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New physics in $b \to s$ transitions

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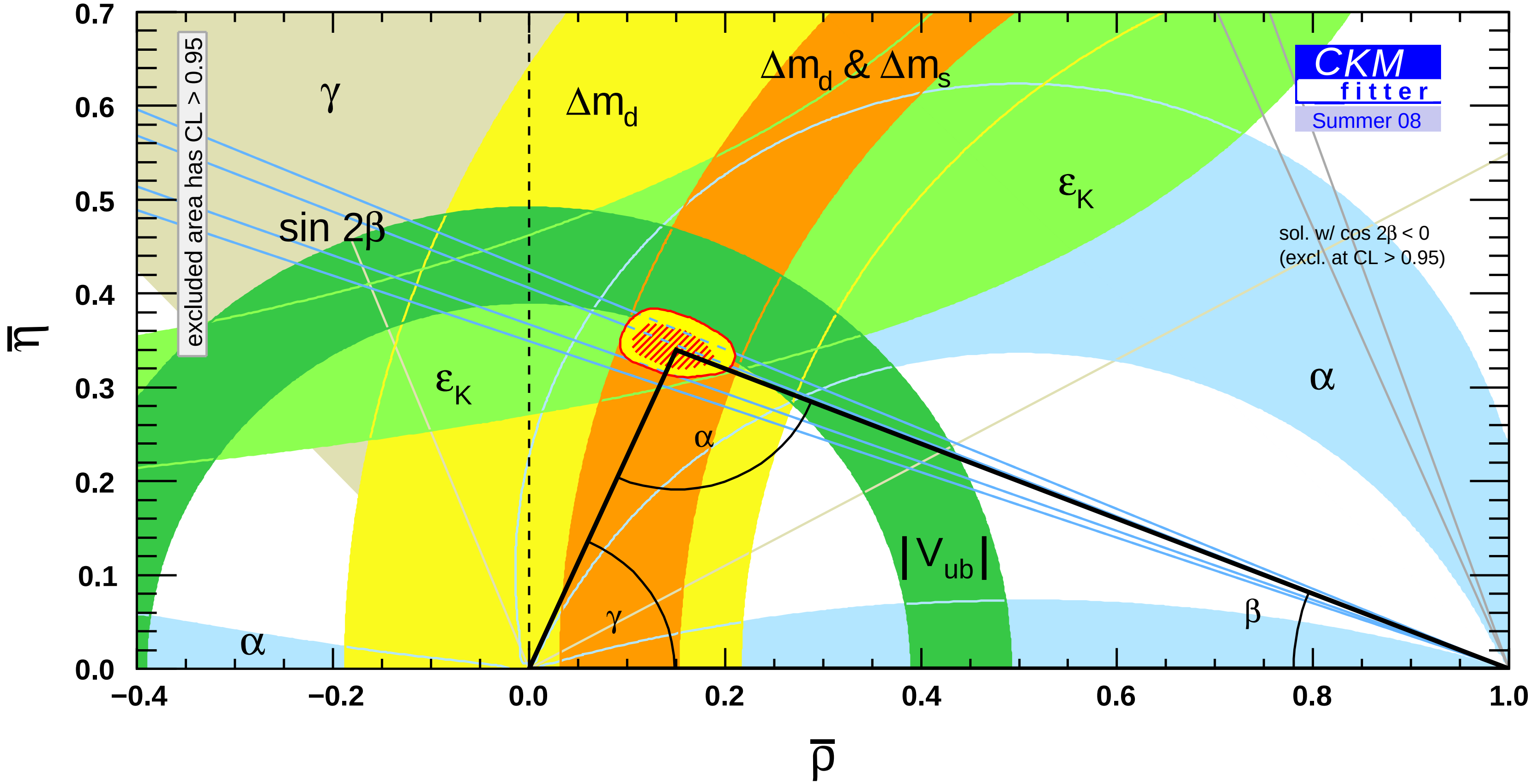
Outline

1. Status of B physics
2. Physics beyond the Standard Model
3. B_s decays and electroweak penguins
4. Summary

1. Status of B physics

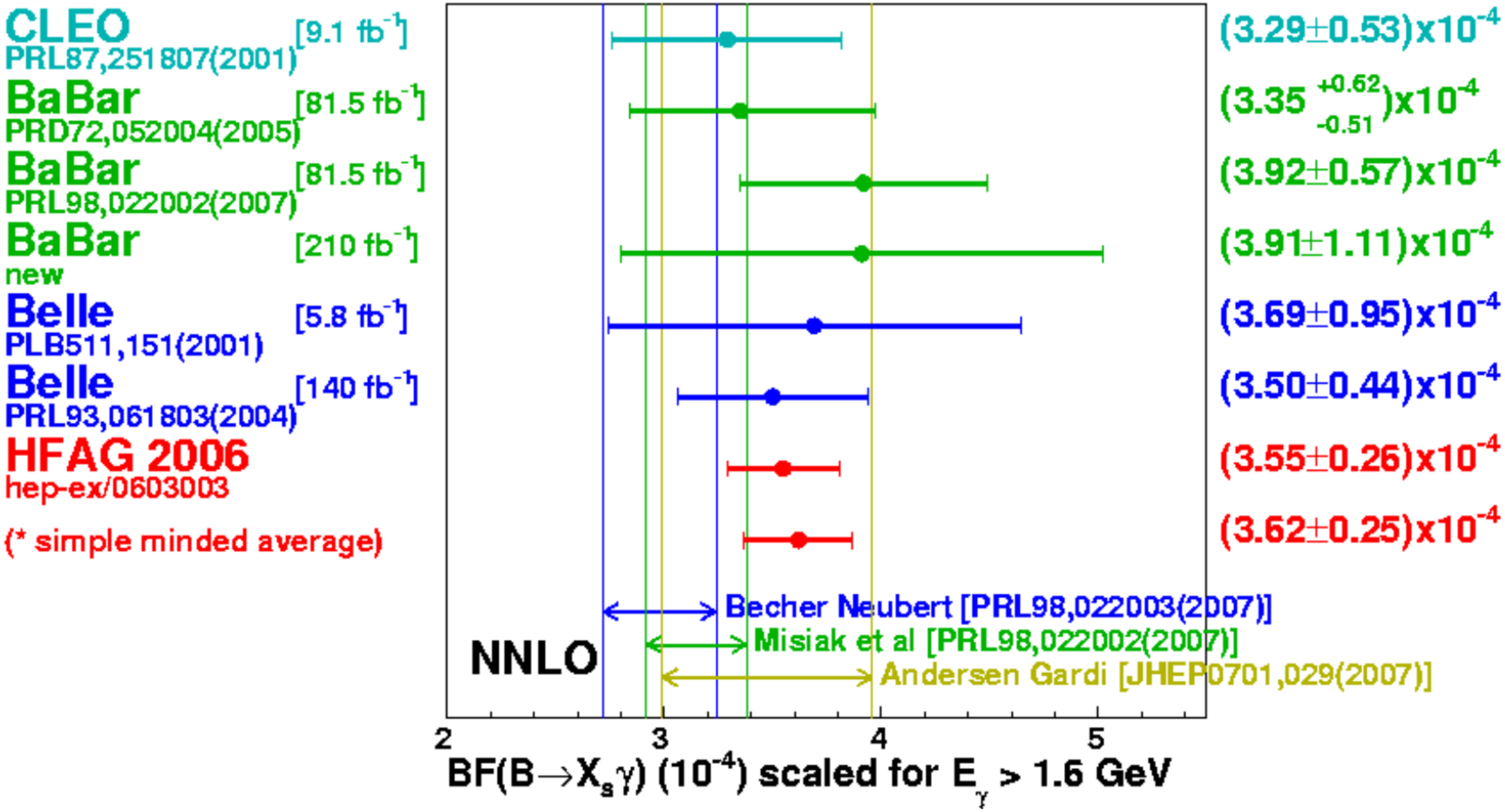
Experimental status of the unitarity triangle



consistent with the Standard Model

CKM mechanism excellently confirmed.

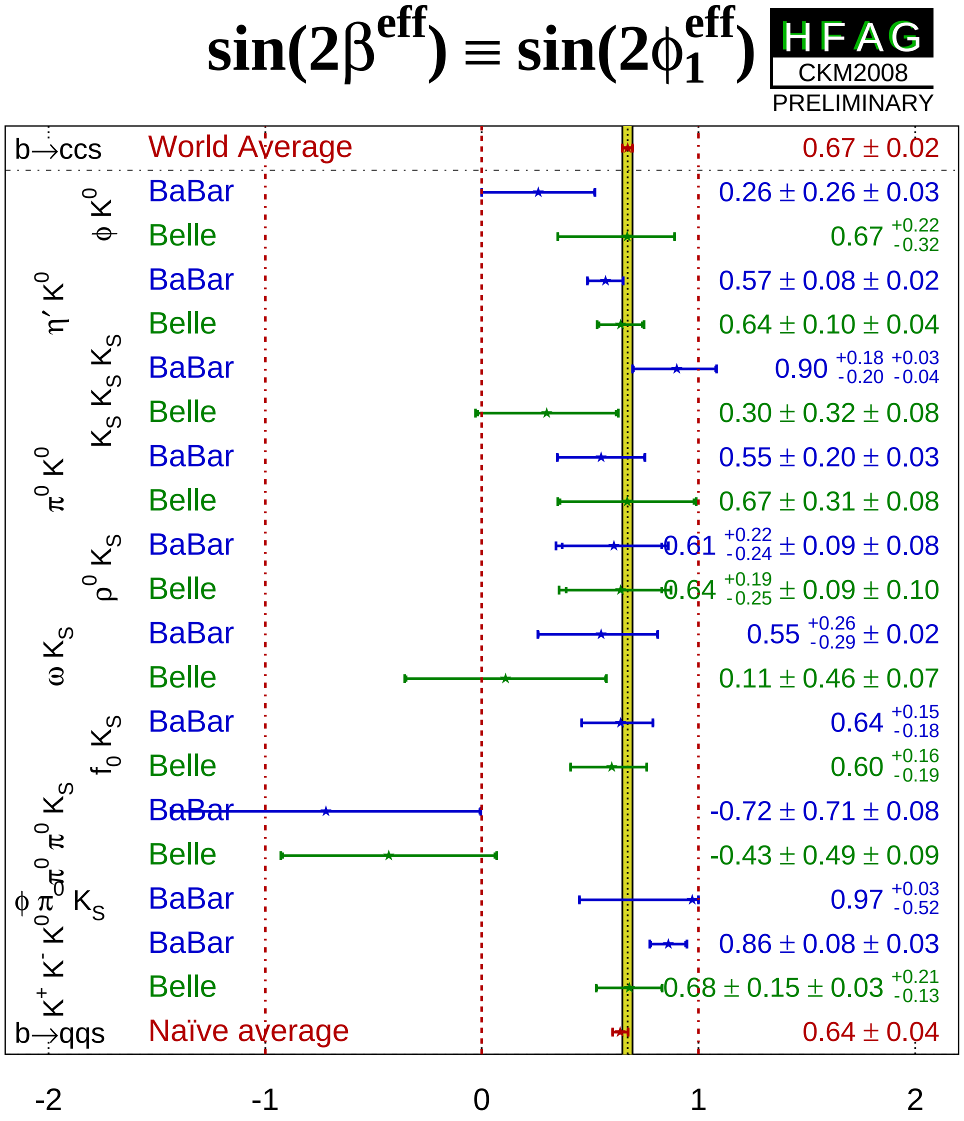
Experimental status of $b \to s\gamma$



consistent with the Standard Model prediction within $\sim 1.5\sigma$:

$$\mathcal{B}(B \to X_s\gamma) \;=\; (2.98 \pm 0.26)\cdot 10^{-4} \qquad \text{Becher,Neubert 2006}$$

Experimental status of CP asymmetries in $b \to s$ transitions



Naive average agrees with the Standard Model expectation.

Better figure of merit: absolute deviation from the Standard Model.

	Physics probed:
Unitarity Triangle:	$b \to d$, $s \to d$, $b \to u$
$B \to X_s\gamma$:	$b_R \to s_L$
$\cancel{CP}$ in $b \to s$ transitions:	$b \to s$

$\Rightarrow$ Yukawa sector is the dominant source of flavour violation.

The Standard Model works too well:

Flavour problem of TeV scale physics

	Physics probed:
Unitarity Triangle:	$b \to d$, $s \to d$, $b \to u$
$B \to X_s \gamma$:	$b_R \to s_L$
$C\!\!\!/P$ in $b \to s$ transitions:	$b \to s$

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The Standard Model works too well:

Flavour problem of TeV scale physics

In the Minimal Supersymmetric Standard Model (MSSM) all potential new sources of flavour violation come from the SUSY breaking sector. The success of the flavour physics programs at the B factories and the Tevatron severely constrains the associated parameters in the squark mass matrices.

$\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing

The phase $\phi_s = \arg(-M_{12}/\Gamma_{12})$ is negligibly small in the Standard Model:

$$\phi_s^{\mathrm{SM}} = 0.2^\circ.$$

Define the complex parameter Δ_s through

$$M_{12}^s \equiv M_{12}^{\mathrm{SM,s}} \cdot \Delta_s\,, \qquad \Delta_s \equiv |\Delta_s| e^{i\phi_s^\Delta}.$$

In the Standard Model $\Delta_s = 1$.

The CDF measurement

$$\Delta m_s = (17.77 \pm 0.10 \pm 0.07)\ \mathrm{ps}^{-1}$$

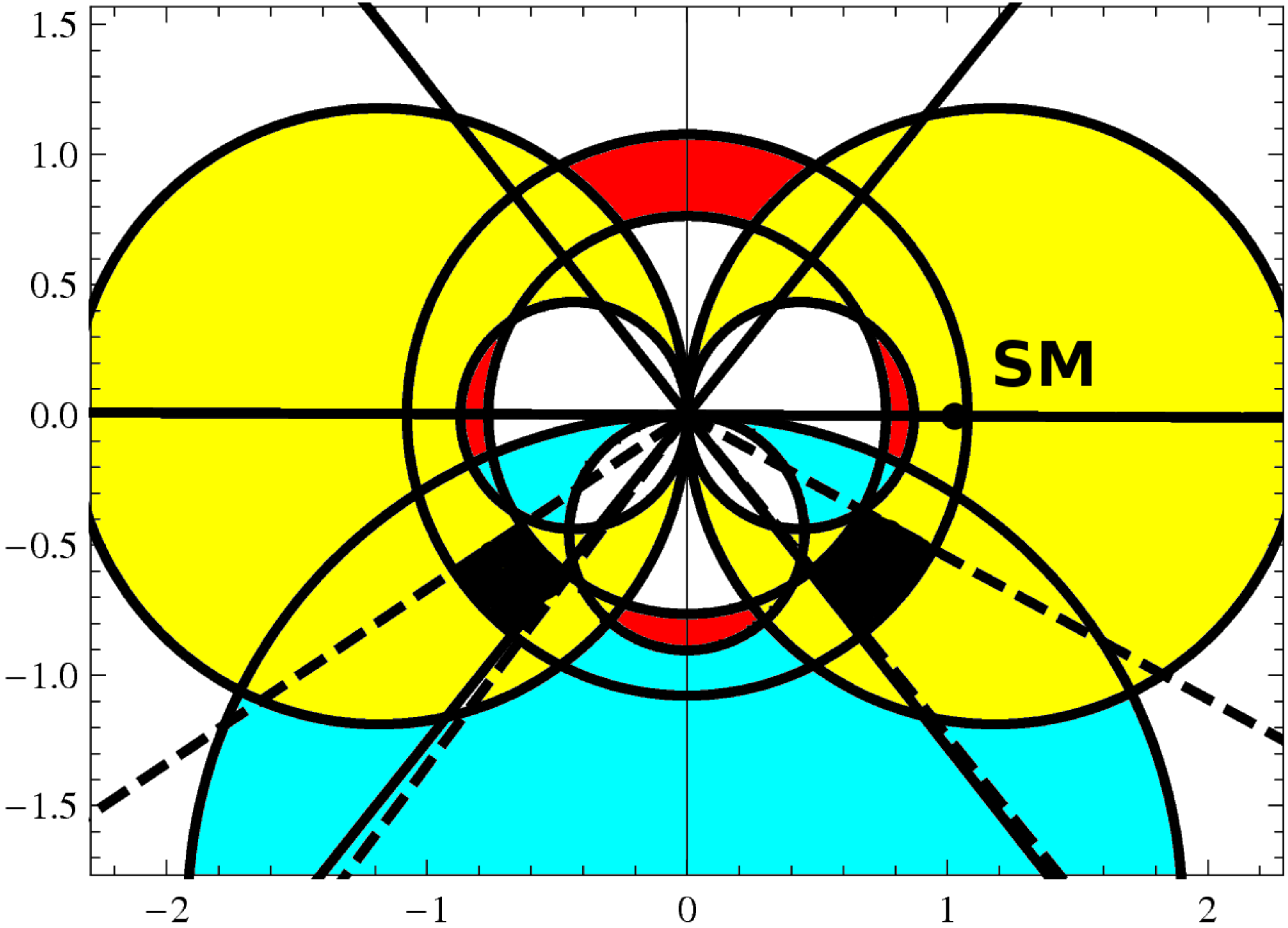
and

$$f_{B_s}\sqrt{B} = 221 \pm 46\ \mathrm{MeV}$$

imply

$$|\Delta_s| = 0.92 \pm 0.32_{\mathrm{(th)}} \pm 0.01_{\mathrm{(exp)}}$$

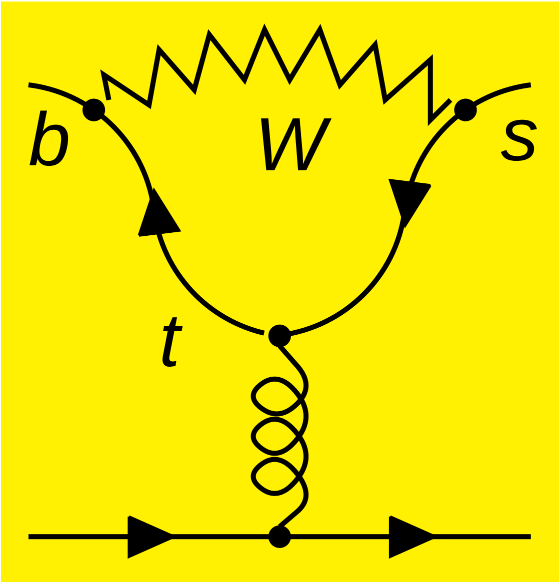
Combining the results from the tagged angular distribution in $\overset{(-)}{B}_s \to J/\psi\phi$ (CDF and DØ), the semileptonic CP asymmetry $a_{\rm fs}^s$ and $\Delta\Gamma_s$ gives:



There is currently some room for new physics in the $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing data.

$\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing is more sensitive to new physics in $b \to s$ transitions than $b \to s$ penguin decays are. Typically models giving $\mathcal{O}(1)$ effects in $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing affect $b \to s$ penguin decays at a level below the current sensitivity of BELLE and BaBar. $\Rightarrow$ LHCb topic.

Phenomenological reason to study $b \to s\bar{q}q$, $q = u, d, s$, rather than $b \to d\bar{q}q$ transitions:
Penguin dominates over tree diagram even for $q = u$, because $|V_{ub}V_{us}| \approx 10^{-4} \ll |V_{tb}V_{ts}| \approx 0.04$.



2. Physics beyond the Standard Model

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LHCb will help to understand the couplings and mixing patterns of the new particles to be found by ATLAS and CMS.
There is a fair chance that LHCb finds clear deviations from the Standard Model well ahead of the high-p_T experiments ATLAS and CMS.

Physics beyond the Standard Model: phenomena

- Gravity. It is associated with the Planck scale $M_P = G_N^{-1/2} \approx 10^{19}$ GeV.

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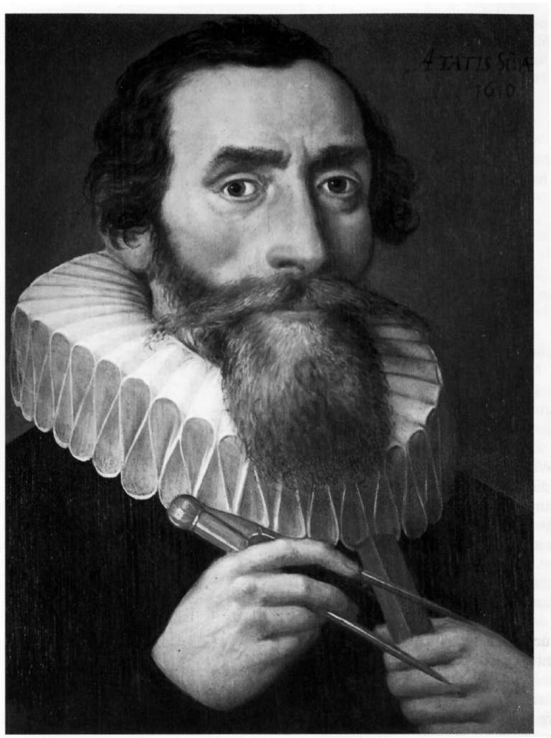
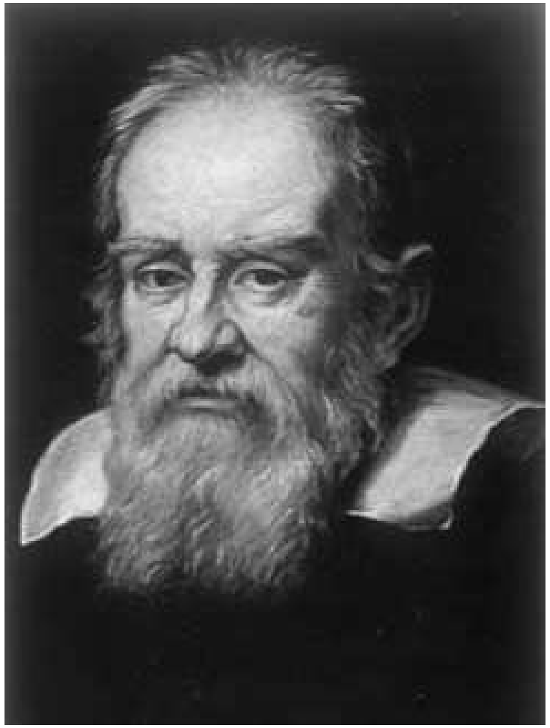
Pioneers of physics beyond the Standard Model:





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- Dark Matter... not to speak of Dark Energy:
  We don't understand 95% of the universe's energy budget.

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  $\Rightarrow$ We don't understand the remaining 5% either!

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- Dark Matter. . . not to speak of Dark Energy.
- Matter-antimatter asymmetry of the universe (too little CP violation, too heavy Higgs).
- Flavour oscillations of neutrinos unless one adds a dimension-5 term, which brings in (the inverse of) a new mass scale $M \sim 10^{15}$ GeV.

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The Standard Model has a severe fine-tuning problem. . . the hypercharge

$$Q = T_3 + Y$$

electric charge $\nearrow$ · three-component of the weak isospin $\uparrow$ · hypercharge $\nwarrow$

right-handed fermions: $T_3 = 0$
left-handed up-type fermions: $T_3 = 1/2$
left-handed down-type fermions: $T_3 = -1/2$

$U(1)_Y$ coupling: $\propto g_1 Y$.
The normalisations of the coupling g_1 and the charges are arbitrary.

Y and therefore Q of any fermion could be any real number: π, $\sqrt{2}$, 1.602, $\ldots$

But: E.g. $Q(\nu) = 0$ and $Q(e) = 3Q(d)$ to all digits behind the decimal point, because neutrinos and atoms are electrically neutral.

Why is Y quantised?

Grand unified theories (GUTs) and supersymmetry

In the Standard Model the hypercharge Y is tuned from the experimentally observed electric charges.

fermions:	$\begin{pmatrix} u_L, u_L, u_L \\ d_L, d_L, d_L \end{pmatrix}$	u_R, u_R, u_R	d_R, d_R, d_R	$\begin{pmatrix} \nu_{e,L} \\ e_L \end{pmatrix}$	e_R
hypercharge Y:	$1/6$	$2/3$	$-1/3$	$-1/2$	-1

Is there a symmetry argument for Y?

Global symmetry of the Standard Model (without dim-5 term): $U(1)_{B-L}$

$B-L$: baryon number minus lepton number

fermion:	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	u_R	d_R	$\begin{pmatrix} \nu_{e,L} \\ e_L \end{pmatrix}$	e_R	$\nu_{e,R}$
$Y-(B-L)/2$:	0	$1/2$	$-1/2$	0	$-1/2$	$1/2$

$\Rightarrow$ Is $Y-(B-L)/2$ the z-component of a right-handed isospin?

The magic relation $Y = T_3^R + (B-L)/2$ with a right-handed weak isospin T_3^R allows us to embed

$$U(1)_Y \subset SU(2)_R \times U(1)_{B-L}$$

Nice: The spontaneous symmetry breaking

$$SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \to SU(3) \times SU(2)_L \times U(1)_Y$$

also breaks U_{B-L} and induces Majorana masses for neutrinos.

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. . . but why is $B-L$ quantised?

The fermions also nicely fit into $SU(5)$ multiplets:

$$\underline{5} \equiv \begin{pmatrix} d^c \\ d^c \\ d^c \\ \nu_{e,L} \\ e_L \end{pmatrix} \qquad \underline{10} \equiv \begin{pmatrix} 0 & u^c & -u^c & u_L & d_L \\ -u^c & 0 & u^c & u_L & d_L \\ u^c & -u^c & 0 & u_L & d_L \\ -u_L & -u_L & -u_L & 0 & e^c \\ -d_L & -d_L & -d_L & -e^c & 0 \end{pmatrix}$$

Here the fields with superscript c denote the charge–conjugated fields of the right–handed fermions.

That this works is highly non–trivial: it requires that

- there are 15 chiral fields per generation,
- the hypercharges sum to zero separately for the $\underline{5}$ and the $\underline{10}$,
- two of the four $SU(3)$ triplets are $SU(2)$ singlets and the other two combine to $SU(2)$ doublets,
- the remaining three colourless fields form a singlet and a doublet with respect to $SU(2)$.

So at high energies, where $SU(5)$ is unbroken, the 15 fermions of each generation unify to just two particles, a $\underline{5}$ and a $\underline{10}$.

Can we get them into a single symmetry multiplet?

Can we reconcile $SU(5)$ and $SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$?

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Yes: The 15 fermion fields of one Standard Model generation and an extra right-handed neutrino field fit into a $\underline{16}$ of

$$SO(10)$$

and $SO(10) \supset SU(5)$
and $SO(10) \supset SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.

Ende GUT - alles GUT?

$$
\begin{tikzcd}[column sep=small]
 & SU(3) \times SU(2)_L \times U(1)_Y \arrow[dl] \arrow[dr] & \\
SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \arrow[dr] & & SU(5) \arrow[dl] \\
 & SO(10) &
\end{tikzcd}
$$

$SO(10)$

$SO(10)$ sheds light on some of the open questions of the Standard Model:

- symmetry group: $SU(3) \times SU(2)_L \times U(1)_Y \subset SO(10)$
- particle content and quantum numbers: Each fermion generation combines into a 16-dimensional spinor.
- free parameters: Only one gauge coupling. But no progress with the Higgs sector and only little insight into Yukawa couplings.
- neutrino masses: The Majorana mass of the ν_R is roughly equal to the $SO(10)$ breaking scale. Its low energy effect is the desired dimension-5 Majorana mass term.
- U(1)$_{B-L}$ is gauged and broken at the $SO(10)$ breaking scale.
  $\Rightarrow$ attractive mechanism for leptogenesis and baryogenesis.

Supersymmetry

Hierarchy problem: GUTs contain particles, which are heavier than those of the Standard Model by 14 orders of magnitude. Their quantum effects destabilize the Higgs mass.

Superpartners (fermions $\leftrightarrow$ bosons) with masses below 1 TeV tame the quantum corrections to the Higgs mass.

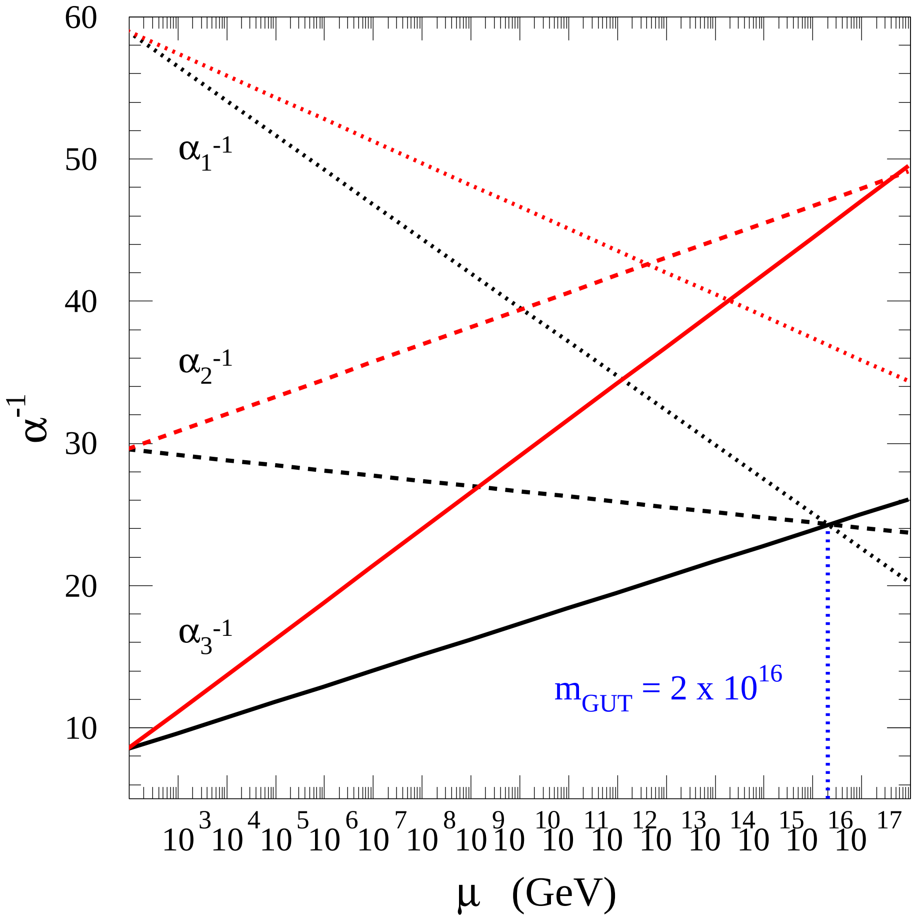
Supersymmetric theories can explain dark matter through the lightest supersymmetric particle (LSP) and provide attractive mechanisms for baryogenesis.

The unification of gauge couplings required by GUTs is improved.

The proton lifetime predicted from GUTs is reconciled with experimental bounds.

Supersymmetric theories can embed gravity.

Inverse gauge couplings with and without supersymmetry:



The GUT scale determined from the intersection of the couplings agrees sufficiently well with the right-handed neutrino mass.

Linking quarks to neutrinos in GUTs

Flavour mixing:

quarks: Cabibbo-Kobayashi-Maskawa (CKM) matrix

leptons: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

Consider SU(5) multiplets:

$$\overline{\mathbf{5}}_{\mathbf{1}} = \begin{pmatrix} d_R^c \\ d_R^c \\ d_R^c \\ e_L \\ \nu_e \end{pmatrix}, \qquad \overline{\mathbf{5}}_{\mathbf{2}} = \begin{pmatrix} s_R^c \\ s_R^c \\ s_R^c \\ \mu_L \\ \nu_\mu \end{pmatrix}, \qquad \overline{\mathbf{5}}_{\mathbf{3}} = \begin{pmatrix} b_R^c \\ b_R^c \\ b_R^c \\ \tau_L \\ \nu_\tau \end{pmatrix}.$$

If the observed large atmospheric neutrino mixing angle stems from a rotation of $\overline{\mathbf{5}}_{\mathbf{2}}$ and $\overline{\mathbf{5}}_{\mathbf{3}}$, it will induce a large $\tilde{b}_R - \tilde{s}_R$-mixing (Moroi).

$\Rightarrow$ new $b_R - s_R$ transitions from gluino–squark loops

Chang, Masiero and Murayama have sketched a supersymmetric GUT model in which new $b_R - s_R$ transitions governed by the atmospheric neutrino mixing angle occur. These transitions are induced by loop diagrams with squarks and gluinos.
All other FCNC transitions ($b \to d$, $s \to d$, ...) are governed by the usual CKM matrix.

The CMM model is based on the symmetry breaking chain
SO(10)$\to$ SU(5) $\to$ SU(3)$\times$SU(2)$_L\times$U(1)$_Y$.

“Most minimal flavour violation”

In the CMM model one can simultaneously diagonalise the Yukawa matrices for up-type quarks, Y_u, and for the neutrinos, Y_N.

All flavour violation stems from the Yukawa matrix of the down-type quarks, Y_d. In a basis of weak eigenstates:

$$\mathsf{Y}_d = V_{\mathrm{CKM}}^{*} \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix} U_{\mathrm{PMNS}}$$

Passing from the weak basis to a basis of quark mass eigenstates diagonalises Y_d and puts V_{CKM} and U_{PMNS} into the couplings of the W-boson, just as in the Standard Model.

In the weak basis the mass matrix for the right-handed down squarks reads:

$$\mathsf{m}^2_{\tilde{d}}(M_Z) = \mathsf{diag}\left(m^2_{\tilde{d}},\, m^2_{\tilde{d}},\, m^2_{\tilde{d}} - \Delta_{\tilde{d}}\right).$$

with a calculable real parameter $\Delta_{\tilde{d}}$.

Rotating Y_d to diagonal form puts the large atmospheric neutrino mixing angle into $\mathsf{m}^2_{\tilde{d}}$:

$$U^\dagger_{\mathrm{PMNS}}\, \mathsf{m}^2_{\tilde{d}}\, U_{\mathrm{PMNS}} = \begin{pmatrix} m^2_{\tilde{d}} & 0 & 0 \\ 0 & m^2_{\tilde{d}} - \frac{1}{2}\,\Delta_{\tilde{d}} & -\frac{1}{2}\,\Delta_{\tilde{d}}\, e^{i\xi} \\ 0 & -\frac{1}{2}\,\Delta_{\tilde{d}}\, e^{-i\xi} & m^2_{\tilde{d}} - \frac{1}{2}\,\Delta_{\tilde{d}} \end{pmatrix}$$

The CP phase ξ affects $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing!

Phenomenology

We have considered $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing, $b \to s\gamma$, $\tau \to \mu\gamma$, vacuum stability bounds, lower bounds on sparticle masses and the mass of the lightest Higgs boson.

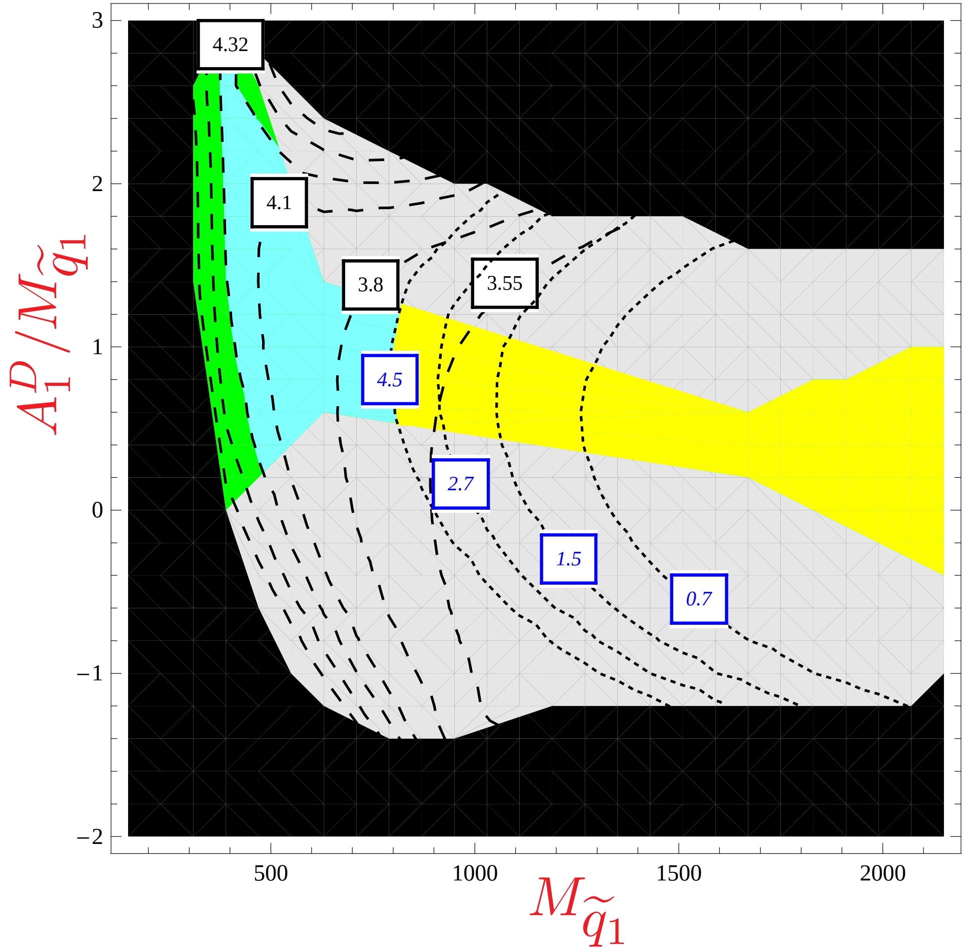
The analysis involves 7 parameters in addition to those of the Standard Model.

Collaborators:

Sebastian Jäger, Markus Knopf, Waldemar Martens,
Christian Scherrer and Sören Wiesenfeldt

Constraints from $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing, $\tau \to \mu\gamma$ and $b \to s\gamma$ on $M_{\tilde{q}1}$ and $A_1^u/M_{\tilde{q}1}$

Contour plot for $M_{\tilde{g}} = 350\,\mathrm{GeV}$, $\arg\mu = 0$:



Black: negative soft masses^2

Green: excluded by $\tau \to \mu\gamma$
and $b \to s\gamma$

Blue: excluded by $\tau \to \mu\gamma$

Gray: excluded by $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing

Yellow: allowed

dashed lines: $10^4 \cdot Br(b \to s\gamma)$; dotted lines: $10^8 \cdot Br(\tau \to \mu\gamma)$.

3. B_s decays and electroweak penguins

The CMM model can accomodate a large CP phase in $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing, and leads to small deviations in the CP asymmetries of gluonic $b \to s$ penguin amplitudes. There are no large effects in electroweak penguin amplitudes.

To discriminate among different models of new physics in $b \to s$ transitions, one should study electroweak penguins as well.

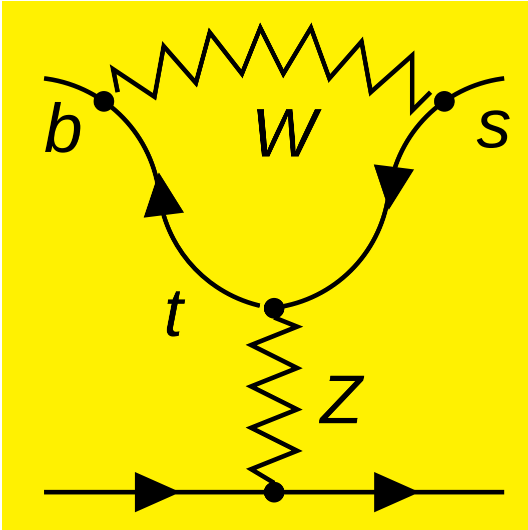
In recent years the study of electroweak penguins has been motivated by the "$B \to \pi K$ puzzle", whose experimental support is currently fading away.

Electroweak penguins

Standard Model:

Three ways to probe electroweak penguins:

1. Isospin violation, e.g. in combined analysis of $B \to \pi K$ modes.
2. Coupling to neutrinos, e.g. in $K \to \pi \nu \overline{\nu}$.
3. C or P violation, e.g. in $B_{s,d} \to \ell^+ \ell^-$, $A_{\rm FB}(B \to K \ell^+ \ell^-)$.



Reason: suppression or elimination of otherwise dominant gluonic and photonic penguins.

Important: In models of new physics there is a priori no correlation between 1, 2 and 3. E.g. one can have new sources of strong isospin violation without new couplings to neutrinos.

Isospin violation

The combined analysis of $B \to \pi K$ involves several decay modes and needs some theoretical input such as flavour symmetries ("U-spin").

"Smoking gun" processes would be $B_s \to \phi\pi^0$ and $B_s \to \phi\rho^0$, which are pure $\Delta I = 1$ decays: B_s and ϕ have no strong isospin and π^0 and ρ^0 have $I = 1$.

work in progress by Lars Hofer, Dominik Scherer and Leonardo Vernazza

SM branching fraction: $\mathcal{B}(B_s \to \phi\rho^0) \sim 3 \cdot 10^{-7}$.
SM mixing-induced CP asymmetry: 16%.

Enhancement of $\mathcal{B}(B_s \to \phi\rho^0)$ if last year's central values of the $B \to \pi K$ data were real (and the new physics sits in C_9): factor of 35!

4. Summary

- Supersymmetric GUTs are the “standard way beyond the Standard Model”.
- It is plausible to detect new sources of flavour violation (beyond the CKM mechanism) in $b \to s$ transitions. Neutrino data clearly show large mixing between the second and third generation of leptons.
- $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing is typically more sensitive to new physics than gluonic $b \to s$ penguin decays.

  $\Rightarrow$ The increased precision of LHCb matters.
- Electroweak penguins: Strong isospin violation can be excellently studied in $B_s \to \phi\rho^0$.

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