Recent results on hot topics from

Menu card

- Charm mixing in $D \to K\pi$ decays
- Mixing and CPV in $D \to K^0_S\pi^+\pi^-$
- Looking for CPV in $D^0 \to \pi^0\pi^0$
- Lepton $A_{\rm FB}$ in $B \to X_S\ell^+\ell^-$ decays
- BF and A_{CP} in $B^0 \to \eta' K^\star(892)^0$
- Amplitude analysis of $B \to J/\psi K\pi$

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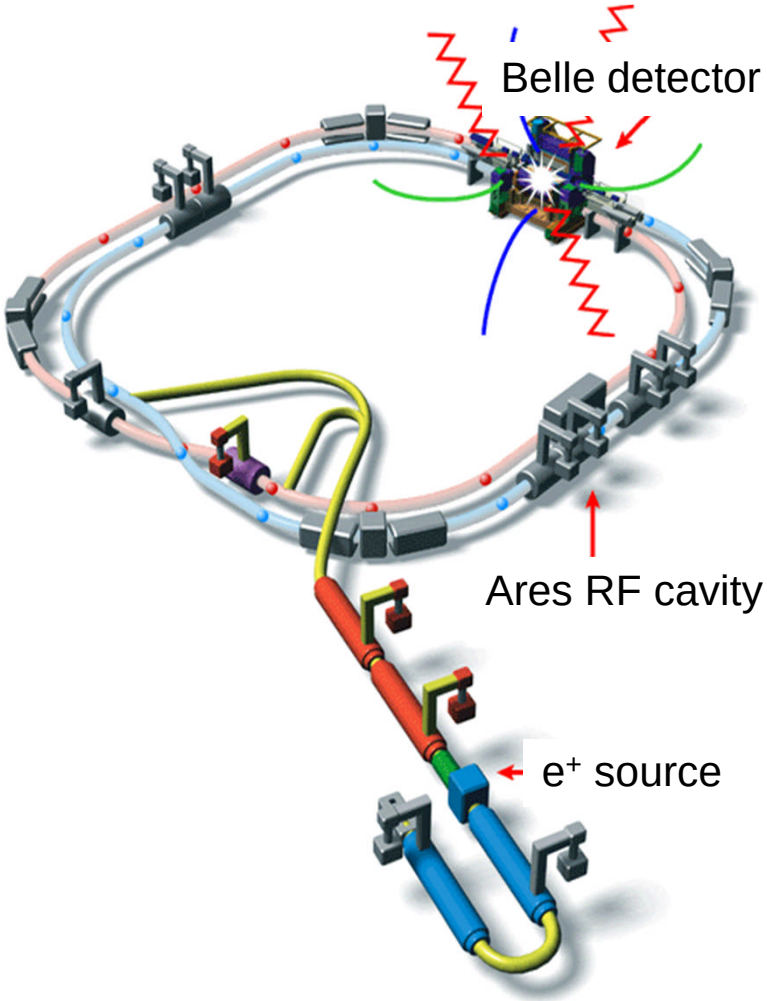
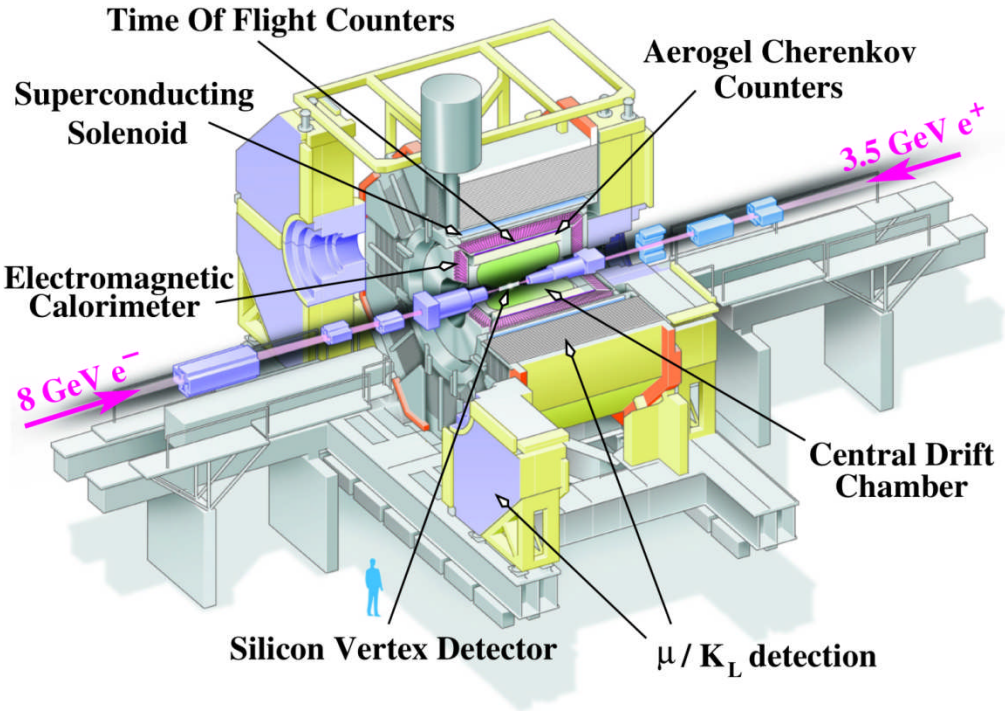
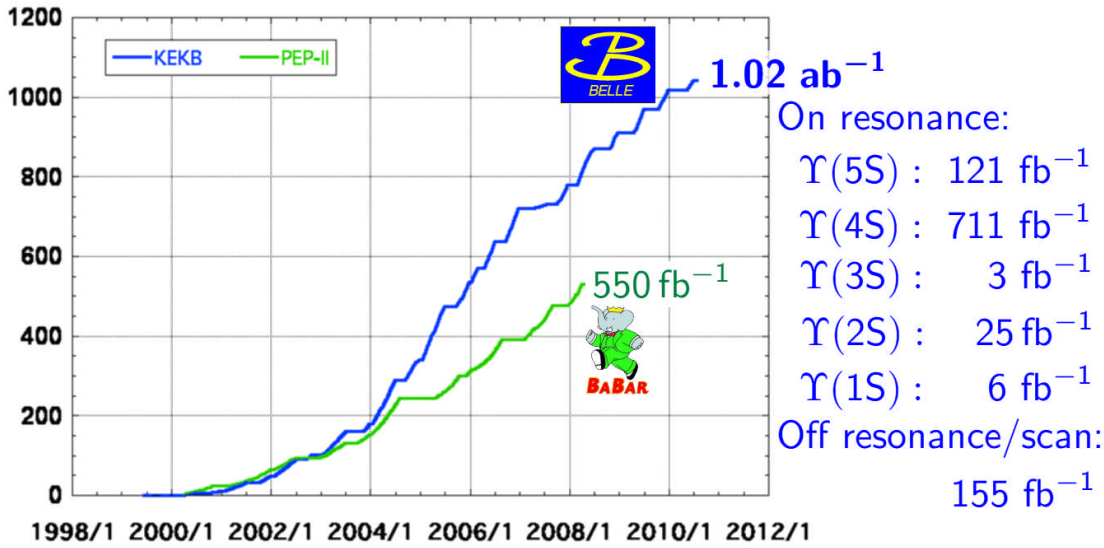
Fifth Workshop on Theory, Phenomenology and Experiments in Flavour Physics - Capri 2014

23-25 May 2014 *Villa Orlandi, Anacapri, Capri Island, Italy*
Europe/Rome timezone

Experiment and dataset







- Multitasking magnetic spectrometer that operated at KEKB asymmetric-energy e^+e^- collider in Japan
- Recorded the data at various $\Upsilon(nS)$ resonances till June 2010

$D^0\overline{D}^0$ mixing in $D \to K\pi$ decays

- Measure the time-dependent ratio of the $D^0 \to K^+\pi^-$ (wrong-sign) to $D^0 \to K^-\pi^+$ (right-sign) decay rates
- Tag RS and WS decays through the decay chain $D^{*+} \to D^0\left(K^{\mp}\pi^{\pm}\right)\pi_s^+$ by comparing charge of the pion from the D decay with that from the D^* decay

"Wrong-sign" $D^{*+} \to D^0\pi^+,\ D^0 \to K^+\pi^-$

interference: mixing, double Cabibbo-suppression (DCS)

$$R(\tilde{t}/\tau) \equiv \frac{\Gamma_{\rm WS}(\tilde{t}/\tau)}{\Gamma_{\rm RS}(\tilde{t}/\tau)} \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

Mixing
$$\begin{cases} x \equiv \Delta m/\Gamma & x' \equiv x\cos\delta + y\sin\delta \\ y \equiv \Delta\Gamma/2\Gamma & y' \equiv y\cos\delta - x\sin\delta \end{cases}$$

δ = relative phase

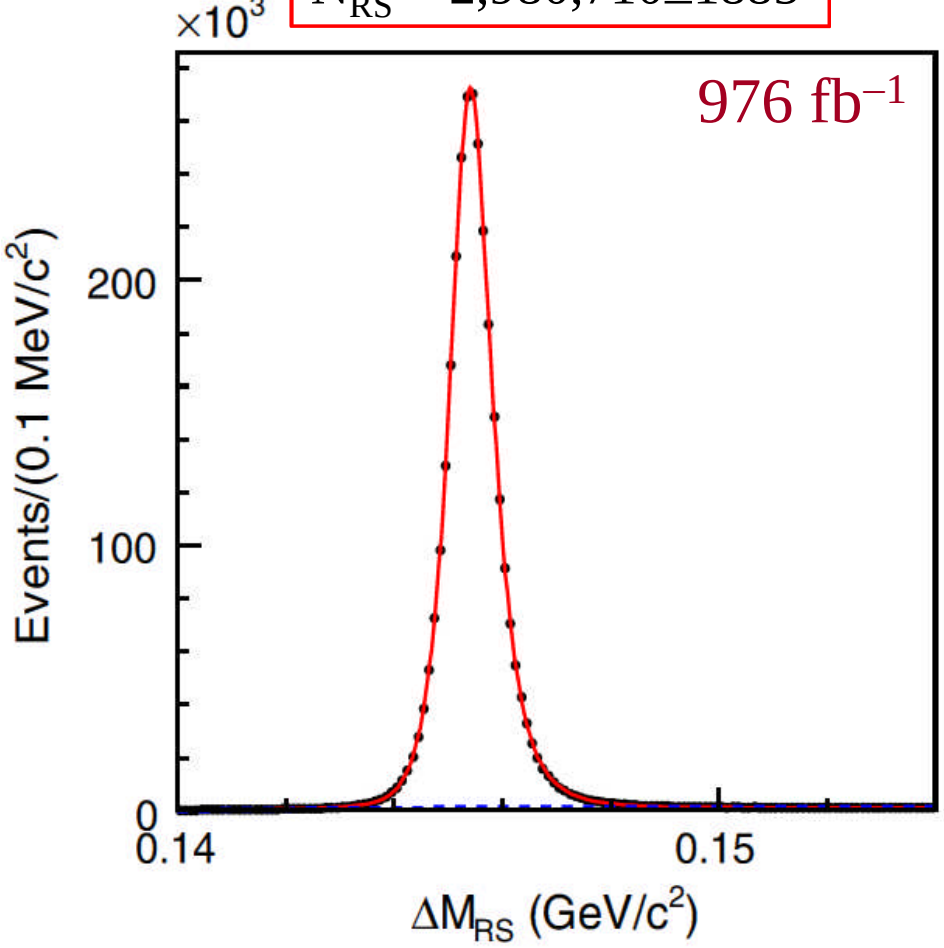
DCS $R_D \equiv \Delta\Gamma(DCS)/\Delta\Gamma(CF)$

- Take the resolution effect into account in the measurement of mean decay time of the tagged D's

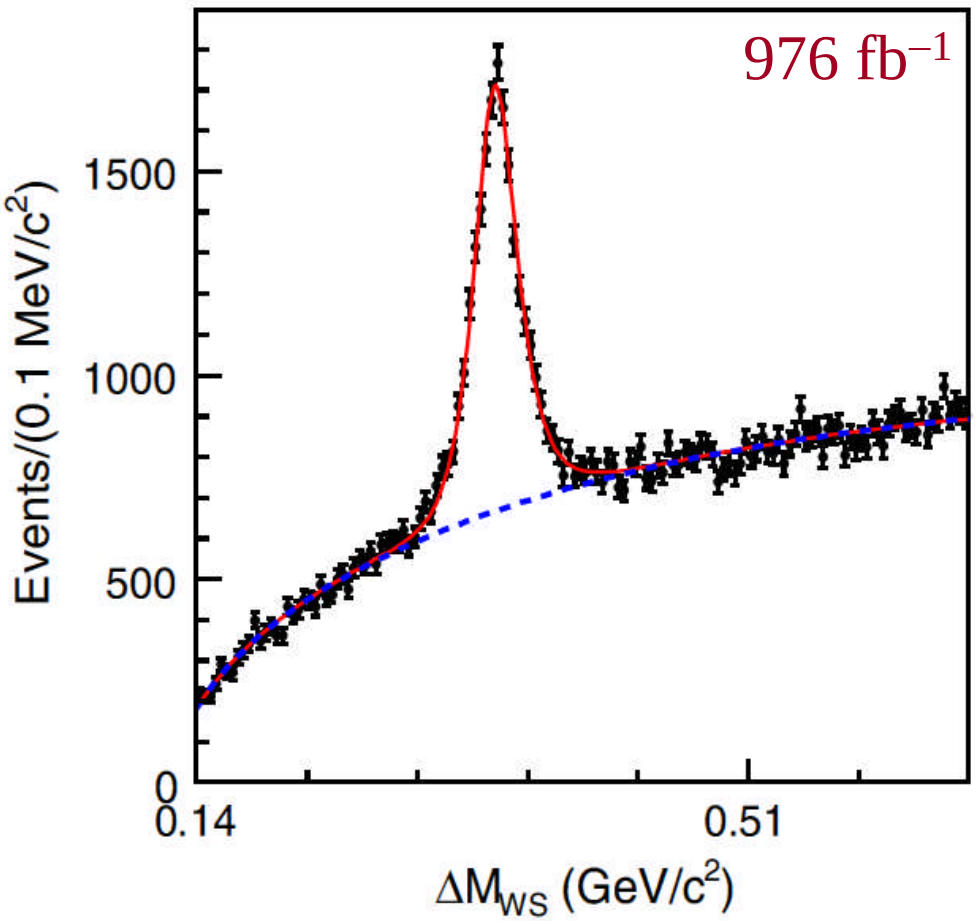
Event yields in RS and WS decays

PRL 112, 111801 (2014)

N_{RS} = 2,980,710±1885



N_{WS} = 11,478±177



- Signal: A sum of a Gaussian and a Johnson distribution of common mean

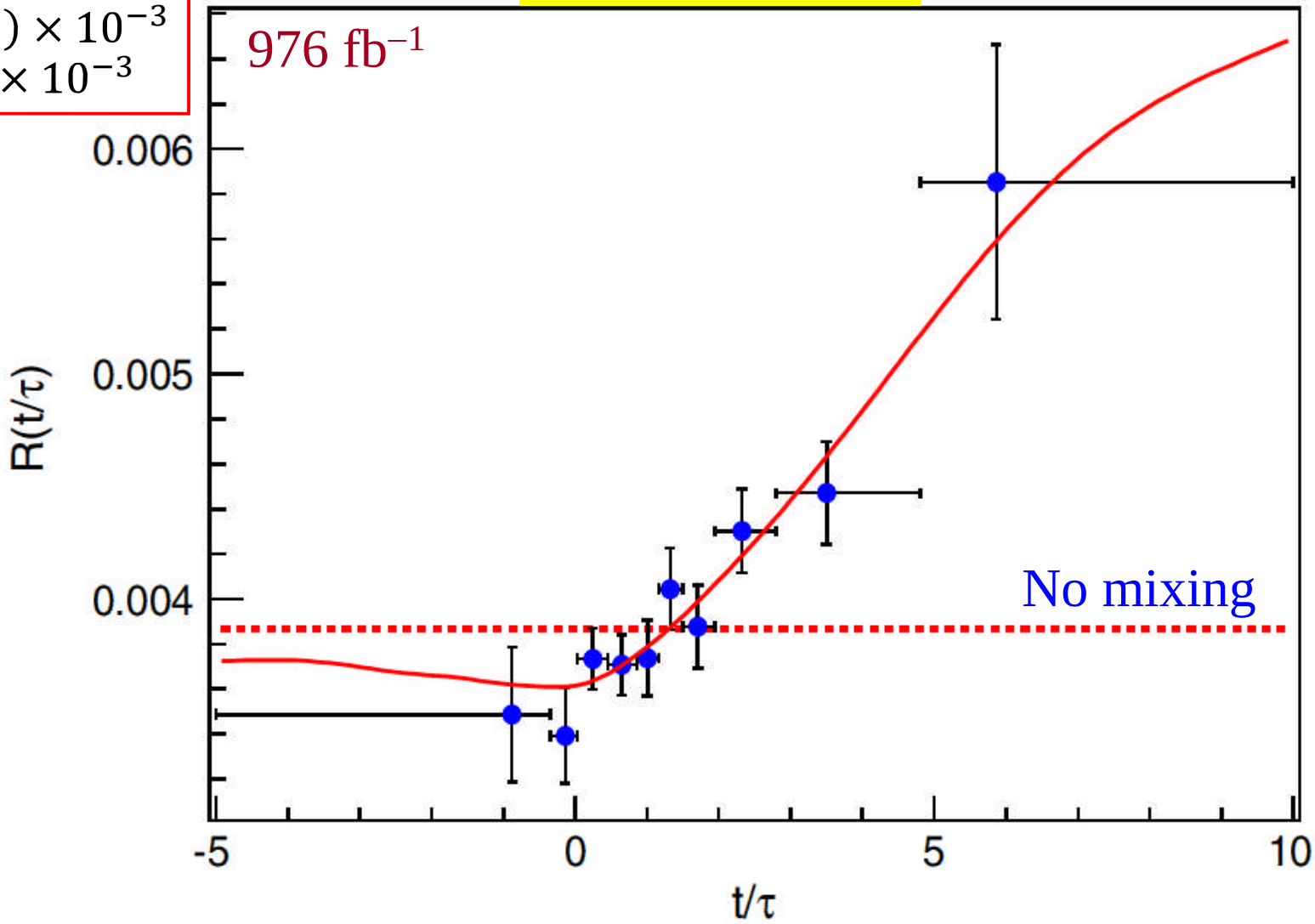
Biometrika 36, 149 (1949)

- Background: An empirical threshold function $(x - m_\pi)^\alpha e^{-\beta(x-m_\pi)}$

Observation of D^0-$\bar{D}^0$ mixing

$$R_D = (3.53 \pm 0.13) \times 10^{-3}$$
$$x'^2 = (0.09 \pm 0.22) \times 10^{-3}$$
$$y' = (4.6 \pm 3.4) \times 10^{-3}$$

PRL 112, 111801 (2014)



- No mixing hypothesis is ruled out at the 5.1 standard deviation (σ) level
- Constitutes the first observation of D^0-$\bar{D}^0$ mixing in e^+e^- collisions

CP violation in charm decays

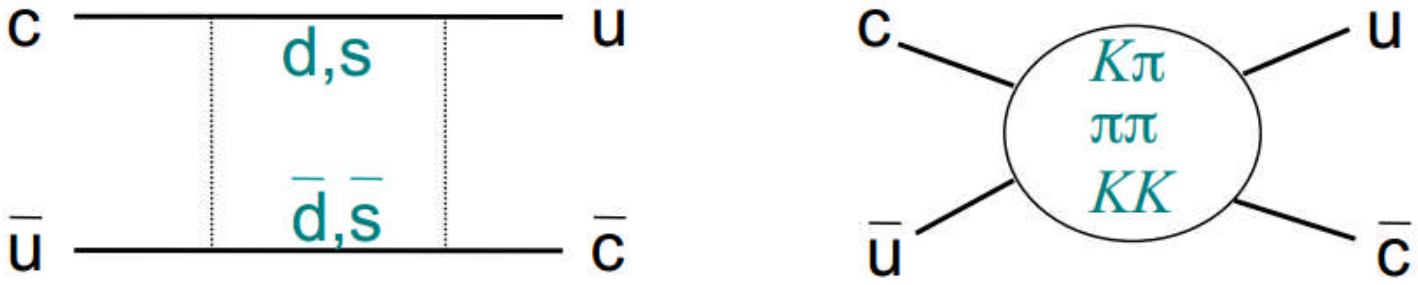
- Provides an interesting test bed for new physics as the standard model (SM) predicts a very small asymmetry, owing to
  - Large GIM/CKM suppression
  - Lack of a large hierarchy in the down-type quark masses

- Typical SM value of the order of 10^{-3} ⇨ most promising candidates to study are singly Cabibbo-suppressed (SCS) decays

Grossman, Kagan and Nir
PRD 75, 036008 (2007)

- While talking about a percentage effect, we need a good control on the SM predictions, something that is in general lacking in this sector due to long-distance effects

An example of "short vs. long"



- Further, with D^0-$\bar{D}^0$ mixing being firmly established, what about CP violation (CPV) in the mixing or due to interference between mixing and decay?

Current expectation for direct CP violation

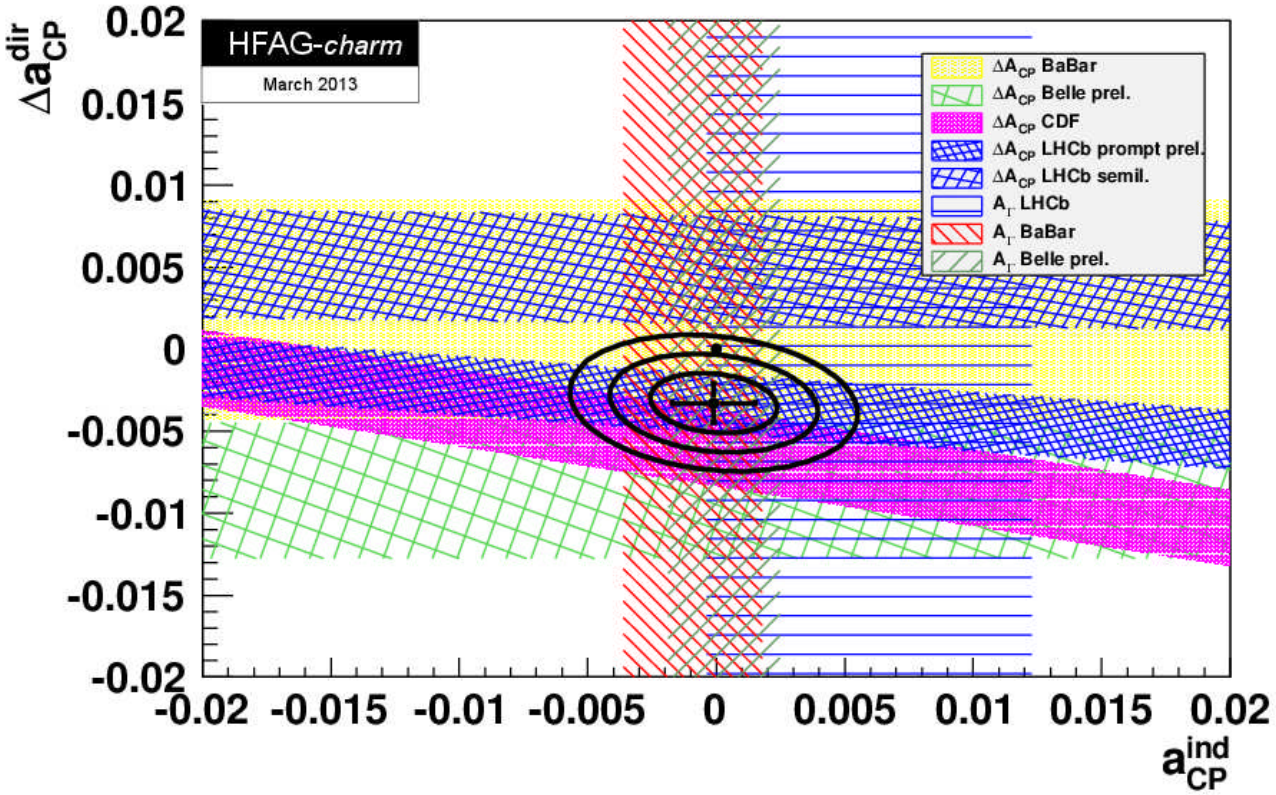
$$A_\Gamma^f \equiv \frac{\tau(\overline{D}^0 \to f) - \tau(D^0 \to f)}{\tau(\overline{D}^0 \to f) + \tau(D^0 \to f)} \approx -a_{CP}^{\rm ind}$$

$$A_{CP}^f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

JPG 39, 045005 (2012)

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = \left(1 + y\cos\phi\frac{\langle t\rangle}{\tau}\right)\Delta a_{CP}^{\rm dir} + \left(\frac{\Delta\langle t\rangle}{\tau}\right)a_{CP}^{\rm ind}$$

$x \equiv \Delta m/\Gamma$, $y \equiv \Delta\Gamma/\Gamma$ and $\phi \equiv \arg(q/p)$, where Δm and $\Delta\Gamma$ are the mass and width difference between two D mass eigenstates, Γ is their average width and (p, q) are the two complex coefficients that relate mass to flavor eigenstates



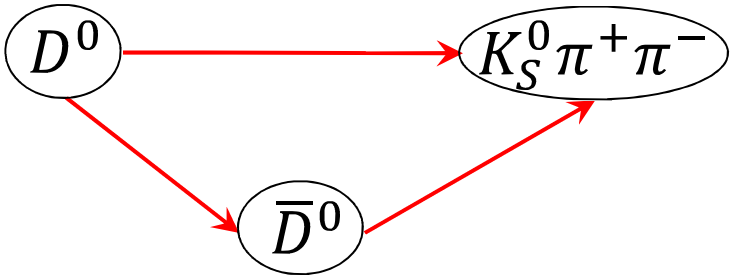
$$a_{CP}^{\rm ind} = (+0.015 \pm 0.052)\%$$

$$\Delta a_{CP}^{\rm dir} = (-0.333 \pm 0.120)\%$$

- No CPV (0,0) point: $\Delta\chi^2 = 7.8$, CL = 2% (excluded at 2σ)

Study of mixing and CPV in $D^0 \to K_S^0\pi^+\pi^-$

- Determine D^0-$\bar{D}^0$ mixing and CPV effects by studying the time-dependent decay rate of self-conjugated $D^0 \to K_S^0\pi^+\pi^-$ decays



- Expressing A_f ($\bar{A}_f$), amplitude of the D^0 ($\bar{D}^0$) decay into $f \equiv K_S^0\pi^+\pi^-$, as a function of the Dalitz plot variables ($m^2_{K_S^0\pi^+}, m^2_{K_S^0\pi^-}$), the corresponding time-dependent decay rates are:

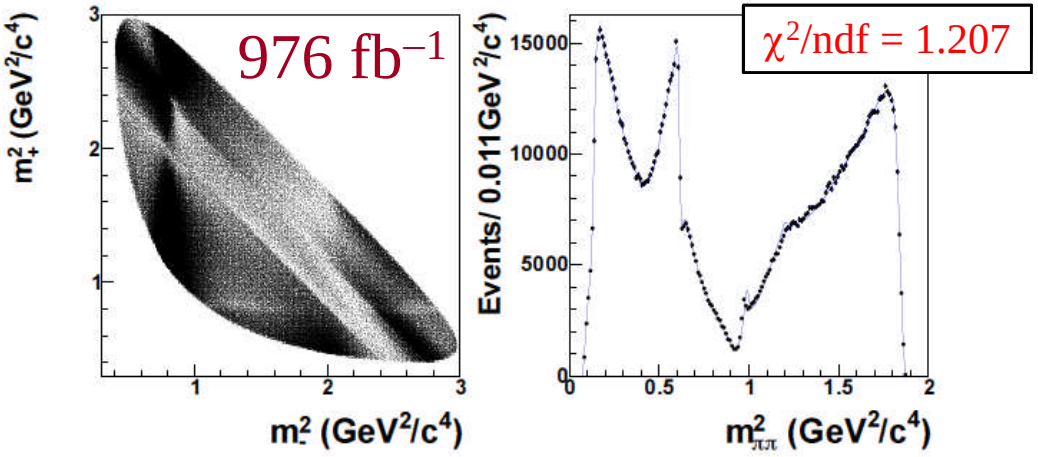
$$|\mathcal{M}(f,t)|^2 = \frac{e^{-\Gamma t}}{2}\{(|\mathcal{A}_f|^2 + |\tfrac{q}{p}|^2|\mathcal{A}_{\bar{f}}|^2)\cosh(\Gamma y t) + (|\mathcal{A}_f|^2 - |\tfrac{q}{p}|^2|\mathcal{A}_{\bar{f}}|^2)\cos(\Gamma x t) + 2\Re(\tfrac{q}{p}\mathcal{A}_{\bar{f}}\mathcal{A}_f{}^*)\sinh(\Gamma y t) - 2\Im(\tfrac{q}{p}\mathcal{A}_{\bar{f}}\mathcal{A}_f{}^*)\sin(\Gamma x t)\}$$

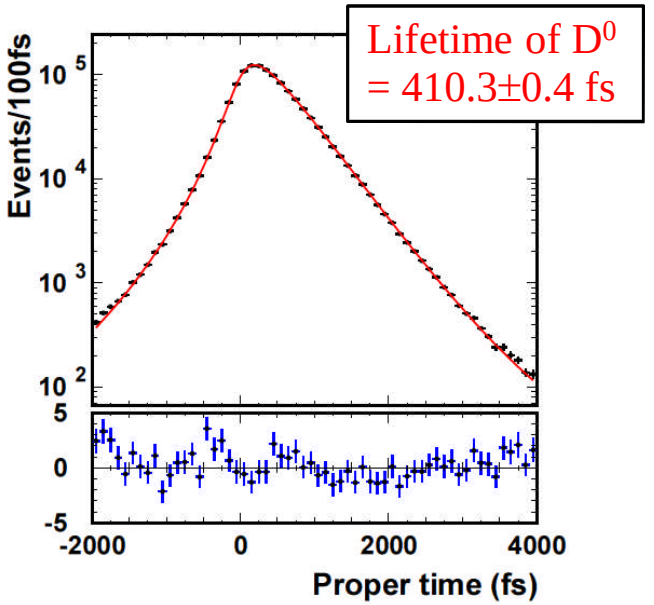
$$|\overline{\mathcal{M}}(f,t)|^2 = \frac{e^{-\Gamma t}}{2}\{(|\mathcal{A}_{\bar{f}}|^2 + |\tfrac{p}{q}|^2|\mathcal{A}_f|^2)\cosh(\Gamma y t) + (|\mathcal{A}_{\bar{f}}|^2 - |\tfrac{p}{q}|^2|\mathcal{A}_f|^2)\cos(\Gamma x t) + 2\Re(\tfrac{p}{q}\mathcal{A}_f\mathcal{A}_{\bar{f}}{}^*)\sinh(\Gamma y t) - 2\Im(\tfrac{p}{q}\mathcal{A}_f\mathcal{A}_{\bar{f}}{}^*)\sin(\Gamma x t)\}$$

- Γ is the mean decay width of the two mass eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$
- x and y are the D^0-$\bar{D}^0$ mixing parameters, defined earlier
- p and q are complex coefficients that satisfy $|p|^2 + |q|^2 = 1$ in case of no CP violation, whereas possible CPV can lead to ${}^q/_p \neq 1$

Mixing and CPV results from $D^0 \to K^0_S\pi^+\pi^-$

- Time-dependent fit to the Dalitz plot (shown below together with one of its projections)





Fit type	Parameter	Fit result
No CPV	$x(\%)$	$0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06}$
CPV	$x(\%)$	$0.56 \pm 0.19^{+0.04+0.06}_{-0.08-0.08}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.07}$
	$\lvert q/p\rvert$	$0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$
	$\arg(q/p)(^\circ)$	$-6 \pm 11 \pm 3^{+3}_{-4}$

arXiv:1404.2412, to appear in PRD(R)

Assume no direct CP violation $\Rightarrow$ $A_f = \bar{A}_f$ for the $K^0_S\pi^+\pi^-$ mode

- 2.5σ away from the no-mixing hypothesis
- No evidence for indirect CP violation

Why worry about CPV in $D^0 \to \pi^0\pi^0$?

- Large CP asymmetries expected in the decay for new physics scenarios having large penguin contributions as well as large chromomagnetic dipole operators

Decay mode	Large penguins	Large c.d.o.
$D^0 \to \pi^+\pi^-$	3.96 (4.40)	5.18 (3.70)
$D^0 \to \pi^0\pi^0$	0.93 (1.01)	8.63 (6.19)
...	...	...

$\times 10^{-3}$

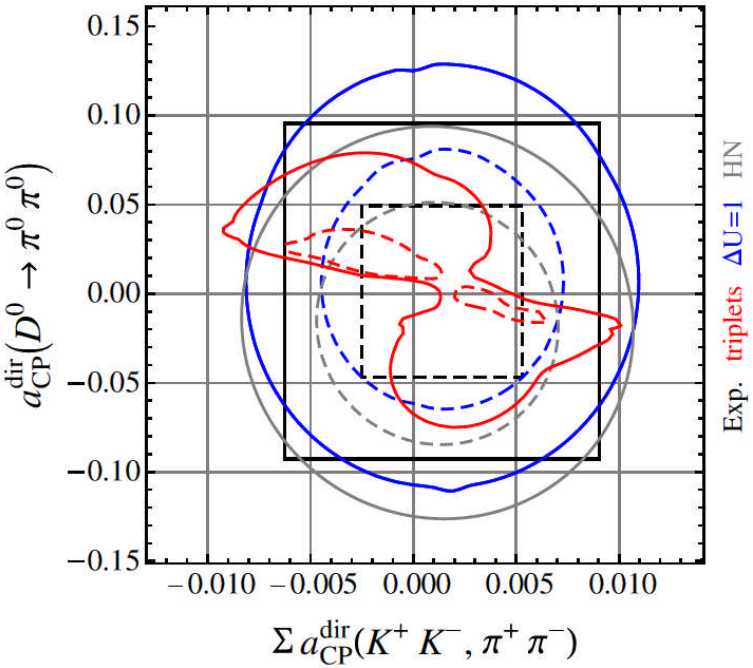
Cheng and Chiang, PRD 86, 014014 (2012)

- Large penguin contribution is predicted for $D^0 \to \pi^0\pi^0$

Bhattacharya, Gronau and Rosner, PRD 85, 014014 (2012)

- Some NP models e.g., triplet model, predict a sizeable CP asymmetry in $D^0 \to \pi^0\pi^0$

Hiller, Jung and Schacht, PRD 87, 014024 (2013)



- Need a precise measurement that can be only done at the e^+e^- flavor factories

How do we measure CPV in $D^0 \to \pi^0\pi^0$?

- Charge of the accompanying "slow" pion in the decay process $D^{*+} \to D^0\pi_s^+$ determines flavor of the neutral charm meson (whether a D^0 or a $\bar{D}^0$)

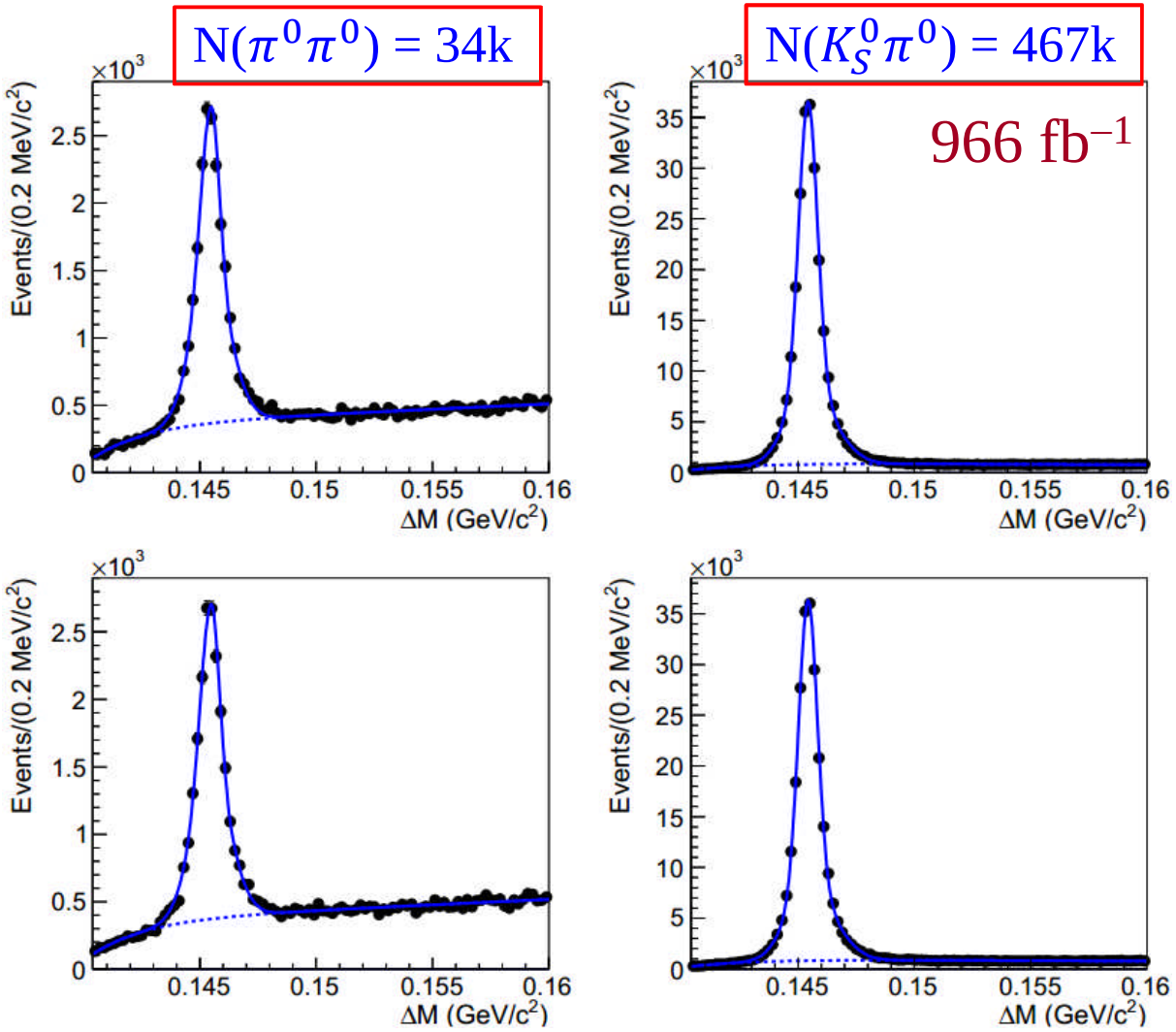
arXiv:1404.2412, to appear in PRL

- Measure

$$A_{\rm rec} = \frac{N_{\rm rec}^{D^{*+}\to D^0\pi_s^+} - N_{\rm rec}^{D^{*-}\to \bar{D}^0\pi_s^-}}{N_{\rm rec}^{D^{*+}\to D^0\pi_s^+} + N_{\rm rec}^{D^{*-}\to \bar{D}^0\pi_s^-}}$$

in $D^0 \to \pi^0\pi^0$ and $D^0 \to K_S^0\pi^0$ (control) decay modes

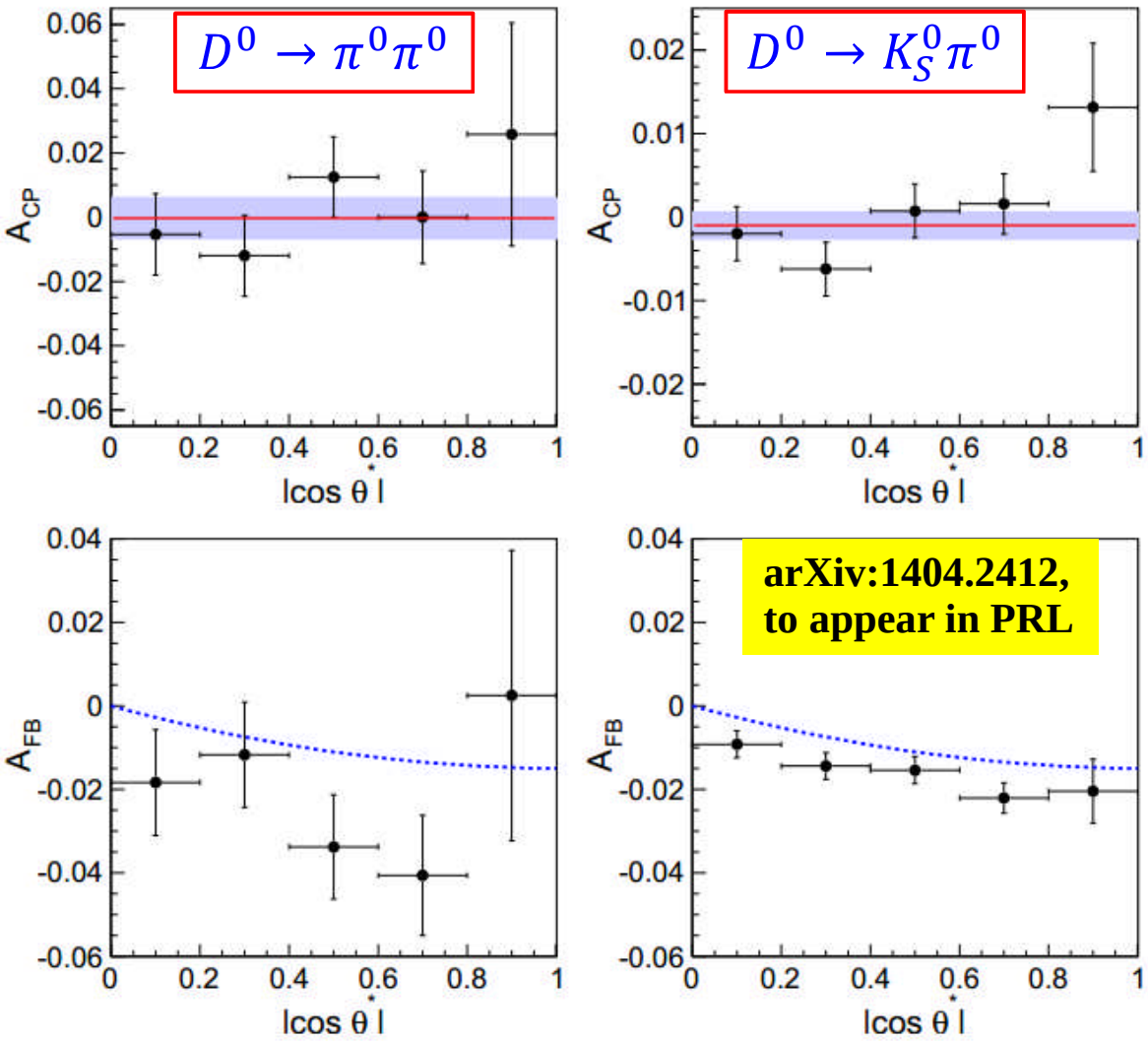
- Has three contributions: a) underlying A_{CP}, b) forward-backward asymmetry $(A_{\rm FB})$, and c) detection asymmetry between π_s^+ and π_s^- $(A_\varepsilon^{\pi_s})$



- $A_\varepsilon^{\pi_s}$ is determined subtracting $A_{\rm rec}$ of the "untagged" $D^0 \to K^-\pi^+$ decay from that of the "tagged" $D^{*+} \to D^0\pi_s^+$; $D^0 \to K^-\pi^+$ decay

CPV results for $D^0 \to \pi^0\pi^0$ and $K^0_S\pi^0$

- $A_{\rm FB}$ is an odd function of $\cos\theta^\star$, $\theta^\star$ being the $D^\star$ polar angle in the center of mass frame: $A_{\rm FB} = {}^1\!/_2\,[A^{\rm cor}_{\rm rec}(\cos\theta^\star) - A^{\rm cor}_{\rm rec}(-\cos\theta^\star)]$
- A_{CP} is independent of kinematics ➡ $A_{CP} = {}^1\!/_2\,[A^{\rm cor}_{\rm rec}(\cos\theta^\star) + A^{\rm cor}_{\rm rec}(-\cos\theta^\star)]$, where $A^{\rm cor}_{\rm rec}$ is already corrected for $A_\varepsilon^{\pi_s}$ $[O(0.1\%)]$



$A_{CP}(D^0 \to \pi^0\pi^0) = (-0.03 \pm 0.64 \pm 0.10)\%$

- Measured CP asymmetry is an order-of-magnitude improvement over the previous result of CLEO

PRD 63, 071101 (2001)

- $A_{CP}\left(D^0 \to K^0_S\pi^0\right) = (-0.21 \pm 0.16 \pm 0.07)\%$ supersedes our earlier result

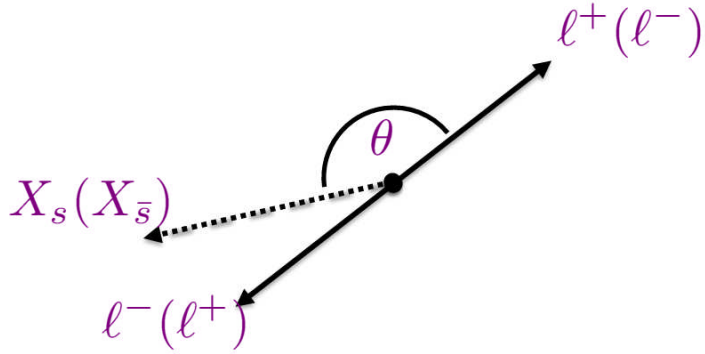
PRL 106, 211801 (2011)

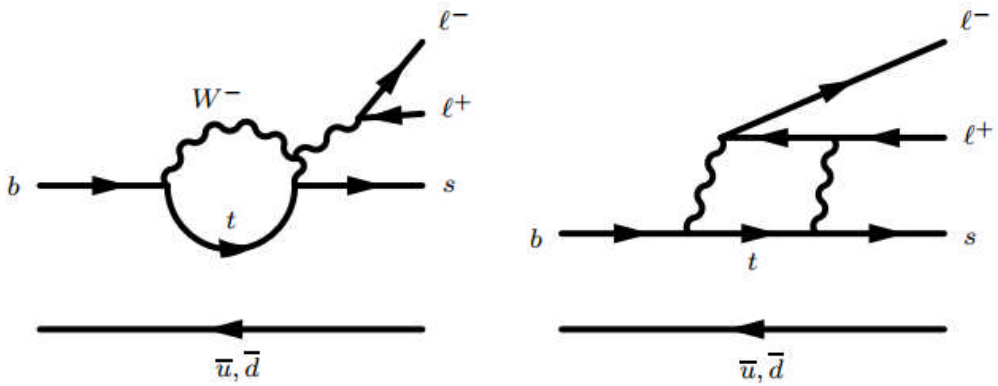
- Dashed blue curves represent leading-order predictions for $A_{FB}(e^+e^- \to c\bar{c})$

ZPC 30, 125 (1986)

Lepton forward-backward asymmetry in $B \to X_s \ell^+ \ell^-$

$$A_{\rm FB} \equiv \frac{\Gamma(b\to s\ell^+\ell^-;\cos\theta>0)-\Gamma(b\to s\ell^+\ell^-;\cos\theta<0)}{\Gamma(b\to s\ell^+\ell^-;\cos\theta>0)+\Gamma(b\to s\ell^+\ell^-;\cos\theta<0)}$$





- Contributions from electroweak loop and W^+W^- box diagrams

$$\frac{dA_{\rm FB}}{dq^2} = -3\Gamma_0 m_b^3 (1-s)^2 s\, C_{10} {\rm Re}(C_9 + \tfrac{2}{s} C_7)$$

- C_7, C_9 and C_{10} are the Wilson coefficients representing electromagnetic loop, electroweak vector and axial-vector contributions, respectively
- $\Gamma_0 = \frac{G_F^2}{48\pi^3}\frac{\alpha^2}{16\pi^2}|V_{tb}V_{ts}^\star|^2$ and $s = q^2/m_b^2$ with $q^2 = m^2_{\ell^+\ell^-}$ **PRD 75, 034016 (2007)**

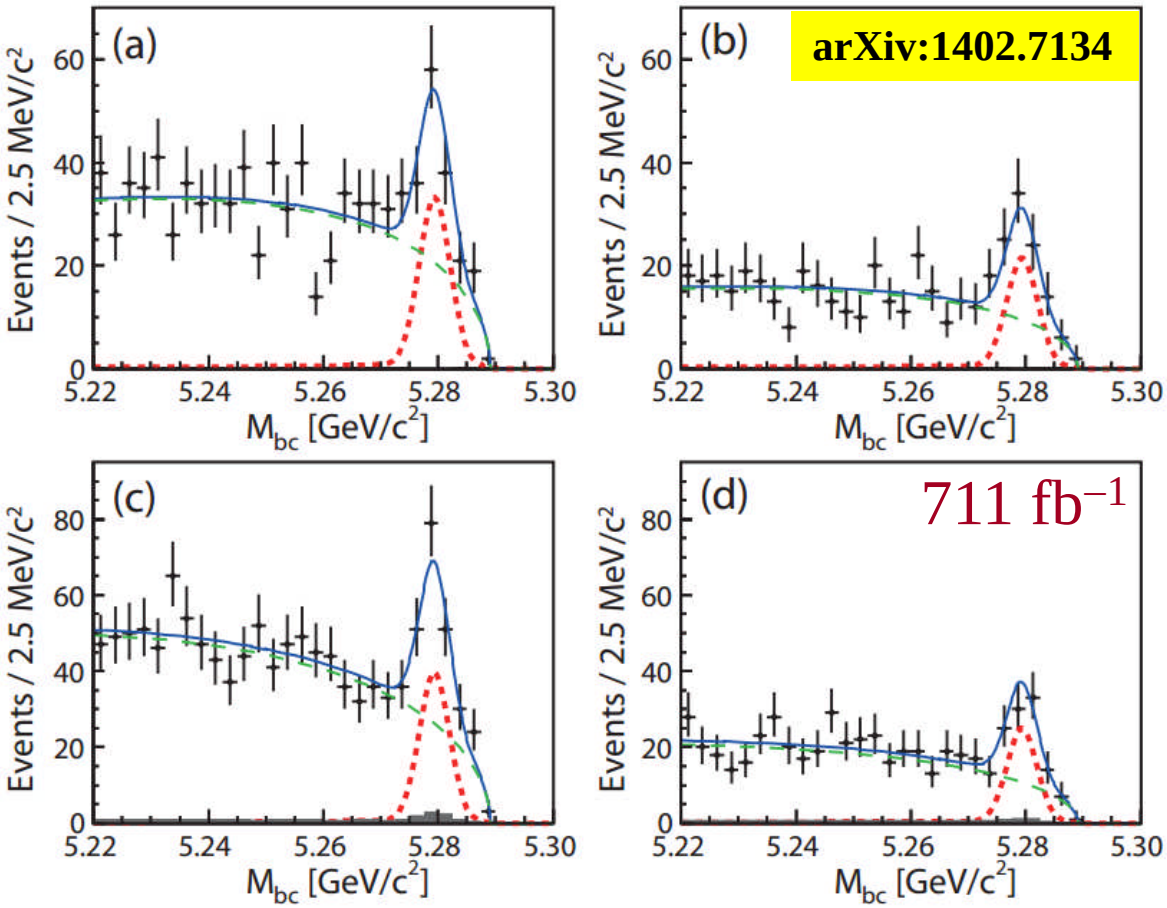
- Previously measured by Belle in exclusive decays viz., $B \to K^{(*)}\ell^+\ell^-$ **PRL 103, 171801 (2009)**
- Inclusive $A_{\rm FB}$ has a comparatively smaller theory uncertainty

Semi-inclusive reconstruction of $B \to X_S \ell^+ \ell^-$

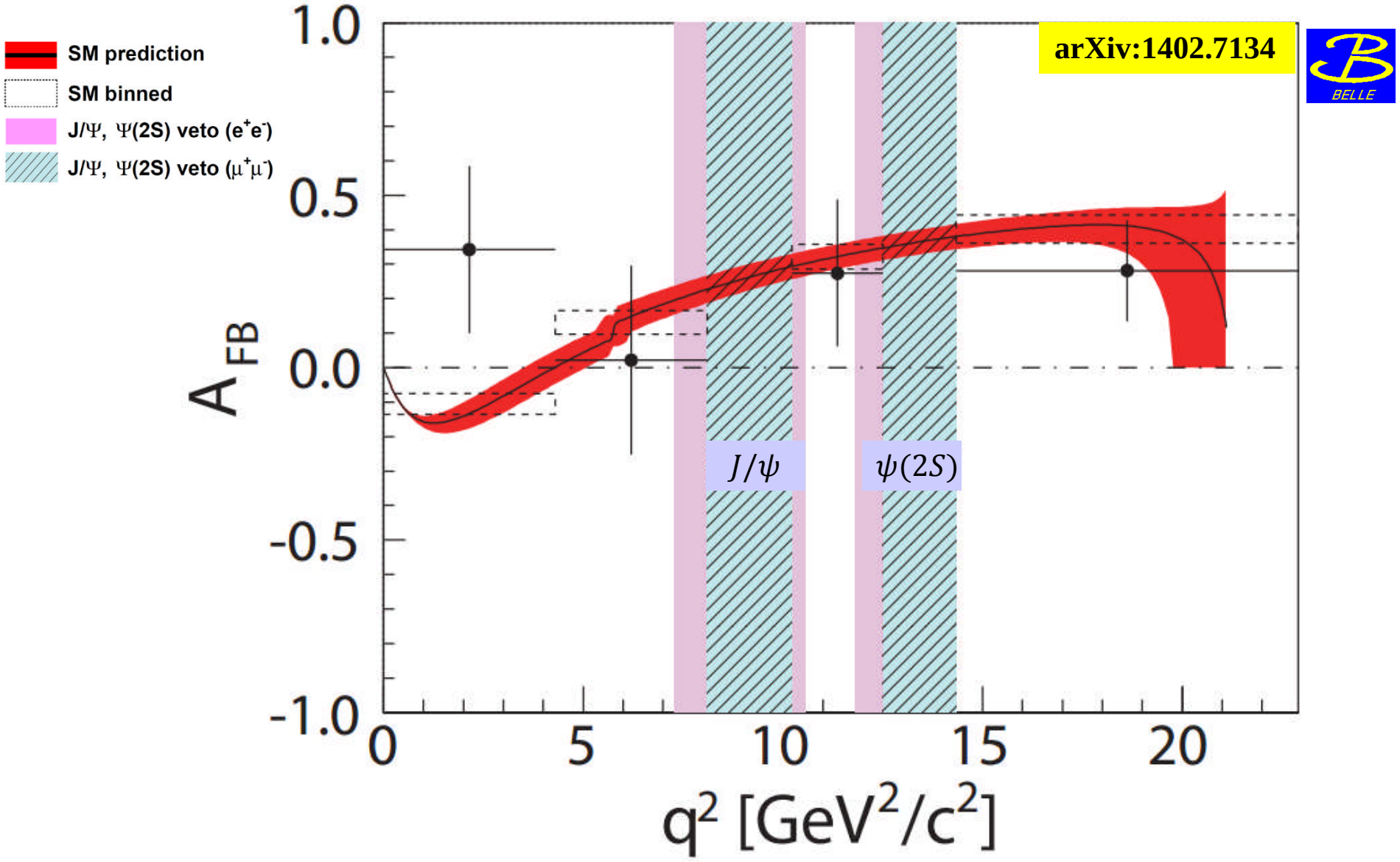
- 18 exclusive hadronic final states with $X_S = \{K\}\{n\pi\}$, $K = K^{\pm}, K^0_S$ and $n = 1 \ldots 4$, where at most one pion can be neutral, and two leptons ($\ell = e, \mu$)
- In case of $B^0(\bar{B}^0)$ decays, only self-tagging modes with a $K^+(K^-)$ are used
- Event reconstruction using two kinematic variables: M_{bc} and ΔE
- Background suppression based on a neural network and veto the J/ψ and $\psi(2S)$ regions

- To reduce cross-feed from the modes not used in A_{FB} measurement (total 8), we remove them once the best candidate selection is done

- Plots on right are for (a) $X_S e^+ e^-$; $\cos\theta > 0$, (b) $X_S e^+ e^-$; $\cos\theta < 0$, (c) $X_S \mu^+ \mu^-$; $\cos\theta > 0$ and (d) $X_S \mu^+ \mu^-$; $\cos\theta < 0$

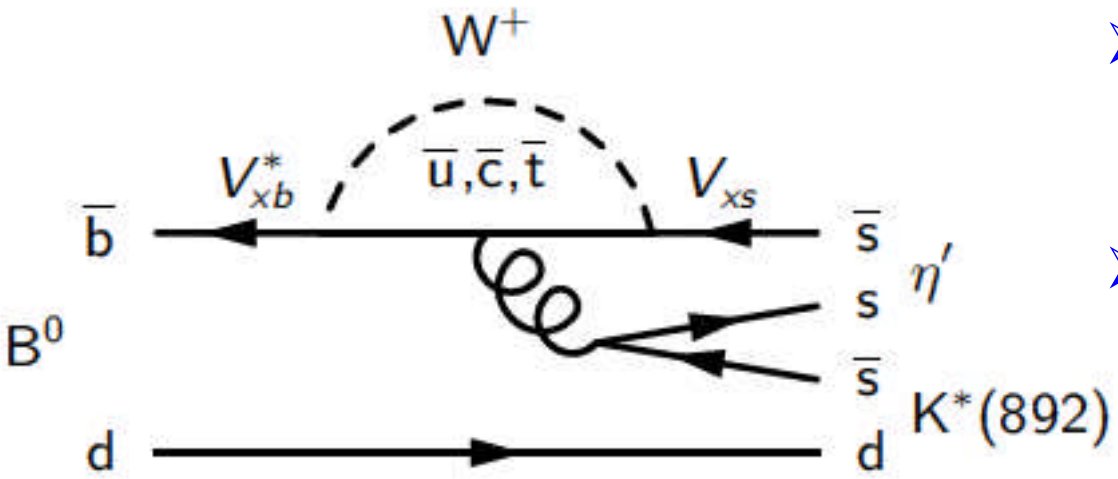


Results on A_{FB}: $B \to X_s \ell^+ \ell^-$



- Low q^2: 1.8σ away from the SM expectation
- High q^2: consistent with the SM and $A_{\mathrm{FB}} < 0$ is excluded at the 2.3σ level

BF and A_{CP} measurement in $B^0 \to \eta' K^\star(892)^0$



- Dominant contribution from the $b \to s$ loop transition
- Possible new physics can appear in the loop

- Previous Belle analysis based on 535×10^6 $B\bar{B}$ pairs put a 90% confidence-level upper limit

$$\mathcal{B}[B^0 \to \eta' K^\star(892)^0] < 2.6 \times 10^{-6}$$ **PRD 75, 092002 (2007)**

- BABAR claimed a signal at the 4σ level and reported

$$\mathcal{B}[B^0 \to \eta' K^\star(892)^0] = [3.1^{+0.9}_{-0.8}(\text{stat.}) \pm 0.30(\text{syst.})] \times 10^{-6}$$ **PRD 82, 011502 (2010)**

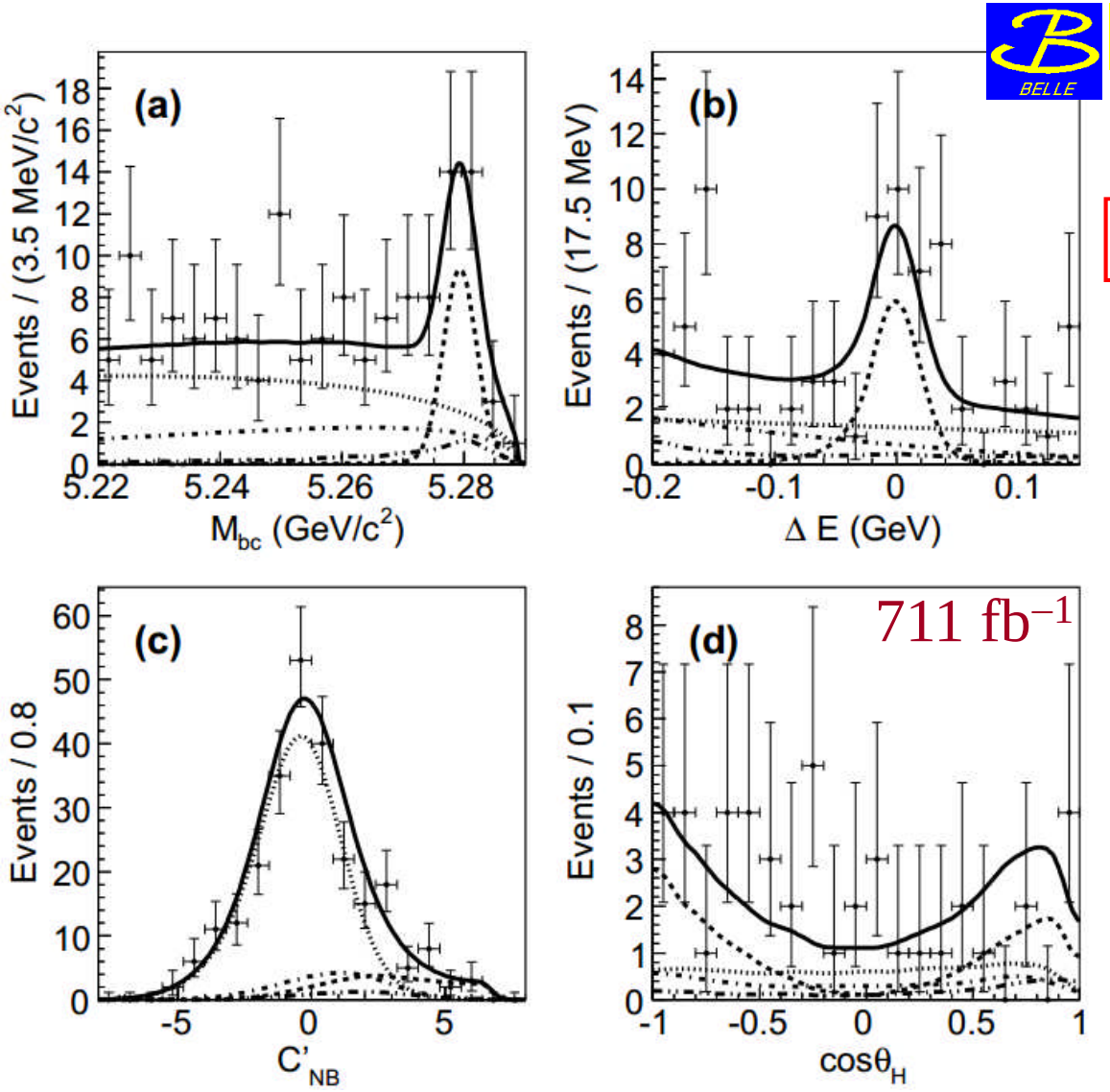
- On the theory front, the branching fraction is predicted to be in the range of $(1.2\text{-}6.3)\times10^{-6}$

PRD 75, 054003 (2007) **NPB 675, 333 (2003)**

PRD 78, 034011 (2008) **PRD 69, 34001 (2004)**

BF and A_{CP} results for $B^0 \to \eta' K^\star(892)^0$

- Reconstructed from $\eta' \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$ and $K^\star(892) \to K^+\pi^-$
- 4D extended maximum likelihood fit comprising M_{bc}, ΔE, C'_{NB} (continuum suppression variable), and $\cos\theta_H$ (cosine of the $K^\star$ helicity angle)



Preliminary

- We measure

$$\mathcal{B}(B^0 \to \eta' K^*(892)) = [2.6^{+0.7}_{-0.6}(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-6}$$

- Constitutes the first observation of the decay (5σ significance)

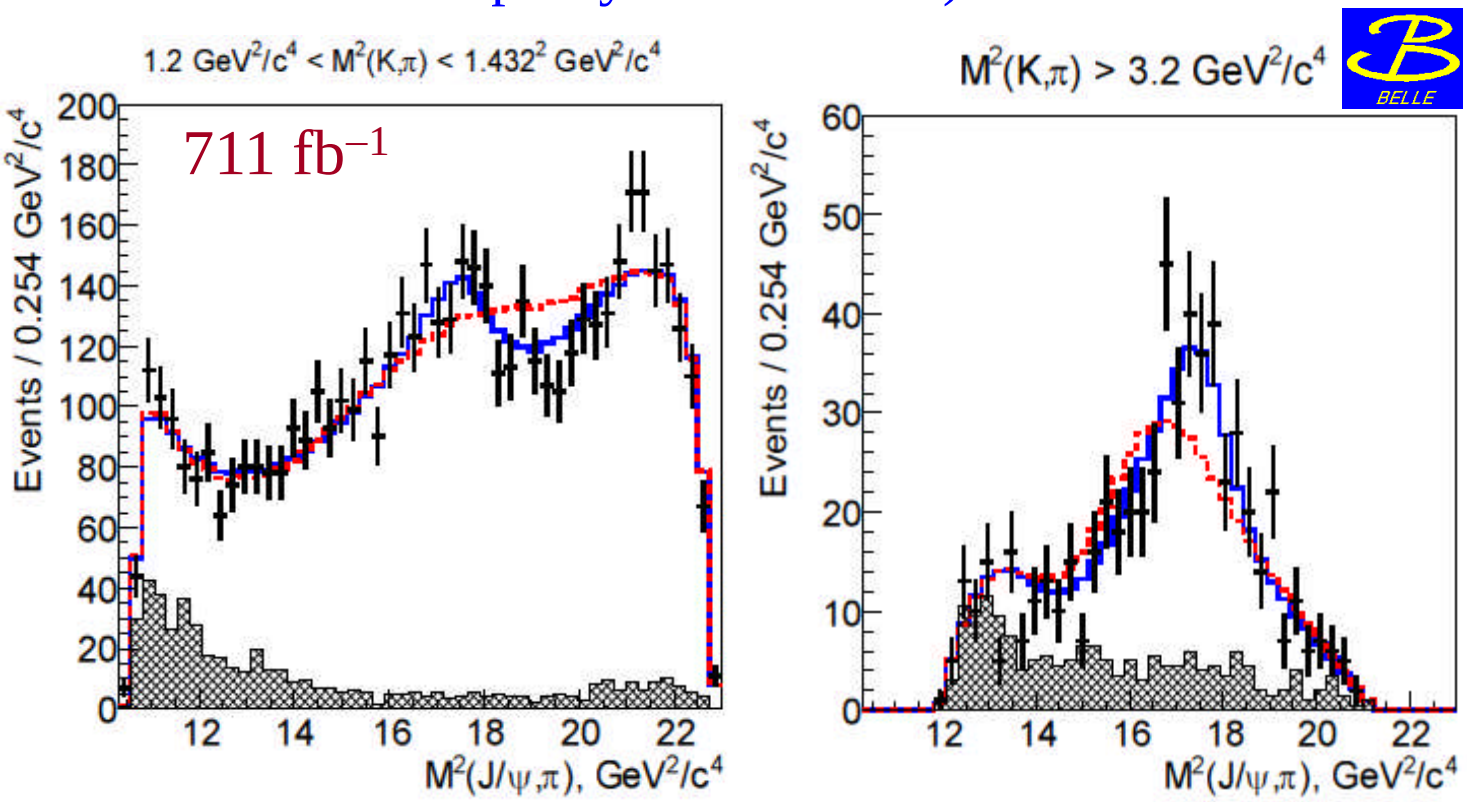
- A_{CP} is obtained by splitting the obtained yields according to the flavor of the decaying B meson $[B^0(\bar{B}^0) \to K^+(K^-)]$

$$\mathcal{A}_{CP} = -0.22 \pm 0.29(\text{stat}) \pm 0.03(\text{syst})$$

Amplitude analysis of $B \to J/\psi K\pi$

- Look for possible exotic, charmonium-like resonances in the $J/\psi\pi$ system

- 4D amplitude analysis comprising $(M^2_{K\pi}, M^2_{J/\psi\pi}, \cos\theta, \phi)$, where θ is the J/ψ helicity angle and ϕ is the angle between the two planes containing $J/\psi(\ell^+\ell^-)$ and $(K\pi)$ systems in the B rest frame
- Resonances: 10 $K^\star$ resonances and the $Z_c(4430)^+$state for the $J/\psi\pi$ system; additional Z_c^+ states are used for a cross-check
- Tried out five spin-parity hypotheses: $0^-, 1^+, 1^-, 2^+, 2^-$ for the $Z_c^+(J^P = 0^+$ is forbidden due to parity conservation)



- Projections of the $J/\psi\pi$ invariant mass including a new Z_c^+ state along with the $Z_c(4430)$
- Red dashed lines with the $Z_c(4430)$ only

Observation of a new state in $B \to J/\psi K\pi$

J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV/c^2	4220 ± 14	4315 ± 40	4196 ± 27	4209 ± 14	4203 ± 24
Width, MeV	71 ± 20	220 ± 80	370 ± 61	64 ± 18	121 ± 53
Significance	3.3σ	2.3σ	8.2σ	3.9σ	1.9σ

- A new Z_c^+ state [$Z_c(4200)^+$] with $J^P = 1^+$ is found with 7.2σ significance

$$M = 4196^{+31+17}_{-29-6}\ \mathrm{MeV}/c^2,\ \Gamma = 370^{+70+70}_{-70-85}\ \mathrm{MeV}$$

- Other J^P hypotheses are excluded: $0^-(6.7\sigma), 1^-(7.7\sigma), 2^-(5.2\sigma), 2^+(7.6\sigma)$
- Evidence for the $Z_c(4430)^+$ at the 4.0σ significance level

Preliminary

$$\mathcal{B}(\bar{B}^0 \to J/\psi K^-\pi^+) = (1.15 \pm 0.01 \pm 0.05) \times 10^{-3}$$

$$\mathcal{B}(\bar{B}^0 \to J/\psi K^*(892)) = (1.19 \pm 0.01 \pm 0.08) \times 10^{-3}$$

$$\mathcal{B}(\bar{B}^0 \to Z_c(4430)^+ K^-) \times \mathcal{B}(Z_c(4430)^+ \to J/\psi\pi^+) = (5.4^{+4.0+1.1}_{-1.0-0.9}) \times 10^{-6}$$

$$\mathcal{B}(\bar{B}^0 \to Z_c(4200)^+ K^-) \times \mathcal{B}(Z_c(4200)^+ \to J/\psi\pi^+) = (2.2^{+0.7+1.1}_{-0.5-0.6}) \times 10^{-5}$$

$$\frac{\mathcal{B}(Z_c(4430)^+ \to \psi(2S)\pi^+)}{\mathcal{B}(Z_c(4430)^+ \to J/\psi\pi^+)} \sim 10$$

Summary and outlook

- Though close to five years have passed away since the last data taking, Belle continues to produce high-quality results
- A small sample of those are presented here, based on the full data statistics
  - First observation of D^0-$\bar{D}^0$ mixing using $D \to K\pi$ decays in e^+e^- collisions
  - 2.5σ indication for D^0-$\bar{D}^0$ mixing and no sign of CPV in $D \to K_S^0\pi^+\pi^-$
  - An order-of-magnitude improvement over the previous result for A_{CP} in the $D \to \pi^0\pi^0$ decay
  - 1.8σ discrepancy with respect to the SM prediction for the lepton forward-backward asymmetry at low q^2 in inclusive $B \to X_s\ell^+\ell^-$ decays
  - First observation of the $b \to s$ penguin decay $B \to \eta' K^\star(892)^0$
  - Observation of another charged charmonium-like state in $B \to J/\psi K\pi$
- The unique explorations at the intensity frontier will continue with the start of Belle II
  - Refer to yesterday's talk by P. Urquijo