Heavy Flavor and the CKM Matrix

Stéphane T'JAMPENS

LAPP (CNRS/IN2P3 et Université de Savoie)

On behalf of the LHCb collaboration
Including results from ATLAS/CMS, BaBar/Belle and CDF/DØ

Outline

CKM Matrix

- Moduli
- Phases (CP violation)
  - Gamma
  - Charm

Bounds on New Physics with FCNCs

- Mixing in B_s
- Rare Decays:
  - $B_s \rightarrow \mu\mu$
  - $B_s \rightarrow K^*\mu\mu$

Future: LHCb Upgrade, BelleII and SuperB

selected highlights (apologies if your analysis is not mentioned)

CKM Matrix: Quark-Mixing Matrix

In SM, Weak-charged transitions mix quarks of different generations:

➔ encoded in quark-mixing matrix

- Cabibbo (1963): universality of weak-coupling constant → unitary matrix
- Kobayashi-Maskawa (1973): 1 CP-violating phase with 3 families

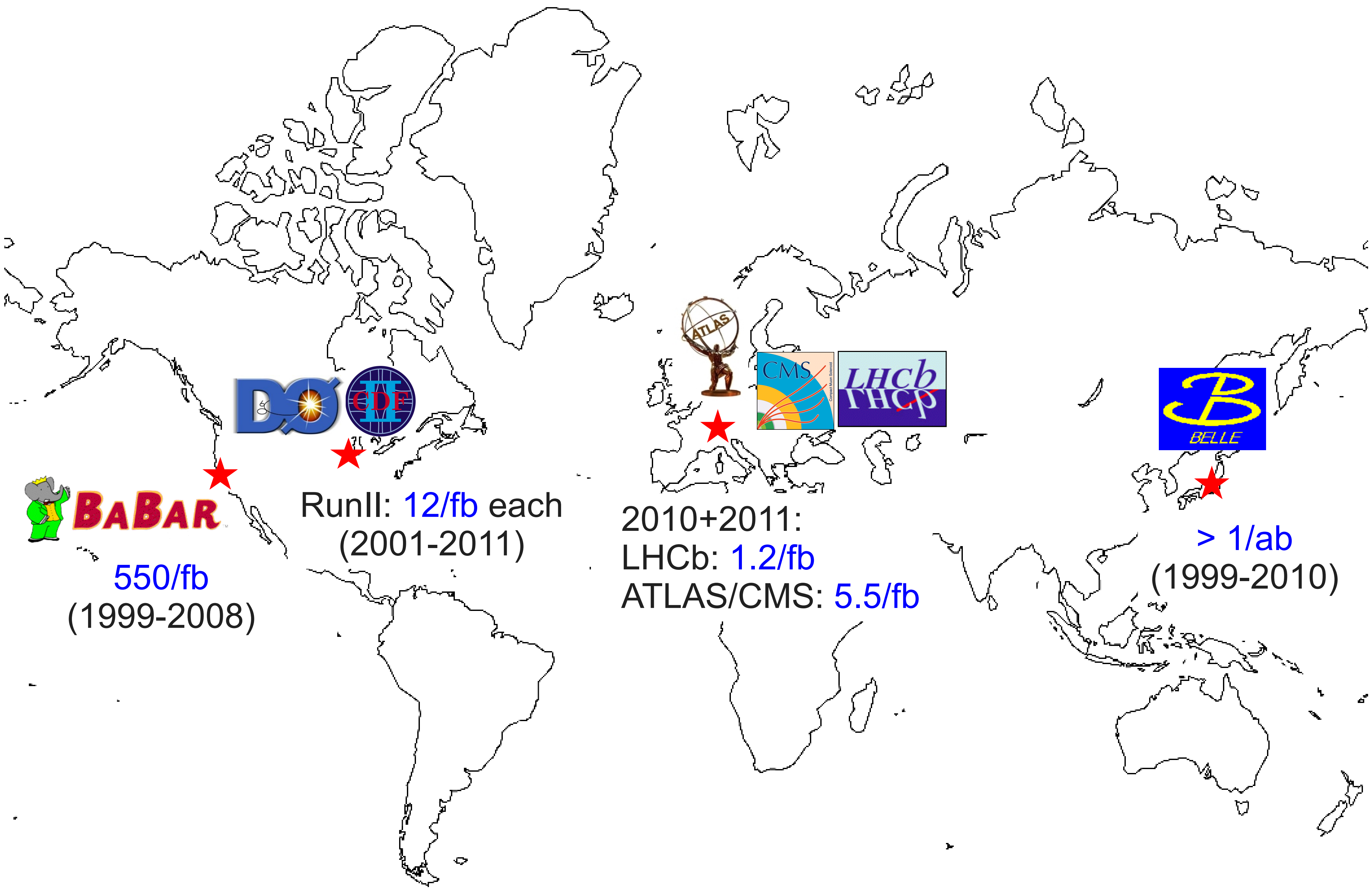
➔ Cabibbo-Kobayashi-Maskawa (CKM) Matrix

Hierarchy: Wolfenstein parametrization (1983)

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

4 parameters (A, λ, ρ, η): SM testable and predictive
(correlation among measurements)

Some of the Main Flavor-Physics Experiments



CKM Matrix

Moduli

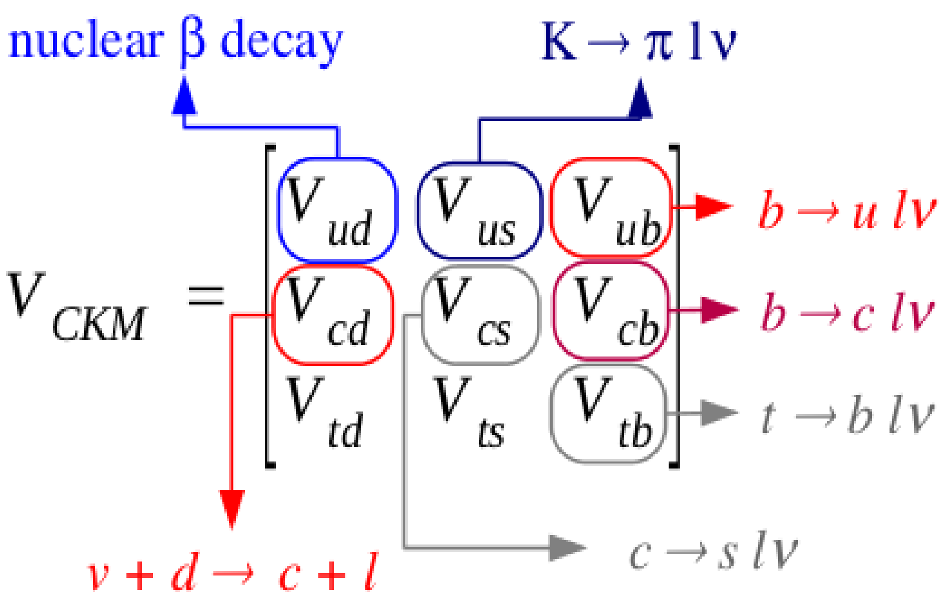
CKM Matrix: Moduli

CKM matrix: free parameters determined experimentally

Goal: high precision of CKM parameters

- pin down the SM flavor couplings and search for NP
- Data = weak ⊗ QCD: precise lattice-QCD calculations (few % or better) required

See Van der Water, Witzel, Bouchard



Excellent determination (error ~ 0.03%)

Very good determination (error ~ 0.4 %)

Good determination (error ~ 2 – 3%)

Non-negligible error (5 – 12%)

Not competitive with unitarity constraints

Lingering difference: V_{ub} inc. > V_{ub} excl. (2.4σ) (idem V_{cb}: 2.1σ) See Urquijo, Kwon

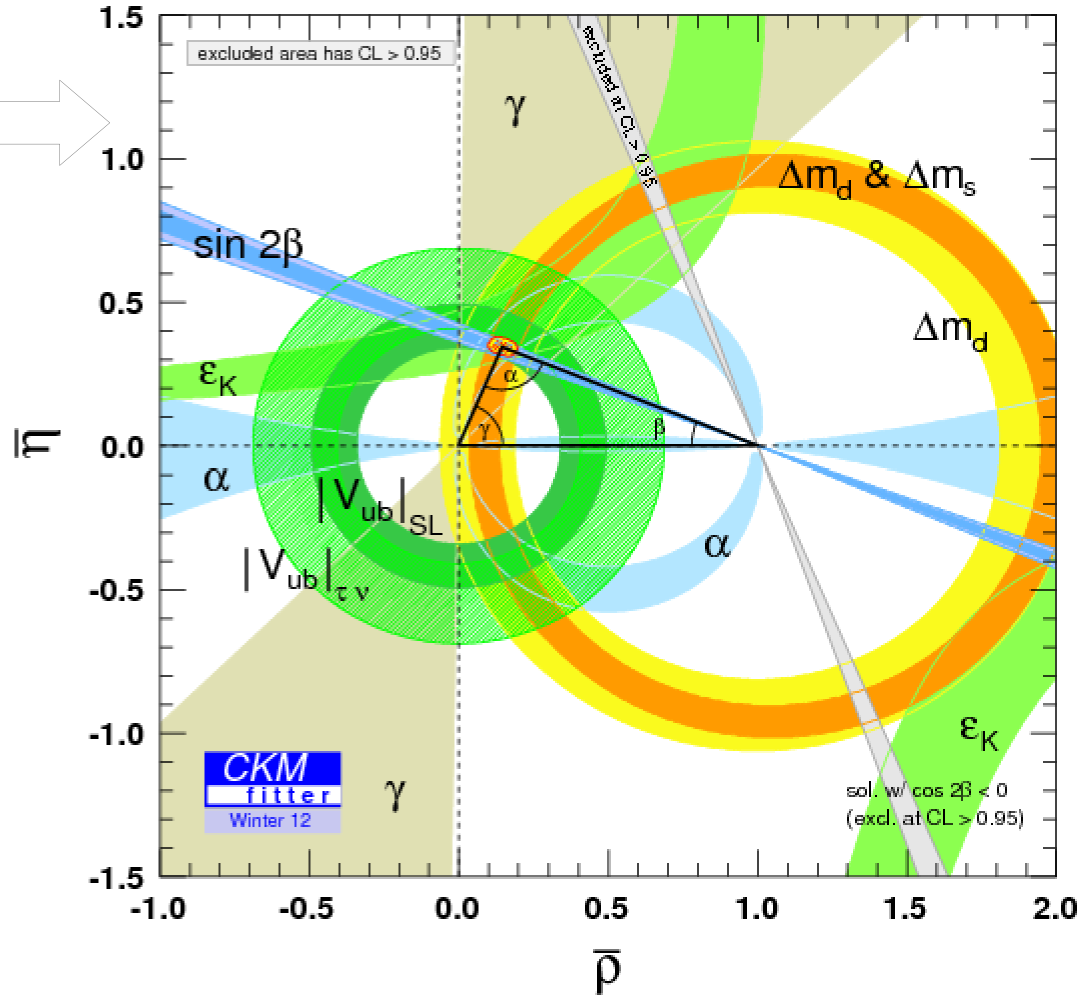
CKM Matrix

Phases $\rightarrow$ CP violation

KM Ansatz: Tested to be Dominant CPV Phase at EW Scale

Inputs:

- **A, λ**: $|V_{ud}|$, $|V_{us}|$, $|V_{cb}|$
- $\bar{\rho}, \bar{\eta}$:
  - → $|V_{ub}|$, $B \to \tau\nu$, Δm_d, $\Delta m_d \& \Delta m_s$, $|\varepsilon_K|$, $\sin 2\beta$, α, γ **See Yusa**
- Lattice-QCD (LQCD)



Impressive accomplishments

Overall consistency at 2σ level

CKM dominant source of flavor and CPV violation. Is CKM sufficient?

Some discrepancies:

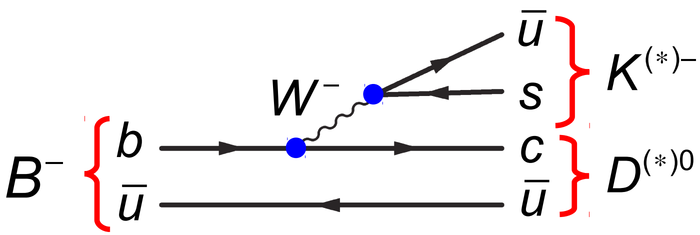
- $|V_{ub}|$, $|V_{cb}|$
- $B \to \tau\nu$ vs $\sin 2\beta$: 2.8σ

$B \to D^{(*)}\tau\nu$: 3.4σ (BaBar) **arXiv:1205.5442**

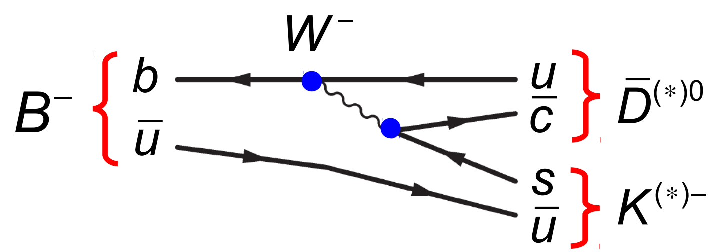
Need to overall improve precision but especially on γ (18%) for reference UT (β: 3%, α: 5%) and on LQCD inputs

CKM Matrix: Gamma (Direct CPV)

See Perazzini for gamma in B → hh



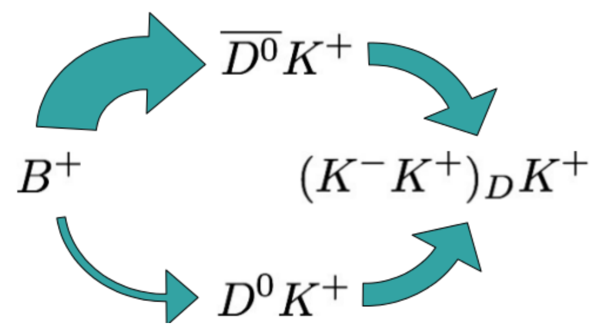
Tree: dominant
b → c



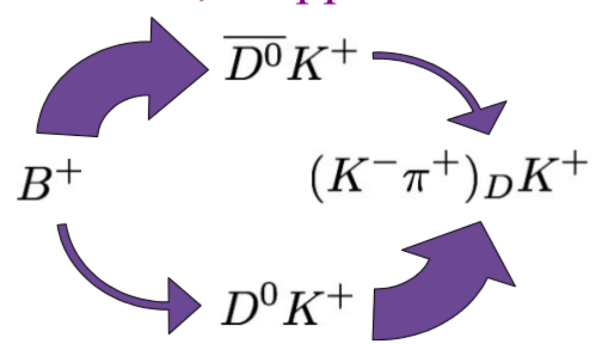
Tree: color-suppressed
b → u

- GLW: D decays into CP eigenstate (KK, ππ, …)
- ADS: D decays to Doubly-Cabibbo Suppressed states
- GGSZ: D decays to $K_S\pi+\pi-$ (interference in Dalitz plot)

“GLW”



“ADS”, “suppressed”



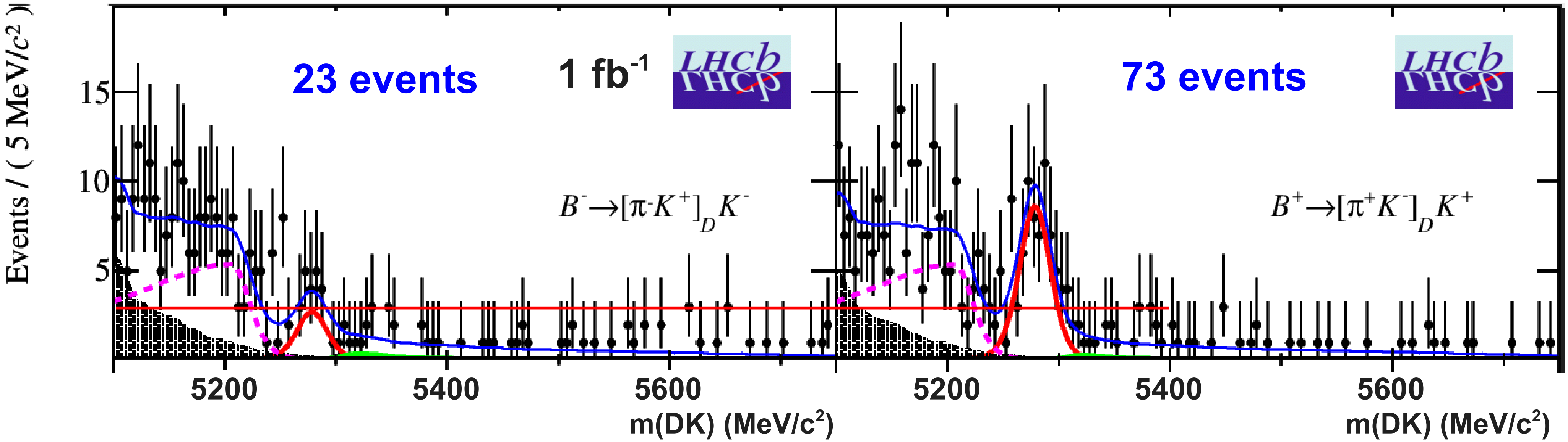
Observables sensitive to γ:

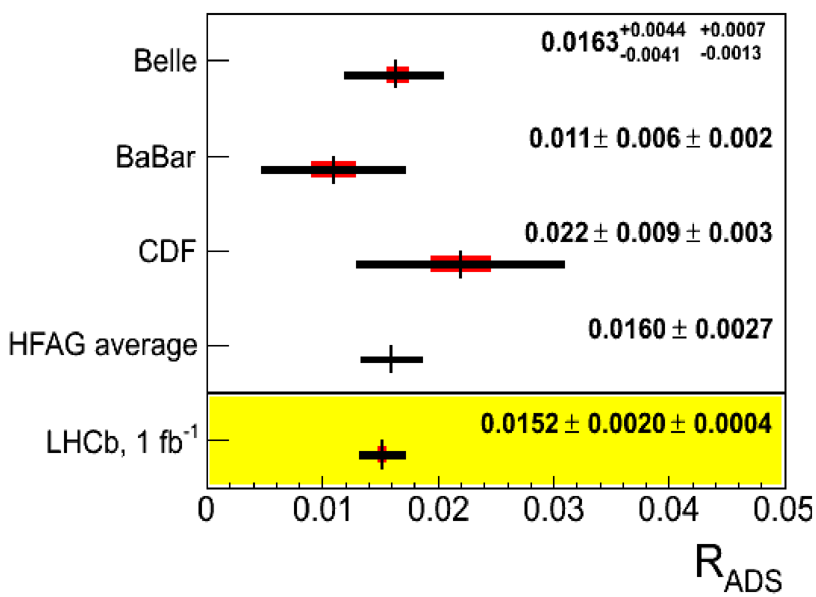
Asymmetry of decay rates: $$A = \frac{\Gamma(B^-) - \Gamma(B^+)}{\Gamma(B^-) + \Gamma(B^+)}$$

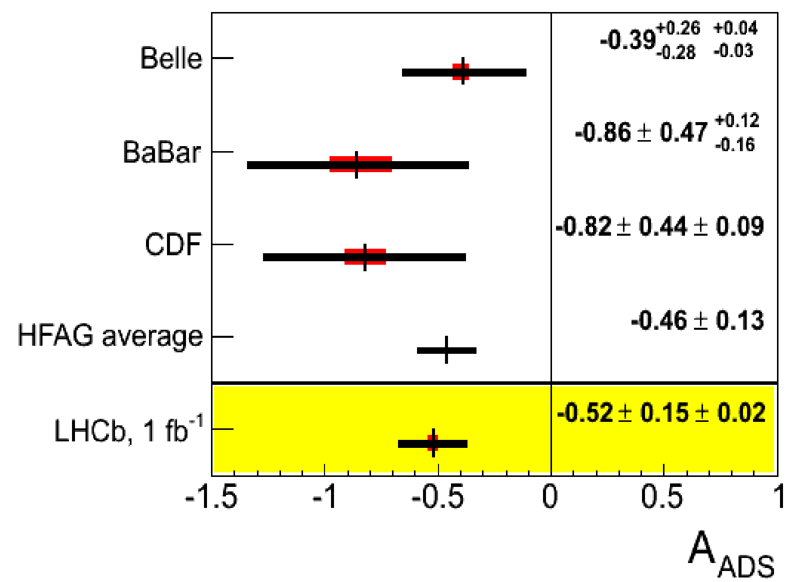
Ratio of branching ratios: $$R = \frac{\Gamma(B^-) + \Gamma(B^+)}{\Gamma(B^-_{\mathrm{fs}}) + \Gamma(B^+_{\mathrm{fs}})}$$

CKM Matrix: Gamma (Direct CPV)

See Akiba







R_{ADS}: first observation of ADS mode with 10σ significance

(A_{ADS}: 4σ evidence of direct CPV)

LHCb: PLB 712 (2012) 203

CDF: PRD 84 (2011) 091504

BaBar: PRD 82 (2010) 072006

Belle: PRL 106 (2011) 231803

CKM Matrix: direct CPV in Charm

See Harr

$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$ in $D^{*+} \rightarrow D^0\pi^+$; $D^0 \rightarrow h^+h^-$

See Cinabro for CPV in mixing

Production and detector asymmetries cancel out.

LHCb: 0.58 fb^{-1}: 1.44M KK, 0.38M ππ

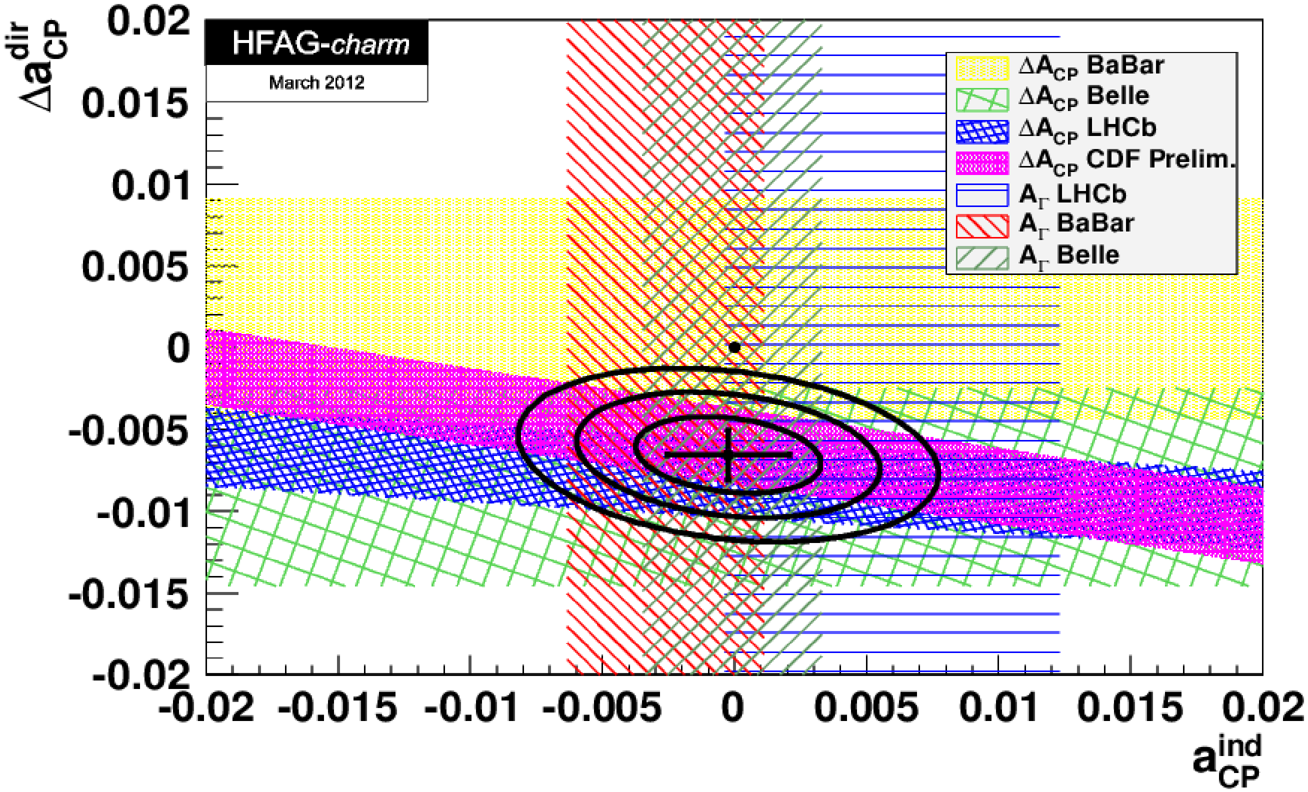
ΔA_{CP} = (-0.82 ± 0.21(stat) ± 0.11 (syst))%

PRL108 (2011) 111602

CDF: 10 fb^{-1}: 1.21M KK, 0.55M ππ

ΔA_{CP} = (-0.62 ± 0.21(stat) ± 0.10 (syst))%

CDF note 10784



No CPV point: 3.8σ

Triggered many theoretical works: Is it SM or NP?

More work needed to answer the question

See Petrov

Precision Flavor Physics

Unraveling the Flavor

Structure of BSM

Key words: experimental precision – theoretical cleanliness

Theory to Interpret Flavor Measurements

Framework: Operator Product Expansion: separate low and high energies

$$A(B_q \to f) \propto \frac{G_F}{\sqrt{2}} V_{tb} V_{tq}^* \sum_i C_i(\mu) \langle \mathcal{O}_i \rangle (\mu)$$

Wilson coefficients:
- short distance
- computed perturbatively

Matrix element of local operator:
- long distance
- the difficult part: QCD

→ LQCD and analytic methods

NP is in Wilson coefficients $C_i = C_i^{SM} + C_i^{NP}$ or new local operators O_i

[C_i^{NP} generically suppressed by a factor of order M_W^2/Λ_{NP}^2 wrt C_i^{SM}]

➔ Learn about the Dirac, chirality and CP structure of BSM

Probing the BSM Flavor Structure

Determine SM values of CKM elements using theoretical-clean tree-level processes and of Wilson coefficients (NNLO available) [control over penguin pollution also important]

Study processes which are suppressed in the SM: FCNCs
(GIM suppression and possibly CKM and/or helicity suppression)
➔ privileged probes highly sensitive to high scales (short-distance physics)

Measure with good accuracy these rare processes and determine the allowed room for new physics

Such chain has already been closed, with good accuracy, for $b \to d$ and $s \to d$ $\Delta F=2$ observables (K and B_d meson-antimeson mixing)

Mixing in B_s

($\Delta F=2$ FCNC)

B_s Mixing: $\Delta\Gamma_s$, Φ_s

See Sparkes, Eklund

"Golden mode": $B_s \to J/\psi\Phi$ → need angular distribution to disentangle the mixture of CP-odd and CP-even amplitudes

LHCb-CONF-2012-002

$\Delta\Gamma_s$ = 0.116 ± 0.018(stat.) ± 0.006(syst.) ps^{-1} >5σ

Φ_s = -0.001 ± 0.101(stat.) ± 0.027(syst.) rad

~21k $J/\psi\Phi$ (1 fb^{-1})

Adding $B_s \to J/\psi\pi\pi$:

Φ_s = -0.002 ± 0.083(stat.) ± 0.027(syst.) rad

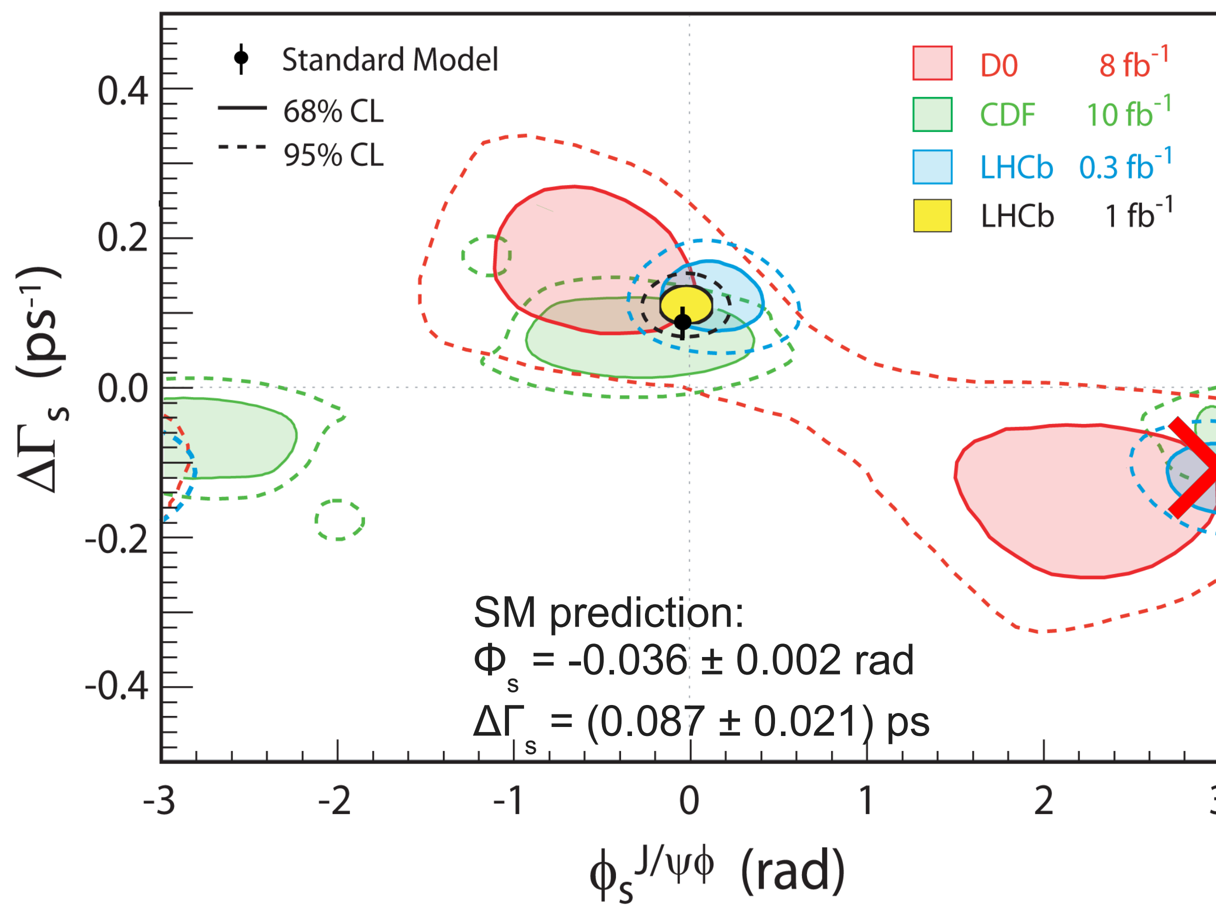
arXiv:1204.5675

~11k $J/\psi\Phi$ (9.6 fb^{-1})

CDF note 10778

$\Delta\Gamma_s$ = 0.068 ± 0.026(stat.) ± 0.007(syst.) ps^{-1}

Φ_s within [-0.60, 0.12] rad at 68% CL (SM sol.)



arXiv:1202.4717

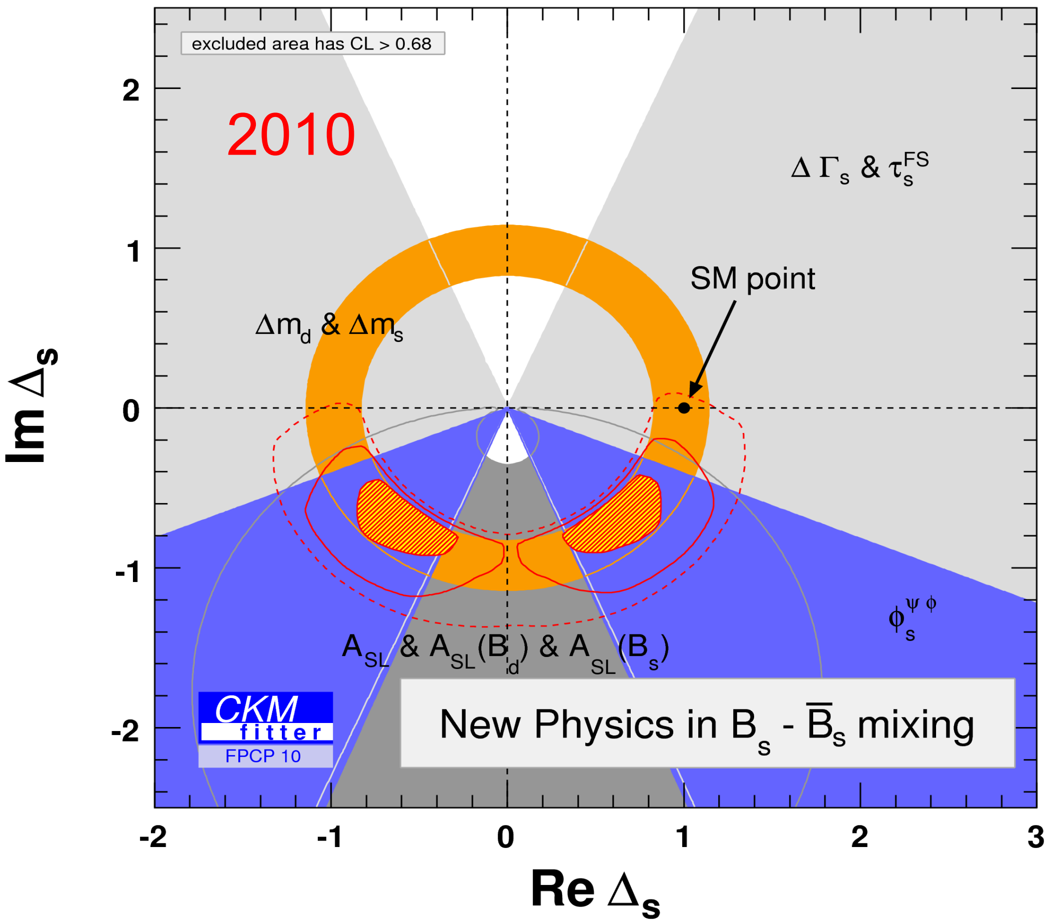
NP in Mixing

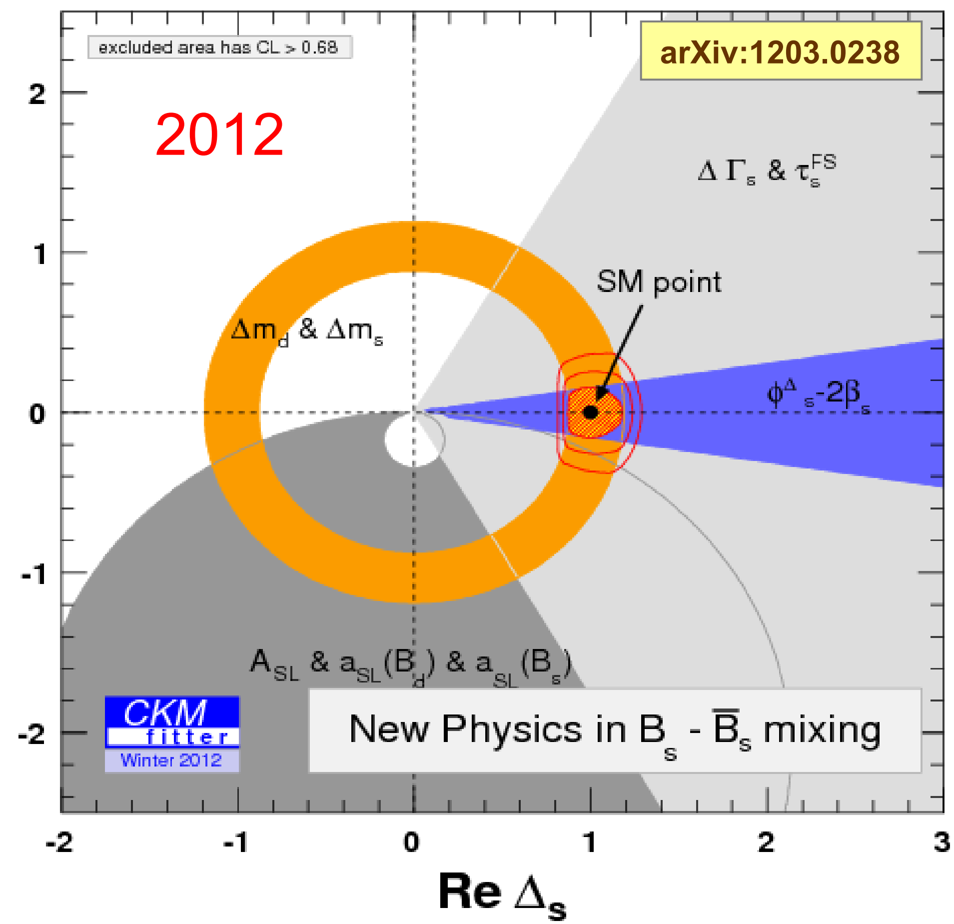
See Webber

2011 DØ (9 fb^{-1}): ~3.9σ deviation from SM in B semileptonic asymmetry A_{SL}

D0: PRD 84 (2011) 052007

Simple model-independent parametrization of NP in all ΔF=2 observables: $M_{12}^{s} = M_{12}^{SM,s} \cdot \Delta_s$





Independent cross-check for A_{SL} is crucial.

Sizable NP still allowed: O(30%) in B_s meson mixing

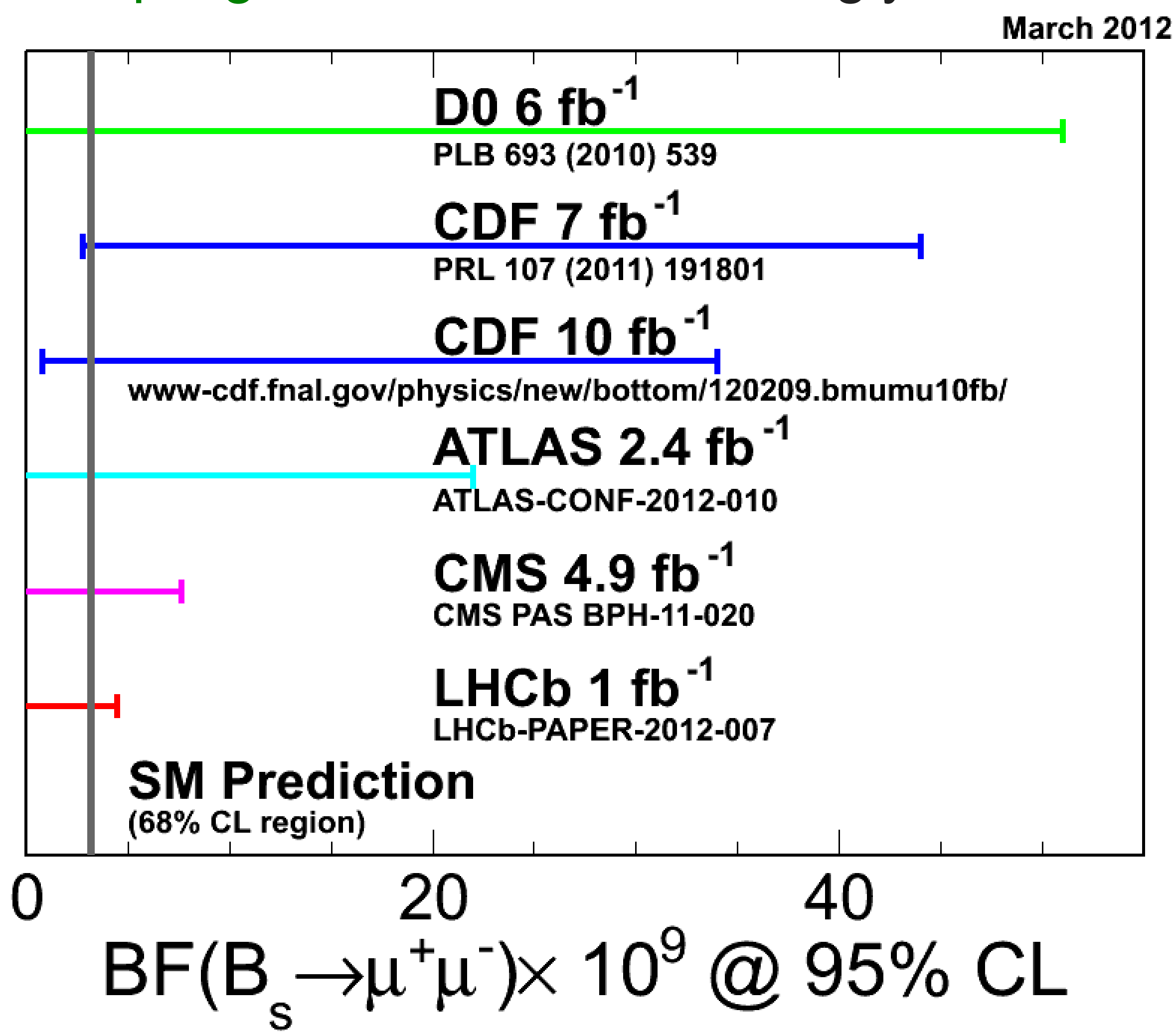
Rare Decays

($\Delta F=1$ FCNC)

$B_s \to \mu\mu$

See Eerola

$B_s \to \mu\mu$: helicity-suppressed FCNC, sensitive to (pseudo)scalar $S^{(')}$ and $P^{(')}$ couplings which could be strongly enhanced by NP.



SM:

CKMFitter Moriond12

$$BF(B_s \to \mu\mu) = (3.64^{+0.21}_{-0.32}) \times 10^{-9}$$

Limit @ 95% CL - BFx10^9	L [fb^{-1}]
D0: < 51	6.1
CDF: [0.8, 34]	10
ATLAS: < 22	2.4
CMS: < 7.7	4.9
LHCb: < 4.5	1

We are getting close to SM value!

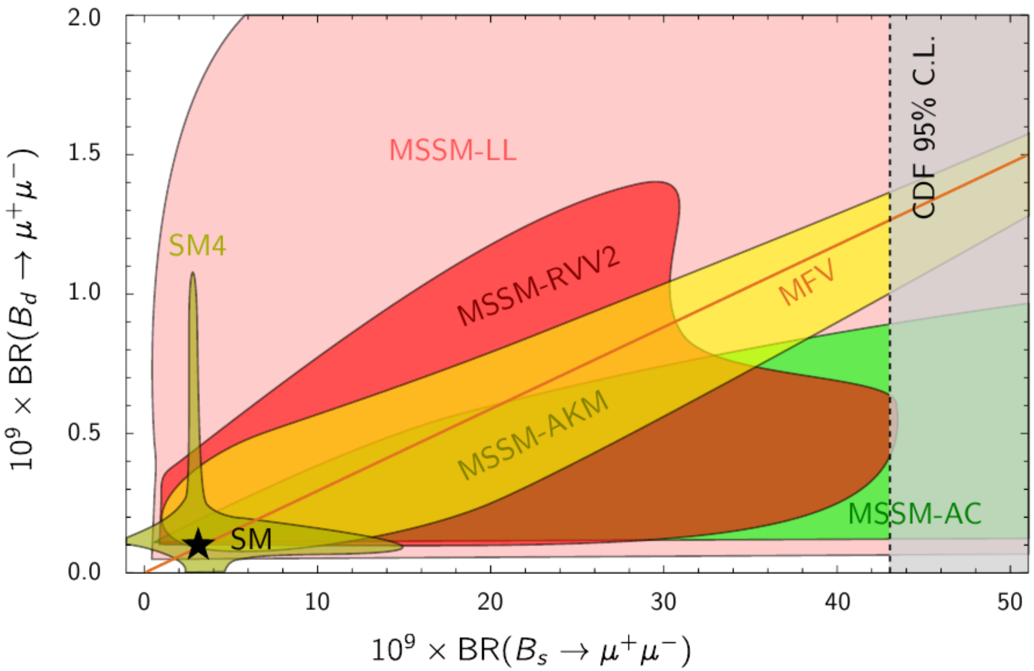
Whole Run II sample (10 fb^{-1}, +30% data): last summer deviation not reinforced by new data, but still >2σ for bkg-only hypothesis (2.8σ in summer 2011)

$B_s \to \mu\mu$: Constraints on MSSM Models

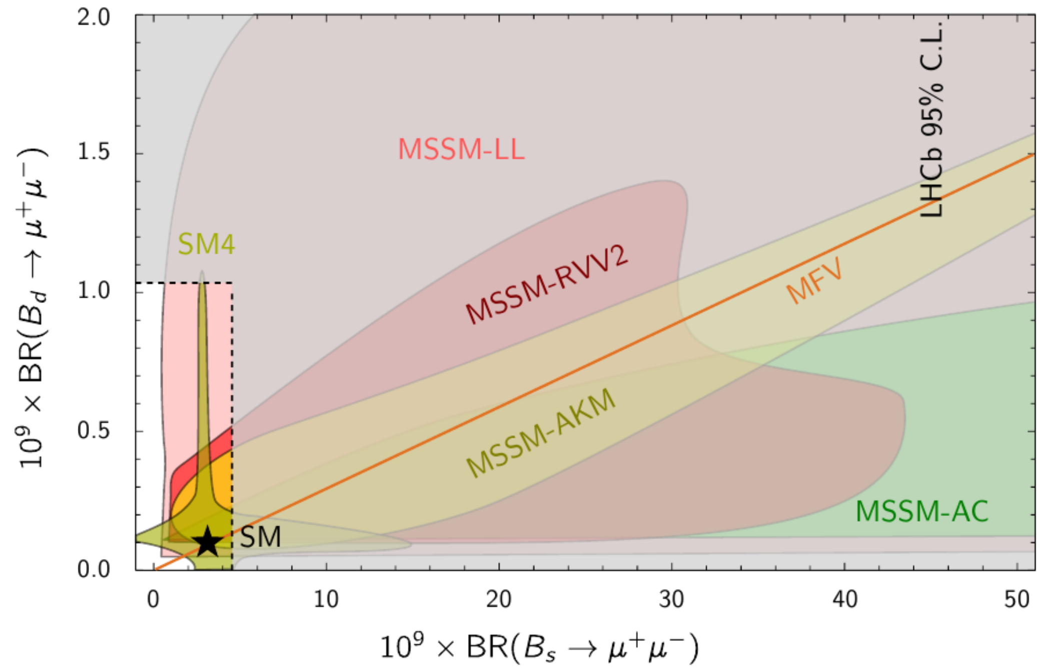
Straub – MoriondEW12
arXiv:1205.6094

See also Mahmoudi – MoriondQCD12
arXiv:1205.3099

2011



2012



Large fraction of the parameter space excluded

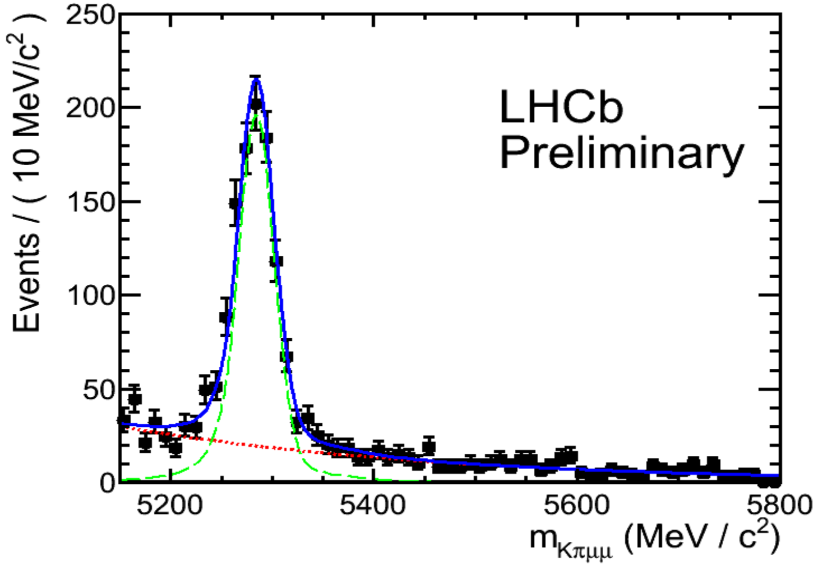
$B_d \rightarrow K^*\mu\mu$

See Owen

$b \rightarrow s$ FCNC mediated by EW penguins: sensitive to $C^{(')}_{7,9,10}$ Wilson coefficients (electromagnetic dipole and semileptonic operators).

LHCb-CONF-2012-008

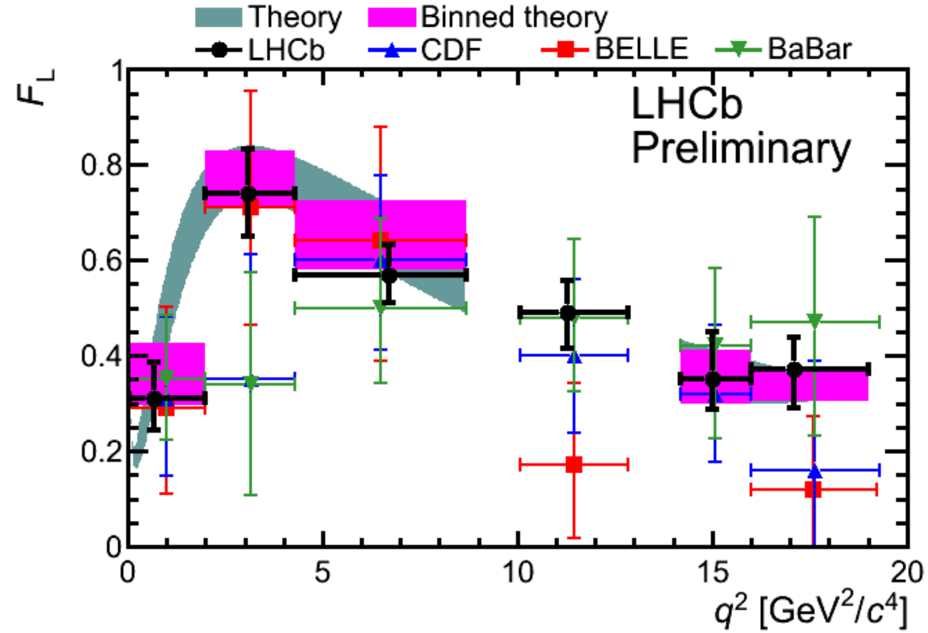
Observes 900 candidates (1 fb^{-1}) (BABAR + Belle + CDF ~ 600). Largest sample in the world, just as clean as at the B factories



Decay described by three angles and dimuon invariant mass squared (θ_μ , θ_K , Φ, q^2).

Angular distribution of decay products and q^2-dependence of $K^*\mu\mu$ provides many observables:

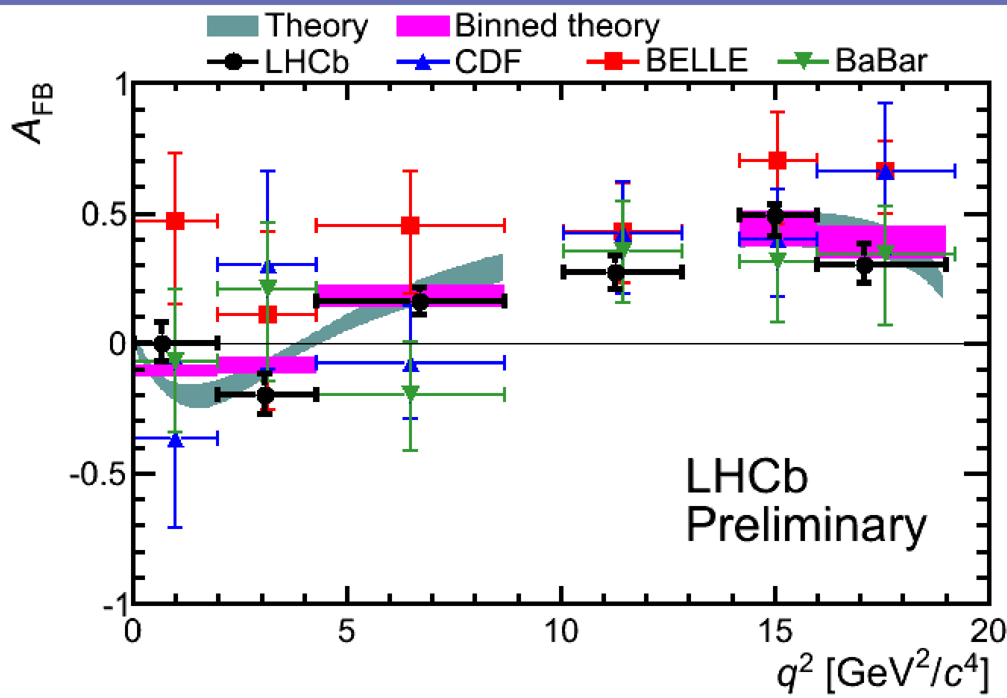
- F_L: fraction of K^* long. polarization
- A_{FB}: forward-backward asymmetry
- $S_3 \propto A_2 (1 - F_L)$: asym. in K^* trans. polarization
- A_{Im}: T-odd CP asymmetry

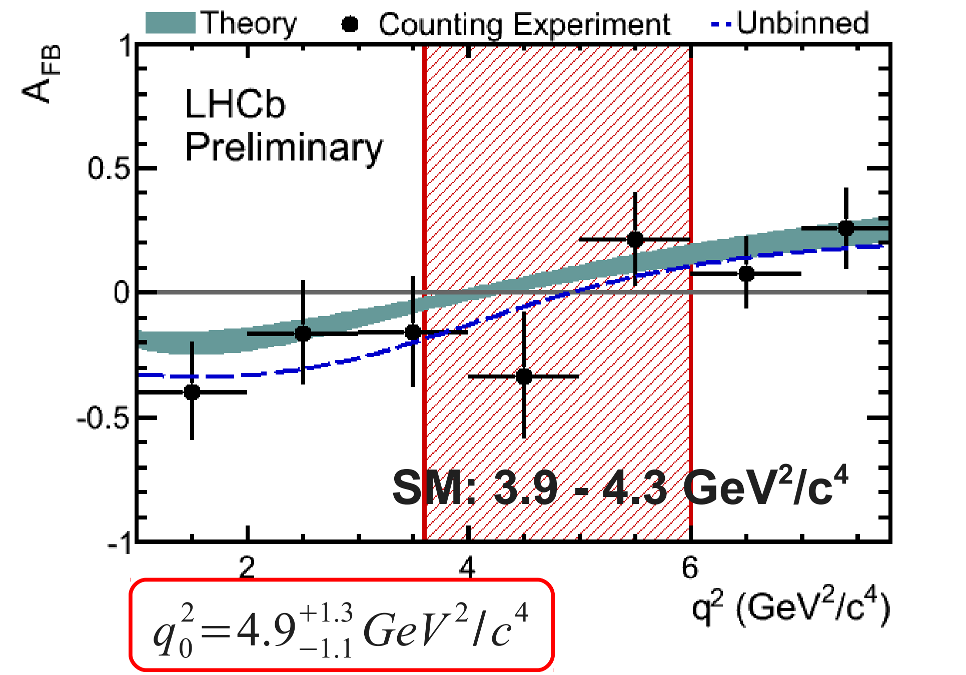


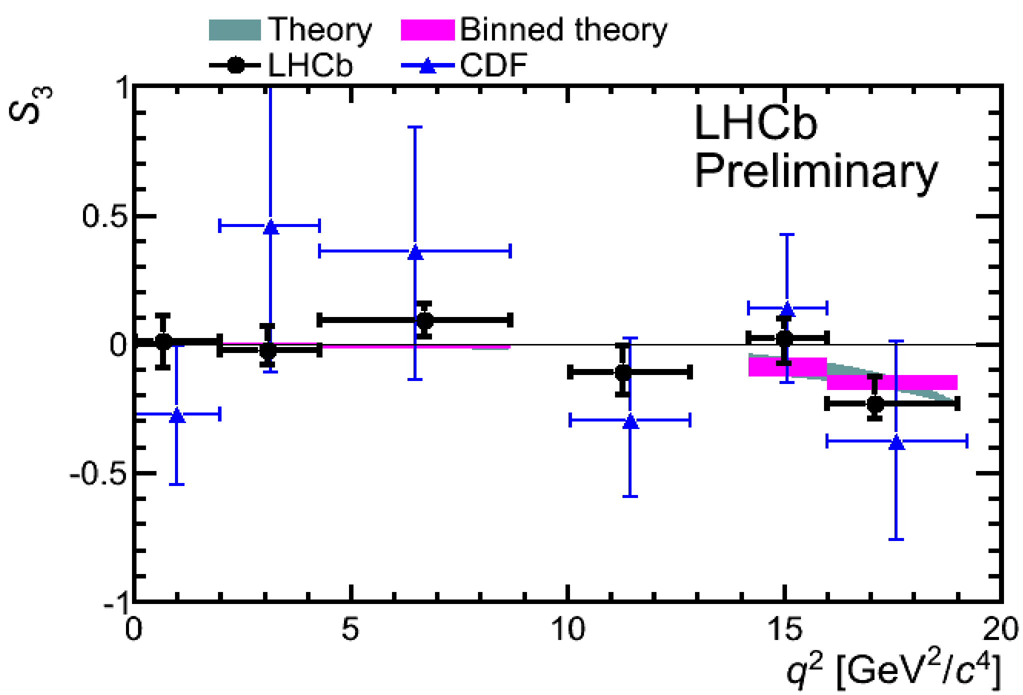
$B_d \to K^* \mu\mu$: Results

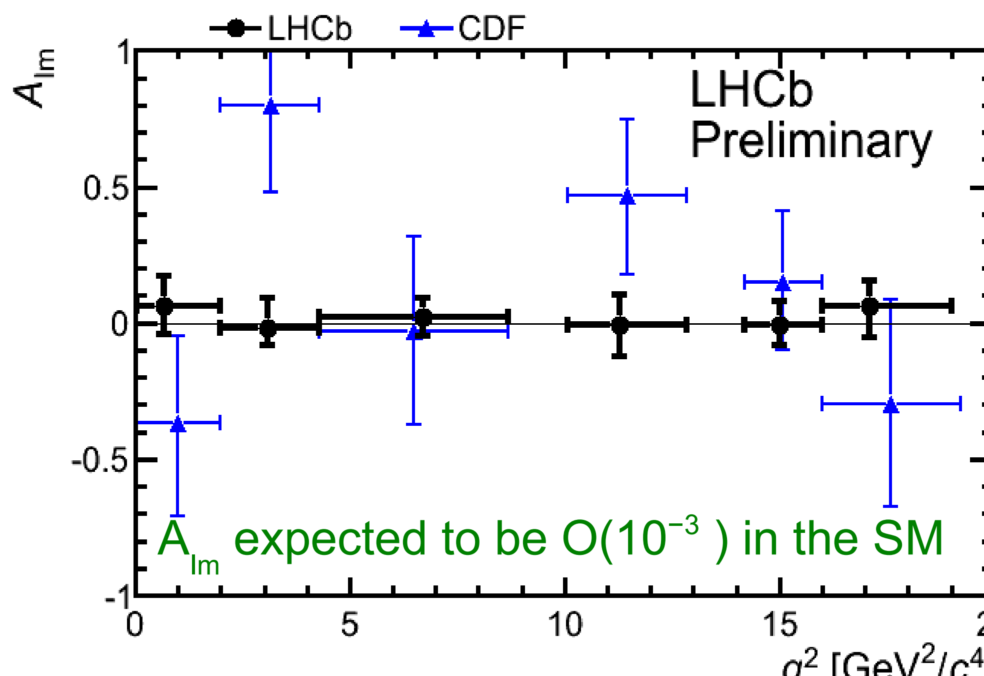
Theory: Bobeth at al. [arXiv:1105.0376]
CDF, PRL 108 (2012), Belle, PRL 103 (2009)
BaBar prelim., Lake Louise 2012

See Owen





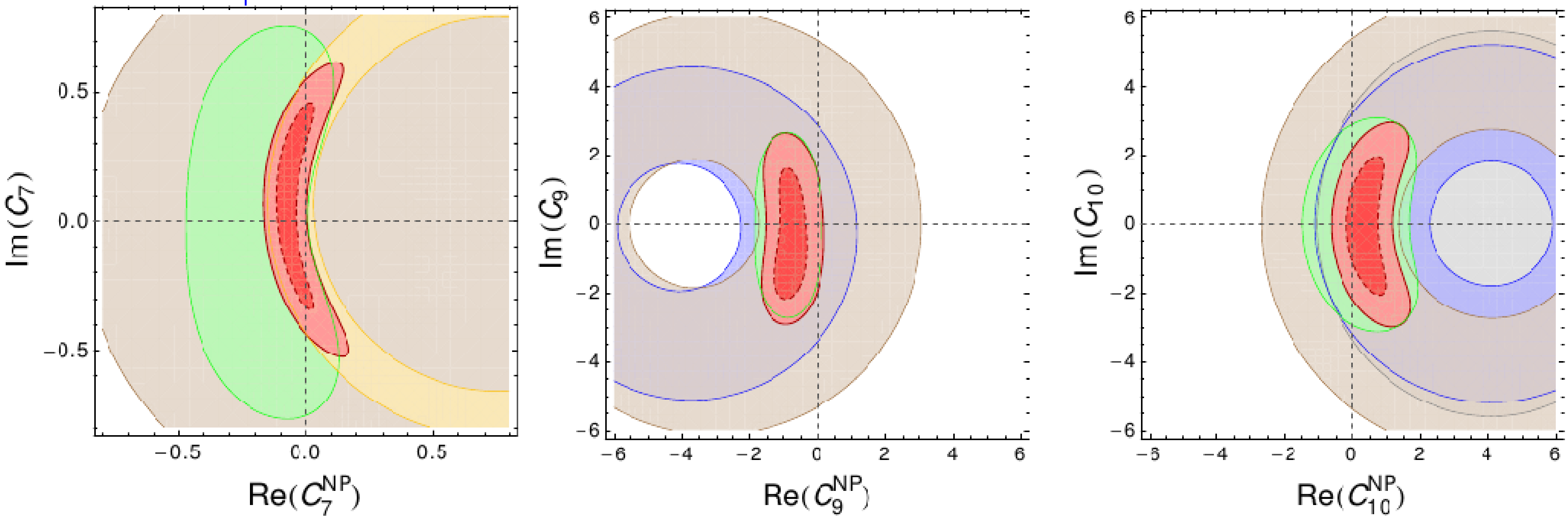




Bounds on Wilson Coefficients from ΔF=1 FCNC Decays

Varying 1 Wilson coefficient at a time. $C_i = C_i^{SM} + C_i^{NP}$ *preliminary*

Generic NP: $C_i^{NP} \in \mathbb{C}$ (free parameters)



$BR(B \to X_s \ell^+ \ell^-)$ $BR(B \to X_s \gamma)$ $B \to K^* \mu^+ \mu^-$ $BR(B \to K \mu^+ \mu^-)$ $BR(B_s \to \mu^+ \mu^-)$

Red: combined 1σ and 2σ constraints

Straub *et al.* [arXiv:1111.1257 – JHEP 1202:106] + update 1205.xxxx

Over-constraining Wilson coefficients with many measurements in a global fit (similar to UT global fit): best sensitivity to small NP effects

Toward High-Precision Flavor Physics

LHCb Upgrade

BelleII & SuperB

LHCb Upgrade, BelleII and SuperB

See Eklund, Nishimura, Wormser

LOI: LHCC-2011-001
FTDR:LHCC-2012-007

Upgrade

- L=1 – 2 × 10^{33} cm^{-2} s^{-1}
- 50 fb^{-1}
- Commissioning: 2019

Belle II

BelleII physics:1002.5012
BelleII TDR:1011.0352

- L=8 × 10^{35} cm^{-2} s^{-1}
- 50 ab^{-1}
- Commissioning: late 2014

SuperB

SuperB physics: 1008.1541
SuperB detector: 1007.4241

- L= 1 × 10^{36} cm^{-2} s^{-1}
- 75 ab^{-1}
- Commissioning: 2016

Sensitivity to key observables: very broad and complementary physics program down to SM theory error

LHCb Upgrade

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–$12°$ [19, 20]	4°	0.9°	negligible
	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K_S^0$)	0.8° [18]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

BelleII/SuperB (50 ab^{-1})

Observable	SM Theory	Current Expt.	Super Flavor Factories
$S(B \to \phi K^0)$	0.68	0.56 ± 0.17	± 0.03
$S(B \to \eta' K^0)$	0.68	0.59 ± 0.07	± 0.02
γ from $B \to DK$		$\pm 11°$	$\pm 1.5°$
A_{SL}	-5×10^{-4}	-0.0049 ± 0.0038	± 0.001
$S(B \to K_S\pi^0\gamma)$	< 0.05	-0.15 ± 0.20	± 0.03
$S(B \to \rho\gamma)$	< 0.05	-0.83 ± 0.65	± 0.15
$A_{\mathrm{CP}}(B \to X_{s+d}\gamma)$	< 0.005	0.06 ± 0.06	± 0.02
$\mathcal{B}(B \to \tau\nu)$	1.1×10^{-4}	$(1.64 \pm 0.34) \times 10^{-4}$	$\pm 0.05 \times 10^{-4}$
$\mathcal{B}(B \to \mu\nu)$	4.7×10^{-7}	$< 1.0 \times 10^{-6}$	$\pm 0.2 \times 10^{-7}$
$\mathcal{B}(B \to X_s\gamma)$	3.15×10^{-4}	$(3.55 \pm 0.26) \times 10^{-4}$	$\pm 0.13 \times 10^{-4}$
$\mathcal{B}(B \to X_s\ell^+\ell^-)$	1.6×10^{-6}	$(3.66 \pm 0.77) \times 10^{-6}$	$\pm 0.10 \times 10^{-6}$
$\mathcal{B}(B \to K\nu\bar{\nu})$	3.6×10^{-6}	$< 1.3 \times 10^{-5}$	$\pm 1 \times 10^{-6}$
$A_{\mathrm{FB}}(B \to K^*\ell^+\ell^-)_{q^2<4.3\,\mathrm{GeV}^2}$	-0.09	0.27 ± 0.14	± 0.04

arXiv:1205.2671

Conclusion (messages to bring home)

Flavor Physics:
sensitive to very high energy scale: offers indirect insights into the structure of matter and its interactions

Past decade: very impressive improvement in the flavor sector (both theory and experiments)

O(100%) NP ruled out in flavor-physics. But still sizable NP O(10-30%) allowed (compatible with all low-energy flavor measurements)
➔ still a large potential for NP discovery.

(Very) likely, NP effects will be small but by no means unobservables!
➔ toward **high-precision** flavor physics
What matters is the experimental precision and the theoretical cleanliness for interpretation of short-distance physics

Excited decade to come for flavor physics: we shall learn a lot.
We are just at the beginning.

"precision measurements at a given energy scale allow us to make predictions concerning the next energy scale"

John Iliopoulos
Dirac Medal award

arXiv:0805.4768

BACKUP SLIDES

Wilson coefficients

Wilson coeff.	description	SM	enhancement in models
$C_{1,2}$	charged current	YES	
$C_{3,...,6}$	QCD penguins	YES	SUSY
$C_{7,8}$	γ, g-dipole	YES	SUSY, large $\tan\beta$
$C_{9,10}$	(axial-)vector	YES	SUSY
$C_{S,P}$	(pseudo-)scalar	$\sim m_l m_b / m_W^2$	SUSY, large $\tan\beta$, R-parity viol.
$C'_{S,P}$	(pseudo-)scalar flipped	$\sim m_l m_s / m_W^2$	SUSY, R-parity viol.
$C'_{3,...,6}$	QCD peng. flipped	$\sim m_s / m_b$	SUSY
$C'_{7,8}$	γ, g-dipole flipped	$\sim m_s / m_b$	SUSY, esp. large $\tan\beta$
$C'_{9,10}$	(axial-)vector flipped	$\sim m_s / m_b$	SUSY
$C_{T,T5}$	tensor	negligible	leptoquarks

G. Hiller, arXiv:0911.4054

$\rightarrow$ Need for many orthogonal observables!

$B \to K^* \ell^+ \ell^-$: most promising observables

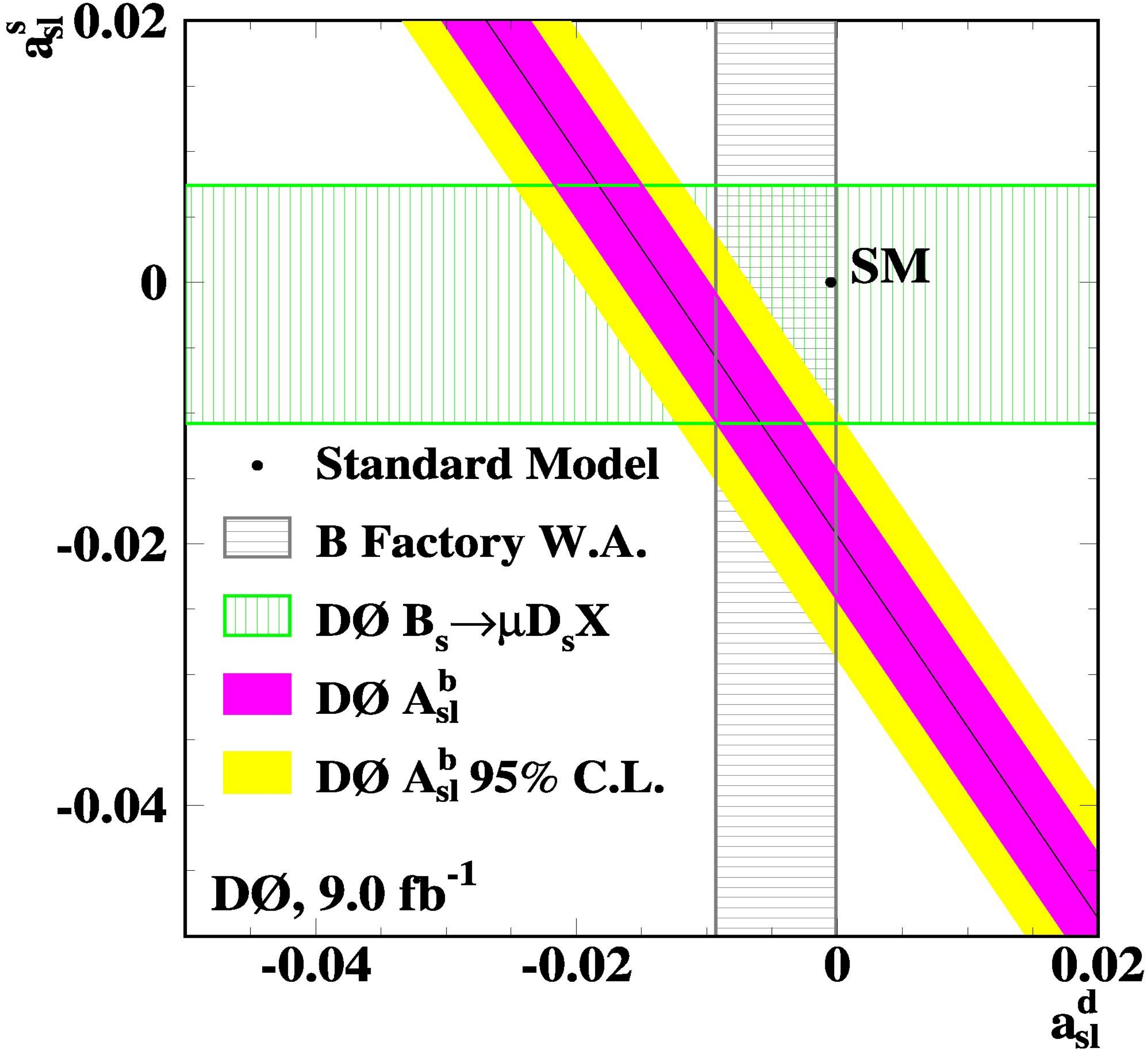
Most promising observables in the early LHC era:

	Obs.	# angles	C_i	C'_i	also known as	measured?
CP averaged obs.	F_L	1	×	×	$-S_2^c$	×
	A_{FB}	1	×		$\frac{3}{4}\ S_6^s$	×
	S_3	1		×	$\frac{1}{2}(1 - F_L)\ A_T^{(2)}$	×
	S_5	2	×	×		
T-odd CP asymm.	A_9	1		×	A_{im}	×
	A_7	2	×	×		
	A_8	3	×	×		

accessible from #-dimensional angular distribution

sensitive to right-handed currents

NP in Mixing



a_{sl}^s
0.02
0
-0.02
-0.04
SM
• Standard Model
B Factory W.A.
DØ $B_s \to \mu D_s X$
DØ A_{sl}^b
DØ A_{sl}^b 95% C.L.
DØ, 9.0 fb^{-1}
-0.04
-0.02
0
0.02
a_{sl}^d