Recent results on CP violation at B factories

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on behalf of the ***BABAR*** and **Belle** collaborations

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Outline

- Introduction to CP violation measurements at B factories

- First evidence for cos 2β > 0 and resolution of the CKM Unitarity Triangle ambiguity by a time dependent Dalitz plot analysis of $B^0 \to D^{(*)}h^0$ with $D \to K_S^0\pi^+\pi^-$ decays.

Preliminary, will be submitted to PRL & PRD this month

- Evidence for CP violation in $B^+ \to K^*(892)\,\pi^0$ from a Dalitz plot analysis of $B^+ \to K_S^0\pi^+\pi^0$ decays.

Phys. Rev. D **96**, 072001 (2017)

- Measurement of the inclusive electron spectrum from B meson decays and determination of $|V_{ub}|$

Phys. Rev. D **95**, 072001 (2017)

Weak interaction (charged current $W^{\pm}$) - quarks

3 quarks families

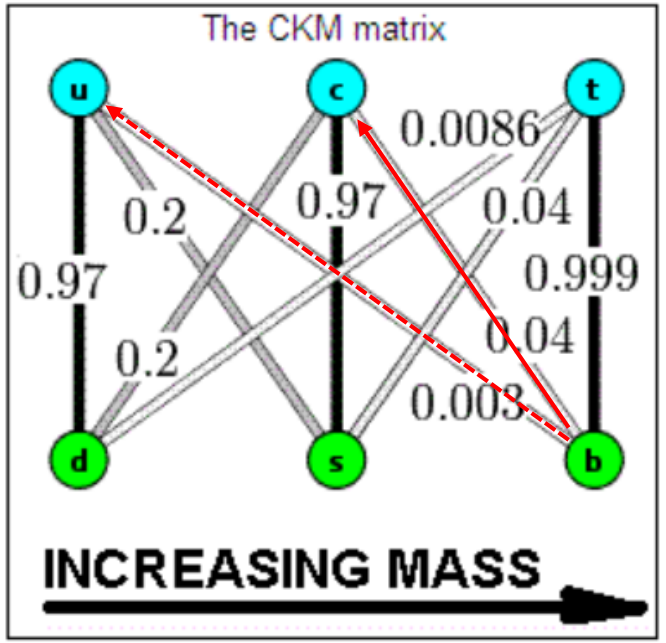
$W^{\pm}$ coupling

$$\begin{bmatrix} u \\ d' \end{bmatrix} \begin{bmatrix} c \\ s' \end{bmatrix} \begin{bmatrix} t \\ b' \end{bmatrix}$$

Almost (but different from) a diagonal matrix

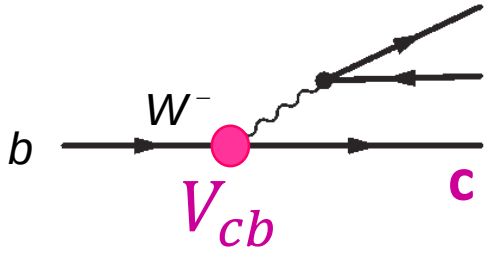
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

weak eigenstates — Cabibbo Kobayashi Maskawa (CKM) matrix — mass eigenstates

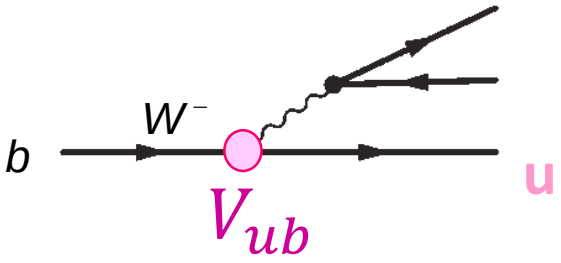


B meson produced in flavor eigenstate

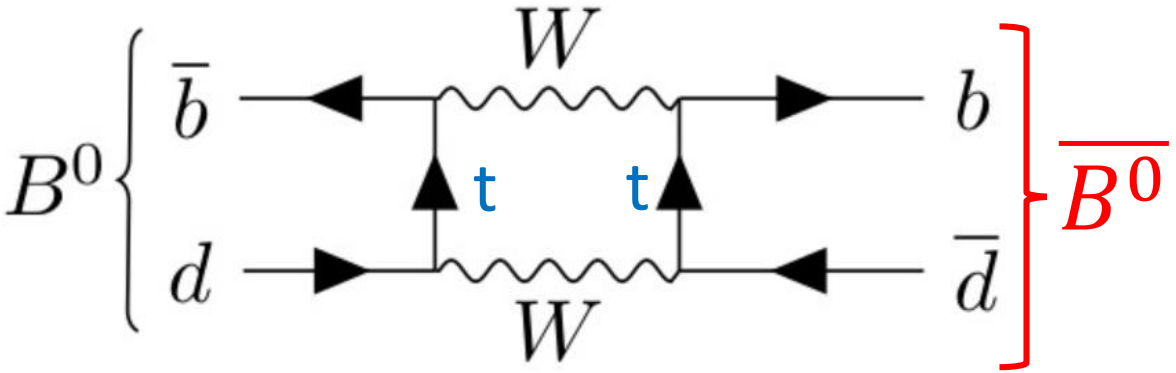
Relatively long lifetime for B decay ~ **1.5 ps**



Dominant Charm decay



« charmless decay »



B^0-$\overline{B^0}$ mixing : time dependent

Oscillation period ~ 12 ps

CP violation

- In Standard Model: due to complex CKM unitary matrix

- Wolfenstein parameterization:

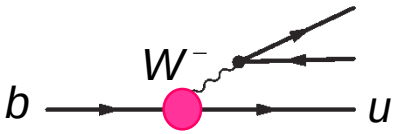
$$V_{CKM} = \begin{pmatrix} V_{ud} V_{us} V_{ub} \\ V_{cd} V_{cs} V_{cb} \\ V_{td} V_{ts} V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- with $\lambda \cong 0.22$, $A \cong 0.83$
- CP violation if $\eta \neq 0$.

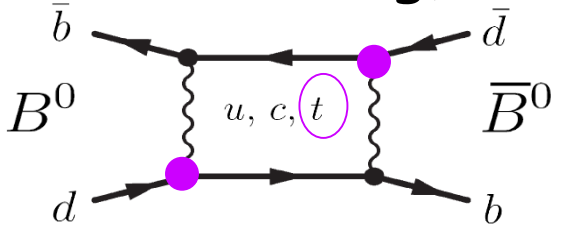
The unitarity triangle

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

γ = phase of V_{ub}
(b→u transition)



β = phase of V_{td}
(B^0-$\overline{B}^0$ mixing)



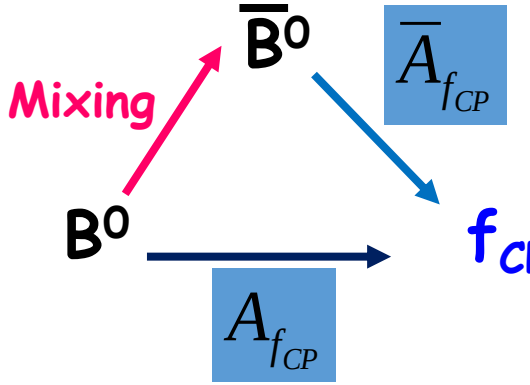
$$\frac{V_{ub}^{*}V_{ud}}{\left|V_{cd}V_{cb}^{*}\right|}$$

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

$\alpha = \pi-\beta-\gamma \Rightarrow$ process involving both B^0 mixing and b→u transition

OVERCONSTRAIN (ρ, η) BY MEASURING 3 ANGLES AND TWO SIDES

CP violation in the interference between mixing and decay



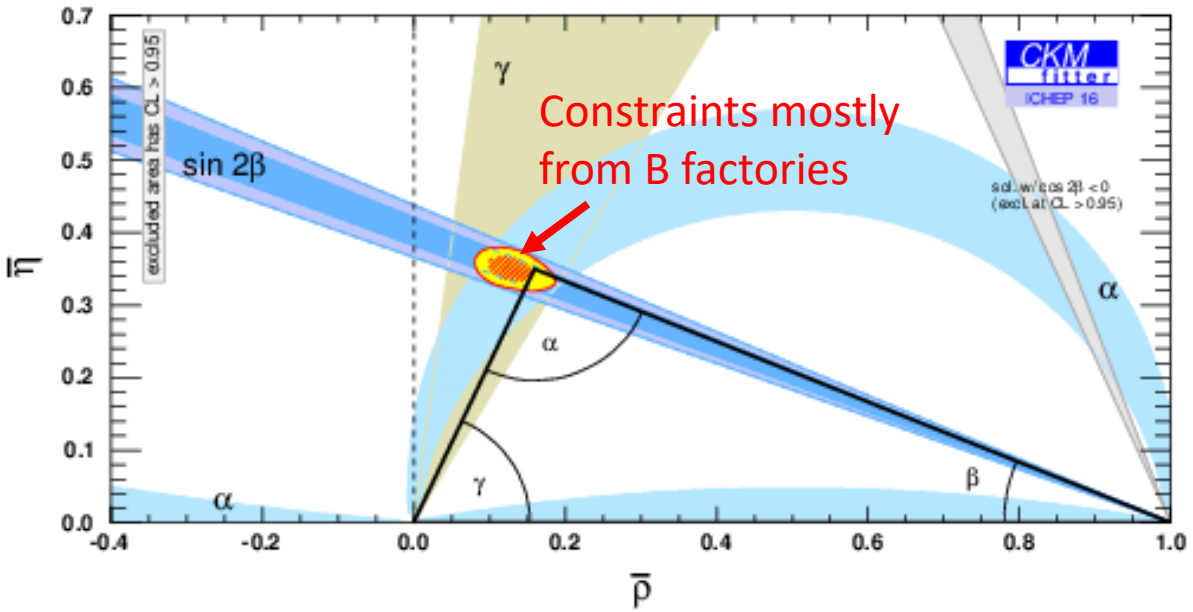
f_{CP} CP final state, such as golden channel $J/\Psi\ K^0_{S,L}$,…

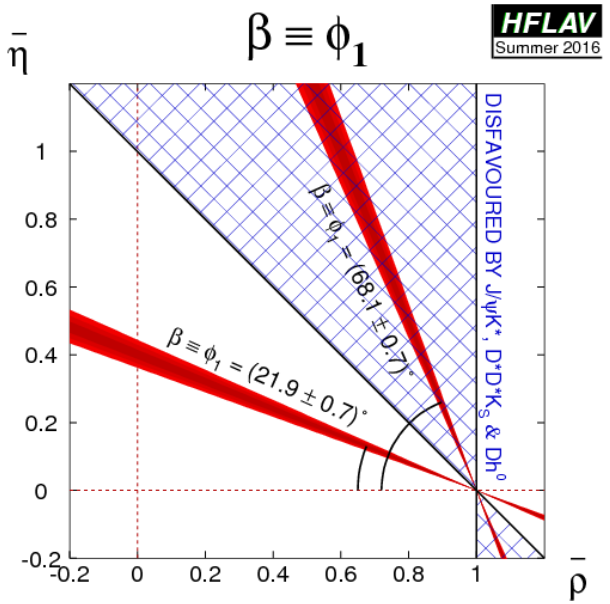
$$P[B^0 \to f_{CP}](t) \neq P[\overline{B^0} \to f_{CP}](t)$$

No CP violation in B mixing & no direct CP violation in B decay:

Decay time t dependent analysis to extract sin 2β in $b \to c$ decays. Time dependent Asymmetry $\propto \sin(2\beta) \times \sin(\Delta m_d \Delta t)$

Measurement of sin 2β (= sin $2\phi_1$) [1] leads to β= 21.9° or β= π/2 -21.9° = 68.1° *





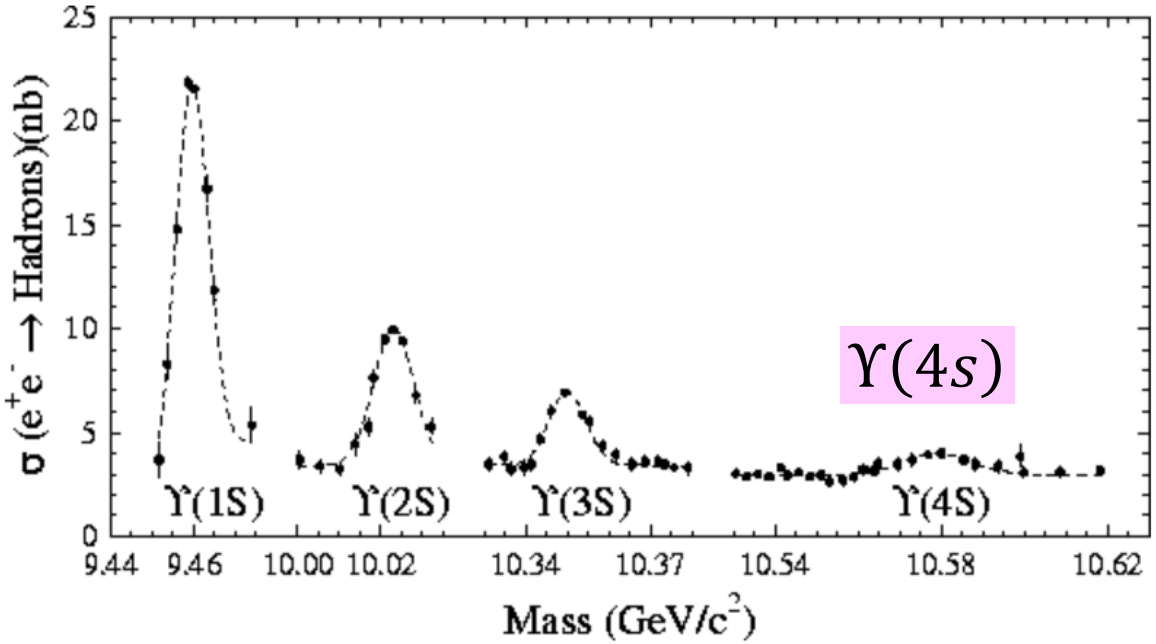
*** CKMttter Group, J. Charles et al., http://ckmtter.in2p3.fr/**

Precise measurements but ambiguity on β !

$\Upsilon(4s)$ $b\bar{b}$ bound state

- **Upsilon system** : bound state of a **b quark and anti b quark**, bound together somewhat analogously to the electron and proton of a hydrogen atom.
- **Various excited states (resonances)** of this system can be created by tuning the e^+e^- accelerator energy
- Also **"continuum"** $e^+e^- \rightarrow q\bar{q}$ **background** is created (q ≠ b)

$$e^+e^- \rightarrow \Upsilon(4s) \rightarrow b\bar{b} \rightarrow B^0\overline{B^0} \text{ or } B^+B^-$$



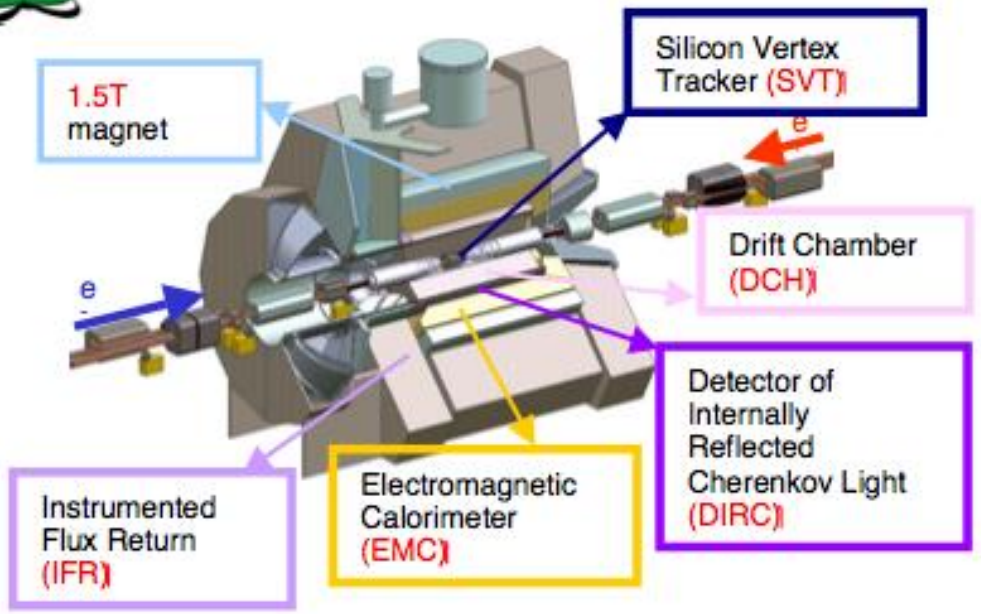
Flavor specific B mesons
Produced by strong interaction
(conserving CP)

$B^0\overline{B^0}$ is produced in a **coherent state**
remains so until one of the B meson decays

B mesons almost at **rest in the $\Upsilon(4s)$ frame**

The B factories

BaBar experiment, PEP-II, SLAC

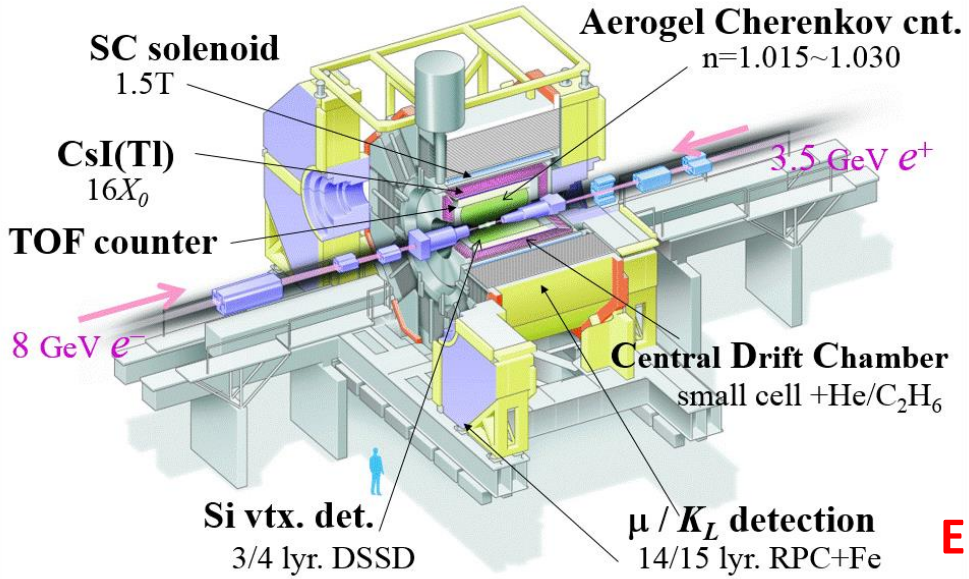


3.1 GeV e^+ & 9 GeV e^- beams

$L = 1.2 \times 10^{34}\ cm^{-2}s^{-1}$

$\int L\,dt = 530\ fb^{-1}$ @ $\Upsilon(4S)$+off (~10%)

Belle experiment, KEKB, KEK, Japan



3.5 GeV e^+ & 8 GeV e^- beams

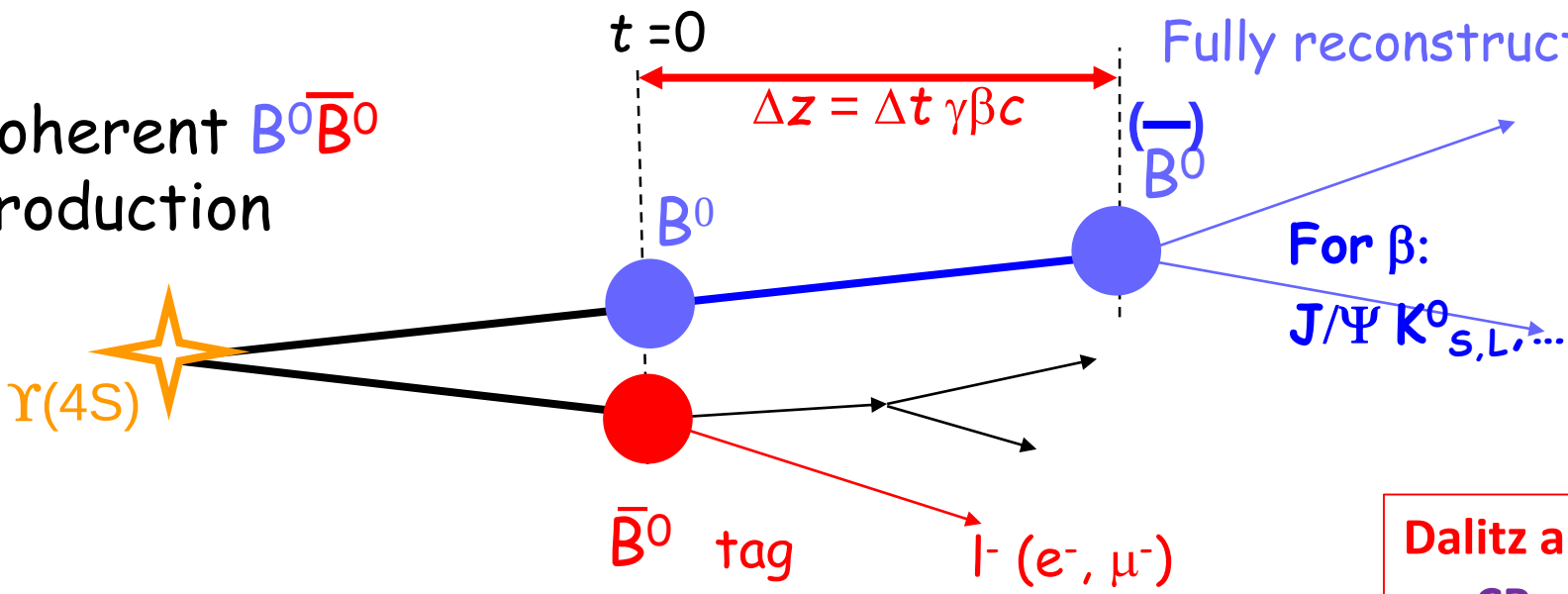
$L = 2.1 \times 10^{34}\ cm^{-2}s^{-1}$ (world record)

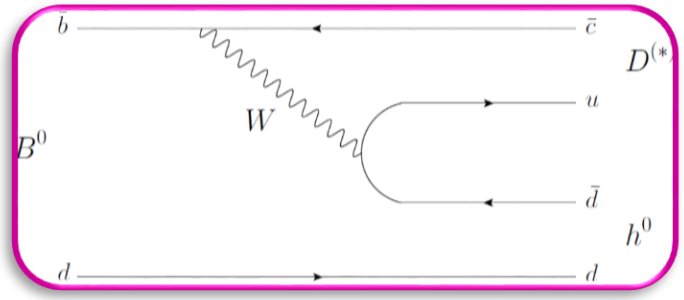
$\int L\,dt \sim$ 800 fb $^{-1}$ @ Υ(4s) + off (~10%)

Energy asymmetry : Boost Υ(4s) & B mesons to measure their decay time

More than 1 billion $B\bar{B}$ pairs accumulated at B factories

CP Violation Measurement





This talk

$D^{(*)}\ h^0 \in [\pi^0, \eta, \omega]$

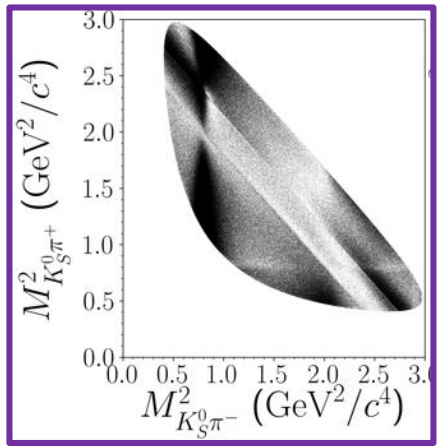
$D \rightarrow K^0_S\ \pi^+\pi^-$

- Exclusive B^0 meson reconstruction.
- Time measurement: $\Delta z \approx 250$ mm, $\sigma\Delta z \approx 170$ mm.

Dalitz analysis of D decays to disentangle :

- CP eigenstates ($K^0_S\rho^0(770)$,...)
- Flavor specific decays ($K^{*\pm}(892)\pi^{\mp}$,...)
- Non resonant contributions

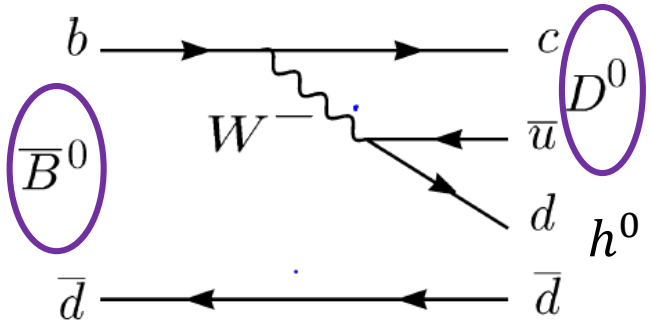
with same final state $K^0_S\ \pi^+\pi^-$



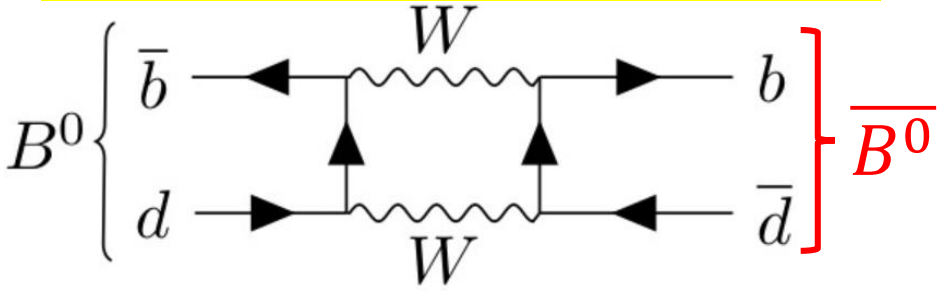
Dalitz plot : function of the Lorentz invariants $\mathbf{M^2_{K^0_S\pi^-}}$ and $\mathbf{M^2_{K^0_S\pi^+}}$

Complex structures

Time dependent Dalitz plot analysis of $B^0 \to D^{(*)}h^0$ with $D \to K^0_S\pi^+\pi^-$



B^0-$\overline{B^0}$ mixing : time dependent



$$|M_{B^0}(\Delta t)|^2 = \left| \boldsymbol{\overline{D^0}} \times \cos(\Delta m \Delta t/2) - ie^{+2i\beta} \times \boldsymbol{D^0} \times \sin(\Delta m \Delta t/2) \right|^2$$

$$|M_{\bar{B}^0}(\Delta t)|^2 = \left| \boldsymbol{D^0} \times \cos(\Delta m \Delta t/2) - ie^{-2i\beta} \times \boldsymbol{\overline{D^0}} \times \sin(\Delta m \Delta t/2) \right|^2$$

Interference beteween $\boldsymbol{D^0}$ and $\boldsymbol{\overline{D^0}}$

Time dependent Dalitz plot analysis of $B^0 \to D^{(*)}h^0$ with $D \to K^0_S\pi^+\pi^-$

Time dependent analysis of the B^0 and $\overline{B^0}$ mesons decays : extract both sin 2β and cos 2β *

* A. Bondar, T. Gershon, and P. Krokovny, Phys. Lett. B 624, 1 (2005)

$$\mathrm{P_{sig}}(\Delta t) \propto \left[|\mathcal{A}_{\bar{D}^0}|^2 + |\mathcal{A}_{D^0}|^2\right]$$

Flip signs for B^0 / $\overline{B^0}$ tag

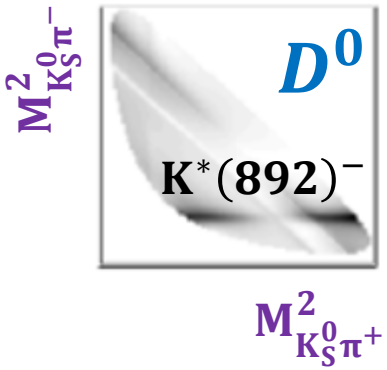
$$\mp \left(|\mathcal{A}_{\bar{D}^0}|^2 - |\mathcal{A}_{D^0}|^2\right)\cos(\Delta m \Delta t)$$

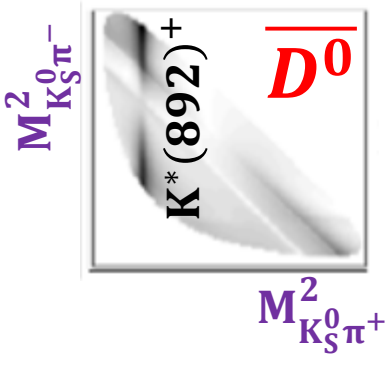
$$\pm 2\eta_{h^0}(-1)^L\left[\mathrm{Im}\left(\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0}\right)\cos(2\beta) - \mathrm{Re}\left(\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0}\right)\sin(2\beta)\right]\sin(\Delta m \Delta t)$$

$$\times e^{-\frac{\Delta t}{\tau_{B^0}}}$$

no *CP* violation in the neutral *D* meson system

$A_{D^0} \equiv A\left(\mathbf{M^2_{K^0_S\pi^+}}, \mathbf{M^2_{K^0_S\pi^-}}\right)$ **and** $A_{\overline{D^0}} \equiv A\left(\mathbf{M^2_{K^0_S\pi^-}}, \mathbf{M^2_{K^0_S\pi^+}}\right)$





Need to know well $D \to K^0_S\pi^+\pi^-$ Dalitz plot structure !

Dalitz plot amplitude model

$$\mathcal{A}_{D^0}(m^2_{K^0_S\pi^+}, m^2_{K^0_S\pi^-}) = \sum_{r\neq(K\pi,\pi\pi)_{L=0}} a_r e^{i\phi_r} \mathcal{A}_r(m^2_{K^0_S\pi^+}, m^2_{K^0_S\pi^-}) + \mathcal{A}_{K\pi_{L=0}}(s) + F_1(s)$$

Quasi 2 bodies (resonance)

- Cabibbo-favored: $K^*(892)^-$, $K_2^*(1430)^-$, $K^*(1680)^-$, $K^*(1410)^-$
- Cabibbo-suppressed: $K^*(892)^+$, $K_2^*(1430)^+$, $K^*(1410)^+$
- *CP* eigenstates: $\rho(770)^0, \omega(782), f_2(1270), \rho(1450)^0$

K π S-wave + $K_0^*(1430)$: LASS *

π π S-wave : K Matrix **

*LASS Collaboration, D. Aston et al., Nucl. Phys. B 296, 493 (1988).

** S.U. Chung et al., Ann. Phys. 507 404 (1995).

Fit amplitudes and phases from the Dalitz plot information

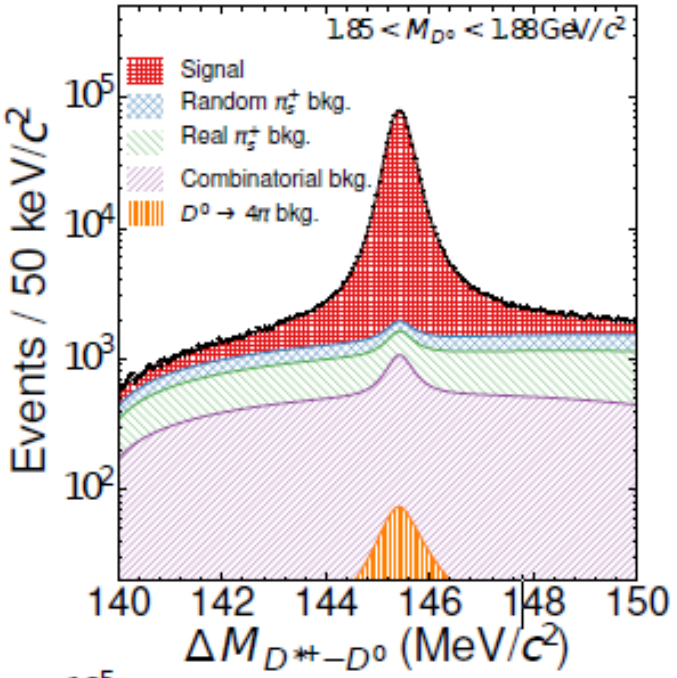
Time dependent Dalitz plot analysis of $B^0 \to D^{(*)}h^0$ with $D \to K_S^0\pi^+\pi^-$ decays : analysis steps

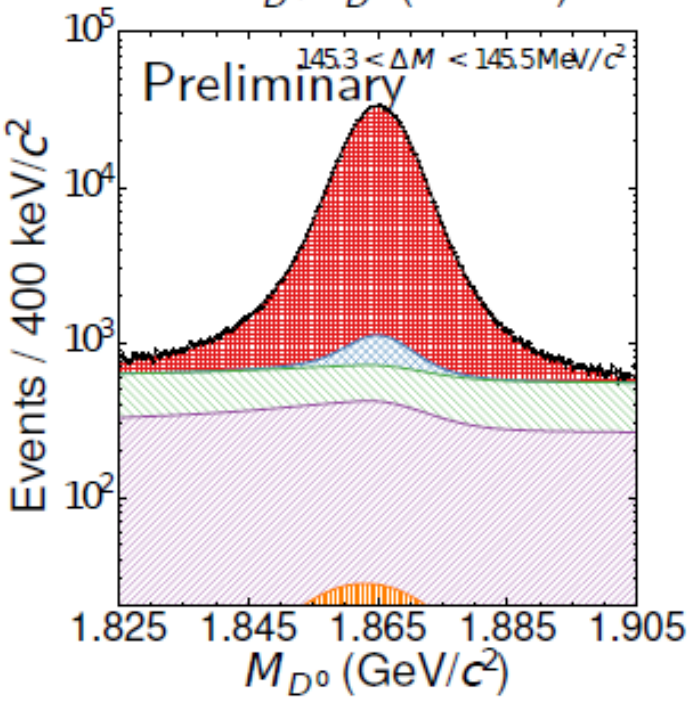
1. Dalitz Plot analysis of $D \to K_S^0\pi^+\pi^-$ from $D^{*+} \to D^0\pi_s$ in $e^+e^- \to c\bar{c}$
2. Extract signal yield from $\overline{B^0} \to D^{(*)0}h^0$ decays:
   - $(D^{*0} \to D^0\pi^0)$, $D^0 \to K_s^0\pi^+\pi^-$.
   - $h^0 = \pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$ and $\omega \to \pi^+\pi^-\pi^0$
3. Time dependent CP analysis of the $\overset{(-)}{B} \to \overset{(-)}{D}h^0$ decays

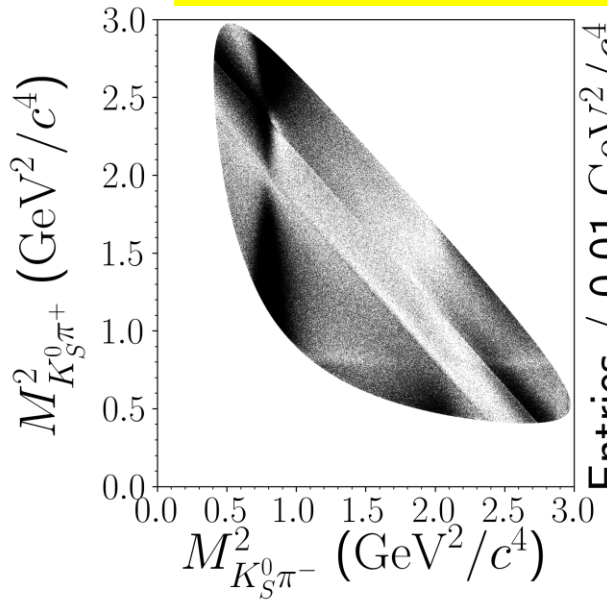
Dalitz Plot :

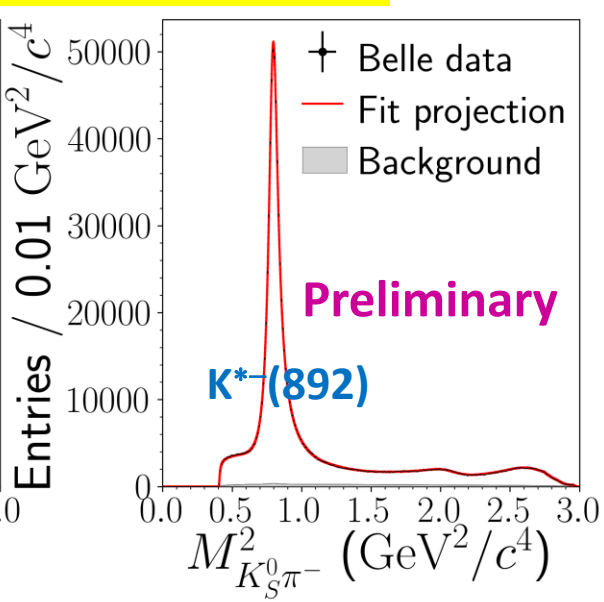
- From flavor-tagged $D^{*+} \to D^0\pi_s^+$ decays in $e^+e^- \to c\bar{c}$ data (Belle, 924 fb^{-1}) p*(D^0) > 2.5 (3.1) GeV/c at Υ(4S) (Υ(5S));
- Fit to D^0 mass versus ΔM = $M_{D^{*+}}$ - M_{D^0} to define signal candidates.
- Fit $D^0 \to K_S^0\pi^+\pi^-$ Dalitz plot (amplitudes, phases, …).

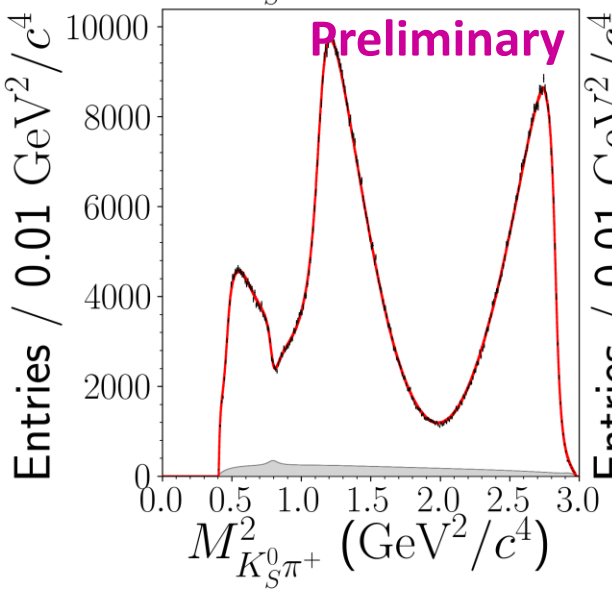
$D \to K^0_S \pi^+ \pi^-$ Dalitz plot

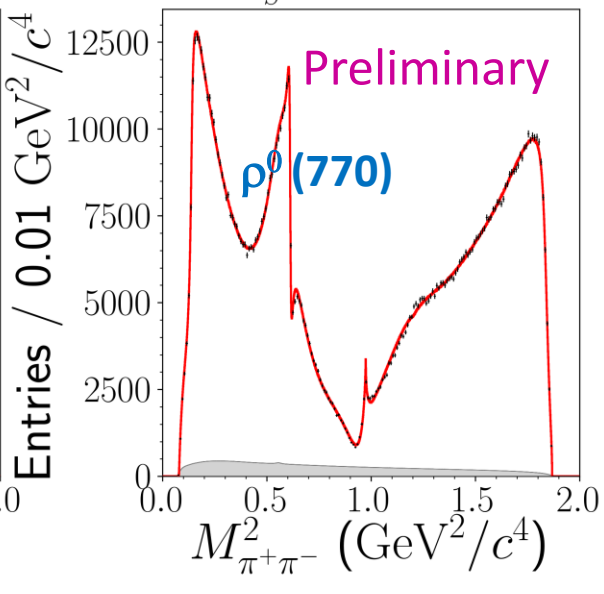












Large statistics ! > 1.2 million events

BELLE

$e^+e^- \to c\bar{c}$ data

Dominant contributions:

- **K*−(892) π^+**
  Flavor specific
- **ρ0(770) K^0_S**
  CP eigenstate
- Non resonant

$\overline{B^0} \to D^{(*)0} h^0$ signal yield

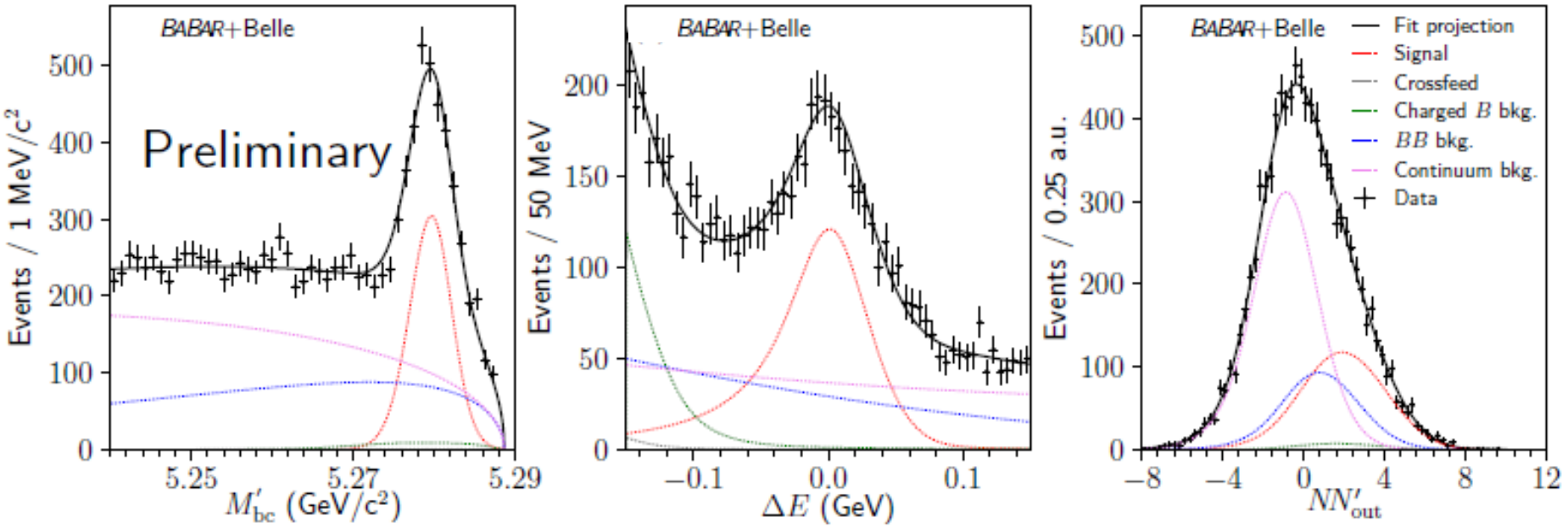
- Reconstruct B^0 decay modes : $D^0\pi^0, D^0\eta, D^0\omega, D^{*0}\pi^0, D^{*0}\,\eta$ with similar selections on BABAR and Belle data.
- Neural Net (NN) combining event-shape variables to reject continuum $e^+e^- \to q\bar{q}$
- 3-dim maximum Likelihood fit to M'_{bc} , ΔE and NN'$_{\text{out}}$

Peaks at B meson mass for signal

$$M'_{bc} = \sqrt{E^{*2}_{\text{beam}} - \left(\vec{p}^{\,*}_{D^{(*)0}} + \frac{\vec{p}^{\,*}_{h^0}}{|\vec{p}^{\,*}_{h^0}|}\sqrt{(E^{*}_{\text{beam}} - E^{*}_{D^{(*)0}})^2 - m^2_{h^0}}\right)^2}\,; \qquad \Delta E = E^*_B - E^*_{\text{beam}}$$

Peaks at 0 for signal

*** : in Υ(4s) frame**



Signal events :

- 1129 ± 48 (BABAR)
- 1567 ± 56 (Belle)

Time dependent CP analysis of the $\overline{B}^{(0)} \to \overline{D}^{(0)} h^0$ decays

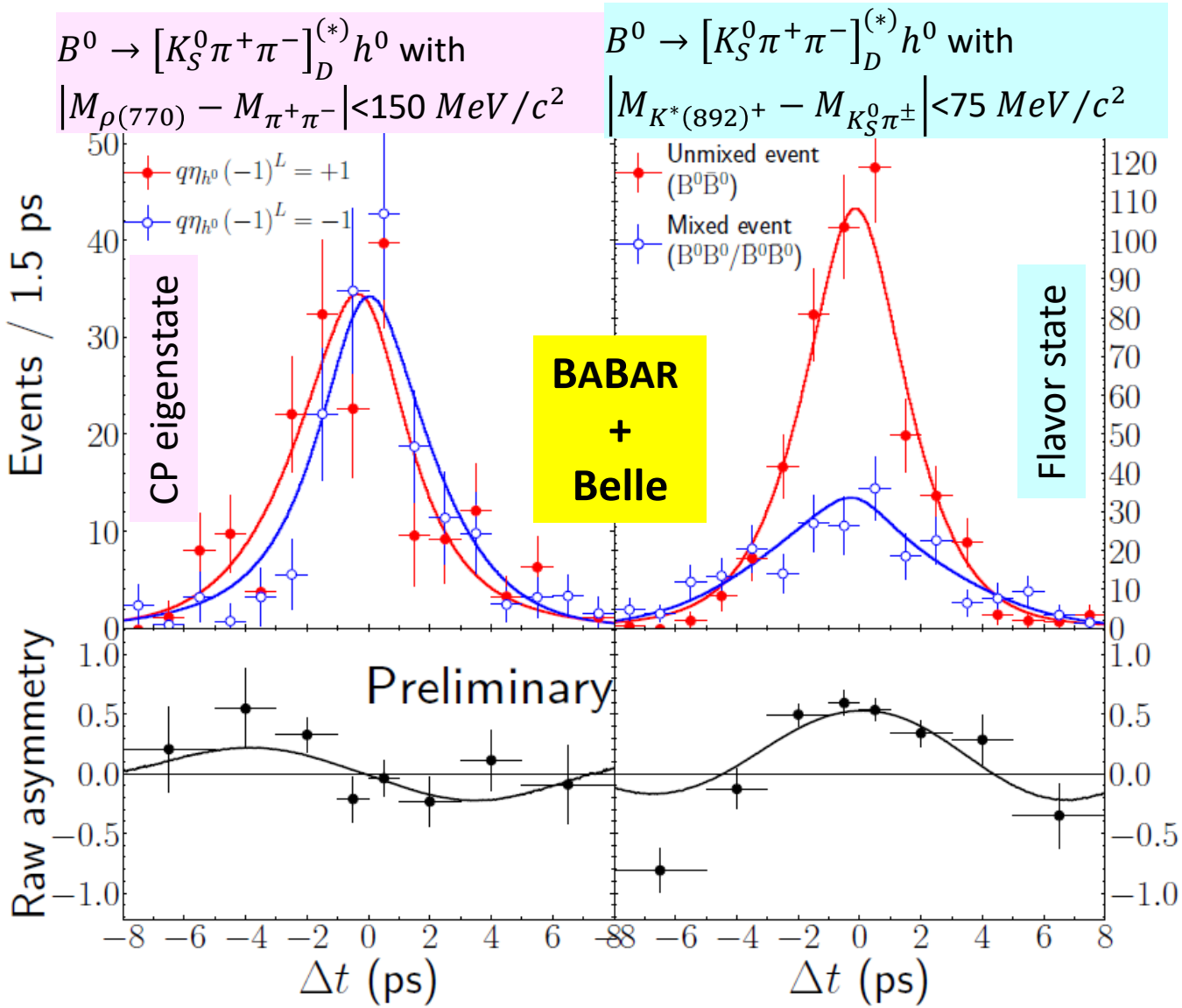
Fit proper time distributions independently to BABAR and Belle data (different $\Upsilon(4s)$ boost, different detector and reconstruction, …)

$$\ln P = \sum_i \ln P_i^{BABAR} + \sum_j \ln P_j^{Belle}$$

BABAR events : i ; Belle events : j

Allows to apply resolution models and flavor-tagging algorithms specific to each experiment

But use common $D \to K_S^0 \pi^+ \pi^-$ Dalitz plot model



- Most precise measurement of cos 2β
- First evidence for cos 2β > 0 (3.7 σ)
- Exclusion of second solution : π/2-β = (68.1 ±0.7)° (7.3 σ)
- Exclusion of β = 0 (5.1 σ)
- Observation of CP violation in $B^0 \to D^{(*)}h^0$

$$\sin 2\beta = 0.80 \pm 0.14\,(stat.) \pm 0.06\,(syst) \pm 0.03\,(model)$$
$$\cos 2\beta = 0.91 \pm 0.22\,(stat.) \pm 0.09\,(syst) \pm 0.07\,(model)$$
$$\beta = [22.5 \pm 4.4\,(stat.) \pm 1.2\,(syst) \pm 0.6\,(model)]^\circ$$

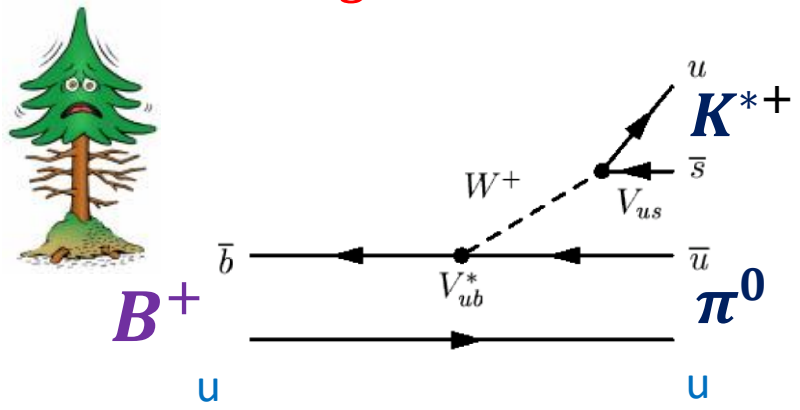
World average
$\boldsymbol{sin\,2\beta = 0.69 \pm 0.02}$

Dalitz plot analysis of $B^+ \to K_S^0 \pi^+ \pi^0$ decays.

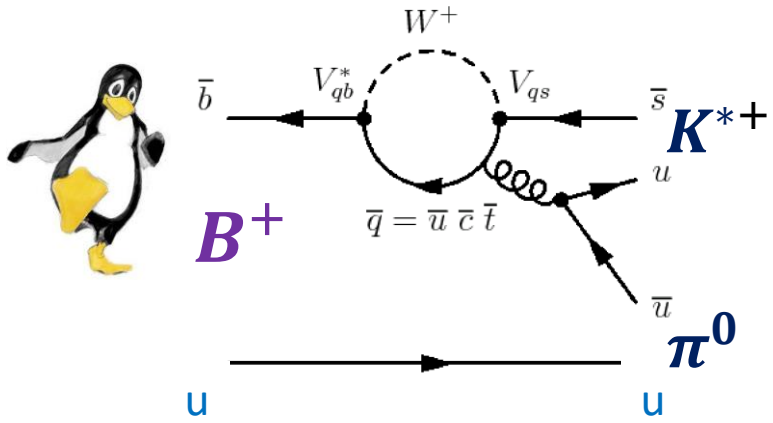
Direct CP violation due to tree-penguin interference (different CKM phases)

For processes involving tree b → u, penguin diagrams are also involved

Tree Diagram



Penguin Diagram



Phys. Rev. D **96**, 072001 (2017)

Evidence for CP violation

$$P(B^+ \to K^{*+}(892)\,\pi^0) \neq P(B^- \to K^{*-}(892)\,\pi^0)$$

Constrain γ angle of unitarity triangle using other B→ $K\ \pi\ \pi$ decays from isospin analysis (to disentangle tree and penguin diagrams)

Search for new physics : K π puzzle

QCD may be a cause of apparently anomalous CP violation $\Delta A_{CP}(K\pi) = A_{CP}(K^+\pi^-) - A_{CP}(K^+\pi^0) \neq 0$

- Look for similar effects in K*π & Kρ system

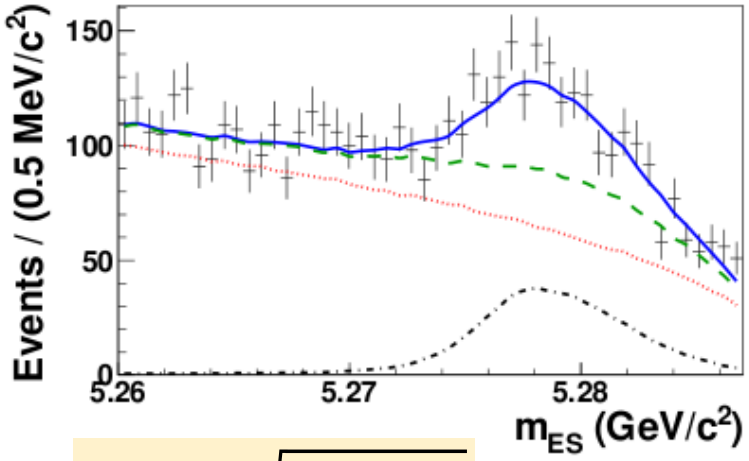
$B^+ \to K_S^0 \pi^+ \pi^0$

Phys. Rev. D **96**, 072001 (2017)

B → charmless decay, CKM supressed, small Branching Fractions

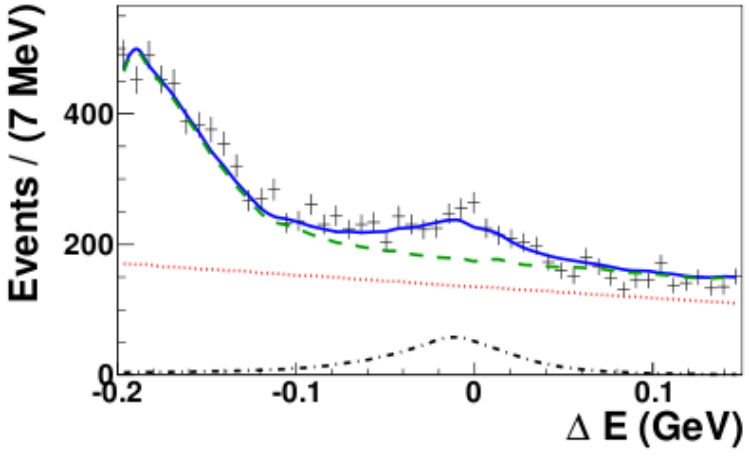
- Separated from background with ΔE, m_{ES} and boosted decision tree (BDT) output
- Simultaneous fit with Dalitz plot distribution

Signal yield of 1014 ± 60 decays

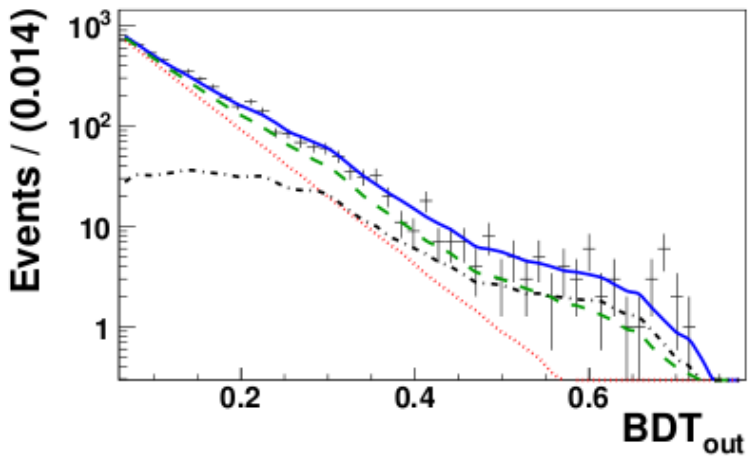


$$m_{ES} = \sqrt{E_X^2 - p_B^2}$$

$$E_X = (s/2 + \boldsymbol{p}_{e^+e^-}.\boldsymbol{p}_B)/E_{e^+e^-}$$



$$\Delta E = E_B^* - \sqrt{s}/2$$



Total fit

Signal

Total backgrounds

Continuum background

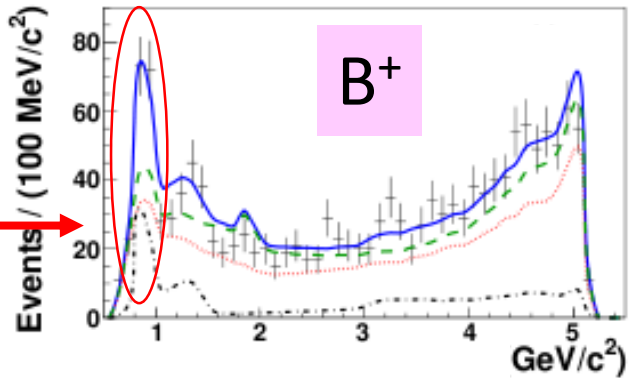
$B^+ \to K^0_S \pi^+ \pi^0$

Phys. Rev. D **96**, 072001 (2017)

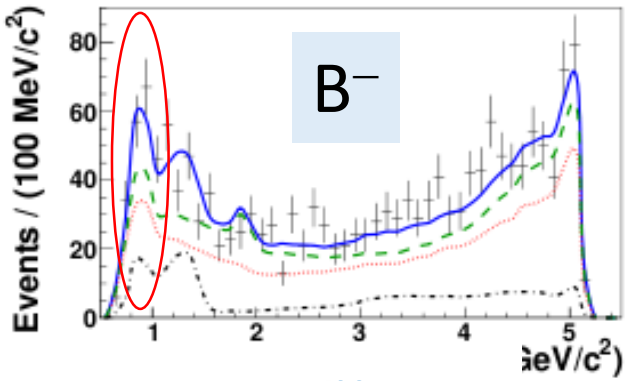
Evidence for CP violation in $B^+ \to K^{*+}(892)\,\pi^0$

3.4 σ

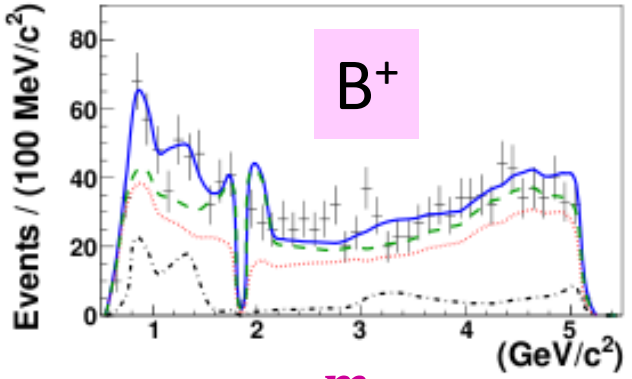
Decay channel	A_{CP}
$K^0\pi^+\pi^0$	$0.07 \pm 0.05 \pm 0.03^{+0.02}_{-0.03}$
$K^*(892)^0\pi^+$	$-0.12 \pm 0.21 \pm 0.08^{+0.0}_{-0.11}$
$K^*(892)^+\pi^0$	$-0.52 \pm 0.14 \pm 0.04^{+0.04}_{-0.02}$
$K_0^*(1430)^0\pi^+$	$0.14 \pm 0.10 \pm 0.04^{+0.13}_{-0.05}$
$K_0^*(1430)^+\pi^0$	$0.26 \pm 0.12 \pm 0.08^{+0.12}_{-0.0}$
$\rho(770)^+K^0$	$0.21 \pm 0.19 \pm 0.07^{+0.23}_{-0.19}$



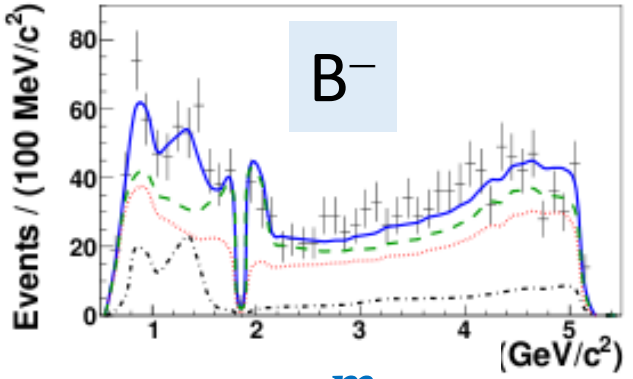
$m_{K_S\pi^+}$



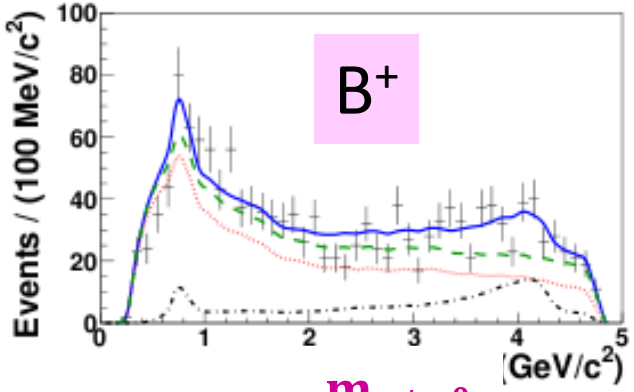
$m_{K_S\pi^-}$



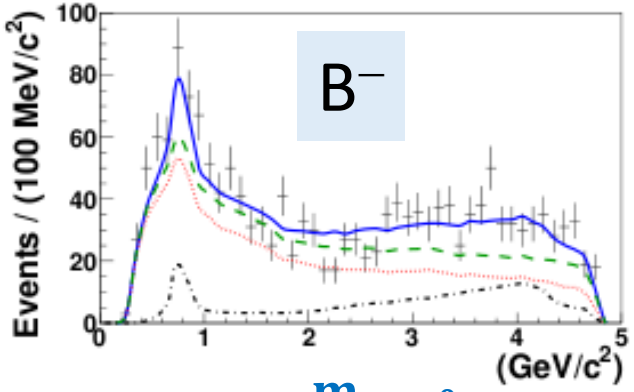
$m_{K_S\pi^0}$



$m_{K_S\pi^0}$



$m_{\pi^+\pi^0}$



$m_{\pi^-\pi^0}$

Dalitz plot projections

$B^+ \to K^0_S \pi^+ \pi^0$

Phys. Rev. D **96**, 072001 (2017)

Decay channel	$\mathcal{B}(10^{-6})$
$K^0\pi^+\pi^0$	$31.8 \pm 1.8 \pm 2.1^{+6.0}_{-0.0}$
$K^*(892)^0\pi^+$	$10.1 \pm 1.7 \pm 1.0^{+0.2}_{-0.3}$
$K^*(892)^+\pi^0$	$6.4 \pm 0.9 \pm 0.4^{+0.2}_{-0.3}$
$K^*_0(1430)^0\pi^+$	$34.6 \pm 3.3 \pm 4.2^{+1.9}_{-1.8}$
$K^*_0(1430)^+\pi^0$	$11.9 \pm 1.7 \pm 1.0^{+0.0}_{-1.3}$
$\rho(770)^+K^0$	$6.5 \pm 1.1 \pm 0.8^{+0.0}_{-1.7}$

First measurement of the branching fraction and CP asymmetry for $B^+ \to K^*_0(1430)^+ \pi^0$ (5.4 σ for BF).

Combine results for BF & CP asymmetries of $B^+ \to K^*(892)^0 \pi^+$, $B^+ \to K^*_0(1430)^0 \pi^+$, and $B^+ \to K^*(892)^+ \pi^0$ with the previous BABAR measurements.

Phys. Rev. D **96**, 072001 (2017)

Decay channel	$\mathcal{B}(10^{-6})$	A_{CP}
$K^*(892)^0\pi^+$	$10.5 \pm 0.6 \pm 0.9$	$0.025 \pm 0.050 \pm 0.016$
$K^*(892)^+\pi^0$	$6.8 \pm 0.8 \pm 0.5$	$-0.39 \pm 0.12 \pm 0.03$
$K^*_0(1430)^0\pi^+$	$34.1 \pm 1.1 \pm 4.3$	$0.040 \pm 0.033 \pm 0.033$

Search for new physics : K π puzzle

$\Delta A_{CP}(K\pi) = A_{CP}(K^+\pi^-) - A_{CP}(K^+\pi^0) = 0.122 \pm 0.022 \neq 0$ (5.5 σ) ; zero in SM but QCD effects

$\Delta A_{CP}(K^*\pi) = A_{CP}(K^{*+}\pi^0) - A_{CP}(K^{*+}\pi^-) = 0.16 \pm 0.13$ consistent with zero

Phys. Rev. D **96**, 072001 (2017)

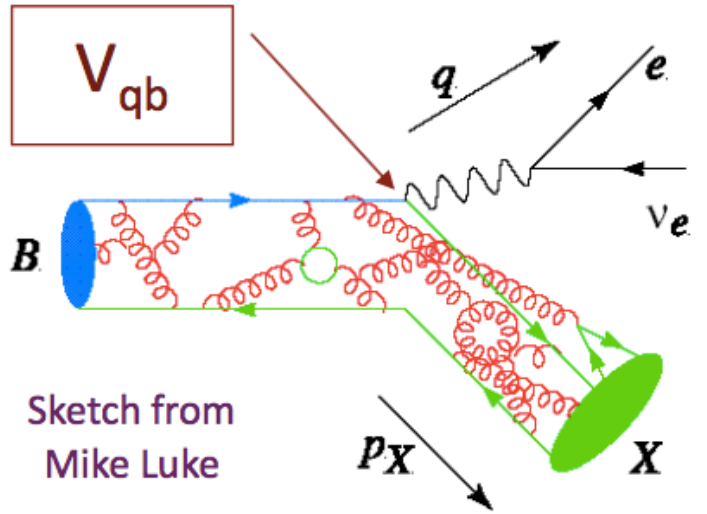
Vub measurement

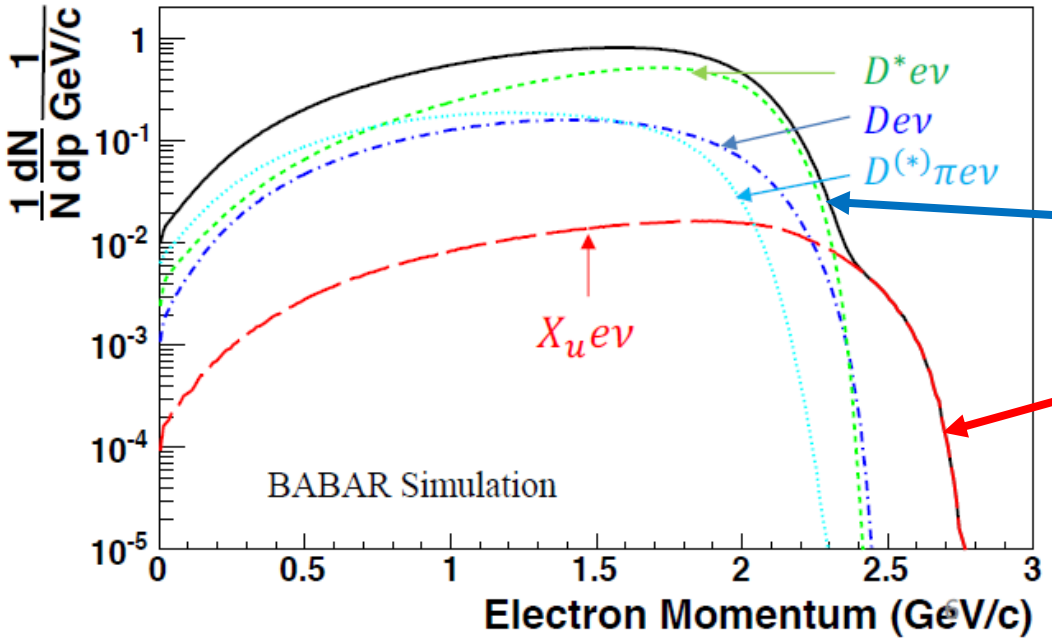
Importance of V_{ub}

- Length of one of the sides of the unitarity triangle
- The one opposite the best-measured CP-violating angle β

Extracted from $b \to u\ell\nu$ decay rates,
measured exclusively or inclusively
$B \to \pi\ell\nu$, etc. $B \to X_u\ell\nu$

Phys. Rev. D **95**, 072001 (2017)





V_{ub} measurement requires model for
$B \to X_c\ell\nu$ and
$B \to X_u\ell\nu$ distributions.

Vub measurement

Phys. Rev. D **95**, 072001 (2017)

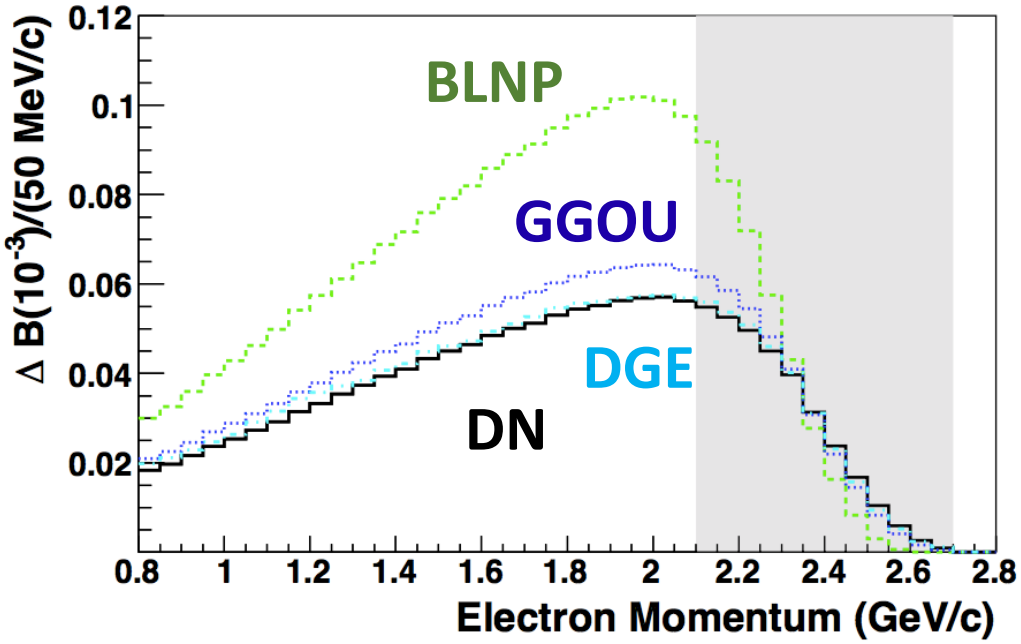
Measurement of the inclusive electron spectrum from B meson decays and determination of $|V_{ub}|$

Supersedes previous BABAR result with ~5 times more data
B. Aubert et al. (BABAR Collaboration), Phys. Rev. D 73, 012006 (2006).

Different theoretical QCD calculations for the electron momentum spectrum
Uncertainties largest near the endpoint!

- **DN** : DeFazio, and Neubert, JHEP 9906, 017 (1999) (superceded by BLNP)
- **BLNP** : Bosch, Lange, Neubert, Paz, Nucl. 894 Phys. B 699, 335 (2004)
- **GGOU** : Gambino, Giordano, Ossola, Uraltsev, JHEP 908 10, 058 (2007)
- **DGE** : Andersen, Gardi, JHEP 0601, 097 (2006)

Theoretical models span the full space of theoretical uncertainties



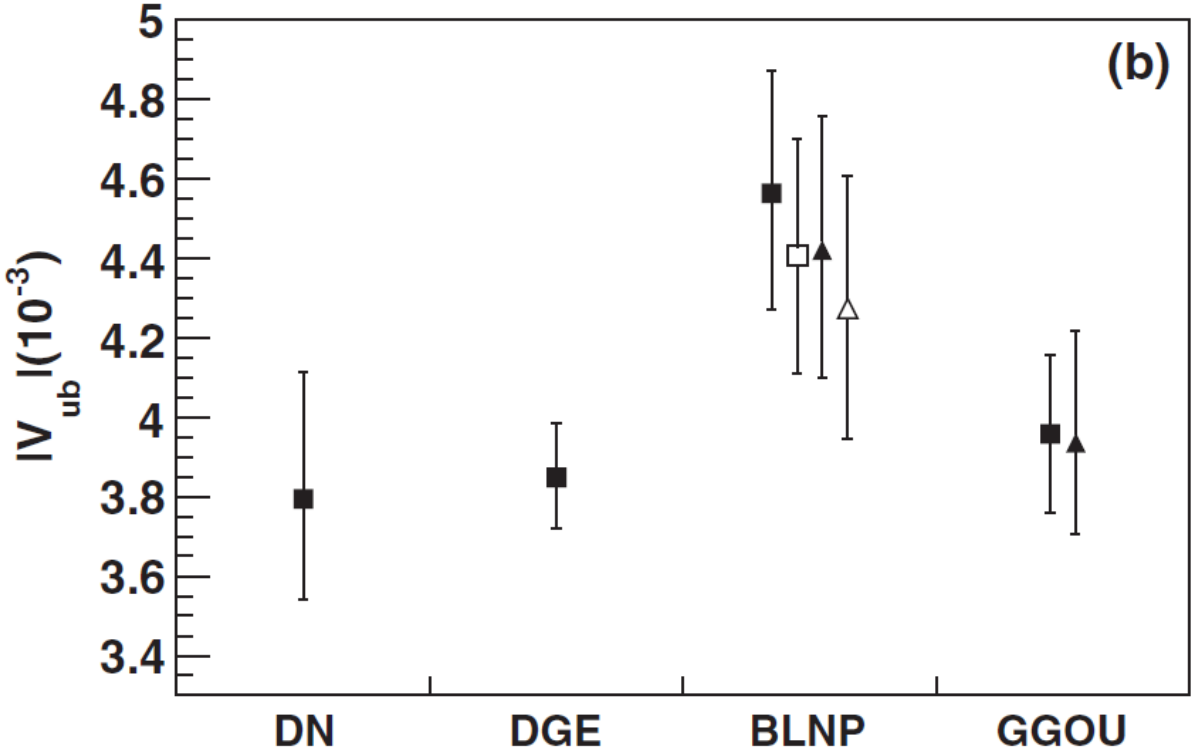
Vub measurement

RESULTS

Phys. Rev. D **95**, 072001 (2017)

$$|V_{ub}|\,(10^{-3})$$

- **DN** : $3.794 \pm 0.107_{exp}$ $^{+0.292}_{-0.219\ SF}$ $^{+0.078}_{-0.068\ theory}$
- **BLNP** : $4.563 \pm 0.126_{exp}$ $^{+0.230}_{-0.208\ SF}$ $^{+0.162}_{-0.163\ theory}$
- **GGOU** : $3.959 \pm 0.104_{exp}$ $^{+0.164}_{-0.154\ SF}$ $^{+0.042}_{-0.079\ theory}$
- **DGE** : $3.848 \pm 0.108_{exp}$ $^{+0.084}_{-0.070\ theory}$



Results correspond to solid squares on plot

exp : from BF measurement ;

SF : from shape function parameters (accounts for b quark motion inside B meson)

Other points than squares on the plot : based on different theoretical asumptions and experimental measurements to extract parameters

Summary and outlook

- First evidence for cos 2β > 0 and resolution of the CKM Unitarity Triangle ambiguity by a time dependent Dalitz plot analysis of $B^0 \to D^{(*)}h^0$
  - BABAR and Belle data combined : First evidence for cos 2β > 0 (3.7 σ)
  - Theoretically clean channel : Important for Belle II (50 x more statistics)for precise β measurements
  - Preliminary result, will be submitted to PRL and PRD this month.

- Evidence for CP violation (3.4 σ) in $B^+ \to K^*(892)\,\pi^0$ from a Dalitz plot analysis of $B^+ \to K_S^0\pi^+\pi^0$ decays.

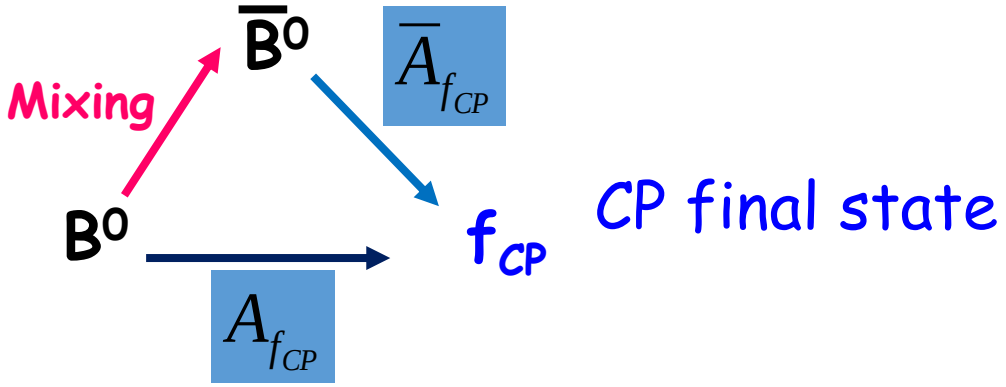
Phys. Rev. D **96**, 072001 (2017)

- New inclusive |Vub| measurements with the full statistics.
  - Important measurement to constrain the Unitarity Triangle
  - Supersedes old result with 5 times more statistics
  - Still important uncertainties from theoretical QCD calculations

Phys. Rev. D **95**, 072001 (2017)

BACK-UP Slides

CP violation in the interference between mixing and decay



Time-dependent CP asymmetry

$$A_{f_{CP}}(\Delta t) = \frac{\Gamma(\overline{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\overline{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})} = S_{f_{CP}} \sin(\Delta m_d \Delta t) - C_{f_{CP}} \cos(\Delta m_d \Delta t)$$

$$\lambda_{f_{CP}} \approx e^{-2i\beta} \times \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$

Mixing

$S \neq 0$: Indirect *CP* violation

$$S_{f_{CP}} = \frac{2\,\Im(\lambda_{f_{CP}})}{1 + |\lambda|^2_{f_{CP}}}$$

$C \neq 0$: Direct *CP* violation

$$C_{f_{CP}} = \frac{1 - |\lambda|^2_{f_{CP}}}{1 + |\lambda|^2_{f_{CP}}}$$

27

Time-dependent CP asymmetry

$$C_{f_{CP}} = \frac{1-|\lambda|^2_{f_{CP}}}{1+|\lambda|^2_{f_{CP}}} \qquad \lambda_{f_{CP}} \approx e^{-i2\beta} \times \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}} \qquad S_{f_{CP}} = \frac{2\,\Im(\lambda_{f_{CP}})}{1+|\lambda|^2_{f_{CP}}}$$

If only one diagram involved in $B^0 \to f_{CP}$ decay, no direct CP violation:

$$\left|A_{f_{CP}}\right| = \left|\bar{A}_{f_{CP}}\right| \Rightarrow C_{f_{CP}} = 0 \qquad \lambda_{f_{CP}} \approx e^{-i2\beta} \times e^{-i2\phi_{CKM}}, \quad S_{f_{CP}} = -\sin\left(2\times\left[\beta+\phi_{CKM}\right]\right)$$

ϕ_{CKM} is the CKM phase in $A_{f_{CP}}$

- 0 (ex: $b \to c$): sin2β measurement
- γ (ex: $b \to u$): sin2α measurement