Heavy flavor physics after the Higgs discovery

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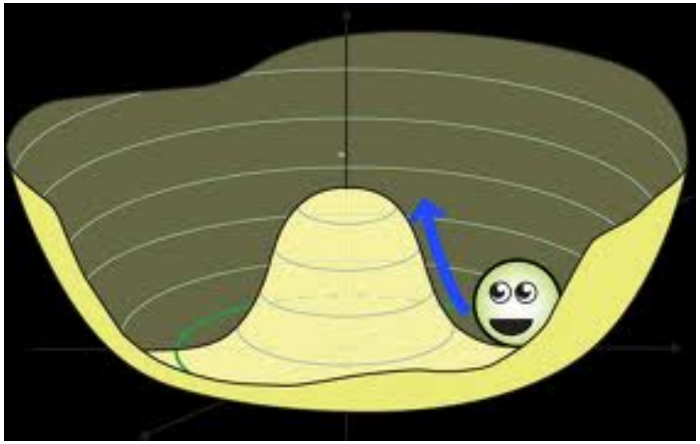
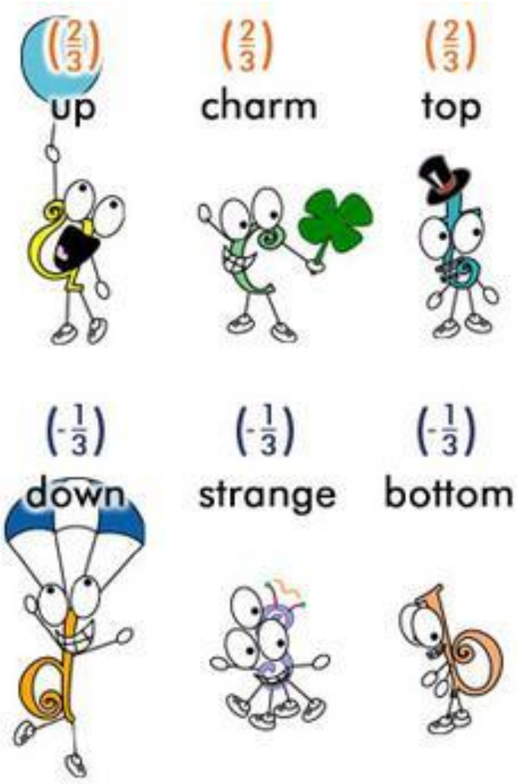
Mass generation

Physics of flavor



Implication

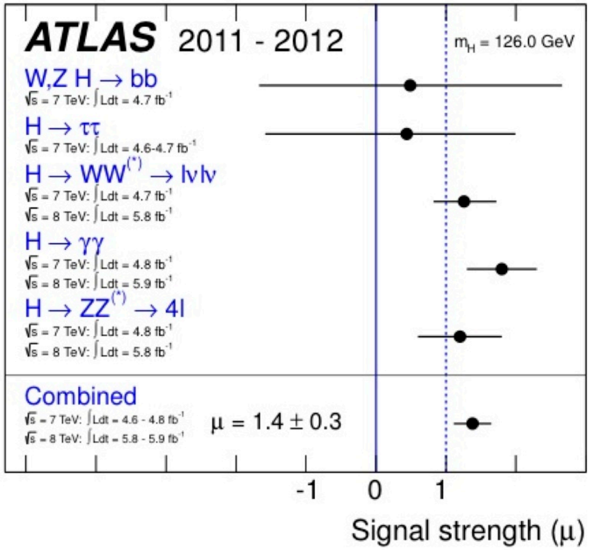
Understanding

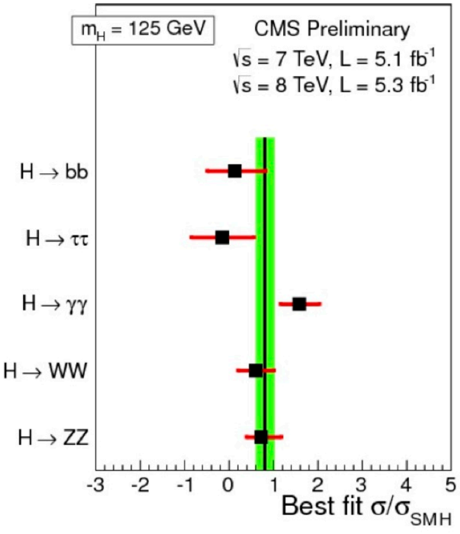


National HEP Conference
Wuhan, China, 18-23 April 2014

The big picture

Understanding the Higgs





- W/Z: seem to understand the mass generation
- **Fermions: picture unclear**
  - ➢ **mass generation?** $y_e \bar{L} H e_R + h.c. \rightarrow y_e \frac{v}{\sqrt{2}} \left(\bar{e}_L e_R + \bar{e}_R e_L \right)$
  - ➢ **flavor mixing?** $J^{\mu +} = \frac{1}{\sqrt{2}} \bar{u}_L^i \gamma^\mu d_L^i \rightarrow \frac{1}{\sqrt{2}} \bar{u}_L^i \gamma^\mu (U_u^{L\dagger} U_d^L)^{ij} d_L^j$

Quark mixing in the SM

$$\mathcal{L}_{\rm SM} = \underbrace{\mathcal{L}_G(\psi, W, \phi)}_{\text{kinetic energy + gauge IA}} + \underbrace{\mathcal{L}_H(\phi)}_{\text{Higgs potential} \rightarrow \text{spontaneous symmetry breaking}} + \underbrace{\mathcal{L}_Y(\psi, \phi)}_{\text{Yukawa IA} \rightarrow \text{fermion masses}}$$

EWSB & diagonalisation of Yukawa mass matrix ⇒ CKM quark mixing matrix

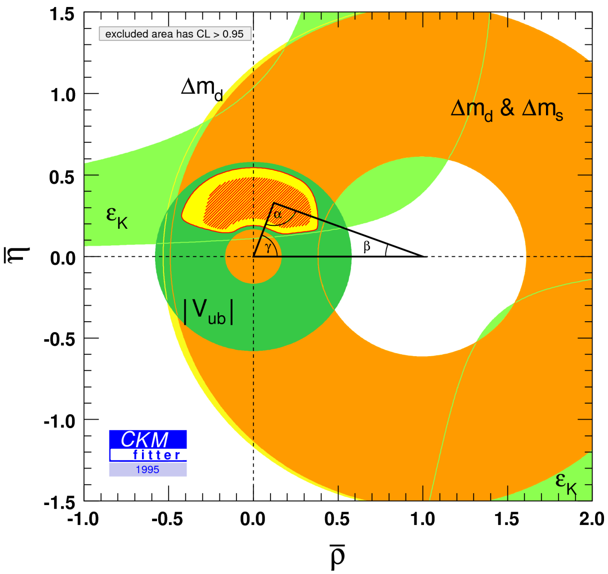
$$V_{CKM} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

L.Wolfenstein PRL 51 (1983) 1945

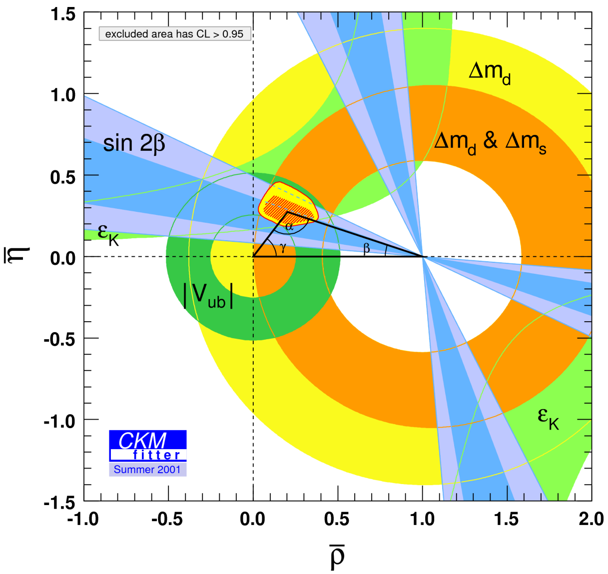
CP violation accommodated by a single complex phase

Triumph of CKM

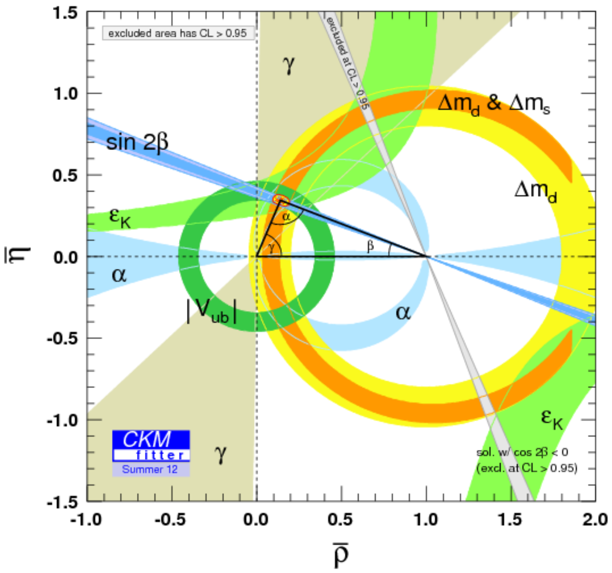
1995 (top discovery)



2001 (B factory turn-on)



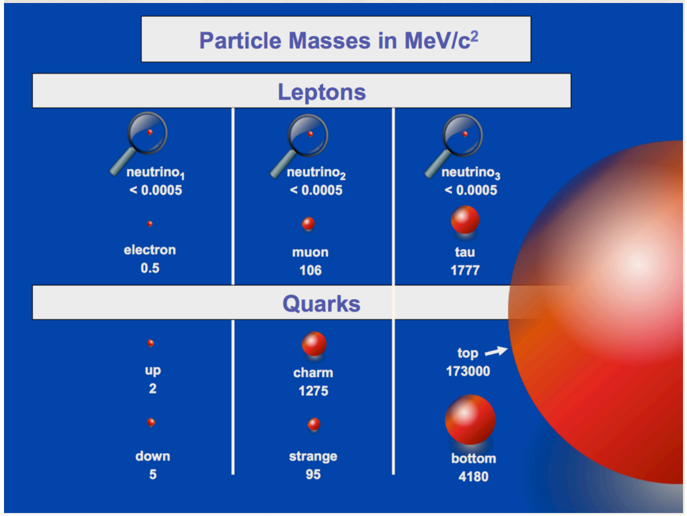
2013 (Precision flavour physics)

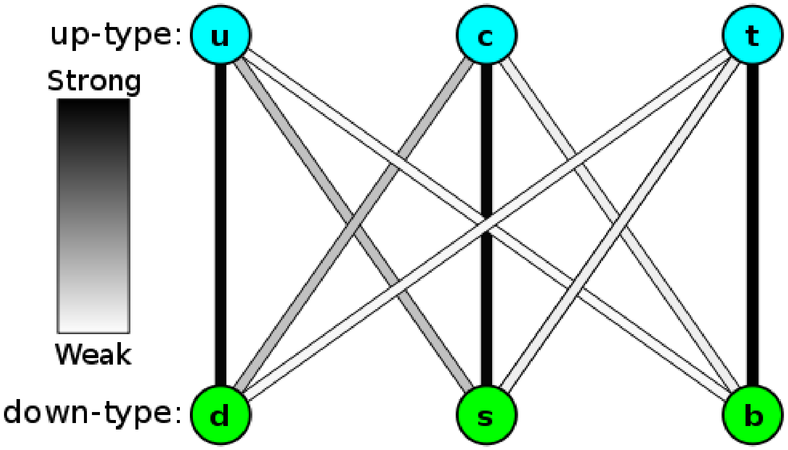


Overall very successful to describe collider data

Though no explanation of the matter dominance in the Universe …

Flavor is still a mystery





- What is the dynamic origin of the patterns of fermion masses and flavor mixing?
- What are sources of flavor symmetry breaking & CP violation (beyond Yukawa couplings)?

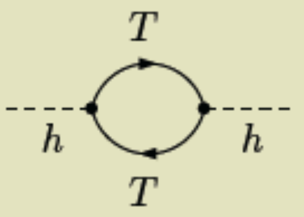
New physics (NP) beyond the SM is expected

Is there a NP flavor problem?

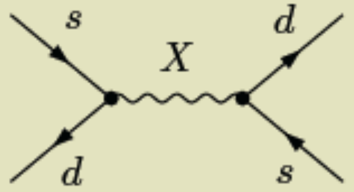
$$\mathcal{L}_{\rm EFT} = \underbrace{\Lambda_{\rm UV}^2\,\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2}_{} + \mathcal{L}_{\rm SM}^{\rm gauge} + \mathcal{L}_{\rm SM}^{\rm Yukawa} + \underbrace{\overset{\nu\text{ mass}}{\frac{\mathcal{L}^{(5)}}{\Lambda_{\rm UV}}} + \overset{\text{FCNC}}{\frac{\mathcal{L}^{(6)}}{\Lambda_{\rm UV}^2}}}_{} + \ldots$$

electroweak symmetry breaking $\Downarrow$ Higgs mass

$\Downarrow$



$$\sim \frac{g_T^2}{16\pi^2}\Lambda_{\rm UV}^2$$



$$\sim \frac{g_X^2}{\Lambda_{\rm UV}^2}$$

no fine-tuning $\Downarrow$

bounds on flavor mixing $\Downarrow$ assuming *generic* flavor structure

$\Lambda_{\rm Higgs} < \sim 1\,\text{TeV}$

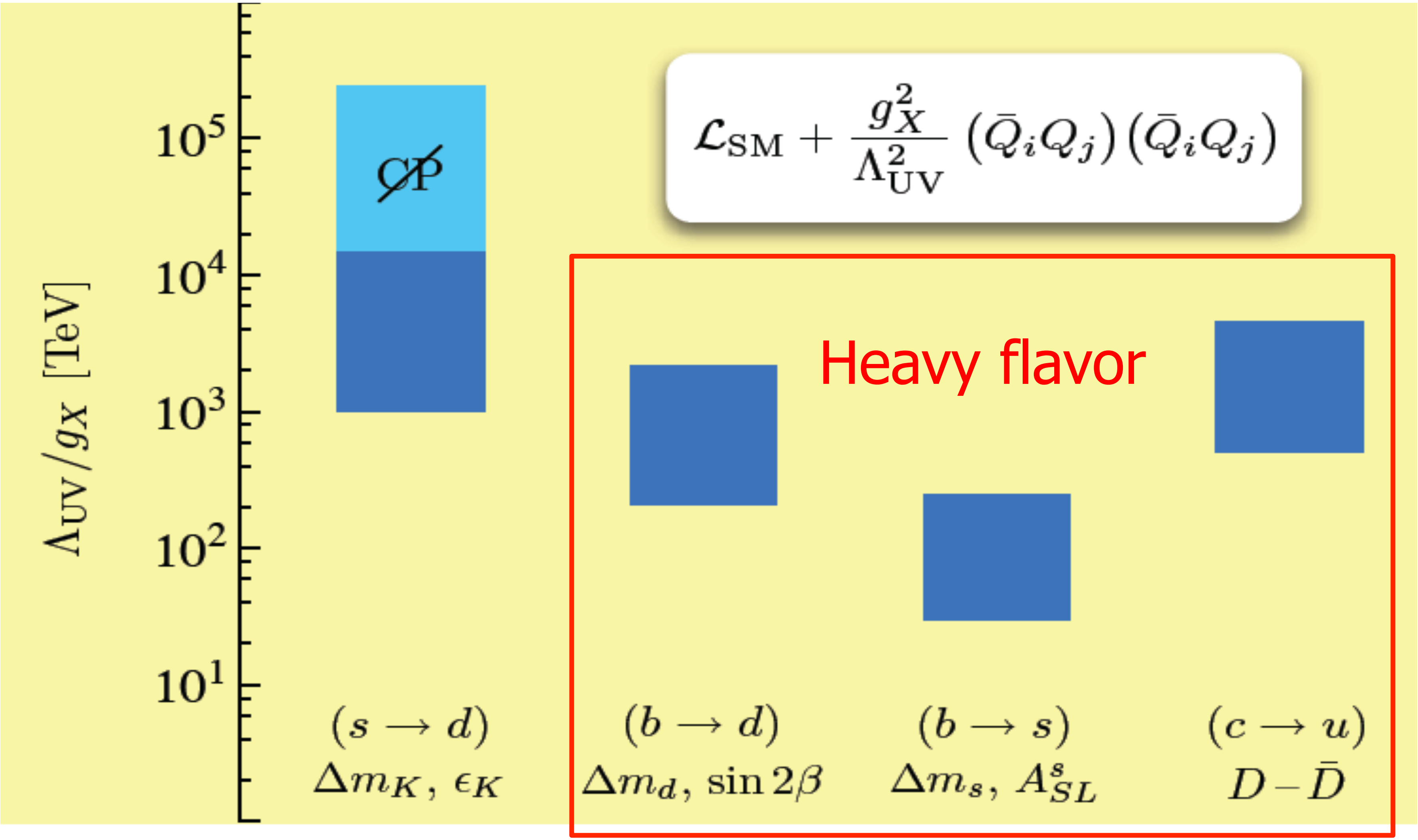
(unless nature is fine tuned)

$\Lambda_{\rm flavor} \gg 1\,\text{TeV}$

(unless NP is special)

NP FCNC must be suppressed to be consistent with data.

Bounds from FCNC data



Generic bounds on New Physics scale (for g_X~1)

Possible scenarios

NP below 1 TeV excluded with 8 TeV LHC data

I. Weakly interacting NP at few TeV with mild flavor symmetry breaking

II. NP above few TeV, Higgs fine-tuned, new particles too heavy for LHC

Either way, there will be small but detectable deviations from SM in some observables.

Major goal of flavor physics in coming years: search for NP at high precision and in wide scope!

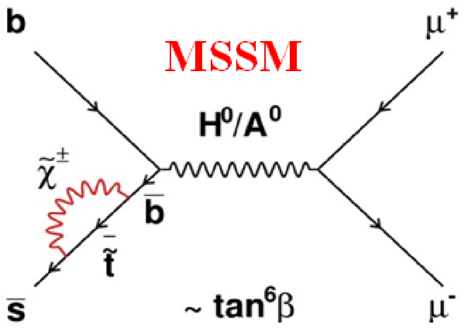
Rare decays

$B_s \rightarrow \mu^+\mu^-$ discovery

- Sensitive to NP scalar couplings
- SM: FCNC and helicity suppression

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.56 \pm 0.30) \times 10^{-9}$$

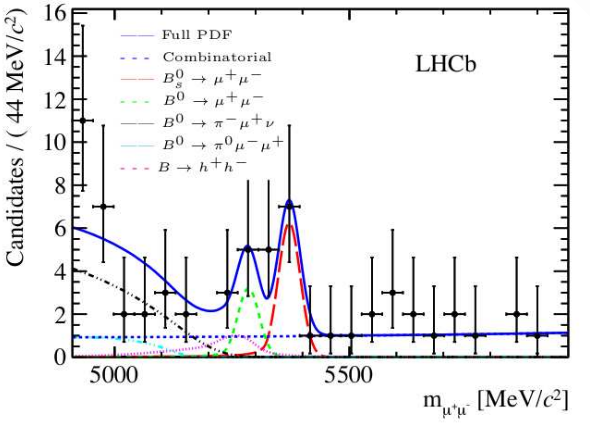
EPJC 72(2012)2172

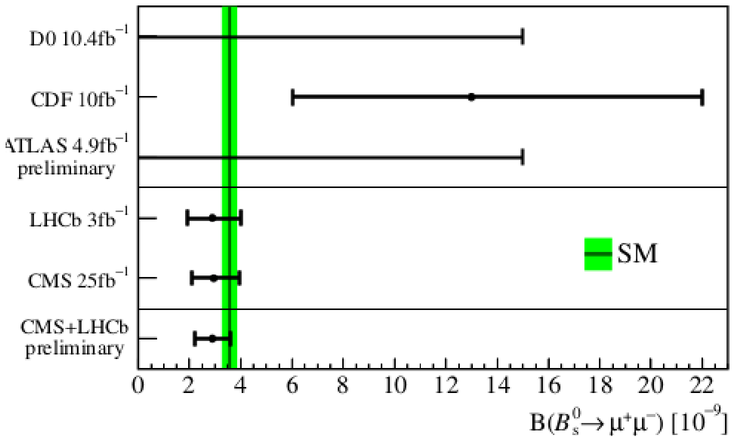


- CMS+LHCb measurement

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

CMS-PAS-BPH-13-007
LHCb-CONF-2013-012

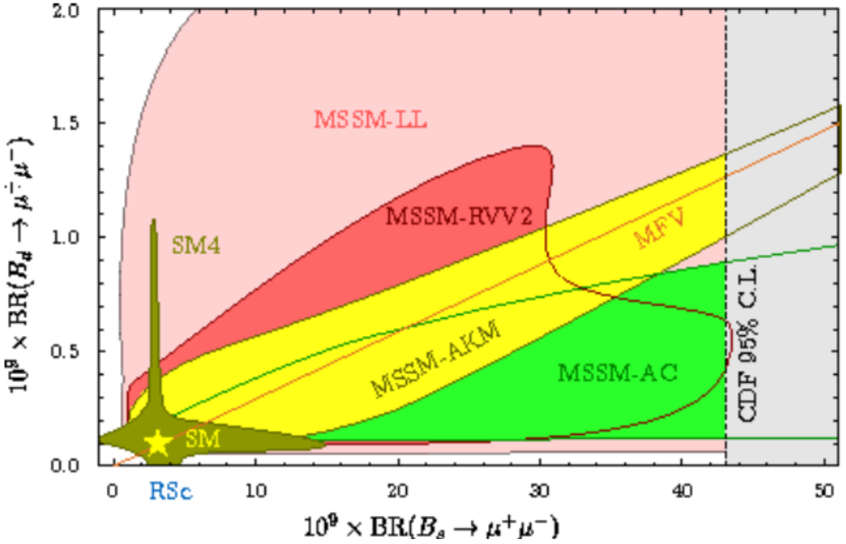




NP model killing

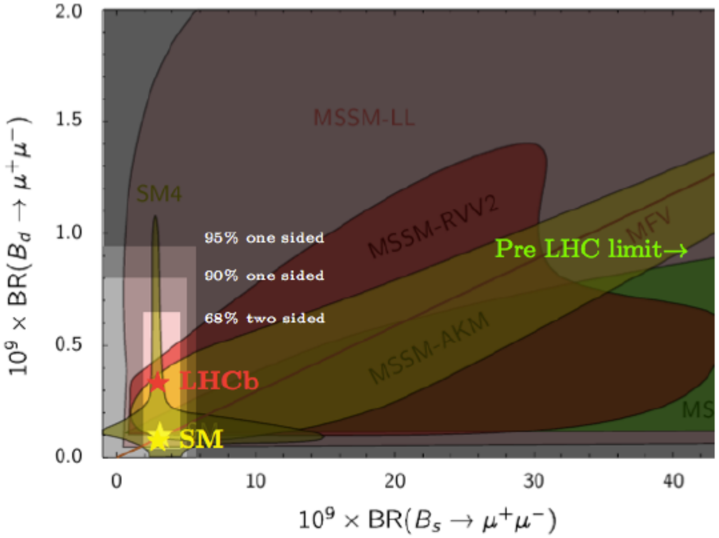
Before the LHC results

[D.Straub arXiv:1205.6094]



After the LHC results

Cartoon of plot from
[D.Straub arXiv:1205.6094]

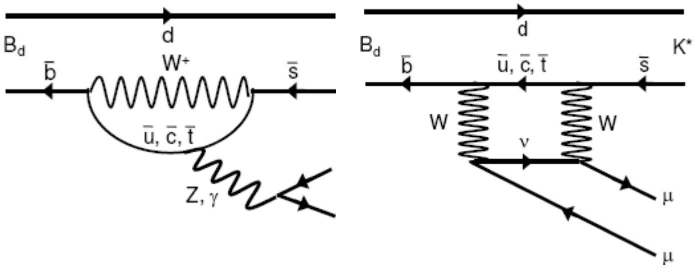


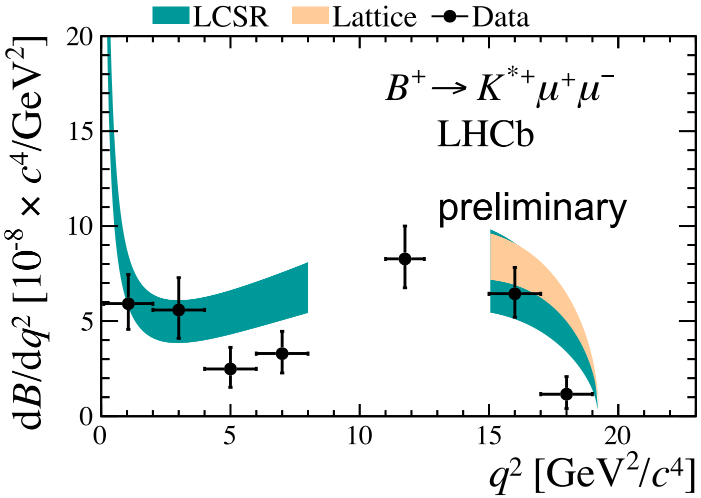
Next goals

- Precision measurement of Br($B_s \to \mu^+\mu^-$)
- Discover $B_d \to \mu^+\mu^-$ (large NP effect still possible)
- Monitor Br($B_s \to \mu^+\mu^-$) /Br($B_d \to \mu^+\mu^-$) (power test of MFV)

$B^0 \to K^* \mu^+ \mu^-$

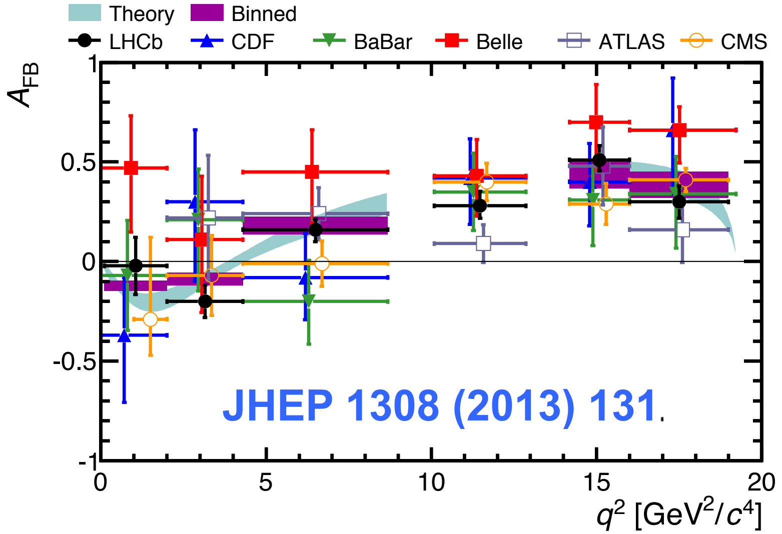
Sensitive to NP in EW loop





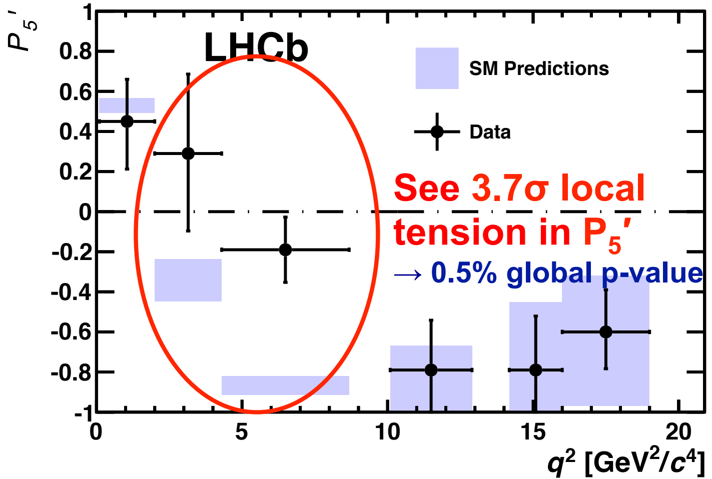
Angular observables A_{FB}, $P_{4\text{-}8}'$ insensitive to form factors

NP? SM not understood? Poor precision?



JHEP 1308 (2013) 131.

$1\mathrm{fb}^{-1}$ results, PRL 111 (2013) 191801



See 3.7σ local tension in P_5'

→ 0.5% global p-value

Lepton flavor violation

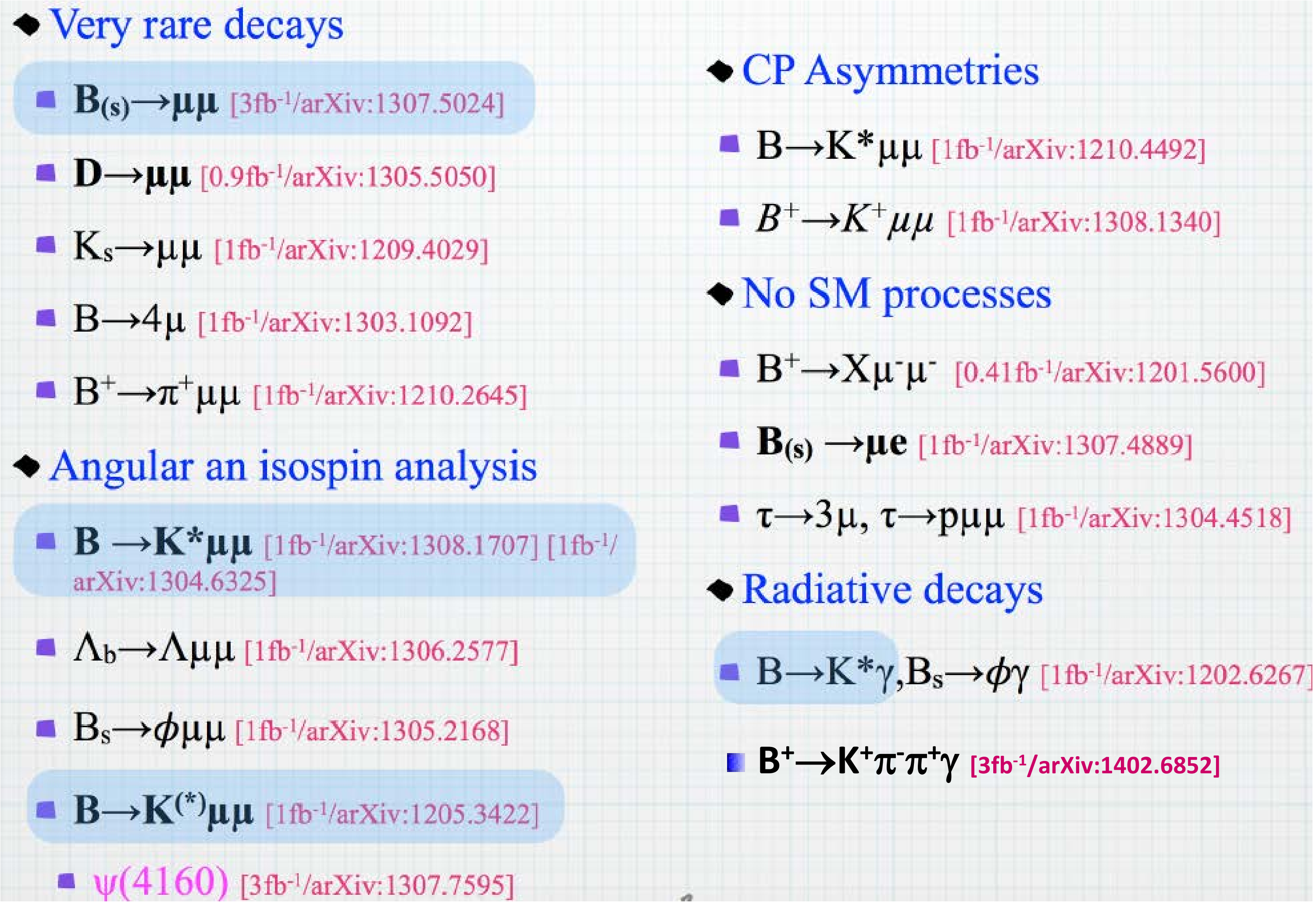
LHCb results

BR	@ 90(95)% CL	
$B_s^0 \to e^+\mu^-$	$1.1\ (1.4)\ \times 10^{-8}$	PRL 111 (2013) 141801, LHCb World's best
$B^0 \to e^+\mu^-$	$2.8\ (3.7)\ \times 10^{-9}$	
$\tau^- \to \mu^-\mu^+\mu^-$	$8.3(10.2)\ \times 10^{-8}$	Competitive with Belle
$\tau^- \to \bar{p}\mu^+\mu^-$	$4.6(5.9)\ \times 10^{-7}$	World's first PLB 724 (2013) 36, LHCb
$\tau^- \to p\mu^-\mu^-$	$5.4(6.9)\ \times 10^{-7}$	

$\tau^- \to \mu^-\mu^+\mu^-$ Best limit from BELLE 2.1×10^{-8}@ 90% CL

PLB 687 (2010) 139, Belle

New results at a glance



◆ Very rare decays

- **$B_{(s)}\to\mu\mu$** [3fb^{-1}/arXiv:1307.5024]
- **$D\to\mu\mu$** [0.9fb^{-1}/arXiv:1305.5050]
- $K_s\to\mu\mu$ [1fb^{-1}/arXiv:1209.4029]
- $B\to 4\mu$ [1fb^{-1}/arXiv:1303.1092]
- $B^+\to\pi^+\mu\mu$ [1fb^{-1}/arXiv:1210.2645]

◆ Angular an isospin analysis

- **$B\to K^*\mu\mu$** [1fb^{-1}/arXiv:1308.1707] [1fb^{-1}/arXiv:1304.6325]
- $\Lambda_b\to\Lambda\mu\mu$ [1fb^{-1}/arXiv:1306.2577]
- $B_s\to\phi\mu\mu$ [1fb^{-1}/arXiv:1305.2168]
- **$B\to K^{(*)}\mu\mu$** [1fb^{-1}/arXiv:1205.3422]
  - $\psi(4160)$ [3fb^{-1}/arXiv:1307.7595]

◆ CP Asymmetries

- $B\to K^*\mu\mu$ [1fb^{-1}/arXiv:1210.4492]
- $B^+\to K^+\mu\mu$ [1fb^{-1}/arXiv:1308.1340]

◆ No SM processes

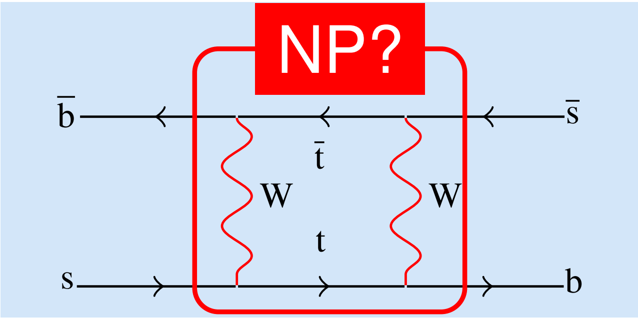
- $B^+\to X\mu^-\mu^-$ [0.41fb^{-1}/arXiv:1201.5600]
- **$B_{(s)}\to\mu e$** [1fb^{-1}/arXiv:1307.4889]
- $\tau\to 3\mu$, $\tau\to p\mu\mu$ [1fb^{-1}/arXiv:1304.4518]

◆ Radiative decays

- $B\to K^*\gamma, B_s\to\phi\gamma$ [1fb^{-1}/arXiv:1202.6267
- **$B^+\to K^+\pi^-\pi^+\gamma$** [3fb^{-1}/arXiv:1402.6852]

B mixing and CPV

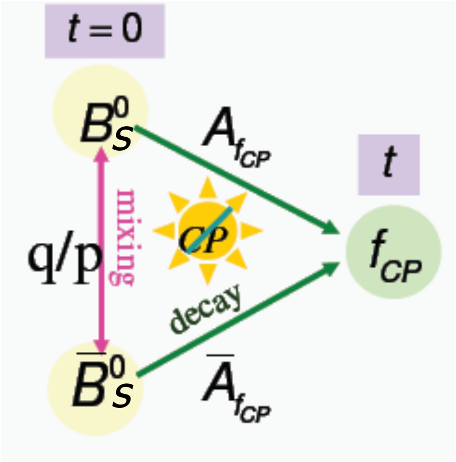
Probes of NP in B_s mixing



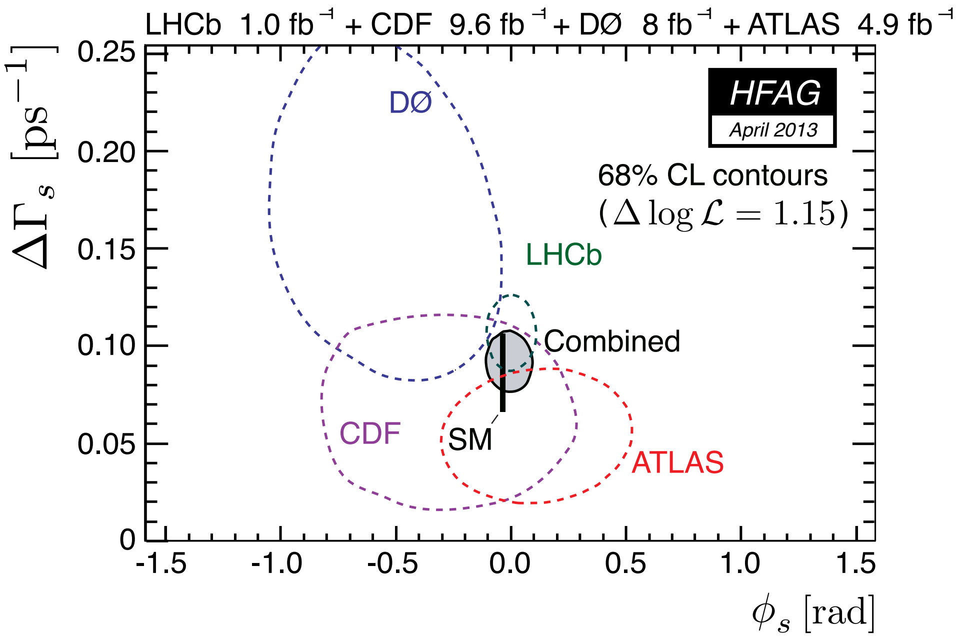
$$i\frac{d}{dt}\begin{pmatrix}|B_s(t)\rangle\\|\bar{B}_s(t)\rangle\end{pmatrix}=\left(\begin{bmatrix}M_{11} & M_{12}\\ M_{12}^{*} & M_{11}\end{bmatrix}-\frac{i}{2}\begin{bmatrix}\Gamma_{11} & \Gamma_{12}\\ \Gamma_{12}^{*} & \Gamma_{11}\end{bmatrix}\right)\begin{pmatrix}|B_s(t)\rangle\\|\bar{B}_s(t)\rangle\end{pmatrix}$$

M_{12} causing B_s mixing, sensitive to NP

- CPV in mixing: $a^s_{fs} \approx |\Gamma_{12}/M_{12}|\sin\phi_{12}$ where $\phi_{12}=\arg(-M_{12}/\Gamma_{12})$
- Mass difference: $\Delta m_s = m_H - m_L \approx 2|M_{12}| \propto (V_{ts}^{*}V_{tb})^2$
- Width difference: $\Delta\Gamma_s = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\phi_{12}$
- Phase difference ϕ_s between $B_s \to f_{CP}$ and $B_s \to B_s \to f_{CP}$



ϕ_s and $\Delta\Gamma_s$ from $B_s \rightarrow J/\Psi h^+h^-$



Agrees with
SM expectation

LHCb dominating

PRD 87 (2013) 112010, LHCb, 1fb^{-1}

LHCb: ϕ_s = 0.01 ± 0.07 ± 0.01 rad

$\Delta\Gamma_s$ = 0.100 ± 0.016 ± 0.003 ps^{-1}

SM: ϕ_s = - 0.036 ± 0.002 rad,

$\Delta\Gamma_s$ = 0.087 ± 0.021 ps^{-1}

PRD 84 (2011) 033005, Charles *et al.*

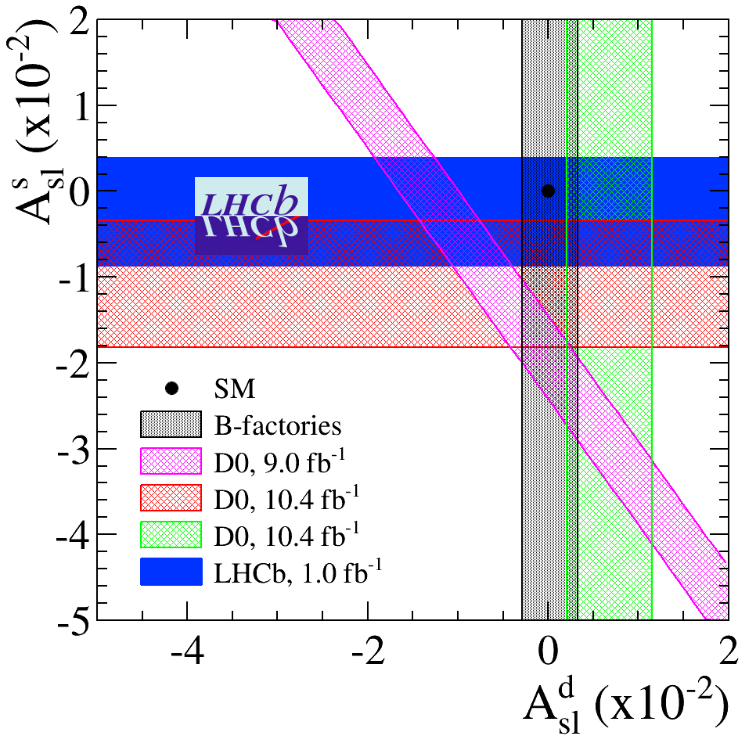
2-fold ambiguity resolved
PRL 108 (2012) 241801
following method in
JHEP 09(2009)074, Xie et al.

CPV in B_s mixing: a^s_{fs}

!

$$A^{s}_{meas}\,!\!=\!!\,\underbrace{\frac{\mathrm{N}"D_s^{-}\mu^{+}\#\$\varepsilon"\mu^{+}\#-\mathrm{N}"D_s^{+}\mu^{-}\#\$\varepsilon"\mu^{-}\#}{\mathrm{N}"D_s^{-}\mu^{+}\#\$\varepsilon"\mu^{+}\#+\mathrm{N}"D_s^{+}\mu^{-}\#\$\varepsilon"\mu^{-}\#}}_{A_\mu^c\ \text{\% "0\&04 ' 0\&25\#\%}} - \underbrace{A_{track}}_{\text{\% "0\&02 ' 0\&13\#\%}} - \overbrace{A_{bkg}}^{\text{\% "0\&05 ' 0\&05\#\%}}$$

$$\text{\% "}-\text{0\&03 ' 0\&25 ' 0\&18\%\#}$$



Most precise measurement

$a^s_{fs} = 2A^s_{meas} = -0.06 \pm 0.50 \pm 0.36$ %

Consistent with SM

Δm_s

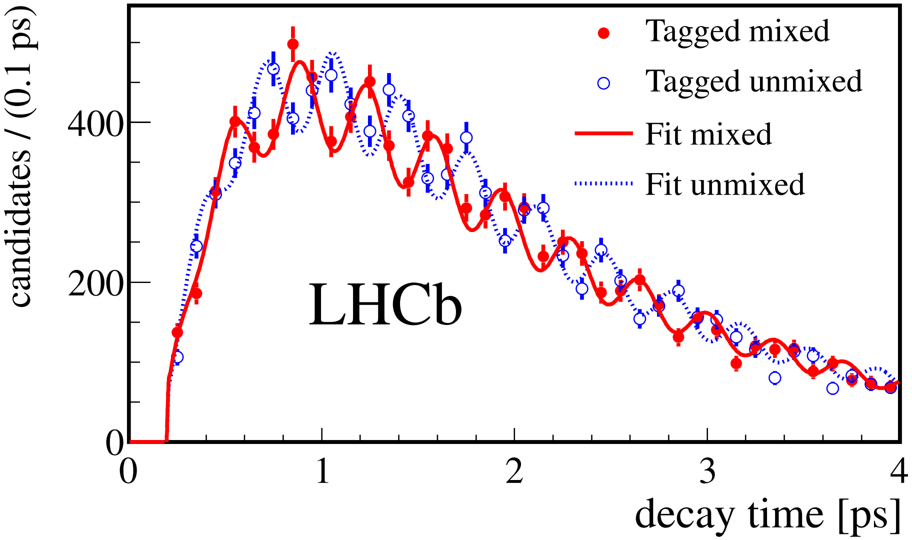
World's most precise Δm_s measurement (from $B_s \rightarrow D_s^+\pi^-$)

$\Delta m_s = 17.768 \pm 0.023 \pm 0.006\ \mathrm{ps}^{-1}$

NJP 15 (2013) 053021, LHCb

SM prediction: $\Delta m_s = 17.3 \pm 2.6\ \mathrm{ps}^{-1}$

arXiv: 1102.4274, Lenz & Nierste



$\Delta m_s \propto f_{Bs}{}^2 B_{Bs}$

Uncertainty of SM prediction dominated by uncertainty of hadronic parameters from lattice QCD

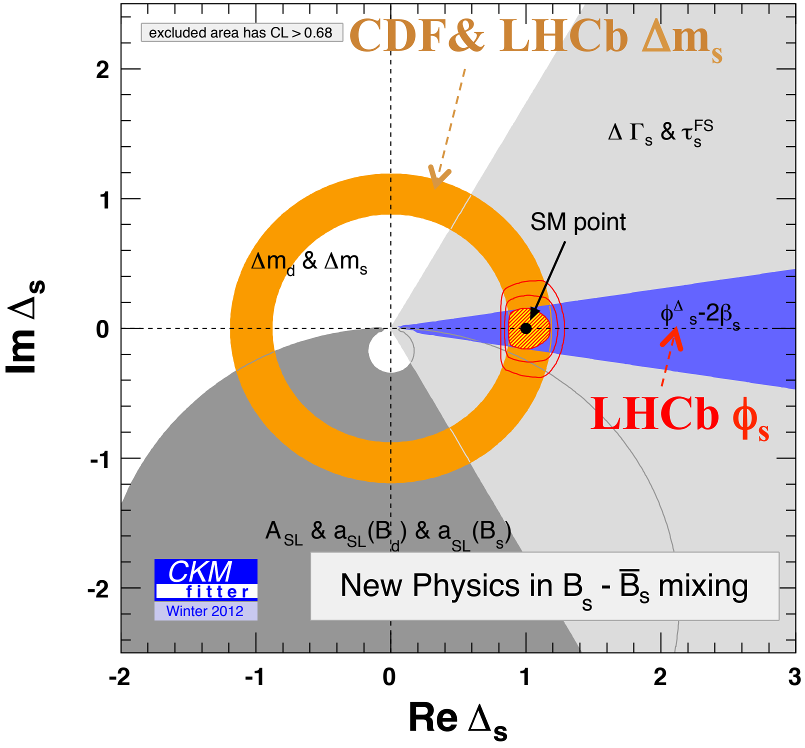
B_s mixing: implication

- Model independent analysis of NP in B_s mixing

$$M_{12}^{s} = M_{12}^{SM,s}\Delta_s$$

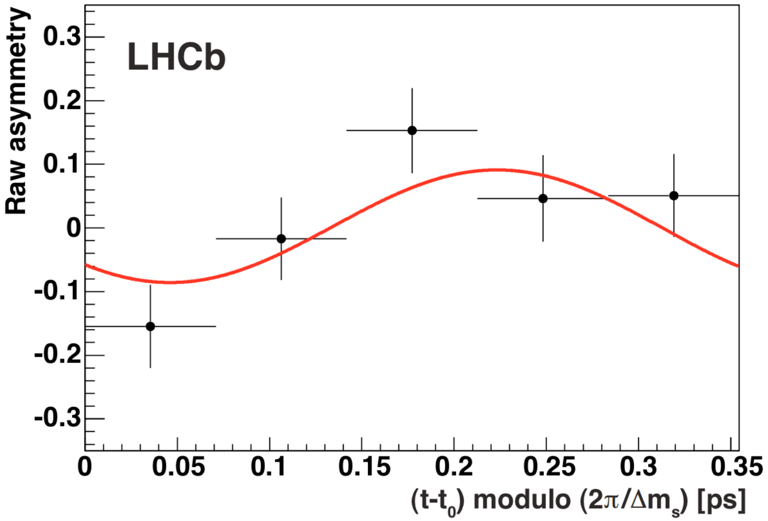
Lenz et al., arXiv:1203.0238

Major constraints on NP in M_{12} come from Δm_s and ϕ_s



- B_s mixing is SM-like
  - Room for *O*(10%) NP contribution in B_s mixing
- Similar situation for B_d mixing

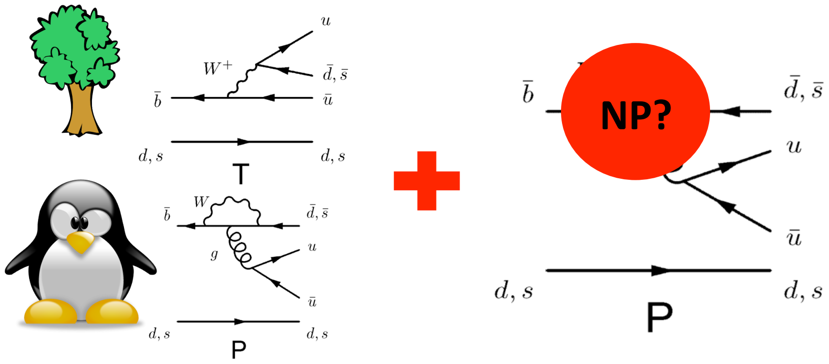
CPV in $B_s \to K^+K^-$



JHEP 10(2013)183, LHCb

$$\mathcal{A}(t) = \frac{-C_f \cos(\Delta m_s t) + S_f \cos(\Delta m_s t)}{\cosh\left(\frac{\Delta\Gamma_s}{2} t\right) - A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_s}{2} t\right)}$$

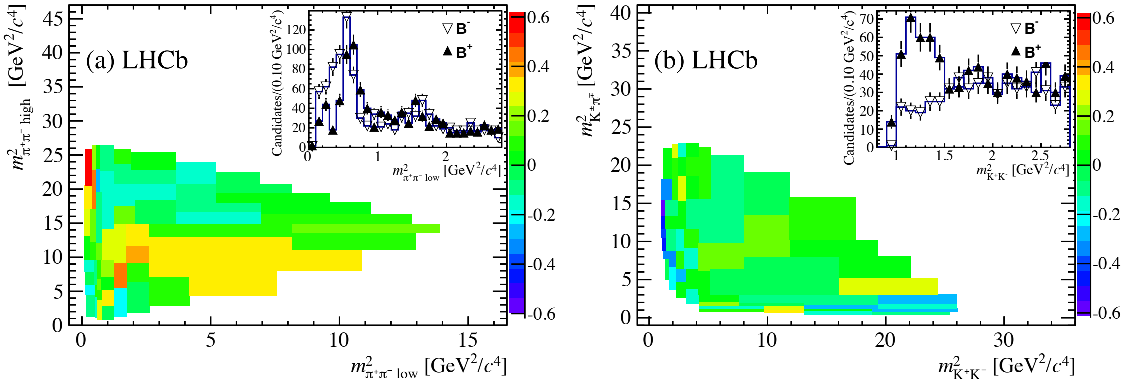
$$C_{KK} = 0.14 \pm 0.11\,(\text{stat}) \pm 0.03\,(\text{syst}),$$
$$S_{KK} = 0.30 \pm 0.12\,(\text{stat}) \pm 0.04\,(\text{syst}),$$



Next step: use SU(3) symmetry for combination with $B^0 \to \pi^+\pi^-$ to determine ϕ_s and γ

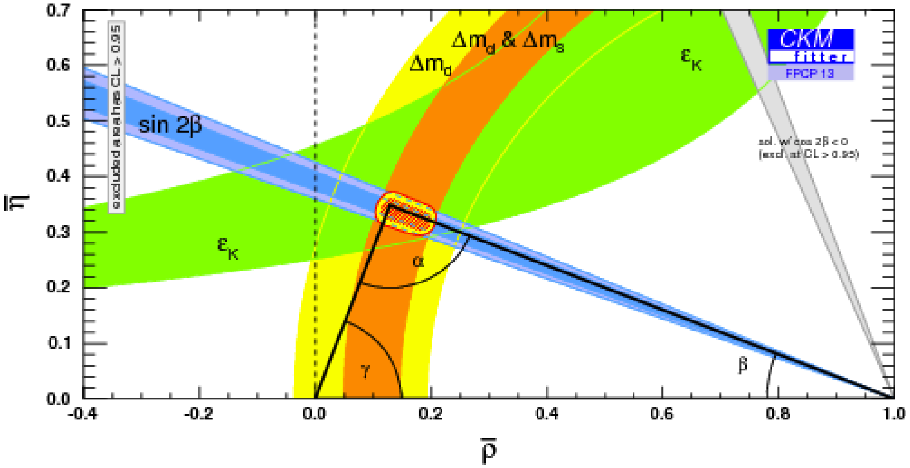
CPV in $B^+ \rightarrow h_1^+ h_1^- h_2^+$

- Significant CPV observed, which depends on Dalitz space, e.g. PRL 112 (2014) 011801, LHCb



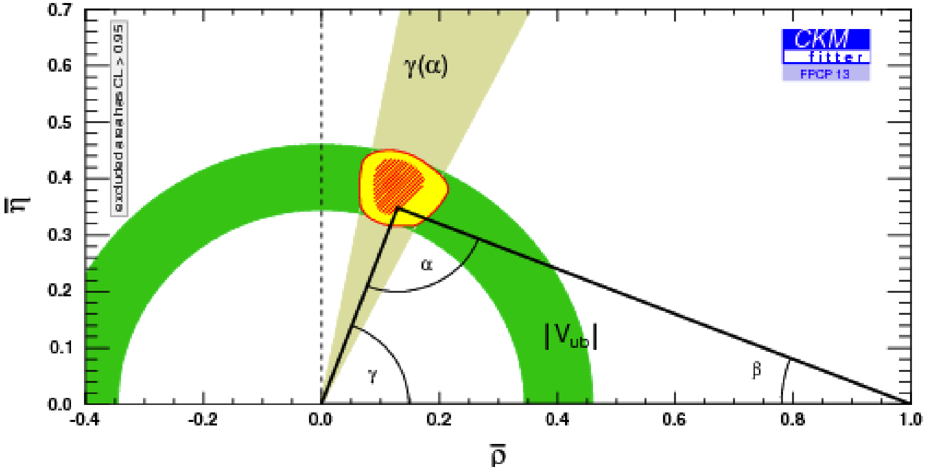
- Triggered theoretical interests
  - pQCD formalism, arXiv:1402.5280, Wang, Hu, Li, Lü
  - Light resonance, PRD 87 (2013) 076007, Zhang, Guo, Yang
  - SU(3) flavor symmetry breaking, arXiv:1307.7186, Xu, Li, He
  - B_s three body decays, arXiv:1401.5514, Cheng & Chua

Loop vs tree determination



Loop processes

Sensitive to NP



tree processes

“standard candle”

Consistent picture, room for *O*(10%) NP contribution

○ Need higher precision, particularly for γ and V_{ub}

○ Need to reduce theoretical uncertainty, particularly penguin pollutions in $B_d \rightarrow J/\Psi K_s$ for $\sin 2\beta$

γ measurements

- Tree processes B→Dh

See ref. in arXiv: 1402.2844

LHCb $1\,\mathrm{fb}^{-1}$: $\gamma=(67\pm12)^\circ$

Belle: $\gamma=(68\pm15)^\circ$

Babar: $\gamma=(69\pm17)^\circ$

Combination $\gamma = 68.0^{+8.0}_{-8.5}{}^\circ$ *(CKMFitter, FPCP 2013)*

- Indirect determination (*CKMFitter*)

$\gamma=(66.6\pm6.4)^\circ$

V_{ub} problem

Inclusive $B \to X_u \ell \nu$

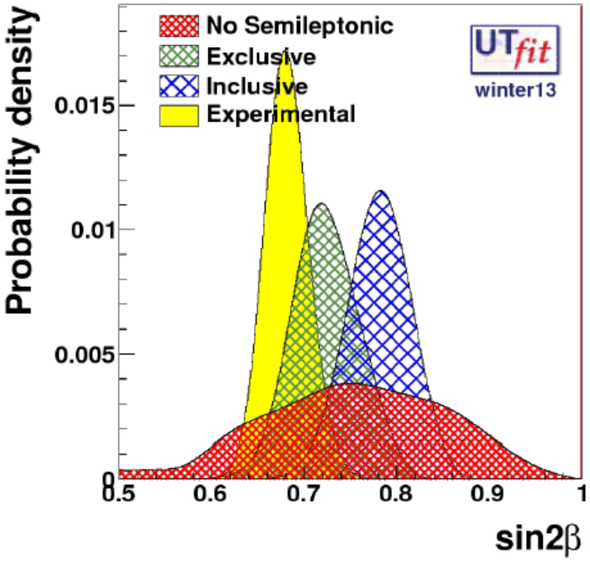
$$|V_{ub}| = (4.41 \pm 0.15_{\text{exp}}{}^{+0.15}_{-0.17}{}_{\text{th}}) \cdot 10^{-3}$$

Kinematic constraints due to charm background.
HQE + resummation.

Exclusive $B \to \pi \ell \nu$

$$|V_{ub}| = (3.23 \pm 0.31) \cdot 10^{-3}$$

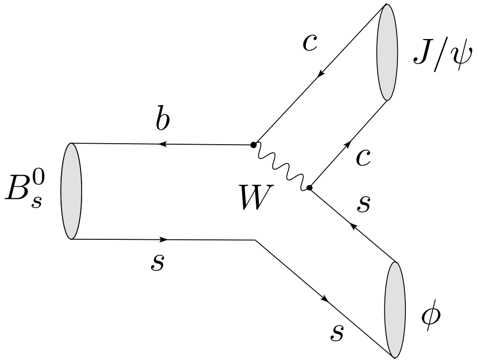
Lattice QCD form factor
QCD sum rules
analyticity

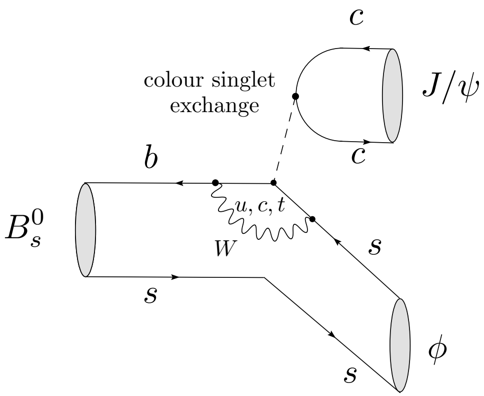


- $V_{ub} - \sin 2\beta - \epsilon_K$ connection
- Bet on exclusive ...

Penguin problem

Tree





Penguin suppressed by λ^2

What is the effect of the penguin on CPV?

pQCD calculation: very small ~10^{-3}

PLB 672 (2009) 349, Gronau & Rosner

arXiv: 1309.0313, Liu, Wang & Xie

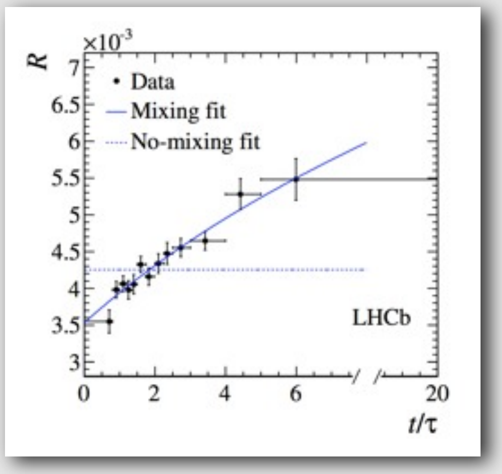
SU(3) flavor symmetry constraint: up to 0.1

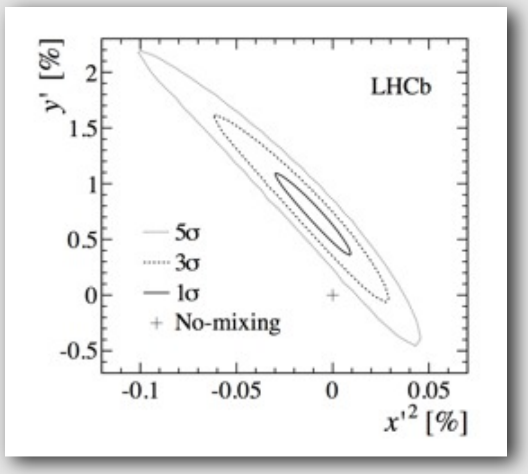
PRD 79 (2009) 014005, Faller, Fleischer & Mannel

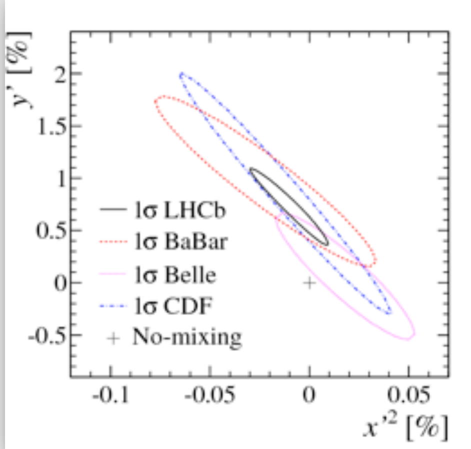
cf. experimental error <0.01 after LHCb upgrade

Charm mixing and CPV

D^0 mixing discovery



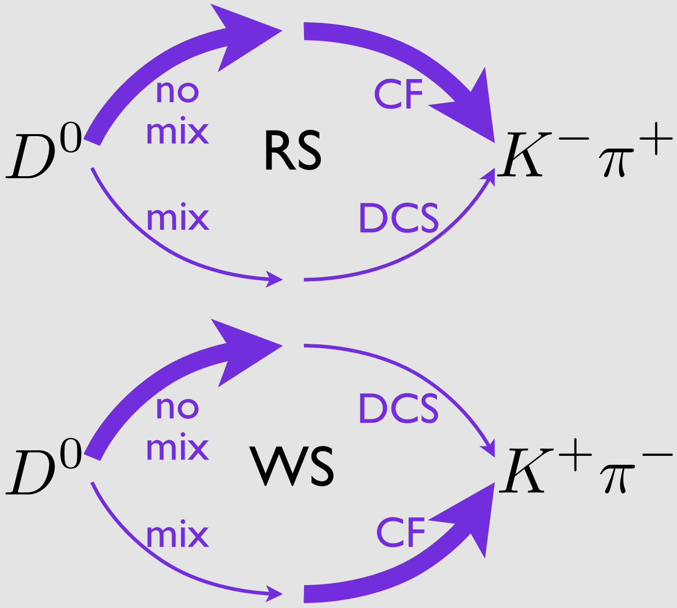




$$R(t) \equiv \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_d + \sqrt{R_D}\,y'\frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

- First single-experiment measurement >5σ significance
- Rotation of mixing parameters by strong phase difference

No−mixing (x’=0, y’=0) excluded



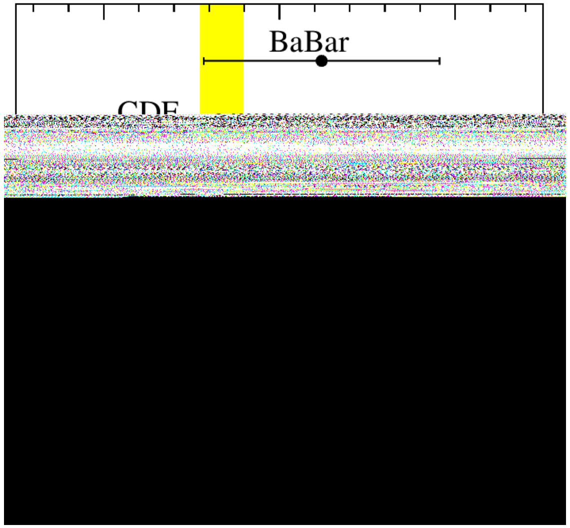
PRL 110 (2013) 101802

Charm CPV

- First evidence for CPV in charm (LHCb, PRL 108 (2012) 111602) supported by some (CDF, Phys. Rev. Lett. 109 (2012) 111801; Belle, arXiv:1212.5320) but not all (LHCb, PLB 723 (2013) 33; LHCb-CONF-2013-003) measurements

$$A_{CP} = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\overline{D^0} \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\overline{D^0} \to h^+h^-)}$$

$$\Delta A_{CP} \equiv A_{CP}(KK) - A_{CP}(\pi\pi)$$



- D^* tagged sample (preliminary)

$$\Delta A_{CP} = (-0.34 \pm 0.15\,(stat) \pm 0.10\,(sys))\ \%$$

- μ tagged sample

$$\Delta A_{CP} = (+0.49 \pm 0.30\,(stat) \pm 0.14\,(sys))\ \%$$

Consistent with no CP violation hypothesis

No indication of CPV in any D decays or in D^0 mixing.
Controversial question: how big can D CPV be in SM?

Charm phenomenology

Charm quarks are too light for HQE and too heavy for ChPT?

$$\Lambda_{QCD}/m_c \sim 0.3 \qquad \text{vs} \qquad \Lambda_{QCD}/m_b \sim 0.1$$

Good realm to test various approaches

➡ HQE might still work
e.g. Lenz, Rauh, Phys.Rev. D88 (2013) 034004

➡ Lattice QCD may one day be able to provide input on hadronic matrix elements of open charm decays.
e.g. Carrasco et al., PoS LATTICE2012 (2012) 105

Exotics

$B \rightarrow D^{(*)} \tau^+ \nu$ puzzle

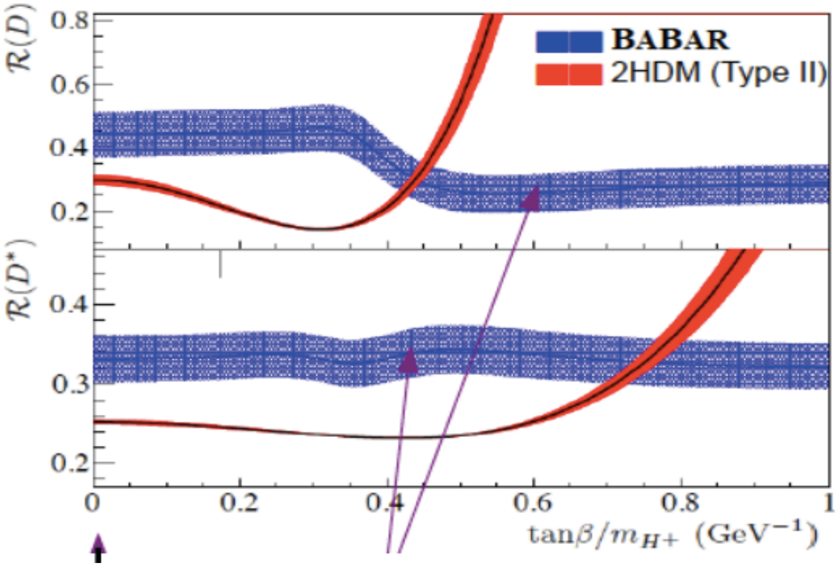
	Babar **PRL 109 (2012) 101802**	**SM: HQET** **PRD 85 (2012) 094025, Fajfer et al**	**SM: pQCD** **PRD 89 (2014) 014030, Fang,Wang, Xiao**
R(D)	0.440±0.058±0.042	0.297±0.017	$0.430^{+0.021}_{-0.026}$
R(D*)	0.332±0.024 ±0.018	0.252±0.003	0.301±0.013

$$R(D) = \frac{\Gamma(\overline{B} \rightarrow D\tau\nu)}{\Gamma(\overline{B} \rightarrow D\ell\nu)} \qquad R(D^*) = \frac{\Gamma(\overline{B} \rightarrow D^*\tau\nu)}{\Gamma(\overline{B} \rightarrow D^*\ell\nu)}$$

Charged Higgs? Not from 2HDM

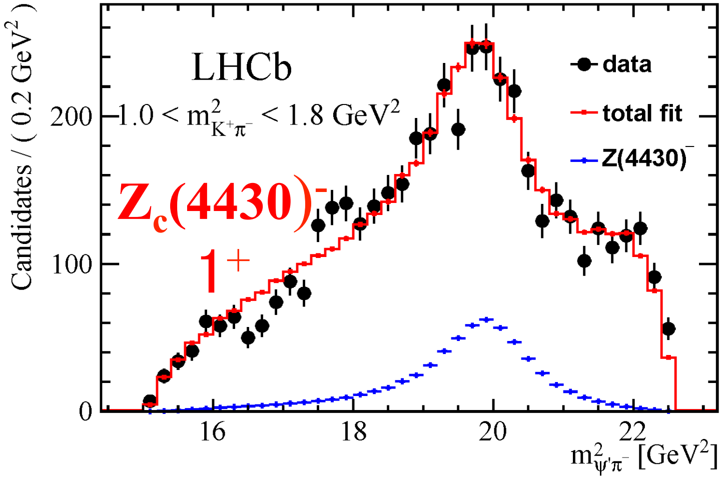
SM prediction reliability?

Measurement biases?

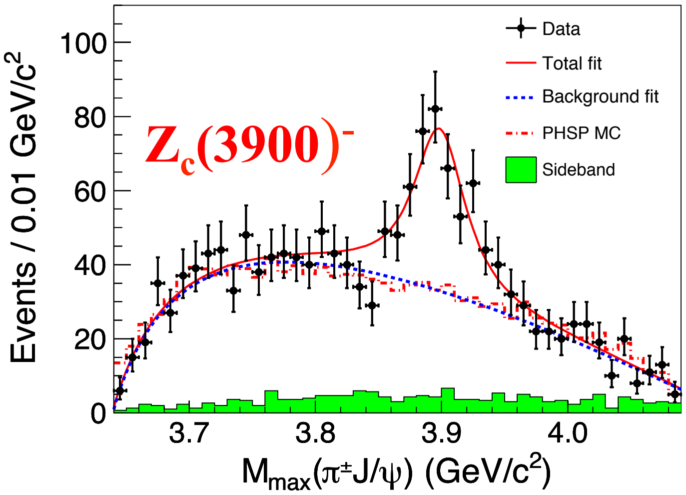


Charged “charmonium” particles

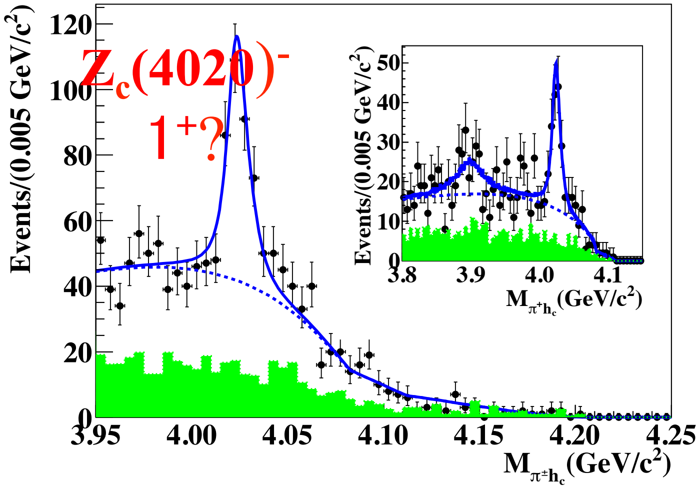
arXiv: 1404.1903, LHCb



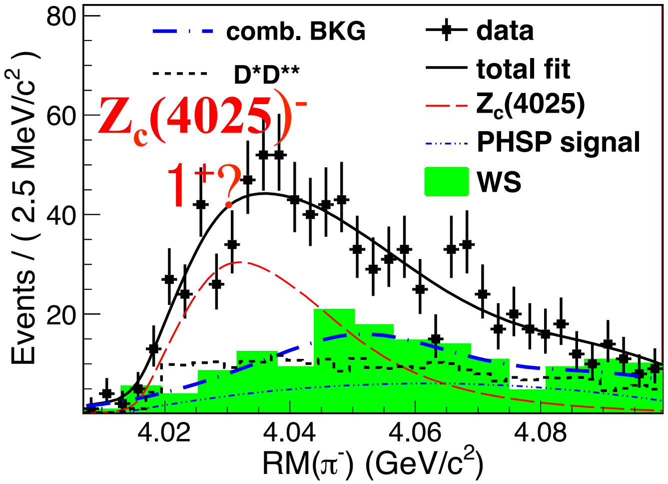
PRL 110 (2013) 252001, BES III



PRL 111 (2013) 242001, BES III

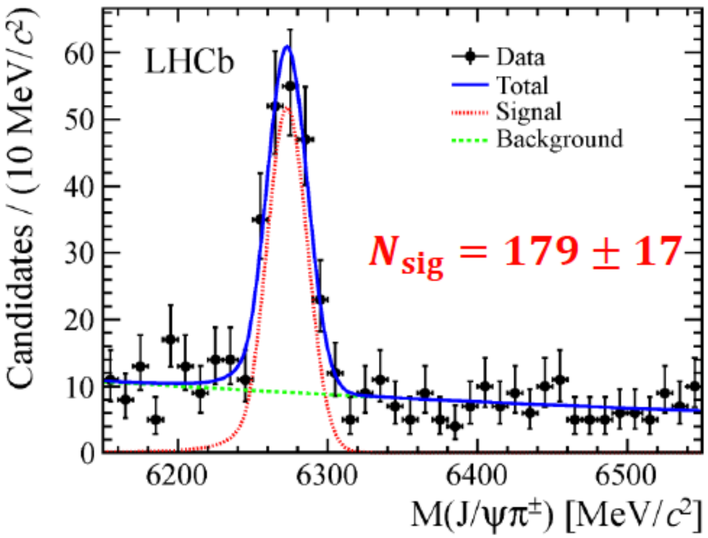


arXiv: 1308.2760, BES III



Understanding QCD

B_c physics



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

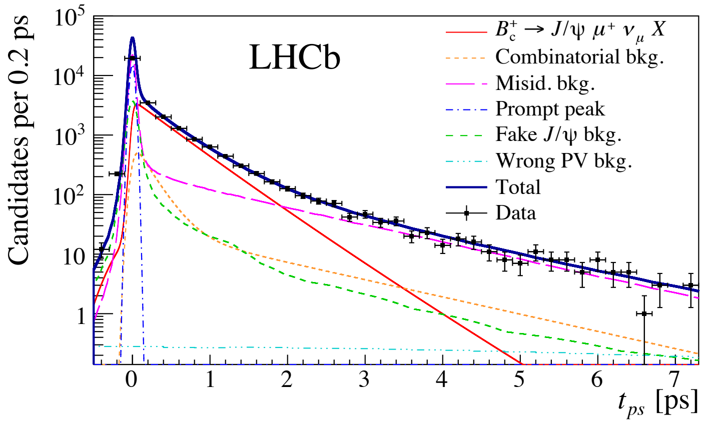
PRL 109 (2012) 232001, LHCb

Relative production cross section

Consistent with theory calculations

EPJC 38 (2004) 267, Chang & Wu

PRD 89 (2014) 034008, Qiao et al.



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

arXiv: 1401.6932, LHCb

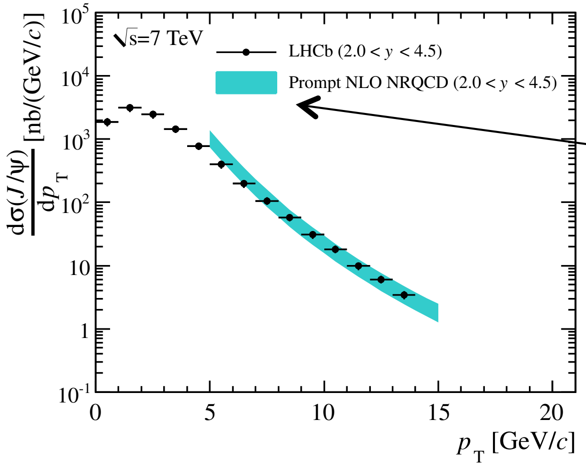
Most precise B_c lifetime measurement

$\tau = 509 \pm 8 \pm 12$ fs

J/Ψ production

EPJC 71 (2011) 1645, LHCb

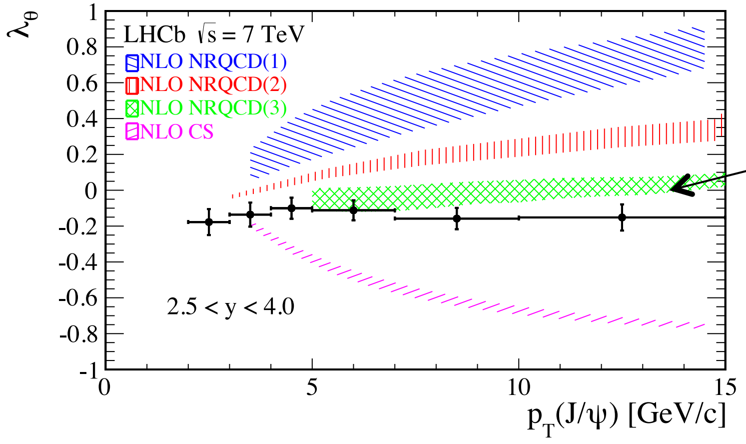
Cross section



PRL 106 (2011) 042002,
Ma, Wang & Chao

EPJC 73 (2013) 2631, LHCb

polarisation

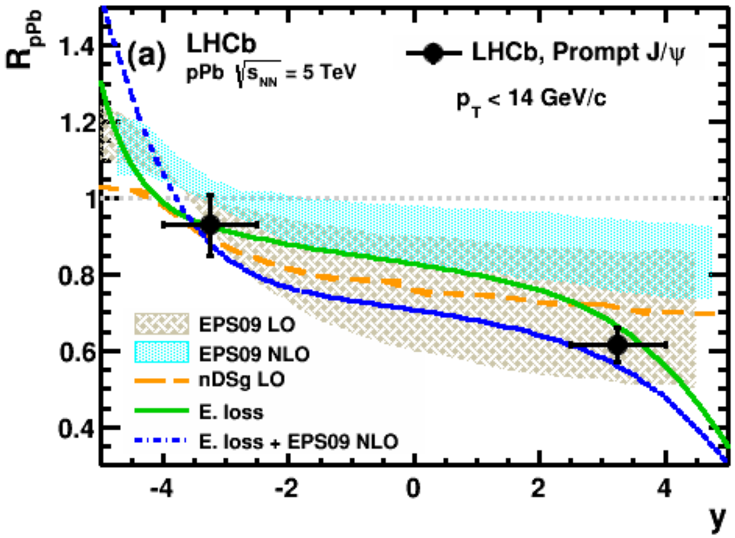


PRL 108 (2012) 242004, Chao et al.;
arXiv:1209.4610, Shao & Chao

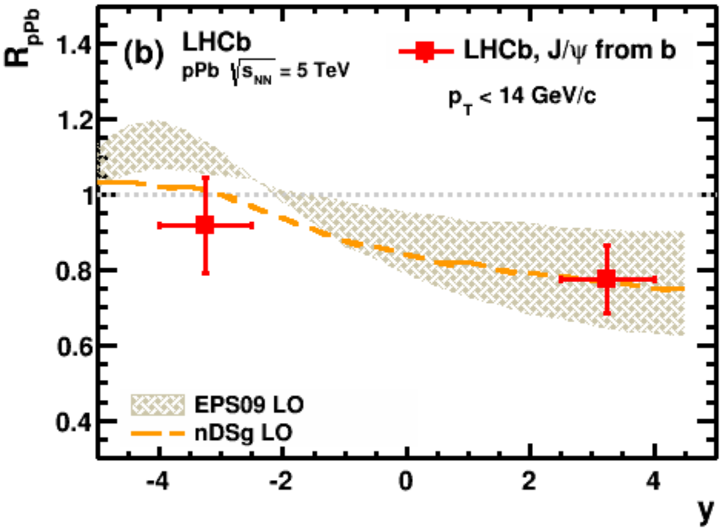
J/ψ production in p-Pb collisions

JHEP 1306 (2013) 064, LHCb

Nuclear modification factor: $R_{pA}(y) = \frac{1}{A} \cdot \frac{d\sigma_{pA}}{dy}(y)/\frac{d\sigma_{pp}}{dy}(y)$



Prompt J/ψ



J/Ψ from b

Clear cold nuclear matter effect identified in p-Pb collisions: benchmark for search of QGP signals in Pb-Pb data

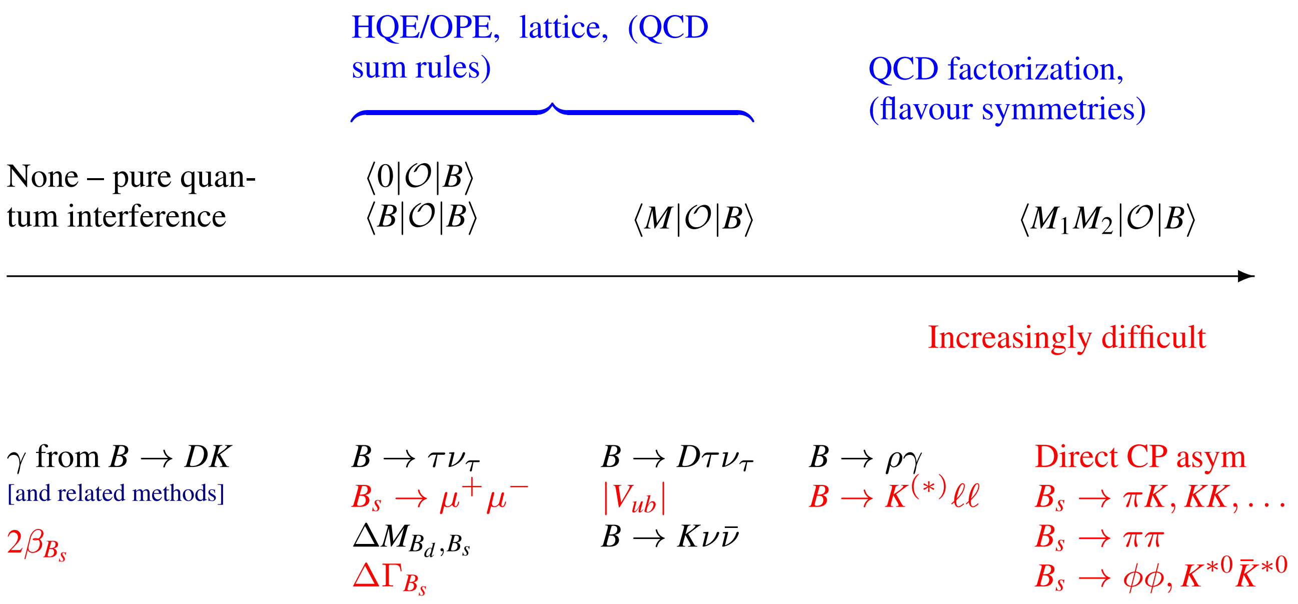
On Lattice QCD side

Hadronic parameters	**2002** **[hep-ph/0211359]**	**2014** **[www.utfit.org]**
B_k	0.86 (17%)	0.766（1.3%）
f_{Bs}	0.238 MeV (13%)	0.227 (2%)
f_{Bs}/f_B	1.24 (6%)	1.20 (1.8%)
B_{Bs}	1.34 (9%)	1.33 (4.5%)
B_{Bs}/B_B	1.00 (3%)	1.06 (10%)

Important progresses made in methods, computation power and algorithms

Further improvement desirable

Hadronic matrix elements



HQE/OPE, lattice, (QCD sum rules)

QCD factorization, (flavour symmetries)

None – pure quantum interference

$\langle 0|\mathcal{O}|B\rangle$
$\langle B|\mathcal{O}|B\rangle$

$\langle M|\mathcal{O}|B\rangle$

$\langle M_1 M_2|\mathcal{O}|B\rangle$

Increasingly difficult

γ from $B \to DK$
[and related methods]
$2\beta_{B_s}$

$B \to \tau\nu_\tau$
$B_s \to \mu^+\mu^-$
$\Delta M_{B_d,B_s}$
$\Delta\Gamma_{B_s}$

$B \to D\tau\nu_\tau$
$|V_{ub}|$
$B \to K\nu\bar{\nu}$

$B \to \rho\gamma$
$B \to K^{(*)}\ell\ell$

Direct CP asym
$B_s \to \pi K, KK, \ldots$
$B_s \to \pi\pi$
$B_s \to \phi\phi, K^{*0}\bar{K}^{*0}$

Many efforts made in pQCD (e.g. NNLO for radiative decays, NLO (EW) and NNLO (QCD) for $B_s \to \mu^+\mu^-$)

No suitable method to reliably account for long distance contributions (e.g. penguin pollution in b→c cbar s decays, charm sector)

Wish list to theoreticians

- Significant improvement in precision of hadronic parameters from Lattice QCD

Form factors, bag parameters, decay constants, ME, …

- Reliable QCD calculation methods

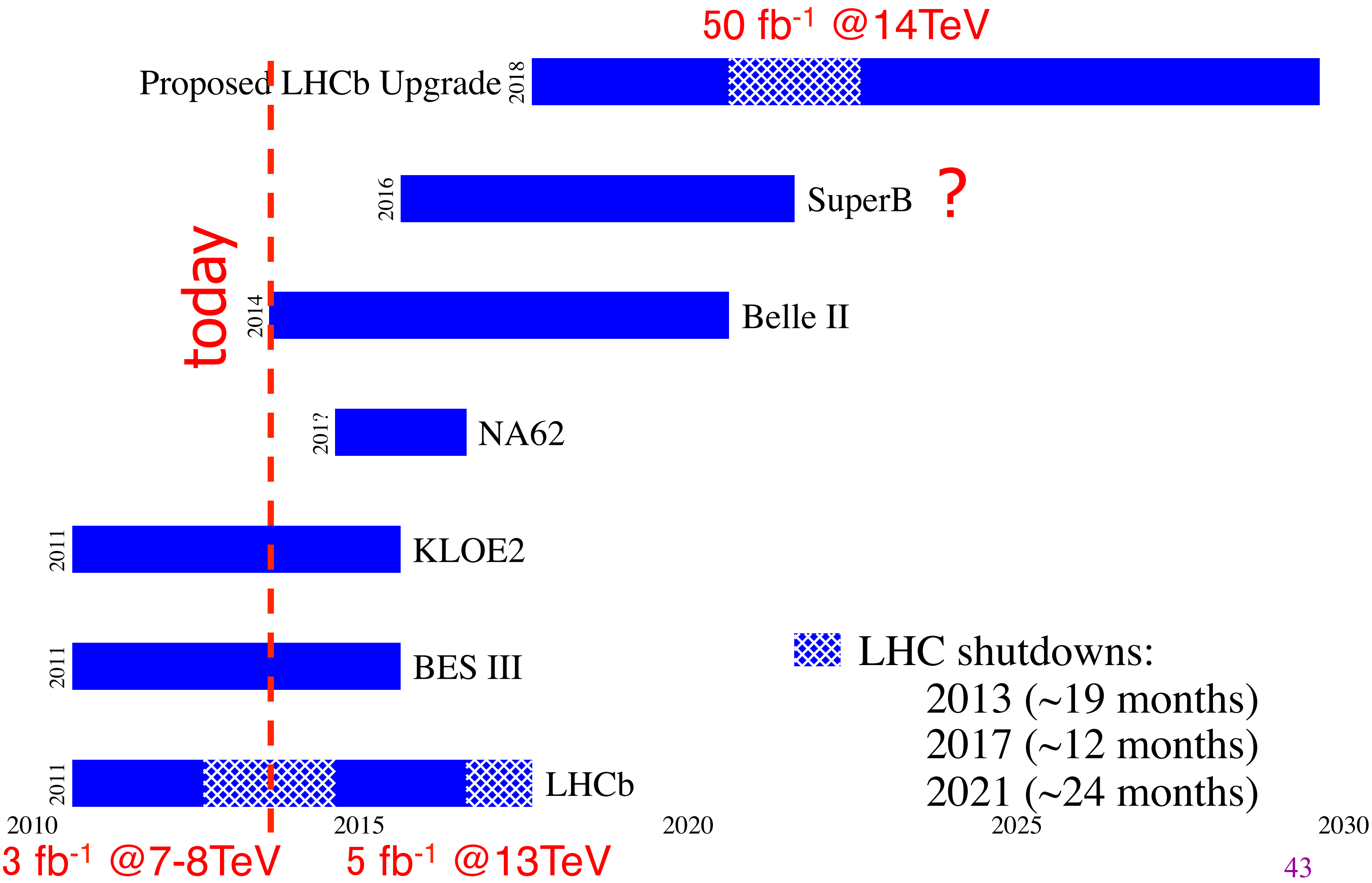
SM predictions of CPV in B & charm sector
penguin pollution in b→c cbar s decays
SM prediction of R(D) and R(D*)
…

- Identification of many new observables

Clean, sensitive to NP and measurable

Future prospects

Flavor landscape till 2030



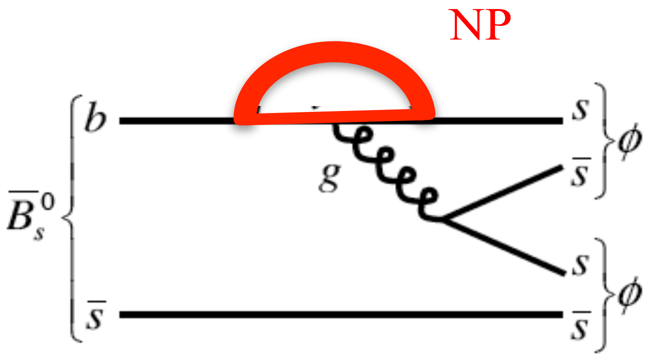
LHCb upgrade physics sensitivity

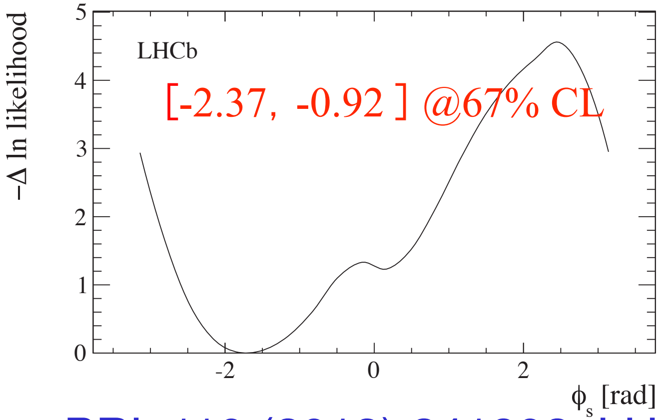
Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [137]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [213]	0.045	0.014	~ 0.01
	a_{sl}^s	6.4×10^{-3} [43]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	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 [43]	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 penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [67]	0.025	0.008	0.02
	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [67]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	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 ($B \to D^{(*)}K^{(*)}$)	$\sim$ 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}	–

10 times better precision in major heavy flavor measurements (B mixing and CPV, charm mixing and CPV and rare decays)

Promising modes for upgrade

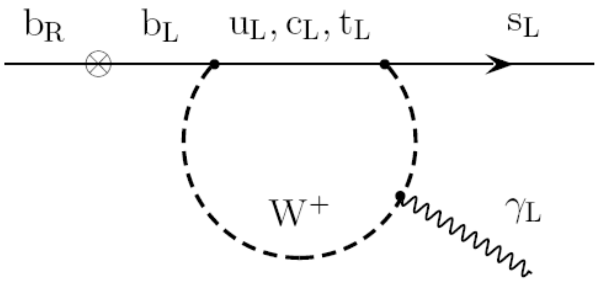
- CPV in $B_s \to \phi\phi$: probing NP in $b \to s$ penguin





PRL 110 (2013) 241802, LHCb

- $B_s \to \phi\gamma$: probing right handed NP



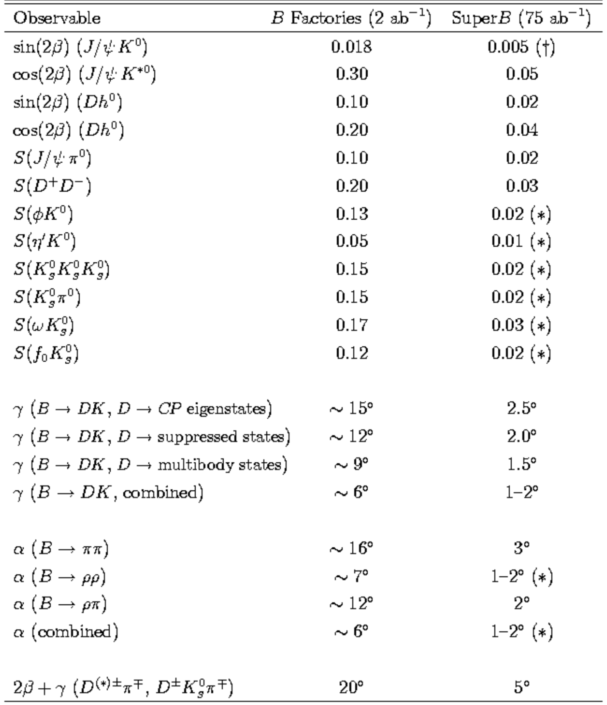
Measure effective lifetime to determine photon polarization

PLB 664 (2008) 174, Muheim, Xie, Zwicky

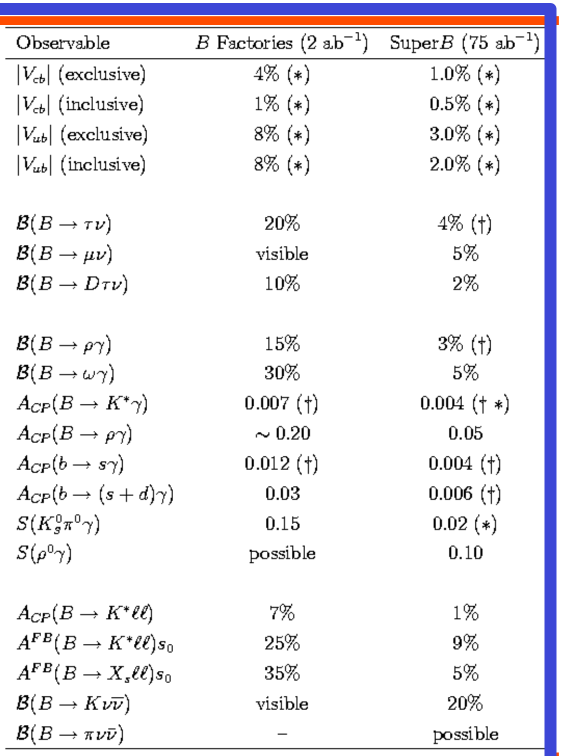
Belle II physics program

Strengths: radiative B decays
decays into ν
V_{ub}, V_{cb}

B Physics @ Y(4S)

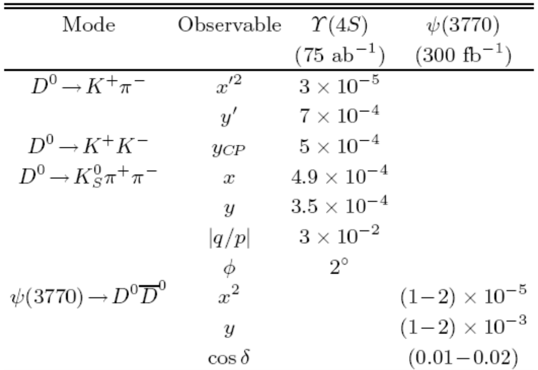


Observable	B Factories (2 ab^{-1})	Super$B$ (75 ab^{-1})
$\sin(2\beta)$ $(J/\psi\, K^0)$	0.018	0.005 (†)
$\cos(2\beta)$ $(J/\psi\, K^{*0})$	0.30	0.05
$\sin(2\beta)$ (Dh^0)	0.10	0.02
$\cos(2\beta)$ (Dh^0)	0.20	0.04
$S(J/\psi\, \pi^0)$	0.10	0.02
$S(D^+D^-)$	0.20	0.03
$S(\phi K^0)$	0.13	0.02 (∗)
$S(\eta' K^0)$	0.05	0.01 (∗)
$S(K^0_s K^0_s K^0_s)$	0.15	0.02 (∗)
$S(K^0_s \pi^0)$	0.15	0.02 (∗)
$S(\omega K^0_s)$	0.17	0.03 (∗)
$S(f_0 K^0_s)$	0.12	0.02 (∗)
γ $(B \to DK,\ D \to CP$ eigenstates)	$\sim 15°$	2.5°
γ $(B \to DK,\ D \to$ suppressed states)	$\sim 12°$	2.0°
γ $(B \to DK,\ D \to$ multibody states)	$\sim 9°$	1.5°
γ $(B \to DK$, combined)	$\sim 6°$	1–2°
α $(B \to \pi\pi)$	$\sim 16°$	3°
α $(B \to \rho\rho)$	$\sim 7°$	1–2° (∗)
α $(B \to \rho\pi)$	$\sim 12°$	2°
α (combined)	$\sim 6°$	1–2° (∗)
$2\beta + \gamma$ $(D^{(*)\pm}\pi^\mp,\ D^\pm K^0_s \pi^\mp)$	20°	5°



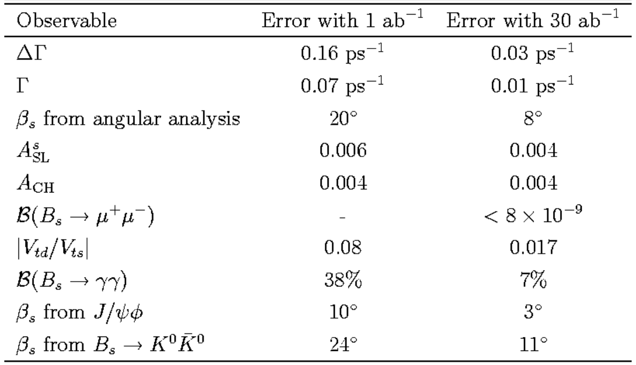
Observable	B Factories (2 ab^{-1})	Super$B$ (75 ab^{-1})
$\|V_{cb}\|$ (exclusive)	4% (∗)	1.0% (∗)
$\|V_{cb}\|$ (inclusive)	1% (∗)	0.5% (∗)
$\|V_{ub}\|$ (exclusive)	8% (∗)	3.0% (∗)
$\|V_{ub}\|$ (inclusive)	8% (∗)	2.0% (∗)
$\mathcal{B}(B \to \tau\nu)$	20%	4% (†)
$\mathcal{B}(B \to \mu\nu)$	visible	5%
$\mathcal{B}(B \to D\tau\nu)$	10%	2%
$\mathcal{B}(B \to \rho\gamma)$	15%	3% (†)
$\mathcal{B}(B \to \omega\gamma)$	30%	5%
$A_{CP}(B \to K^*\gamma)$	0.007 (†)	0.004 († ∗)
$A_{CP}(B \to \rho\gamma)$	~ 0.20	0.05
$A_{CP}(b \to s\gamma)$	0.012 (†)	0.004 (†)
$A_{CP}(b \to (s+d)\gamma)$	0.03	0.006 (†)
$S(K^0_s \pi^0 \gamma)$	0.15	0.02 (∗)
$S(\rho^0\gamma)$	possible	0.10
$A_{CP}(B \to K^*\ell\ell)$	7%	1%
$A^{FB}(B \to K^*\ell\ell)s_0$	25%	9%
$A^{FB}(B \to X_s\ell\ell)s_0$	35%	5%
$\mathcal{B}(B \to K\nu\overline{\nu})$	visible	20%
$\mathcal{B}(B \to \pi\nu\bar{\nu})$	–	possible

Charm mixing and CPV



Mode	Observable	$\Upsilon(4S)$ (75 ab^{-1})	$\psi(3770)$ (300 fb^{-1})
$D^0 \to K^+\pi^-$	x'^2	3×10^{-5}	
	y'	7×10^{-4}	
$D^0 \to K^+K^-$	y_{CP}	5×10^{-4}	
$D^0 \to K^0_S\pi^+\pi^-$	x	4.9×10^{-4}	
	y	3.5×10^{-4}	
	$\|q/p\|$	3×10^{-2}	
	ϕ	2°	
$\psi(3770) \to D^0\overline{D}^0$	x^2		$(1-2) \times 10^{-5}$
	y		$(1-2) \times 10^{-3}$
	$\cos\delta$		$(0.01-0.02)$

B_s Physics @ Y(5S)



Observable	Error with 1 ab^{-1}	Error with 30 ab^{-1}
$\Delta\Gamma$	0.16 ps^{-1}	0.03 ps^{-1}
Γ	0.07 ps^{-1}	0.01 ps^{-1}
β_s from angular analysis	20°	8°
$A^s_{\rm SL}$	0.006	0.004
$A_{\rm CH}$	0.004	0.004
$\mathcal{B}(B_s \to \mu^+\mu^-)$	-	$< 8 \times 10^{-9}$
$\|V_{td}/V_{ts}\|$	0.08	0.017
$\mathcal{B}(B_s \to \gamma\gamma)$	38%	7%
β_s from $J/\psi\phi$	10°	3°
β_s from $B_s \to K^0\bar{K}^0$	24°	11°

What will we learn in 2030?

- Reduce errors of key flavor measurements by a factor of 10
  - Probe few % NP contribution in FCNC processes
- Obtain the pattern of many flavor observables in B and D decays
  - May tell us a lot about the allowed form of NP and severely limit NP parameter space
- Measure CP violation in B and D systems very precisely
  - Hopefully tell us whether there is new source of CP violation

Conclusions

- 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.
- Regardless of whether LHC will discover NP or not, flavor physics will tell us a lot.
- Go for higher precision, wider scope & better understanding of SM!