BOSTJAN GOLOB
UNIVERSITY OF LJUBLJANA/
JOZEF STEFAN INSTITUTE

University
of Ljubljana

"Jozef Stefan"
Institute

ALSO WITH

BELLE

Belle II

INTRODUCTION

FACILITIES

SPECTROSCOPY

MIXING

CPV

(RARE) DECAYS

2ND OPEN BELLE II PHYSICS WEEK
KEK
28TH OCT - 1ST NOV 2019

Disclaimer

overview of experimental methods (not exhaustive) with selected examples

choice of subjects, and especially examples, had to be made;

speaker is to be blamed for not showing your favorite measurement

Frequently used references:

PDG: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018).

HFLAV: Heavy Flavor Averaging Group, https://hflav.web.cern.ch/

PBF : The Physics of the B Factories, A. Bevan, B. Golob, T. Mannel. S. Prell, B. Yabsley eds., Eur. Phys. J. C 74 (2014) .

BIIPB: E. Kou, P. Urquijo etn al. (Belle II Coll.), arXiv:1808.10567

SETTING THE SCENE

K. TRABELSI
????

ON DEPUTY SPOKESPERSON'S REQUEST:

1964: CPV IN KAON SYSTEM
$K_L \rightarrow 45\ (2\pi)\ /\ 23 \cdot 10^3\ (3\pi)$

J. CRONIN, V. FITCH,
1980

1999 - 2010: BEAUTY IS THE NEW STRANGE
LARGE CPV IN B^0 *SYSTEM (2001)*
WITH ~7 · 10^2 $B^0 \rightarrow J/\psi\, K_S$

2015 - : CHARM IS THE NEW BEAUTY
CPV IN D^0 DECAYS (2019)
WITH 1.4 · 10^7 $D^0 \rightarrow \pi\pi$

* SOME EXPLANATION OF THIS DIFFERENT DATA SIZES
P. 58

M. KOBAYASHI,
T. MASKAWA,

2008

PRECISE CHARM MEASUREMENTS REQUIRE LARGE DATA SAMPLES AND GOOD CONTROL OF SYSTEMATIC UNCERTAINTIES

WHY (NOT) CHARM PHYSICS?

CHARM QUARK:

- UPLIKE

PROCESSES WITH CHARM HADRONS ARE PROBING POTENTIAL NEW PHYSICS IN UPLIKE SECTOR

- SEMI-HEAVY

PROCESSES WITH CHARM HADRONS ARE SUBJECT TO RELATIVELY LARGE HADRONIC UNCERTAINTIES ($\sim 1/m_c$)

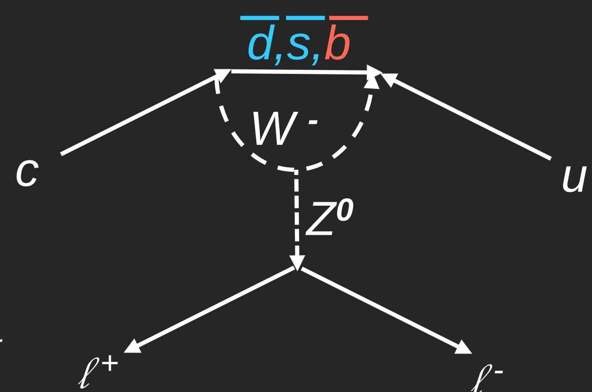
MORE ON GIM P. 29

- SUPPRESSED

FCNC (LOOP PROCESSES)

HEAVILY SUPPRESSED

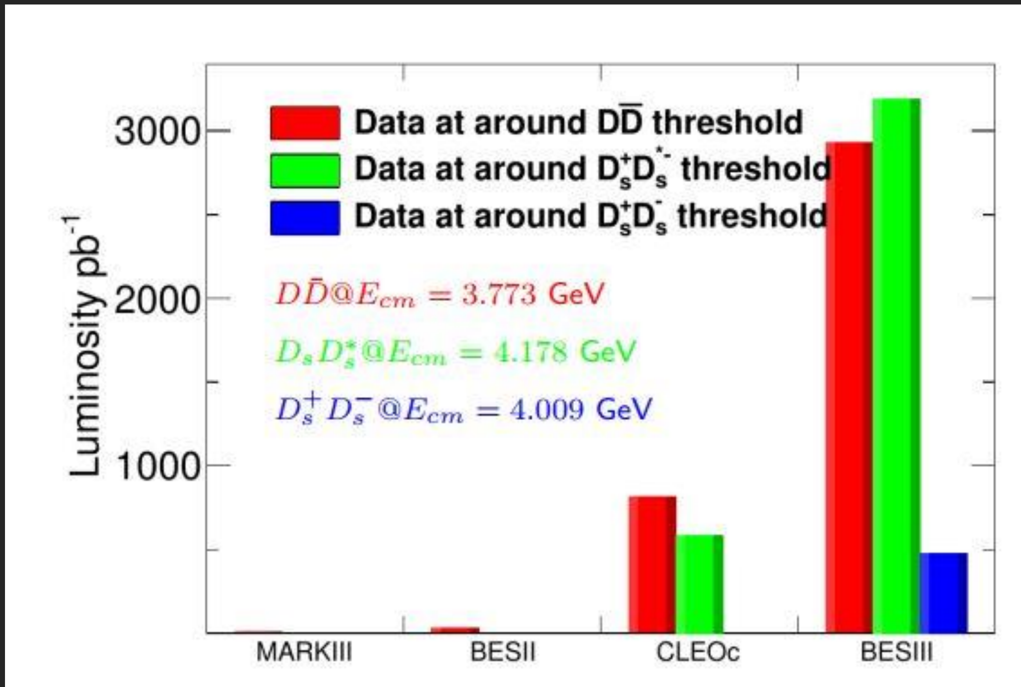
$D^0 \to \ell^+\ell^-$



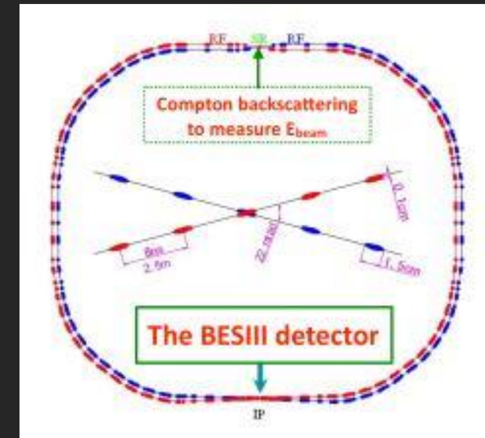
$$\left|V_{cb}^{*}V_{ub}\right|$$

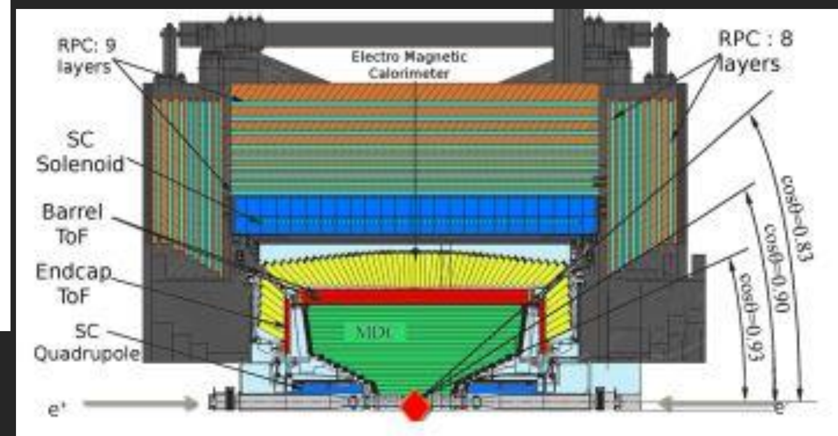
$$\frac{m_s^2 - m_d^2}{m_W^2}$$

BES III @ BEPC2



MORE ON P. 59





$e^+e^- \to \psi(3770) \to D\bar{D}$

$\sigma \sim$ few nb, *few* $\cdot\, 10^7$ $D\bar{D}$

- BACKGROUND FREE SAMPLES
- TAGGING (SINGLE MESON RECONSTRUCTION, BOTH MESONS RECONSTRUCTION)
- $\varepsilon \sim$ O(10%)

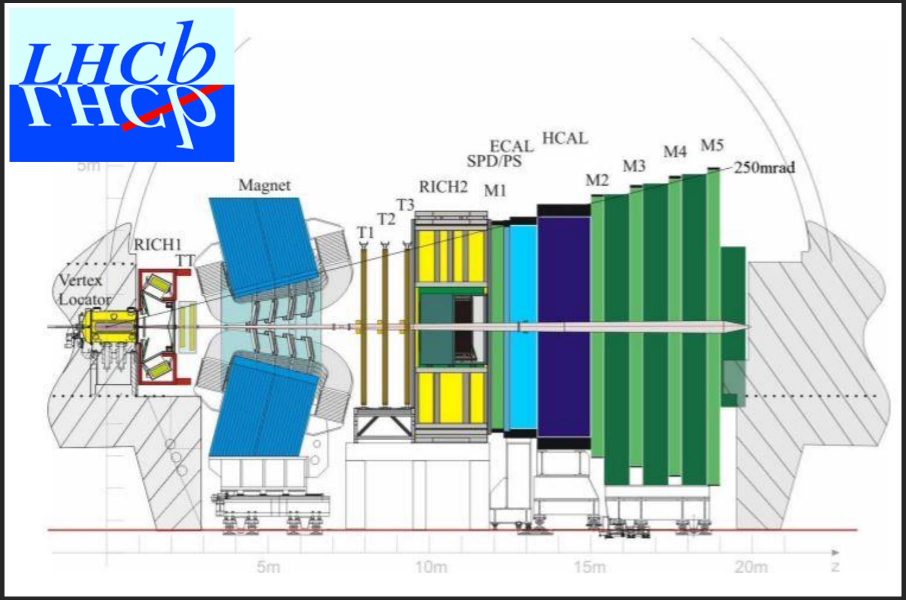
LHCb @ LHC

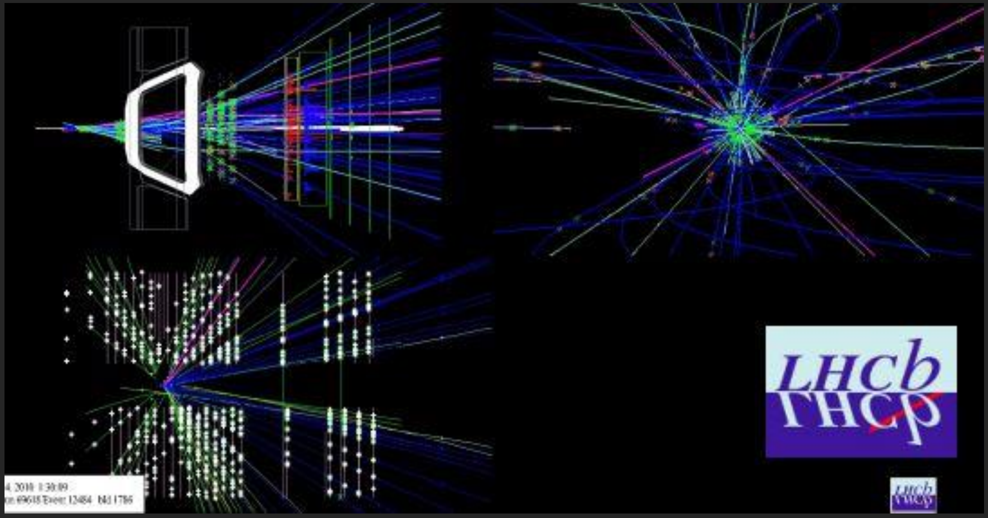
$$\sigma(pp \to D^0 X) = 2072 \pm 2 \pm 124\,\mu b,$$
$$\sigma(pp \to D^+ X) = 834 \pm 2 \pm 78\,\mu b,$$
$$\sigma(pp \to D_s^+ X) = 353 \pm 9 \pm 76\,\mu b,$$
$$\sigma(pp \to D^{*+} X) = 784 \pm 4 \pm 87\,\mu b,$$

R. Aaij et al.. (LHCb Coll.), JHEP 03 (2016) 159

$\int L dt$ = 9 fb^{-1}
~ 10^{10} D^{*+}

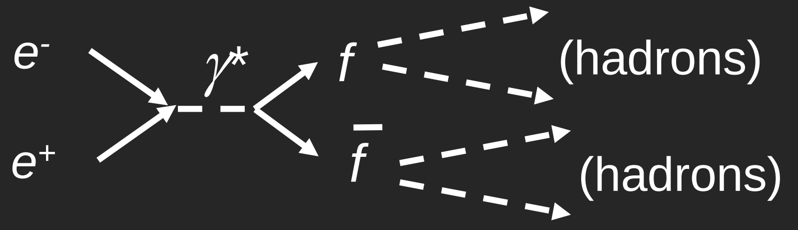
- complicated triggers, vtxing
- ε ~ O(0.1%)





BELLE (II) @ (SUPER)KEKB

– $\sigma(e^+e^- \to c\bar{c})$ @ $\sqrt{s}$ ~ 10.6 GEV ~ 1.3 NB
(N.B. $\sigma(e^+e^- \to \Upsilon(4S) \to B\bar{B})$ = 1.1 NB)



X_c	$\sigma(X_c Y)$ [PB]
$D^0 \to K^-\pi^+$	$1449 \pm 2 \pm 64 \pm 38$
$D^+ \to K^-\pi^+\pi^+$	$654 \pm 1 \pm 36 \pm 46$
$D_s^+ \to \phi\pi^+$	$231 \pm 2 \pm 92 \pm 77$
$\Lambda_c^+ \to p^+K^-\pi^+$	$189 \pm 1 \pm 66 \pm 66$
$D^{*0} \to D^0\pi^0$	$510 \pm 3 \pm 84 \pm 39$
$D^{*+} \to D^0\pi^+$	$598 \pm 2 \pm 77 \pm 20$
$D^{*+} \to D^+\pi^0$	$590 \pm 5 \pm 78 \pm 53$

R. SEUSTER ET AL.. (BELLE COLL.), PHYS.REV. D73, 032002 (2006)

Σ~ 2.5 NB ~ 2 $\cdot$ 1.3 NB *

* WHY SUMMING ONLY THESE? P. 60

$\int L dt$ = 1 AB^{-1}
~ 1.5 $\cdot 10^9$ D^0

- FULL RECONSTRUCTION (TAGGING) POSSIBLE
- ε ~ O(1%)

Belle (II) @ (SuperKEKB)

Production in $B \to h_c X$

h_c	<N(h_c)>/B decay
$D^0 \to K^-\pi^+$	$0.644 \pm 0.003 \pm 0.024 \pm 0.021$
$D^+ \to K^-\pi^+\pi^+$	$0.248 \pm 0.004 \pm 0.033 \pm 0.020$
$D_s^+ \to \phi\pi^+$	$0.122 \pm 0.015 \pm 0.033 \pm 0.030$
$\Lambda_c^+ \to p^+K^-\pi^+$	$0.042 \pm 0.011 \pm 0.033 \pm 0.018$
$D^{*0} \to D^0\pi^0$	$0.217 \pm 0.014 \pm 0.020 \pm 0.018$
$D^{*+} \to D^0\pi^+$	$0.218 \pm 0.007 \pm 0.020 \pm 0.015$
$\to D^+\pi^0$	$0.202 \pm 0.014 \pm 0.022 \pm 0.018$

~ 1.05 h_c / B decay

~ $8 \cdot 10^8$ $B \to D^0 X$ in Belle dataset

R. Seuster et al.. (Belle Coll.), Phys.Rev. D73, 032002 (2006)

LHCb @ LHC

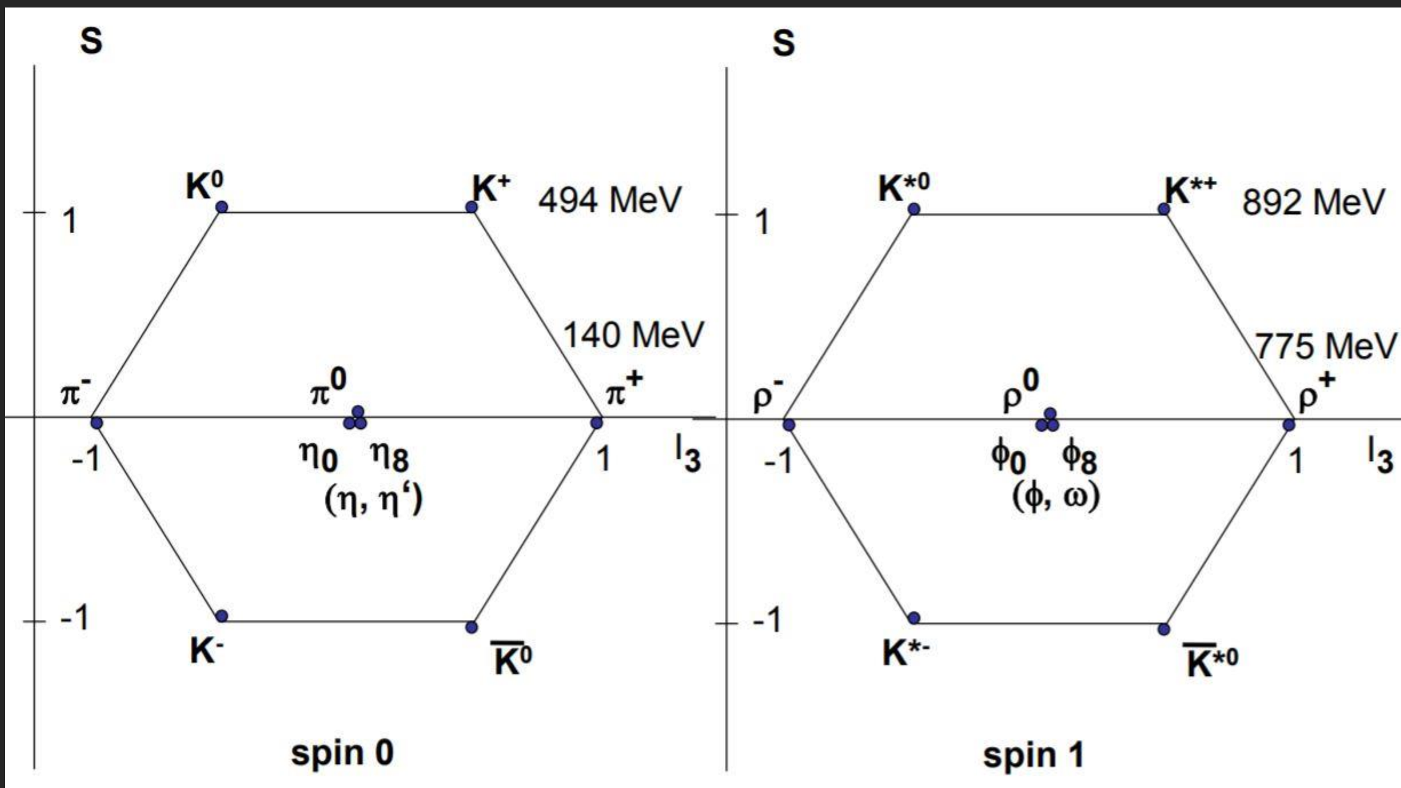
also cascade production R. Aaij et al.. (LHCb Coll.), JHEP 12 (2017) 026

$$\sigma(pp \to B^\pm X, \sqrt{s} = 7\,\text{TeV}) = 43.0 \pm 0.2 \pm 2.5 \pm 1.7\,\mu\text{b}$$
$$\sigma(pp \to B^\pm X, \sqrt{s} = 13\,\text{TeV}) = 86.6 \pm 0.5 \pm 5.4 \pm 3.4\,\mu\text{b}$$

$\to$ ~$8 \cdot 10^{11}$ $B \to h_c X$

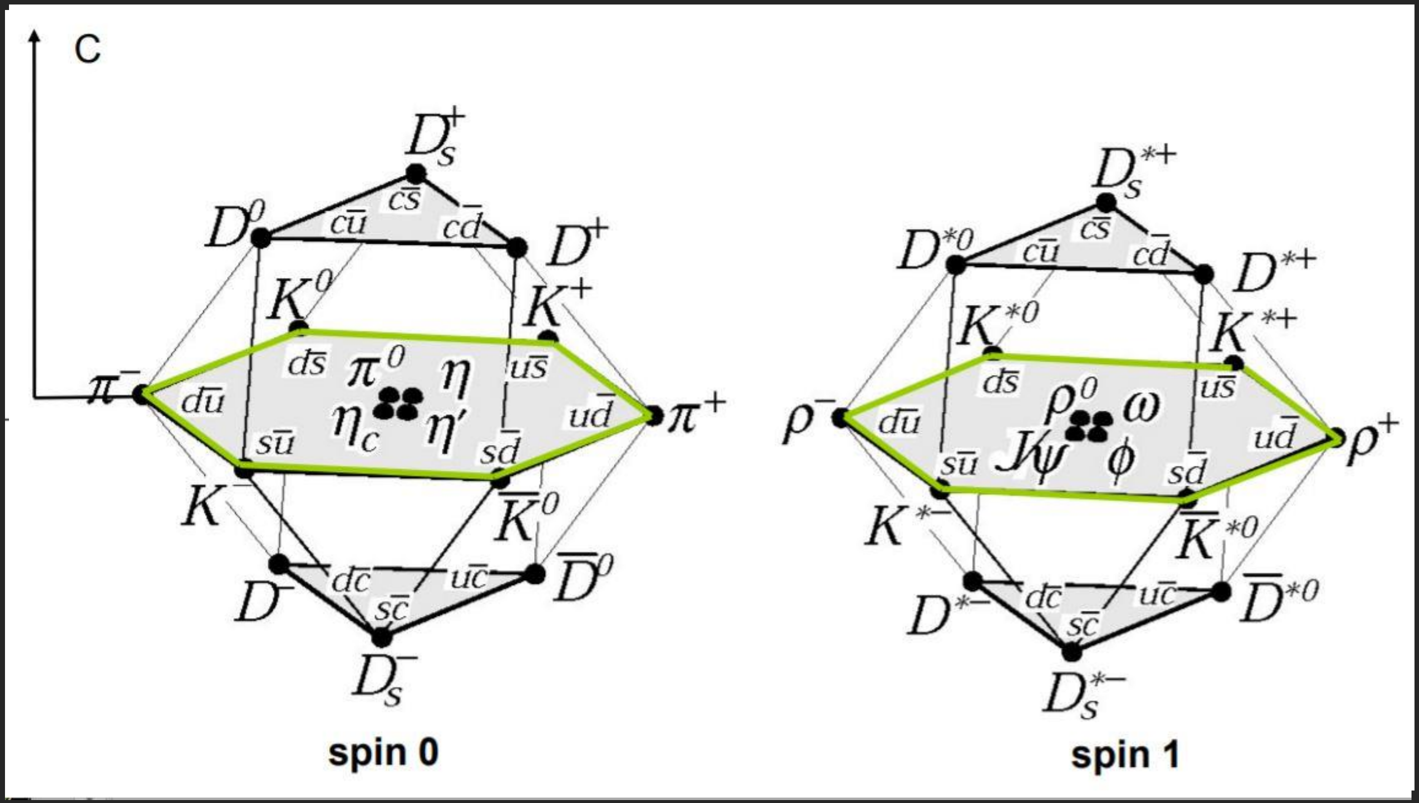
Conventional mesons

Quark model for *u, d, s*



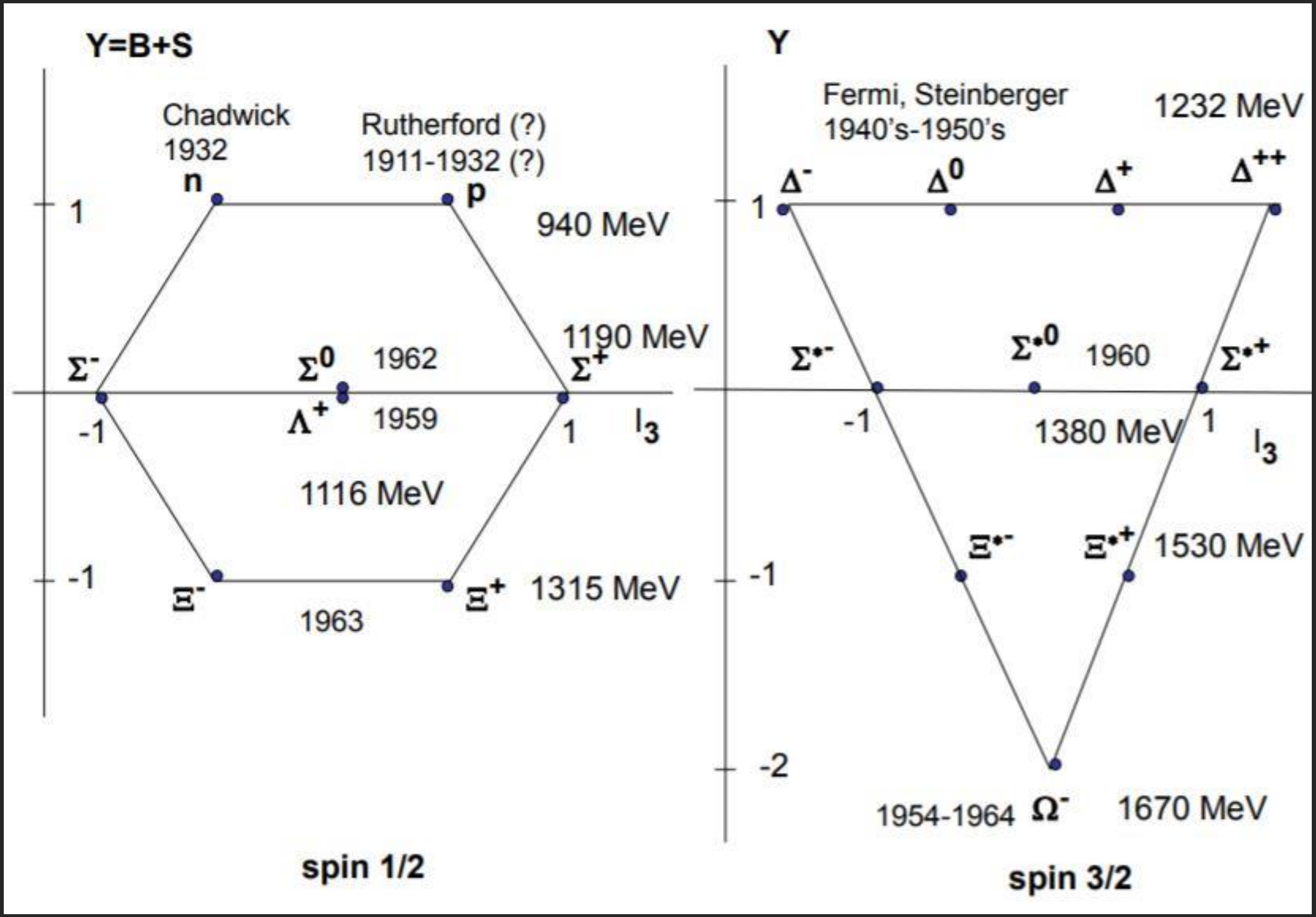
CONVENTIONAL MESONS

QUARK MODEL FOR *u, d, s*
+ *c*



CONVENTIONAL BARYONS

QUARK MODEL FOR *u, d, s*



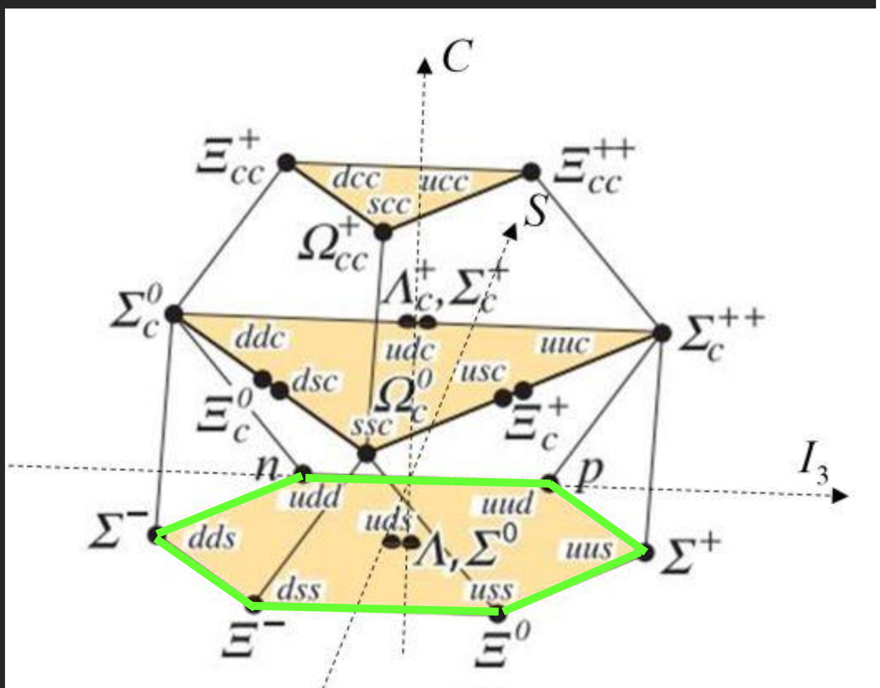
CONVENTIONAL BARYONS

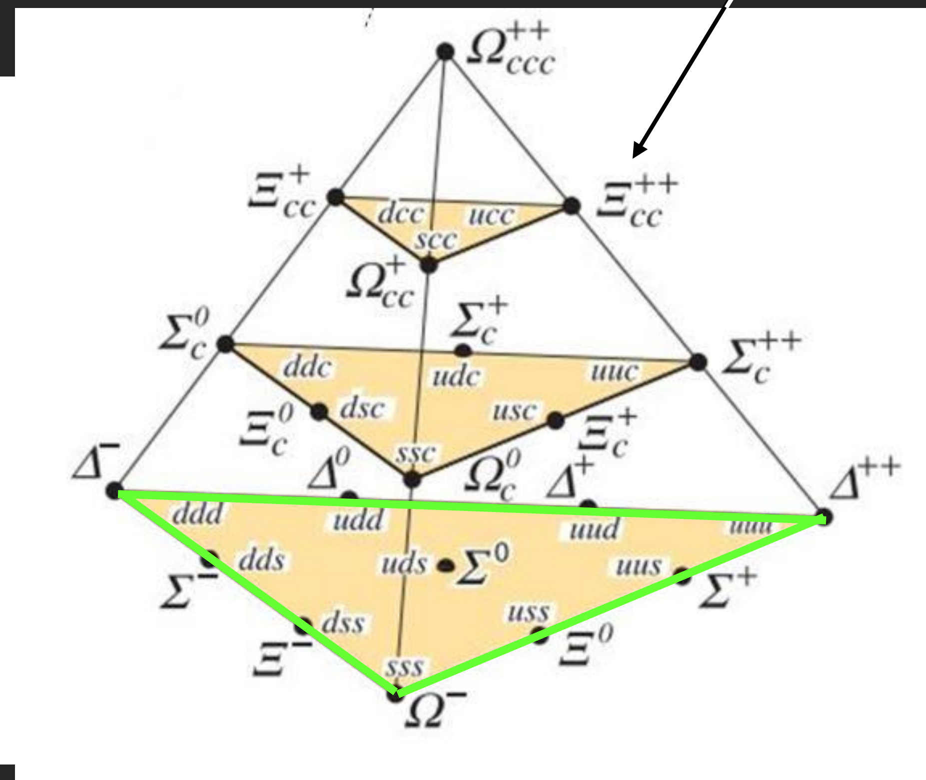
*LONGSTANDING PUZZLE ABOUT Ξ_{cc} P. 61

R. AAIJ ET AL.. (LHCB COLL.), PRL 119,112001 (2017)

QUARK MODEL FOR u, d, s + c

OBSERVED* ONLY IN 2017

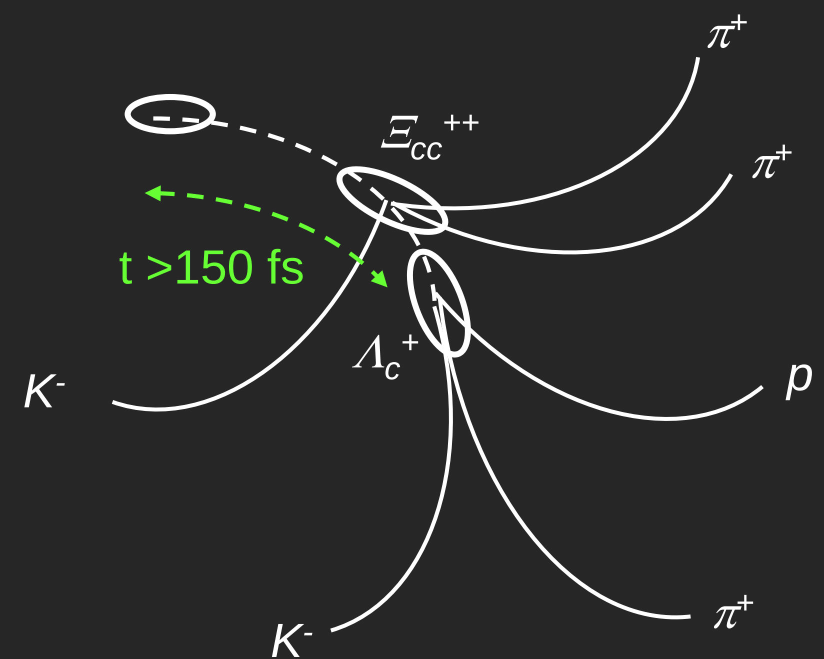




CHARM QUARKS ENRICH SPECTRUM OF CONVENTIONAL HADRONS AND ENABLE TESTS OF QUARK MODEL AND QCD FOR (SEMI)HEAVY HADRONS

Ξ_{cc}@ LHCb

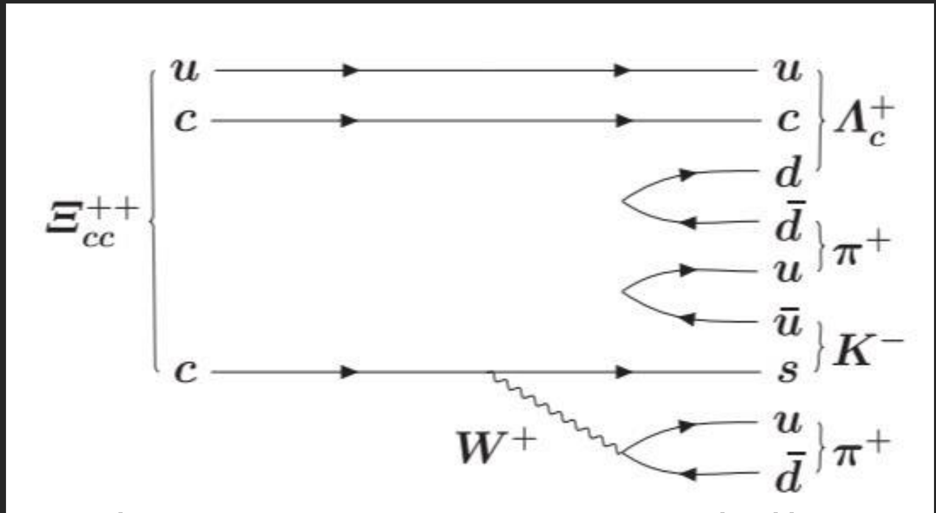
PRECISE VTXING FOR BKG REJECTION



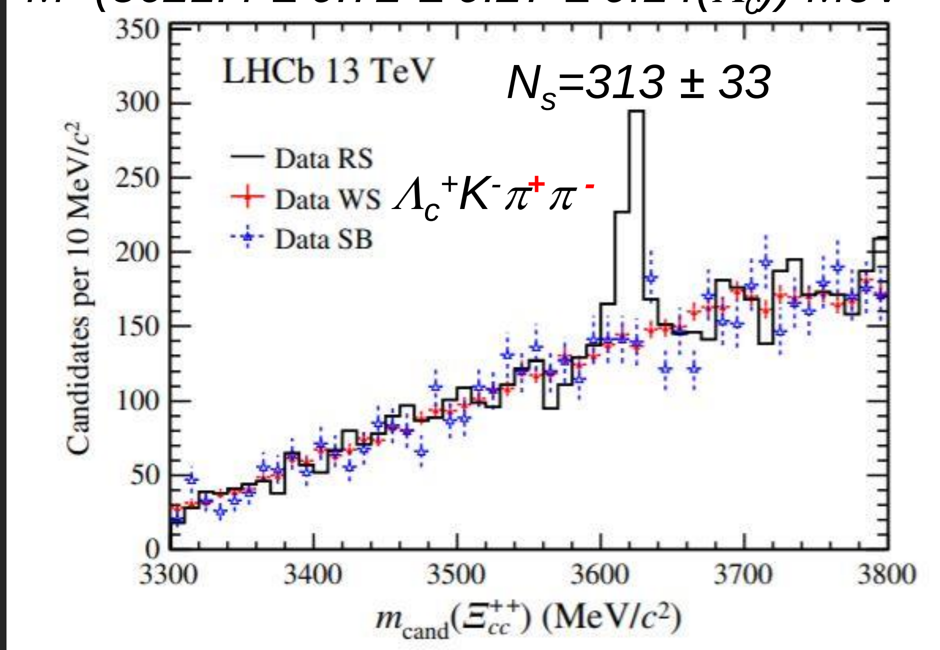
ALSO $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$

R. Aaij et al.. (LHCb Coll.), PRL 121,162002 (2018)

$$\frac{\mathcal{B}(\Xi_{cc}^{++}\to\Xi_c^+\pi^+)}{\mathcal{B}(\Xi_{cc}^{++}\to\Lambda_c^+K^-\pi^+\pi^+)} \approx 0.5$$



$M=(3621.4 \pm 0.72 \pm 0.27 \pm 0.14(\Lambda_c))$ MeV



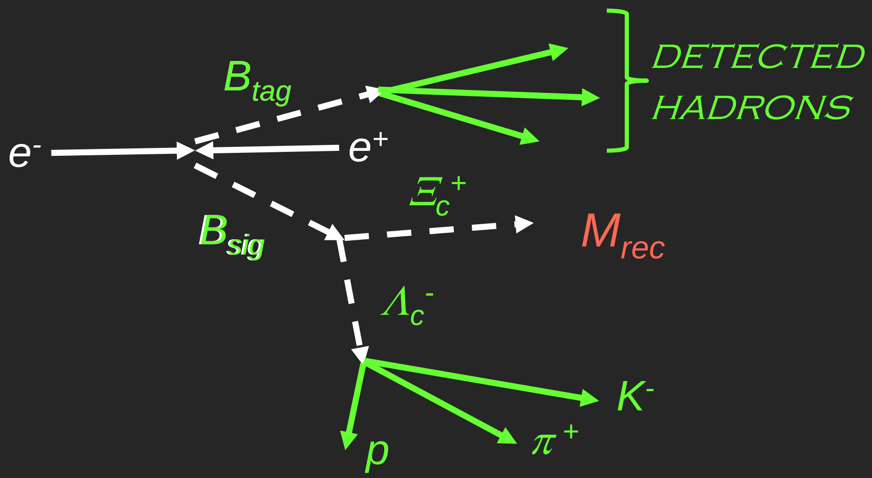
R. Aaij et al.. (LHCb Coll.), PRL 119,112001 (2017)

Absolute* Br measurements

Br($\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$) possible
because Br($\Xi_c^+ \to \Xi^- \pi^+ \pi^+$) known

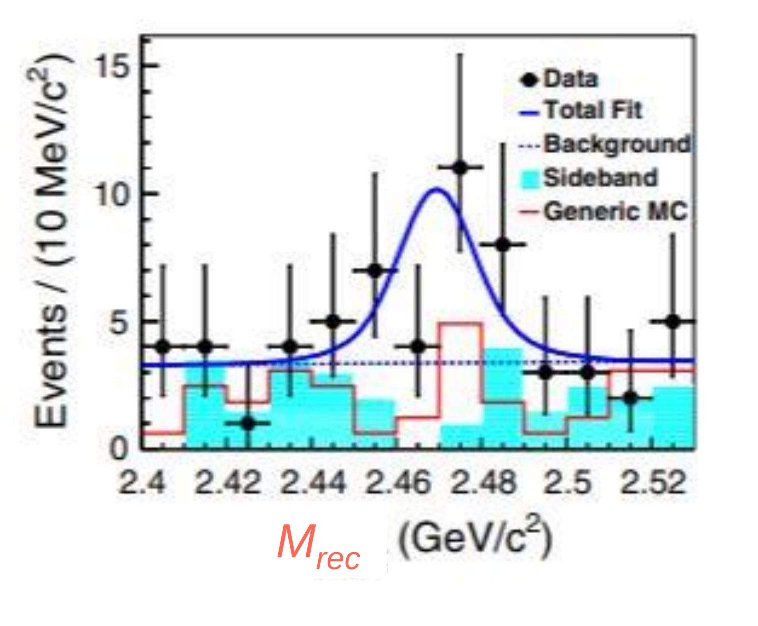
1) Br($B \to \Xi_c^+ \Lambda_c^-$)

Hadronic tagging (FEI @ Belle II)



* as opposed to relative w.r.t. some other decay

Y. B. Li et al.. (Belle Coll.), PRD 100, 031101(R) (2019)



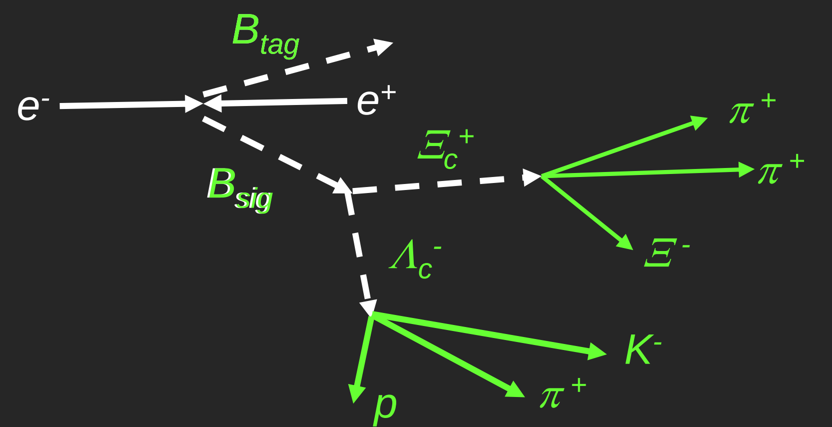
Absolute* Br measurements

Br($\Xi_{cc}^{++} \rightarrow \Xi_c^+\pi^+$) possible
because Br($\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$) known

1) Br($B \rightarrow \Xi_c^+ \Lambda_c^-$)

2) Br($B \rightarrow \Xi_c^+ \Lambda_c^-$) · Br($\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$)

Hadronic tagging (FEI @ Belle II)



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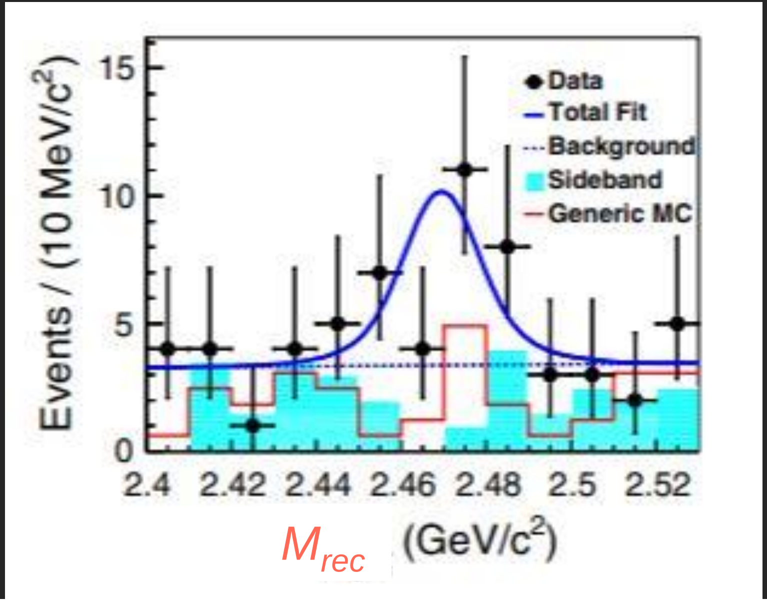
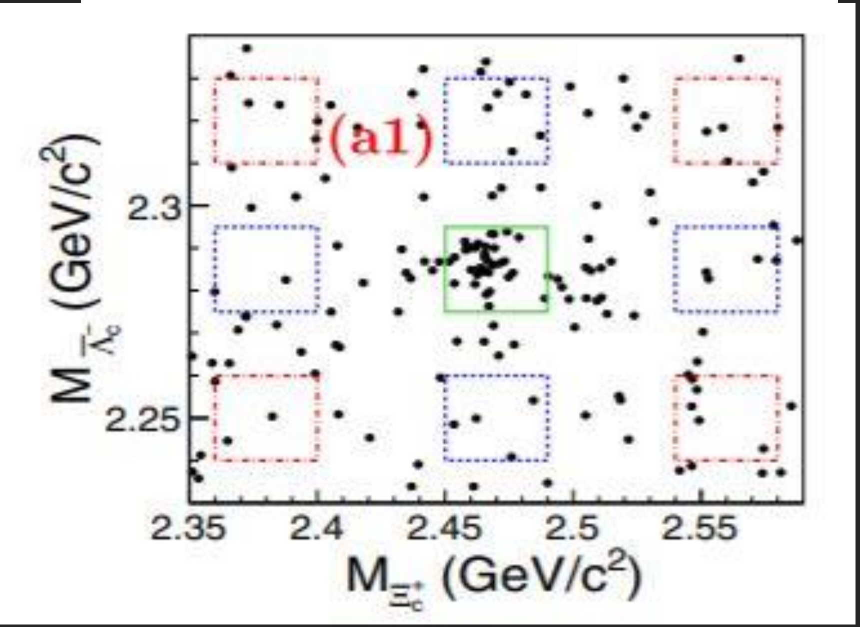
Y. B. Li et al.. (Belle Coll.), PRD 100, 031101(R) (2019)

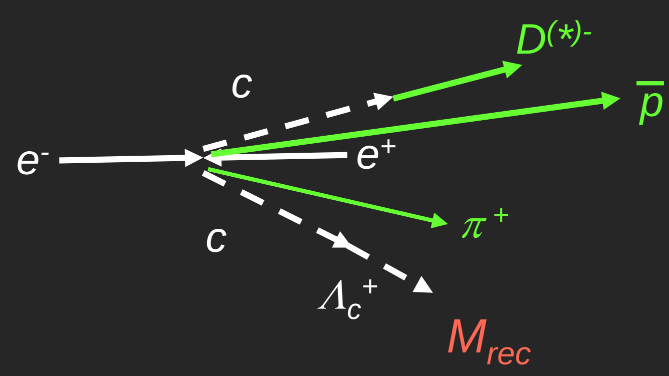


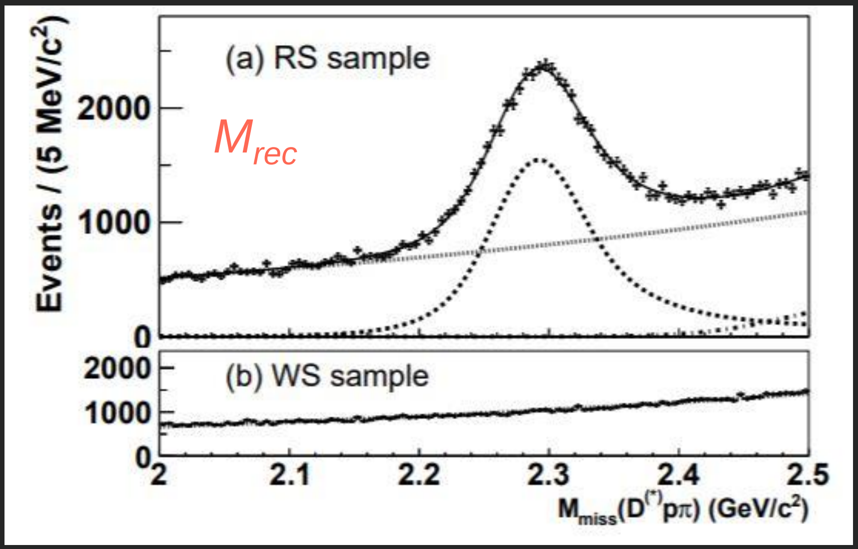


Absolute Br measurements

A. Zupanc et al.. (Belle Coll.), PRL 113, 042002 (2014)

Br($\Lambda_c^+ \to p K^- \pi^+$)

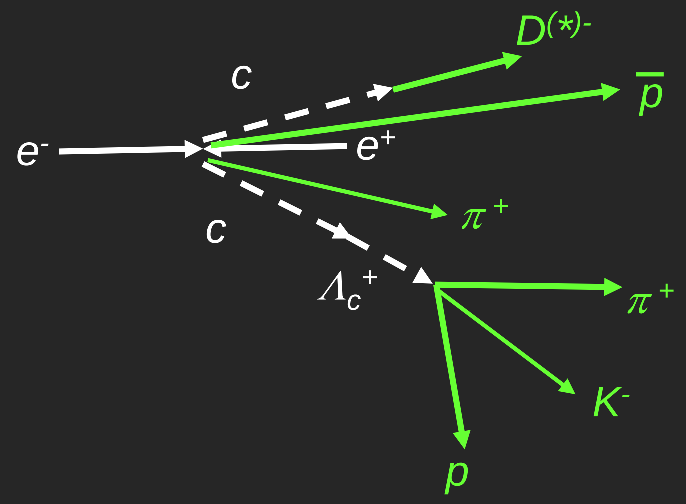


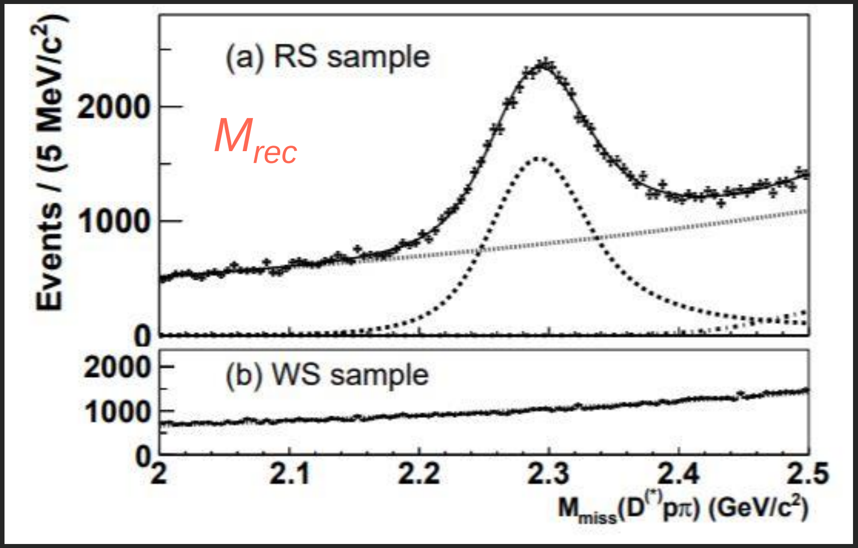


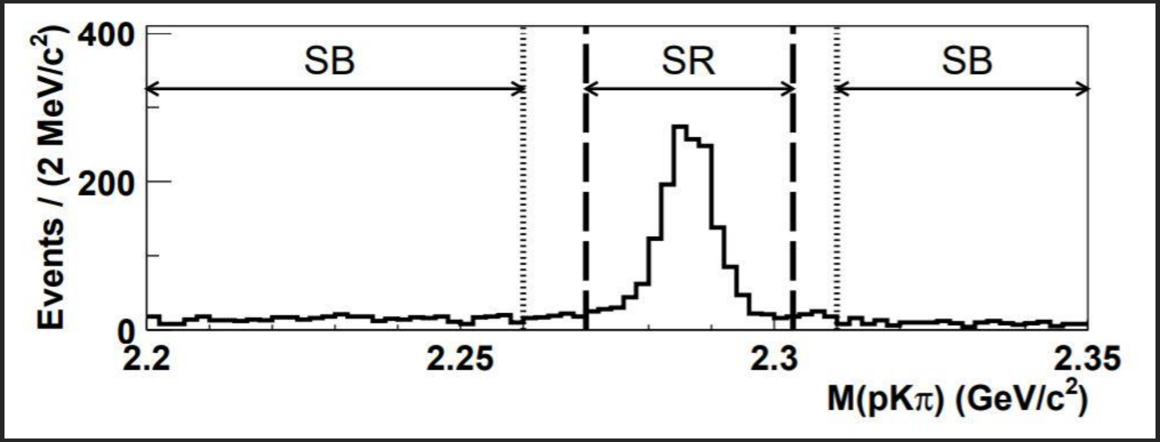
A. Zupanc et al.. (Belle Coll.), PRL 113, 042002 (2014)

Absolute Br measurements

Br($\Lambda_c^+ \to p K^- \pi^+$)





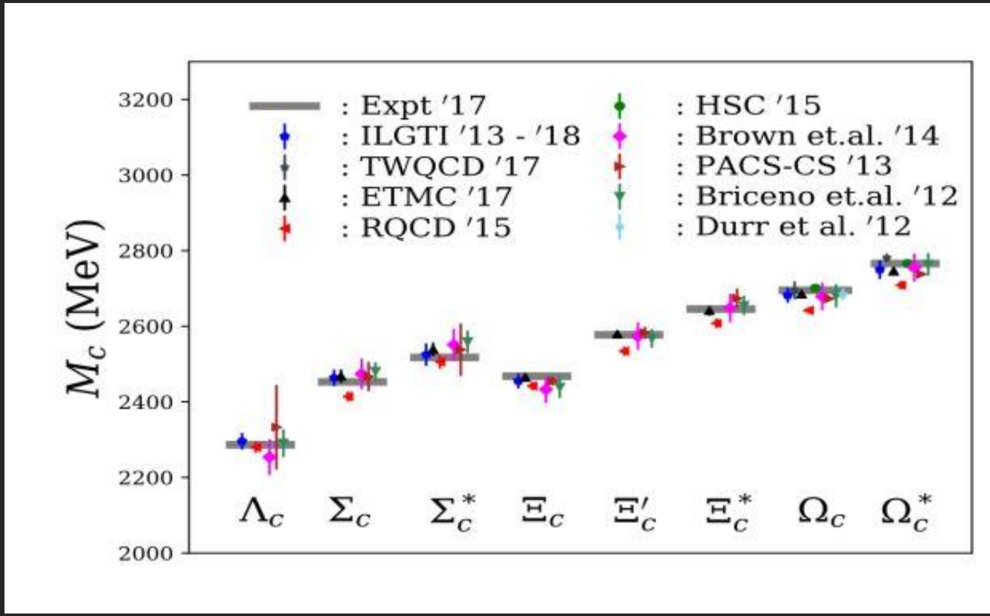


before: ±26%
(for many years)
after: ±5%

comparison to LQCD

charmed baryons

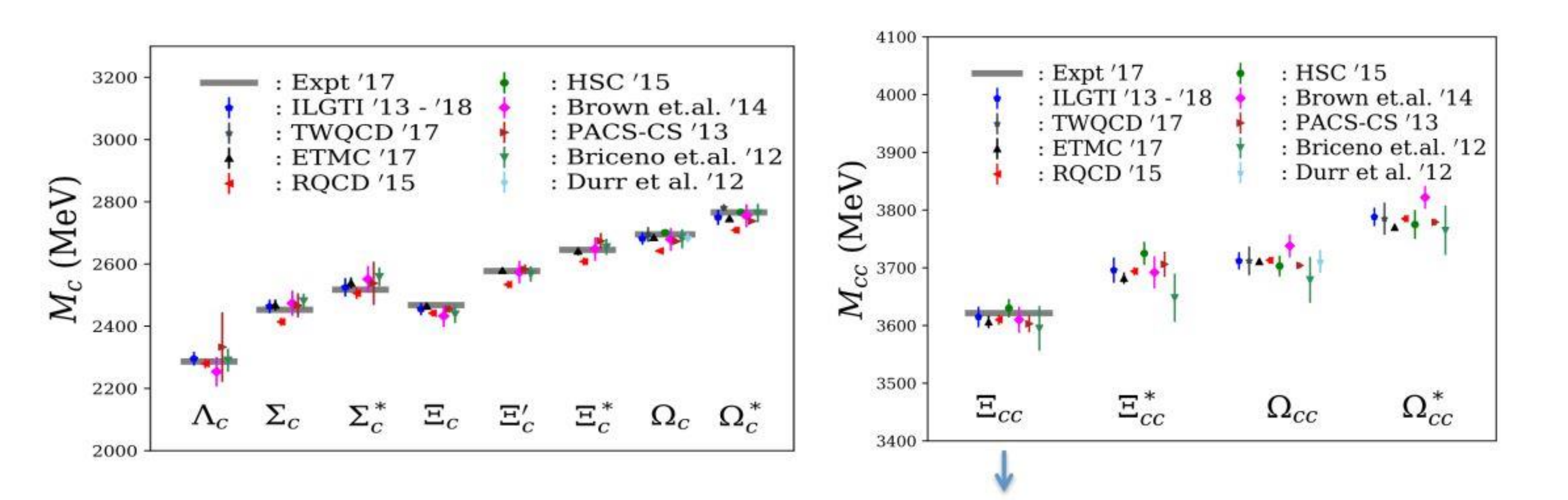
S. Prelovsek, Beauty 2019



Comparison to LQCD

Charmed baryons

S. Prelovsek, Beauty 2019



R. Aaij et al.. (LHCb Coll.), PRL 119,112001 (2017)

test of LQCD methods

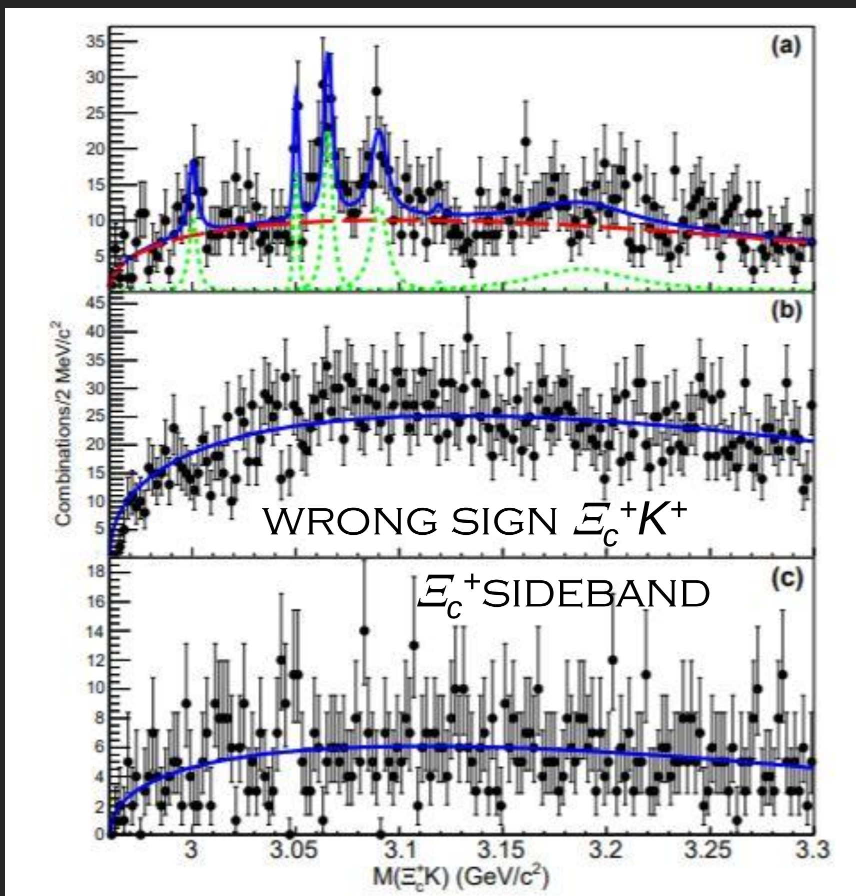
Spectroscopy Ω_c

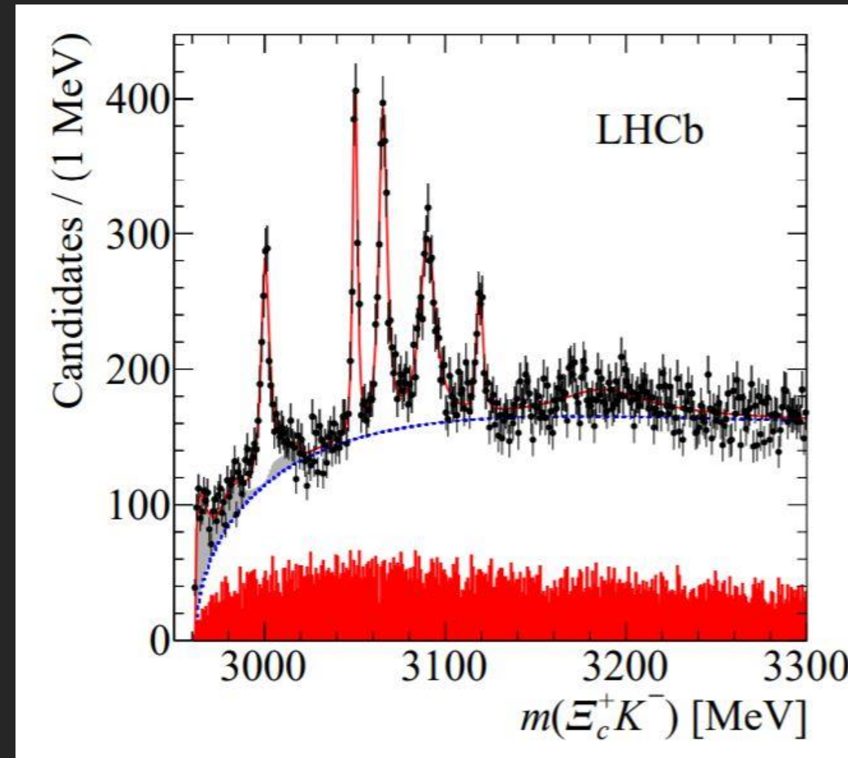
Excited states

excited Ω_c

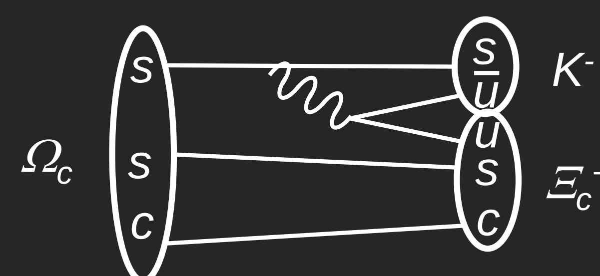
$\Omega_c^* \to \Xi_c^+(p\, K^- \pi^+)\, K^-$

(n.b. $m(\Omega_c)$=2.695 GeV)





R. Aaij et al.. (LHCb Coll.), PRL118, 182001 (2017)

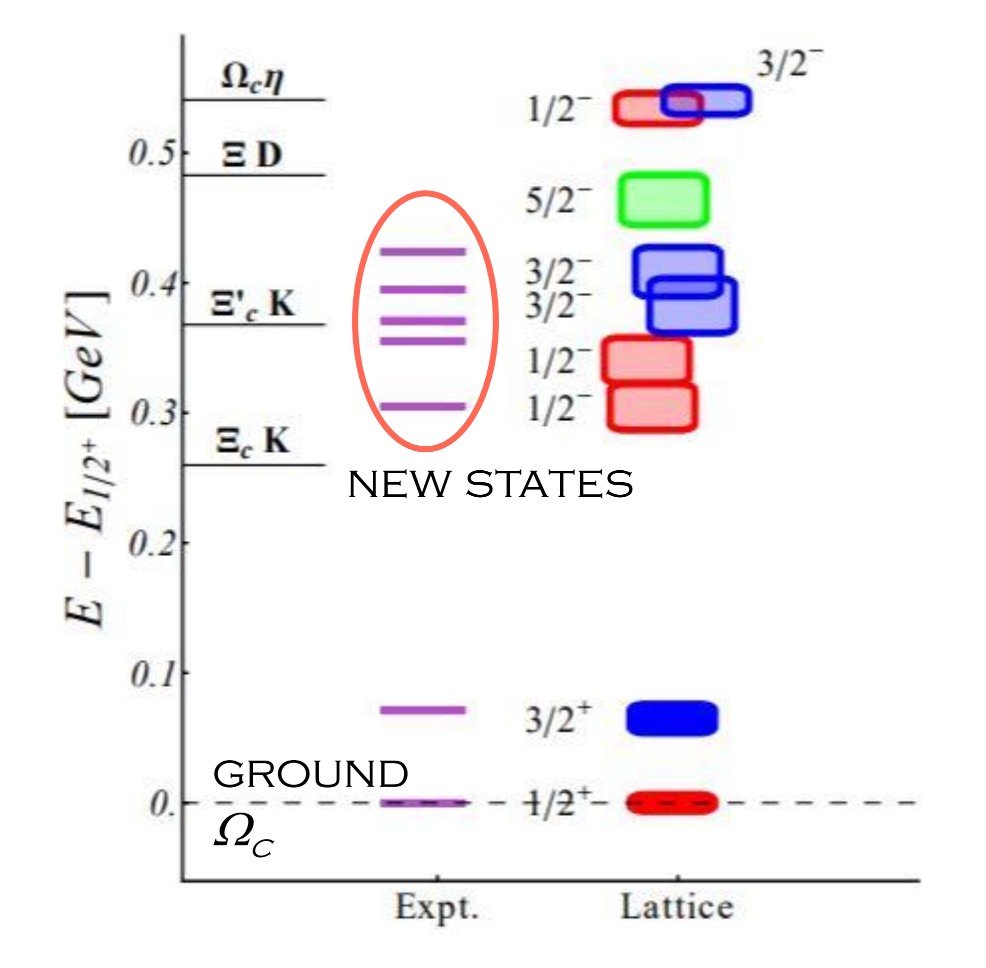


J. Yelton et al.. (Belle Coll.), PRD 97, 051102 (2018)

COMPARISON TO LQCD

EXCITED Ω_c

QUANTUM NUMBERS NOT MEASURED



M. PADMANATH, N. MATHUR, PRL 119, 042001 (2017)

UNCONVENTIONAL HADRONS

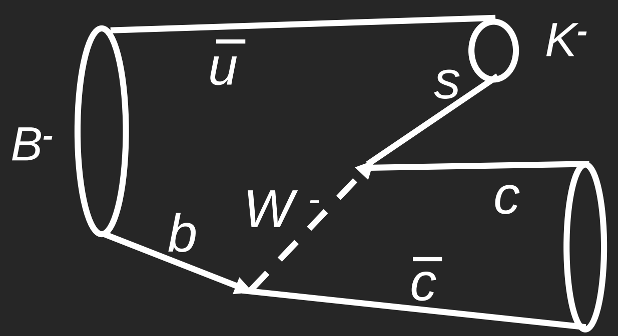
QCD: NO APRIORI LIMITATIONS ON HADRONS BEING COMPOSED ONLY AS $|q_1\bar{q}_2>$ OR $|q_1 q_2 q_3>$

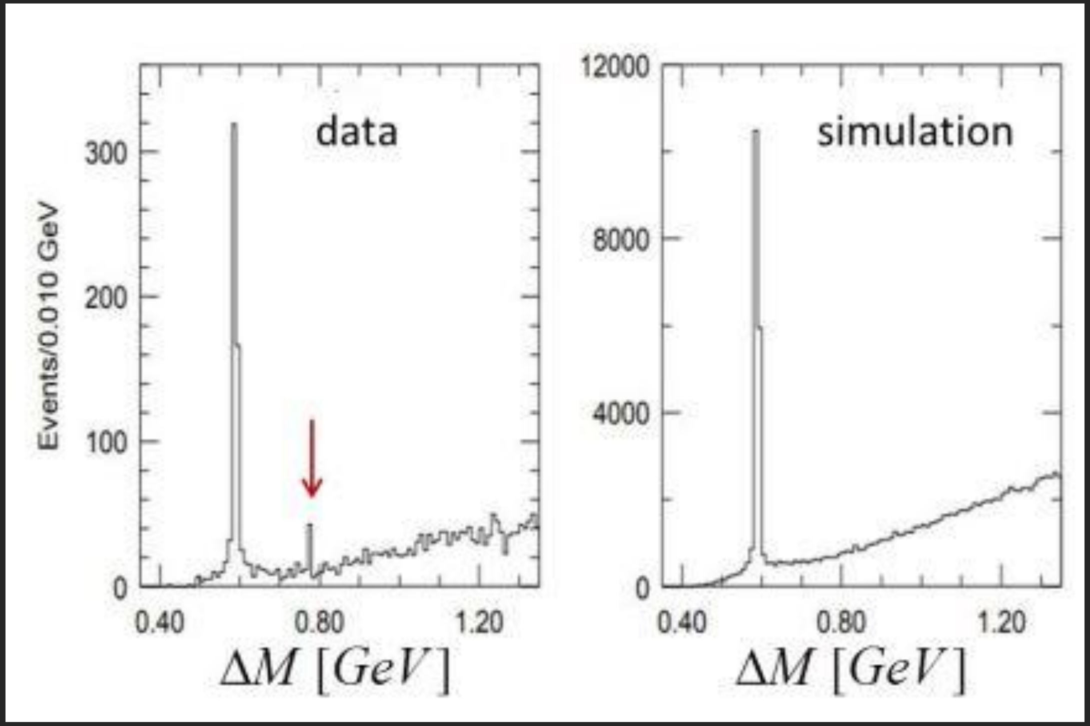
HADRONS WITH OTHER COMPOSITION: EXOTIC EXPLANATION ABOUT EXOTICS P. 62

FIRST EXAMPLE: *X(3872)*

$B^+ \to K^+ J/\psi\, (\ell^+ \ell^-)\, \pi^+ \pi^-$

$\Delta M = M(\pi^+ \pi^- \ell^+ \ell^-) - M(\ell^+ \ell^-)$





S.-K. CHOI ET AL. (BELLE COLL.), PRL 91, 262001 (2003)
(MOST CITED BELLE PAPER!)

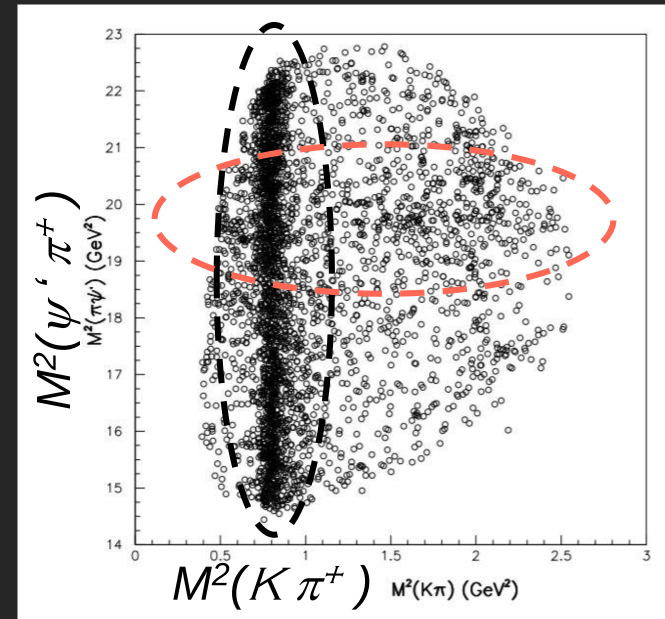
$B^+ \to K^+ X(\to J/\psi\, (\ell^+ \ell^-)\, \pi^+ \pi^-)$

MOST PROBABLY MIXTURE OF
$c\bar{c}$ & $c\bar{q}\bar{c}q$ *WHY? P. 63*
X(3872) ON LATTICE P. 64

Spectroscopy $Z^+(4430)$

Unconventional hadrons

S.-K. Choi et al. (Belle Coll.), PRL 100, 142001 (2008)

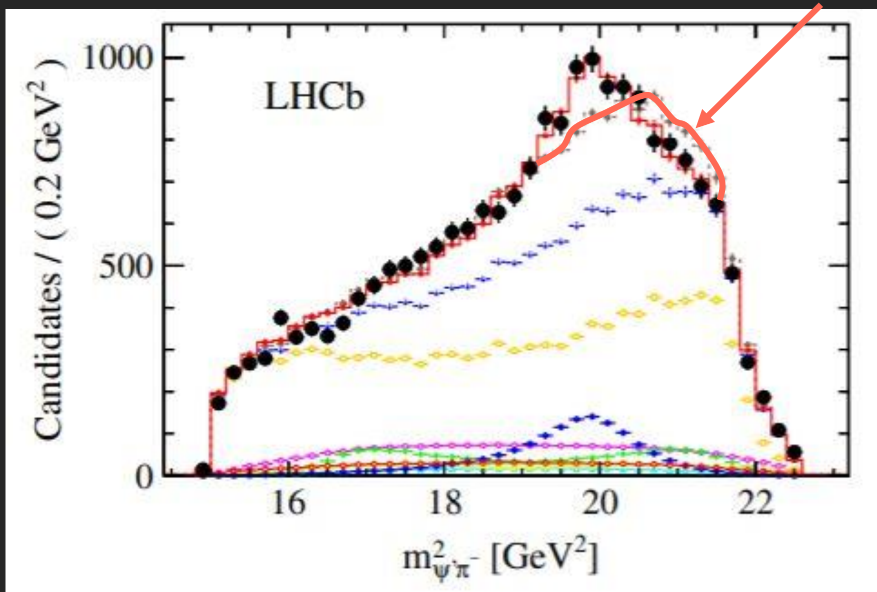


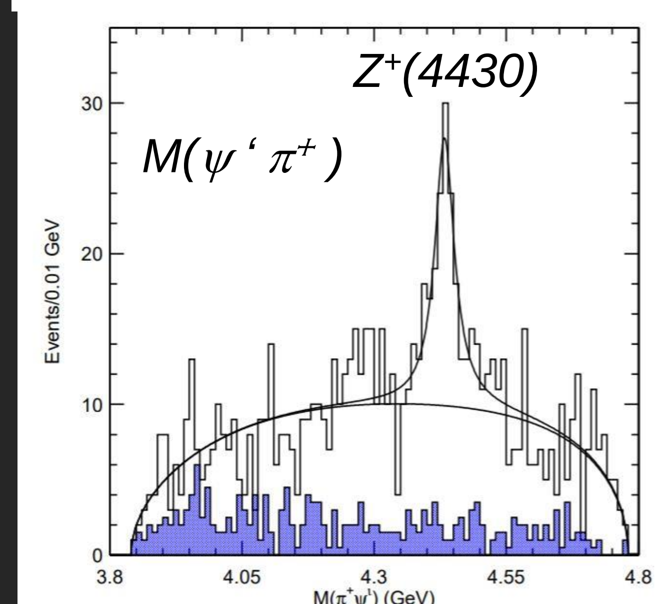
if $c\bar{q}\bar{c}q$, why not $c\bar{u}\bar{c}d$?

$B \to K\,\psi(2S)\,\pi^+$ more exotic states, including PQ's p.66

R. Aaij et al. (LHCb Coll.), PRL 112, 222002 (2014)

fit w/o $Z^+(4430)$





For new states: angular analysis to determine spin & parity!

e.g.: X(3915) in $B \to K\,\omega\,J/\psi$

is it $\chi_c(2P)\,(2^{++})$ or something else

UNCONVENTIONAL HADRONS

S.-K. CHOI ET AL. (BELLE COLL.), PRL 100,142001 (2008)

$B \to K \psi(2S) \pi^+$

$$Br(B^0 \to K^{\mp} Z^{\pm}) Br(Z^{\pm} \to \pi^{\pm} \psi') = (4.1 \pm 1.0 \pm 1.4) \cdot 10^{-5}$$

$$\Gamma = (45^{+18+30}_{-13-13})\ MeV$$

SYST. UNCERTAINTY DOMINATED BY BKG.;
MAJORITY OF BKG. COMBINATORIAL FROM B

121 ± 30 $Z^+(4430)$ SIGNAL EVTS FROM 605 fb^{-1}

200 ± 40 $Z^+(4430)$ SIGNAL EVTS / ab^{-1}

AT CERTAIN POINT NEED TO REDUCE BKG. (FOR LOWER SYST. UNCERTAINTY) →
LOWERING ε (LARGER STAT. UNCERTAINTY) ..... FEI !

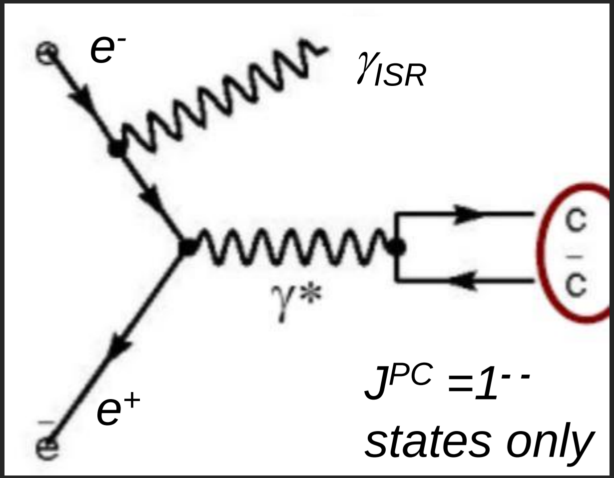
SOME TRIVIAL STATISICS P. 65

ASSUMING P WITH FEI IMPROVED BY 6X & ε_{FEI} ~ 1% :
NEED L ~ 15 ab^{-1} TO REACH SAME STAT. UNCERTAINTY AS AT 605 fb^{-1}
(AND PRESUMABLY MUCH LOWER SYST. UNCERTANTY)

ISR PRODUCTION

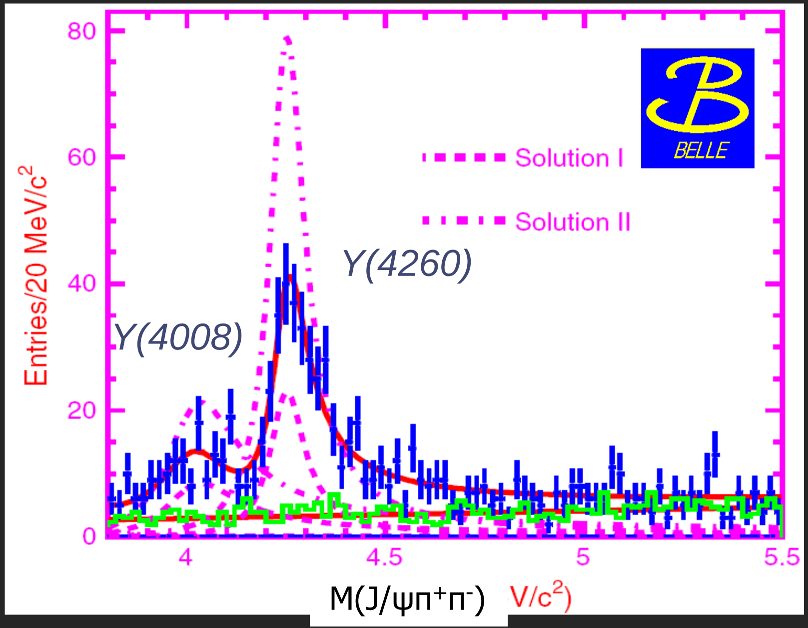
$e^+e^-\to J/\psi\pi^+\pi^-\gamma_{ISR}$ AND $\psi(2S)\pi^+\pi^-\gamma_{ISR}$

γ_{ISR} *MAY BE RECONSTRUCTED (TAGGED ANALYSIS) OR NOT (UNTAGGED, PROCESS IDENTIFIED THROUGH MISSING MASS)*

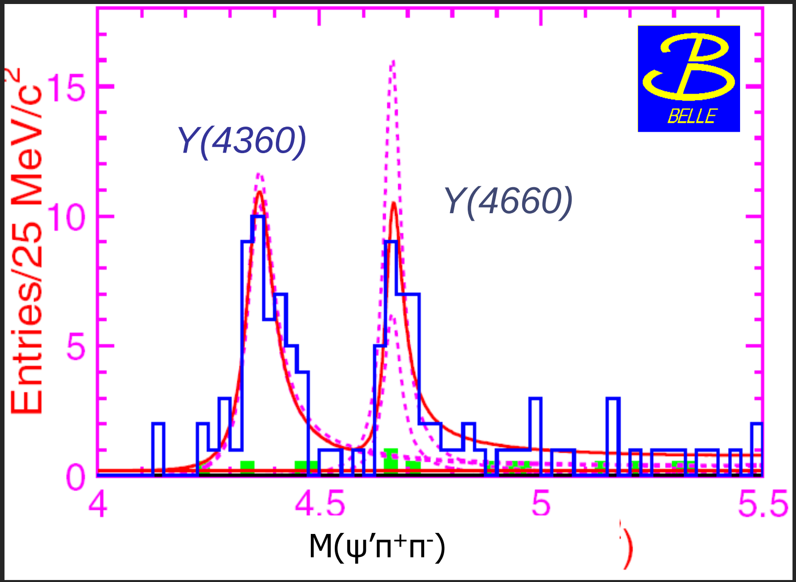


ISR PRODUCTION P. 67

C.Z. YUAN ET AL. (BELLE COLL.), PRL 99, 182004 (2007)



X.L. WANG ET AL. (BELLE COLL.), PRL 99, 142002 (2007)



Exotic ZOO

reconstructed in

$B \to X\,K$

State	J^{PC}
X(3872)	1^{++}
Y(3940)	J^{P+}
Z(3930)	2^{++}
Y(4140)	J^{P+}
X(4160)	0^{P+}
Y(4260)	1^{--}
X(4350)	J^{P+}
Y(4350)	1^{--}
Y(4660)	1^{--}

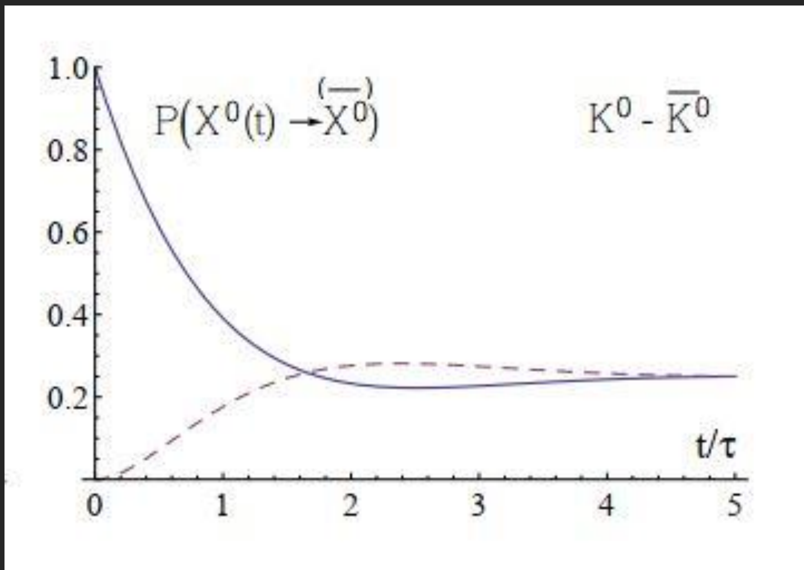
$e^+e^- \to \gamma_{ISR}\,X$

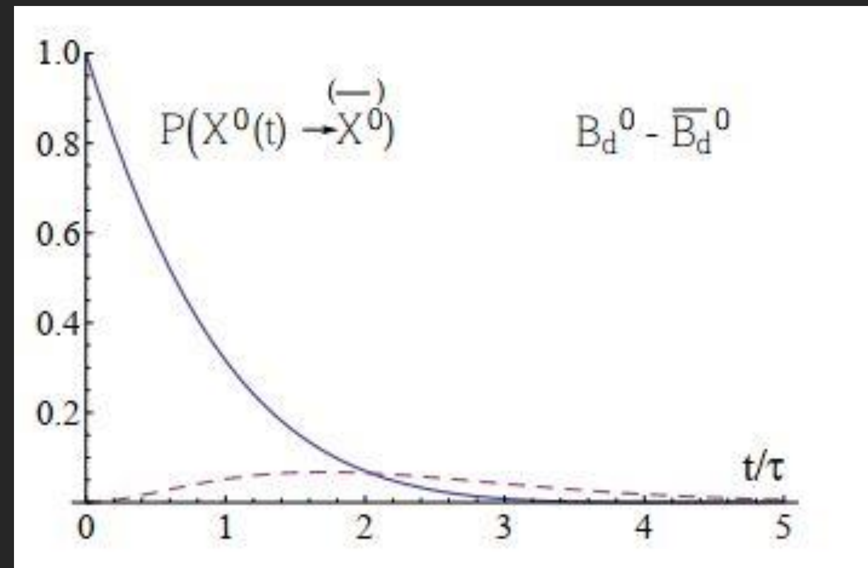
State	J^{PC}
Y(4260)	1^{--}
Y(4350)	1^{--}
Y(4660)	1^{--}

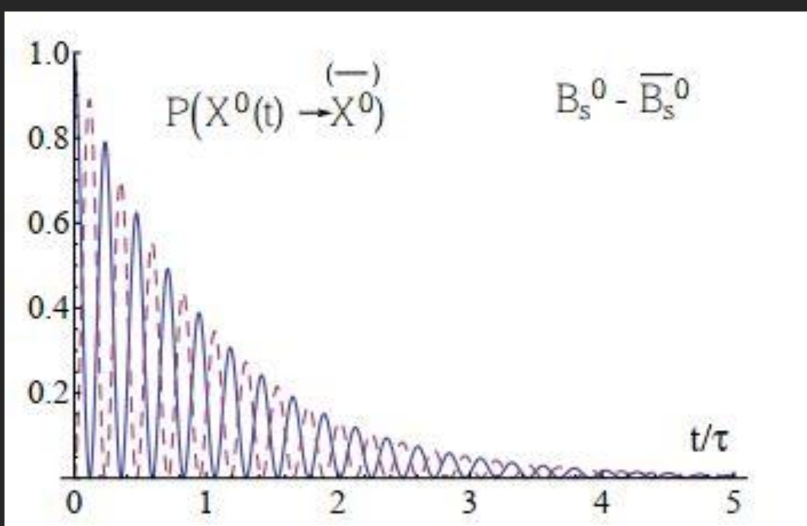
PBF

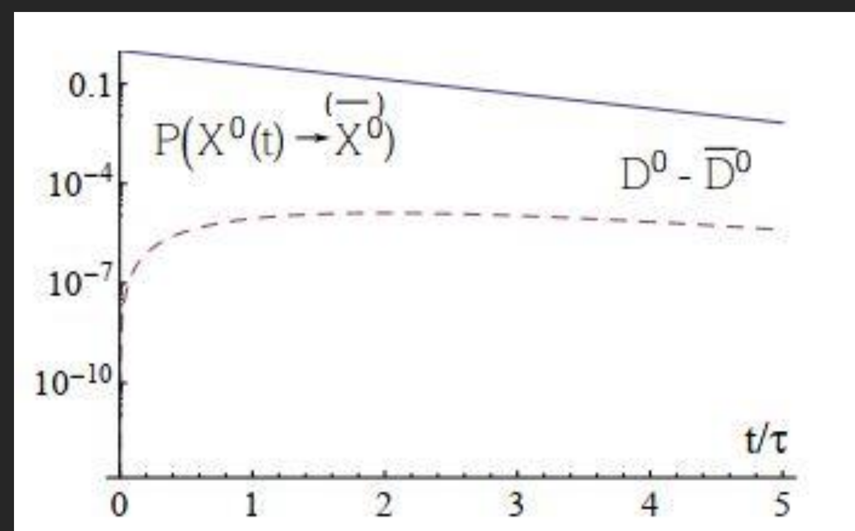
Spectroscopy of charmed hadrons represents a testbed for (L)QCD; several unconventional states represent a chalenge for theoretical description

Oscillations $M^0 \leftrightarrow \overline{M}^0$









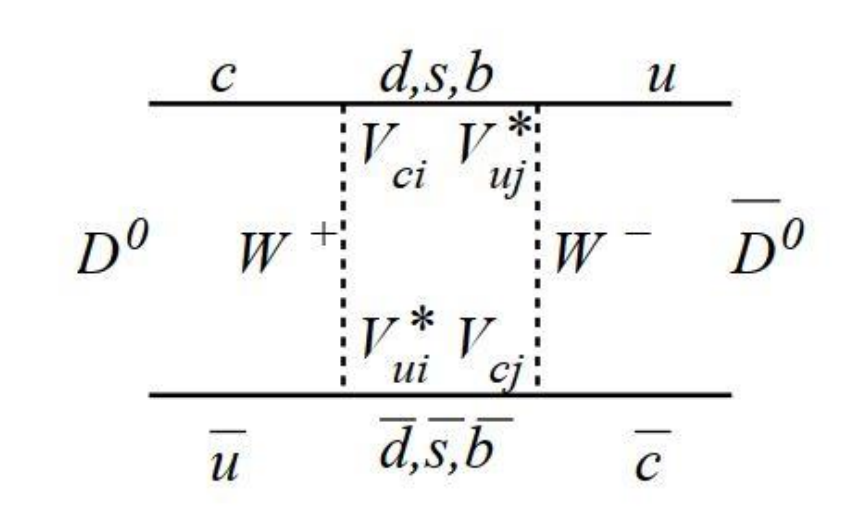
PBF

Oscillations $M^0 \leftrightarrow \overline{M}^0$

Meson	Discovery year and place	Mixing parameter
K^0	1950 Caltech	
Mixing	1956 Columbia	$x \approx 1, \quad y \approx 1$
B_d^0	1983 CESR	
Mixing	1987 DESY	$x \approx 0.8, \quad y \sim 0$
B_s^0	1992 LEP	
Mixing	2006 Fermilab	$x \approx 26, \quad y \sim 0.05$
D^0	1976 SLAC	
Mixing	2007 KEK, SLAC	$x \sim 0.01, \quad y \sim 0.01$

PBF

WHY SO SMALL?



$$\langle \overline{D}^0 | H^{\Delta C=2} | D^0 \rangle =$$

$$= \sum_{i,j=d,s,b} V_{ui}^* V_{ci} V_{cj} V_{uj}^* \mathcal{F}(m_W^2, m_i^2, m_j^2)$$

$$\mathcal{F}(m_W^2, m_i^2, m_j^2) \propto f_0 m_W^2 + f_1 m_i^2 + f_2 m_j^2 + f_3 m_i m_j + \mathcal{O}(m_W^{-2})$$

$$\langle \overline{D}^0 | H^{\Delta C=2} | D^0 \rangle = \frac{G_F^2 m_c^2}{4\pi^2} V_{cs}^* V_{cd}^* V_{ud} V_{us} \frac{(m_s^2 - m_d^2)^2}{m_c^4} \times \langle \overline{D}^0 | \overline{u}\gamma_\mu (1-\gamma^5) c \overline{u} \gamma^\mu (1-\gamma^5) c | D^0 \rangle \, .$$

DOUBLY CABIBBO SUPP.

VANISHES IN EXACT $SU(3)_{FLAVOR}$

D^0 MIXING PARAMETERS ARE DRIVEN BY DIFFICULT TO CALCULATE LONG-DISTANCE EFFECTS. NO LQCD CALCULATIONS EXIST (YET).

Phenomenology

$$\left|D_{1,2}\right\rangle = p\left|D^0\right\rangle \pm q\left|\overline{D}^0\right\rangle$$

Time evolution

flavor states ≠ H_{EFF} eigenstates:
(defined flavor) (defined $m_{1,2}$ and $\Gamma_{1,2}$)

$$x \equiv \frac{m_1 - m_2}{\overline{\Gamma}};\ y \equiv \frac{\Gamma_1 - \Gamma_2}{2\overline{\Gamma}};$$

$$\left|D^0(t)\right\rangle = \left[\left|D^0\right\rangle \cosh\left(\frac{ix+y}{2}\overline{\Gamma}t\right) - \frac{q}{p}\left|\overline{D}^0\right\rangle \sinh\left(\frac{ix+y}{2}\overline{\Gamma}t\right)\right] e^{-i\overline{m}t - \frac{\overline{\Gamma}}{2}t}$$

SM: $|x|, |y| \le \mathcal{O}(10^{-2})$ $|x|, |y| << 1 \Rightarrow$

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

$$\frac{dN(D^0 \to f)}{dt} \propto e^{-\overline{\Gamma}t}\left\langle f \middle| D^0 \right\rangle \left| 1 - \frac{q}{p}\frac{\left\langle f \middle| \overline{D}^0 \right\rangle}{\left\langle f \middle| D^0 \right\rangle}\frac{ix+y}{2}\overline{\Gamma}t \right|^2$$

$$\frac{dN(\overline{D}^0 \to f)}{dt} \propto e^{-\overline{\Gamma}t}\left\langle f \middle| \overline{D}^0 \right\rangle \left| 1 - \frac{p}{q}\frac{\left\langle f \middle| D^0 \right\rangle}{\left\langle f \middle| \overline{D}^0 \right\rangle}\frac{ix+y}{2}\overline{\Gamma}t \right|^2$$

„master“ formulae for t-dependent rates (up to $O(x,y)$)

more details p. 68

PHENOMENOLOGY

$$\left|D_{1,2}\right\rangle = p\left|D^0\right\rangle \pm q\left|\overline{D}^0\right\rangle$$

TIME EVOLUTION

FLAVOR STATES (DEFINED FLAVOR) ≠ H_{EFF} EIGENSTATES: (DEFINED $m_{1,2}$ AND $\Gamma_{1,2}$)

$$x \equiv \frac{m_1 - m_2}{\overline{\Gamma}};\ y \equiv \frac{\Gamma_1 - \Gamma_2}{2\overline{\Gamma}};$$

$$\left|D^0(t)\right\rangle = \left[\left|D^0\right\rangle \cosh\left(\frac{ix+y}{2}\overline{\Gamma}t\right) - \frac{q}{p}\left|\overline{D}^0\right\rangle \sinh\left(\frac{ix+y}{2}\overline{\Gamma}t\right)\right] e^{-i\overline{m}t - \frac{\overline{\Gamma}}{2}t}$$

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

SM: $|x|, |y| \leq \mathcal{O}(10^{-2})$ $|x|, |y| << 1 \Rightarrow$

$$\frac{dN(D^0 \to f)}{dt} \propto e^{-\overline{\Gamma}t}\left\langle f\middle|D^0\right\rangle\left|1 - \frac{q}{p}\frac{\left\langle f\middle|\overline{D}^0\right\rangle}{\left\langle f\middle|D^0\right\rangle}\frac{ix+y}{2}\overline{\Gamma}t\right|^2$$

$$\frac{dN(\overline{D}^0 \to f)}{dt} \propto e^{-\overline{\Gamma}t}\left\langle f\middle|\overline{D}^0\right\rangle\left|1 - \frac{p}{q}\frac{\left\langle f\middle|D^0\right\rangle}{\left\langle f\middle|\overline{D}^0\right\rangle}\frac{ix+y}{2}\overline{\Gamma}t\right|^2$$

„MASTER“ FORMULAE FOR t-DEPENDENT RATES (UP TO $O(x,y)$)

MORE DETAILS P. 68

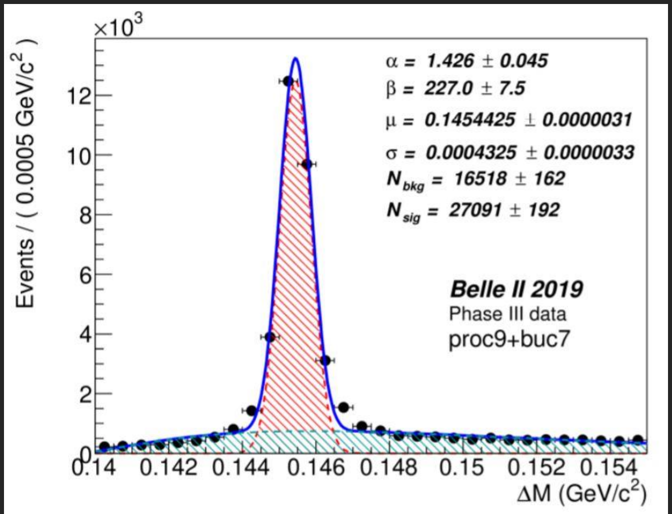
DECAY TIME DISTRIBUTION OF EXPERIMENTALLY ACCESSIBLE STATES D^0, $\overline{D}^0$ SENSITIVE TO MIXING PARAMETERS x AND y, DEPENDING ON FINAL STATE

D^0 Mixing Exp. Methods

General features of meas's

Tagging
(Belle, LHCb)
$D^{*+} \to D^0 \pi_s^+$
charge of $\pi_s \Rightarrow$ flavor of D^0;
$\Delta M = M(D^0\pi_s) - M(D^0)$
(or $q = \Delta M - m_\pi$) $\Rightarrow$
background reduction
$\varepsilon_{D^*} \sim 80\%$, $\omega_{D^*} \sim 0.2\%$

kinematic reconstr.
p. 71

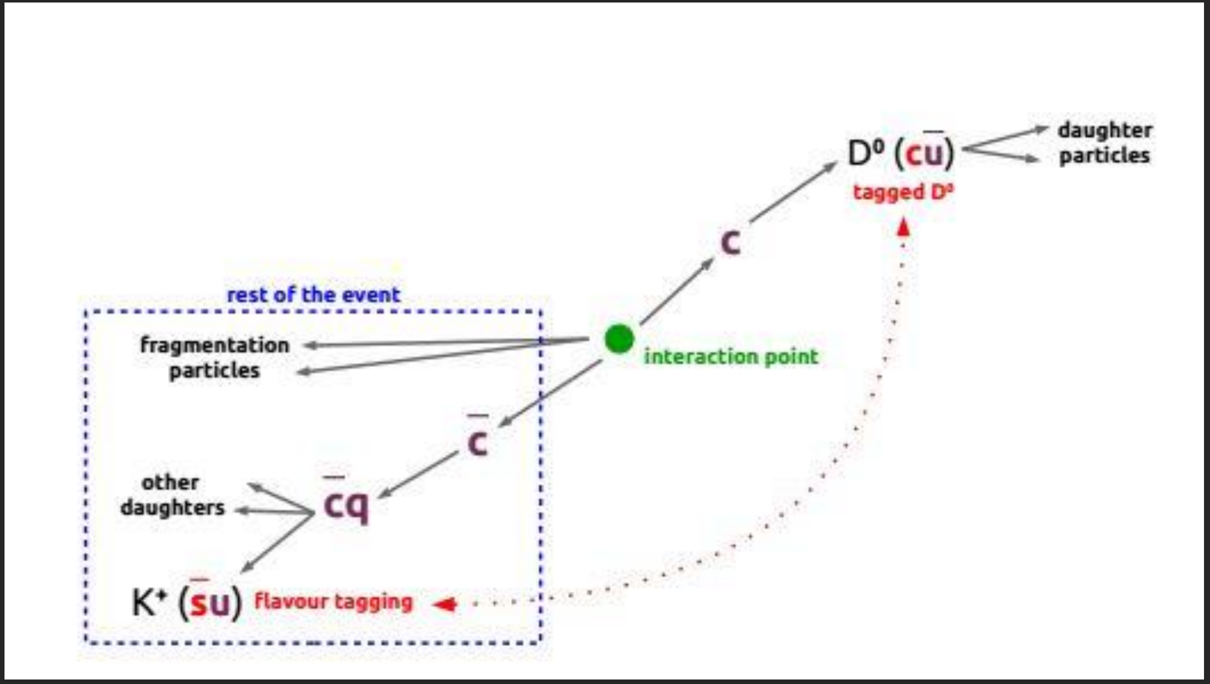


S. Sandilya et al. (Belle II Coll.), B2GM Oct 2019

BIIPB

RestOfEvent (Belle)
$\varepsilon_{D^*} \sim 27\%$, $\omega_{D^*} \sim 13\%$
3x more produced D^0's

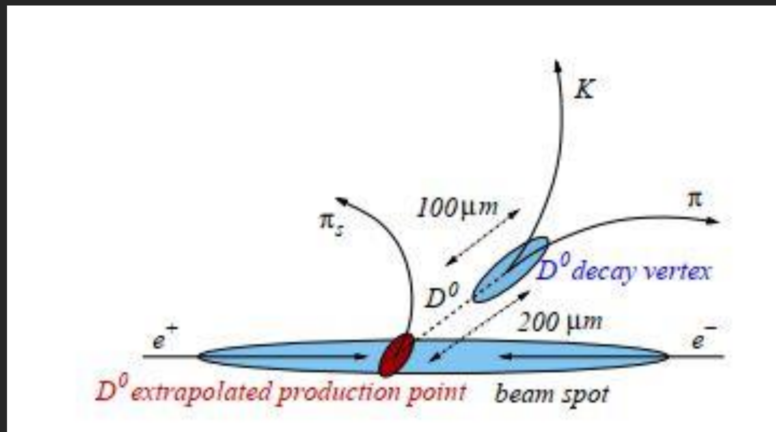
$\sigma(A_{CP})$ reduced by ~15%
using also ROE

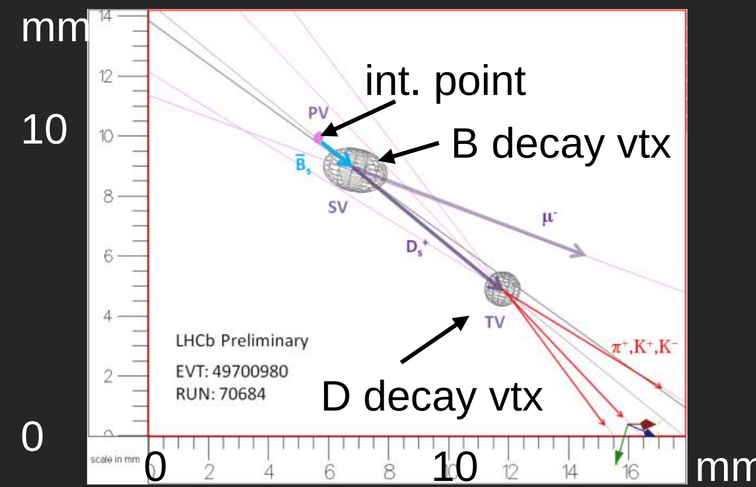


B semil. decays (LHCb)
$b \to c\,\mu^- \bar{\nu}$

General features of meas's

Decay time resol. p. 72





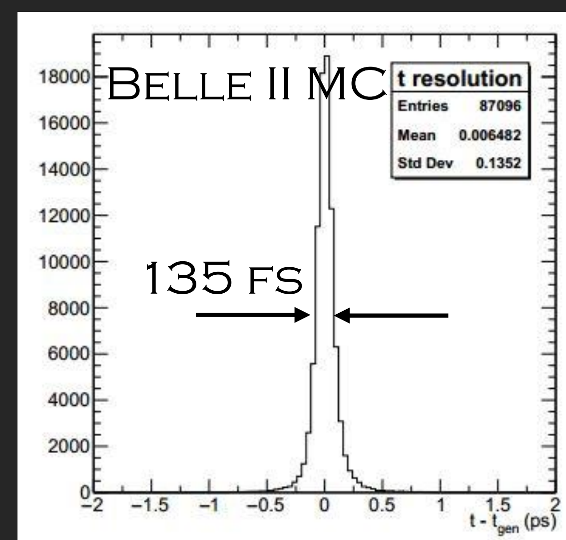
decay time (Belle): D^0 decay products vertex; D^0 momentum & int. region;

Belle $\sigma(t_{D0})$~270 fs

Belle II: $\sigma(t_{D0})$ ~ 100 fs

(LHCb): primary vtx, *B* decay vtx, *D* decay vtx;

~2x better $\sigma(t_{D0})$



BIIPB

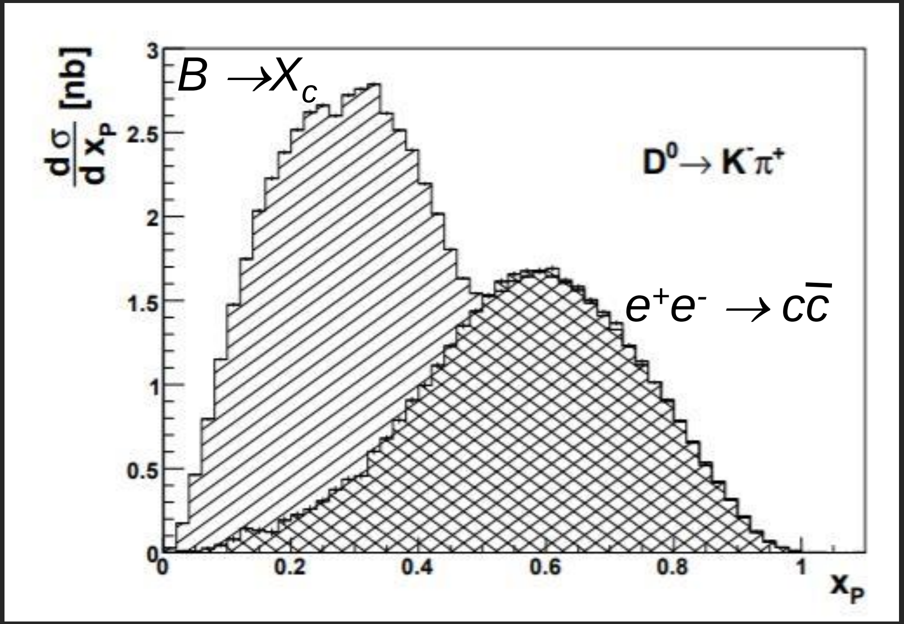
General features of meas's

R. Seuster et al.. (Belle Coll.), Phys.Rev. D73, 032002 (2006)

Belle

$p^*(D^*) > 2.5$ GeV/c

eliminates D^0 from $b \to c$



LHCb

can separate prompt and cascade production using vtxing

$$x_p = \frac{p^*}{\sqrt{s/4 - m_h^2}}$$

D^0 Mixing CP eigenstates

$D^0 \to K^+K^-,\ \pi^+\pi^-$

$$\left|D^0\right\rangle = \frac{1}{\sqrt{2}}\left[\left|D_1\right\rangle + \left|D_2\right\rangle\right]$$

$$\left|\overline{D}^0\right\rangle = \frac{1}{\sqrt{2}}\left[\left|D_1\right\rangle - \left|D_2\right\rangle\right]$$

CPV will be addressed later;
in charm system (and SM) CPV is small
⇒ discuss mixing w/o CPV (i.e. $q=p=1/\sqrt{2}$)

$CP\,|K^+K^-,\ \pi^+\pi^-\rangle = +\,|K^+K^-,\ \pi^+\pi^-\rangle$
$\langle f_{CP}^+|D^0\rangle = \langle f_{CP}^+|D_1\rangle = \langle f_{CP}^+|\overline{D}^0\rangle$
$\langle f_{CP}^-|D^0\rangle = \langle f_{CP}^-|D_2\rangle = -\langle f_{CP}^-|\overline{D}^0\rangle$

if no CPV:
$CP\,|D_1\rangle = |D_1\rangle$
$|D_1\rangle$ is CP even state
(phase convention as in PDG p. 69);

only $|D_1\rangle$ component of $D^0/\overline{D}^0$ decays to
K^+K^- / $\pi^+\pi^-$;
measuring lifetime in these decays ⇒ $\tau=1/\Gamma_1$;
measuring lifetime in Flavor specific final state ⇒ $\tau=1/\overline{\Gamma}$;

$$\frac{dN(D^0(\overline{D}^0)\to f_{CP}^+)}{dt} \propto e^{-\overline{\Gamma}t}\left[1-y\overline{\Gamma}t\right] \approx e^{-\overline{\Gamma}t}e^{-y\overline{\Gamma}t} = e^{-(1+y)\overline{\Gamma}t}$$

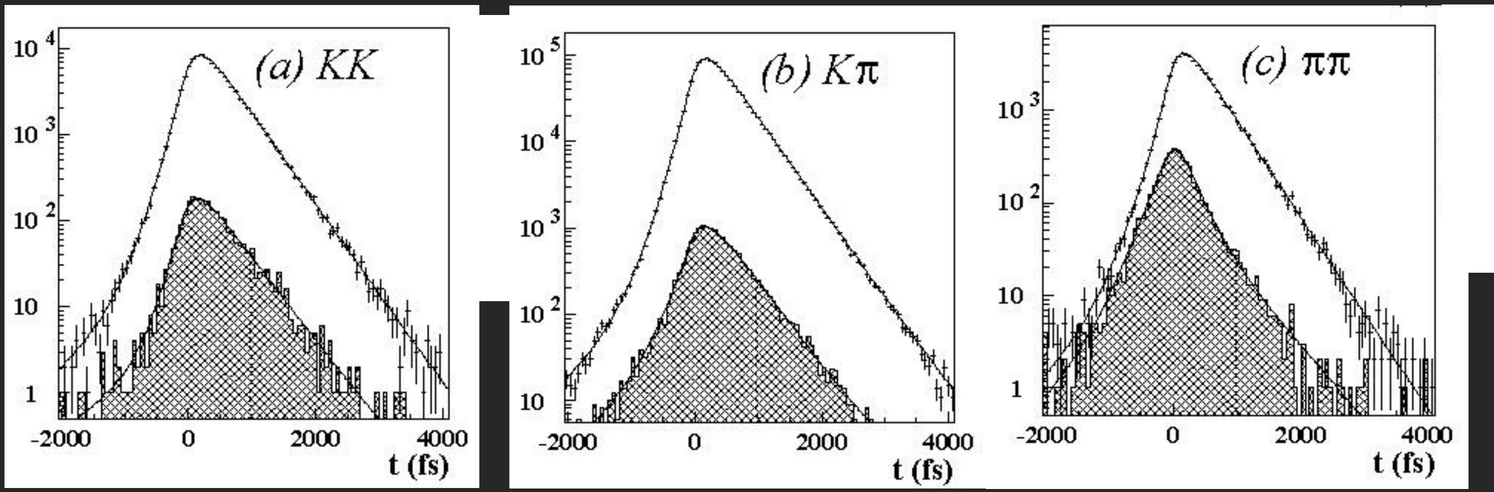
more on time evolution

$D^0 \to K^+K^-, \pi^+\pi^-$

BY MEASURING EFFECTIVE LIFETIMES IN
$D^0 \to K^+K^-, \pi^+\pi^-$
AND IN $D^0 \to K^-\pi^+$
ONE CAN DETERMINE y

$$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1$$

M. Staric et al., (Belle Coll.), PRL 98, 211803 (2007)



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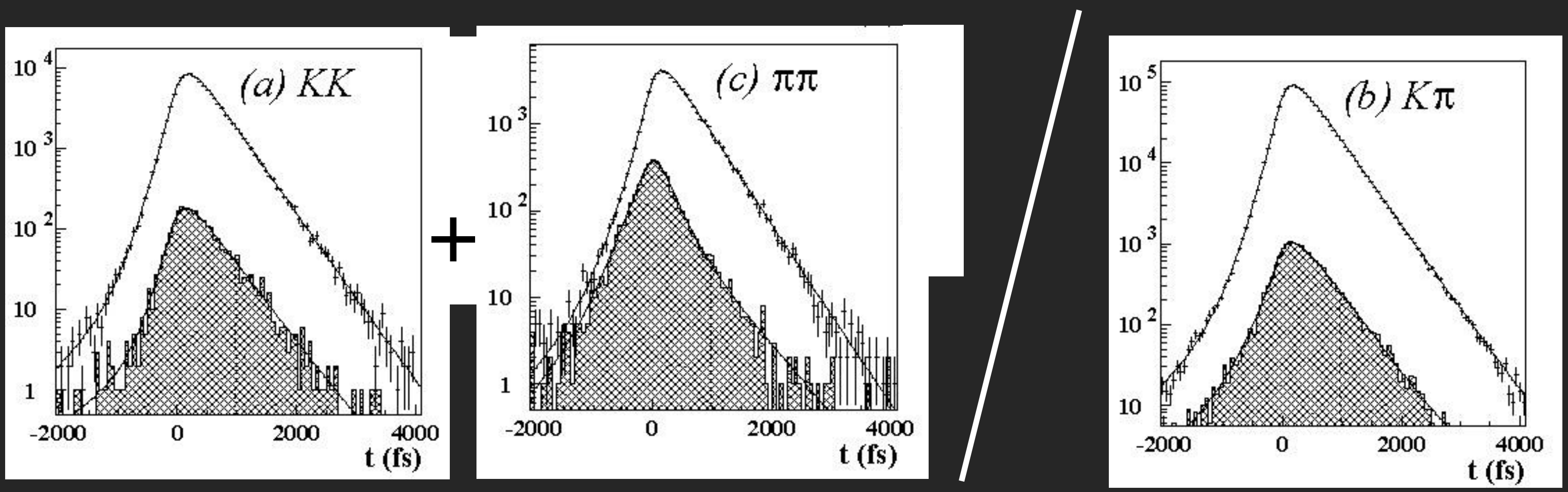
M. STARIC ET AL., (BELLE COLL.), PRL 98, 211803 (2007)

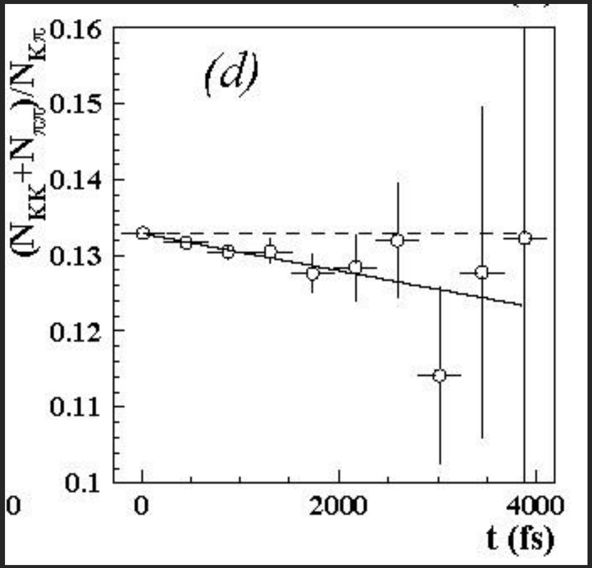


D^0 Mixing CP eigenstates

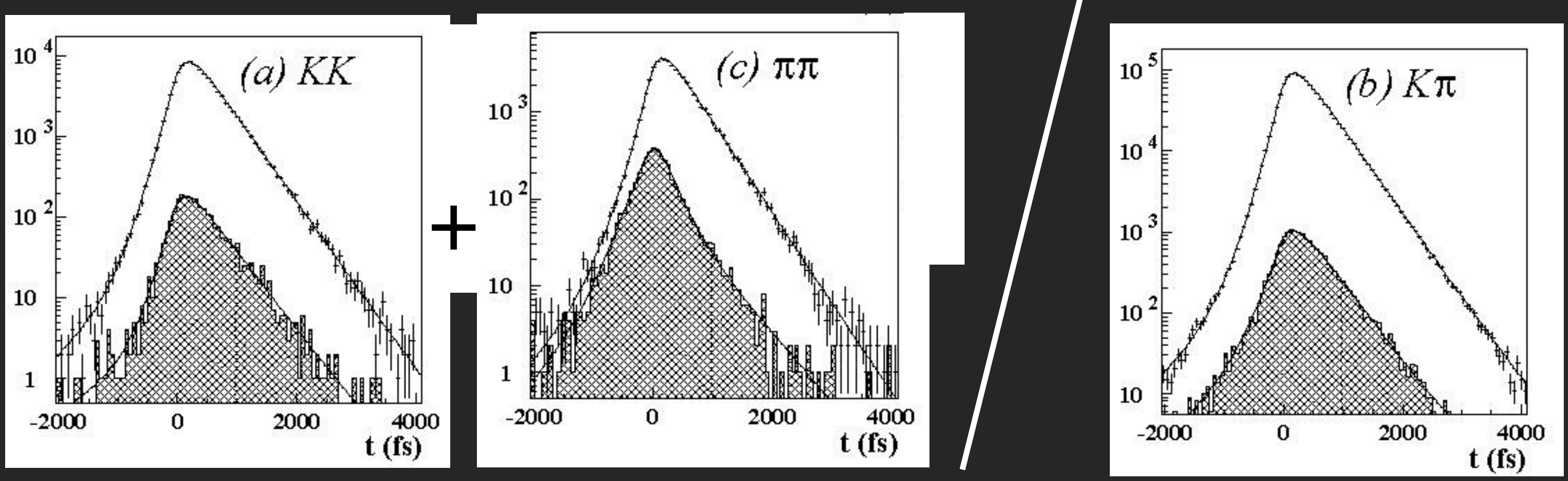
$D^0 \to K^+K^-, \pi^+\pi^-$

By measuring effective lifetimes in $D^0 \to K^+K^-, \pi^+\pi^-$ and in $D^0 \to K^-\pi^+$ one can determine y

$$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1$$



M. Staric et al., (Belle Coll.), PRL 98, 211803 (2007)

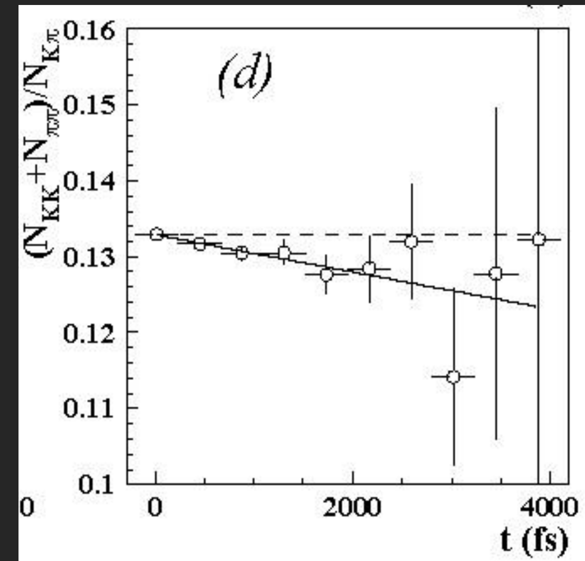


D^0 Mixing CP eigenstates

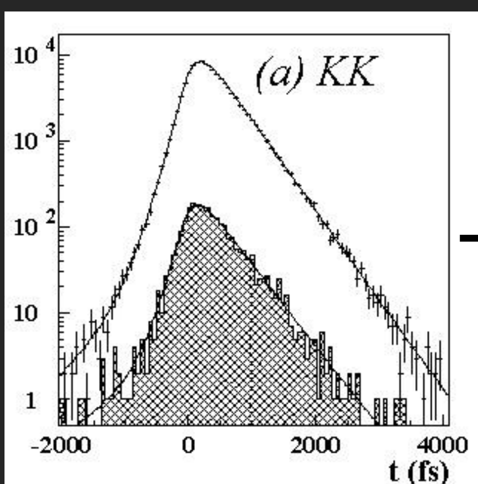
$D^0 \to K^+K^-,\ \pi^+\pi^-$

By measuring effective lifetimes in
$D^0 \to K^+K^-,\ \pi^+\pi^-$
and in $D^0 \to K^-\pi^+$
one can determine y

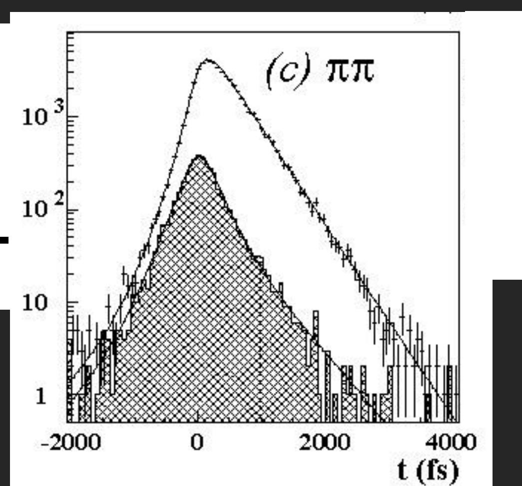
$$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1$$

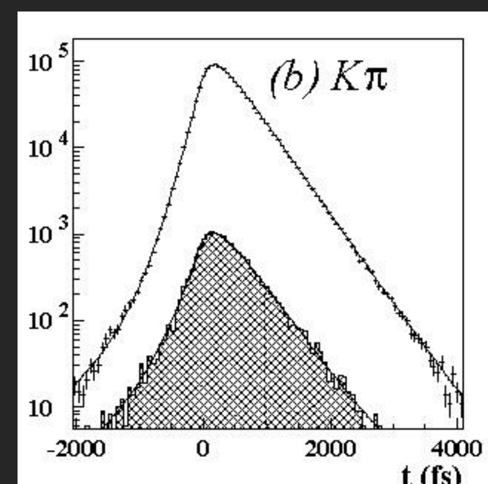


M. Staric et al., (Belle Coll.), PRL 98, 211803 (2007)



+





χ^2/ndf= 1.084 (ndf=289)

First evidence of D^0 mixing
(back-to-back with BaBar's $D^0 \to K^+\pi^-$)

$$y_{CP} = (1.31 \pm 0.32 \pm 0.25)\%$$

$D^0 \to K^+K^-, \pi^+\pi^-$

BY MEASURING EFFECTIVE LIFETIMES IN
$D^0 \to K^+K^-, \pi^+\pi^-$
AND IN $D^0 \to K^-\pi^+$
ONE CAN DETERMINE y

D^0 Mixing CP eigenstates

$D^0 \to \phi K_s$, ωK_s

CP-odd states
lower stat. precision

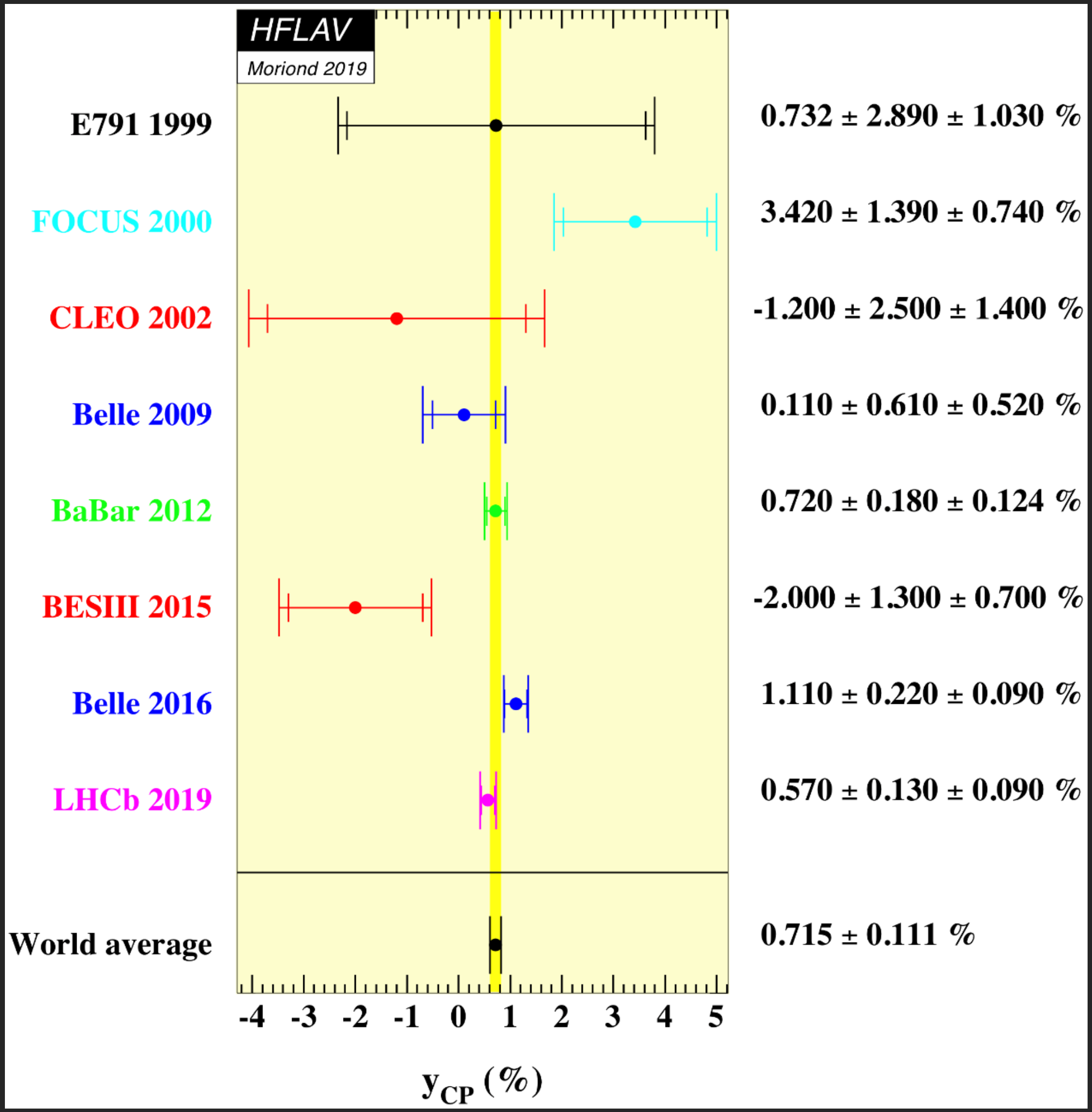
Averaging

$$y_{CP} = (0.715 \pm 0.111)\%$$

D^0 mesons, like other M^0, do mix, with the lowest probability of all*

*actually, t - integrated mixing probability p. 69

$$p(D^0 \to \overline{D}^0) = \frac{x^2 + y^2}{2(1 + x^2)}$$



HFLAV

D^0 MIXING HADRONIC WS

$D^0 \to K^+\pi^-$

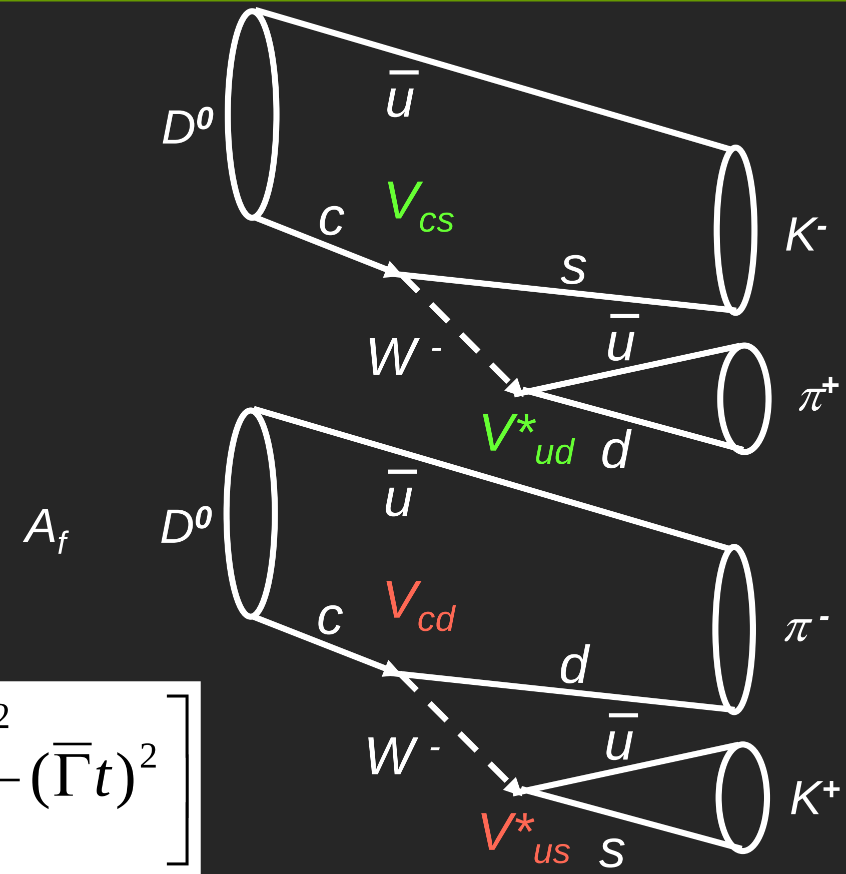
DCS DECAYS

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} = \left|\frac{q}{p}\right| \frac{1}{r} e^{i(\delta_f + \varphi)}$$

$f = K^+\pi^-$

$\delta_{K\pi}$: (UNKNOWN) PHASE DIFFERENCE BETWEEN A_f AND $\overline{A}_f$

$|A_f / \overline{A}_f| = r << 1$



$$\frac{dN(D^0 \to f)}{dt} \propto e^{-\overline{\Gamma}t}\left[r^2 - r y' \overline{\Gamma} t + \frac{x'^2 + y'^2}{4} (\overline{\Gamma} t)^2 \right]$$

$$\frac{dN(\overline{D}^0 \to f)}{dt} \propto e^{-\overline{\Gamma}t}\left[1 - r y \cos(\delta_{K\pi}) \overline{\Gamma} t + \ldots \right]$$

$$y' = y\cos(\delta_{K\pi}) - x\sin(\delta_{K\pi})$$

$$x' = x\cos(\delta_{K\pi}) + y\sin(\delta_{K\pi})$$

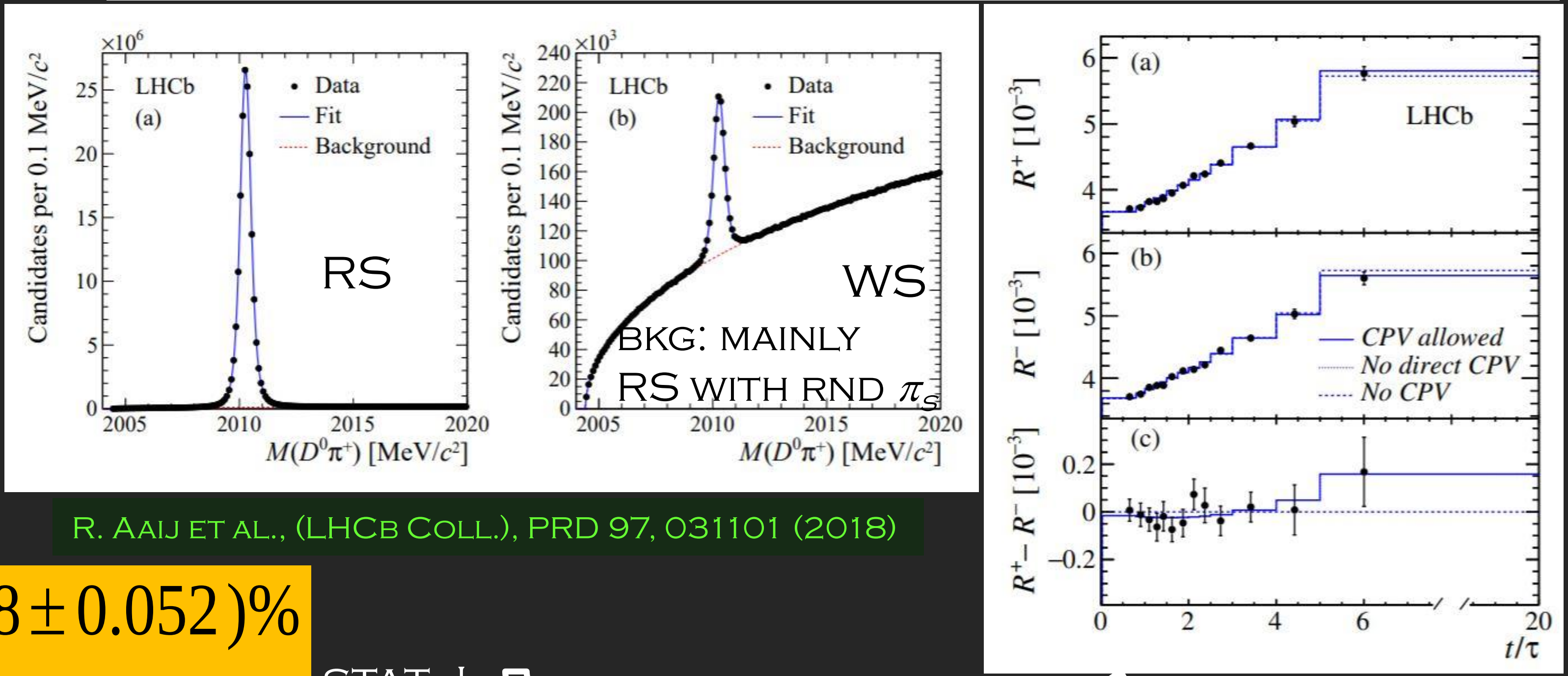
$$\mathcal{O}\left(\frac{ry}{r^2} = \frac{y}{r} \sim 1\right)$$

$$\mathcal{O}\left(\frac{ry}{1} = ry << 1\right)$$

D^0 Mixing Hadronic WS

$D^0 \to K^+\pi^-$

$$\frac{dN(D^0\to f)}{dt}\Big/\frac{dN(\overline{D}^0\to f)}{dt}=\left[1-\frac{y'}{r}\overline{\Gamma}t+\frac{x'^2+y'^2}{4r^2}(\overline{\Gamma}t)^2\right]$$



R. Aaij et al., (LHCb Coll.), PRD 97, 031101 (2018)

$$y'=(0.528\pm0.052)\%$$
$$x'^2=(3.9\pm2.7)\cdot10^{-5}$$

stat.+ syst.

fit in bins of t/τ

result using primary D^*'s (requiring D^* vtx consistent with primary)
main syts. uncertainty (~1/2 of stat.) from remaining secondary D^*s
@ B-Factories: not ratio but individual t-dependent rates fitted

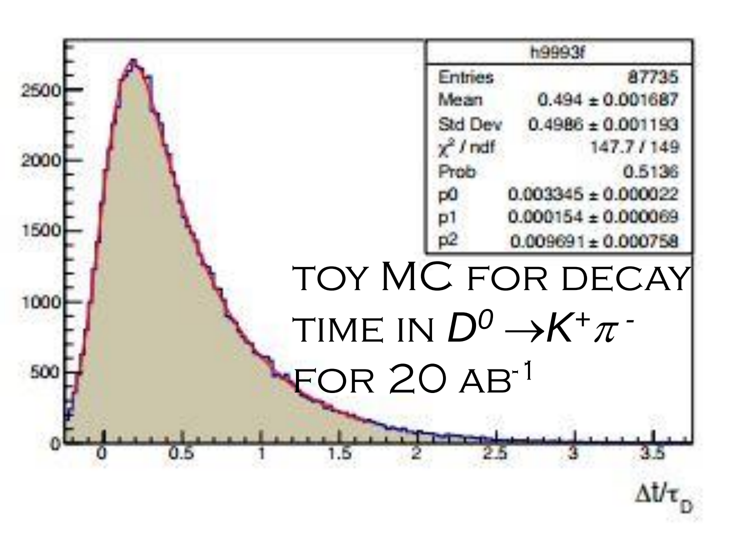
D^0 Mixing Hadronic WS

$D^0 \to K^+\pi^-$

D. Asner et al., (Cleo-c Coll.), PRD 86, 112001 (2012)

$$\cos\delta_{K\pi} = 0.81\,^{+0.22}_{-0.18}\,^{+0.07}_{-0.05}$$

$\delta_{K\pi}$ can be determined using quantum correlated $D^0\overline{D}^0$ pairs at BES III;
however, currently only Cleo-c meas. exists, and $\delta_{K\pi}$ is more precisely determined by combination of y', y and x meas's.



toy MC for decay time in $D^0 \to K^+\pi^-$ for 20 ab^{-1}

BIIPB

Belle II expectations:

	5 ab^{-1}	20 ab^{-1}	50 ab^{-1}	Current best
$\sigma(x'^2)$ [10^{-5}]	10	5	3	2.7
$\sigma(y')$ [%]	0.15	0.07	0.05	0.05

BIIPB (5–50 ab^{-1}) HFLAV (current best)

including 20% and 12% additional uncertainty due to bkg. & systematics, respectively (?)

Multi-body self conjugated states

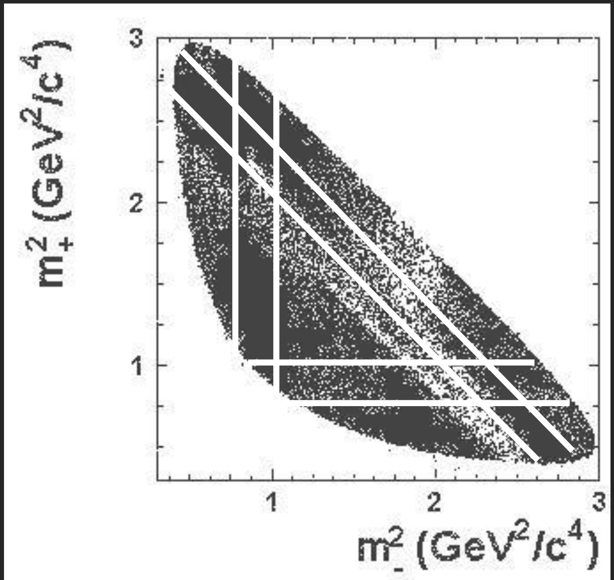
$D^0 \to K_S \pi^+ \pi^-$

different types of interm. states;

CF: $D^0 \to K^{*-} \pi^+$
DCS: $D^0 \to K^{*+} \pi^-$
CP: $D^0 \to \rho^0 K_S$

if $f = \bar{f} \Rightarrow$ populate same Dalitz plot;
relative phases determined (unlike $D^0 \to K^+ \pi^-$);

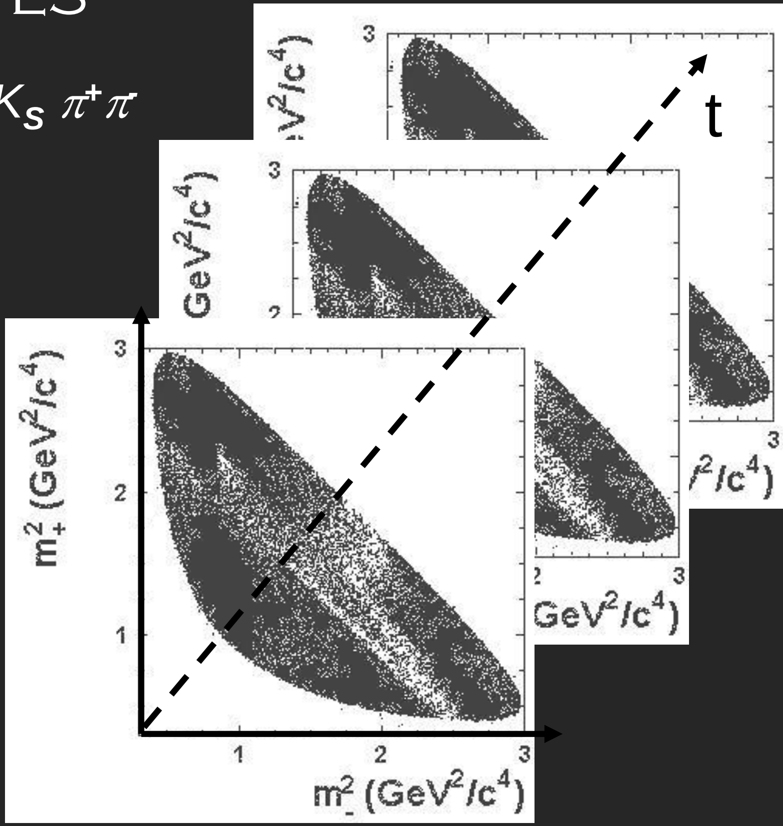
$D^0 \to K_S \pi^+ \pi^-$



Multi-body self conjugated states

$D^0 \to K_S \pi^+ \pi^-$

$D^0 \to K_S \pi^+ \pi^-$



different types of interm. states;

CF: $D^0 \to K^{*-} \pi^+$
DCS: $D^0 \to K^{*+} \pi^-$
CP: $D^0 \to \rho^0 K_S$

if $f = \bar{f} \Rightarrow$ populate same Dalitz plot;
relative phases determined (unlike $D^0 \to K^+ \pi^-$);

specific regions of Dalitz plane $\to$ specific admixture of interm. states $\to$ specific t dependence $f(x, y)$;

Multi-body self conjugated states

$D^0 \to K_S \pi^+ \pi^-$

t-dependent decay ampl. depends on Dalitz variables;
contains D^0 and $\overline{D^0}$ part (due to mixing) that propagate differently in time,
$\lambda_{1,2} = f(x,y)$;

$m_\pm^2 = m^2(K_S\pi^\pm)$;

$$\mathcal{M}(m_-^2, m_+^2, t) \equiv \langle K_S \pi^+ \pi^- | D^0(t) \rangle =$$
$$= \frac{1}{2} \mathcal{A}(m_-^2, m_+^2)\left[e^{-i\lambda_1 t} + e^{-i\lambda_2 t}\right] +$$
$$+ \frac{1}{2} \overline{\mathcal{A}}(m_-^2, m_+^2)\left[e^{-i\lambda_1 t} - e^{-i\lambda_2 t}\right]$$

$D^0 \to f$; $\overline{D^0} \to f$

Instantaneous amplitude:
sum of intermediate states with (unknown) relative strong phases

$$\mathcal{A}(m_-^2, m_+^2) = = \sum a_r\, e^{i\Phi_r} B(m_-^2, m_+^2) + a_{NR}\, e^{i\Phi_{NR}}$$

$$\overline{\mathcal{A}}(m_-^2, m_+^2) = = \sum a_r\, e^{i\Phi_r} B(m_+^2, m_-^2) + a_{NR}\, e^{i\Phi_{NR}}$$

By studying the decay time evolution of Dalitz plane → access directly x, y

Multi-body self conjugated states

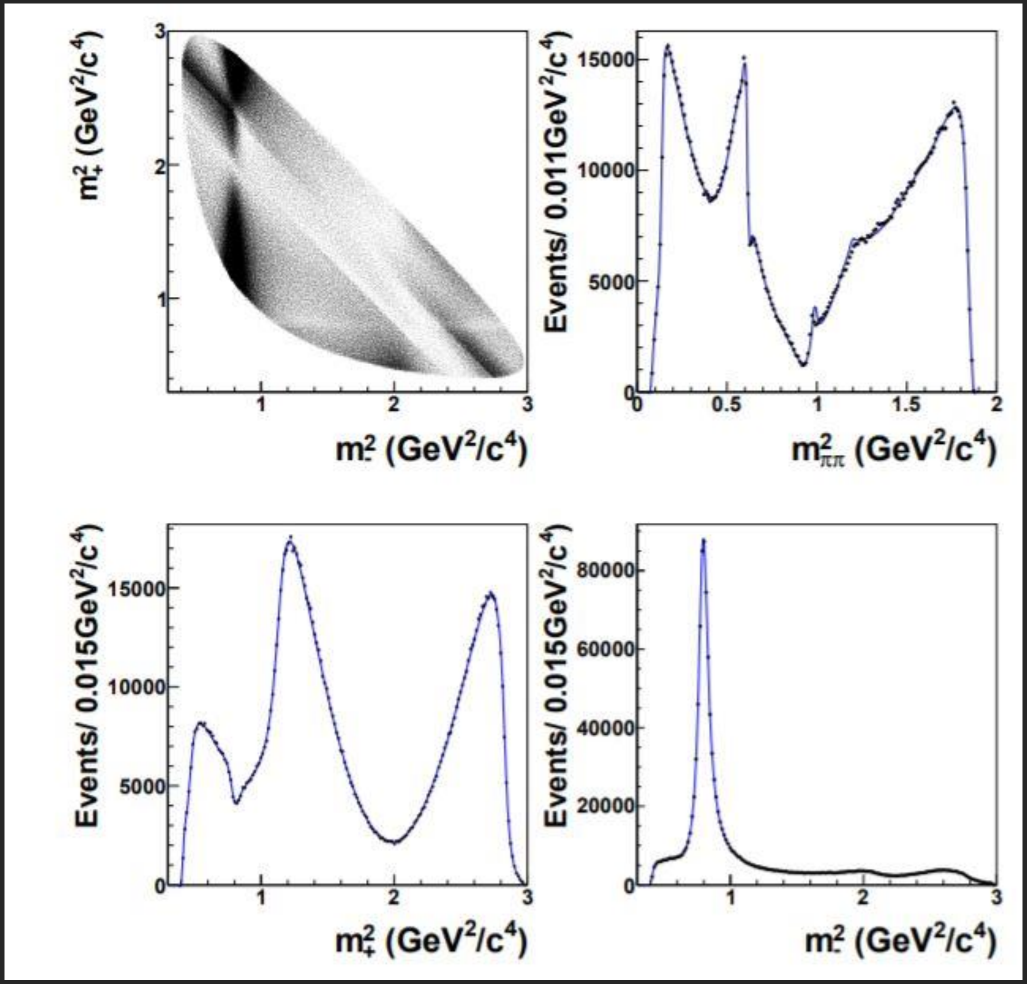
$D^0 \to K_S \pi^+ \pi^-$

no CPV result:

$$x = (0.56 \pm 0.19 \pm^{0.03}_{0.09} \pm^{0.06}_{0.09})\%$$

$$y = (0.30 \pm 0.15 \pm^{0.04}_{0.05} \pm^{0.03}_{0.06})\%$$

↑ uncertainty due to Dalitz model

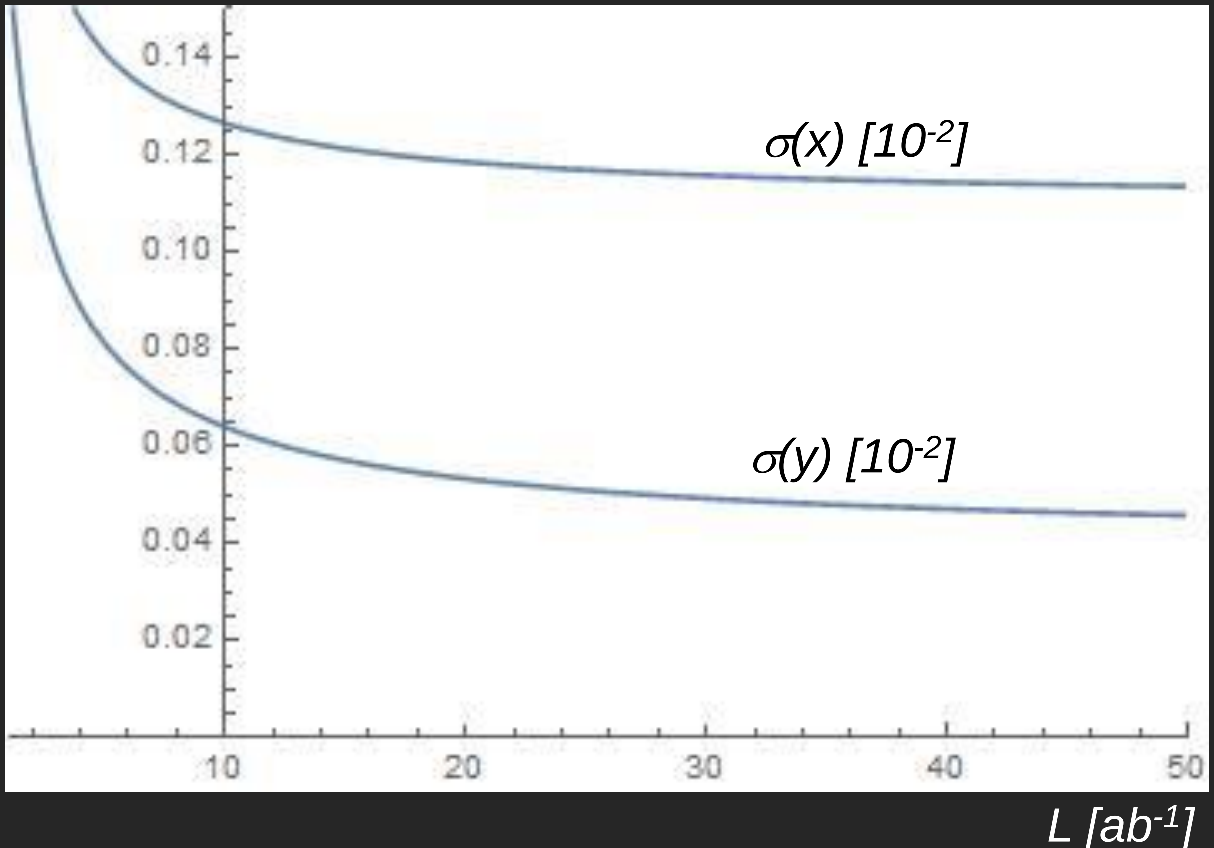


T. Peng et al., (Belle Coll.), PRD 89, 091103 (2014)

MULTI-BODY SELF CONJUGATED STATES

$D^0 \to K_S \pi^+ \pi^-$

BIIPB



BELLE II:
SYST. UNCERTAINTY DOMINATES @ FEW AB^{-1}

IN TURN, SYST. UNCERTAINTY DOMINATED BY THE MODEL UNCERTAINTY

CAN THIS BE EVADED?

BY MEASURING STRONG PHASE VARIATION ACROSS DALITZ PLANE USING COHERENT $D^0\bar{D}^0$ PAIRS (BES III)

MULTI-BODY SELF CONJUGATED STATES

$D^0 \to K_S \pi^+ \pi^-$

A. BONDAR, A. POLUEKTOV AND V. VOROBIEV, PRD 82, 034033 (2010)
A. GIRI, Y. GROSSMAN, A. SOFFER, AND J. ZUPAN, PR D 68, 054018 (2003)

MODEL INDEPENDENT METHOD

DALITZ- AND *t*- DEPENDENT AMPLITUDE UP TO $O(x^2,y^2)$

NOTATION: $\frac{q}{p} = r_{CP} e^{i\alpha_{CP}}$

$$\mathcal{P}_{D^0}(m_{12}^2, m_{13}^2, t) = \Gamma e^{-\Gamma t}\Big[a_{12,13}^2 + r_{CP}\, a_{12,13}\, a_{13,12}\, \Gamma t\, \{y_D \cos(\delta_{12,13} - \delta_{13,12} - \alpha_{CP}) + x_D \sin(\delta_{12,13} - \delta_{13,12} - \alpha_{CP})\}\Big]$$

C. THOMAS, G. WILKINSON, JHEP 2012:185

INTEGRATING OVER DALITZ- AND *t*-BIN

2N symmetric bins

$$\int_i \int_{t_a}^{t_b} \mathcal{P}_{D^0}(m_{12}^2, m_{13}^2, t)\, \mathrm{d}t\, \mathrm{d}m_{12}^2\, \mathrm{d}m_{13}^2 =$$
$$n\Big\{(e^{-\Gamma t_a} - e^{-\Gamma t_b})T_i + [\Gamma(e^{-\Gamma t_a} t_a - e^{-\Gamma t_b} t_b) + (e^{-\Gamma t_a} - e^{-\Gamma t_b})]$$
$$\times \{r_{CP}\sqrt{T_i T_{-i}}(y_D[c_i \cos(\alpha_{CP}) + s_i \sin(\alpha_{CP})] + x_D[s_i \cos(\alpha_{CP}) - c_i \sin(\alpha_{CP})])\}\Big\}$$

$$T_i \equiv \int_i a_{12,13}^2\, \mathrm{d}m_{12}^2\, \mathrm{d}m_{13}^2\,,$$
$$c_i \equiv \frac{1}{\sqrt{T_i T_{-i}}} \int_i a_{12,13}\, a_{13,12} \cos(\delta_{12,13} - \delta_{13,12})\, \mathrm{d}m_{12}^2\, \mathrm{d}m_{13}^2\,,$$
$$s_i \equiv \frac{1}{\sqrt{T_i T_{-i}}} \int_i a_{12,13}\, a_{13,12} \sin(\delta_{12,13} - \delta_{13,12})\, \mathrm{d}m_{12}^2\, \mathrm{d}m_{13}^2\,.$$

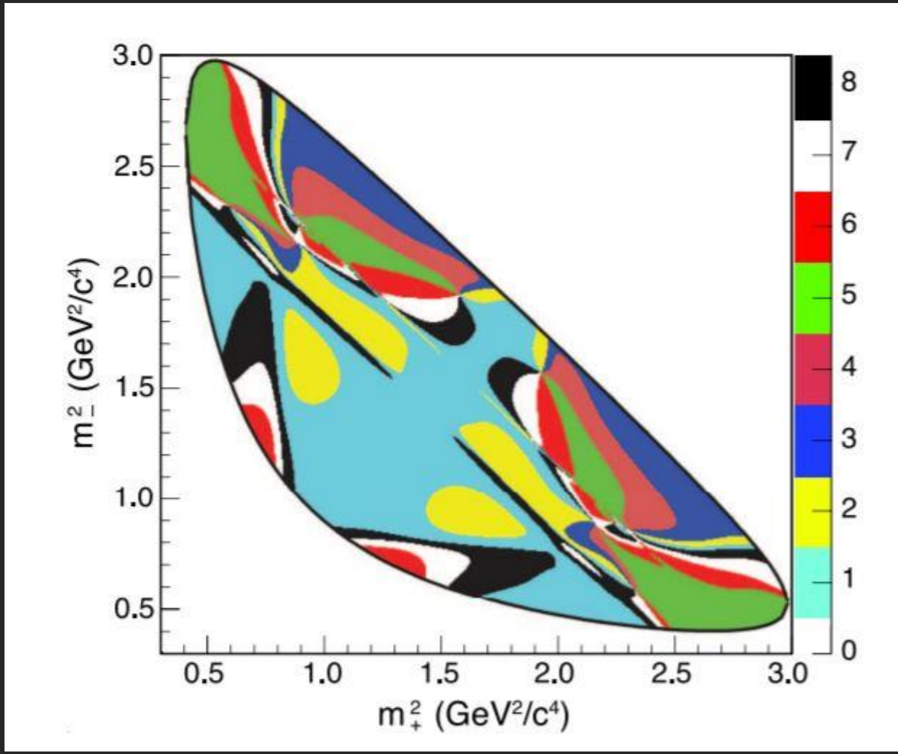
$c_{-i}=c_i$
$s_{-i}=-s_i$

IN LIMIT OF NO MIXING AND NO CPV
\# OF EVENTS FROM D^0 IN *i*-TH BIN
→ FREE PARAM. OF FIT
COSINE AND SINE OF AVERAGE STRONG PHASE DIFFERENCE $D^0/\bar{D}^0$ IN BIN *i* WEIGHTED BY RATE
→ QUANTUM CORR. $D^0\bar{D}^0$ PAIRS

Multi-body self conjugated states

$D^0 \to K_S \pi^+ \pi^-$

J. Libby et al. (Cleo-c Coll.), PRD 82,112006 (2010)



model independent method

binning of Dalitz plane based on

A. Poluektov et al. (Belle Coll.), PR D 81, 112002 (2010)

($\Delta\delta \sim$ const. across bin)

results using L=0.8 fb^{-1}

i	c_i	s_i
	Equal $\Delta\delta_D$ Belle	
1	$0.710 \pm 0.034 \pm 0.038$	$-0.013 \pm 0.097 \pm 0.031$
2	$0.481 \pm 0.080 \pm 0.070$	$-0.147 \pm 0.177 \pm 0.107$
3	$0.008 \pm 0.080 \pm 0.087$	$0.938 \pm 0.120 \pm 0.047$
4	$-0.757 \pm 0.099 \pm 0.065$	$0.386 \pm 0.208 \pm 0.067$
5	$-0.884 \pm 0.056 \pm 0.054$	$-0.162 \pm 0.130 \pm 0.041$
6	$-0.462 \pm 0.100 \pm 0.082$	$-0.616 \pm 0.188 \pm 0.052$
7	$0.106 \pm 0.105 \pm 0.100$	$-1.063 \pm 0.174 \pm 0.066$
8	$0.365 \pm 0.071 \pm 0.078$	$-0.179 \pm 0.166 \pm 0.048$

J. Libby et al. (Cleo-c Coll.), PRD 82,112006 (2010)

t-dependence of Dalitz

Method p. 76

uncertainties on c_i , s_i *propagate to measured variables (as syst. uncertainty);*
still stat. dominated → BESIII has 3 fb^{-1} of data, planning to record 10 fb^{-1} more

MULTI-BODY SELF CONJUGATED STATES
$D^0 \to K_S \pi^+ \pi^-$

MODEL INDEPENDENT METHOD

T. PENG ET AL., (BELLE COLL.), PRD 89, 091103 (2014) : $1.33 \cdot 10^6$ D^* TAGGED $D^0 \to K_S \pi^+ \pi^-$ / ab^{-1}

C. THOMAS, G. WILKINSON, JHEP 2012:185 : $100 \cdot 10^6$ D^* TAGGED $D^0 \to K_S \pi^+ \pi^-$:

$\sigma(x) = [\pm 0.017 \pm 0.076(c_i, s_i)]\ 10^{-2}$

$\sigma(y) = [\pm 0.019 \pm 0.087(c_i, s_i)]\ 10^{-2}$

CLEO-C (0.8 fb^{-1})

LHCB SAME STAT. UNCERTAINTY WITH ~ADDITIONAL 1 fb^{-1} (IN ADDITION TO EXISTING 9 fb^{-1})

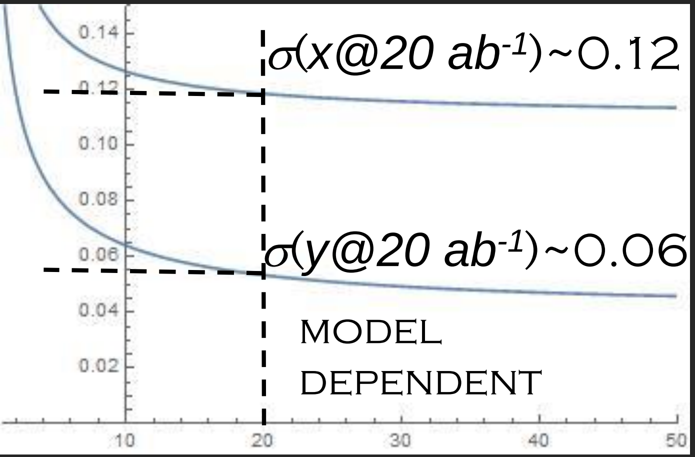
$27 \cdot 10^6$ D^* TAGGED $D^0 \to K_S \pi^+ \pi^-$: (BELLE II @20 ab^{-1})

$\sigma(x) = [\pm 0.032 \pm 0.039(c_i, s_i)]\ 10^{-2}$

$\sigma(y) = [\pm 0.036 \pm 0.045(c_i, s_i)]\ 10^{-2}$

BESIII (3 fb^{-1}) (JUST NAIVE SCALING WITH L)

I. BEDIAGA ET AL. (LHCB COLL.), LHCB-PUB-2018-009



Where do we stand?

HFLAV

Inputs to fit

y_{CP}	$(0.715 \pm 0.111)\%$	World average (COMBOS combination) of $D^0 \to K^+K^- / \pi^+\pi^- / K^+K^-K^0$
x (no CPV) y (no CPV)	$0.56 \pm 0.19\ ^{+0.067}_{-0.127}$ $0.30 \pm 0.15\ ^{+0.050}_{-0.078}$	
x (no CPV) y (no CPV)	$(-0.86 \pm 0.53 \pm 0.17)\%$ $(0.03 \pm 0.46 \pm 0.13)\%$	LHCb $D^0 \to K^0_S \pi^+\pi^-$ results using 1 fb^{-1} ($\sqrt{s}$ = 7 TeV) Correlation coefficient = +0.37, no CPV.
x y	$(0.16 \pm 0.23 \pm 0.12 \pm 0.08)\%$ $(0.57 \pm 0.20 \pm 0.13 \pm 0.07)\%$	BaBar $D^0 \to K^0_S \pi^+\pi^-$ and $D^0 \to K^0_S K^+K^-$ combined; Correlation coefficient = +0.0615, no CPV.
x y	$(1.5 \pm 1.2 \pm 0.6)\%$ $(0.2 \pm 0.9 \pm 0.5)\%$	BaBar $D^0 \to \pi^0\pi^+\pi^-$ Correlation coefficient = −0.006, no CPV.
$(x^2+y^2)/2$	$(0.0130 \pm 0.0269)\%$	World average (COMBOS combination) of $D^0 \to K^+ l^- \nu$ results
x" y"	$(2.61\ ^{+0.57}_{-0.68} \pm 0.39)\%$ $(-0.06\ ^{+0.55}_{-0.64} \pm 0.34)\%$	BaBar $K^+\pi^-\pi^0$ result; correlation coefficient = −0.75. Note: $x'' = x\cos\delta_{K\pi\pi} + y\sin\delta_{K\pi\pi}$, $y'' = y\cos\delta_{K\pi\pi} - x\sin\delta_{K\pi\pi}$.
R_D x^2 y $\cos\delta$ $\sin\delta$	$(0.533 \pm 0.107 \pm 0.045)\%$ $(0.06 \pm 0.23 \pm 0.11)\%$ $(4.2 \pm 2.0 \pm 1.0)\%$ $0.81\ ^{+0.22}_{-0.18}\ ^{+0.07}_{-0.05}$ $-0.01 \pm 0.41 \pm 0.04$	CLEO-c $\Psi(3770)$ results; correlation coefficients: 1 0 0 −0.42 0.01 1 −0.73 0.39 0.02 1 −0.53 −0.03 1 0.04 1

Where do we stand?

HFLAV

Inputs to fit

R_D x'^2 y'	$(0.351 \pm 0.035)\%$ $(0.008 \pm 0.018)\%$ $(0.43 \pm 0.43)\%$	CDF $K^+\pi^-$ results for 9.6 fb^{-1}. Correlation coefficients: 1 0.90 −0.97 0.90 1 −0.98 −0.97 −0.98 1
R_D^+ x'^{2+} y'^+	$(0.3454 \pm 0.0045)\%$ $(0.0061 \pm 0.0037)\%$ $(0.501 \pm 0.074)\%$	LHCb $K^+\pi^-$ results for 5.0 fb^{-1} ($\sqrt{s}$ = 7, 8 TeV) Correlation coefficients: 1 0.843 −0.935 0.843 1 −0.963 −0.935 −0.963 1
R_D^- x'^{2-} y'^-	$(0.3454 \pm 0.0045)\%$ $(0.0016 \pm 0.0039)\%$ $(0.554 \pm 0.074)\%$	LHCb $K^+\pi^-$ results for 5.0 fb^{-1} ($\sqrt{s}$ = 7, 8 TeV) Correlation coefficients: 1 0.846 −0.935 0.846 1 −0.964 −0.935 −0.964 1

WHERE DO WE STAND?

HFLAV

INPUTS TO FIT

R_D x'^{2+} y'^{+}	$(0.303 \pm 0.0189)\%$ $(-0.024 \pm 0.052)\%$ $(0.98 \pm 0.78)\%$	BaBar $K^+\pi^-$ results; correlation coefficients: 1 +0.77 −0.87 +0.77 1 −0.94 −0.87 −0.94 1
A_D x'^{2-} y'^{-}	$(-2.1 \pm 5.4)\%$ $(-0.020 \pm 0.050)\%$ $(0.96 \pm 0.75)\%$	BaBar $K^+\pi^-$ results; correlation coefficients same as above.
R_D x'^{2} y'	$(0.353 \pm 0.013)\%$ $(0.009 \pm 0.022)\%$ $(0.46 \pm 0.34)\%$	Belle $K^+\pi^-$ no-CPV results using 976 fb^{-1}. Correlation coefficients: 1 +0.737 −0.865 +0.737 1 −0.948 −0.865 −0.948 1
$(x^2+y^2)/4$	$(0.0048 \pm 0.0018)\%$	LHCb 3.0 fb^{-1} pp collisions at $\sqrt{s}$ = 7, 8 TeV $D^0 \to K^+\pi^-\pi^+\pi^-$

Where do we stand?

No mixing point

$$x = (0.50 \pm^{0.13}_{0.14})\%$$

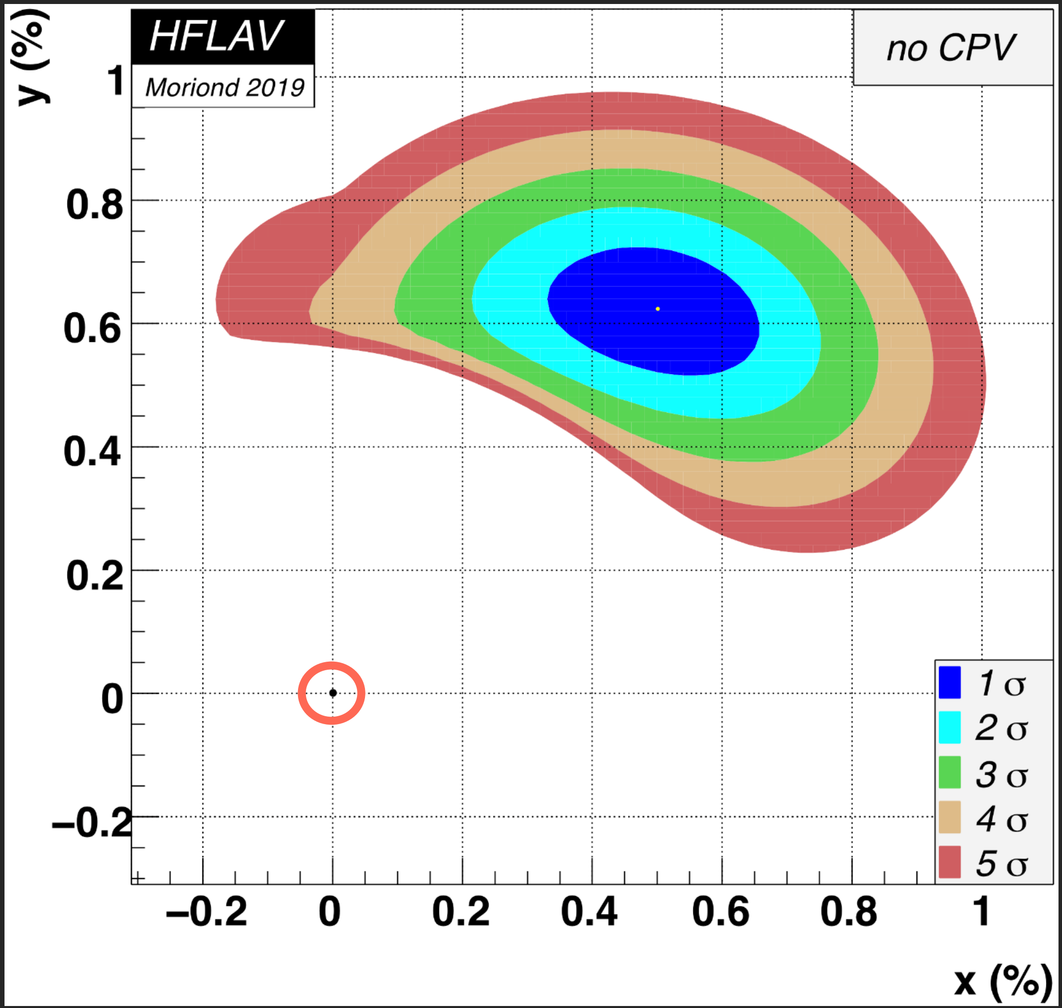
$$y = (0.62 \pm 0.07)\%$$

repeat from p. 29, w/o any disclaimer:

D^0 mesons, like other M^0, do mix, with the lowest probability of all

$P(D^0 \to \overline{D}^0) \sim 3 \cdot 10^{-5}$

HFLAV



D^0 mixing is data driven field (n.b. x, y needed for CPV predictions)

Additional material

UNCERTAINTIES

$$A = \frac{N - \overline{N}}{N + \overline{N}} \Rightarrow \frac{\sigma_A}{A} = \frac{1}{\sqrt{2}} \frac{1}{A} \frac{\sigma_N}{N}$$

!

ASYMMETRY (B^0, D^0)

$$r = \frac{N'}{N} \Rightarrow \frac{\sigma_r}{r} = \sqrt{2} \frac{\sigma_N}{N}$$

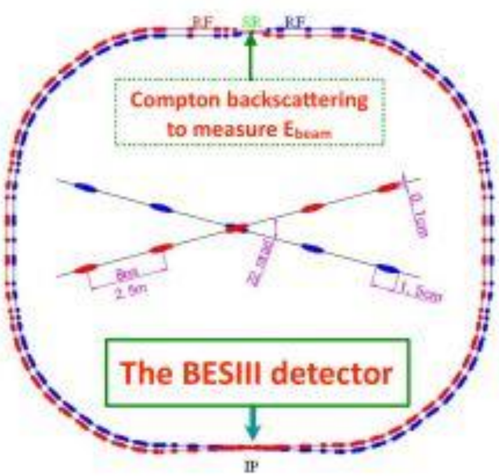
RATIO (K_L)

BACK

Facilities - BES III

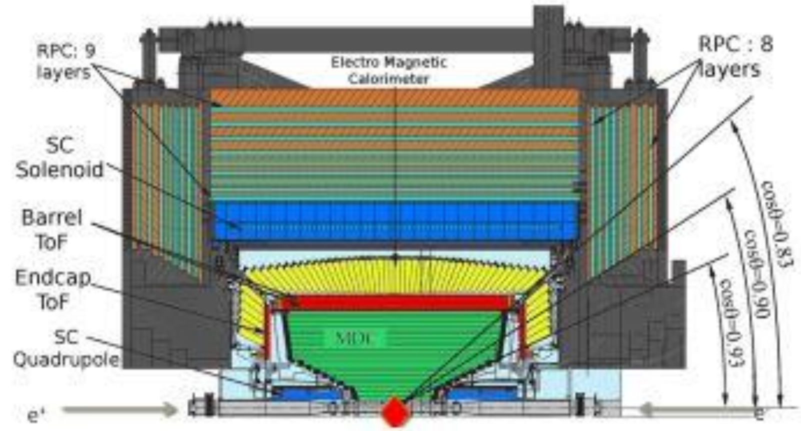
BESIII Experiment

Beijing Electron Positron Collider II(BEPCII)



- Double ring e^+e^- collider
- E_{cm} : $2 \sim 4.6$ GeV, operated since 2008
- Designed Luminosity : $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ was achieved in April 2016!
- Beam crossing angle: 22 mrad

(Beijing Spectrometer III) BESIII



- Acceptance: 93% of 4π
- MDC: $\sigma_p/p = 0.5\%$ at 1 GeV
- EMC: $\sigma_E/E = 2.5\%$ at 1 GeV
- ToF: σ = 80ps (110 ps) in barrel (endcap)
- 9 layer RPC Muon System
- Superconducting Solenoid: 1 T

BACK

L. Zhang, Beauty 2019

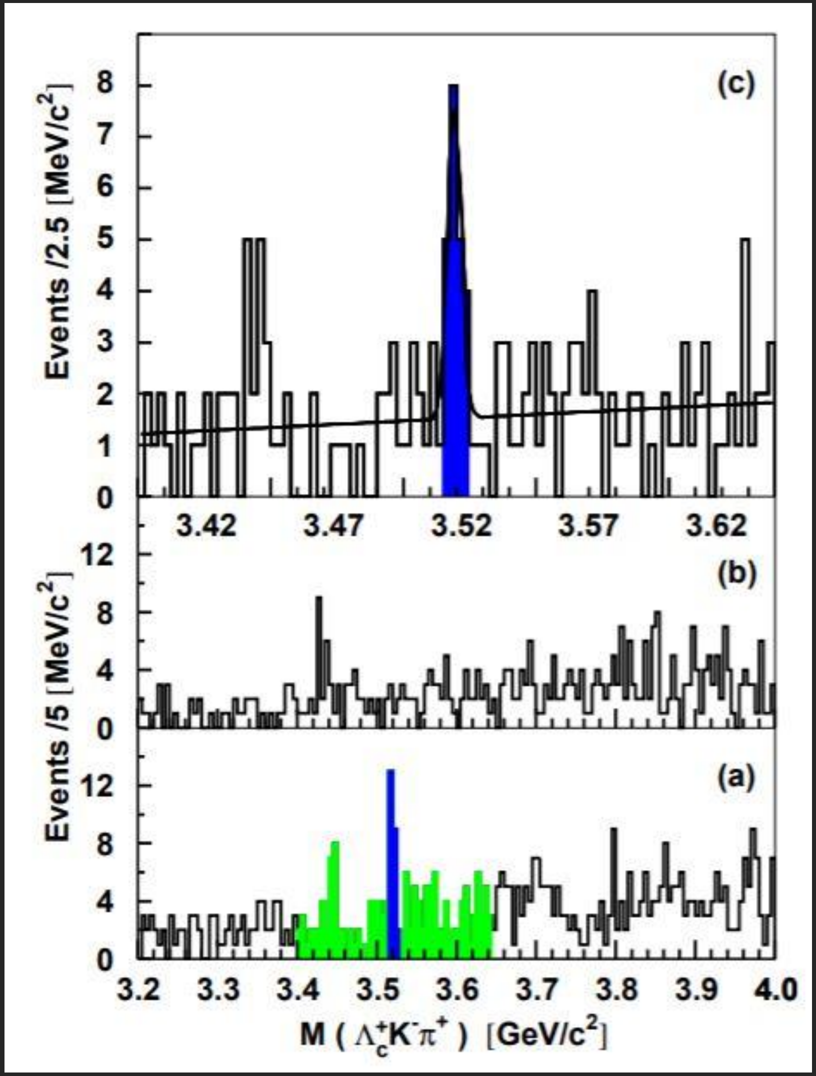
Facilities - BES III

~ 1.3 nb is σ for two c quarks $\rightarrow$ at least two charmed hadrons

$\sigma(e^+e^- \rightarrow X_c\, Y)$ given in the table are not independent
(e.g. $\sigma(e^+e^- \rightarrow D\, Y)$ includes $\sigma(e^+e^- \rightarrow D^*\, Y)$ with $D^* \rightarrow D$ ....);
hence we include only $\sigma(e^+e^- \rightarrow D\, Y)$ in the sum

BACK

SPECTROSCOPY Ξ_{cc}



M. MATTSON ET AL. (SELEX COLL.), PRL 89, 112001 (2002)

SELEX: Σ^- BEAM ON TARGET; PRODUCTION OF CHARM HADRONS; FERMILAB

HYPOTETICAL
$\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$

NEVER CONFIRMED BY BABAR, BELLE OR LHCB

BACK

Exotic mesons

States other than $q_1\underline{q}_2$, $q_1q_2q_3$ not forbidden in SM;
exotic J^{PC} (e.g. 0^{+-}, 1^{-+}, 2^{+-},... forbidden for $q\underline{q}$);
exotic decay modes (not possible from $q\underline{q}$);
strange properties (widths,...);

Pentaquarks:
$q_1q_2q_3q_4q_5$;
Hybrids:
$c\underline{c}$ + g's;
Tetraquarks:
diquark-antidiquark, $[c\underline{q}][\underline{c}q]$
Molecules:
$M(c\underline{q})M(\underline{c}q)$, loosely bound mesons

Back

Spectroscopy X(3872)

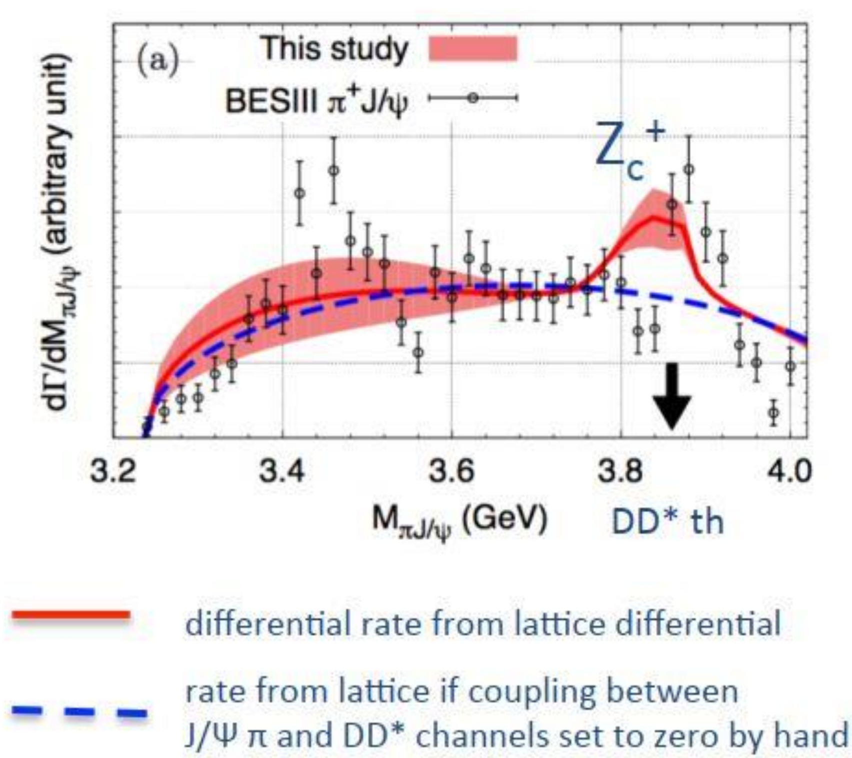
since $m(X(3872)) \sim m(D)+m(D^*)$
$\rightarrow$ DD^* molecule?

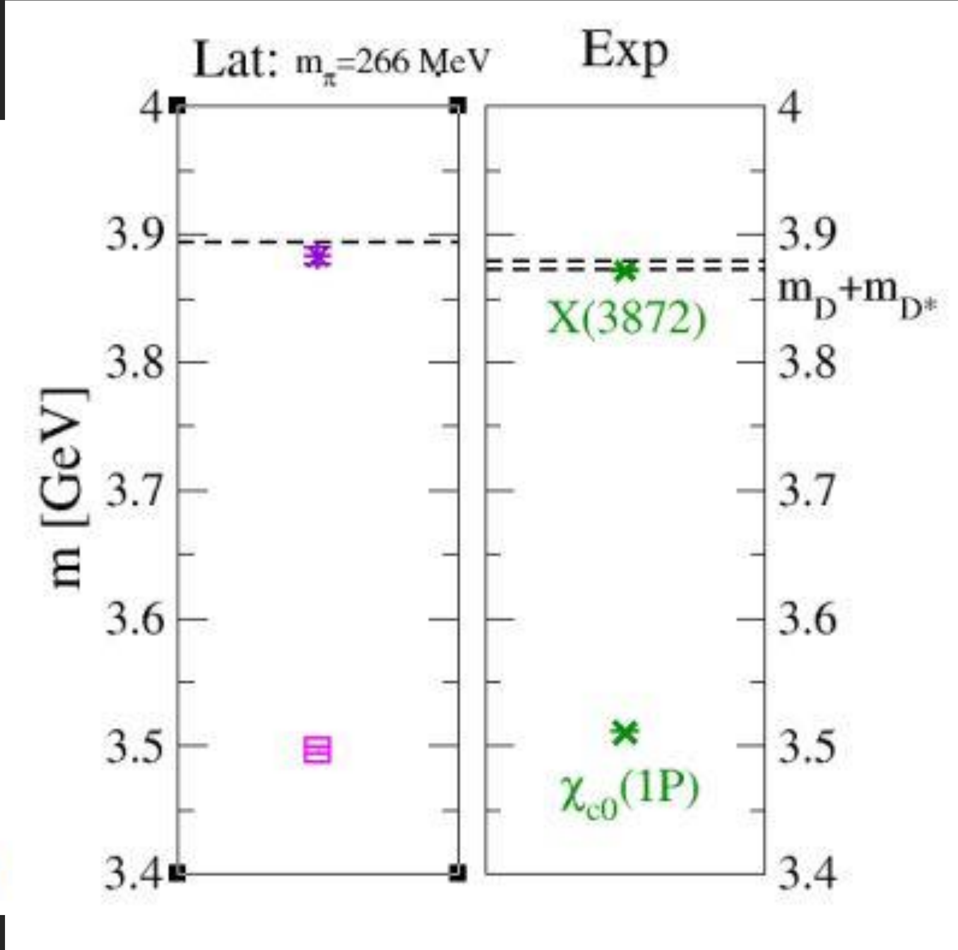
such a molecule is ideal mixture of isospin components:
$|I,I_3\rangle = |0,0\rangle + |1,I_3\rangle$;
$X(3872)$ decays to $J/\psi\,\rho\,(\pi\pi)$ $(I=1)$ and $J/\psi\,\omega\,(\pi\pi\pi)$ $(I=0)$;
due to limited phase space for $J/\psi\,\omega$ it would decay preferentially (strongly) to $J/\psi\,\rho$;
experiment: $Br(J/\psi\,\rho) \sim Br(J/\psi\,\omega)$; isospin violation?
$\Rightarrow$ new models with addition of $c\bar{c}$ $(I=0)$

back

X(3872) on lattice attempt for $Z_c^+(3900)$

S. Prelovsek, L. Leskovec, PRL 111, 192001 (2013)





Y. Ikeda et al. (HALQCD Coll.), PRL 117, 242001 (2016)

BACK

SPECTROSCOPY $Z^{+}(4430)$

APPROXIMATE DEPENDENCE OF RELATIVE ACCURACY OF YIELD ON LUMINOSITY AND PURITY

$$\frac{\sigma_{Ns}}{N_s} = \frac{\sqrt{N_s + N_b}}{N_s}; \quad P = \frac{N_s}{N_s + N_b}, \quad \frac{\sigma_{Ns}}{N_s} = \sqrt{\frac{L_0}{N_{s0}}\frac{1}{\sqrt{LP}}} \left(= \sqrt{\frac{L_0}{L}} \left(\frac{\sigma_{Ns}}{N_s}\right)_0 \right)$$

$$\left(P = 1 \Rightarrow \frac{\sigma_{Ns}}{N_s} = \sqrt{\frac{1}{N_s}} \right)$$

INTRODUCING FEI WITH EFF. $\varepsilon \sim 1\%$, IMPROVING PURITY TO $P' \sim 0.5$

$$\frac{\sigma_{Ns}}{N_s} = \sqrt{\frac{L_0}{N_{s0}}\frac{1}{\sqrt{\varepsilon L P'}}}$$

REQUIRING SAME STAT. UNCERTAINTY

$$\frac{\sigma_{Ns}}{N_s} = \left(\frac{\sigma_{Ns}}{N_s}\right)_0$$

$\Rightarrow$ L ~ 15 AB^{-1}

BACK

Spectroscopy P_c

$P_c^+ \to J/\psi\, p$

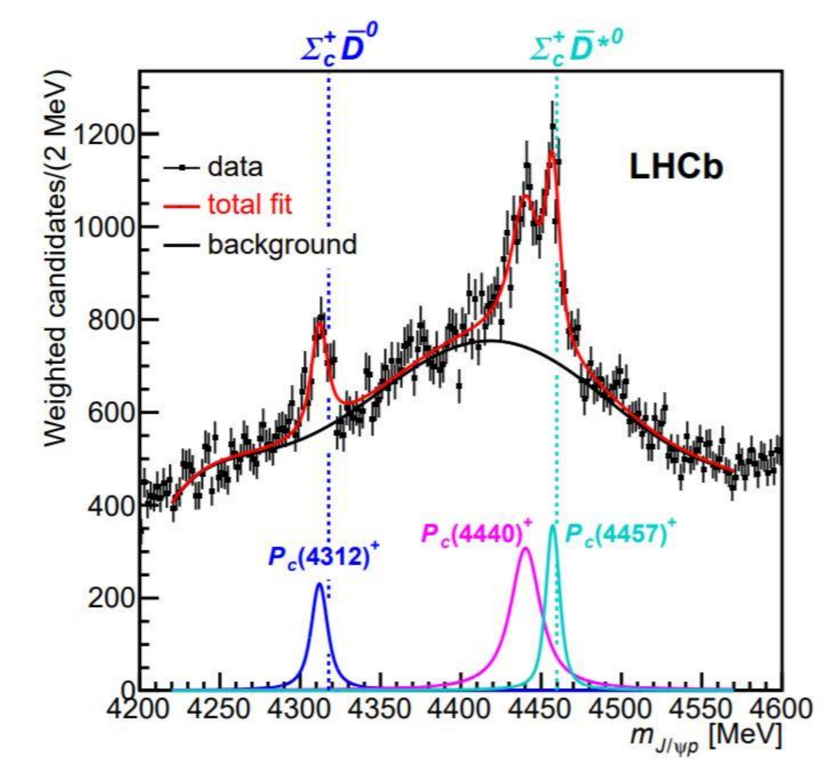
$uudc\bar{c}$

R. Aaij et al. (LHCb Coll.), PRL 115, 072001 (2015)

LQCD: P_c does not appear in $J/\psi\, p \to P_c^+ \to J/\psi\, p$ scattering, decoupled from other channels

U. Skerbis, S. Pfrelovsek, PRD 99, 094505 (2019)

UPDATE



R. Aaij et al. (LHCb Coll.), PRL 122, 222001 (2019)

BACK

Spectroscopy *ISR*

ISR production

$$x = 2E_{\gamma_{ISR}} / \sqrt{s}$$

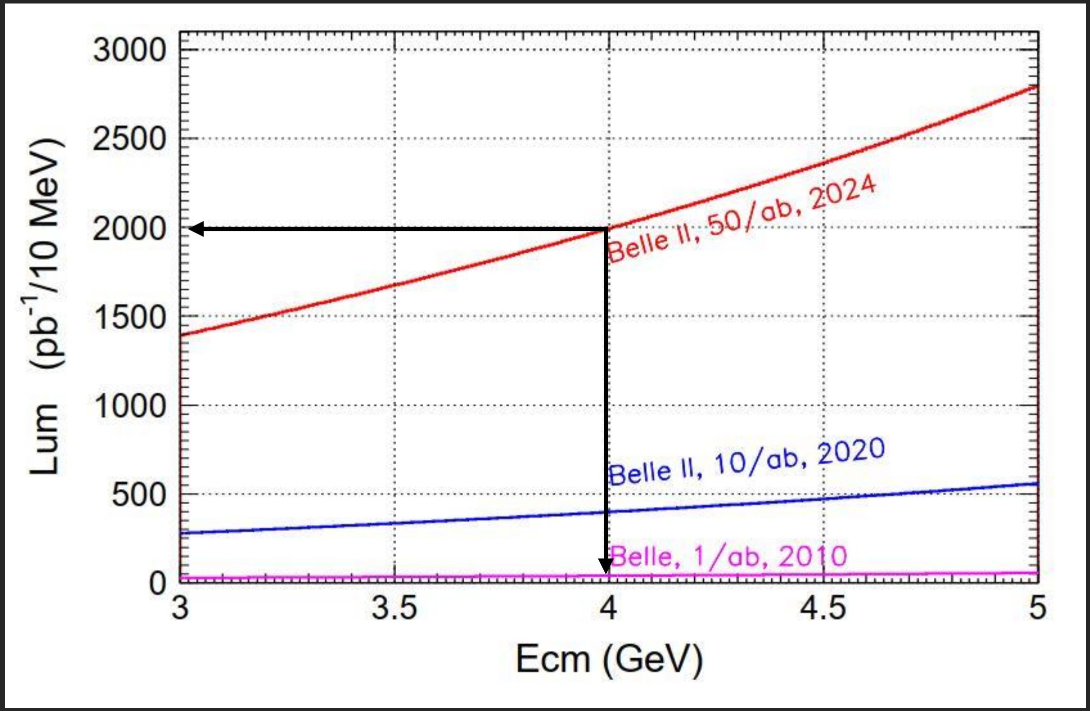
diff. cross section for ISR production

cross section for $e^+e^- \to f$ production

$$\frac{\sigma_f(s,x)}{dx} = W(s,x)\sigma_f(s(1-x))$$

probab. for γ_{ISR} emission (known to better than 1%)

effective luminosity



at L=50 ab^{-1} we will have 2 fb^{-1} luminosity to produce ISR event with $\sqrt{s'} \in$ [4 GeV - 5 MeV, 4 GeV+5 MeV]

B2PB

BACK

D^0 Mixing Time Evolution

$$\left|\psi(t=0)\right\rangle = a(0)\left|P^0\right\rangle + b(0)\left|\overline{P}^0\right\rangle$$

$$\left|\psi(t)\right\rangle = a(t)\left|P^0\right\rangle + b(t)\left|\overline{P}^0\right\rangle + \ldots$$

$$i\frac{\partial}{\partial t}\begin{bmatrix}\left|P^0(t)\right\rangle \\ \left|\overline{P}^0(t)\right\rangle\end{bmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{bmatrix}\left|P^0(t)\right\rangle \\ \left|\overline{P}^0(t)\right\rangle\end{bmatrix}$$

$$\left|P_{1,2}\right\rangle = p\left|P^0\right\rangle \pm q\left|\overline{P}^0\right\rangle$$

$$\begin{bmatrix} M - i\frac{\Gamma}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{12}^* - i\frac{\Gamma_{12}^*}{2} & M - i\frac{\Gamma}{2}\end{bmatrix}\begin{bmatrix} p \\ \pm q\end{bmatrix} = \lambda_{1,2}\begin{bmatrix} p \\ \pm q\end{bmatrix}$$

$$\lambda_{1,2} = M - i\frac{\Gamma}{2} \pm \frac{q}{p}\left[M_{12} - i\frac{\Gamma_{12}}{2}\right] \equiv m_{1,2} - i\frac{\Gamma_{1,2}}{2}, \quad \left(\frac{q}{p}\right)^2 = \frac{M_{12}{*} - i\frac{\Gamma_{12}{*}}{2}}{M_{12} - i\frac{\Gamma_{12}}{2}}$$

$$\left|P_{1,2}(t)\right\rangle = e^{-i\lambda_{1,2}t}\left|P_{1,2}(t=0)\right\rangle$$

BACK

D^0 Mixing Phase convent.

$$\left|D_{1,2}\right\rangle = p\left|D^0\right\rangle \pm q\left|\overline{D}^0\right\rangle$$

$$\hat{C}\hat{P}\left|D^0\right\rangle = +\left|\overline{D}^0\right\rangle$$

no CPV: $$\hat{C}\hat{P}\left|D_{1,2}\right\rangle = \left|\overline{D}^0\right\rangle \pm \left|D^0\right\rangle = \pm\left|D_{1,2}\right\rangle$$

time evolution:

$$\left|D^0(t)\right\rangle = \left[\left|D^0\right\rangle \cosh\left(\frac{ix+y}{2}\overline{\Gamma}t\right) - \frac{q}{p}\left|\overline{D}^0\right\rangle \sinh\left(\frac{ix+y}{2}\overline{\Gamma}t\right)\right] e^{-i\overline{m}t-\frac{\overline{\Gamma}}{2}t}$$

$$\left|\overline{D}^0(t)\right\rangle = \left[\left|\overline{D}^0\right\rangle \cosh\left(\frac{ix+y}{2}\overline{\Gamma}t\right) - \frac{p}{q}\left|D^0\right\rangle \sinh\left(\frac{ix+y}{2}\overline{\Gamma}t\right)\right] e^{-i\overline{m}t-\frac{\overline{\Gamma}}{2}t}$$

$$\left|\left\langle\overline{D}^0 \middle| D^0(t)\right\rangle\right|^2 = \left|\frac{q}{p}\right|^2 \left|\sinh\left(\frac{ix+y}{2}\overline{\Gamma}t\right)\right|^2 e^{-\overline{\Gamma}t} \quad \left|\left\langle D^0 \middle| D^0(t)\right\rangle\right|^2 = \left|\cosh\left(\frac{ix+y}{2}\overline{\Gamma}t\right)\right|^2 e^{-\overline{\Gamma}t}$$

$$r = \int_0^\infty \left|\left\langle\overline{D}^0 \middle| D^0(t)\right\rangle\right|^2 dt \Big/ \int_0^\infty \left|\left\langle\overline{D}^0 \middle| D^0(t)\right\rangle\right|^2 dt + \int_0^\infty \left|\left\langle D^0 \middle| D^0(t)\right\rangle\right|^2 dt = \frac{x^2+y^2}{2(1+x^2)}$$

BACK

D^0 Mixing Time evolution

time evolution:

$$|x|,|y|<<1 \Rightarrow \frac{dN(D^0\to f)}{dt} \propto e^{-\bar{\Gamma}t}\left|\langle f|D^0\rangle - \frac{q}{p}\frac{ix+y}{2}\langle f|\bar{D}^0\rangle\bar{\Gamma}t\right|^2$$

$$|x|,|y|<<1 \Rightarrow \frac{dN(\bar{D}^0\to f)}{dt} \propto e^{-\bar{\Gamma}t}\left|\langle f|\bar{D}^0\rangle - \frac{p}{q}\frac{ix+y}{2}\langle f|D^0\rangle\bar{\Gamma}t\right|^2$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

$$\frac{dN(D^0\to f)}{dt} \propto e^{-\bar{\Gamma}t}|A_f|^2\left|1-\lambda_f\frac{ix+y}{2}\bar{\Gamma}t\right|^2$$

$$\frac{dN(\bar{D}^0\to f)}{dt} \propto e^{-\bar{\Gamma}t}|\bar{A}_f|^2\left|1-\lambda_f^{-1}\frac{ix+y}{2}\bar{\Gamma}t\right|^2$$

$$\mathrm{Re}\left(\frac{1}{\lambda_f}\right) = \frac{1}{|\lambda_f|^2}\cos\phi_\lambda$$

$$\mathrm{Im}\left(\frac{1}{\lambda_f}\right) = -\frac{1}{|\lambda_f|^2}\sin\phi_\lambda$$

$$\phi_\lambda = \arg(\lambda_f)$$

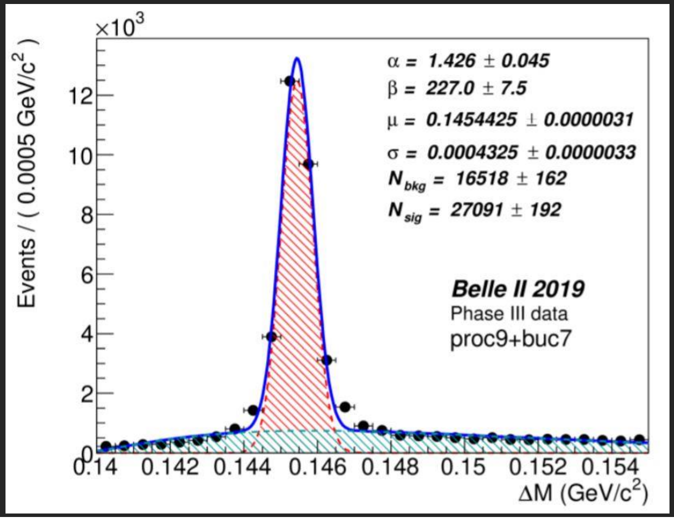
$$\frac{dN(D^0\to f)}{dt} \propto e^{-\bar{\Gamma}t}|A_f|^2\left[1-y\,\mathrm{Re}(\lambda_f)\bar{\Gamma}t + x\,\mathrm{Im}(\lambda_f)\bar{\Gamma}t\right]$$

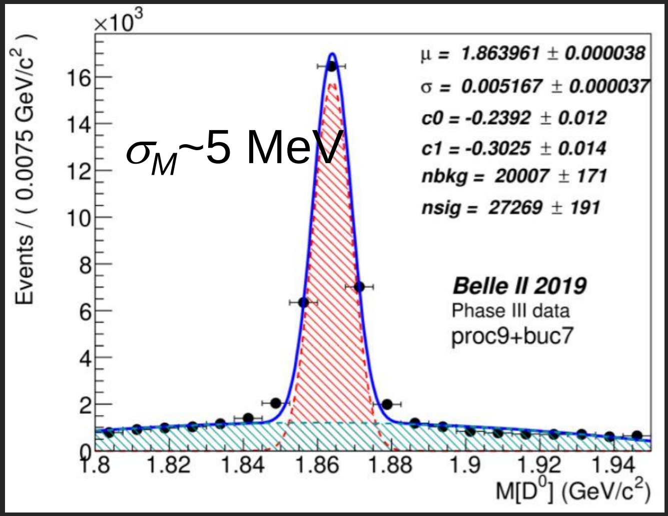
$$\frac{dN(\bar{D}^0\to f)}{dt} \propto e^{-\bar{\Gamma}t}|\bar{A}_f|^2\left[1-y\frac{1}{|\lambda_f|^2}\mathrm{Re}(\lambda_f)\bar{\Gamma}t - x\frac{1}{|\lambda_f|^2}\mathrm{Im}(\lambda_f)\bar{\Gamma}t\right]$$

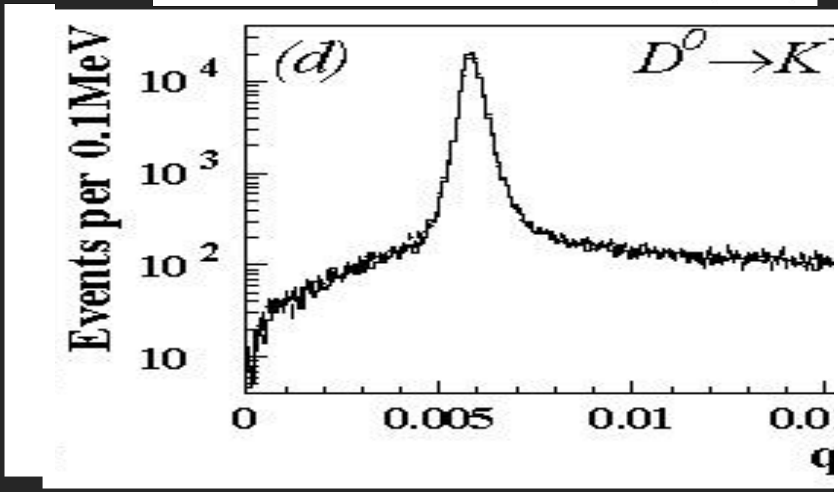
BACK

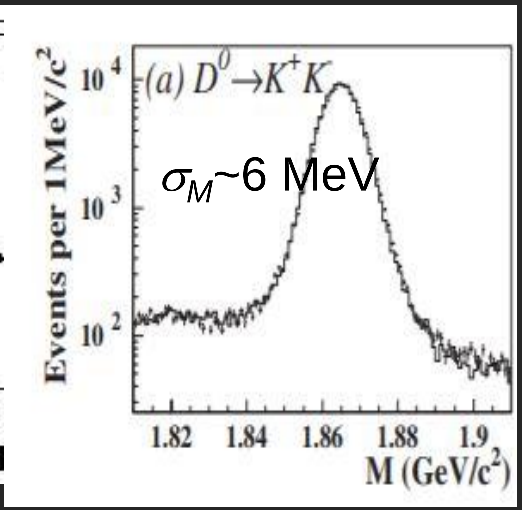
TAGGING WITH D*'S

S. SANDILYA ET AL. (BELLE II COLL.), B2GM OCT 2019









M. STARIC ET AL. (BELLE COLL.), PRL 98, 211803 (2007)

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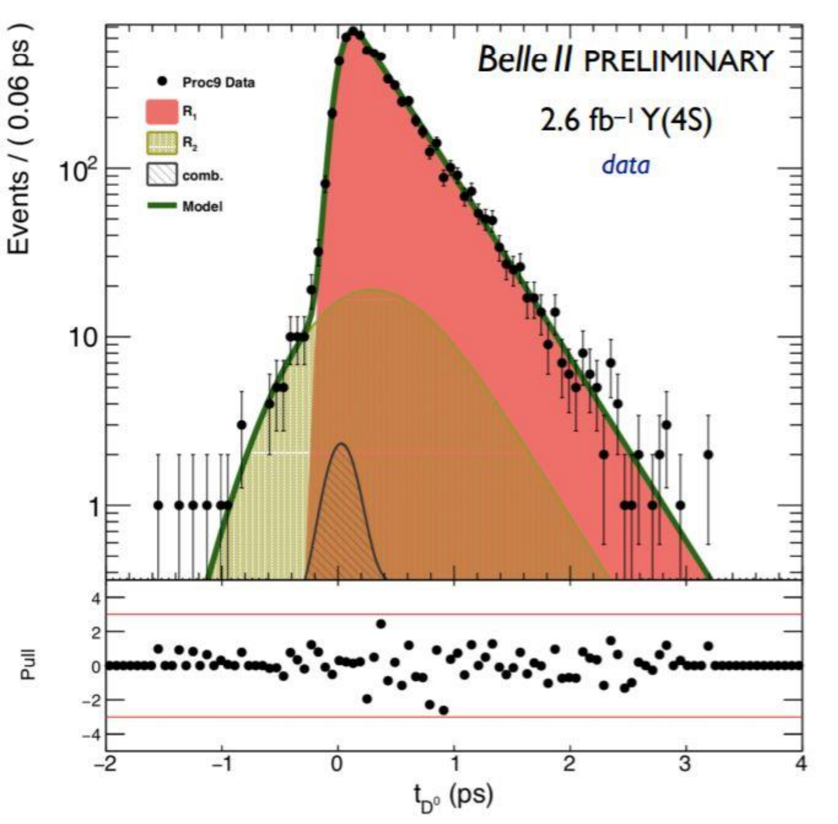
D^0 Mixing Exp. Methods

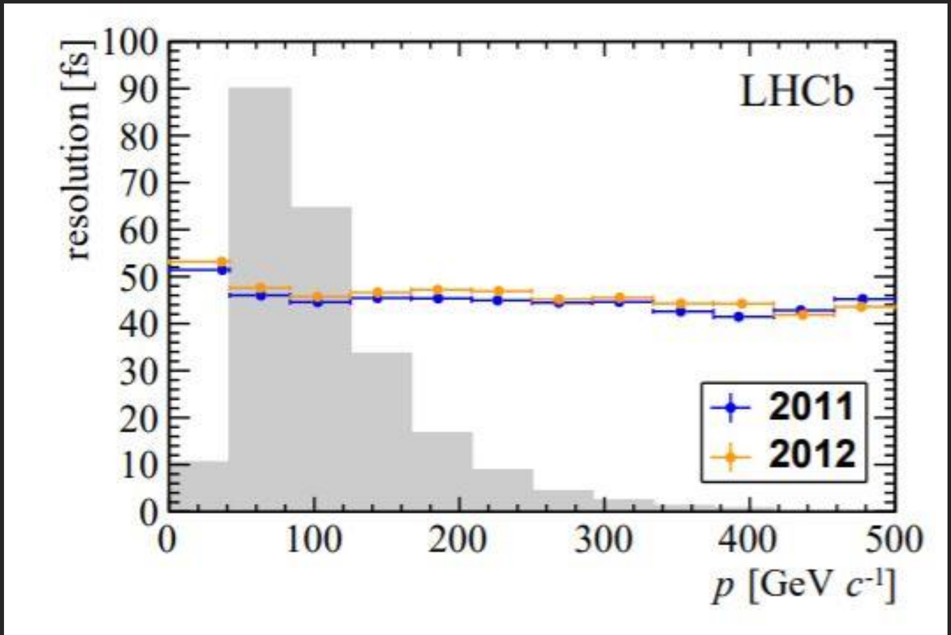
G. de Marino, G. Casarosa et al. (Belle II Coll.), B2GM Oct 2019



Decay time

Belle II
$D^* \to D^0(K\pi)\pi$
$<\sigma_t> \sim$ 100 fs

LHCb
$B_s \to J/\psi\, \phi$
$<\sigma_t> \sim$ 40 fs



R. Aaij et al. (LHCb Coll.), Int. J. Mod. Phys. A 30, 1530022 (2015)

BACK

D^0 Mixing CP eigenstates

$$\lambda_f = \frac{q}{p}\eta_f$$

$$|A_f| = |\overline{A}_f| = |A|$$

$$\phi_f = \arg(\lambda_f) = \arg(\frac{q}{p}) \equiv \phi$$

η_f=+1 CP even states
η_f =-1 CP odd states

$$\langle f_{CP}|D^0\rangle = \frac{1}{\sqrt{2}}\left[\langle f_{CP}|D_1\rangle + \langle f_{CP}|D_2\rangle\right]$$

$$\langle f_{CP}|\overline{D}^0\rangle = \frac{1}{\sqrt{2}}\left[\langle f_{CP}|D_1\rangle - \langle f_{CP}|D_2\rangle\right]$$

$$\langle f_{CP}^+|D^0\rangle = \frac{1}{\sqrt{2}}\langle f_{CP}^+|D_1\rangle = \langle f_{CP}^+|\overline{D}^0\rangle$$

$$\langle f_{CP}^-|D^0\rangle = \frac{1}{\sqrt{2}}\langle f_{CP}^-|D_2\rangle = -\langle f_{CP}^-|\overline{D}^0\rangle$$

$$\frac{dN(D^0 \to f)}{dt} \propto e^{-\overline{\Gamma}t}|A|^2\left[1-\eta_f y\left|\frac{q}{p}\right|\cos\phi\overline{\Gamma}t + \eta_f x\left|\frac{q}{p}\right|\sin\phi\overline{\Gamma}t\right]$$

$$\frac{dN(\overline{D}^0 \to f)}{dt} \propto e^{-\overline{\Gamma}t}|A|^2\left[1-\eta_f y\left|\frac{p}{q}\right|\cos\phi\overline{\Gamma}t - \eta_f x\left|\frac{p}{q}\right|\sin\phi\overline{\Gamma}t\right]$$

BACK

D^0 Mixing CP eigenstates

$$\frac{dN(D^0 \to f)}{dt} \propto e^{-\overline{\Gamma}t}|A|^2\left[1-\eta_f y\left|\frac{q}{p}\right|\cos\phi\overline{\Gamma}t+\eta_f x\left|\frac{q}{p}\right|\sin\phi\overline{\Gamma}t\right]$$

$$\frac{dN(\overline{D}^0 \to f)}{dt} \propto e^{-\overline{\Gamma}t}|A|^2\left[1-\eta_f y\left|\frac{p}{q}\right|\cos\phi\overline{\Gamma}t-\eta_f x\left|\frac{p}{q}\right|\sin\phi\overline{\Gamma}t\right]$$

$$\frac{dN(D^0 \to f)}{dt}+\frac{dN(\overline{D}^0 \to f)}{dt} \propto e^{-\overline{\Gamma}t}|A|^2\left[1-y_{CP}\overline{\Gamma}t\right]$$

$$y_{CP} \underbrace{=}_{\substack{q=p \\ Af=\overline{A}f}} y$$

y_{CP} taking into account CPV is given in 2nd part of lectures

K^+K^-, $\pi^+\pi^-$: CP even states

$K_S\phi$, $K_S\omega$: CP odd states

BACK

D^0 Mixing Hadronic WS

$f=K^+\pi^-$

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} = \left|\frac{q}{p}\right|\frac{1}{r}e^{i(\delta_f+\varphi)}$$

$$\frac{dN(D^0\to f)}{dt} \propto e^{-\overline{\Gamma}t}\left|\overline{A}_{K+\pi-}\right|^2\left[r^2 - ry\left|\frac{q}{p}\right|\cos(\delta_{K\pi}+\phi)\overline{\Gamma}t + rx\left|\frac{q}{p}\right|\sin(\delta_{K\pi}+\phi)\overline{\Gamma}t\right]$$

$$\frac{dN(\overline{D}^0\to f)}{dt} \propto e^{-\overline{\Gamma}t}\left|\overline{A}_{K+\pi-}\right|^2\left[1 - ry\left|\frac{p}{q}\right|\cos(\delta_{K\pi}+\phi)\overline{\Gamma}t + rx\left|\frac{p}{q}\right|\sin(\delta_{K\pi}+\phi)\overline{\Gamma}t\right]$$

neglecting CPV (and going to 2nd order in x, y):

$$\frac{dN(D^0\to f)}{dt} \propto e^{-\overline{\Gamma}t}\left|\overline{A}_{K+\pi-}\right|^2\left[r^2 - ry'\overline{\Gamma}t + \frac{x'^2+y'^2}{4}(\overline{\Gamma}t)^2\right]$$

$$y' = y\cos(\delta_{K\pi}) - x\sin(\delta_{K\pi})$$

$$x' = x\cos(\delta_{K\pi}) + y\sin(\delta_{K\pi})$$

BACK

D^0 Mixing Dalitz

METHOD OF STRONG PHASE DIFFERENCE D^0 / $\bar{D}^0$ *DETERM.* USING COHERENT PRODUCTION OF D MESON PAIRS J. LIBBY ET AL. (CLEO-C COLL.), PRD 82,112006 (2010)

$\psi(3770)$ $(CP= +1) \rightarrow D_1\, D_2$;

if $D_1 \rightarrow CP+ \Rightarrow D_2$ is CP-; (CP-TAGGED)

$$CP = CP(D_1)CP(D_2)(-1)^{\ell=1}$$

if $D_1 \rightarrow D^0 \rightarrow f_{flav} \Rightarrow D_2$ is $\bar{D}^0$ (FLAVOR-TAGGED)

EVTS IN BIN *i* FOR FLAVOR TAGGED (D^0) DECAY:

$$K_i = A_D \int_i |f_D(m_+^2, m_-^2)|^2 dm_+^2 dm_-^2 = A_D F_i$$

(SAME FOR $\bar{D}^0$ WITH $m_+ \leftrightarrow m_-$)

J. LIBBY ET AL. (CLEO-C COLL.), PRD 82,112006 (2010)

DALITZ DIST. FOR CP TAGGED *(CP+, CP-)* DECAYS

$$f_{CP\pm}(m_+^2, m_-^2) = \frac{1}{\sqrt{2}}[f_D(m_+^2, m_-^2) \pm f_D(m_-^2, m_+^2)]$$

\# EVTS IN BIN *i*
FOR CP TAGGED *(CP+, CP-)* DECAY:

$$M_i^\pm = h_{CP\pm}(K_i \pm 2c_i\sqrt{K_iK_{-i} + K_{-i}})$$

FLAVOR-TAGGED:

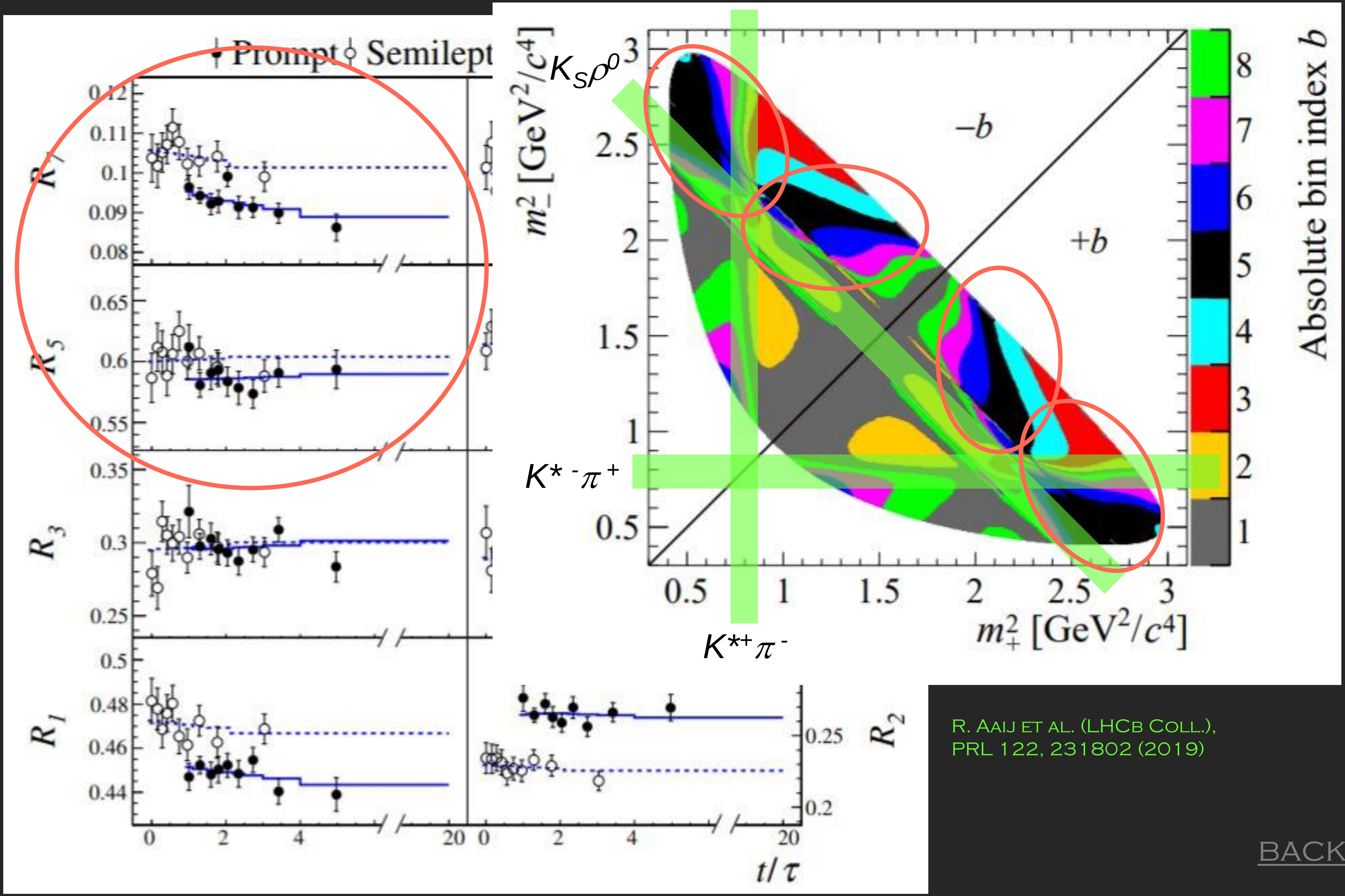
$$K_i = A_D \int_i |f_D(m_+^2, m_-^2)|^2 dm_+^2 dm_-^2 = A_D F_i$$

$$c_i \equiv \frac{1}{\sqrt{F_iF_{-i}}} \int_i |f_D(m_+^2, m_-^2)||f_D(m_-^2, m_+^2)| \cos[\Delta\delta_D(m_+^2, m_-^2)] dm_+^2 dm_-^2$$

$$s_i \equiv \frac{1}{\sqrt{F_iF_{-i}}} \int_i |f_D(m_+^2, m_-^2)||f_D(m_-^2, m_+^2)| \sin[\Delta\delta_D(m_+^2, m_-^2)] dm_+^2 dm_-^2$$

BACK

D^0 Mixing Dalitz



R. Aaij et al. (LHCb Coll.), PRL 122, 231802 (2019)

BACK