Heavy Flavor Physics at Future Colliders

CD Lü

thanks I. Bigi, H.B. Li, Y. Li and E. Passemar etc.

Outline

- Introduction & Motiation
- Flavor physics at CEPC as a super Z factory
- Rare decays
- a possible b physics experiments at SPPC
- Summary

1. Introduction & Motivation

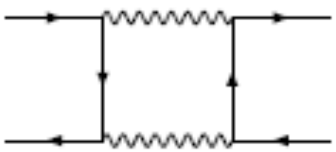
From the historic view, flavor physics had played important roles in searching for the " New Physics"

- 1963: concept of flavour mixing [Cabibbo].
- 1964: discovery of CP violation in $K_L \to \pi^+\pi^-$ [Christenson *et al.*].
- 1970: introduction of the charm quark to suppress the flavour-changing neutral currents (FCNCs) [Glashow, Iliopoulos & Maiani].
- 1973: quark-flavour mixing with 3 generations allows us to accommodate CP violation in the SM [Kobayashi & Maskawa].
- 1974: estimate of the charm-quark mass with the help of the K^0–$\bar{K}^0$ mixing frequency [Gaillard & Lee].
- 1980s: the large top-quark mass was first suggested by the large B^0–$\bar{B}^0$ mixing seen by ARGUS (DESY) and UA1 (CERN).

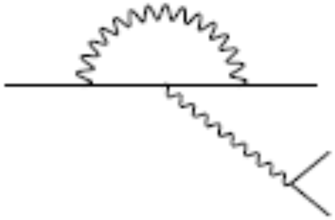
flavour physics has since continued to progress ...

Main Driving Force for Flavour Studies

- New Physics (NP): → typically new patterns in the flavour sector
  - supersymmetric (SUSY) scenarios;
  - left–right-symmetric models;
  - models with extra Z' bosons;
  - scenarios with extra dimensions;
  - "little Higgs" scenarios ...



- Sensitivity to NP through virtual quantum effects:



- Interplay with direct NP searches at ATLAS & CMS:[1]
  - If NP particles are produced and detected through their decays at the LHC, flavour-physics information helps to determine/narrow the underlying NP model and to establish new sources of CP violation.
  - NP effects could in fact show up *first* in the flavour sector, also if NP particles are too heavy to be produced directly at the LHC.
  - Fortunately, theory will be confronted with LHC data soon...

Well motivated:

Baryon asymmetry of the Universe: $$\left.\frac{n_{\mathcal{B}}}{n_\gamma}\right|_{\rm WMAP} = (5.1^{+0.3}_{-0.2}) \times 10^{-10}$$ WMAP

SM expectation (KM CPV phase): $$\left.\frac{n_{\mathcal{B}}}{n_\gamma}\right|_{SM} \approx 10^{-20}$$

too small by
10 orders-of-mag.

Additional source of CPV is required:

lepton-sector (ν's)?
4th generation quarks)?
(SUSY has ~40 CPV phases)

New Physics CPV searches are ~QCD-uncertainty-free!

Challenging the Standard Model through Flavour Studies

Before searching for NP, we have to understand the SM picture!

- The key problem:

  ◇ *impact of strong interactions* → "hadronic" uncertainties

- The B-meson system is a *particularly promising* flavour probe:

  – Offers various strategies to eliminate the hadronic uncertainties and to determine the hadronic parameters from the data.

  – Simplifications through the large b-quark mass.

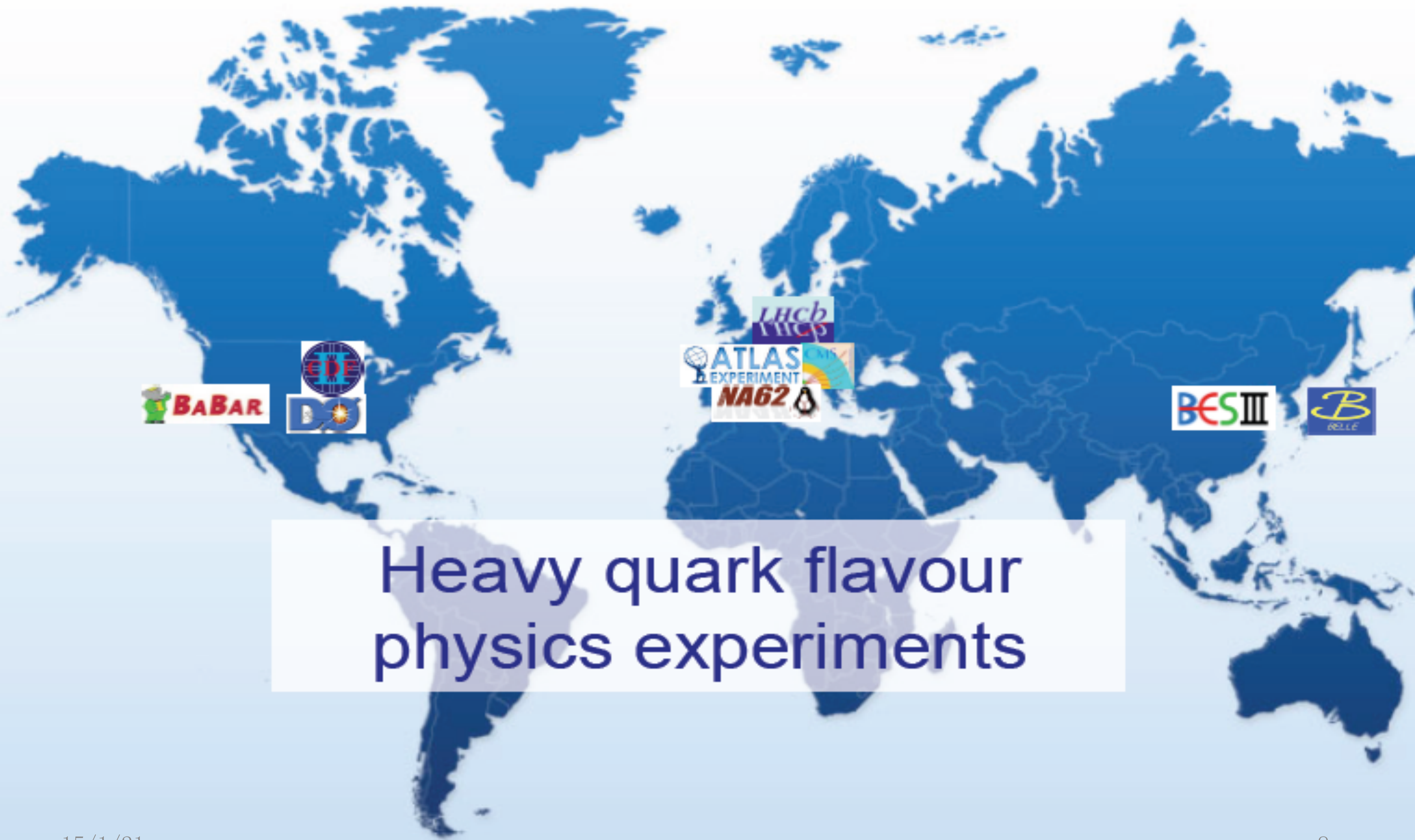
  – Tests of clean SM relations that could be spoiled by NP ...

- This feature led to the "rise of the B mesons":

  – K decays dominated for more than 30 years: *discovery* of (indirect) CP violation [$\rightarrow \varepsilon_K$] and direct CP violaton [$\rightarrow$ Re$(\varepsilon'/\varepsilon)$].

  – Since this decade the stage is governed by B mesons

Where Do We Study in Flavor Phyiscs



2. Flavor physics at CEPC as a super Z factory

On the way to the CEPC proposed as a Higgs factory, it starts with a Z^0 factory & very high luminosity, which tests the detector.

Luminosity: 8×10^{35} cm $^{-2}$s^{-1}

Integrated: 40 ab^{-1} in 2 years

Status of R_b and A_{FB}^b

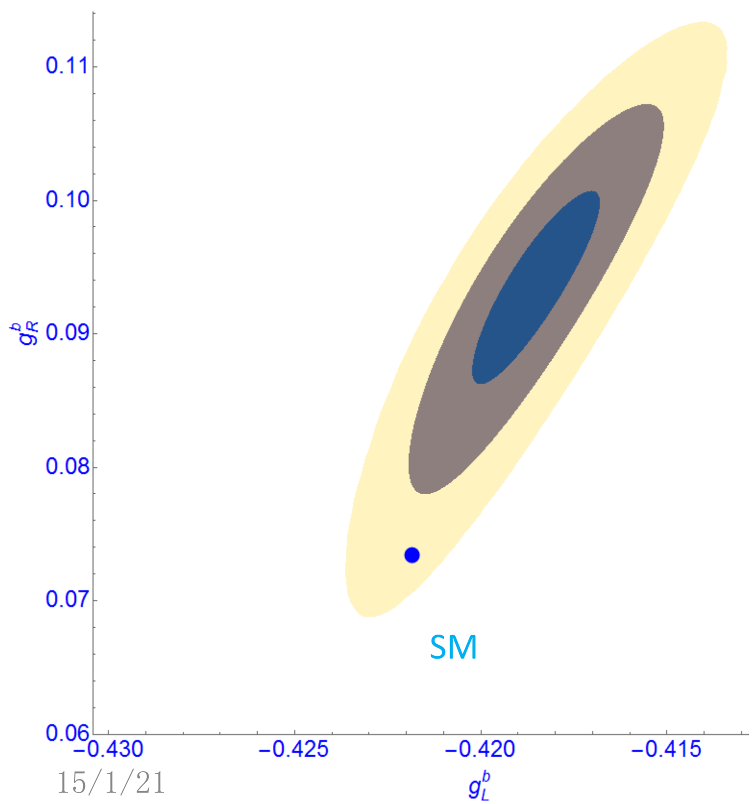
- Exp: $R_b = 0.21629 \pm 0.00066, A_{FB}^b = 0.0992 \pm 0.0016;$
- SM: **Global fit combining LEP, SLC and LHC by Gfitter**

$$R_b = 0.21578 \pm 0.00011, A_{FB}^b = 0.1032 \pm 0.0004.$$

Discrepancy:

$R_b, 0.8\sigma;$

$A_{FB}^b, 2.4\sigma.$



If we take the data seriously, it indicates new physics
· to enhance the g_R value, or
· to introduce new systematic effect, e.g., new vector like quarks mixing with the b quark,

extensions

- one can measure the total & regional ratios of

$$\Gamma\left(Z \to b\bar{b}b\bar{b}\right)/\Gamma\left(Z \to b\bar{b}\right) \qquad \Gamma\left(Z \to c\bar{c}c\bar{c}\right)/\Gamma\left(Z \to c\bar{c}\right)$$

$$\Gamma\left(Z \to b\bar{b}c\bar{c}\right)/\Gamma\left(Z \to b\bar{b}\right)$$

- It would be very interesting to measure

$$\Gamma\left(Z \to l^+l^-b\bar{b}\right) \qquad \Gamma\left(Z \to l^+l^-c\bar{c}\right)$$

The expected numbers of b−hadrons are estimated by assuming an instantaneous luminosity of 8×10^{35}cm^{-2}s^{-1} at Z^0 factory with two-year running at two collision points. For comparison, we also list the number of b-hadrons at the Belle-II with an integrated luminosity of about 50 ab^{-1} at Y(4S) or Y(5S) peak.

b-hadron	Fraction in decays of $Z^0 \to b\bar{b}$	Number of b-hadron at Z^0 peak	Fraction in $\Upsilon(4S)/(5S)$ decays	Number of b-hadron at $\Upsilon(4S)/(5S)$
B^0	0.404 ± 0.009	22.0×10^{10}	0.486 ± 0.006 ($\Upsilon(4S)$)	4.9×10^{10}
B^+	0.404 ± 0.009	22.0×10^{10}	0.514 ± 0.006 ($\Upsilon(4S)$)	5.1×10^{10}
B_s	0.103 ± 0.009	5.4×10^{10}	0.201 ± 0.030 ($\Upsilon(5S)$)	0.6×10^{10}
b baryons	0.089 ± 0.015	4.8×10^{10}	–	–

CP Violation in the SM

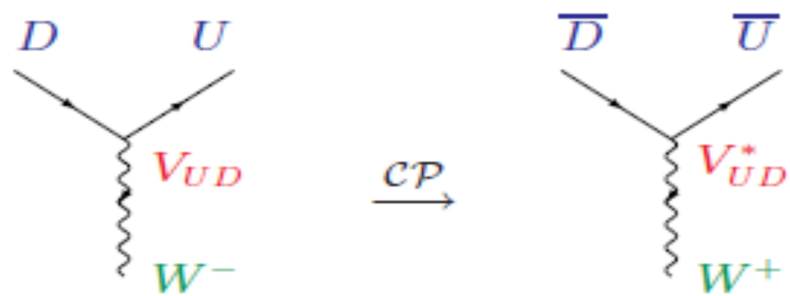
- Emerges in the "charged-current" quark interactions: $D \to W^- U$

$$\mathcal{L}_{\text{int}}^{\text{CC}} = -\frac{g_2}{\sqrt{2}} (\bar{u}_\text{L}, \bar{c}_\text{L}, \bar{t}_\text{L}) \gamma^\mu \hat{V}_\text{CKM} \begin{pmatrix} d_\text{L} \\ s_\text{L} \\ b_\text{L} \end{pmatrix} W_\mu^\dagger + \text{h.c.}$$

  - $\hat{V}_\text{CKM}$: Cabibbo–Kobayashi–Maskawa (CKM) matrix.
  - This "quark-mixing" matrix connects the flavour states of the down, strange and bottom quarks with their mass eigenstates through a unitary transformation ($\longrightarrow$ relation to the Higgs/Yukawa sector):

$$\Rightarrow \boxed{\hat{V}_\text{CKM}^\dagger \cdot \hat{V}_\text{CKM} = \hat{1} = \hat{V}_\text{CKM} \cdot \hat{V}_\text{CKM}^\dagger}$$

- CP-conjugate transitions:



$$\boxed{V_{UD} \xrightarrow{\mathcal{CP}} V_{UD}^*}$$

Experiment Information on CKM

- If we use the tree-level processes listed below and assume a unitary CKM matrix for 3 generations, the following limits emerge at the 90% C.L.:

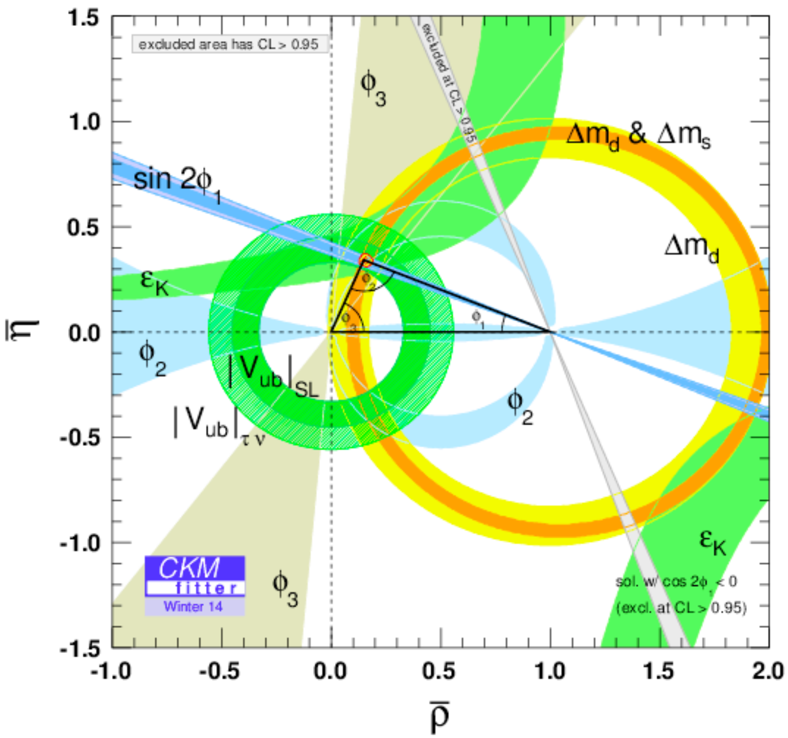
$$|\hat{V}_{\rm CKM}| = \begin{pmatrix} 0.9739\text{–}0.9751 & 0.221\text{–}0.227 & 0.0029\text{–}0.0045 \\ 0.221\text{–}0.227 & 0.9730\text{–}0.9744 & 0.039\text{–}0.044 \\ 0.0048\text{–}0.014 & 0.037\text{–}0.043 & 0.9990\text{–}0.9992 \end{pmatrix}$$

  - $|V_{ud}|$: nuclear beta decays, neutron decays;
  - $|V_{us}|$: $K \to \pi \ell \overline{\nu}$ decays;
  - $|V_{cd}|$: ν production of charm off valence d quarks;
  - $|V_{cs}|$: charm-tagged W decays; ratio of hadronic W decays to leptonic decays (also ν production and semi-leptonic D decays);
  - $|V_{cb}|$: exclusive and inclusive $b \to c\ell\overline{\nu}$ decays;
  - $|V_{ub}|$: exclusive and inclusive $b \to u\ell\overline{\nu}$ decays;
  - $|V_{tb}|$: very crude direct info from $t \to b\ell^+\nu$:

$\Rightarrow$ interesting hierarchical pattern ...

Results from Global Fits to Data (CKMFitter Group)

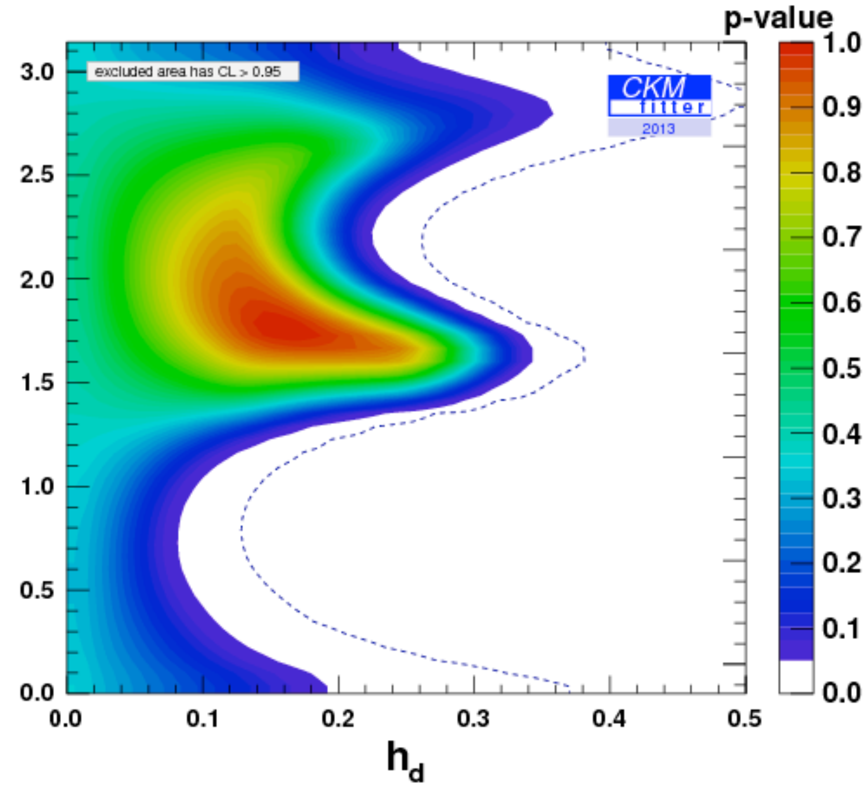
Great progress on ϕ_3 or γ (first from B factories and now in the last two years from LHCb). These measure the phase of V_{ub}



Looks good
(except for an issue with $|V_{ub}|$)

Similar results from UTFIT

NP Phase



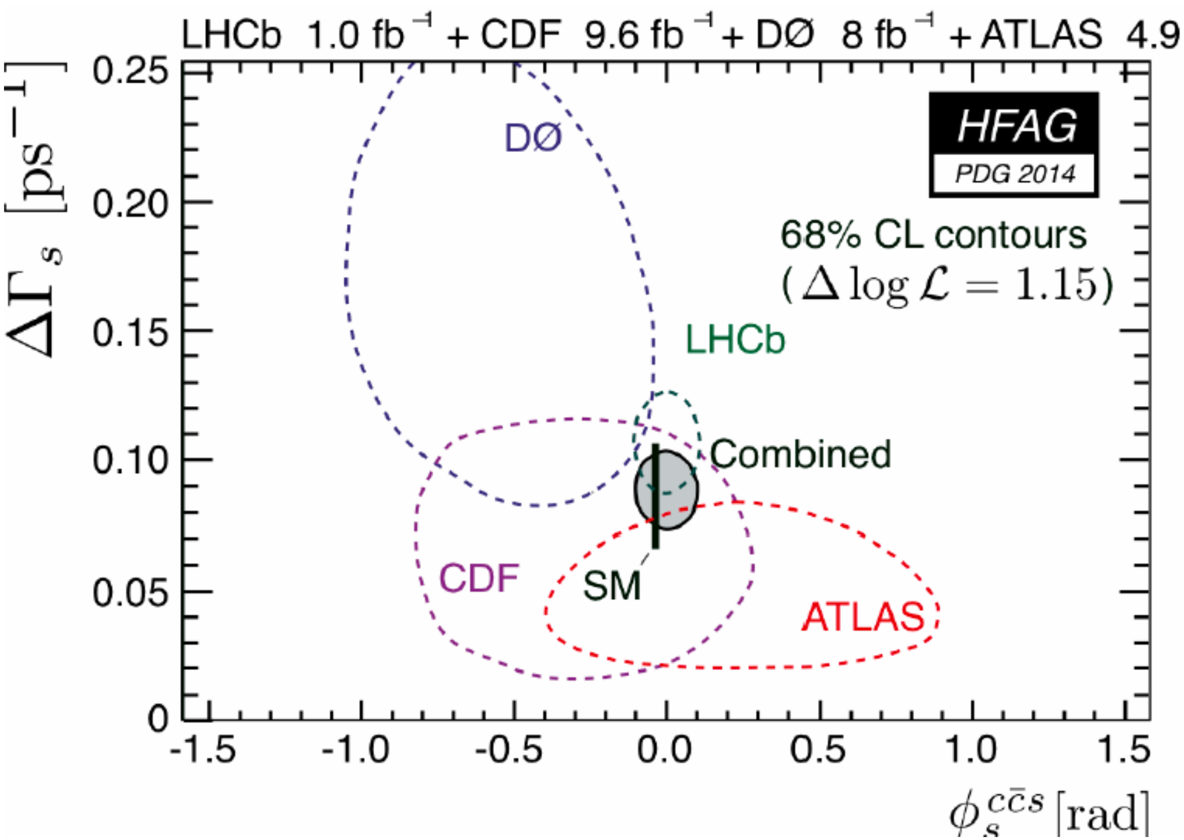
NP/SM amplitude ratio

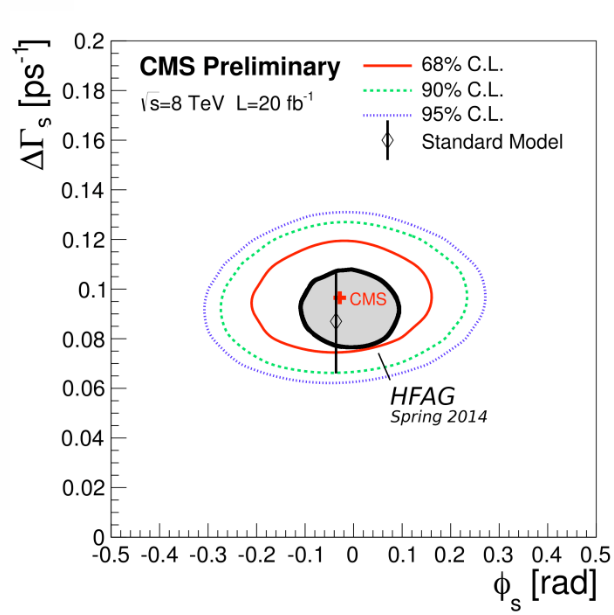
But a 10-20% NP amplitude in B_d mixing is perfectly compatible with all current data.

SM Prediction Vs Data

Observable	Measurement	Source	SM prediction
		B_s system	
Δm_s (ps^{-1})	17.719 ± 0.043	HFAG 2012	17.3 ± 2.6
	$17.725 \pm 0.041 \pm 0.026$	LHCb ($0.34 fb^{-1}$)	
$\Delta\Gamma_s$ (ps^{-1})	0.105 ± 0.015	HFAG 2012	0.087 ± 0.021
	$0.116 \pm 0.018 \pm 0.006$	LHCb ($1.0 fb^{-1}$)	
ϕ_s (rad)	$-0.044^{+0.090}_{-0.085}$	HFAG 2012	-0.036 ± 0.002
	$-0.002 \pm 0.083 \pm 0.027$	LHCb ($1.0 fb^{-1}$)	
$a^s_{\rm sl}$ (10^{-4})	$-17 \pm 91 ^{+14}_{-15}$	D0 (no $A^b_{\rm SL}$)	$0.29^{+0.09}_{-0.08}$
	-105 ± 64	HFAG 2012 (including $A^b_{\rm SL}$)	
		Admixture of B and B_s systems	
$A^b_{\rm SL}$ (10^{-4})	$-78.7 \pm 17.1 \pm 9.3$	D0	-2.0 ± 0.3
		B system	
Δm_d (ps^{-1})	0.507 ± 0.004	HFAG 2012	0.543 ± 0.091
$\Delta\Gamma_d/\Gamma_d$	0.015 ± 0.018	HFAG 2012	0.0042 ± 0.0008
$\sin 2\beta$	0.679 ± 0.020	HFAG 2012	$0.832 ^{+0.013}_{-0.033}$
$a^d_{\rm sl}$ (10^{-4})	-5 ± 56	HFAG 2012	$-6.5 ^{+1.9}_{-1.7}$

Results on the phase of Bs-anti Bs mixing (i.e. phase of Vts)





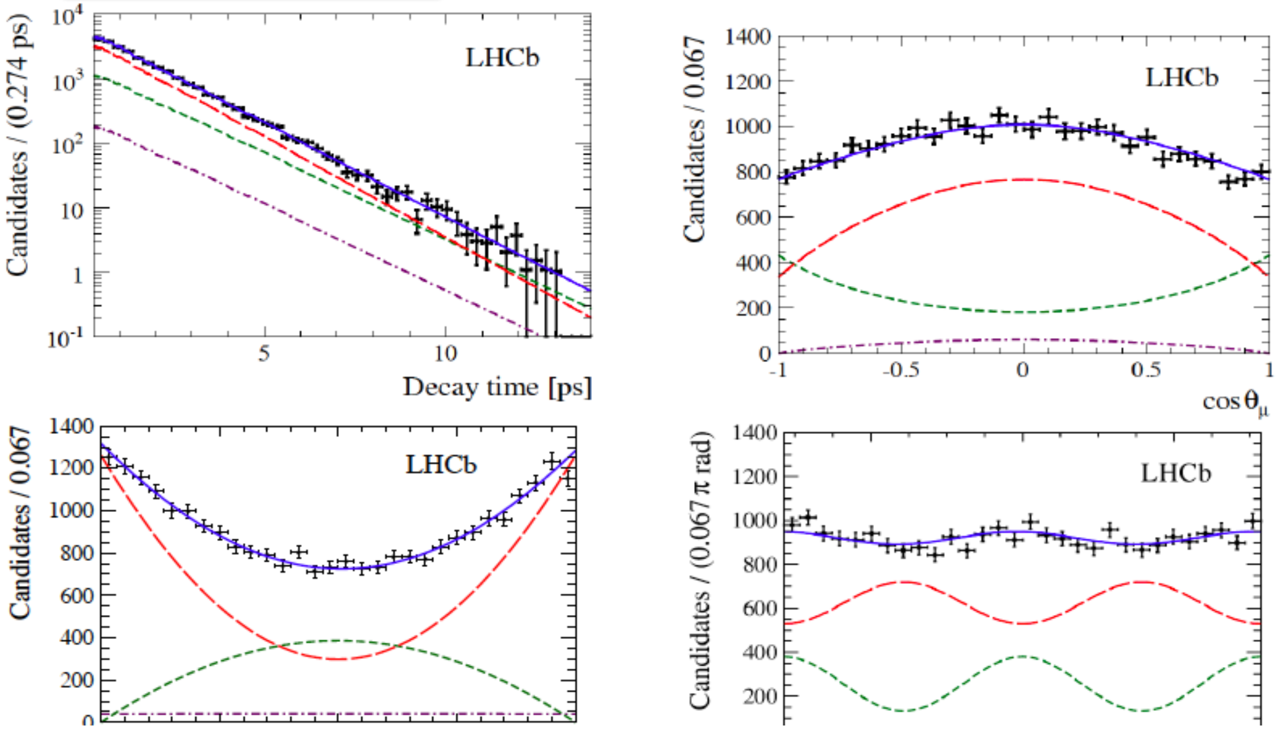
R. Aaij: Does not include arXiv: 1405.4140 using $J/\psi\pi\pi$ decays, which are dominantly S-wave.

Does not include new CMS result at ICHEP2014 (G. Fedi)

Golden Process to Search for NP in Bs-Mixing

$B_s \to J/\psi\phi$ angular and decay time projections

PRD 87 (2013)112010,arXiv:1304.2600



$$\Phi_s = +0.07 \pm 0.09 \pm 0.01\, rad$$

$B_s \to J/\psi\varphi$ is a pseudo-scalar to V V decay (mixture of two CP eigenstates). This requires multi-dimensional angular analysis.

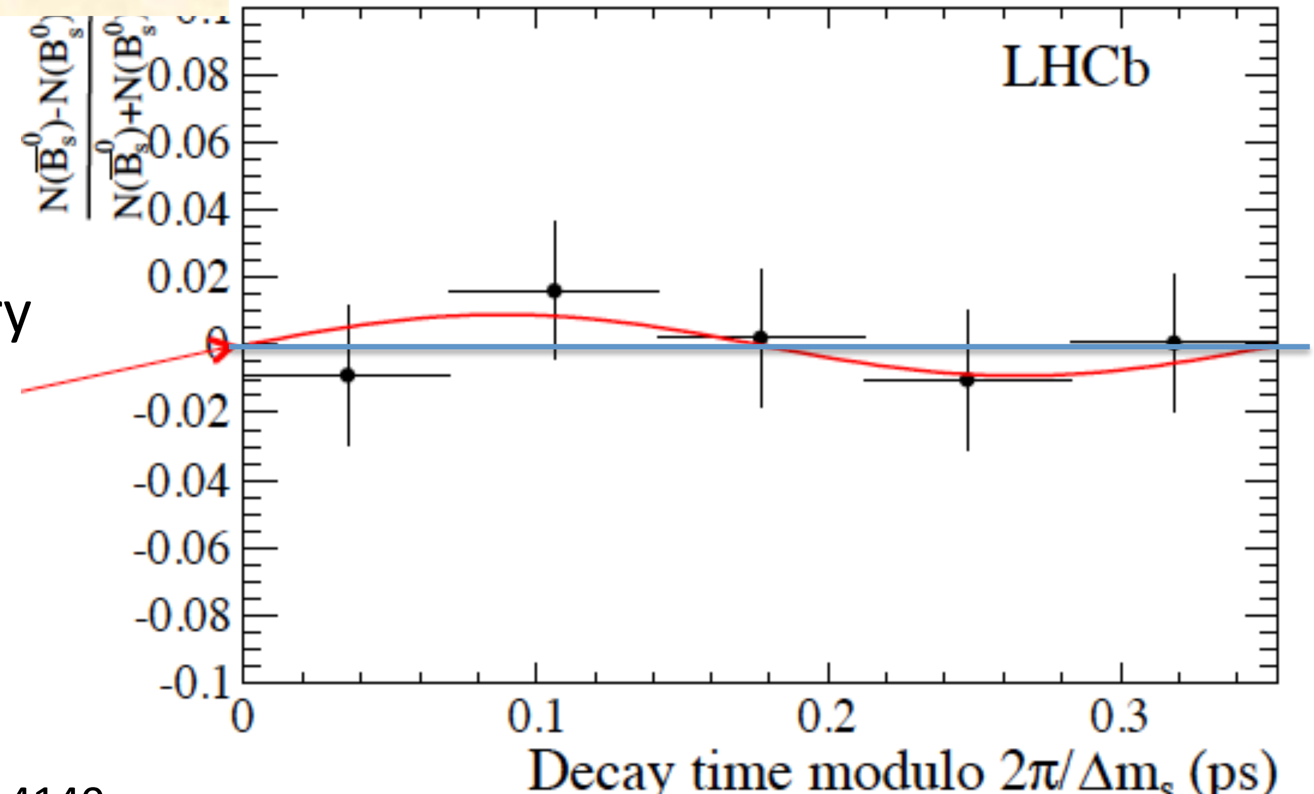
However, Bs →J/ψ $f_0(980)$ is a pure CP eigenstate since the f_0 is a scalar

Stone & Zhang pointed out that this mode provides more statistics and a more straightforward analysis. Phys. Rev. D79 (2009) 074024

Φ_s=(70±68±8) mrad

Red curve: expectation for Φ_s = 70 mrad

Asymmetry



arXiv: 1405.4140

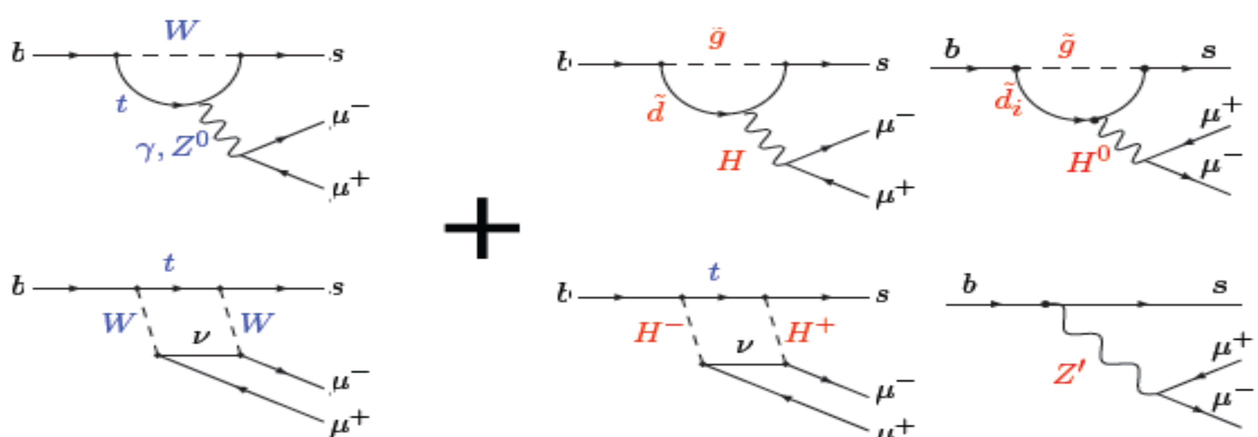
3. Rare Decays of $B_{(s)}$ Meson

- High **energy**:
  "real" new particles can be produced and discovered via their decays

- High **precision**:
  "virtual" new particles can be discovered in loop processes

**Direct and indirect searches are both needed,
both equally important,
and complement each other**

Example: Rare quark decays: Contribution of NP as correction to the SM



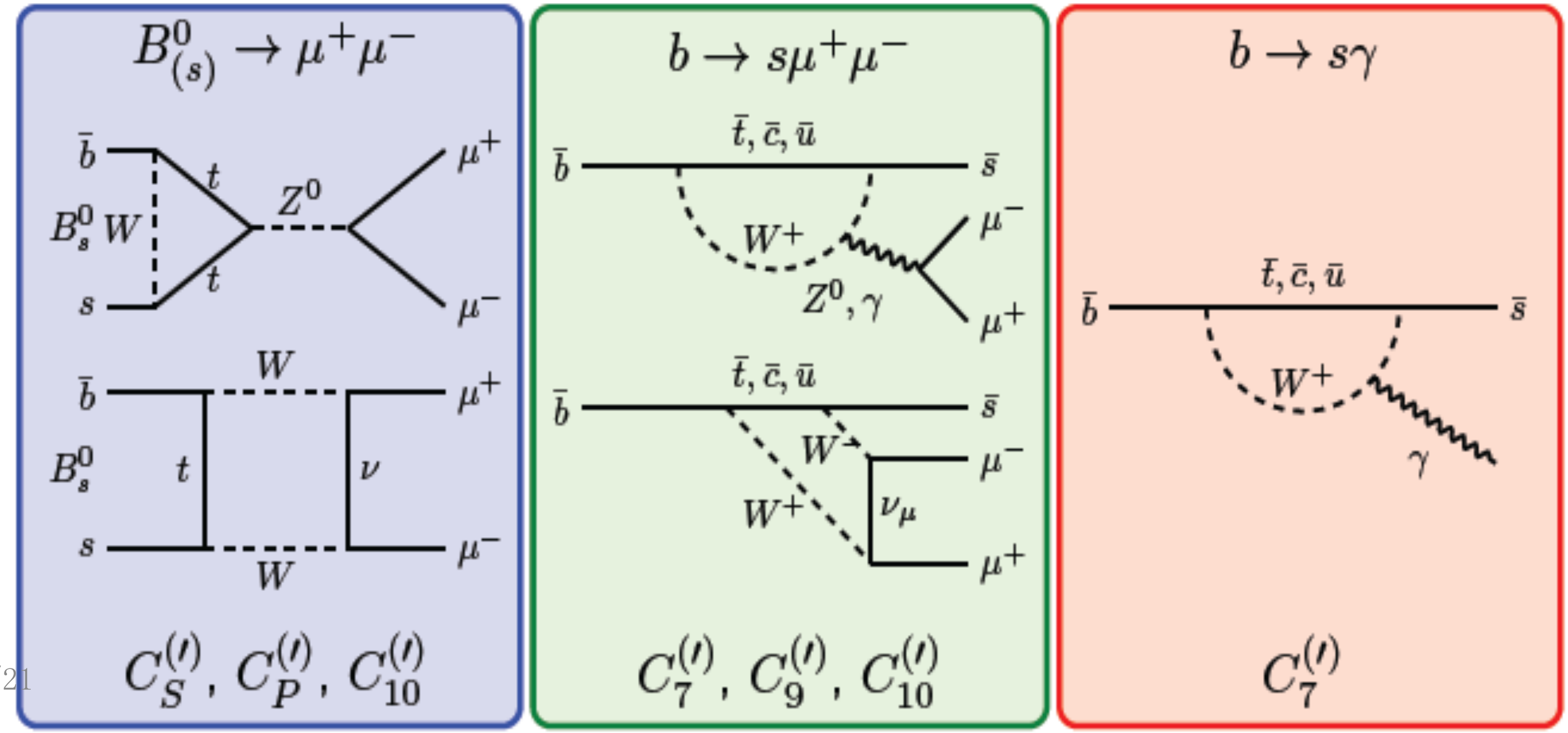
$$A = A_0 \left(\frac{c_{SM}}{m_W^2} + \frac{c_{NP}}{\Lambda_{NP}^2} \right)$$

Example:

- $b \to s\, \ell^+\ell^-$ decays allow precise tests of Lorentz structure
  - Sensitive to new phenomena via non-standard couplings
  - Best described with effective field theory

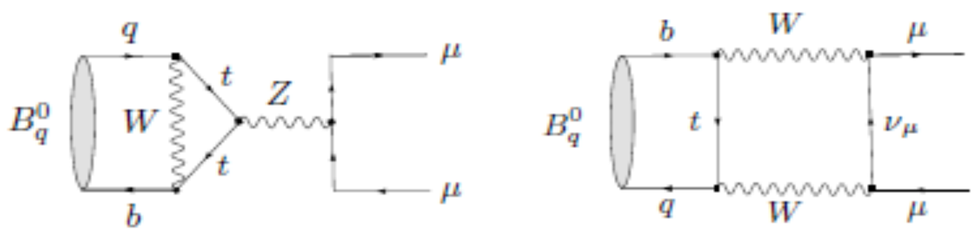
$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \Big[\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C'_i(\mu) O'_i(\mu)}_{\substack{\text{right-handed part} \\ \text{suppressed in SM}}} \Big]$$

$i = 1,2$	Tree
$i = 3-6,8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9,10$	Electroweak penguin
$i = S$	Higgs (scalar) penguin
$i = P$	Pseudoscalar penguin



The Rare Decays $B_q \to \mu^+\mu^-$ $(q \in \{d, s\})$

- Originate from Z penguins and box diagrams in the Standard Model:



- Corresponding low-energy effective Hamiltonian:

$$\mathcal{H}_{\rm eff} = -\frac{G_{\rm F}}{\sqrt{2}}\left[\frac{\alpha}{2\pi \sin^2\Theta_{\rm W}}\right] V_{tb}^* V_{tq} \eta_Y Y_0(x_t)(\bar{b}q)_{\rm V-A}(\bar{\mu}\mu)_{\rm V-A}$$

  - α: QED coupling; $\Theta_{\rm W}$: Weinberg angle.
  - η_Y: short-distance QCD corrections (calculated ...)
  - $Y_0(x_t \equiv m_t^2/M_W^2)$: Inami–Lim function, with top-quark dependence.

- Hadronic matrix element: $\to$ very simple situation:
  - Only the matrix element $\langle 0|(\bar{b}q)_{\rm V-A}|B_q^0\rangle$ is required: f_{B_q}

$\Rightarrow$ belong to the cleanest rare B decays!

Theory prediction: Standard Model

decay	SM
$B_s \rightarrow \mu^+\mu^-$	$3.65 \pm 0.23 \times 10^{-9}$
$B^0 \rightarrow \mu^+\mu^-$	$1.1 \pm 0.1 \times 10^{-10}$

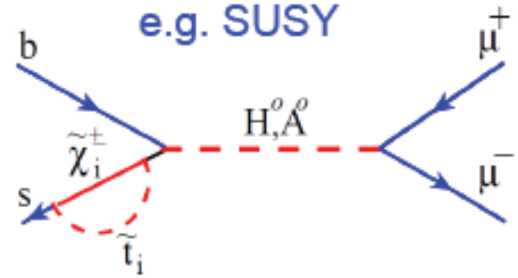
SM: Bobeth et al: PRL 112 101801 (2014)

Left handed couplings
→ helicity suppressed

Discovery channel for New Phenomena

Example: MSSM
(with R-parity conservation)

$$BR(B_S \rightarrow \mu^+\mu^-) \propto \frac{\tan^6 \beta}{m_A^4}$$

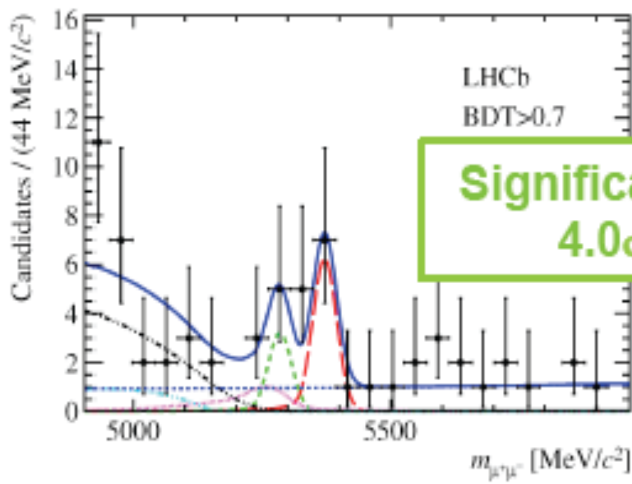


→ $B_{s,d} \rightarrow \mu^+\mu^-$ strongly constrains SUSY parameter space

→ Ratio B_s / B^0: Stringent test of minimal flavour violation hypothesis

- **Nov 2012: LHCb found the first evidence for $B_s \to \mu^+\mu^-$ using $2.1 fb^{-1}$**
- Update: full dataset: $3fb^{-1}$
  - Improved BDT
  - Expected sensitivity: **5.0σ**

PRL 111 (2013) 101805



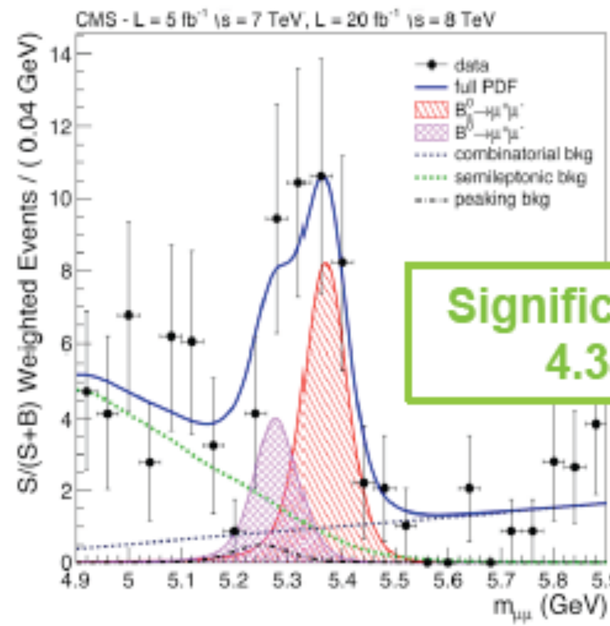
Significance: 4.0σ

$$BR(B_s \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}) \times 10^{-9}$$

$$BR(B^0 \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}) \times 10^{-10}$$

$$BR(B^0 \to \mu^+\mu^-) < 7 \times 10^{-10} @95\%CL$$

- Update to $25fb^{-1}$
  - Cut based → BDT based
  - Improved variables
  - Expected sensitivity: **4.8σ**



Significance: 4.3σ

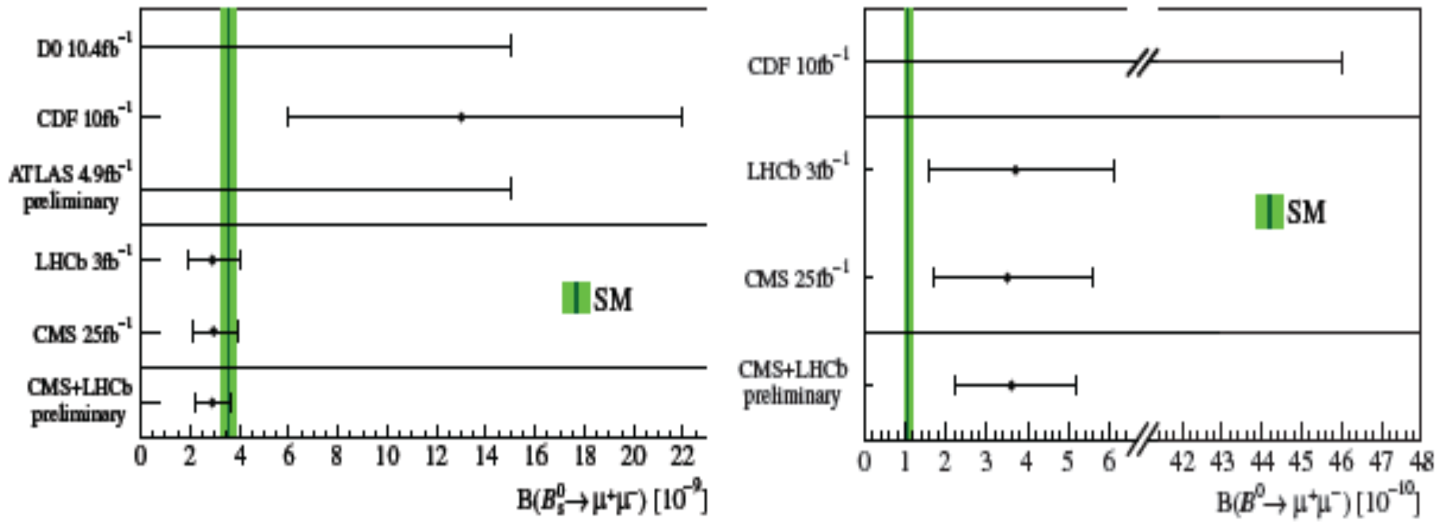
$$BR(B_s \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$$

$$BR(B^0 \to \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10}$$

$$BR(B^0 \to \mu^+\mu^-) < 11 \times 10^{-10} @95\%CL$$

PRL 111 (2013) 101804

Combined LHCb + CMS result



D0: PRD87(2013)072006
CDF: PRD87(2013)072003
ATLAS: ATLAS-CONF-2013-076
LHCb: PRL 111 (2013) 101805
CMS: PRL 111 (2013) 101804

- Preliminary combination of results

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.6\,^{+1.6}_{-1.4}) \times 10^{-10}$$

SM: $BR(B_s) = (3.65 \pm 0.23)\ 10^{-9}$
$BR(B^0) = (1.1 \pm 0.1)\ 10^{-10}$
PRL 112 101801 (2014)

$B_s^0 \to \mu^+\mu^-$ is observed at more than 5σ

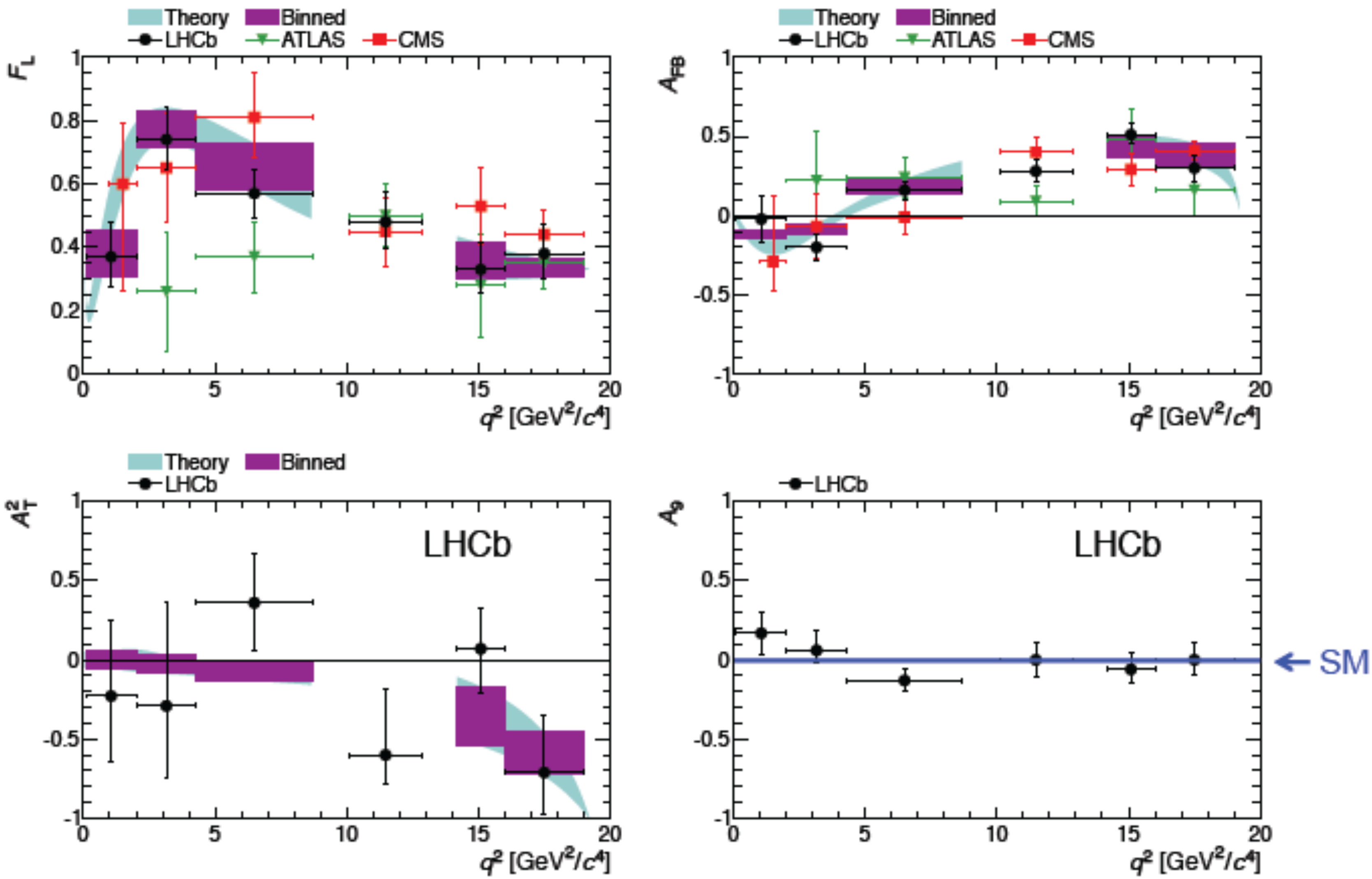
- FCNC decays $b \to s\ (d)\ \ell^+\ell^-$: large variety of final states
  - Allows detailed test of the structure of the underlying interaction
  - Effects in one decay can be cross checked in others

# of events	BaBar $433 fb^{-1}$	Belle $605 fb^{-1}$	CDF $9.6 fb^{-1}$	LHCb 1 / 3 fb^{-1}	ATLAS $5 fb^{-1}$	CMS $5 fb^{-1}$
$B^0 \to K^{*0}\ell^+\ell^-$	137±44*	247±54*	288±20	2361±56	466±34	415±29
$B^+ \to K^{*+}\ell^+\ell^-$			24±6	162±16		
$B^+ \to K^+\ell^+\ell^-$	153±41*	162±38*	319±23	4746±81		
$B^0 \to K^0_s\ell^+\ell^-$			32±8	176±17		
$B_s \to \phi\ell^+\ell^-$			62±9	174±15		
$\Lambda_b \to \Lambda\ell^+\ell^-$			51±7	78±12		
$B^+ \to \pi^+\ell^+\ell^-$		limit		25±7		

Babar arXiv:1204.3933
Belle arXiv:0904.0770
CDF arXiv:1107.3753 + 1108.0695 + ICHEP 2012
ATLAS (preliminary) [ATLAS-CONF-2013-038]
CMS (preliminary) [CMS-BPH-11-009]
LHCb arxiv:1403.8044 +1305.2168 +1306.2577 +JHEP12(2012)125

*mixture of B^0 and $B^\pm$ and $\ell = e,\mu$
other experiments: $\ell = \mu$ only

ATLAS (prelim.) [ATLAS-CONF-2013-038] , CMS 5.2 fb^{-1} [PLB 727 (2013) 77] , LHCb 1 fb^{-1} [JHEP 08 (2013) 131]



Theory prediction from Bobeth et al. [JHEP 07 (2011)] and references therein.

Test of lepton universality

$3fb^{-1}$
arXiv:1406.6482

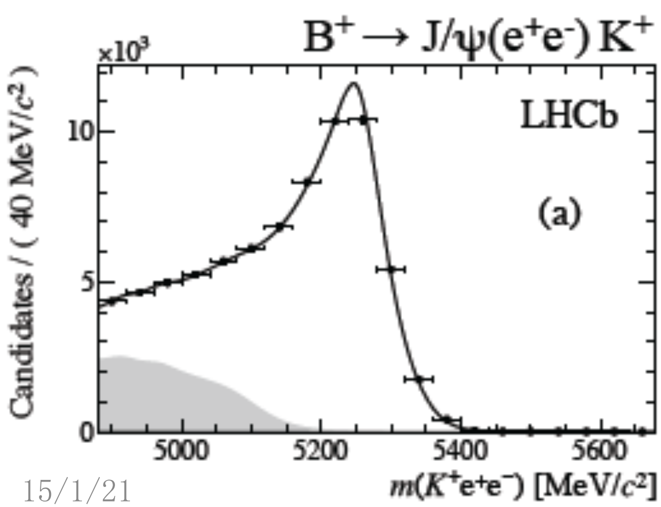
- In the SM, couplings to all leptons are universal

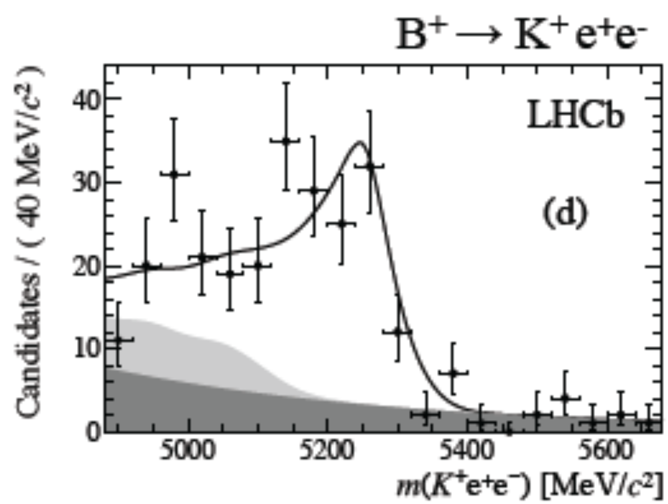
- Test lepton universality in $B^+ \to K^+ \mu^+\mu^- / B^+ \to K^+ e^+e^-$

$$R_K = \frac{\int_{q^2=1\,\mathrm{GeV}^2/c^4}^{q^2=6\,\mathrm{GeV}^2/c^4} (\mathrm{d}\mathcal{B}[B^+ \to K^+\mu^+\mu^-]/\mathrm{d}q^2)\mathrm{d}q^2}{\int_{q^2=1\,\mathrm{GeV}^2/c^4}^{q^2=6\,\mathrm{GeV}^2/c^4} (\mathrm{d}\mathcal{B}[B^+ \to K^+e^+e^-]/\mathrm{d}q^2)\mathrm{d}q^2} \stackrel{\mathrm{SM}}{=} 1 \pm \mathcal{O}(10^{-3})$$

SM: JHEP 12 (2007) 040

- Selection of the $B^+ \to K^+ e^+e^-$ decay experimentally challenging due to bremsstrahlung emission from $e^\pm$

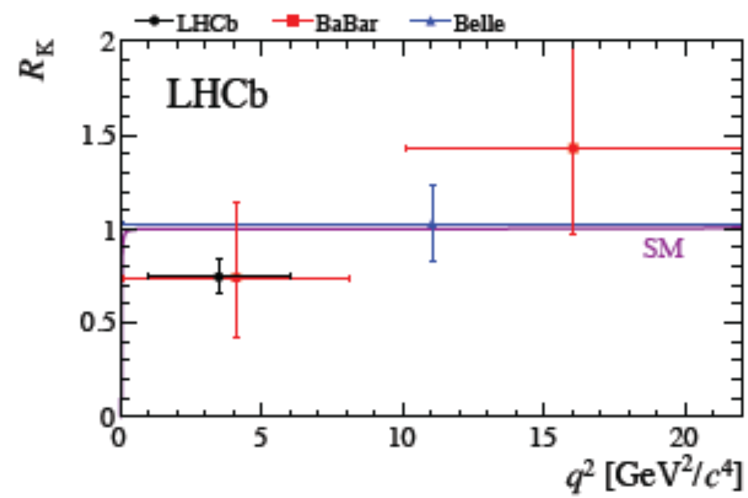




Candidates triggered by the $e^\pm$

Test of lepton universality

- Correct for bremsstrahlung using calorimeter photons (E_T>75MeV)
- Migration of events into/out of the $1 < q^2 < 6$ GeV^2 region corrected using MC
- Double ratio with resonant decay $B^+ \rightarrow J/\psi(e^+e^-) K^+$ measured



- In 3fb^{-1} LHCb determines

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat})^{+0.036}_{-0.036}(\text{syst})$$

(consistent with SM at 2.6σ)

LHCb-PAPER-2014-024 [Preliminary],

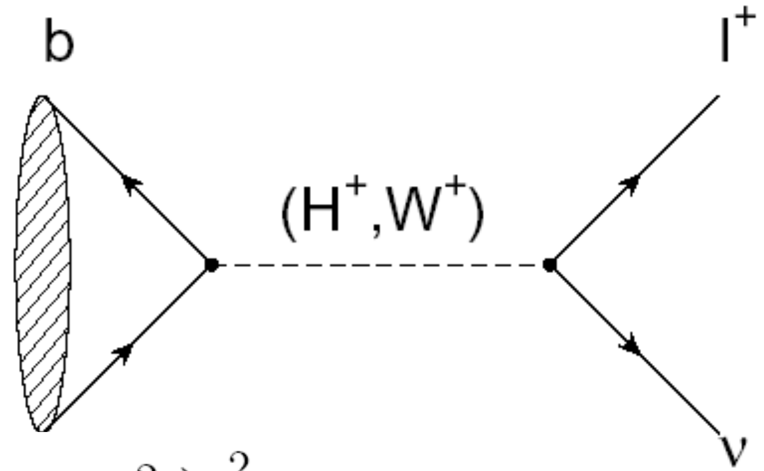
Belle [PRL 103 (2009) 171801] ,

BaBar [PRD 86 (2012) 032012]

$B^+ \to \tau^+ \nu_\tau$

(Decays with **Large** Missing Energy)

Sensitivity to new physics from a **charged Higgs**



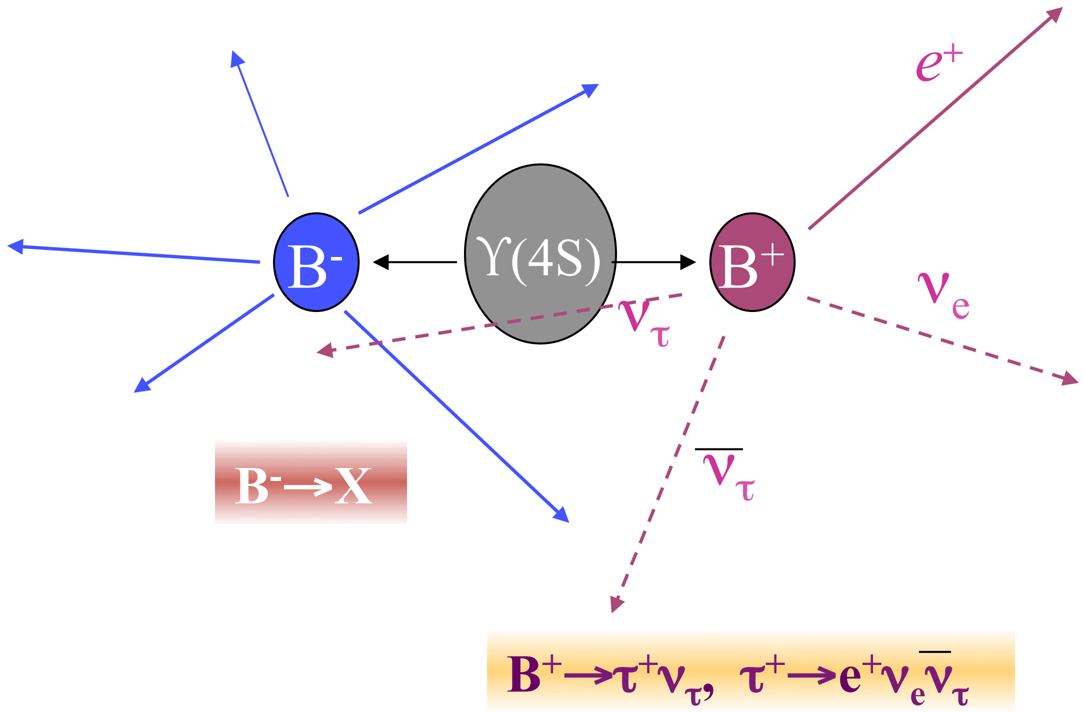
$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = \frac{G_F^2 m_B}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

$$\mathcal{B}_{(B\to\tau\nu)} = \mathcal{B}_{SM} \times \left(1 - \tan^2\beta \frac{m_{B\pm}^2}{m_{H\pm}^2}\right)$$

The B meson decay constant, determined by the B wavefunction at the origin.

($|V_{ub}|$ taken from indep. measurements.)

However, the measurement of $B \rightarrow \tau\, \nu$ is non-trivial



Most of the sensitivity is from tau modes with 1-prong

The experimental signature is rather difficult: B decays to a single charged track + nothing

(This may be hard at a hadron collider)

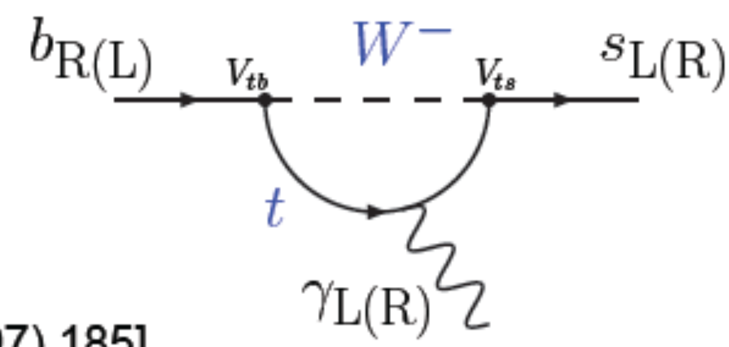
Photon polarization in $b \to s\gamma$ decays

- First penguin decay ever observed: $B^0 \to K^* \gamma$

  CLEO, PRL 71 (1993) 674

- Inclusive and exclusive BR($b \to s\gamma$) compatible with SM (B-factories)

- Yet untested: photon polarization in $b \to s\gamma$
  - SM: photons predominantly left-handed (C_7 / C_7' ~ m_b / m_s)



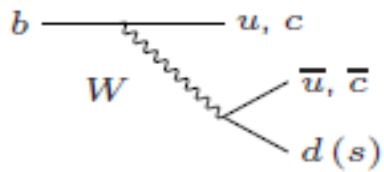
- Can test C_7 / C_7' using
  - Mixing induced CPV [Altwood, PRL79 (1997) 185]
  - Λ_b Baryons [Hiller, Kagan, PRD65 (2002) 074038]
  - **$B \to K^{**} \gamma$ decays such as $B^+ \to K(1270)^+ \gamma$ [Gronau, Pirjol PRD66 (2002) 054008]**

Non-Leptonic B Decays

$\rightarrow$ only quarks in the final states!

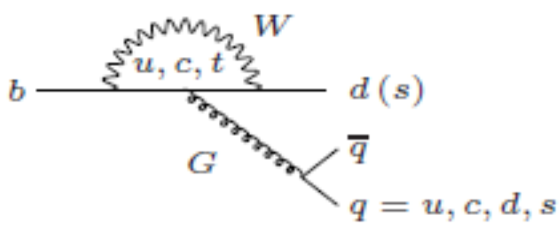
Topologies & Classification

- Tree diagrams:

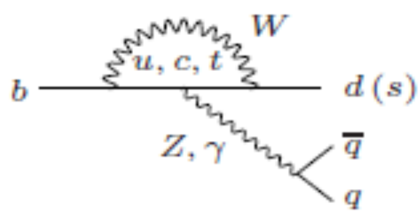


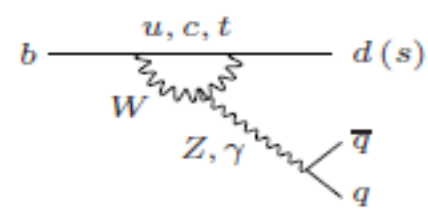
- Penguin diagrams:

  ◇ QCD penguins:

  ◇ Electroweak (EW) penguins:

- Classification (depends on the flavour content of the final state):
  - Only tree diagrams.
  - Tree and penguin diagrams.
  - Only penguin diagrams.

Direct CP Violation

- The most straightforward CP asymmetry ("direct" CP violation):[3]

$$\mathcal{A}_{\rm CP} \equiv \frac{\Gamma(B \to f) - \Gamma(\overline{B} \to \overline{f})}{\Gamma(B \to f) + \Gamma(\overline{B} \to \overline{f})} = \frac{|A(B \to f)|^2 - |A(\overline{B} \to \overline{f})|^2}{|A(B \to f)|^2 + |A(\overline{B} \to \overline{f})|^2}$$

$$= \frac{2|A_1||A_2|\sin(\delta_1 - \delta_2)\sin(\varphi_1 - \varphi_2)}{|A_1|^2 + 2|A_1||A_2|\cos(\delta_1 - \delta_2)\cos(\varphi_1 - \varphi_2) + |A_2|^2}$$

- Provided the two amplitudes satisfy the following requirements:

  i) non-trivial CP-conserving strong phase difference $\delta_1 - \delta_2$;

  ii) non-trivial CP-violating weak phase difference $\varphi_1 - \varphi_2$:

$\Rightarrow$ **CP violation originates through interference effects!**

- Goal: extraction of $\varphi_1 - \varphi_2$ ($\to$ UT angle) from the measured $\mathcal{A}_{\rm CP}$!
- Problem: uncertainties related to the strong amplitudes $|A_{1,2}|e^{i\delta_{1,2}}$ ...

Impact of New Physics

- Theoretical description through effective low-energy Hamiltonians:
  - The NP particles (such as the charginos, squarks in the MSSM) are "integrated out" as the W boson and the top quark in the SM:
    - Initial conditions for RG evolution: $C_k(\mu = M_W) \to C_k^{\rm SM} + C_k^{\rm NP}$
  - Operators, which are absent or strongly suppressed in the SM, may actually play an important rôle:
    - Operator basis: $\{Q_k\} \to \{Q_k^{\rm SM}, Q_l^{\rm NP}\}$
- Popular NP scenario: *Minimal Flavour Violation (MFV)*
  - Flavour and CP violation still governed by the SM Yukawa matrices.
  - Essentially no effects in CP asymmetries, but various interesting correlations between rare decay observables, mixing parameters, etc.

- General case: new sources of flavour and CP violation through NP

$\rightarrow$ *two main avenues for NP to manifest itself in the data ...*

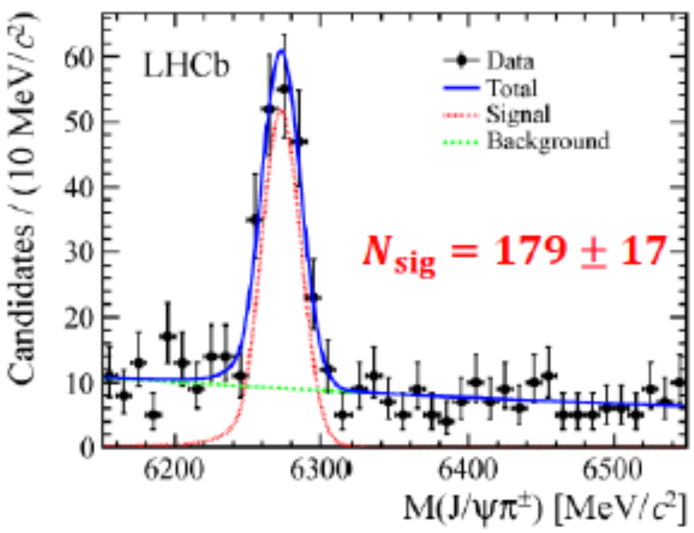
It makes even more sense to measure CP asymmetries in many-body final states , especially in Bs decays

$$\begin{aligned}
\Delta A_{CP}(B^\pm \to K^\pm \pi^+ \pi^-) &= +0.032 \pm 0.008_{\rm stat} \pm 0.004_{\rm syst} \pm 0.007_{\psi K^\pm} \\
\Delta A_{CP}(B^\pm \to K^\pm K^+ K^-) &= -0.043 \pm 0.009_{\rm stat} \pm 0.003_{\rm syst} \pm 0.007_{\psi K^\pm} \\
A_{CP}(B^\pm \to K^\pm \pi^+ \pi^-)|_{\rm regional} &= +0.678 \pm 0.078_{\rm stat} \pm 0.032_{\rm syst} \pm 0.007_{\psi K^\pm} \\
A_{CP}(B^\pm \to K^\pm K^+ K^-)|_{\rm regional} &= -0.226 \pm 0.020_{\rm stat} \pm 0.004_{\rm syst} \pm 0.007_{\psi K^\pm}
\end{aligned}$$

data of even more CKM suppressed B^+ decays give [5]:

$$\begin{aligned}
\Delta A_{CP}(B^\pm \to \pi^\pm \pi^+ \pi^-) &= +0.117 \pm 0.021_{\rm stat} \pm 0.009_{\rm syst} \pm 0.007_{\psi K^\pm} \\
\Delta A_{CP}(B^\pm \to \pi^\pm K^+ K^-) &= -0.141 \pm 0.040_{\rm stat} \pm 0.018_{\rm syst} \pm 0.007_{\psi K^\pm} \\
\Delta A_{CP}(B^\pm \to \pi^\pm \pi^+ \pi^-)|_{\rm regional} &= +0.584 \pm 0.082_{\rm stat} \pm 0.027_{\rm syst} \pm 0.007_{\psi K^\pm} \\
\Delta A_{CP}(B^\pm \to \pi^\pm K^+ K^-)|_{\rm regional} &= -0.648 \pm 0.070_{\rm stat} \pm 0.013_{\rm syst} \pm 0.007_{\psi K^\pm}
\end{aligned}$$

Bc Meson/Unique from super B factory



$B_c^+ \to J/\psi\pi^+$

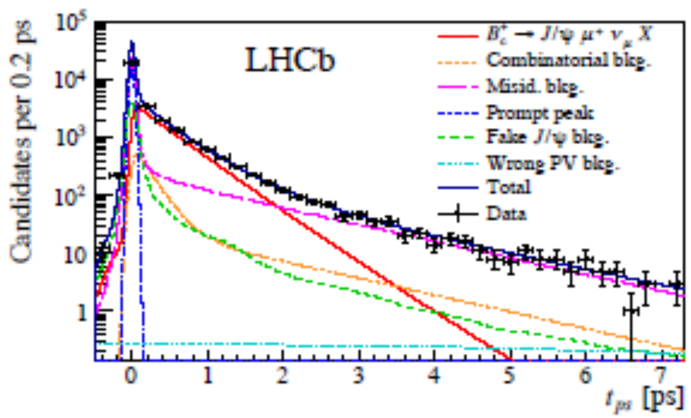
PRL 109 (2012) 232001, LHCb

Relative production cross section

Consistent with theory calculations

EPJC 38 (2004) 267, Chang & Wu

PRD 89 (2014) 034008, Qiao et al.



$B_c^+ \to J/\psi\mu^+\nu X$

arXiv: 1401.6932, LHCb

Most precise B_c lifetime measurement

τ=509 ±8 ±12 fs

35

More Topics on Bc Meson

- The spectrums of Bc mesons
- The life time and decay width
- The weak decays of Bc meson with Charm
- The weak decays of Bc meson without Charm
- The Production of Bc meson in future colliders

CP asymmetries in beauty baryons' decays

- first and second classes that are CKM suppressed.
- In the first class of Λ_b decays one gets $p\pi^-$, $p\pi^-\pi^0$, pK^-K^0, ΛK^-, $p\pi^-\pi^+\pi^-$, $p\pi^-K^+K^-$, etc.
- In the second class one probes pK^-, $pK^-\pi^0$, $pK_S\pi^-$, ΛK^+K^- etc.
- Ξ^-_b decays lead to $\Lambda^0\pi^-$, $\Lambda^0\pi^-\pi^0$ etc. and Λ^0K^-, $\Lambda^0K^-\pi^0$, $\Lambda^0\bar{K}^0\pi^-$ etc.
- For Ξ^0_b decays one probes $\Sigma^+\pi^-$, $\Lambda^0\pi^+\pi^-$,Σ^+K^-, $\Lambda^0\pi^+K^-$ etc.
- For obvious reasons we list only first class of Ω^-_b , namely $\Xi^0\pi^-$, Ω^-K^0

D phyiscs

- Belle II produces first competition, and one think about the impact of huge boosts at a Z^0 factory.
- No CPV has been found yet anywhere in D(s) and charm baryons' decays.
- With huge data, CP asymmetry study in multi -body D decays are also possible.
- The semi-inclusive decay of $Z^0 \rightarrow \Lambda_c X$ is listed as be (1.53±0.33)% in the PDG. We expect that about 3×10^{10} Λ_c baryons will be produced at the Z^0 factory

τ physics ($10^{10}\ \tau^+\tau^-$)

- High boost of τ lepton in Z factory help some measurements
- One goal is to probe CP violation
- Studying $\tau^- \to K_S\pi^-\nu_\tau$, $\tau^- \to K^-\pi^-\pi^+\nu_\tau$, $\tau^- \to \pi^- K^-K^+\nu_\tau$, $\tau^- \to (3\pi)^-\nu_\tau$ or $\tau^- \to (4\pi)^-\nu_\tau$ will allow to constrain the CP violating sector of some models involving several Higgs doublets, left-right symmetry or leptoquarks.

Charged Lepton Flavor Violation

- **MEG experiment: Br($\mu^+ \to e^+\gamma$) < 5.7×10^{-13} (90% CL)**
- **$\tau \to \mu\gamma$ in Z factory, one expects to reach a sensitivity on the branching ratio of 10^{-10}**
- **we can probe charged lepton flavor violation in τ production of $Z^0 \to \tau^\pm\mu^\mp/\tau^\pm e^\mp$ & even in $H^0 \to \tau^\pm\mu^\mp/\tau^\pm e^\mp$.**
- **the hadronic τ LFV modes $\tau \to lP$ or $\tau \to lPP$ are sensitive to a large number of BSM operators: scalar, pseudo scalar, vector, axial-vector, gluonic ones**

Anomalous magnetic moment of τ (g-2)

- the very short lifetime of the τ lepton (2.9×10^{-13} s) makes impossible for the determination

high boost in Z factory makes it easier

- more precise measurements of $e^+e^- \rightarrow e^+\gamma^*\gamma^*e^- \rightarrow e^+\tau^+\tau^-e^-$ at a machine such as CEPC will certainly allow for a remarkable improvement in the existing experimental bound

We are expecting to reach a similar sensitivity of EDM with the Belle II project.

Flavor physics at SPPC, if we have a LHCb -like detector

Type	Observable	Current precision	LHCb 2018	SPPC	Theory uncertainty
B_s^0 mixing	$2\beta_s$ $(B_s^0 \to J/\psi\ \phi)$	0.10 [137]	0.025	0.008	~ 0.003
	$2\beta_s$ $(B_s^0 \to J/\psi\ f_0(980))$	0.17 [213]	0.045	0.014	~ 0.01
	$a_{\rm sl}^s$	6.4×10^{-3} [43]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [43]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.08 [67]	0.025	0.008	0.02
	$s_0\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [67]	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.25 [76]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [85]	8 %	2.5 %	~ 10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	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–$12°$ [243, 257]	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° [43]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

Summary

- **Heavy flavor physics offers an opportunity to probe NP far above 1 TeV. It is also a necessary ingredient to fully understand the Higgs sector and mass generation mechanism.**
- Huge boosts at a Z^0 factory will help significantly in the competition with Belle II about the information for underlying dynamics.
- This Z factory would produce excellent landscapes for baryons' decays with no competition.
- One can probe rare decays in beauty & charm hadrons (including baryons) and τ.
- To probe EDMs lepton flavor violation of the τ leptons

Flavor and top physics @ 100 TeV workshop

4-7 March 2015
IHEP
Asia/Shanghai timezone

- Overview
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- Timetable
- Contribution List
- Author index
- Registration
  - Registration Form
- Visa
- List of registrants

A 100 TeV collider will have the ability to probe directly our microscopic nature at distances well beyond that of the LHC or any other known experiment. It would thus become the most powerful microscope ever built. Furthermore, such a machine would be potentially capable of producing more than 10^{11} tops and an order of magnitude more bottom and charm quarks than the LHC. Thus, it would allow for an exploration of the complementary weakly coupled regime with unprecedented accuracy. This fantastic large number of heavy flavor object in principle might lead to qualitatively new ways of looking for non-Standard Model physics, in a way that complement known existing experimental strategies as well as the searches at the boundary of the energy frontier. We therefore propose to organise a 4-day focused workshop during March 4 - 7, 2015 at the IHEP that would bring world experts, in both theory and experiment, to discuss top and flavor physics at a 100 TeV future facility.

Starts Mar 4, 2015 08:00
Ends Mar 7, 2015 18:00
Asia/Shanghai

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