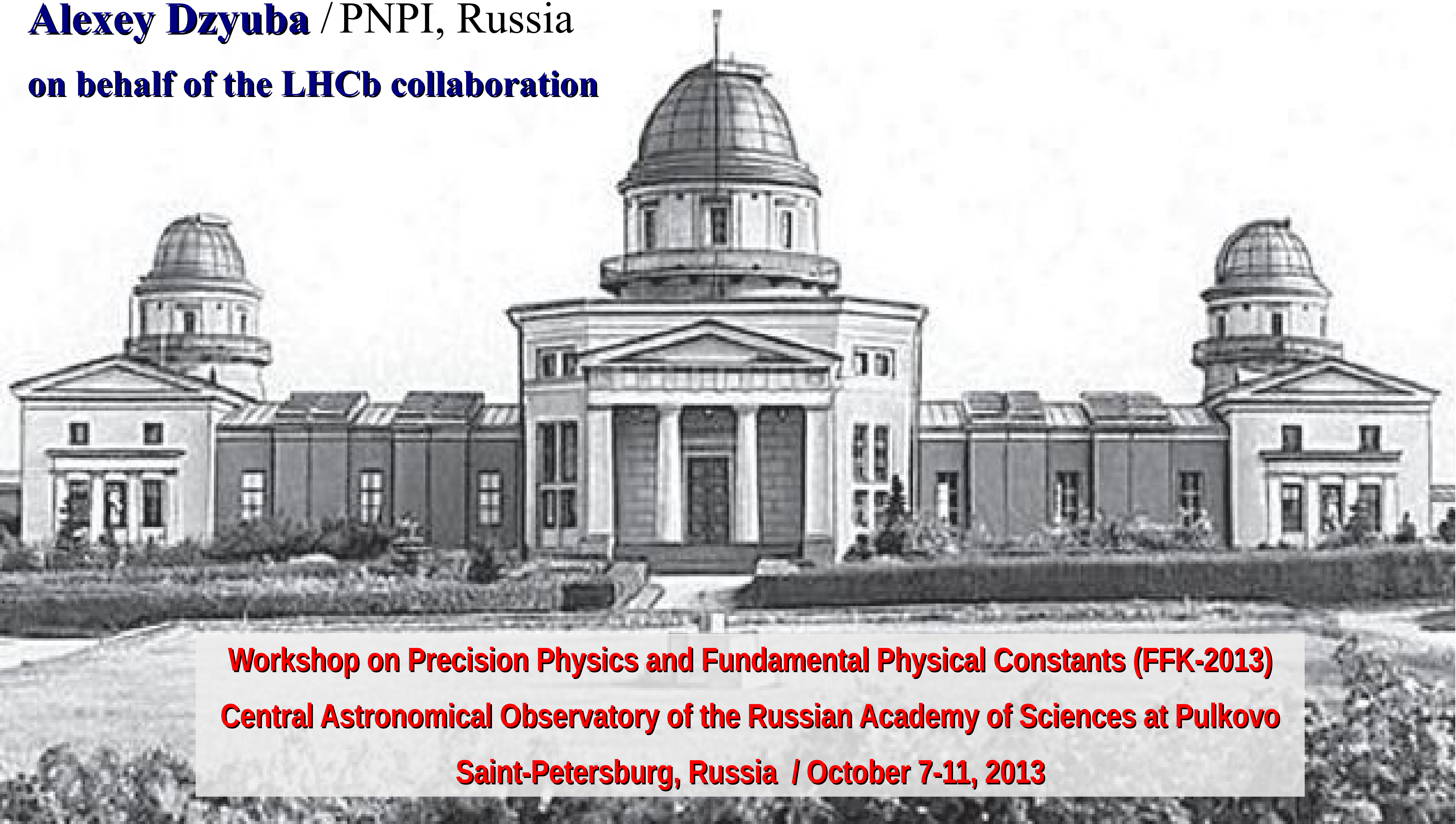
LHCb precision measurements

7th of October 2013

Alexey Dzyuba / PNPI, Russia

on behalf of the LHCb collaboration



Workshop on Precision Physics and Fundamental Physical Constants (FFK-2013)

Central Astronomical Observatory of the Russian Academy of Sciences at Pulkovo

Saint-Petersburg, Russia / October 7-11, 2013

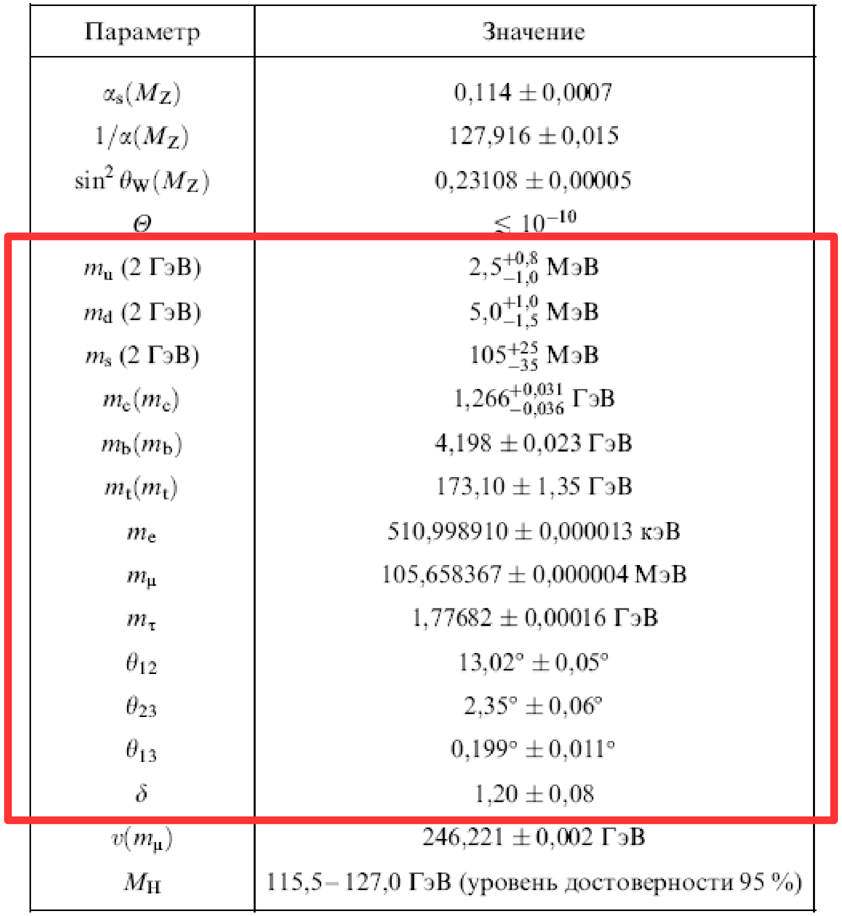
Outline

Main goal of this talk: Show how precise LHCb measurements in b- and c-sectors make constraints on fundamental prameters of Standard Model (SM) and provide a New Physics (NP) searches.

- Standard Model (SM) and its difficulties
  - Cabibbo-Kobayashi-Maskawa (CKM) matrix, CP violation (CPV)
  - Why and where to find New Physics (NP)? MFV or not?
  - Power of indirect measurements
- LHCb setup (apparatus, physical program *etc.*)
- Selected results
  - Mixing, CP violation, CKM γ in B systems
  - Mixing and CP violation in charm sector
  - Rare decays ($B \to 2\mu$, $B \to K^*2\mu$)
- Summary and Outlook (what can be achieved after upgrade?)

Introduction

Standard Model



Параметр	Значение
$\alpha_s(M_Z)$	$0{,}114 \pm 0{,}0007$
$1/\alpha(M_Z)$	$127{,}916 \pm 0{,}015$
$\sin^2\theta_W(M_Z)$	$0{,}23108 \pm 0{,}00005$
Θ	$\lesssim 10^{-10}$
m_u (2 ГэВ)	$2{,}5^{+0{,}8}_{-1{,}0}$ МэВ
m_d (2 ГэВ)	$5{,}0^{+1{,}0}_{-1{,}5}$ МэВ
m_s (2 ГэВ)	105^{+25}_{-35} МэВ
$m_c(m_c)$	$1{,}266^{+0{,}031}_{-0{,}036}$ ГэВ
$m_b(m_b)$	$4{,}198 \pm 0{,}023$ ГэВ
$m_t(m_t)$	$173{,}10 \pm 1{,}35$ ГэВ
m_e	$510{,}998910 \pm 0{,}000013$ кэВ
m_μ	$105{,}658367 \pm 0{,}000004$ МэВ
m_τ	$1{,}77682 \pm 0{,}00016$ ГэВ
θ_{12}	$13{,}02^\circ \pm 0{,}05^\circ$
θ_{23}	$2{,}35^\circ \pm 0{,}06^\circ$
θ_{13}	$0{,}199^\circ \pm 0{,}011^\circ$
δ	$1{,}20 \pm 0{,}08$
$v(m_\mu)$	$246{,}221 \pm 0{,}002$ ГэВ
M_H	115,5 – 127,0 ГэВ (уровень достоверности 95 %)

Flavour sector of SM

No doubt that SM is great achievement!

(no conflict with HEP)

Reasons for NP:

1) Neutrino sector
   - mass
   - oscillations

2) Radiative correction to M(Higgs)
   - fine tuning
   - desert between M_{EW} and M_{GUT}

3) Astrophysics
   - dark matter
   - baryon asymmetry of Universe **(CPV is needed)**

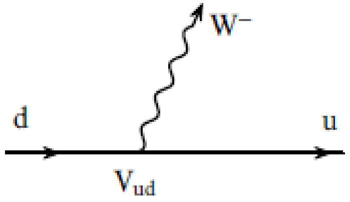
SUSY good candidate to solve 2) & 3)

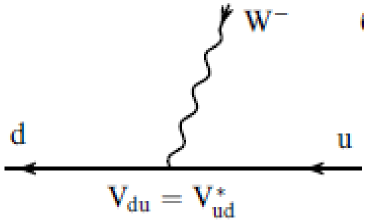
Cabibbo-Kobayashi-Maskawa

- **Flavour eigenstates do not coincide with week eigenstates**
- **Mixing matrix V_{CKM}**
- **CP violating phase appears than there are 3 generations of fermions**
- **Elements of the CKM matrix appear at the decay vertexes**

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$A(\mathrm{d} \to \mathrm{u}) \propto \mathrm{i}\, \frac{g_2}{2\sqrt{2}}\, \bar{u} V_{\mathrm{ud}} \gamma_\mu (1+\gamma_5) d \qquad A(\mathrm{u} \to \mathrm{d}) \propto \mathrm{i}\, \frac{g_2}{2\sqrt{2}}\, \bar{d} V^*_{\mathrm{ud}} \gamma_\mu (1+\gamma_5) u$$





Wolfenstein parametrization

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\varrho - \mathrm{i}\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \varrho - \mathrm{i}\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4).$$

$$s_{ij} = \sin\vartheta_{ij},\ c_{ij} = \cos\vartheta_{ij} \qquad c_{13} = c_{23} = 1$$

$$s_{12} = \lambda\,, \quad s_{23} = A\lambda^2\,, \quad s_{13}\exp(-\mathrm{i}\delta) = A\lambda^3(\rho - \mathrm{i}\eta)$$

$$s_{12} = \lambda = 0{,}222 \pm 0{,}002\,, \quad s_{23} = O(10^{-2})\,, \quad s_{13} = O(10^{-3})$$

Unitarity of CKM matrix

Unitarity is a very important property of V_{CKM}

$$V^{+}_{\mathrm{CKM}} V_{\mathrm{CKM}} = V_{\mathrm{CKM}} V^{+}_{\mathrm{CKM}} = 1 \qquad VV^{+} = \sum_{l} V_{al} V^{*}_{bl} = \delta_{ab} \,,$$

$$a, b = \mathrm{u, c, t} \quad l, m = \mathrm{d, s, b} \qquad V^{+}V = \sum_{a} V^{*}_{al} V_{am} = \delta_{lm} \,,$$

Neutral Currents can be written in the first order of EW theory as:

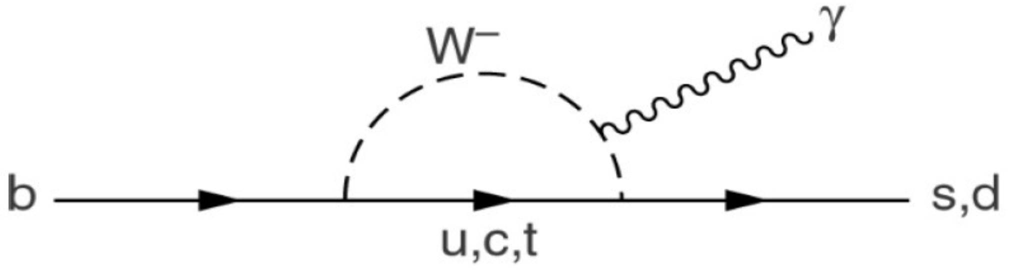
$$(\bar{\mathrm{u}}\,\bar{\mathrm{c}}\,\bar{\mathrm{t}}\,)\,\gamma_{\mu}(a + c\gamma_5)\begin{pmatrix}\mathrm{u}\\ \mathrm{c}\\ \mathrm{t}\end{pmatrix} + (\bar{\mathrm{d}}\,'\bar{\mathrm{s}}\,'\bar{\mathrm{b}}\,')\,\gamma_{\mu}(a + c\gamma_5)\begin{pmatrix}\mathrm{d}\,'\\ \mathrm{s}\,'\\ \mathrm{b}\,'\end{pmatrix} =$$

$$= (\bar{\mathrm{u}}\,\bar{\mathrm{c}}\,\bar{\mathrm{t}}\,)\,\gamma_{\mu}(a + c\gamma_5)\begin{pmatrix}\mathrm{u}\\ \mathrm{c}\\ \mathrm{t}\end{pmatrix} + (\bar{\mathrm{d}}\,\bar{\mathrm{s}}\,\bar{\mathrm{b}})\,\gamma_{\mu}(a + c\gamma_5)V^{+}_{\mathrm{CKM}} V_{\mathrm{CKM}}\begin{pmatrix}\mathrm{d}\\ \mathrm{s}\\ \mathrm{b}\end{pmatrix}.$$

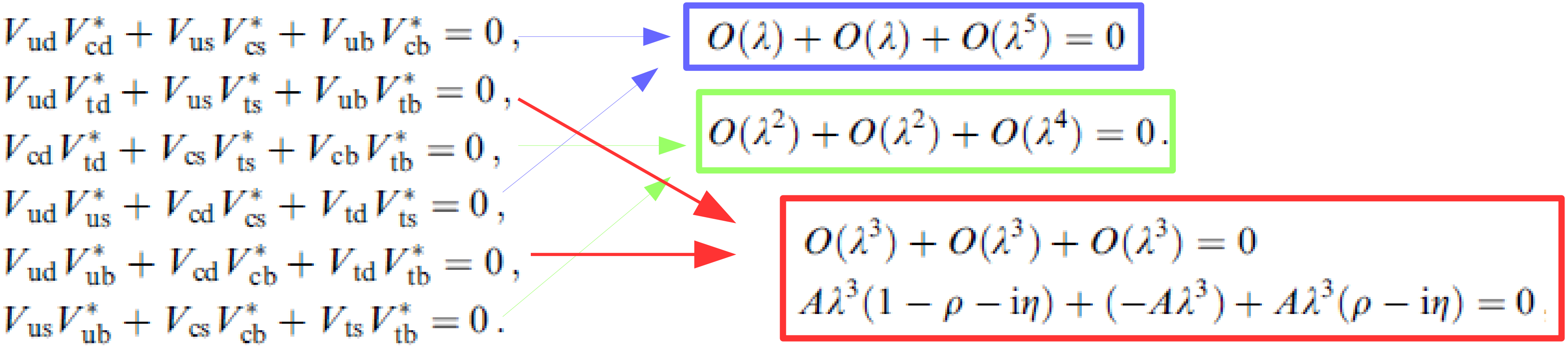
As a result Flavour Changing Neutral Currents (FCNC) is forbidden at tree level but can appear at the loop level!

$$\xcancel{(\bar{\mathrm{u}}\,\mathrm{c})_{V-A,\,V+A}\,, \quad (\bar{\mathrm{d}}\,\mathrm{s})_{V-A,\,V+A}\,, \quad \ldots}$$

For example :



Unitarity triangles



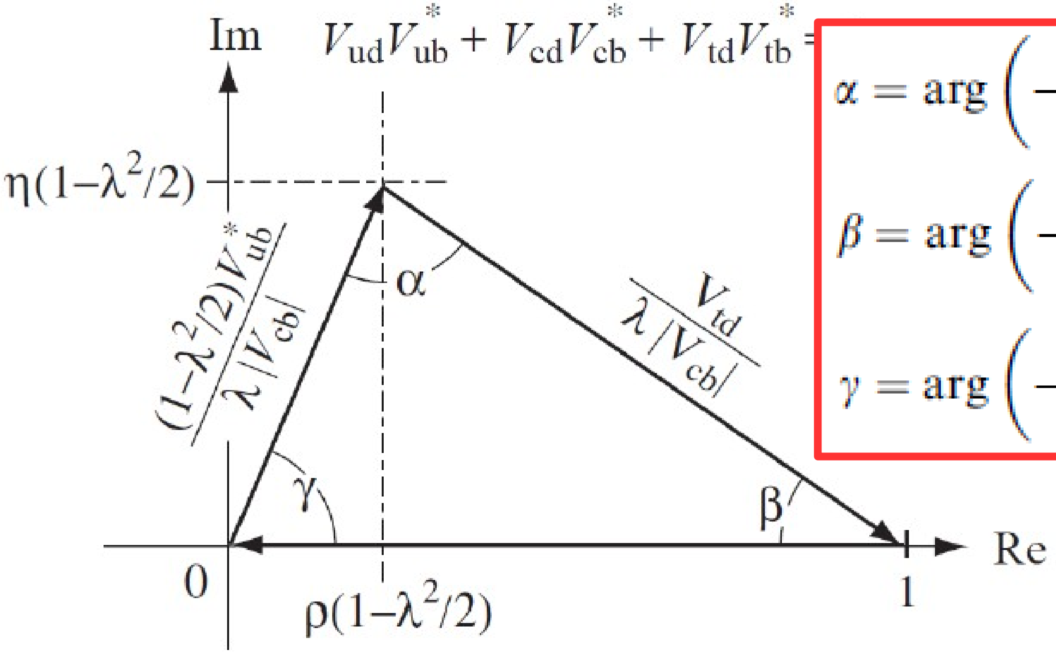
$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0\,,$$
$$V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0\,,$$
$$V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0\,,$$
$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0\,,$$
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0\,,$$
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0\,.$$

$$O(\lambda) + O(\lambda) + O(\lambda^5) = 0$$

$$O(\lambda^2) + O(\lambda^2) + O(\lambda^4) = 0\,.$$

$$O(\lambda^3) + O(\lambda^3) + O(\lambda^3) = 0$$
$$A\lambda^3(1-\rho-i\eta) + (-A\lambda^3) + A\lambda^3(\rho-i\eta) = 0$$

- **Two of six relation have all three contribution of same size**
- **Can be drawn as triangle at the complex plane**
- **Almost all SM CPV is sitting here**
- **Parameters of the triangle can be measured at the decays**



$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$
$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$
$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Unitarity triangles

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0\,,$$
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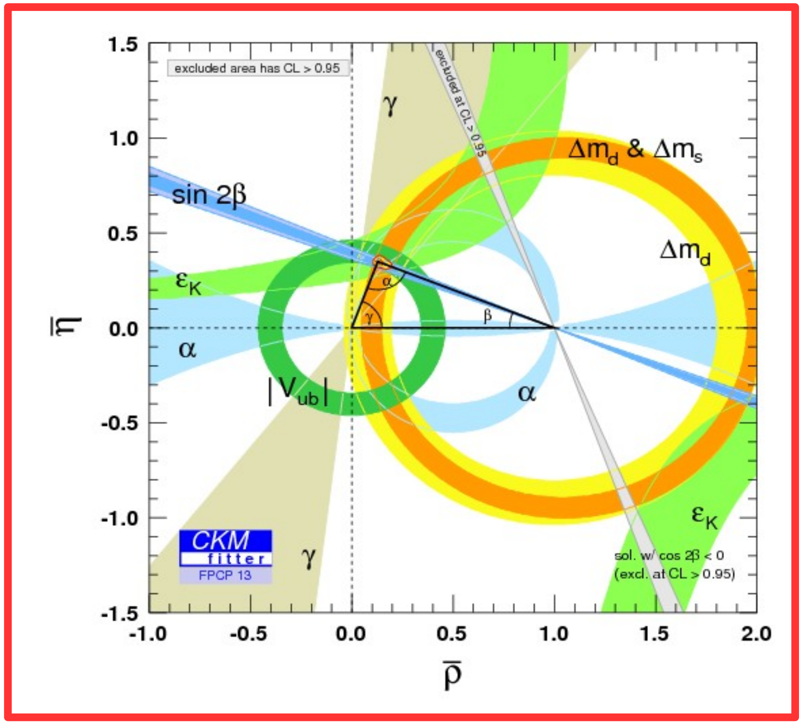
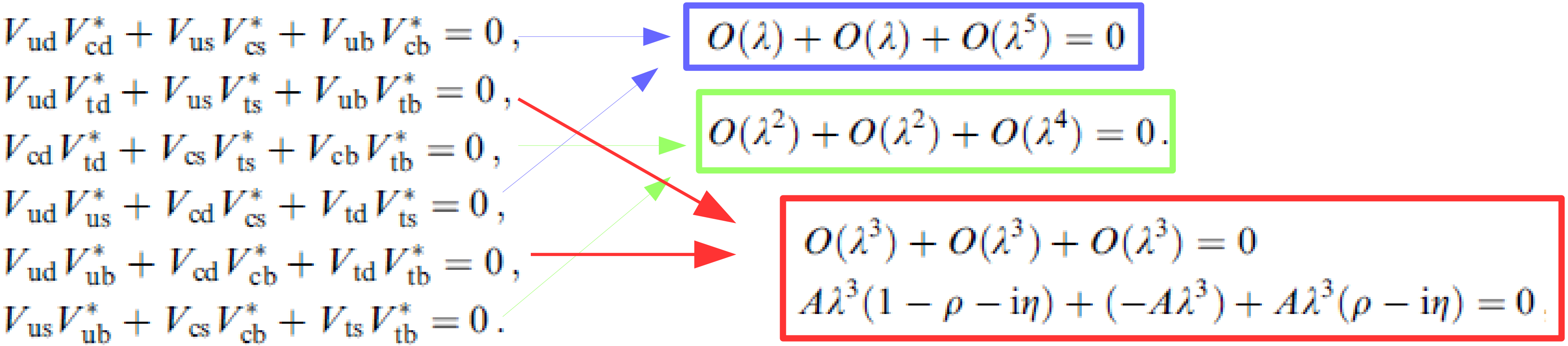
$$\boxed{\begin{aligned} &O(\lambda^3) + O(\lambda^3) + O(\lambda^3) = 0 \\ &A\lambda^3(1-\rho-i\eta) + (-A\lambda^3) + A\lambda^3(\rho-i\eta) = 0 \end{aligned}}$$



$$\bar\rho = \rho\left(1 - \frac{\lambda^2}{2}\right), \qquad \bar\eta = \eta\left(1 - \frac{\lambda^2}{2}\right)$$

- **Many different experimental constraints**
- **There are another fitting groups**
- **In this talk I will show LHCb results on γ, Δm**

Unitarity triangles



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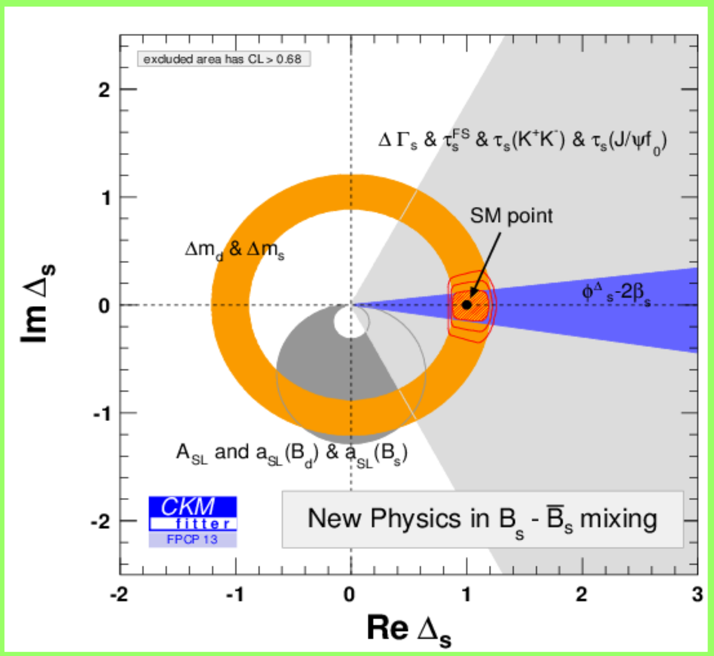


- **Other triangles are also very important**
- **In this talk I will show LHCb results on φs**
- **Note: Another consequence of V_{CKM} unitarity is that squares of elements in raws and columns must be equal to one. [see for example RPP 73, 046301]**

NP and flavour symmetry; Wilson's coefficients

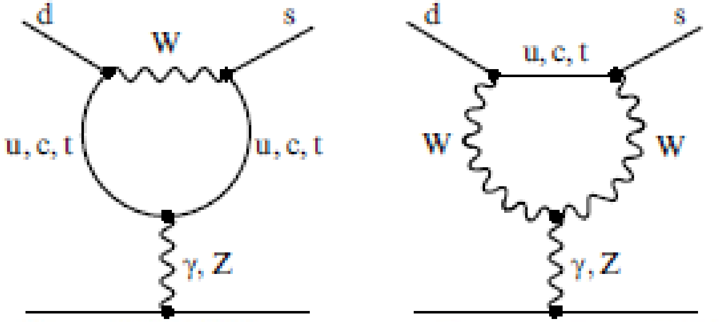
- **Progress of theory calculations allows to take into account QCD corrections needed for SM FCNC implementation to decays. (Calculation of C_i in SM as well as quite precise predictions for certain processes)**
- **H_{eff} is an effective way to test different classes of possible NPs, because C_i depend on their flavour structures.**
- **Minimal Flavour Violation (MFV) paradigm: NP has same source of FV as SM => real numbers, same CPV effects, relations like:**

$$\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_d \to \mu^+\mu^-)} = \frac{\tau_{B_s} f_{B_s}^2 m_{B_s} |V_{ts}|^2}{\tau_{B_d} f_{B_d}^2 m_{B_d} |V_{td}|^2}$$

$\Delta F = 1$ operators in the SM and in MFV

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} \frac{e^2}{16\pi^2} V_{tb} V_{ts}^* \sum_i C_i O_i + \text{h.c.}$$

Example



$O_9 = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$ $O_{10} = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$

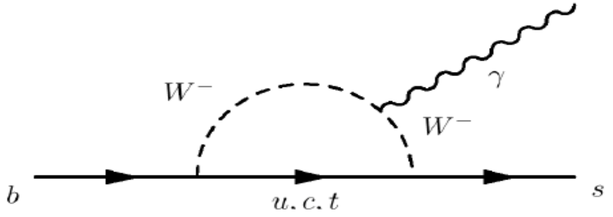
- **If NP contains additional FV sources of C_i become complex as well as new CPV effects might appear!**

Indirect measurements at LHC

- How NP related to flavour physics?
- Is NP weakly coupled to flavour sector (MFV) or at very high scale?

  Important to have a **probes beyond LHC energies** (direct observation)!
- Better to use processes which are either forbidden either highly suppressed in SM

  Flavour Changing Neutral Currents (FCNC) can be such a probe



- Other possibilities **Lepton Flavour Violation (LFV) m_{LQ}>100TeV**

  [not discussed here, but see LHCb result on B→eμ in PRL 111, 141801]
- **CPV in charm sector**

Power of indirect measurements

Example #1: CP violation in kaon system

Has been done when only 3 quark were known

1972 Kabayashi-Maskawa 6-quark model

~ 13 years before Upsilon discovery

Example #2: Weak neutral current (Gargamelle bubble chamber)

~ 10 years before Z discovery at UA1/2

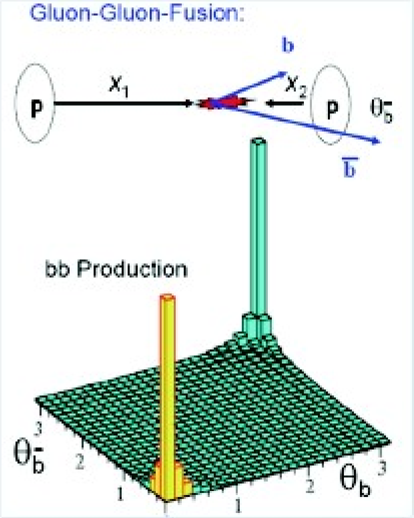
Example #3: ARGUS collaboration report large B-mixing

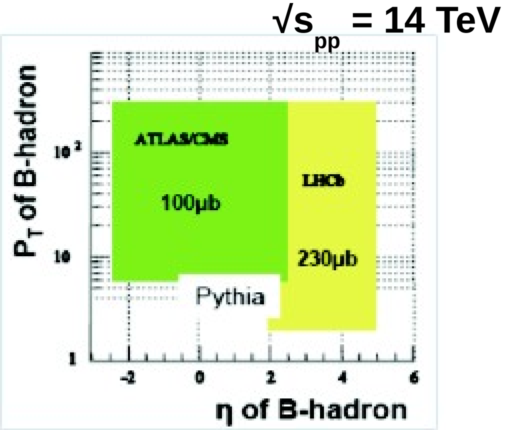
Suggest large mass of top quark

~8 years *t* has been discovered at Tevatron

LHCb features

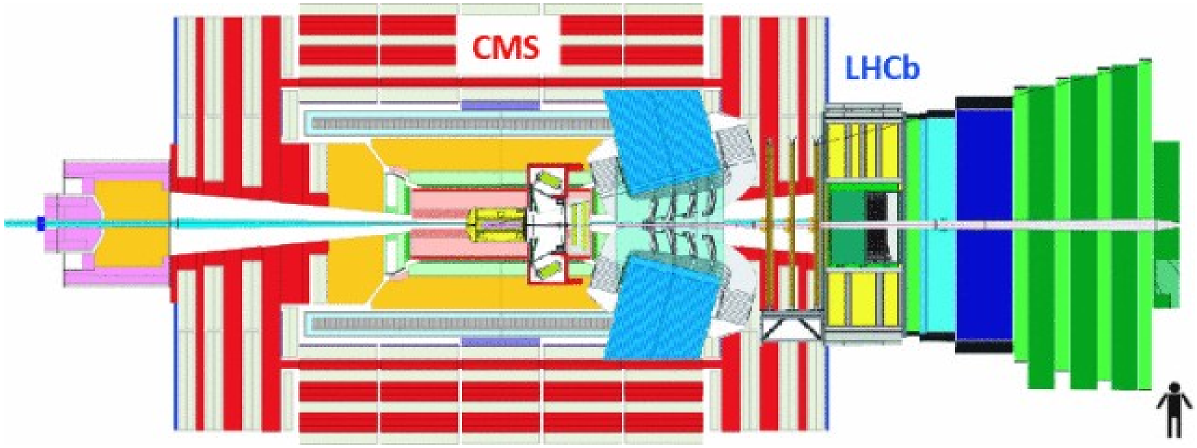
Beauty and charm production





- **LHCb: forward spectrometer** $2 < \eta < 5$

  (ATLAS & CMS: $|\eta|<2.5$)



- In LHCb acceptance (*pp*-collisions $\sqrt{s}$ = 7TeV)

$$\sigma(b\bar{b}) = 75.3 \pm 5.4 \pm 13.0\ \mu b$$

Phys.Lett.B694 (2010) 209-216

$$\sigma(c\bar{c}) = 1419 \pm 12 \pm 116\ \mu b \sim 20 \times \sigma(b\bar{b})$$

Largest charm samples in the world

Nucl.Phys.B871 (2013) 1

Experimental setup

$\epsilon_{PID}(\mu) \approx 97\ \%$

MisID ($\pi \to \mu$) $\approx 3\ \%$

$\epsilon_{PID}(K) \approx 95\ \%$

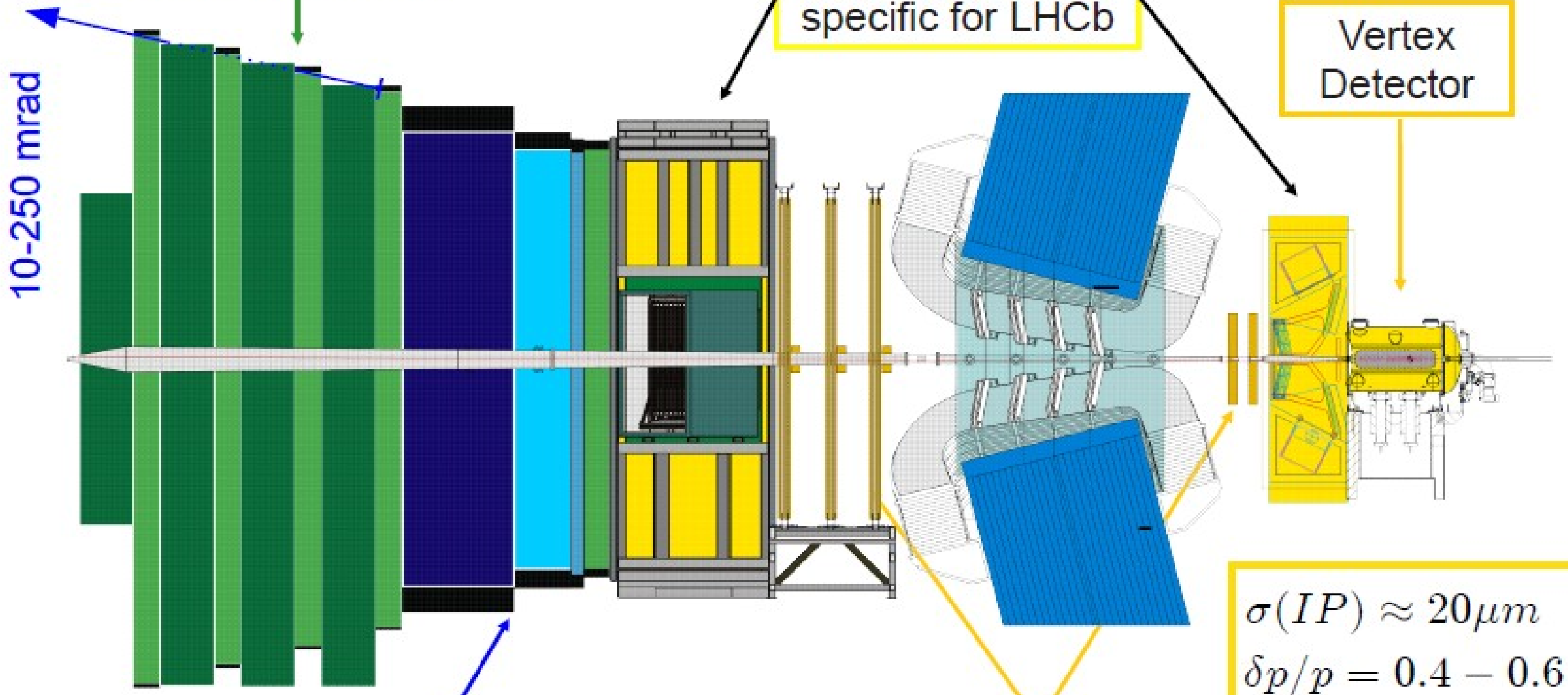
MisID ($K \to \pi$) $\approx 5\ \%$

Muon System

RICH Detectors specific for LHCb

JINST 3, (2008) S08005

Vertex Detector



$\sigma(IP) \approx 20 \mu m$

$\delta p/p = 0.4 - 0.6\ \%$

$\epsilon_{track} > 96\ \%$

$\frac{\sigma}{E} \approx 1\% \otimes \frac{10\%}{\sqrt{E[GeV]}}$

$\epsilon_{PID}(e) \approx 95\ \%$

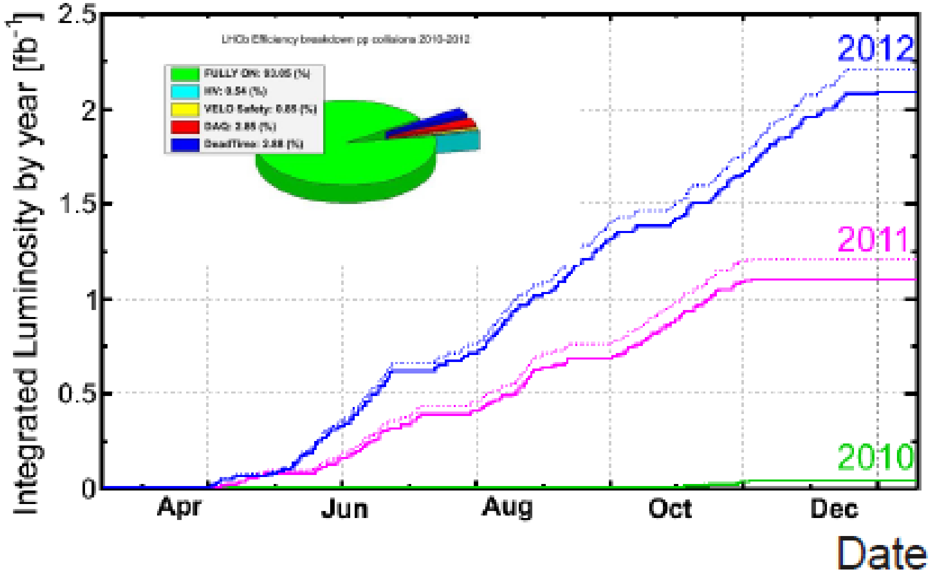
MisID ($e \to h$) $\approx 5\ \%$

Calorimeters

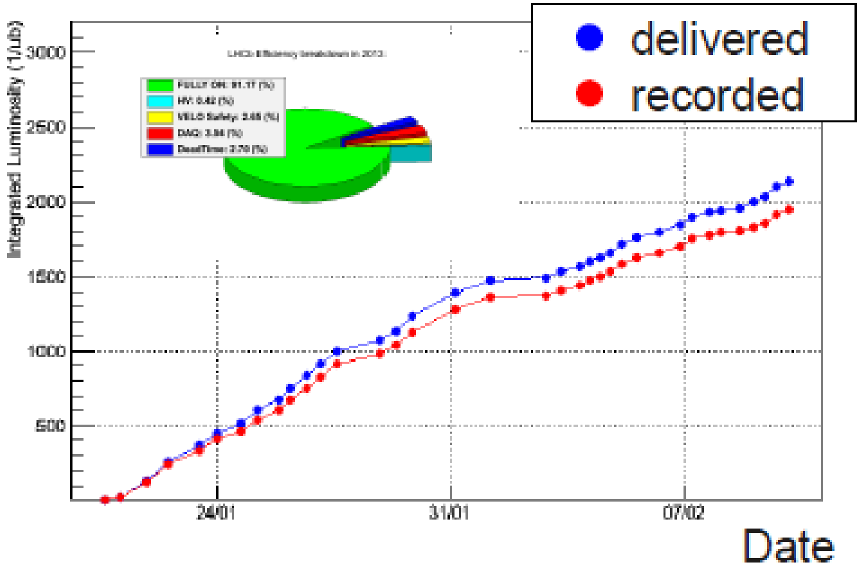
Tracking System

Operation in 2010/12

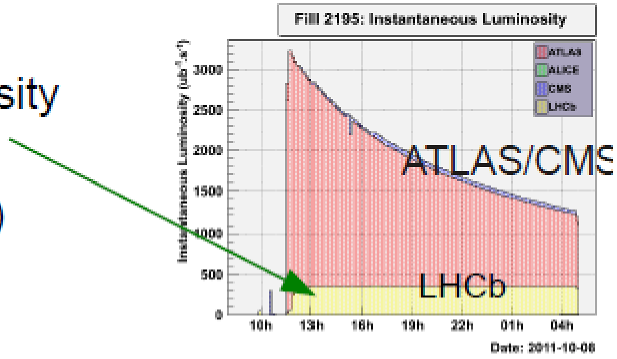
pp-collisions at $\sqrt{s}$ = 7 & 8 TeV (2011-12)



pPb-collisions at $\sqrt{s_{NN}}$ = 5 TeV in 2013



- LHCb operates with high efficiency
- Take data at constant instantaneous luminosity rate: $\mathcal{L} \approx 4 \times 10^{32}\, cm^{-2} s^{-1}$
  (factor 2 larger than design luminosity)
- Visible pp interactions per bunch crossing
  μ = 1.7 (50 ns bunch spacing)



We also have set of pp data at $\sqrt{s}$ =2.76 TeV (collected in 2011)

LHCb data analysis

Efficient trigger (L0/HLT1/HLT2): 40MHz → 5kHz

Tagging if needed

Event selection

Kinematical and topological info
(pT, p, IP, vertex and track quality)

PID information

Cut based or multivariate selection
BDT, Neurobayes, *etc.*

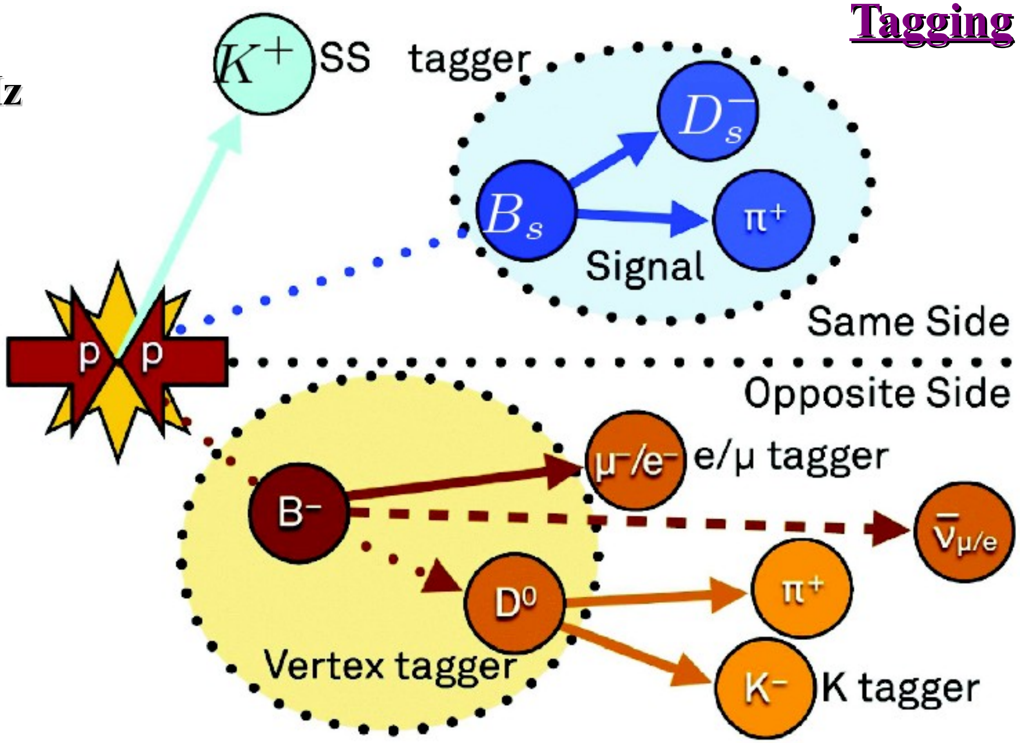
Optimization of selection
Using MC
Using small sample of real data

Angular analysis++

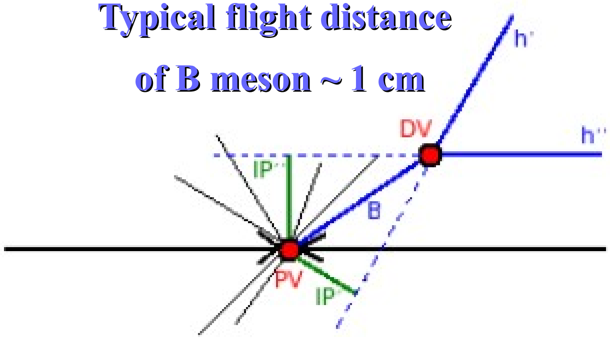
Check for systematics

And a lot of other checks!

Tagging



Typical flight distance of B meson ~ 1 cm



Selection using IP:

PV = Primary Vertex

DV = Daughter Vertex

(secondary vertex)

Physics program of LHCb

GOAL: **Search for evidence of NP in CP violation and rare decays of beauty and charm hadrons.**
(Probing large mass scales via study of virtual quantum loops of new particles)

LHCb results are available in more that 160 papers submitted to journals and 110 conference contributions

https://cds.cern.ch/collection/LHCb%20Conference%20Contributions?ln=en
https://cds.cern.ch/collection/LHCb%20Papers?ln=en

Main direction of searches:

1) Rare decays
  RD with di-muons
2) Properties of the B systems
  CPV, Δms; Γs, ΔΓ, φs ; CKM γ determination
3) Mixing and CPV in the D systems
  Mixing observ., ΔA(CP)

Partially covered in this talk

4) Spectroscopy and production of heavy quarks

5) Electroweak physics

6) Soft QCD physics, pA and Ap results

Not covered =(

Properties of the B (B^+, B^0, B_s) systems

1) Direct CP asymmetry in $B_{(s)}^0$ decays

2) B_s^0 oscillation frequency measurement

3) Mixing induced CPV in B_s^0, e.g: $B_s^0 \rightarrow J/\psi\phi$ and $B_s^0 \rightarrow J/\psi f(980)$

4) CKM angle γ

Direct CP asymmetry in $B_{(s)}^{0}$ decays

Direct CP asymmetry hard to calculate,
but "easy" to measure

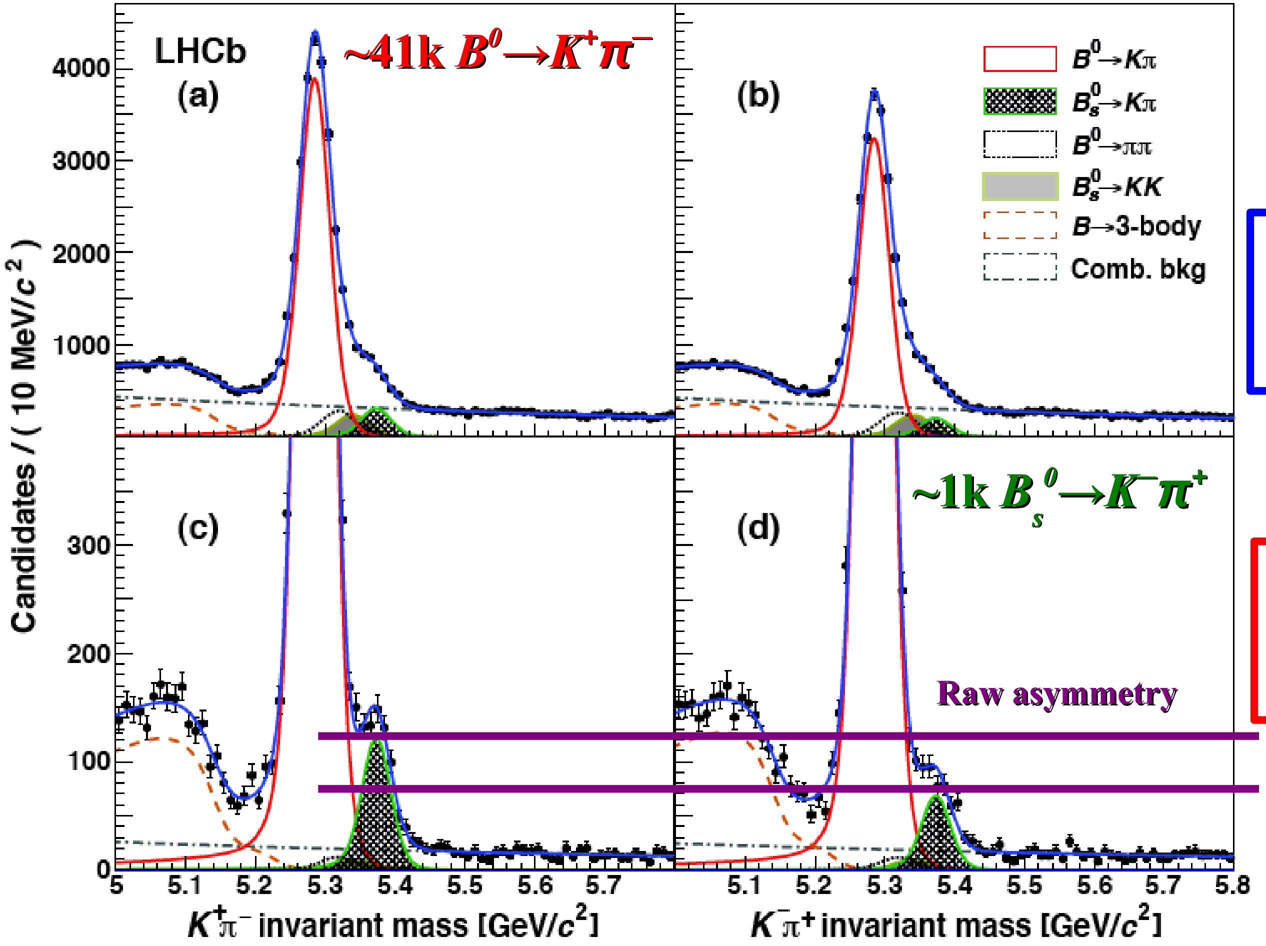
1 fb^{-1} dataset, PRL 110, 221601

CP asymmetry: $A_{CP} = A_{\rm raw} - A_{\Delta}$

$$A_{\Delta}(B^0_{(s)} \to K\pi) = \zeta_{d(s)} A_{\rm D}(K\pi) + \kappa_{d(s)} A_{\rm P}(B^0_{(s)})$$

Detection asymmetry

Production asymmetry



~41k $B^0 \to K^+\pi^-$

~1k $B_s^0 \to K^-\pi^+$

Raw asymmetry

Oscillation considered in the analysis!

$A_{CP}(B^0 \to K^+\pi^-)$ =

= -0.080 ± 0.007$_{\rm stat}$ ± 0.003$_{\rm syst}$

World best precision

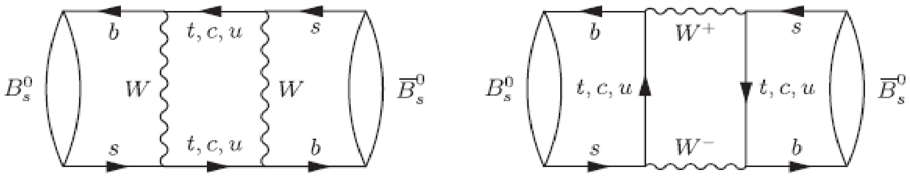
$A_{CP}(B_s^0 \to K^-\pi^+)$ =

= 0.27 ± 0.04$_{\rm stat}$ ± 0.01$_{\rm syst}$

1st observation (6.5σ) of direct CP asymmetry in B_s^0 system

Oscillation frequency for B_s

Corresponding SM box-diagrams



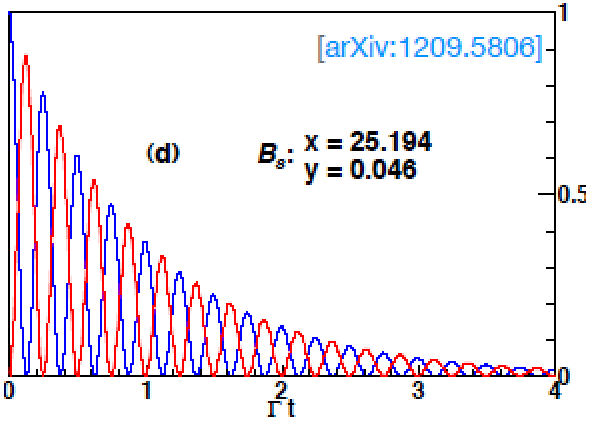
B_s: Fast oscillations

Excellent time resolution required!

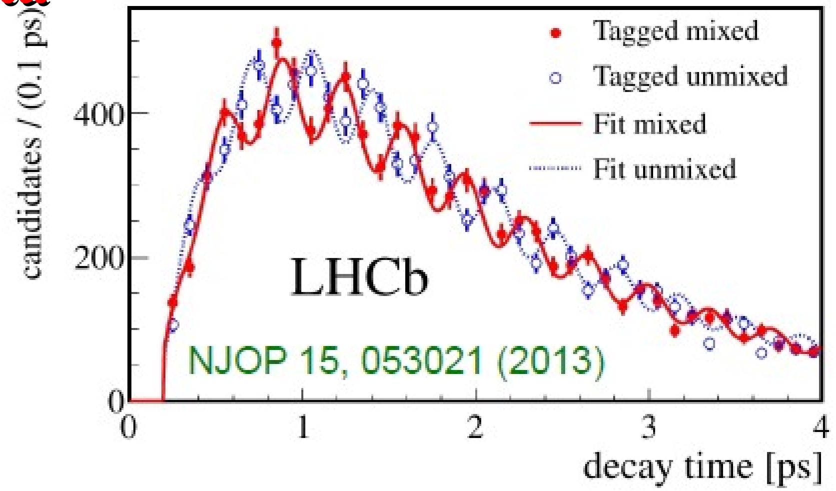
$$\Gamma = (\Gamma_L + \Gamma_H) / 2;$$

$$\Delta m_s = M_H - M_L$$

$$x = (M_H - M_L) / \Gamma; \qquad y = (\Gamma_L - \Gamma_H) / 2\Gamma$$



Data



NJOP 15, 053021 (2013)

Measure time dependent decay rate of $B_s \to D_s^- \pi^+$ and $\bar{B}_s \to D_s^+ \pi^-$

- $PDF \propto \left[e^{-\Gamma t} \cdot \left(cosh \left(\frac{\Delta\Gamma}{2} t \right) \pm D\, cos(\Delta m\, t) \right) \right] \otimes R(\sigma_t)$
- Mean decay time resolution 44 fs

flavour tagging

event-by-event decay time resolution

$$\boxed{\Delta m_s = 17.768 \pm 0.023\,(stat) \pm 0.006\,(syst)\ ps^{-1}}$$

Most precise measurement up to date

Agreement with world average & SM

Also measured in semileptonic decays [arXiv:1308.1302] !

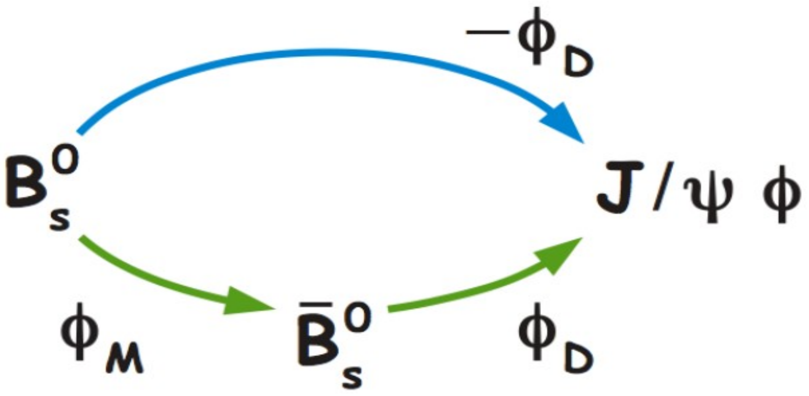
Mixing induced CP violation in B_s

- Decay of particle and antiparticle to same state
- **CP violating phase** predicted to be **very small in SM**

  CKMfitter group [PRD 84, 033005]

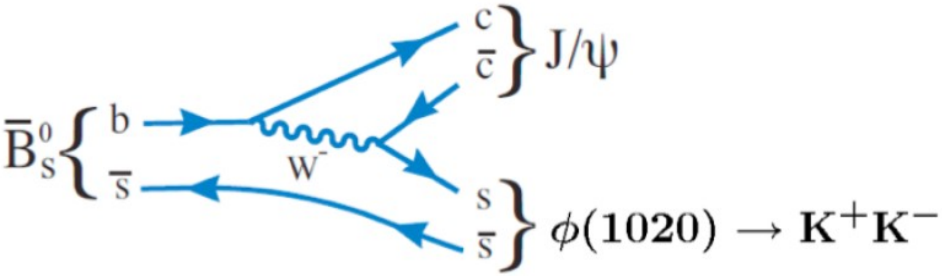
$$\boxed{\phi_s^{SM} = -2\beta_s = (-0.0363 \pm 0.0016)\,\mathrm{rad}}$$

- **Observable very sensitive to NP !**



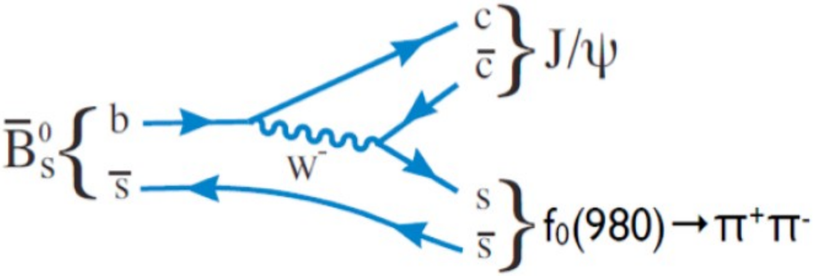
- LHCb measured it in two modes (1 fb^{-1} dataset)

  [PRD 87,112010]



- Measurement of time-dependent CP asymmetry

$$A_{\mathrm{CP}}(t) \sim (1 - 2\omega_{\mathrm{tag}})\, D(\sigma_t)\, \sin(\Delta m_s(t))\, \sin(\phi_s)$$



- **Tagging and high decay time resolution required!**

Mixing induced CP violation in B_s

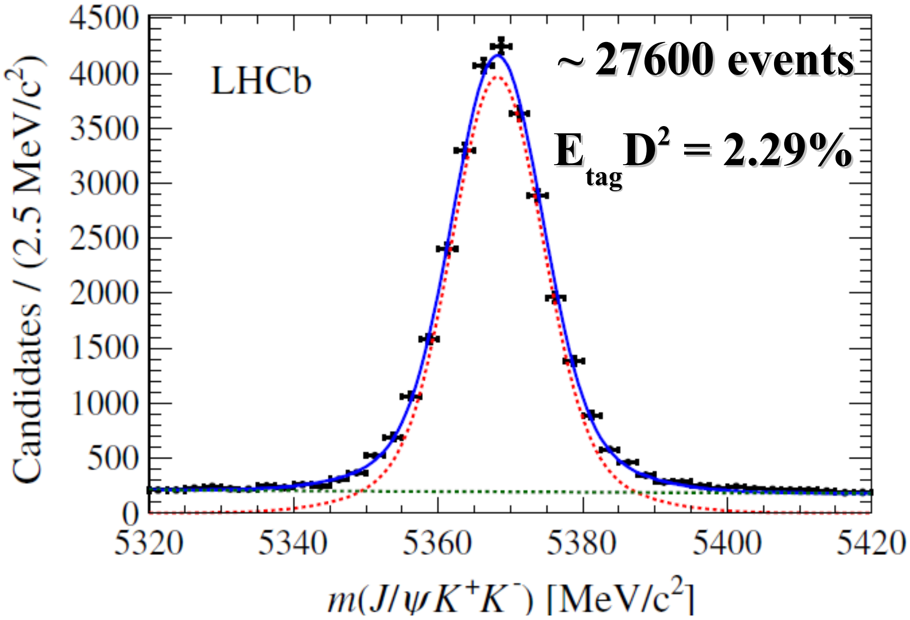
$B^0_s \to J/\psi\phi$

- **Narrow *ϕ(1020)*: experimentally clean**
- **VV final state: mixture of CP even/odd components**
- **Time-dependent angular analysis**
- **Fit of more than 10 physics parameters**
- **Δms from $B_s \to D_s \pi$ decay**

$$\phi_s = 0.07 \pm 0.09(\text{stat}) \pm 0.01(\text{syst})\ \text{rad},$$

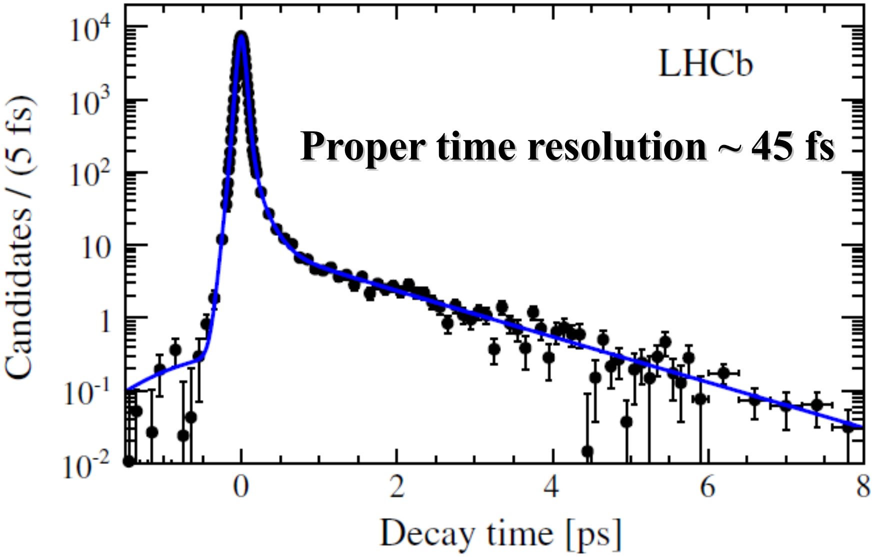
$$\Gamma_s = 0.663 \pm 0.005(\text{stat}) \pm 0.006(\text{syst})\ \text{ps}^{-1}$$

$$\Delta\Gamma_s = 0.100 \pm 0.016(\text{stat}) \pm 0.003(\text{syst})\ \text{ps}^{-1}$$



~ 27600 events

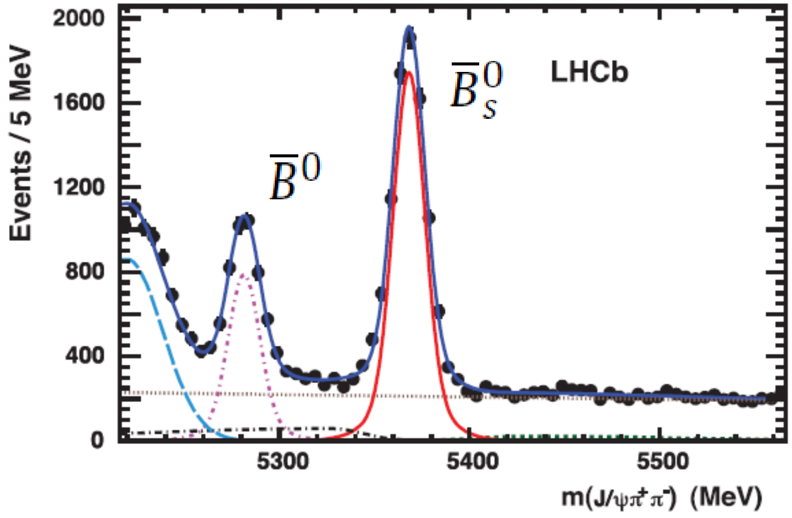
$E_{tag}D^2 = 2.29\%$

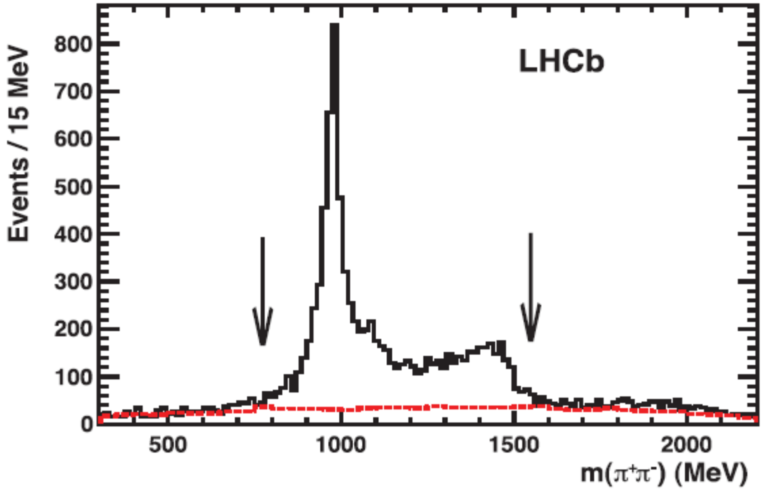


Proper time resolution ~ 45 fs

[PRD 87, 112010]

Mixing induced CP violation in B_s





Consistent with SM prediction!

$B^0_s \to J/\psi\pi^+\pi^-$

- **Dominated by $f_0 \to \pi^+\pi^-$**
- **BF~35% of $B^0_s \to J/\psi\phi$**
- **CP-odd final state**
- **No angular analysis is required**
- **Constrain Γ_s and $\Delta\Gamma_s$ to $B^0_s \to J/\psi\phi$ result**

[PLB 713, 378] $\phi_s = -0.019^{+0.173+0.004}_{-0.174-0.003}$ rad.

Combined fit of $B^0_s \to J/\psi\phi$ and $J/\psi\,\pi^+\pi^-$

$$\phi_s = 0.01 \pm 0.07(\text{stat}) \pm 0.01(\text{syst})\ \text{rad},$$

$$\Gamma_s = 0.661 \pm 0.004(\text{stat}) \pm 0.006(\text{syst})\ \text{ps}^{-1}$$

$$\Delta\Gamma_s = 0.106 \pm 0.011(\text{stat}) \pm 0.007(\text{syst})\ \text{ps}^{-1}$$

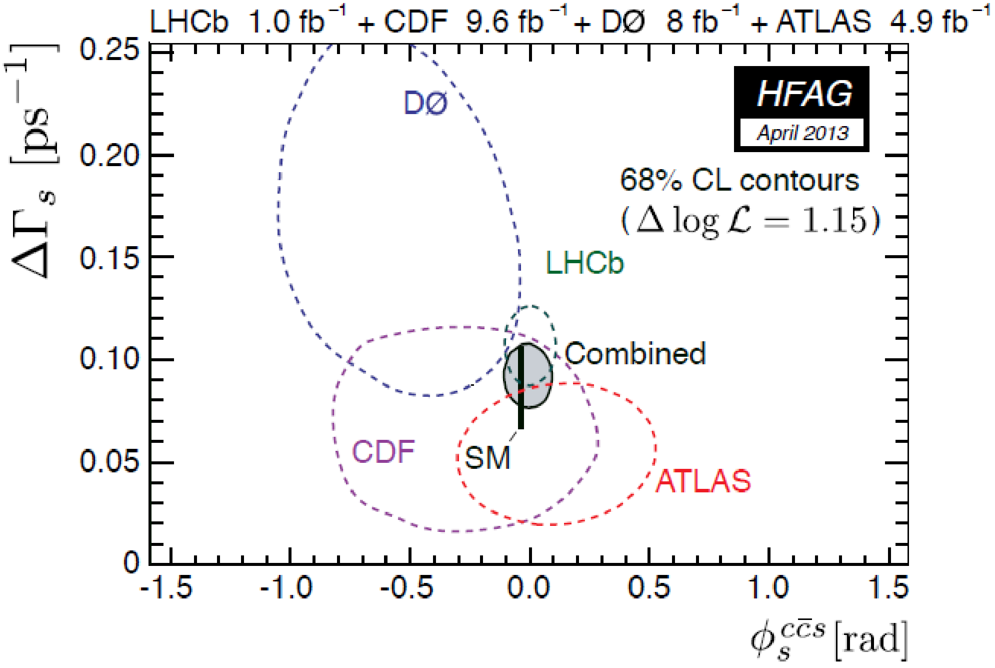
[PRD 87, 112010]

Constrain on NP parameters

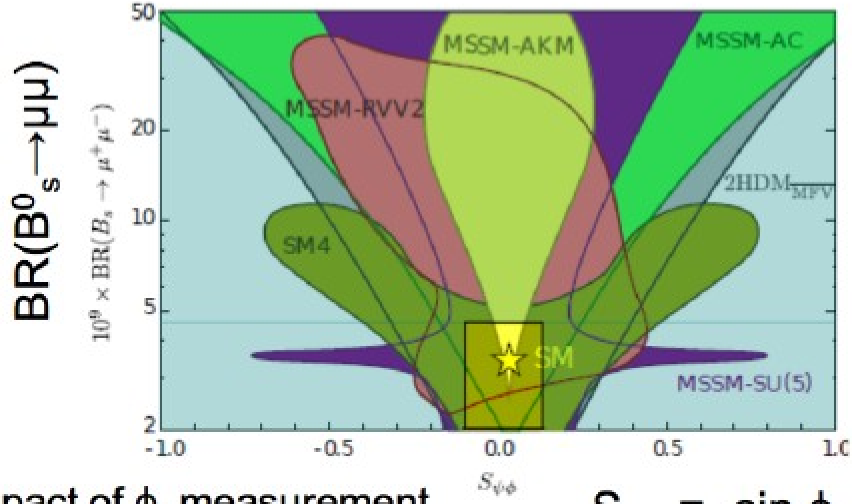
Consistent with SM prediction

and data from other experiments!

HFAG preliminary



based on [arXiv:1107.0266]



Impact of ϕ_s measurement (together with BR($B^0_s \to \mu\mu$)

$S_{\psi\varphi} = -\sin \phi_s$

Parameters of CKM triangle

CKM angle γ measured with high uncertainty!

$$\gamma = \arg\left[-V_{ud}V_{ub}^{*}/(V_{cd}V_{cb}^{*})\right]$$

(but very precise SM prediction for these observable)

Leading diag.

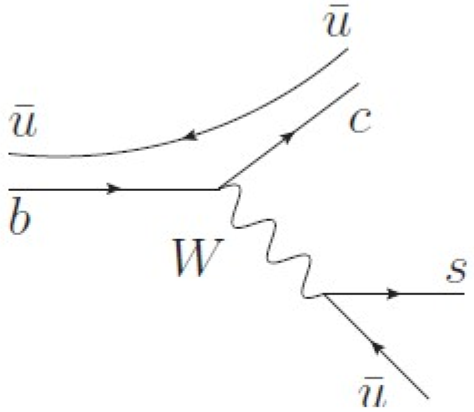
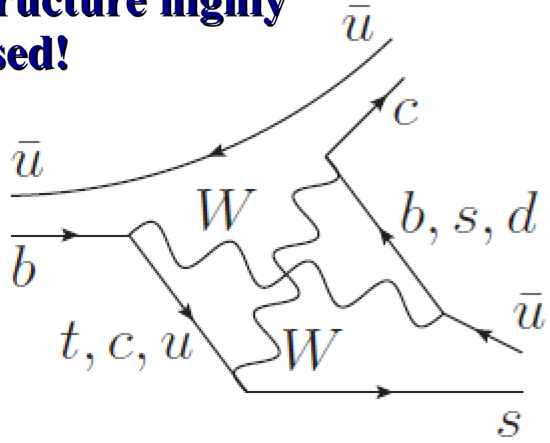
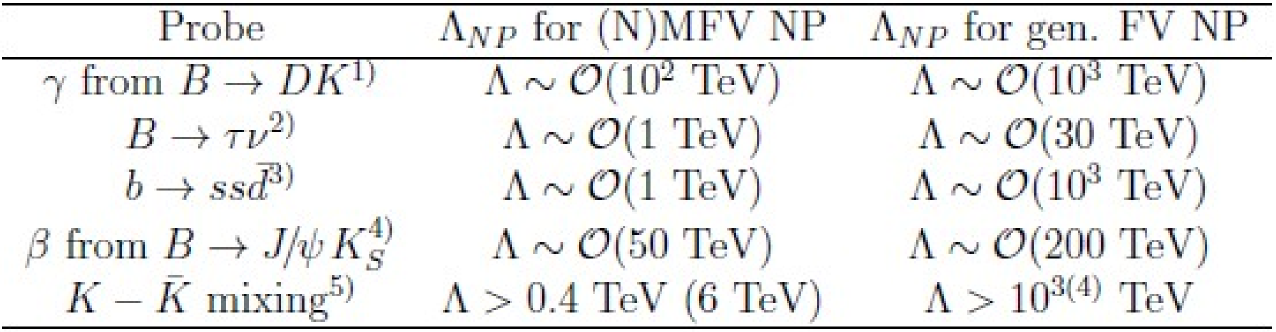


Diagram with other CKM structure highly suppressed!



$$\delta\gamma/\gamma < \mathcal{O}(10^{-6})$$

Very high potential for NP searches!



Probe	Λ_{NP} for (N)MFV NP	Λ_{NP} for gen. FV NP
γ from $B \to DK^{1)}$	$\Lambda \sim \mathcal{O}(10^2\ \text{TeV})$	$\Lambda \sim \mathcal{O}(10^3\ \text{TeV})$
$B \to \tau\nu^{2)}$	$\Lambda \sim \mathcal{O}(1\ \text{TeV})$	$\Lambda \sim \mathcal{O}(30\ \text{TeV})$
$b \to ss\bar{d}^{3)}$	$\Lambda \sim \mathcal{O}(1\ \text{TeV})$	$\Lambda \sim \mathcal{O}(10^3\ \text{TeV})$
β from $B \to J/\psi K_S^{4)}$	$\Lambda \sim \mathcal{O}(50\ \text{TeV})$	$\Lambda \sim \mathcal{O}(200\ \text{TeV})$
$K - \bar{K}$ mixing$^{5)}$	$\Lambda > 0.4$ TeV (6 TeV)	$\Lambda > 10^{3(4)}$ TeV

EPJ C 73 (2012) 2373

GLW / ADS / GGLZ methods

Gronau-London-Wyler (GLW) D in $\mathcal{CP}$-eigenstate $(D \to KK,\ \pi\pi)$

[PLB 265, 172 (1991)]

$$R_{CP\pm} = \frac{2[\Gamma(B^- \to D_{CP\pm}K^-) + \Gamma(B^+ \to D_{CP\pm}K^+)]}{\Gamma(B^- \to D^0K^-) + \Gamma(B^+ \to \overline{D}^0K^+)}$$

$$A_{CP\pm} = \frac{\Gamma(B^- \to D_{CP\pm}K^-) - \Gamma(B^+ \to D_{CP\pm}K^+)}{\Gamma(B^- \to D_{CP\pm}K^-) + \Gamma(B^+ \to D_{CP\pm}K^+)}\,.$$

$$R_{CP\pm} = 1 + r_B^2 \pm 2r_B\cos\delta_B\cos\gamma$$

$$A_{CP\pm} = \frac{\pm 2r_B\sin\delta_B\sin\gamma}{R_{CP\pm}}\,.$$

Atwood-Dunietz-Sony (ADS)

D Cabibbo-allowed $(D^0 \to K^-\pi^+)$ and doubly Cabibbo-suppressed $(D^0 \to K^+\pi^-)$ states.

[PRL 78, 3257 (1997)]

$$R_{\rm ADS} = \frac{\Gamma(B^- \to D[\to \pi^-K^+]K^-) + \Gamma(B^+ \to D[\to \pi^+K^-]K^+)}{\Gamma(B^- \to D[\to K^-\pi^+]K^-) + \Gamma(B^+ \to D[\to K^+\pi^-]K^+)}$$

$$A_{\rm ADS} = \frac{\Gamma(B^- \to D[\to \pi^-K^+]K^-) - \Gamma(B^+ \to D[\to \pi^+K^-]K^+)}{\Gamma(B^- \to D[\to \pi^-K^+]K^-) + \Gamma(B^+ \to D[\to \pi^+K^-]K^+)}$$

$$R_{\rm ADS} = r_B^2 + r_D^2 + 2r_B\,r_D\cos\gamma\cos(\delta_B + \delta_D)$$

$$A_{\rm ADS} = 2r_B\,r_D\sin\gamma\sin(\delta_B + \delta_D)/R_{\rm ADS}$$

Giri, **G**ro**s**sman, **S**offer and **Z**upan (**GGSZ**) deals with self conjugate 3-body final states :
f = D →$K_S\pi\pi$ and K_SKK. Phys.Rev. D68 (2003) 054018

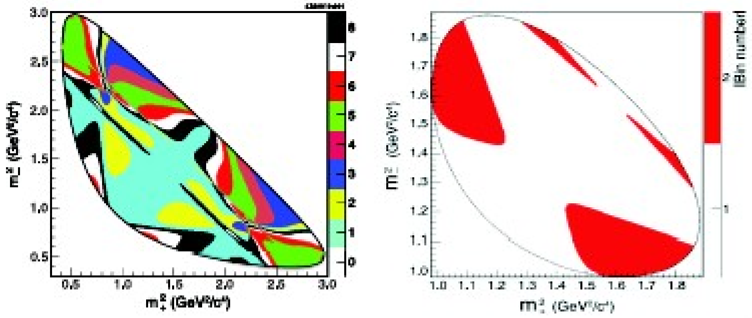
Strong phase varies over the 3-body phase space.

$$x_\pm = r_B\cos(\delta_B \pm \gamma) \qquad y_\pm = r_B\sin(\delta_B \pm \gamma)$$

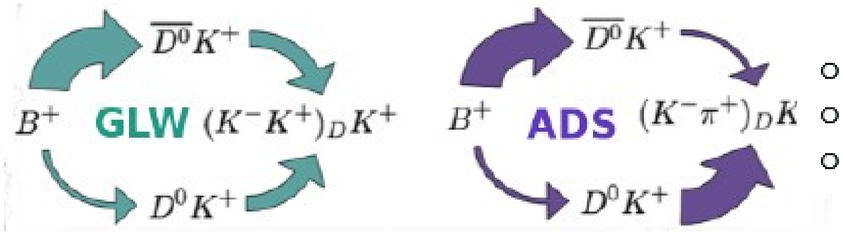
$$N^+_{\pm i} = h_{B^+}[K_{\mp i} + (x_+^2 + y_+^2)K_{\pm i} + 2\sqrt{K_iK_{-i}}(x_+c_{\pm i} \mp y_+s_{\pm i})]$$

$$N^-_{\pm i} = h_{B^-}[K_{\pm i} + (x_-^2 + y_-^2)K_{\mp i} + 2\sqrt{K_iK_{-i}}(x_-c_{\pm i} \pm y_-s_{\pm i})]$$

Binned Dalitz plot phase variation measured by CLEO-c : CLEO, Phys. Rev. D 82 (2010) 112006



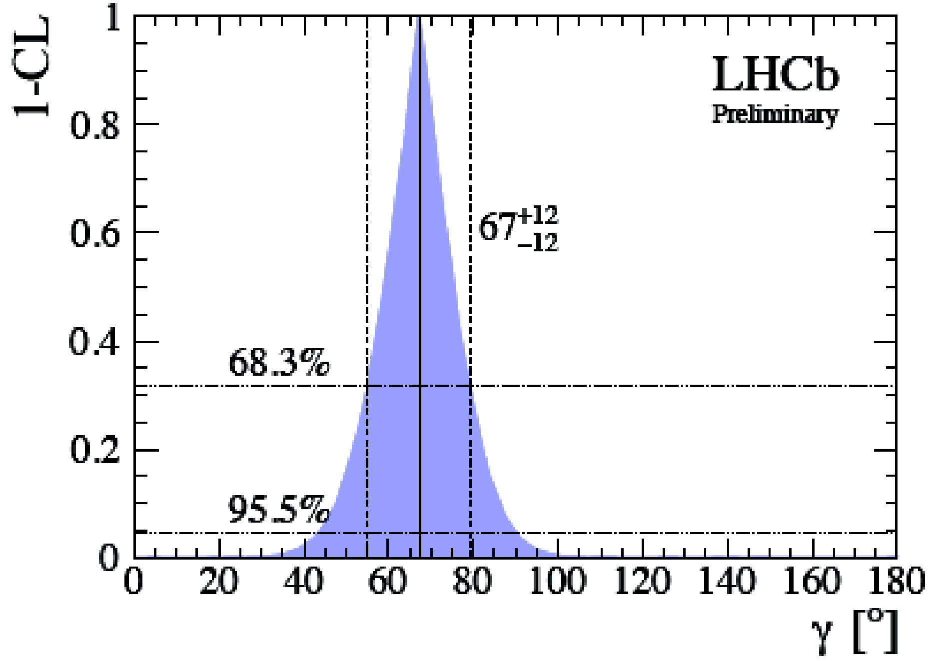
Result on CKM γ



- ○ **(Two-body GLW/ADS) :** B →Dh, D→ hh [**Phys. Lett. B712 (2012) 203**]
- ○ **(Four-body ADS) :** B →Dh, D→ Kπππ [**LHCb-PAPER-2012-055; arxiv:1303.4646**]
- ○ **(GGSZ) :** B →DK, D→ $K_S$hh [**Phys. Lett. B718 (2012) 43**]

The combined results for B → DK decays using 1 fb^{-1} (7 TeV) from GLW/ADS/GGSZ plus 2 fb^{-1} (8 TeV) from GGSZ :

B → DK combination



Confidence intervals

$$\gamma \in [43.9, 89.5]^\circ \text{ at } 95\%\,\text{CL}$$
$$\gamma \in [55.1, 79.1]^\circ \text{ at } 68\%\,\text{CL}$$

Best fit value

$$\gamma = (67 \pm 12)^\circ \text{ at } 68\%\,\text{CL}$$

Submitted to Phys. Lett. B - arxiv:1305.2050

LHCb-CONF-2013-006 **LHCb-CONF-2013-004**

Mixing and CPV in charm sector

D^0 mixing

$|D^0\rangle \; |\bar{D}^0\rangle$

Flavor eigenstates

- Well defined flavor

$|D_1\rangle \; |D_2\rangle$

Hamiltonian eigenstates

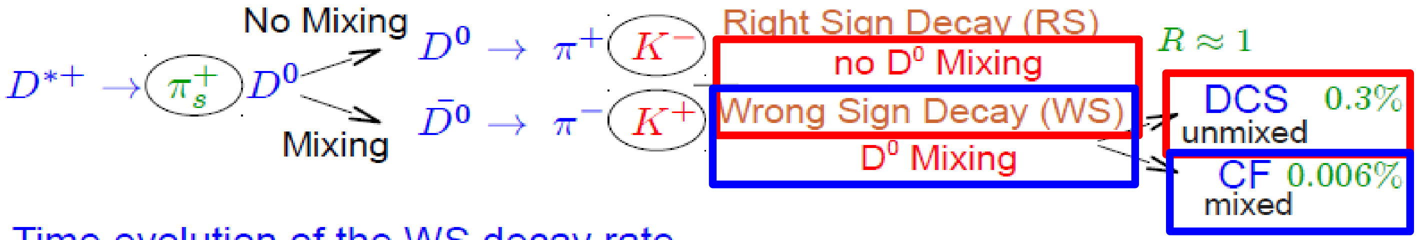
- Well defined m and Γ
- Define the mixing parameters

Mixing determines the time evolution of the flavor eigenstates

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

$$x = \frac{m_1 - m_2}{\Gamma} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \qquad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

- Event classes - flavour tagging at production and decay



No Mixing

Mixing

$D^{*+} \to \pi_s^+ D^0$

$D^0 \to \pi^+ K^-$

$\bar{D}^0 \to \pi^- K^+$

Right Sign Decay (RS)

no D^0 Mixing

$R \approx 1$

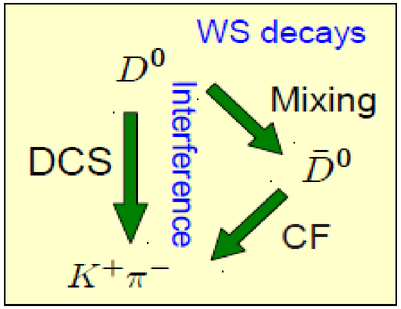
Wrong Sign Decay (WS)

D^0 Mixing

DCS 0.3% unmixed

CF 0.006% mixed

- Time evolution of the WS decay rate



- assume CP conservation and $|x| \ll 1$; $|y| \ll 1$

$$T_{WS}(t) \propto e^{-\Gamma t}\left(\underbrace{R_D}_{\text{DCS}} + \underbrace{\sqrt{R_D}\,y'\,\Gamma t}_{\text{Interference}} + \underbrace{\frac{x'^2 + y'^2}{4}(\Gamma t)^2}_{\text{Mixing}}\right)$$

- $\delta_{K\pi}$ is the strong phase between CF and DCS amplitudes ($D^0 \to K\pi$)

$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$$
$$y' = -x\sin\delta_{K\pi} + y\cos\delta_{K\pi}$$

$$y'^2 + x'^2 = x^2 + y^2$$

D^0 mixing

$|D^0\rangle\ |\bar{D}^0\rangle$

Flavor eigenstates

- Well defined flavor

$|D_1\rangle\ |D_2\rangle$

Hamiltonian eigenstates

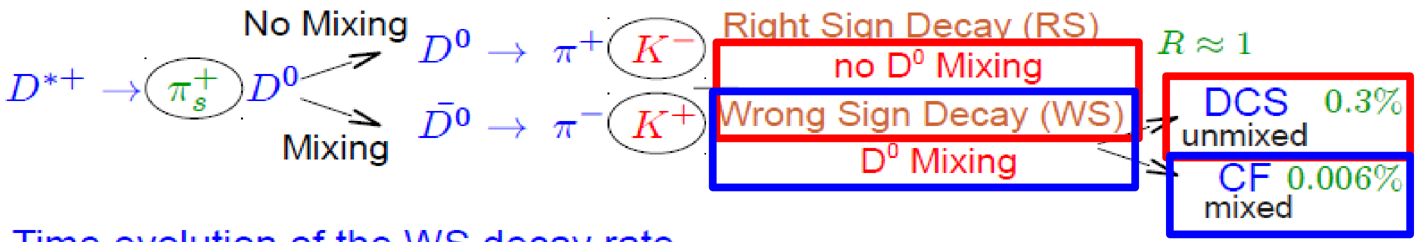
- Well defined m and Γ
- Define the mixing parameters

Mixing determines the time evolution of the flavor eigenstates

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

$$x = \frac{m_1 - m_2}{\Gamma} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \qquad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

- Event classes - flavour tagging at production and decay



No Mixing

Mixing

$D^{*+} \to \pi_s^+ D^0$

$D^0 \to \pi^+ K^-$

$\bar{D}^0 \to \pi^- K^+$

Right Sign Decay (RS)

no D^0 Mixing

Wrong Sign Decay (WS)

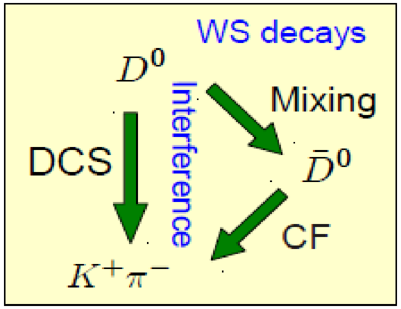
D^0 Mixing

$R \approx 1$

DCS 0.3%
unmixed

CF 0.006%
mixed

- Time evolution of the WS decay rate



WS decays

D^0

Mixing

DCS

Interference

$\bar{D}^0$

CF

$K^+\pi^-$

- assume CP conservation and $|x| \ll 1$; $|y| \ll 1$

$$T_{WS}(t) \propto e^{-\Gamma t}\left(\underbrace{R_D}_{\text{DCS}} + \underbrace{\sqrt{R_D}\,y'\,\Gamma t}_{\text{Interference}} + \underbrace{\frac{x'^2+y'^2}{4}(\Gamma t)^2}_{\text{Mixing}}\right)$$

- $\delta_{K\pi}$ is the strong phase between CF and DCS amplitudes ($D^0 \to K\pi$)

$$x' = x\ cos\,\delta_{K\pi} + y\ sin\,\delta_{K\pi}$$
$$y' = -x\ sin\,\delta_{K\pi} + y\ cos\,\delta_{K\pi}$$

$$y'^2 + x'^2 = x^2 + y^2$$

LHCb already reported about first observation of *D^0* mixing (by single experiment, 9σ) **PRL 110, 101802**

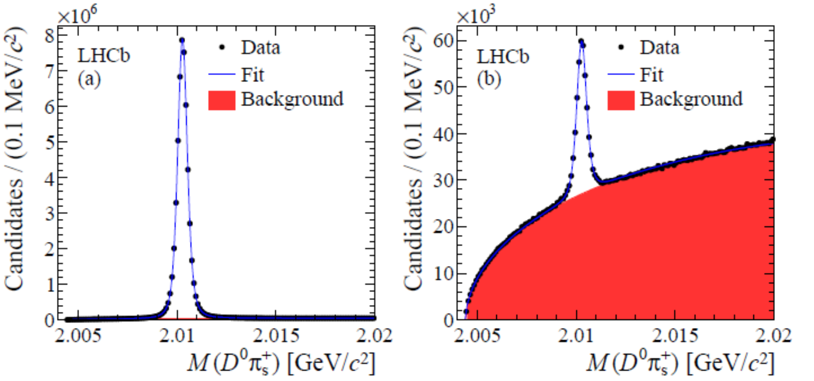
Newest results on D^0 mixing (and CPV)

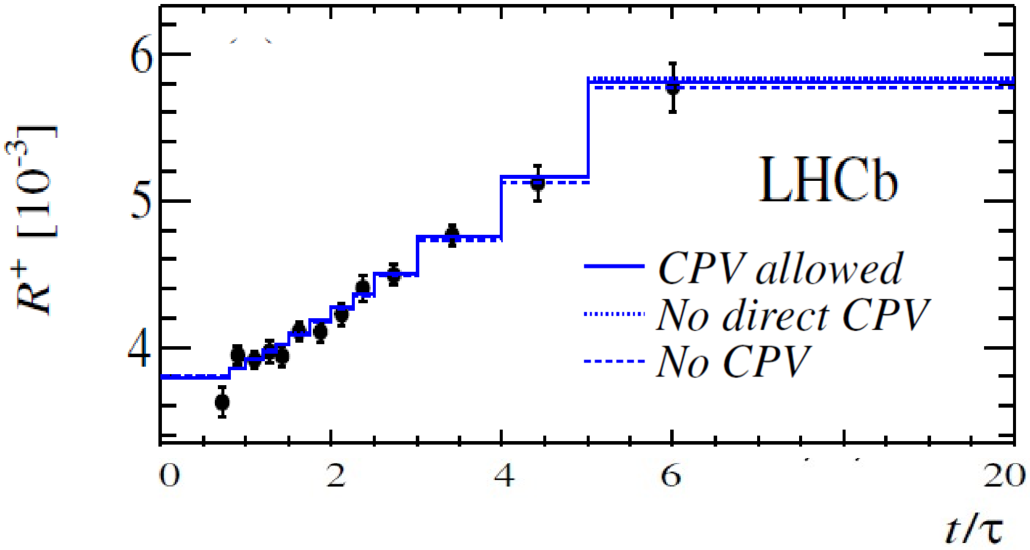
Wrong-sign-to-Right-sign ratio:

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

R$^+$ = R(t) WS-to-RS ratio for $D^0 \rightarrow K^+\pi^-$ decay

RS: **230** × WS ev. **WS:** 2.3×10^5 ev.





Result of the fit with no-CPV assumption:

R_D	$[10^{-3}]$	$3.568 \pm 0.058 \pm 0.033$
y'	$[10^{-3}]$	$4.8 \pm 0.8 \pm 0.5$
x'^2	$[10^{-5}]$	$5.5 \pm 4.2 \pm 2.6$
χ^2/ndf		$86.4/101$

In case of no-CPV and no-Mixing assumption should be constant!

World-best result!

[arXiv:1309.6534]

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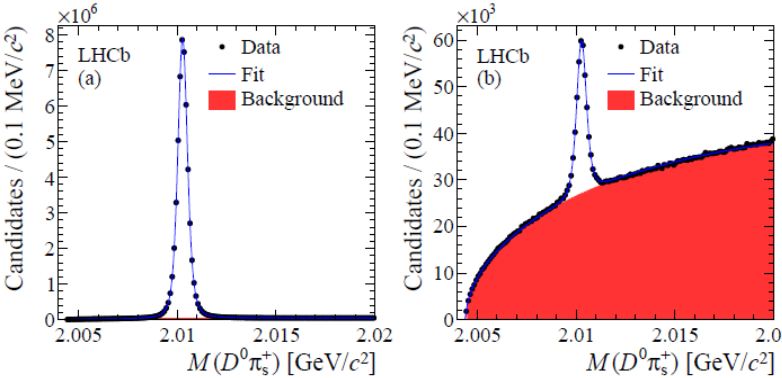
Wrong-sign-to-Right-sign ratio:

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

RS: 230 × WS ev. **WS:** 2.3×10^5 ev.



Fit with CPV assumptions has been also done

Direct CPV:

$$A_D \equiv (R_D^+ - R_D^-)/(R_D^+ + R_D^-)$$

Mixing-Induced CPV:

$$x'^{\pm} = |q/p|^{\pm 1}(x' \cos\phi \pm y' \sin\phi)$$
$$y'^{\pm} = |q/p|^{\pm 1}(y' \cos\phi \mp x' \sin\phi)$$

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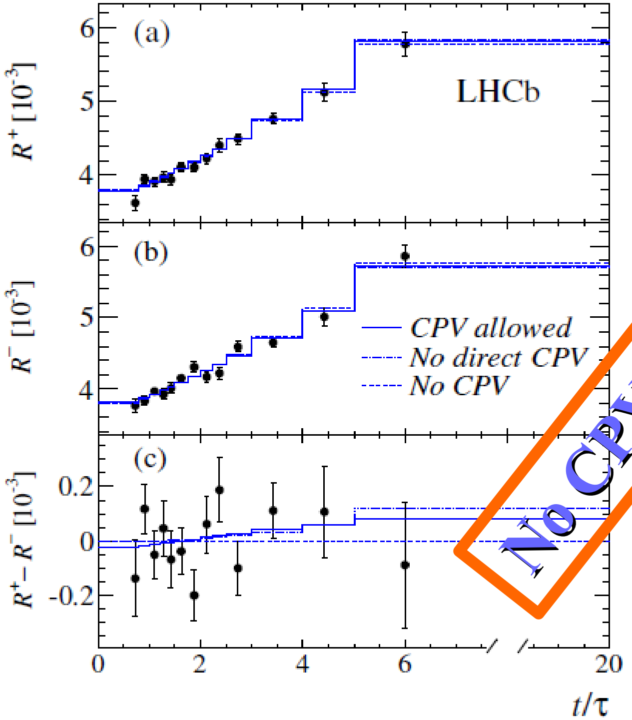
World-best result!



No CPV effects found!

[arXiv:1309.6534]

Newest results on D^0 mixing (and CPV)

Wrong-sign-to-Right-sign ratio:

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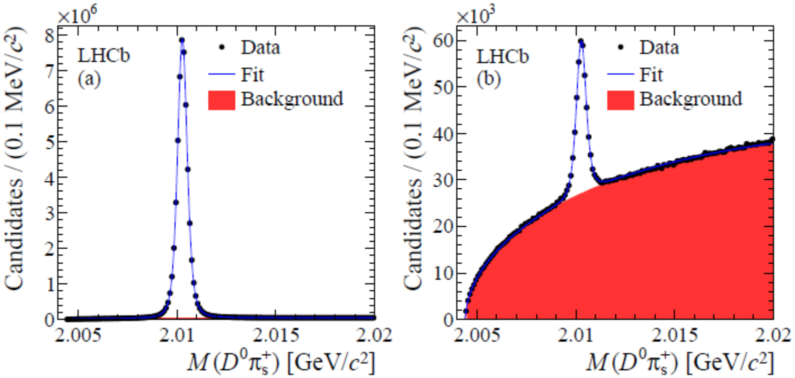

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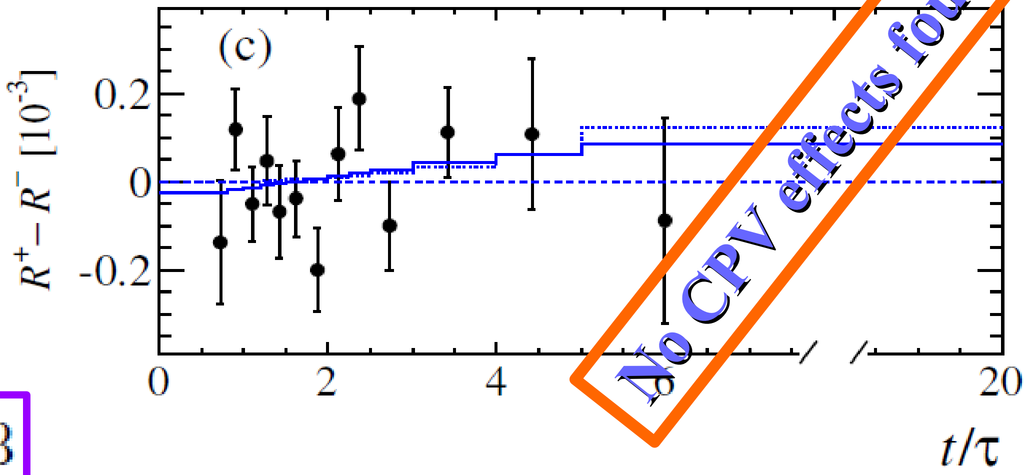
$$x'^{\pm} = |q/p|^{\pm 1}(x' \cos\phi \pm y' \sin\phi)$$
$$y'^{\pm} = |q/p|^{\pm 1}(y' \cos\phi \mp x' \sin\phi)$$



No CPV effects found!

World-strongest constraints!

$A_D = (-0.7 \pm 1.9)\%$

$0.75 < |q/p| < 1.24$ at the 68.3% confidence level

[arXiv:1309.6534]

CP violation in *D* decays

In SM direct CP violation predicted to be small ~ 10^{-3} - 10^{-4}

Access via asymmetry measurement

$$A_{CP}(f;t) \equiv \frac{\Gamma(D^0(t)\to f) - \Gamma(\bar{D}^0(t)\to f)}{\Gamma(D^0(t)\to f) + \Gamma(\bar{D}^0(t)\to f)} = \underbrace{a_{CP}^{dir}(f)}_{\text{CPV in decay}} + \underbrace{\frac{t}{\tau}a_{CP}^{ind}}_{\text{CPV in mixing + interfer}}$$

CP eigenstate

LHCb: Time integrated difference of asymmetries

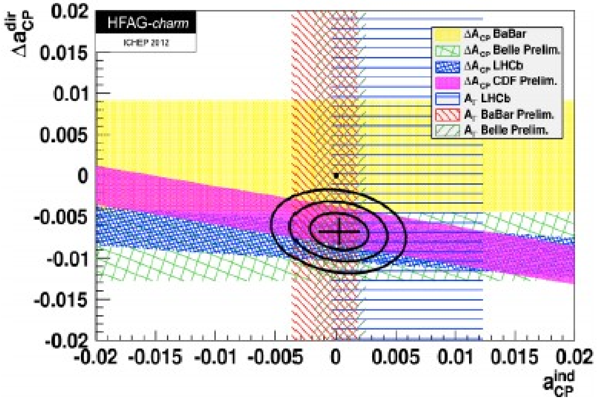
$$\begin{aligned}\Delta A_{CP} &= A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)\\ &= [a_{CP}^{dir}(K^+K^-) - a_{CP}^{dir}(\pi^+\pi^-)] + \frac{\Delta <t>}{\tau}a_{CP}^{ind}\end{aligned}$$

With 0.6fb^{-1} data sample LHCb found 3.5σ evidence of direct CP violation

$$\Delta(\mathcal{A}^{\mathrm{CP}}) = \mathcal{A}^{\mathrm{CP}}(D^0 \to K^+K^-) - \mathcal{A}^{\mathrm{CP}}(D^0 \to \pi^+\pi^-)$$

$$= [-0.82 \pm 0.21(\mathrm{stat}) \pm 0.11(\mathrm{syst})]\%$$

PRL108, 111602



Later some indication came from other experiments

Led to discussion: “Is it sign from NP?”

CP violation in *D* decays

In **SM direct CP violation** predicted to be **small** ~ 10^{-3} - 10^{-4}

Access via asymmetry measurement

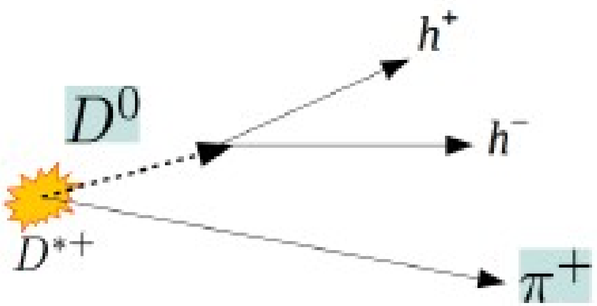
$$A_{CP}(f;t) \equiv \frac{\Gamma(D^0(t)\to f) - \Gamma(\bar{D}^0(t)\to f)}{\Gamma(D^0(t)\to f) + \Gamma(\bar{D}^0(t)\to f)} = \underbrace{a_{CP}^{dir}(f)}_{\text{CPV in decay}} + \underbrace{\frac{t}{\tau}a_{CP}^{ind}}_{\text{CPV in mixing + interfer}}$$

CP eigenstate

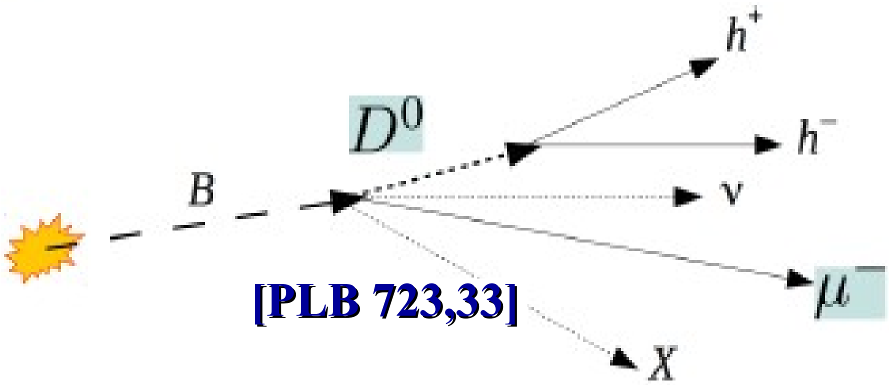
LHCb measured **time integrated difference of asymmetries**

$$\begin{aligned}\Delta A_{CP} &= A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)\\ &= [a_{CP}^{dir}(K^+K^-) - a_{CP}^{dir}(\pi^+\pi^-)] + \frac{\Delta <t>}{\tau}a_{CP}^{ind}\end{aligned}$$

Two complementary analysis with 1 fb^{-1} data sample



[LHCb-CONF-2013-003]



[PLB 723,33]

CP violation in *D* decays

LHCb results:

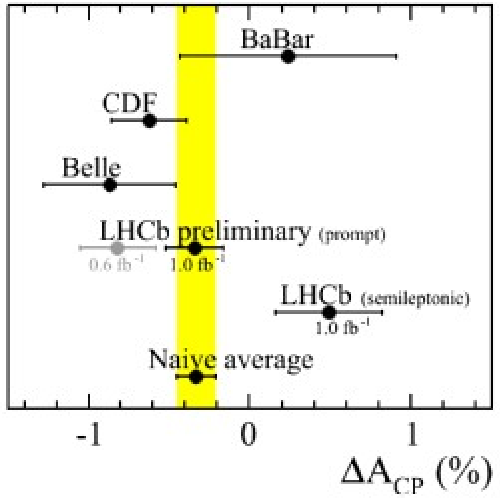
[LHCb-CONF-2013-004]

- D^* tagged sample (preliminary)

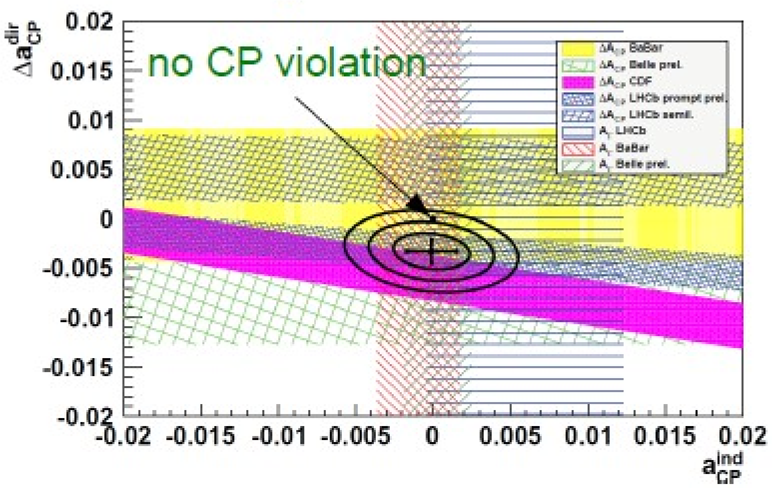
  $\Delta A_{CP} = (-0.34 \pm 0.15\,(stat) \pm 0.10\,(sys))\ \%$

- μ tagged sample **[PLB 723,33]**

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



Consistent with no CPV hypothesis!



HFAG averages:

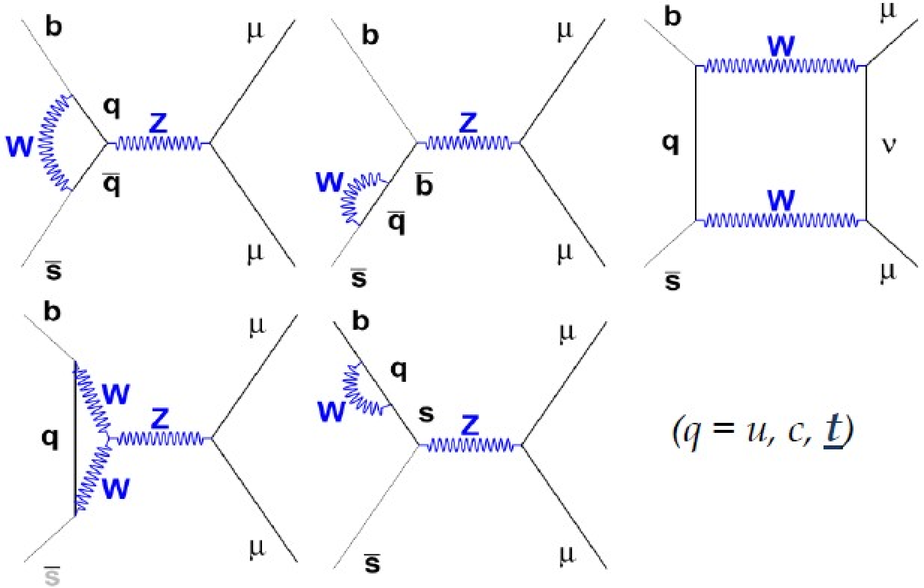
$$a^{ind}_{CP} = (-0.010 \pm 0.162)\ \%$$

$$\Delta a^{dir}_{CP} = (-0.329 \pm 0.121)\ \%$$

Note: ΔA_{CP} measurements in $D^+ \to \phi\pi^+$ and $D_s^+ \to K_s^0\pi^+$ are compatible with 0 arXiv:1303.4906, not discussed here

Rare decays

Rare decays $B_{(s)}^{0} \to \mu^+\mu^-$



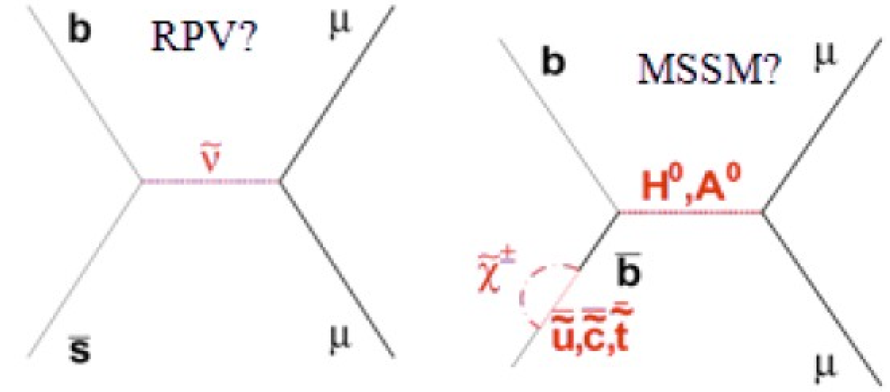
(*q* = *u*, *c*, *t*)

Helicity suppressed in SM [arXiv 1303.3820]

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.25 \pm 0.17) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$$

$\Delta\Gamma_s$ correction [PRD 86, 014027]

$$\mathcal{B}(B_s \to \mu^+\mu^-)_{<t>} = \frac{1 + \mathcal{A}^{\mu\mu}_{\Delta\Gamma}.\Delta\Gamma_s/2\Gamma_s}{1 - (\Delta\Gamma_s/2\Gamma_s)^2}.\mathcal{B}(B_s \to \mu^+\mu^-) = (3.56 \pm 0.18) \times 10^{-9}$$



5% precision SM calculations!

Sensitive to new scalar, pseudoscalar, axial-vector particles in loops

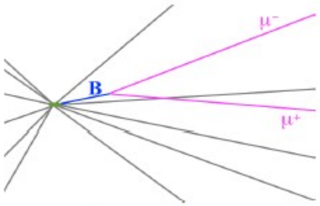
In MSSM:

$$c_{S,P}^{MSSM\,2} \propto \frac{m_b^2 m_\mu^2 \tan^6\beta}{M_A^4}$$

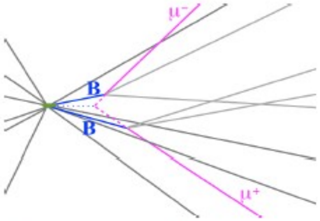
Some words about analysis strategy

- Blind analysis of 3fb^{-1}of data (full 2011-12 sample)
- Robust selection cuts for reduction of combinatorics
- Boosting Decision Tree (BDT) method using 9 topological variables (to avoid correlation with M$_{inv}$)

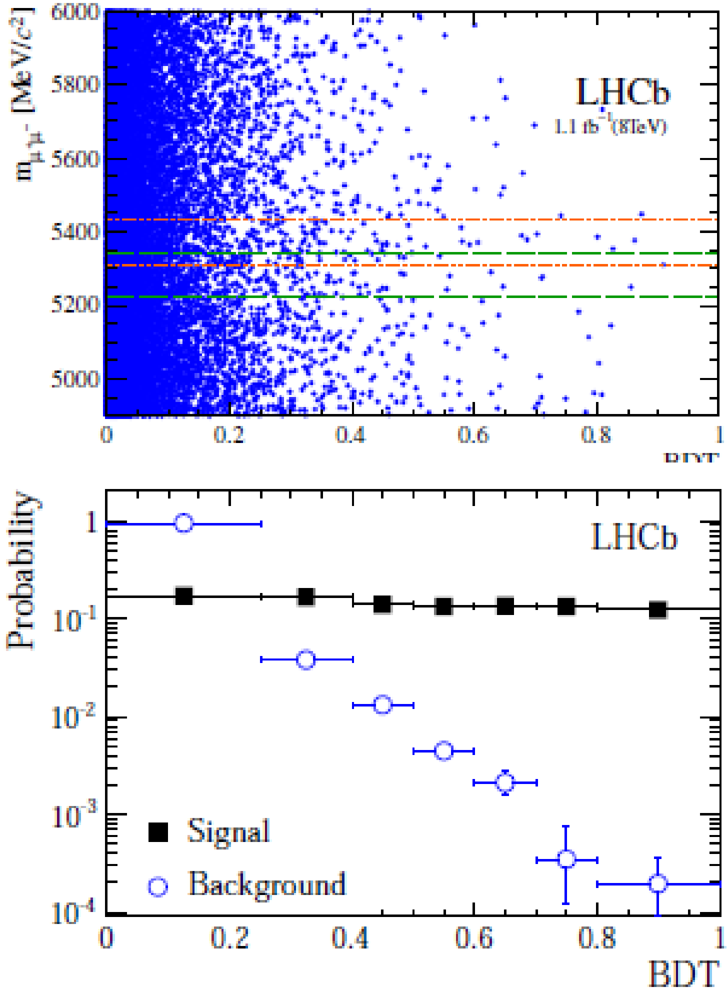
PRL 110, 021801



(a) $B^0_{d,s} \to \mu^+\mu^-$ signal



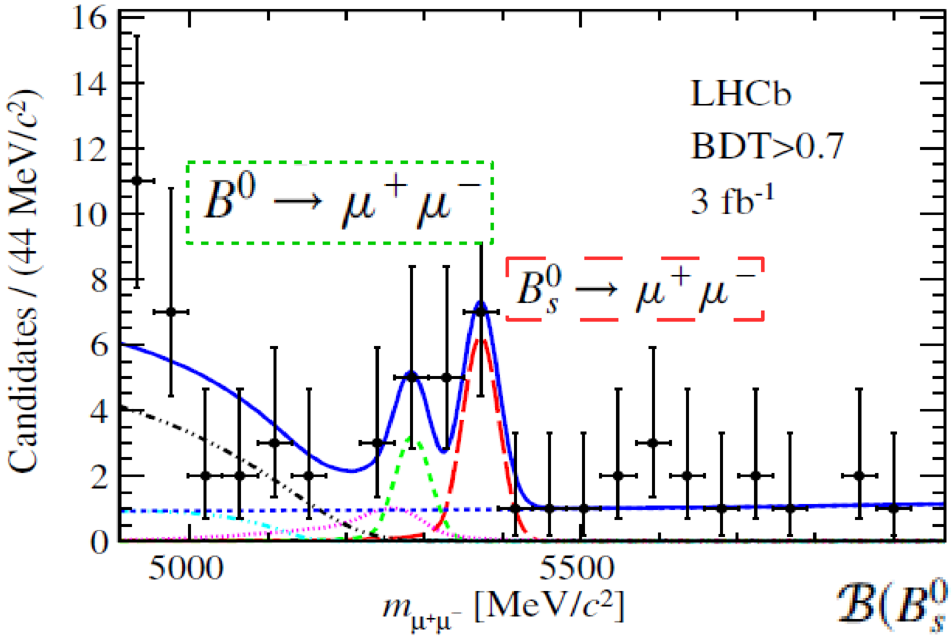
(b) $bb \to \mu^+\mu^- X$ background



- BDT *trained* on signal and bkg MC
- BDT *calibrated* on data using *B->h$^+$h$^-$* as signal and mass sidebands for bkg.
- 8 BDT bins. In each bin, the compatibility of the observed events with <u>bkg only</u> and <u>SM+bkg</u> hypotheses is calculated.

PRL 111, 101805

Result: first evidence of $B_s^0 \to \mu^+\mu^-$



Background sources:

$m_{\mu\mu} \in [4900, 6000]$ MeV$/c^2$

	Yield in full BDT range	Fraction with BDT > 0.7 [%]
$B^0_{(s)} \to h^+h'^-$	15 ± 1	28
$B^0 \to \pi^-\mu^+\nu_\mu$	115 ± 6	15
$B^0_s \to K^-\mu^+\nu_\mu$	10 ± 4	21
$B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$	28 ± 8	15
$\Lambda^0_b \to p\mu^-\bar{\nu}_\mu$	70 ± 30	11

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(\text{stat})^{+0.3}_{-0.1}(\text{syst})) \times 10^{-9}$$

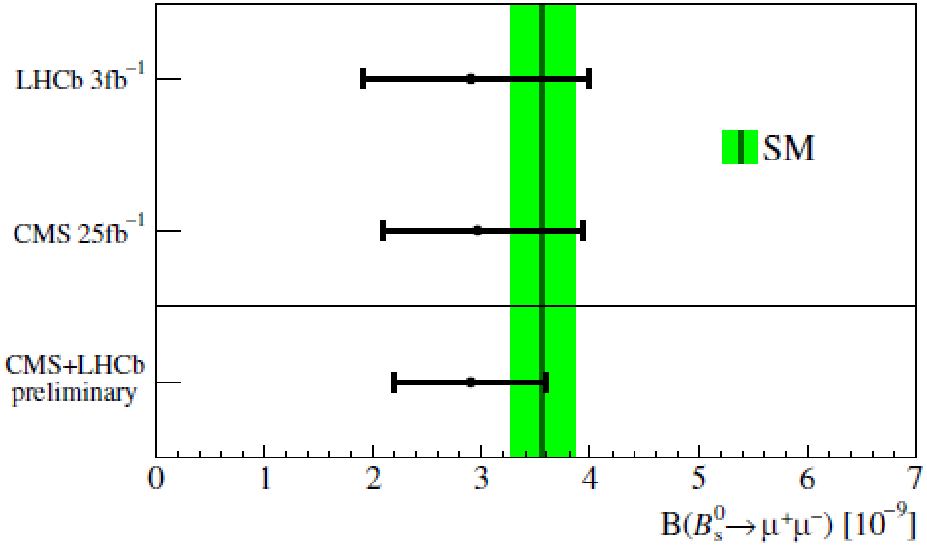
Statistical significance 4σ for B_s^0 signal!

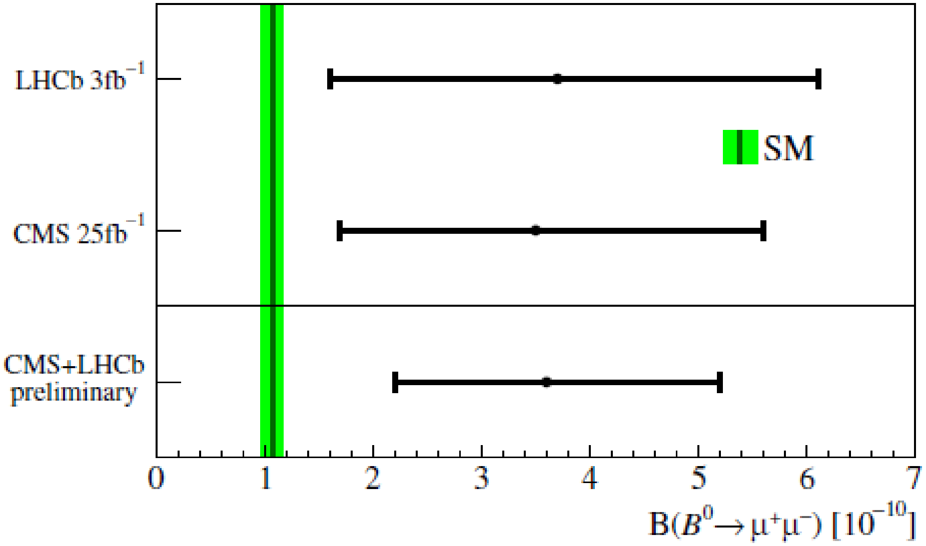
Consistent with SM prediction!

Upper limit for $B^0 \to \mu^+\mu^-$

	90% C.L.	95% C.L.
Expected bkg	3.5×10^{-10}	4.4×10^{-10}
Expected bkg + SM	4.5×10^{-10}	5.4×10^{-10}
Observed	6.3×10^{-10}	7.4×10^{-10}

Combination of CMS and LHCb results





$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}\,,$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.6\,^{+1.6}_{-1.4}) \times 10^{-10}\,,$$

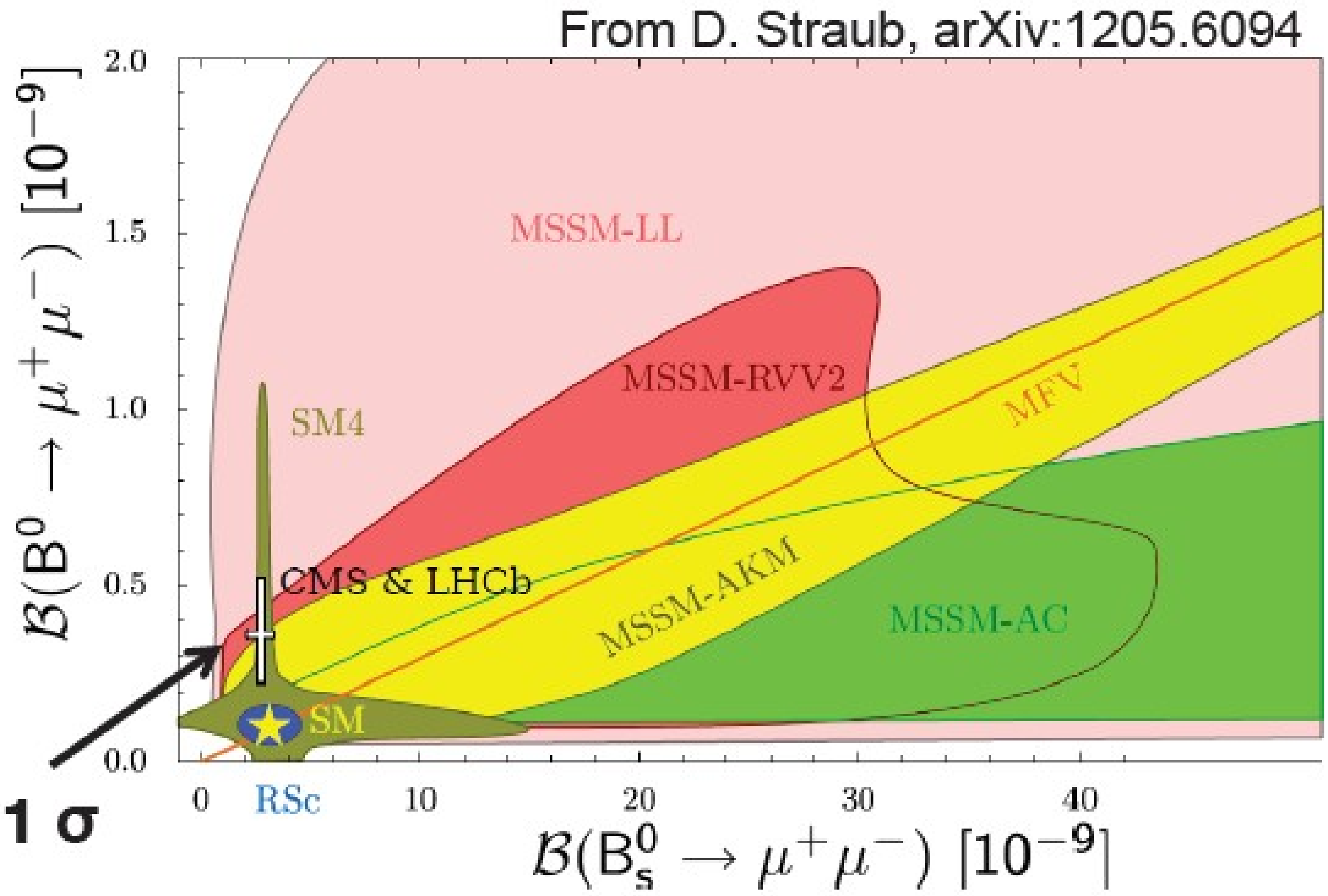
First evidence of the decay!

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

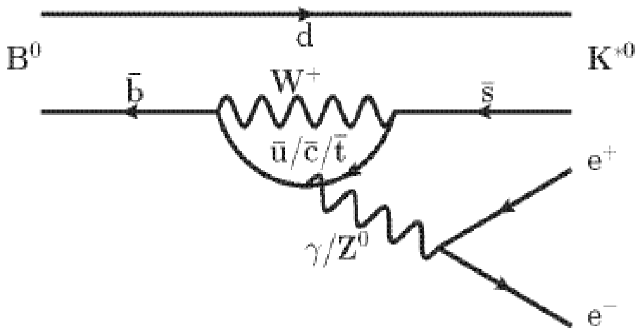
Result vs NP

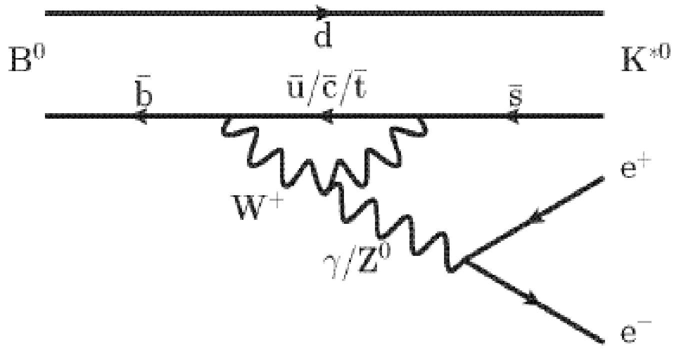
Any model that violates flavour via (pseudo)scalar is constrained.

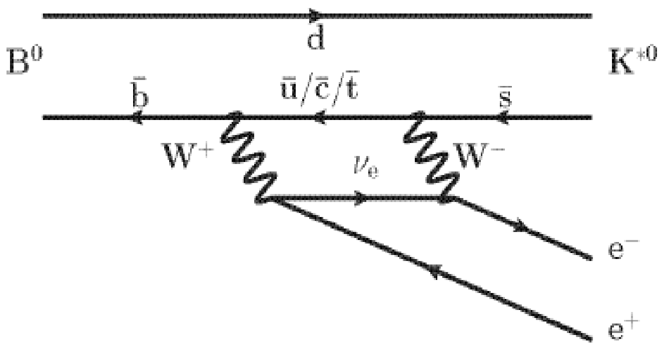
High *tanβ* SUSY too


From D. Straub, arXiv:1205.6094

B-hadron → Hadron + $\mu^+\mu^-$, *D* → $\pi\mu^+\mu^-$







FCNC processes with **a lot of observables**

Clear experimental signatures with low background

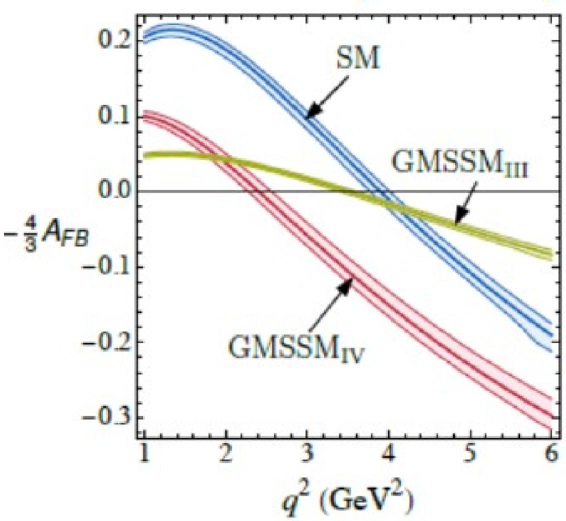
Well developed SM calculations

NP can be found in

- Rates
- Angular distributions
- Asymmetries

As an example zero-crossing point at forward-backward asymmetry for ***B^0*** → ***K****$\mu^+\mu^-$ is well predicted within SM and has potential for NP searches.

Altmannshofer et al. [arXiv:0811.1214]



$b\to x l^+ l^-$ and $c\to x l^+ l^-$ menu @ LHCb

A lot of channels = a lot of new (Apr-Sep 2013) results

$b\to s l^+ l^-$

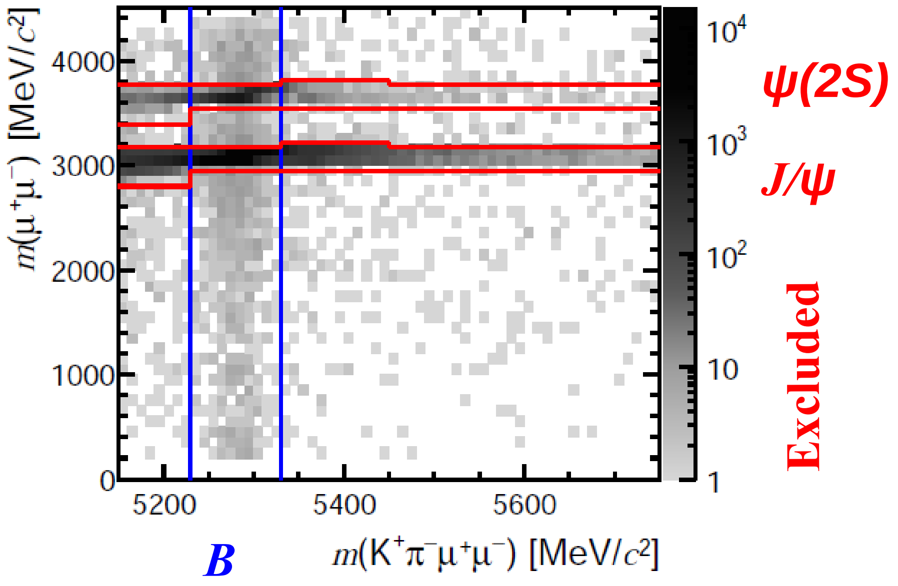
$B^0\to K^*\mu^+\mu^-$	**JHEP8(2013)131 / 1308.1340**	**1st multiD angular analysis**
$B^0\to K\mu^+\mu^-$	PRL 110, 031801	CP asymmetry
$B^+\to K^+\mu^+\mu^-$	1308.1707 / 1308.1340	ψ(4160) / CP asymmetry
$B^0\to \varphi^*\mu^+\mu^-$	arXiv:1305.2168	1st angular analysis
$B^0\to K^*e^+e^-$	JHEP 05,(2013)159	1st evidence in low q2
$\Lambda_b\to \Lambda\mu^+\mu^-$	PLB725, 25	baryons, 1st @ LHC

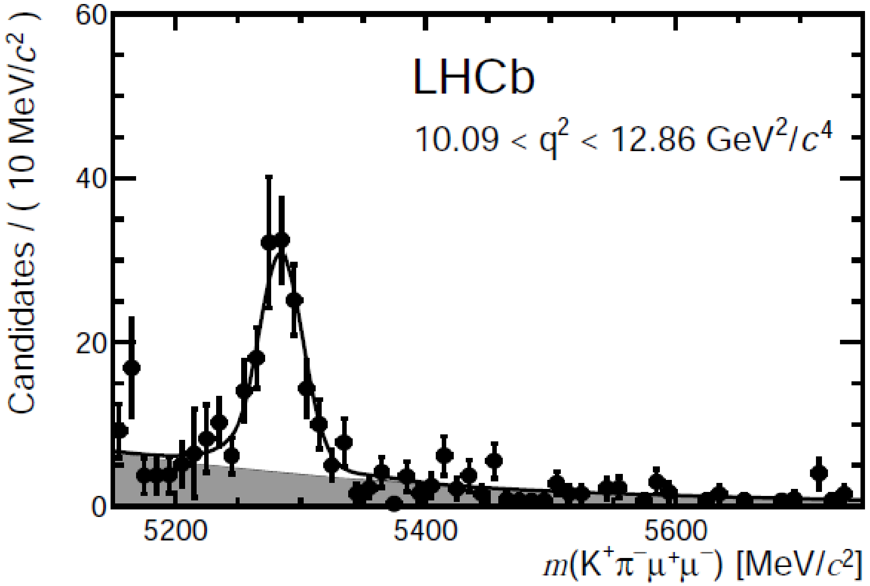
$c\to u l^+ l^-$

$D_{(s)}^+\to \pi^+\mu^+\mu^-$ $D_{(s)}^+\to \pi^-\mu^+\mu^+$	arXiv:1304.6365	factor ~50 improvement in limit

Analysis of $B \to K^* \mu^+ \mu^-$

[arXiv:1304.6325]





$$\frac{d\mathcal{B}}{dq^2} = \frac{1}{q^2_{\max} - q^2_{\min}} \frac{N_{\text{sig}}}{N_{K^{*0}J/\psi}} \boxed{\frac{\varepsilon_{K^{*0}J/\psi}}{\varepsilon_{K^{*0}\mu^+\mu^-}}} \times \mathcal{B}(B^0 \to K^{*0}J/\psi) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)$$

- **Loose preselection cuts**
- **Using BDT trained on proxy *B→K*J/ψ***
- **Background from upper B sideband**
- **Choice of variables to avoid biases on angles and $q^2=m^2(\mu\mu)$**
- **Final selection from BDT decay time, flight direction, trk/vtx quality, p_T, PID**
- **BR measured relative to *B→K*J/ψ***

Analysis of $B \rightarrow K^*\mu^+\mu^-$

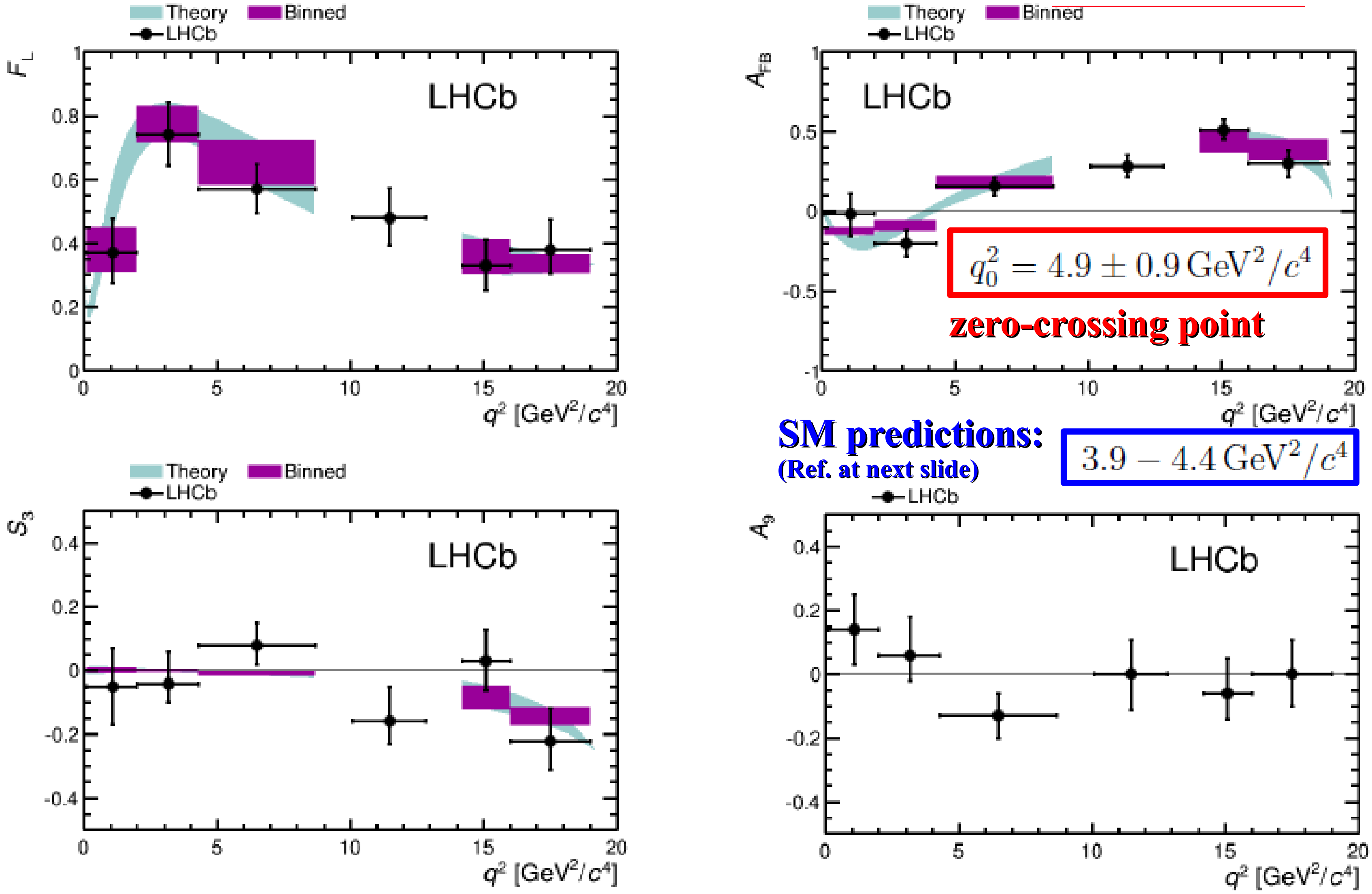
- Branching fraction measured differential in q^2 and 3 decay angles
- Limited statistics: $\phi + \pi \quad \text{if } \phi < 0$
- Parametric in 4 angular observables F_L, A_{FB}, S_3, A_9, from CP asymmetries and averages of decay amplitudes
- Theoretical uncertainties smaller in angular analysis (hadronic form factors)

First multi-dimensional angular analysis

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}} \propto \Big[F_{\mathrm{L}}\cos^2\theta_K + \frac{3}{4}(1-F_{\mathrm{L}})(1-\cos^2\theta_K) - F_{\mathrm{L}}\cos^2\theta_K(2\cos^2\theta_\ell - 1) + \frac{1}{4}(1-F_{\mathrm{L}})(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) + S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} + \frac{4}{3}A_{\mathrm{FB}}(1-\cos^2\theta_K)\cos\theta_\ell + A_9(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi} \Big]$$

Analysis of $B \to K^* \mu^+ \mu^-$

JHEP 08 (2013) 131



$$\boxed{q_0^2 = 4.9 \pm 0.9\,\mathrm{GeV}^2/c^4}$$

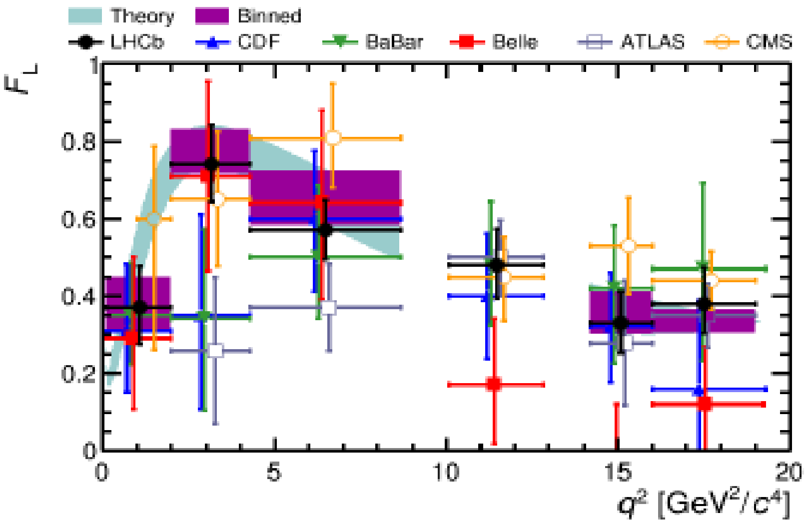
zero-crossing point

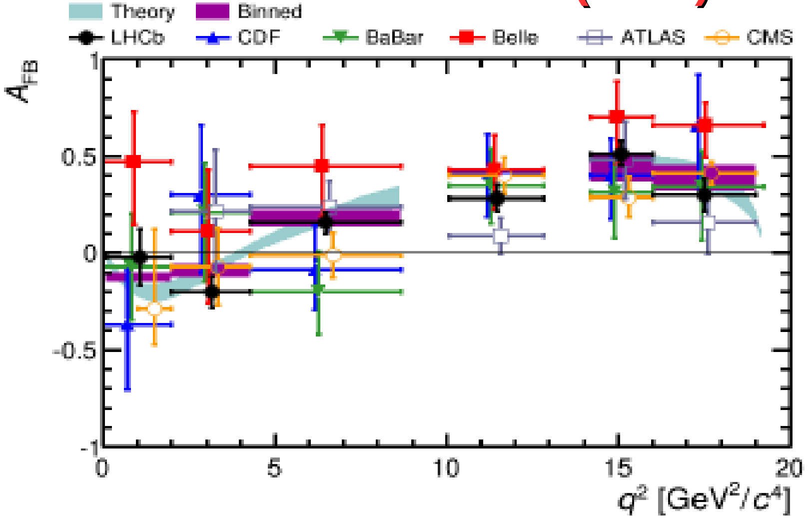
SM predictions: $\boxed{3.9 - 4.4\,\mathrm{GeV}^2/c^4}$

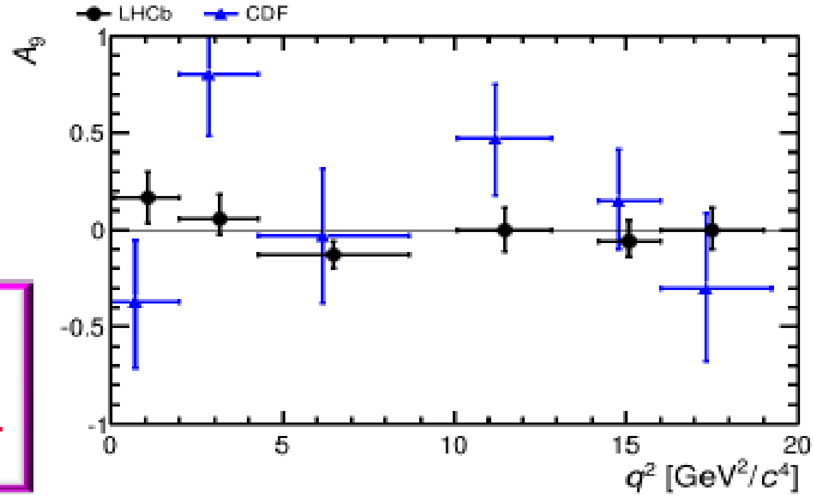
(Ref. at next slide)

Analysis of $B \to K^* \mu^+ \mu^-$

JHEP 08 (2013) 131







All experiments consistent with SM

CDF: Phys. Rev. Lett. 108 081807
Babar: Phys. Rev. D. 73. 092001
Belle: Phys. Rev. Lett. 103 (2009) 171801
ATLAS: ATLAS-CONF-2013-038
CMS: CMS-PAS-BPH-11-009

SM predictions

Bobeth,Hiller,van Dyk,Wacker, JHEP 01 (2012) 107
Beneke,Feldmann,Seidel,Eur.Phys.J.C41(2005) 173
Ali,Kramer,Zhu, Eur.Phys.J.C47(2006) 625

Further analysis of $B \rightarrow K^{*}\mu^{+}\mu^{-}$

$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$

$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$

$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$

$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$

$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

$$\boxed{P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}}.}$$

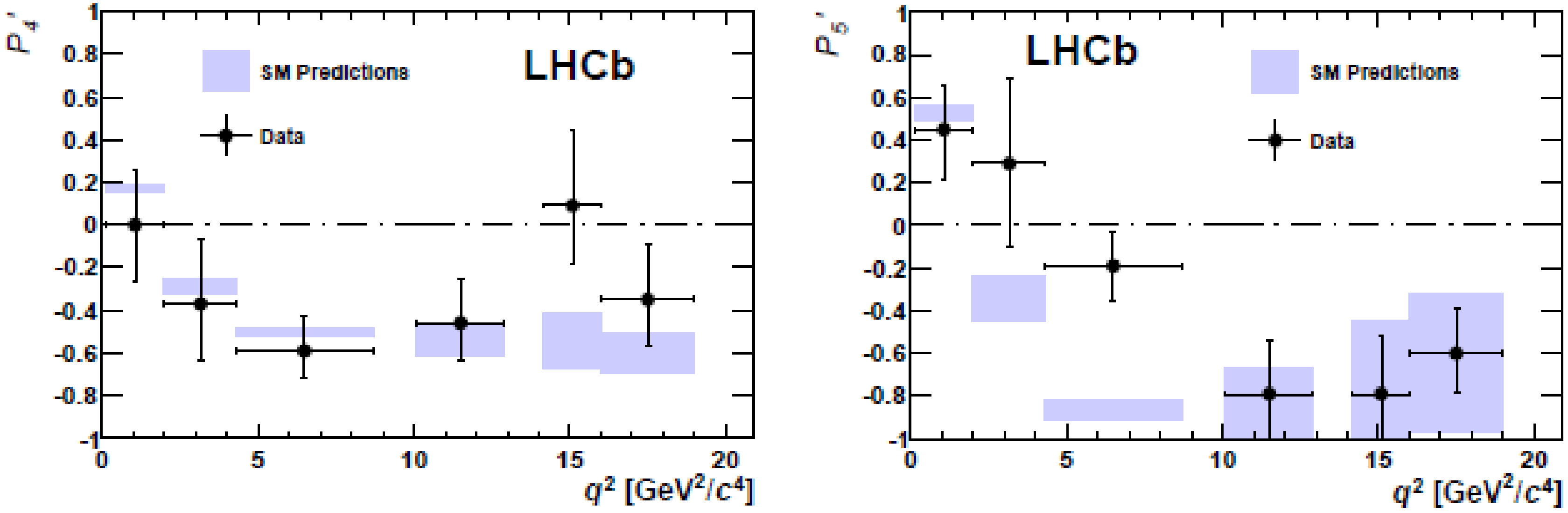
Further analysis of $B \to K^{*}\mu^{+}\mu^{-}$

$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\left[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell \right.$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$\left. + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi \right],$$

$$\boxed{P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}.}$$

$P'_{6,8}$ predicted to be small!

[arXiv:1308.1707]



Further analysis of $B \rightarrow K^{*}\mu^{+}\mu^{-}$

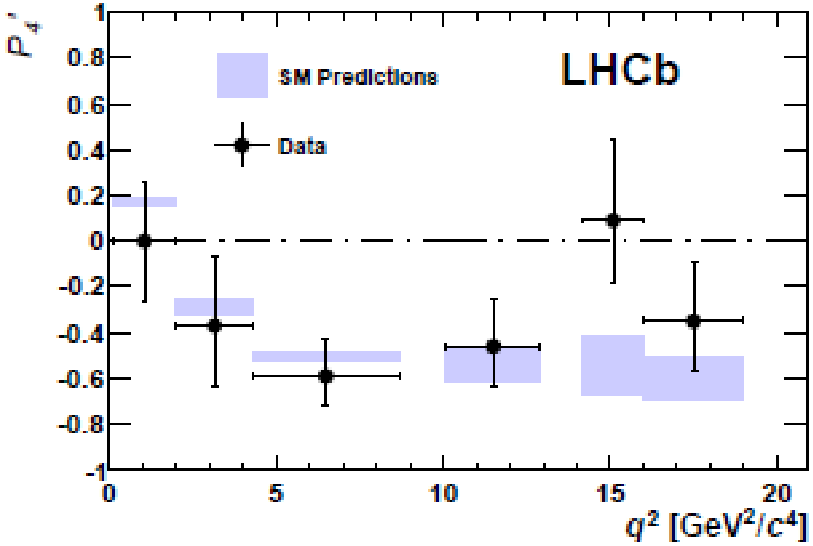
$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\left[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell \right.$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$\left. + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi \right],$$

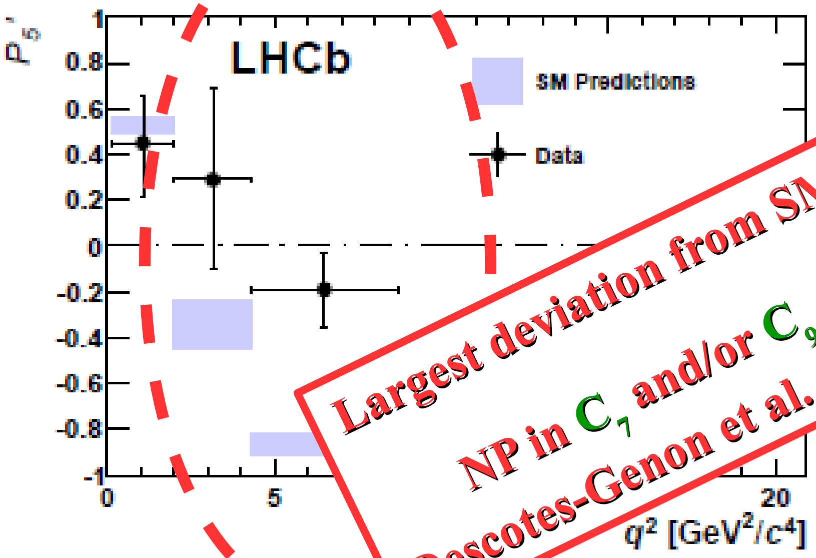
$$\boxed{P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}.}$$

$P'_{6,8}$ predicted to be small!

[arXiv:1308.1707]

$3.7\,\sigma \quad 4.30 < q^2 < 8.68\,\mathrm{GeV}^2/c^4$
$2.5\,\sigma \quad 1.0 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$





Largest deviation from SM at LHC !

NP in C_7 and/or C_9 as suggested

Descotes-Genon et al. arXiv:1307.5683 ?

Summary

LHCb, the forward spectrometer for precision studies in flavour physics domain

Excellent performance of the LHC and LHCb has led to a lot of physics results

- **Test of SM**
- **Search for NP**
- **Make CP violation measurements in b- and c-sectors**

World best quality of the results in charm and beauty physics!

Remember, that presented here measurements use mainly the 1 fb^{-1} dataset

(**70% of the 2010-12 data still in progress**)

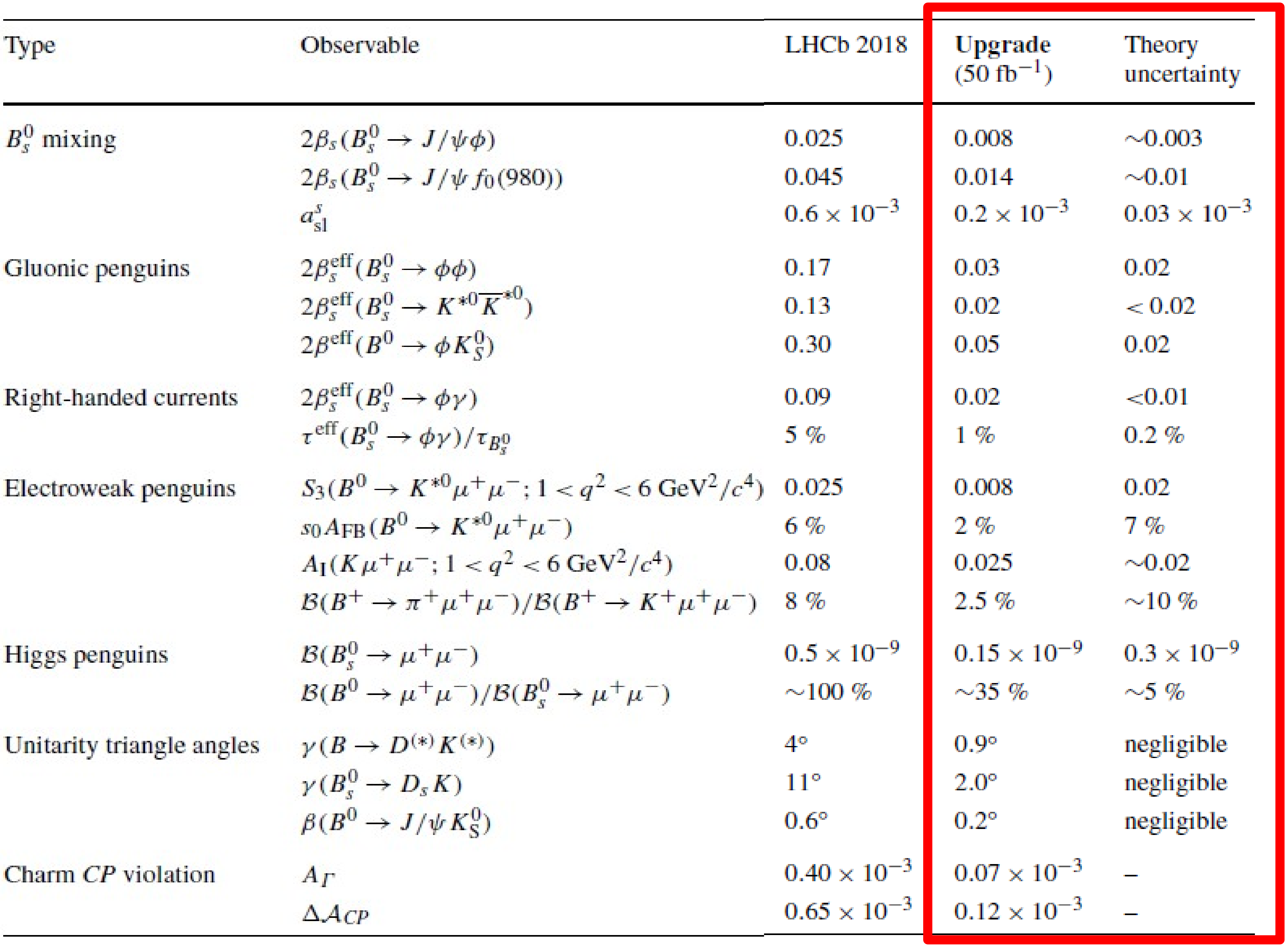
OUTLOOK:

1) Plan to have more than ~ 5 fb^{-1} at $\sqrt{s} = 13$ TeV during next LHC run (2015-18)

=> ~ **8 times higher statistics in 2019** (in comparison with presented results)

2) **Upgrade** (next slide)

Outlook. ***Theory vs. 50 fb^{-1}***



Type	Observable	LHCb 2018	Upgrade (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s(B_s^0 \to J/\psi\phi)$	0.025	0.008	$\sim$0.003
	$2\beta_s(B_s^0 \to J/\psi f_0(980))$	0.045	0.014	$\sim$0.01
	$a_{\rm sl}^s$	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
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\overline{K}^{*0})$	0.13	0.02	$<$ 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	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	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.025	0.008	0.02
	$s_0 A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.08	0.025	$\sim$0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	8 %	2.5 %	$\sim$10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$\sim$100 %	$\sim$35 %	$\sim$5 %
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	4°	0.9°	negligible
	$\gamma(B_s^0 \to D_s K)$	11°	2.0°	negligible
	$\beta(B^0 \to J/\psi K_S^0)$	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	0.65×10^{-3}	0.12×10^{-3}	–

EPJ C 73 (2012) 2373