Importance of Flavour Factories in the LHC Era

new physics search in flavour physics

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RAL, June 1 2005

Opportunities in Flavour Physics

- Introduction
  - QCD $\leftrightarrow$ New Physics
  - Interplay of Flavour and Collider Physics
- Exploration of Higher Scales via Rare Decays
  - Inclusive Rare Decays $\bar{B} \to X_s \gamma$, $\bar{B} \to X_s \ell^+ \ell^-$
  - $K \to \pi \nu \bar{\nu}$
- $B \to \pi\pi$, $B \to K\pi$
  - QCD Factorization, SCET
  - Nonfactorizable Contributions
- Correlation of Collider and Flavour Physics via Squark Mixing
- CP Violating Observables

Reviews of Modern Physics 75 (2003) 1159

Introduction

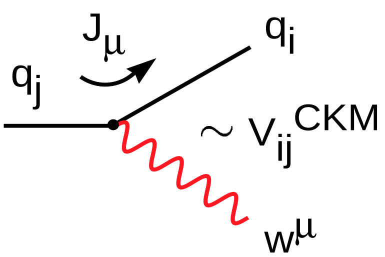
$$\mathcal{L}_{SM} = \mathcal{L}_{Gauge}(A_i, \psi_i) + \mathcal{L}_{Higgs}(\Phi, \psi_i, v)$$

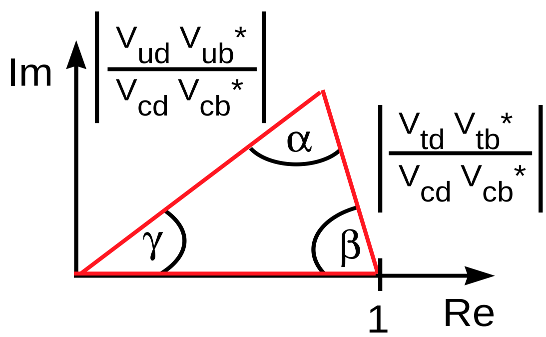
- Electroweak precision data of LEP (CERN), SLC (SLAC), TEVATRON (FERMILAB) confirmed SM predictions within the gauge sector up to a precision of 0.1%.

- Scalar Higgs particle Φ not found yet: mechanism of electroweak symmetry breaking is an open issue.

- Flavour physics:testing the SM beyond the gauge interactions (differences between fermion families Ψ_i)

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} \left[(\bar{\nu}_e,\ \bar{\nu}_\mu,\ \bar{\nu}_\tau)\, \gamma^\mu \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix} + (\bar{u}_L,\ \bar{c}_L,\ \bar{t}_L)\, \gamma^\mu\, V_{CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} \right] W_\mu^\dagger$$





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

- Focus: * neutrino physics * B meson physics

- Interplay of LHC and ILC:
  Complementarity of discovery and precision machine

  $\Rightarrow$ LHC/ILC study group

- However: ILC will not be built before 2016 (optimistic!)

- Obvious question:
  What is the role of the flavour factories in this game?

- Experimental 'Roadmap' of flavour physics:

  - e^+e^--B-experiments:
    B factories (Babar,Belle) $\geq$ 1999, CLEO III $\geq$ 2000,
    Upgraded B factories, Super B factories $\geq$ 2010

  - Hadronic B-experiments:
    Tevatron II $\geq$ 2001, LHC (Atlas,CMS,LHCb) $\geq$ 2007,
    ((BTeV $\geq$ 2009))

  - Kaon-experiments:
    Kopio,BNL ($K_L \to \pi^0 \nu\bar{\nu}$),
    NA 48/3,CERN ($K^+ \to \pi^+ \nu\bar{\nu}$) $\geq$ 2010

- Interplay of flavour and collider physics
  - Exploration of higher scales via rare decays
  - Correlations between B and collider physics
    via squark mixing within Susy

- Main issues of the B physics program:
  - Mechanism of CP violation in the B system
  - Indirect effects of new physics in rare B decays
  - Studies of strong interactions, QCD, SCET

- New physics:
  - No strict argument that new flavour physics must appear at the electroweak scale
  - Baryon asymmetry: one needs more sources of CP violation, not necessarily relevant at low energies .
  - Flavour sector leads to severe constraints for new physics.
  - Flavour structure is a model-dependent issue.

- Decays of B mesons:

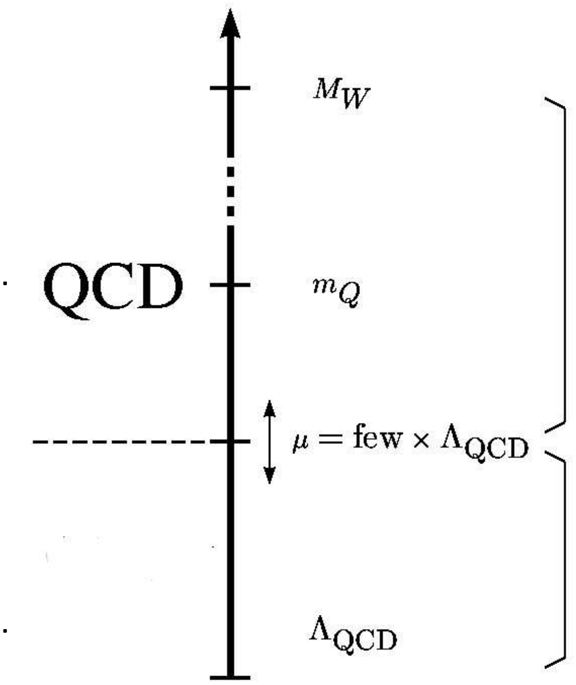
  $B^0_{d,(s)} = \bar{b}d(s),\ \bar{B}^0_{d,(s)} = b\bar{d}(\bar{s}),\ B^+_u = \bar{b}u,\ B^-_u = b\bar{u}$

  * b quark heaviest quark with pronounced hadronic bound states (QCD tests)
  * rich CKM phenomenology
  * independent test of the mechanism of CP violation ($\leftrightarrow$ K system)
  * interplay of strong and weak interaction

  $\Rightarrow$ problem of long-distance strong interactions restricts opportunities in flavour physics significantly

  (see hadronic uncertainties in present $g-2$ analysis)

Separation of scales necessary !



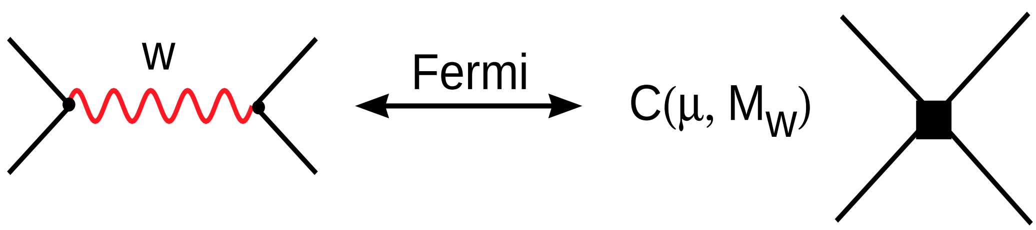
short-distance physics
perturbative

long-distance physics
nonperturbative

- Operator product expansion:
  Factorization of short-distance and long-distance physics

  Example: QCD at electroweak scale $\mu^2 \approx M_W^2$:
  C_i: effective couplings $< \mathcal{O}_i >$: matrix elements

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} \sum C_i(\mu, M_{heavy}) \; \mathcal{O}_i(\mu)$$



- $\Lambda_{QCD} << m_Q = m_b$: $1/m_b$ expansion allows for separation of effects $\mu^2 \approx m_b^2$, $m_b \Lambda_{QCD}$
  $\Rightarrow$ effective theories: HQET, SCET

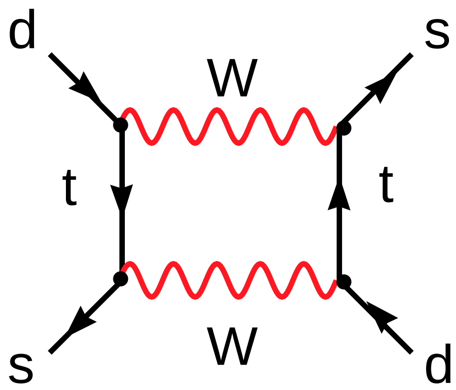
- $\mu^2 \approx \Lambda_{QCD}^2$: long-distance hadronic parameters
  lattice-QCD , U-spin symmetry, QCD sum rules, chiral perturbation theory, ...

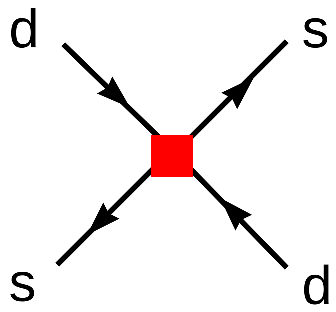
- $\mu^2 \approx M_{New}^2 >> M_W^2$:
  'new physics' effects: $C_i^{SM}(M_W) + C_i^{New}(M_W)$

Exploration of higher scales via flavour observables

$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \sum_i \frac{c_i^{New}}{\Lambda} \mathcal{O}_i^{(5)} + \ldots$$

- SM as effective theory valid up to cut-off-scale Λ
- $K^0 - \bar{K}^0$-mixing $\mathcal{O}^6 = (\bar{s}\,d)^2 \quad \Rightarrow \quad \Lambda > 100\,\text{TeV}$





$\Rightarrow c^{SM}/M_W^2 \times (\bar{s}\,d)^2$ $\qquad$ $c^{New}/\Lambda^2 \times (\bar{s}\,d)^2$

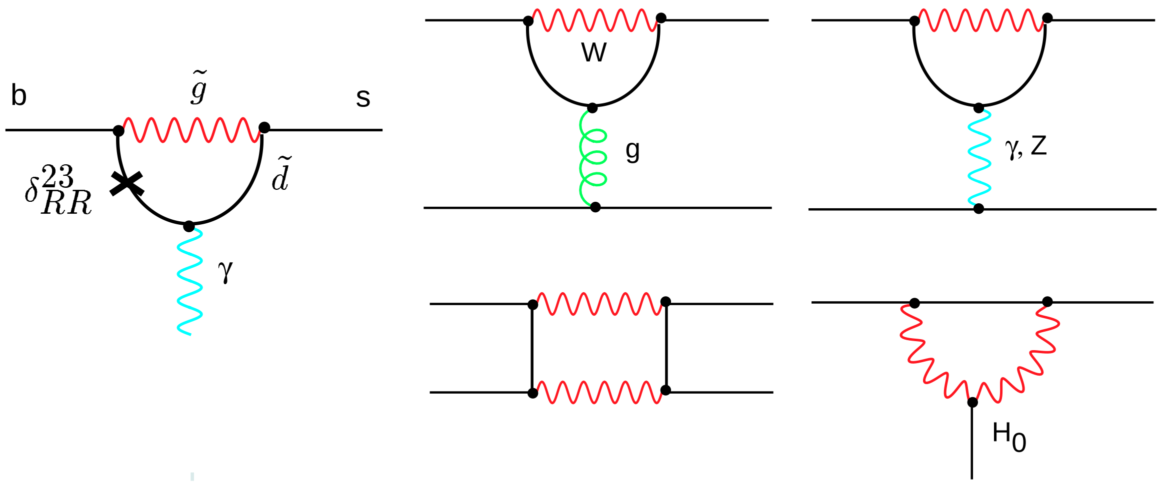
- Natural stabilisation of Higgs boson mass $\Rightarrow \Lambda \sim 1\text{TeV}$
  i.e. supersymmetry, superpartner: $\Lambda_{SUSY} \precsim 1$ TeV
  (but: little hierarchy problem)
- Expectation:
  flavour mixing restricted by additional symmetries
  Rare decays and specific CP violating observables allow to analyse flavour symmetry breaking

$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \sum_i \frac{c_i^{New}}{\Lambda} \mathcal{O}_i^{(5)} + \ldots$$

- Flavourblind elektroweak structure of $\mathcal{O}_i$:

  - connects various (theoretically clean !) observables:

  i.e. $A_{CP}(B_d \to \Phi K_S) \Leftrightarrow BR(B \to X_s\gamma)$



  - allows for model-independent analysis:

$$BR(B \to X_s\ell^+\ell^-), A_{FB}(B \to X_s\ell^+\ell^-), A_{CP}(B \to X_s\gamma),$$
$$BR(B \to \ell^+\ell^-), BR(K^+ \to \pi^+\nu\bar{\nu}), BR(B \to X_s\nu\bar{\nu}), \ldots$$

- Flavour part of $\mathcal{O}_i$:

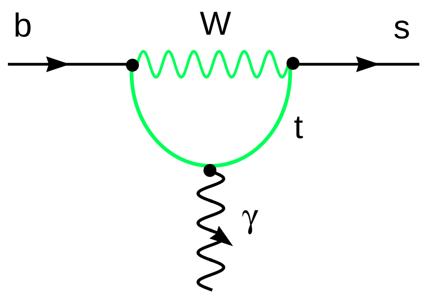
  - new flavour structures, i.e. squark-mixing in SUSY

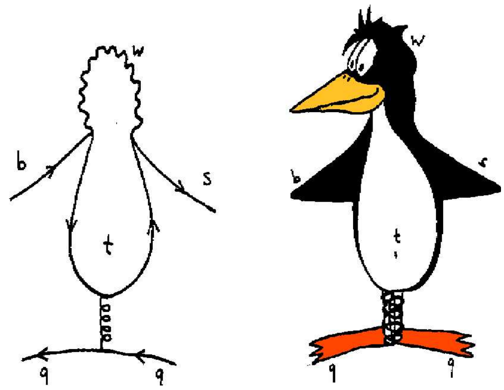
  or

  - minimal flavour violation

  * flavour symmetry / CP broken by Yukawa couplings only
  * $[b \to s] \leftrightarrow [b \to d] \leftrightarrow [s \to d]$
  * RG-invariant definition (d'Ambrosio et al.)

- Rare B decays like $b \to s\,\gamma$ or $b \to s\,\ell^+\ell^-$ directly probe the SM at the one-loop level.

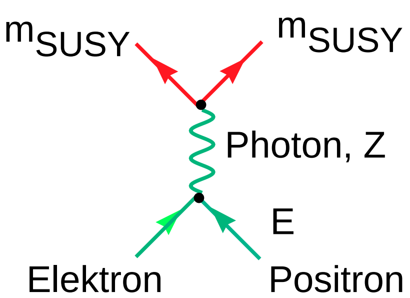




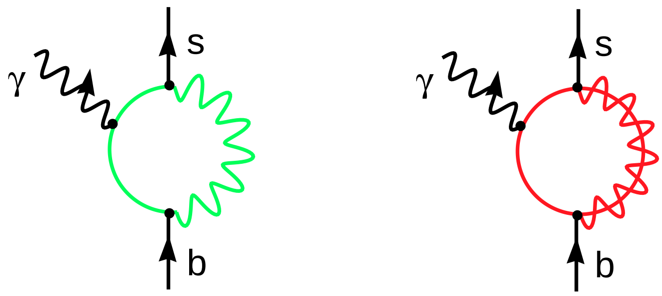
- Search strategies for new degrees of freedom beyond the SM (i.e. for supersymmetry)

Direct:

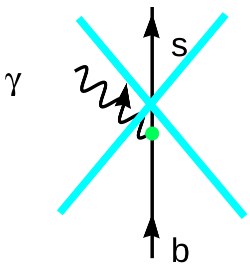
Indirect:



$2m_{SUSY}c^2 \leq E$

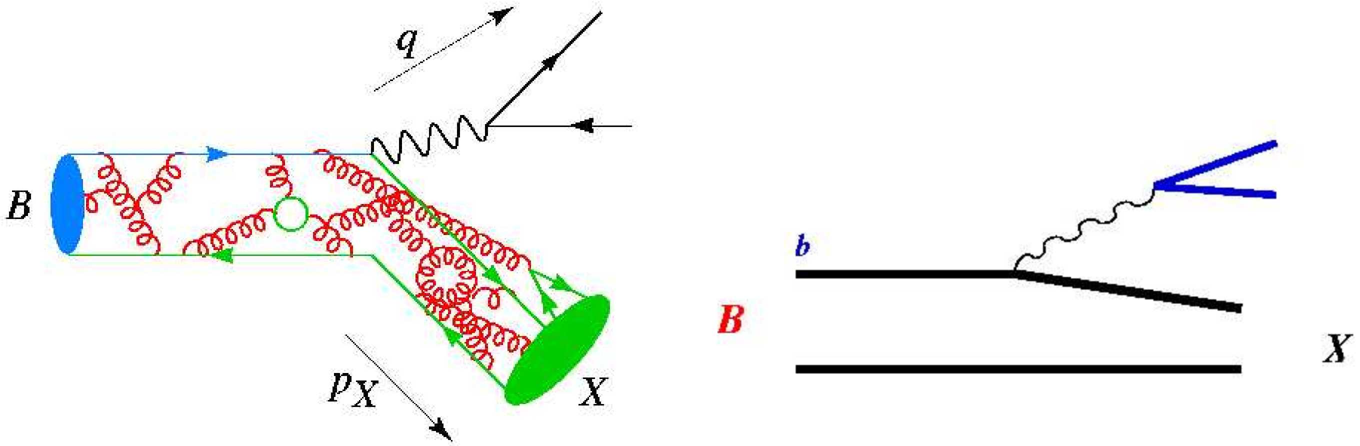


- High sensitivity for 'New Physics', because



$\leftrightarrow$ elektroweak precision data (10% $\leftrightarrow$ 0.1%)

This indirect information is analogous to some direct information a linear collider could provide.



Crucial problem:
Separation of new physics effects and hadronic uncertainties!

* focus on inclusive modes:

$$\Gamma(\bar{B} \to X_s \gamma) \stackrel{m_b \to \infty}{\longrightarrow} \Gamma(b \to X_s^{parton} \gamma)\,, \quad \Delta^{nonpert.} \sim \Lambda^2_{QCD}/m_b^2$$

No linear term Λ_{QCD}/m_b
Perturbatively calculable contribution dominant

* focus on ratios of exclusive modes like asymmetries
(hadronic uncertainties partially cancel out)

* focus on specific decays like $B \to \ell^+\ell^-$ or $K \to \pi\nu\bar{\nu}$
(hadronic matrix elements known from experiment)

Perturbative corrections in inclusive decays

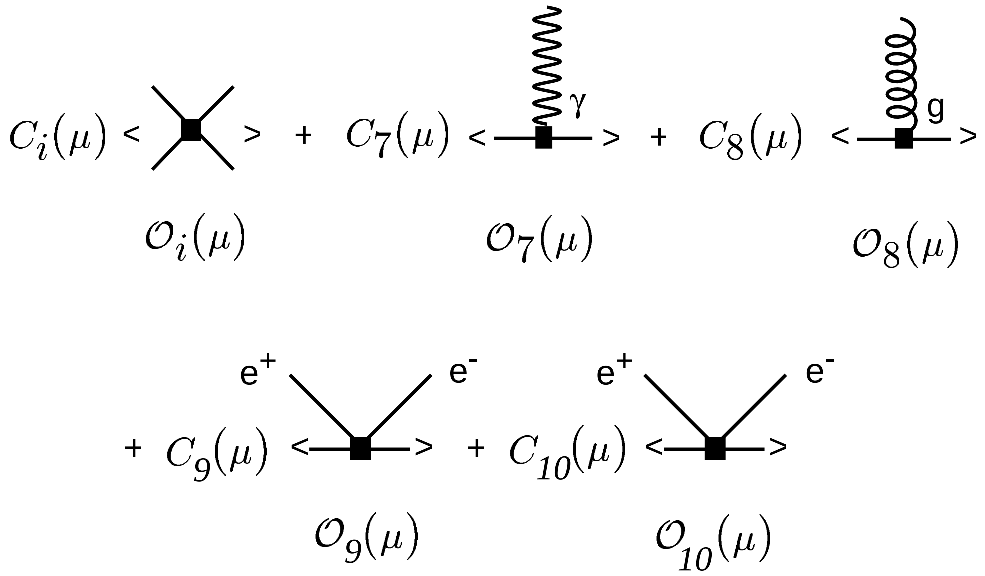
- Electroweak two-loop corrections play a subdominant role

- Perturbative QCD corrections are large and lead to $\alpha_s(M_W)Log(m_b^2\,/\,M_W^2)$ $\longrightarrow$ resummation of Logs necessary:

LL	Leading Logs	$G_F\,(\alpha_s\,Log\,)^N$	$N = 0, 1, ..$
NLL	Next-to-Leading Logs	$G_F\,\alpha_s\,(\alpha_s\,Log\,)^N$	

- Effective field theory $(\mu \approx M_W)$

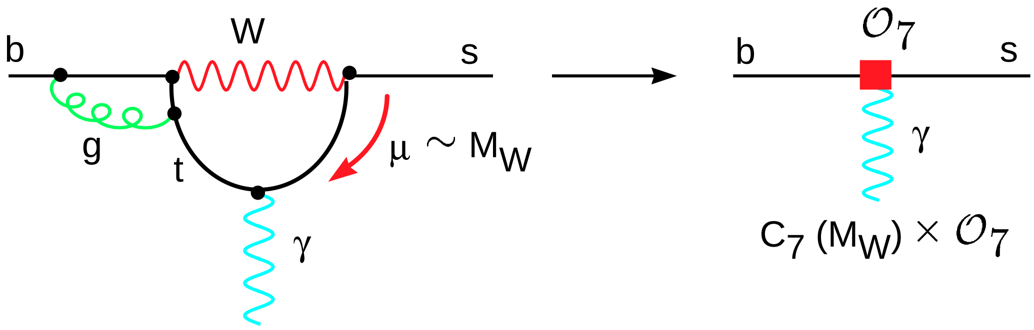
  $H_{eff}(b \to s\ell^+\ell^-) = -\frac{4G_F}{\sqrt{2}}\,V_{bt}V_{st}^*\,\sum_{i=1}^{10} C_i(\mu)\;\mathcal{O}_i(\mu)$



C_i: dynamical information on physics $\mu > M_W$
$\mathcal{O}_i$: effective dynamics (5 quarks und γ,$gluon$) $\mu < M_W$

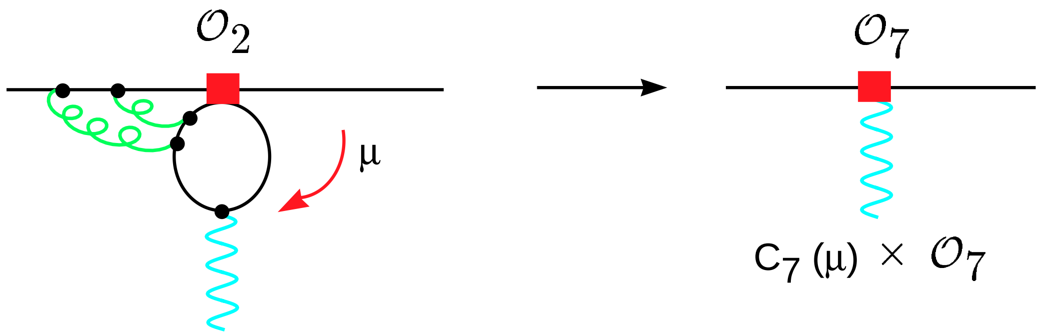
* Initial conditions $C_i(\mu \simeq M_W)$
(Adel, Yao)   (Greub, Hurth)

* sensitivity for 'new physics'   * no large logs

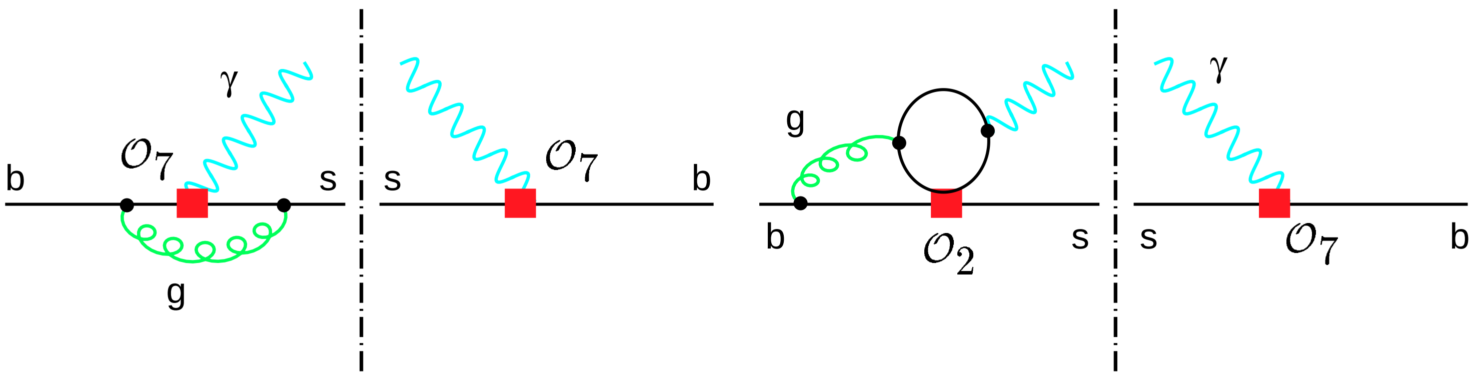


* Coefficients γ_{ij} in $\mu \frac{d}{d\mu} C_i(\mu) = \gamma_{ij} C_j(\mu)$ $\Rightarrow$ $C_i(\mu \simeq m_b)$
(Chetyrkin, Misiak, Münz)   (Gambino, Gorbahn, Haisch)

QCD-mixing of operators:
'new physics' information in $C_7(M_W)$ gets covered up



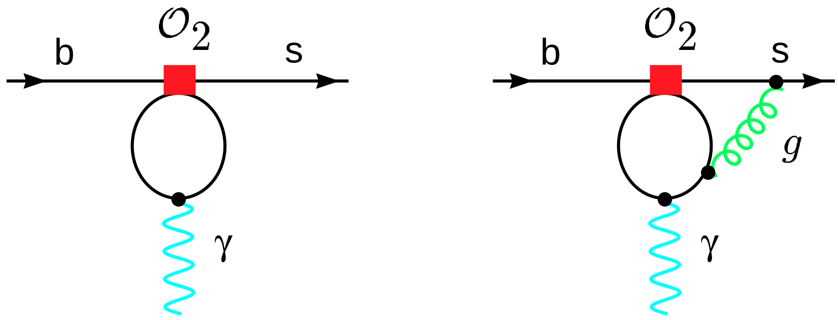
* Matrix elements $\prec O_i(\mu \simeq m_b) \succ$
(Greub, Hurth, Wyler)   (Buras et al.)
* perturbative contributions are dominant
* $\Gamma(B \to X) \sim Im \prec B|H_{eff} H_{eff}|B \succ$



* two-loop diagrams of operator $\mathcal{O}_2$

Present status of $\bar{B} \to X_s\gamma$

Problem: renormalization scheme of the charm mass (NNLL)



$$m_c^{\text{pole}}/m_b^{\text{pole}} = 0.29 \pm 0.02 \;\Leftrightarrow\; m_c^{\overline{\text{MS}}}(\mu)/m_b^{1S} = 0.23 \pm 0.05$$

$\Rightarrow$ central value $\sim +11\%$ (Gambino, Misiak)

Our experience $\overline{\text{MS}}$-scheme favored $\Rightarrow$ $m_c/m_b = 0.23^{+0.08}_{-0.05}$

Present NLL Prediction: (Hurth, Lunghi, Porod)

$$BR(\bar{B} \to X_s\gamma) \times 10^4 = \left(3.79 \; {}^{+0.26}_{-0.44}\Big|_{m_c/m_b} \pm 0.02_{\text{CKM}} \pm 0.25_{\text{param}} \pm 0.15_{\text{scale}}\right)$$

NNLL QCD calculation needed for uncertainty $\ll 10\%$!
(work in progress !)

Experiment:

$$BR(\bar{B} \to X_s\gamma) = (3.52 \pm 0.30) \times 10^{-4}$$

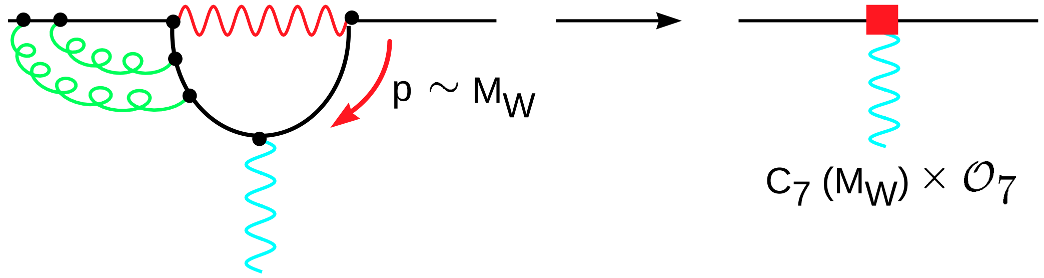
CLEO, ALEPH, BELLE, BABAR

The $\bar{B} \to X_s\gamma$ data already leads to significant restrictions on the parameter space of various extensions of the SM.

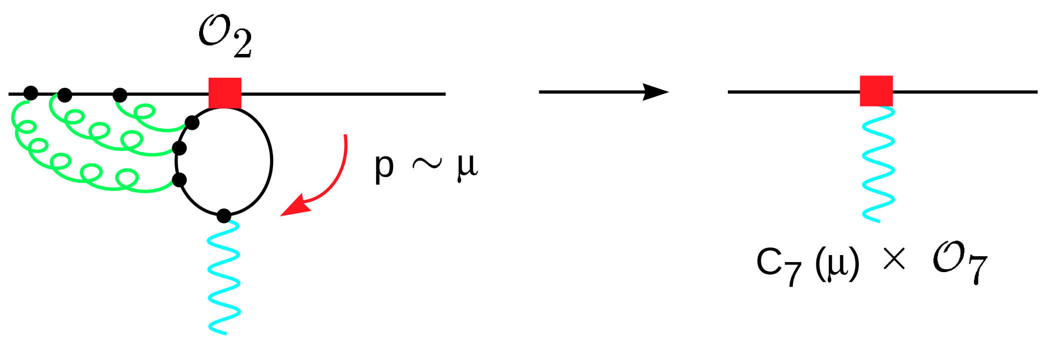
Clearly, this indirect information will be most valuable when the general nature of new physics will be identified in the direct search (LHC).

NNLL-QCD — work in progress

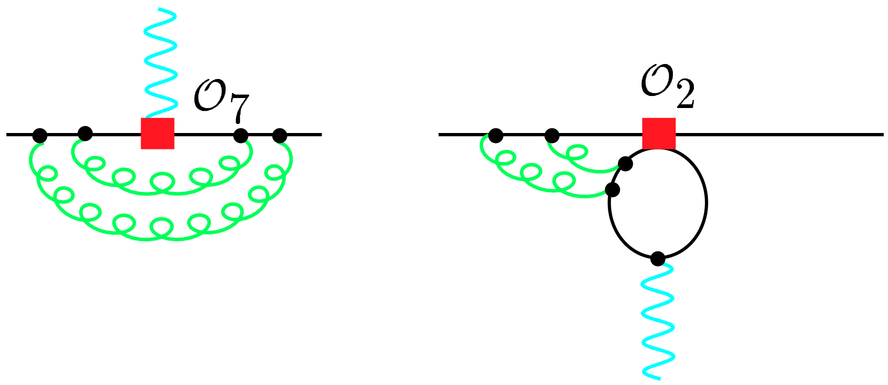
- Initial conditions $C_i(\mu \simeq M_W)$ DONE!! Misiak,Steinhauser



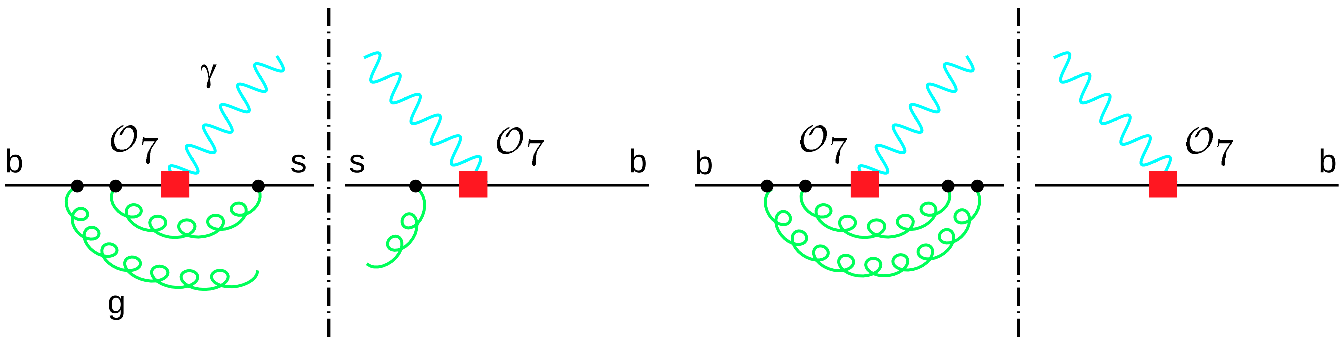
- Coefficients γ_{ij} in $\mu \frac{d}{d\mu} C_i(\mu) = \gamma_{ij} C_j(\mu)$ $\Rightarrow$ $C_i(\mu \simeq m_b)$



- Matrix elements: $\prec O_7(\mu \simeq m_b) \succ$ $\prec O_2(\mu \simeq m_b) \succ$



- $\prec O_7(\mu \simeq m_b) \succ$ Asatrian, Greub, Hurth



Estimate of the reduction of the scheme dependence at NNLL:
Asatrian et al. hep-ph/0505068 12.4% → 5.1%

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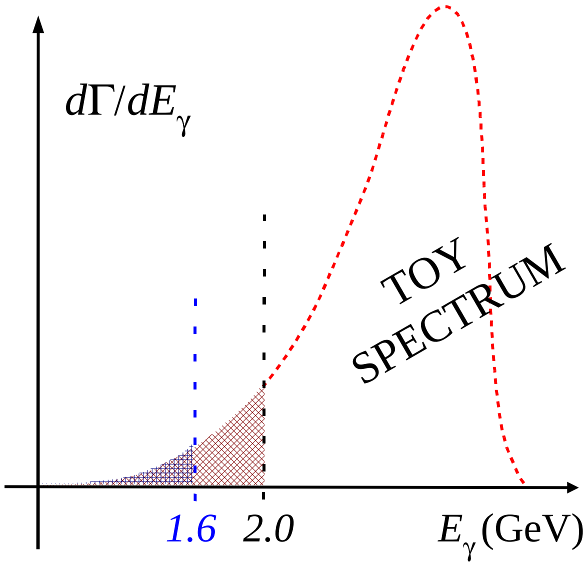
Experimental issues

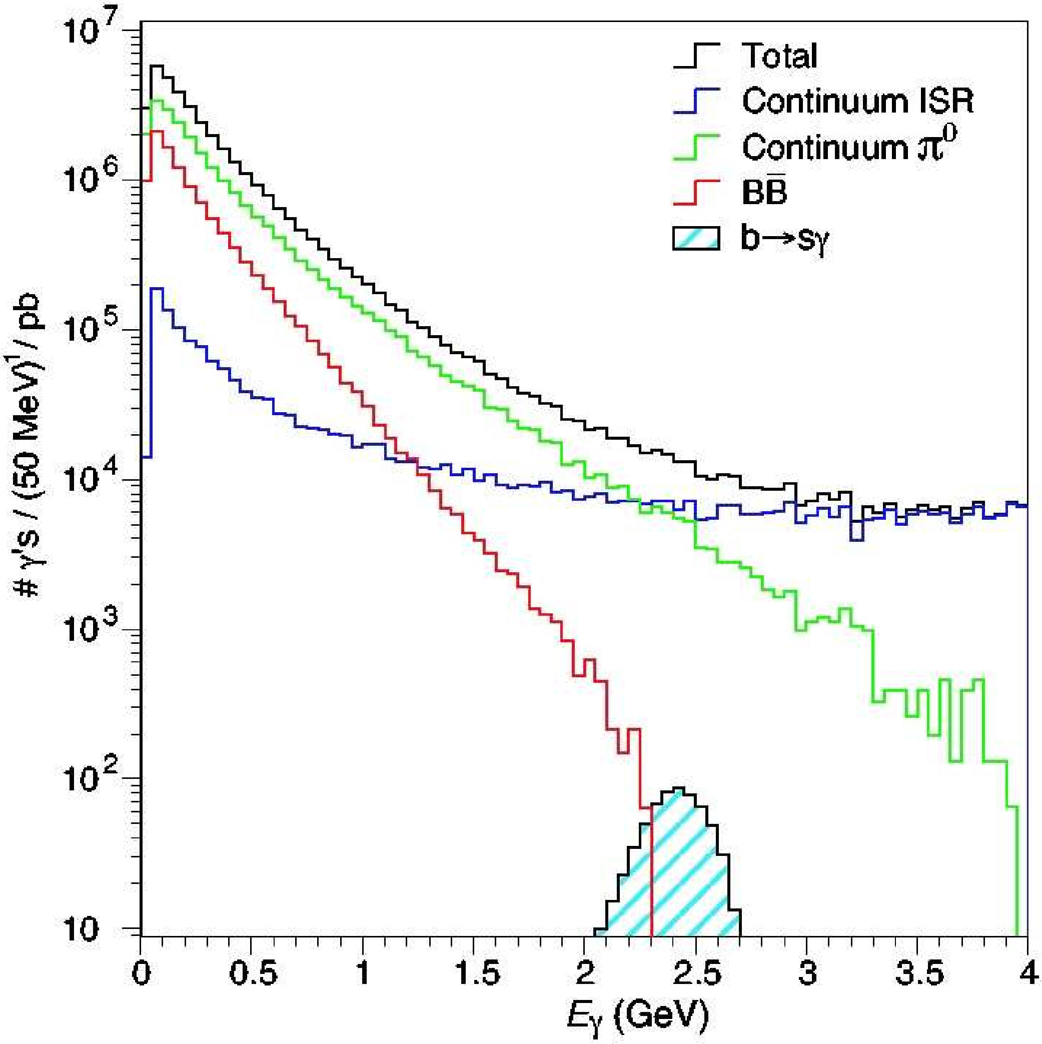


* Extrapolation necessary (systematic uncertainty)

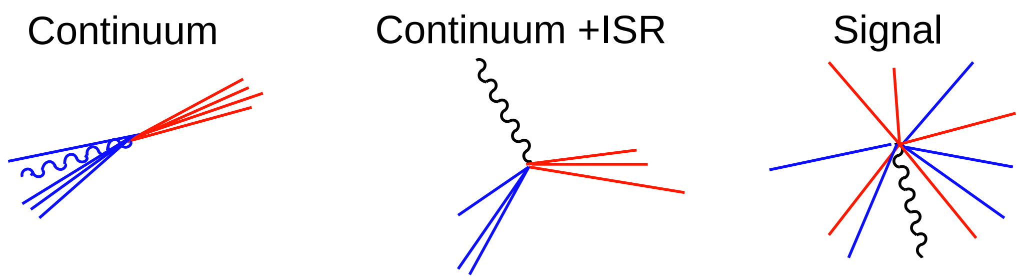
* Latest Belle measurement (2004): Cut at $1.8 GeV$

* Shape of photon spectrum not sensitive for new physics !

CLEO

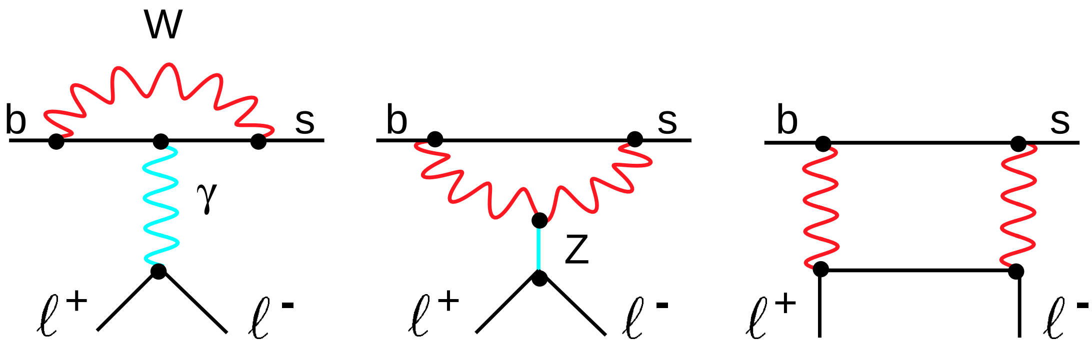


Total
Continuum ISR
Continuum π^0
$B\bar{B}$
$b \to s\gamma$
γ's / (50 MeV)^1 / pb
E_γ (GeV)



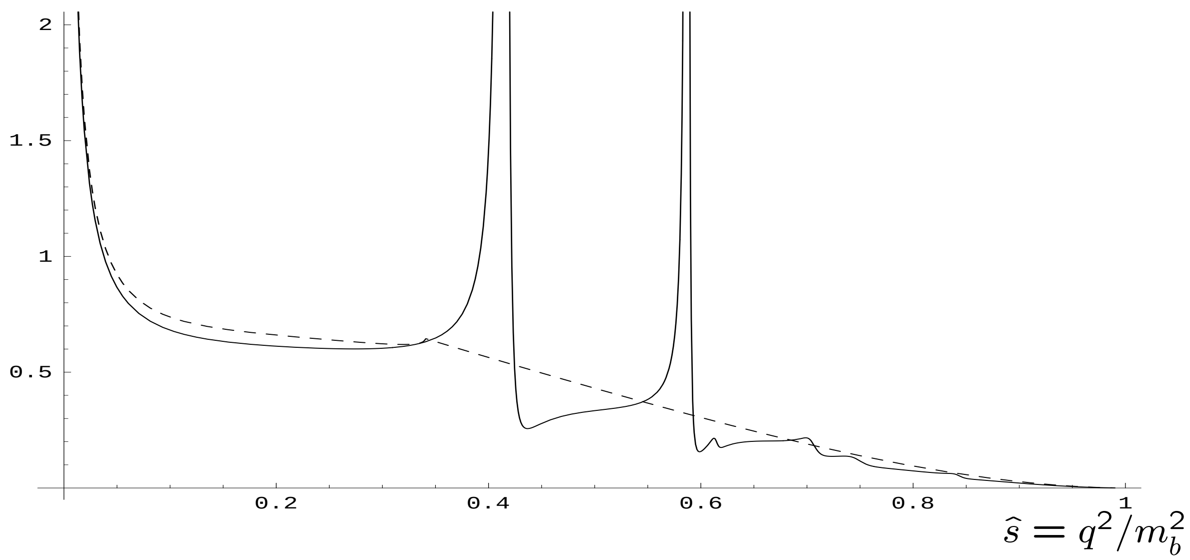
Continuum
Continuum +ISR
Signal

$\bar{B} \to X_s \ell^+ \ell^-$: Dilepton mass spectrum



- on-shell-$c\bar{c}$-resonances
  cuts: $1\text{GeV}^2 < q^2 < 6\text{GeV}^2$ und $14.4\text{GeV}^2 < q^2$:
  perturbative contributions dominant

$\frac{d}{d\hat{s}} BR(\bar{B} \to X_s l^+ l^-) \times 10^{-5}$



- Theory NNLL QCD: Ghinculov, Hurth, Isidori, Yao

  $$BR(\bar{B} \to X_s \ell^+ \ell^-)_{Cut:\ q^2 \in [1GeV^2, 6GeV^2]} = (1.63 \pm 0.20) \times 10^{-6}$$

  $$BR(\bar{B} \to X_s l^+ l^-)_{Cut:\ q^2 > 14.4GeV^2} = (4.04 \pm 0.78) \times 10^{-7}$$

  NNLL QCD corrections $q^2 \in [1GeV^2, 6GeV^2]$

  central value: -14%, perturbative error: $13\% \to 6.5\%$

Experimental issues

- Semi-Inclusive Measurements ($m(\ell^+\ell^-) > 0.2 GeV$)

  Belle, PRL 90 (2003) 021801 :
  $BR(\bar{B} \to X_s \ell^+\ell^-) = (6.1 \pm 1.4(stat) + 1.4 - 1.1(syst))10^{-6}$

  Update ICHEP 2004:
  $BR(\bar{B} \to X_s \ell^+\ell^-) = (4.11 \pm 0.83(stat) + 0.74 - 0.70(syst))10^{-6}$

  Babar, PRL 93 (2004) 081802 :
  $BR(\bar{B} \to X_s \ell^+\ell^-) = (5.6 \pm 1.5(stat) \pm 0.6(syst) \pm 1.1(mod))10^{-6}$

  – in agreement with corresponding SM prediction:
    $(4.6 \pm 0.8) \times 10^{-6}$ (Ghinculov,Hurth,Isidori,Yao))
    not sensitive yet for NNLL

  – semiinclusive: modelling of hadronic mass distribution

- Separate experimental data on two perturbative windows in dilepton mass spectrum desirable (Babar already made first separate measurements with large errors)

- End of Babar and Belle (1/ab): 15% accuracy possible

- LHCb: only semi-inclusive analysis possible without the π_0 modes

- Fully inclusive measurement possible within a Super-B factory

$\bar{B} \to X_s \ell^+ \ell^-$: Forward-backward-charge-asymmetry

$$A_{\rm FB} \equiv \frac{1}{\Gamma_{semilep}} \left(\int_0^1 d(\cos\theta) \frac{d^2\Gamma}{dq^2 d\cos\theta} - \int_{-1}^0 d(\cos\theta) \frac{d^2\Gamma}{dq^2 d\cos\theta} \right)$$

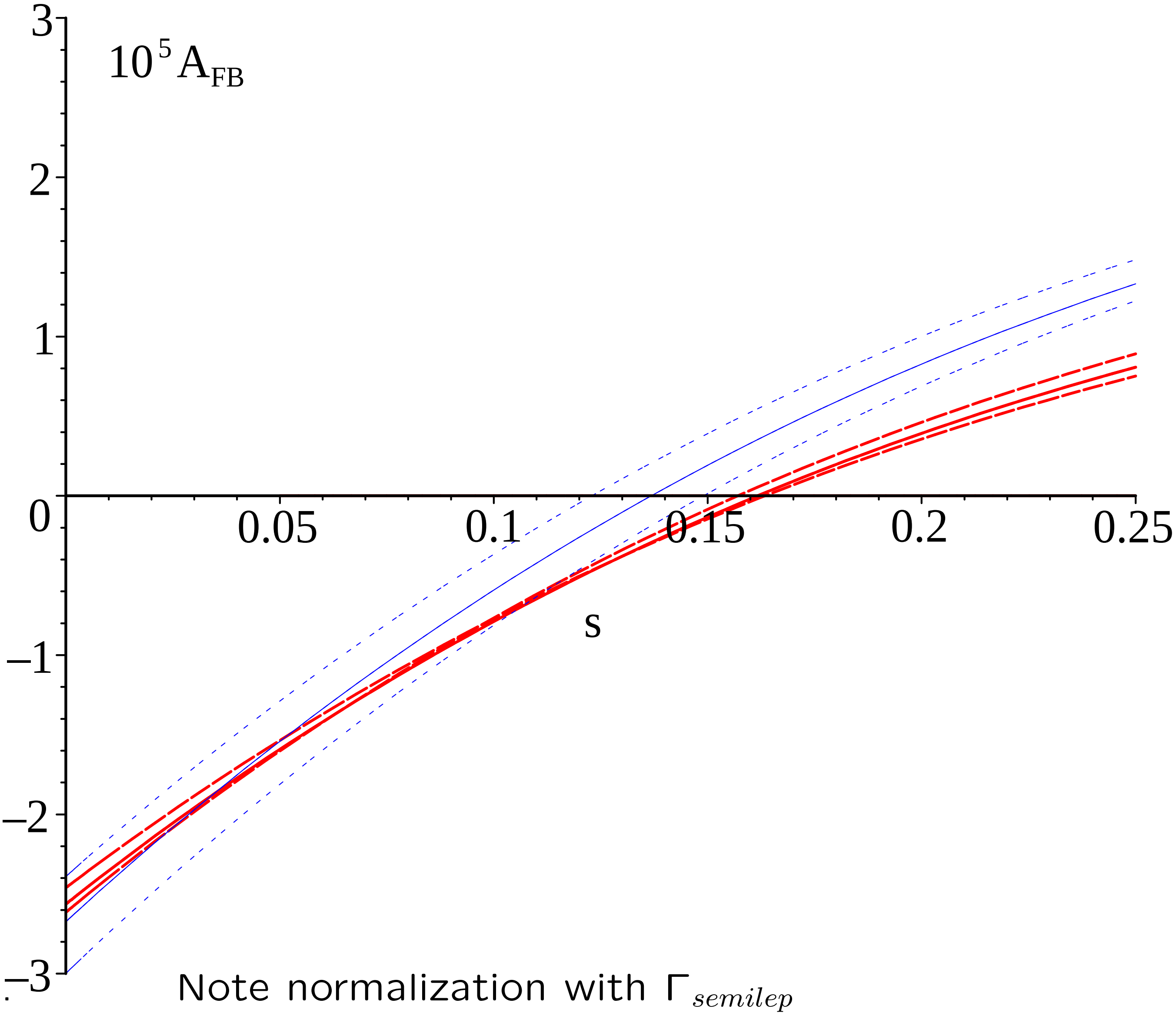
(θ angle between l^+ and B momenta in dilepton CMS)

$$A_{FB}(q_0^2) = 0 \quad \text{for} \quad q_0^2 \sim C_7/C_9$$

NNLL corrections induce large $\sim$ 16% Shift of the Zero

$$q_0^2 = (3.90 \pm 0.25) GeV^2 \quad \text{Precision test of SM !}$$

Ghinculov, Hurth, Isidori, Yao
Asatrian, Bieri, Greub, Hovhannisyan

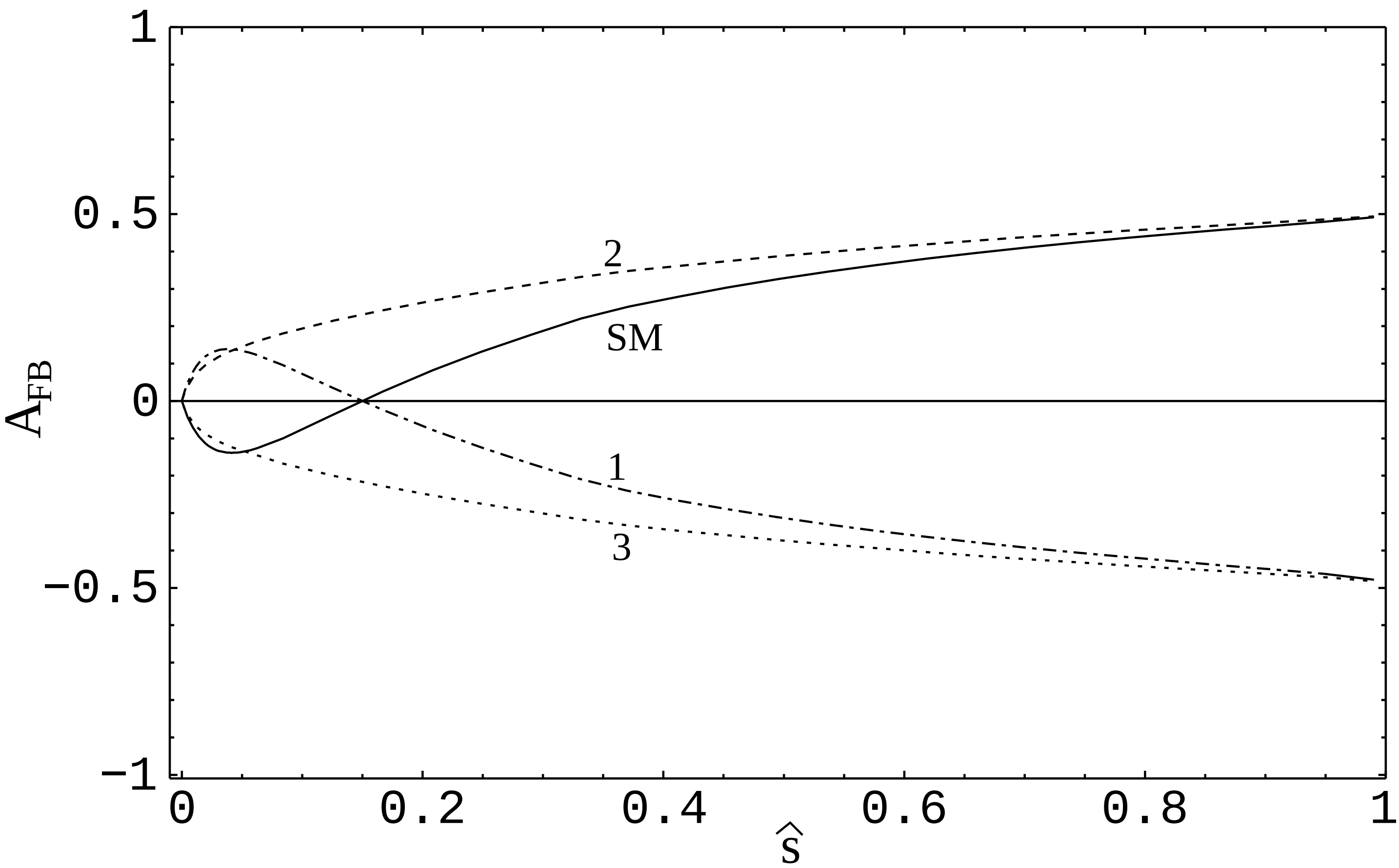


Note normalization with $\Gamma_{semilep}$

New physics search

Four different shapes of the 'normalized' FB asymmetry $\overline{A}_{FB}$ for the decay $\bar{B} \to X_s \ell^+ \ell^-$ within the MSSM compatible with the present data.

Hiller et al.



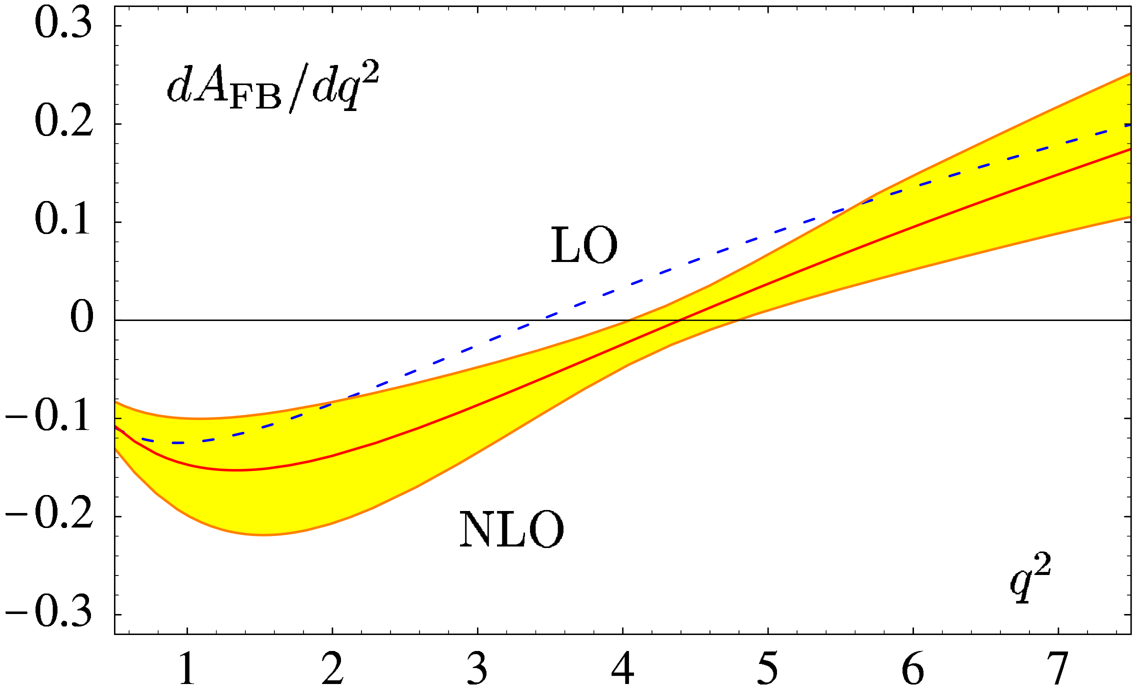
Already a rough measurement of the shape could lead to a signal for new physics !

$$A_{FB} \sim Re[\, C_{10}^{*}(\, s\, C_9^{eff}(s) + f(s) C_7^{eff}\,)\,]$$

SM: large q^2: $\mathcal{O}_9(+vector) \times \mathcal{O}_{10}(axialvector)$
. small q^2: $\mathcal{O}_7(-vector) \times \mathcal{O}_{10}(axialvector)$

FB-charge-asymmetry in $B \to K^* \ell^+ \ell^-$

Beneke,Feldmann,Seidel



- In contrast to the branching ratio the zero of the FBA is almost insensitive to hadronic uncertainties. At LO the zero depends on the short-distance Wilson coefficients only:

$$q_0^2 = q_0^2(C_7, C_9), \quad q_0^2 = (3.4 + 0.6 - 0.5) GeV^2 \quad (LO)$$

- NLO contribution calculated within QCD factorization approach leads to a large shift:

$$q_0^2 = (4.39 + 0.38 - 0.35) GeV^2 \quad (NLO)$$

- Issue of power corrections $(1/m_b)$!

- Theoretical errors in branching ratio Ball et al. :

$\Delta BR(B \to K^* \mu^+ \mu^-) = ({}^{+26}_{-17}, \pm 6, {}^{+6}_{-4}, {}^{-0.7}_{+0.4}, \pm 2)\%$

conclusions on inclusive rare B decays

- Model-independent analysis of $b \to s\ell^+\ell^-$ and $b \to s\gamma$

  Global fit to the Wilson coefficients C_7, C_9, C_{10}

  - $\Gamma(B \to X_s\gamma)$
  - $d\Gamma(B \to X_s\ell^+\ell^-) \,/\, d\hat{s}$
    Invariant dilepton mass distribution
  - $A(s) = \int_{-1}^{1} dcos\theta \; d^2\Gamma(B \to X_s\ell^+\ell^-) \,/\, dsdcos\theta \;\; sgn(cos\theta)$
    Forward-Backward Charge Asymmetry

  $\Rightarrow$ Determines magnitude + sign of C_7, C_9, C_{10}

  In MFV the sign of C_7 is already fixed by $b \to s\ell^+\ell^-$ data
  Gambino, Haisch, Misiak

- For new physics search measurements of kinematical distributions are needed (high statistics necessary !):

  Super-B: 7% accuracy in s_0 possible

- Impact of NNLL (NLL) QCD calculations crucial !

Super-B reports
of KEK, hep-ph/0406071, and of SLAC, hep-ph/0503261.

Future role of kaon physics: Kopio, NA48/3

- BNL–E787: three events 3/2004 !

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = \left(1.47 \, {}^{+\,1.3}_{-\,0.9}\right) \times 10^{-10}$$

- Present SM theory (in future error below 5% possible):

$$BR(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{SM}} = (0.80 \pm 0.11) \times 10^{-10} \ .$$

What makes the neutrino modes $K \to \pi\nu\bar{\nu}$ so attractive?

- leading hadronic matrix element is known from K_{l3} decays: $< \pi \,|\, (\bar{s}d)_{V-A} \,|\, K >$

- amplitude dominated by short-distance due to quadratic GIM: $A^q \sim m_q^2 V_{qs} V_{qd}$

Neutrino modes as theoretically clean as inclusive B decays !

$\Rightarrow$ highly sensitive probe for degrees of freedom at higher scales

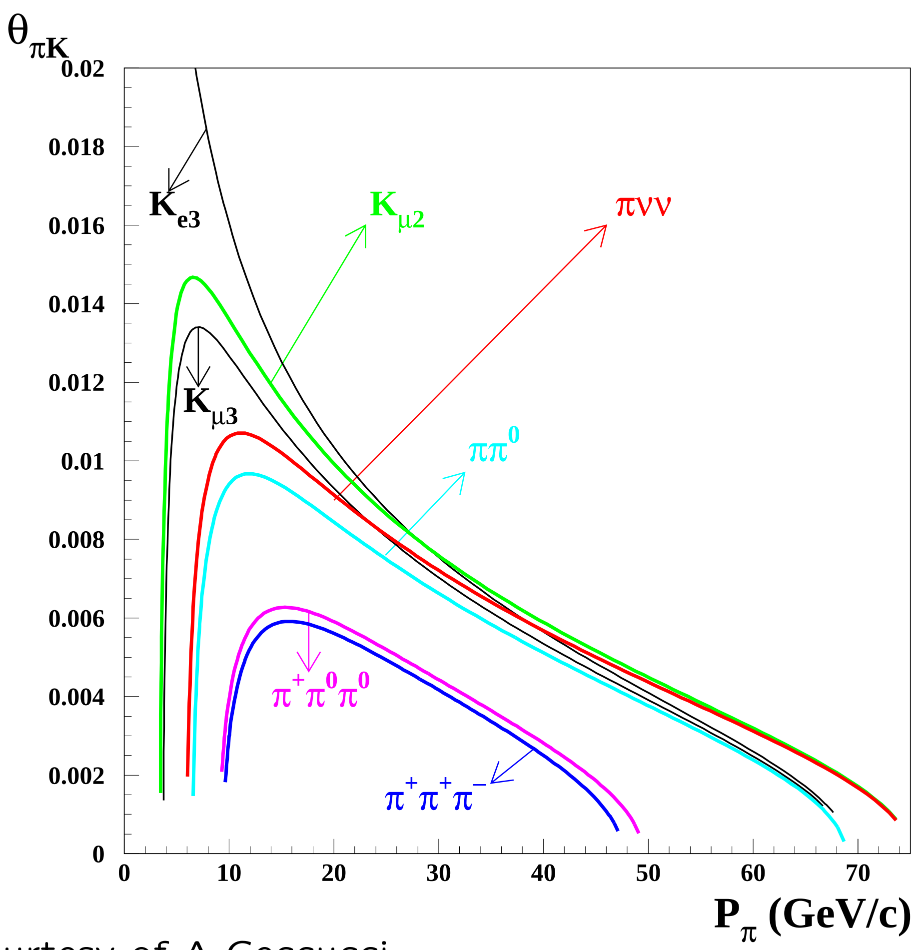
Proposed experiment at CERN, NA48/3: 'decay in flight'

80 $K^+ \to \pi^+ \nu \bar{\nu}$ events in about two years of data taking

(4×10^{12} kaon decays/SPS year, 10% acceptance, SM)

main background: $K^+ \to \pi^+ \pi^0$

(γ veto much easier because of high energy kaon beam)



courtesy of A.Ceccucci

$P_K = 75 GeV/c$

- BNL–E787: 2 events !

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = \left(1.57 \begin{array}{c} + \\ - \end{array} \begin{array}{c} 1.75 \\ 0.82 \end{array}\right) \times 10^{-10}$$

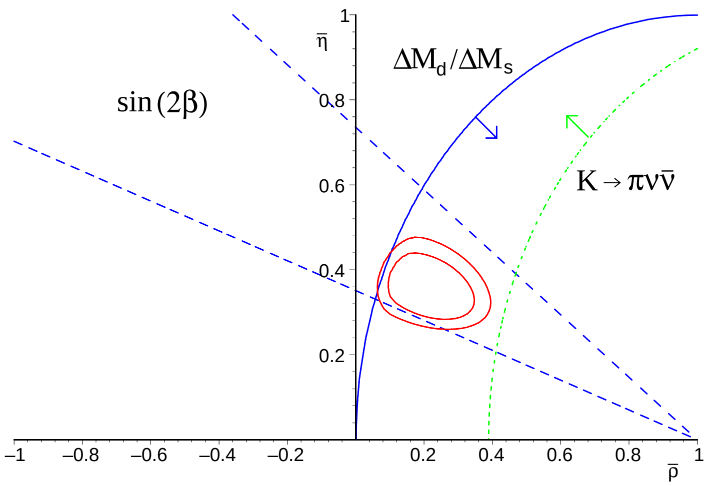
- BNL–E787: Third event 3/2004 !

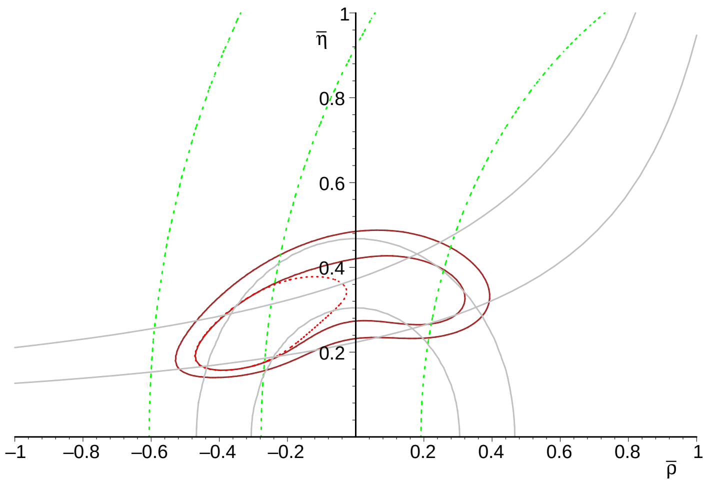
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = \left(1.47 \begin{array}{c} + \\ - \end{array} \begin{array}{c} 1.3 \\ 0.9 \end{array}\right) \times 10^{-10}$$

- SM Theory:

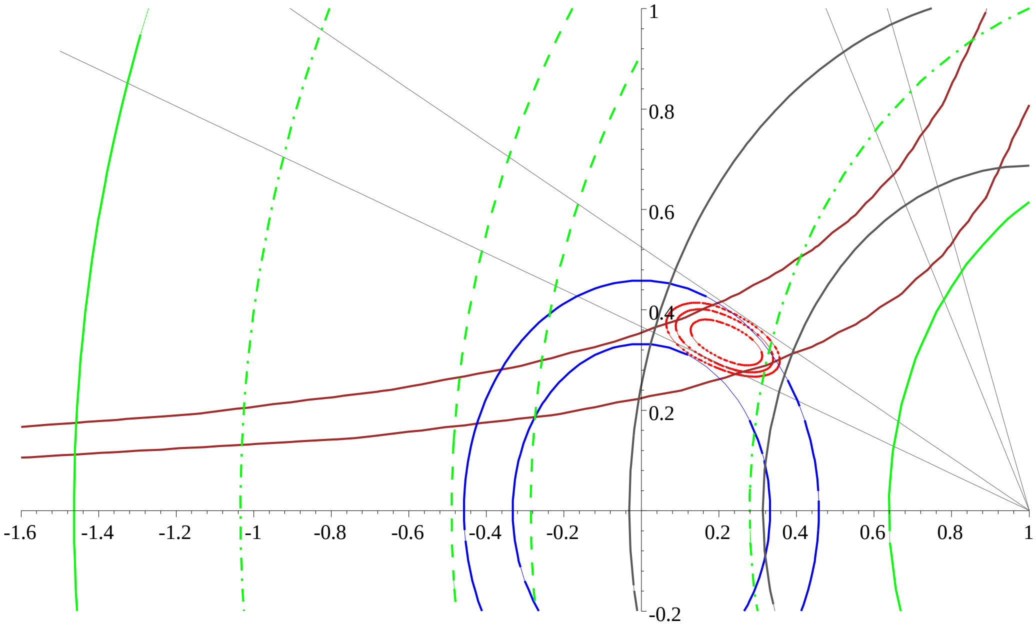
$$BR(K^+ \to \pi^+ \nu\bar{\nu})_{\rm SM} = (0.72 \pm 0.21) \times 10^{-10} \ .$$

D'Ambrosio, Isidori: some speculation





Update after third event (D'Ambrosio, Isidori)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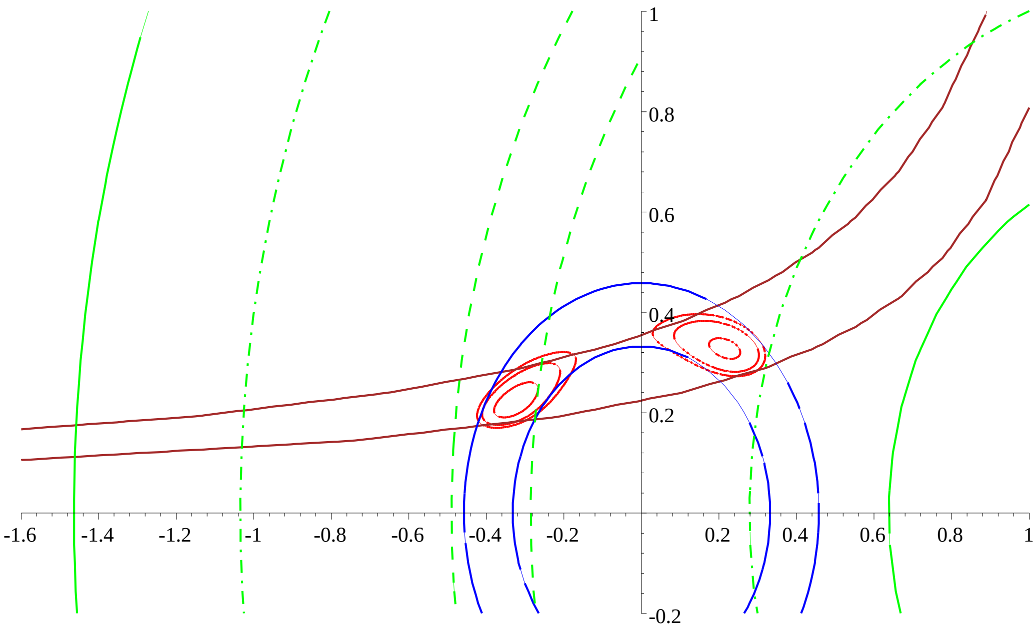
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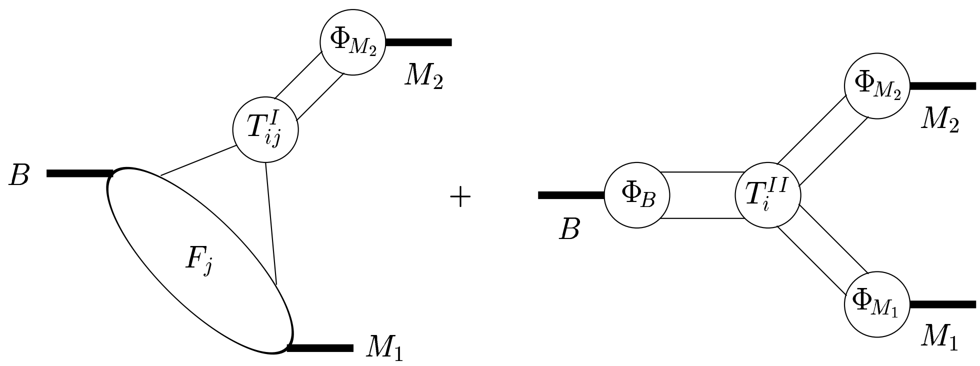
Hadronic charmless B decays

- QCD factorization theorems for $B \to \pi\pi$ and $B \to K\pi$



$$\begin{aligned} \langle \pi K | Q_i | B \rangle \quad &= \quad F_0^{B\to\pi}\, T^{\mathrm{I}}_{K,i} * f_K \Phi_K + F_0^{B\to K}\, T^{\mathrm{I}}_{\pi,i} * f_\pi \Phi_\pi \\ &\quad + T^{\mathrm{II}}_i * f_B \Phi_B * f_K \Phi_K * f_\pi \Phi_\pi \,, \\ &\quad + \text{terms suppressed } by\ 1/m_b \end{aligned}$$

- Factorization in B-decays
  - Short-distance effects are identified and can be systematically calculated in perturbation theory
  - Non-perturbative effects parametrized in terms of a few universal functions (parton distributions, form factors, light-cone distribution amplitudes)
  - Hope to achieve necessary accuracy to extract CKM elements
  - Limiting factor:
    Insufficient information on power-suppressed terms
    Challenge for nonperturbative methods !

- Quantum field theoretical description: SCET (no OPE !)
  HQET is not applicable to B decays in which some of the outgoing, light particles have momenta of order m_b.

Phenomenolgical approach to $B \to \pi\pi$

Feldmann,Hurth

- Use pure QCD-factorization part ($\neq$ BBNS) + general isospin analysis of the nonfactorizable part.

- Infer information on nonfactorizable parameters from experimental data by producing random parameters values and calculating the χ^2-value

  $A_i(I, \Delta I) = A_i^F(I, \Delta I) + A_i^{NF}(I, \Delta I)$

  $A_i^{NF}(I, \Delta I) := r_i(I, \Delta I)\, e^{i\phi_i(I,\Delta I)}\, A_{\pi\pi}$

- Nonfactorizable corrections are numerically not negligible

  Default scenario in the BBNS approach where all parameters $r_i(I, \Delta I)$ are small is disfavoured by data !
  ('so-called $B \to \pi\pi$ puzzle')

- We also identify model dependence in phenomenological studies due to additional assumptions.

  - BBNS
    Identification/parametrization of dominant $1/m_b$ effects
    (only simple $1/m_b$ SCET operators considered,
    not most general parametrization is used)

  - charming penguins
    Dominance of certain flavour topologies
    in naive quark picture
    (relation to QCD/SCET unclear)

  - $SU(3)$
    Application of approximate flavour symmetries
    (hadronic errors difficult to estimate)

Standard Isopin Analysis: $\lambda_i^{(q)} = V_{ib} V_{iq}^*$

$$
\begin{aligned}
\sqrt{2}\,\langle \pi^-\pi^0 | H_{\text{eff}} | B^- \rangle &\simeq \lambda_u^{(d)}\,[3A_u(2,3/2)] + \lambda_c^{(d)}\,[3A_c(2,3/2)] \ , \\
\langle \pi^+\pi^- | H_{\text{eff}} | \bar{B}^0 \rangle &\simeq \lambda_u^{(d)}\,[-A_u(0,1/2) + A_u(2,3/2)] \ , \\
&\quad +\lambda_c^{(d)}\,[-A_c(0,1/2) + A_c(2,3/2)] \\
\sqrt{2}\,\langle \pi^0\pi^0 | H_{\text{eff}} | \bar{B}^0 \rangle &\simeq \lambda_u^{(d)}\,[A_u(0,1/2) + 2A_u(2,3/2)] \\
&\quad +\lambda_c^{(d)}\,[A_c(0,1/2) + 2A_c(2,3/2)] \ ,
\end{aligned}
$$

$A_i(I,\Delta I)$: I denotes the total isospin I of the final state and ΔI the isospin of the operators in the weak effective hamiltonian.

$$A_i(I,\Delta I) = A_i^F(I,\Delta I) + A_i^{NF}(I,\Delta I)$$

- Factorizable Part:
  A_i^F fixed by QCD factorization with overall normalization:
  $A_{\pi\pi} = \frac{iG_F}{\sqrt{2}}\,(m_B^2 - m_\pi^2)\,F_0^{B\to\pi}(m_\pi^2)\,f_\pi$

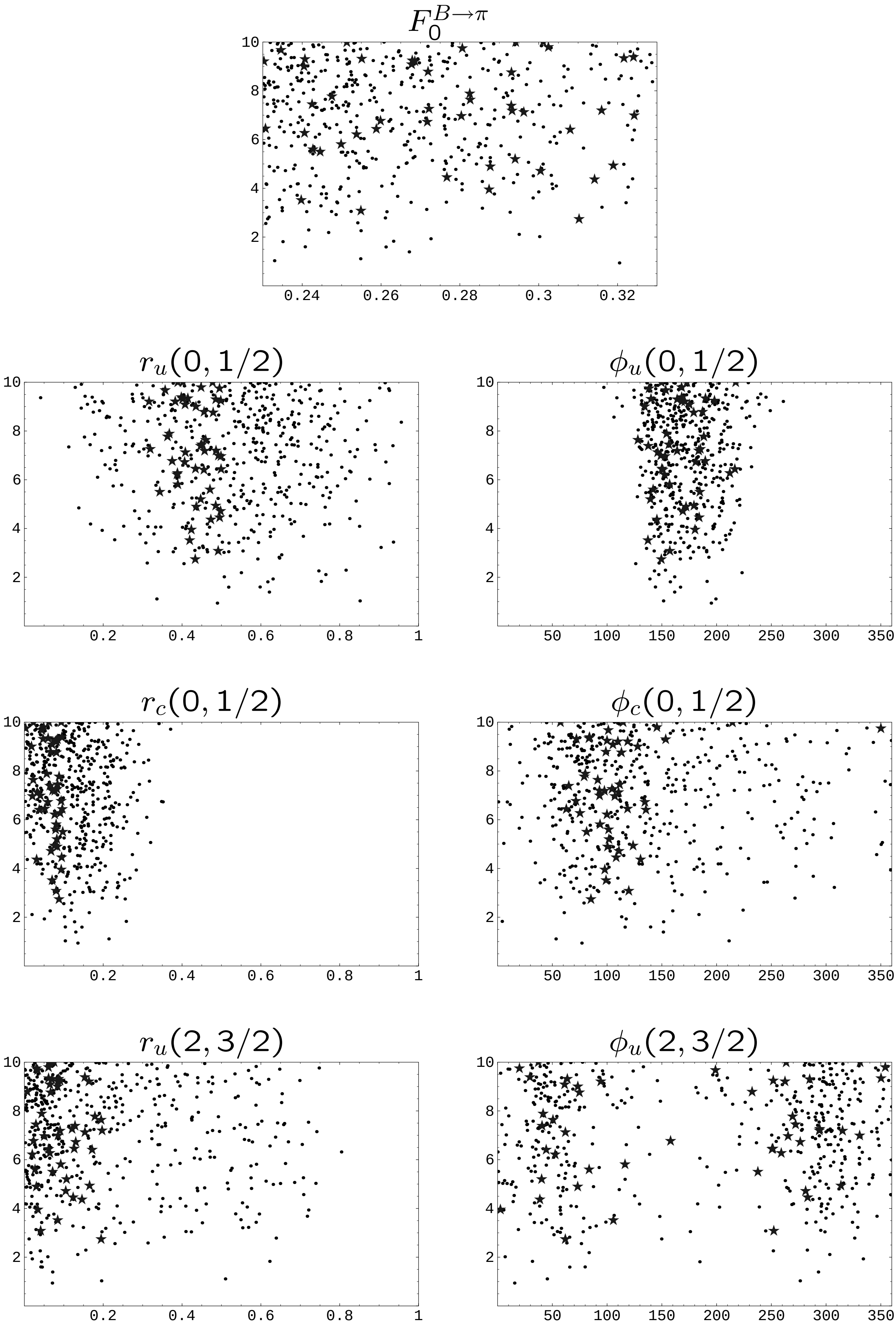
- Nonfactorizable Part:
  $A_i^{NF}(I,\Delta I) := r_i(I,\Delta I)\,e^{i\phi_i(I,\Delta I)}\,A_{\pi\pi}$

  * Unconstrained scenario:

$$
\begin{aligned}
0.23 \le F_0^{B\to\pi}(m_\pi^2) &\le 0.33 \ , \\
0 \le r_{u,c}(I,\Delta I) &\le 1.0 \ , \\
0^\circ \le \phi_{u,c}(I,\Delta I) &\le 360^\circ \ ,
\end{aligned}
$$

  * Constrained scenario:
  $r_u(0,1/2) < 0.5$, $\quad r_u(2,3/2) < 0.2$, $\quad r_c(0,1/2) < 0.1$,

Test also model assumptions of various approaches like dominance of hard-scattering or annihilation terms !



dots for unconstrained, stars for constrained scenario.

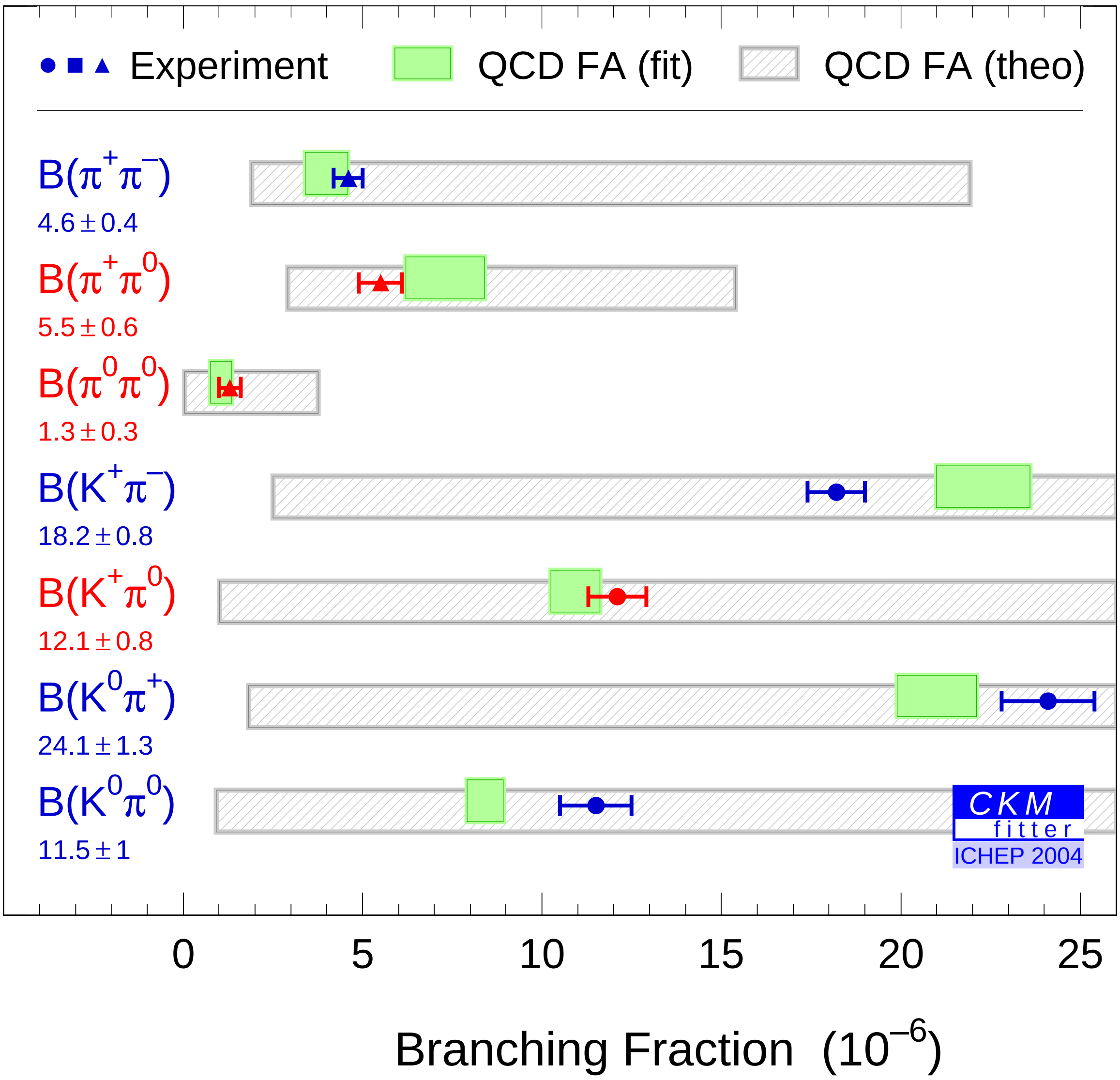
BBNS versus Experiment

$B \to \pi\pi$ data not well in line with QCD factorization

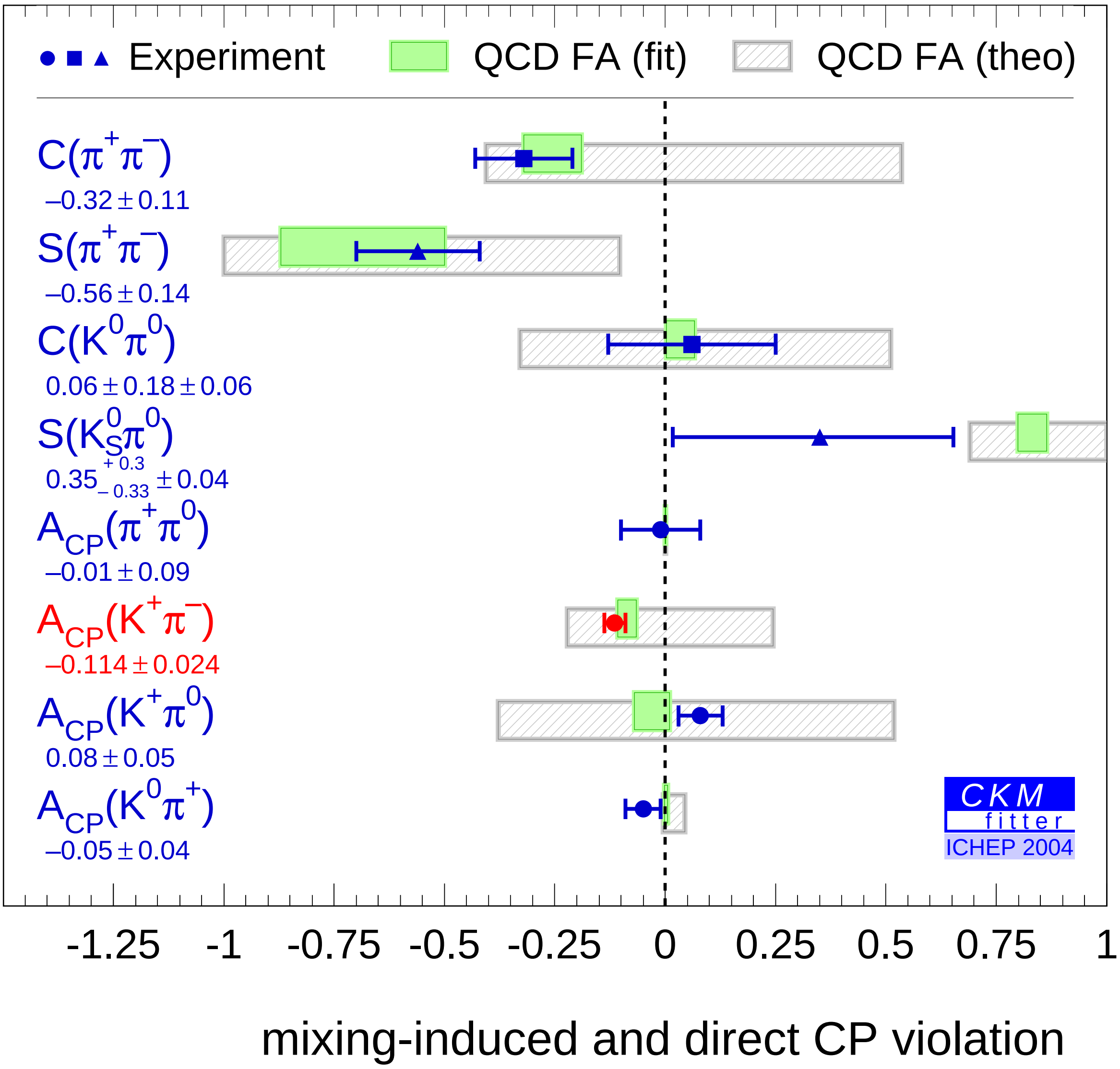
* large modification of some hadronic input parameters ? (Beneke,Neubert hep-ph/0308039)

* safe conclusion: data indicates nonfactorizable contributions are sizable (see scatter plots) !

* Fits of BBNS by CKM Fitter group:
(the latter fact is not directly manifest in plots)



Fit of theoretical parameters to data
Uncorrelated scan over all theoretical parameters



Definitions:

$$A_{\rm CP}[\pi^+\pi^0] \;=\; \frac{\Gamma[\bar{B}^- \to \pi^-\pi^0] - \Gamma[\bar{B}^+ \to \pi^+\pi^0]}{\Gamma[\bar{B}^- \to \pi^-\pi^0] + \Gamma[\bar{B}^+ \to \pi^+\pi^0]}\,,$$

$$S_{\pi\pi}^{+-} = \frac{2{\rm Im}\lambda_{\pi\pi}}{1+|\lambda_{\pi\pi}|^2}\,, \qquad C_{\pi\pi}^{+-} = \frac{1-|\lambda_{\pi\pi}|^2}{1+|\lambda_{\pi\pi}|^2}\,,$$

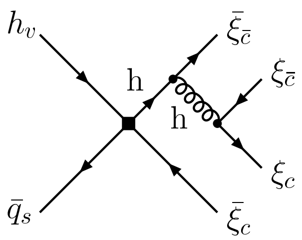
$$\lambda_{\pi\pi} = \frac{q}{p}\,\frac{\mathcal{A}[\bar{B}^0 \to \pi^+\pi^-]}{\mathcal{A}[B^0 \to \pi^+\pi^-]} \simeq e^{-2i\beta}\,\frac{\mathcal{A}[\bar{B}^0 \to \pi^+\pi^-]}{\mathcal{A}[B^0 \to \pi^+\pi^-]}$$

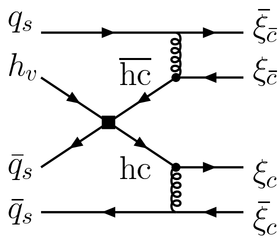
SCET approach

- $1/m_b$ contributions of matrix elements of nonfactorizable SCET operators

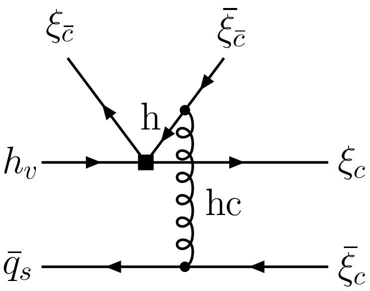
  For example:

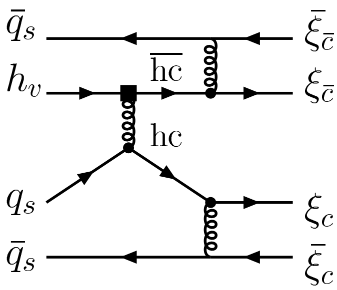
  * annihilation topologies to $B \to PP$





  * Hard-scattering contributions to $B \to PP$





  left:
  one-gluon exchange included in the BBNS analysis

  right:
  contributions from higher-Fock-states not necessarily suppressed (nonfactorizable endpoint configurations)

conclusions on $B \to \pi\pi$:

- Use the future data to test various theoretical assumptions on dynamics with the help of a general isospin analysis of the nonfactorizable contributions.

- Challenge for theory:

development of non-perturbative methods within SCET:

SCET sum rules De Fazio,Feldmann,Hurth hep-ph/0504088

Is there a R_n-puzzle in $B \to K\pi$?

CP averaged branching ratios:

$$R = \frac{\tau_{B^+}}{\tau_{B^0}} \frac{\mathrm{BR}[B_d^0 \to \pi^- K^+] + \mathrm{BR}[\bar{B}_d^0 \to \pi^+ K^-]}{\mathrm{BR}[B_d^+ \to \pi^+ K^0] + \mathrm{BR}[B_d^- \to \pi^- \bar{K}^0]} = 0.82 \pm 0.056$$

$$R_n = \frac{1}{2} \frac{\mathrm{BR}[B_d^0 \to \pi^- K^+] + \mathrm{BR}[\bar{B}_d^0 \to \pi^+ K^-]}{\mathrm{BR}[B_d^0 \to \pi^0 K^0] + \mathrm{BR}[\bar{B}_d^0 \to \pi^0 \bar{K}^0]} = 0.789 \pm 0.075$$

$$R_c = 2 \frac{\mathrm{BR}[B_d^+ \to \pi^0 K^+] + \mathrm{BR}[B_d^- \to \pi^0 K^-]}{\mathrm{BR}[B_d^+ \to \pi^+ K^0] + \mathrm{BR}[B_d^- \to \pi^- \bar{K}^0]} = 1.004 \pm 0.084$$

- pre-ICHEP04 data:
  $R = 0.91 \pm 0.07$, $R_n = 0.76 \pm 0.10$, $R_c = 1.17 \pm 0.12$

- Approach based on QCD factorization (BBNS)
  $R = 0.91^{+0.13}_{-0.11}$, $R_n = 1.16^{+0.22}_{-0.19}$, $R_c = 1.15^{+0.19}_{-0.17}$

- SM-Fit to $\pi\pi$ + $SU(3)_F$ (Buras et al)
  $R = 0.94^{+0.03}_{-0.03}$, $R_n = 1.14^{+0.08}_{-0.07}$, $R_c = 1.11^{+0.06}_{-0.07}$
  (Note: errors reflect only experimental uncertainties of $B \to \pi\pi$)

Does the R_n puzzle guide us to new physics?

- large nonfactorizable contributions allow for large $SU(3)_F$ or isospin-violating effects (Feldmann, Hurth)
  ('so-called $\pi\pi$ puzzle solves $K\pi$ puzzle')

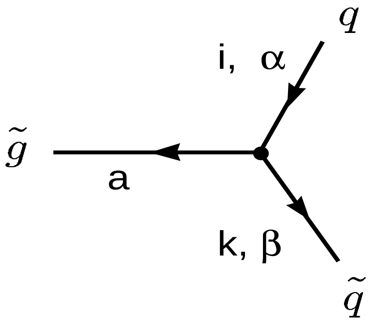
- radiative corrections to decays with charged particles in the final states may not have been taken into account properly in the experimental analysis ($B^0 \to \pi^+ K^-$ not yet updated !!)

- possible underestimation of π_0 detection efficiency ($R_n * R_c$)

Correlations between B and collider physics via squark mixing within SUSY

- In the unconstrained MSSM there are (too many ?) new contributions to flavour violation
  - CKM induced contributions from H^+, χ^+ exchanges
  - flavour mixing in the sfermion mass matrix

- Gluino-quark-squark coupling
  $-ig_s T^a_{\beta\alpha}(\Gamma^{ki}_{QL} P_L - \Gamma^{ki}_{QR} P_R)$



- Possible disalignment of quarks and squarks
  - quark mass matrices are diagonal !
  - squarks are rotated 'parallel' to their fermionic superpartners !
  - in general not mass eigenstates: $\tilde{q}_{L,R} = \Gamma^+_{QL,R}\tilde{q}_i$

  Sfermion mass matrix in uMSSM in $\tilde{q}_{L,R}$ basis:

$$\mathcal{M}^2_D = (F/D)^D_{6\times 6} + \begin{pmatrix} m^2_{Q,LL} & m^2_{D,LR} \\ m^2_{D,RL} & m^2_{D,RR} \end{pmatrix}$$

$$\mathcal{M}^2_U = (F/D)^U_{6\times 6} + \begin{pmatrix} m^2_{Q,LL} & m^2_{U,LR} \\ m^2_{U,RL} & m^2_{U,RR} \end{pmatrix}$$

from F, D terms	from soft breaking
3×3 diagonal submatrices	m^2_i not diagonal

FCNC are induced by off-diagonal (off-generational) terms in $m^2_{LL}, m^2_{RR}, m^2_{LR}$

- Low energy constraints
  - K-physics: ϵ'/ϵ, K^0-$\bar{K}^0$ mixing, . . .
    significantly constrain $1-2$ and $1-3$ mixing
  - B-physics: $b \to s\gamma$, ΔM_{B_s}, . . .
    most important beyond SM contributions: H^+, $\tilde{\chi}_i^+$, $\tilde{g}$

- Correlations to Collider Physics (Hurth,Porod)
  - squark decays:

$$\begin{aligned} \tilde{u}_i &\to u_j\tilde{\chi}_k^0\,,\, d_j\tilde{\chi}_l^+ \\ \tilde{d}_i &\to d_j\tilde{\chi}_k^0\,,\, u_j\tilde{\chi}_l^- \end{aligned}$$

    with $i=1,..,6$, $j=1,2,3$, $k=1,..,4$ and $l=1,2$.
  - these decays are governed by the same mixing matrices as the contributions to flavour violating low-energy observables.

Squarks can have large flavourviolating decay modes (compatible with present data from flavour physics).

Strategy

- take SPS1a as starting point:

  $M_0 = 100$ GeV, $M_{1/2} = 250$ GeV
  $A_0 = -100$ GeV, $\tan\beta = 10$, $\mu > 0$
  $\Rightarrow$
  $M_2 = 192$ GeV, $\mu = 351$ GeV
  $m_{H^+} = 403$ GeV $m_{\tilde{g}} = 594$ GeV, $m_{\tilde{t}_1} = 400$ GeV
  $m_{\tilde{t}_2} = 590$ GeV, $m_{\tilde{q}_R} \simeq 550$ GeV, $m_{\tilde{q}_L} \simeq 570$ GeV

  (SPheno 2.0)

- vary off-diagonal squark mass entries.

- accept points with $2 \leq 10^4$ BR$(b \to s\gamma) \leq 4.5$ and $\Delta M_{B_s} \geq 14$ ps^{-1}

- For simplicity: real parameters only

- QCD corrections for $b \to s\gamma$ as given in Borzumati et al., Phys. Rev. D62, 075005 (2000) and Besmer et al., Nucl.Phys.B609:359 (2001)

- ΔM_{B_s}, as given in Baek et al. , Phys. Rev. D64, 095001 (2001)

$\Rightarrow$ Typical results:

Branching ratios (in %) of u-type squarks

	$\tilde{\chi}_1^0 c$	$\tilde{\chi}_1^0 t$	$\tilde{\chi}_2^0 c$	$\tilde{\chi}_2^0 t$	$\tilde{\chi}_3^0 c$	$\tilde{\chi}_3^0 t$	$\tilde{\chi}_4^0 c$	$\tilde{\chi}_4^0 t$	$\tilde{\chi}_1^+ s$	$\tilde{\chi}_1^+ b$	$\tilde{\chi}_2^+ s$	$\tilde{\chi}_2^+ b$
$\tilde{u}_1$	4.7	18	5.2	9.6	6×10^{-3}	0	0.02	0	11.3	46.4	2×10^{-3}	4.7
$\tilde{u}_2$	.19.6	1.1	0.4	17.5	2×10^{-2}	0	6×10^{-2}	0	0.5	57.5	3×10^{-3}	2.9
$\tilde{u}_3$	7.3	3.7	20	1.4	6×10^{-2}	0	0.6	0	40.3	3.1	1	18.5
$\tilde{u}_6$	5.7	0.4	11.1	5.3	4×10^{-2}	5.7	0.6	13.2	22.9	13.1	0.6	8.0

Branching ratios (in %) of d-type squarks

	$\tilde{\chi}_1^0 s$	$\tilde{\chi}_1^0 b$	$\tilde{\chi}_2^0 s$	$\tilde{\chi}_2^0 b$	$\tilde{\chi}_3^0 s$	$\tilde{\chi}_3^0 b$	$\tilde{\chi}_4^0 s$	$\tilde{\chi}_4^0 b$	$\tilde{\chi}_1^- b$	$\tilde{\chi}_1^- t$	$\tilde{\chi}_2^- b$	$\tilde{\chi}_2^- t$	$\tilde{u}_1 W^-$
$\tilde{d}_1$	1.2	5.7	8.4	30.6	2×10^{-2}	1.5	0.2	0.9	16.6	34.1	0.6	0	0
$\tilde{d}_2$	.17.4	5.8	5.1	15.7	7×10^{-2}	7.4	0.3	09.2	9.7	19.7	0.7	0	8.8
$\tilde{d}_4$	14.7	21.7	11.3	2.2	5×10^{-2}	10.6	0.5	8.4	22.1	3.6	1.2	0	3.4
$\tilde{d}_6$	1.7	0.5	20.5	6.9	0.1	0.9	1.2	1.3	40.3	10.2	3.4	11.1	1.8

Gluino branching ratios larger than 1%.

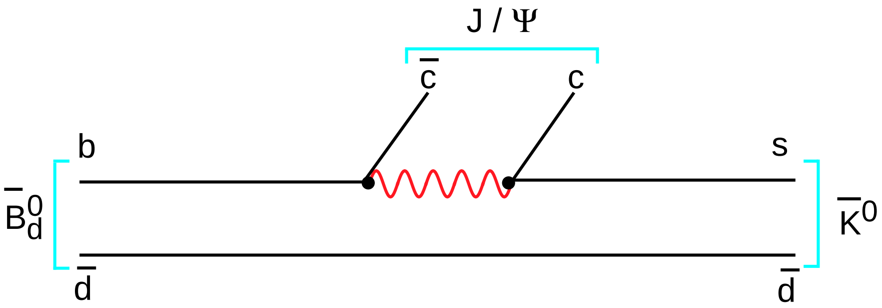
Final state	BR [%]	Final state	BR [%]
$\tilde{u}_1 c$	12.9	$\tilde{d}_1 s$	7.2
$\tilde{u}_1 t$	5.7	$\tilde{d}_1 b$	19.8
$\tilde{u}_2 c$	0.4	$\tilde{d}_2 s$	6.1
$\tilde{u}_2 t$	7.6	$\tilde{d}_2 b$	4.7
$\tilde{u}_3 c$	0.6	$\tilde{d}_3 d$	10.0
$\tilde{u}_4 u$	5.5	$\tilde{d}_4 s$	3.5
$\tilde{u}_5 u$	3.0	$\tilde{d}_4 b$	4.9
		$\tilde{d}_5 d$	2.1

conclusions on correlations via squark mixing

- $b \to s\gamma$ and ΔM_{B_s} (still ?) allow for large mixings between second and third generation squarks, for example $\tilde{t}_i$, $\tilde{c}_i$ can have large flavour violating decay modes,
- makes life at LHC potentially more interesting and more difficult,
- extra information from ILC or flavour factories needed.

CP Violating Observables

- SM is very predictive only one CP-violating parameter. (Kobayashi-Maskawa 1972 !)
- KM mechanism has passed successfully its first precision test:



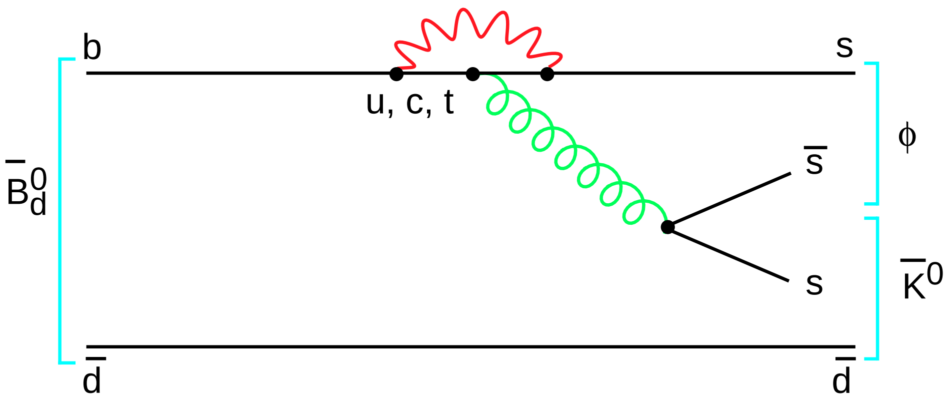
$$A_{\text{CP}}(t) \quad = \quad \frac{\Gamma(\bar{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\bar{B}^0(t) \to f) + \Gamma(B^0(t) \to f)}.$$

$$A_{\text{CP}}(B_d \to J/\psi K_S) = \sin(2\beta)\sin(\Delta m_B t) \qquad \Delta B = 2$$

$$\sin(2\beta) = \begin{cases} 0.741 \pm 0.067 \pm 0.033 & \text{Babar} \\ 0.733 \pm 0.057 \pm 0.028 & \text{Belle} \end{cases}$$

$$\text{SM:} \quad \sin(2\beta) = 0.68 \pm 0.21$$

- Test in $A_{\text{CP}}(B_d \to \Phi K_S)$ is still open: Penguin



- Also direct CP asymmetries in $b \to s/d$ transitions: $\Delta F = 1$:

$$\Delta\Gamma_{CP}(B \to X_{s/d}\gamma) = \Gamma(\bar{B} \to X_{s/d}\gamma) - \Gamma(B \to X_{\bar{s}/\bar{d}}\gamma)$$

$$|\Delta BR_{CP}(B \to X_s\gamma) + \Delta BR_{CP}(B \to X_d\gamma)| \sim 1 \cdot 10^{-9} \approx 0$$

(Hurth, Mannel)

Untagged CP asymmetries in $b \to s/d$ transitions $\quad \Delta F = 1$

$$\Delta\Gamma_{CP}(B \to X_{s/d}\,\gamma) = \Gamma(\bar{B} \to X_{s/d}\gamma) - \Gamma(B \to X_{\bar{s}/\bar{d}}\gamma)$$

KM mechanism CKM unitarity

$\Rightarrow\ J = \mathrm{Im}(\lambda_u^{(s)}\lambda_c^{(s)*}) = (-1)\ \mathrm{Im}(\lambda_u^{(d)}\lambda_c^{(d)*})$

$+$ U spin symmetry of matrix elements $d \leftrightarrow s$:

$$\Delta\Gamma_{CP}(B \to X_s\gamma) + \Delta\Gamma_{CP}(B \to X_d\gamma) = b_{inc}\Delta_{inc}$$

b_{exc}: 'relative U-spin-breaking'; $|b_{inc}| \sim m_s^2/m_b^2 \sim 5 \cdot 10^{-4}$
Δ_{exc}: 'typical size' of CP violating rate difference

$$|\Delta BR_{CP}(B \to X_s\gamma) + \Delta BR_{CP}(B \to X_d\gamma)| \sim 1 \cdot 10^{-9} \approx 0$$

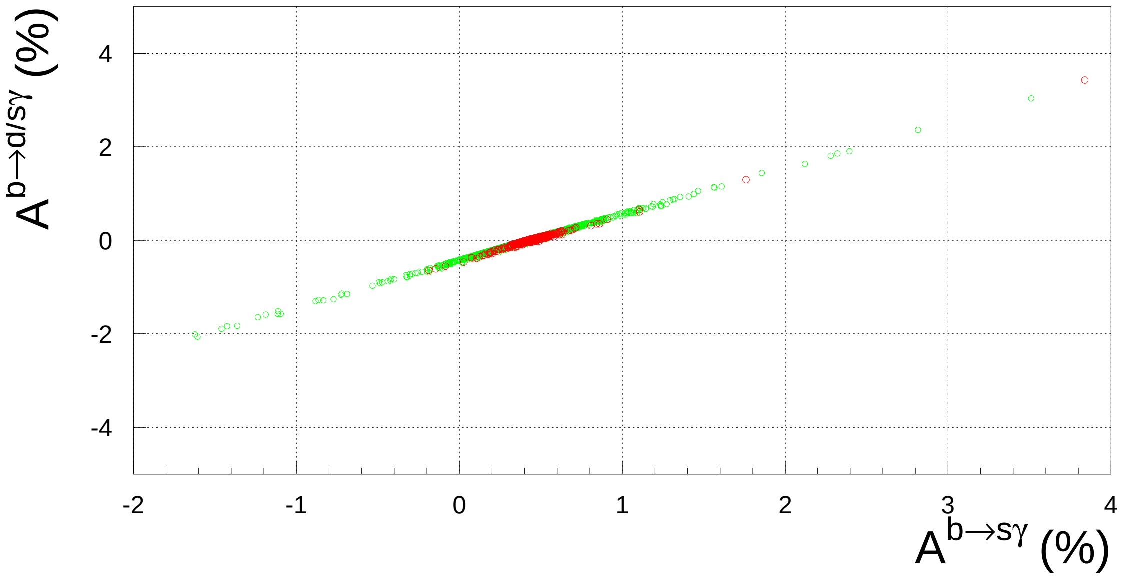
Clean test, whether new CP phases are active or not
(Hurth, Mannel)

Experiment: (Super-) Babar $\pm 3\%$ ($\pm 0.3\%$) precision possible

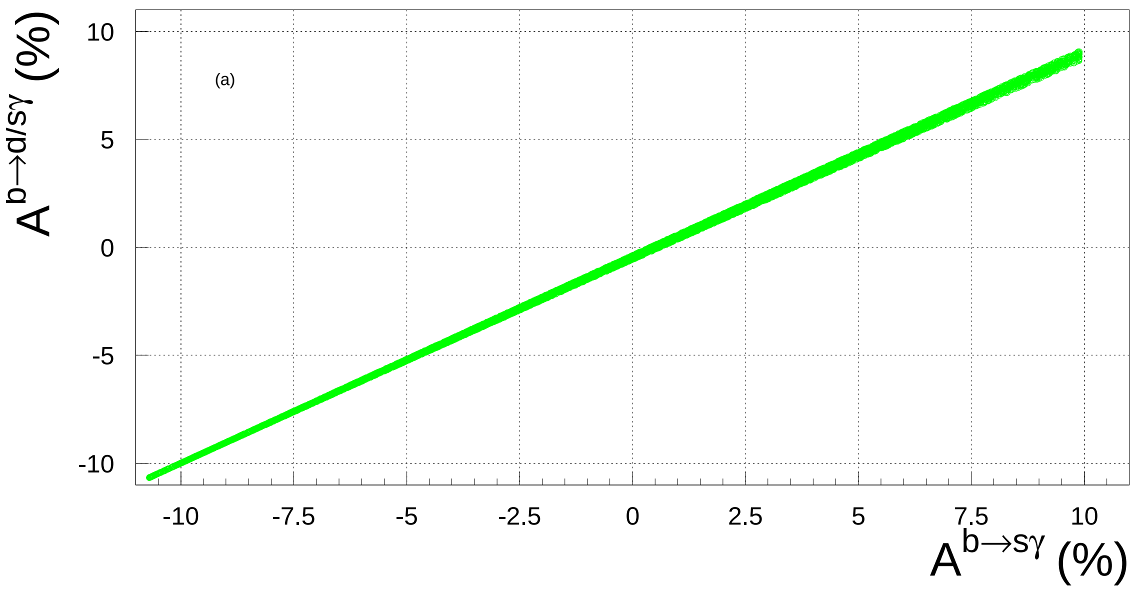
$$A_{CP}(b \to (s+d)\,\gamma) = \frac{A_{CP}^{b\to s\gamma} + R_{ds}\; A_{CP}^{b\to d\gamma}}{1+R_{ds}}, \quad R_{ds} = \Sigma\Gamma_d/\Sigma\Gamma_s$$

Experiment: Babar $\pm 3\%$ (Super-Babar $\pm 0.3\%$) uncertainty

MFV with (flavourblind) phases



Model-independent analysis C_7^s; squark mixing δ_{23}:



(Hurth, Lunghi, Porod)

Experimental Issues

- Inclusive untagged measurement with other-side-lepton tag
  - efficiencies on $A_{CP}^{b\to s\gamma}$ and on $A_{CP}^{b\to d\gamma}$ the same
  - advantage of a high photon energy cut at 2.2GeV can be used
  - present 81fb^{-1} data set leads to an estimated 11% precision, dominated by statistical error Libby,Babar
  - Extrapolation Libby,Babar

$1ab^{-1}$	3%	end of Babar/Belle
$10ab^{-1}$	1%	one-year running SuperBabar
$50ab^{-1}$	0.3%	end of SuperBabar

- Planned: Inclusive tagged measurement
  - independent data sample with an additional kaon tag
  - smaller mistag fraction
- Semi-inclusive measurement
  - not clear if quark-hadron duality applicable if only 50% of the rate available

conclusions on direct CP

- Untagged CP asymmetry favoured observable, perhaps even more information, cleaner than tagged A_{CP}
- Discrimination power between various scenarios
- Restricted indirect sensitivity for $A_{CP}^{b\to d\gamma}$ through tagged + untagged A_{CP}

FLAVOUR IN THE ERA OF THE LHC

a Workshop
on the interplay of flavour and collider physics

First meeting: CERN, November 7-11 2005

http://mlm.home.cern.ch/mlm/FlavLHC.html

The goal of this Workshop is to outline and document a programme for flavour physics for the next decade, addressing in particular the complementarity and synergy between the LHC and the flavour factories vis a vis the discovery and exploration potential for new physics.

The format of the Workshop will follow the standard CERN experience, with an opening meeting with plenary sessions and with the start of the WG activities, followed by 2-3 meetings of the WG's to take place during the following year, and a final plenary meeting at the end.