Future Prospects In Flavour Physics

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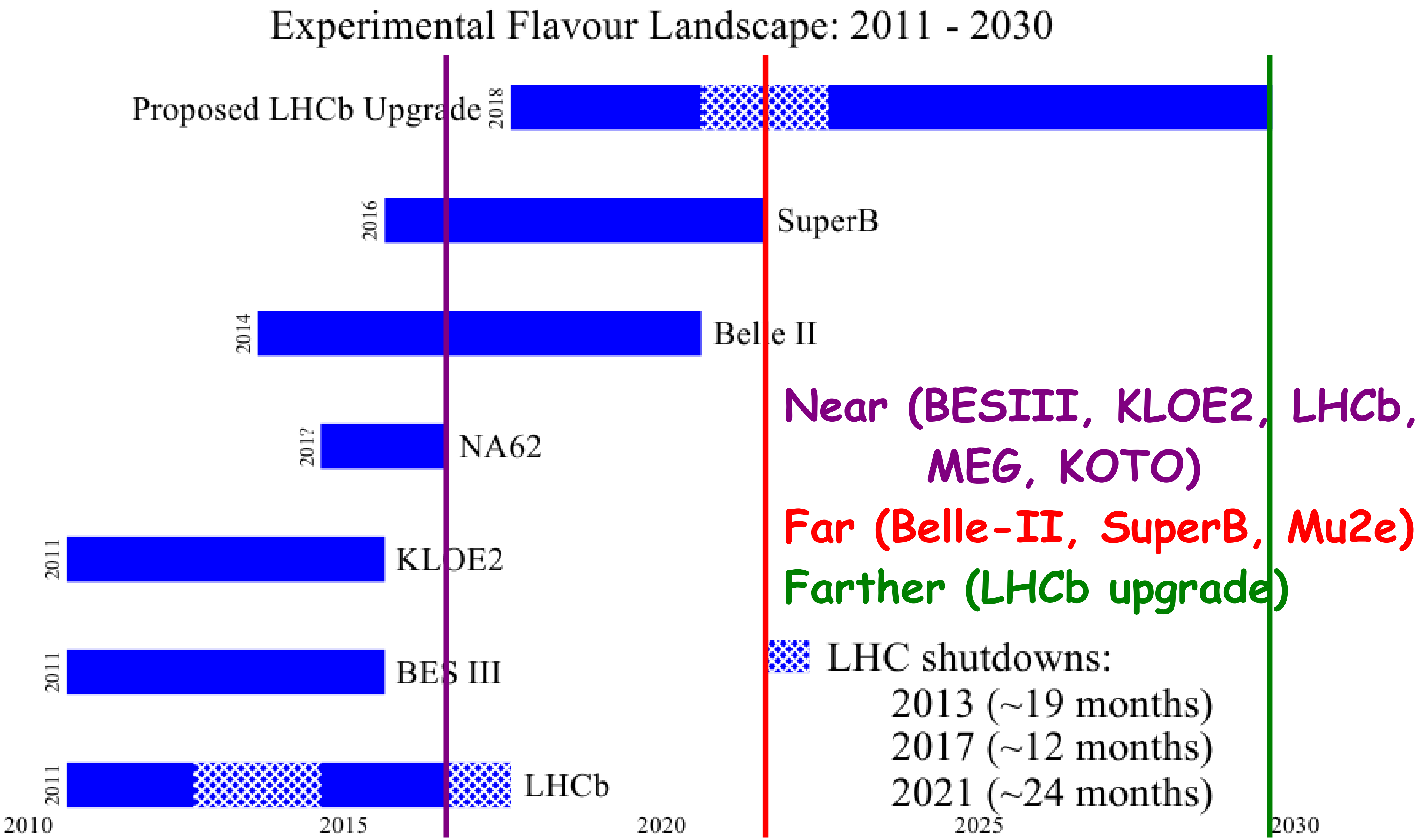
** timeline of flavour physics experiments

** going BSM with flavour physics: why and why now

** the twofold role of flavour physics in next years

Timeline of flavor experiments

arXiv:1109.5028



Relevant dates are when full samples are collected

Going BSM with flavour physics: why?

Indirect searches look for new physics through virtual effects of new particles in loop corrections

* SM FCNCs and CP-violating processes occur at the loop level

* SM FV and CPV are governed by the weak interactions and suppressed by mixing angles

* SM quark CPV comes from a single source (neglecting θ_{QCD})

New Physics does not necessarily share the SM pattern of FV and CPV: very large NP effects are possible

Past (SM) successes in anticipating heavy flavours:

1970: charm from $K^0 \to \mu^+\mu^-$ (GIM)

1973: 3rd generation from ϵ_K (Kobayashi & Maskawa)

mid 80s+: heavy top from semileptonic decays & Δm_B

Going BSM with flavour physics: why now?

* current and next-generation flavour experiments will be able to improve the experimental precision/sensitivity by one order of magnitude

* enough NP-insensitive observables to pin down the SM contribution with the required accuracy

* several NP-sensitive observables not limited by systematics or theoretical uncertainties

Overall, the NP sensitivity extends to (i) the TeV region for SM-like flavour violation and to (ii) tens of TeV or more in less constrained cases

Precision flavour physics & theory uncertainties

no theory improvements needed	$\beta(J/\psi\ K)$, $\gamma(DK)$, $\alpha(\pi\pi)$*, lepton FV and UV, CPV in $B \to X_{s+d}\gamma$, D and τ decays zero of FB asymmetry $B \to X_s l^+ l^-$	NP insensitive or null tests of the SM or SM already known with the required accuracy
improved lattice QCD	meson mixing, $B \to D(*) l\nu$, $B \to \pi(\rho) l\nu$ $B \to K^*\gamma$, $B \to \rho\gamma$, $B \to l\nu$, $B_s \to \mu\mu$	target error: ~1-2% Feasible (see below)
improved OPE+HQE	$B \to X_{u,c} l\nu$, $(B \to X_s\gamma)$	target error: ~1-2% Possibly feasible with large samples. Detailed studies required
improved QCDF/SCET or flavour symmetries	S from TD A_{CP} in $b \to s$ transitions	target error: ~2-3% large and hard to improve uncertainties on small corrections. FS+data can bound the th. error

Lattice QCD keeps up

lattice QCD can reach the O(1%) precision goal on time

V. Lubicz, SuperB CDR, arXiv:0709.0451
updated in arXiv:1008.1541

Measurement	Hadronic Parameter	Status End 2006	6 TFlops (Year 2009)	**Status End 2009**	60 TFlops (Year 2011)	1-10 PFlops (Year 2015)
$K \to \pi l \nu$	$f_+^{K\pi}(0)$	0.9 %	0.7 %	0.5 %	0.4 %	< 0.1 %
ε_K	$\hat{B}_K$	11 %	5 %	5 %	3 %	1 %
$B \to l \nu$	f_B	14 %	3.5-4.5 %	5 %	2.5-4.0 %	1.0-1.5 %
Δm_d	$f_{Bs}\sqrt{B_{B_s}}$	13 %	4-5 %	5 %	3-4 %	1-1.5 %
$\Delta m_d/\Delta m_s$	ξ	5 %	3 %	2 %	1.5-2 %	0.5-0.8 %
$B \to D/D^* l \nu$	$\mathcal{F}_{B\to D/D^*}$	4 %	2 %	2 %	1.2 %	0.5 %
$B \to \pi/\rho l \nu$	$f_+^{B\pi},\ldots$	11 %	5.5-6.5 %	11 %	4-5 %	2-3 %
$B \to K^*/\rho\,(\gamma, l^+l^-)$	$T_1^{B\to K^*/\rho}$	13 %	——	13 %	——	3-4 %

Flavour Golden Modes

	No Result	Moderately precise	Precise	Very precise
Experiment:	Red	Yellow	Blue	Green
Theory:		Moderately clean	Clean, needs Lattice	Clean

based on arXiv:1109.5028

Observable/mode Luminosity	Current $\sim 1\,\mathrm{ab}^{-1}$	LHCb (2017) $5\,\mathrm{fb}^{-1}$	Super*B* (2022) $75\,\mathrm{ab}^{-1}$	LHCb upgrade $50\,\mathrm{fb}^{-1}$	Theory	
τ Decays						
$\tau \to \mu\gamma$	Yellow	Yellow	Green	Yellow	Green	benefit from polarised e⁻ beam
$\tau \to e\gamma$	Yellow	Yellow	Green	Yellow	Green	
$B_{u,d}$ Decays						
$B \to \tau\nu, \mu\nu$	Yellow	Red	Blue	Red	Blue	very precise with improved detector
$B \to K^{(*)+}\nu\overline{\nu}$	Red	Red	Green	Red	Green	statistically limited: ang. analysis with >75ab^{-1}
S in $B \to K^0_S\pi^0\gamma$	Yellow	Red	Green	Red	Yellow	right handed currents
S (other penguin modes)	Yellow	Yellow	Green	Blue	Yellow	SuperB measures many more modes
A_{CP} $(B \to X_s\gamma)$	Blue	Yellow	Green	Yellow	Green	systematic error is main challenge
BR$(B \to X_s\gamma)$	Blue	Yellow	Green	Yellow	Yellow	control systematic error with data
BR$(B \to X_s ll)$	Yellow	Red	Green	Red	Green	
BR$(B \to K^{(*)} ll)$	Yellow	Blue	Green	Green	Yellow	SuperB measures e mode well, LHCb does μ
B_s Decays						
$B_s \to \mu\mu$	Red	Blue	Red	Green	Green	
β_S from $B_s \to J/\psi\,\phi$	Red	Blue	Red	Green	Green	
$B_s \to \gamma\gamma$	Red	Red	Blue	Red	Green	
a_{sl}	Red	Blue	Green	Green	Green	
D Decays						
Mixing parameters	Yellow	Blue	Green	Green	Green	
CP Violation	Red	Blue	Green	Green	Green	clean NP search
Precision Electroweak						
$\sin^2\theta_W$ at $\Upsilon(4S)$	Red	Red	Green	Red	Green	
$\sin^2\theta_W$ at Z-Pole	Green	Blue	Red	Green	Yellow	b fragmentation limits interpretation at Z polebas

Comparison of present and future flavour experiments on "golden modes" (an incomplete list)

Observable/mode Luminosity	Current $\sim 1\,\mathrm{fb}^{-1}$	LHCb (2017) $5\,\mathrm{fb}^{-1}$	Super*B* (2022) $75\,\mathrm{ab}^{-1}$	LHCb upgrade $50\,\mathrm{fb}^{-1}$	Theory	
α	Blue	Blue	Green	Blue	Yellow	LHCb can only use ρπ
β from $b \to c\bar{c}s$	Blue	Blue	Green	Green	Green	
$B_d \to J/\psi\,\pi^0$	Yellow	Red	Green	Red	Green	βtheory error Bd
$B_s \to J/\psi\,K^0_S$	Red	Yellow	Red	Blue	Green	βtheory error Bs
γ	Yellow	Blue	Green	Green	Green	
$\lvert V_{ub}\rvert$ inclusive	Blue	Yellow	Green	Blue	Blue	need an e+e− environment to do a precision measurement using semi-leptonic B decays.
$\lvert V_{ub}\rvert$ exclusive	Blue	Yellow	Green	Blue	Blue	
$\lvert V_{cb}\rvert$ inclusive	Blue	Yellow	Green	Blue	Blue	
$\lvert V_{cb}\rvert$ exclusive	Blue	Yellow	Green	Blue	Blue	

The twofold role of flavour physics

Depending on the scenario, flavour physics can be used in two "modes" with different aimings

1. "NP-Lagrangian reconstruction" mode
   - external information on NP required
   - main tool: correlations among observables
   - need theoretical control on uncertainties of both SM and NP contributions

2. "Discovery" mode
   - look for deviation from the SM whatever the origin
   - need theoretical control of the SM contribution only
   - in general, cannot provide precise information on NP scale, but a positive result would be a strong evidence that NP is not too far (i.e. in the multi-TeV region)

MSSM: flavour violation in the squark sector

LHCb, SuperB

LHC, ILC - HE frontier

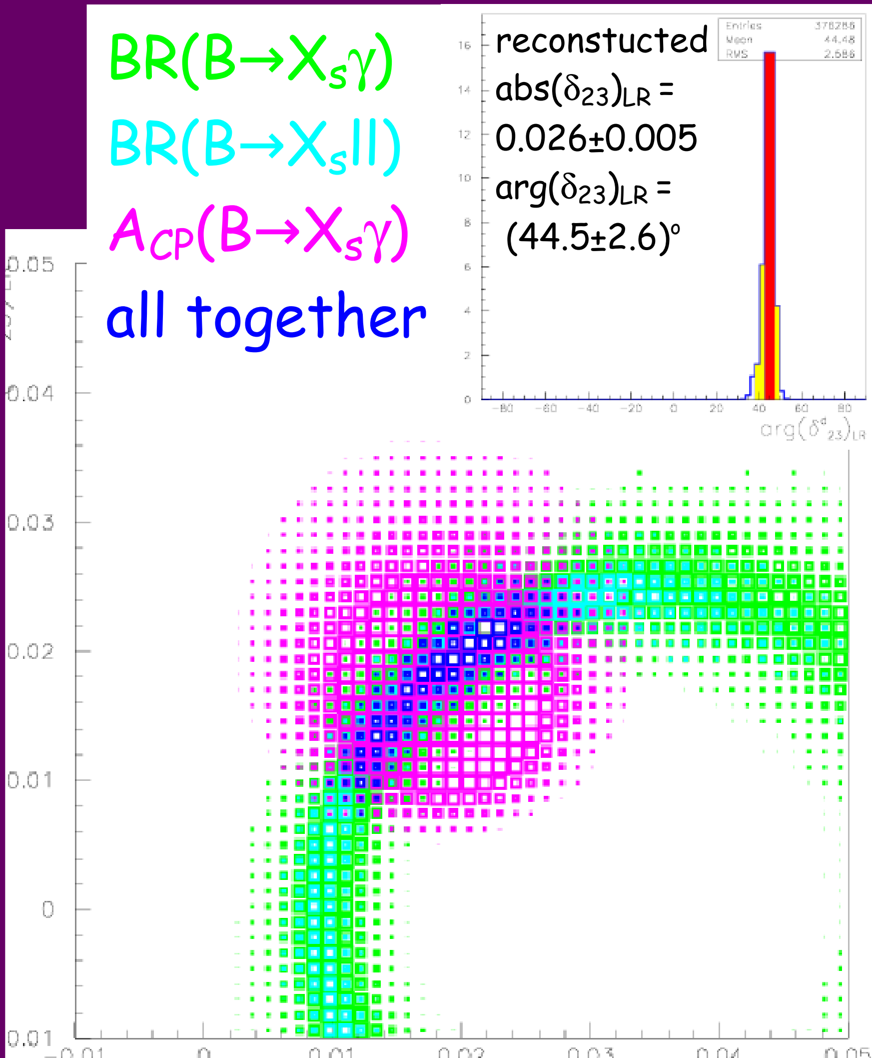
$$M^2_{\tilde{d}} \approx \begin{pmatrix} m^2_{\tilde{d}_L} & m_d(A_d - \mu \tan\beta) & (\Delta^d_{12})_{LL} & (\Delta^d_{12})_{LR} & (\Delta^d_{13})_{LL} & (\Delta^d_{13})_{LR} \\ & m^2_{\tilde{d}_R} & (\Delta^d_{12})_{RL} & (\Delta^d_{12})_{RR} & (\Delta^d_{13})_{RL} & (\Delta^d_{13})_{RR} \\ & & m^2_{\tilde{s}_L} & m_s(A_s - \mu \tan\beta) & (\Delta^d_{23})_{LL} & (\Delta^d_{23})_{LR} \\ & & & m^2_{\tilde{s}_R} & (\Delta^d_{23})_{RL} & (\Delta^d_{23})_{RR} \\ & & & & m^2_{\tilde{b}_L} & m_b(A_b - \mu \tan\beta) \\ & & & & & m^2_{\tilde{b}_R} \end{pmatrix}$$

and similarly for $M^2_{\tilde{u}}$

NP scale: $m_{\tilde{q}}$

FV & CPV couplings: $(\delta^d_{ij})_{AB} = (\Delta^d_{ij})_{AB} / m^2_{\tilde{q}}$

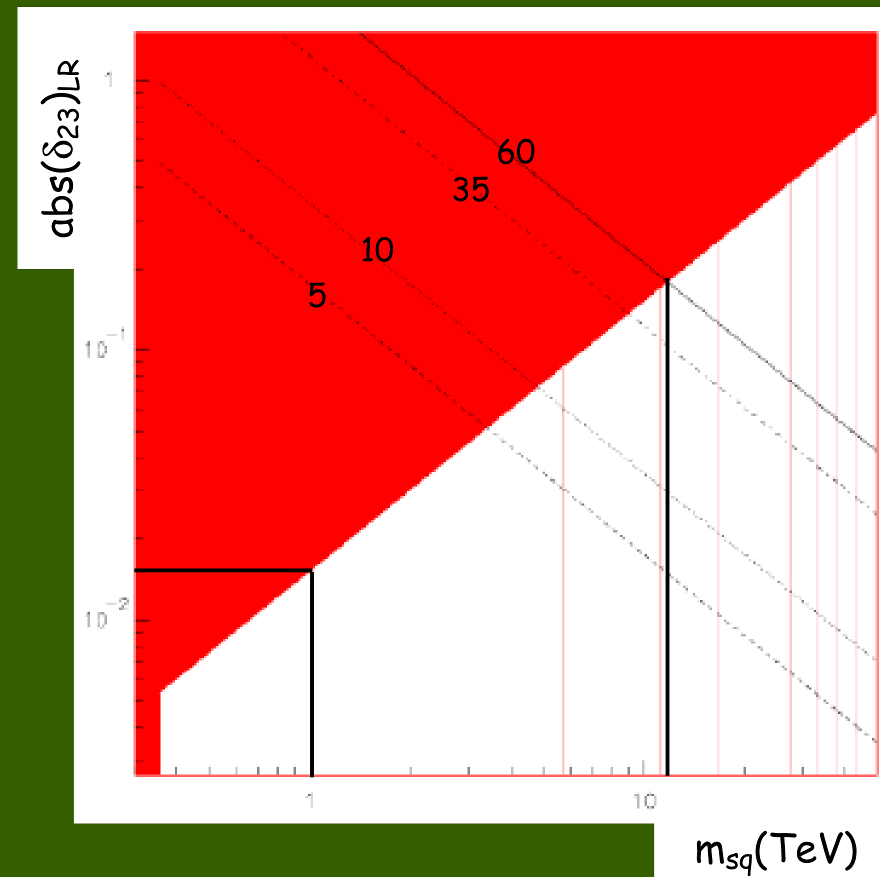
Determination of $(\delta^d_{23})_{LR}$ using SuperB data



$\mathrm{Im}(\delta^d_{23})_{LR}$ vs $\mathrm{Re}(\delta^d_{23})_{LR}$

reconstruction of $(\delta^d_{23})_{LR} = 0.028\ e^{i\pi/4}$ for $\Lambda = m_{\tilde{g}} = m_{\tilde{q}} = 1$ TeV

"3σ" sensitivity plot



i) sensitive to $m_{\tilde{q}} < 20$ TeV

ii) sensitive to $|(\delta^d_{23})_{LR}| > 10^{-2}$ for $m_{\tilde{q}} < 1$ TeV

OVERALL SUSY ASSESSMENT

see also Paradisi's talk

studying correlations in flavour observables, together with high-p_t info, we can learn about:

* the SUSY-breaking mechanism
* the flavour breaking mechanism
* the underlying presence of a GUT structure
* the origin of lepton flavour violation

Observable/mode	charged Higgs high $\tan\beta$	MFV NP low $\tan\beta$	non-MFV NP 2-3 sector	NP in Z penguins	Right-handed currents	LHT	SUSY AC	RVV2	AKM	δLL	FBMSSM	GUT-CMM
$\tau \to \mu\gamma$							⋆⋆⋆	⋆⋆⋆	⋆	⋆⋆⋆	⋆⋆⋆	⋆⋆⋆
$\tau \to \ell\ell\ell$						⋆⋆⋆						?
$B \to \tau\nu, \mu\nu$	⋆⋆⋆(CKM)											
$B \to K^{(*)+}\nu\bar{\nu}$			⋆	⋆⋆⋆			⋆	⋆	⋆	⋆	⋆	?
S in $B \to K^0_S\pi^0\gamma$			⋆⋆		⋆⋆⋆							
S in other penguin modes			⋆⋆⋆(CKM)		⋆⋆⋆		⋆⋆⋆	⋆⋆	⋆	⋆⋆⋆	⋆⋆⋆	?
$A_{CP}(B \to X_s\gamma)$			⋆⋆⋆		⋆⋆		⋆	⋆	⋆	⋆⋆⋆	⋆⋆⋆	?
$BR(B \to X_s\gamma)$		⋆	⋆⋆		⋆							⋆⋆
$BR(B \to X_s\ell\ell)$			⋆⋆	⋆	⋆							?
$B \to K^{(*)}\ell\ell$ (FB Asym)							⋆	⋆	⋆	⋆⋆⋆	⋆⋆⋆	?
a^s_{sl}			⋆⋆⋆			⋆⋆⋆						⋆⋆⋆
Charm mixing							⋆⋆⋆	⋆	⋆	⋆	⋆	
CPV in Charm	⋆⋆									⋆⋆⋆		

more information in arXiv:1008.1541, arXiv:0909.1333, and arXiv:0810.1312

Conclusions

* intense experimental activity programmed for the next 20 years in all flavour sectors: entering the era of precision flavour physics

* a serious challenge for theory to keep up with the expected experimental precision.
  Yet perspectives are encouraging

* twofold goal:
  - study the flavour structure of new particles at the TeV scale
  - getting hint/evidence for the presence of NP in the multi-TeV region

Spare Slides

arXiv:1109.5028

Observable	Current value	Experiment	Precision
$\mathrm{BR}(B_s \to \mu\mu)$ $(\times 10^{-9})$	$<$ ~~15~~[a]	LHCb	± 1
	4.5	LHCb upgrade	± 0.3
$2\beta_s$ from $B_s^0 \to J/\psi\phi$ (rad)	~~0.13~~ $\pm$ ~~0.19~~[b]	LHCb	0.019
	0.002 0.038	LHCb upgrade	0.006
S in $B_s \to \phi\gamma$ *		LHCb	0.07
		LHCb upgrade	0.02
$K^+ \to \pi^+ \nu\overline{\nu}$ (% BR measurement)	7 events	NA62	100 events (10%)
$K_L^0 \to \pi^0 \nu\overline{\nu}$		KOTO	3 events (observe)
$BR(\mu \to e\gamma)$ $(\times 10^{-13})$	$<$ ~~280~~ 24	MEG	< 1
$R_{\mu e}$	$< 7 \times 10^{-12}$	COMET/Mu2E	$< 6 \times 10^{-17}$

Observable/mode	Current now	LHCb (2017) 5 fb^{-1}	Super$B$ (2021) 75 ab^{-1}	Belle II (2021) 50 ab^{-1}	LHCb upgrade (10 years of running) 50 fb^{-1}	theory now
			τ Decays			
$\tau \to \mu\gamma$ $(\times 10^{-9})$	< 44		< 2.4	< 5.0		
$\tau \to e\gamma$ $(\times 10^{-9})$	< 33		< 3.0	< 3.7 (est.)		
$\tau \to \ell\ell\ell$ $(\times 10^{-10})$	$< 150 - 270$	< 244 [a]	$< 2.3 - 8.2$	< 10	< 24 [b]	
			$B_{u,d}$ Decays			
$\mathrm{BR}(B \to \tau\nu)$ $(\times 10^{-4})$	1.64 ± 0.34		0.05	0.04		1.1 ± 0.2
$\mathrm{BR}(B \to \mu\nu)$ $(\times 10^{-6})$	< 1.0		0.02	0.03		0.47 ± 0.08
$\mathrm{BR}(B \to K^{*+}\nu\overline{\nu})$ $(\times 10^{-6})$	< 80		1.1	2.0		6.8 ± 1.1
$\mathrm{BR}(B \to K^{+}\nu\overline{\nu})$ $(\times 10^{-6})$	< 160		0.7	1.6		3.6 ± 0.5
$\mathrm{BR}(B \to X_s\gamma)$ $(\times 10^{-4})$	3.55 ± 0.26		0.11	0.13	0.23	3.15 ± 0.23
$A_{CP}(B \to X_{(s+d)}\gamma)$	0.060 ± 0.060		0.02	0.02		$\sim 10^{-9}$
$B \to K^*\mu^+\mu^-$ (events)	250[c]	8000	10-15k[d]	7-10k	100,000	-
$\mathrm{BR}(B \to K^*\mu^+\mu^-)$ $(\times 10^{-6})$	1.15 ± 0.16		0.06	0.07		1.19 ± 0.39
$B \to K^*e^+e^-$ (events)	165	400	10-15k	7-10k	5,000	-
$\mathrm{BR}(B \to K^*e^+e^-)$ $(\times 10^{-6})$	1.09 ± 0.17		0.05	0.07		1.19 ± 0.39
$A_{FB}(B \to K^*\ell^+\ell^-)$	0.27 ± 0.14[e]	[f]	0.040	0.03		-0.089 ± 0.020
$B \to X_s\ell^+\ell^-$ (events)	280		8,600	7,000		-
$\mathrm{BR}(B \to X_s\ell^+\ell^-)$ $(\times 10^{-6})$[g]	3.66 ± 0.77[h]		0.08	0.10		1.59 ± 0.11
S in $B \to K_S^0\pi^0\gamma$	-0.15 ± 0.20		0.03	0.03		-0.1 to 0.1
S in $B \to \eta' K^0$	0.59 ± 0.07		0.01	0.02		± 0.015
S in $B \to \phi K^0$	0.56 ± 0.17	0.15	0.02	0.03	0.03	± 0.02
			B_s^0 Decays			
$\mathrm{BR}(B_s^0 \to \gamma\gamma)$ $(\times 10^{-6})$	< 8.7		0.3	$0.2 - 0.3$		0.4 - 1.0
A_{SL}^s $(\times 10^{-3})$	-7.87 ± 1.96 [i]	[j]	4.	5. (est.)		0.02 ± 0.01
			D Decays			
x	$(0.63 \pm 0.20\%$	0.06%	0.02%	0.04%	0.02%	$\sim 10^{-2}$ [k]
y	$(0.75 \pm 0.12)\%$	0.03%	0.01%	0.03%	0.01%	$\sim 10^{-2}$ (see above).
y_{CP}	$(1.11 \pm 0.22)\%$	0.05%	0.03%	0.05%	0.01%	$\sim 10^{-2}$ (see above).
$\lvert q/p \rvert$	$(0.91 \pm 0.17)\%$	10%	2.7%	3.0%	3%	$\sim 10^{-3}$ (see above).
$\arg\{q/p\}$ $(^\circ)$	-10.2 ± 9.2	5.6	1.4	1.4	2.0	$\sim 10^{-3}$ (see above).
			Other processes Decays			
$\sin^2\theta_W$ at $\sqrt{s} = 10.58\,\mathrm{GeV}/c^2$			0.0002	[l]		clean

arXiv:1109.5028

Observable/mode	Current now	LHCb (2017)	Super$B$ (2021)	Belle II (2021)	LHCb upgrade (10 years of running)	theory now
		$5\,\mathrm{fb}^{-1}$	$75\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$	$50\,\mathrm{fb}^{-1}$	
α from $u\overline{u}d$	6.1°	$5^{\circ\,a}$	1°	1°	^{b}	$1-2^\circ$
β from $c\overline{c}s$ (S)	0.9° (0.024)	0.5° (0.008)	0.1° (0.002)	0.3° (0.007)	0.2° (0.003)	clean
S from $B_d \to J/\psi\pi^0$	0.21		0.014	0.021 (est.)		clean
S from $B_s \to J/\psi K_S^0$		?			?	clean
γ from $B \to DK$	11°	$\sim 4^\circ$	1°	1.5°	0.9°	clean
$\lvert V_{cb}\rvert$ (inclusive) %	1.7		0.5%	0.6 (est.)		dominant
$\lvert V_{cb}\rvert$ (exclusive) %	2.2		1.0%	1.2 (est.)		dominant
$\lvert V_{ub}\rvert$ (inclusive) %	4.4		2.0%	3.0		dominant
$\lvert V_{ub}\rvert$ (exclusive) %	7.0		3.0%	5.0		dominant