Weak Decays, CP Violation and the CKM Matrix: Experimental Status

Tim Gershon
University of Warwick

WIN'09
22nd International Workshop on Weak Interactions and Neutrinos

14th September 2009

Outline of the talk

- Charged leptons
  - $(g\text{-}2)_\mu$ and associated measurements
  - charged lepton flavour violation: μ and τ decays
- Quarks & hadrons
  - flavour oscillations and CP violation
  - assorted measurements of CKM matrix elements and searches for new physics
    - kaons: $|V_{us}|$; lepton universality tests; rare decays
    - bottom: Unitarity Triangle angles; rare decays
- Global fits and summary

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- Necessarily selective
- Apologies for omissions
- Focus on
  - New physics sensitive channels
  - New results
  - Future prospects

ALL RESULTS ARE PRELIMINARY
UNLESS PUBLISHED REFERENCE GIVEN

Charged leptons

Muon Anomalous Magnetic Moment

- Final result of BNL E821

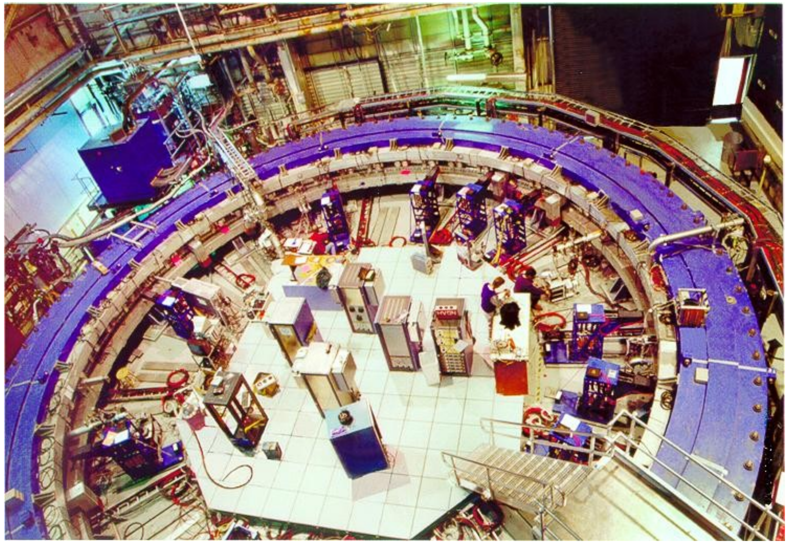
PRD 73 (2006) 072003

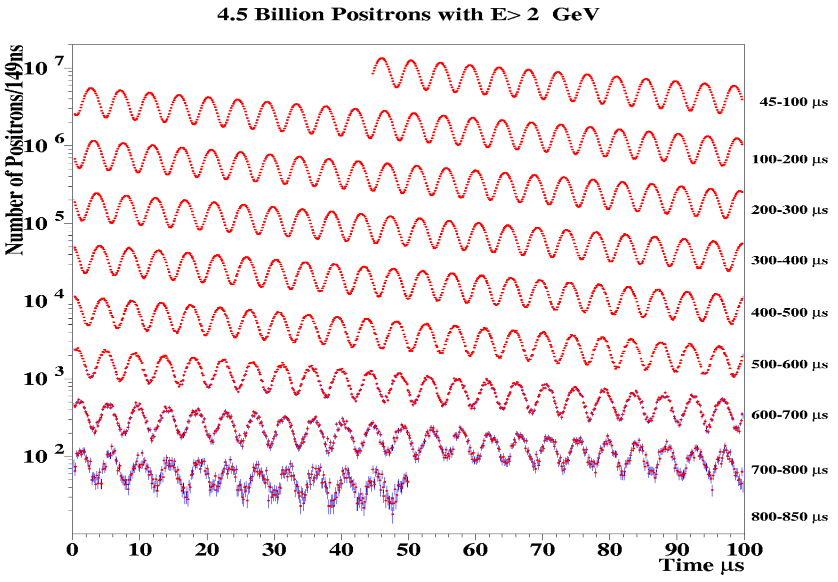
$a_\mu^{exp} = (11\ 659\ 208.0 \pm 5.4 \pm 3.3) \times 10^{-10}$

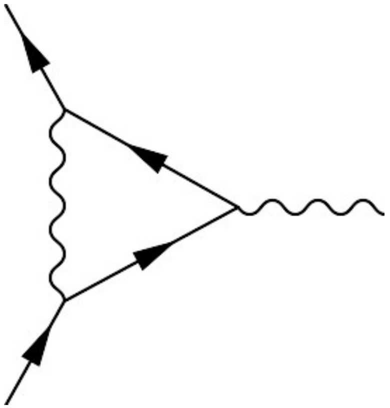
- Standard Model prediction:

$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{week} + a_\mu^{hadronic}$

$a_\mu^{hadronic} = a_\mu^{had,LO} + a_\mu^{had,HO} + a_\mu^{had,LBL}$







Muon Anomalous Magnetic Moment

- Final result of BNL E821

PRD 73 (2006) 072003

$a_\mu^{exp} = (11\,659\,208.0 \pm 5.4 \pm 3.3) \times 10^{-10}$

- Standard Model prediction:

$a_\mu^{SM} = (11\,658\,471.81 \pm 0.02$ (QED)

$+\ 15.32 \pm 0.18$ (weak)

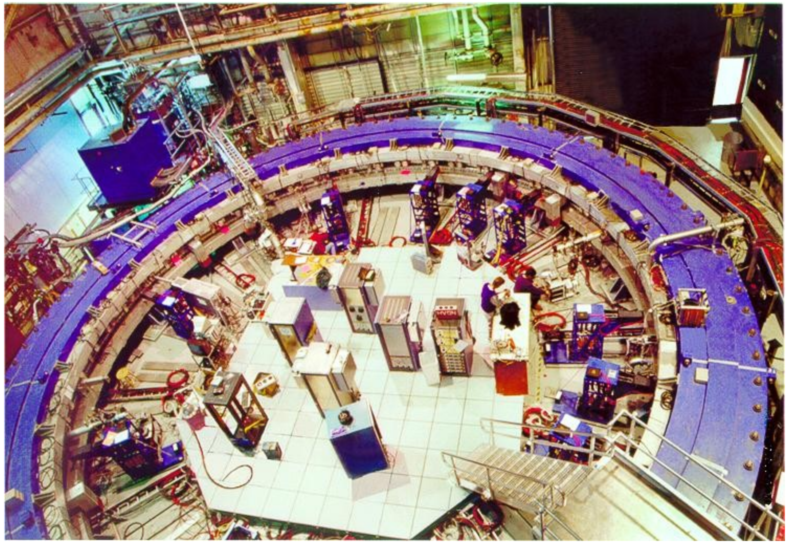
$+\ 690.30 \pm 5.26$ (had,LO)

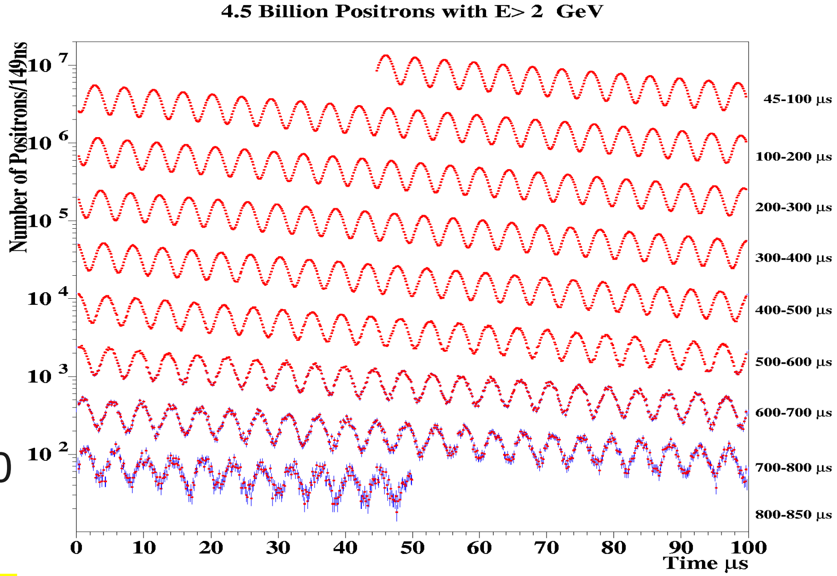
$-\ 10.03 \pm 0.11$ (had,HO)

$+\ 11.60 \pm 3.90$ (had,LBL)$) \times 10^{-10}$

$= (11\,659\,179.00 \pm 6.46) \times 10^{-10}$

- $a_\mu^{exp} - a_\mu^{SM} = (29.0 \pm 9.0) \times 10^{-10}$





F.Jegerlehner & A.Nyffeler, Phys. Rept. 477 (2009) 1110

Muon Anomalous Magnetic Moment

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PRD 73 (2006) 072003

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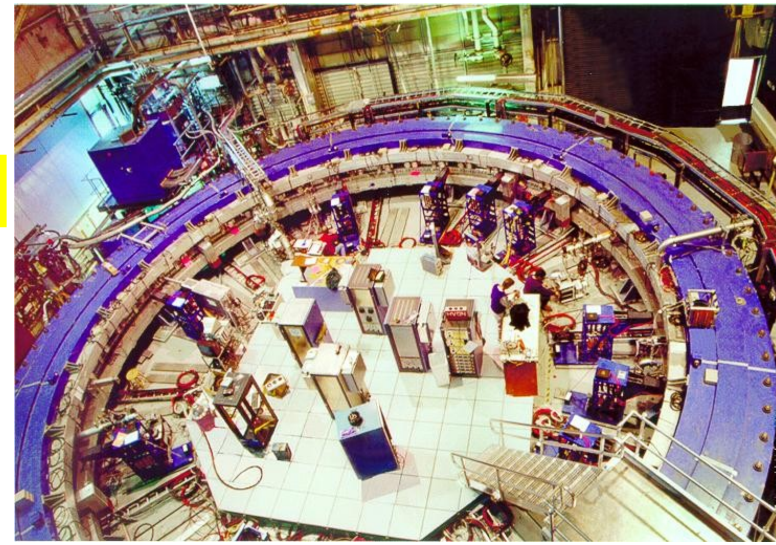
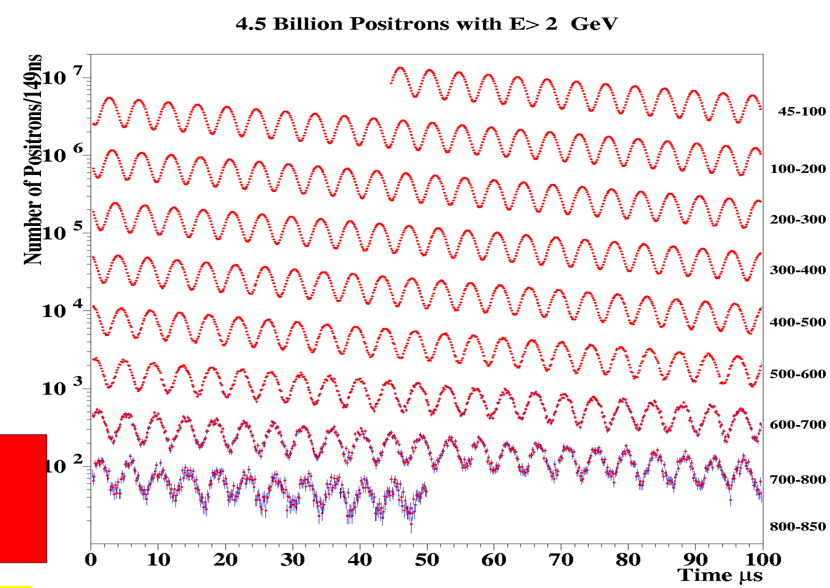
$$= (11\ 659\ 179.00 \pm 6.46) \times 10^{-10}$$

- $a_\mu^{exp} - a_\mu^{SM} =$ **3.2σ** (assuming Gaussian statistics)

F.Jegerlehner & A.Nyffeler, Phys. Rept. 477 (2009) 1110



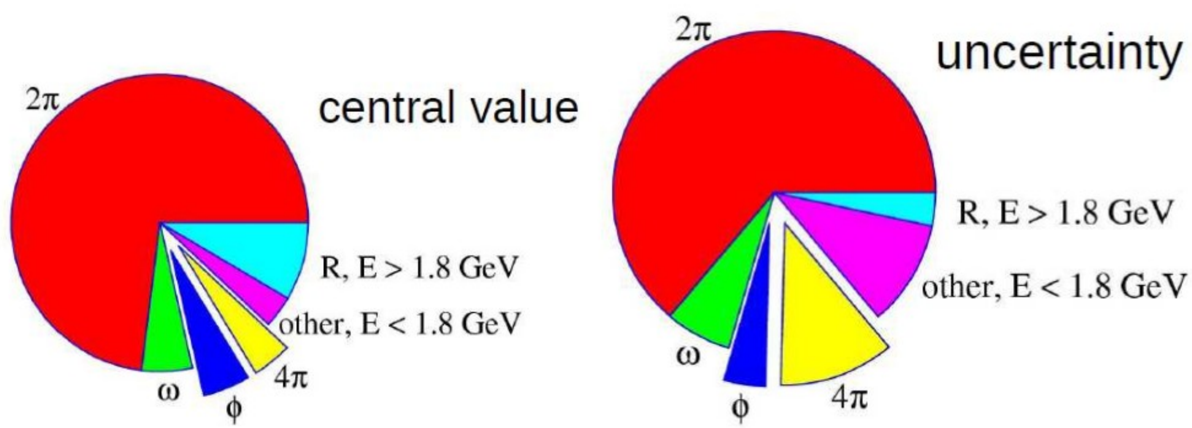


Hadronic vacuum polarisation

M.Davier *et al.*,
arXiv:0908.4300 [hep-ph]

$$a_\mu^{had,LO} = \frac{1}{4\pi^3}\int_{m_{\pi^0}^2}^{\infty} ds\, K(s)\, \sigma_{e^+e^-\to hadrons}$$

- Kernel function $K(s) \sim s^{-1}$ → low s ($e^+e^-\to\pi^+\pi^-(\gamma)$) dominates
- In practise, apply cut off
  - Below 1.8 GeV use data
    - $e^+e^-\to$hadrons ($\pi^+\pi^-$, $\pi^+\pi^-\pi^0$, K^+K^-, etc.) ← NEW MEASUREMENTS KLOE, BABAR
    - $\tau\to\pi\pi^0\nu$ plus theory (isospin breaking, etc.) ← NEW MEASUREMENTS BELLE
  - Above 1.8 GeV calculate from theory (pQCD)



New $e^+e^- \to \pi^+\pi^-(\gamma)$ Results

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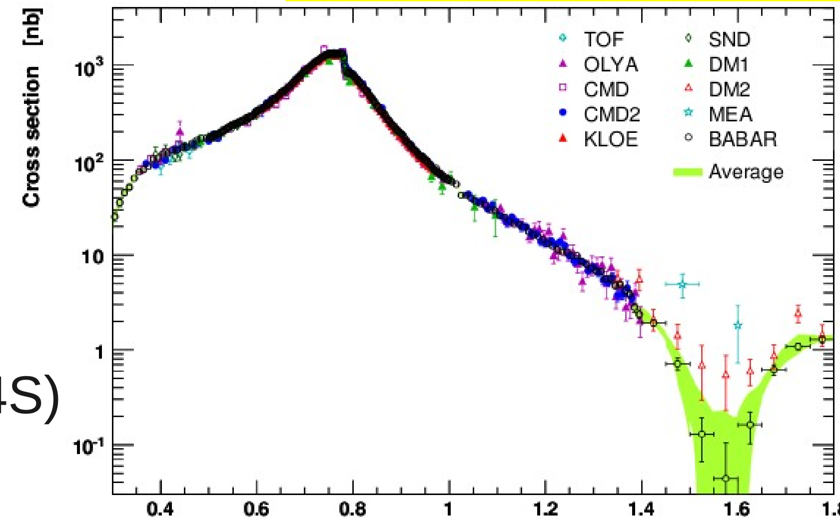


- KLOE PLB 670 (2009) 285
  - 240/pb $e^+e^- \to \pi^+\pi^-(\gamma)\gamma_{ISR}$ at the φ
  - Initial state radiation γ *not* tagged
- BABAR arXiv:0908.3589 [hep-ex]
  - 232/fb $e^+e^- \to \pi^+\pi^-(\gamma)\gamma_{ISR}$ near the $\Upsilon(4S)$
  - Initial state radiation γ *is* tagged
  - Ratio with $e^+e^- \to \mu^+\mu^-(\gamma)\gamma_{ISR}$

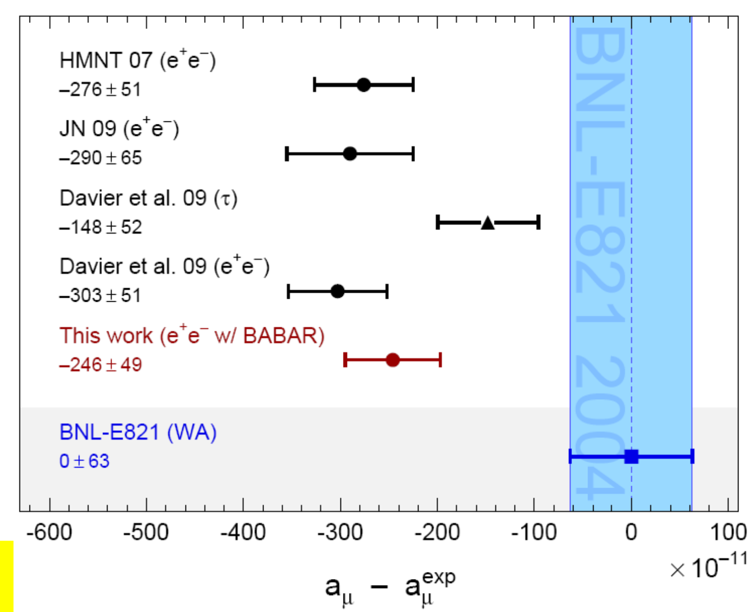
$$a_\mu^{had LO}[e^+e^-] = (695.5 \pm 4.0_{exp} \pm 0.7_{QED}) \times 10^{-10}$$

$$a_\mu^{had LO}[e^+e^-] - a_\mu^{had LO}[\tau] = (6.8 \pm 4.5) \times 10^{-10}$$

$$a_\mu^{SM} = (11\,659\,183.4 \pm 4.9) \times 10^{-10}$$

$$a_\mu^{exp} - a_\mu^{SM} = (24.6 \pm 8.0) \times 10^{-10}$$

recall: was $(29.0 \pm 9.0) \times 10^{-10}$



Including new $a_\mu^{had LBL}$ calculation from J.Prades *et al.*, arXiv:0901.0306 [hep-ph]

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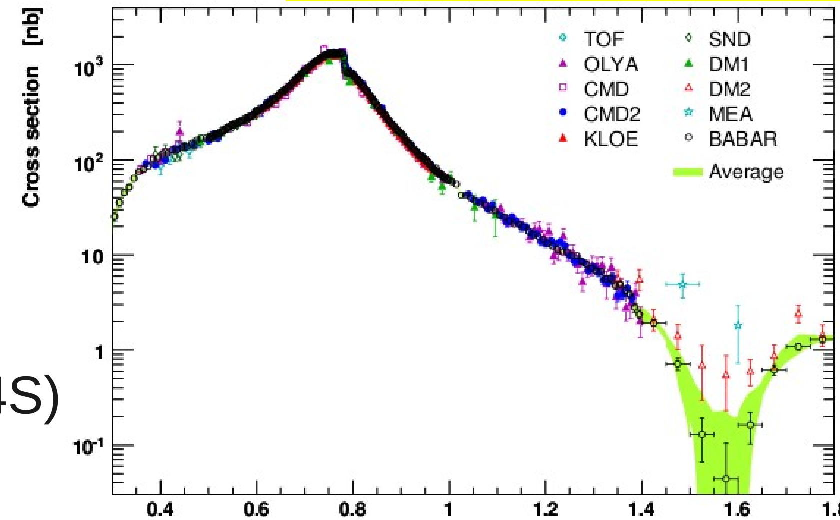

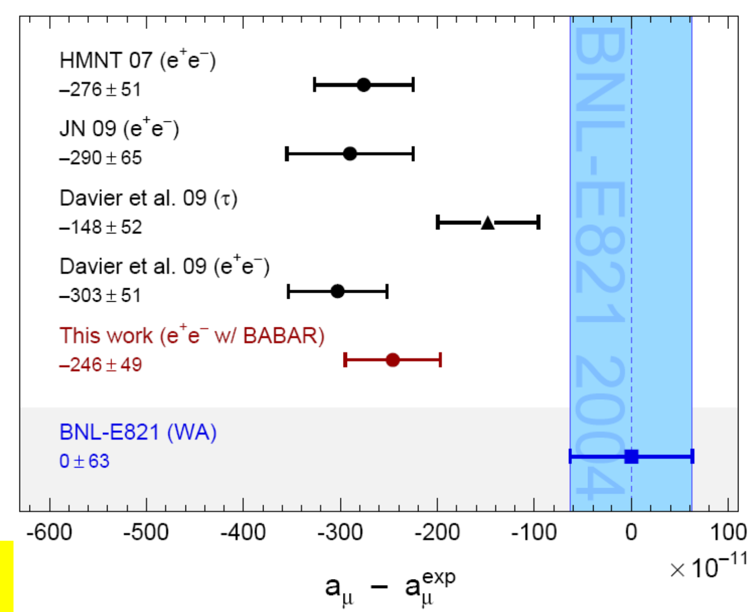

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Prospects for $(g\text{-}2)_\mu$

- Improve experimental precision
  - FERMILAB-PROPOSAL-0989 aims for 0.14 ppm
  - factor of 4 improvement from BNL E821
  - reuse of E821 storage ring at FNAL
- Improve Standard Model expectation
  - further measurements of $e^+e^- \to$ hadrons
  - uncertainty from $\pi\pi \approx$ that from others combined
  - precision studies of tau spectral function
  - KLOE, BESIII, CMD3, SND, BABAR, BELLE
  - continued progress on theory

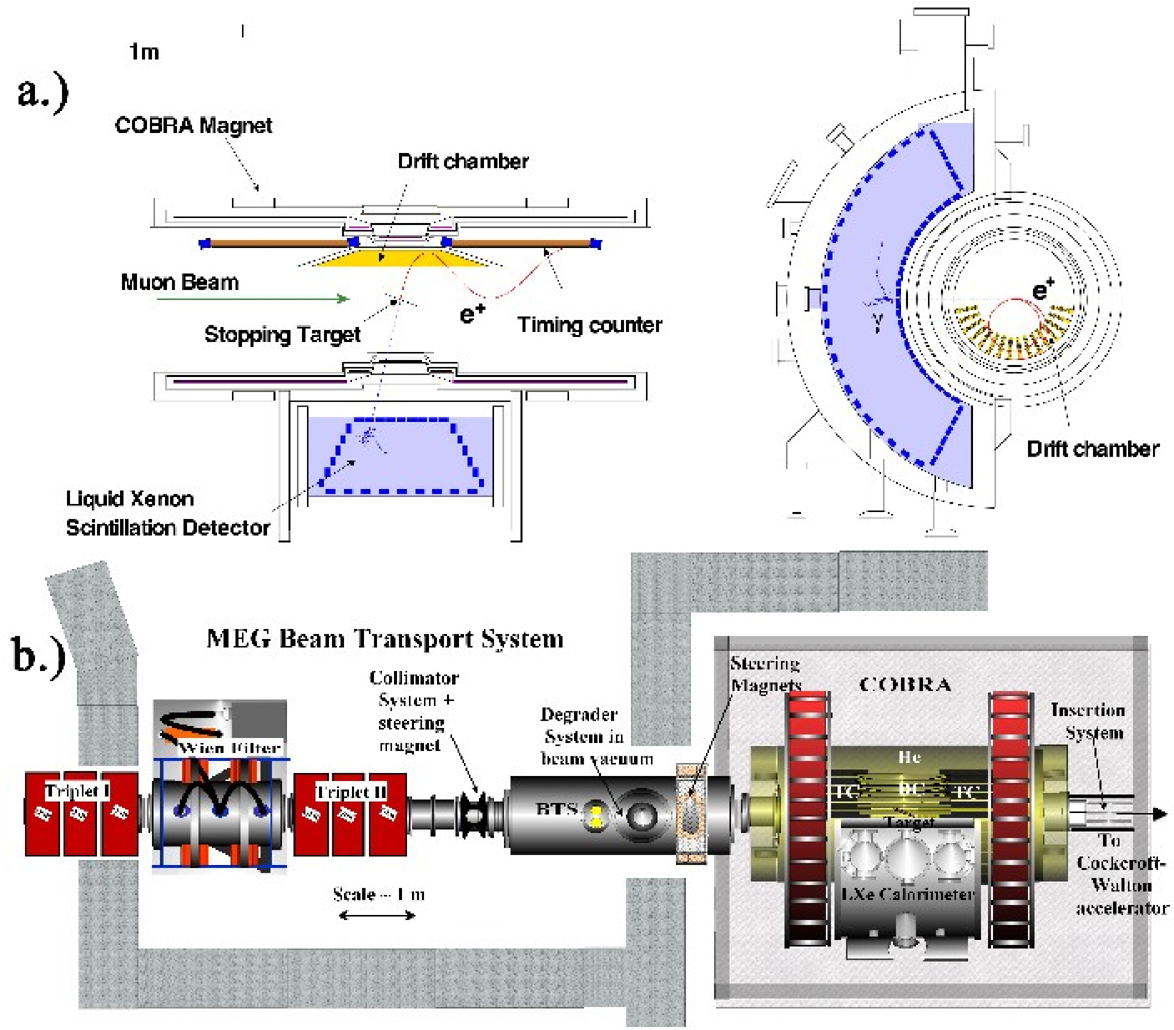
Charged lepton flavour violation

- Lepton flavour conservation: one of the original, and remaining, puzzles of the Standard Model
- Neutrinos oscillate → lepton flavour is violated
- Charged lepton flavour violation (CLFV) suppressed to unobservable levels ($O(10^{-50})$) by small neutrino masses
- CLFV signals: FCNC decays of μ and τ
  - $\mu \to e\gamma$, $\mu \to e$ conversion, $\tau \to \mu\gamma$, $\tau \to \mu\mu\mu$, etc.
- Observable CLFV → smoking gun for new physics
- Many extensions of the SM induce CLFV signals

The muon to electron gamma (MEG) experiment at PSI

$\mu^+ \rightarrow e^+\gamma$

- positive muons → no muonic atoms
- continuous (DC) muon beam → minimise accidental coincidences

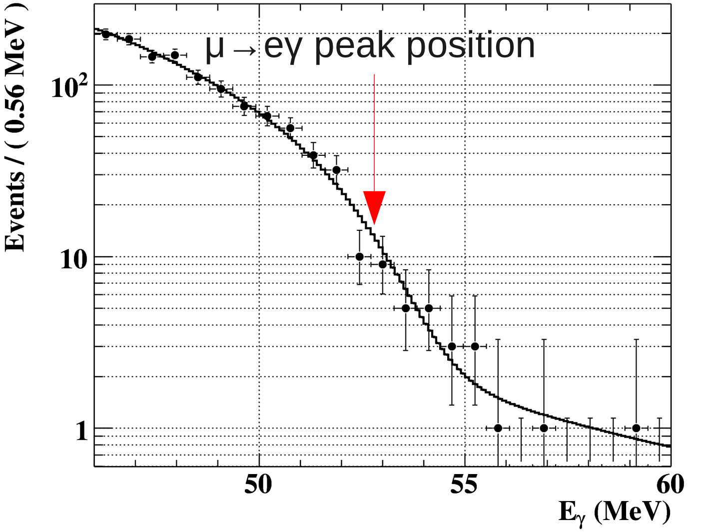


First Preliminary MEG Result

arXiv:0908.2594 [hep-ex]
T.Mori at LP'09

- Experimental challenges
  - control accidental coincidence: require excellent timing on both e and γ
  - distinguish background from radiative muon decay: require excellent (E,p) measurements for both e and γ
- Signal yield determined from simultaneous fit to five discriminating variables: E_γ, E_e, $t_{e\gamma}$, $\theta_{e\gamma}$ and $\varphi_{e\gamma}$
- 90% confidence level upper limit
  - N_{SIG} < 14.7 (Feldmann-Cousins)
- $B(\mu^+ \rightarrow e^+\gamma) < 3 \times 10^{-11}$ @ 90% C.L.
- Current best limit $< 1.2 \times 10^{-11}$

MEGA experiment
PRL 83 (1999) 1521

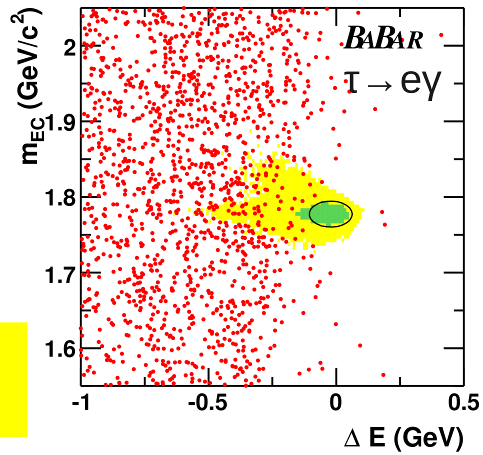


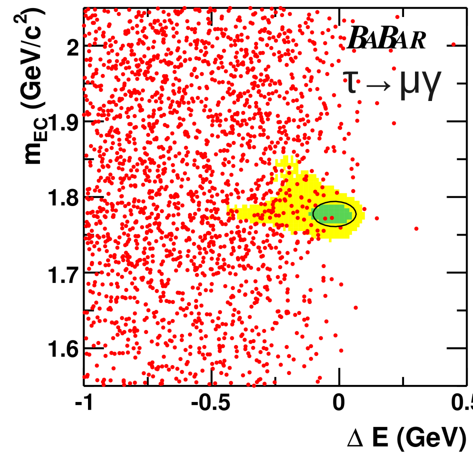
Lepton Flavour Violating τ Decays

$\tau \to e\gamma$ and $\tau \to \mu\gamma$ at BABAR
Data sample of 4.8×10^{8} τ pairs

$B(\tau \to e\gamma) < 3.3 \times 10^{-8}$ (90% C.L.)

$B(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$ (90% C.L.)

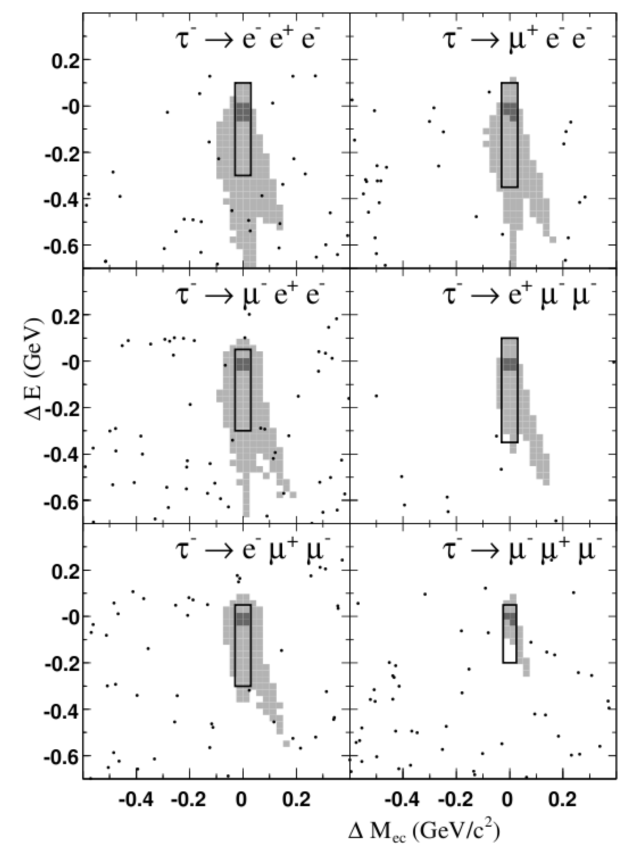




arXiv:0908.2381 [hep-ex]
(see also Belle PLB 666 (2008) 16)

$\tau \to lll$ at BABAR
Data sample of 4.3×10^{8} τ pairs

Mode	Eff. [%]	$N_{\rm bgd}$	$UL_{90}^{\rm exp}$	$N_{\rm obs}$	$UL_{90}^{\rm obs}$ / 10^{-8}
$e^-e^+e^-$	8.6 ± 0.2	0.12 ± 0.02	3.4	0	2.9
$\mu^-e^+e^-$	8.8 ± 0.5	0.64 ± 0.19	3.7	0	2.2
$\mu^+e^-e^-$	12.7 ± 0.7	0.34 ± 0.12	2.2	0	1.8
$e^+\mu^-\mu^-$	10.2 ± 0.6	0.03 ± 0.02	2.8	0	2.6
$e^-\mu^+\mu^-$	6.4 ± 0.4	0.54 ± 0.14	4.6	0	3.2
$\mu^-\mu^+\mu^-$	6.6 ± 0.6	0.44 ± 0.17	4.0	0	3.3



A. Cervelli at CIPANP 2009
(see also Belle: Y.Miyazaki at EPS2009)

... and many more!
Full listings available from
HFAG tau decay subgroup
http://www.slac.stanford.edu/xorg/hfag/tau

Prospects for Lepton Flavour Violation

- MEG still taking data
- New generations of μ – e conversion experiments
  - COMET at J-PARC, followed by PRISM/PRIME
  - mu2e at FNAL, followed by Project X
  - Potential improvements of $O(10^4) – O(10^6)$ in sensitivities!
- τ LFV a priority for next generation e^+e^- flavour factories
  - SuperKEKB/Belle2 at KEK
  - SuperB in Italy
  - O(100) improvements in luminosity → O(10) – O(100) improvements in sensitivity (depending on background)
  - LHC experiments have some potential to improve $\tau \to \mu\mu\mu$

Quarks and hadrons

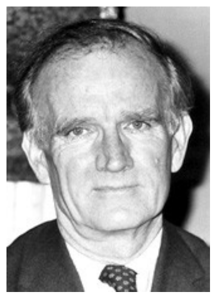
The Cabibbo-Kobayashi-Maskawa Quark Mixing Matrix

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

- A 3x3 unitary matrix
- Described by 4 real parameters – allows CP violation
  - PDG (Chau-Keung) parametrisation: θ_{12}, θ_{23}, θ_{13}, δ
  - Wolfenstein parametrisation: λ, A, ρ, η
- Highly predictive

Flavour oscillations, CP violation and Nobel Prizes

- 1964 – Discovery of CP violation in K^0 system
- 1980 – Nobel Prize to Cronin and Fitch

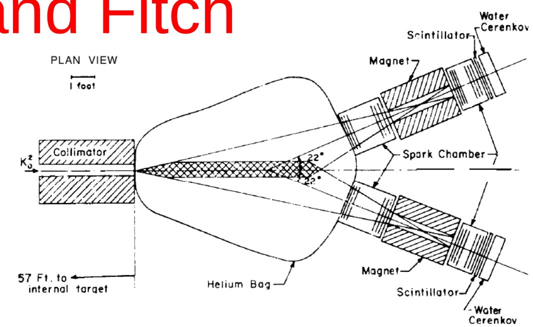


Fig. 1. Plan view of the apparatus as located at the A. G. S.

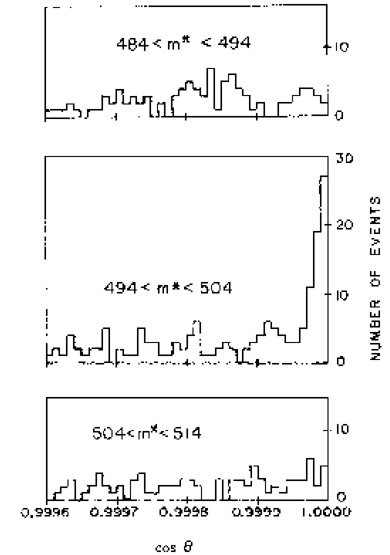
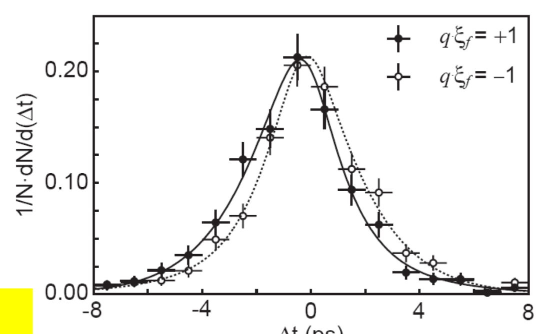


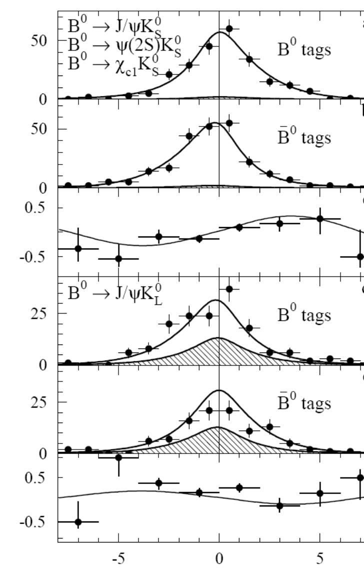
FIG. 3. Angular distribution in three mass ranges for events with cos θ > 0.9995.

PRL 13 (1964) 138

- 2001 – Discovery of CP violation in B_d system
- 2008 – Nobel Prize to Kobayashi and Maskawa


Prog.Theor.Phys. 49 (1973) 652





Belle PRL 87 (2001) 091802

BABAR PRL 87 (2001) 091801

Flavour oscillations, CP violation and Nobel Prizes

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- 1980 – Nobel Prize to Cronin and Fitch

PRL 13 (1964) 138

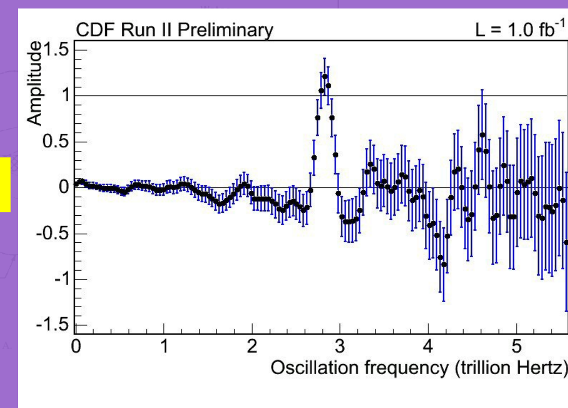
- 2001 – Discovery of CP violation in B system
- 2008 – Nobel Prize to Kobayashi and Maskawa

Prog.Theor.Phys. 49 (1973) 652

- Discovery of oscillations → discovery of CP violation → Nobel Prize
  - can take 30 years

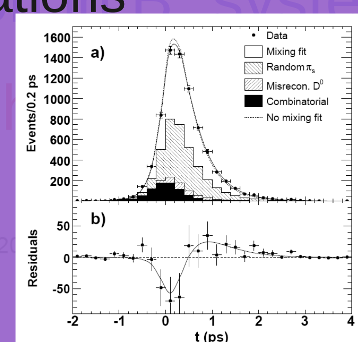
- 2006 Discovery of B_s oscillations

CDF PRL 97 (2006) 242003

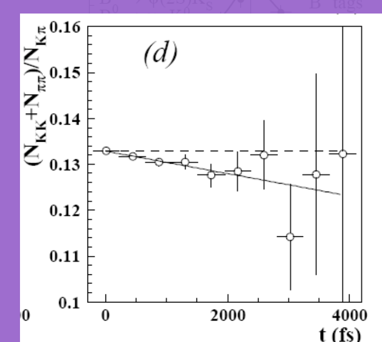


  - no discovery of CP violation yet

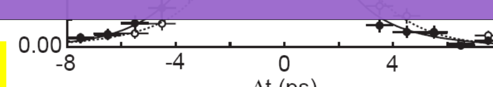
- 2007 Discovery of charm oscillations
  - no CP violation yet



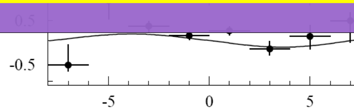
BABAR PRL 98 (2007) 211802



Belle PRL 98 (2007) 211803



Belle PRL 87 (2001) 091802



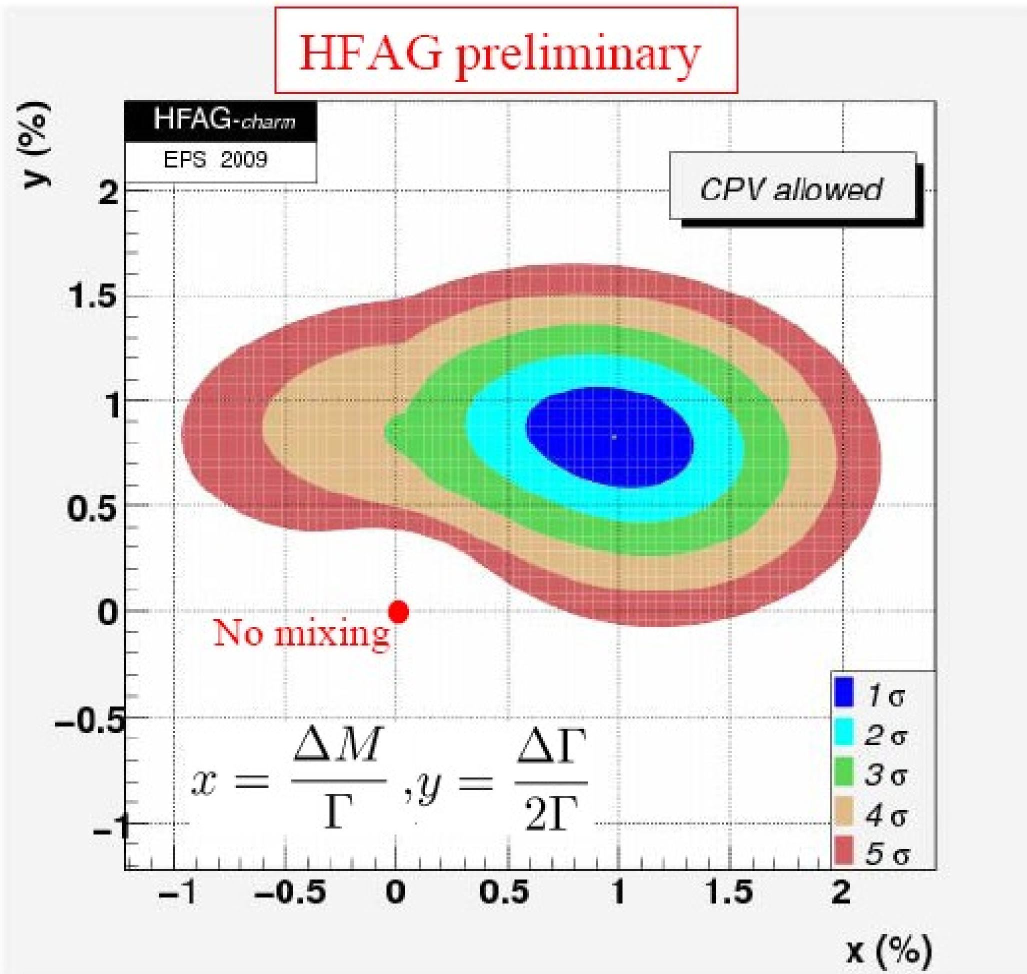
BABAR PRL 87 (2001) 091801

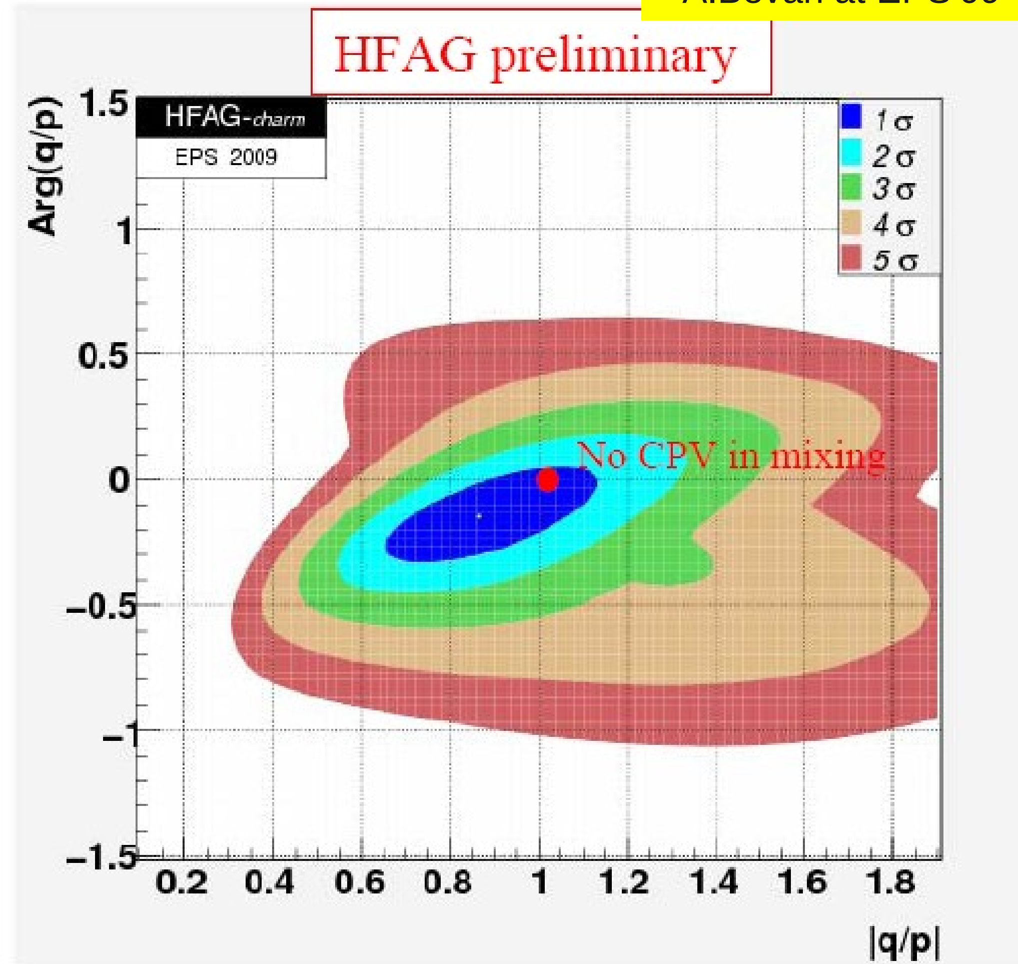
Charm mixing and CP violation

Including results from BABAR, Belle, CDF, CLEO(c), FOCUS

Latest new results Belle arXiv:0905.4185 [hep-ex] BABAR arXiv:0908.0761 [hep-ex]

A.Bevan at EPS'09



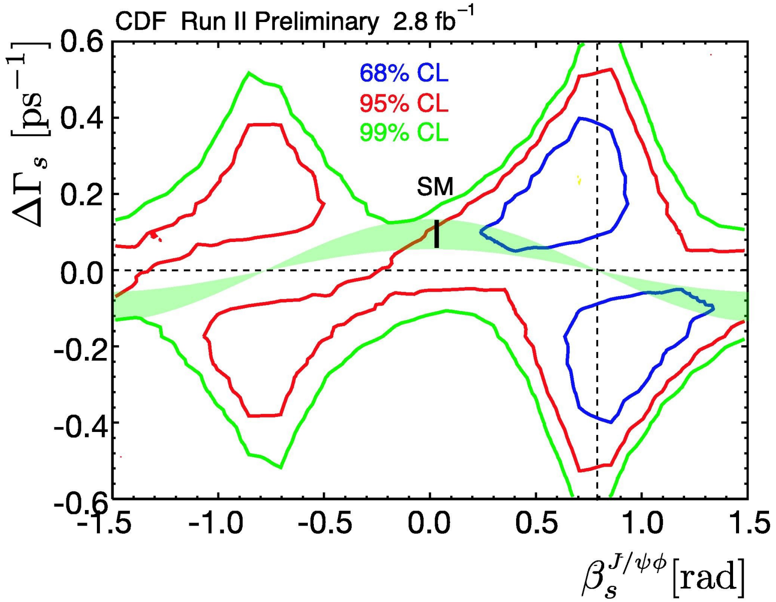


- Mixing established (though still no single measurement > 5σ)
- No indication of CP violation

B_s oscillations and CP violation

- Tevatron measurements using tagged $B_s \rightarrow J/\psi\phi$
- Angular analyses of vector-vector final state
- Results depend on $\Delta\Gamma$

CDF note 9787



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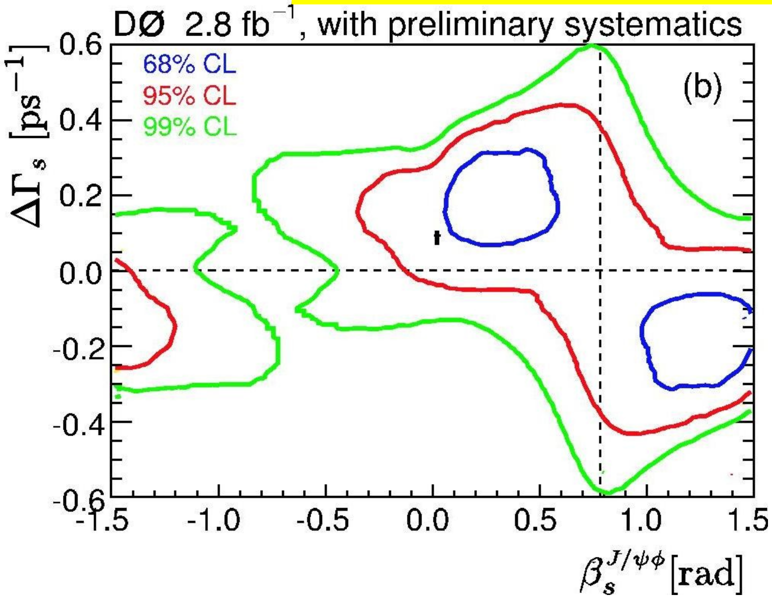

B_s oscillations and CP violation

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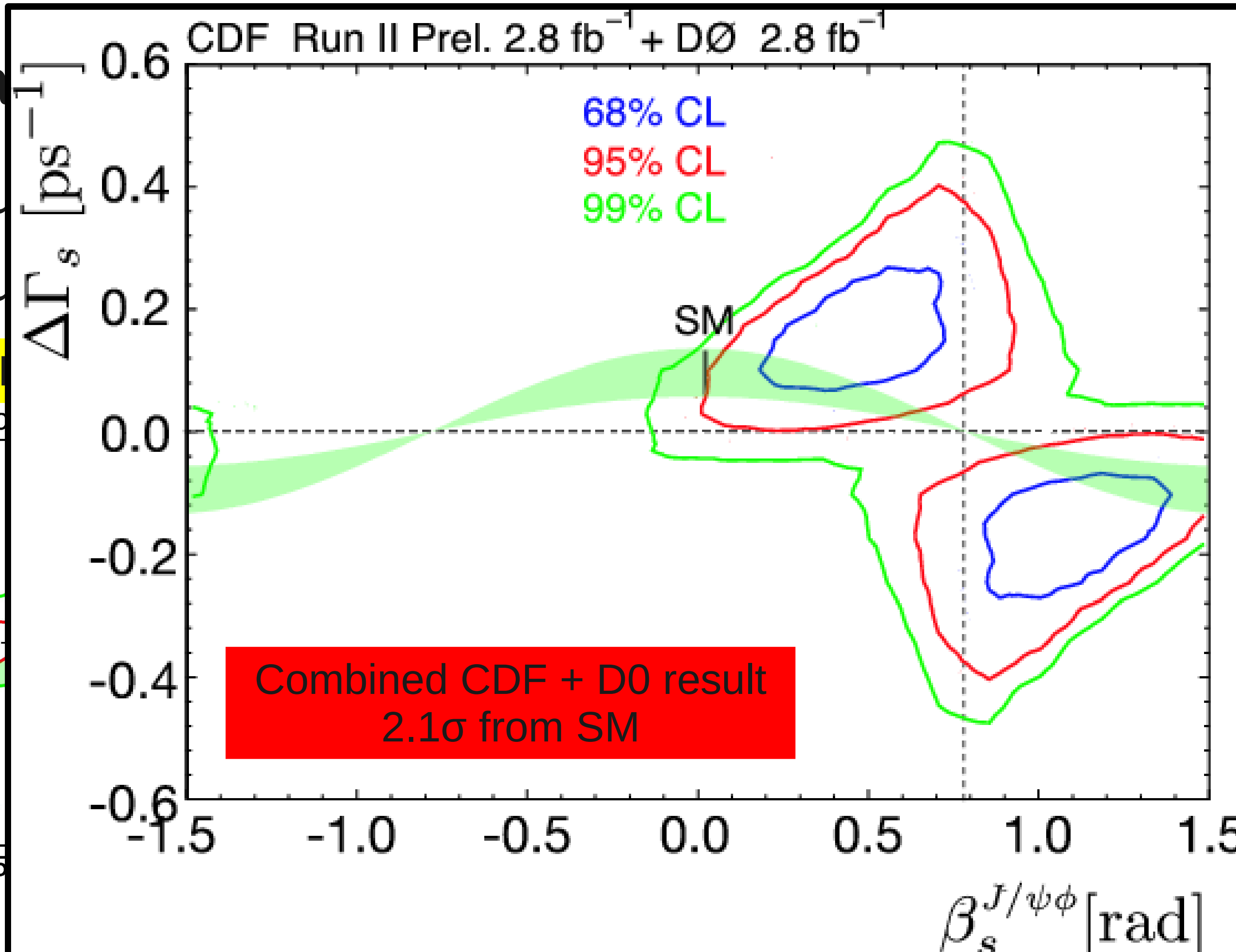
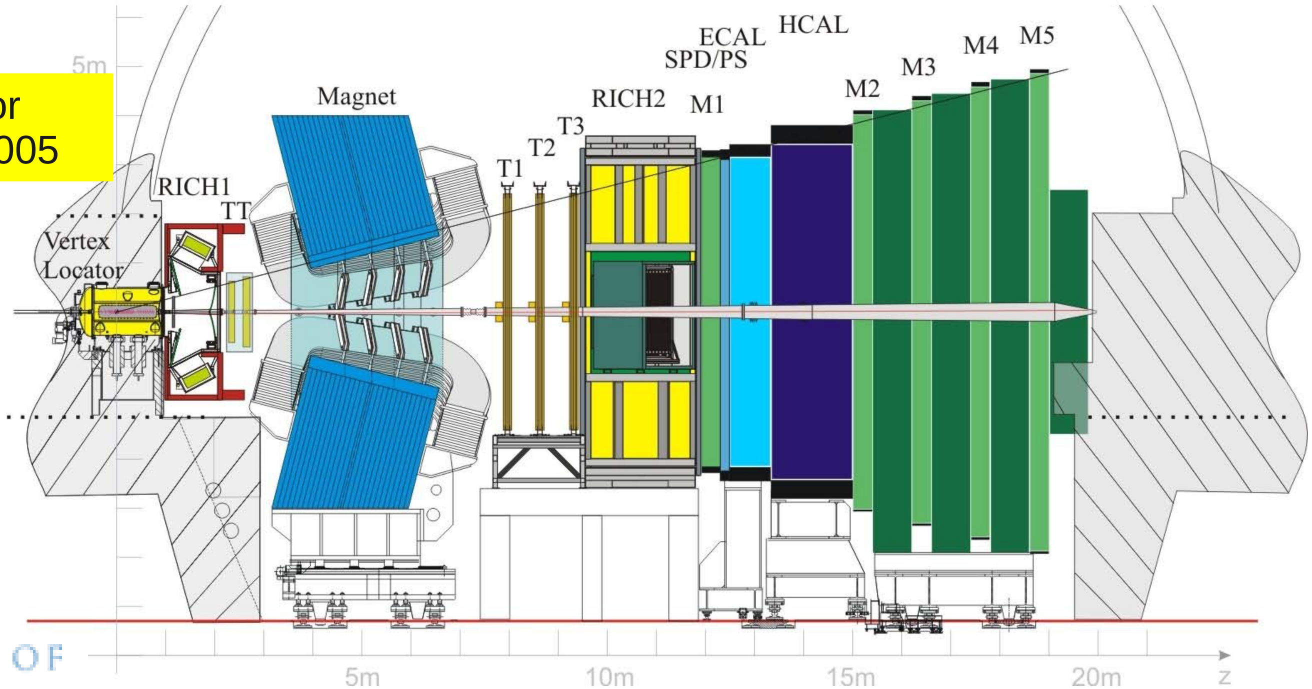


Future prospects for CP violation in B_s and charm oscillations

- More results still to come from B factories & Tevatron
- LHCb will improve world's best measurements with 1 year of data (at nominal luminosity)
  - excellent prospects for $B_s \rightarrow J/\psi\phi$ and $D^0 \rightarrow hh$ with early data

The LHCb Detector
JINST 3 (2008) S08005



CKM Matrix – Magnitudes

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

CKM Matrix – Magnitudes

PDG 2008
See also S.Prell at LP'09

semileptonic / leptonic kaon decays
hadronic tau decays

superallowed $0^+ \rightarrow 0^+$ β decays

semileptonic / leptonic B decays

$$\begin{pmatrix} 0.97418 \pm 0.00027 & 0.2255 \pm 0.0019 & (3.93 \pm 0.36) \times 10^{-3} \\ 0.230 \pm 0.011 & 1.04 \pm 0.06 & (41.2 \pm 1.1) \times 10^{-3} \\ (8.1 \pm 0.6) \times 10^{-3} & (38.7 \pm 2.3) \times 10^{-3} & > 0.74 \end{pmatrix}$$

semileptonic charm decays
charm production in neutrino beams

semileptonic B decays

semileptonic / leptonic charm decays

B_d oscillations

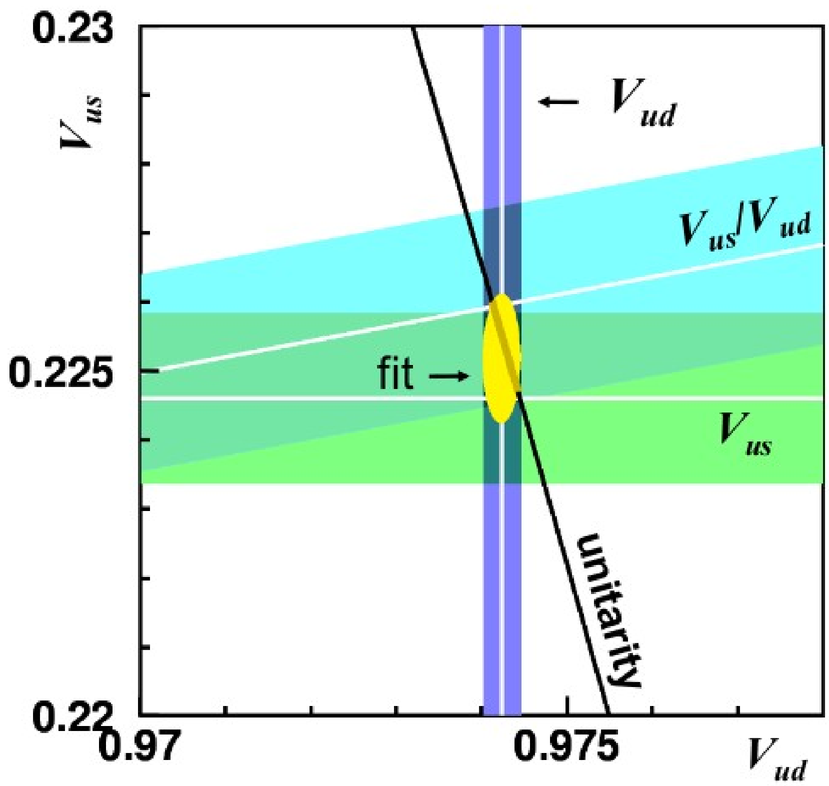
single top production

B_s oscillations

theory inputs (eg., lattice calculations) required

$|V_{us}|$ and $|V_{ud}|$ fit by flavianet

M.Palutan at Kaon'09
see also http://ific.uv.es/flavianet/



We use $f_+(0) = 0.9644(49)$, $f_K/f_\pi = 1.189(7)$

from RBC/UKQCD '07

Now can fit:

- V_{us} from $Kl3$ ← KLOE, KTeV, BNL E685, ISTRA+, NA48
- V_{us}/V_{ud} from $K_{\mu 2}/\pi_{\mu 2}$
- V_{ud} from β decay ← New survey of superallowed $0^+ \rightarrow 0^+$ β decays J.Hardy & I.Towner, PRC 79 (2009) 055502

$V_{ud} = 0.97424(22)$
$V_{us} = 0.2252(9)$
$\chi^2/\text{ndf} = 0.52/1$ (47%)

$$V_{ud}^2 + V_{us}^2 - 1 = -0.0001(6)$$

Uncertainty from $|V_{us}|^2$ now comparable to that from $|V_{ud}|^2$

Significant further improvement difficult

Lepton Universality in K_{l2} Decays

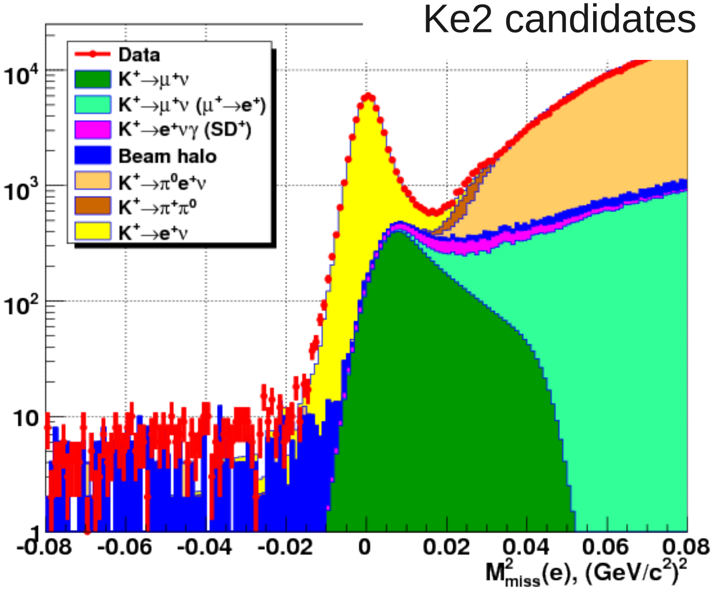
E.Goudzovski at Kaon'09
See also KLOE arXiv:0907.3594 [hep-ex]

$$R_K = \frac{\Gamma(K^+ \to e\,\nu_e)}{\Gamma(K^+ \to \mu\,\nu_\mu)} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1 + \delta R_{QED}) = (2.477 \pm 0.001) \times 10^{-5}$$

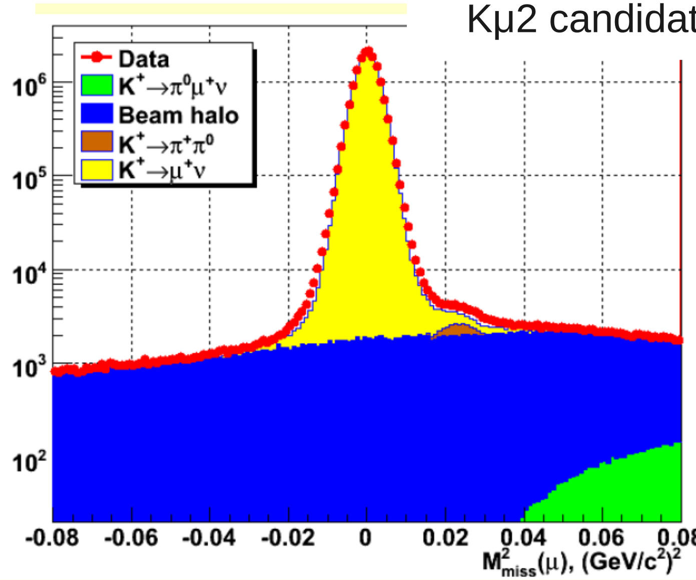
Standard Model prediction

Preliminary results from 40% of NA62 data

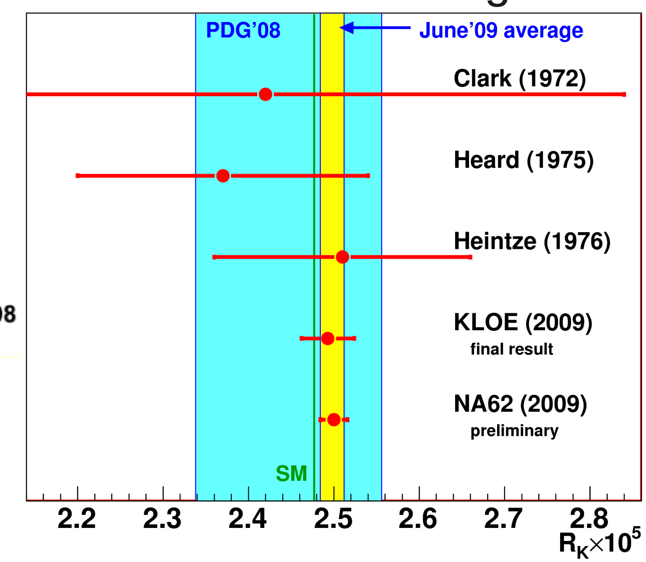
Ke2 candidates



Kμ2 candidates



New world average



$R_K = (2.500 \pm 0.012\ (stat) \pm 0.011\ (syst)) \times 10^{-5}$

Expected final precision $\delta R_K / R_K < 0.5\%$

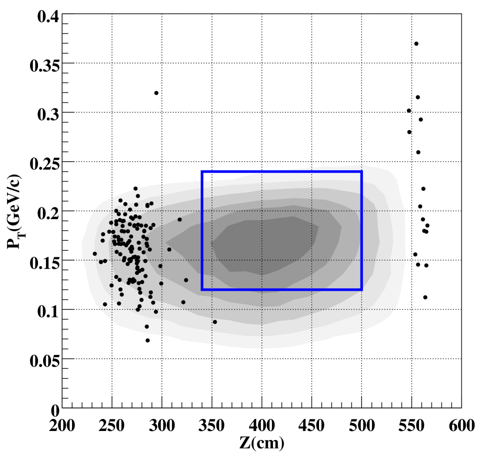
Rare kaon decays: $K_L \rightarrow \pi^0\nu\nu$

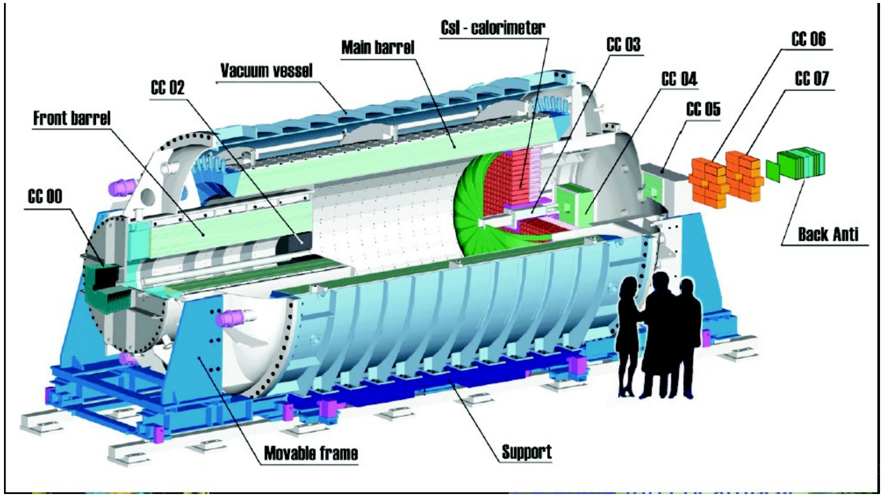
- Theoretically clean Standard Model probe
- Extremely rare ($O(10^{-11})$) → highly sensitive to new physics
- Main challenges: knowledge of beam, detector hermeticity

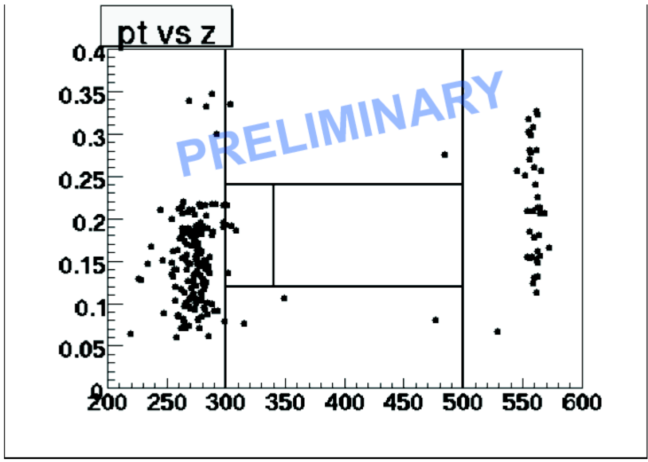
PRL 100 (2008) 201802

KEK-E391a

H.Morii at Kaon'09







$B(K_L \rightarrow \pi^0\nu\nu) < 6.7 \times 10^{-8}$ at 90% CL

Independent data sets

02-04/2005

$B(K_L \rightarrow \pi^0\nu\nu) < 6.8 \times 10^{-8}$ at 90% CL

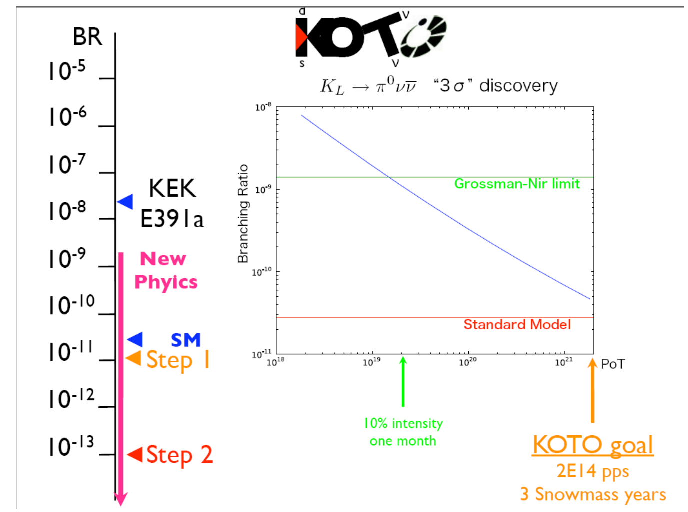
11-12/2005

Combination in progress

Future prospects for kaon physics

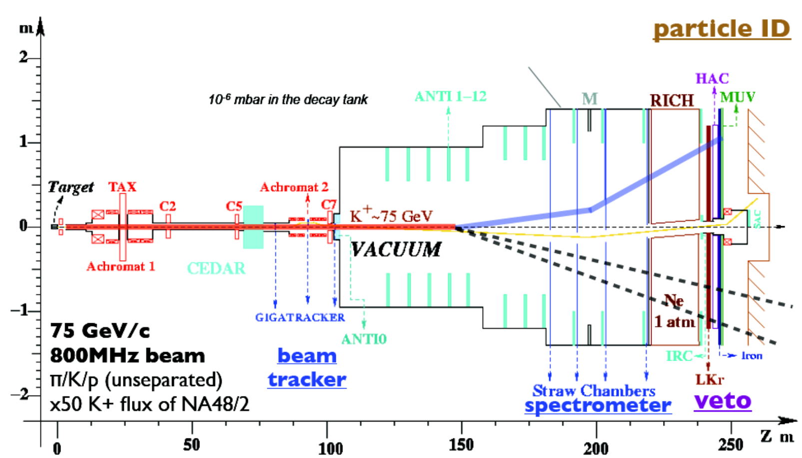
T.Komatsubara at LP'09

- Main focus on the golden $K \to \pi\nu\nu$ decays
- $K_L \to \pi^0\nu\nu$
  - KOTO experiment (JPARC)
  - Same technique as KEK-E391a



BNL-E949
PRL 101 (2008) 191802
PRD 79 (2009) 092004

- $K^+ \to \pi^+\nu\nu$
  - $B(K^+ \to \pi^+\nu\nu) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ (7 events)
  - NA62 (CERN)
  - kaon decay in flight
  - Expect ~50 events/year



CKM Matrix – Phases

P.Harrison *et al.*, arXiv:0904.3077 [hep-ph]

- Can form a matrix of angles between pairs of CKM matrix elements
  - Φ_{ij} = phase between remaining elements when row i and column j removed
  - unitarity implies sum of phases in any row or column = 180°

$$\Phi = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} \Phi_{ud} & \Phi_{us} & \Phi_{ub} \\ \Phi_{cd} & \Phi_{cs} & \Phi_{cb} \\ \Phi_{td} & \Phi_{ts} & \Phi_{tb} \end{pmatrix} \end{array} \simeq \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1^o & 22^o & 157^o \\ 67^o & 90^o & 23^o \\ 112^o & 68^o & 0^o \end{pmatrix} \end{array}$$

$\beta \equiv \varphi_1$ (22^o)

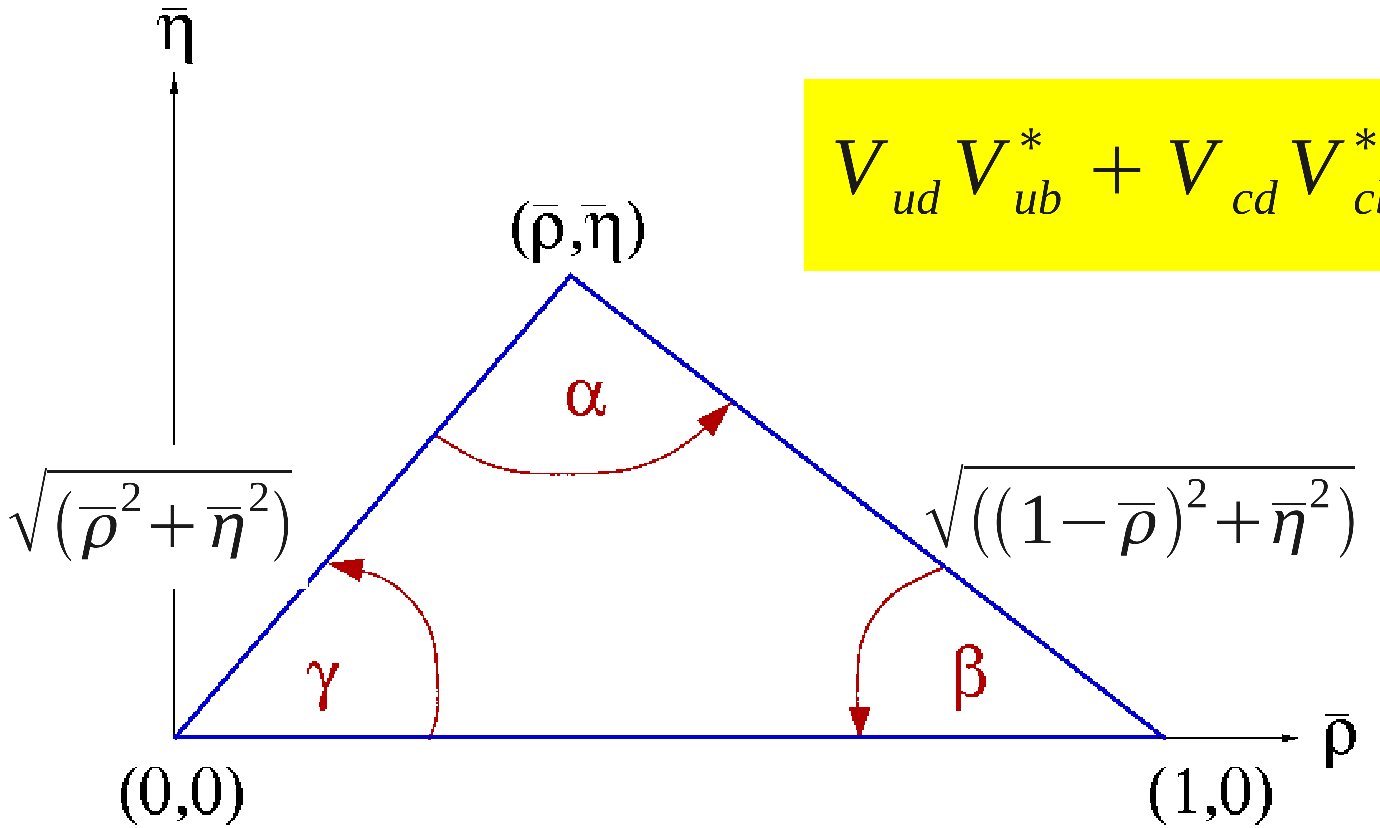
$\alpha \equiv \varphi_2$ (90^o)

$\gamma \equiv \varphi_3$ (68^o)

"The Unitarity Triangle" (the s column)

The Unitarity Triangle

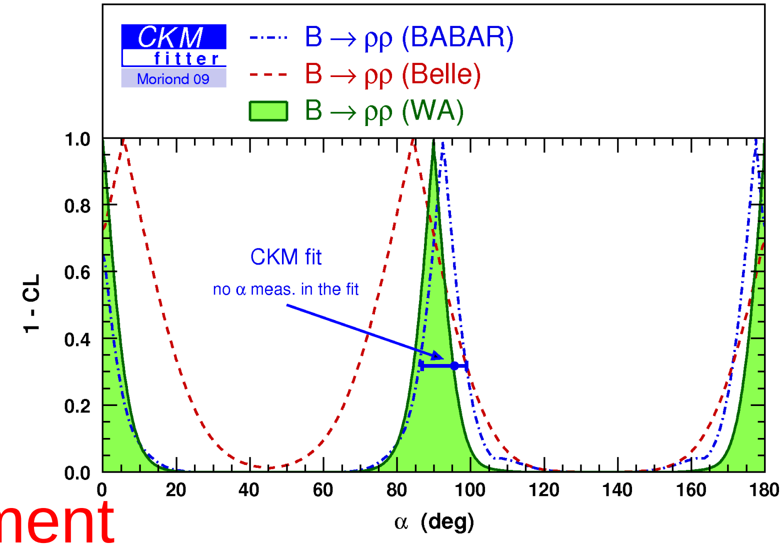
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



$$\alpha \equiv \phi_2 = \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right], \quad \beta \equiv \phi_1 = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right], \quad \gamma \equiv \phi_3 = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right].$$

Measurement of α

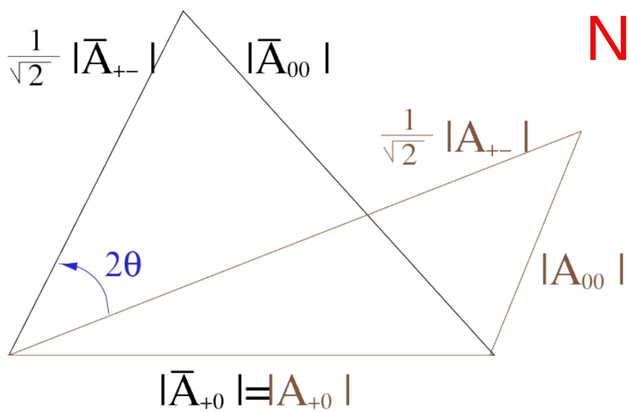
http://ckmfitter.in2p3.fr/



- Now a precise measurement

$$\alpha = (89.0^{+4.4}_{-4.2})°$$

- Dominated by B → ρρ system
- Analysis uses isospin triangle

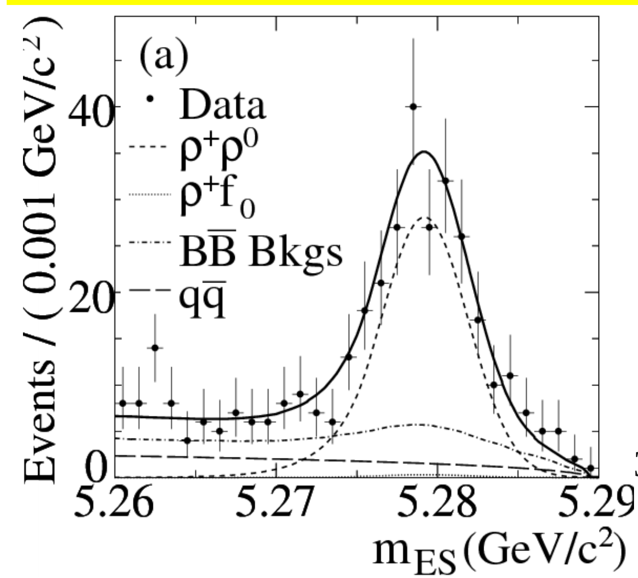


M.Gronau & D.London,
PRL 65 (1990) 3381

New $B^+ \to \rho^+\rho^0$ measurement

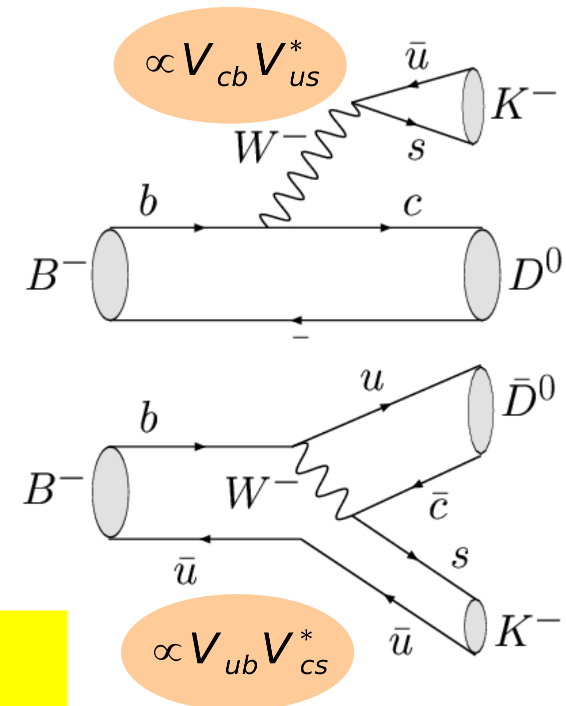
- large amplitude
- stretches triangles base
- reduction in θ ≈ Δα

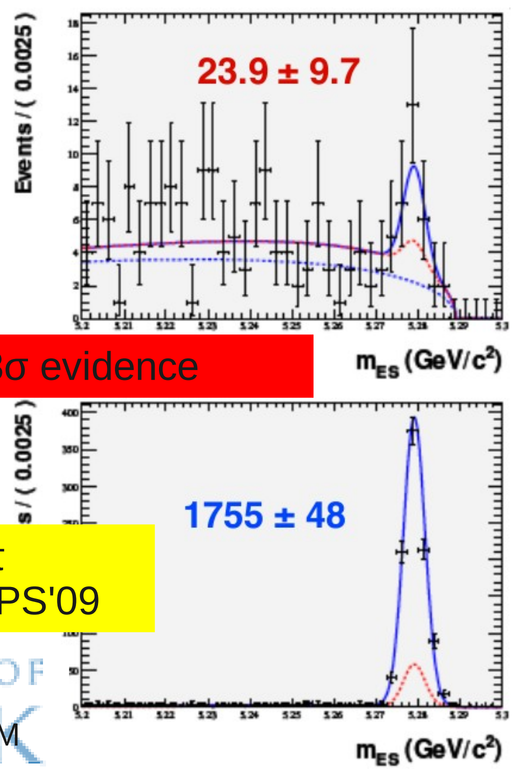
BABAR PRL 102 (2009) 141802



Measurement of γ from B→DK

- Exploit interference between diagrams
- Difficulty:
  - smallness of suppressed amplitude
- Now beginning to see a signal?

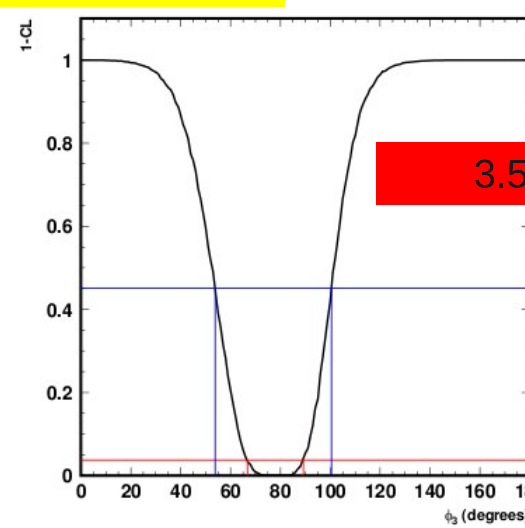




3σ evidence

BABAR D→Kπ
N.Lopez March at EPS'09

Belle D→K_Sππ
A.Poluektov at EPS'09



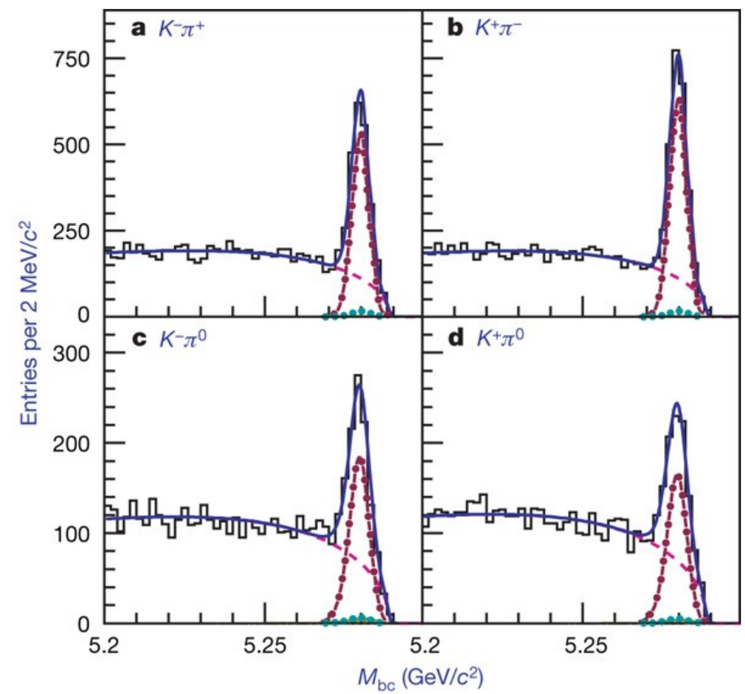
3.5σ evidence

Charmless hadronic B decays

- Direct CP violation in B→Kπ sensitive to γ
  - too many hadronic parameters ⇒ need theory input

NB. interesting deviation from naïve expectation

Belle Nature 452 (2008) 332

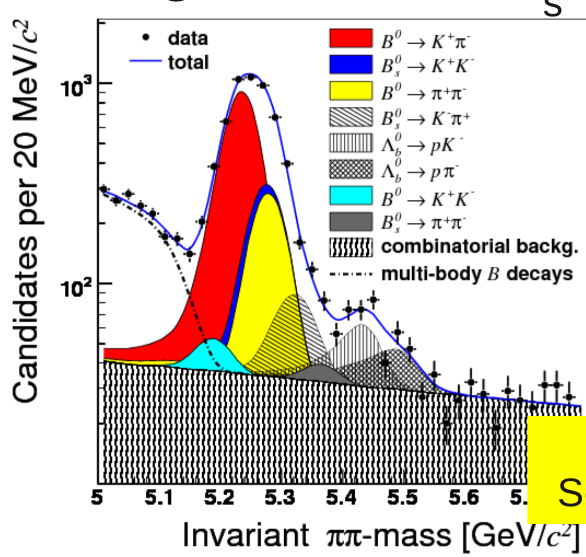


"Kπ puzzle"

$$A_{CP}(K^-\pi^+)=(-9.8^{+1.2}_{-1.1})\% \quad A_{CP}(K^-\pi^0)=(5.0\pm2.5)\%$$
$$\Delta(A_{CP})=(-14.8\pm2.8)\%$$

HFAG averages
BABAR PRD 76 (2007) 091102 & arXiv:0807.4226; also CDF

- Gaining knowledge also on B_s→hh

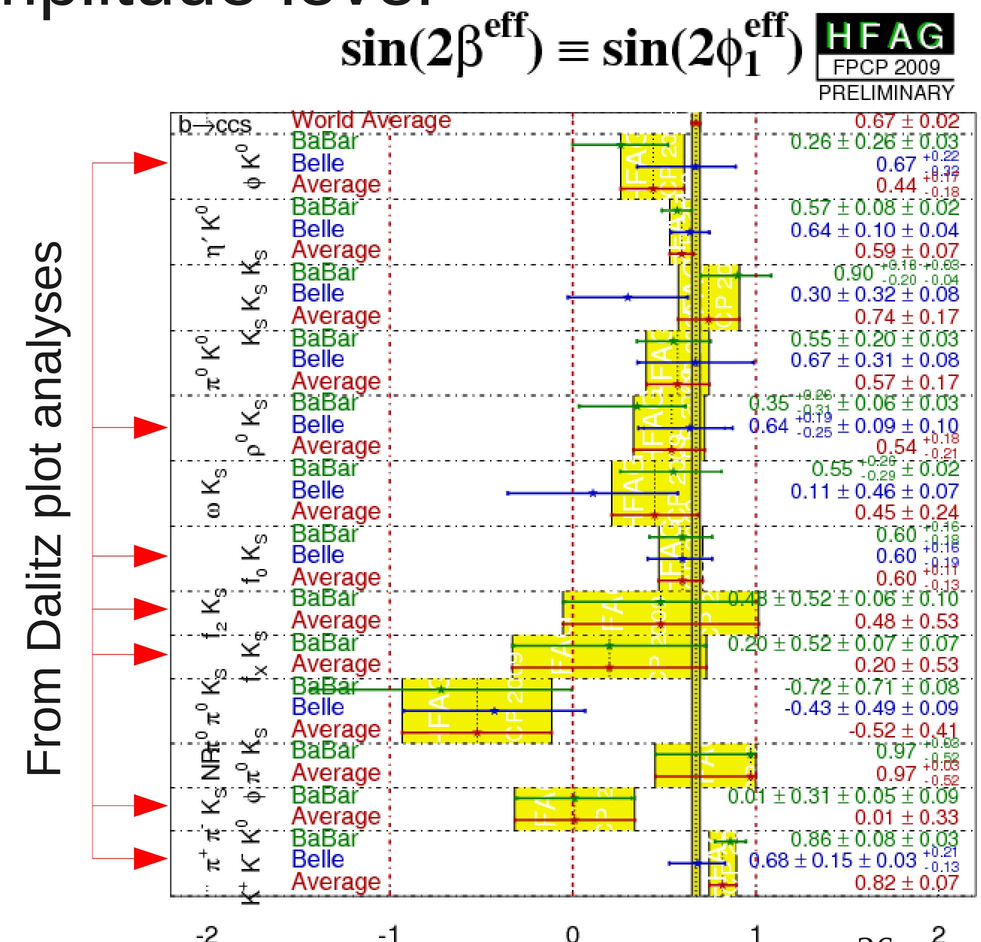


CDF PRL 103 (2009) 031801
See also Belle: R.Louvot at EPS 2009

Charmless hadronic B decays Dalitz plot analyses

- Dalitz analyses measure both magnitude and phases, ie. probe dynamics at the amplitude level
- Time-dependent analyses
  - $B \rightarrow K_S\pi^+\pi^-$, $B \rightarrow K_S K^+K^-$
  - additional sensitivity to β
- Interference of K*π bands
  - Various $B \rightarrow K\pi\pi$ channels
  - additional sensitivity to γ

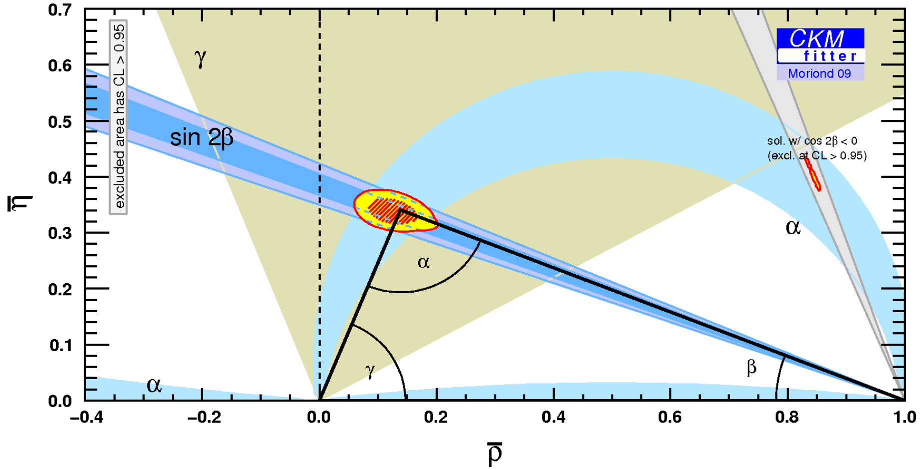
BABAR arXiv:0905.3615
Belle PRD 79 (2009) 072004



No smoking gun for difference between $b \rightarrow ccs$ and $b \rightarrow qqs$

Prospects for Unitarity Triangle angles

http://ckmfitter.in2p3.fr/



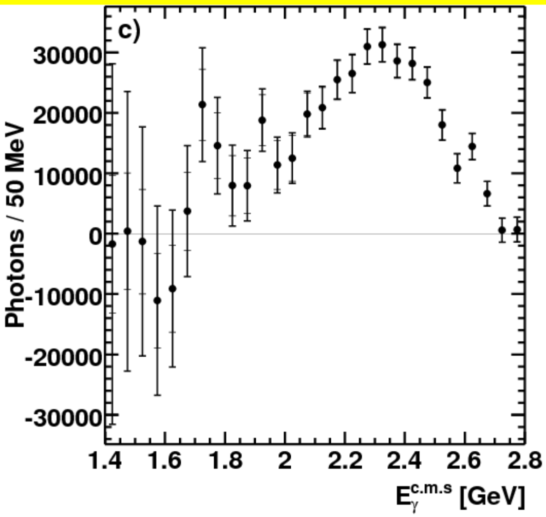
- Refine understanding of α
  - $B^+ \to \rho^+ \rho^0$ from Belle
- Improve γ measurement
  - good prospects for LHCb
- Resolve Kπ puzzle
  - need better $K_S \pi^0$ measurement: Belle2 & SuperB
- Improve $B_s \to hh$ measurements
  - more to come from CDF; then LHCb (plus e^+e^- Υ(5S) data)
- Charmless hadronic B decay Dalitz plot analyses
  - CDF, LHCb, Belle2, SuperB

Rare B Decays

- A wide range of probes of new physics

b→sγ photon energy spectrum

Belle arXiv:0907.1384 [hep-ex]

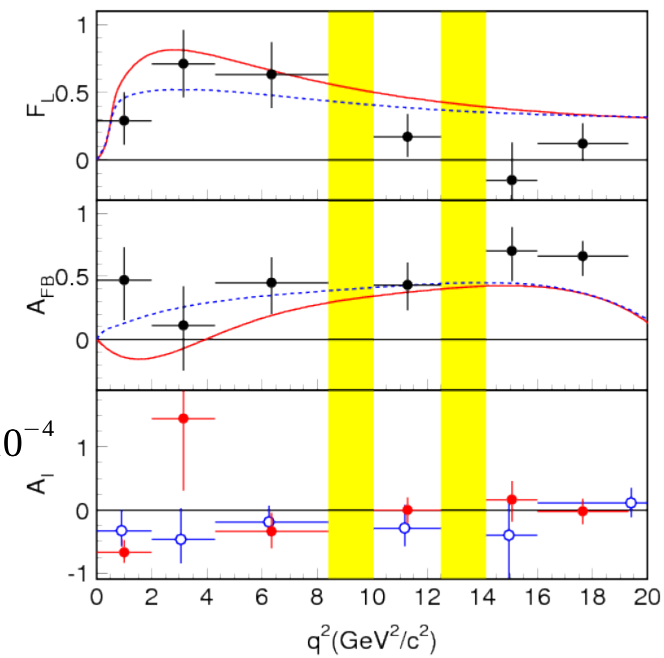


$$B(B\to X_s\gamma)_{E_\gamma>1.7\,GeV}=(3.45\pm0.15\pm0.40)\times10^{-4}$$

consistent with the SM prediction

kinematic distributions in B→K*ll

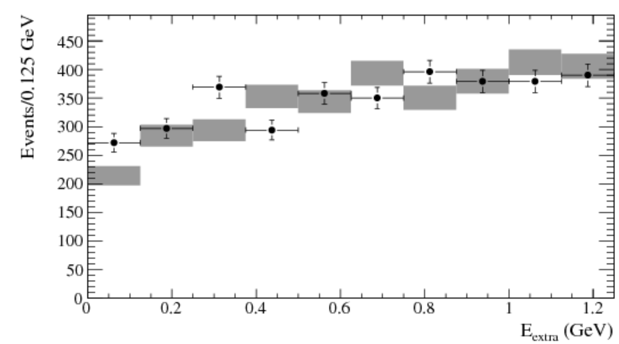
Belle arXiv:0907.1384 [hep-ex]
See also BABAR PRD79 (2009) 031102(R)



Hints of discrepancies with the SM?

rate of B→τν decay

BaBar arXiv:0809.4027 [hep-ex]
See also BABAR PRD 77 (2008) 011107
Belle 0809.3834 [hep-ex] &
PRL 97 (2006) 251802



World average

B(B→τν) = (173 ± 35) x 10^{-6}

Consistent with (1σ above) SM prediction

T.Iijima at LP'09

Rare B Decays: $B_s \rightarrow \mu\mu$

- A potential new physics discovery channel

CDF Public Note 9892

New upper limits from CDF (3.7/fb):

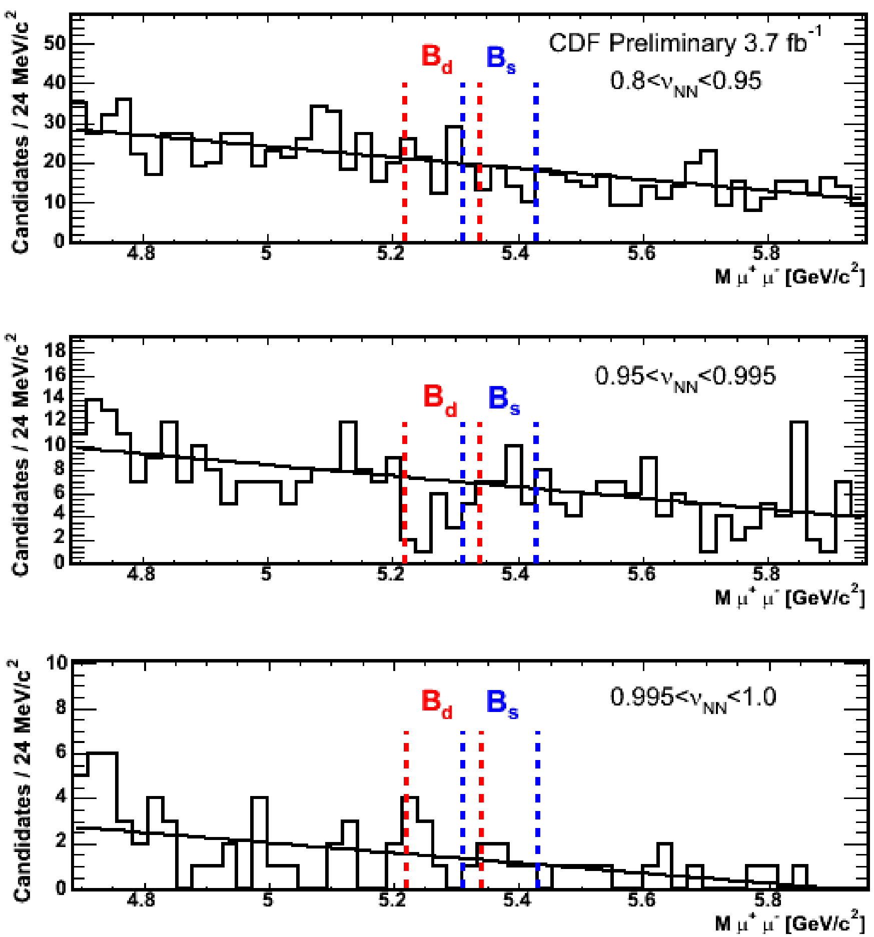
$\mathcal{B}(B_s \rightarrow \mu\mu) < 4.3 \times 10^{-8}$ @95% CL

$\mathcal{B}(B_d \rightarrow \mu\mu) < 7.6 \times 10^{-9}$ @95% CL

Still some way above SM prediction

D0 CONF 5906

New expected upper limit from D0 (5/fb)

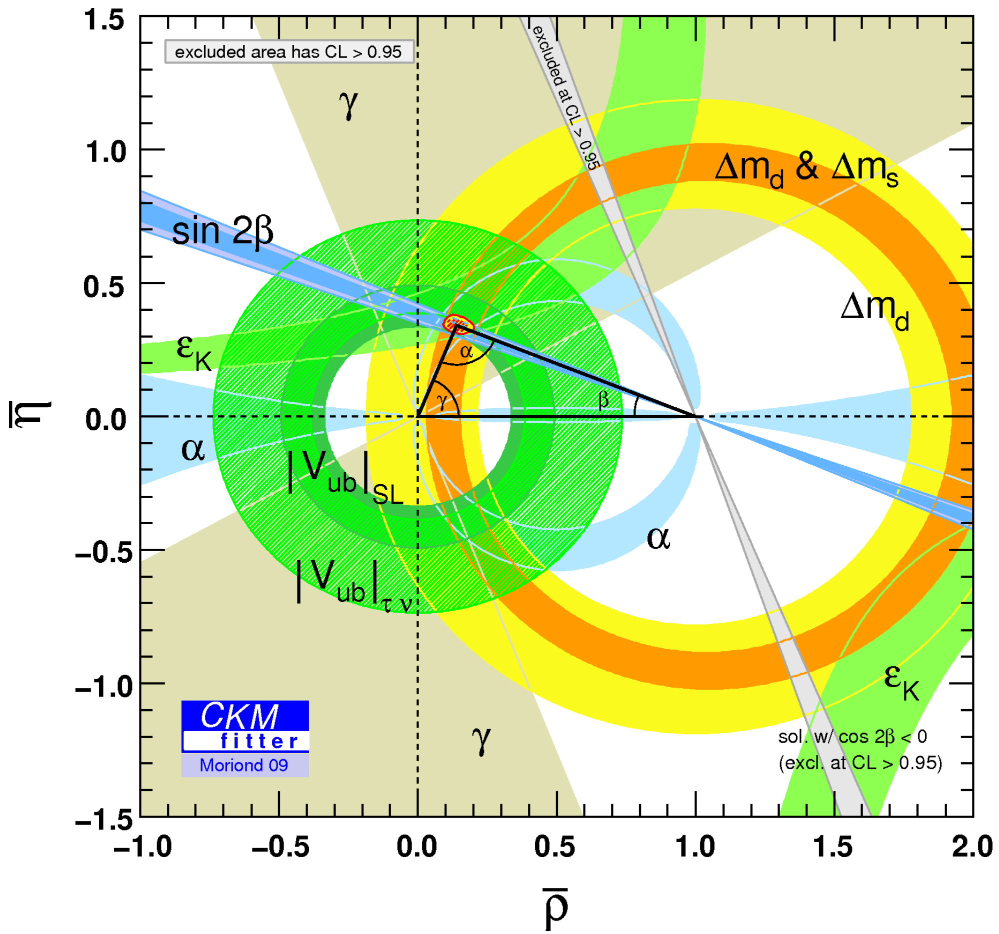


Prospects for rare B decays

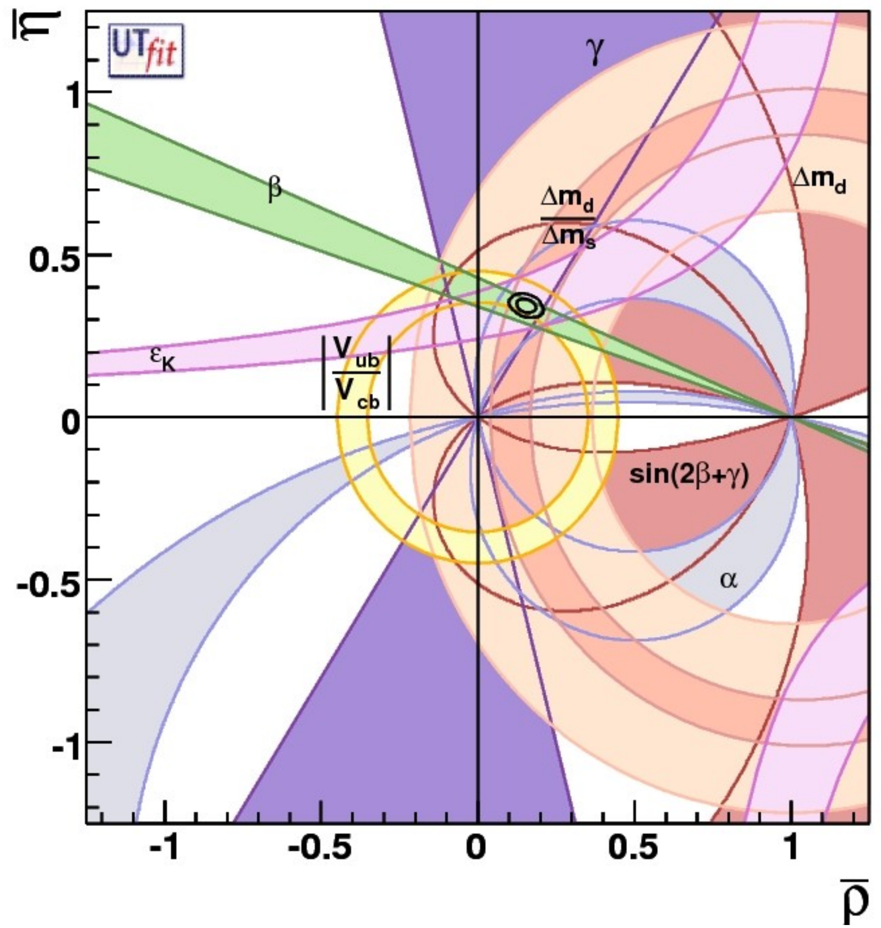
- Excellent prospects for LHCb for many important channels
  - $B_s \to \mu\mu$, $B \to K^*ll$, $B_s \to \varphi\gamma$, etc.
  - ATLAS and CMS can also contribute for some channels
- Many more important channels can only be studied in e^+e^- environment : Belle2 & SuperB
  - $B \to \tau\nu$, inclusive measurements, $B \to K_S\pi^0\gamma$, $B \to K\nu\nu$, etc.

Putting it all together – Unitarity Triangle

http://ckmfitter.in2p3.fr/



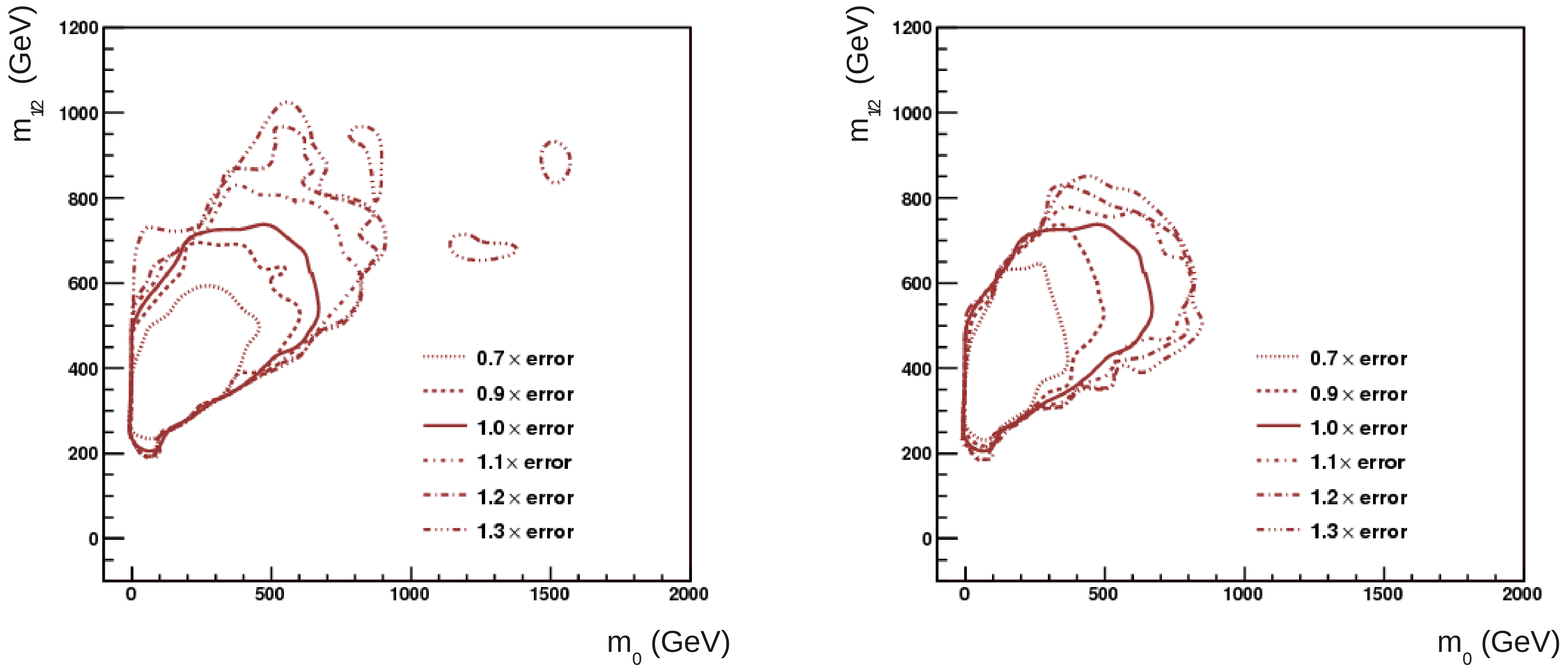
http://www.utfit.org/



Putting it all together – Constraints on New Physics

Constraints on CMSSM parameter space including flavour observables

O.Buchmueller *et al.*, JHEP 0809:117,2008



Effects of varying the uncertainty of (left) $(g\text{-}2)_\mu$ and (right) $B(b\rightarrow s\gamma)$

N.B. Not all latest data is included

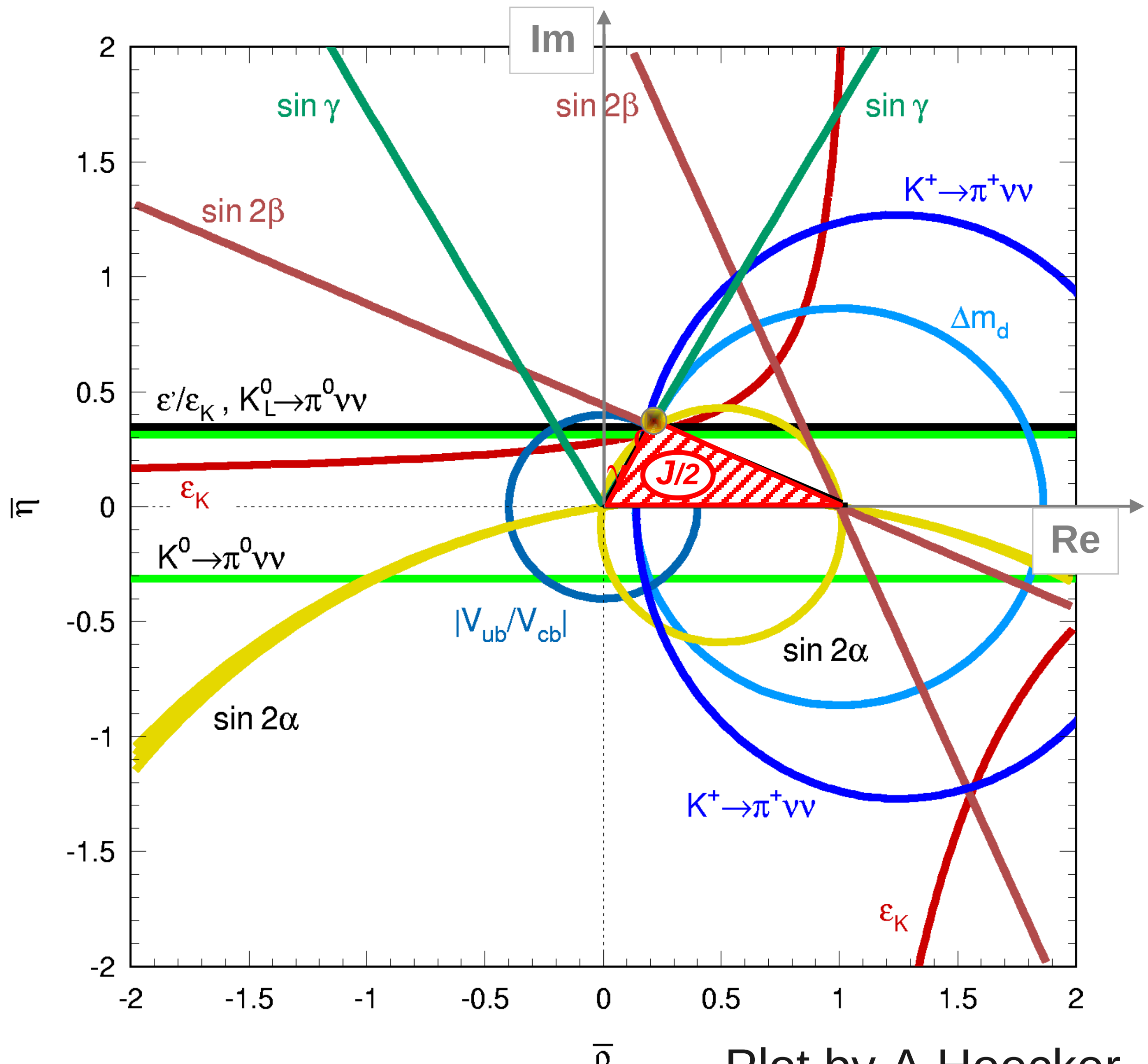
Summary

- Many, many new results continue to appear
- Is new physics running out of hiding places?
  - Most significant discrepancy with the Standard Model is in $(g\text{-}2)_\mu$ – now 3.1σ
  - Several other hints around 2σ
- Future prospects for the field look good
  - LHCb will pin down many of the remaining poorly known sectors ... an upgrade will fully exploit potential
  - New dedicated experiments for muons, kaons, charm
  - Super flavour factories for B, tau, charm

Projects in Europe, USA, Asia: a worldwide programme

Back-up Material

All measurements must agree

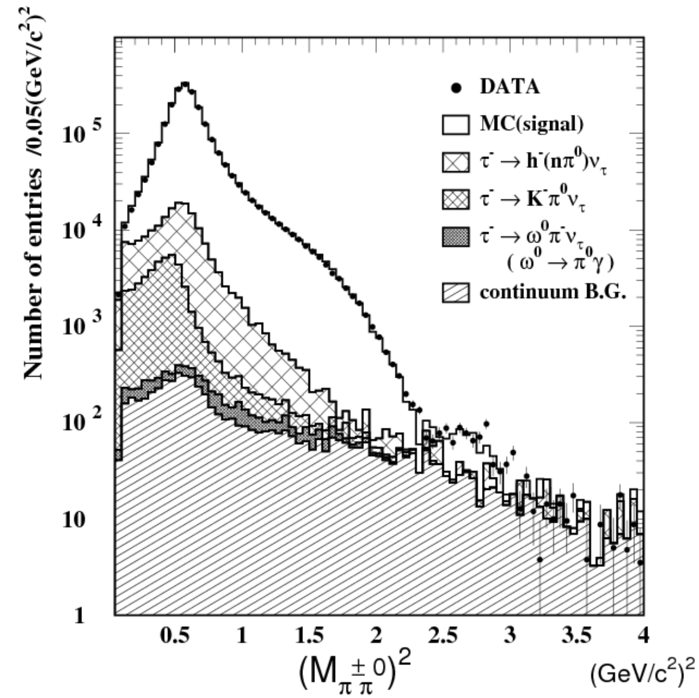


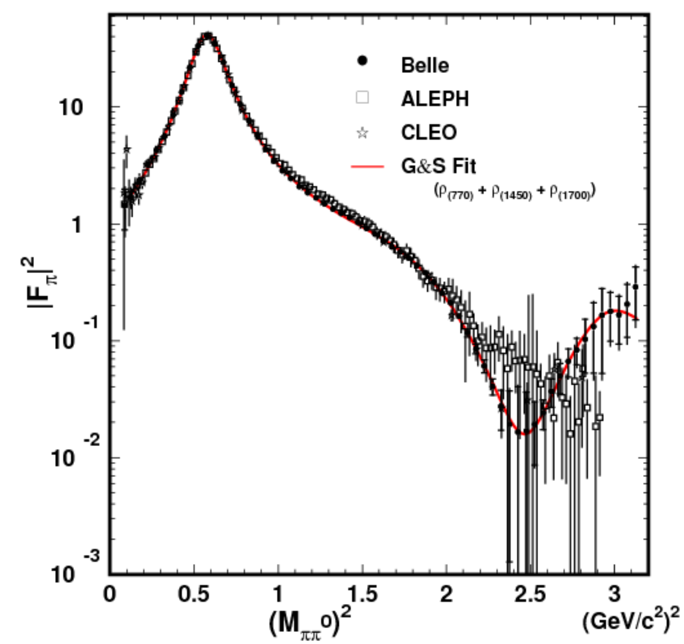
Plot by A.Hoecker

New $\tau\rightarrow\pi\pi^0\nu$ Results

- Belle
  - $e^+e^-\rightarrow\tau^+\tau^-$ near the Υ(4S)
  - 72.2/fb

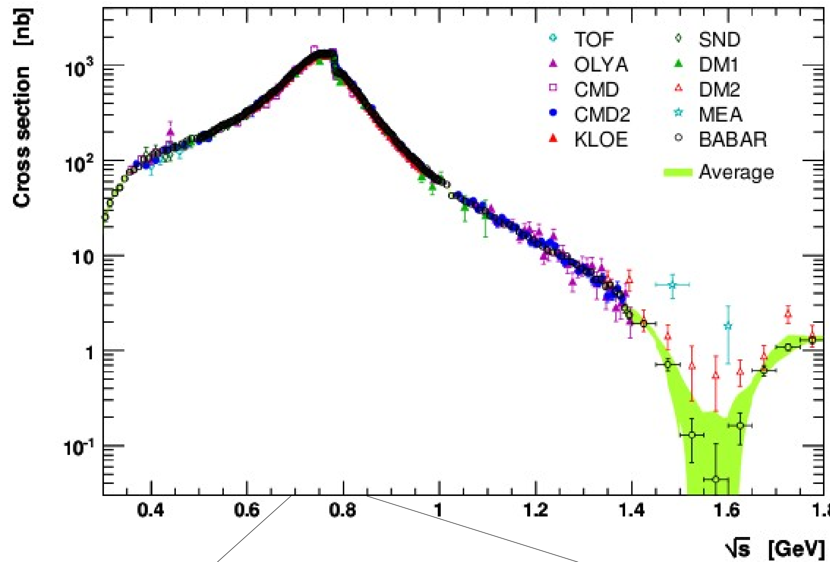
PRD 78 (2008) 072006

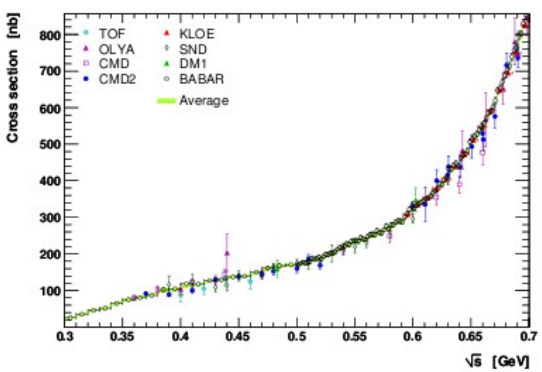


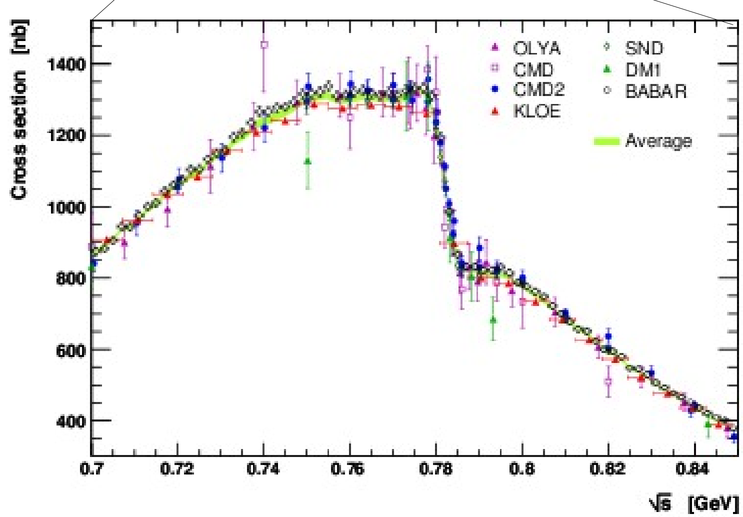


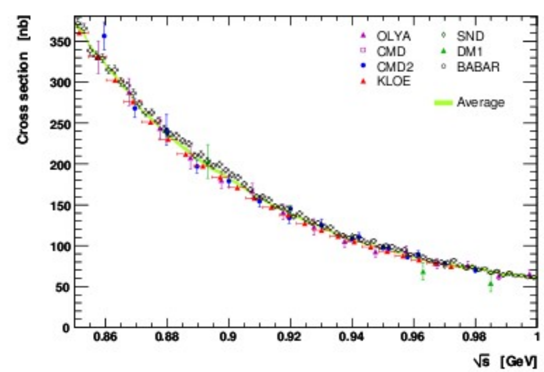
New $e^+e^- \rightarrow \pi^+\pi^-(\gamma)$ Results: ρ Region

M.Davier *et al.*,
arXiv:0908.4300 [hep-ph]









More Lepton Flavour Violating τ Decays

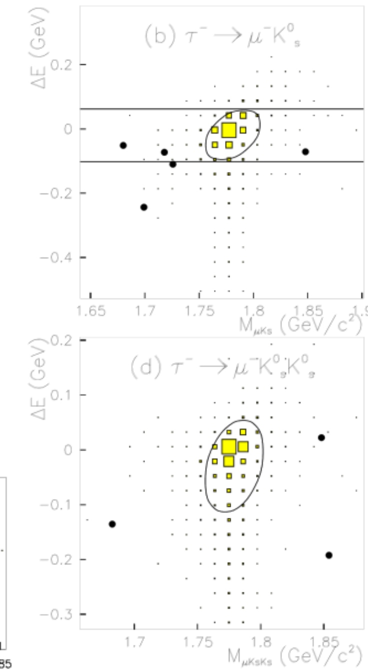
Y.Miyazaki at EPS2009
(see also BABAR PRD 79 (2009) 012004)

$\tau \to lK_S$ and $\tau \to lK_SK_S$ at Belle

Data sample of 671/fb (≈ 6.1 x 10^8 τ pairs)

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	s_{90}	$\mathcal{B}$ ($\times 10^{-8}$)
$\tau^- \to e^- K_S^0$	10.2	0.18±0.18	6.6	0	2.25	2.6
$\tau^- \to \mu^- K_S^0$	10.7	0.35±0.21	6.8	0	2.10	2.3
$\tau^- \to e^- K_S^0 K_S^0$	5.82	0.07±0.07	11.2	0	2.44	7.1
$\tau^- \to \mu^- K_S^0 K_S^0$	5.08	0.12±0.08	11.3	0	2.40	8.0

90% C.L. upper limits

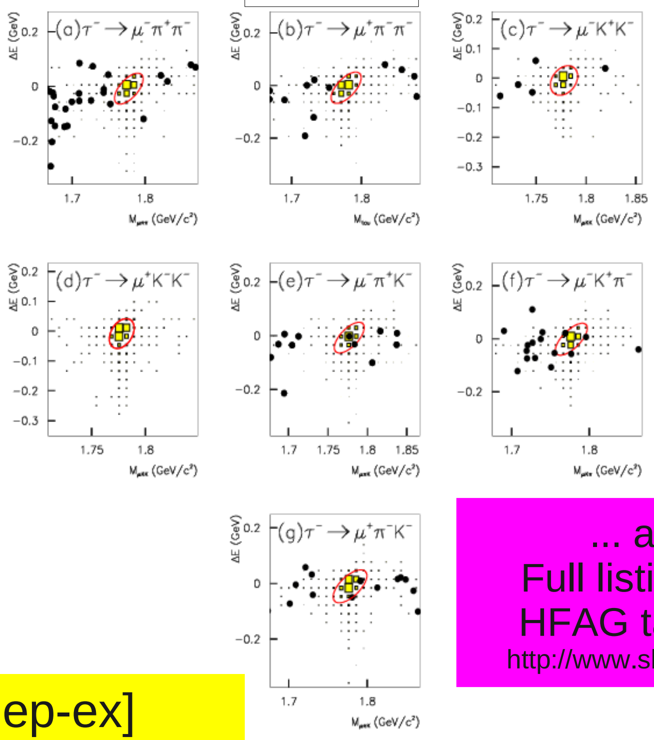


$\tau \to lhh$ at Belle

Data sample of 671/fb (≈ 6.1 x 10^8 τ pairs)

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	s_{90}	$\mathcal{B}$ (10^{-8})
$\tau^- \to \mu^-\pi^+\pi^-$	3.69	1.12 ± 0.38	5.9	0	1.53	3.3
$\tau^- \to \mu^+\pi^-\pi^-$	3.84	0.73 ± 0.25	5.9	0	1.77	3.7
$\tau^- \to e^-\pi^+\pi^-$	3.99	0.34 ± 0.15	6.0	0	2.15	4.4
$\tau^- \to e^+\pi^-\pi^-$	3.91	0.10 ± 0.07	6.0	1	4.21	8.8
$\tau^- \to \mu^-K^+K^-$	2.40	0.52 ± 0.23	6.7	0	1.92	6.8
$\tau^- \to \mu^+K^-K^-$	2.07	0.00 ± 0.06	6.8	0	2.46	9.6
$\tau^- \to e^-K^+K^-$	3.50	0.11 ± 0.08	6.5	0	2.35	5.4
$\tau^- \to e^+K^-K^-$	3.28	0.05 ± 0.05	6.6	0	2.43	6.0
$\tau^- \to \mu^-\pi^+K^-$	2.63	0.67 ± 0.14	6.3	2	5.05	16
$\tau^- \to e^-\pi^+K^-$	3.02	0.33 ± 0.19	6.4	0	2.12	5.8
$\tau^- \to \mu^-K^+\pi^-$	2.60	1.04 ± 0.32	6.3	1	3.34	10
$\tau^- \to e^-K^+\pi^-$	2.98	0.57 ± 0.19	6.4	0	1.90	5.2
$\tau^- \to \mu^+K^-\pi^-$	2.61	1.37 ± 0.21	6.3	1	3.16	9.4
$\tau^- \to e^+K^-\pi^-$	2.83	0.10 ± 0.07	6.4	0	2.40	6.7

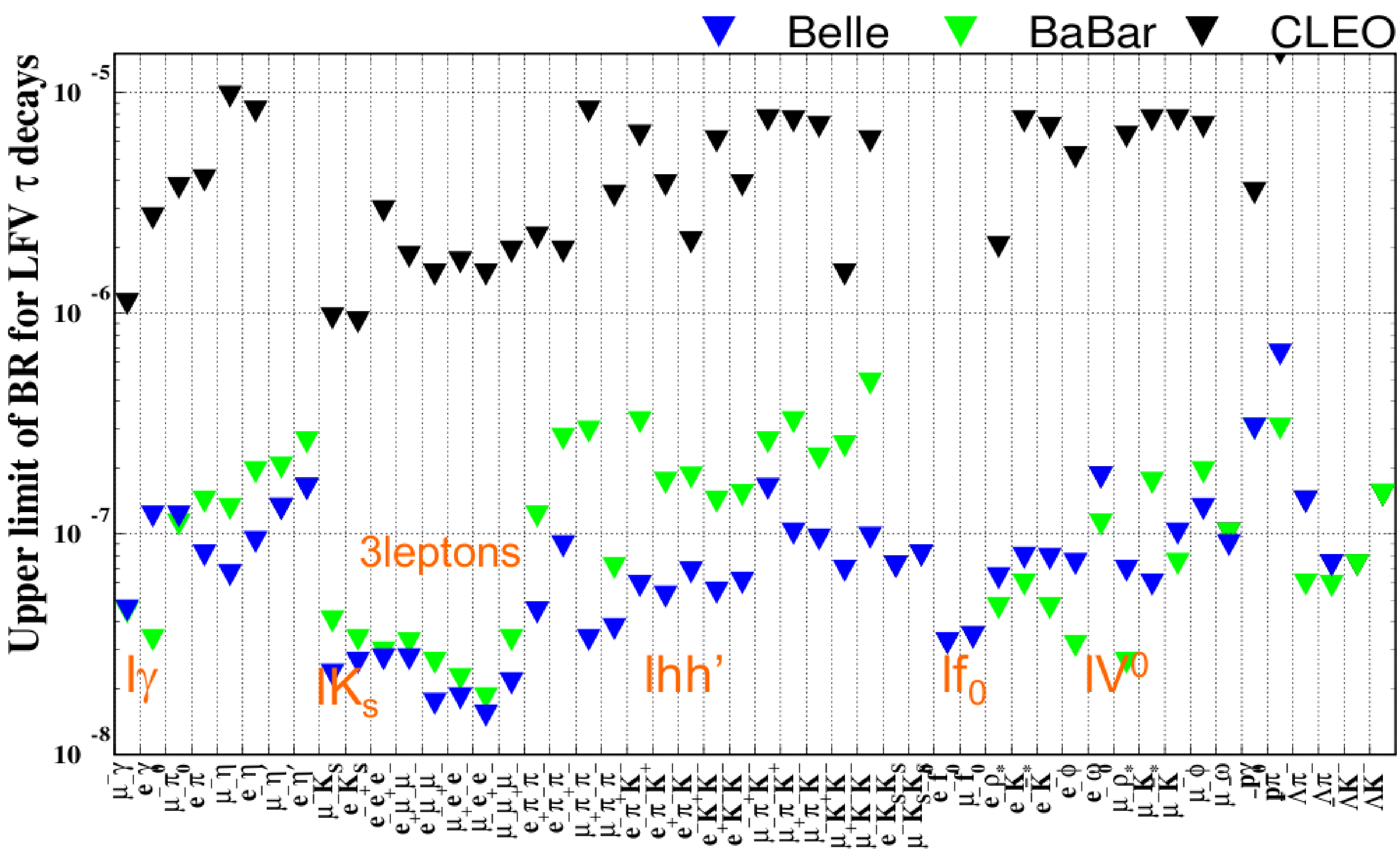
90% C.L. upper limits



... and many more!
Full listings available from
HFAG tau decay subgroup
http://www.slac.stanford.edu/xorg/hfag/tau

arXiv:0908.3156 [hep-ex]
(see also BABAR PRL 95 (2005) 191801)

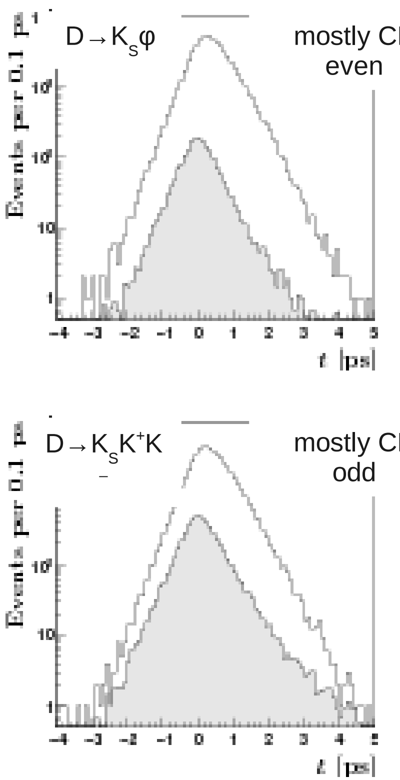
Compendium of τ LFV Results



Charm mixing and CP violation

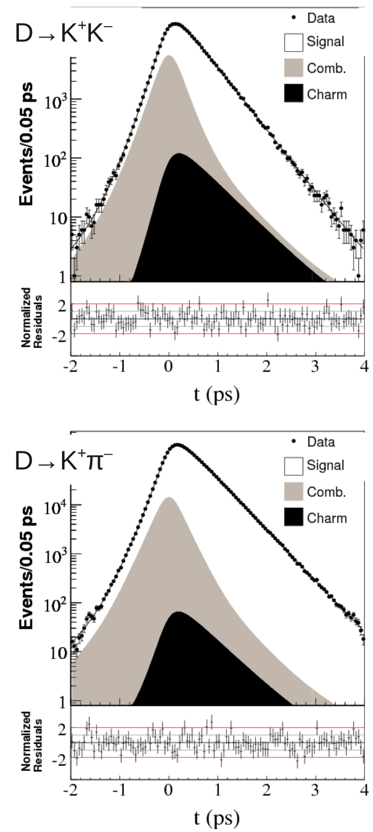
- Results from BABAR, Belle, CDF, CLEO

Belle arXiv:0905.4185 [hep-ex]



y_{CP} = (0.11 ± 0.61 (stat) ± 0.52 (syst))%

BABAR arXiv:0908.0761 [hep-ex]



CP even

almost flavour-specific

y_{CP} = (1.12 ± 0.26 (stat) ± 0.22 (syst))%

y_{CP} ~ ΔΓ and modified by CP violation in mixing

CKM Matrix – Magnitudes

semileptonic / leptonic kaon decays
hadronic tau decays

superallowed $0^+ \rightarrow 0^+$ β decays

semileptonic / leptonic B decays

$$\begin{pmatrix} 0.97418 \pm 0.00027 & 0.2255 \pm 0.0019 & (3.93 \pm 0.36) \times 10^{-3} \\ 0.230 \pm 0.011 & 1.04 \pm 0.06 & (41.2 \pm 1.1) \times 10^{-3} \\ (8.1 \pm 0.6) \times 10^{-3} & (38.7 \pm 2.3) \times 10^{-3} & > 0.74 \end{pmatrix}$$

semileptonic charm decays
charm production in neutrino beams

semileptonic B decays

semileptonic / leptonic charm decays

B_d oscillations

B_s oscillations

single top production

from loop processes
(no tree-level determinations)

Testing CKM Unitarity

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$
$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1$$
$$|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$$

$$|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 1 \qquad |V_{us}|^2 + |V_{cs}|^2 + |V_{ts}|^2 = 1 \qquad |V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1$$

Most precise test

PDG 2008 numbers

For further improvement need

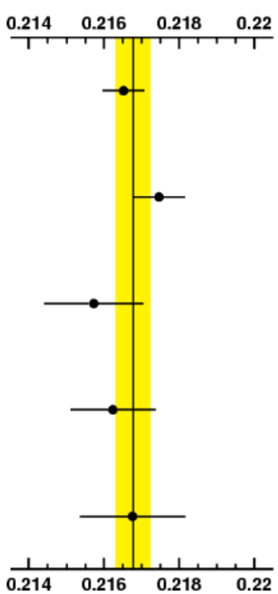
- better $|V_{ud}|^2$ measurement 0.94902 ± 0.00053
- better $|V_{us}|^2$ measurement 0.05085 ± 0.00085
- $|V_{ub}|^2$ contribution is negligible 0.000015 ± 0.000003

New survey of superallowed $0^+ \rightarrow 0^+$ β decays PRC 79 (2009) 055502

$|V_{us}|$ from kaon decays

- Measurements from KLOE, KTeV, BNL E685, ISTRA+, NA48
- Combination by flavianet

M.Palutan at Kaon'09
see also http://ific.uv.es/flavianet/



Approx. contrib. to % err from:

	$\lvert V_{us}\rvert f_+(0)$	% err	BR	τ	Δ	Int
K_Le3	**0.21652(56)**	**0.25**	0.11	**0.20**	0.11	0.10
$K_L\mu3$	**0.21746(69)**	**0.32**	0.17	**0.19**	0.11	0.15
K_Se3	**0.21572(132)**	**0.61**	**0.60**	0.03	0.11	0.10
$K^{\pm}e3$	**0.21624(113)**	**0.52**	**0.31**	0.06	**0.41**	0.09
$K^{\pm}\mu3$	**0.21676(141)**	**0.65**	**0.48**	0.06	**0.41**	0.15

Average: $|V_{us}| f_+(0)$ = 0.21660(47) χ^2/ndf = 3.03/4 (55%)

$f_+(0)$ = 0.9644(49) from RBC/UKQCD '07

Kl3 average: $|V_{us}|$ = 0.2246(12)

$B_s \rightarrow \varphi\varphi$

- New hadronic $b \rightarrow s$ penguin dominated decay mode
- Approximately as clean theoretically as $B \rightarrow \varphi K_S$

CDF preliminary
See D.Tonelli at Beauty'09