Precision measurements of the CKM mechanism at Belle

Wolfgang Dungel

Institute for high energy physics
Austrian Academy of Sciences

"Physics in progress",
April 29, 2010

Wolfgang Dungel, dungel (at) hephy.oeaw.ac.at

A short overview

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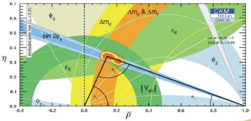

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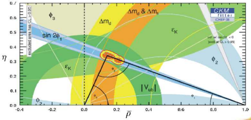

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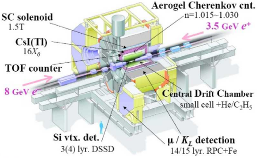

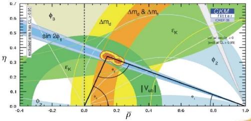

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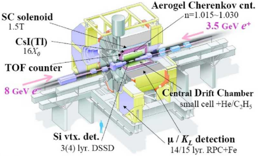

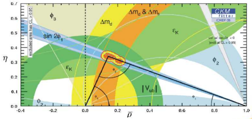

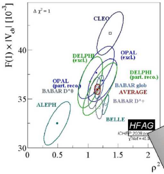

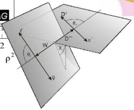

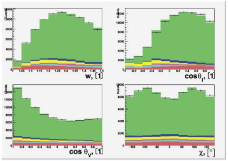

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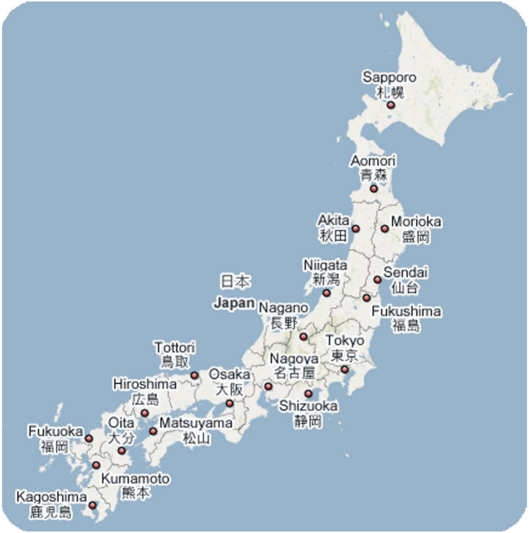
Geography



Geography


Sapporo
札幌
Aomori
青森
Akita
秋田
Morioka
盛岡
Niigata
新潟
Sendai
仙台
日本
Japan
Nagano
長野
Fukushima
福島
Toky
東京
Tottori
鳥取
Nagoya
名古屋
Osaka
大阪
Hiroshima
広島
Shizuoka
静岡
Oita
大分
Matsuyama
松山
Fukuoka
福岡
Kumamoto
熊本
Kagoshima
鹿児島

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CP Violation and the CKM matrix

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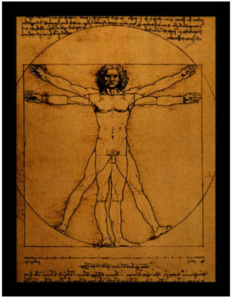
Symmetries



What does "symmetry" mean?

- Investigate properties of a system
- Change system in some way, "transformation"
- Do physical quantities change?

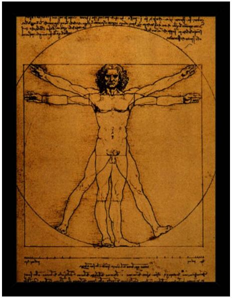
If not:

- System is symmetric

If they do:

- "Symmetry is violated!"

Symmetries



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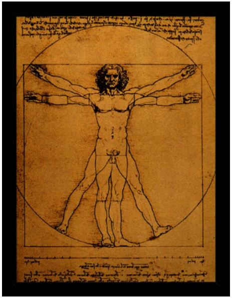

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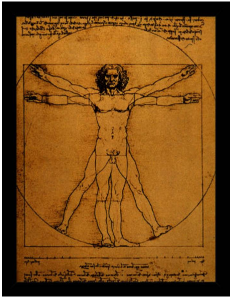

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The big puzzle

The big puzzle - Cosmology

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Lets assume ...

- “Big bang” is accurate
- Processes can only produce matter and anti-matter in equal parts

- Where did the anti-matter go?

Observations

- There is no evidence for anti-matter galaxies etc.

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... how can we exist?

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Of course ...

That's the wrong question!

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The actual question

Are our current theories wrong?

- Perhaps - would be exciting of course!
- ... but not necessarily.

One necessary ingredient for explanation

- Development of an excess of baryons over anti-baryons
- "Baryogenesis"

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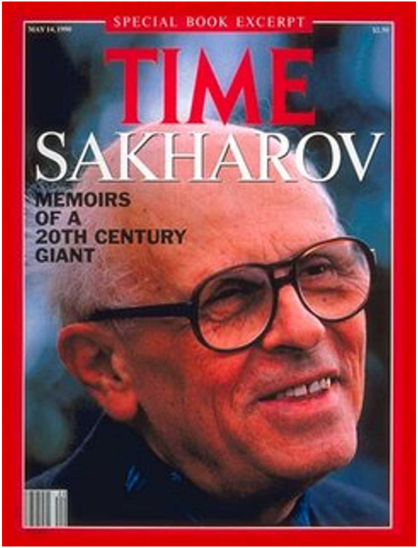
The quest giver - Andrei Sakharov



Sakharov conditions

The three conditions for Baryogenesis by Andrei Sakharov

- Universe out of equilibrium - Ok(?)
    - Expanding universe (?)
- Violation of baryon number conservation - Ok(?)
    - e.g. grand unification in early universe - no conservation
- Some processes not the same for matter and antimatter
    - CP violation
    - First experimental observation in K^0 decays
    - Nobelprize 1980: Val Fitch and Jim Cronin

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A short history of CPV

- 1964: Christensen, Cronin†, Fitch† and Turlay observe CP violation in neutral kaon decays (Nobelprize 1980)
- 1966: Andrei Sakharov emphasizes the cosmological importance of CP violation (baryon density of the universe)
- 1973: Kobayashi and Maskawa propose their explanation of CP violation using three generations of quarks
- 2001-present: Belle and BaBar are able to probe the KM mechanism in detail
- 2008: !!!!!

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The KM mechanism

Charged current interaction in SM

$$-\mathcal{L}_{W^\pm} = \frac{g}{\sqrt{2}}\, \bar{u}_{Li}\, V_{ij}\, d_{Rj}\, W^+_\mu + h.c$$

[Kobayashi, Maskawa,Prog. Theor. Phys. 49,652 (1973)]

CKM matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Cabbibo-Kobayashi-Maskawa matrix
- V_{CKM} is a unitary 3×3 matrix of coupling constants of weak transitions
- Parametrized by four indepentend parameters (three angles, one phase)
- KM phase is responsible for all CP violating phenomena observed so far!

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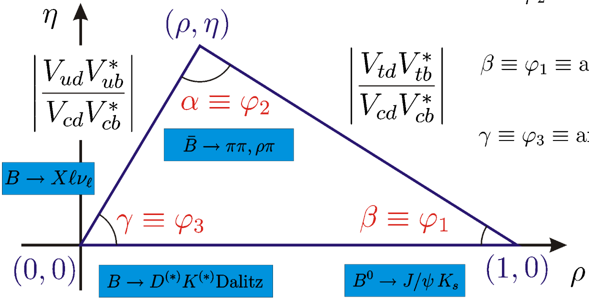
Unitary triangle

$$\sum_i V_{ij} V_{ik}^* = \delta_{jk} \Rightarrow V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



$$\alpha \equiv \varphi_2 \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\beta \equiv \varphi_1 \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\gamma \equiv \varphi_3 \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

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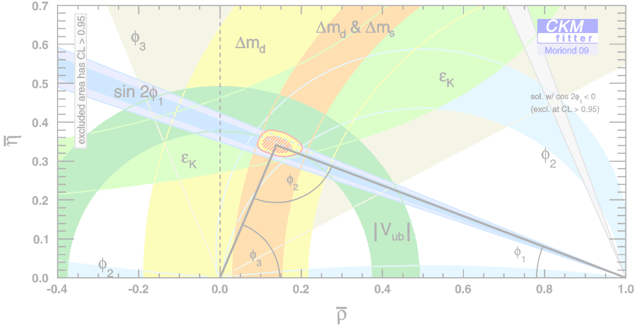
Unitarity and the experiment

- In a way, expectation was that B-factories would find large deviations from KM mechanism ...



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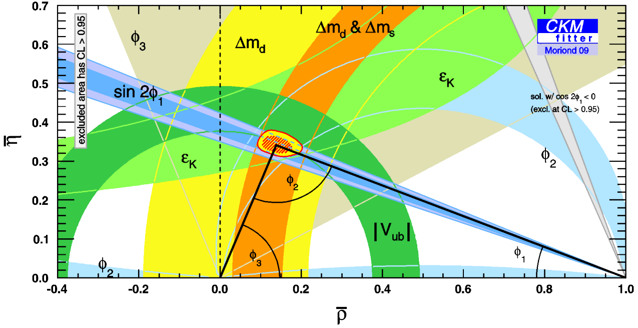

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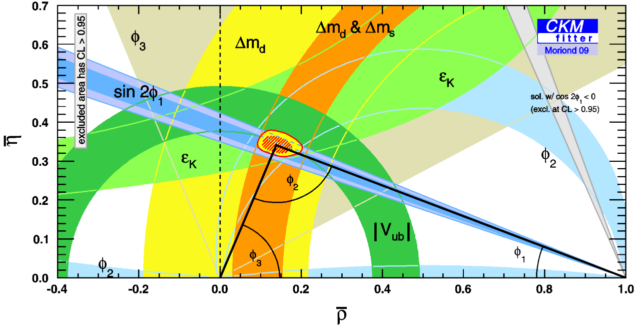

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The Nobel Prize in Physics 2008

Nambu Yoichiro

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Kobayashi Makoto

Copyright: KEK

Maskawa Toshihide

Copyright: Kyoto University

- “for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics”

- “for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature”

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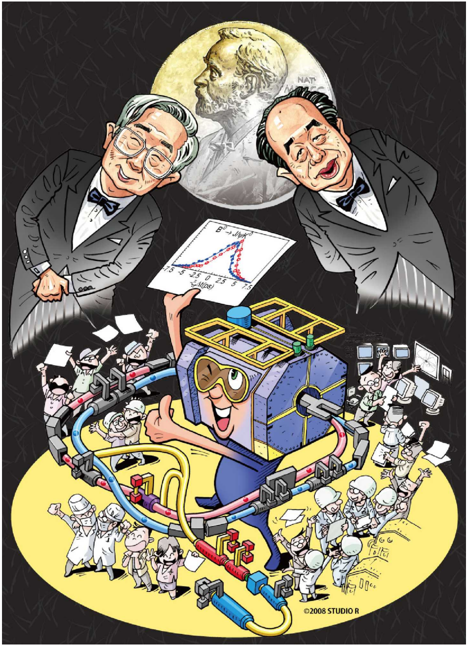

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The Belle experiment

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札幌
Aomori
青森
Akita
秋田
Morioka
盛岡
Niigata
新潟
Sendai
仙台
日本
Japan
Nagano
長野
Fukushima
福島
Tottori
鳥取
Nagoya
名古屋
東京
Osaka
大阪
Hiroshima
広島
Shizuoka
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Oita
大分
Matsuyama
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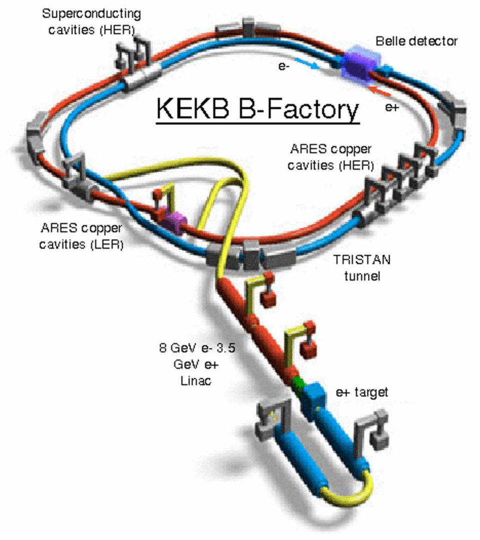
KEK-B


Superconducting cavities (HER)
Belle detector
e-
KEKB B-Factory
e+
ARES copper cavities (HER)
ARES copper cavities (LER)
TRISTAN tunnel
8 GeV e- 3.5 GeV e+ Linac
e+ target

Some technical details

Setup

- $8.0\,\mathrm{GeV}\ e^- \times 3.5\,\mathrm{GeV}\ e^+$ collider
- $E_{c.m.} = 10.58\ \mathrm{GeV}$, "$\Upsilon(4S)$"

- KEK-B $E_{c.m.}$: first production resonance for real B mesons
- If $B\bar{B}$ pair created: nearly in rest in c.m. system
- Asymmetric collider: $\Lambda_{lab,c.m.} \neq \mathbb{I}$
- Time dilation! B flight length can be resolved!

- Due to the momentum in z direction:
  - Measurement of z position of decays $\Leftrightarrow$ time stamps

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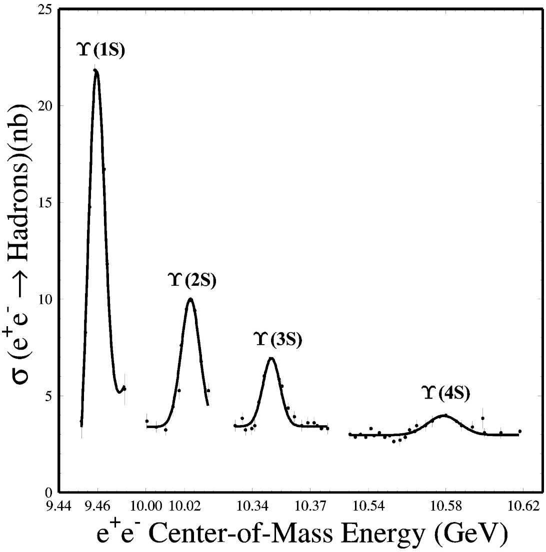

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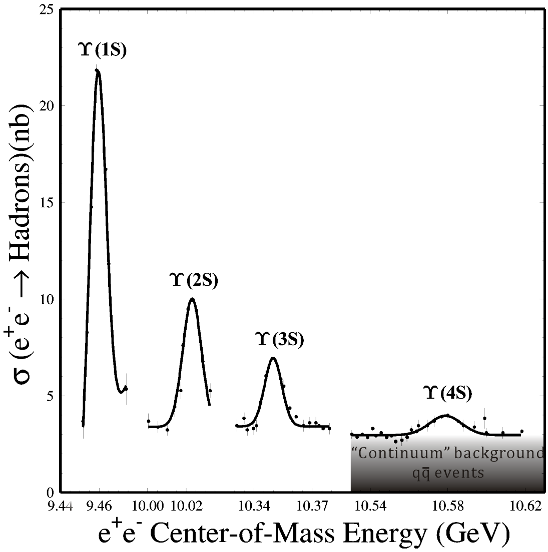
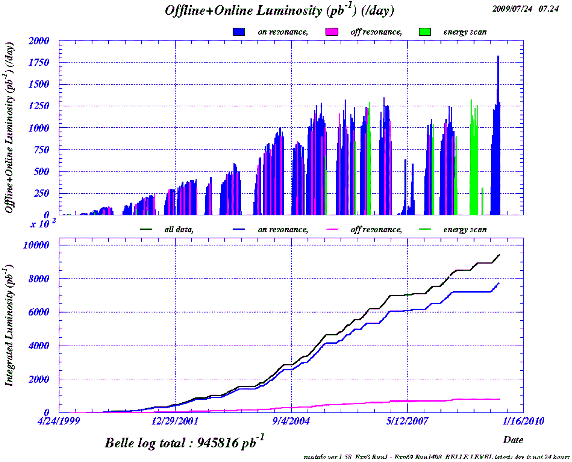
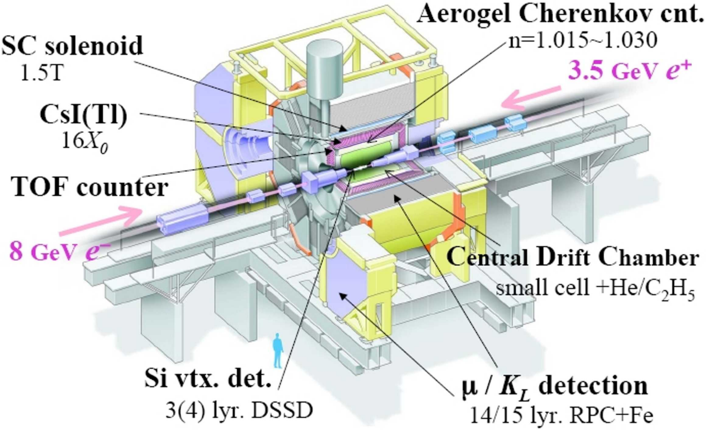


Luminosity

- Record: $\mathcal{L}_{peak} \approx 2.1 \times 10^{34} cm^{-2} s^{-1}$
- That's more than twice the design value!
- $\int dt\, \mathcal{L} \approx 1000 \text{fb}^{-1}$, $\approx 900 \times 10^6$ $B\bar{B}$ events



Schematic view of Belle



Wolfgang Dungel, dungel (at) hephy.oeaw.ac.at

The Collaboration

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Where Belle excels in ...

Precision measurements

- Publication of first observation is (often) not enough
- Aim is to actually understand effects in terms of a theoretical picture
- Precision is nescessary to test any given theory

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- Publication of first observation is (often) not enough
- Aim is to actually understand effects in terms of a theoretical picture
- Precision is nescessary to test any given theory

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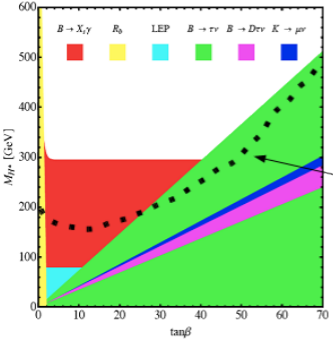

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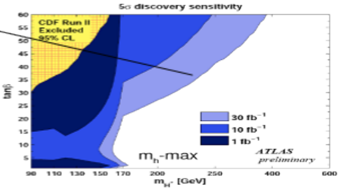

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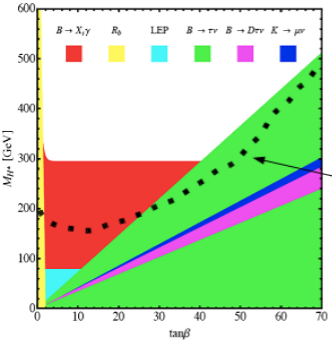

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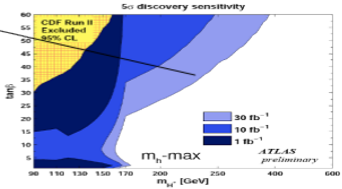

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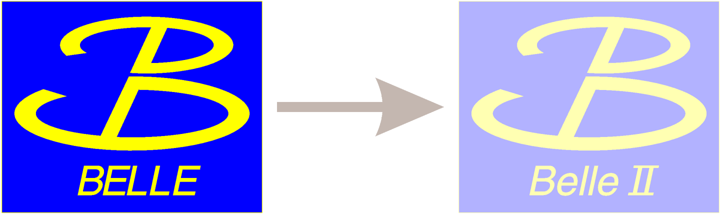

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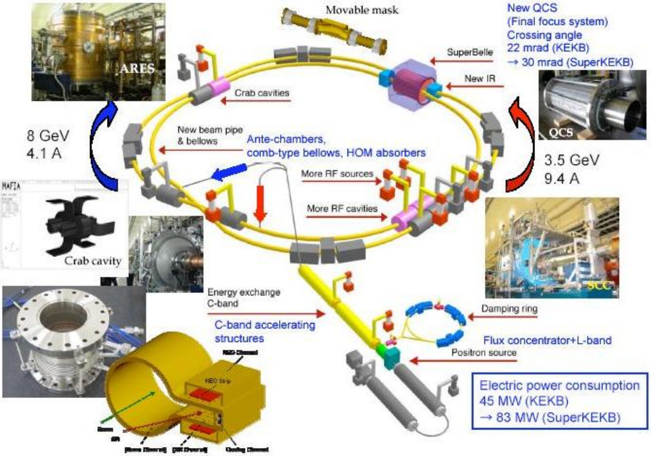
From KEKB to SuperKEKB



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SuperKEKB versus SuperB

- Two concepts to reach peak luminosity $\mathcal{O}(10^{36} cm^{-2} s^{-1})$

High current scheme

- "Increase number of particles"
- Currents of both beams are increased
- High power consumption (and thus costs)
- High beam background
- Favored by KEK

Nano beams

- "Increase particle density"
- Emittance of beams is reduced
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In the end ...

- The best of both worlds will be used
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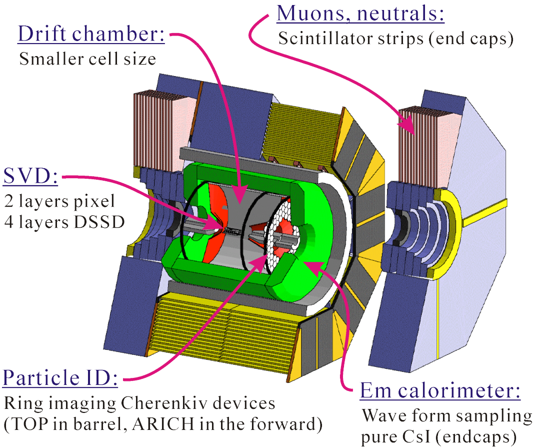

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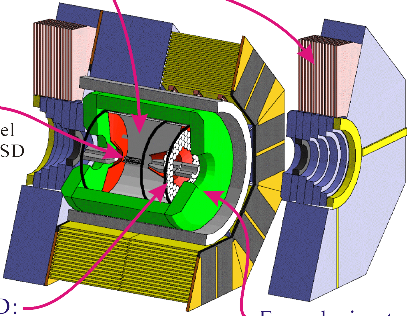

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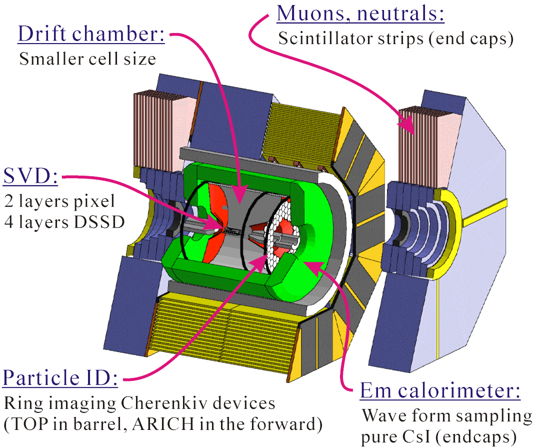

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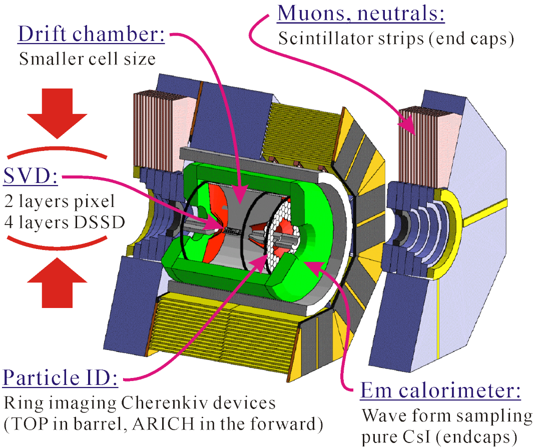

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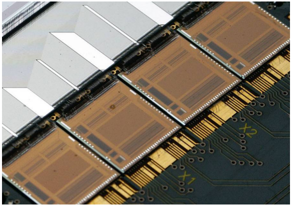
Silicon strip detector

- Will be built by HEPHY
- Modules, electronics, mechanics



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- Front-end chip: APV25
- 6 consecutive time samples for hit time reconstruction

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- In outer layers, integrate read-out into module
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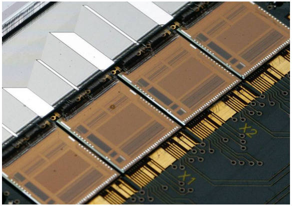

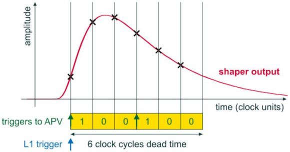

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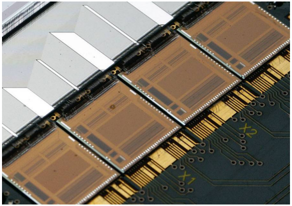

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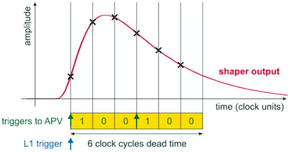

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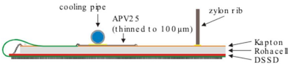

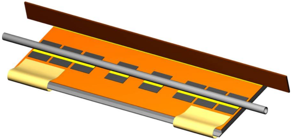

Timeline - as seen in 2009

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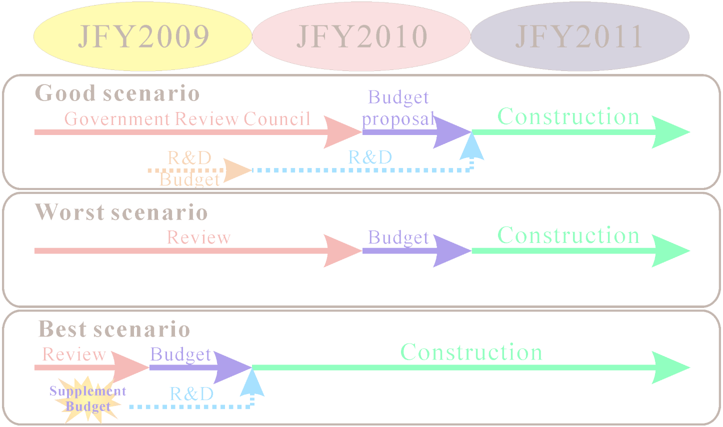

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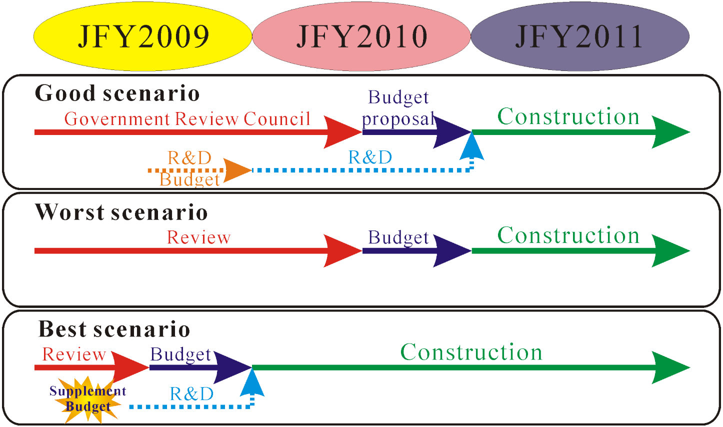

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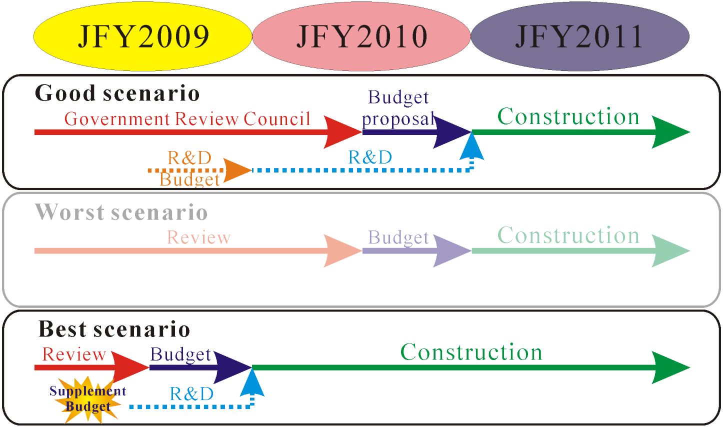

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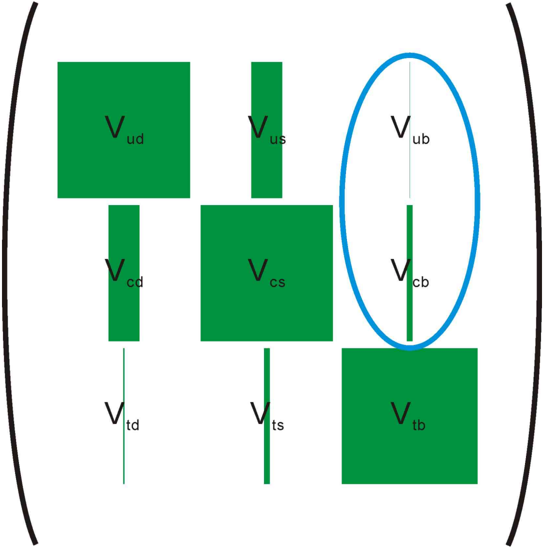
The CKM matrix



Measurement of the form factors of the decay $B^0 \to D^{*-}\ell^+\nu$ and determination of the CKM matrix element $|V_{cb}|$

Measurement of the form factors of the decay $B^+ \to \bar{D}^{*0}\ell^+\nu$ and determination of the CKM matrix element $|V_{cb}|$

dungel(at)hephy.oeaw.ac.at   schwanda(at)hephy.oeaw.ac.at

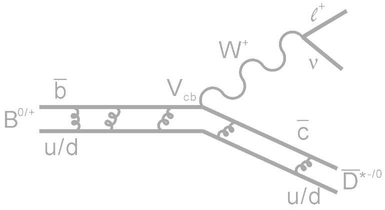
In a nutshell

- Two similar analyses
- Systematic uncertainty not identical

- Preliminary results shown at ICHEP08 and EPS09

Wolfgang Dungel, dungel (at) hephy.oeaw.ac.at

How to determine $|V_{cb}|$?



- Fundamental process: $b \to cW^-$
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- But: There are no free quarks, only composite particles!
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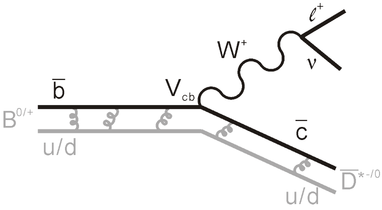

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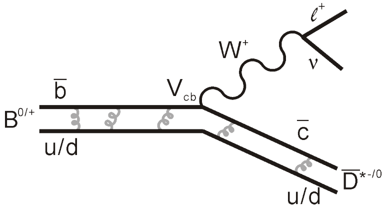

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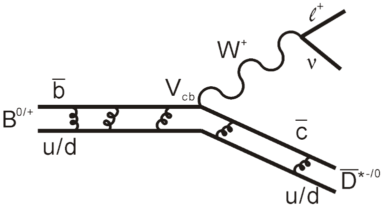

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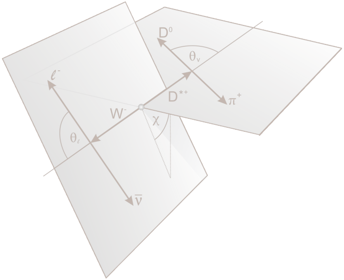
Differential decay width

Kinematic variables

- $w = \frac{p_B^{\mu} \cdot p_{D^*,\mu}}{m_{B^0}\, m_{D^*}} = a + b\,q^2$
- $\cos\theta_\ell$, $\cos\theta_V$, χ



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$$\frac{d^4\Gamma(B \to D^* \ell^+ \nu_\ell)}{dw\, d(\cos\theta_\ell)\, d(\cos\theta_V)\, d\chi}$$

$$= \frac{6 m_B m_{D^*}^2}{8(4\pi)^4} \sqrt{w^2 - 1}(1 - 2wr + r^2) G_F^2 |V_{cb}|^2$$

$$\times \{(1 - \cos\theta_\ell)^2 \sin^2\theta_V H_+^2(w)$$

$$+ (1 + \cos\theta_\ell)^2 \sin^2\theta_V H_-^2(w)$$

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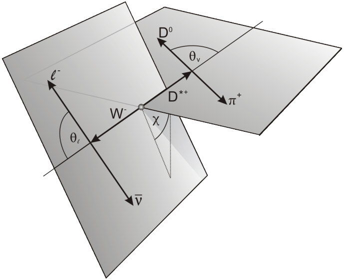

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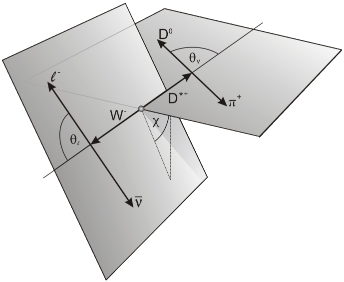

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Results to be obtained

- $\mathcal{F}(1)|V_{cb}|$
- Form factor parameters

Considered final states

- Only signal is reconstructed
- $\bar{B} \to D^* \ell^- \bar{\nu}_\ell$,
  - $D^* \to D^0 \pi_s$
    - $D^0 \to K^- \pi^+$
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Systematics

- B^0 and B^+ show different π_s systematic uncertainty

$B^0 \to D^{*-} \ell^+ \nu$

- Shown at ICHEP08
- $N_{sig} = 69,345 \pm 377$

$B^+ \to \bar{D}^{*0} \ell^+ \nu$

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- $N_{sig} = 27,106 \pm 367$

B^0 signal purity and background fractions

B^+ signal purity and background fractions

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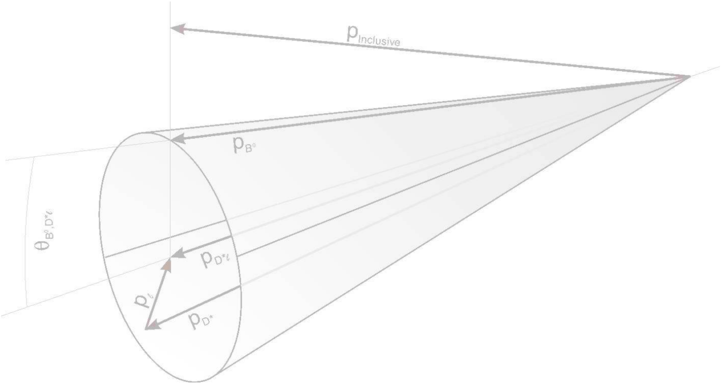
Reconstruction of the B rest frame



- $D^*\ell$ reconstruction yields 1D space of B candidates
- Combined with inclusive sum of remaining event: “best B”

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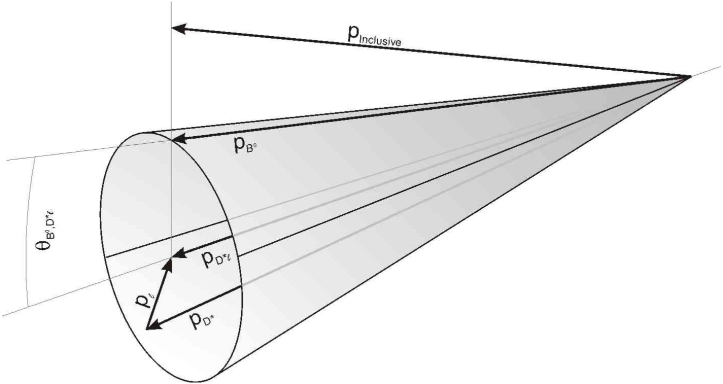
Reconstruction of the B rest frame



- $D^*\ell$ reconstruction yields 1D space of B candidates
- Combined with inclusive sum of remaining event: "best B"

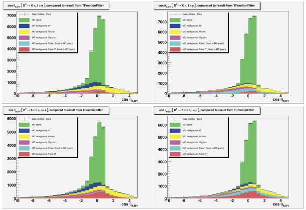
Background

Investigated using MC

- $B \to D^{**}\ell\nu$, $B \to D^{*}X\ell\nu$
- Signal correlated
- Uncorrelated
- Fake Lepton
- …

Off-resonance data

- Continuum: $q\bar{q}$ decays



HMCMLL, TFractionFitter

- Determine norm of MC components from fit to data
- Use fit to $\cos\theta_{B^0,D^*\ell}$ distribution(B^0) resp. 2D fit to $\cos\theta_{B^0,D^*\ell}$ vs. Δm distribution (B^+)

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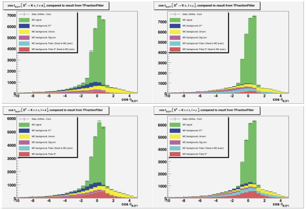

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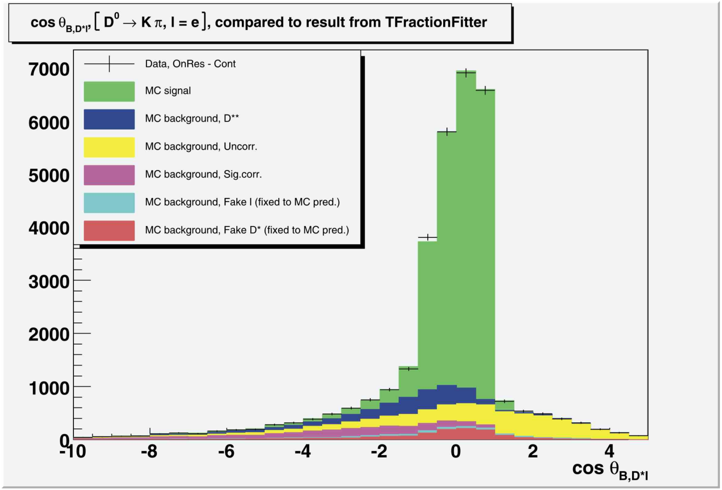
One example - $B^0, K\pi, e$



χ^2 function

Fundamental idea

- Binned least squares fit to the four 1D distributions
- Have to take correlation between distributions into account

χ^2 function

$$\chi^2 = \sum_i \sum_j \left(N_i^{rec} - N_i^{bkg} - N_i^{exp}\right) \left(C^{-1}\right)_{ij} \left(N_j^{rec} - N_i^{bkg} - N_j^{exp}\right)$$

- N_i^{rec}: reconstructed number of events in bin i
- N_i^{bkg}: estimated number of background events
- N_i^{exp}: theoretical prediction, considering efficiency and detector response
- C: covariance matrix, correlations $\Rightarrow$ not diagonal

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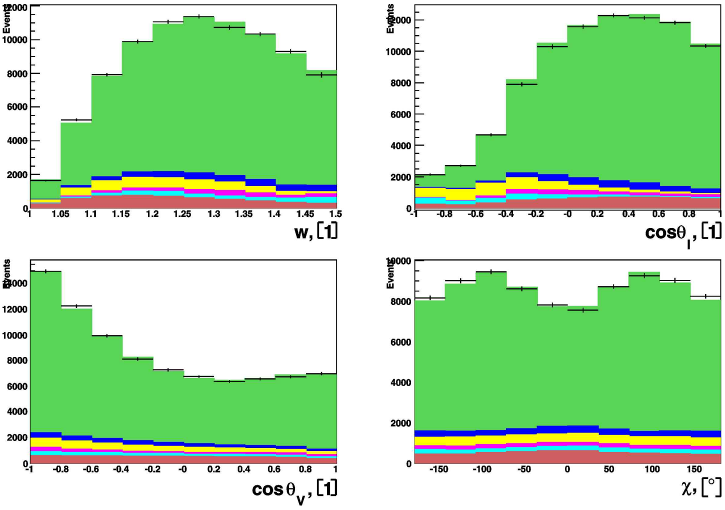
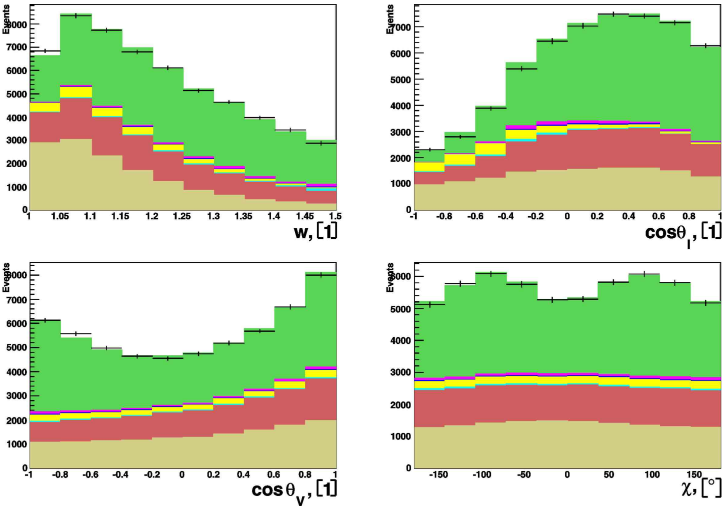
dungel (at)
hephy.oeaw.ac.at

Plots of preliminary results - B^0



Plots of preliminary results - B^+



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Preliminary results

	$B^0 \to D^{*-}\ell\nu$	$B^+ \to \bar{D}^{*0}\ell\nu$
ρ^2	$1.293 \pm 0.045 \pm 0.029$	$1.376 \pm 0.074 \pm 0.056$
$R_1(1)$	$1.495 \pm 0.050 \pm 0.062$	$1.620 \pm 0.091 \pm 0.092$
$R_2(1)$	$0.844 \pm 0.034 \pm 0.019$	$0.805 \pm 0.064 \pm 0.036$
$R_{K3\pi/K\pi}$	2.153 ± 0.011	2.072 ± 0.023
$\mathcal{B}(B \to D^*\ell^+\nu_\ell)$	$(4.42 \pm 0.03 \pm 0.25)\%$	$(4.84 \pm 0.04 \pm 0.56)\%$
$\mathcal{F}(1)\,\lvert V_{cb}\rvert \times 10^3$	$34.4 \pm 0.2 \pm 1.0$	$35.0 \pm 0.4 \pm 2.2$
$\chi^2/\mathrm{n.d.f.}$	$138.8/155$	$187.8/155$
P_{χ^2}	82.0%	3.7%

Subsamples - B^0
Systematic error - B^0
Correlations - B^0
Test of the parametrization
Subsamples - B^+
Systematic error - B^+
Correlations - B^+

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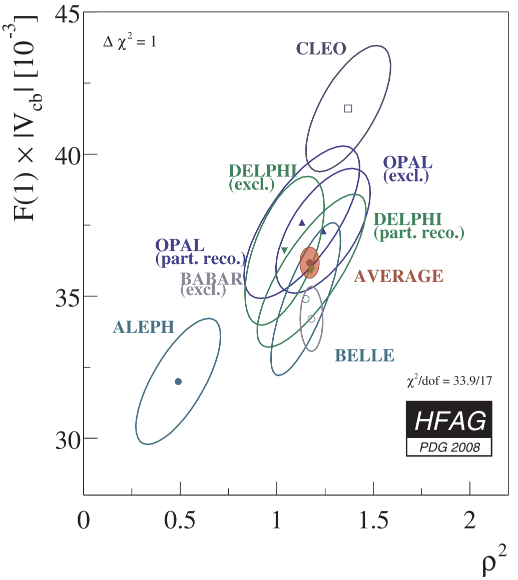
... and preliminary systematic error

Breakdown of the systematic error components (for B^0)

	ρ^2	$R_1(1)$	$R_2(1)$	$\mathcal{B}(B^0)$	$\mathcal{F}(1)\,|V_{cb}|$
Stat. error	0.050	0.060	0.043	0.030	0.22
D^{**}	0.015	0.038	0.011	0.051	0.25
Uncorr.	0.009	0.028	0.002	0.003	0.04
Sig.corr.	0.003	0.003	0.007	0.028	0.14
Fake ℓ	0.020	0.037	0.009	0.002	0.04
Fake D^*	0.012	0.011	0.009	0.034	0.33
Continuum	0.003	0.008	0.000	0.001	0.02
Trk., det.eff.	-	-	-	0.221	0.86
$\mathcal{B}\left(D^0\right)$	-	-	-	0.081	0.31
$\mathcal{B}(D^*)$	-	-	-	0.033	0.13
B^0 life time	-	-	-	0.026	0.10
$N_{B\bar{B}}$	-	-	-	0.036	0.14
$f_{+-}/f_{0\bar{0}}$	0.003	0.011	0.005	0.001	0.04
Syst. error	0.029	0.062	0.019	0.251	1.04

And finally - the world average



World average ...

- $|V_{cb}|$ has been measured before, with lower accuracy
- The aim is to include them all in one fit to determine “truth”
- The fundamental idea of having several experiments ...
- Cross check the findings!

The aim for $|V_{cb}|$ from exclusive decays

- Do a full four-dimensional average!

The Heavy Flavor Averaging Group - HFAG

- Collaboration of experts in the field
- Many by people from Belle and BaBar ...
- Has been formed in 2002

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... and problems

Things to consider for the world average

- Statistical independence is (usually) guaranteed
- But: both statistical and systematic uncertainties important
- Some sources of systematic errors are independent ...
- ... others are not ...

And some devious details ...

- New Belle and BaBar results report all parameters
- Older measurements at LEP determined only $|V_{cb}|$ and ρ^2
- ... but the values depend on R_1 and R_2!
- The combination proceeds via a Taylor expansion of the $|V_{cb}| : \rho^2$ measurements

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The algorithms

The findings up until recently

- An algorithm called `|vcbCombos|` was used
- Written and maintained by colleagues at SLAC
- It considered all important issues ...
- ... and it behaved strangely ...

- $\chi^2/n.d.f$ was implausibly large
- Especially when adding new Belle B^0 result

The way out

- I wrote a new algorithm, from scratch, as a check
- To have a fancy name, I called it `Meteor`

- `|vcbCombos|` misappreciates uncertainties on $|V_{cb}|$
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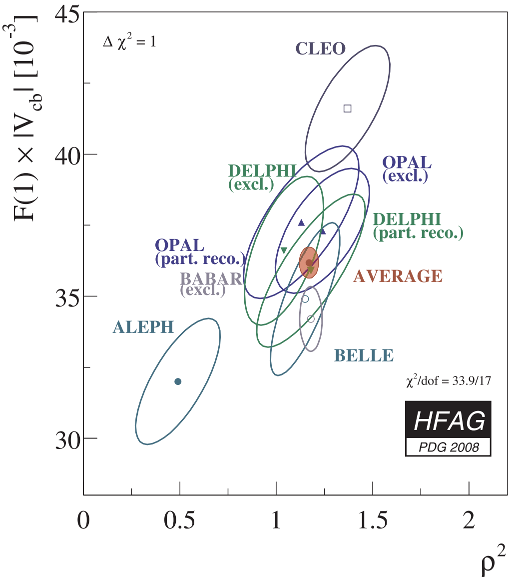
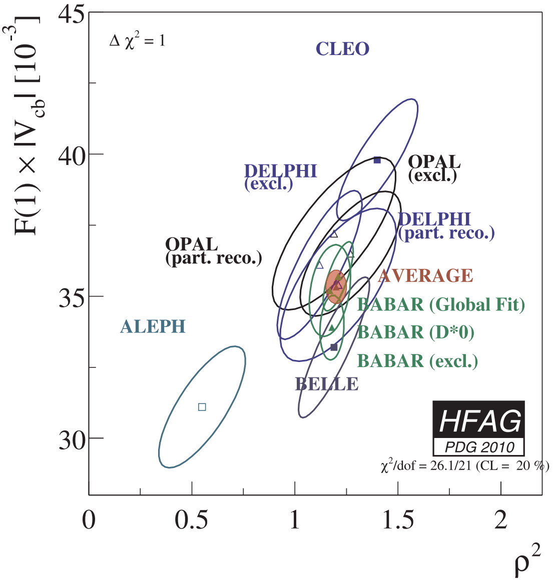
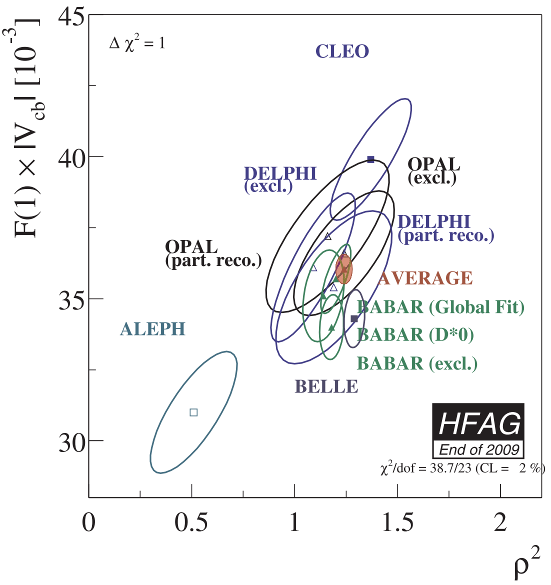
Using the previous algorithm ...



... and the new one



And trusting the new Belle result:



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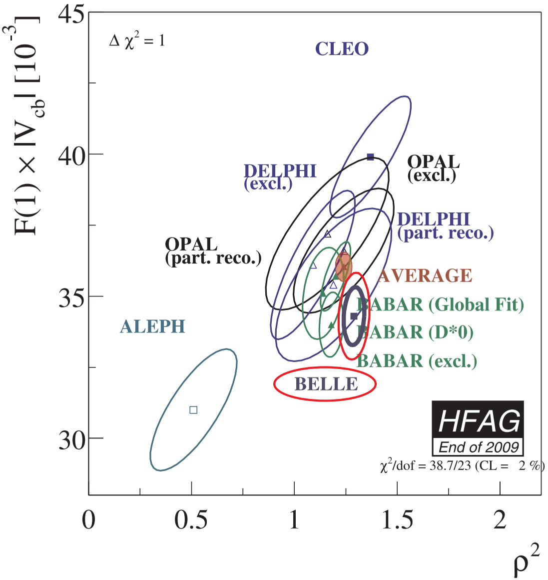

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The numbers in PDG2010 update

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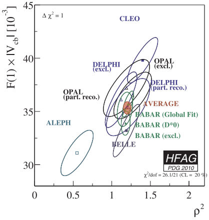
- i.e. the old Belle result is still being used here for now



$|V_{cb}|$ from $B \to D^* \ell \nu$ decays

$$\mathcal{F}(1)|V_{cb}| = (35.33 \pm 0.59) \times 10^{-3}$$

$$\rho^2 = 1.20 \pm 0.05$$

$$R_1(1) = 1.43 \pm 0.06$$

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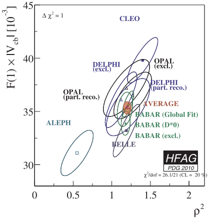

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Summary

- CP Violation and the KM mechanism
- Belle, KEKB and Belle-II
- Analysis of exclusive $B^0 \to D^{*-} \ell^+ \nu_\ell$ decays

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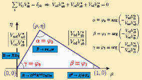
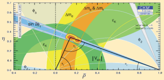

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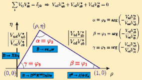
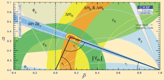

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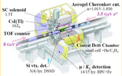

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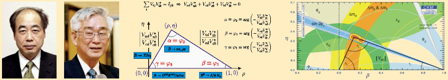

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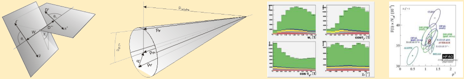
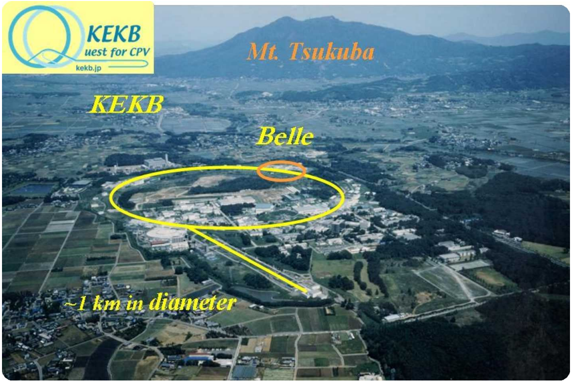


Thanks for your attention!



Precision measurements of the CKM mechanism at Belle

Wolfgang Dungel

Institute for high energy physics
Austrian Academy of Sciences

"Physics in progress",
April 29, 2010

References I

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J.D. Richman, P.R. Burchat
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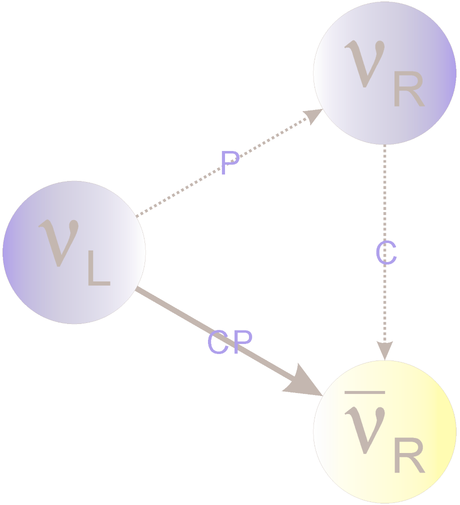
BELLE Collaboration.
Measurement of the form factors of the decay $B^0 \to D^{*-}\ell^+\nu_\ell$ and determination of the CKM matrix element $|V_{cb}|$.
arXiv: hep-ex/0810.1657

BABAR Collaboration.
Determination of the Form Factors for the Decay $B_0 \to D^{*-}l^+\nu_l$ and of the CKM Matrix Element $|V_{cb}|$.
arXiv: hep-ex/0607076.

Example of a CP transformation



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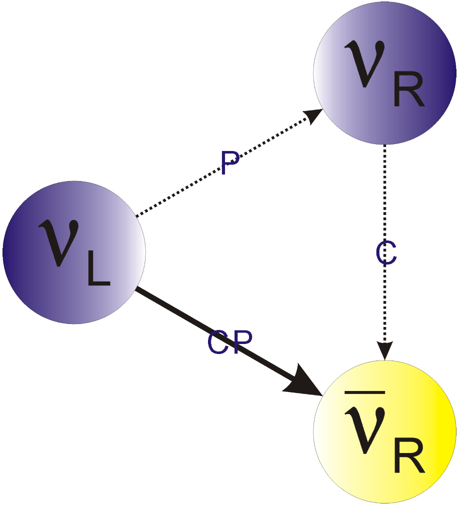

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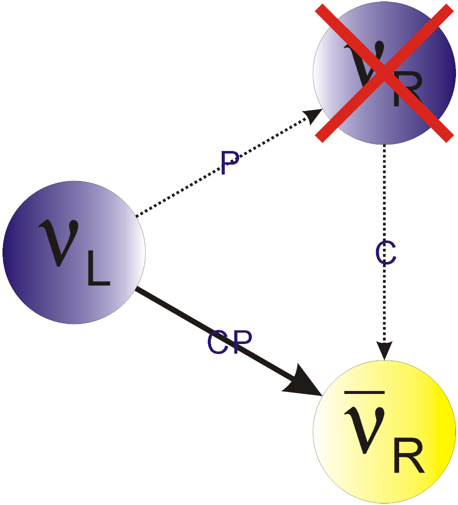

Backup - The Belle experiment

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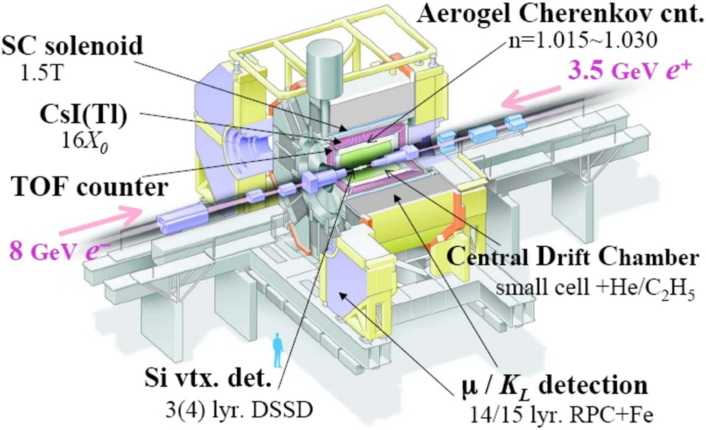
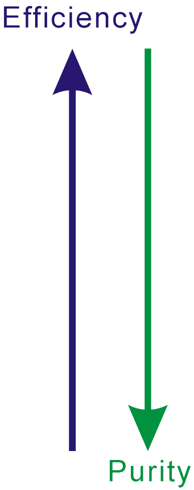
The Belle Collaboration

The Belle Detector



Tags at Belle



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- High efficiency

Semileptonic tag

- Good statistics, clean events
- Kinematics not fully determined

Full reconstruction tag

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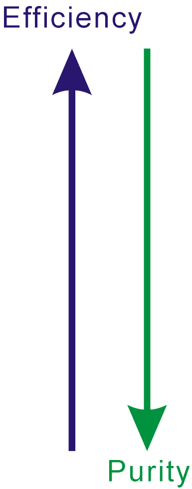
- Low statistics

Tags at Belle



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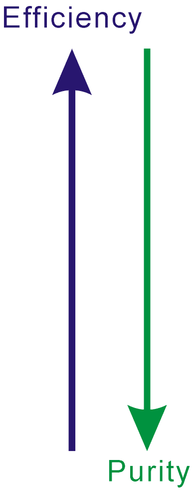

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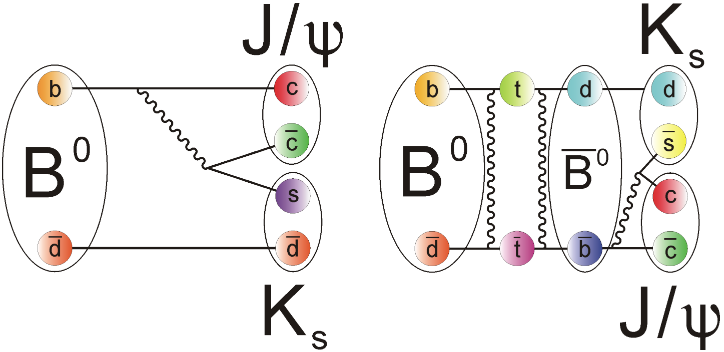
Nobel prize 2008

The "Golden mode" - $B^0 \to J/\Psi K_s^0$



- CP violation through interference

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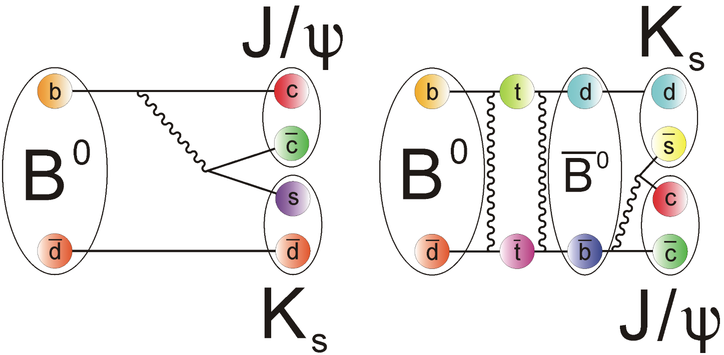
The “Golden mode” - $B^0 \to J/\Psi K_s^0$



- CP violation through interference

HQET and parametrization

Helicity amplitudes

- $H_{\pm} = f_{\pm}(w)\, h_{A_1}(w) \left(1 \mp \sqrt{\frac{w-1}{w+1}} R_1(w)\right)$
- $H_0 = f_0(w)\, h_{A_1}(w) \left(1 + \frac{w-1}{1-\frac{m_{D^*}}{m_B}} \left(1 - R_2(w)\right)\right)$

Parametrization by CLN

- $h_{A_1}(w) = h_{A_1}(1)\,(1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3)$
  $z = \frac{\sqrt{w+1}-\sqrt{2}}{\sqrt{w+1}+\sqrt{2}}$
- $R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2$
- $R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2$

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Covariances between bins of the marginal distributions

Covariances

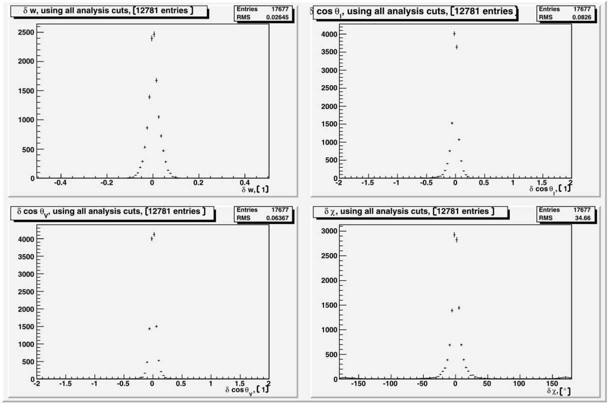
$$\mathrm{Cov}_{ij} = \mathrm{Cov}(n_i, n_j) = N \cdot (p_{ij} - p_i p_j)\,, \forall i \neq j$$

- N: Total number of events
- n_{ij}: Bin content of the bin (i, j) of 2d histogram
- n_k: Bin content of the bin k of a 1d histogram
- $p_x = \frac{n_x}{N}$

Special cases

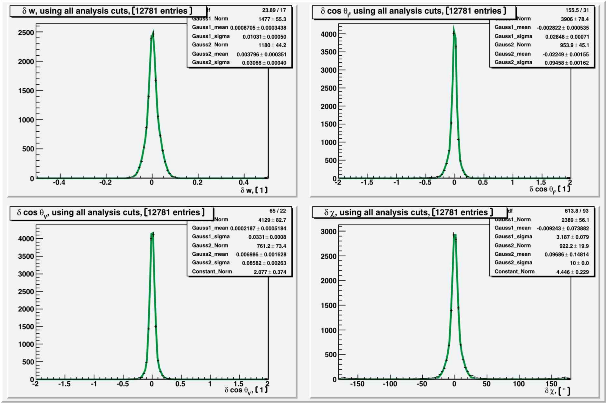
- Independent variables: $p_{ij} = p_i p_j \to \mathrm{Cov}_{ij} \equiv 0$
- Perfect anti-correlation: $n_{ij} = 0 \to \mathrm{Cov}_{ij} < 0$
- Positive correlation: $p_{ij} > p_i p_j \to \mathrm{Cov}_{ij} > 0$

Resolutions in kinematic variables



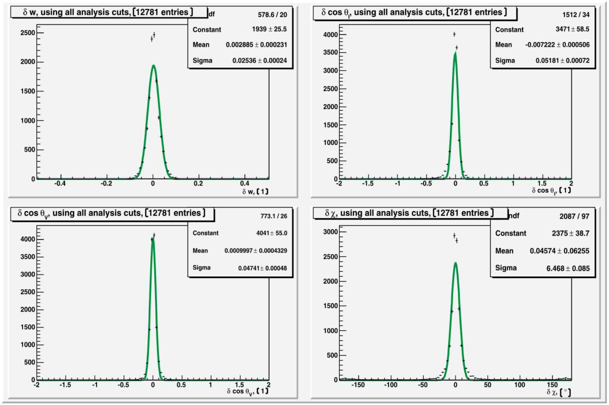
- Resolutions are approximately double gaussians
- Almost identical for B^0 and B^+

Resolutions in kinematic variables



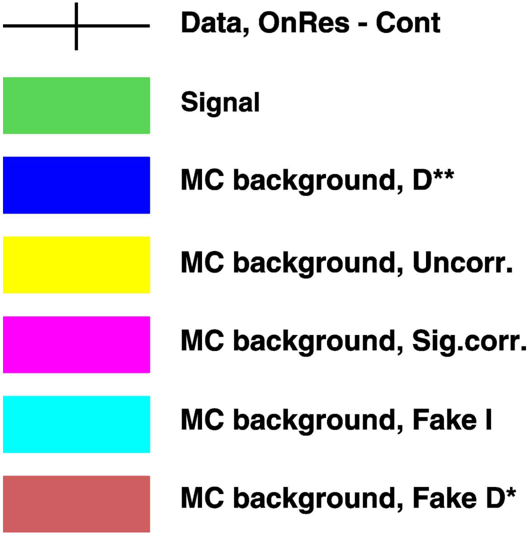
- Resolutions are approximately double gaussians
- Almost identical for B^0 and B^+

Resolutions in kinematic variables



- For easier comparison: Gaussian assumption
- $\delta_{\mathrm{w}} = 0.025$, $\delta_{\cos\theta_\ell} = 0.052$, $\delta_{\cos\theta_V} = 0.047$, $\delta_\chi = 6.47^\circ$

Color scheme



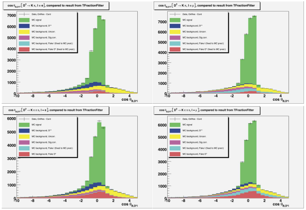
Background investigation

Investigated using MC

- Fake D^*
- Fake Lepton
- Uncorrelated
- $B \to D^{**}\ell\nu$, $B \to D^* X \ell\nu$
- Signal correlated

Off-resonance data

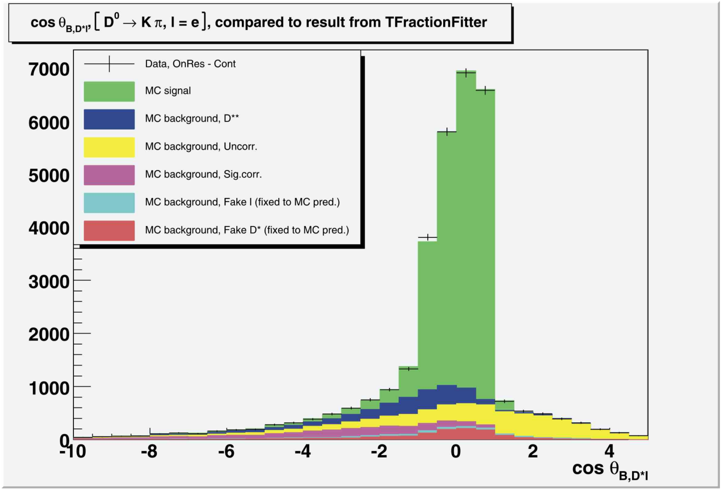
- Continuum: $q\bar{q}$ decays



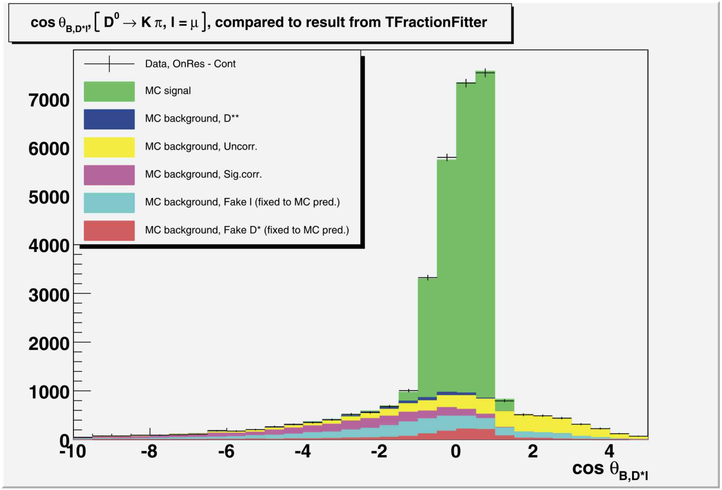
HMCMLL, TFractionFitter

- Determine norm of MC components from fit to data
- Use one dimensional distribution $\cos\theta_{B^0,D^*\ell}$

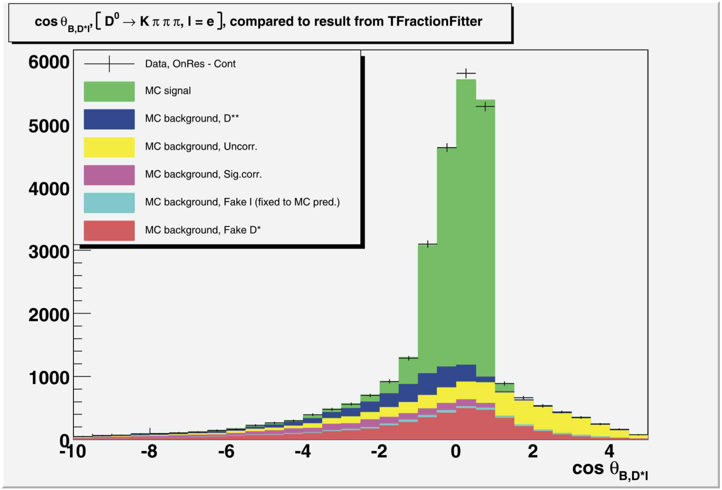
TFractionFitter result - $K\pi$, e sample



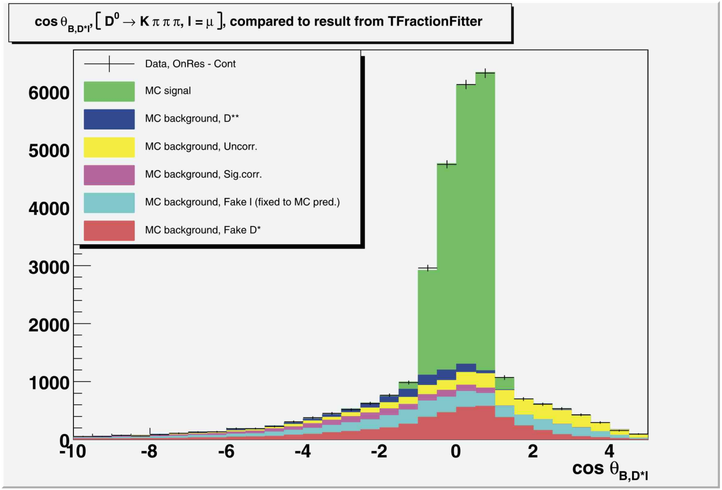
TFractionFitter result - $K\pi, \mu$ sample



TFractionFitter result - $K3\pi$, e sample



TFractionFitter result - $K3\pi, \mu$ sample



Background and signal purity

Fractions of the components

sample	$K\pi$, e	$K\pi$, μ	$K3\pi$, e	$K3\pi$, μ
signal	$(80.95 \pm 1.06)\%$	$(80.92 \pm 0.98)\%$	$(73.17 \pm 1.71)\%$	$(72.22 \pm 1.46)\%$
D^{**}	$(4.73 \pm 0.87)\%$	$(1.24 \pm 0.85)\%$	$(5.21 \pm 1.18)\%$	$(2.85 \pm 1.10)\%$
uncorrelated	$(5.36 \pm 0.27)\%$	$(4.38 \pm 0.29)\%$	$(5.42 \pm 0.58)\%$	$(4.17 \pm 0.54)\%$
correlated	$(1.69 \pm 0.26)\%$	$(2.42 \pm 0.28)\%$	$(2.04 \pm 0.69)\%$	$(2.25 \pm 0.59)\%$
fake ℓ	0.68 % (fixed)	3.62% (fixed)	0.72% (fixed)	4.04% (fixed)
fake D^*	2.96% (fixed)	2.91% (fixed)	$(8.78 \pm 2.63)\%$	$(9.63 \pm 2.15)\%$
continuum	3.62% (fixed)	4.51% (fixed)	4.81% (fixed)	4.87% (fixed)

Back to overview page

Results for all subsamples

Fit results for all subsamples and the total sample

sample	$K\pi$, e	$K\pi$, μ	$K3\pi$, e
ρ^2	$1.329 \pm 0.072 \pm 0.017$	$1.221 \pm 0.075 \pm 0.046$	$1.238 \pm 0.133 \pm 0.053$
$R_1(1)$	$1.455 \pm 0.077 \pm 0.046$	$1.608 \pm 0.087 \pm 0.099$	$1.085 \pm 0.125 \pm 0.044$
$R_2(1)$	$0.782 \pm 0.055 \pm 0.014$	$0.853 \pm 0.055 \pm 0.027$	$0.980 \pm 0.087 \pm 0.027$
$R_{K3\pi/K\pi}$	2.153 (fixed)	2.153 (fixed)	2.153 (fixed)
$\mathcal{B}(B^0)$	$4.43 \pm 0.03 \pm 0.25$	$4.41 \pm 0.03 \pm 0.26$	$4.42 \pm 0.04 \pm 0.25$
$\mathcal{F}(1)\|V_{cb}\|$	$34.3 \pm 0.4 \pm 1.0$	$33.5 \pm 0.4 \pm 1.0$	$35.6 \pm 0.8 \pm 1.3$
$\chi^2/\text{n.d.f.}$	$29.2/36$	$37.4/36$	$19.2/36$
P_{χ^2}	78.2%	40.4%	99.0%

sample	$K3\pi$, μ		total sample
ρ^2	$1.436 \pm 0.121 \pm 0.062$		$1.293 \pm 0.045 \pm 0.029$
$R_1(1)$	$1.643 \pm 0.163 \pm 0.112$		$1.495 \pm 0.050 \pm 0.062$
$R_2(1)$	$0.842 \pm 0.105 \pm 0.038$		$0.844 \pm 0.034 \pm 0.019$
$R_{K3\pi/K\pi}$	2.153 (fixed)		2.153 ± 0.011
$\mathcal{B}(B^0)$	$4.47 \pm 0.04 \pm 0.26$		$4.42 \pm 0.03 \pm 0.25$
$\mathcal{F}(1)\|V_{cb}\|$	$35.6 \pm 0.7 \pm 1.3$		$34.4 \pm 0.2 \pm 1.0$
$\chi^2/\text{n.d.f.}$	$17.9/36$		$138.8/155$
P_{χ^2}	99.5%		82.0%

Back to results page

Preliminary systematic error

	ρ^2	$R_1(1)$	$R_2(1)$	$\mathcal{B}(B^0)$	$\mathcal{F}(1)\,\lvert V_{cb}\rvert$
Stat. error	0.050	0.060	0.043	0.030	0.22
D^{**}	0.015	0.038	0.011	0.051	0.25
Uncorr.	0.009	0.028	0.002	0.003	0.04
Sig.corr.	0.003	0.003	0.007	0.028	0.14
Fake ℓ	0.020	0.037	0.009	0.002	0.04
Fake D^*	0.012	0.011	0.009	0.034	0.33
Continuum	0.003	0.008	0.000	0.001	0.02
Trk., det.eff.	-	-	-	0.221	0.86
$\mathcal{B}\left(D^0\right)$	-	-	-	0.081	0.31
$\mathcal{B}\left(D^*\right)$	-	-	-	0.033	0.13
B^0 life time	-	-	-	0.026	0.10
$N_{B\bar{B}}$	-	-	-	0.036	0.14
$f_{+-}/f_{0\bar{0}}$	0.003	0.011	0.005	0.001	0.04
Syst. error	0.029	0.062	0.019	0.251	1.04

Back to results page

Correlations

Correlations between the fit parameters

Parameters	Global	Correlations ρ^2	$R_1(1)$	$R_2(1)$	$R_{K3\pi/K\pi}$
$\mathcal{F}(1)\,\lvert V_{cb}\rvert$	0.99168	0.635	-0.285	-0.220	0.011
ρ^2	0.99732		0.388	-0.870	0.040
$R_1(1)$	0.95366			-0.511	0.001
$R_2(1)$	0.99342				0.002
$R_{K3\pi/K\pi}$	0.41362				

Back to results page

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Color scheme

- (OnRes - Continuum) data
- Signal
- MC background, Sig.corr.
- MC background, D**
- MC background, Uncorr.
- MC background, Fake Lepton
- MC background, Comb D*
- MC background, Fake D^0

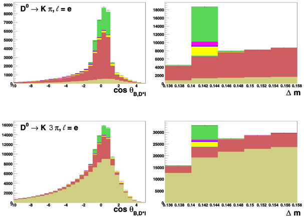
Background investigation

Investigated using MC

- Fake D^0
- Combinatoric D^*
- Fake Lepton
- Uncorrelated
- $B \to D^{**}\ell\nu$, $B \to D^* X \ell\nu$
- Signal correlated

Off-resonance data

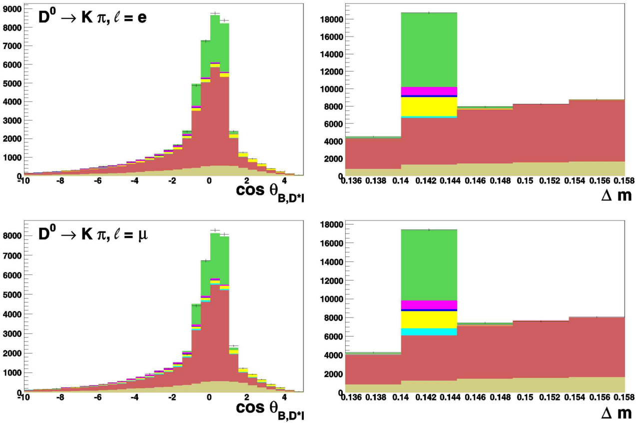
- Continuum: $q\bar{q}$ decays



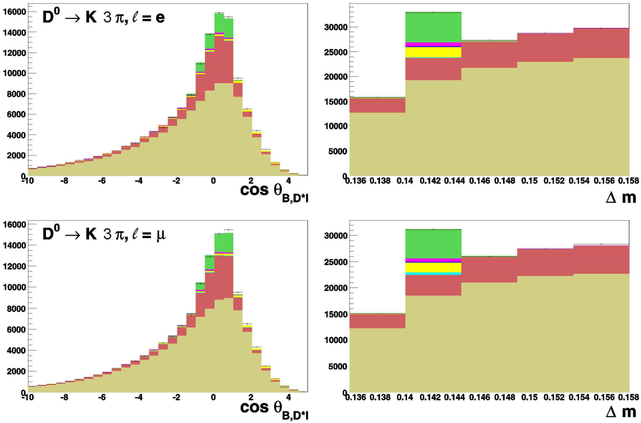
HMCMLL, TFractionFitter

- Determine norm of MC components from fit to data
- Use 2D distribution $\cos\theta_{B^0,D^*\ell}$ vs. Δm

Plot of TFractionFitter result - $D^0 \rightarrow K\pi$ modes



Plot of TFractionFitter result - $D^0 \longrightarrow K3\pi$ modes



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Background and signal purity

Fractions of the components

	$K\pi$, e	$K\pi$, μ	$K3\pi$, e	$K3\pi$, μ
Raw yield	13035	12262	16989	16350
Signal events	8133 ± 205	7447 ± 201	5987 ± 229	5539 ± 222
Signal	$(62.39 \pm 1.57)\%$	$(60.73 \pm 1.64)\%$	$(35.24 \pm 1.35)\%$	$(33.88 \pm 1.36)\%$
Signal correlated	$(1.27 \pm 0.31)\%$	$(1.46 \pm 0.32)\%$	$(1.16 \pm 0.26)\%$	$(1.34 \pm 0.31)\%$
D^{**}	$(0.77 \pm 0.98)\%$	$(0.73 \pm 0.98)\%$	$(0.39 \pm 0.50)\%$	$(0.36 \pm 0.47)\%$
Uncorrelated	$(4.97 \pm 0.54)\%$	$(4.25 \pm 0.45)\%$	$(3.48 \pm 0.41)\%$	$(3.30 \pm 0.38)\%$
Fake ℓ	$(0.31 \pm 0.10)\%$	$(1.94 \pm 0.59)\%$	$(0.18 \pm 0.06)\%$	$(0.95 \pm 0.29)\%$
Combinatoric D^{*0}	$(24.76 \pm 0.51)\%$	$(24.30 \pm 0.48)\%$	$(16.35 \pm 0.69)\%$	$(15.19 \pm 0.67)\%$
Fake D^0	$(2.91 \pm 0.25)\%$	$(3.12 \pm 0.23)\%$	$(38.53 \pm 0.50)\%$	$(39.45 \pm 0.51)\%$
Continuum	$(2.63 \pm 0.43)\%$	$(3.46 \pm 0.51)\%$	$(4.68 \pm 0.50)\%$	$(6.14 \pm 0.56)\%$

Back to overview page

Results for all subsamples

	$D^0 \to K\pi, \ell = e$	$D^0 \to K\pi, \ell = \mu$	$D^0 \to K3\pi, \ell = e$
ρ^2	$1.199 \pm 0.125 \pm 0.051$	$1.370 \pm 0.129 \pm 0.057$	$1.723 \pm 0.162 \pm 0.062$
$R_1(1)$	$1.507 \pm 0.135 \pm 0.095$	$1.568 \pm 0.158 \pm 0.089$	$1.840 \pm 0.271 \pm 0.110$
$R_2(1)$	$0.868 \pm 0.093 \pm 0.036$	$0.839 \pm 0.110 \pm 0.032$	$0.585 \pm 0.198 \pm 0.049$
$R_{K3\pi/K\pi}$	2.072	2.072	2.072
$\mathcal{B}(B^+ \to \bar{D}^{*0}\ell^+\nu_\ell)$	$4.91 \pm 0.05 \pm 0.58$	$4.77 \pm 0.05 \pm 0.57$	$4.83 \pm 0.07 \pm 0.57$
$\mathcal{F}(1)\lvert V_{cb}\rvert \times 10^3$	$34.3 \pm 0.6 \pm 2.2$	$35.0 \pm 0.6 \pm 2.3$	$36.5 \pm 1.0 \pm 2.4$
χ^2 / ndf.	48.3 / 36	40.6 / 36	39.6 / 36
P_{χ^2}	8.3 %	27.5 %	31.3 %

	$D^0 \to K3\pi, \ell = \mu$	Fit to total sample
ρ^2	$1.434 \pm 0.209 \pm 0.086$	$1.376 \pm 0.074 \pm 0.056$
$R_1(1)$	$1.813 \pm 0.273 \pm 0.107$	$1.620 \pm 0.091 \pm 0.093$
$R_2(1)$	$0.764 \pm 0.191 \pm 0.052$	$0.805 \pm 0.064 \pm 0.037$
$R_{K3\pi/K\pi}$	2.072	2.072 ± 0.023
$\mathcal{B}(B^+ \to \bar{D}^{*0}\ell^+\nu_\ell)$	$4.83 \pm 0.07 \pm 0.58$	$4.84 \pm 0.04 \pm 0.57$
$\mathcal{F}(1)\lvert V_{cb}\rvert \times 10^3$	$34.8 \pm 1.0 \pm 2.3$	$35.0 \pm 0.4 \pm 2.2$
χ^2 / ndf.	44.2 / 36	187.8 / 155
P_{χ^2}	16.3 %	3.7 %

Back to results page

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Breakdown of the preliminary systematic error

	ρ^2	$R_1(1)$	$R_2(1)$	$\mathcal{F}(1)\|V_{cb}\| \times 10^3$	$\mathcal{B}(B^+ \to \bar{D}^{*0}\ell^+\nu_\ell)$
Value	1.376	1.620	0.805	34.98	4.841
Statistical Error	0.074	0.091	0.064	0.37	0.044
π_s^0 & tracking	0.027	0.025	0.012	1.97	0.491
LeptonID	0.012	0.024	0.011	0.39	0.096
Norm - Signal Corr.	0.007	0.002	0.007	0.13	0.038
Norm - D^{**}	0.005	0.023	0.002	0.04	0.041
Norm - Uncorr	0.014	0.074	0.025	0.28	0.023
Norm - Fake ℓ	0.017	0.028	0.010	0.05	0.024
Norm - Comb D^{*0}	0.008	0.014	0.008	0.11	0.028
Norm - Fake D^0	0.009	0.014	0.007	0.06	0.020
Norm - Continuum	0.004	0.005	0.001	0.00	0.003
Shape - Uncorr	0.014	0.003	0.005	0.10	
Shape - Comb D^{*0}	0.027	0.005	0.008	0.21	
Shape - Fake D^0	0.024	0.003	0.008	0.17	
$\mathcal{B}(D^0 \to K\pi)$				0.32	0.089
$\mathcal{B}(D^{*0} \to D^0\pi^0)$				0.82	0.227
B^+ life time				0.12	0.033
$N(\Upsilon(4S))$				0.14	0.040
f_{+-}/f_{00}	0.003	0.006	0.003	0.15	0.043

Back to results page

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Correlations

Correlations between the fit parameters

- Table shows statistical/systematic/total correlation coefficients

	$\mathcal{F}(1)\|V_{cb}\|$	ρ^2	$R_1(1)$	$R_2(1)$
$\mathcal{F}(1)\|V_{cb}\|$	1.000	0.455/0.399/0.295	-0.222 /-0.219/-0.179	-0.054/-0.024/-0.019
ρ^2		1.000	0.648/ 0.413/ 0.540	-0.889/-0.751/-0.841
$R_1(1)$			1.000	-0.749/-0.873/-0.763
$R_2(1)$				1.000

Back to results page

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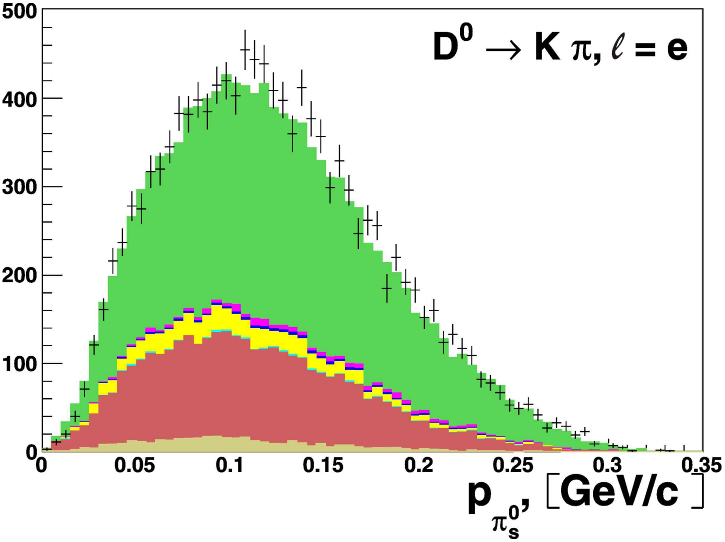
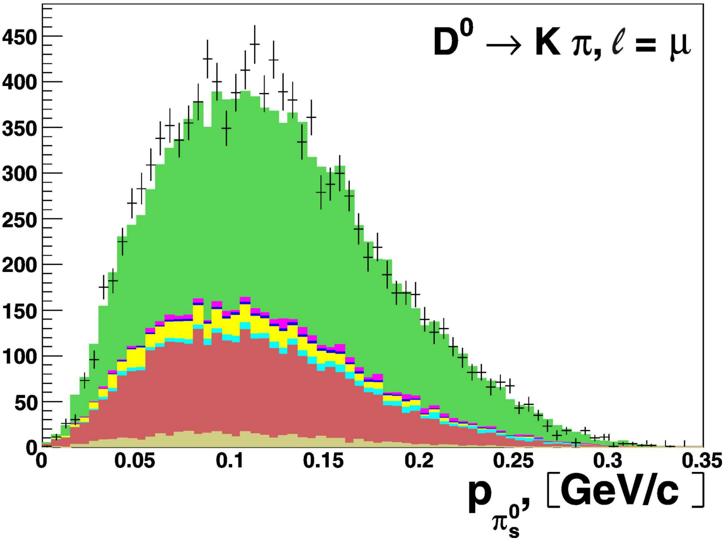
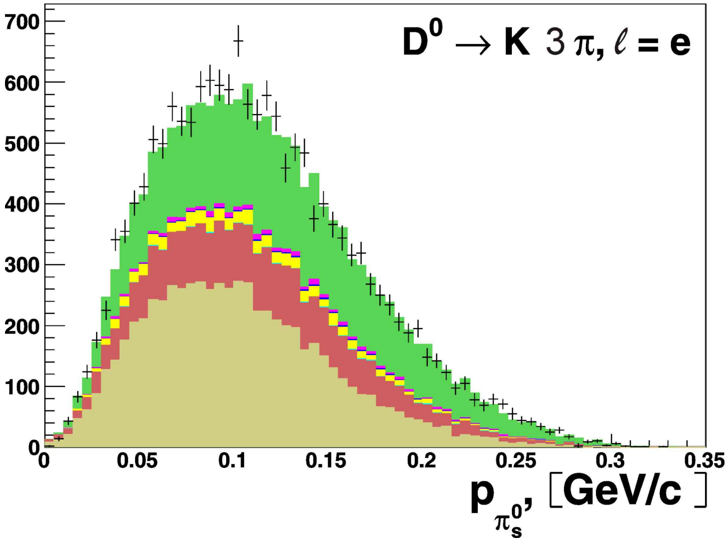
$p_{\pi_s^0}$ distribution - $K\pi$, e channel



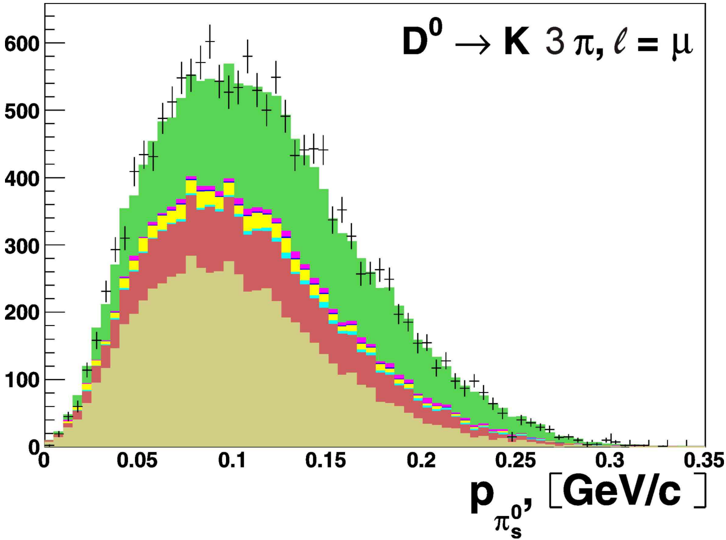
$p_{\pi_s^0}$ distribution - $K\pi, \mu$ channel



$p_{\pi_s^0}$ distribution - $K3\pi, e$ channel

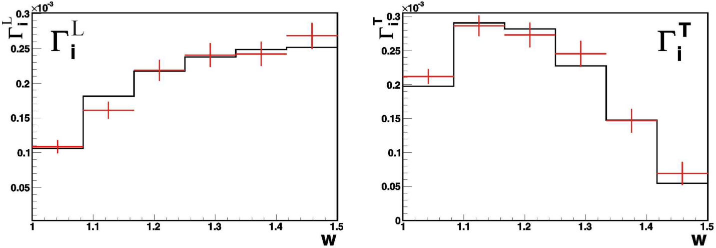


$p_{\pi_s^0}$ distribution - $K3\pi, \mu$ channel



Explicit test of the parametrization - B^+

- Result of discussions with theoreticians in Karlsruhe
- Extract shapes of longitudinal and transversal helicity amplitudes from a 2D fit
- Good agreement with parametrized result



(The statistical error is shown in these plots)

Back to results page

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Check of Γ_L

	$D^0 \to K\pi,\ \ell = e$	$D^0 \to K\pi,\ \ell = \mu$
$\Gamma^{00},\ w \in (1, \frac{13}{12})$	$(1.025 \pm 0.119 \pm 0.120) \times 10^{-4}$	$(1.176 \pm 0.146 \pm 0.137) \times 10^{-4}$
$\Gamma^{00},\ w \in (\frac{13}{12}, \frac{7}{6})$	$(1.544 \pm 0.165 \pm 0.176) \times 10^{-4}$	$(1.689 \pm 0.177 \pm 0.192) \times 10^{-4}$
$\Gamma^{00},\ w \in (\frac{7}{6}, \frac{15}{12})$	$(2.238 \pm 0.213 \pm 0.237) \times 10^{-4}$	$(2.121 \pm 0.216 \pm 0.238) \times 10^{-4}$
$\Gamma^{00},\ w \in (\frac{15}{12}, \frac{8}{6})$	$(2.677 \pm 0.244 \pm 0.268) \times 10^{-4}$	$(2.059 \pm 0.240 \pm 0.228) \times 10^{-4}$
$\Gamma^{00},\ w \in (\frac{8}{6}, \frac{17}{12})$	$(2.406 \pm 0.235 \pm 0.256) \times 10^{-4}$	$(2.426 \pm 0.263 \pm 0.263) \times 10^{-4}$
$\Gamma^{00},\ w \in (\frac{17}{12}, 1.5)$	$(2.907 \pm 0.250 \pm 0.301) \times 10^{-4}$	$(2.384 \pm 0.273 \pm 0.278) \times 10^{-4}$

	fit to total sample	central value of parametrized fit
$\Gamma^{00},\ w \in (1, \frac{13}{12})$	$(1.087 \pm 0.092 \pm 0.123) \times 10^{-4}$	1.062×10^{-4}
$\Gamma^{00},\ w \in (\frac{13}{12}, \frac{7}{6})$	$(1.611 \pm 0.121 \pm 0.179) \times 10^{-4}$	1.812×10^{-4}
$\Gamma^{00},\ w \in (\frac{7}{6}, \frac{15}{12})$	$(2.186 \pm 0.151 \pm 0.238) \times 10^{-4}$	2.175×10^{-4}
$\Gamma^{00},\ w \in (\frac{15}{12}, \frac{8}{6})$	$(2.406 \pm 0.172 \pm 0.262) \times 10^{-4}$	2.379×10^{-4}
$\Gamma^{00},\ w \in (\frac{8}{6}, \frac{17}{12})$	$(2.421 \pm 0.175 \pm 0.258) \times 10^{-4}$	2.483×10^{-4}
$\Gamma^{00},\ w \in (\frac{17}{12}, 1.5)$	$(2.683 \pm 0.186 \pm 0.298) \times 10^{-4}$	2.514×10^{-4}

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Check of Γ_T

	$D^0 \to K\pi . \ell = e$	$D^0 \to K\pi . \ell = \mu$
$\Gamma^T, w \in (1, \frac{13}{12})$	$(2.267 \pm 0.153 \pm 0.264) \times 10^{-4}$	$(1.939 \pm 0.152 \pm 0.228) \times 10^{-4}$
$\Gamma^T, w \in (\frac{13}{12}, \frac{7}{6})$	$(2.695 \pm 0.214 \pm 0.307) \times 10^{-4}$	$(3.015 \pm 0.216 \pm 0.348) \times 10^{-4}$
$\Gamma^T, w \in (\frac{7}{6}, \frac{15}{12})$	$(2.786 \pm 0.253 \pm 0.310) \times 10^{-4}$	$(2.678 \pm 0.261 \pm 0.299) \times 10^{-4}$
$\Gamma^T, w \in (\frac{15}{12}, \frac{8}{6})$	$(2.298 \pm 0.249 \pm 0.246) \times 10^{-4}$	$(2.673 \pm 0.295 \pm 0.290) \times 10^{-4}$
$\Gamma^T, w \in (\frac{8}{6}, \frac{17}{12})$	$(1.557 \pm 0.242 \pm 0.162) \times 10^{-4}$	$(1.369 \pm 0.250 \pm 0.144) \times 10^{-4}$
$\Gamma^T, w \in (\frac{17}{12}, 1.5)$	$(0.588 \pm 0.205 \pm 0.056) \times 10^{-4}$	$(0.862 \pm 0.284 \pm 0.099) \times 10^{-4}$

	fit to total sample	central value of parametrized fit
$\Gamma^T, w \in (1, \frac{13}{12})$	$(2.117 \pm 0.108 \pm 0.248) \times 10^{-4}$	1.975×10^{-4}
$\Gamma^T, w \in (\frac{13}{12}, \frac{7}{6})$	$(2.865 \pm 0.152 \pm 0.327) \times 10^{-4}$	2.908×10^{-4}
$\Gamma^T, w \in (\frac{7}{6}, \frac{15}{12})$	$(2.732 \pm 0.181 \pm 0.303) \times 10^{-4}$	2.819×10^{-4}
$\Gamma^T, w \in (\frac{15}{12}, \frac{8}{6})$	$(2.454 \pm 0.191 \pm 0.263) \times 10^{-4}$	2.276×10^{-4}
$\Gamma^T, w \in (\frac{8}{6}, \frac{17}{12})$	$(1.468 \pm 0.174 \pm 0.154) \times 10^{-4}$	1.478×10^{-4}
$\Gamma^T, w \in (\frac{17}{12}, 1.5)$	$(0.693 \pm 0.170 \pm 0.070) \times 10^{-4}$	0.547×10^{-4}

Precision measurements of the CKM mechanism at Belle

Wolfgang Dungel

Institute for high energy physics
Austrian Academy of Sciences

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Institut für Hochenergiephysik

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