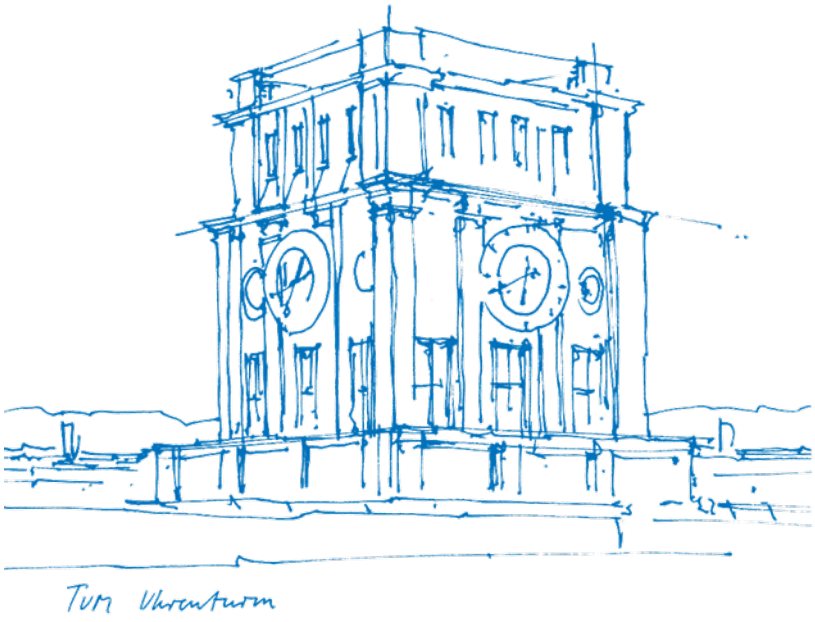
Leptonic, Semileptonic, and Rare Charm Decays at the B Factories

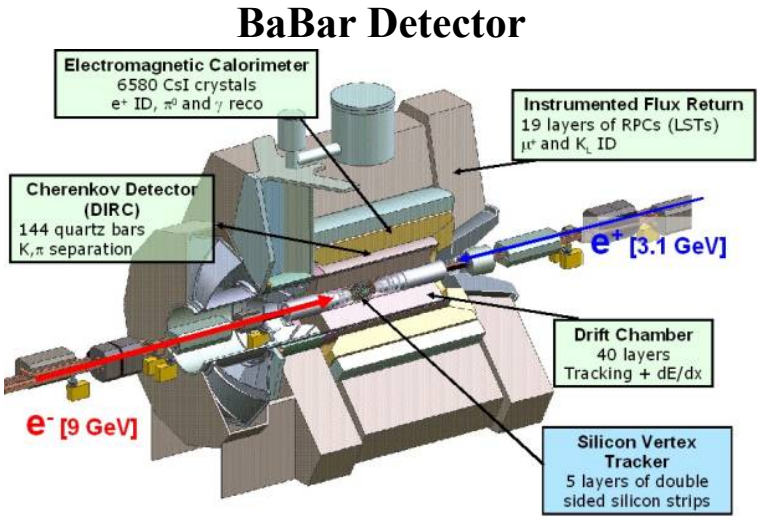
Dima Levit
Technische Universität München
Physikdepartment E18

The 9th International Workshop on Charm Physics
Novosibirsk, Russian Federation



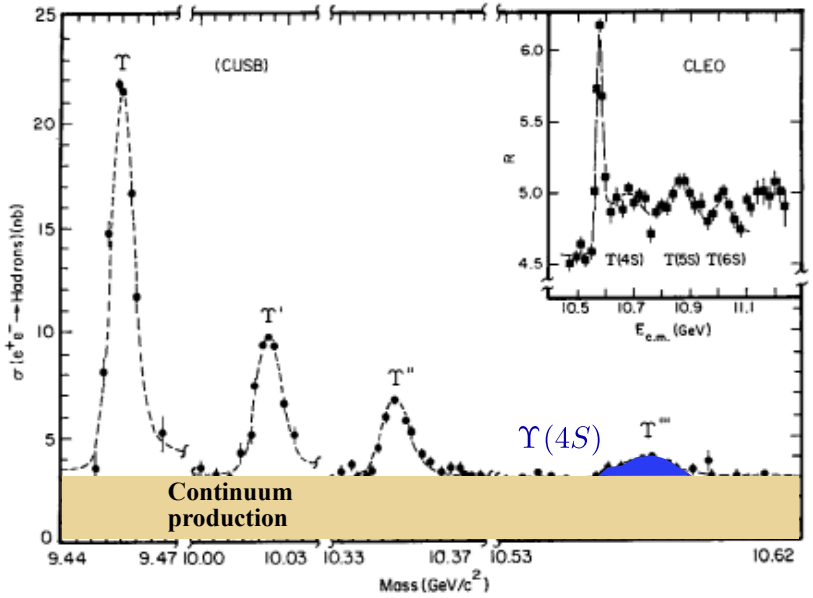
Overview

B Factories



- Large data sample
  Belle $1\,\text{ab}^{-1}$
  BaBar $530\,\text{fb}^{-1}$
- Acceptance close to 4π
- Clean environment

  $\Rightarrow$ Very high reconstruction efficiency of charged and **neutral** particles
- Good knowledge about beam energy



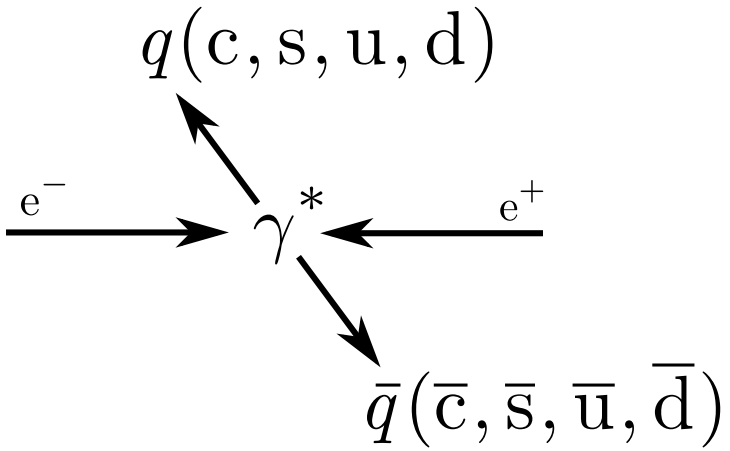


Figure: Cross-section for inclusive production in the upsilon system*

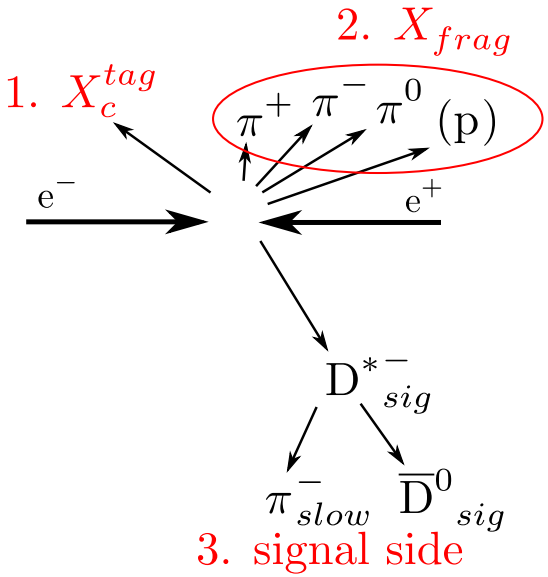
	N($q\,\bar{q}$) @ Belle ($1\,\mathrm{ab}^{-1}$)	N($q\,\bar{q}$) @ BaBar ($530\,\mathrm{fb}^{-1}$)	N($q\,\bar{q}$) @ Belle II ($50\,\mathrm{ab}^{-1}$)
$\sigma(\mathrm{c\bar{c}}) = 1.3\,\mathrm{nb}$	13×10^8	7.9×10^8	650×10^8
$\sigma(\mathrm{b\bar{b}}) = 1.1\,\mathrm{nb}$	7.7×10^8	4.7×10^8	385×10^8

- c $\bar{\mathrm{c}}$ production comparable with b $\bar{\mathrm{b}}$

$\Rightarrow$ **B-factories are also charm factories**

Experimental Methods

- D reconstruction from the D^*: $D^* \to D\pi_{slow}$
  - $\vec{p}(\pi_{slow}) < 600\,MeV/c$
  - flavour tagging by π_{slow}
  - observables $M(D)$ and $\Delta M = M(D\pi_{slow}) - M(D)$
- Full event interpretation



  - $M_{recoil}(D^*_{sig}) = \sqrt{E^2_{beam} - P^2(X_c^{tag} X_{frag})}$

Introduction

Leptonic Decays

Semileptonic Decays

Rare, Photonic, and Radiative Charm Decays

$D_s \to \ell \bar{\nu}_\ell$

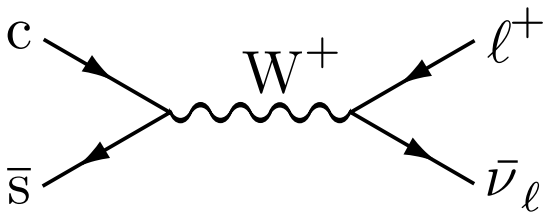
- Calculation of the D_s decay constant from the branching fraction

$$B(D_s \to \ell \bar{\nu}_\ell) = \frac{\tau_{D_s} m_{D_s}}{8\pi} f_{D_s}{}^2 G_F^2 |V_{cs}|^2 m_\ell^2 \left(1 - \frac{m_\ell^2}{m_{D_s}^2}\right)^2$$

- Test of the theoretical predictions

Lattice QCD	$f_{D_s} = (249.0 \pm 1.2)\,\text{MeV}$	(PDG, 2017)
QCD sum rules	$f_{D_s} = (240 \pm 10)\,\text{MeV}$	(Wang, 2015)
Light-front quark model	$f_{D_s} = (264.5 \pm 17.5)\,\text{MeV}$	(Hwang, 2010)

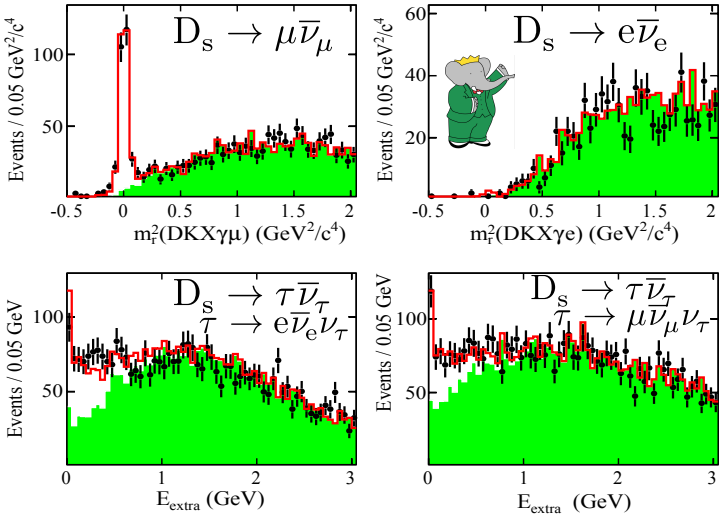
- Test of the lepton flavour universality with V-A suppression
  - $R_{\mu/\tau} = \frac{B(D_s \to \mu \bar{\nu}_\mu)}{B(D_s \to \tau \bar{\nu}_\tau)} \simeq 0.1$
  - $R_{e/\tau} = \frac{B(D_s \to e \bar{\nu}_e)}{B(D_s \to \tau \bar{\nu}_\tau)} \simeq 3.5 \times 10^{-6}$

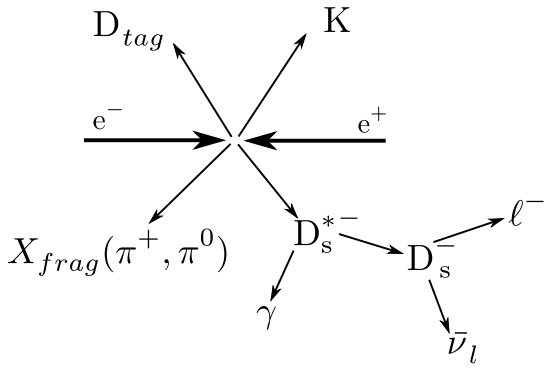


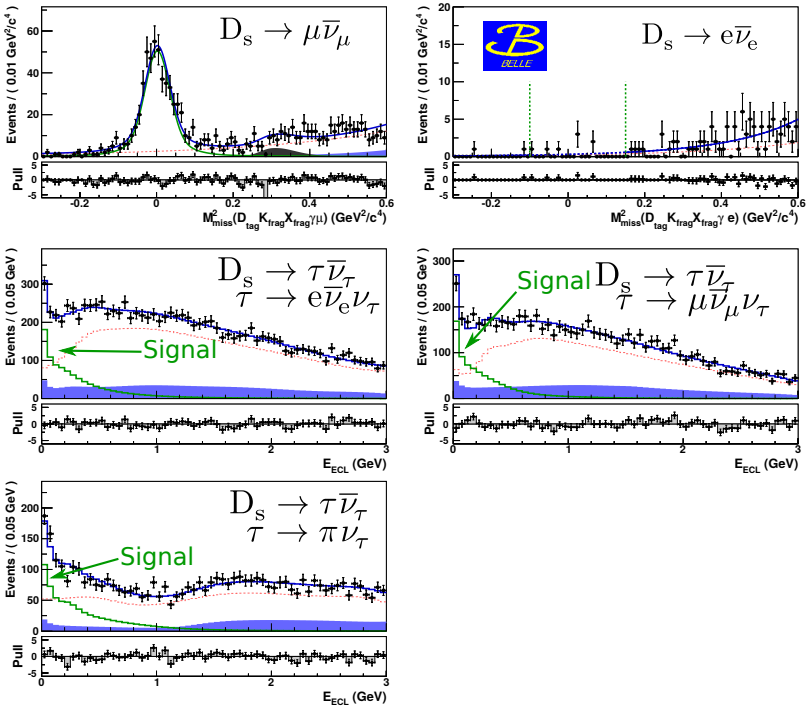
$D_s \to \ell \bar{\nu}_\ell$

- BaBar measurement with 521 fb^{-1} †
- Belle measurement with 913 fb^{-1} ‡

- $D_s \to \ell \bar{\nu}_\ell, l = e, \mu$
  - fit to $m^2_{recoil}(D_{tag} K_{frag} X_{frag} \gamma \ell)$
- $D_s \to \tau \bar{\nu}_\tau$
  - $\tau^- \to \ell \bar{\nu}_l \nu_\tau$ (Belle/BaBar)
  - $\tau^- \to \pi^- \nu_\tau$ (Belle)
  - fit to extra energy in electro-magnetic calorimeter







†del Amo Sanchez et al., Phys. Rev. D 82, 091103(R), 2010

‡Zupanc et al., JHEP09 (2013) 139

$D_s \to \ell \bar{\nu}_\ell$

Mode	$B_{Belle}, \%$	$B_{BaBar}, \%$	$R_{\ell/\tau}$ predictions
$D_s \to \tau \bar{\nu}_\tau$	$5.70 \pm 0.21 \pm 0.30$	$5.00 \pm 0.35 \pm 0.49$	1
$D_s \to \mu \bar{\nu}_\mu$	$0.531 \pm 0.028 \pm 0.020$	$0.602 \pm 0.038 \pm 0.034$	0.1
$D_s \to e \bar{\nu}_e$	< 0.0083 at 90 % CL	< 0.0230 at 90 % CL	3.5×10^{-6}

Table: Branching fraction measurements

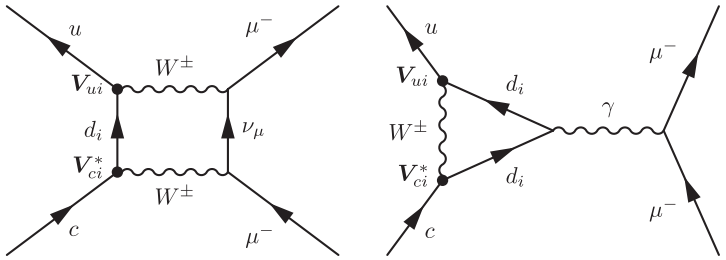
- Consistent with lepton flavour universality

Experiment/Method	f_{D_s}, MeV
Belle	$255.5 \pm 4.2 \pm 4.8 \pm 1.8(\tau_{D_s})$
BaBar	$258.6 \pm 6.4 \pm 7.5$
Belle II with 50 ab^{-1}	± 0.9
Lattice QCD	249.0 ± 1.2
QCD sum rules	240.0 ± 10.0
Light-front quark model	264.5 ± 17.5

Table: D_s decay constant

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

- $D^0 \to \ell^+\ell^-$: flavour-changing neutral currents
  - suppression in the SM through the GIM mechanism: $B \sim 10^{-13}$



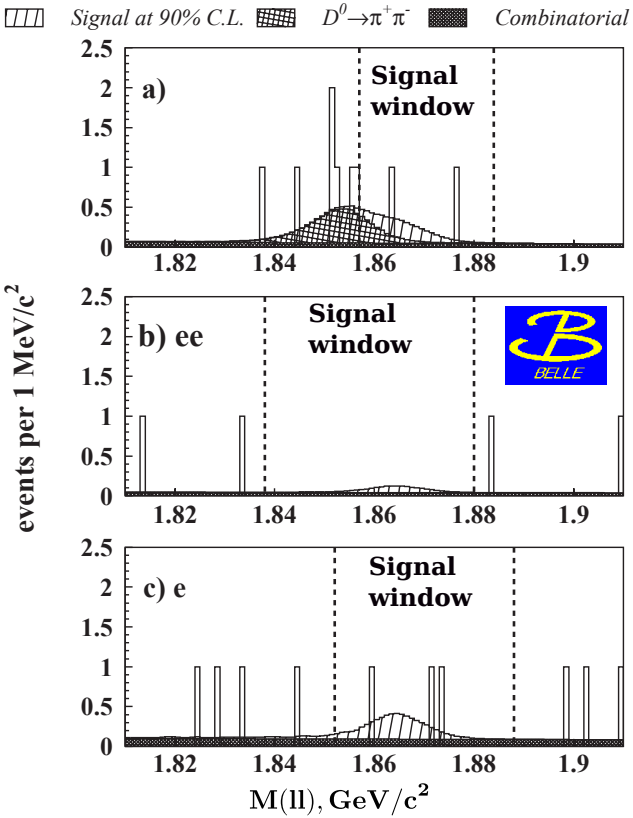
  - R-parity violating supersymmetry[§]
    - $B(D^0 \to e^-e^+) \sim 10^{-12}$
    - $B(D^0 \to \mu^-\mu^+) \sim 10^{-8}$
  - Leptoquark model[¶]
    - $B(D^0 \to \mu^-\mu^+) \sim 8 \times 10^{-7}$
- Lepton flavour violation: $D^0 \to e^\pm\mu^\mp$
  - forbidden in SM
  - SM extension with non-degenerate neutrinos and non-zero neutrino mixing: $B \sim 10^{-14}$[‖]

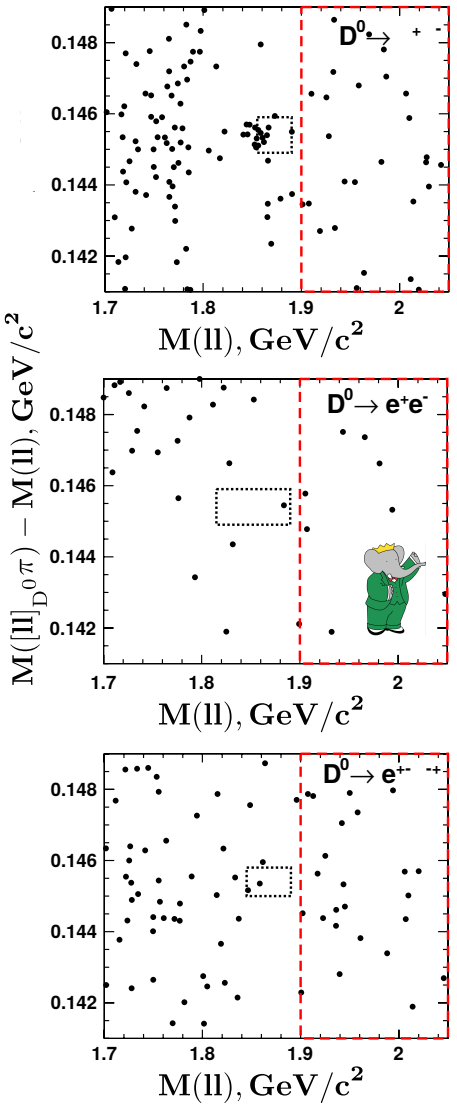
[§] E. Golowich et al., Phys. Rev. D 79, 114030, 2009
[¶] I. Doršner et al., Phys. Lett. B 682, 67-73, 2009
[‖] G. Burdman et al., Phys. Rev. D 66, 014009, 2002

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

- BaBar measurement with 486 fb^{-1} **
- Belle measurement with 660 fb^{-1} ††

- Event reconstruction through decay chain $D^{*+} \to D^0\pi^+_{slow}, D^0 \to \ell^+\ell^-$





** J.P. Lees at al., Phys. Rev. D 86, 032001, 2012

†† M. Petric et al., Phys. Rev. D 81, 091102(R), 2010

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

Mode	B_{Belle}, at 90 % CL, 660 fb^{-1}	B_{BaBar}, at 90 % CL, 486 fb^{-1}	Belle II projections
$D^0 \to \mu^-\mu^+$	$< 1.40 \times 10^{-7}$	$[0.60, 8.10] \times 10^{-7}$	0.16×10^{-7}
$D^0 \to e^-e^+$	$< 0.79 \times 10^{-7}$	$< 1.70 \times 10^{-7}$	0.09×10^{-7}
$D^0 \to e^\pm\mu^\mp$	$< 2.60 \times 10^{-7}$	$< 3.30 \times 10^{-7}$	0.30×10^{-7}

Table: Branching fraction measurements

$\Rightarrow$ No evidence for lepton flavour violation

$\Rightarrow$ Disfavours leptoquark model

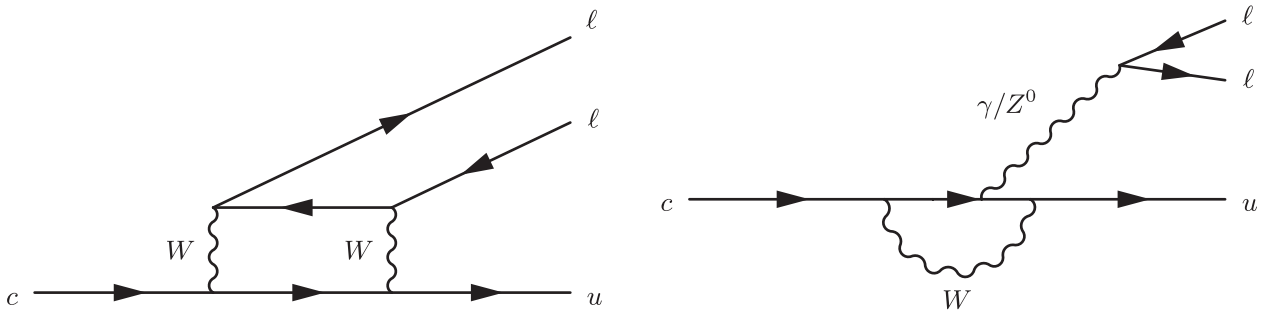
Introduction

Leptonic Decays

Semileptonic Decays

Rare, Photonic, and Radiative Charm Decays

Forbidden Semileptonic Decays



- $X_c^+ \to h\ell\ell$, with $X_c^+ : D^+, D_s^+, \Lambda_c^+$
- tree level $c \to s$ transition via $X_c^+ \to \phi\pi^+, \phi \to \ell^+\ell^-$
  - $B(D^+ \to \pi^+[\ell^+\ell^-]_\phi) \approx 2 \times 10^{-6}$
  - $B(D_s \to \pi^+[\ell^+\ell^-]_\phi) \approx 10^{-5}$
  - outside of $m(\ell^+\ell^-) \simeq m(\phi)$ FCNC contribution
    - ⇒ greatly suppressed in SM
    - ⇒ enhancement through R-parity violating supersymmetry models: $B \sim 10^{-5}$
- Lepton flavour violation decays $X_c^+ \to h^+ e^\pm \mu^\mp$
  - prohibited in the SM
- Lepton number violation $X_c^+ \to h^- \ell^+ \ell^+$
  - prohibited in the SM

Forbidden Semileptonic Decays

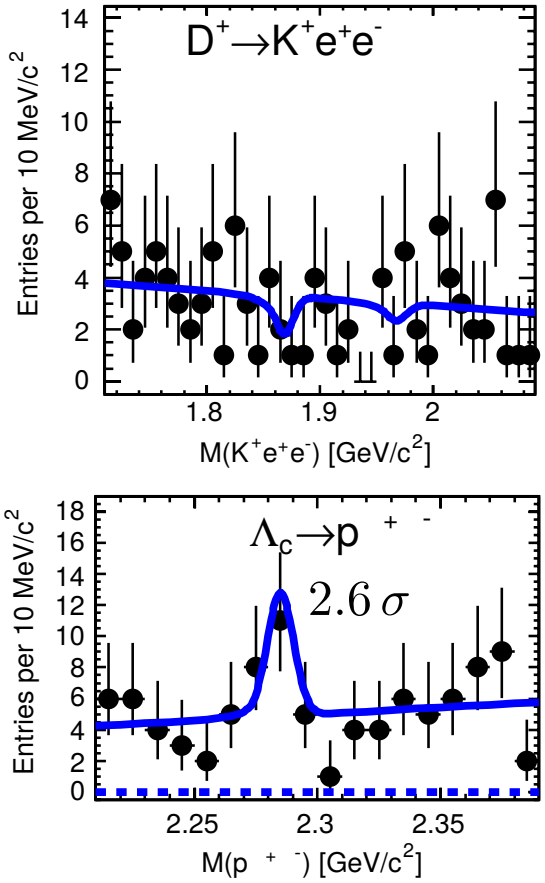
- BaBar measurement with 384 fb^{-1} ‡‡
- Combinations of an hadron and a pair of leptons
- Signal yield from fit to the M(hll)
- **Results:** no significant signal observed in 35 decay modes
  - 90 % upper limits on the BR between

$$\mathrm{B}(\mathrm{D}^+ \to \mathrm{K}^+\mathrm{e}^-\mathrm{e}^+) \quad < 1 \times 10^{-6}$$

$$\mathrm{B}(\Lambda_c^+ \to \mathrm{p}\mu^-\mu^+) \quad < 4.4 \times 10^{-5}$$

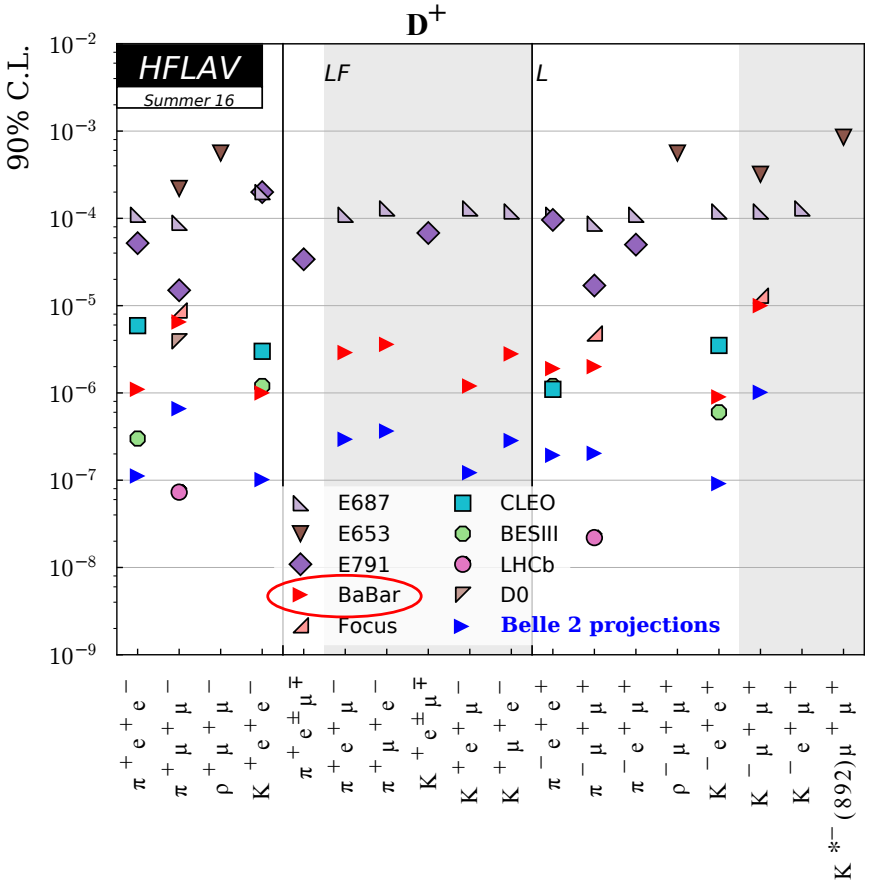
⇒ improves experimental constraints in 32 decay modes

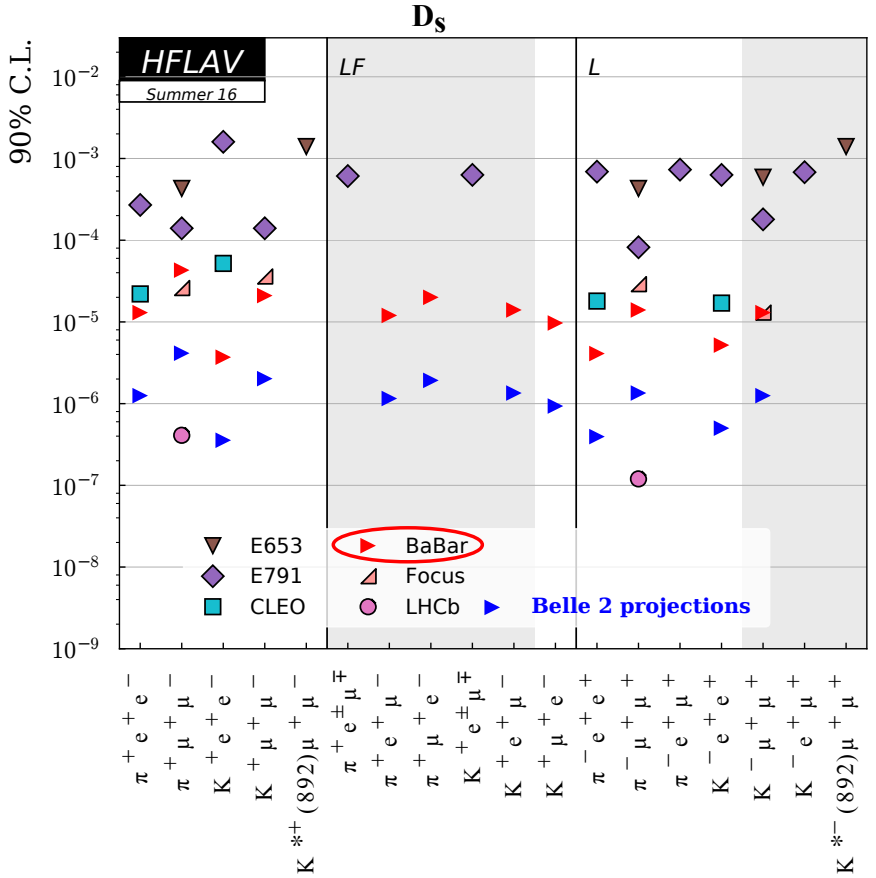
⇒ disfavours R-parity violating supersymmetry models



‡‡ J. P. Lees, Phys. Rev. D 84, 072006, 2011

Forbidden Semileptonic Decays





Introduction

Leptonic Decays

Semileptonic Decays

Rare, Photonic, and Radiative Charm Decays

$D^0 \to \gamma\gamma$

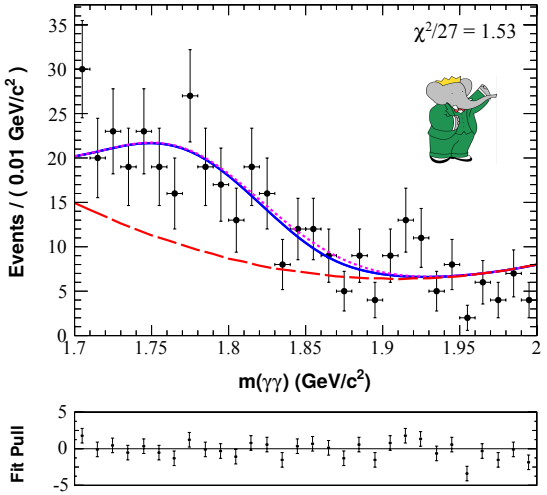
- Flavour-changing neutral currents forbidden at the tree level in the SM by the GIM mechanism
  - short distance contributions $B(D^0 \to \gamma\gamma) \sim 10^{-11}$ *
- Long-distance enhancement due to the Vector Meson Dominance
  - $B(D^0 \to \gamma\gamma) \simeq (3.5^{+4.0}_{-2.6}) \times 10^{-8}$ *
- Minimal supersymmetric standard model prediction
  - gluinos exchange: $B(D^0 \to \gamma\gamma) \sim 6 \times 10^{-6}$ †

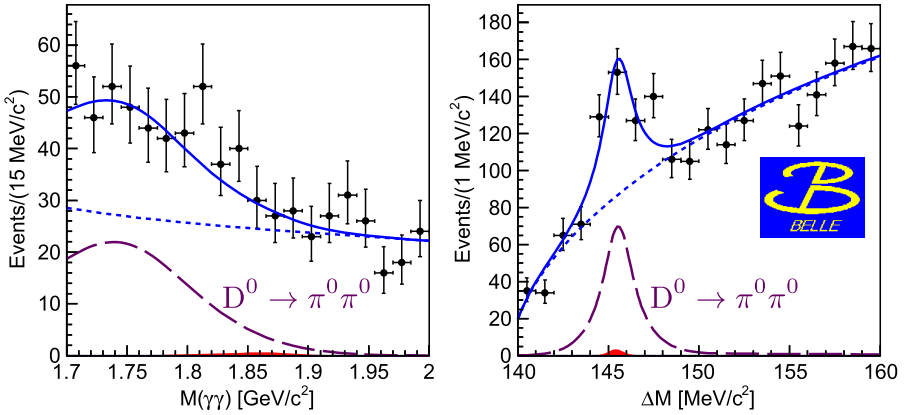
* G. Burdman et al., Phys. Rev. D 66, 014009, 2002

†S. Prelovsek, D. Wyler, Phys. Lett. B 500, 304, 2001

$D^0 \to \gamma\gamma$

- BaBar measurement with $470.5\,\text{fb}^{-1}$ ‡
- Belle measurement with $832\,\text{fb}^{-1}$ §
- Reconstruction of the decay chain $D^{*+} \to D^0\pi^+_{\text{slow}}, D^0 \to \gamma\gamma$
  - normalized to $D^0 \to K^0_S\pi^0$
- Signal yield
  - Belle: fit to $M(\gamma\gamma)$ and $\Delta M(D^{*+} - D^0)$
  - BaBar: fit to $M(\gamma\gamma)$





‡J.P. Lees et al., Phys. Rev. D 85, 091107(R), 2012

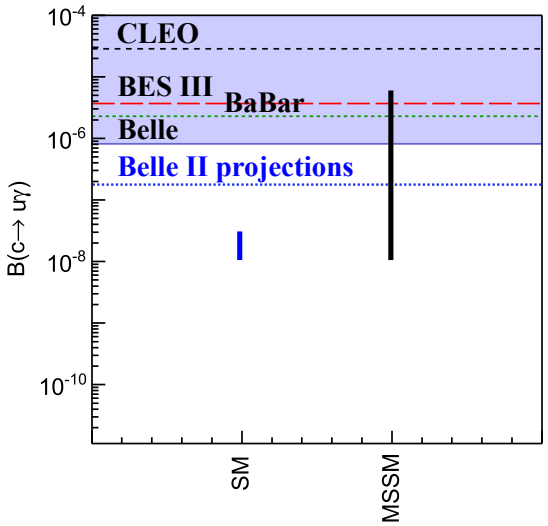
§N.K. Nisar et al., Phys. Rev. D 93, 051102(R), 2016

$D^0 \to \gamma\gamma$

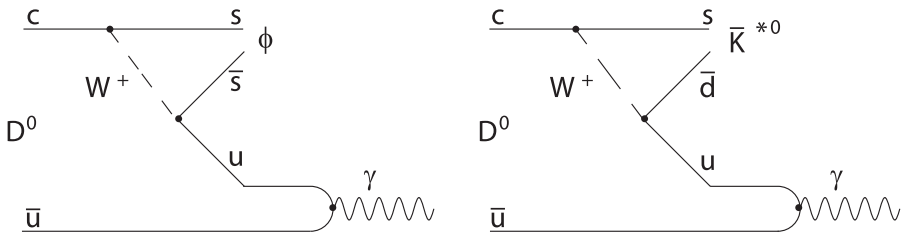
Experiment	$B(D^0 \to \gamma\gamma)$
BaBar	$< 2.2 \times 10^{-6}$ @ 90 % CL
Belle	$< 8.5 \times 10^{-7}$ @ 90 % CL

Table: Branching fraction measurements

$\Rightarrow$ sensitive to gluino exchange in the minimal supersymmetric model



CP Violation in $D^0 \to V\gamma$ Decays



- Long range contributions dominate in the SM
  - long range contributions $\sim 10^{-5}$
  - short range contributions $\sim 10^{-8}$

  $\Rightarrow$ test of the QCD calculations
- CP-violation in the decays $D^0 \to V\gamma$ due to the weak phase in the SM $\sim 10^{-3}$[¶]
  - chromomagnetic operators in the extension of the SM can enhance CP-violation

  $\Rightarrow$ $\left|a_{V\gamma}\right| \geqslant O(\%)$ would be a clear sign of the new physics[‖]

[¶] J. Brod et al., Phys. Rev. D 86, 014023, 2012

[‖] G. Isidori and J. F. Kamenik, Phys. Rev. Lett. 109, 171801, 2012

$D^0 \to \overline{K}^{0*}\gamma, D^0 \to \phi\gamma, D^0 \to \rho^0\gamma$

- Belle measurement with $943\,\text{fb}^{-1}$ **
- Reconstruction of the decay chain $D^{*+} \to D^0\pi^+_{\text{slow}}, D^0 \to V\gamma$:

$D^0 \to \rho^0\gamma$		$D^0 \to \pi^+\pi^-$
$D^0 \to \phi\gamma$	normalized to	$D^0 \to K^+K^-$
$D^0 \to \overline{K}^{0*}\gamma$		$D^0 \to K^-\pi^+$

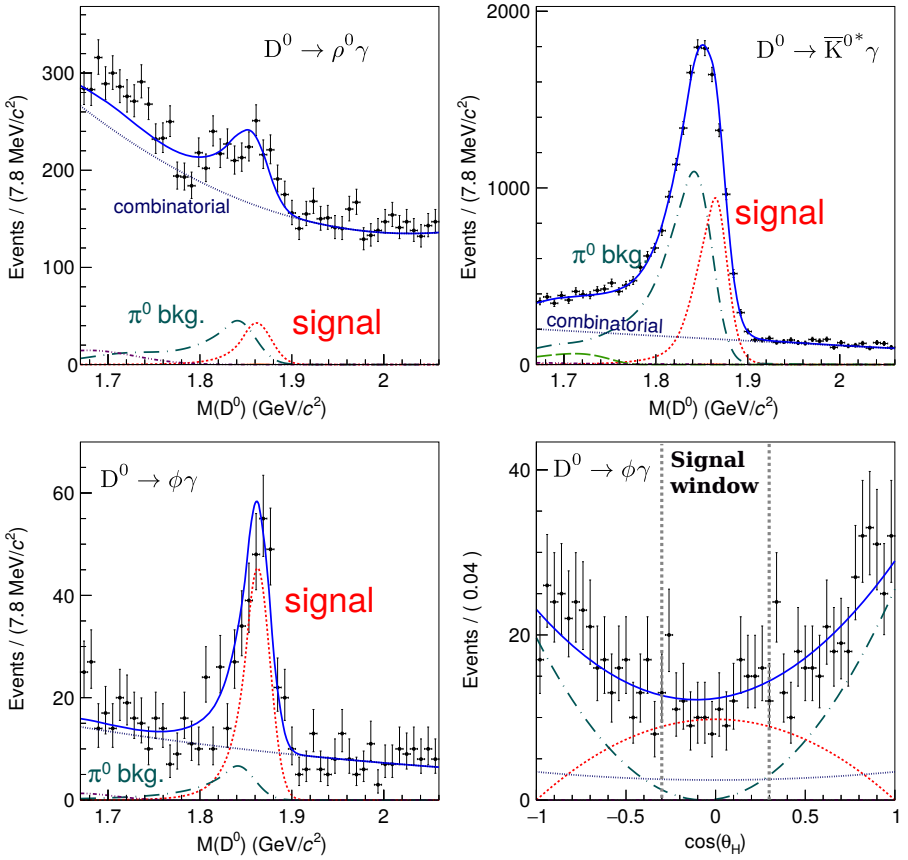
- CP-asymmetry extraction:

$$A_{\text{raw}} = \frac{N(D^0 \to f) - N(\overline{D}^0 \to \bar{f})}{N(D^0 \to f) + N(\overline{D}^0 \to \bar{f})}$$

$$A_{\text{raw}} = A_{CP} + A_{FB} + A_\varepsilon^\pm$$

$$A_{CP}^{\text{sig}} = A_{\text{raw}}^{\text{sig}} - A_{\text{raw}}^{\text{norm}} + A_{CP}^{\text{norm}}$$

$\Rightarrow$ A_{FB} and $A_\varepsilon^\pm$ cancel



**T. Nanut et al., PRL 118, 051801, 2017

$D^0 \to V\gamma$

Mode	$B_{Belle}, 10^{-5}$	$B_{BaBar}, 10^{-5}$ (387.1 fb^{-1})	A_{CP}, Belle
$D^0 \to \phi\gamma$	$2.76 \pm 0.19 \pm 0.10$	$2.78 \pm 0.30 \pm 0.27$	$-0.094 \pm 0.066 \pm 0.001$
$D^0 \to \overline{K}^{0*}\gamma$	$46.60 \pm 2.10 \pm 2.10$	$32.80 \pm 2.00 \pm 2.70$	$-0.003 \pm 0.020 \pm 0.000$
$D^0 \to \rho^0\gamma$	$1.77 \pm 0.30 \pm 0.07$	–	$+0.056 \pm 0.152 \pm 0.006$

Table: Measurement results

- Constistent with no CP-violation
- First measurement of the branching fraction for the decay $D^0 \to \rho^0\gamma$
- Statistical uncertainties on A_{CP} measurement with 50 ab^{-1} @ Belle II

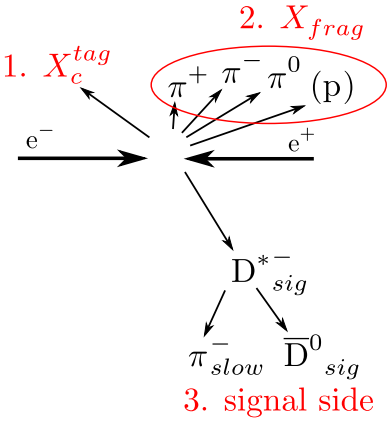
Mode	Belle with 943 fb^{-1}	Belle II with 50 ab^{-1}
$D^0 \to \phi\gamma$	± 0.066	± 0.010
$D^0 \to \overline{K}^{0*}\gamma$	± 0.020	± 0.003
$D^0 \to \rho^0\gamma$	± 0.152	± 0.020

$D^0 \to$ Invisible

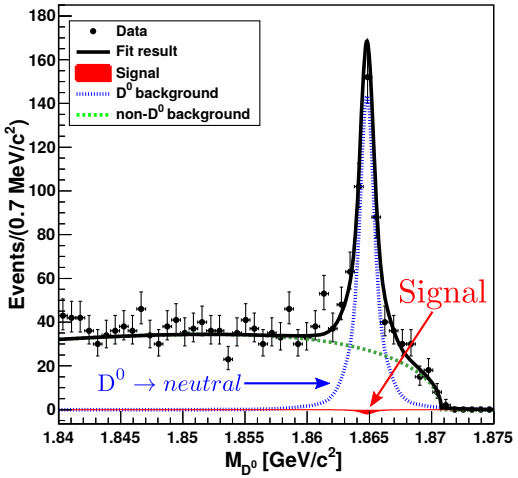
- $D^0 \to \nu\bar{\nu}$ helicity suppressed in the SM
  - $B(D^0 \to \nu\bar{\nu}) = 1.1 \times 10^{-30}$
- possible enhancements by non-SM D^0 decays

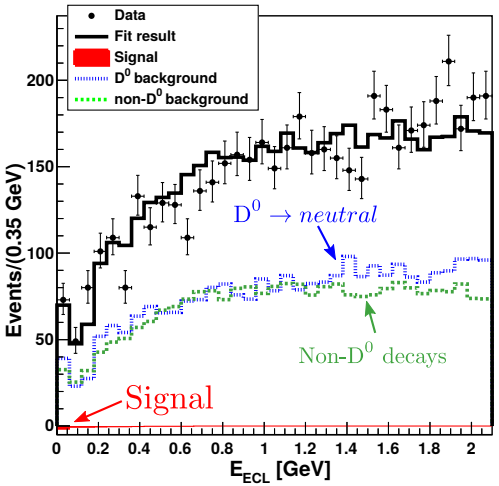
$D^0 \to$ Invisible

- Belle measurement with $924\,\text{fb}^{-1}$ ††
- Reconstruct everything except D^0



- $M_{recoil}(X_c^{tag} X_{frag} \pi_{slow})$
- **Result:**
  $B(D^0 \to \text{invisible}) < 9.4 \times 10^{-5}$ @ 90 % CL
  $\Rightarrow$ no sign of the decay
  $\Rightarrow$ dark matter coupling = $O(10^{-15})$ ‡‡





††Y.-T. Lai et al., Phys. Rev. D 95, 011102(R), 2017
‡‡A. Badin and A. A. Petrov, Phys. Rev. D 82, 034005, 2010

Summary and Outlook

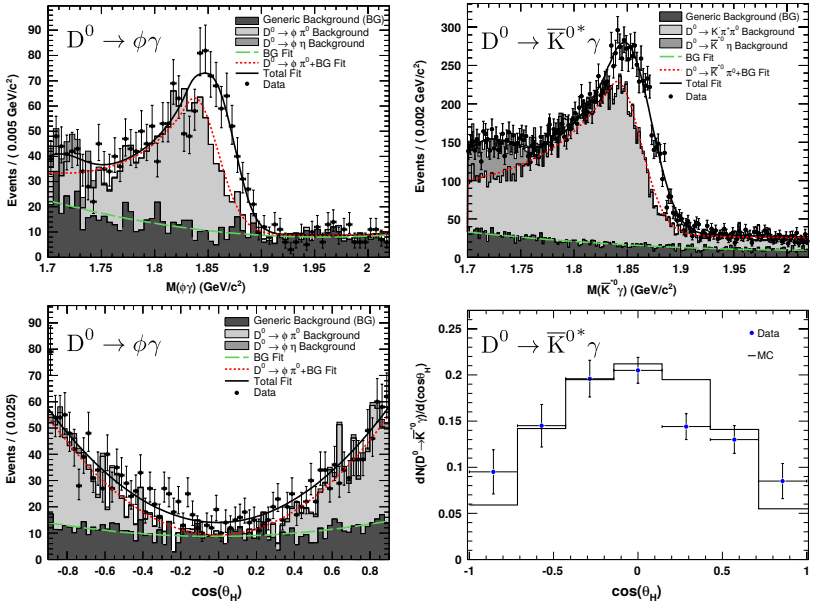
- Measurements of the leptonic, semileptonic, and rare charm decays at the B-factories
  - precise measurement of the D_s decay constant
  - search for FCNC in the leptonic D^0 decays
  - most precise limits on many the forbidden leptonic and semileptonic decays
  - probing new physics contributions in photonic D^0 decay
  - CP-violation measurement in radiative D^0 decays
- Belle II starts physics run in 2019
  - goal: $50\,ab^{-1}$ of the integrated luminosity

$\Rightarrow$ increased sensitivity to physics beyond the Standard Model

Backup Slides

$D^0 \to \overline{K}^{0*}\gamma, D^0 \to \phi\gamma$

- BaBar measurement with $387.1\,fb^{-1}$ §§
- Reconstruction of the decay chain $D^{*+} \to D^0\pi^+_{slow}, D^0 \to V(\overline{K}^{0*}, \phi)\gamma$
  - normalized to $D^0 \to K^-\pi^+$
  - π^+_{slow} tags the flavour of the D^0
- Peaking background through $D^0 \to \phi\pi^0$ and $D^0 \to K^-\pi^+\pi^0$
  - suppressed by π^0 veto
  - further suppression through helicity angle Θ_H cut
- Signal yield from the 2D fit to the $M(V\gamma)$ and $\cos(\Theta_H)$ distributions



§§B. Aubert et al., Phys. Rev. D 78, 071101(R), 2008