Going Beyond SM with Heavy Flavours

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The puzzles of flavour physics

- **The CP puzzle:** $n_b/n_\gamma \sim \mathcal{O}(10^{-9})$, SM predicts $\sim \mathcal{O}(10^{-18})$
  BSM source for CP violation?
- Unknown parameters: 12 masses, 6 mixing angles, 2 (possibly) phases (+ Majorana)
  Horizontal symmetries?
- Large hierarchy: $m_{\nu_e}/m_t \leq 10^{-14}$
  Fermion localization in warped ED?

We will concentrate mostly on B physics, will also touch charm

Why is flavour physics important ?

- Better understanding of SM for $N_{gen} > 1$
  — Window to top and triple-gauge dynamics (e.g. $B^0 - \overline{B}^0$ mixing, $b \to s\gamma$, $Z \to b\bar{b}$, $B_s \to \mu\mu$)
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BaBar@SLAC : e^+e^-, 429 fb^{-1}, 4.7×10^8 $B\bar{B}$ pairs

Belle@KEK : e^+e^-, over 1 ab^{-1}, 7.72×10^8 $B\bar{B}$ pairs

LHCb : 1 fb^{-1} at $\sqrt{s} = 7$ TeV, 1.1 fb^{-1} at 8 TeV
7 TeV: $\sigma(pp \to b\bar{b}X) = (89.6 \pm 6.4 \pm 15.5)$ μb, scales linearly with $\sqrt{s}$

Ultimately, 5 fb^{-1}/yr, total $\mathcal{L}_{int} = 50$ fb^{-1},
$\sim$ 200-fold increase over 1 fb^{-1} sample

ATLAS and CMS also have dedicated flavour physics programme

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Reach of Flavour Physics

Direct detection

- NP@a few TeV: within reach of LHC@14 TeV
- NP $>$ a few TeV: beyond LHC

Indirect detection

Flav. structure	a few TeV	$>$ a few TeV
Anarchy	O(1) **X**	small ($<$ O(1))
Small misalignment	small (O(0.1))	tiny (O(0.01-0.1))
Alignment (MFV)	tiny (O(0.01))	out of reach $<$ O(0.01)

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Plan of the talk

1. **Some interesting B physics observables**
2. **Beyond-SM hints?**
3. **Beyond-SM through Beauty: B-physics observables and cMSSM**
4. **Beyond-SM through Charm: Mixing, Direct CPV**

Caveat emptor: Top and neutrinos excluded

Some interesting observables

Unitarity Triangle

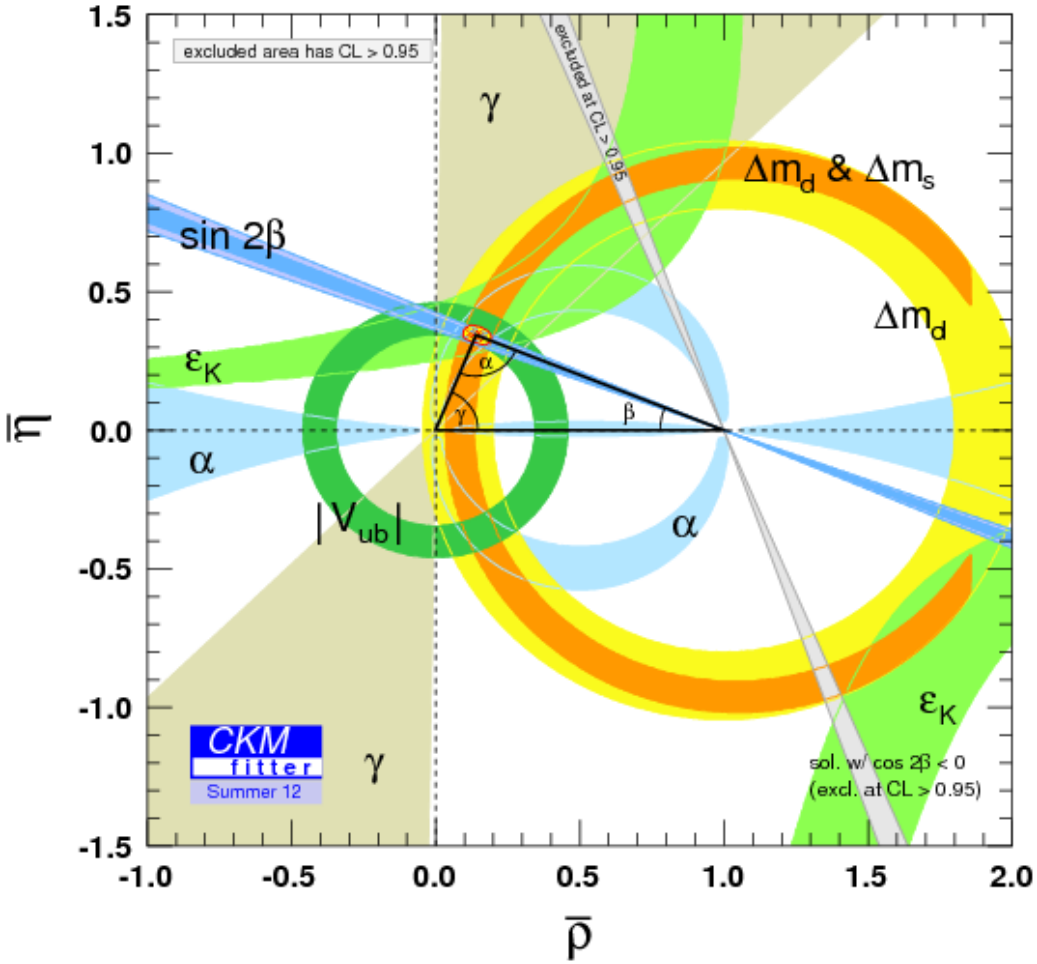
$$
\begin{aligned}
V &= \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \\
&= \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)
\end{aligned}
$$

$V_{td} = |V_{td}| \exp(-i\beta)$, $V_{ub} = |V_{ub}| \exp(-i\gamma)$

Wolfenstein parametrisation

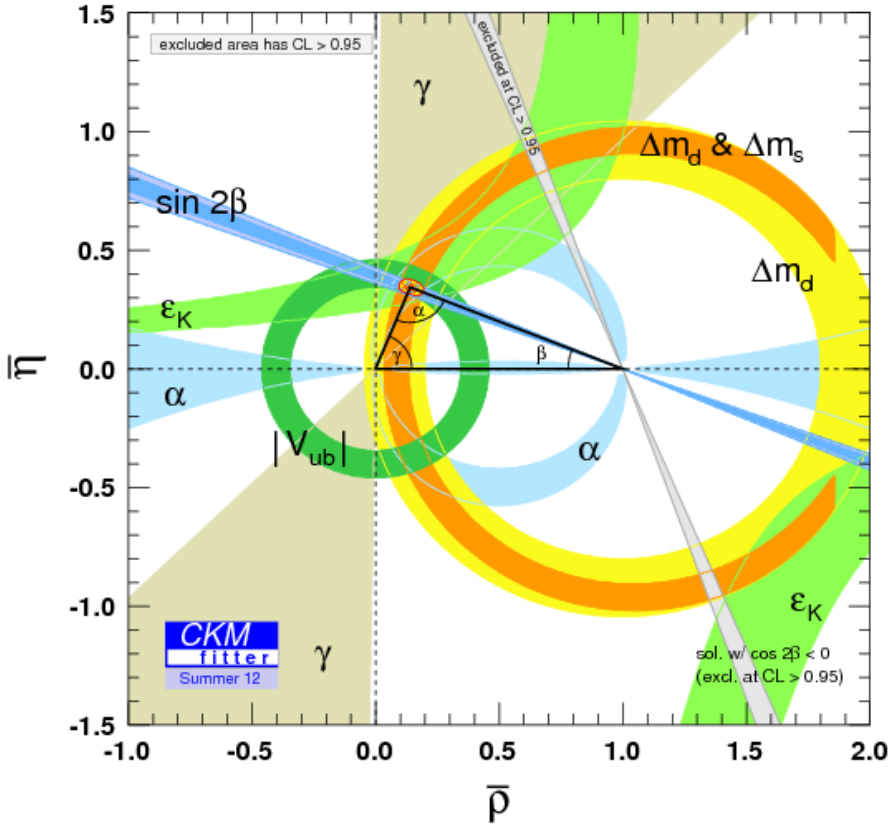
$\lambda = 0.22543^{+0.00059}_{-0.00094}$, $A = 0.802^{+0.029}_{-0.011}$,

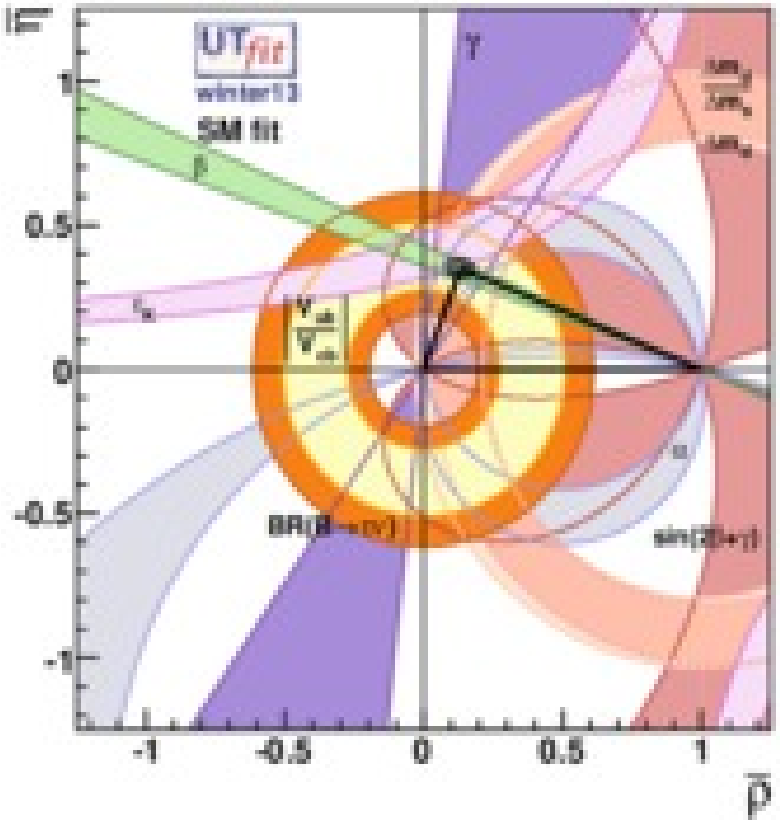
$\rho(1-\frac{1}{2}\lambda^2) = 0.140 \pm 0.027$, $\eta(1-\frac{1}{2}\lambda^2) = 0.343 \pm 0.015$



α	$90.5^{+4.3}_{-4.1}$
β direct	$21.38^{+0.79}_{-0.77}$
β indirect	$25.39^{+0.92}_{-2.11}$
β average	$21.73^{+0.78}_{-0.74}$
γ	$67.7^{+4.1}_{-4.3}$

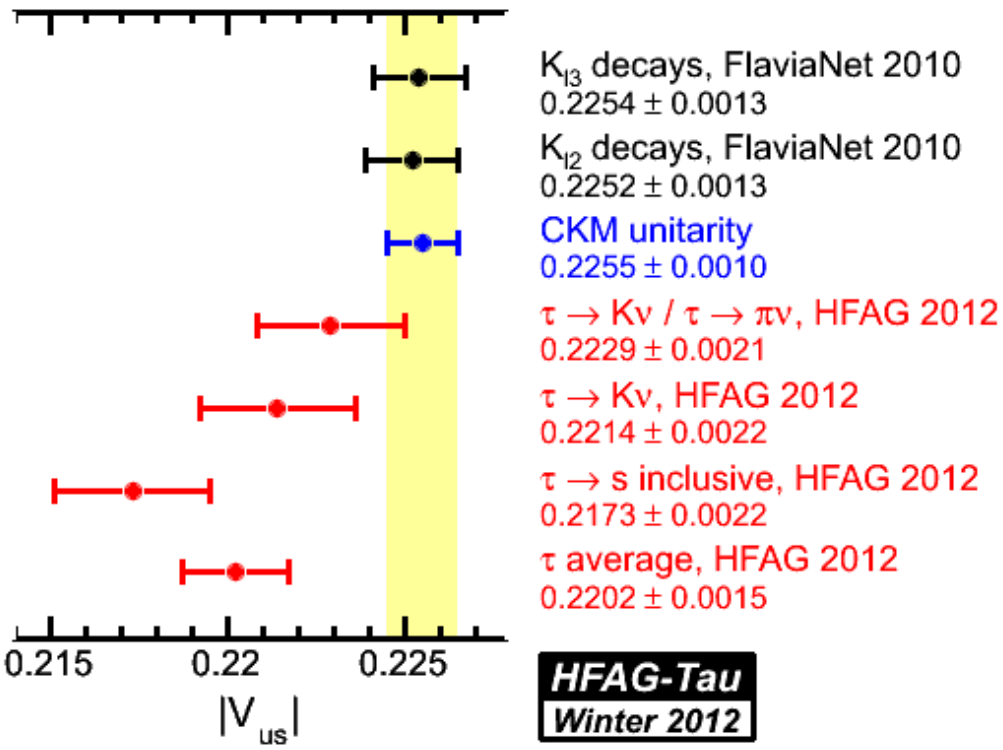
Note the tension in β, caused by the $|V_{ub}|$ band.


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
|V_ub|
α
ε_K
γ
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
CKM fitter
Summer 12
η̄
ρ̄


UTfit
winter13
SM fit
γ
η̄
ρ̄

The CKM paradigm seems to be vindicated, NP should be subleading

But even the mundane is not so mundane



$B_d - \overline{B_d}$ and $B_s - \overline{B_s}$ Mixing

$$H = \begin{pmatrix} M_q - \frac{i}{2}\Gamma_q & M_q^{12} - \frac{i}{2}\Gamma_q^{12} \\ M_q^{12*} - \frac{i}{2}\Gamma_q^{12*} & M_q - \frac{i}{2}\Gamma_q \end{pmatrix}$$

$$\left.\frac{\Delta M}{\Gamma}\right|_{B_d} = 0.770(8) \qquad \left.\frac{\Delta M}{\Gamma}\right|_{B_s} = 26.74(22)$$

$$\left.\frac{\Delta \Gamma}{\Gamma}\right|_{B_d} = (42 \pm 8) \times 10^{-4}\ (\mathrm{SM}) \qquad 0.015 \pm 0.018\ (\mathrm{Delphi,\ BaBar,\ Belle})$$

$$\left.\frac{\Delta \Gamma}{\Gamma}\right|_{B_s} = 0.137 \pm 0.027\ (\mathrm{SM}) \qquad 0.159 \pm 0.023\ (\mathrm{LHCb})$$

$$\frac{M_q^{12}}{M_{q,SM}^{12}} \equiv \mathrm{Re}\Delta_q + i\mathrm{Im}\Delta_q = |\Delta_q| \exp(2i\Phi_{q,NP})$$

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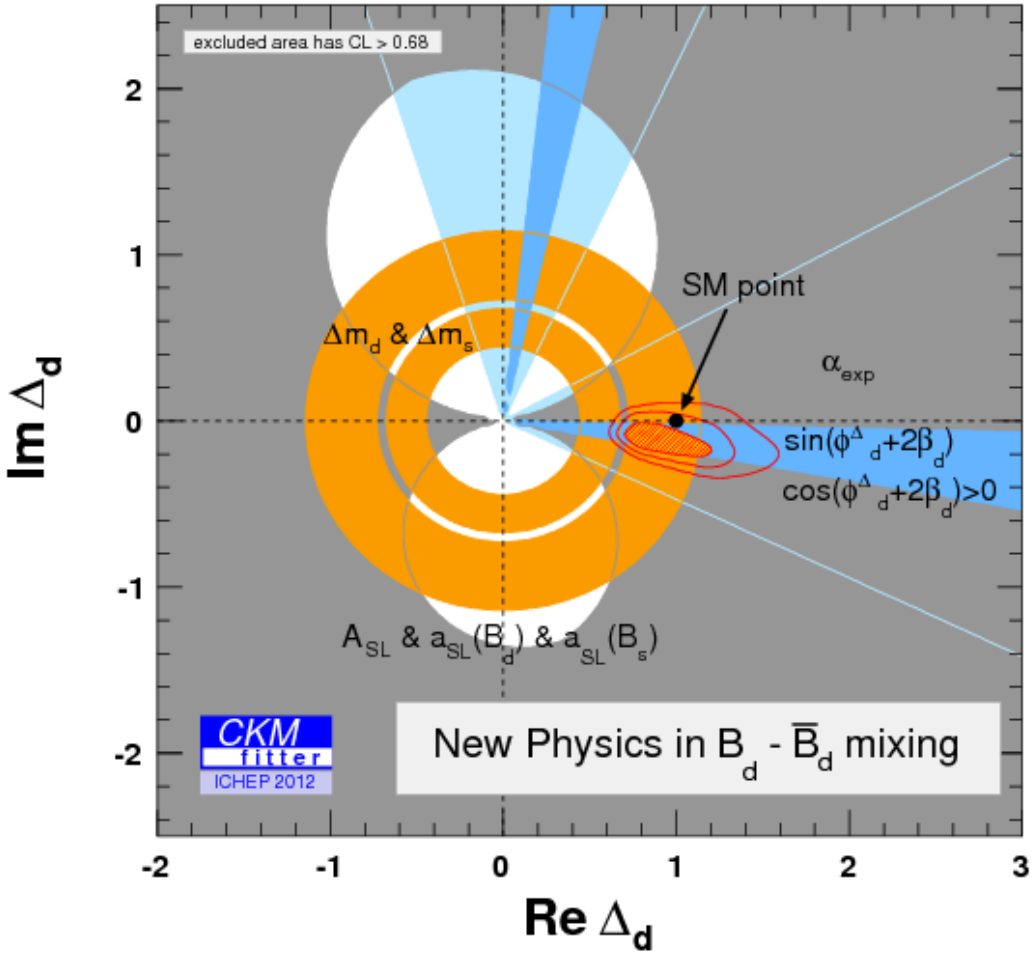
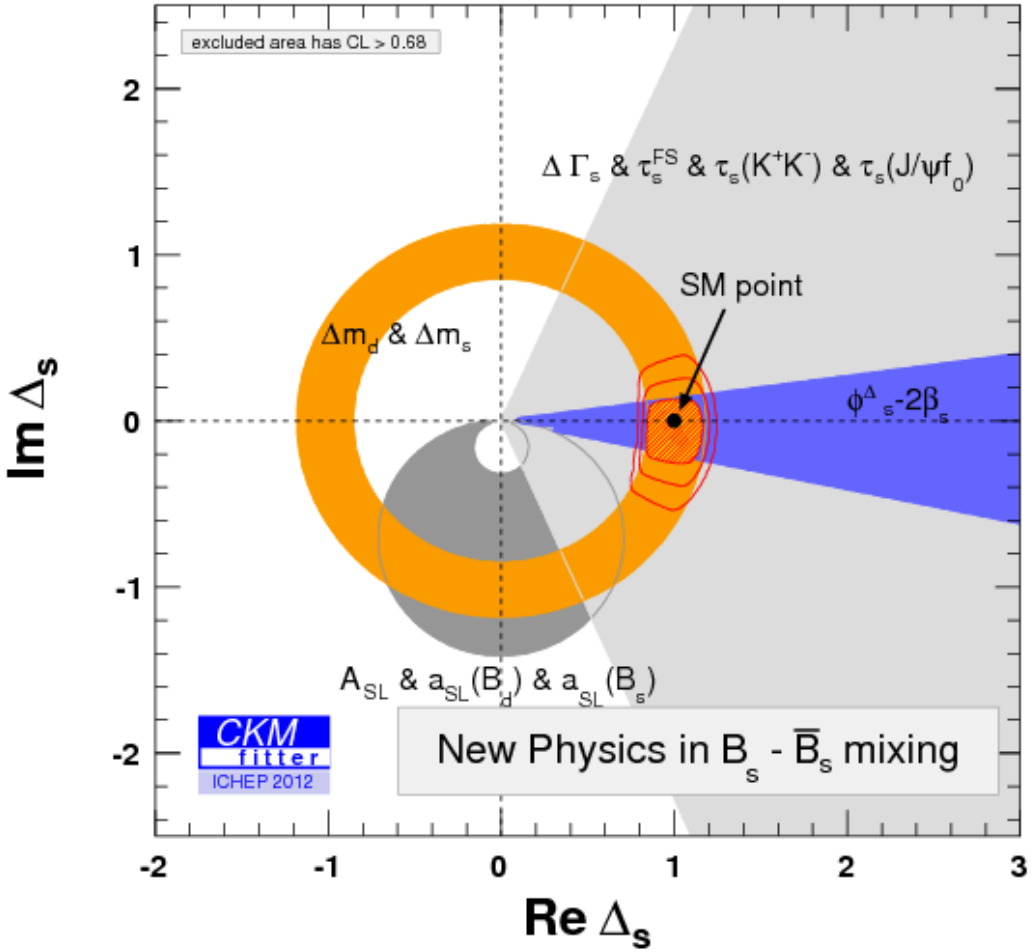


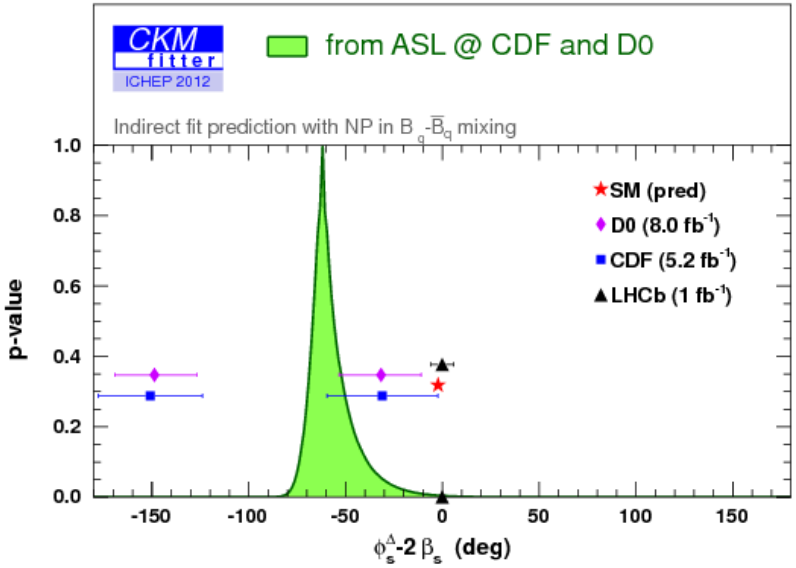
The tension is mostly due to V_{ub} coming from $B^+ \to \tau\nu$, even though new Belle result brings the tension down.

$B_d - \overline{B_d}$ and $B_s - \overline{B_s}$ Mixing



Does not include dimuon results from D0. All other results are consistent with SM. A_{SL} is 3.3σ away.

- The $2\beta_s$ discrepancy — now consistent with SM ?
  — Any need to introduce BSM in $B_s - \overline{B_s}$ mixing ?



Be careful

$\beta_s^{J/\psi\phi} = \arg[-V_{cb}V_{cs}^*/V_{tb}V_{ts}^*] = 0.019(1)$ (SM)
$\beta_s^{sl} = -\frac{1}{2}\phi_s$, $\phi_s = \arg(-M_{12s}/\Gamma_{12s}) = -0.0020(3)$ (SM),
$A_{sl} = (\Delta\Gamma_s/\Delta M_s)\tan\phi_s$

Some recent results from LHCb

1. $\Delta M_s = 17.768 \pm 0.024$ ps^{-1} SM: 17.3 ± 2.6
2. $\beta_s^{J/\psi\phi} = 0.020^{+0.042}_{-0.045}$ (direct), 0.0182 ± 0.0008 (global fit)
   SM: 0.019 ± 0.001
3. $\Delta\Gamma_s = 0.095 \pm 0.014$ ps^{-1} (now measured to be positive)
   SM: 0.087 ± 0.021 ps^{-1}
4. $Br(B_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$,
   $Br(B_d \to \mu^+\mu^-) < 9.4 \times 10^{-10}$ consistent with SM
5. $A_{FB}(B \to K^*\ell^+\ell^-)$: zero crossing at $q^2 = 4.9 \pm 1.1$ GeV^2
   consistent with SM ($\sim 4.0 - 4.3$ GeV^2)
6. $A_{CP}(B_s \to K^-\pi^+) = 0.27 \pm 0.04 \pm 0.01$: first 5σ CP violation in B_s
7. Isospin asymmetry in $B \to K\mu^+\mu^-$
   Direct CPV from charm (Moriond 13 update) Hold on !

Caution !!!

Need a better control over nuisance parameters

- Quark masses and CKM elements
- Form factors, decay constants
  Lattice people doing a commendable job
  uncertainty associated with LCD amplitudes
- Subleading Λ/m corrections
  Also, higher orders in α_s, but they can be summed in most cases
- renormalization scale (μ) dependence

Hunting grounds

1. $b \to s\gamma$, $b \to s\ell^+\ell^-$, $B_s \to \ell^+\ell^-$
   — Possible new operators from BSM, angular distributions and asymmetries affected
2. $B \to D^{(*)}\tau\nu$, $B \to \tau\nu$
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Example: 2HDM and $b \to s\gamma$

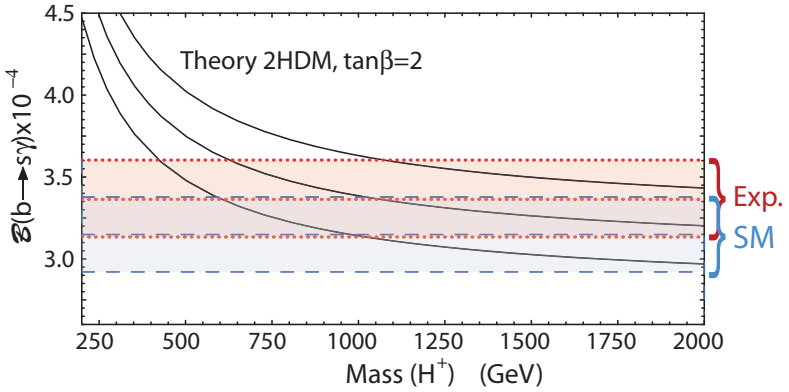
$$\Gamma(\bar{B} \to X_s\gamma) = \Gamma(b \to s\gamma) + O(\Lambda_{QCD}/m_b)$$

$$A_{CP} = \frac{\Gamma(\bar{B} \to X_s\gamma) - \Gamma(B \to X_{\bar{s}}\gamma)}{\Gamma(\bar{B} \to X_s\gamma) + \Gamma(B \to X_{\bar{s}}\gamma)}$$

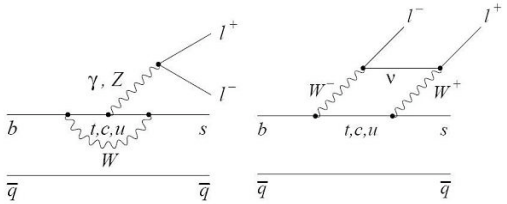
Measured with cut $E_\gamma > E_0 \sim 2$ GeV: $A_{CP} = -(1.2 \pm 2.8)\%$

$$Br(b \to s\gamma) = (3.37 \pm 0.23) \times 10^4 \ (\mathrm{exp}), (3.15 \pm 0.23) \times 10^{-4} \ (\mathrm{SM})$$

Strong constraint on 2HDM:



Example: $B \to K^* \ell^+ \ell^-$

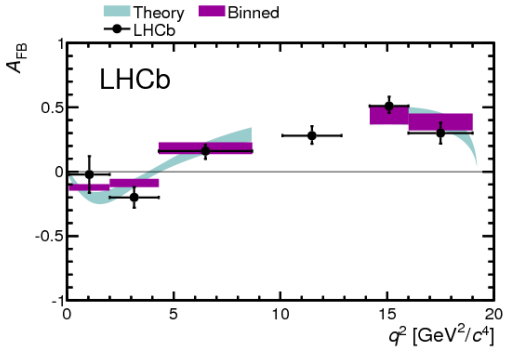


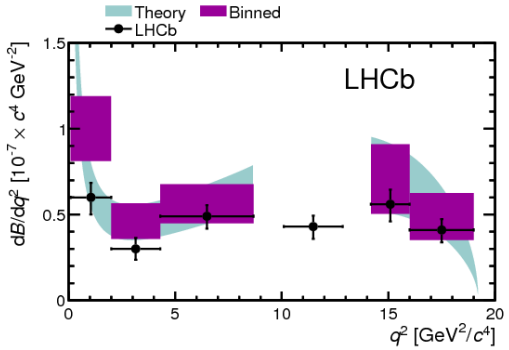
$A_{FB}(q^2)$ from γ–Z interference

Zero-crossing point is clean, almost free from hadronic uncertainties

Theory (SM): $q_0^2 = [4.0 - 4.3] \pm 0.3$ GeV^2

(Beneke et al. 0412400, Bobeth et al. 1111.2558)





Tensions with SM: NP or mirage?

$B \to K\pi$ CP asymmetries

$A_{CP} = [\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})] \,/\, [\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})]$

$A_{CP}(B^+ \to K^+\pi^0) = 0.040 \pm 0.021 \; : \; \overbrace{b \to s\bar{u}u \,,\, b \to s\bar{d}d}^{\text{Related by SU(2)}}$

$A_{CP}(B^0 \to K^+\pi^-) = -0.086 \pm 0.007 \; : \; b \to s\bar{u}u$

$$\Delta A_{CP} \equiv A_{CP}(\pi^0 K^-) - A_{CP}(\pi^+ K^-) = (12.6 \pm 2.2)\,\% \,,\, \left(1.9^{+5.8}_{-4.8}\right)\%(SM)$$

Possible resolution: NP that mimics a large EWP [Nandi and AK '04]

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No such anomaly in $B \to \pi\pi$ or $B_s \to K\pi$. Is $b \to s$ troublesome?
Large P_{EW} affects $Br(B^+ \to K^+\pi(\rho)^0)$ / $Br(B^0 \to K^+\pi(\rho)^-)$, consistent with SM
Poorly understood SM?

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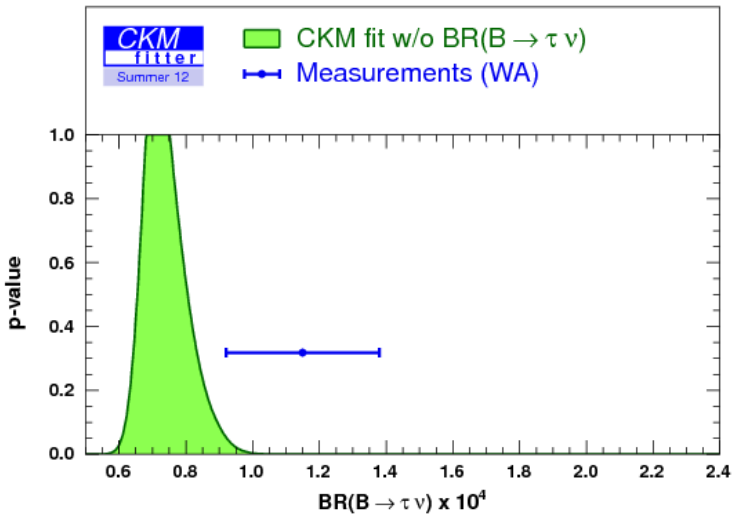
$B \to \tau\nu$

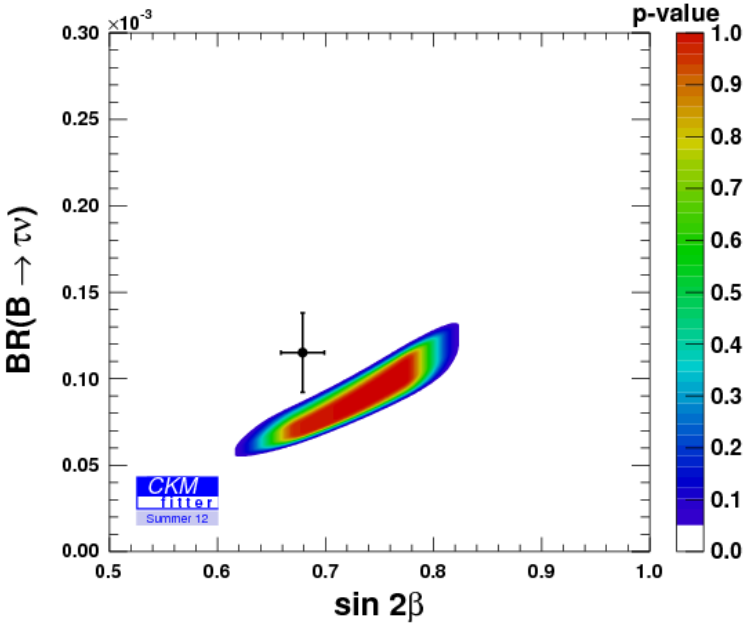
- Completely analogous to $\pi^+ \to \mu^+\nu_\mu$:

$$\Gamma(B \to \tau\nu_\tau) = \frac{1}{8\pi} G_F^2 |V_{ub}|^2 f_B^2 m_\tau^2 m_B \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2$$

- World average:
  $Br(B \to \tau\nu) = (16.8 \pm 3.1) \times 10^{-5}$ (pre-2012)
  $Br(B \to \tau\nu) = (11.5 \pm 2.3) \times 10^{-5}$ (summer 2012, after Belle)
  (BaBar: $(17.9 \pm 4.8) \times 10^{-5}$, Belle: $(7.2^{+2.7}_{-2.5} \pm 1.1) \times 10^5$)
- Theory: $Br(B \to \tau\nu)_{\rm SM} = \left(7.57^{+0.98}_{-0.61}\right) \times 10^{-5}$
- Tension at 1.6σ only, has come down from 2.8σ
- Only source of uncertainties: f_B and V_{ub}
- Lattice QCD: $f_B = 191 \pm 13$ MeV

$B \to \tau\nu$


CKM fitter
Summer 12
CKM fit w/o BR(B → τ ν)
Measurements (WA)
p-value
BR(B → τ ν) x 10^4


×10^-3
p-value
BR(B → τν)
sin 2β
CKM fitter
Summer 12

$B \to \tau\nu$

- an SM-only explanation would require

$$|V_{ub}| = (4.22 \pm 0.51) \times 10^{-3}$$

- Inconsistent with the indirect determination of V_{ub} from the sides of the Unitarity Triangle (UT),

$$|V_{ub}|_{\text{indirect}} = (3.49 \pm 0.13) \times 10^{-3}$$

or the average of direct inclusive ($B \to X_u \ell\nu$) and exclusive ($B \to \pi\ell\nu$) measurements,

$$|V_{ub}|_{\text{measured}} = (3.92 \pm 0.09 \pm 0.45) \times 10^{-3}$$

How well do we know V_{ub} ?

$B \to \tau\nu$

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$$\boxed{\text{How well do we know } V_{ub} \text{ ?}}$$

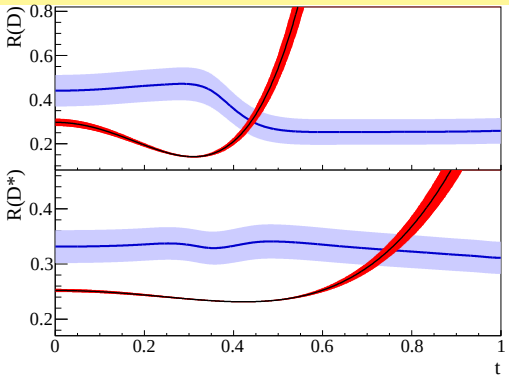
$B \to D(D^*)\tau\nu$

$$R(D^{(*)}) = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}\ell\nu)}$$

$$\mathrm{SM}: \quad R(D) = 0.297 \pm 0.017\,, \qquad R(D^*) = 0.252 \pm 0.003$$

$$\mathrm{BaBar}: \quad R(D) = 0.440 \pm 0.058 \pm 0.042\,, \qquad R(D^*) = 0.332 \pm 0.024 \pm 0.018\,.$$

$$\frac{R(D)_{exp}}{R(D)_{SM}} = 1.481 \times (1 \pm 0.173)\,, \quad \frac{R(D^*)_{exp}}{R(D^*)_{SM}} = 1.317 \times (1 \pm 0.091)\,.$$



$B \to \tau\nu$ and $B \to D(D^*)\tau\nu$

Possible resolutions:

- Tensor operators (Biancofiore et al. 1302.1042)
- Special type of charged Higgs (Celis et al. 1210.8443)
- Some new interaction involving only gen-3 fields (Choudhury, Ghosh, AK, 1210.5076)

— Fed to lower generations through CKM like rotations
— Anomalous top decays? Still unobservably small
— Prediction: sizable enhancement in $B_c \to \tau\nu$
— **Is gen-3 special? Only window to BSM?**

The dimuon anomaly

$$A_{sl}^b = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)}$$

$$D\emptyset\ 9.0\ \mathrm{fb}^{-1}: \quad A_{sl}^b = (-7.87 \pm 1.96) \times 10^{-3}$$

Can be expressed as individual flavour-specific (fs) semileptonic asymmetries coming from B_d and B_s:

$$A_{sl}^b = (0.595 \pm 0.022)\, a_{fs}^d + (0.405 \mp 0.022)\, a_{fs}^s$$

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3.9σ discrepancy

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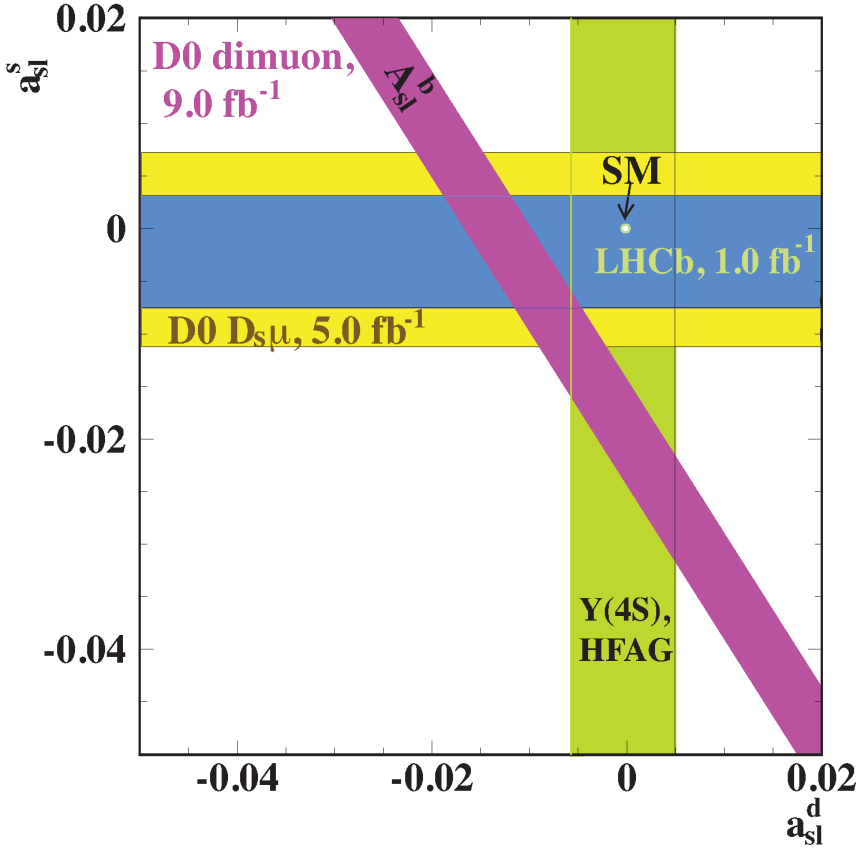

$$a_{fs}^d = 0.0038 \pm 0.0036 \text{ (HFAG)},$$
$$a_{fs}^s = (-0.0022 \pm 0.0052) \text{ (LHCb + D0)}$$

The dimuon anomaly

The only way to resolve the dimuon anomaly is to introduce some operators that give new absorptive parts in $B_s - \overline{B_s}$ mixing.

$$\text{Large } \phi_s \Rightarrow \text{Large } a_{fs}^s \Rightarrow \text{Large } A_{sl}^b$$

Possibly, the only option still left is $(\bar{s}\Gamma^A b)(\bar{\tau}\Gamma^A \tau)$

(Dighe, AK, Nandi, PRD 2007, 2010; Bauer and Dunn, PLB 2011)

$B_s \to \tau^+\tau^-$? $B \to X_s\tau^+\tau^-$? Lifetime difference between B_d and B_s?
— Can be managed, still, but will soon be under pressure from LHCb

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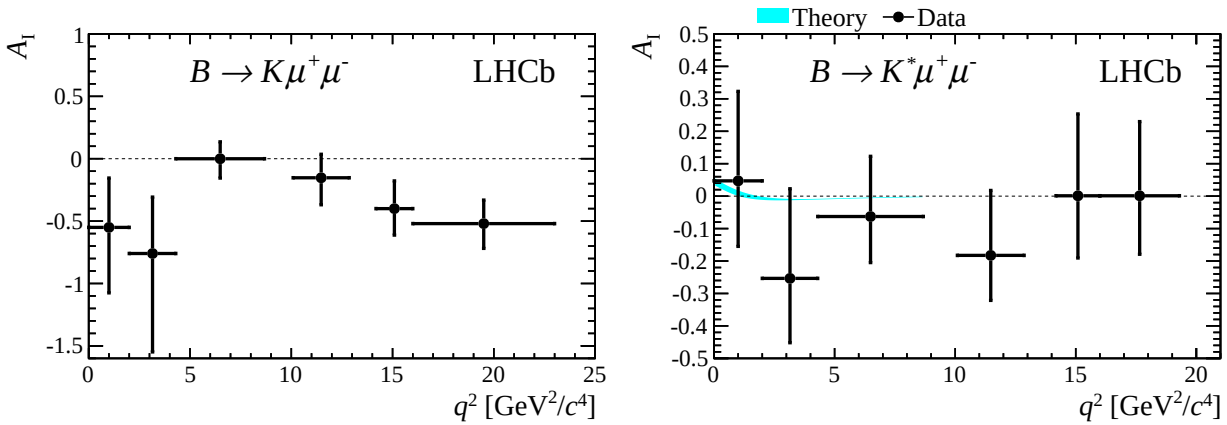
Isospin asymmetry

$$A_I = \frac{Br(B^0 \to K^{0(*)}\mu^+\mu^-) - \frac{\tau_0}{\tau_+} Br(B^+ \to K^{+(*)}\mu^+\mu^-)}{Br(B^0 \to K^{0(*)}\mu^+\mu^-) + \frac{\tau_0}{\tau_+} Br(B^+ \to K^{+(*)}\mu^+\mu^-)}$$

- $A_I = 0$ in naive factorization
- ISR from spectator can contribute up to $\sim 1\%$ unless q^2 is very small
- $B \to K^*\mu\mu$ is consistent with SM
- $B \to K\mu\mu$: 4.4σ away from zero, integrated over all q^2

(LHCb, 1205.3422)



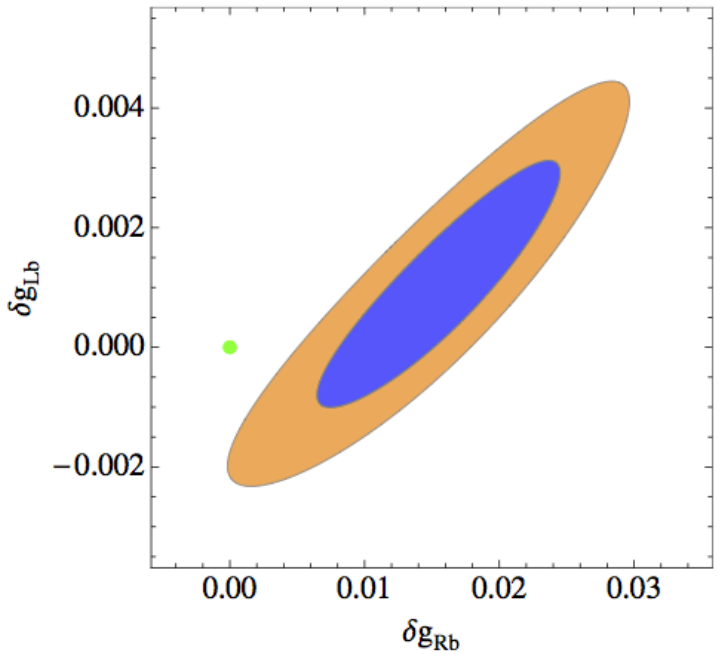
The resurrection of R_b

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{hadrons})}$$

R_b (SM) has gone down from 0.21576(8) to 0.21474(3) after the computation of full two-loop effects (Freitas and Huang 2012)
2.4σ discrepancy with R_b (exp) $= 0.21629(66)$.

A^b_{FB} has a discrepancy of 2.5σ
SM: $0.1032^{+0.0004}_{-0.0006}$
exp: 0.0992 ± 0.0016

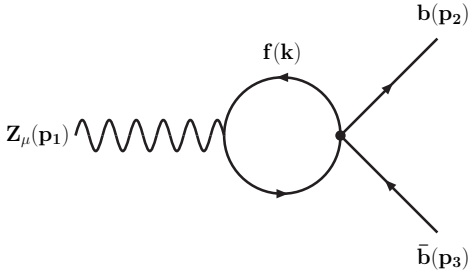
Possible resolution: slightly increase $Z - b_R - \bar{b_R}$ coupling



(Batell et al. 1209.6382)

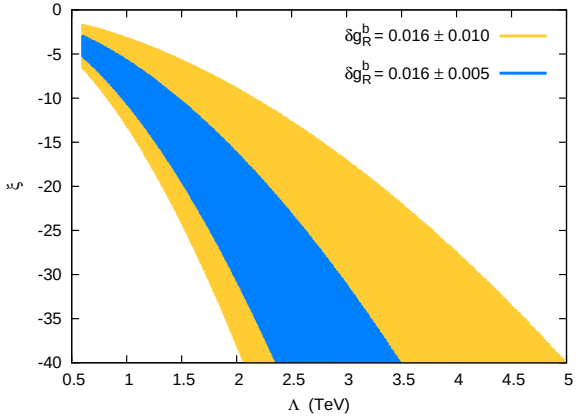
Introduce an effective operator (Choudhury, AK, Saha, 1305.7199)

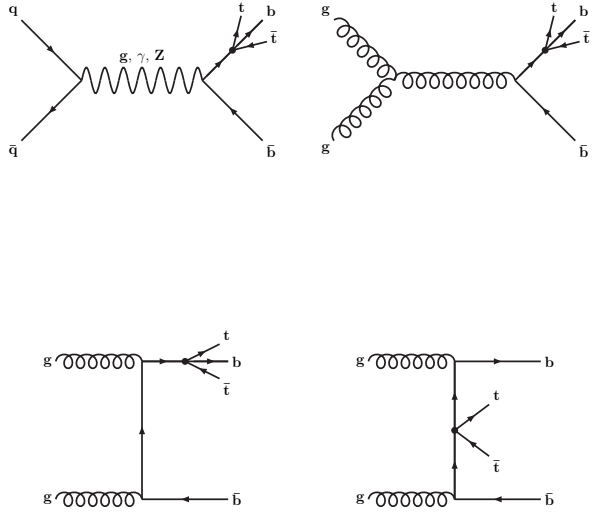
$$\frac{\xi}{\Lambda^2}\left[\bar{f}\gamma_\mu(v_f + a_f\gamma_5)f\right]\left[\bar{b}\gamma^\mu(v_b + a_b\gamma_5)b\right]$$

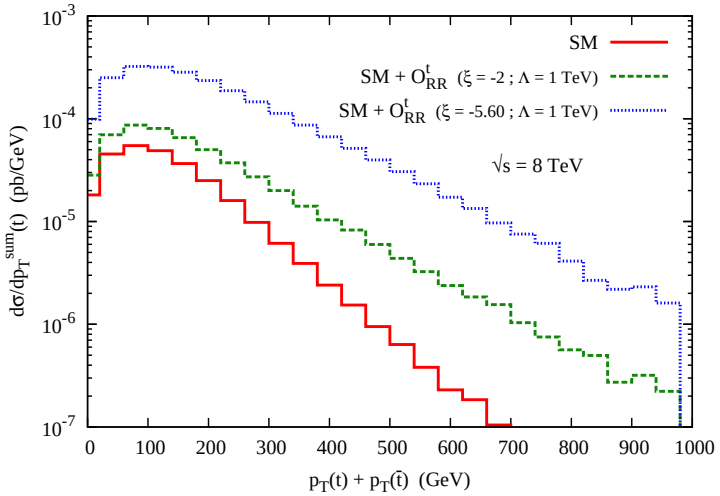


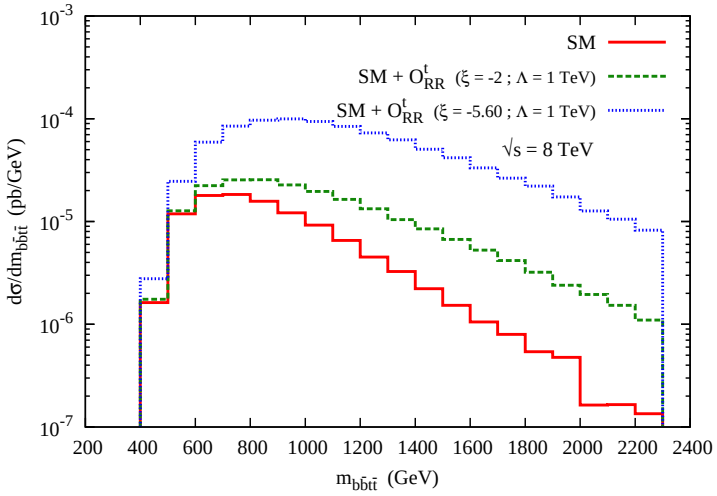
Shift in R-coupling needed: $\mathcal{O}^t_{RR} = \frac{\xi}{\Lambda^2}(\bar{t}_R\gamma_\mu t_R)(\bar{b}_R\gamma^\mu b_R)$

Concentrate on $pp \to t\bar{t}b\bar{b}$






SM
SM + O^t_{RR} (ξ = -2 ; Λ = 1 TeV)
SM + O^t_{RR} (ξ = -5.60 ; Λ = 1 TeV)
√s = 8 TeV
$d\sigma/dp_T^{sum}(t)$ (pb/GeV)
$p_T(t) + p_T(\bar{t})$ (GeV)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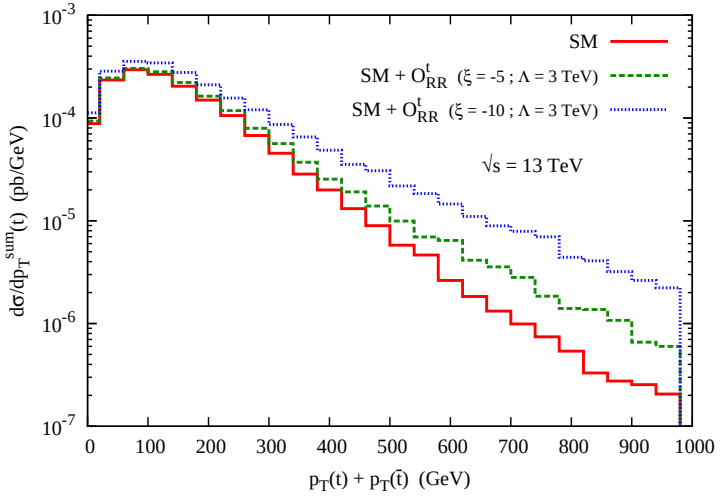
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SM + O^t_{RR} (ξ = -10 ; Λ = 3 TeV)
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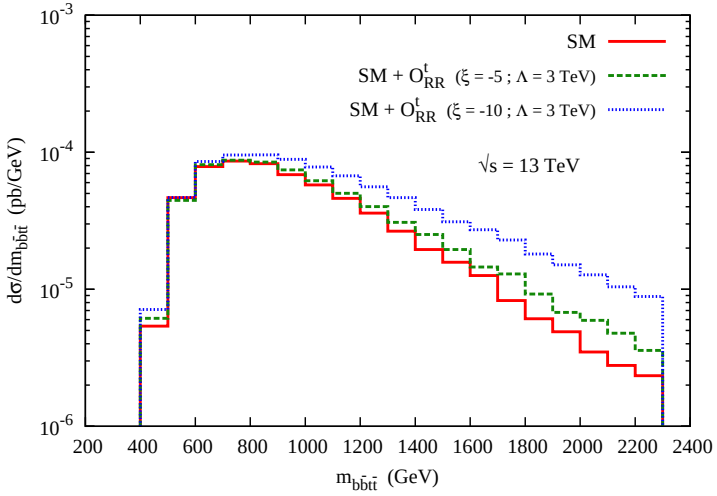
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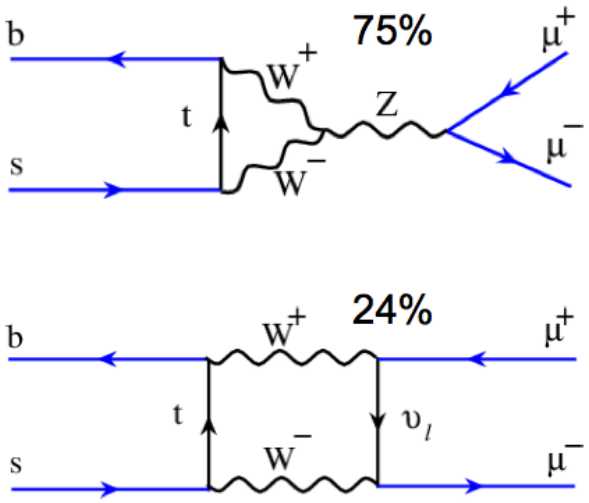
B-physics observables and cMSSM

$B_s \to \mu\mu$



Theoretically clean. LD effects negligible

Sensitive probe to FCNC effects, like new penguins

Standard Model (Buras et al. 1208.0934)

$$Br(B_s \to \mu\mu) = (3.23 \pm 0.27) \times 10^{-9}$$
$$Br(B_d \to \mu\mu) = (1.07 \pm 0.10) \times 10^{-10}$$

Maximum uncertainty from f_{B_s}. This is for $f_{B_s} = 227$ MeV
[MILC: 242(10); HPQCD: 225(4); ETMC: 234(6)]

Expert advice: Take HPQCD central values but MILC errors

includes leading NLO EW and full NLO QCD
But $\sim 10\%$ enhancement for nonzero $\Delta\Gamma_s$ (de Bruyn et al. 1204.1735)
Time-averaged SM: $Br(B_s \to \mu\mu) = (3.54 \pm 0.30) \times 10^{-9}$

LHCb (1211.2674)

$$Br(B_s \to \mu\mu) = (3.2^{+1.5}_{-1.2}) \times 10^{-9},$$
$$Br(B_d \to \mu\mu) < 9.4 \times 10^{-10} \text{ @95\% } CL$$

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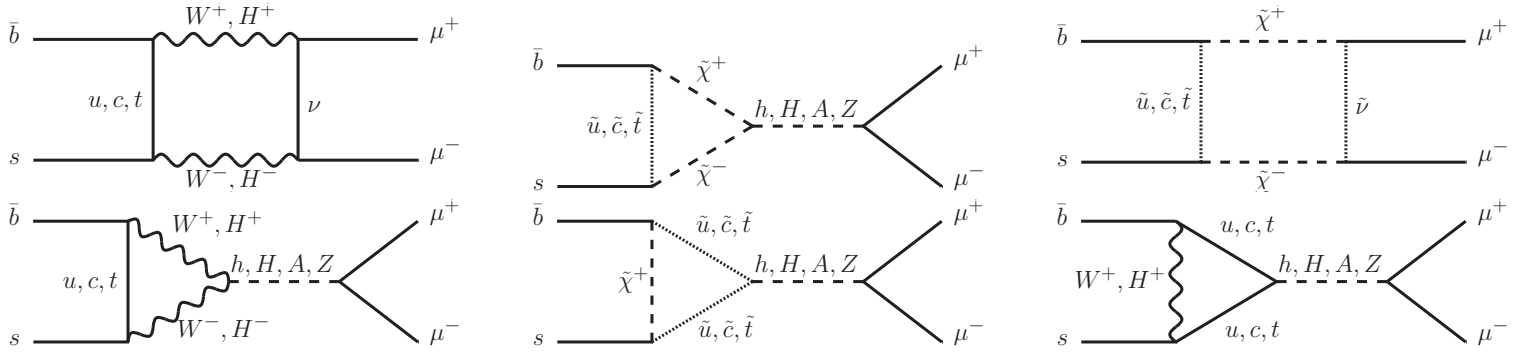
$B_s \to \mu\mu$ in SUSY

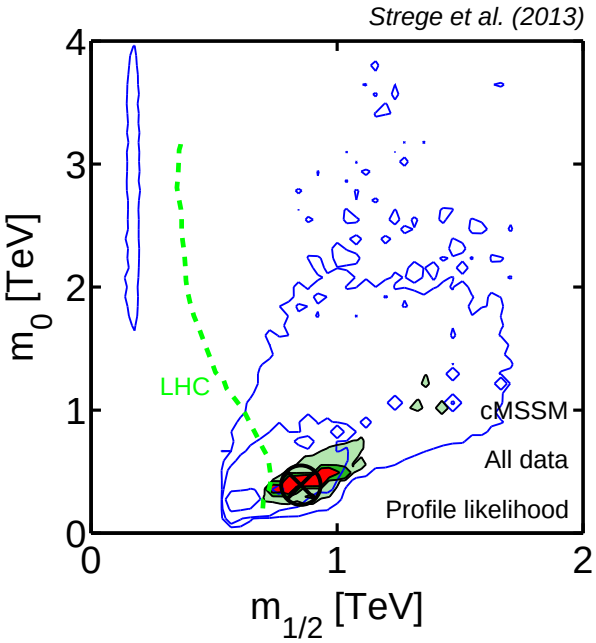


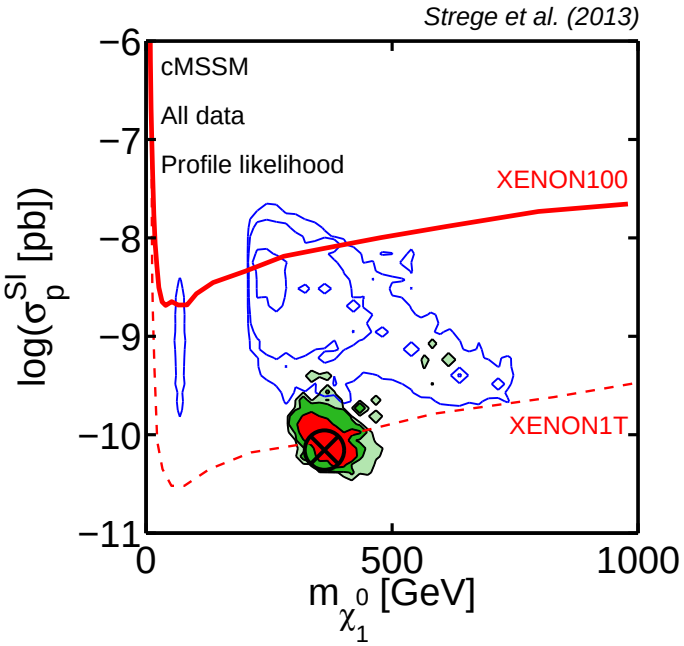
$$Br(B_s \to \mu\mu) \approx 3.5 \times 10^{-5} \left(\frac{m_t}{m_A}\right)^4 \left(\frac{\tan\beta}{50}\right)^6 \times \left(\frac{f_{B_s}}{230\ MeV}\right)^2 \left(\frac{V_{ts}}{0.040}\right)^2$$

(Buras et al. NPB 659, 2003)

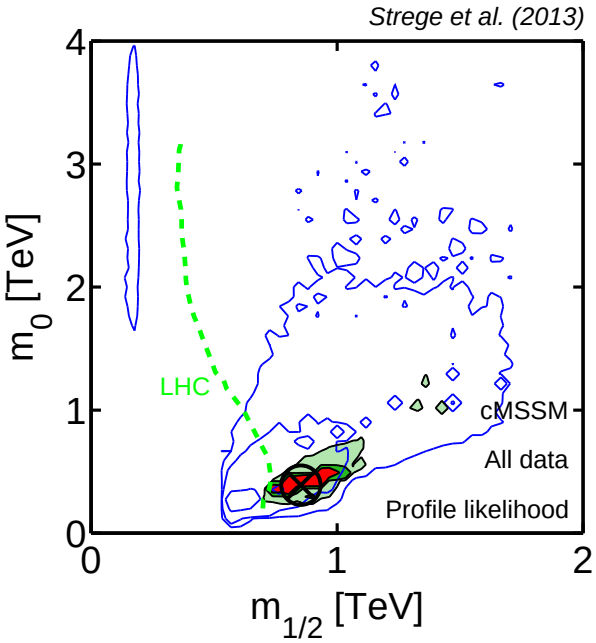
Observable	Mean value μ	Uncertainties σ (exper.)	τ (theor.)
M_W [GeV]	80.399	0.023	0.015
$\sin^2\theta_{eff}$	0.23153	0.00016	0.00015
$\delta a_\mu^{\rm SUSY} \times 10^{10}$	28.7	8.0	2.0
$Br(b \to s\gamma) \times 10^4$	3.55	0.26	0.30
$R_{\Delta M_{B_s}}$	1.04	0.11	-
$Br(B \to \tau\nu)$	1.63	0.54	-
$R(D) \times 10^2$	41.6	12.8	3.5
$Br(D_s \to \tau\nu) \times 10^2$	5.38	0.32	0.2
$Br(D_s \to \mu\nu) \times 10^3$	5.81	0.43	0.2
$Br(D \to \mu\nu) \times 10^4$	3.82	0.33	0.2
$\Omega_\chi h^2$	0.1109	0.0056	0.012
m_h [GeV]	125.8	0.6	2.0
$Br(B_s \to \mu\mu)$	3.2×10^{-9}	1.5×10^{-9}	10%
m_0, $m_{1/2}$	ATLAS, 5.8, $\sqrt{s} = 8$ TeV, 2012 limits		
m_A, $\tan\beta$	CMS, 4.7, $\sqrt{s} = 7$ TeV, 2012 limits		
$m_\chi - \sigma^{SI}_{\chi^0-p}$	XENON100 2012 limits (224.6 $\times$ 34 kg days)		

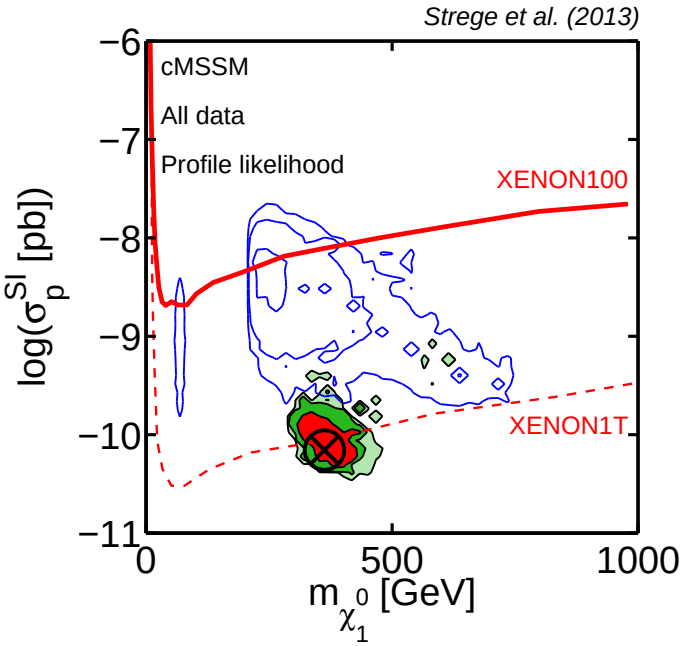
(Strege et al. 1212.2636)





Large fine-tuning needed (0.07% or worse)





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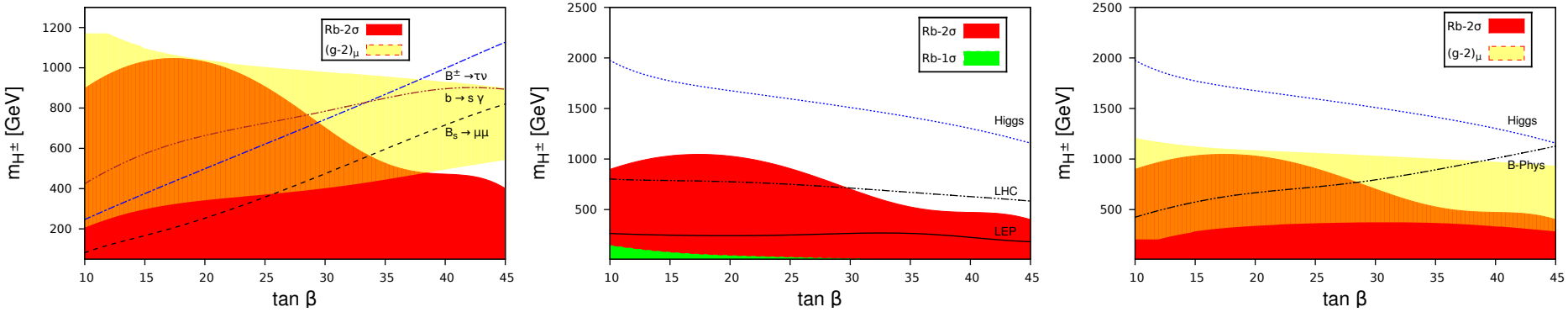
SUSY contribution decouples for heavy chargino and charged Higgs.



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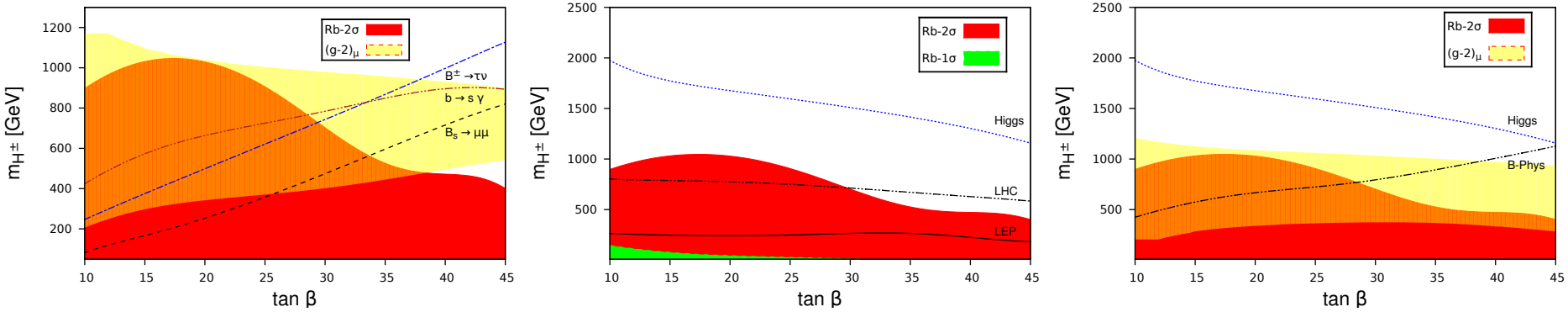

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NP in Charm

Small mixing and CP violation

D-$\bar{D}$ mixing is suppressed in SM
small masses for u and c, small CKM for b

$$x = \Delta M/\Gamma = 0.0063 \pm 0.0020$$
$$y = \Delta\Gamma/2\Gamma = 0.0075 \pm 0.0012 \qquad (\mathrm{HFAG},\ 1207.1158)$$

Relevant CP violation $\sim 0.1\%$ (Nir, 0510413)

LD effects are also important ... NP search is not easy

Direct CP violation in SCS decays

- $\Delta A_{CP} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$
- Common wisdom: DCPV in charm above 0.1% is a *clear signal for NP*

$$\Delta A_{CP} \sim 0.13\% \times \mathrm{Im}(\Delta R)$$

0.13% from CKM suppression, $\arg(V_{cs}^* V_{us}/V_{cd}^* V_{ud}) \sim \lambda^4$
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\Delta A_{CP} &= (-0.87 \pm 0.41 \pm 0.06)\% \quad [\mathrm{Belle},\ \mathrm{July2012}] \\
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Moriond 2013: $(+0.49 \pm 0.30 \pm 0.14)\%$ (1303.2614) — μ-tagging?

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Outlook for the future

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4. Taking all numbers at face value, SM is disfavoured at more than 3σ but the deviations do not point to a single NP model. **Maybe we are not smart enough.**
5. B Physics observables ($B_s \to \mu\mu$, $b \to s\gamma$, ΔM_d, ΔM_s, A_{CP}) plus m_h, R_b, DM and $(g-2)_\mu$ are more than complementary to direct searches. **For example, cMSSM is in a bad shape.**

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4. Taking all numbers at face value, SM is disfavoured at more than 3σ but the deviations do not point to a single NP model. **Maybe we are not smart enough.**
5. B Physics observables ($B_s \to \mu\mu$, $b \to s\gamma$, ΔM_d, ΔM_s, A_{CP}) plus m_h, R_b, DM and $(g-2)_\mu$ are more than complementary to direct searches. **For example, cMSSM is in a bad shape.**
6. There can be unexpected surprises like direct CPV in D decays. **Better understanding of SM dynamics needed.**

Conclusions

1. **Flavour is one of the most pressing problems. Where to get the large CP violation from?**
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Thank you.

Backup slides

Hunting grounds for NP

1. $\gamma = \arg(V_{ub}^*)$
   — Can be determined even from tree-level $B \to DK$ decays only
   — $B \to DK$, D to CP eigenstates
   — $B \to DK$, D through DCS
   — $B \to DK$, D through 3-body self-conjugate final
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2. Semileptonic $B \to K^{(*)}\mu^+\mu^-, \phi\mu^+\mu^-, \pi\mu^+\mu^-$
   — FB asymmetry, isospin asymmetry, differential decay widths
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