Flavour Physics & CP Violation
Lecture 2 of 4

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Contents

- Part 1
  - What is flavour physics & why is it interesting?
- Part 2
  - What do we know from previous experiments?
- Part 3
  - What do we hope to learn from current experiments?
- Part 4
  - The future of flavour physics

Flavour for new physics discoveries

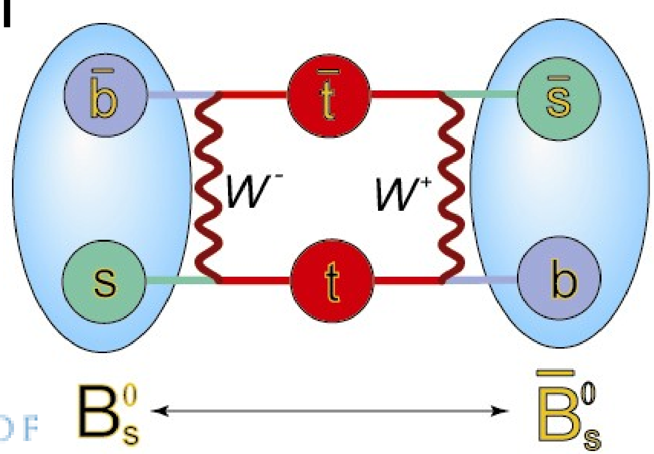
A lesson from history

- New physics shows up at precision frontier before energy frontier
  - GIM mechanism before discovery of charm
  - CP violation / CKM before discovery of bottom & top
  - Neutral currents before discovery of Z
- Particularly sensitive – loop processes
  - Standard Model contributions suppressed / absent
  - flavour changing neutral currents (rare decays)
  - CP violation
  - lepton flavour / number violation / lepton universality

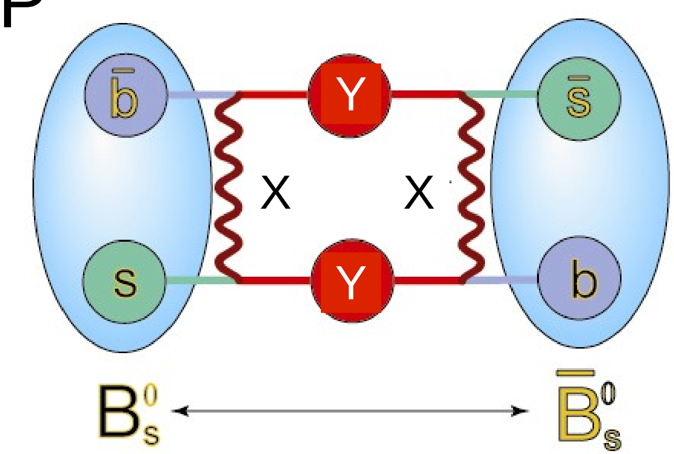
Loop diagrams for discovery

- Contributions from virtual particles in loops allow to probe far beyond the energy frontier
- History shows this approach to be a powerful discovery tool
- Interplay with high-p_T experiments:
  - NP discovered: probe the couplings
  - NP not discovered: explore high energy parameter space
- NP contributions to tree-level processes also possible in some models

SM



NP



The GIM mechanism

$K^+ \to \mu^+\nu_\mu$ & $\pi^0\mu^+\nu_\mu$ so why not $K^0 \to \mu^+\mu^-$ & $\pi^0\mu^+\mu^-$?

- GIM (Glashow, Iliopoulos, Maiani) mechanism (1970)

  no tree level flavour changing neutral currents

  suppression of FCNC via loops

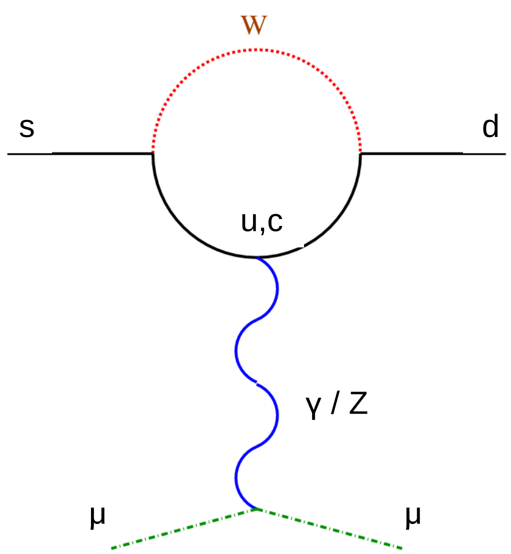
- Requires that quarks come in pairs (predicting charm)

$$A = V_{us}V_{ud}^* f(m_u/m_W) + V_{cs}V_{cd}^* f(m_c/m_W)$$

$$\text{2x2 unitarity: } V_{us}V_{ud}^* + V_{cs}V_{cd}^* = 0$$

$$m_u, m_c < m_W \therefore f(m_u/m_W) \sim f(m_c/m_W) \therefore A \sim 0$$

$$\text{kaon mixing} \Rightarrow \text{predict } m_c$$



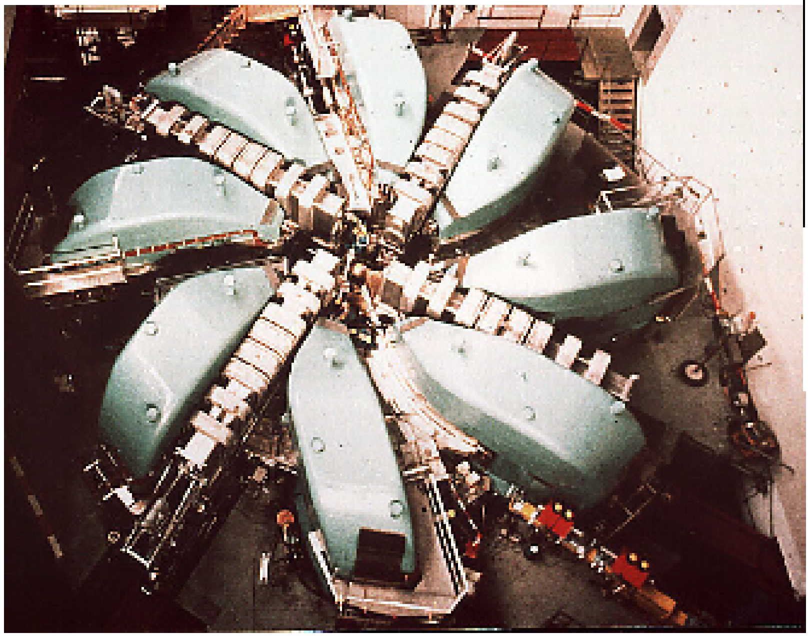
Lepton flavour violation

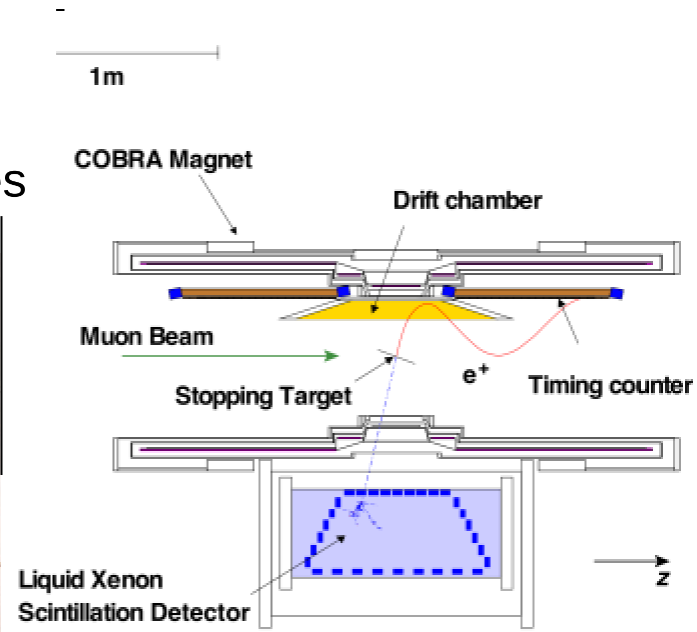
- Why do we not observe the decay $\mu \rightarrow e\gamma$?
  - exact (but accidental) lepton flavour conservation in the SM with $m_\nu = 0$
  - SM loop contributions suppressed by $(m_\nu/m_W)^4$
  - but new physics models tend to induce larger contributions
    - unsuppressed loop contributions
    - generic argument, true in most common models

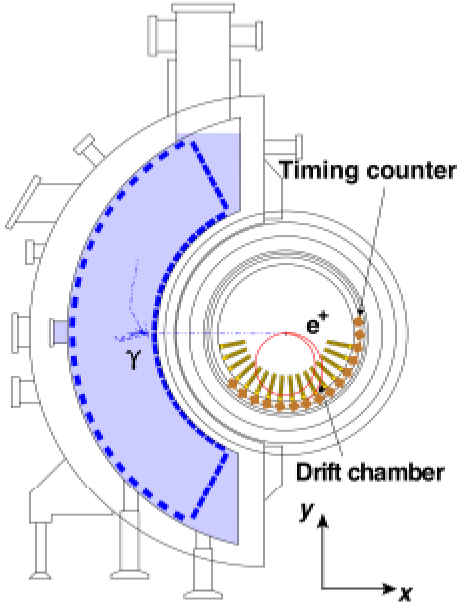
The muon to electron gamma (MEG) experiment at PSI

$\mu^+ \to e^+\gamma$

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

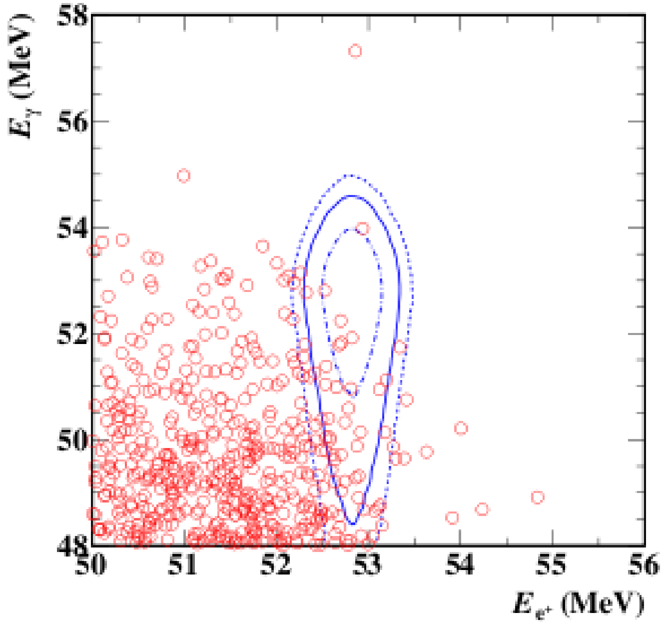


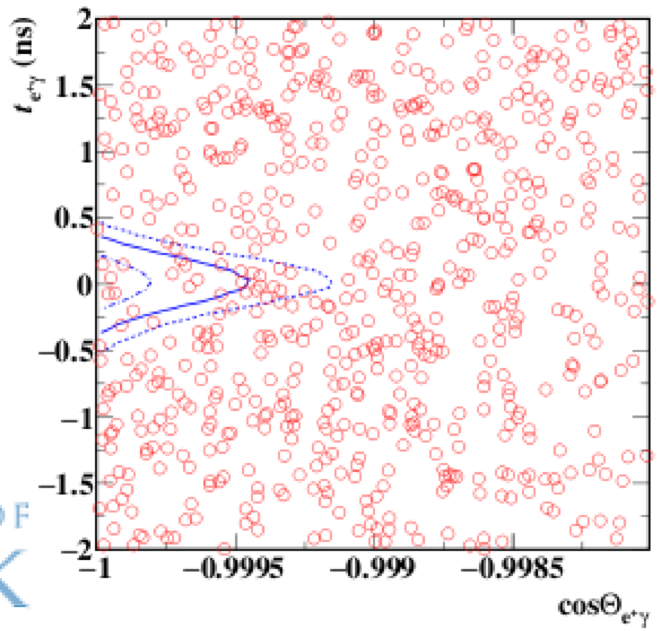


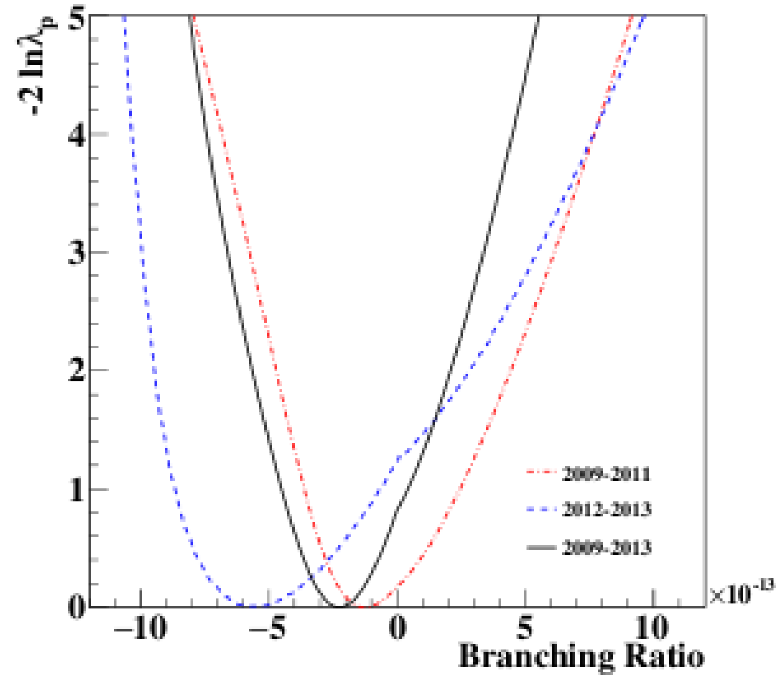


NPB 834 (2010) 1

MEG results



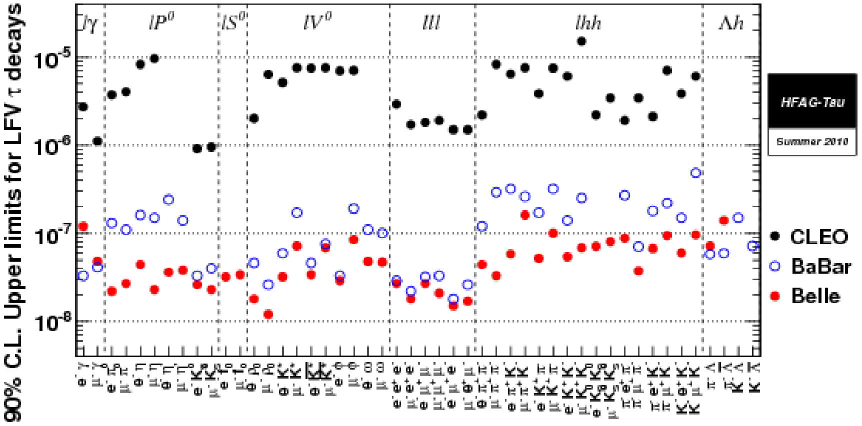




$B(\mu^+ \rightarrow e^+\gamma) < 4.2\ 10^{-13}$ @ 90% CL
arXiv:1605.05081

Prospects for Lepton Flavour Violation

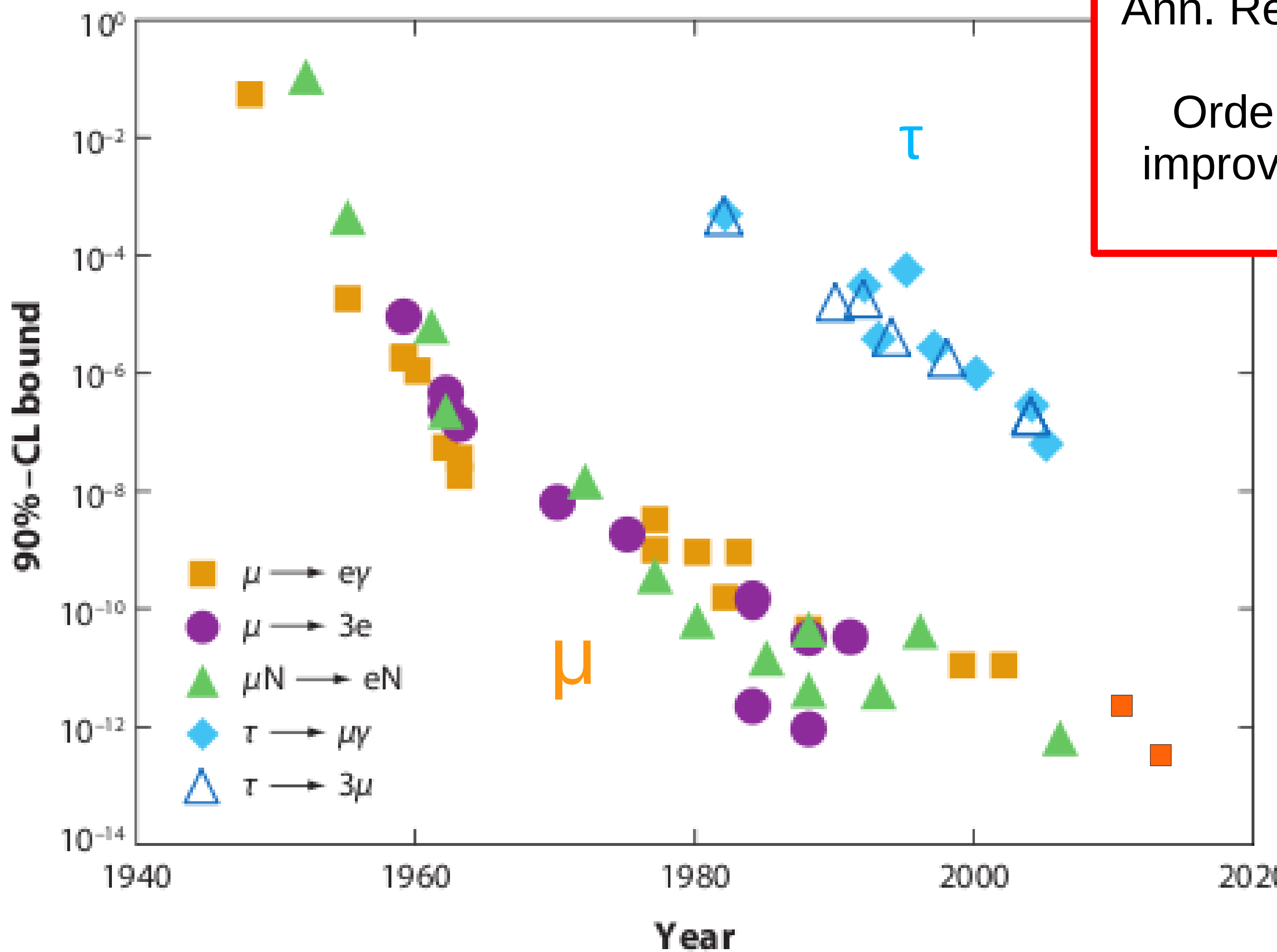
- An upgrade of MEG is planned
- New generations of μ – e conversion experiments
  - COMET at J-PARC, followed by PRISM/PRIME
  - mu2e at FNAL, followed by Project X
  - Potential improvements of $O(10^4)$ – $O(10^6)$ in sensitivities!
- τ LFV a priority for next generation e^+e^- flavour factories
  - 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 $\tau \rightarrow \mu\mu\mu$



Charged lepton flavour violation

Modified from
Ann. Rev. 58 (2008) 315

Order of magnitude improvement every ~8 years



Well worth pushing down a few more orders of magnitude

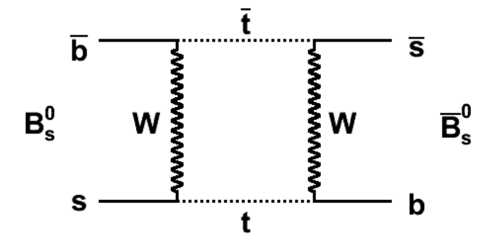
Searching for NP in mixing loops

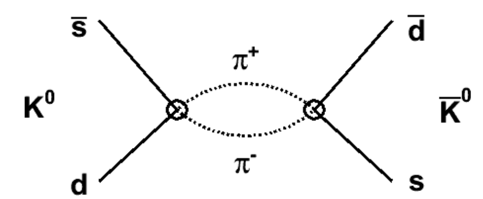
Various types of mixing

- quark mixing (CKM)
- flavour SU(2)
  - $u\bar{u}$ and $d\bar{d}$ states mix to form π^0 and η mesons
    - members of isospin triplet and singlet, respectively
- flavour SU(3)
  - η and η' mix
    - identical quantum numbers therefore allowed
- neutral meson mixing
  - flavours differ … but flavour is not conserved

Neutral meson oscillations

- We have flavour eigenstates M^0 and $\overline{M}^0$
  - M^0 can be K^0 ($\bar{s}d$), D^0 ($c\bar{u}$), B_d^0 ($\bar{b}d$) or B_s^0 ($\bar{b}s$)
- These can mix into each other
  - via short-distance or long-distance processes





- Time-dependent Schrödinger eqn.

$$i\frac{\partial}{\partial t}\begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix} = H\begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix} = \left(M - \frac{i}{2}\Gamma \right)\begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix}$$

  - H is Hamiltonian; M and Γ are 2x2 Hermitian matrices
- CPT theorem: $M_{11} = M_{22}$ & $\Gamma_{11} = \Gamma_{22}$

particle and antiparticle have equal masses and lifetimes

Solving the Schrödinger equation

- Physical states: eigenstates of effective Hamiltonian

$$M_{S,L} = p\, M^0 \pm q\, \bar{M}^0$$

p & q complex coefficients that satisfy $|p|^2 + |q|^2 = 1$

label as either S,L (short-, long-lived) or L,H (light, heavy) depending on values of Δm & $\Delta\Gamma$ (labels 1,2 usually reserved for CP eigenstates)

  - CP conserved if physical states = CP eigenstates ($|q/p| = 1$)

- Eigenvalues

$$\lambda_{S,L} = m_{S,L} - \tfrac{1}{2}i\Gamma_{S,L} = (M_{11} - \tfrac{1}{2}i\Gamma_{11}) \pm (q/p)(M_{12} - \tfrac{1}{2}i\Gamma_{12})$$

$$\Delta m = m_L - m_S \qquad \Delta\Gamma = \Gamma_S - \Gamma_L$$

$$(\Delta m)^2 - \tfrac{1}{4}(\Delta\Gamma)^2 = 4(|M_{12}|^2 + \tfrac{1}{4}|\Gamma_{12}|^2)$$

$$\Delta m \Delta\Gamma = 4\mathrm{Re}(M_{12}\Gamma_{12}^*)$$

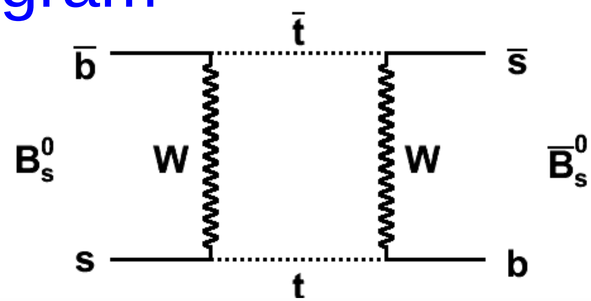
$$(q/p)^2 = (M_{12}^* - \tfrac{1}{2}i\Gamma_{12}^*)/(M_{12} - \tfrac{1}{2}i\Gamma_{12})$$

Simplistic picture of mixing parameters

- Δm: value depends on rate of mixing diagram
  - together with various other constants ...

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{tb}|^2 |V_{td}|^2$$

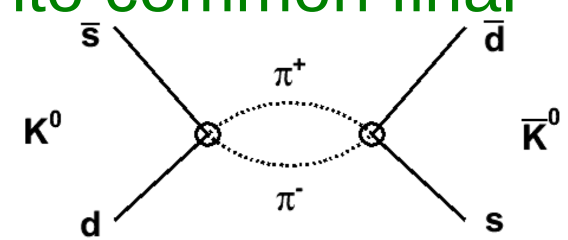
  - that can be made to cancel in ratios



remaining factors can be obtained from lattice QCD calculations

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

- ΔΓ: value depends on widths of decays into common final states (CP-eigenstates)
  - large for K^0, small for D^0 & B_d^0



- $q/p \approx 1$ if $\arg(\Gamma_{12}/M_{12}) \approx 0$ ($|q/p| \approx 1$ if $M_{12} \ll \Gamma_{12}$ or $M_{12} \gg \Gamma_{12}$)
  - CP violation in mixing when $|q/p| \neq 1$

$$\left(\epsilon = \frac{p-q}{p+q} \neq 0 \right)$$

Simplistic picture of mixing parameters

	Δm $(x = \Delta m/\Gamma)$	$\Delta\Gamma$ $(y = \Delta\Gamma/(2\Gamma)))$	$\lvert q/p\rvert$ $(a_{sl} \approx 1 - \lvert q/p\rvert^2)$
K^0	large ~ 500	$\sim$ maximal ~ 1	small $(3.32 \pm 0.06) \times 10^{-3}$
D^0	small $(0.63 \pm 0.19)\%$	small $(0.75 \pm 0.12)\%$	small $0.52\,^{+0.19}_{-0.24}$
B^0	medium 0.770 ± 0.008	small 0.008 ± 0.009	small -0.0003 ± 0.0021
B^0_s	large 26.49 ± 0.29	medium 0.075 ± 0.010	small -0.0109 ± 0.0040

well-measured only recently (see later)

More precise measurements needed (SM prediction well known)

Constraints on NP from mixing

- All measurements of Δm & ΔΓ consistent with SM
  - K^0, D^0, B_d^0 and B_s^0
- This means $|A_{NP}| < |A_{SM}|$ where $\mathcal{A}_{\rm SM}^{\Delta F=2} \approx \frac{G_F^2 m_t^2}{16\pi^2} (V_{ti}^* V_{tj})^2 \times \langle \overline{M} | (\overline{Q}_{Li} \gamma^\mu Q_{Lj})^2 | M \rangle \times F\left(\frac{M_W^2}{m_t^2}\right)$
- Express NP as perturbation to the SM Lagrangian
  - couplings c_i and scale $\Lambda > m_W$ $\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}(\text{SM fields})$
- For example, SM like (left-handed) operators $\Delta\mathcal{L}^{\Delta F=2} = \sum_{i\neq j} \frac{c_{ij}}{\Lambda^2} (\overline{Q}_{Li} \gamma^\mu Q_{Lj})^2$

Ann.Rev.Nucl.Part.Sci. 60 (2010) 355

Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Bounds on Λ in TeV ($c_{ij}=1$) Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Bounds on c_{ij} ($\Lambda = 1$ TeV) Im	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

Similar information pictorially

Operator	Bounds on Λ in TeV ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
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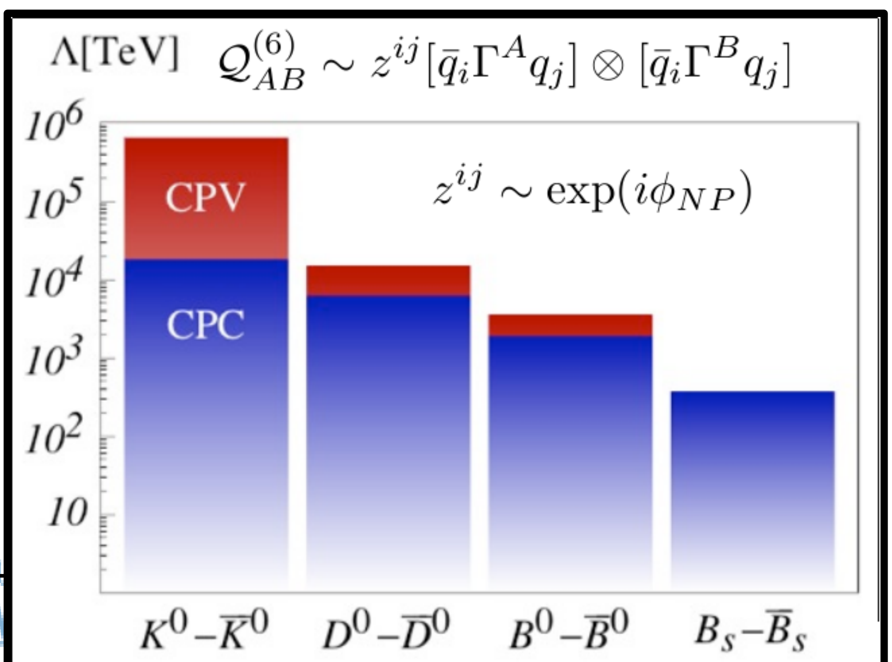
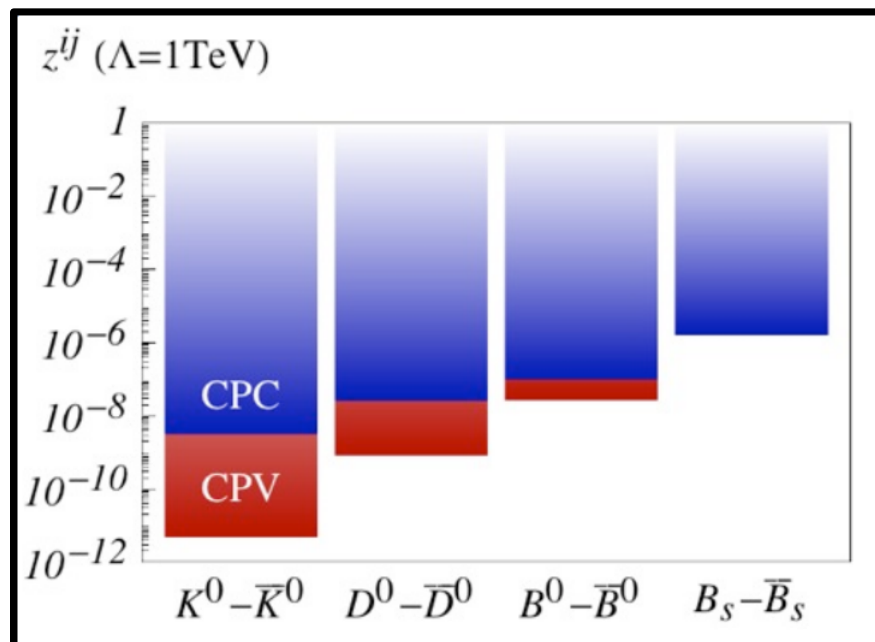
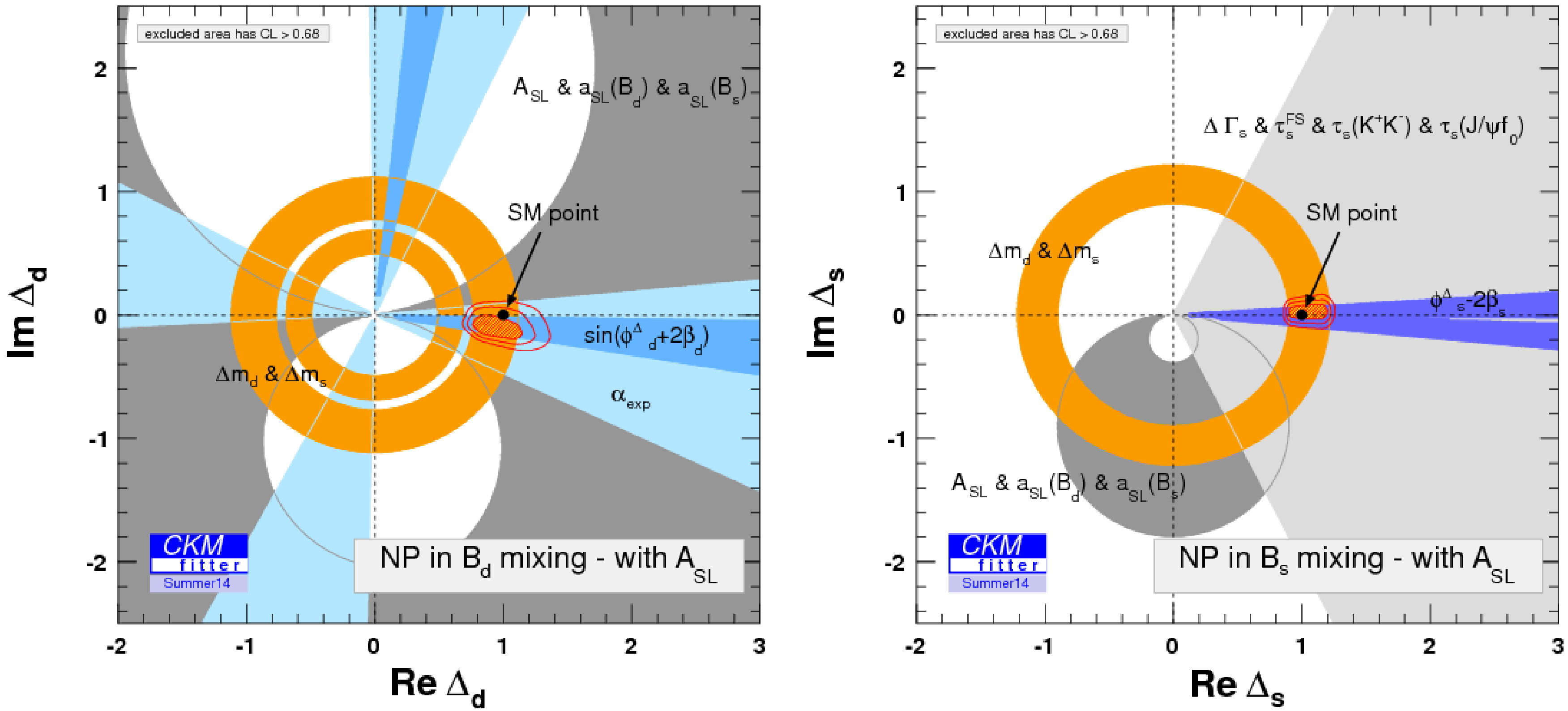
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}





Similar story – but including more (& more up-to-date) inputs, and in pictures



arXiv:1501.05013

New Physics Flavour Problem

- Limits on NP scale at least 100 TeV for generic couplings
  - model-independent argument, also for rare decays
- But we need NP at “the TeV scale” to solve the hierarchy problem (and to provide DM candidate, etc.)
- So we need NP flavour-changing couplings to be small
- Why?
  - minimal flavour violation?
    - perfect alignment of flavour violation in NP and SM
  - some other approximate symmetry?
  - flavour structure tells us about physics at very high scales
- There are still important observables that are not yet well-tested

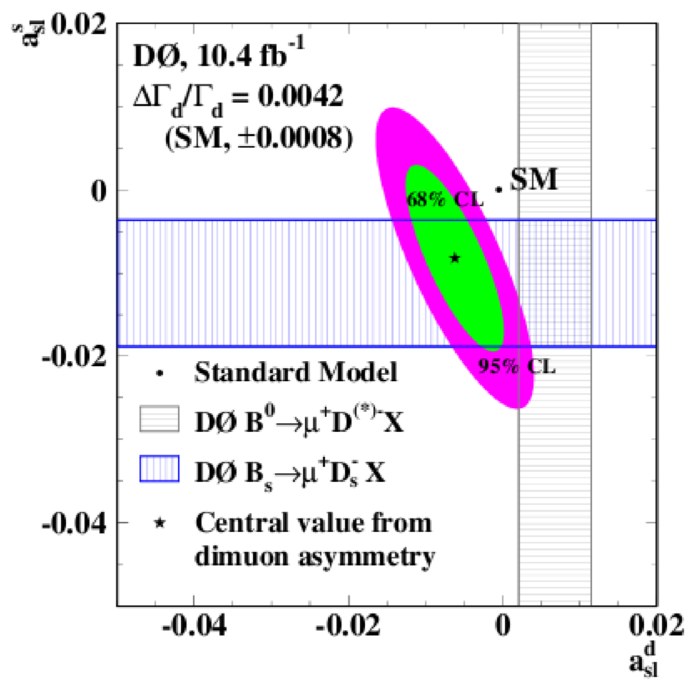
NPB 645 (2002) 155

Like-sign dimuon asymmetry

- Semileptonic decays are flavour-specific
- B mesons are produced in $B\bar{B}$ pairs
- Like-sign leptons arise if one of $B\bar{B}$ pair mixes before decaying
- If no CP violation in mixing N(++) = N(—)
- Inclusive measurement ↔ contributions from both B_d^0 and B_s^0
  - relative contributions from production rates, mixing probabilities & SL decay rates

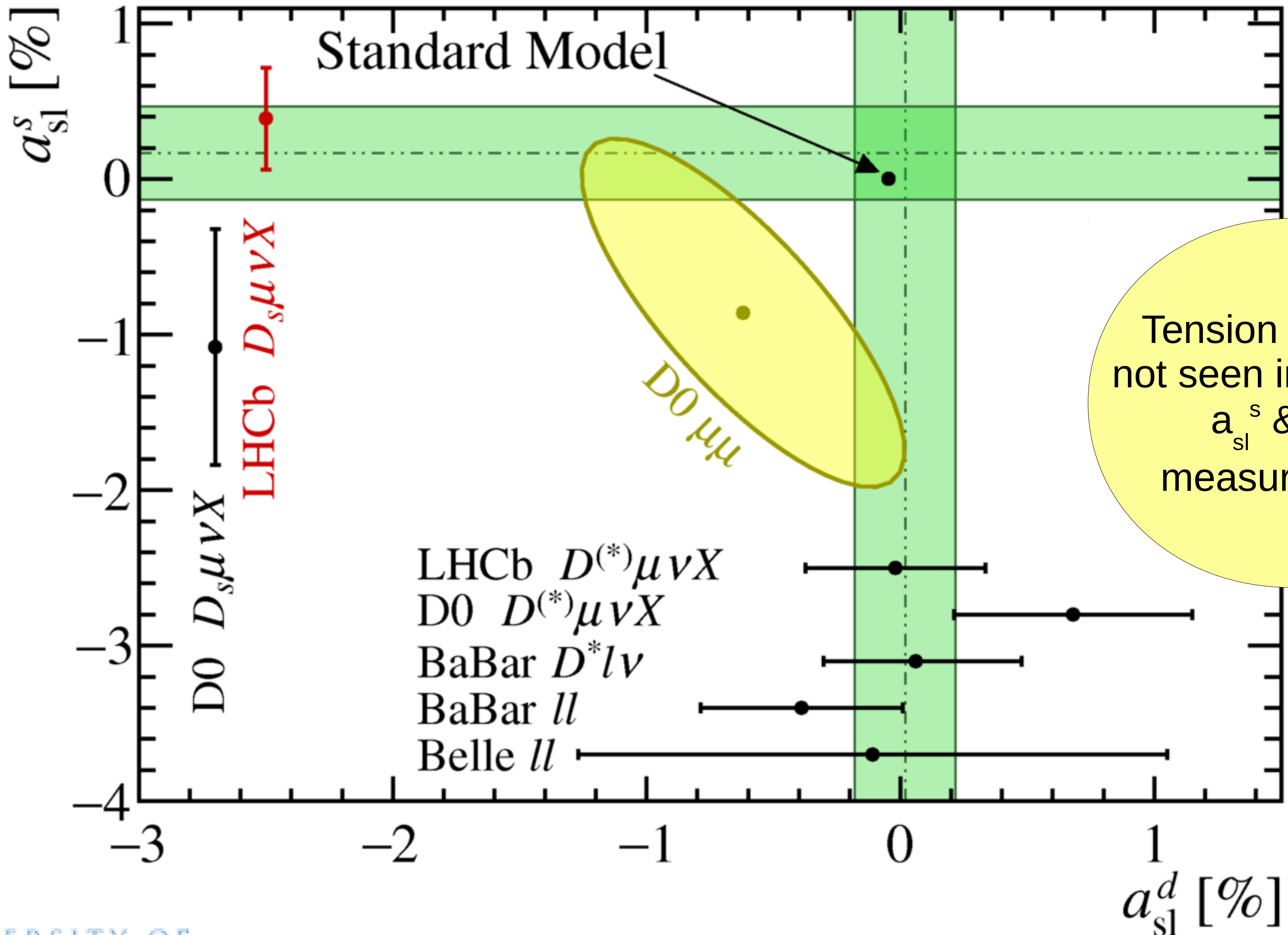
PRD 89 (2014) 012002

$$A_{SL} = (1 - |q/p|^4)/(1+|q/p|^4)$$



Latest $a_{sl}^{s} - a_{sl}^{d}$ plot

arXiv:1605.09768



Tension with SM not seen in separate a_{sl}^{s} & a_{sl}^{d} measurements

What do we know about heavy quark flavour physics as of today?

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

CKM Matrix : parametrizations

- Many different possible choices of 4 parameters
- PDG: 3 mixing angles and 1 phase

PRL 53 (1984) 1802

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

- Apparent hierarchy: $s_{12} \sim 0.2$, $s_{23} \sim 0.04$, $s_{13} \sim 0.004$
  - Wolfenstein parametrization (expansion parameter $\lambda \sim \sin\theta_c \sim 0.22$)

PRL 51 (1983) 1945

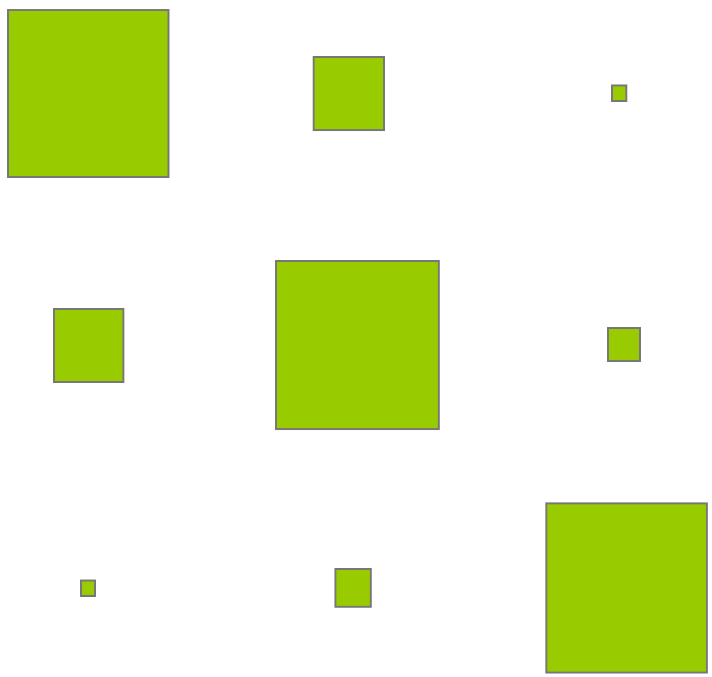
$$V = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}\left(\lambda^4\right)$$

- Other choices, eg. based on CP violating phases

PLB 680 (2009) 328

Hierarchy in quark mixing

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}\left(\lambda^4\right)$$



Very suggestive pattern

No known underlying reason

Situation for leptons (νs) is completely different

Unitarity Tests

- The CKM matrix must be unitary

$$V_{CKM}^{+} V_{CKM} = V_{CKM} V_{CKM}^{+} = 1$$

- Provides numerous tests of constraints between independent observables, such as

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$
$$V_{ud} V_{ub}^{*} + V_{cd} V_{cb}^{*} + V_{td} V_{tb}^{*} = 0$$

CKM Matrix – Magnitudes

PDG 2014

semileptonic / leptonic kaon decays
hadronic tau decays

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

semileptonic / leptonic B decays

$$\begin{pmatrix} 0.97425 \pm 0.00022 & 0.2253 \pm 0.0008 & (4.13 \pm 0.49) \times 10^{-3} \\ 0.225 \pm 0.008 & 0.986 \pm 0.016 & (41.1 \pm 1.3) \times 10^{-3} \\ (8.4 \pm 0.6) \times 10^{-3} & (40.0 \pm 2.7) \times 10^{-3} & 1.021 \pm 0.032 \end{pmatrix}$$

semileptonic charm decays
charm production in neutrino beams

semileptonic B decays

semileptonic / leptonic charm decays

B_d oscillations

single top production

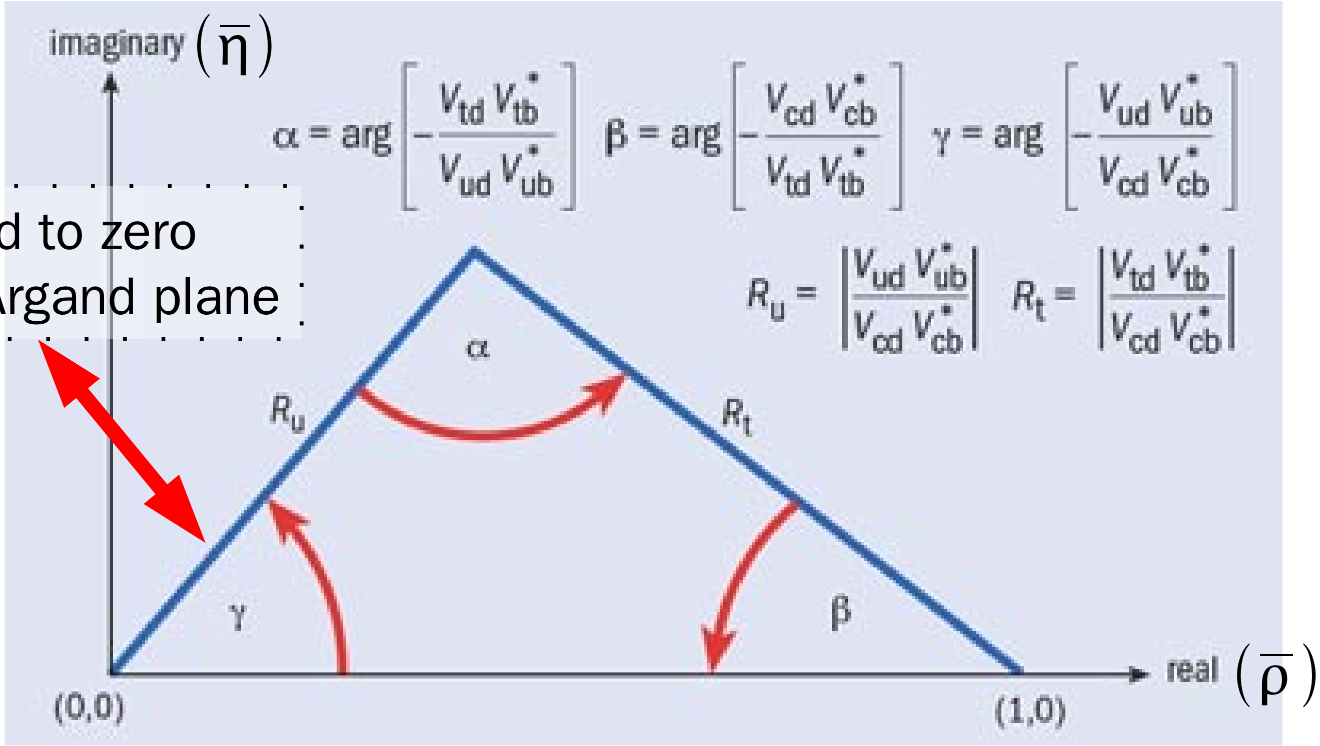
B_s oscillations

theory inputs (eg., lattice calculations) required

The Unitarity Triangle

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

Three complex numbers add to zero
⇒ triangle in Argand plane



Axes are $\overline{\rho}$ and $\overline{\eta}$ where

$$\overline{\rho} + i\overline{\eta} \equiv -\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}$$

$$\rho + i\eta = \frac{\sqrt{1-A^2\lambda^4}(\overline{\rho}+i\overline{\eta})}{\sqrt{1-\lambda^2}\left[1-A^2\lambda^4(\overline{\rho}+i\overline{\eta})\right]}$$

Predictive nature of KM mechanism

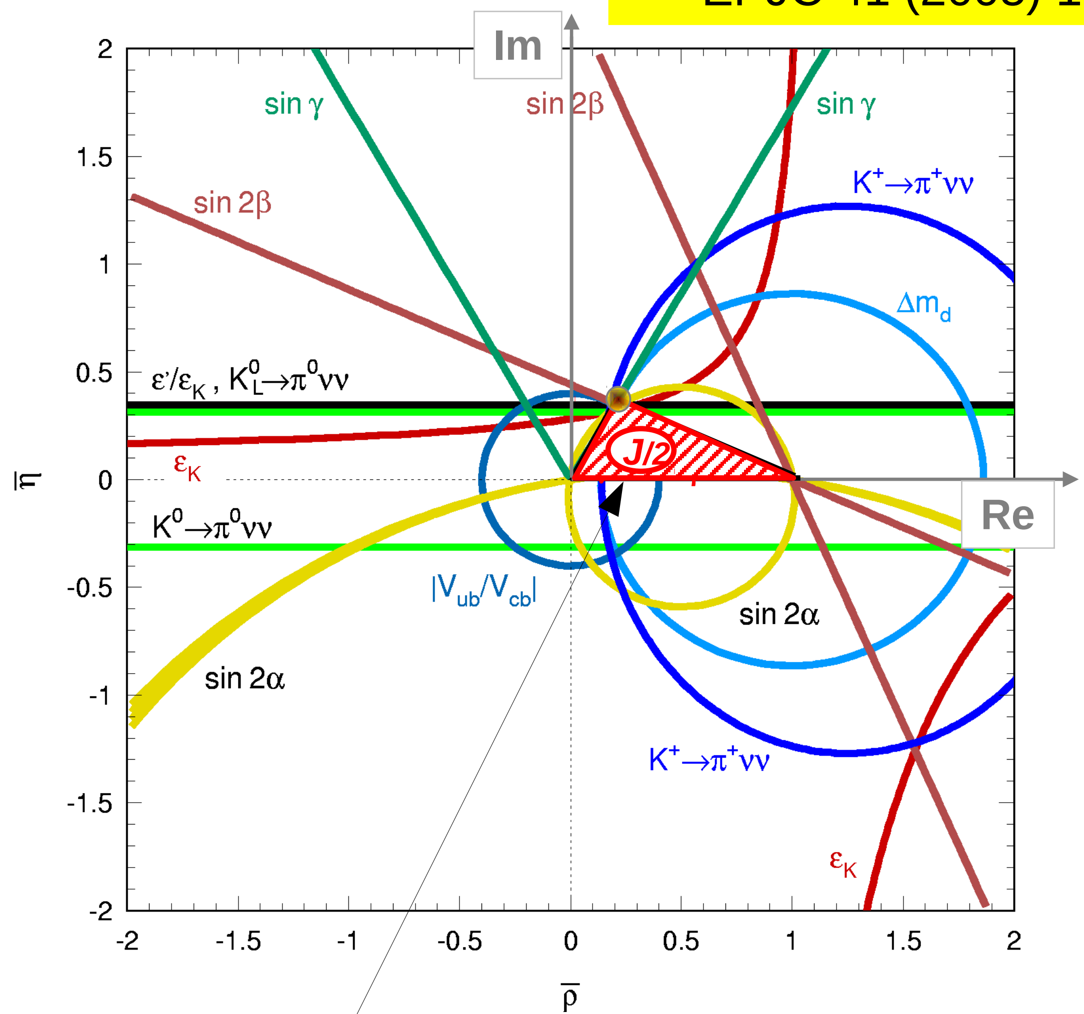
EPJC 41 (2005) 1

In the Standard Model the KM phase is the sole origin of CP violation

Hence:

all measurements must agree on the position of the apex of the Unitarity Triangle

(Illustration shown assumes no experimental or theoretical uncertainties)

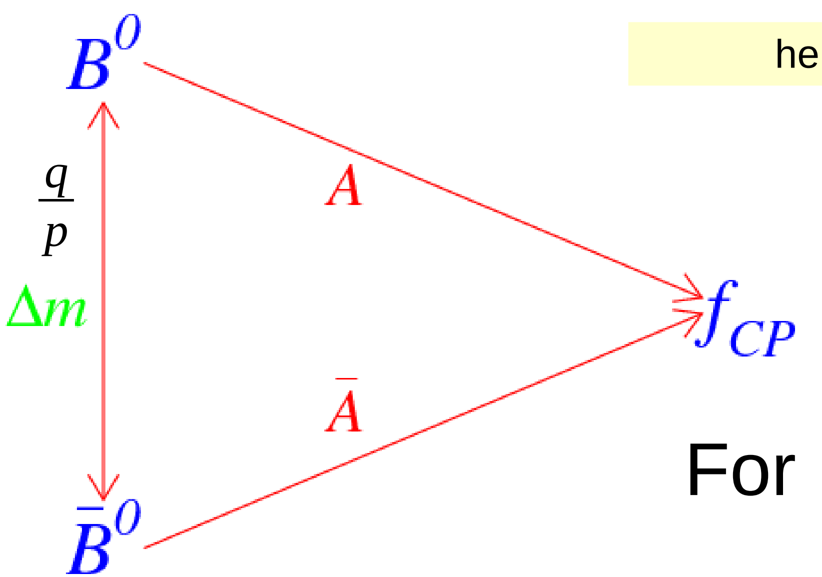


Area of (all of) the Unitarity Triangle(s) is given by the Jarlskog invariant

Time-Dependent CP Violation in the B^0–$\overline{B}^0$ System

- For a B meson known to be 1) B^0 or 2) $\overline{B}^0$ at time t=0, then at later time t:

$$\Gamma\left(B^0_{phys} \rightarrow f_{CP}(t)\right) \propto e^{-\Gamma t}\left(1-\left(S\sin(\Delta m t)-C\cos(\Delta m t)\right)\right)$$
$$\Gamma\left(\overline{B}^0_{phys} \rightarrow f_{CP}(t)\right) \propto e^{-\Gamma t}\left(1+\left(S\sin(\Delta m t)-C\cos(\Delta m t)\right)\right)$$



here assume ΔΓ negligible – will see full expressions later

$$S = \frac{2\,\Im(\lambda_{CP})}{1+|\lambda_{CP}^2|} \qquad C = \frac{1-|\lambda_{CP}^2|}{1+|\lambda_{CP}^2|} \qquad \lambda_{CP} = \frac{q}{p}\frac{\bar{A}}{A}$$

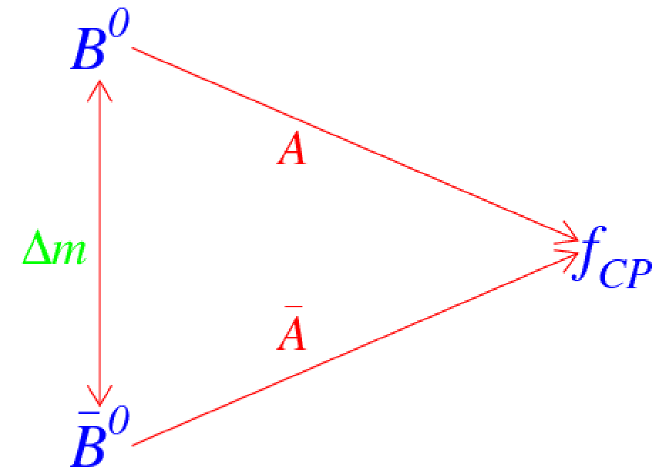
For $B^0 \rightarrow J/\psi\, K_S$, $S = \sin(2\beta)$, $C=0$

NPB 193 (1981) 85

Categories of CP violation

- Consider decay of neutral particle to a CP eigenstate

$$\lambda_{CP} = \frac{q}{p}\frac{\bar{A}}{A}$$



$$\left|\frac{q}{p}\right| \neq 1$$

CP violation in mixing

$$\left|\frac{\bar{A}}{A}\right| \neq 1$$

CP violation in decay

$$\Im\left(\frac{q}{p}\frac{\bar{A}}{A}\right) \neq 0$$

CP violation in interference between mixing and decay

n.b. historical classification of CP violation as “direct” and “indirect” is of little use nowadays (though often misused!)

Asymmetric B factory principle

To measure t require B meson to be moving

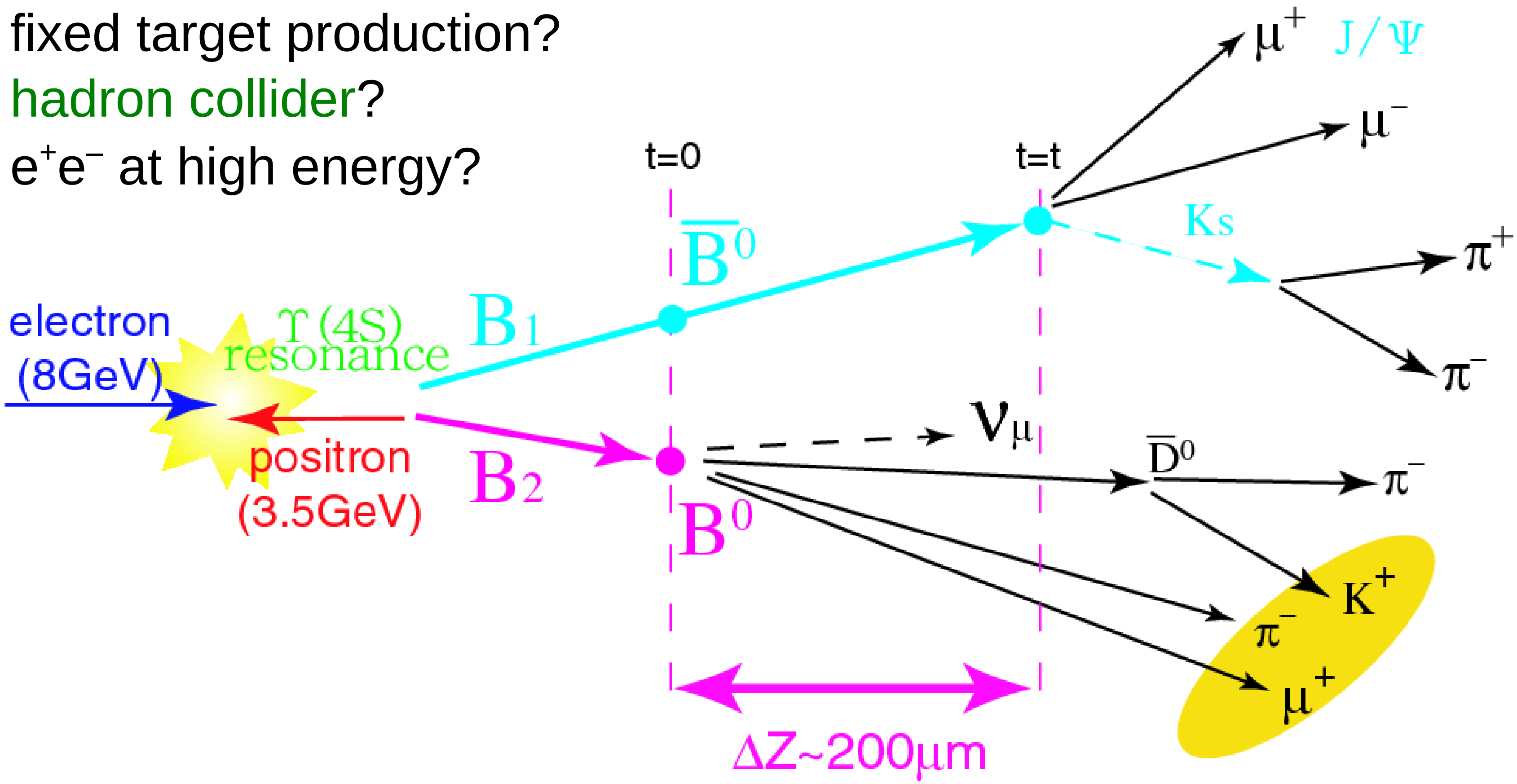
→ e^+e^- at threshold with asymmetric collisions (Oddone)

Other possibilities considered

→ fixed target production?

→ hadron collider?

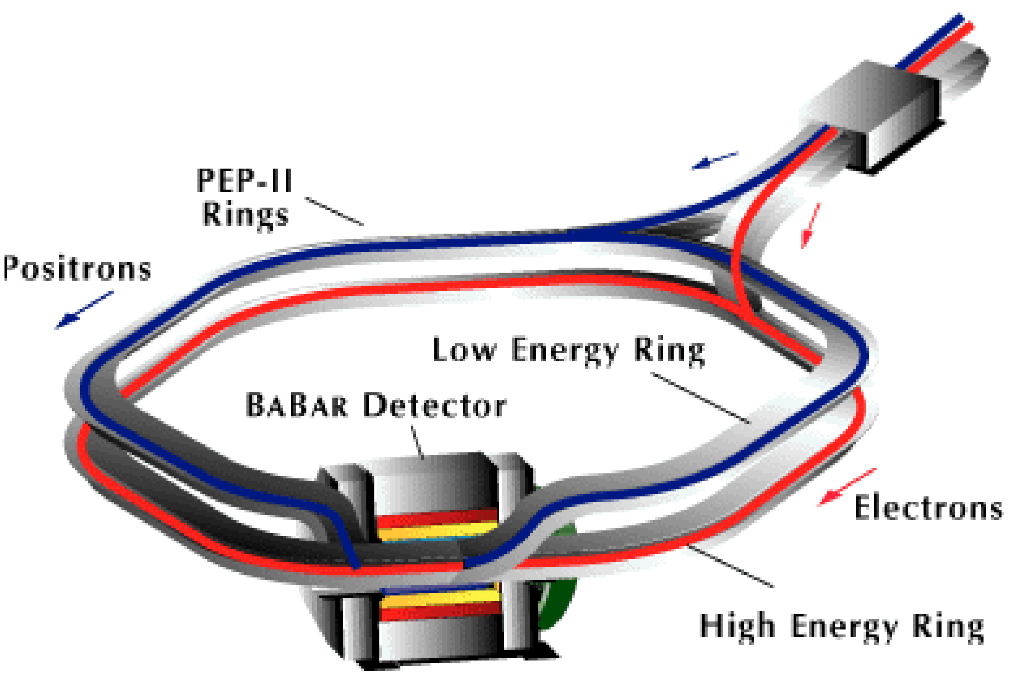
→ e^+e^- at high energy?

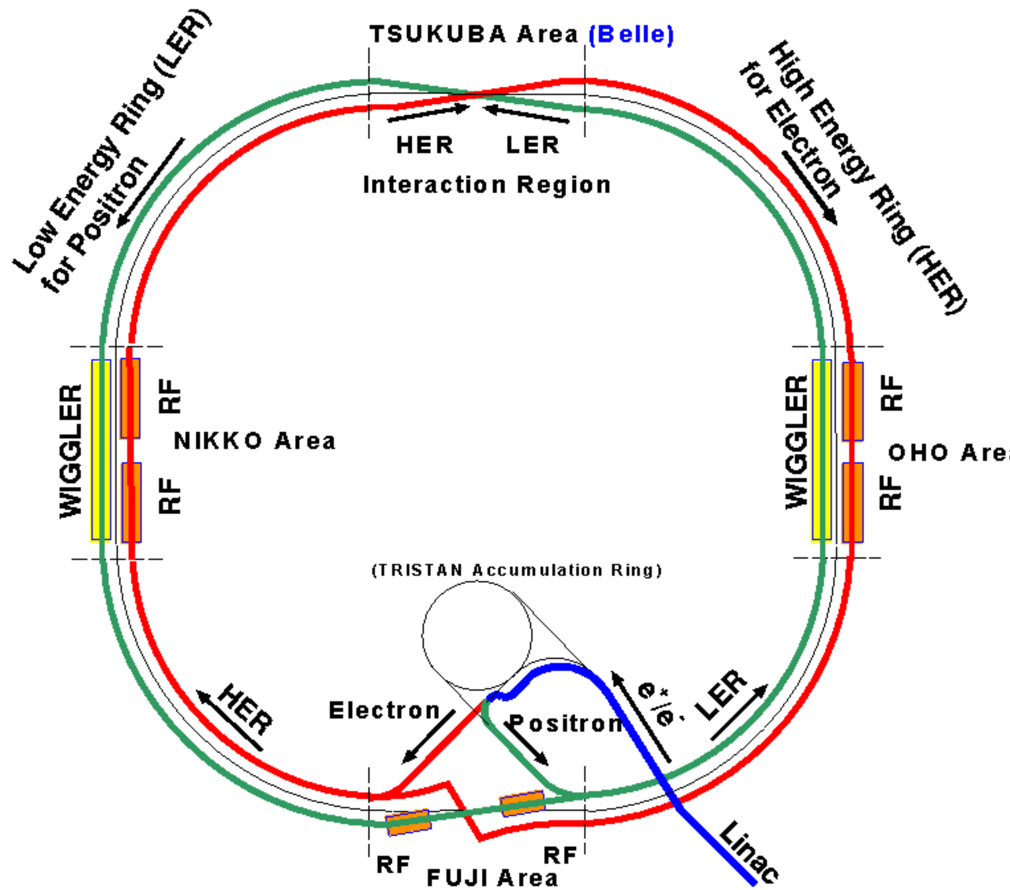


Asymmetric B Factories

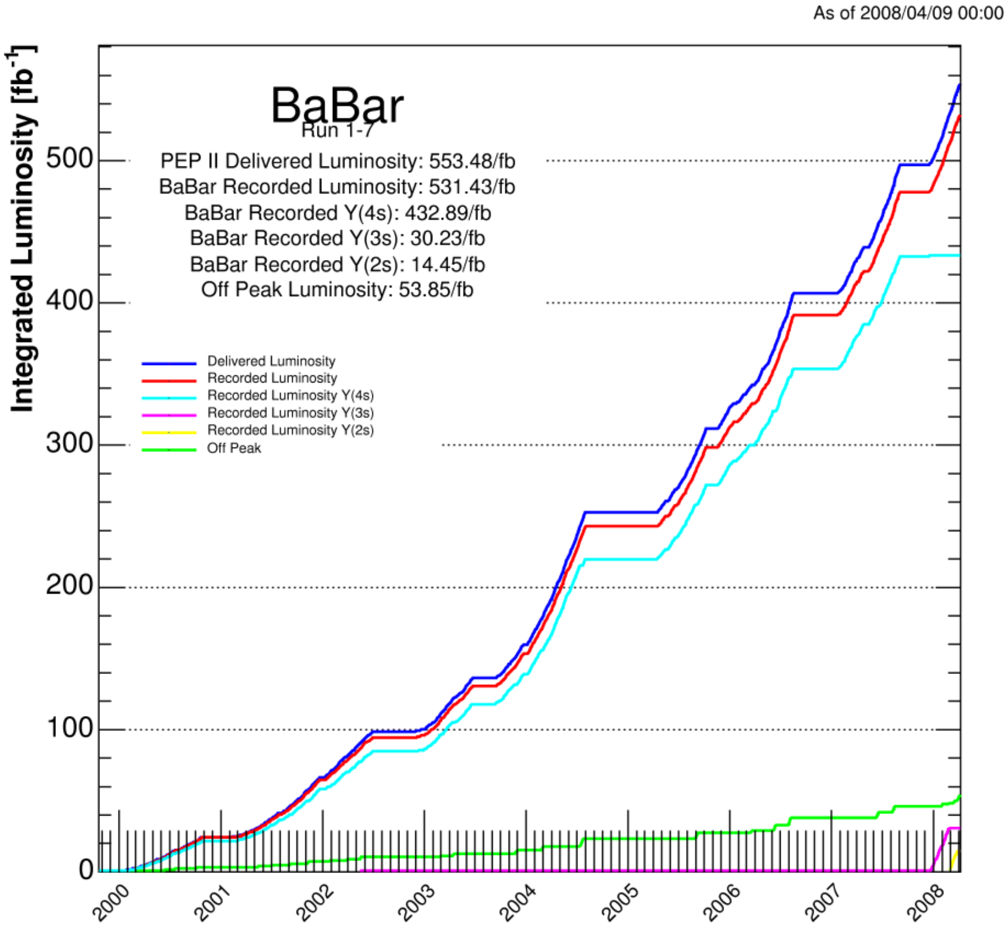
PEPII at SLAC
9.0 GeV e^- on 3.1 GeV e^+

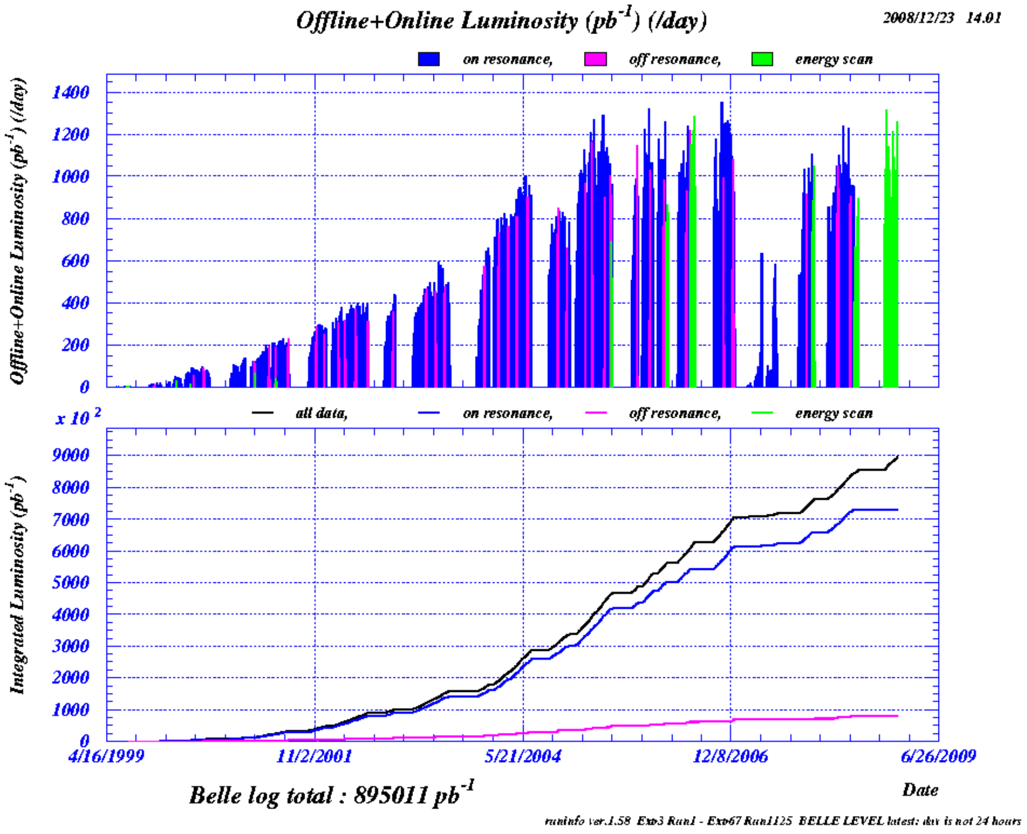
KEKB at KEK
8.0 GeV e^- on 3.5 GeV e^+





B factories – world record luminosities



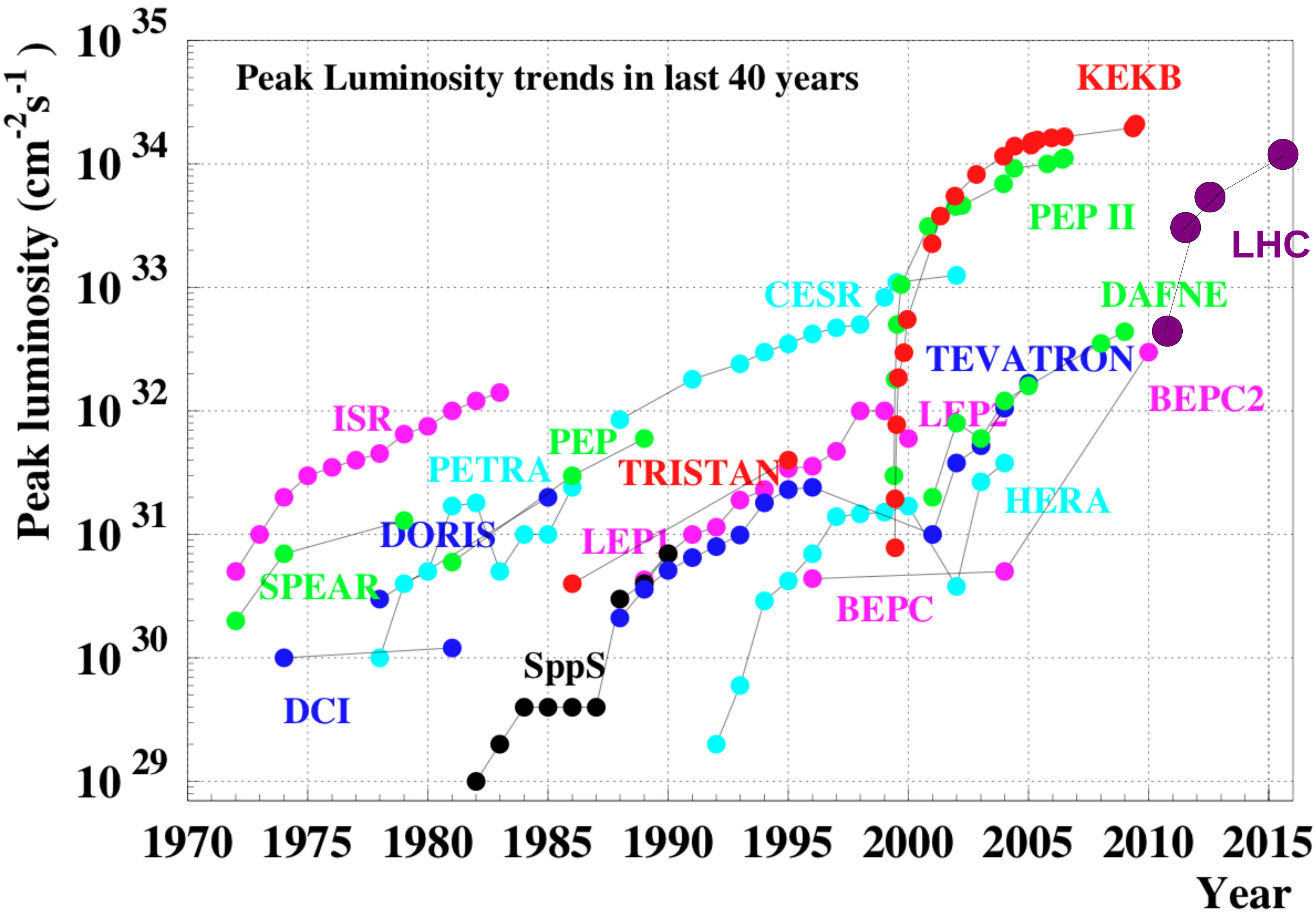


~ 433/fb on Y(4S)

~ 711/fb on Y(4S)

Total over 10^9 $B\bar{B}$ pairs recorded

World record luminosities (2)

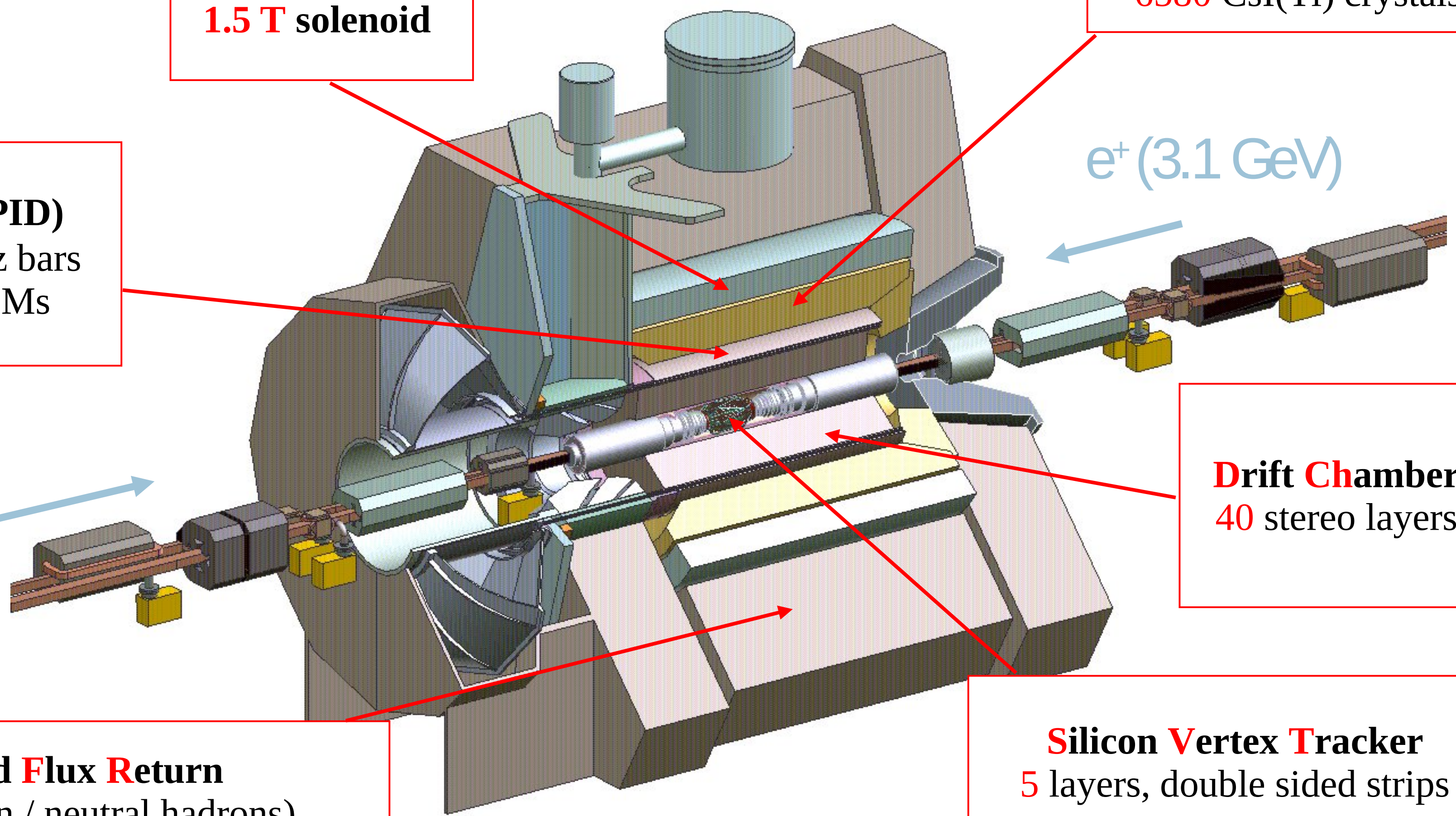


BaBar Detector

1.5 T solenoid

EMC
6580 CsI(Tl) crystals

DIRC (PID)
144 quartz bars
11000 PMs

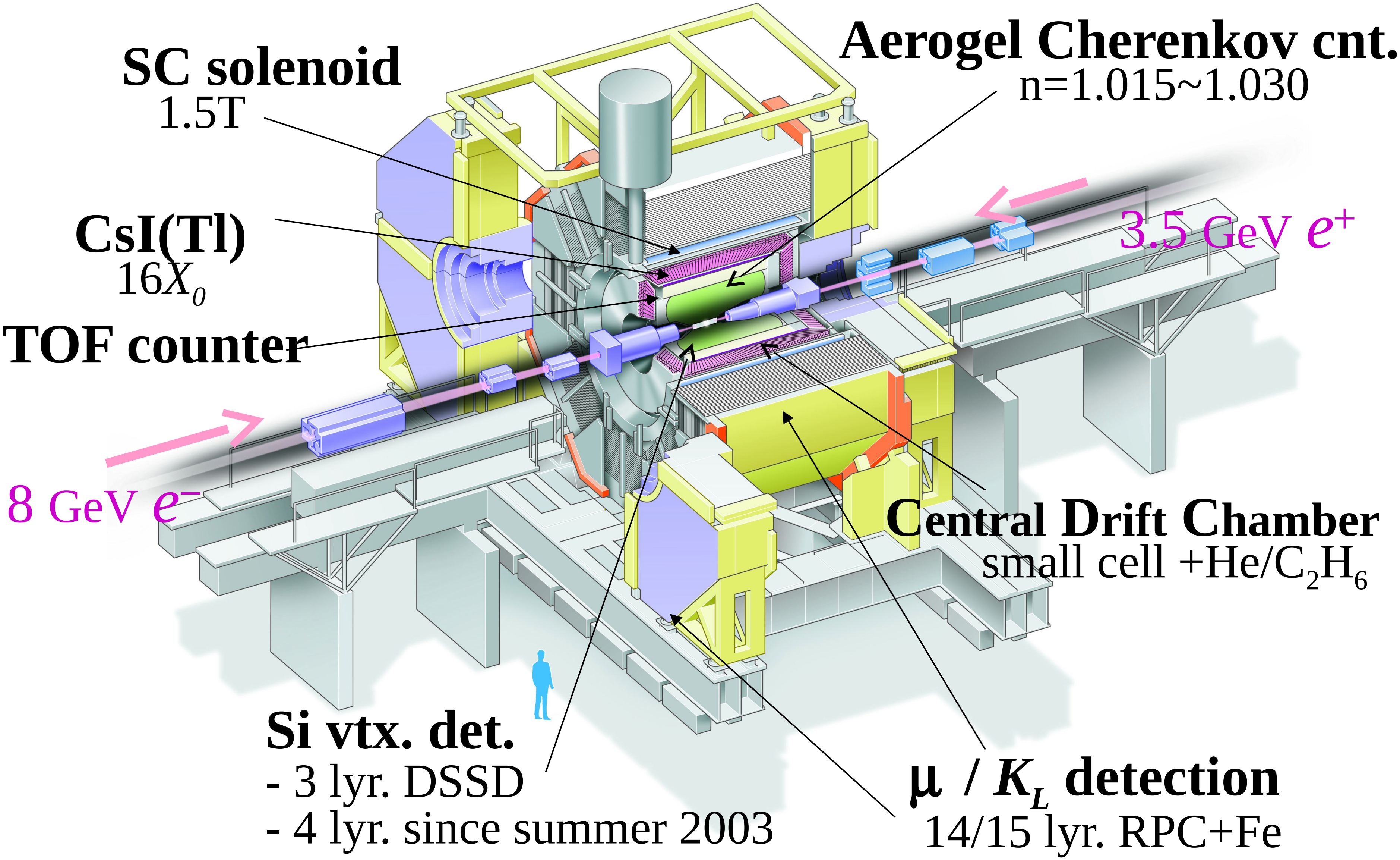


Drift Chamber
40 stereo layers

Silicon Vertex Tracker
5 layers, double sided strips

Instrumented Flux Return
iron / RPCs (muon / neutral hadrons)
2/6 replaced by LST in 2004
Rest of replacement in 2006

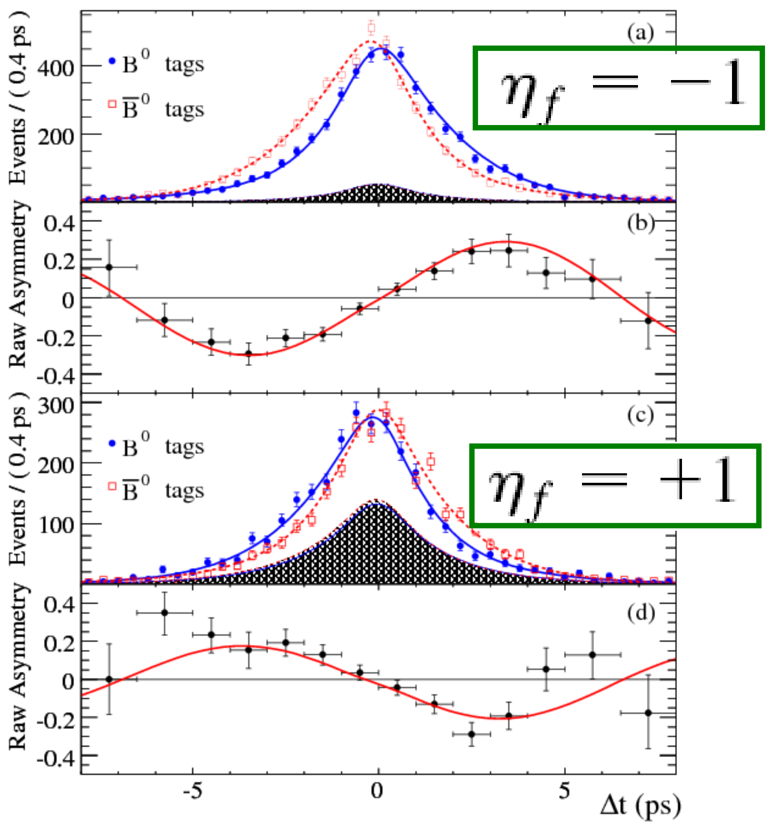
Belle Detector



Results for the golden mode

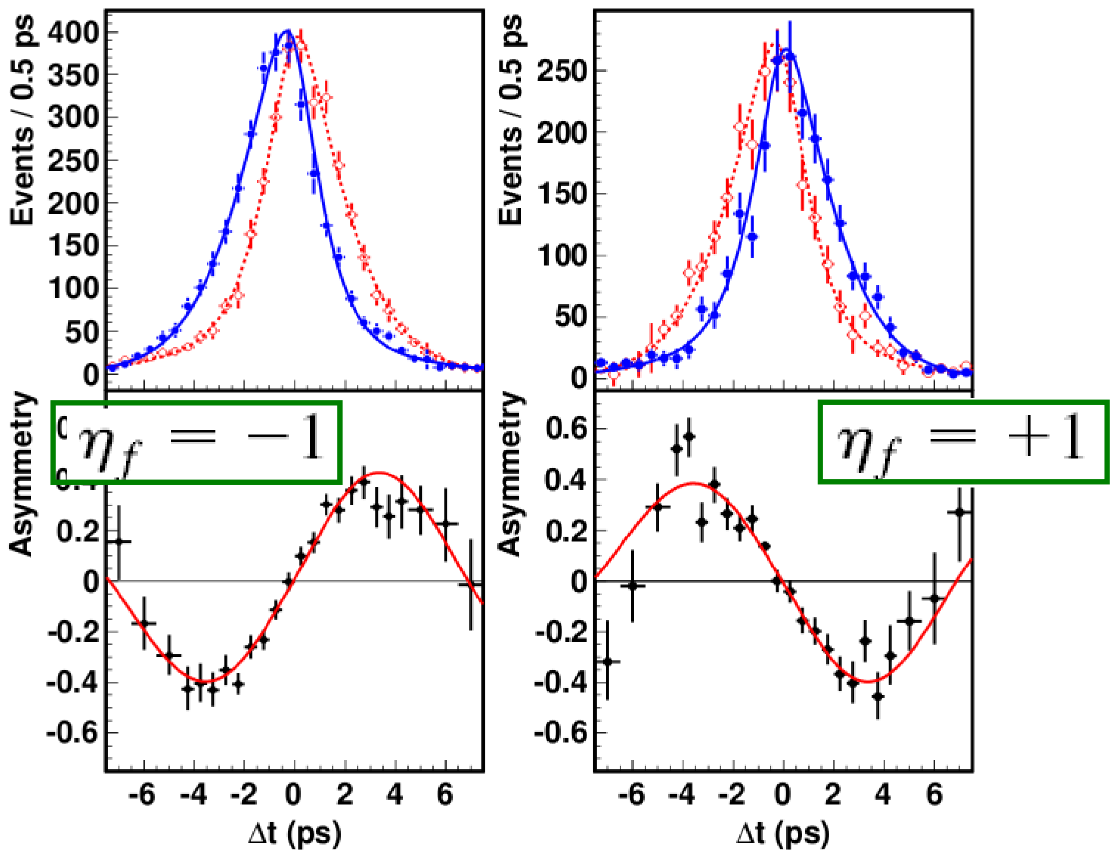
$$B^0 \to J/\psi K^0$$

BABAR



PRD 79 (2009) 072009

BELLE

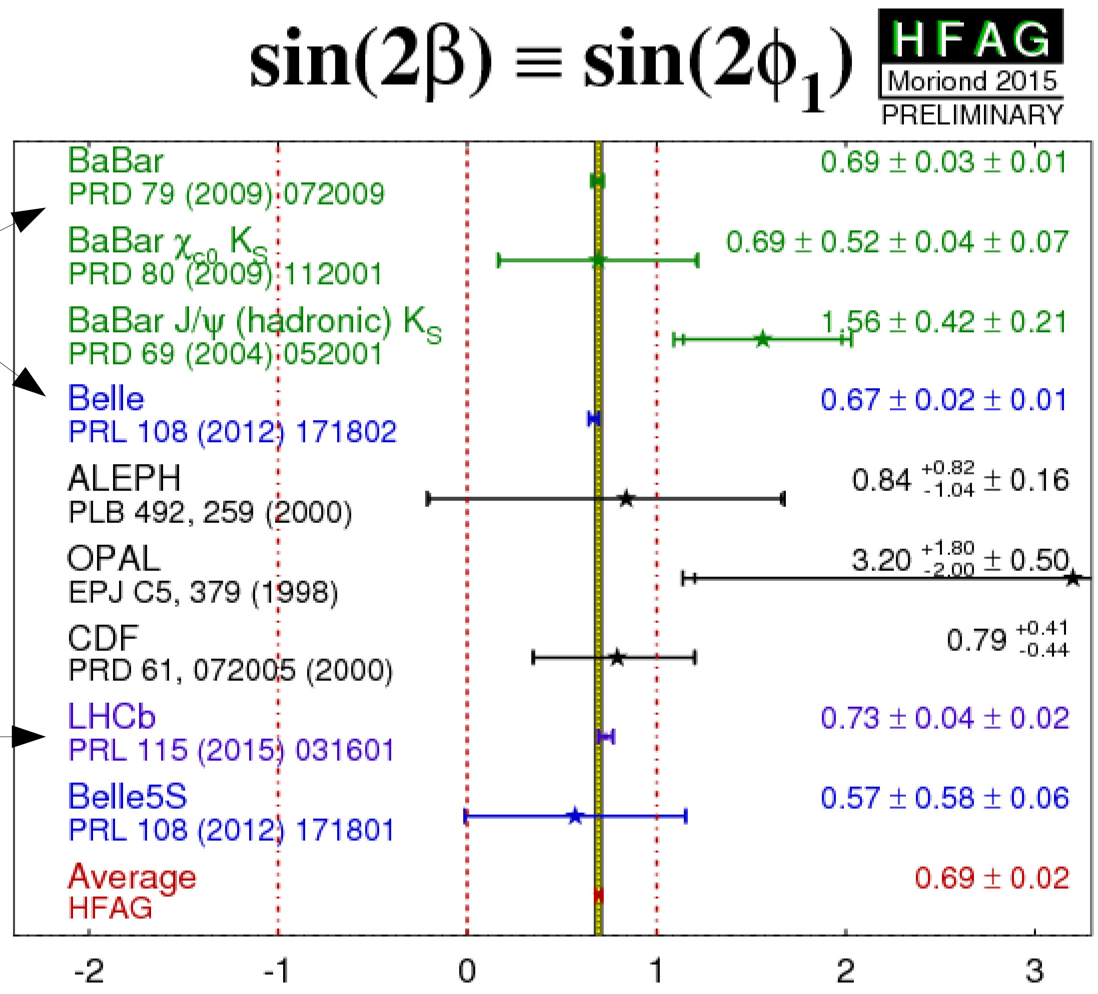


PRL 108 (2012) 171802

Compilation of results

Results on previous slide

Note LHCb also highly competitive

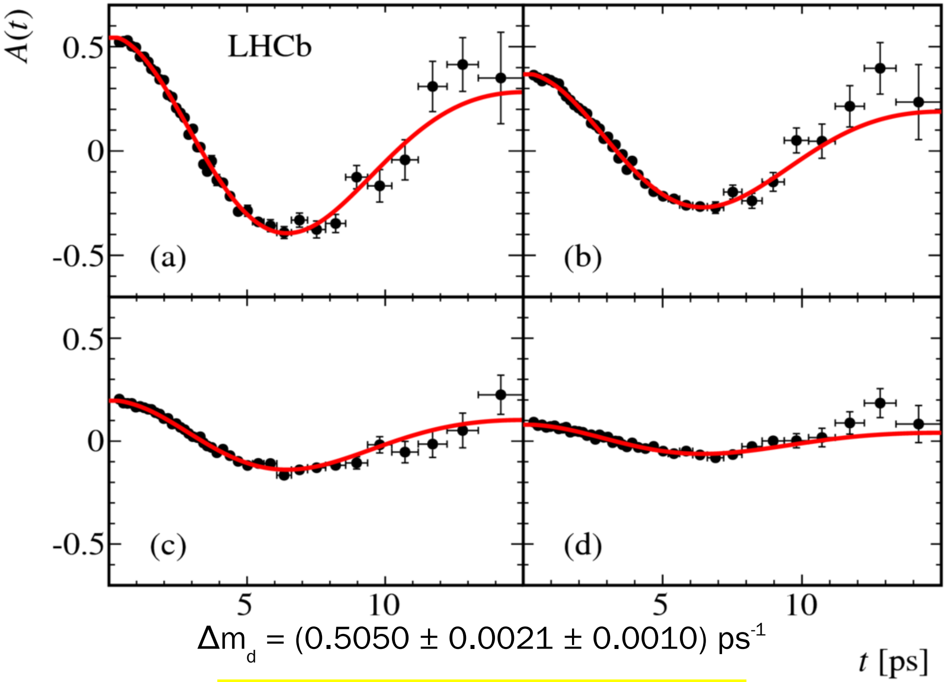


R_t side from B^0–$\overline{B}^0$ mixing

World average based on many measurements

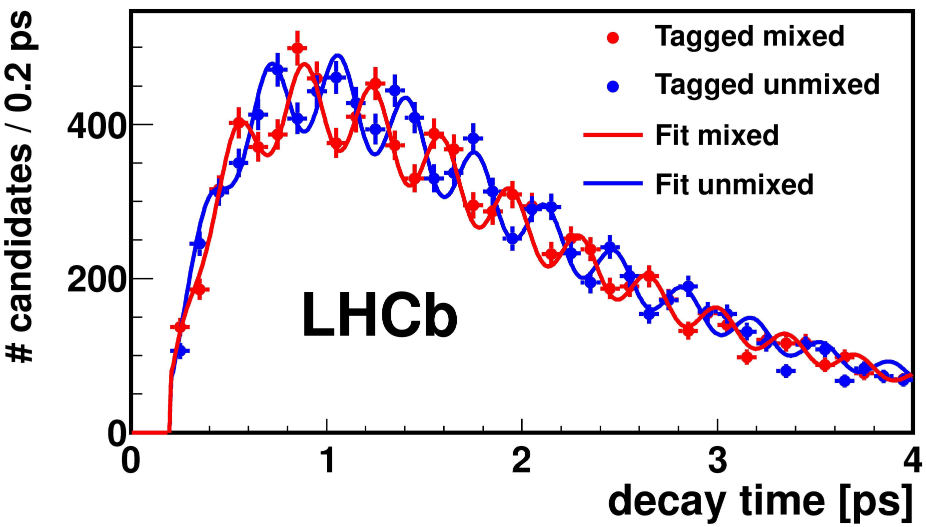
$$R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right| \quad \& \quad \frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{td}|^2}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s} |V_{ts}|^2}$$

$P(\Delta t) = (1 \pm \cos(\Delta m t))e^{-t}/2\tau$



$\Delta m_d = (0.5050 \pm 0.0021 \pm 0.0010)\ \mathrm{ps}^{-1}$

arXiv:1604.03475



$\Delta m_s = (17.768 \pm 0.023 \pm 0.006)\ \mathrm{ps}^{-1}$

NJP 15 (2013) 053021

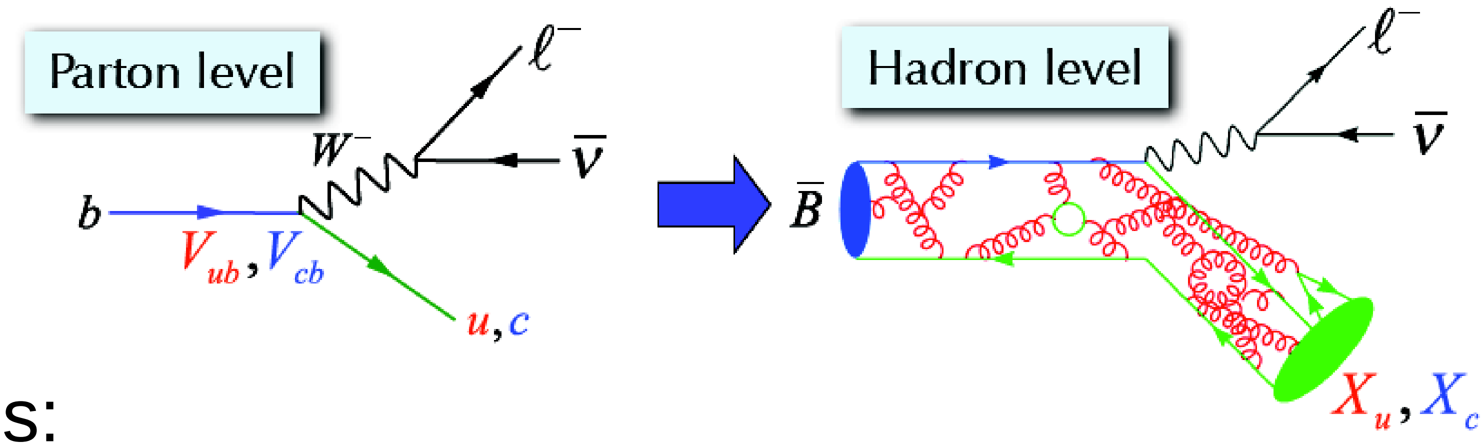
$$|V_{td}/V_{ts}| = 0.216 \pm 0.001 \pm 0.011$$

experimental uncertainty

theoretical uncertainty

R_u side from semileptonic decays

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



- Approaches:
  - exclusive semileptonic B decays, eg. $B^0 \to \pi^- e^+ \nu$
    - require knowledge of form factors
      - can be calculated in lattice QCD at kinematical limit
  - inclusive semileptonic B decays, eg. $B \to X_u e^+ \nu$
    - clean theory, based on Operator Product Expansion
    - experimentally challenging:
      - need to reject $b \to c$ background
      - cuts re-introduce theoretical uncertainties

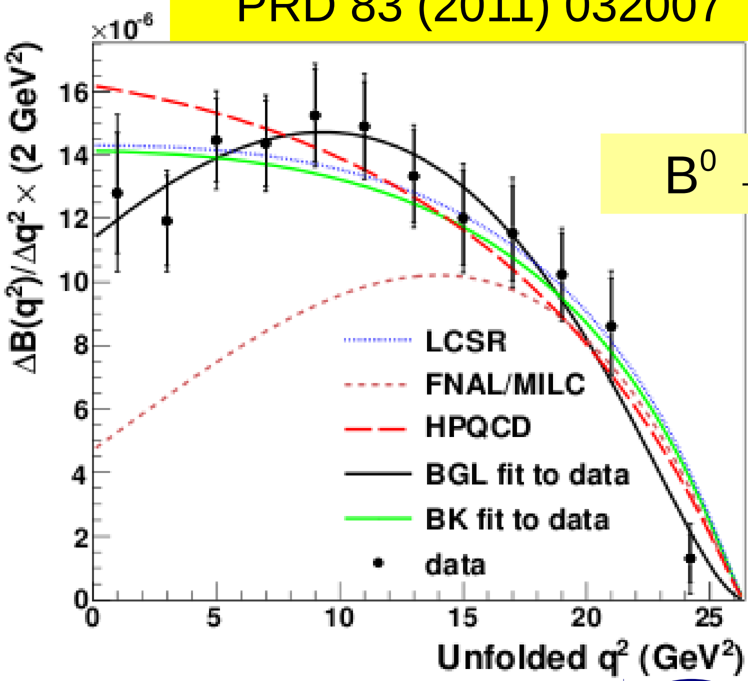
$|V_{ub}|$ from exclusive semileptonic decays

Current best measurements use $B^0 \rightarrow \pi^- l^+ \nu$

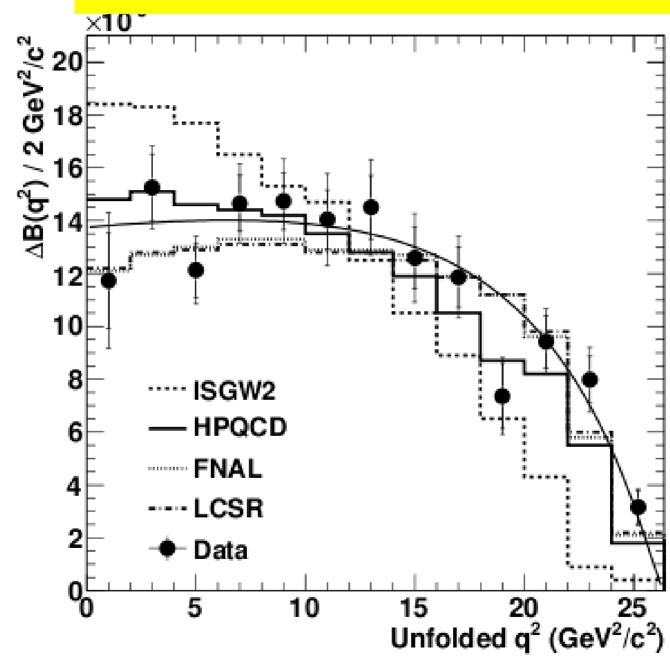
(recent competitive measurement from LHCb with $\Lambda_b \rightarrow p\mu\nu$)

BaBar experiment
PRD 83 (2011) 052011
PRD 83 (2011) 032007

Belle experiment
PRD 83 (2011) 071101(R)



$B^0 \rightarrow \pi^- l \nu$



$$\left|V_{ub}\right| = \left(3.09 \pm 0.08 \pm 0.12 \, {}^{+0.35}_{-0.29}\right) \times 10^{-3}$$

$$\left|V_{ub}\right| = \left(3.43 \pm 0.33\right) \times 10^{-3}$$

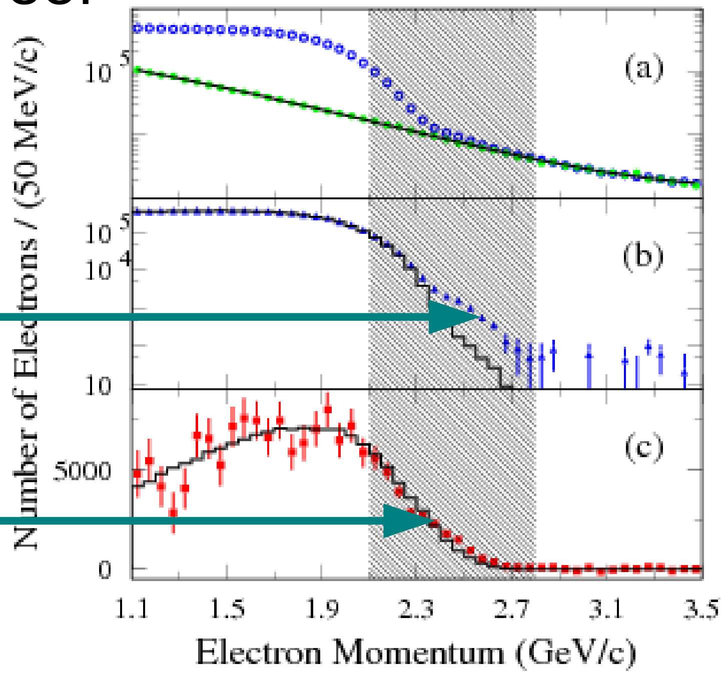
lattice uncertainty

$|V_{ub}|$ from inclusive semileptonic decays

- Main difficulty to measure inclusive $B \to X_u l^+ \nu$
  - background from $B \to X_c l^+ \nu$
- Approaches
  - cut on E_l (lepton endpoint), q^2 ($l\nu$ invariant mass squared), $M(X_u)$, or some combination thereof
- Example: endpoint analysis

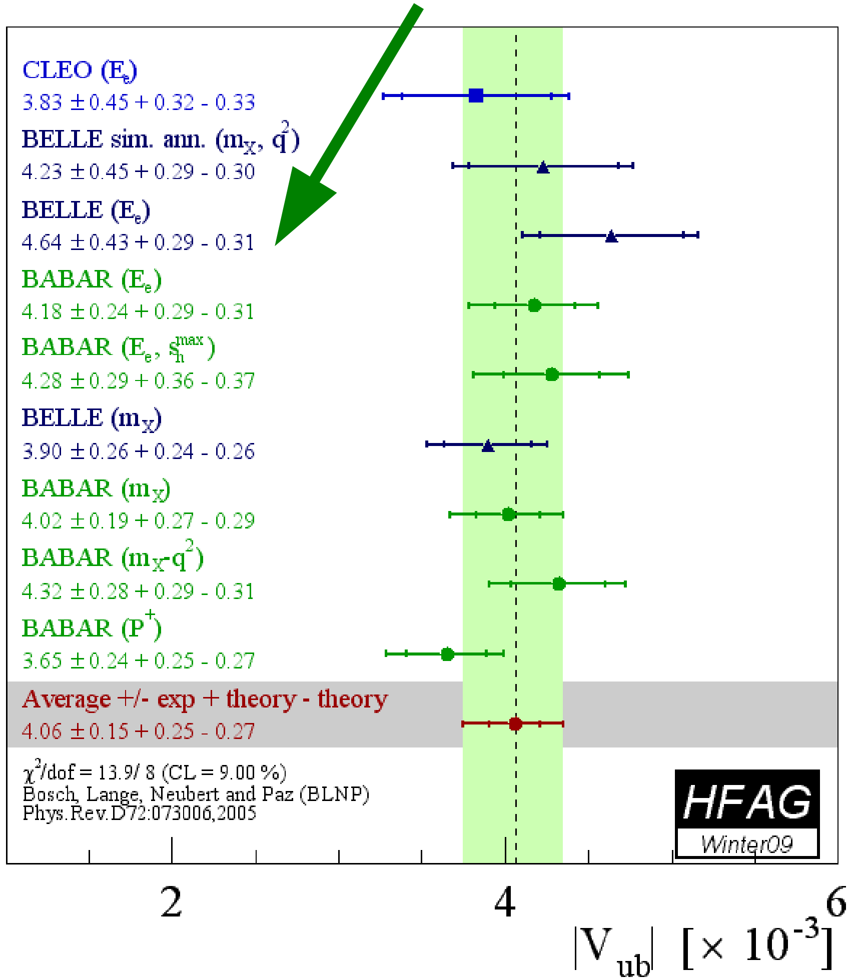
non $B\bar{B}$ background subtracted

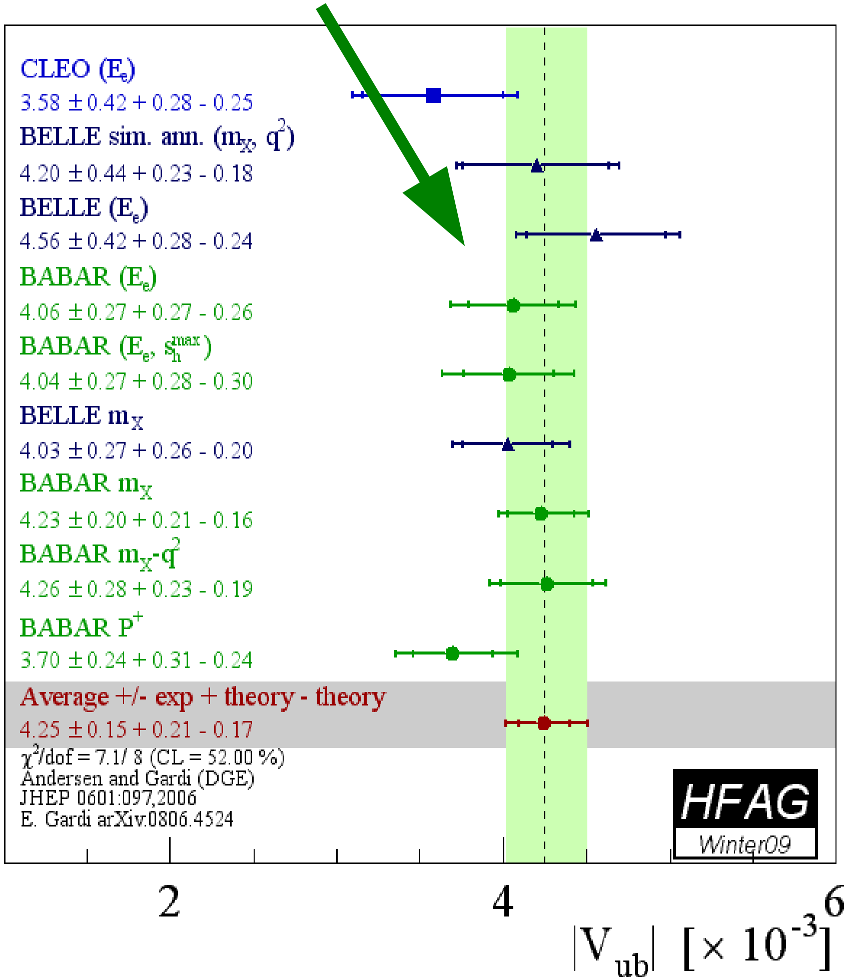
$X_c l^+ \nu$ background subtracted



$|V_{ub}|$ inclusive - compilation

Different theoretical approaches (2 of 4 used by HFAG)

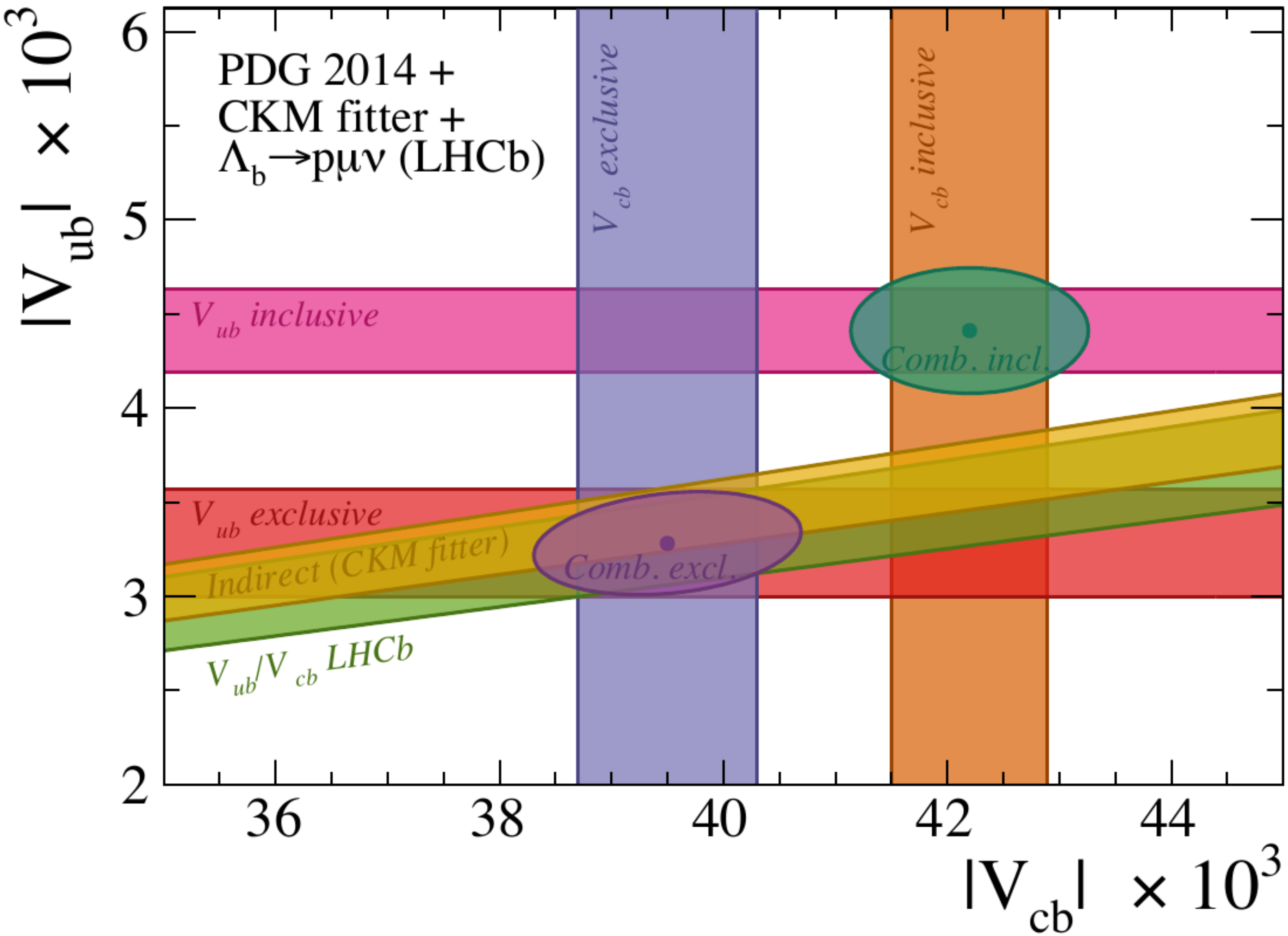




$|V_{ub}|$ average

- Averages on $|V_{ub}|$ from both exclusive and inclusive approaches
  - exclusive: $|V_{ub}| = (3.28 \pm 0.29) \times 10^{-3}$
  - inclusive: $|V_{ub}| = (4.41 \pm 0.22) \times 10^{-3}$
  - notable "tension" between these results
  - in both cases theoretical errors are dominant
    - but some "theory" errors can be improved with more data
  - PDG2014 does naïve average rescaling due to inconsistency to obtain $|V_{ub}| = (4.13 \pm 0.49) \times 10^{-3}$

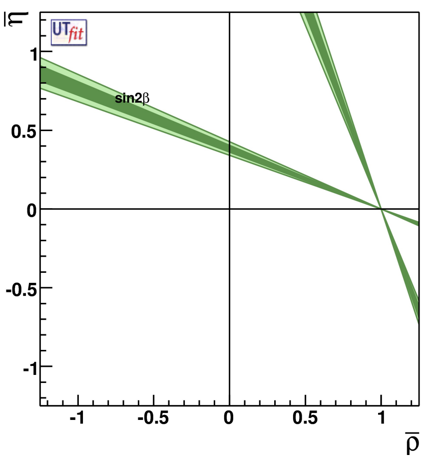
Inclusive vs. exclusive



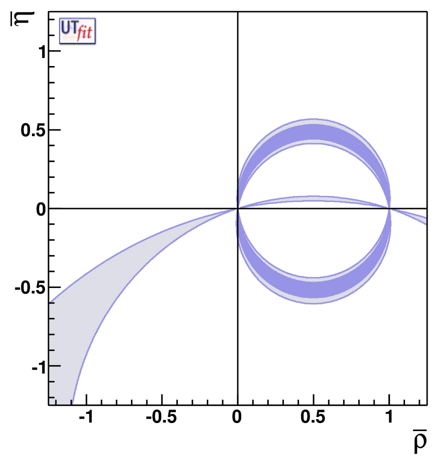
Discrepancies need to be understood!

Partial summary

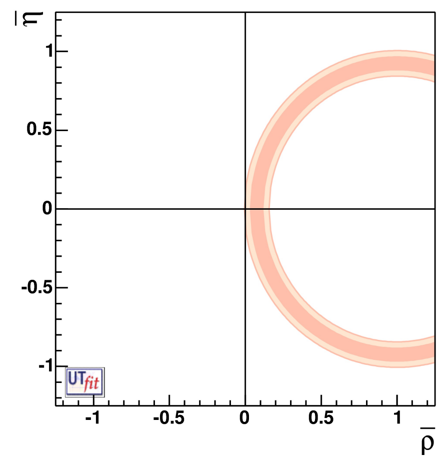
$\sin(2\beta)$



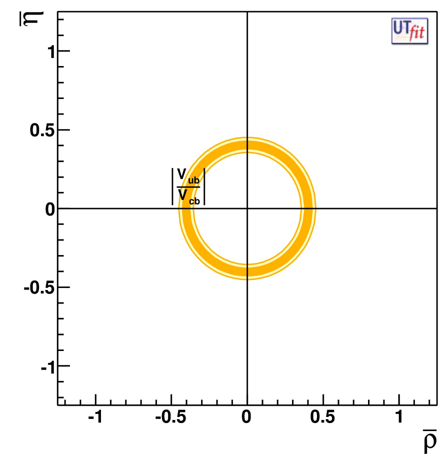
α



$|\Delta m_d / \Delta m_s|$

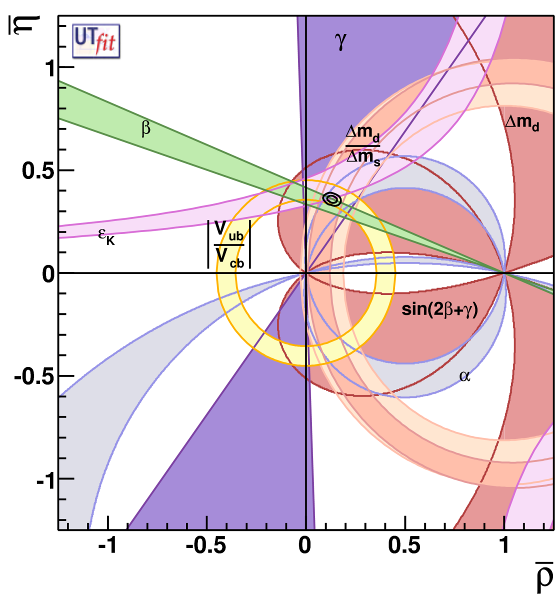


$|V_{ub} / V_{cb}|$



Adding a few other constraints we find

$$\bar{\rho} = 0.132 \pm 0.020$$
$$\bar{\eta} = 0.358 \pm 0.012$$



Consistent with Standard Model fit

- some "tensions"

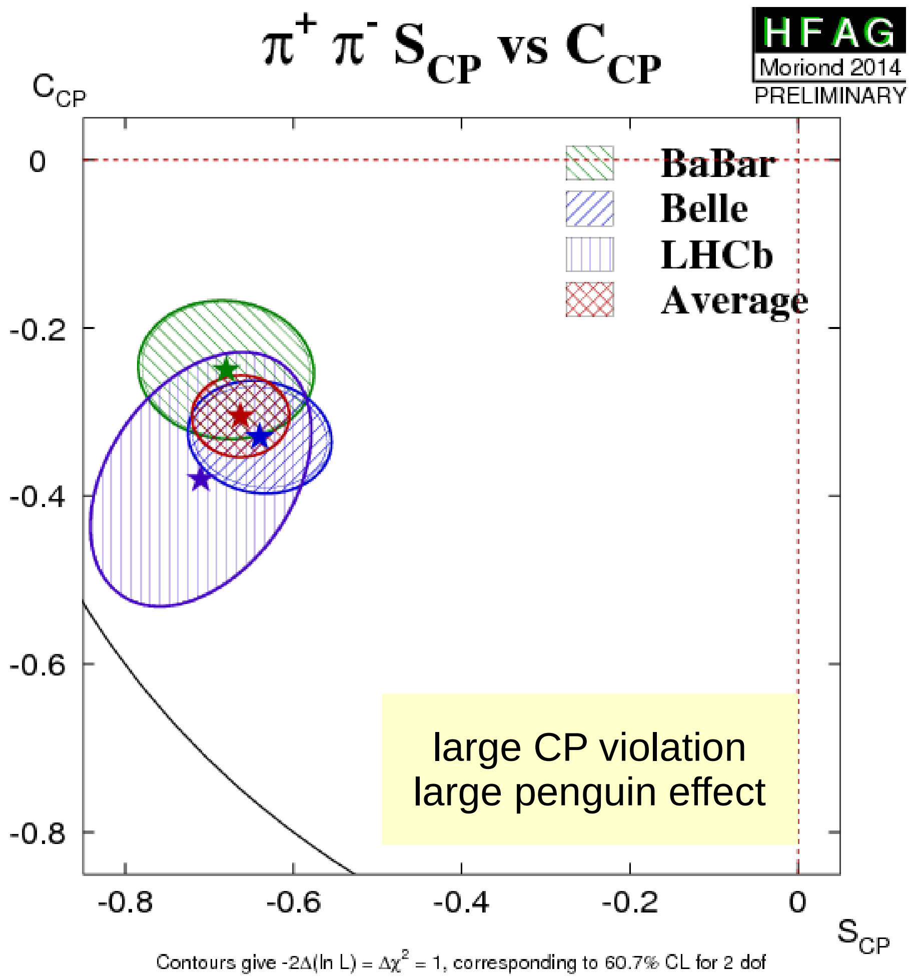
Still plenty of room for new physics

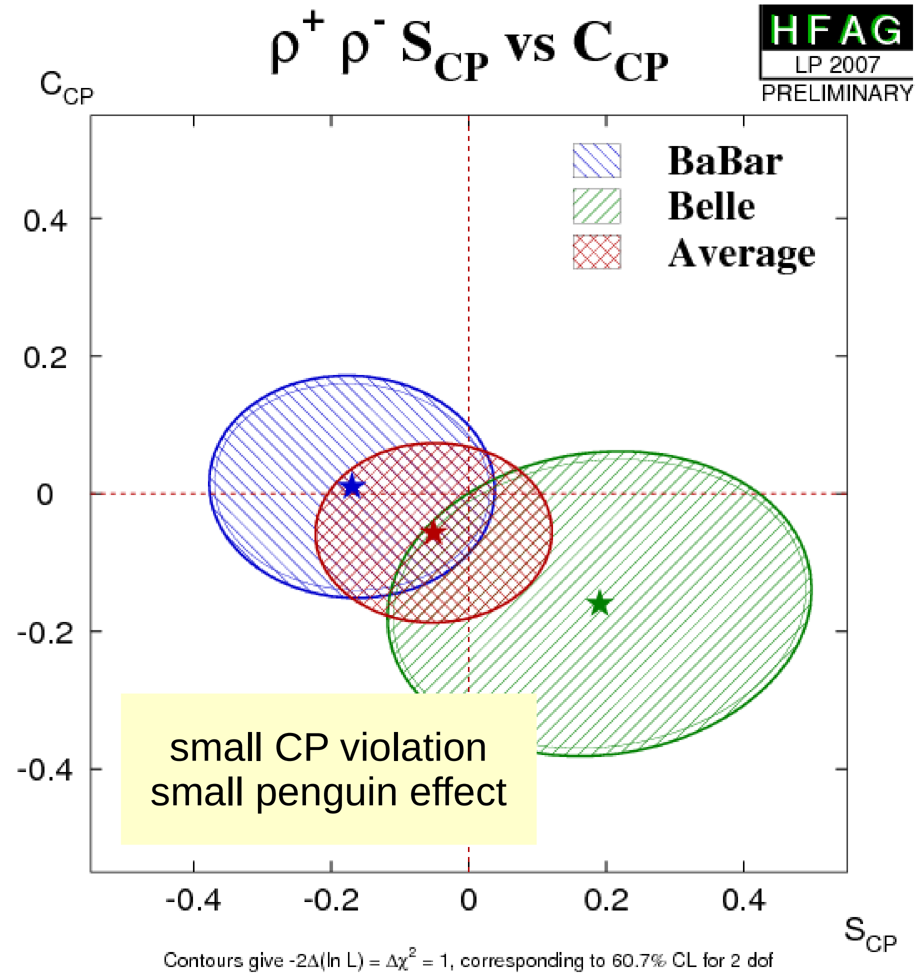
Measurement of α

- Similar analysis using b → u$\bar{u}$d decays (e.g. $B_d^0 \rightarrow \pi^+\pi^-$) probes π–(β+γ) = α
  - but b → du$\bar{u}$ penguin transitions contribute to same final states ⇒ "penguin pollution"
  - C ≠ 0 ⇔ direct CP violation can occur
  - $S \neq +\eta_{CP} \sin(2\alpha)$
- Two approaches (optimal approach combines both)
  - try to use modes with small penguin contribution
  - correct for penguin effect (isospin analysis)

PRL 65 (1990) 3381

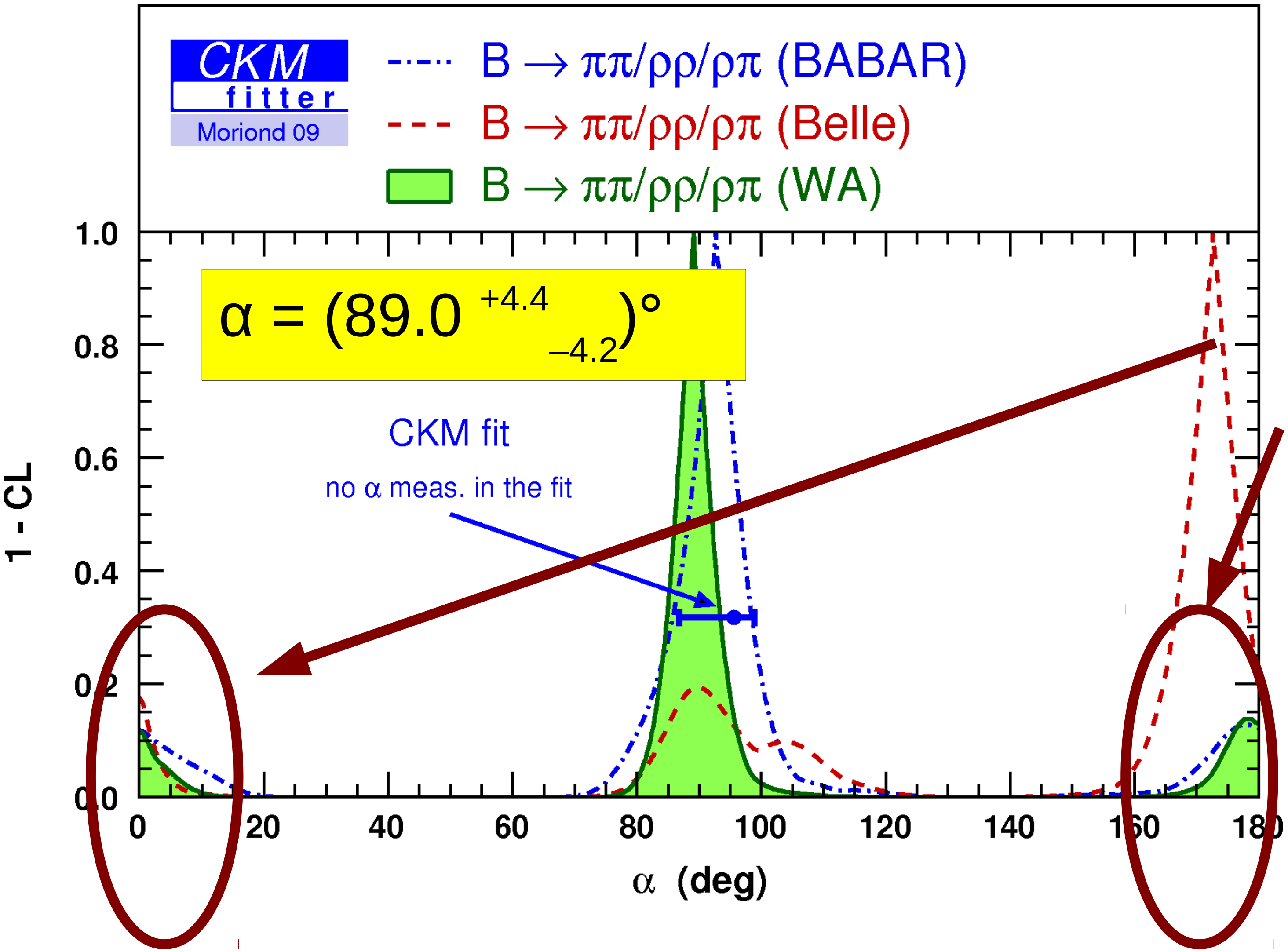
Experimental Situation





improved measurements needed!

Measurement of α



THESE SOLUTIONS RULED OUT BY OBSERVATION OF DIRECT CP VIOLATION IN $B^0 \to \pi^+\pi^-$

Is there any physical significance in the fact that α ≈ 90°?