Precision B Physics in the LHC Era: The Quest for New Physics

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Seminar @ Università di Napoli "Federico II", 10 October 2008

- Introduction & Motivation: Why is B physics interesting?
- Theoretical Framework: Unitarity Triangle, Effective Hamiltonians, ...
- The Current Picture: Implications of Flavour Data for New Physics
- B Physics at the LHC: $\longrightarrow$ New Territory of the B Landscape
- Conclusions & Outlook

Introduction & Motivation

$\longrightarrow$ Why is B physics interesting?

Overview: R.F., Lectures @ 2007 CERN – Latin American School of High-Energy Physics, Viña del Mar, Chile, 18 February – 3 March 2007, arXiv:0802.2882 [hep-ph]

Quark Flavour Physics & CP Violation

$\longrightarrow$ key players in the history of the Standard Model (SM):

- 1963: concept of flavour mixing [Cabibbo].
- 1964: discovery of CP violation in $K_{\rm L} \to \pi^+\pi^-$ [Christenson *et al.*].
- 1970: introduction of the charm quark to suppress the flavour-changing neutral currents (FCNCs) [Glashow, Iliopoulos & Maiani].
- 1973: quark-flavour mixing with 3 generations allows us to accommodate CP violation in the SM [Kobayashi & Maskawa].
- 1974: estimate of the charm-quark mass with the help of the K^0–$\bar{K}^0$ mixing frequency [Gaillard & Lee].
- 1980s: the large top-quark mass was first suggested by the large B^0–$\bar{B}^0$ mixing seen by ARGUS (DESY) and UA1 (CERN).

flavour physics has since continued to progress ...

Status of the Standard Model

- Impressive precision measurements of the SM gauge structure at LEP!

- Still the following question is unanswered:

  Is the breaking of the electroweak symmetry and the generation of the particle masses in fact caused by the "minimal" Higgs mechanism, i.e. through the non-vanishing vacuum expectation value of a scalar field?

- Currently addressed at the Tevatron @ FNAL: data taking continues ...
  - $p\bar{p}$ collisions at 1.96 TeV.

- Exciting new insights are soon expected at the LHC @ CERN:
  - pp collisions at 14 TeV (initial operation at 10 TeV).
  - General purpose detectors ATLAS & CMS: EW symmetry breaking.
  - Start-up phase and commissioning is right now taking place:

$\longrightarrow$ recent CERN press releases:

LHC re-start scheduled for 2009

Geneva, 23 September 2008. Investigations at CERN following a large helium leak into sector 3-4 of the Large Hadron Collider (LHC) tunnel have indicated that the most likely cause of the incident was a faulty electrical connection between two of the accelerator's magnets. Before a full understanding of the incident can be established, however, the sector has to be brought to room temperature and the magnets involved opened up for inspection. This will take three to four weeks. Full details of this investigation will be made available once it is complete.

» Read the press release

Incident in LHC sector 3-4

Geneva, 20 September 2008. During commissioning (without beam) of the final LHC sector (sector 3-4) at high current for operation at 5 TeV, an incident occurred at mid-day on Friday 19 September resulting in a large helium leak into the tunnel.

» Read the press release

LHC progress report, week 1

Geneva, 18 September 2008. After a spectacular start on 10 September, the LHC enjoyed a mixed first week of commissioning with beam. To get beams around the ring in both directions on the first day exceeded all expectations, and the success continued through the night, with several hundred orbits being achieved. »

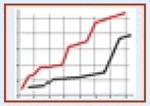
» Read more

First beam in the LHC - accelerating science

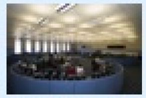
Geneva, 10 September 2008. The first beam in the Large Hadron Collider at CERN was successfully steered around the full 27 kilometres of the world's most powerful particle accelerator at 10h28 this morning. This historic event marks a key moment in the transition from over two decades of preparation to a new era of scientific discovery.

LHC - THE LARGE HADRON COLLIDER

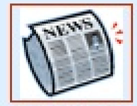
EDMS
CDD
MTF
SEARCH



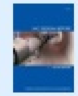
LHC dashboard



LHC Operation



LHC NEWS

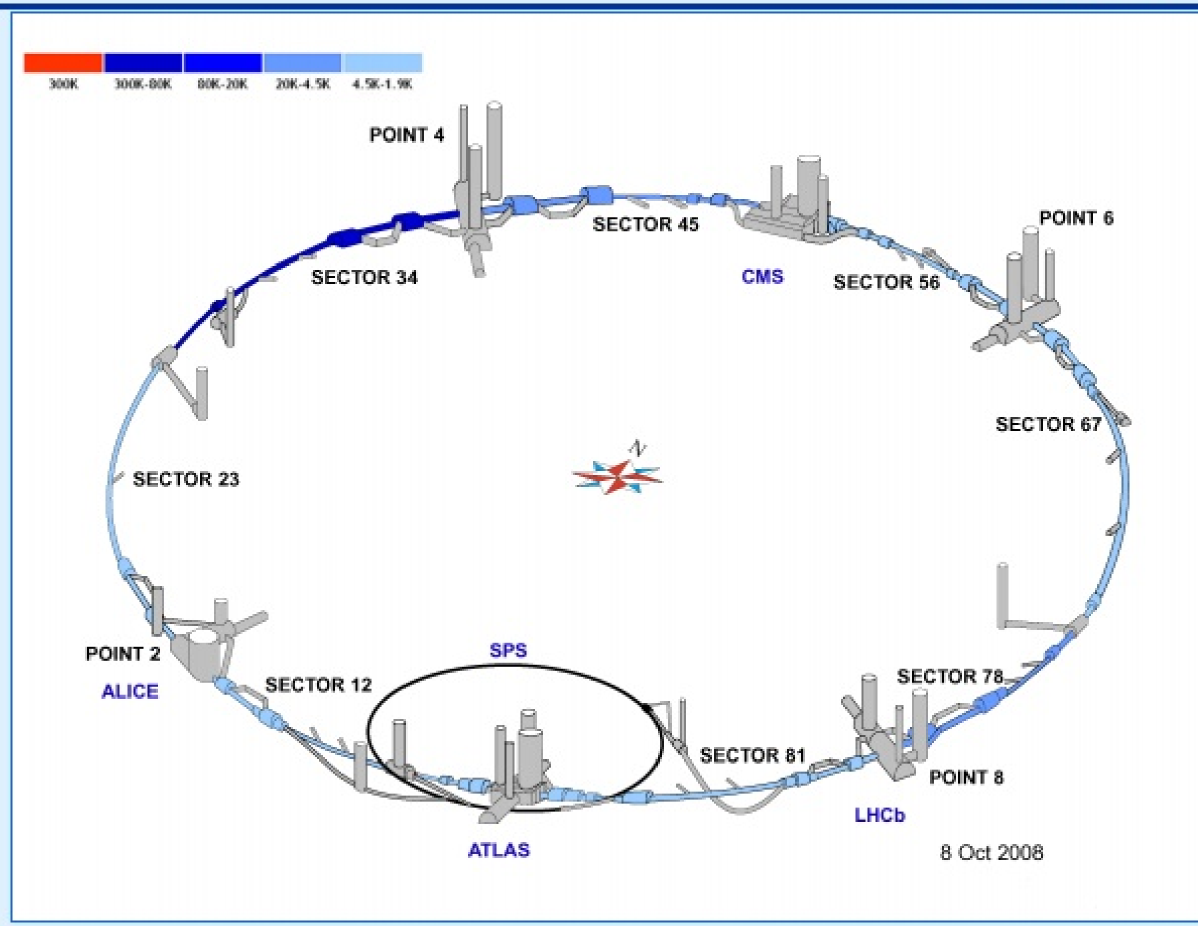


Design report

LHC Co-ordination schedule and status

General Information and Outreach
LHC@ interactions.org
Organization and Committees
Quality Assurance
Publications
Seminars and Workshops
Presentations
Images
Surface Sites
Underground Sites
LHC Experiments

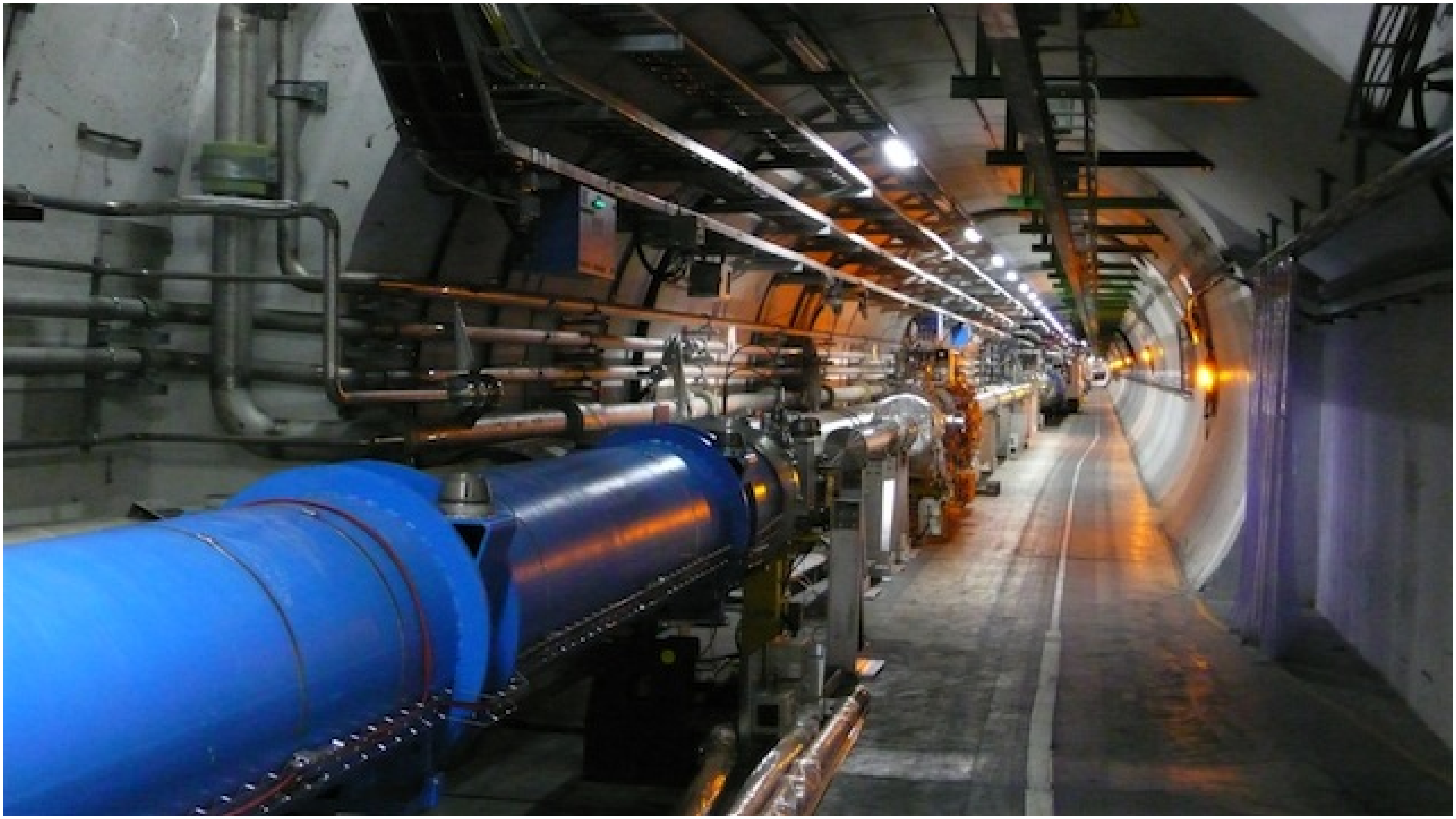
Beam Parameters
Lattice and Optics
Baseline Documentation
Equipment Catalogues
Naming and Conventions
Layouts
Integration
Installation
Hardware Commissioning
Sector Test
Beam Commissioning



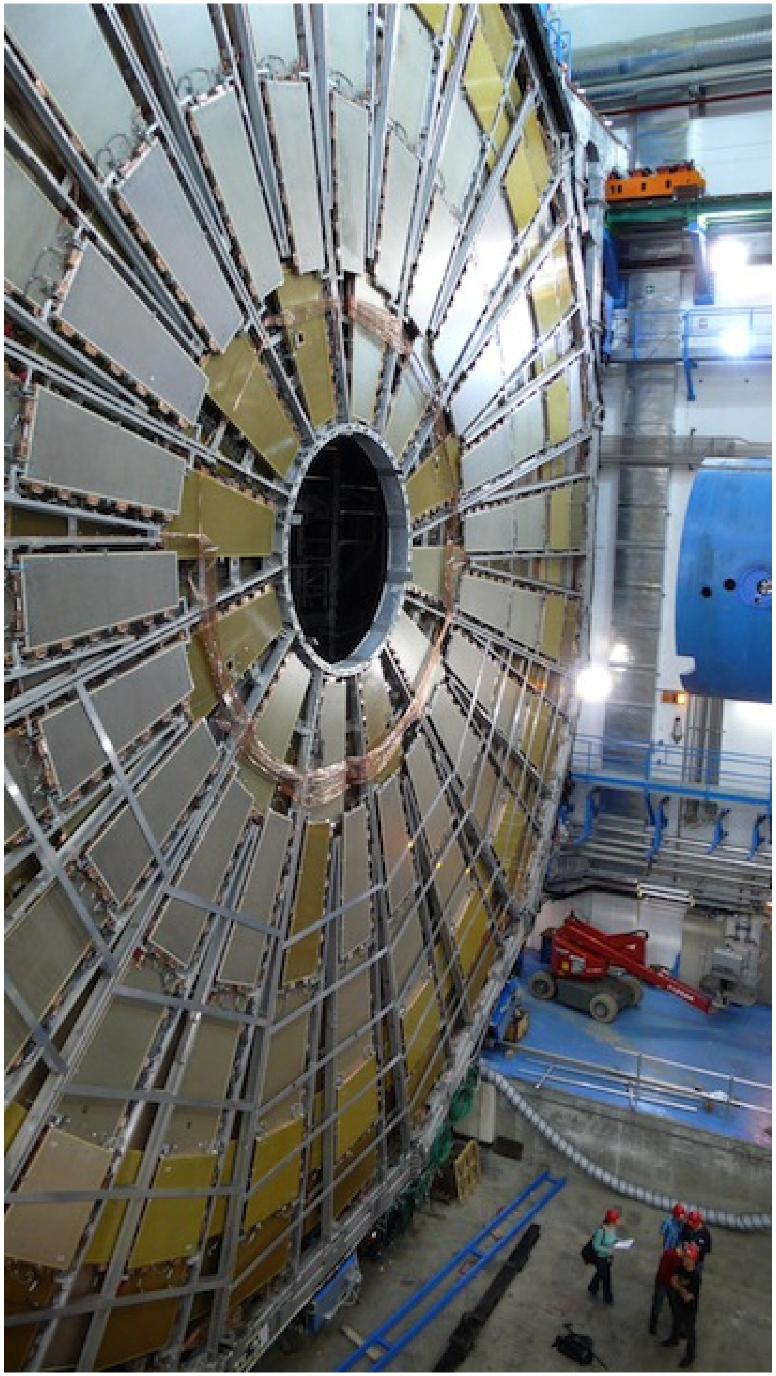
LHC Cooldown Status

Revised: 2008-07-24 LHC Webmaster

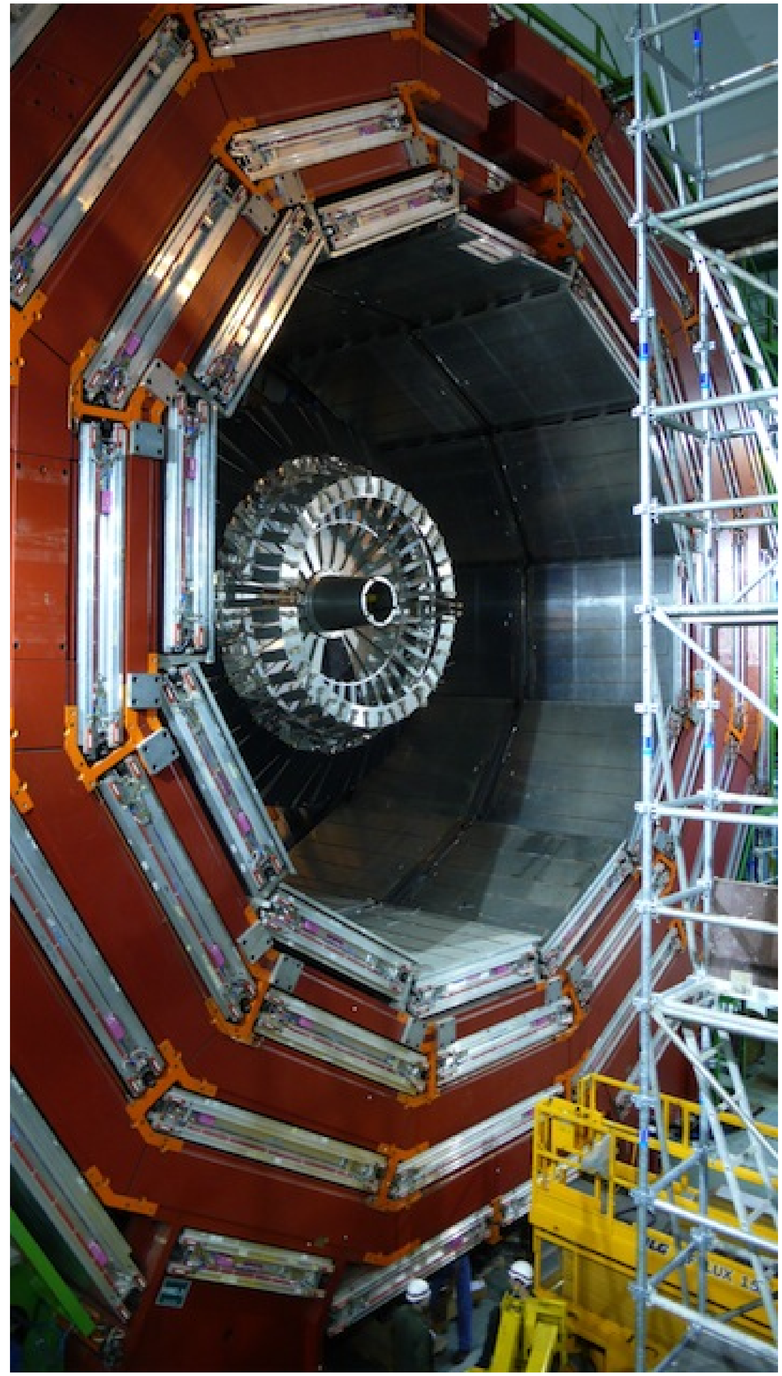
LHC tunnel ($\sim$ 1 year ago):



ATLAS ($\sim$ 1 year ago):



CMS ($\sim$ 1 year ago):



Status of the SM (Continued)

- The Yukawa interactions that give rise to the Fermion masses within the Higgs mechanism lead to a rich quark-flavour phenomenology:
  - The *interplay between theory & experiments* at the "flavour factories" resulted in many new insights into FCNCs and CP violation.
  - With the exception of a few "flavour puzzles" (not yet conclusive because of large errors), the SM flavour sector is in good shape.
  - But still a large territory of the flavour-physics landscape is unexplored:

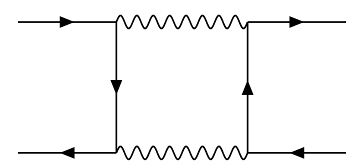
$\longrightarrow$ key target of another LHC experiment: **LHCb**

- We have indications that the SM *cannot* be complete:
  - Neutrino oscillations: $\longrightarrow$ rich lepton-flavour phenomenology, raising questions about CP violation and connections to the quark sector.
  - The long-standing problem of dark matter.
  - Generation of the baryon asymmetry of the Universe, ...

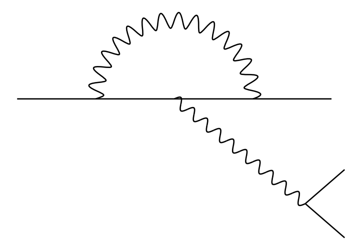
$\oplus$ fundamental theoretical questions (hierarchy problem, etc.)

Main Driving Force for Flavour Studies

- New Physics (NP): $\rightarrow$ typically new patterns in the flavour sector
  - supersymmetric (SUSY) scenarios;
  - left–right-symmetric models;
  - models with extra Z' bosons;
  - scenarios with extra dimensions;
  - "little Higgs" scenarios ...



- Sensitivity to NP through *virtual quantum effects:*



- Interplay with direct NP searches at ATLAS & CMS:[1]
  - If NP particles are produced and detected through their decays at the LHC, flavour-physics information helps us to determine/narrow the underlying NP model and to establish new sources of CP violation.
  - NP effects could in fact first show up in the flavour sector, also if NP particles are too heavy to be produced directly at the LHC.
  - Fortunately, theory will be confronted with LHC data soon...

[1] Addressed within a recent CERN workshop series: `http://flavlhc.web.cern.ch/flavlhc/`

Challenging the Standard Model through Flavour Studies

Before searching for NP, we have to understand the SM picture!

- The key problem:

  ◇ *Impact of strong interactions (QCD)* → "hadronic" uncertainties

- The B-meson system is a *particularly promising* flavour probe:

  – Simplifications through the large b-quark mass $m_b \sim 5\,\text{GeV} \gg \Lambda_{\text{QCD}}$.

  – Offers various strategies to eliminate the hadronic uncertainties and to determine the hadronic parameters from the data.

  – Tests of clean SM relations that could be spoiled by NP ...

- This feature led to the "rise of the B mesons":

  – K decays dominated for more than 30 years: *discovery* of (indirect) CP violation [→ ε_K ('64)] and direct CP violaton [→ Re$(\varepsilon'/\varepsilon)$ ('99)].

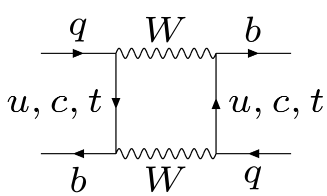
  – Since this decade the stage is governed by B mesons → our focus

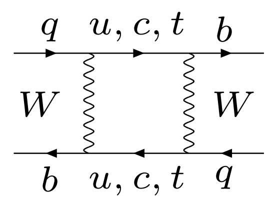
The Main Actors of this Talk: B Mesons

- Charged B mesons: $B^+ \sim u\,\bar{b}$ $\quad B^- \sim \bar{u}\,b$
  $B_c^+ \sim c\,\bar{b}$ $\quad B_c^- \sim \bar{c}\,b$

- Neutral B mesons: $B_d^0 \sim d\,\bar{b}$ $\quad \bar{B}_d^0 \sim \bar{d}\,b$
  $B_s^0 \sim s\,\bar{b}$ $\quad \bar{B}_s^0 \sim \bar{s}\,b$

  – B_q^0–$\bar{B}_q^0$ mixing:





$$\Rightarrow \boxed{|B_q(t)\rangle = a(t)|B_q^0\rangle + b(t)|\bar{B}_q^0\rangle \;:}$$

$*$ Schrödinger equation $\Rightarrow$ mass eigenstates:

$$\boxed{\Delta M_q \equiv M_{\rm H}^{(q)} - M_{\rm L}^{(q)}, \quad \Delta\Gamma_q \equiv \Gamma_{\rm H}^{(q)} - \Gamma_{\rm L}^{(q)}}$$

$*$ Decay rates: $\Gamma(\overset{(-)}{B_q^0}(t) \to \overset{(-)}{f})$:

$$\cos(\Delta M_q t) \;\&\; \sin(\Delta M_q t) \;\longrightarrow\; \text{oscillations!}$$

Where to Study B-Meson Decays?

- B factories: asymmetric e^+e^- colliders @ $\Upsilon(4S) \to B_d^0\bar{B}_d^0,\ B_u^+B_u^-$

  – PEP-II with the *Babar* experiment (SLAC) [terminated in Feb '08];

  – KEK-B with the *Belle* experiment (KEK) [continues ...]:

$$\to \begin{cases} \text{could well establish CP violation in the } B \text{ system;} \\ \text{many interesting results with } \sum \mathcal{O}(10^9)\ B\bar{B} \text{ pairs ...} \end{cases}$$

  – Discussion of a super-B factory, with increase of luminosity by $\mathcal{O}(10^2)$.

- Hadron colliders: $\to$ produce also B_s mesons,[2] as well as B_c, Λ_b, ...

  – Tevatron: CDF and DØ have reported first $B_{(s)}$-decay results ...

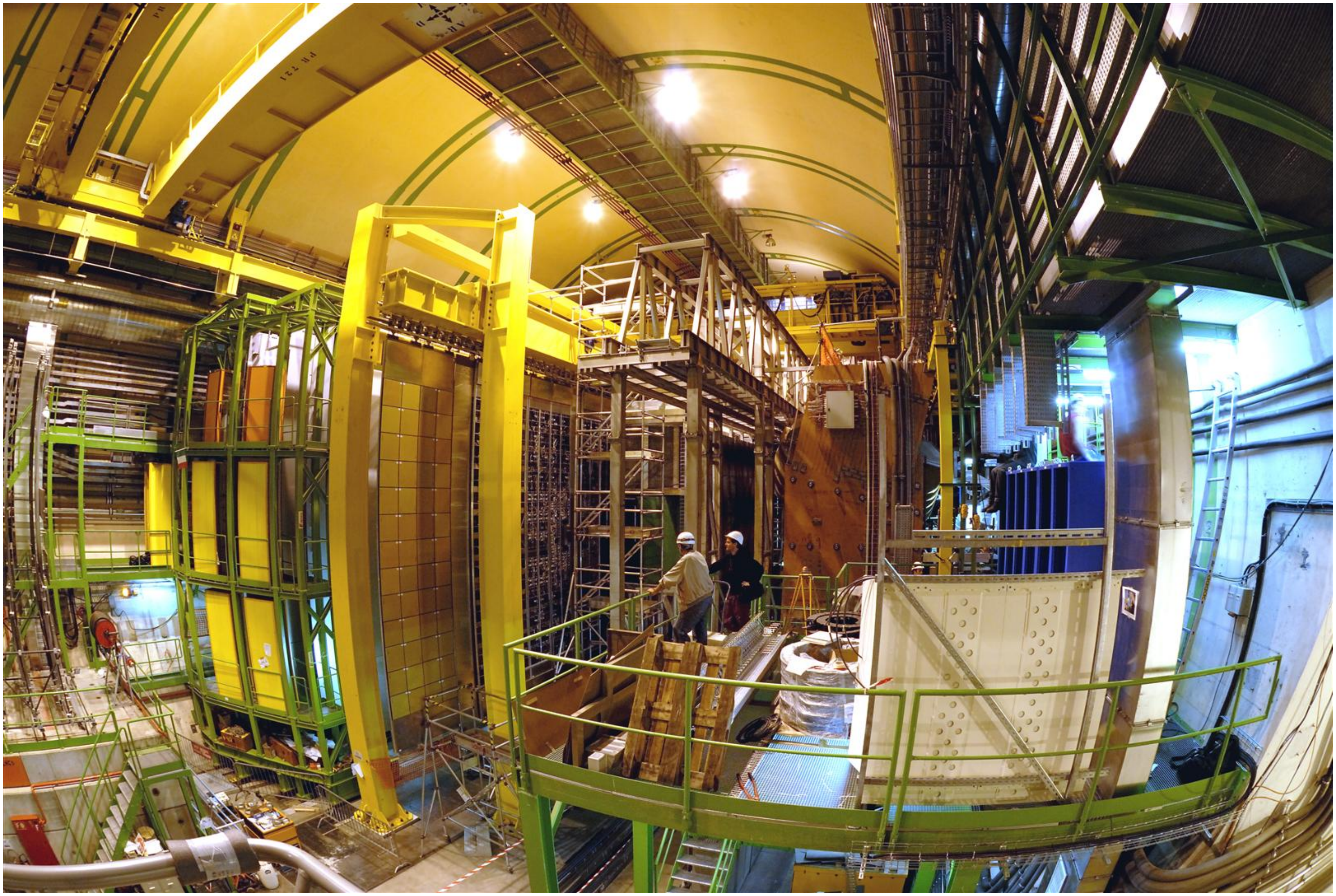
  – ... to be continued at the LHC $\gtrsim$ spring 2009:

ATLAS & CMS (can also address some B physics)

$\oplus$ *dedicated* B-decay experiment: LHCb

[2] Data at $\Upsilon(5S)$ were taken by Belle, allowing also access to B_s decays [hep-ex/0610003].

- <u>A picture of the LHCb experiment (∼ August 2006):</u>



Theoretical Framework

$\longrightarrow$ Unitarity Triangle, Effective Hamiltonians ...

CP Violation in the Standard Model

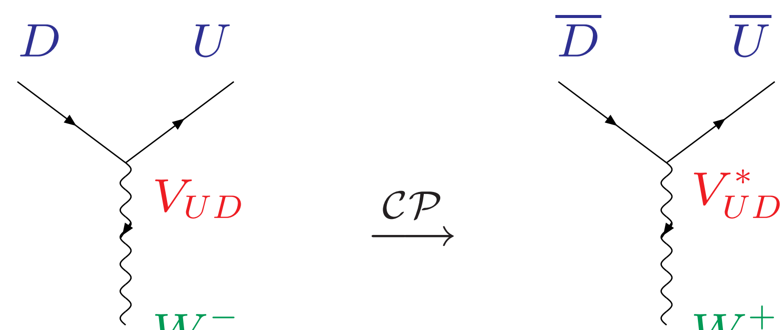
- Emerges in the "charged-current" quark interactions: $D \rightarrow W^- U$

$$\mathcal{L}_{\rm int}^{\rm CC} = -\frac{g_2}{\sqrt{2}} \left(\bar{u}_{\rm L}, \bar{c}_{\rm L}, \bar{t}_{\rm L}\right) \gamma^\mu \, \hat{V}_{\rm CKM} \begin{pmatrix} d_{\rm L} \\ s_{\rm L} \\ b_{\rm L} \end{pmatrix} W_\mu^\dagger + \text{h.c.}$$

  - $\hat{V}_{\rm CKM}$: Cabibbo–Kobayashi–Maskawa (CKM) matrix.
  - This "quark-mixing" matrix connects the flavour states of the down, strange and bottom quarks with their mass eigenstates through a unitary transformation ($\rightarrow$ relation to the Higgs/Yukawa sector):

$$\Rightarrow \boxed{\hat{V}_{\rm CKM}^\dagger \cdot \hat{V}_{\rm CKM} = \hat{1} = \hat{V}_{\rm CKM} \cdot \hat{V}_{\rm CKM}^\dagger}$$

- CP-conjugate transitions:



$$\boxed{V_{UD} \xrightarrow{\mathcal{CP}} V_{UD}^*}$$

$\Rightarrow$ *are there complex phases in the CKM matrix?*

- Parameters of the general quark-mixing matrix for N generations:

$$\underbrace{\frac{1}{2}N(N-1)}_{\text{angles}} + \underbrace{\frac{1}{2}(N-1)(N-2)}_{\text{complex phases}} = (N-1)^2$$

– Two generations: $\longrightarrow$ Cabibbo angle θ_C (1963)

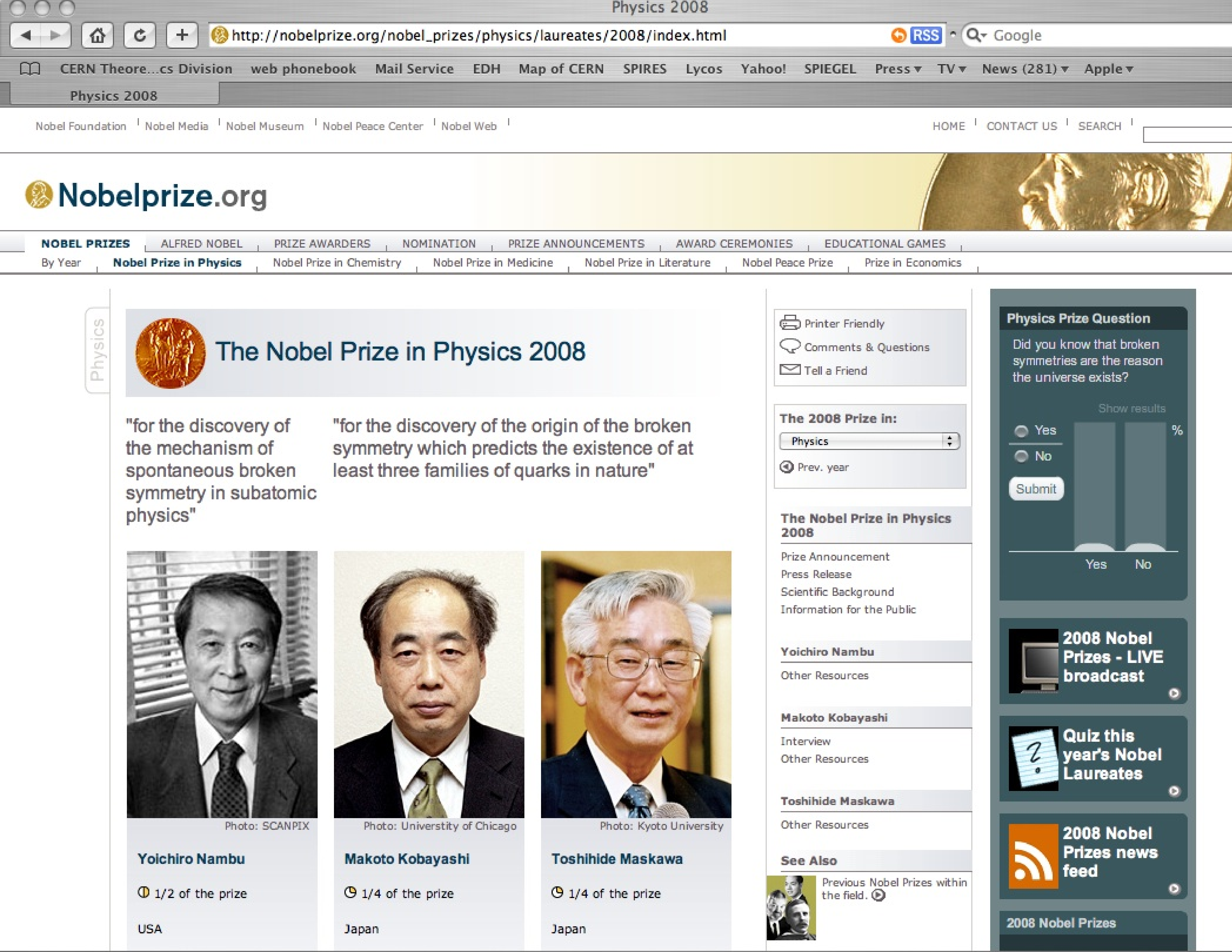
$$\hat{V}_C = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \quad [\sin\theta_C = 0.22 \text{ from } K \to \pi\ell\bar{\nu}_\ell]$$

– Three generations: $\longrightarrow$ Kobayashi & Maskawa (1973)

$\ast$ Parametrization requires three angles and *one complex phase* ...

$\ast$ Complex phase: $\Rightarrow$ allows us to accommodate CP violation

$\longrightarrow$ Kobayashi–Maskawa (KM) mechanism of CP violation


Physics 2008
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AWARD CEREMONIES
EDUCATIONAL GAMES
By Year
Nobel Prize in Physics
Nobel Prize in Chemistry
Nobel Prize in Medicine
Nobel Prize in Literature
Nobel Peace Prize
Prize in Economics
Physics
The Nobel Prize in Physics 2008
"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"
Photo: SCANPIX
Yoichiro Nambu
1/2 of the prize
USA
Photo: Universtity of Chicago
Makoto Kobayashi
1/4 of the prize
Japan
Photo: Kyoto University
Toshihide Maskawa
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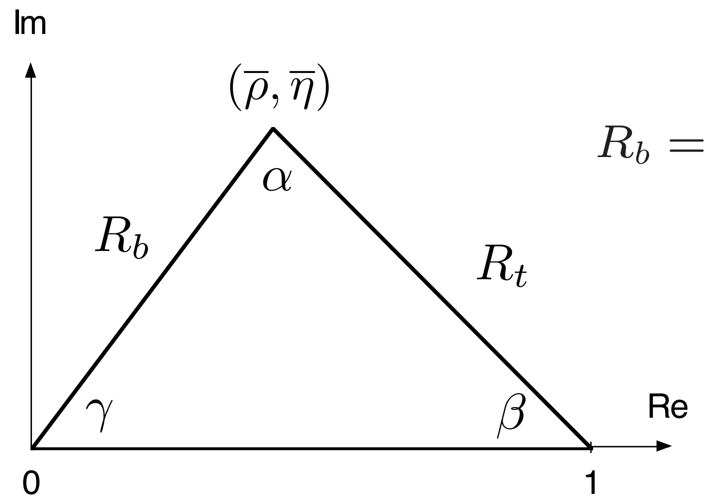
Central Target: Unitarity Triangle (UT)

- Application of the Wolfenstein parametrization: [Wolfenstein (1984)]

$$\hat{V}_{\text{CKM}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\,\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\,\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$\longrightarrow$ phenomenological expansion in $\lambda \equiv |V_{us}| = 0.22$ [from $K \to \pi\ell\bar{\nu}_\ell$]

- Unitarity of the CKM matrix: $\hat{V}^\dagger_{\text{CKM}} \cdot \hat{V}_{\text{CKM}} = \hat{1} = \hat{V}_{\text{CKM}} \cdot \hat{V}^\dagger_{\text{CKM}}$ $\Rightarrow$



$$R_b = \left(1 - \frac{\lambda^2}{2}\right)\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$

$$R_t = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{cb}}\right|$$

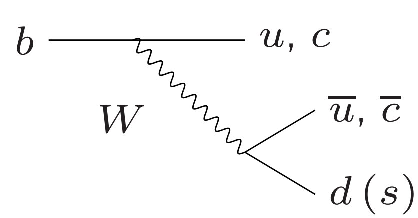
$$\overline{\rho} \equiv (1-\lambda^2/2)\rho, \quad \overline{\eta} \equiv (1-\lambda^2/2)\eta$$

$\longrightarrow$ NLO corrections [Buras *et al.* (1994)]

Key Processes for the Exploration of CP Violation

→ non-leptonic B decays (only quarks in the final states):

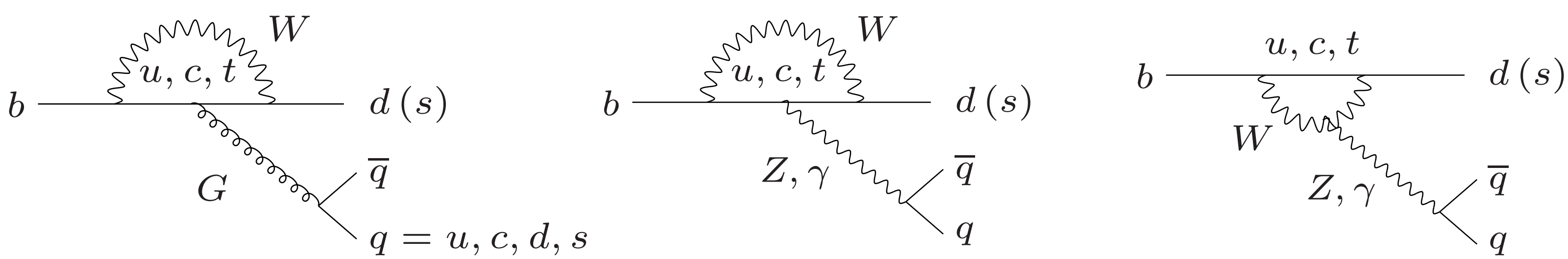
- Tree diagrams:



- "Penguin" diagrams: → loop processes:

  ◇ QCD penguins: ◇ Electroweak (EW) penguins:

  [Important because of large m_t! R.F. (1994)]



Theoretical Tool: Low-Energy Effective Hamiltonians

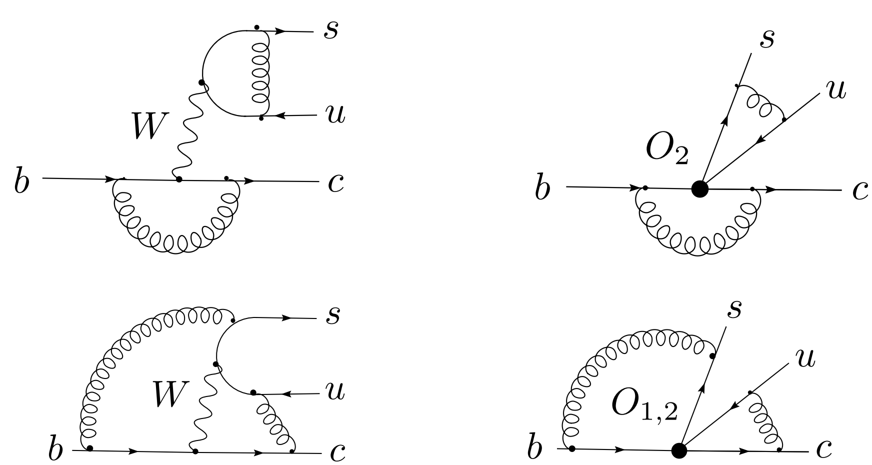
- Separation of the short-distance from the long-distance contributions:

$$\langle \overline{f}|\mathcal{H}_{\text{eff}}|\overline{B}\rangle = \frac{G_{\rm F}}{\sqrt{2}}\sum_j \lambda^j_{\rm CKM}\sum_k C_k(\mu)\,\langle \overline{f}|Q^j_k(\mu)|\overline{B}\rangle$$

[$G_{\rm F}$: Fermi's constant, $\lambda^j_{\rm CKM}$: CKM factors, μ: renormalization scale]

- Short-distance physics: [A.J. Buras *et al.*; ...]

$\longrightarrow$ Wilson coefficients $C_k(\mu)$ $\longrightarrow$ *perturbative* quantities $\longrightarrow$ known!

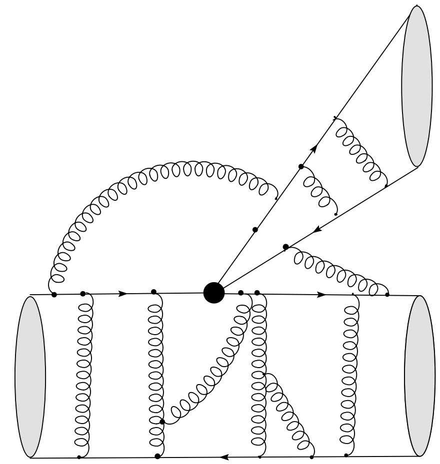


- Long-distance physics:

$\longrightarrow$ matrix elements $\langle \overline{f}|Q^j_k(\mu)|\overline{B}\rangle$ $\longrightarrow$ *non-perturbative* $\longrightarrow$ "unknown"!?

Recent Developments

$$|A_j|e^{i\delta_j} \propto \sum_k \underbrace{C_k(\mu)}_{\text{pert. QCD}} \times \boxed{\langle \overline{f}|Q_k^j(\mu)|\overline{B}\rangle}$$



- QCD factorization (QCDF):

  Beneke, Buchalla, Neubert & Sachrajda (1999–2001); ...

- Perturbative Hard-Scattering (PQCD) Approach:

  Li & Yu ('95); Cheng, Li & Yang ('99); Keum, Li & Sanda ('00); ...

- Soft Collinear Effective Theory (SCET):

  Bauer, Pirjol & Stewart (2001); Bauer, Grinstein, Pirjol & Stewart (2003); ...

- QCD sum rules:

  Khodjamirian (2001); Khodjamirian, Mannel & Melic (2003); ...

$$\boxed{\text{Data} \Rightarrow \textit{theoretical challenge remains} \ldots}$$

$\Rightarrow$ Circumvent the Calculation of the $\langle \overline{f}|Q_k^j(\mu)|\overline{B}\rangle$:

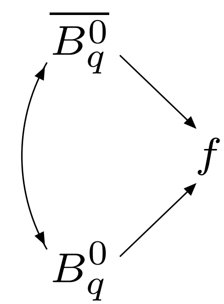
- Amplitude relations allow us in fortunate cases to eliminate the hadronic matrix elements ($\rightarrow$ typically strategies to determine the UT angle γ):

  – *Exact* relations: class of pure "tree" decays (e.g. $B \to DK$).

  – *Approximate* relations, which follow from the *flavour symmetries* of strong interactions, i.e. $SU(2)$ isospin or $SU(3)_\mathrm{F}$:

$$B \to \pi\pi,\ B \to \pi K,\ B_{(s)} \to KK.$$

- Decays of neutral B_d and B_s mesons:



Interference effects through B^0_q–$\overline{B^0_q}$ mixing:

  – Lead to "mixing-induced" CP violation $\mathcal{A}_{\rm CP}^{\rm mix}$, in addition to "direct" CP violation $\mathcal{A}_{\rm CP}^{\rm dir}$ (caused by interference between decay amplitudes).

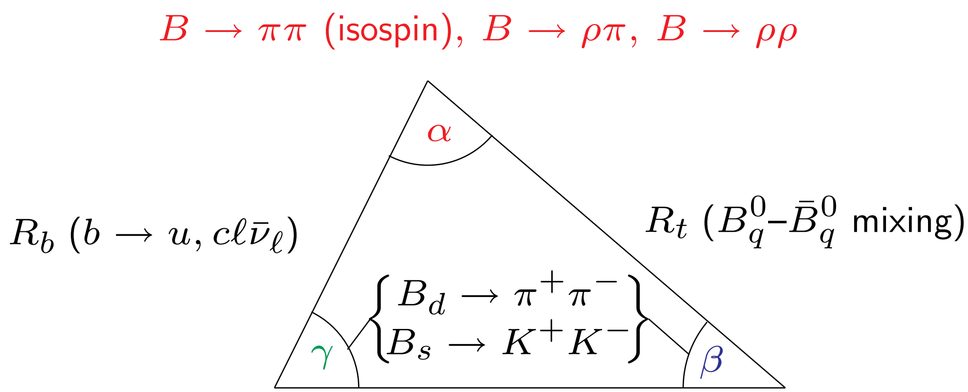
  – If one CKM amplitude dominates:

$$\Rightarrow \textit{hadronic matrix elements cancel!}$$

  $\ast$ Example: $\boxed{B^0_d \to J/\psi\, K_{\rm S} \quad \Rightarrow \quad \sin 2\beta}$ [Bigi, Carter & Sanda ('80–'81)]

A Brief Roadmap of Quark-Flavour Physics

- CP-B studies through various processes and strategies:



$B \to \pi K$ (penguins)

$B_d \to \psi K_S$ $(B_s \to \psi\phi : \phi_s \approx 0)$

$B_d \to \phi K_S$ (pure penguin)

$$\left.\begin{array}{l} B_u^\pm \to K^\pm D \\ B_d \to K^{*0} D \\ B_c^\pm \to D_s^\pm D \end{array}\right\} \text{only trees}$$

$$\left.\begin{array}{l} B_d \to D^{(*)\pm}\pi^\mp : \ \gamma + 2\beta \\ B_s \to D_s^\pm K^\mp : \ \gamma + \phi_s \end{array}\right\} \text{only trees}$$

- Moreover "rare" decays: $B \to X_s\gamma$, $B_{d,s} \to \mu^+\mu^-$, $K \to \pi\nu\bar{\nu}$, ...
  - Originate from loop processes in the SM.
  - Interesting correlations with CP-B studies.

New Physics $\Rightarrow$ Discrepancies

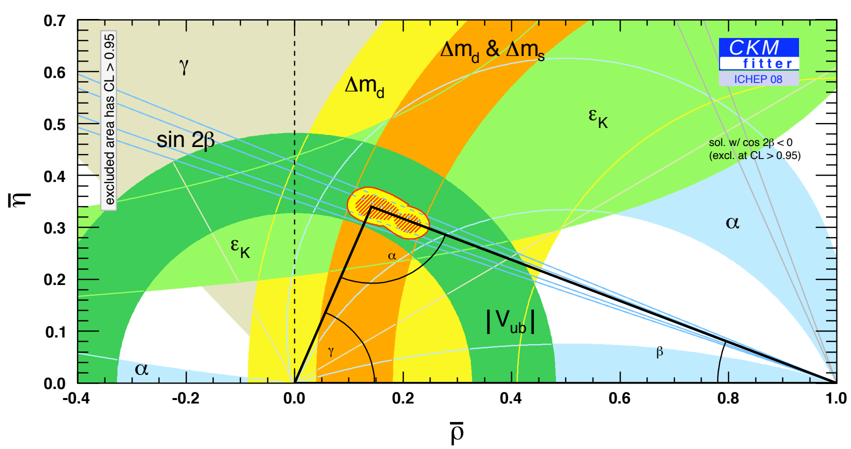
The Current Picture:

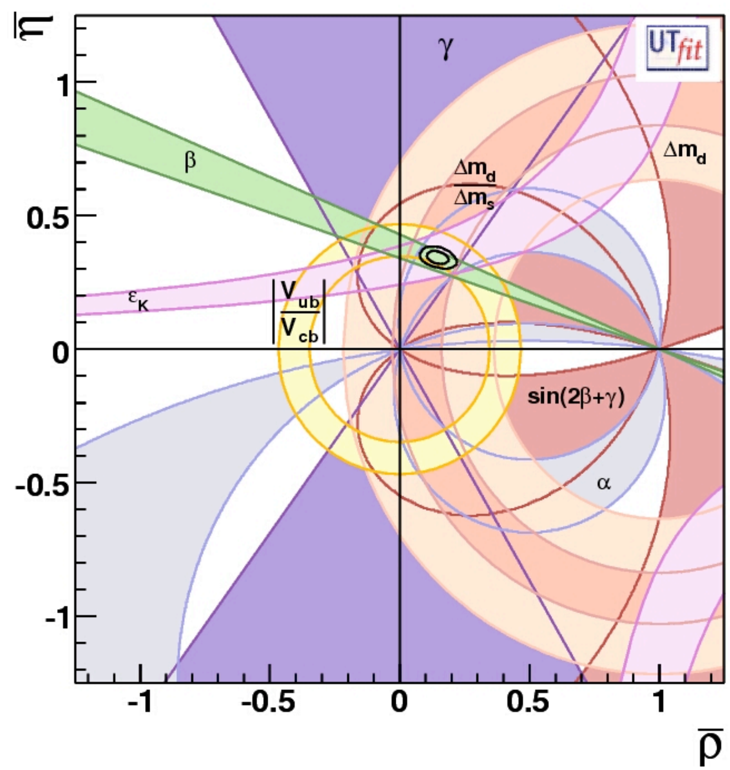
$\longrightarrow$ Implications of Flavour Data for New Physics ...

Status of the Unitarity Triangle

- Two competing groups: $\longrightarrow$ many plots & correlations ...
  - *CKMfitter* Collaboration [http://ckmfitter.in2p3.fr/];
  - *UTfit* Collaboration [http://www.utfit.org]:

$\longrightarrow$ *continuously updated results:*





$\Rightarrow$ impressive global agreement with KM (β vs. $|V_{ub}|$=?) ...

[$|V_{ub}|$ $B \to X_u \ell \nu_\ell, \ldots$: $\longrightarrow$ Giulia Ricciardi @ Napoli; ...]

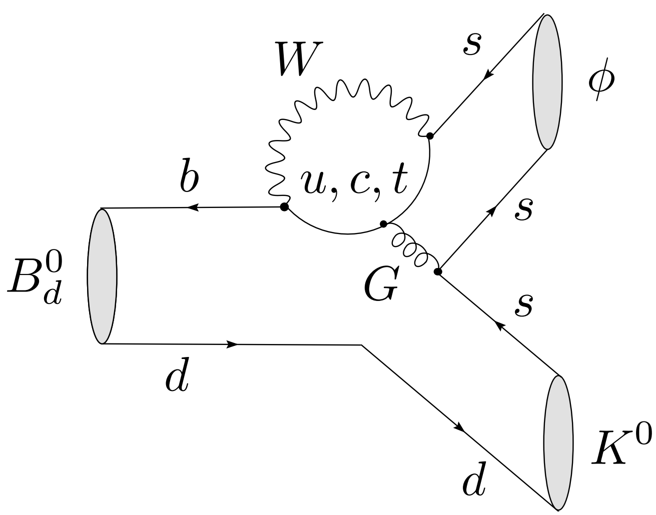
◇ New Physics in Decay Amplitudes:

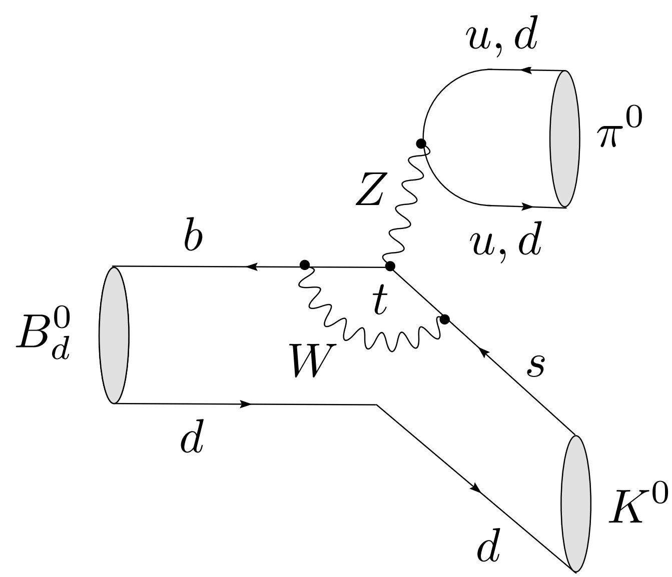
- Typically *small* effects if SM tree processes play the dominant rôle:

$$\longrightarrow \text{example: } B_d^0 \to J/\psi K_{\mathrm{S}}$$

- Potentially *large* effects in the penguin sector through new particles in the loops or new contributions at the tree level, e.g. SUSY, Z' models:

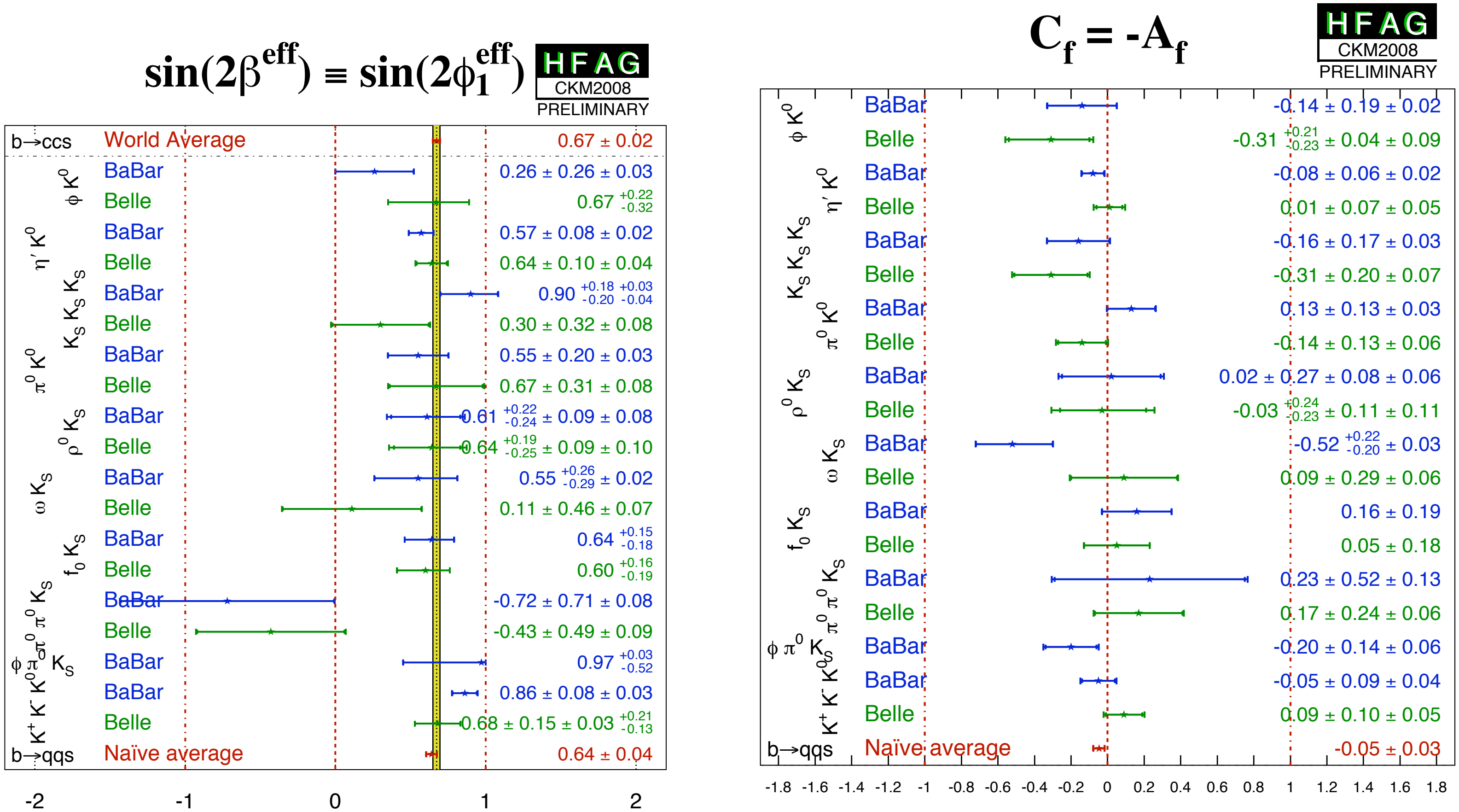
$\longrightarrow$ **hot topic:** decays that are dominated by $b \to s$ penguins ...





CP Violation in $b \to s$ Penguin Modes

- Experimental pattern:



- Moreover: "$B \to \pi K$ puzzle" received quite some attention [Buras & R.F. ('00); Buras, R.F., Recksiegel & Schwab ('03–'06); ...]

$\Rightarrow$ NP could be present, but still cannot be resolved!?

Particularly Interesting Decay: $B^0 \to \pi^0 K^0$

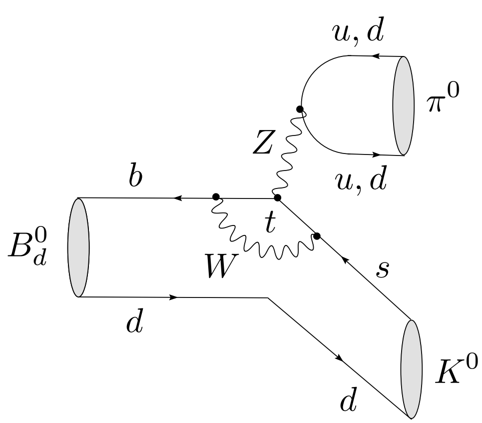
- Time-dependent, CP-violating rate asymmetry:

$$\frac{\Gamma(\bar{B}^0(t) \to \pi^0 K_{\rm S}) - \Gamma(B^0(t) \to \pi^0 K_{\rm S})}{\Gamma(\bar{B}^0(t) \to \pi^0 K_{\rm S}) + \Gamma(B^0(t) \to \pi^0 K_{\rm S})} = A_{\pi^0 K_{\rm S}} \cos(\Delta M_d\, t) + S_{\pi^0 K_{\rm S}} \sin(\Delta M_d\, t)$$

- In the SM, we have – up to doubly Cabibbo-suppressed terms:

$$A_{\pi^0 K_{\rm S}} \approx 0, \quad S_{\pi^0 K_{\rm S}} \equiv (\sin 2\beta)_{\pi^0 K_{\rm S}} \approx \sin 2\beta$$

- EW penguins have a significant impact: $\Rightarrow$ nice for NP to enter!?



$\Rightarrow$ control the hadronic effects in the SM prediction!

(recent: R.F., S. Jäger, D. Pirjol and J. Zupan, arXiv:0806.2900 [hep-ph] $\longrightarrow$)

SM Benchmark for the NP Search in $B^0 \to \pi^0 K^0$

- Isospin relation is the starting point:

$$\sqrt{2}\,A(B^0 \to \pi^0 K^0) + A(B^0 \to \pi^- K^+) = -\underbrace{\left[(\hat{T}+\hat{C})e^{i\gamma} + \hat{P}_{\rm ew}\right]}_{(\hat{T}+\hat{C})(e^{i\gamma} - q e^{i\omega})} \equiv 3A_{3/2}$$

- $A_{3/2}$ can be fixed through $SU(3)$ [assume $\gamma = (65 \pm 10)^\circ$]:

  – EW penguin parameter:

$$q\,e^{i\omega} \equiv -\frac{\hat{P}_{\rm ew}}{\hat{T}+\hat{C}} = \frac{-3}{2\lambda^2 R_b}\frac{C_9(\mu)+C_{10}(\mu)}{C_1(\mu)+C_2(\mu)}R_q = 0.66 \times \frac{0.41}{R_b}R_q$$

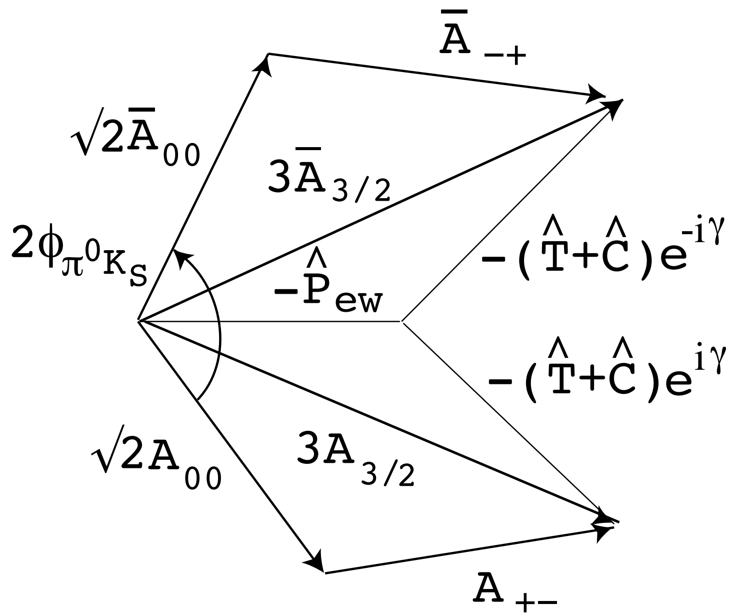
  * $SU(3)$ breaking: assume first $R_q = 1 \pm 0.3$; can be well predicted through factorization techniques + future lattice QCD input.

  – Tree parameter:

$$|\hat{T}+\hat{C}| = R_{T+C}\,|V_{us}/V_{ud}|\,\sqrt{2}|A(B^+ \to \pi^+\pi^0)|$$

  * $R_{T+C} \sim f_K/f_\pi \to 1.22 \pm 0.2$, where the error is very conservative.

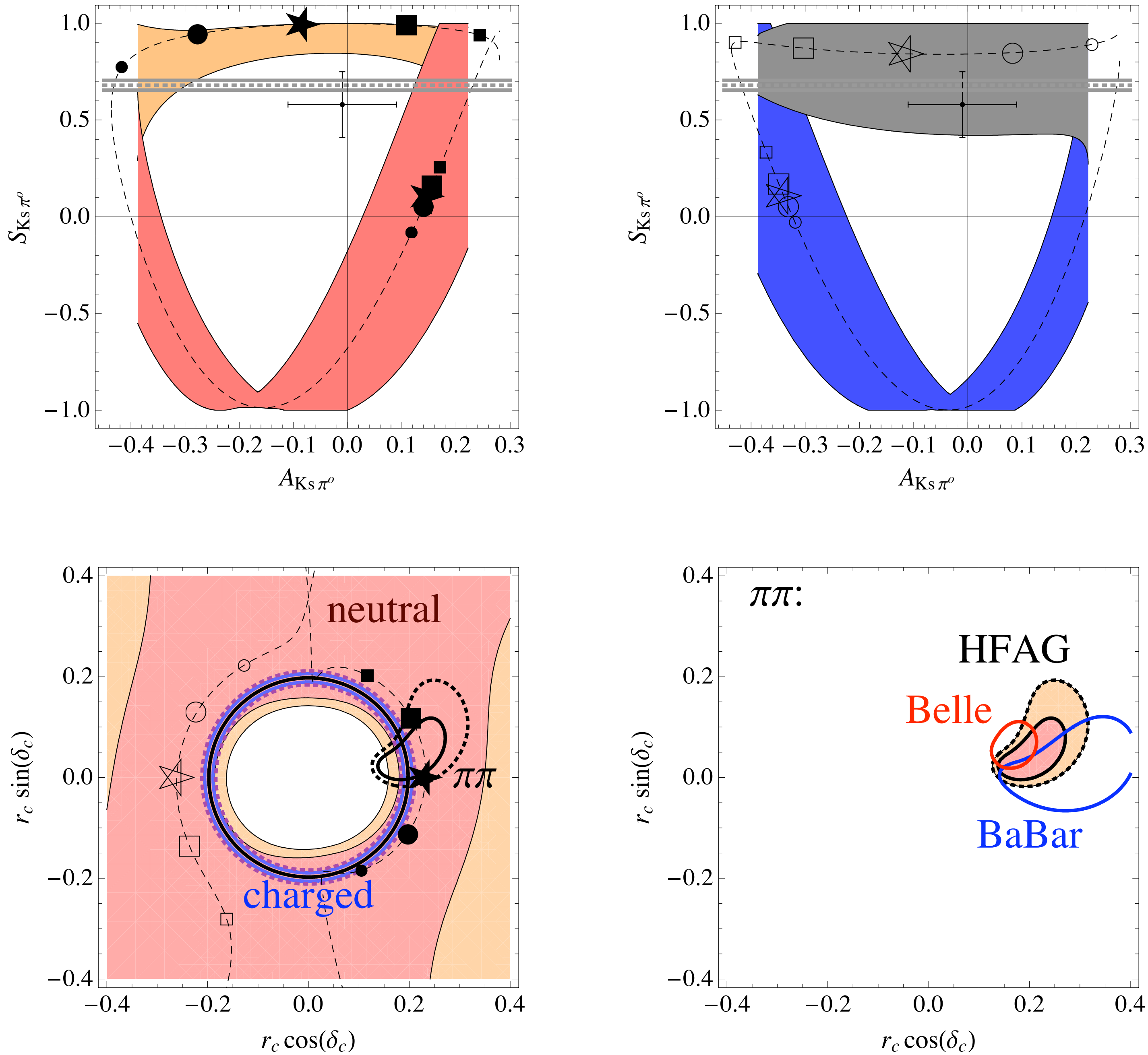
- Triangle construction in the complex plane:



  - Rates for decays and their CP conjugates: triangles can be constructed.
  - Encounter a fourfold ambiguity: the triangles can be flipped around the $A_{3/2}$ and $\bar{A}_{3/2}$ axes (which are fixed as we have just discussed).

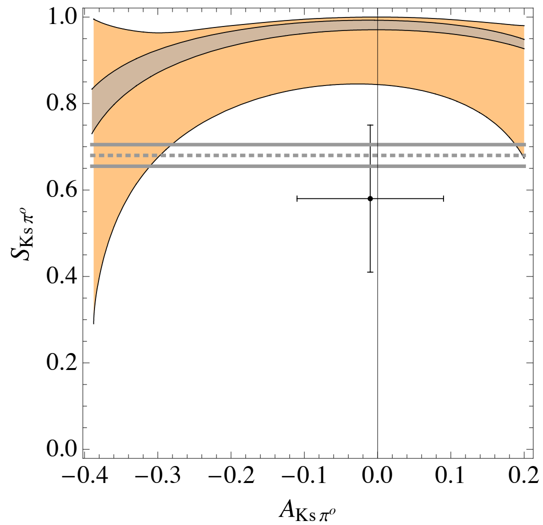
- Prediction for the mixing-induced CP violation in $B^0 \to \pi^0 K_S$:

$$S_{\pi^0 K_S} = \frac{2|\bar{A}_{00} A_{00}|}{|\bar{A}_{00}|^2 + |A_{00}|^2} \sin(2\beta - 2\phi_{\pi^0 K_S}) \Rightarrow \text{current data} \rightarrow$$



$$r_c e^{i\delta_c} = (\hat{T} + \hat{C})/\hat{P};\ B^+ \to \pi^+ K^0 \to |\hat{P}|$$ ("charged" constraint)

- So we are finally left with the following correlation in observable space:

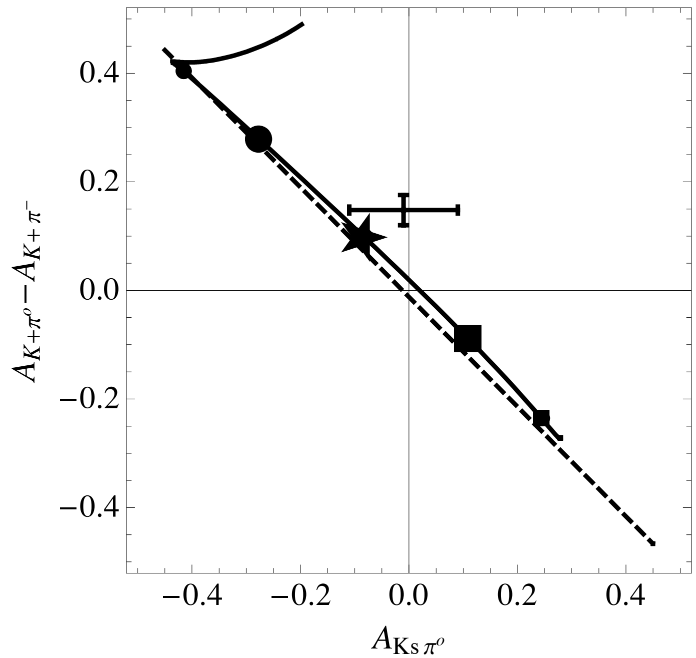


$$S_{\pi^0 K_S} = 0.99^{+0.01}_{-0.08}\Big|_{\rm exp.}{}^{+0.000}_{-0.001}\Big|_{R_{\rm T+C}}{}^{+0.00}_{-0.11}\Big|_{R_q}{}^{+0.00}_{-0.07}\Big|_{\gamma}$$

- Narrow upper band: $\rightarrow$ benchmark scenario for future TH uncertainty
  - Both R_q and R_{T+C} factorize at LO in the $1/m_b$ expansion, and can be well predicted using input from lattice QCD.
  - Use QCDF as a working tool (similar conclusions follow in SCET):
    - R_{T+C}: form-factor dependence essentially cancels $\rightarrow 1.23^{+0.02}_{-0.03}$.
    - R_q is key parameter, governed by $SU(3)$-breaking form-factor ratio: 20% @ lattice: $\rightarrow R_q = 0.908^{+0.052}_{-0.043}$ (present: $R_q = 1.02^{+0.27}_{-0.22}$)

Direct CP Asymmetries

- SM correlation between $A_{\pi^0 K_S}$ and $A_{\pi^0 K^+} - A_{\pi^- K^+}$:



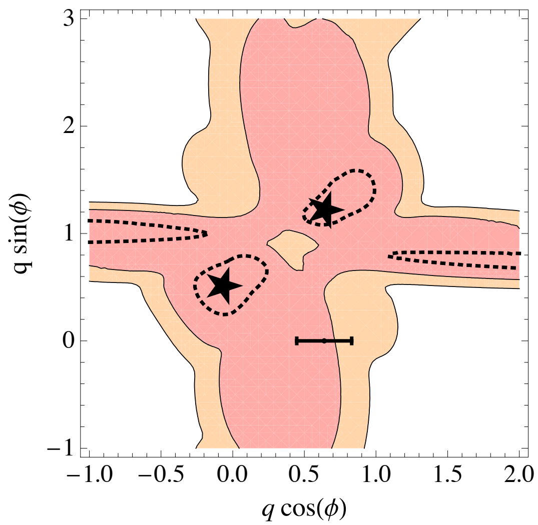
- The difference $A_{\pi^0 K^+} - A_{\pi^- K^+} \neq 0$ has recently received quite some attention as a possible sign of NP [Belle Collaboration, *Nature* **452** (2008) 332].

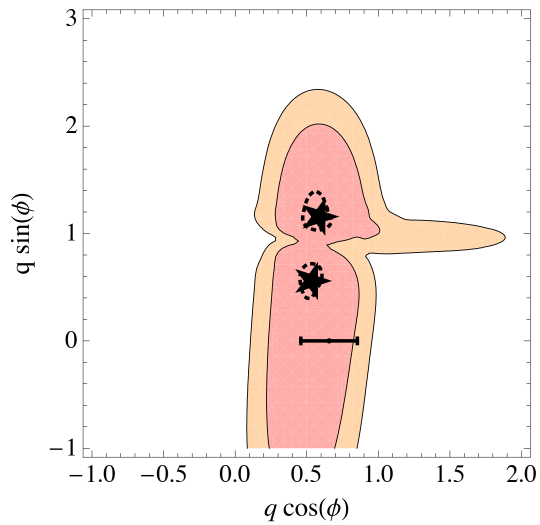
- However, the data can be accommodated in the SM within the error of $A_{\pi^0 K_S}$, although hadronic amplitudes then deviate from the $1/m_b$ pattern...

$\Rightarrow$ reduce the experimental error of $A_{\pi^0 K_S}$

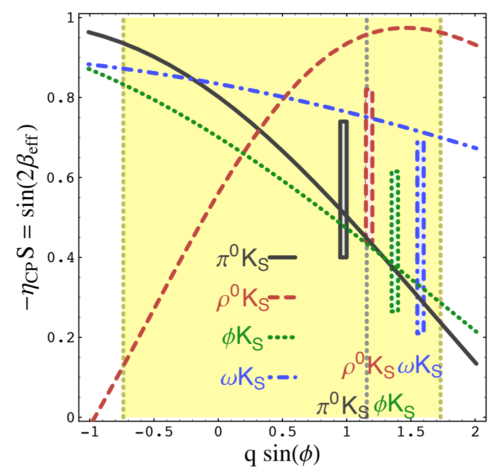
NP Scenario to Resolve the $S_{\pi^0 K_S}$ Discrepancy

- Assume that NP manifests itself as a modified EWP: $q \to qe^{i\phi}$
  - χ^2 fits: only $B \to \pi K$:
  - both $B \to \pi K$ and $B \to \pi\pi$:





- Other penguin-dominated $b \to s$ decays can be accommodated as well:

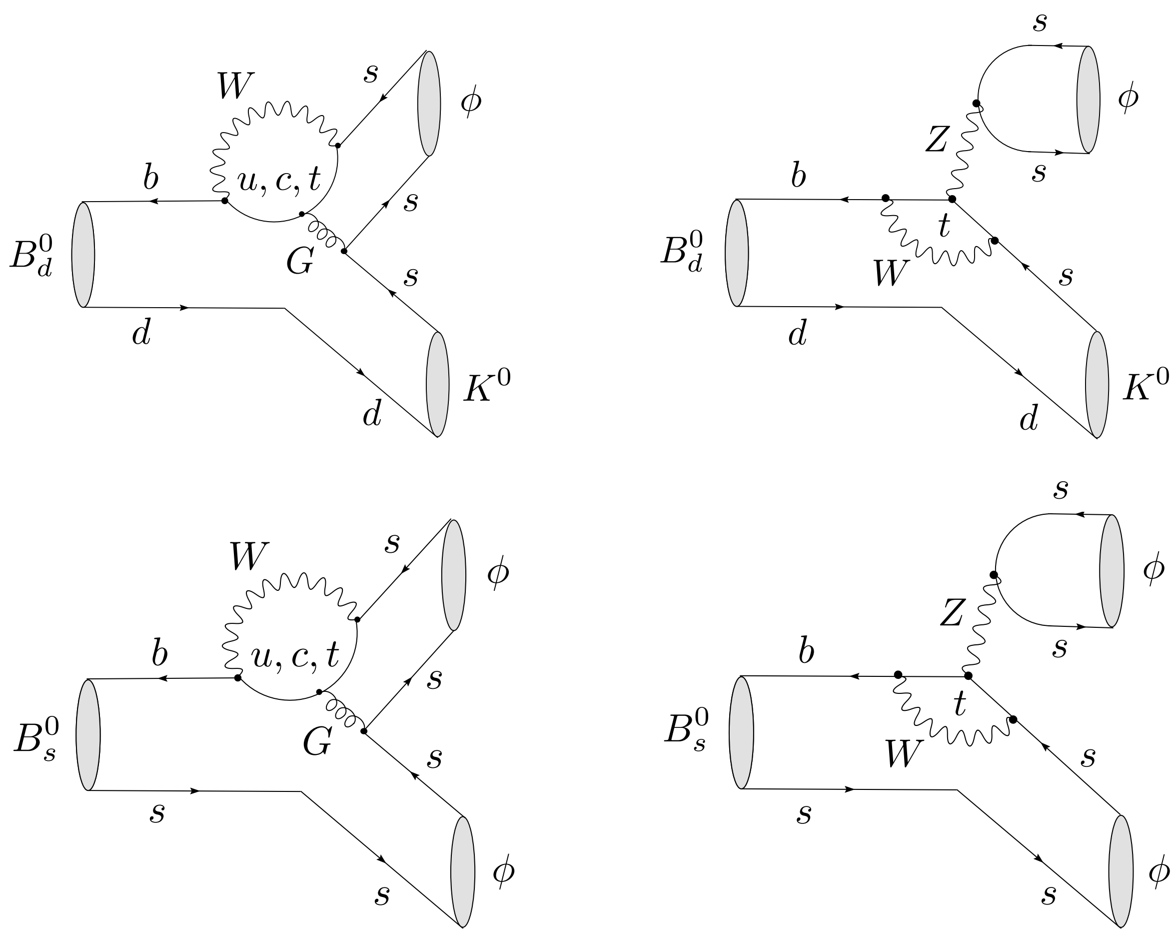


[Illustration in QCDF]

LHCb can also address this topic:

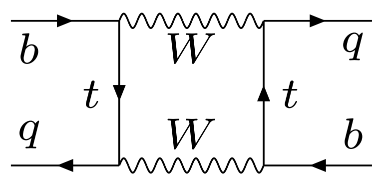
- Most promising channel for this experiment: $B_s^0 \to \phi\phi$

  – Down spectator quark of $B_d^0 \to \phi K_S$ replaced by strange quark:



  – Angular distribution of $B_s^0 \to \phi[\to K^+K^-]\phi[\to K^+K^-]$ ...

◇ New Physics in B_q^0–$\bar{B}_q^0$ mixing:



- NP particles in boxes or tree contributions (e.g. SUSY, Z' models):

$$\boxed{M_{12}^q = M_{12}^{q,\mathrm{SM}} + M_{12}^{q,\mathrm{NP}} \equiv M_{12}^{q,\mathrm{SM}} \left(1 + \kappa_q e^{i\sigma_q}\right)} \Rightarrow$$

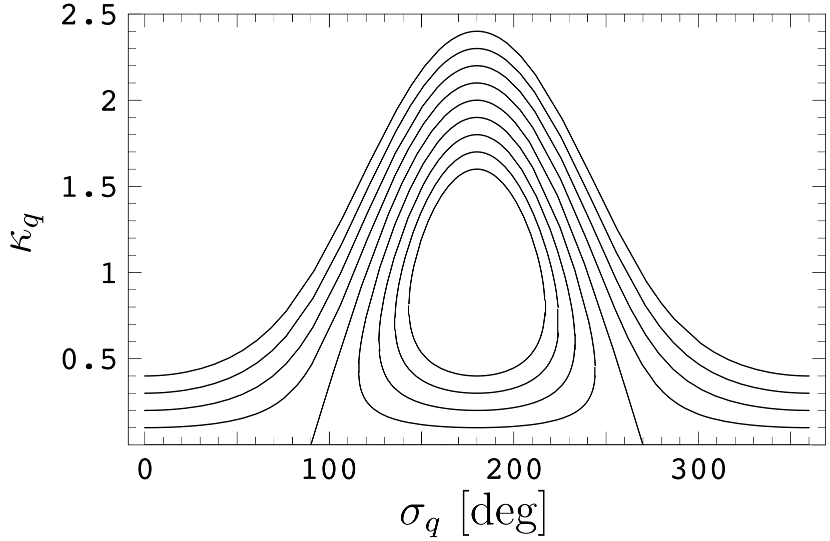
  – Mass difference: $\Delta M_q = \Delta M_q^{\mathrm{SM}} \left|1 + \kappa_q e^{i\sigma_q}\right|$

  – Mixing phase: $\phi_q = \phi_q^{\mathrm{SM}} + \phi_q^{\mathrm{NP}} = \phi_q^{\mathrm{SM}} + \arg(1 + \kappa_q e^{i\sigma_q})$

[Details: P. Ball & R.F. (2006)]

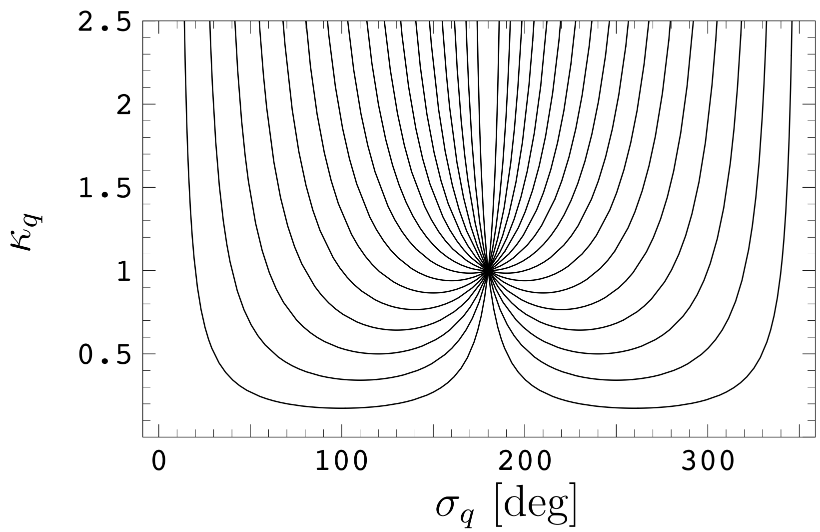
Constraints in the NP Space of B_q^0–$\bar{B}_q^0$ Mixing

- Contours in the σ_q–κ_q plane following from $\rho_q \equiv \Delta M_q / \Delta M_q^{\rm SM}$:



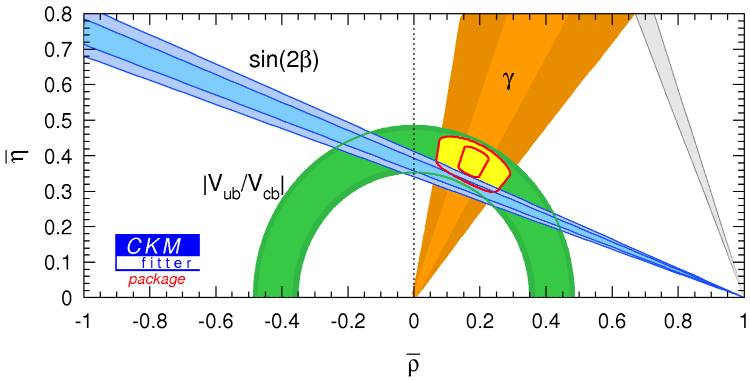
$[0.6 \leq \rho_q \leq 1.4]$

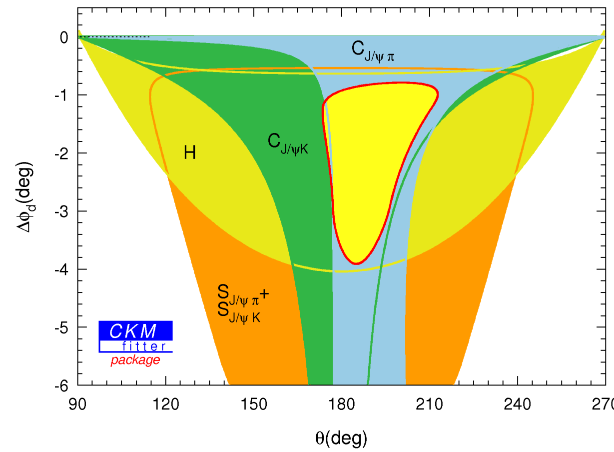
- Contours in the σ_q–κ_q plane following from the NP phase $\phi_q^{\rm NP}$:



$\left[10^\circ \leq |\phi_q^{\rm NP}| \leq 170^\circ\right]$

Implications of the Data for the B_d System





- Tension in the fit of the UT: $(\phi_d)_{J/\psi K^0} - 2\beta_{\rm true} = -(8.7^{+2.6}_{-3.6} \pm 3.8)^\circ$
- Could be NP in B^0_d–$\bar{B}^0_d$ mixing (!?): $\phi_d = 2\beta + \phi_d^{\rm NP}$
- But what about SM effects?: $\to$ doubly Cabibbo-suppressed penguins:

$$\frac{S(J/\psi K_{\rm S})}{\sqrt{1 - C(J/\psi K_{\rm S})^2}} = \sin(\phi_d + \Delta\phi_d)$$

  – $\Delta\phi_d$ fixed through $B^0_d \to J/\psi\pi^0$ data and $SU(3)$ flavour-symmerty:
    * Fit to all current data, allowing also for $SU(3)$ breaking:

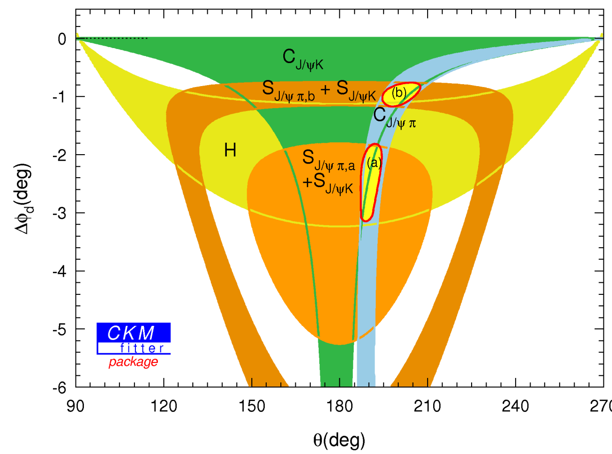
$\Rightarrow$ $\boxed{\Delta\phi_d \in [-6.7, 0.0]^\circ \Rightarrow \text{softens tension in fit of UT!}}$

[S.F., M. Jung, R.F. & T. Mannel (2008); Ciuchini, Pierini & Silvestrini (2005)]

- NP parameters: $\phi_d^{\rm NP} \in [-14.9, 4.0]^\circ$, i.e. no significant effect.

  – However, this still allows for $\kappa_d = |M_{12}^{d,\rm NP}/M_{12}^{d,\rm SM}| \lesssim 0.5$, so that NP contributions could be as large as 50% but cannot be resolved...

- Future perspectives (scenarios):



  – Since the exp. error of $(\phi_d)_{J/\psi K^0}$ could be reduced to $\sim 0.3^\circ$ (LHCb upgrade and e^+e^- super-B factory), these corrections will be crucial.

- Interesting observations:

  – The quality of the B-factory data has essentially reached a level of precision where subleading SM effects have to be included!

  – In the analyses of CP violation in $B^0 \to J/\psi K_{\rm S}$ this is mandatory in order to fully exploit the physics potential for NP searches.

B Physics at the LHC:

$\longrightarrow$ entering a new territory of the B landscape:

high statistics $\oplus$ *complementarity* to B factories:

fully exploit the B_s-meson system!

General Features of the B_s System

- Rapid B_s^0–$\bar{B}_s^0$ oscillations: $\Delta M_s \stackrel{\rm SM}{=} \mathcal{O}(20\,\text{ps}^{-1}) \gg \Delta M_d \stackrel{\rm exp}{=} 0.5\,\text{ps}^{-1}$

  $\Rightarrow$ challenging to resolve them experimentally!

- The width difference $\Delta\Gamma_s/\Gamma_s$ is expected to be of $\mathcal{O}(10\%)$ [$\tau_{B_s} \sim 1.5$ps]:

  – Experimental status: $B_s \to J/\psi\phi$ @ Tevatron $\Rightarrow$

$$\Delta\Gamma_s = \begin{cases} (0.19 \pm 0.07^{+0.02}_{-0.01})\text{ps}^{-1} & \text{[DØ ('08)]} \\ (0.076^{+0.059}_{-0.063} \pm 0.006)\text{ps}^{-1} & \text{[CDF ('07)]} \end{cases}$$

  – May provide interesting CPV studies through "untagged" rates:

$$\langle\Gamma(B_s(t) \to f)\rangle \equiv \Gamma(B_s^0(t) \to f) + \Gamma(\overline{B_s^0}(t) \to f)$$

  * The rapidly oscillating $\Delta M_s t$ terms cancel!
  * Various "untagged" strategies were proposed.

    [Dunietz ('95); R.F. & Dunietz ('96); Dunietz, Dighe & R.F. ('99); ...]

- The CP-violating phase of B_s^0–$\bar{B}_s^0$ mixing is *tiny* in the SM:

$$\boxed{\phi_s \stackrel{\rm SM}{=} -2\lambda^2\eta \approx -2^\circ}$$

$\Rightarrow$ interesting for NP searches!

Hot News of 2006:

- Signals for B_s^0–$\bar{B}_s^0$ mixing at the Tevatron:

  - For many years, only lower bounds on ΔM_s were available from the LEP (CERN) experiments and SLD (SLAC)!

  - Finally, the value of ΔM_s could be pinned down:

    * DØ: $\Rightarrow$ two-sided bound $17\,\mathrm{ps}^{-1} < \Delta M_s < 21\,\mathrm{ps}^{-1}$ (90% C.L.)

      $\Rightarrow$ 2.5 σ @ $\Delta M_s = 19\,\mathrm{ps}^{-1}$; 2007: $\boxed{\Delta M_s = (18.56 \pm 0.87)\,\mathrm{ps}^{-1}}$

    * CDF: $\boxed{\Delta M_s = [17.77 \pm 0.10(\mathrm{stat}) \pm 0.07(\mathrm{syst})]\ \mathrm{ps}^{-1}}$ $\gtrsim 5\sigma$

- Lattice prediction ($f_{B_s}^2 \hat{B}_{B_s}$): [HPQCD collaboration, hep-lat/0610104]

$$\boxed{\Delta M_s^{\mathrm{SM}} = 20.3(3.0)(0.8)\,\mathrm{ps}^{-1}}$$

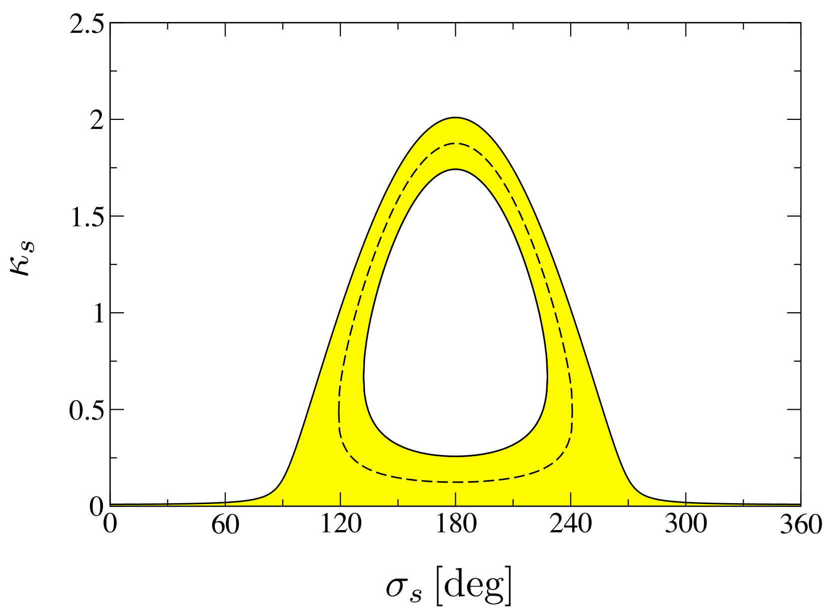
Constraints on NP through ΔM_s

- CKM unitarity and Wolfenstein expansion: $|V_{ts}^* V_{tb}| = |V_{cb}| \left[1 + \mathcal{O}(\lambda^2)\right]$

  $\Rightarrow$ no information on γ and R_b needed (in contrast to ΔM_d)!

- Numerical results: $\rho_s \equiv \Delta M_s / \Delta M_s^{\mathrm{SM}} = 0.88 \pm 0.13 \Rightarrow$

- Allowed region in the σ_s–κ_s plane: [Update of P. Ball & R.F. (2006)]



$\Rightarrow$ plenty of space for NP left!

  – NP usually correlated with $b \to s$ penguin modes (see above): $B^0 \to \pi^0 K_{\mathrm{S}}$, $B^0 \to \phi K_{\mathrm{S}}$, $B_s \to \phi\phi$, ...

Golden Process to Search

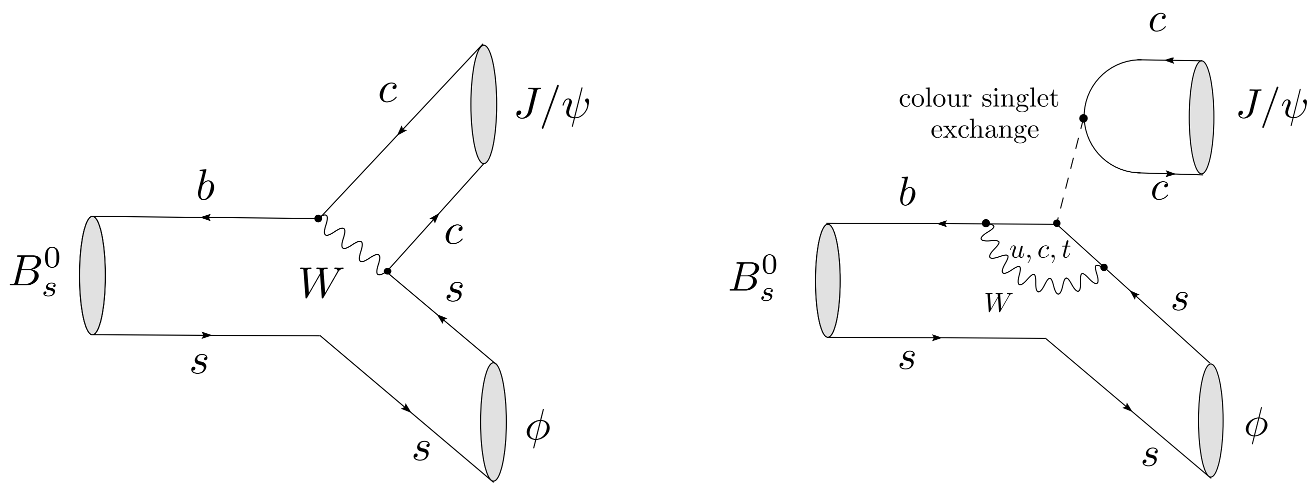
for NP in B_s^0–$\bar{B}_s^0$ Mixing:

$$\boxed{B_s^0 \to J/\psi\phi}$$

$\longrightarrow$ B_s^0 counterpart of $B_d^0 \to J/\psi K_{\rm S}$ ...

[Dighe, Dunietz & R.F. (1999); Dunietz, R.F. & Nierste (2001)]

Let's have a closer look ...



- Amplitude phase structure (robust under NP, as tree dominated):

$\Rightarrow$ hadronic matrix elements cancel in mixing-induced observables!

- There is an important difference with respect to $B_d^0 \to J/\psi K_S$:

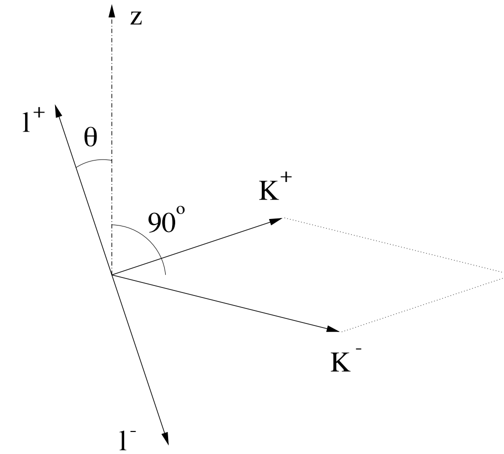
The final state is an admixture of different CP eigenstates!

- *Angular distribution* of the $J/\psi[\to \ell^+\ell^-]\phi[\to K^+K^-]$ decay products:

$\Rightarrow$ different CP eigenstates can be disentangled ...

Simple Case: One-Angle Distribution

$$\frac{d\Gamma(t)}{d\cos\Theta} \propto \underbrace{[P_+(t)]}_{\text{CP even}} \frac{3}{8}\left(1+\cos^2\Theta\right) + \underbrace{[P_-(t)]}_{\text{CP odd}} \frac{3}{4}\sin^2\Theta$$



- *Untagged* data samples: $\longrightarrow$ untagged rates ...

$$P_\pm(t) + \overline{P}_\pm(t) \propto \left[(1 \pm \cos\phi_s)e^{-\Gamma_{\rm L}t} + (1 \mp \cos\phi_s)e^{-\Gamma_{\rm H}t}\right]$$

- *Tagged* data samples: $\longrightarrow$ CP asymmetries ...

$$\frac{P_\pm(t) - \overline{P}_\pm(t)}{P_\pm(t) + \overline{P}_\pm(t)} = \pm \frac{2\sin(\Delta M_s t)\sin\phi_s}{(1 \pm \cos\phi_s)e^{+\Delta\Gamma_s t/2} + (1 \mp \cos\phi_s)e^{-\Delta\Gamma_s t/2}}$$

$$\boxed{B^0_s\text{–}\bar{B}^0_s \text{ mixing phase } \phi_s = (-2\lambda^2\eta)_{\rm SM} + \phi_s^{\rm NP} \approx \phi_s^{\rm NP}} \quad \Rightarrow$$

- CP-violating NP effects would be indicated by the following features:[3]
  - The *untagged* observables depend on *two* exponentials;
  - *sizeable* values of the CP-violating asymmetries.

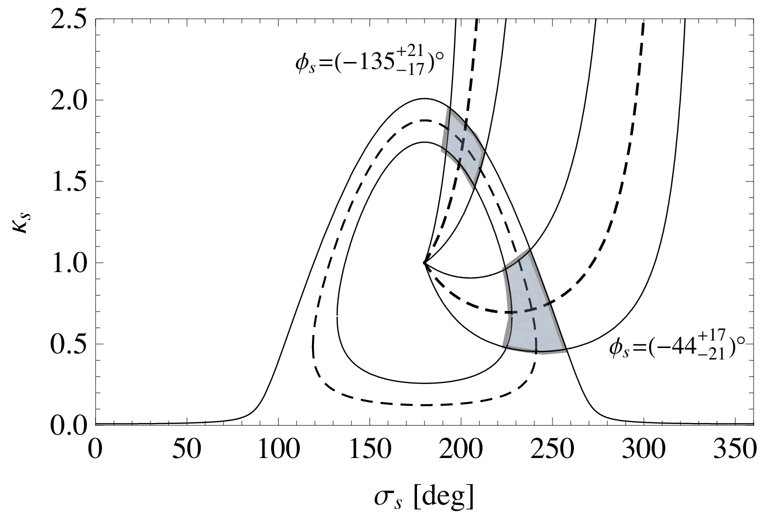
[3] Similar features hold also for the full three-angle distribution: more complicated, but no problem ...

Further News from the Tevatron

- First *tagged* analyses of the $B_s \to J/\psi\phi$ decay by CDF and DØ:
  - T. Aaltonen *et al.* (CDF Collaboration), arXiv:0712.2397 [hep-ex]
  - V.M. Abazov *et al.* (DØ Collaboration), arXiv:0802.2255 [hep-ex]

- UTfit collaboration: arXiv:0803.0659 [hep-ph]
  - Performing an average of CDF and DØ and taking other constraints into account, it is speculated about CP-violating NP in B_s^0–$\bar{B}_s^0$ mixing.

- Heavy Flavour Averaging Group (HFAG): $\phi_s^{\rm NP} = \left(-44^{+17}_{-21}\right)^\circ \vee \left(-135^{+21}_{-17}\right)^\circ$

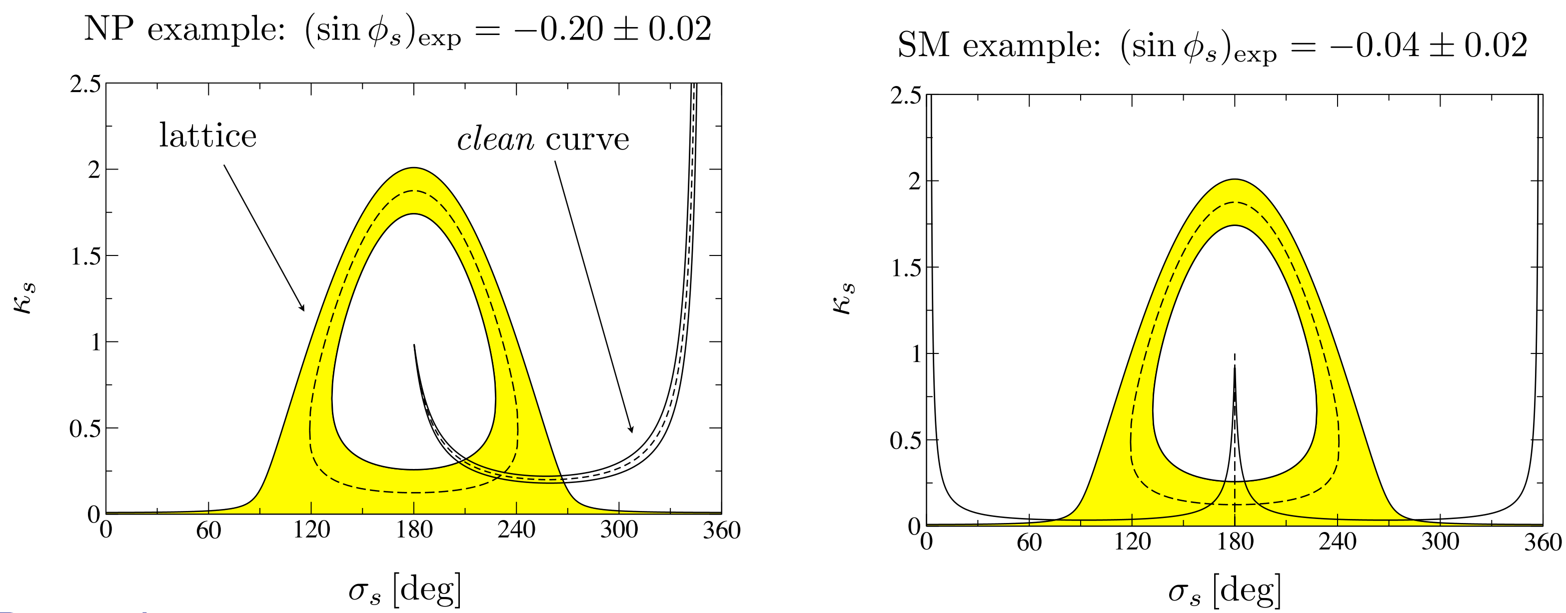


$\Rightarrow$!? Fortunately, ϕ_s is very accessible @ LHCb ...

Prospects for ϕ_s Measurements at the LHC

- Experimental reach @ LHCb: *very impressive ...*
  - One nominal year of operation, i.e. 2 fb^{-1}: $\sigma(\phi_s)_{\rm exp} \sim 1^\circ$
  - LHCb upgrade with integrated lumi of 100 fb^{-1}: $\sigma(\phi_s)_{\rm exp} \sim 0.2^\circ$

- Illustration: $(\sin\phi_s)_{\rm exp} = -0.20 \pm 0.02$ ($\to$ NP @ 10 σ) vs. SM case



- Remarks:
  - It is very challenging to establish NP without new CP-violating effects.
  - But the data still leave a lot of space for such effects in specific NP scenarios (SUSY, Z', ...), which could be detected at the LHC!

[Details: P. Ball & R.F. (2006)]

Further Benchmark Decays

for the

LHCb Experiment

$\longrightarrow$ very rich physics programme ...

[For experimental overviews, see CERN TH Flavour Institute:
http://ph-dep-th.web.cern.ch/ph-dep-th/content2/THInstitutes/2008/flavour/TH-Flavour.html]

Two Major Lines of Research

1. Precision measurements of γ:

- Tree strategies, with expected sensitivities after 1 year of taking data:
  - $B_s^0 \to D_s^{\mp} K^{\pm}$: $\sigma_\gamma \sim 14^\circ$
  - $B_d^0 \to D^0 K^*$: $\sigma_\gamma \sim 8^\circ$ ... to be compared with the
  - $B^{\pm} \to D^0 K^{\pm}$: $\sigma_\gamma \sim 5^\circ$

  current B-factory data: $\gamma|_{D^{(*)}K^{(*)}} = \begin{cases} (67^{+32}_{-25})^\circ & \text{[CKMfitter]} \\ (88 \pm 16)^\circ & \text{[UTfit]} \end{cases}$

- Decays with penguin contributions:
  - $B_s^0 \to K^+ K^-$ and $B_d^0 \to \pi^+\pi^-$: $\sigma_\gamma \sim 5^\circ$
  - $B_s^0 \to D_s^+ D_s^-$ and $B_d^0 \to D_d^+ D_d^-$

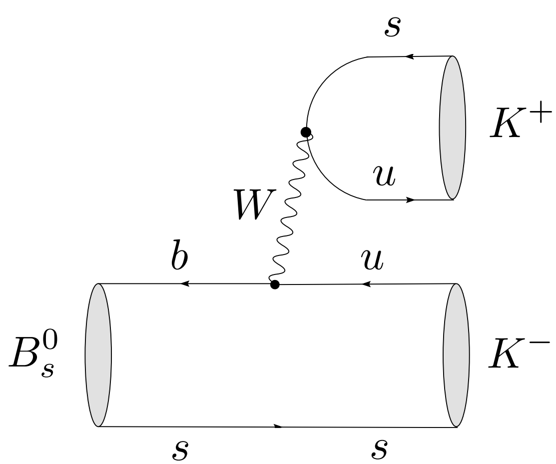
2. Analyses of rare decays which are absent at the SM tree level:

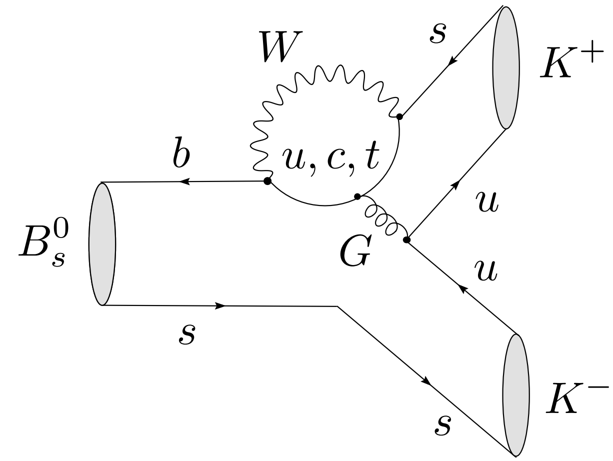
- $B_s^0 \to \mu^+\mu^-$, $B_d^0 \to \mu^+\mu^-$
- $B_d^0 \to K^{*0}\mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$; ...

$\rightarrow$ let's have a closer look at some decays ...

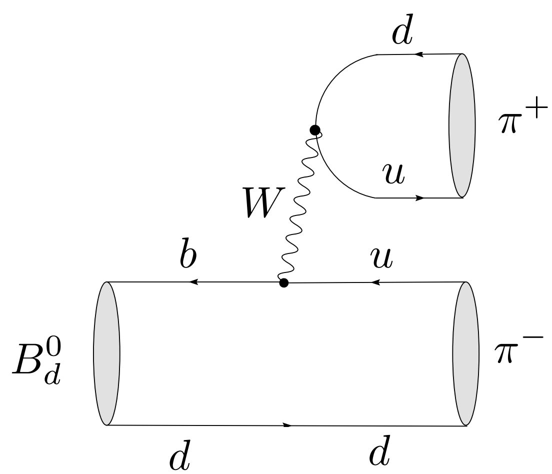
The $B_s \to K^+K^-$, $B_d \to \pi^+\pi^-$ System

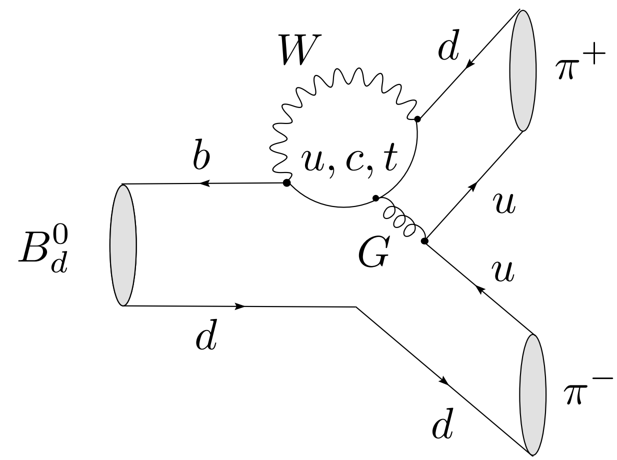
- $B_s^0 \to K^+K^-$:





- $B_d^0 \to \pi^+\pi^-$:





$\Rightarrow$ $\boxed{s \leftrightarrow d}$

- Structure of the decay amplitudes in the Standard Model:

$$A(B_d^0 \to \pi^+\pi^-) \propto \left[e^{i\gamma} - d e^{i\theta}\right]$$

$$A(B_s^0 \to K^+K^-) \propto \left[e^{i\gamma} + \left(\frac{1-\lambda^2}{\lambda^2}\right) d' e^{i\theta'}\right]$$

$$d\, e^{i\theta} = \left.\frac{\text{“penguin”}}{\text{“tree”}}\right|_{B_d\to\pi^+\pi^-}, \quad d'\, e^{i\theta'} = \left.\frac{\text{“penguin”}}{\text{“tree”}}\right|_{B_s\to K^+K^-}$$

[d, d': real hadronic parameters; θ, θ': strong phases]

- General form of the CP asymmetries:

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-) = G_1(d,\theta,\gamma), \quad \mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^+\pi^-) = G_2(d,\theta,\gamma,\phi_d)$$

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to K^+K^-) = G_1'(d',\theta',\gamma), \quad \mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-) = G_2'(d',\theta',\gamma,\phi_s)$$

- $\phi_d = 2\beta$ (from $B_d \to J/\psi K_{\rm S}$) and $\phi_s \approx 0$ are known parameters:

  – $\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-)$ & $\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^+\pi^-)$: $\Rightarrow$ $\boxed{d = d(\gamma)}$ (clean!)

  – $\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to K^+K^-)$ & $\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-)$: $\Rightarrow$ $\boxed{d' = d'(\gamma)}$ (clean!)

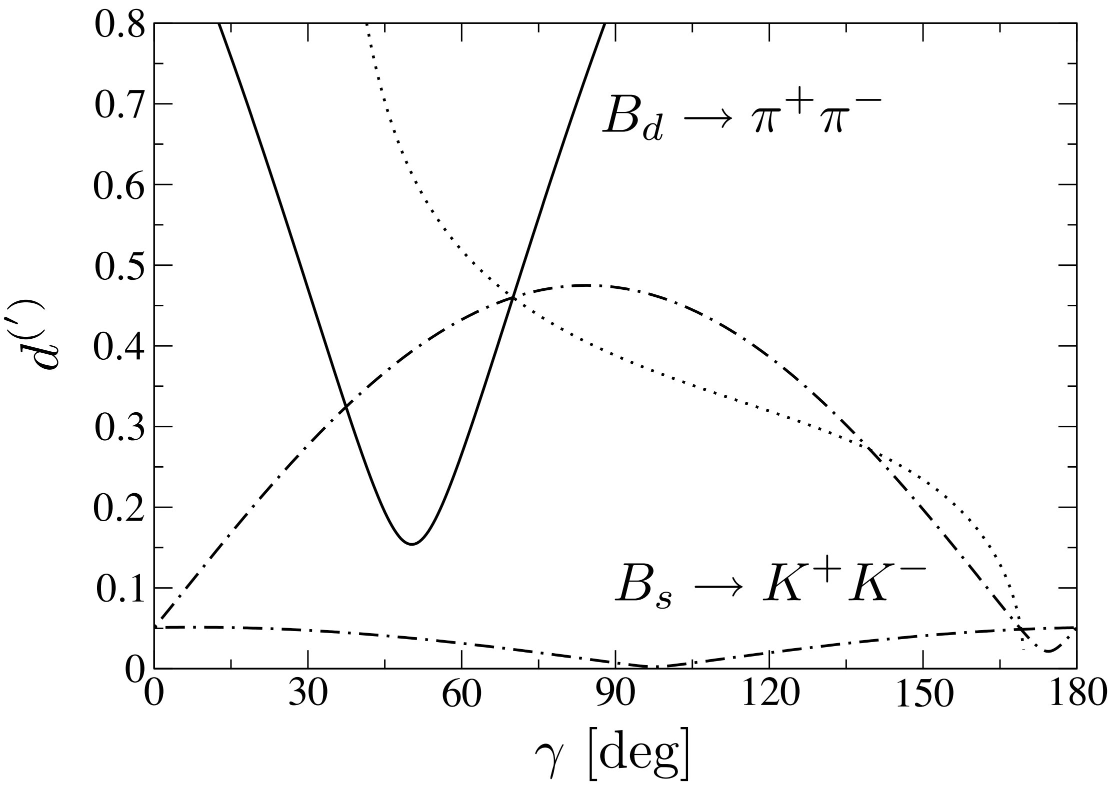
- Example (inspired by the current data):

  - Input parameter:

    * $\phi_d = 42.4°$, $\phi_s = -2°$, $\gamma = 70°$, $d = d' = 0.46$, $\theta = \theta' = 155°$

  - CP asymmetries:

    * $B_d \to \pi^+\pi^-$: $\mathcal{A}_{\rm CP}^{\rm dir} = -0.24$, $\mathcal{A}_{\rm CP}^{\rm mix} = +0.59$
    * $B_s \to K^+K^-$: $\mathcal{A}_{\rm CP}^{\rm dir} = +0.09$, $\mathcal{A}_{\rm CP}^{\rm mix} = -0.23$



- The decays $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ are related to each other through the interchange of all down and strange quarks:[4]

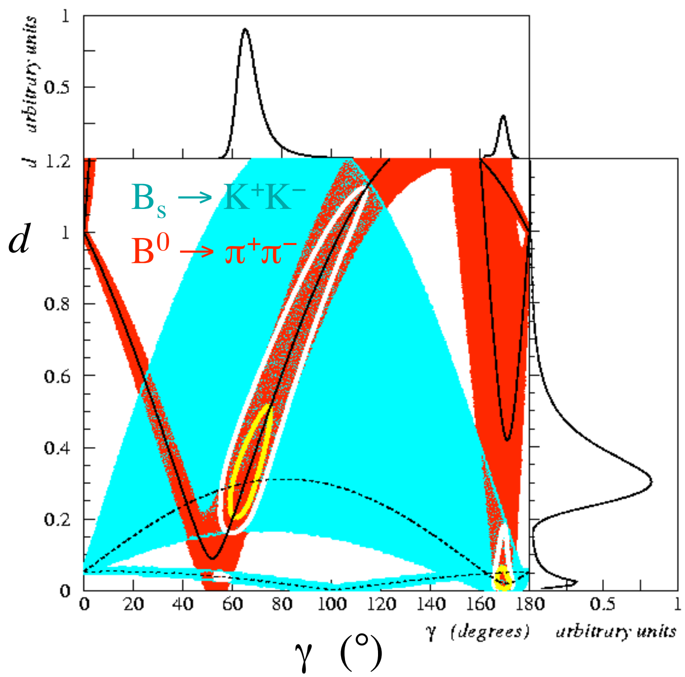
$$\boxed{U\text{-spin symmetry} \quad \Rightarrow \quad d = d', \quad \theta = \theta'}$$

– $d = d'$: $\Rightarrow$ $\boxed{\text{determination of } \gamma,\ d,\ \theta,\ \theta'}$

$\theta = \theta'$: $\Rightarrow$ test of the U-spin symmetry!

[R.F. (1999); current picture: $\gamma = (66.6^{+4.3+4.0}_{-5.0-3.0})^\circ$ arXiv:0705.1121 [hep-ph]]

- Detailed studies show that this strategy is very promising for LHCb:



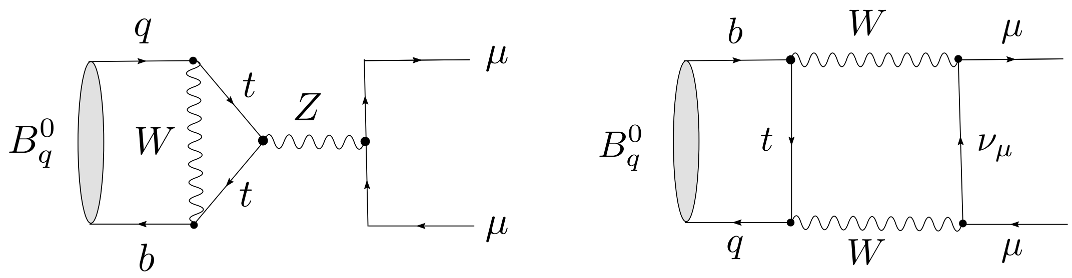
$\rightarrow$ experimental accuracy for γ of a few degrees!

[CERN-LHCb/2003-123 & 124; most recent: A. Carbone @ CERN TH Flavour Institute]

[4] U spin: $SU(2)$ subgroup of the $SU(3)_{\rm F}$ flavour-symmetry group of QCD.

The Rare Decays $B_q \to \mu^+\mu^-$ $(q \in \{d, s\})$

- Originate from Z penguins and box diagrams in the Standard Model:



- Corresponding low-energy effective Hamiltonian:

$$\mathcal{H}_{\rm eff} = -\frac{G_{\rm F}}{\sqrt{2}}\left[\frac{\alpha}{2\pi \sin^2\Theta_{\rm W}}\right] V_{tb}^* V_{tq} \eta_Y Y_0(x_t)(\bar{b}q)_{\rm V-A}(\bar{\mu}\mu)_{\rm V-A}$$

  - α: QED coupling; $\Theta_{\rm W}$: Weinberg angle.
  - η_Y: short-distance QCD corrections (calculated ...)
  - $Y_0(x_t \equiv m_t^2/M_W^2)$: "Inami–Lim function", with top-quark dependence.

- Hadronic matrix element: $\to$ very simple situation:
  - Only the matrix element $\langle 0|(\bar{b}q)_{\rm V-A}|B_q^0\rangle$ is required: f_{B_q}

$\Rightarrow$ belong to the cleanest rare B decays!

- SM predictions: [Blanke, Buras, Guadagnoli, Tarantino ('06)]

  $\rightarrow$ use the data for the ΔM_q to reduce the hadronic uncertainties:

$$\begin{aligned} \text{BR}(B_s \rightarrow \mu^+\mu^-) &= (3.35 \pm 0.32) \times 10^{-9} \\ \text{BR}(B_d \rightarrow \mu^+\mu^-) &= (1.03 \pm 0.09) \times 10^{-10} \end{aligned}$$

- Most recent experimental upper bounds from the Tevatron:

  – CDF collaboration @ 95% C.L.: [CDF Public Note 8956 (2007)]

$$\text{BR}(B_s \rightarrow \mu^+\mu^-) < 5.8 \times 10^{-8}, \quad \text{BR}(B_d \rightarrow \mu^+\mu^-) < 1.8 \times 10^{-8}$$

  – D0 collaboration @ 90% C.L. (95% C.L.): [D0note 5344-CONF (2007)]

$$\text{BR}(B_s \rightarrow \mu^+\mu^-) < 7.5\,(9.3) \times 10^{-8}$$

  $\Rightarrow$ still a long way (?) $\rightarrow$ LHC (understanding of backgrounds essential)

- However, NP may significantly enhance $\text{BR}(B_s \rightarrow \mu^+\mu^-)$:

  – In SUSY secenarios: BR $\sim (\tan\beta)^6$ $\rightarrow$ dramatic enhancement (!);
  [see, e.g., Foster *et al.* and Isidori & Paride ('06) for recent analyses]

  – NP with modified EW penguin sector: sizeable enhancement.

The Rare Decay $B_d^0 \to K^{*0}\mu^+\mu^-$

- Key observable for NP searches: Forward–Backward Asymmetry

$$A_{\rm FB}(\hat{s}) = \frac{1}{{\rm d}\Gamma/{\rm d}\hat{s}}\left[\int_0^1 {\rm d}(\cos\theta)\frac{{\rm d}^2\Gamma}{{\rm d}\hat{s}\,{\rm d}(\cos\theta)} - \int_{-1}^0 {\rm d}(\cos\theta)\frac{{\rm d}^2\Gamma}{{\rm d}\hat{s}\,{\rm d}(\cos\theta)}\right]$$

  - θ is the angle between the B_d^0 momentum and that of the μ^+ in the dilepton centre-of-mass system,
  - and $\hat{s} = s/M_B^2$, with $s = (p_{\mu^+} + p_{\mu^-})^2$.

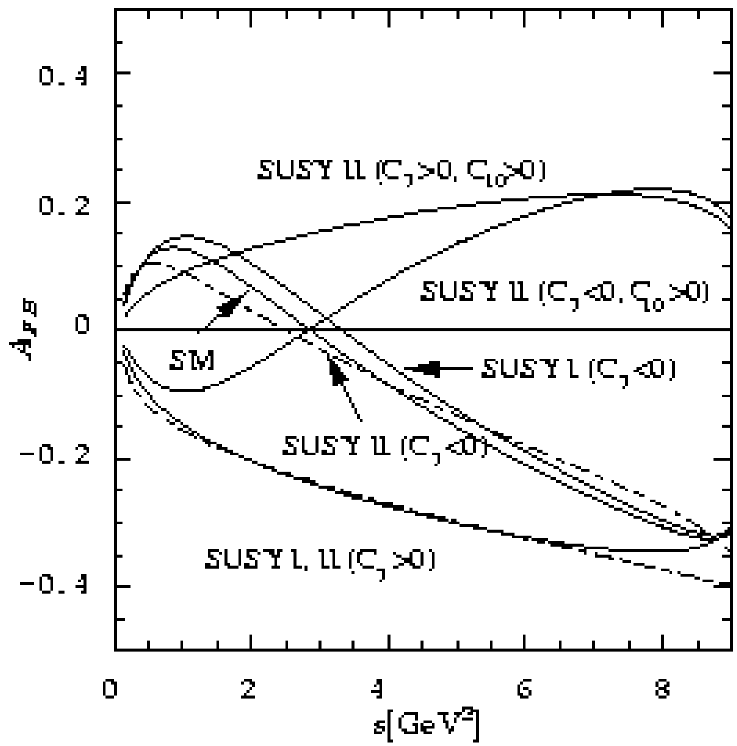
- Particularly interesting:

$$\boxed{A_{\rm FB}(\hat{s}_0)|_{\rm SM} = 0}$$

[Burdman ('98); Ali *et al.* ('00); ...]

  - The value of $\hat{s}_0$ is very robust with respect to hadronic uncertainties!
  - SUSY extensions of the SM:

    $\longrightarrow$ may yield $A_{\rm FB}(\hat{s})$ of opposite sign or without a zero point $\longrightarrow$



[A. Ali *et al.*, *Phys. Rev.* **D61** (2000) 074024]

- Sensitivity at the LHC:
  - LHCb: ~ 4400 decays/year, yielding $\Delta\hat{s}_0 = 0.06$ after one year.
  - ATLAS will collect about 1000 $B^0 \to K^{*0}\mu^+\mu^-$ decays per year.
- Other $b \to s\mu^+\mu^-$ decays under study: $\Lambda_b \to \Lambda\mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$ ...
- Current B-factory data: inclusive $b \to s\ell^+\ell^-$ BRs and the integrated asymmetries $\int A_{\rm FB}$ in accordance with SM, but still large uncertainties.

Conclusions & Outlook

Where do we stand in B Physics?

- Tremendous progress in B physics during the recent years:

  Fruitful interplay between theory and experiment

  - e^+e^- B factories: have produced $\sum \mathcal{O}(10^9)$ $B\bar{B}$ pairs;
  - Tevatron: has recently reported exciting B_s results.

- Status in October 2008:
  - The data agree globally with the Kobayashi–Maskawa picture!
  - But we have also hints for discrepancies: $\longrightarrow$ first signals of NP??

- New perspectives for B-decay studies @ LHC (will resume spring 2009):
  - Large statistics and full exploitation of the B_s physics potential, thereby complementing the physics programme of the e^+e^- B factories.
  - Precision determinations of γ: $\longrightarrow$ key ingredients for NP searches!
  - Powerful studies of rare decays: $B_{s,d} \to \mu^+\mu^-$, ...

$\longrightarrow$ much more stringent CKM consistency tests!

Other Flavour Probes

- Charm physics: $\longrightarrow$ interesting news in spring '07:
  - Observation of D^0–$\bar{D}^0$ mixing at the B factories!
  - The mixing parameters are found in the ball park of the SM predictions, which are affected by large long-distance effects .
  - Striking NP signal would be given by CP-violating effects ...

$\longrightarrow$ *powerful charm-physics programme at LHCb!*

- Kaon physics: $\longrightarrow$ future lies on rare decays $K^+ \to \pi^+\nu\bar{\nu}$, $K_{\rm L} \to \pi^0\nu\bar{\nu}$:
  - Theoretically *very clean!*
  - Proposal to measure $K^+ \to \pi^+\nu\bar{\nu}$ at the CERN SPS;
  - $K_{\rm L} \to \pi^0\nu\bar{\nu}$ studied at E391(a) KEK/J-PARC.
    [G. D'Ambrosio @ Napoli; ...]

- Flavour violation in the lepton sector:
  - Neutrino physics is very exciting, with a great future.
  - Charged lepton sector: e.g. search for $\mu \to e\gamma$ @ MEG (PSI).

$\oplus$ top-quark studies by ATLAS & CMS

Direct Context with LHC & Long-Term Future

- Main goals of the ATLAS and CMS experiments:
  - Exploration of the mechanism of EW symmetry breaking: Higgs!?
  - Hopefully, production and observation of *new* particles ...
  - Then back to the questions of dark matter, baryon asymmetry ...

$\oplus$ complementary and further studies at ILC/CLIC

- Synergy with the quark and lepton flavour sectors:
  - If discovery of new particles, which kind of new physics?
  - Insights into the corresponding new flavour structures and possible new sources of CP violation through studies of flavour processes.
  - Sensitivity on very high energy scales of new physics through precision measurements, also if NP particles cannot be produced at the LHC.

- Long-term future prospects for B-decay studies:
  - Discussion of an upgrade of the LHCb experiment.
  - Discussions of "super B factories" in Italy and Japan...

Recent Activity @ CERN-TH: → many discussions & talks ...