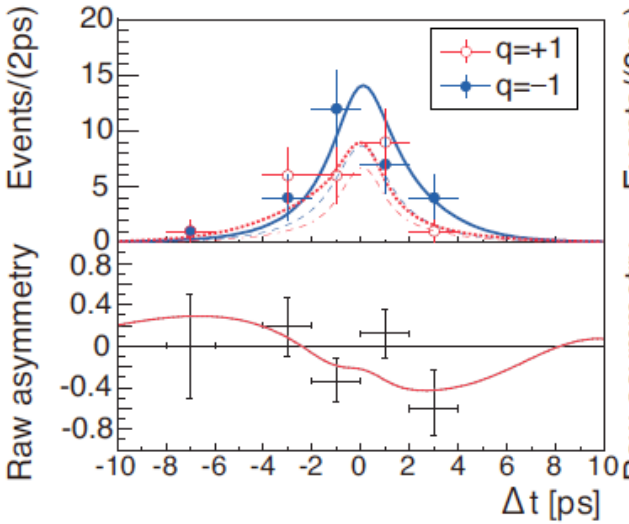
PRD 97, 092003

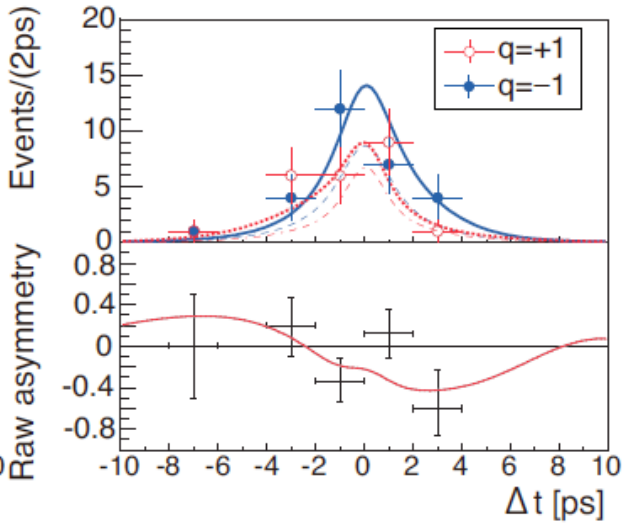
$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \{1 + q\,[\mathcal{S}\sin(\Delta m_d \Delta t) + \mathcal{A}\cos(\Delta m_d \Delta t)]\}, \quad (1)$$

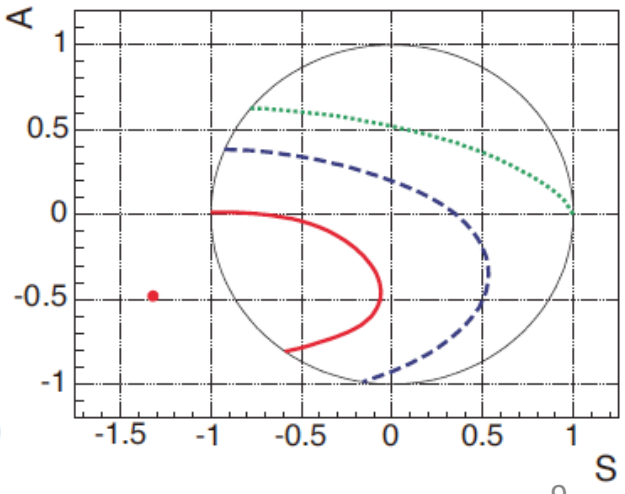
$\mathcal{S}$ - mixing-induced, $\mathcal{B}$ - direct CP violation parameters, q - flavor charge.
Fit to $\mathcal{P}(t)$ modified to incorporate incorrect flavor assignment. Results:
$\mathcal{S} = -1.32 \pm 0.77 \pm 0.36$, $\mathcal{A} = -0.48 \pm 0.41 \pm 0.07$.
The central point is out of the physical region $\mathcal{S}^2 + \mathcal{A}^2 \leq 1$.

Theoretical prediction (SM):

$\mathcal{S} \sim -(2-3)\times 10^{-2}$ (e.g. PRD **73**, 114022 (2006), PLB **642**, 478 (2006)).



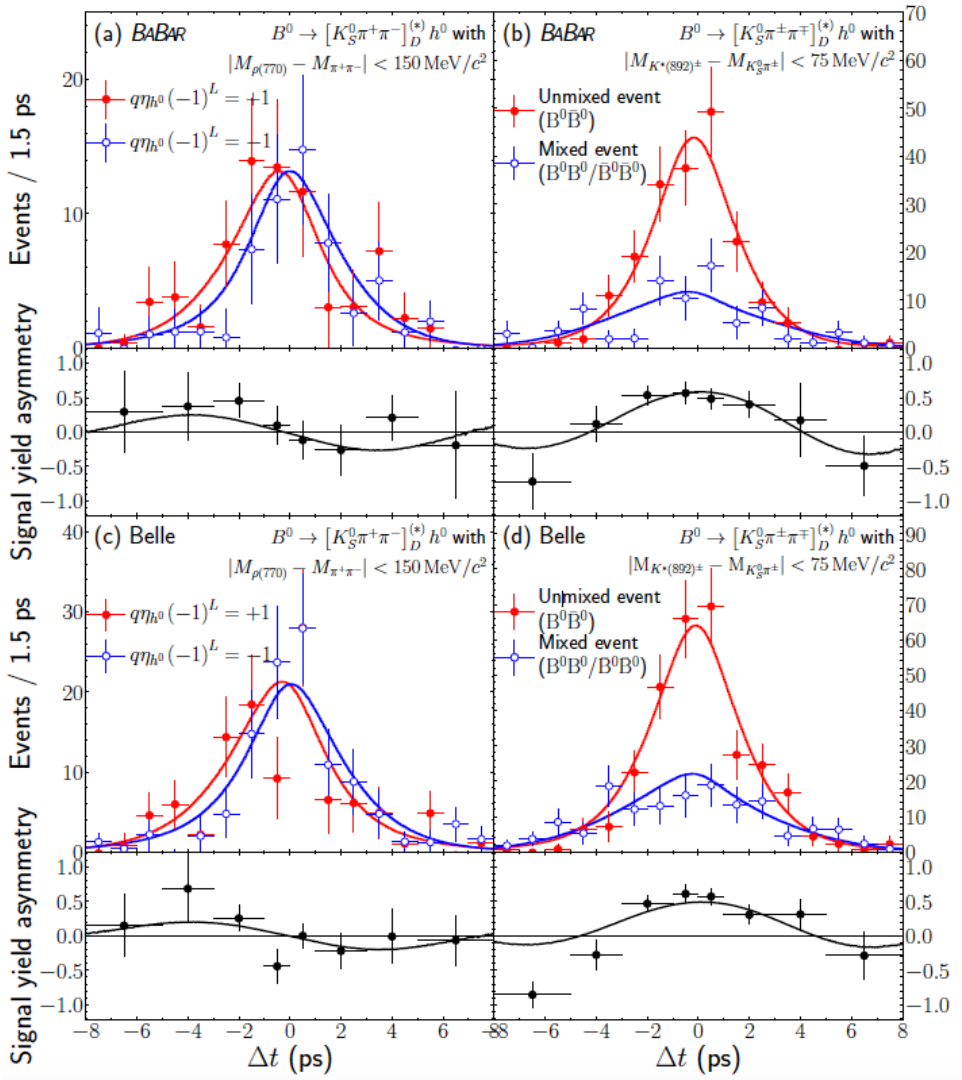




Measurement of cos 2β in $B^0 \to D^{(*)}h^0$

arXiv:1804.06152;1804.06153

Joint analysis combining Belle and BaBar data ($772\text{x}10^6 + 471\text{x}10^6\ B\bar{B}$)



Decay modes

- ✓ $B^0 \to D^0\pi^0,\ D^0\eta,\ D^0\omega,\ D^{*0}\pi^0,\ D^{*0}\eta.$
- ✓ $D^{*0} \to D^0\pi^0,\ D^0 \to K_s^0\pi^+\pi^-$

Analysis strategy

- ✓ The amplitude of $D^0 \to K_s^0\pi^+\pi^-$ is determined by a Dalitz analysis for continuum D mesons
- ✓ A time-dependent Dalitz analysis is performed on $B^0 \to D^{(*)}h^0$ (D decay amplitude is fixed, only sin2β and cos2β are free).

Results:

- ✓ sin2β = 0.80$\pm$0.14$\pm$0.06$\pm$0.03,
- ✓ cos2β = 0.91$\pm$0.22$\pm$0.09$\pm$0.07.
- ✓ 4th uncertainties: $D^0 \to K_s^0\pi^+\pi^-$ amplitude mode
- ✓ β = (22.5$\pm$4.4$\pm$1.2$\pm$0.6)°, the second minimum ($\beta' = \frac{\pi}{2} - \beta$) is excluded by 7.3 σ level

復旦大學
FUDAN UNIVERSITY

Standard model tests

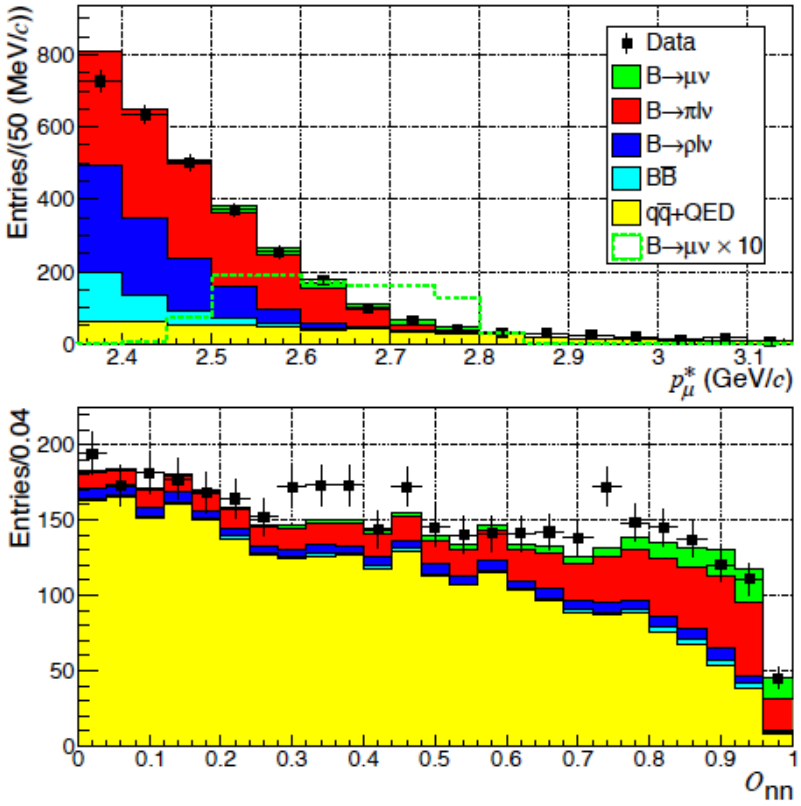
Search for $B^- \to \mu^- \bar{\nu}_\mu$ Decays

arXiv:1712.04123

SM expectation:

$$\mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi} \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

$f_B = 0.186 \pm 0.004$ (from lattice) is the B decay constant.



The SM prediction:

$\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu) = (3.80 \pm 0.31) \times 10^{-7}$.

Initial selection uses accompanying B meson candidate ($M_{bc} > 5.1$ GeV$/c^2$, $-3 < \Delta E < 2$ GeV).

Number of signal events is determined by fitting the distribution of neural network output and muon momentum. Result:

$\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu) = (6.46 \pm 2.22 \pm 1.60) \times 10^{-7}$

Significance: 2.4σ.

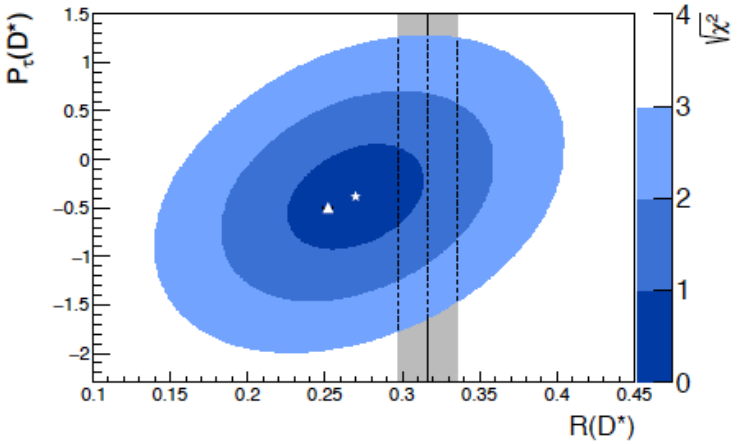
τ polarization in $B^- \to D^* \tau^- \bar{\nu}_\tau$

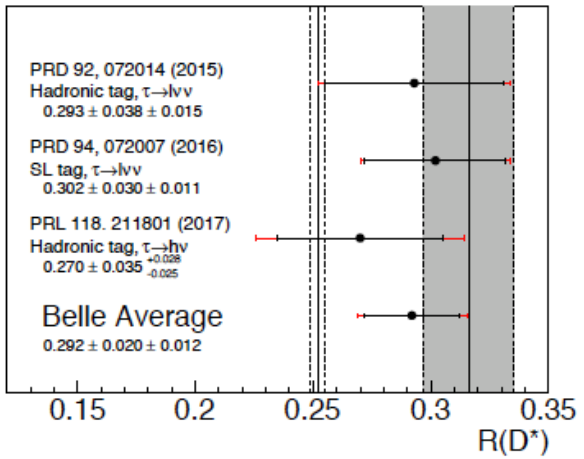
PRD 97, 012004

Measured parameters:

- $R(D^*) = \frac{\mathcal{B}(\bar{B} \to D^* \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^* \ell^- \bar{\nu}_\ell)}$.
  For Belle and Babar, $\ell = e + \mu$; for LHCb, $\ell = \tau$.
- $P_\tau(D^*) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$,
  where Γ^+, Γ^- - decay width with $\lambda_\tau = +1/2$ and $-1/2$.

Results: $R(D^*) = 0.270 \pm 0.035^{+0.028}_{-0.025}$, $P_\tau(D^*) = -0.38 \pm 0.51^{+0.21}_{-0.16}$.



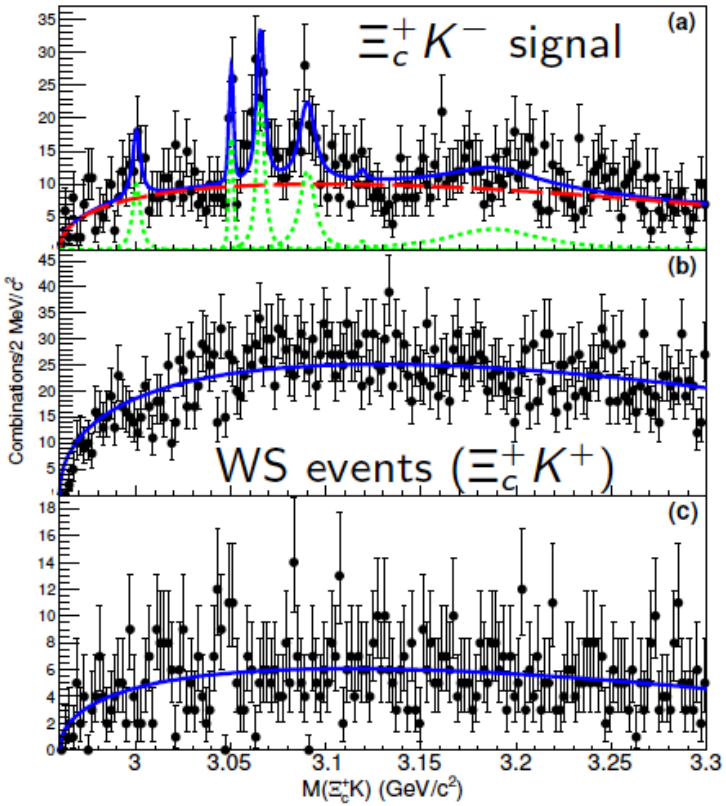


Average of 3 Belle measurements: $R(D^*) = 0.292 \pm 0.020 \pm 0.012$.
It is 1.7σ larger than SM prediction (0.252 ± 0.003).
New world average is 3.5σ larger.

復旦大學
FUDAN UNIVERSITY

Spectroscopy

Excited Ω_c baryons



(c): Ξ_c^+ sidebands ($\Xi_c^+ K^-$)

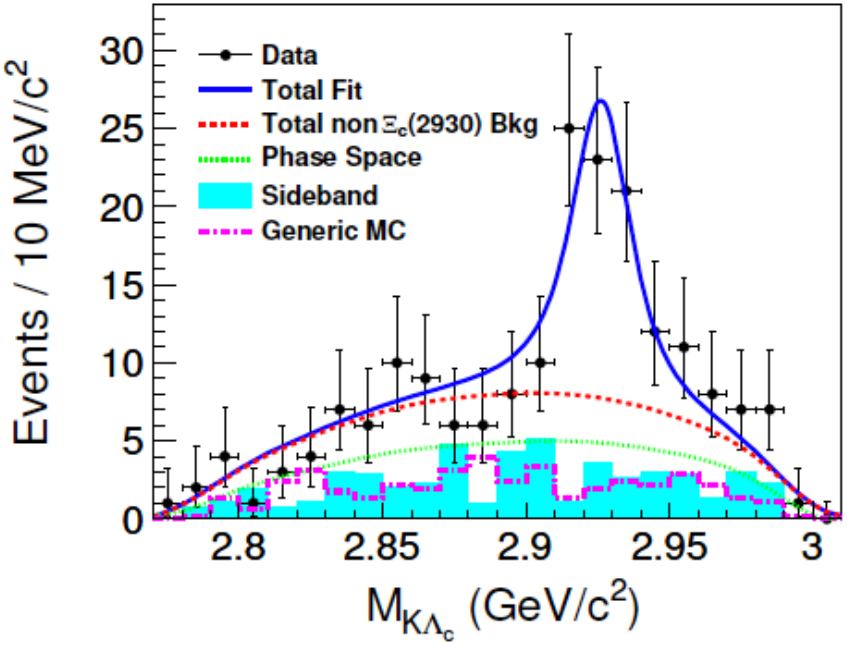
- LHCb observed 5 new narrow Ω_c states in PRL **118**, 182001 (2017).
- Belle searched for continuum production of these states in the same $\Xi_c^+ K^-$ decay mode.
- 4 of 5 states are observed, 2 of them with significance of $> 5\sigma$.
- $\Omega_c(3188)$ is a possible wide state at higher mass (same LHCb analysis).

PRD 97,051102(R)

Confirmed states:

State	$\Omega_c(3000)$	$\Omega_c(3050)$	$\Omega_c(3066)$	$\Omega_c(3090)$
Yield	37.7 ± 11.0	28.2 ± 7.7	81.7 ± 13.9	86.6 ± 17.4
Significance	3.9σ	4.6σ	7.2σ	5.7σ
LHCb Mass	$3000.4 \pm 0.2 \pm 0.1$	$3050.2 \pm 0.1 \pm 0.1$	$3065.5 \pm 0.1 \pm 0.3$	$3090.2 \pm 0.3 \pm 0.5$
Belle Mass	$3000.7 \pm 1.0 \pm 0.2$	$3050.2 \pm 0.4 \pm 0.2$	$3064.9 \pm 0.6 \pm 0.2$	$3089.3 \pm 1.2 \pm 0.2$

Observation of $\Xi_c(2930)^0$ in $B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-$



- The $\Xi_c(2930)^0$ has previously been reported by BaBar in PRD **77**, 031101 (2008) in the same pr , but the significance has not been specified $\Longrightarrow$ its status is unclear.
- Unbinned simultaneous extended maximum likelihood fit to the signal and Λ_c sidebands. The fit is 1-dimensional ($\Lambda_c^+ K^-$).

The $\Xi_c(2930)^0$ is observed with 5.1σ global significance. EPJC 78, 252

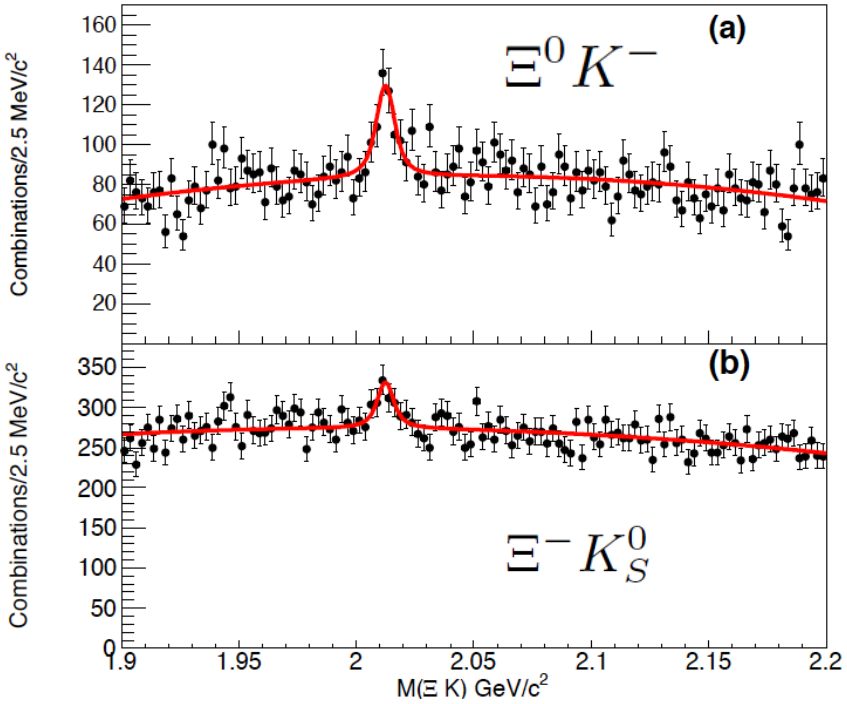
Parameters: $M = 2928.9 \pm 3.0\,^{+0.9}_{-12.0}$ MeV/c^2, $\Gamma = (19.5 \pm 8.4\,^{+5.9}_{-7.9})$ MeV.

$\mathcal{B}(B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-) = (4.80 \pm 0.43 \pm 0.60) \times 10^{-4}$

$\mathcal{B}(B^- \to \Xi_c(2930)^0 \bar{\Lambda}_c^-) \times \mathcal{B}(\Xi_c(2930)^0 \to \Lambda_c^+ K^-) = (1.73 \pm 0.45 \pm 0.21) \times 10^{-4}$

$\mathcal{B}(B^- \to Y(4660) K^-) \times \mathcal{B}(Y(4660) \to \Lambda_c^+ \bar{\Lambda}_c^-) < 1.2 \times 10^{-4}$ (90% C.L.)

Observation of an excited Ω^- baryon



arXiv:1805.09384

- New resonance is observed
- It is found primarily in the decay of the narrow resonances $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$
- No isospin asymmetry is observed

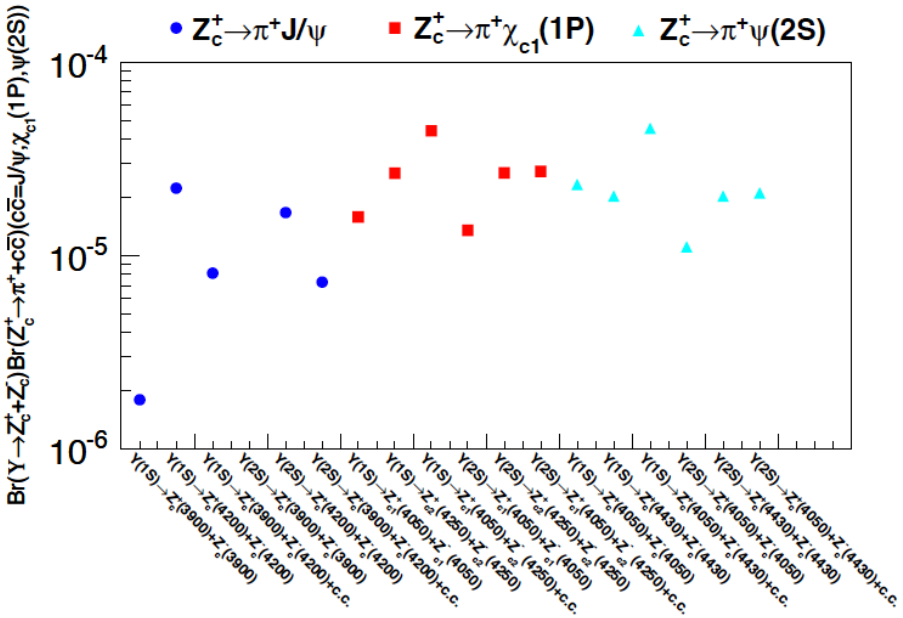
Data	Mode	Mass (MeV/c^2)	Yield	Γ(MeV)	χ^2/d.o.f.	n_σ
$\Upsilon(1S,2S,3S)$	$\Xi^0 K^-$, $\Xi^- K^0_S$ (simultaneous)	2012.4 ± 0.7	$242 \pm 48,\ 279 \pm 71$	$6.4^{+2.5}_{-2.0}$	227/230	8.3
$\Upsilon(1S,2S,3S)$	$\Xi^0 K^-$	2012.6 ± 0.8	239 ± 53	6.1 ± 2.6	115/114	6.9
$\Upsilon(1S,2S,3S)$	$\Xi^- K^0_S$	2012.0 ± 1.1	286 ± 87	6.8 ± 3.3	101/114	4.4
Other	$\Xi^0 K^-$	2012.4 (Fixed)	209 ± 63	6.4 (Fixed)	102/116	3.4
Other	$\Xi^- K^0_S$	2012.4 (Fixed)	153 ± 89	6.4 (Fixed)	133/116	1.7

Search for $\Upsilon(1S, 2S) \to Z_c^+ Z_c^{(\prime)-}$ and $e^+e^- \to Z_c^+ Z_c^{(\prime)-}$

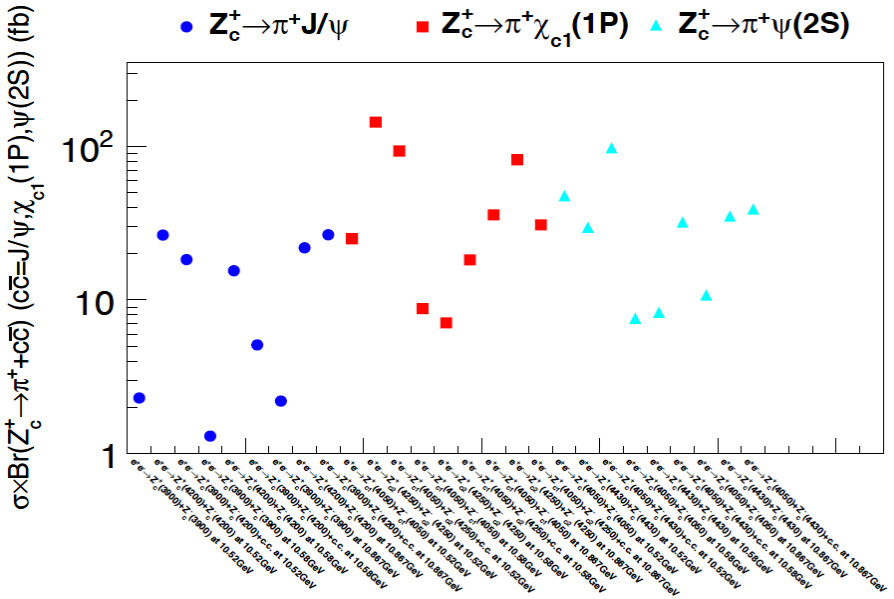
arXiv:1805.02308

- No clear signals are observed in the studied modes
- The 90% C.L. upper limits on the branching fractions are determined
- The reported upper limits are not in contradiction with the naive expectation.

$\mathcal{B}(\Upsilon(1S,2S) \to Z_c^+ Z_c^{(\prime)-}) \times \mathcal{B}(Z_c^+ \to \pi^+ + c\bar{c})$ $(c\bar{c} = J/\psi,\ \chi_{c1}(1P),\ \psi(2S))$



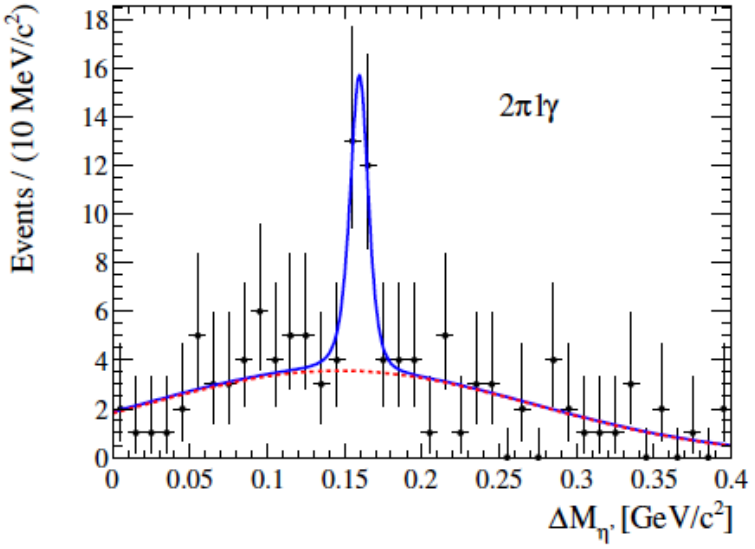
$\sigma(e^+e^- \to Z_c^+ Z_c^{(\prime)-}) \times \mathcal{B}(Z_c^+ \to \pi^+ + c\bar{c})$ $(c\bar{c} = J/\psi,\ \chi_{c1}(1P),\ \psi(2S))$

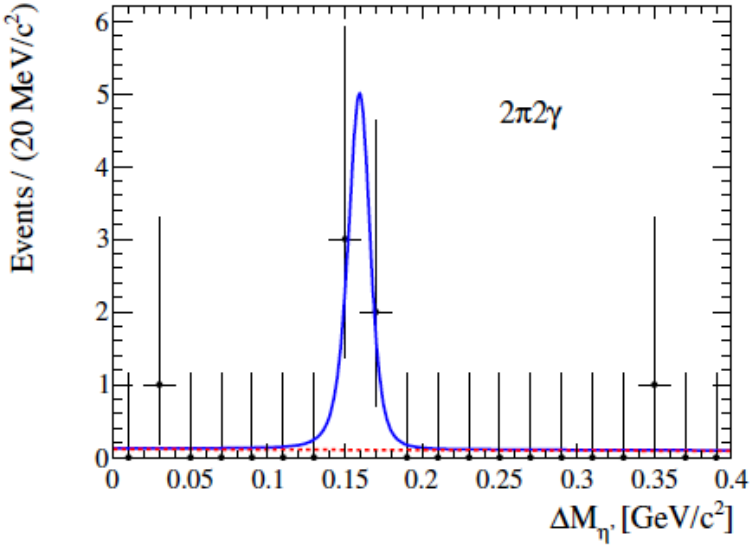


Transitions between quarkonium states

Observation of $\Upsilon(4S) \to \eta'\Upsilon(1S)$

arXiv:1803.10303





Reconstruction: $\eta' \to \rho^0\gamma,\ \pi^+\pi^-\eta(\to \gamma\gamma);\ \Upsilon(1S) \to \mu^+\mu^-$.

η: full reconstruction (left figure) or 1 photon only (right figure).

Background PDF: linear (full reconstruction), Gaussian (partial reconstruction).

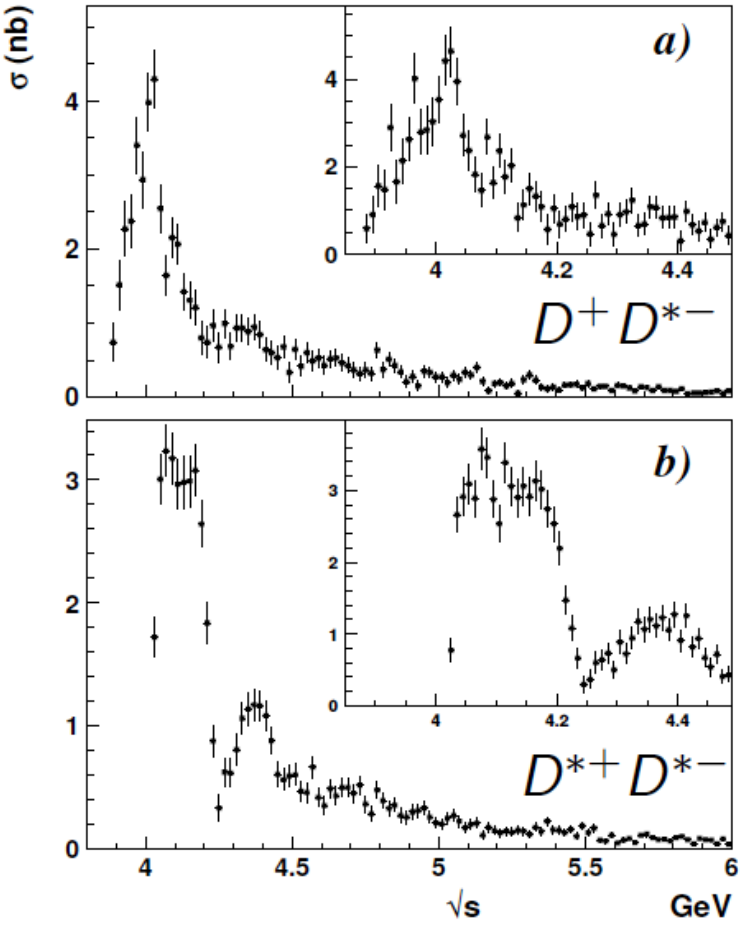
Significance (combined by simultaneous fit): 5.7σ (with systematic uncertainty).

Branching: $\mathcal{B}(\Upsilon(4S) \to \eta'\Upsilon(1S)) = (3.43 \pm 0.88 \pm 0.21) \times 10^{-5}$.

Initial state radiation processes

Angular analysis of $e^+e^- \to D^{(*)\pm}D^{(*)\mp}$

Cross sections:

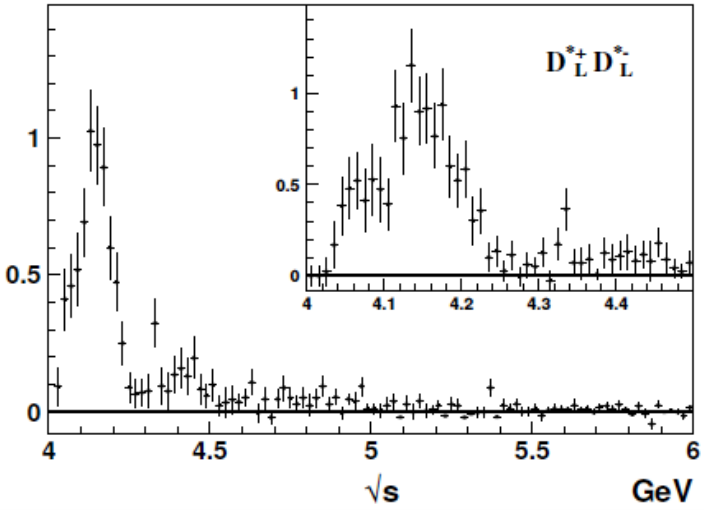


PRD 97, 012002

Partial reconstruction: D^0 from D^{*+} is not reconstructed.

Distributions of the D^* helicity angles measured (for each mass bin):

- $D^{*+}D^{*-}$: no parameters.
- $D^{*+}D^{*-}$: distribution depends on 3 cross sections σ_{LL}, σ_{TL}, σ_{TT} (L: longitudinal, $\lambda = 0$; T: transverse, $\lambda = \pm 1$). Example result:



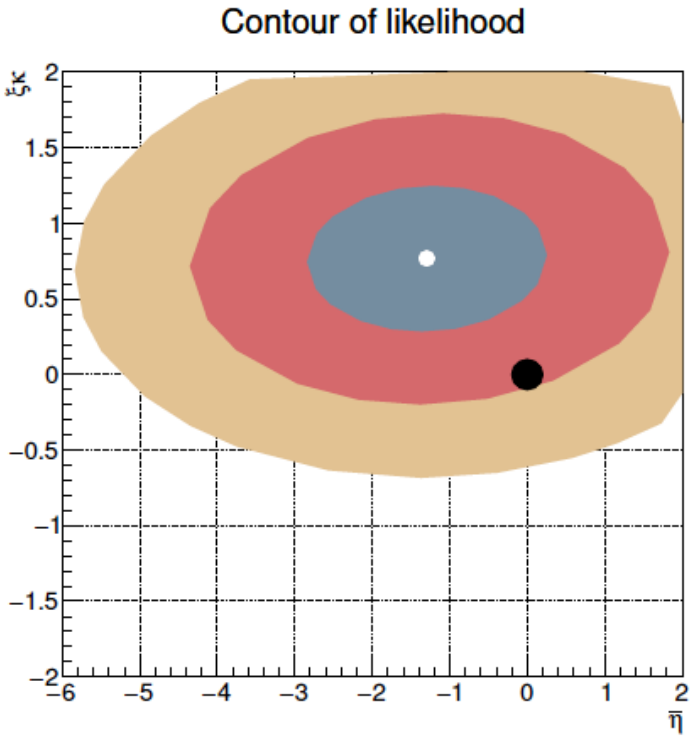
τ physics

Michel parameters of $\bar{\eta}$ and ξ_κ

$$\bar{\eta} = \left|g_{RL}^{V}\right|^2 + \left|g_{LR}^{V}\right|^2 + \frac{1}{8}\left(\left|g_{RL}^{S} + 2g_{RL}^{T}\right|^2 + \left|g_{LR}^{S} + 2g_{LR}^{T}\right|^2\right) + 2\left(\left|g_{RL}^{T}\right|^2 + \left|g_{LR}^{T}\right|^2\right),$$

$$\xi\kappa = \left|g_{RL}^{V}\right|^2 - \left|g_{LR}^{V}\right|^2 + \frac{1}{8}\left(\left|g_{RL}^{S} + 2g_{RL}^{T}\right|^2 - \left|g_{LR}^{S} + 2g_{LR}^{T}\right|^2\right) + 2\left(\left|g_{RL}^{T}\right|^2 - \left|g_{LR}^{T}\right|^2\right).$$

In SM: $g_{LL}^{V} = 1$, other couplings $= 0 \implies \bar{\eta} = \xi\kappa = 0$.



The parameters $\bar{\eta}$ and $\xi\kappa$ are extracted by simultaneous fit to differential cross sections of $\tau^- \to \ell^- \nu_\tau \bar{\nu}_\ell \gamma$. Results:

$\bar{\eta} = -1.3 \pm 1.5 \pm 0.8$,

$\xi\kappa = 0.5 \pm 0.4 \pm 0.2$.

Branching fractions with $E_\gamma > 10$ MeV:

$\mathcal{B}(\tau^- \to e^- \nu_\tau \bar{\nu}_e \gamma) = (1.79 \pm 0.02 \pm 0.10) \times 10^{-2}$,

$\mathcal{B}(\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu \gamma) = (3.63 \pm 0.02 \pm 0.15) \times 10^{-3}$.

Ratio: $4.95 \pm 0.06 \pm 0.20$ (prediction: 4.605).

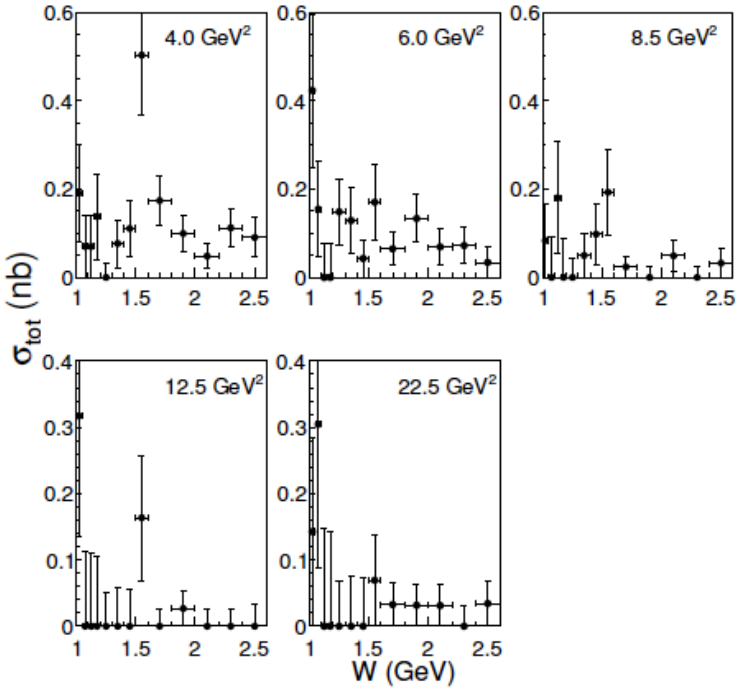
PTEP 2018, 023C01

γγ processes

$\gamma\gamma \to K_S^0 K_S^0$

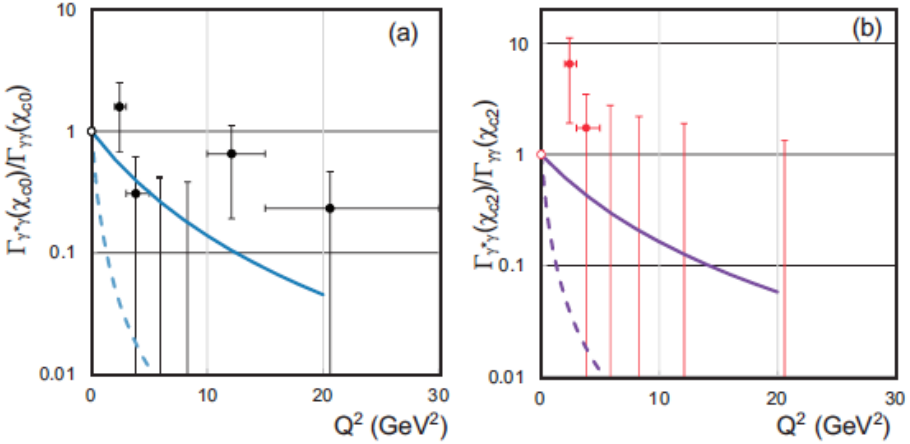
Process: $e^+e^- \to e^+e^- K_S^0 K_S^0$, one of the final-state $e^\pm$ is detected, the other one is not. The cross sections depend on $Q^2 = -m^2_{\gamma^*}$.

Total cross sections in bins of Q^2 (bin center is specified on the histograms).

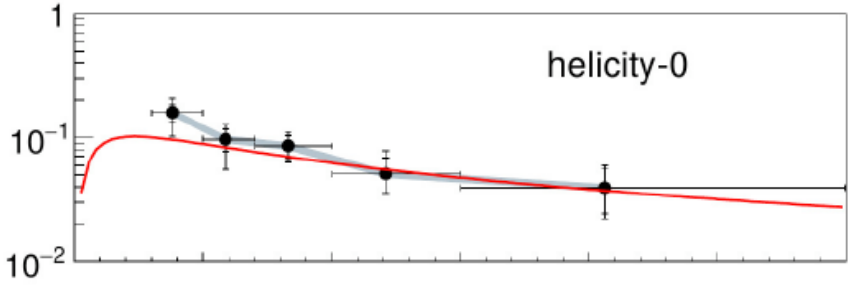


PRD 97, 052003

Differential cross sections for χ_{c0} and χ_{c2}.



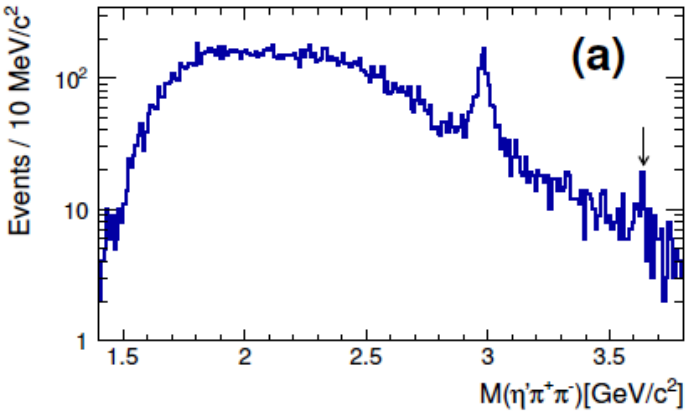
Also, transition form factor of the $f_2'(1525)$ is measured for all helicity components (0, 1, 2).

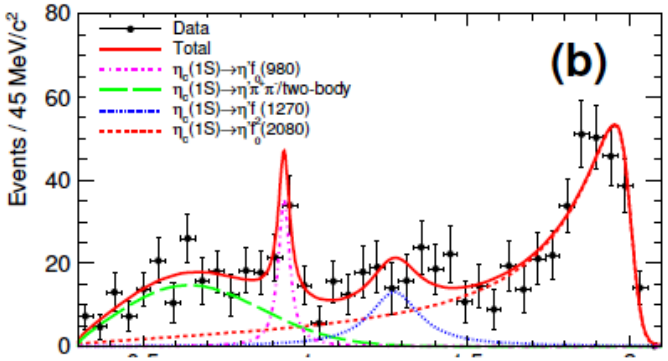


$\gamma\gamma \to \eta_c(1S, 2S) \to \eta'\pi^+\pi^-$

Reconstruction: no $e^{\pm}$ tagging, selection by low p_t.

arXiv:1805.03044



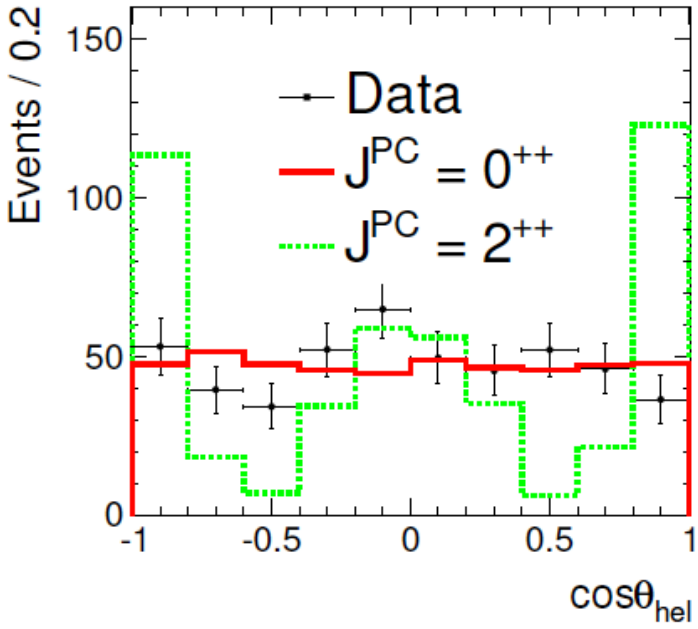


Observed:

- $\eta_c(2S) \to \eta'\pi^+\pi^-$ (5.5σ).
- $\eta_c(1D) \to \eta' f_0(2080)$ (20σ).

Measured:

- $f_0(2080)$: $J^{PC} = 0^{++}$ (exclusion of 2^{++}: 11σ).
- Parameters of η_c, $\eta_c(2S)$, $f_0(2080)$.



Branching fraction and cross section measurements

Branching fraction and cross section measurements

Branching fractions:

- ✓ $B^+ \to X_{c\bar{c}} K^+$, and $B^+ \to \overline{D}^{(*)0}\pi^+$: PRD 97, 012005 (2018)
- ✓ Ω_c^0 hadronic decays: PRD 97, 032001 (2018)
- ✓ $\Lambda_c^+ \to \Sigma^+\pi^+\pi^-$, $\Lambda_c^+ \to \Sigma^+\pi^0\pi^0$, $\Lambda_c^+ \to \Sigma^0\pi^+\pi^0$: arXiv:1802.03421
- ✓ $B \to D^{(*)}\pi l\nu$: arXiv: 1803.06444

Cross sections:

- ✓ $e^+e^- \to$ hyperons, charmed baryons: PRD 97, 072005 (2018)
- ✓ $e^+e^- \to \eta\Upsilon_J, \eta h_b$: arXiv: 1803.03225

復旦大學
FUDAN UNIVERSITY

Thank you for your attention