Overview of Belle results

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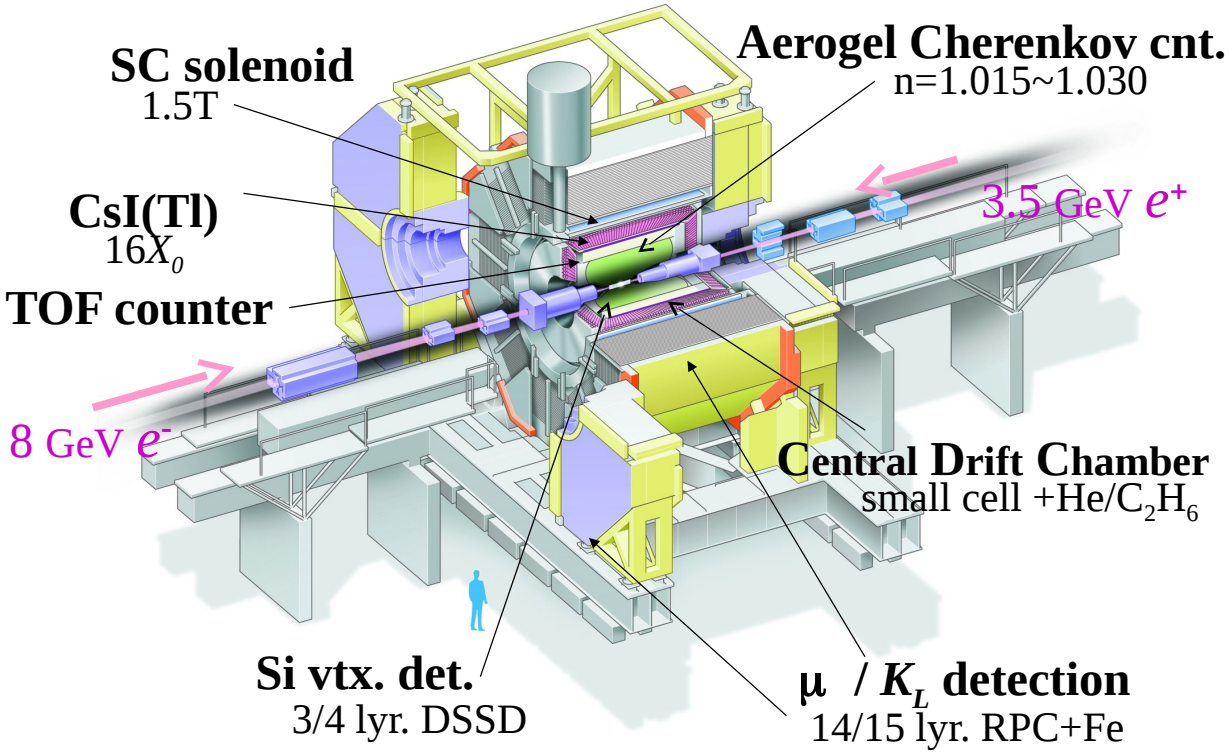
QUARKS-2018, 29 May 2018

Belle Detector



The Belle experiment operated at the asymmetric e^+e^- collider KEKB.
Data samples:

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

Outline

Belle results from 2017 and 2018 are included into this talk. There are following categories by physics subject:

1. CP violation.
2. Standard model tests.
3. Spectroscopy.
4. Transitions between quarkonium states.
5. Initial state radiation processes.
6. τ physics.
7. $\gamma\gamma$ processes.
8. Branching fraction and cross section measurements.

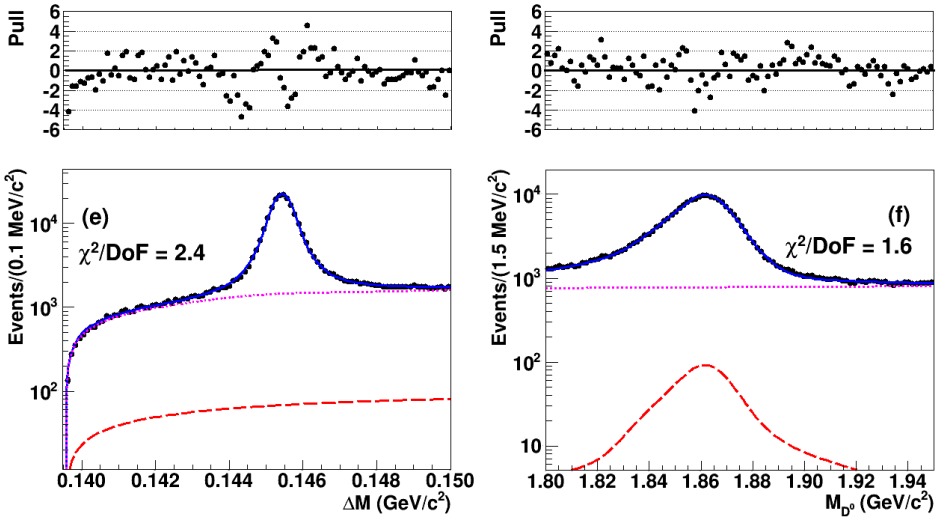
CP violation

T-odd momenta in $D^0 \to K_S^0 \pi^+ \pi^- \pi^0$

PRD 95, 091101

Definitions:

- Momenta: $C_T = p_1 \cdot (p_2 \times p_3)$; for D^0 (C_T): $1 = K_S^0$, $2 = \pi^+$, $3 = \pi^-$; for $\bar{D}^0$ ($\bar{C}_T$): $1 = K_S^0$, $2 = \pi^-$, $3 = \pi^+$.
- CP asymmetries: $A_T = \frac{\Gamma(C_T>0)-\Gamma(C_T<0)}{\Gamma(C_T>0)+\Gamma(C_T<0)}$; $\bar{A}_T$: same with $C_T \to -\bar{C}_T$.
- T-odd asymmetry: $a_{CP}^{T-\text{odd}} = \frac{1}{2}(A_T - \bar{A}_T)$. This quantity is not affected by final-state interactions.



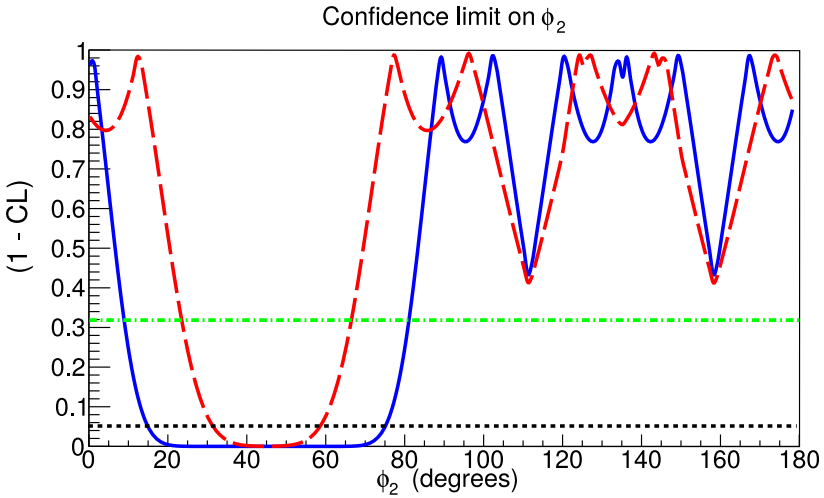
Data set: $M_{D^*} - M_D$, M_D

Result:
$a_{CP}^{T-\text{odd}} = (-0.28 \pm 1.38^{+0.23}_{-0.76}) \times 10^{-3}$.
Consistent with no CPV.
SM: $\mathcal{O}(10^{-3})$ in D decays.

CP asymmetry in $B^0 \to \pi^0\pi^0$

PRD 96, 032007

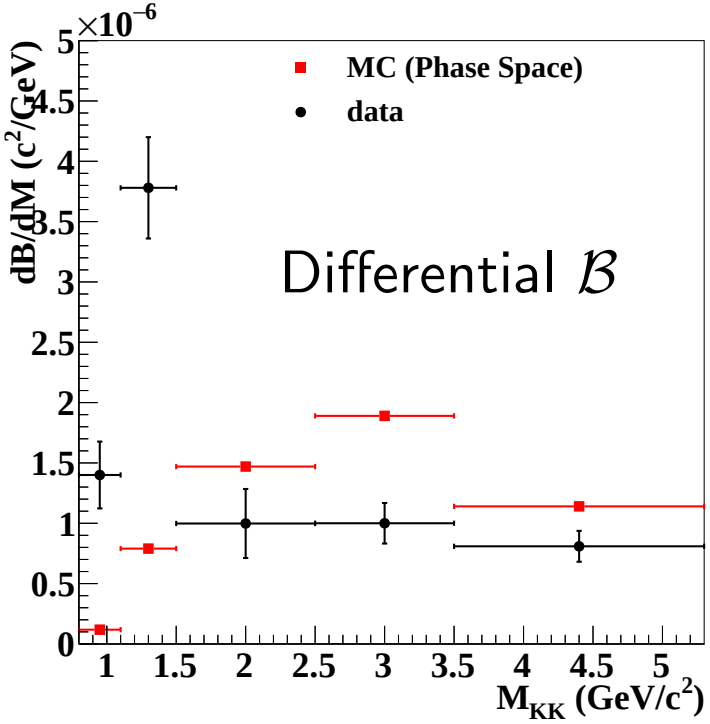
- Definition: $A_{CP} = \frac{\Gamma(\bar{B}^0 \to \pi^0\pi^0) - \Gamma(B^0 \to \pi^0\pi^0)}{\Gamma(\bar{B}^0 \to \pi^0\pi^0) + \Gamma(B^0 \to \pi^0\pi^0)}$.
- Flavor of B is determined by tagging the second B meson by its decay products. The final state is neutral $\Longrightarrow$ the vertex cannot be determined $\Longrightarrow$ additional dilution of B^0 and $\bar{B}^0$ due to mixing.
- The asymmetry is extracted from an unbinned maximum likelihood fit, parameter space: ΔE, $M_{\rm bc}$, classifier (Fisher discriminant) output, "flavor charge" (1 for B^0 and -1 for $\bar{B}^0$).
- Angle α/ϕ_2: from combination with other results ($B^0 \to \pi^+\pi^-$ and $B^+ \to \pi^+\pi^0$), method: see PRL **65**, 3381 (1990).

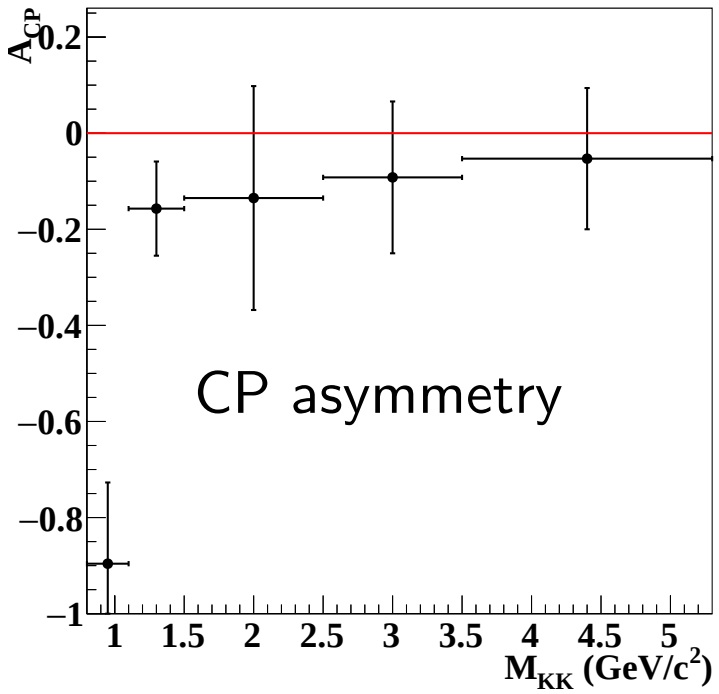


Results:
$A_{CP} = 0.14 \pm 0.36 \pm 0.10$,
$\mathcal{B}(B^0 \to \pi^0\pi^0) =$
$(1.31 \pm 0.19 \pm 0.19) \times 10^{-6}$,
ϕ_2 constraint: see figure (blue solid line; red dashed line is the old constraint from PRD **88**, 092003 (2013)).

CP asymmetry in $B^+ \to K^+K^-\pi^+$

PRD 96, 031101





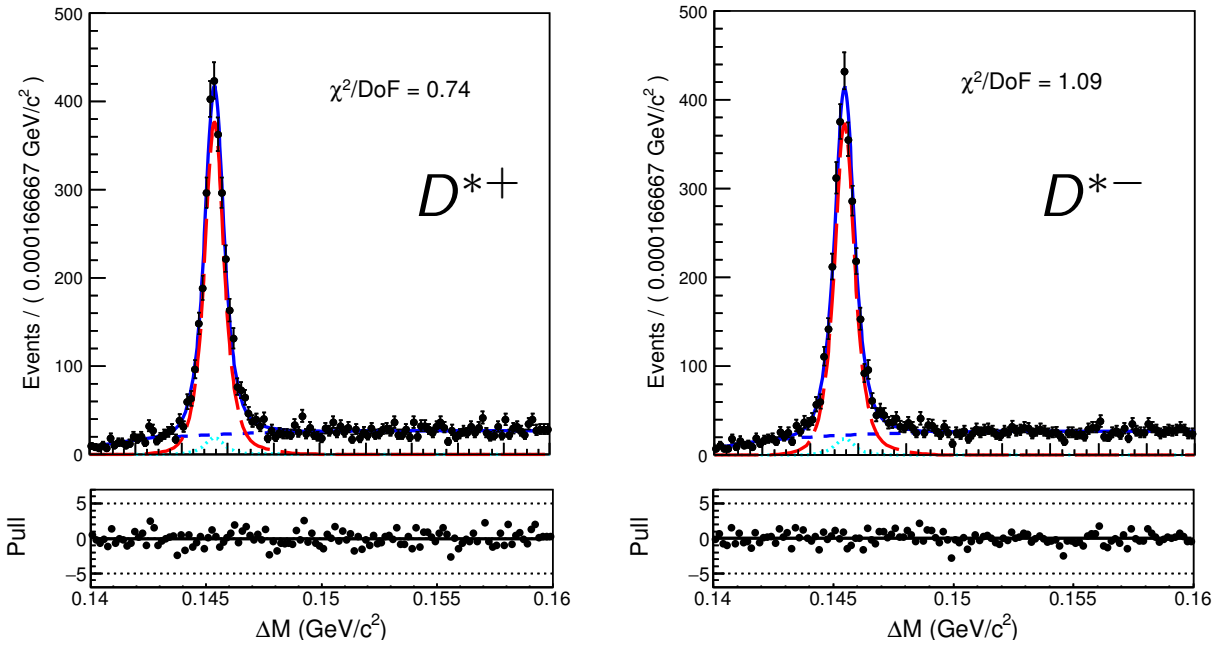
Results: $A_{CP} = -0.170 \pm 0.073 \pm 0.017$,
$\mathcal{B}(B^+ \to K^+K^-\pi^+) = (5.38 \pm 0.40 \pm 0.35) \times 10^{-6}$.

- Excess in K^+K^- low-mass spectrum.
- Large A_{CP} for $M_{K^+K^-} < 1.1$ GeV$/c^2$ (non-zero: 4.8σ). FSI?

This confirms results by BaBar [PRL **99**, 221801 (2007)] and LHCb [PRL **112**, 011801 (2014), PRD **90**, 112004 (2014)].

CP violation in $D^0 \to K_S^0 K_S^0$

PRL 119, 171801

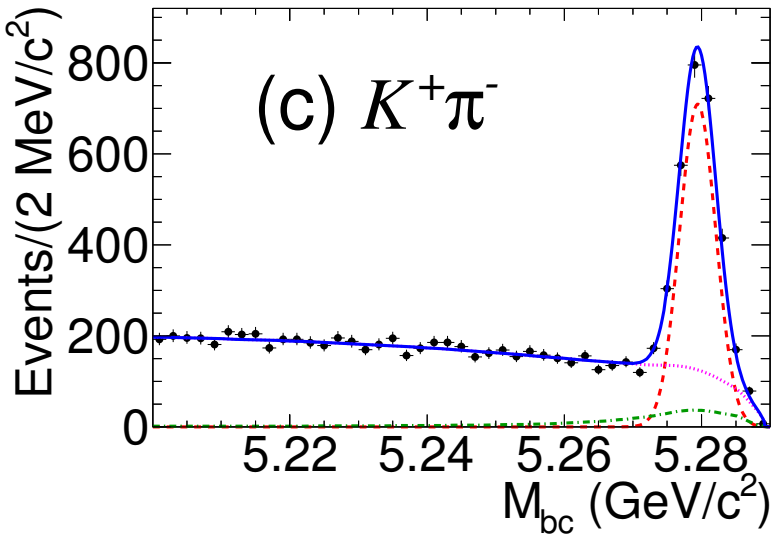


Data set: $M_{D^*} - M_D$

Simultaneous fit to $D^{*+} \to D^0(\to K_S^0 K_S^0)\pi^+$ and $D^{*-} \to \bar{D}^0(\to K_S^0 K_S^0)\pi^-$. Results:
$\mathcal{B}(D^0 \to K_S^0 K_S^0) = (1.321 \pm 0.023 \pm 0.036 \pm 0.030) \times 10^{-4}$,
$A_{CP} = (-0.02 \pm 1.53 \pm 0.02 \pm 0.17) \times 10^{-2}$.
Third uncertainties are that of $\mathcal{B}(D^0 \to K_S^0 \pi^0)$.
Theoretical prediction [PRD **92**, 054036 (2016)]: $A_{CP} < 1.1 \times 10^{-2}$.

CP asymmetry in $B \to K^*(892)\gamma$

PRL 119, 191802



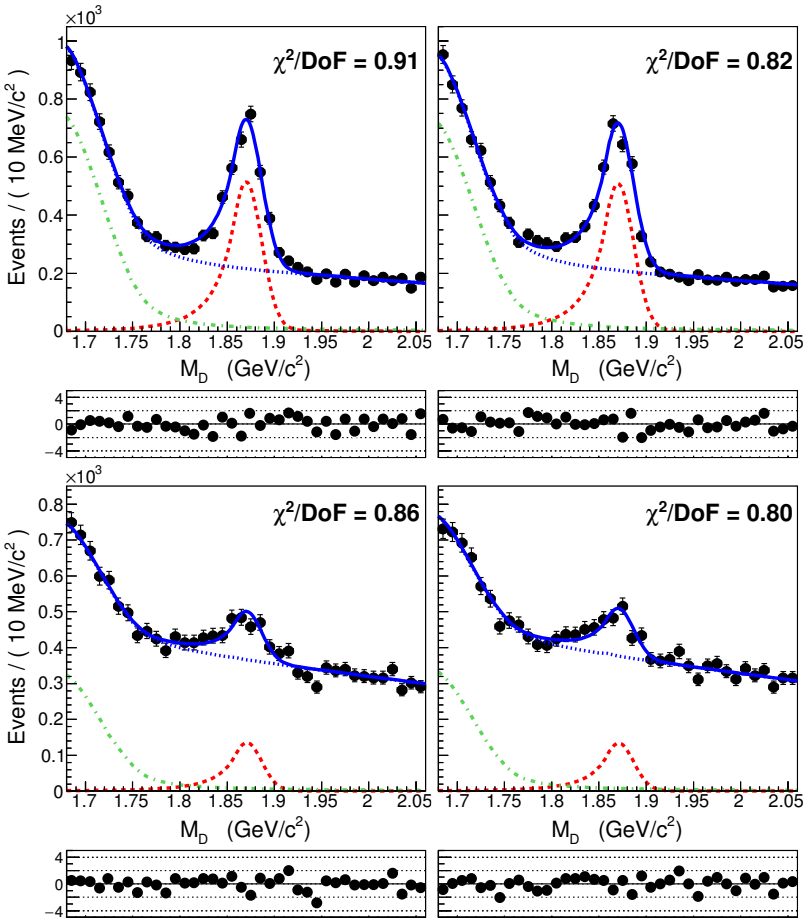
Reconstruction: $K^*(892)^0$: $K_S^0\pi^0$, $K^-\pi^+$; $K^*(892)^+$: $K^+\pi^0$, $K_S^0\pi^+$.
Mass:
$|M_{K\pi} - m_{K^*(892)}| < 75$ MeV$/c^2$, events with $M_{K\pi} < 2$ GeV$/c^2$ are used to calculate the non-$K^*(892)$ contribution.

Data for $B^+ \to K^*(892)(\to K^-\pi^+)\gamma$

- Isospin asymmetry (3.1σ evidence):
  $\Delta_{0+} = \frac{\Gamma(B^0\to K^{*0}\gamma)-\Gamma(B^+\to K^{*+}\gamma)}{\Gamma(B^0\to K^{*0}\gamma)-\Gamma(B^+\to K^{*+}\gamma)} = (6.2 \pm 1.5 \pm 0.6 \pm 1.2) \times 10^{-2}$.
  The fourth uncertainty is that of $\frac{\mathcal{B}(\Upsilon(4S)\to B^+B^-)}{\mathcal{B}(\Upsilon(4S)\to B^0\bar{B}^0)}$.
- Difference of CP asymmetries (consistent with 0):
  $\Delta A_{CP} = A_{CP}(B^+ \to K^{*+}\gamma) - A_{CP}(B^0 \to K^{*0}\gamma) =$
  $(2.4 \pm 2.8 \pm 0.5) \times 10^{-2}$

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).

Raw asymmetry: $A^{\pi\pi}_{\text{raw}} = A^{\pi\pi}_{CP} + A_{FB} + A^{\pi^\pm}_{\epsilon}$, A_{FB} - forward-backward, $A^{\pi^\pm}_{\epsilon}$ - pion detection asymmetry; a normalization channel $D^+ \to K^0_S\pi^+$ is used to correct for them.

Tagged (D^+ from $D^{*+} \to D^+\pi^0$) and untagged samples (no D^{*+} candidates are found) are used. The samples are fitted seprately. Results: $A^{\pi\pi}_{\text{raw}} - A^{K\pi}_{\text{raw}} = (0.81 \pm 1.97 \pm 0.19) \times 10^{-2}$ (tagged), $(4.02 \pm 1.61 \pm 0.32) \times 10^{-2}$ (untagged).

After that, the results are combined, and $A_{CP}(D^+ \to K^0_S\pi^+)$ is added. The final result is: $A_{CP} = (2.31 \pm 1.24 \pm 0.23) \times 10^{-2}$.

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

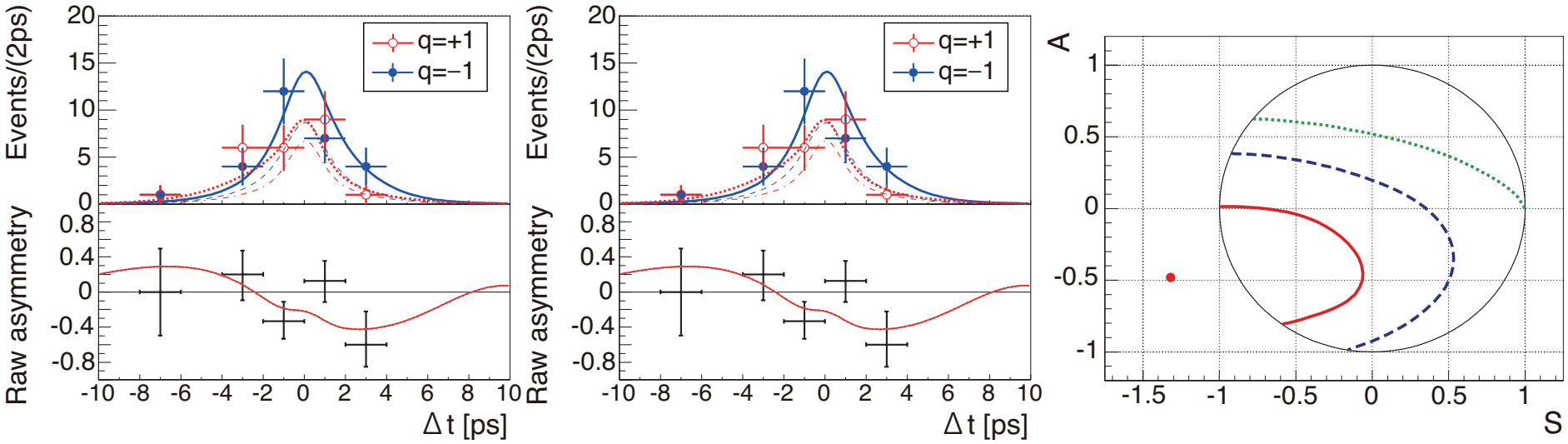
arXiv:1803.07774

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

$\mathcal{S}$ - 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):

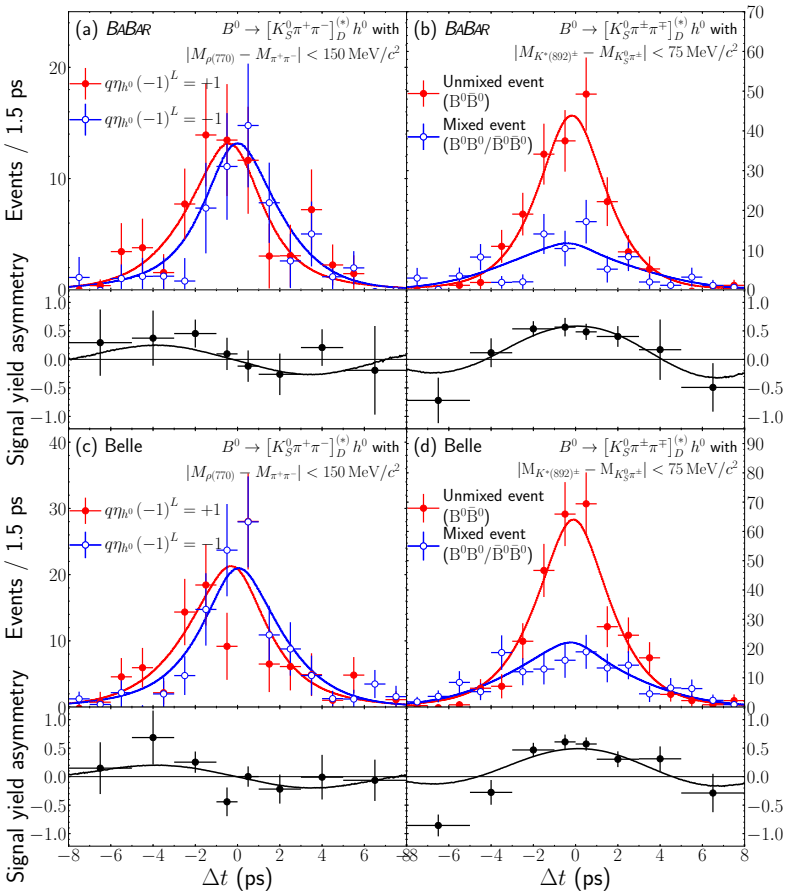
$\mathcal{S} \sim -(2-3)\times 10^{-2}$ (e.g. PRD **73**, 114022 (2006), PLB **642**, 478 (2006)).



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

arXiv:1804.06153

This analysis has been performed by Belle and BaBar.



$D^{*0} \to D^0\pi^0$, $D^0 \to K_S^0\pi^+\pi^-$, $h^0 = \pi^0, \eta, \omega$.
Decay modes (sufficient signal yield):
$B^0 \to D^0\pi^0, D^0\eta, D^0\omega, D^{*0}\pi^0, D^0\eta$.
The ampltitude of $D^0 \to K_S^0\pi^+\pi^-$ is determined by performing a Dalitz analysis of this decay for continuum D mesons. After that, a time-dependent Dalitz analysis is performed (D decay amplitude is fixed, only $\sin 2\beta$ and $\cos 2\beta$ are free). Results:
$\sin 2\beta = 0.80 \pm 0.14 \pm 0.06 \pm 0.03$,
$\cos 2\beta = 0.91 \pm 0.22 \pm 0.09 \pm 0.07$.
The fourth uncertainties are those of the $D^0 \to K_S^0\pi^+\pi^-$ amplitude model. Direct angle measurement (β is a fit parameter):
$\beta = (22.5 \pm 4.4 \pm 1.2 \pm 0.6)$ degrees.

The second minimum ($\beta' = \pi/2 - \beta$) is excluded at 7.3σ level.

Standard model tests

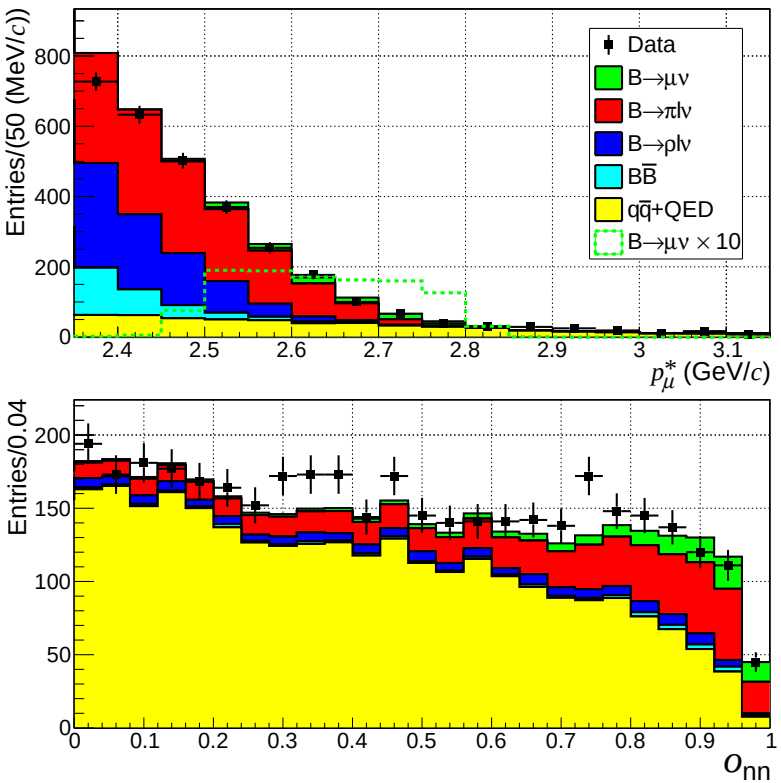
Search for $B^- \to \mu^- \bar{\nu}_\mu$

arXiv:1712.04123

SM expectation:

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

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

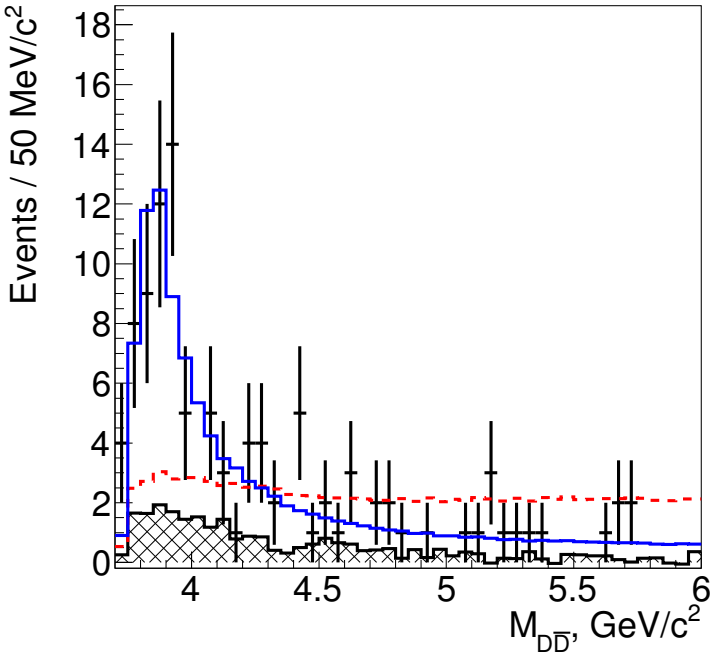


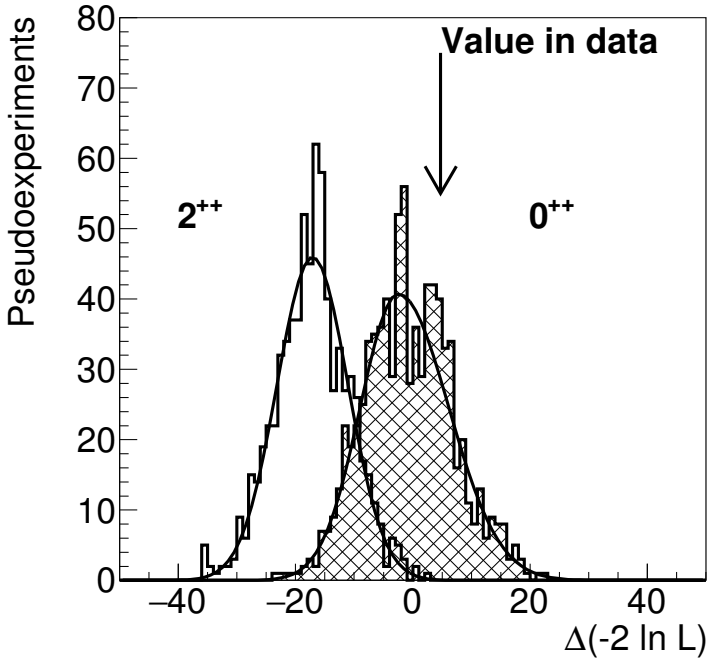
The result is $\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu) = (3.80 \pm 0.31) \times 10^{-7}$.
Initial selection uses accompanying B meson candidate ($M_{bc} > 5.1$ GeV$/c^2$, $-3 < \Delta E < 2$ GeV).
Number of signal events is determined by fitting the distribution of neural network output and muon momentum. Result: $\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu) = (6.46 \pm 2.22 \pm 1.60) \times 10^{-7}$
Significance: 2.4σ.

Spectroscopy

Alternative $\chi_{c0}(2P)$ in $e^+e^- \to J/\psi D\bar{D}$

PRD 95, 112003





Full 6-dimensional amplitude analysis.

A new state $X^*(3860)$ is observed, 6.5σ including systematic error.

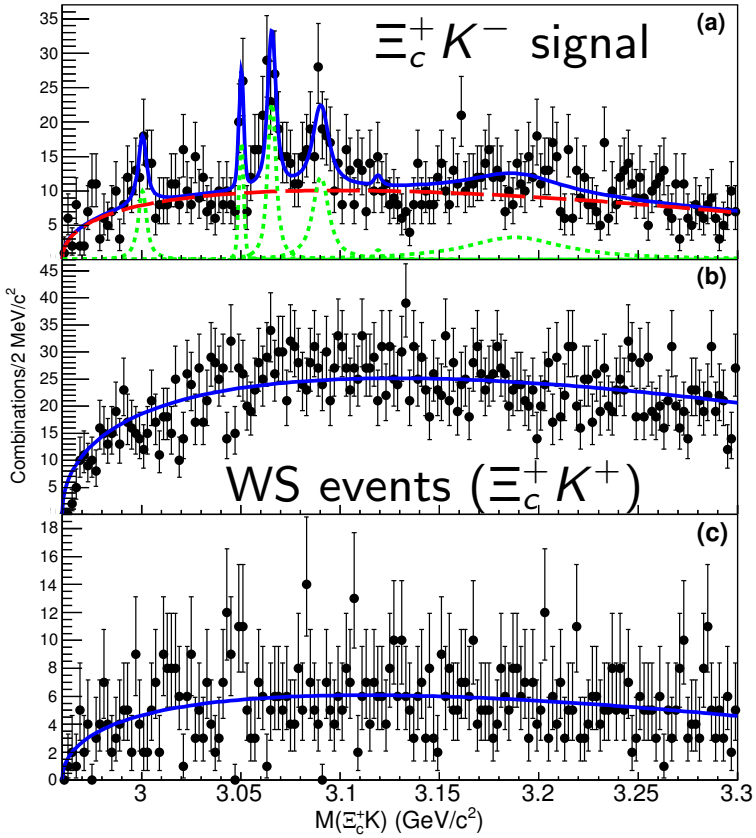
Parameters: $M = 3862^{+26}_{-32}{}^{+40}_{-13}$ MeV$/c^2$, $\Gamma = 201^{+154}_{-67}{}^{+88}_{-82}$ MeV.

$J^{PC} = 0^{++}$ is preferred over 2^{++} at 2.5σ.

Mass, mass difference with the $\chi_{c2}(2P)$, J^{PC}, decay mode, S-wave production $\implies$ the $X^*(3860)$ is a better $\chi_{c0}(2P)$ candidate than the $X(3915)$ that is observed in $B \to J/\psi\omega K$ and $\gamma\gamma \to J/\psi\omega$.

Excited Ω_c baryons

PRD 97, 051102



(c): Ξ_c^+ sidebands ($\Xi_c^+ K^-$)

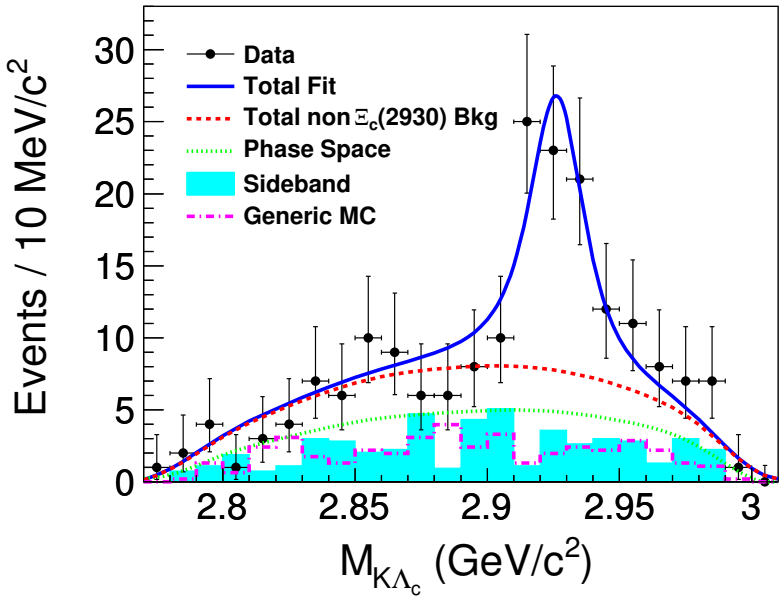
- LHCb observed 5 new narrow Ω_c states in PRL **118**, 182001 (2017).
- Belle searched for continuum production of these states in the same $\Xi_c^+ K^-$ decay mode.
- 4 of 5 states are observed, 2 of them with significance of $> 5\sigma$.
- The $\Omega_c(3119)$ is not observed as well as the $\Omega_c(3188)$ (possible wide state at higher mass from the same LHCb analysis).

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	$3000.7 \pm 1.0 \pm 0.2$	$3050.2 \pm 0.4 \pm 0.2$	$3064.9 \pm 0.6 \pm 0.2$	$3089.3 \pm 1.2 \pm 0.2$

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

EPJC 78, 252

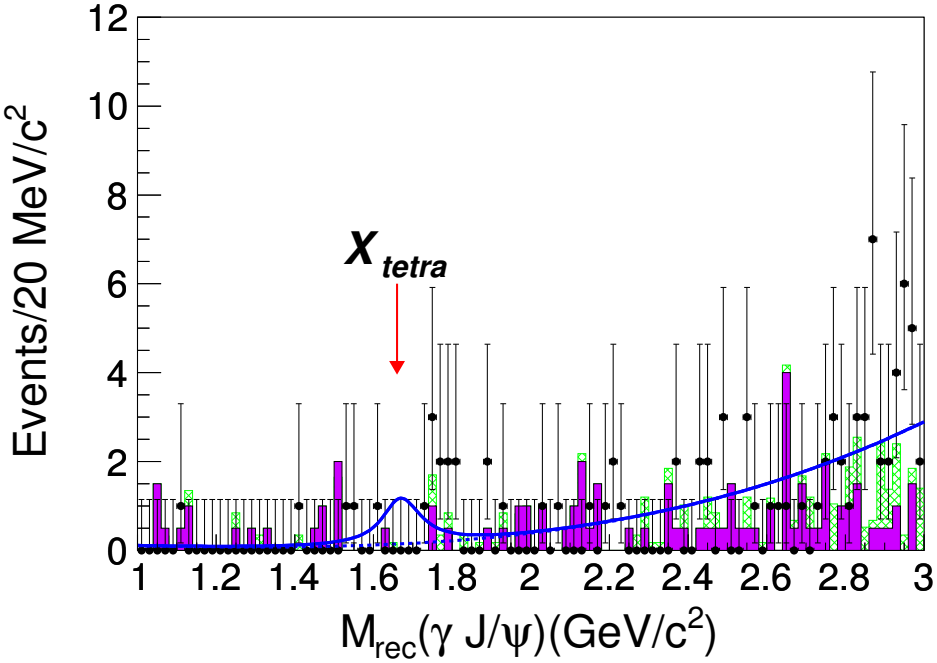


- The $\Xi_c(2930)^0$ has previously been reported by BaBar in PRD **77**, 031101 (2008) in the same process, but the significance has not been specified $\Longrightarrow$ its status is unclear.
- Unbinned simultaneous extended maximum likelihood fit to the signal and Λ_c sidebands. The fit is 1-dimensional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

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

Light tetraquarks in $\Upsilon(1S)$, $\Upsilon(2S)$ decays

PRD 96, 112002



Search for light tetraquarks in $\Upsilon(1S,2S) \to \chi_{c1} + X$, $\Upsilon(1S,2S) \to f_1(1285) + X$, $\chi_{b1} \to J/\psi + X$, $\chi_{b1} \to \omega X$ (the choice of the channels is such that the X state can have $J^{PC} = 0^{--}$) by fits of the recoil mass spectra.

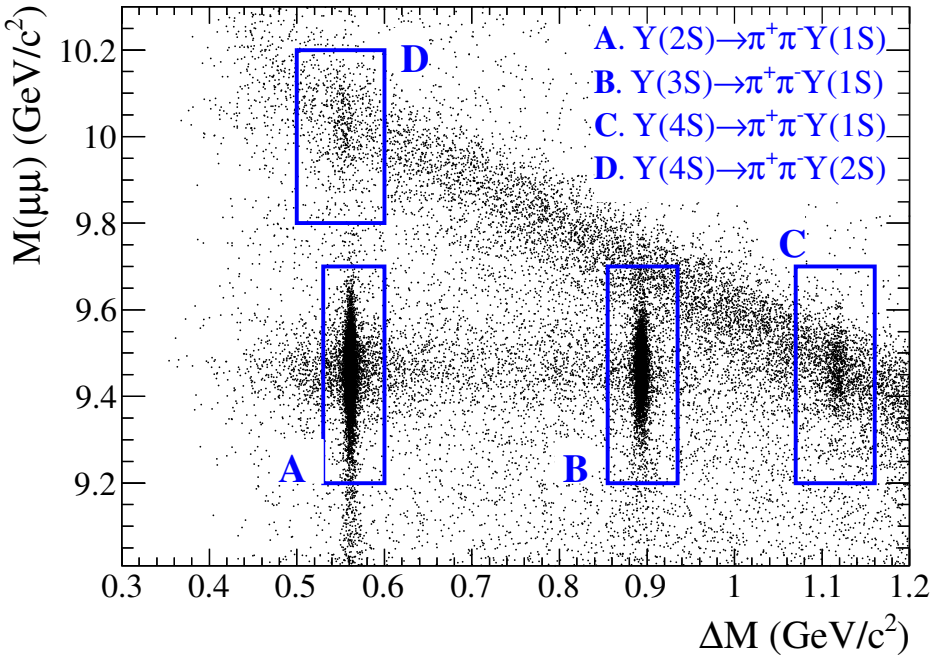
No signal is found, upper limits are calculated as functions of the X mass.
Inclusive branching fractions:

$\mathcal{B}(\Upsilon(1S) \to f_1(1285) + \cdots) = (4.6 \pm 2.8 \pm 1.3) \times 10^{-3}$,
$\mathcal{B}(\Upsilon(2S) \to f_1(1285) + \cdots) = (2.2 \pm 1.5 \pm 0.6) \times 10^{-3}$,
$\mathcal{B}(\chi_{b2} \to J/\psi + ...) = (1.50 \pm 0.34 \pm 0.22) \times 10^{-3}$,
$\mathcal{B}(\chi_{b1} \to \omega + ...) = (4.9 \pm 1.3 \pm 0.6) \times 10^{-2}$,
$\mathcal{B}(\chi_{b0}[\chi_{b1}]) \to J/\psi + ...) < 2.3[1.1] \times 10^{-3}$ (90% C.L.).

Transitions between quarkonium states

η and $\pi^+\pi^-$ transitions from $\Upsilon(4S)$

PRD 96, 052005



$\Upsilon(4S) \to \Upsilon(1S, 2S)\pi^+\pi^-$,
$\Upsilon(4S) \to \Upsilon(1S)\eta$ with
$\Upsilon(1S, 2S) \to \mu^+\mu^-$.
$\Delta M = M_{\mu^+\mu^-\pi^+\pi^-} - M_{\mu^+\mu^-}$

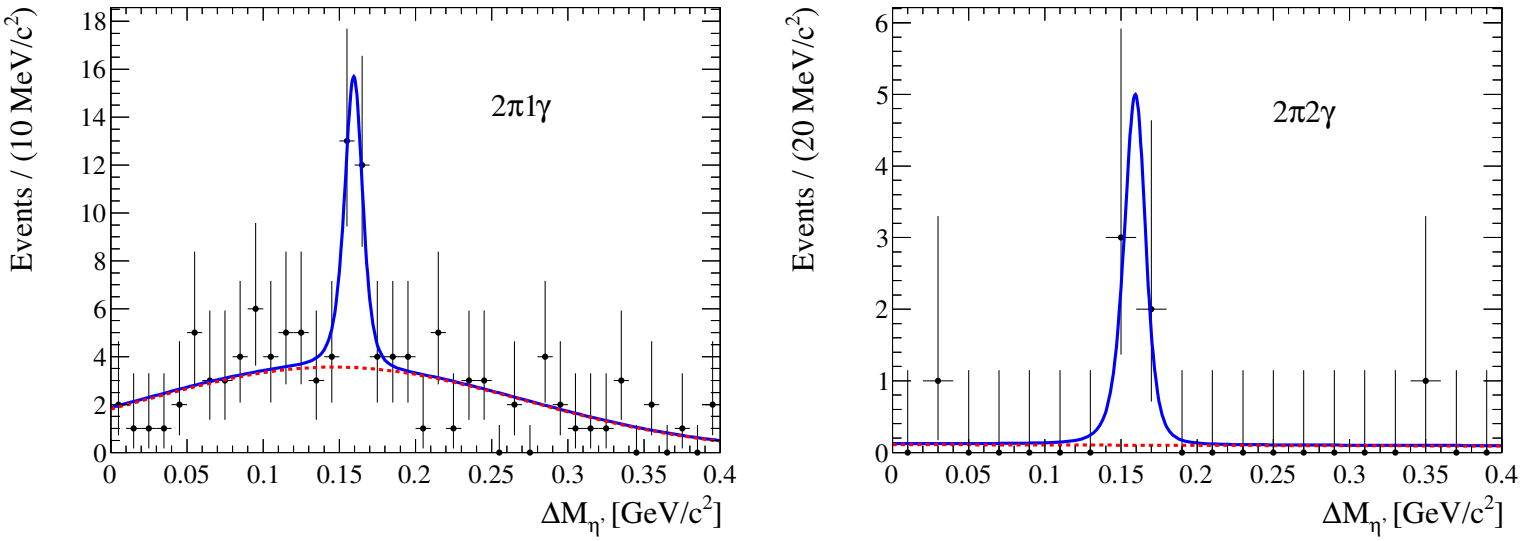
$\mathcal{B}(\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-) = (8.2 \pm 0.5 \pm 0.4) \times 10^{-5}$,
$\mathcal{B}(\Upsilon(4S) \to \Upsilon(2S)\pi^+\pi^-) = (7.9 \pm 1.0 \pm 0.4) \times 10^{-5}$,
$\mathcal{B}(\Upsilon(4S) \to \Upsilon(1S)\eta) = (1.70 \pm 0.23 \pm 0.08) \times 10^{-4}$.

Transition from $\Upsilon(4S)$ via η is not suppressed despite of the b quark spin flip. Confirms similar BaBar result (PRD **78**, 112002).

ISR cross sections at $\Upsilon(4S)$: $\sigma_{\rm ISR}(\Upsilon(2S)) = (17.36 \pm 0.19 \pm 0.69)$ pb, $\sigma_{\rm ISR}(\Upsilon(3S)) = (28.9 \pm 0.5 \pm 1.3)$ pb.

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

arXiv:1803.10303

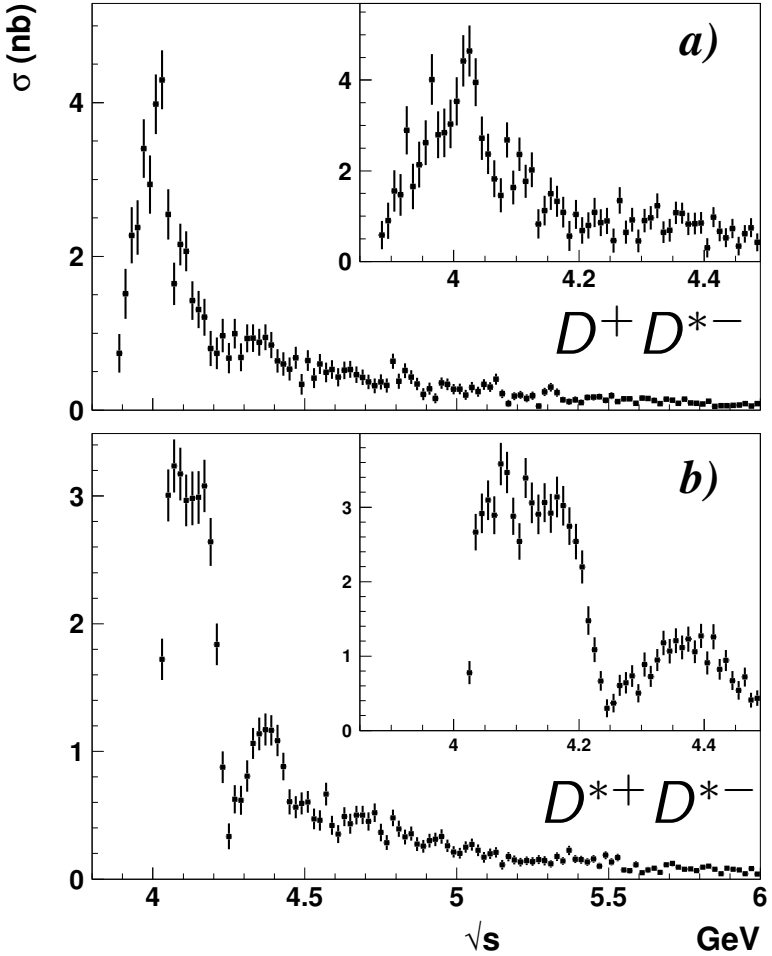


- Reconstruction: $\eta' \to \rho^0\gamma,\ \pi^+\pi^-\eta(\to\gamma\gamma)$; $\Upsilon(1S) \to \mu^+\mu^-$.
- η: full reconstruction (left figure) or 1 photon only (right figure).
- Background PDF: linear (full reconstruction), Gaussian (partial reconstruction).
- Significance (combined by simultaneous 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 $e^+e^- \to D^{(*)\pm}D^{(*)\mp}\gamma_{\rm ISR}$ PRD 97, 012002

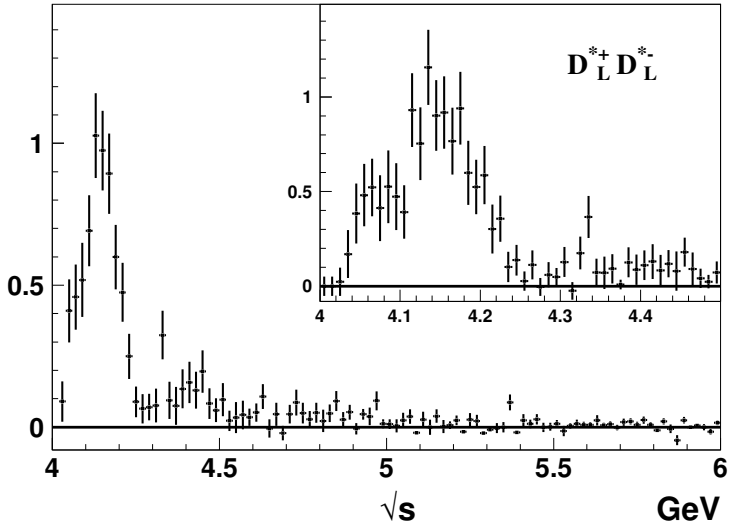
Cross sections:



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

Distributions of the D^* helicity angles are 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

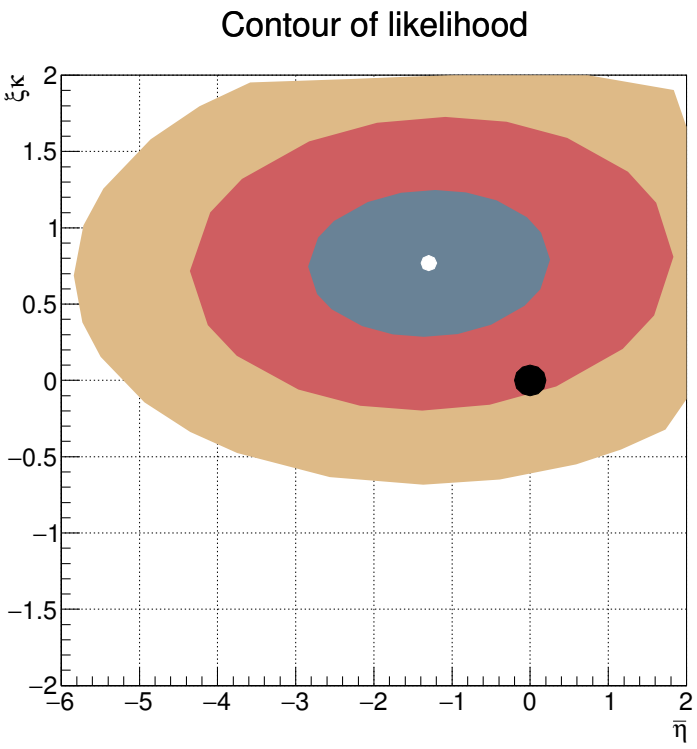
Michel parameters $\bar{\eta}$ and $\xi\kappa$

PTEP 2018, 023C01

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

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

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).

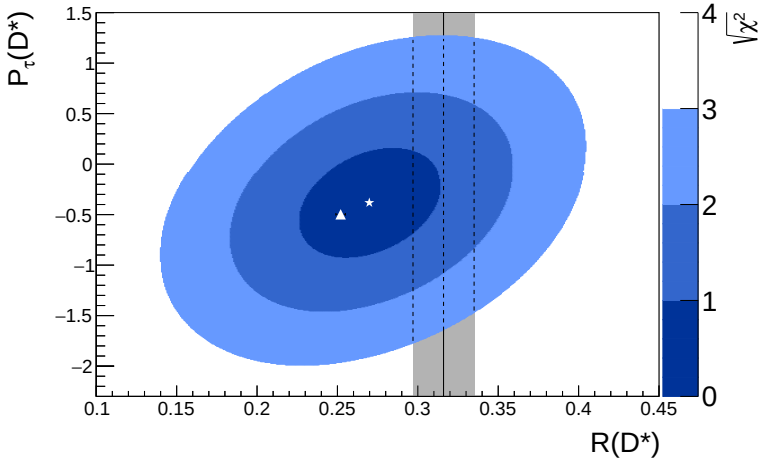
τ polarization in $B^- \to D^* \tau^- \bar{\nu}_\tau$

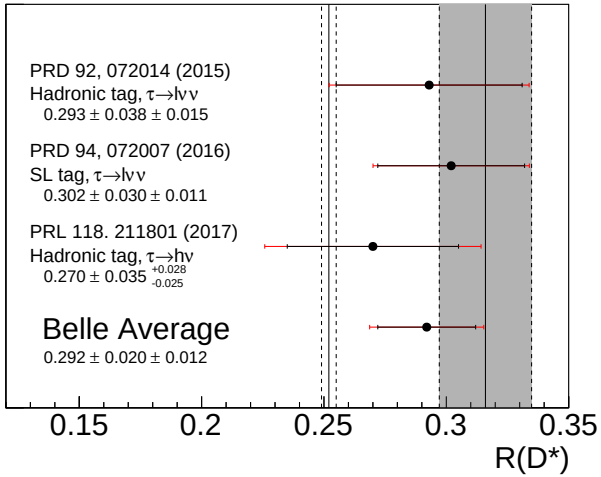
PRD 97, 012004

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, $\ell = e + \mu$ average; for LHCb, $\ell = \mu$.
- $P_\tau(D^*) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$,
  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.

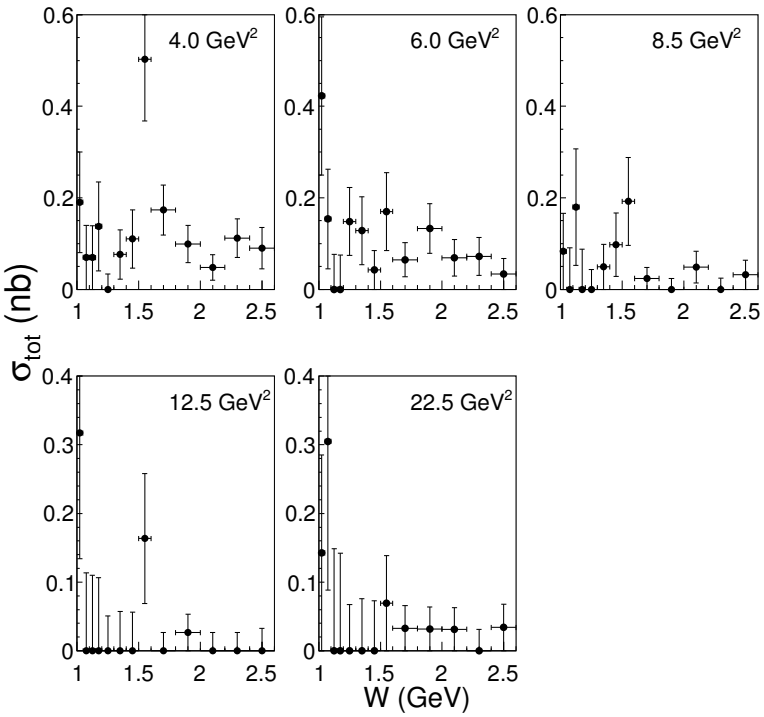
$\gamma\gamma$ processes

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

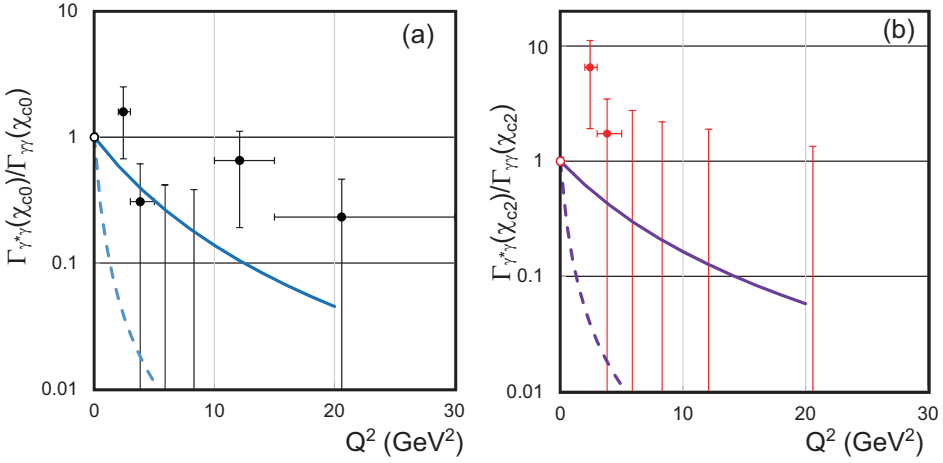
PRD 97, 052003

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 $Q^2 = -m^2_{\gamma^*}$.

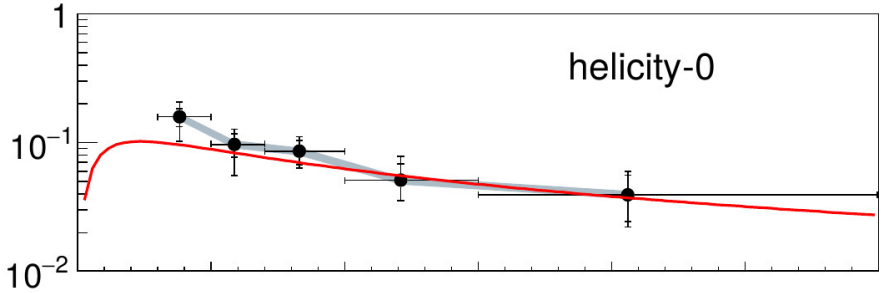
Total cross sections in bins of Q^2 (bin center is specified on the histograms).



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



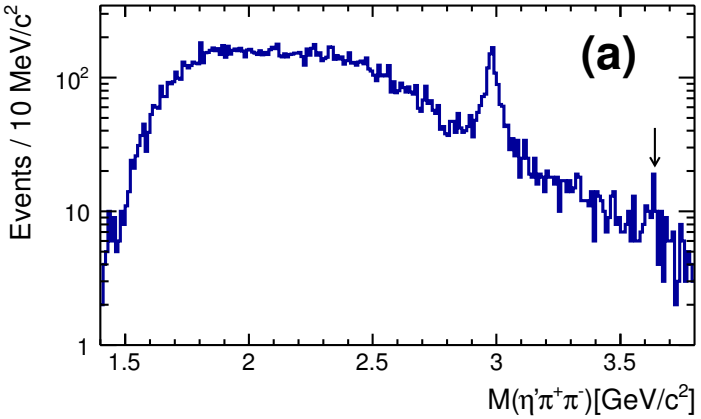
Also, transition form factor of the $f_2'(1525)$ is measured for all helicity components (0, 1, 2).

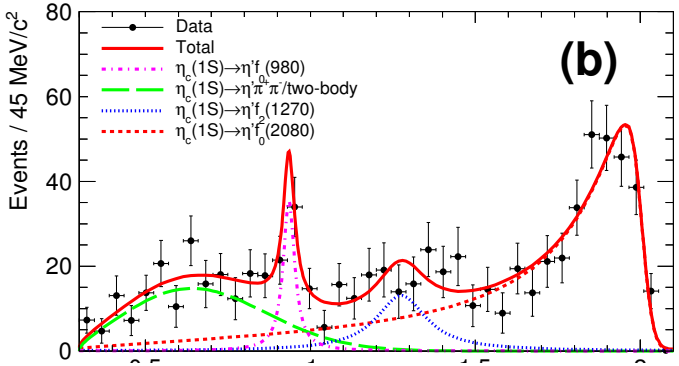


$\gamma\gamma \to \eta_c(1S, 2S) \to \eta'\pi^+\pi^-$

arXiv:1805.03044

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



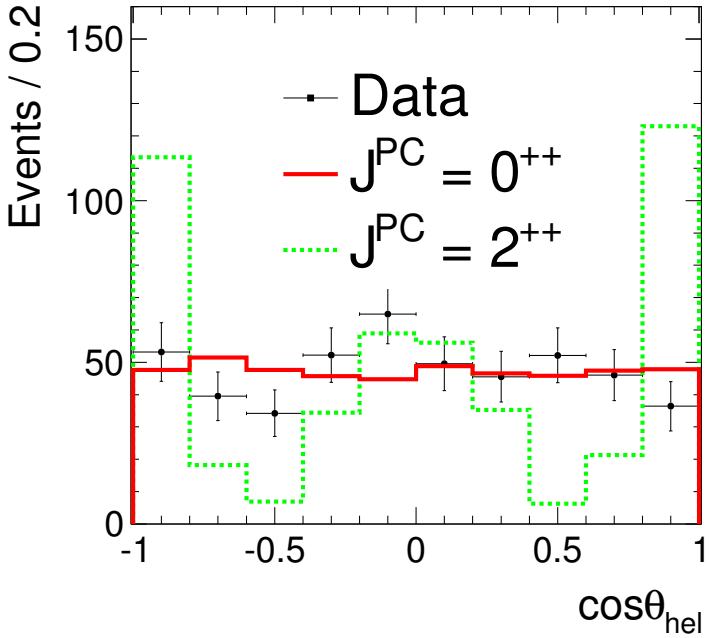


Observed:

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

- $B^+ \to \eta \ell^+ \nu_l$, $B^+ \to \eta' \ell^+ \nu_l$: PRD **96**, 091102 (2017)
- $\Lambda_c^+ \to p\phi\pi^0$, $\Lambda_c^+ \to pK^-\pi^+\pi^0$: PRD **96**, 051102 (2017)
- $B^+ \to X_{c\bar{c}} K^+$, $B^+ \to \bar{D}^{(*)0}\pi^+$: PRD **97**, 012005 (2018)
- Ω_c 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
- $B \to D^{(*)}\pi\ell\nu$: arXiv:1803.06444

Cross sections:

- $e^+e^- \to$ hyperons, charmed baryons: PRD **97**, 072005 (2018)
- $e^+e^- \to hhX$ $(h = \pi, K)$: PRD **96**, 032005 (2017)
- $e^+e^- \to \eta\Upsilon$, $e^+e^- \to \eta h_b$: arXiv:1803.03225

Thank you for attention!