Результаты эксперимента LHCb

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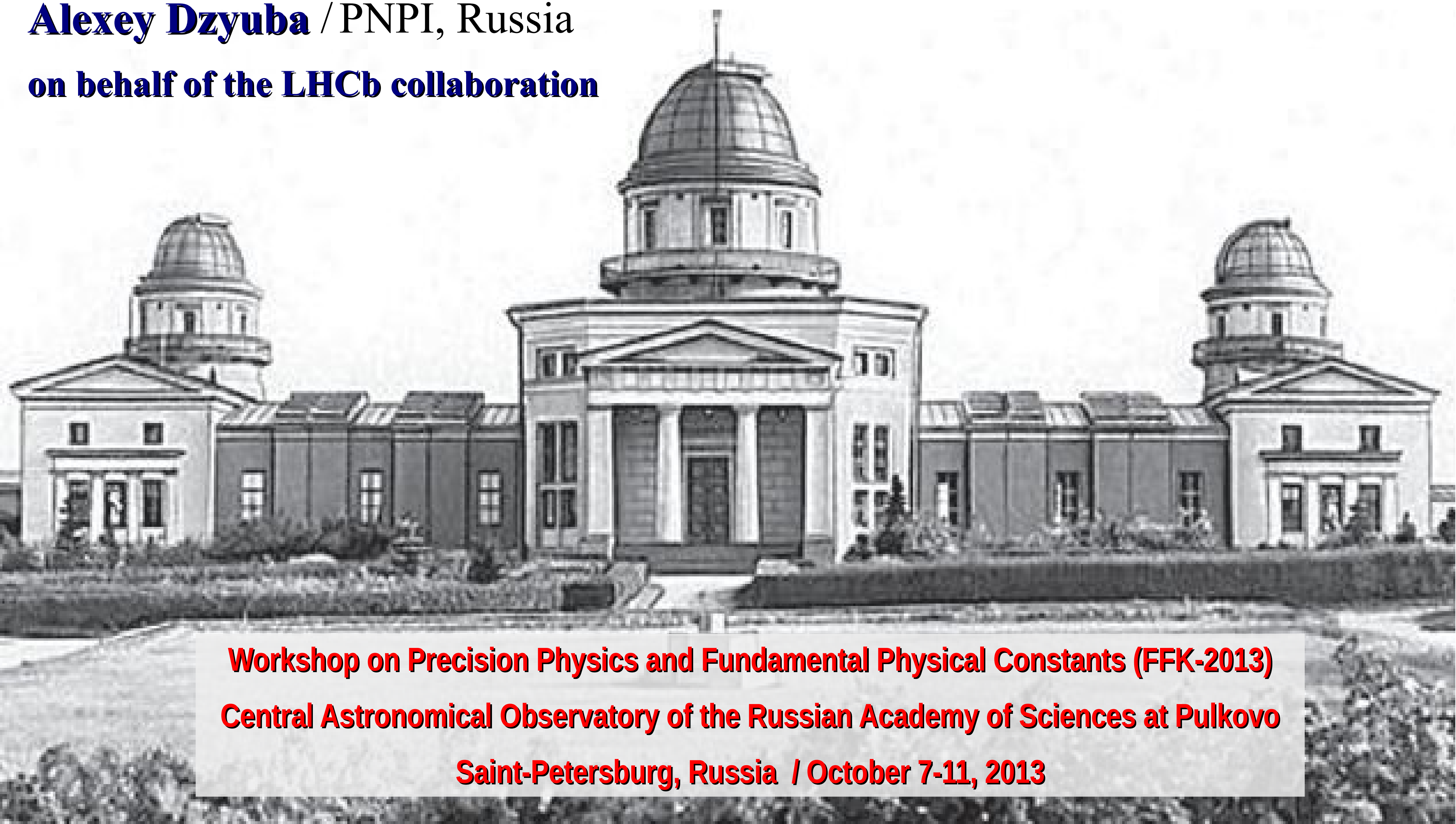
01 октября 2013 г.

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

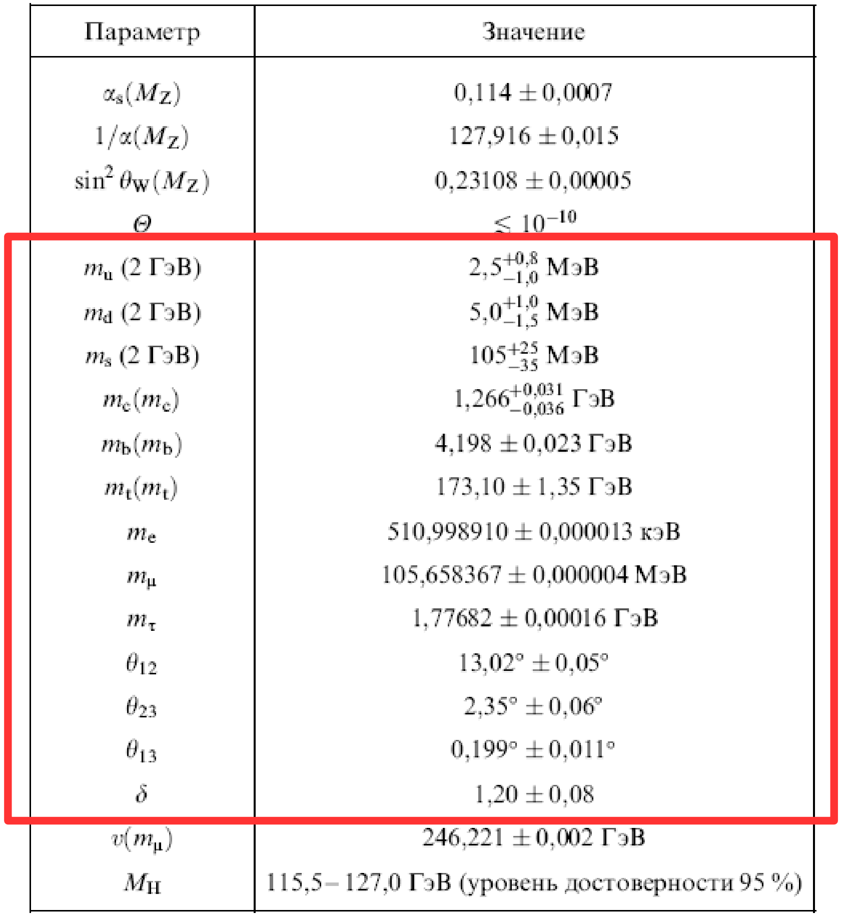
Main goal of this talk: Show how precise LHCb measurements in b- and c-sectors make constraints on fundamental prameters of Standard Model (SM) and provide a New Physics (NP) searches.

- 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

Flavour sector of SM



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 %)

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)**

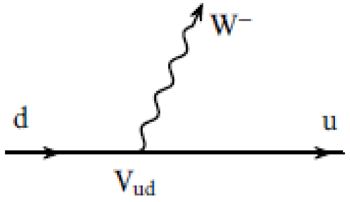
SUSY good candidate to solve 2) & 3)

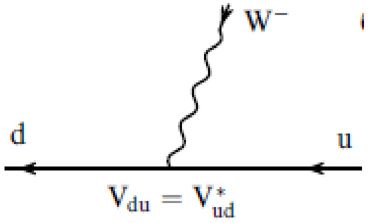
Cabibbo-Kobayashi-Maskawa

- **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**

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

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





Wolfenstein parametrization

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

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

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

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

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:

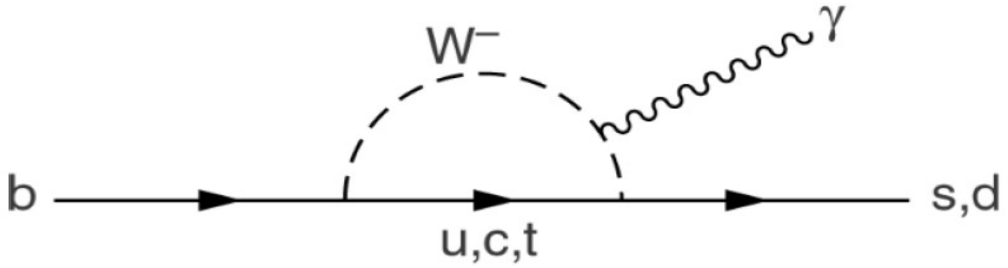
$$(\bar{\mathrm{u}}\,\bar{\mathrm{c}}\,\bar{\mathrm{t}}\,)\gamma_{\mu}(a + c\gamma_5)\begin{pmatrix}\mathrm{u}\\ \mathrm{c}\\ \mathrm{t}\end{pmatrix} + (\bar{\mathrm{d}}\,'\bar{\mathrm{s}}\,'\bar{\mathrm{b}}\,')\gamma_{\mu}(a + c\gamma_5)\begin{pmatrix}\mathrm{d}\,'\\ \mathrm{s}\,'\\ \mathrm{b}\,'\end{pmatrix}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

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

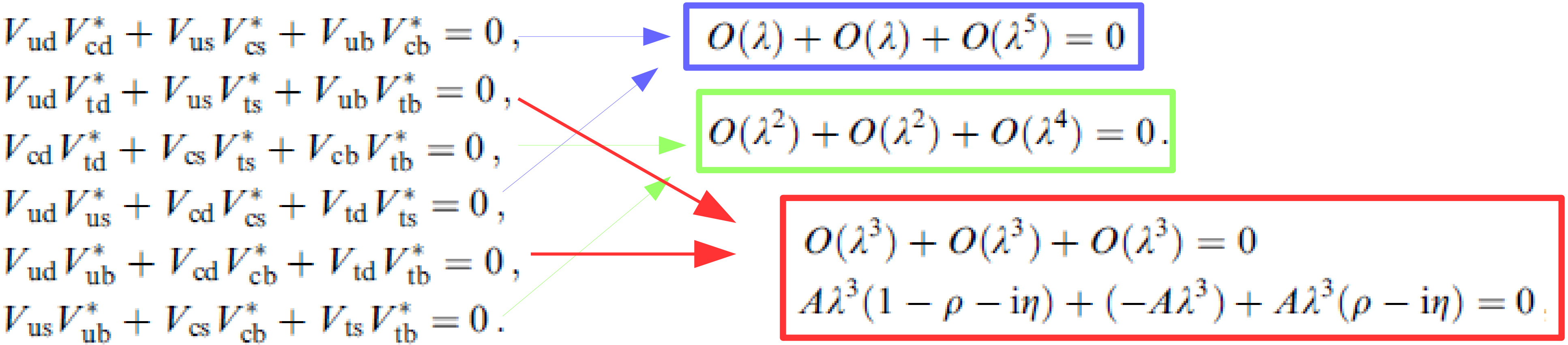
As a result Flavour Changing Neutral Currents (FCNC) is forbidden at tree level but can appear at the loop level!

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

For example :



Unitarity triangles



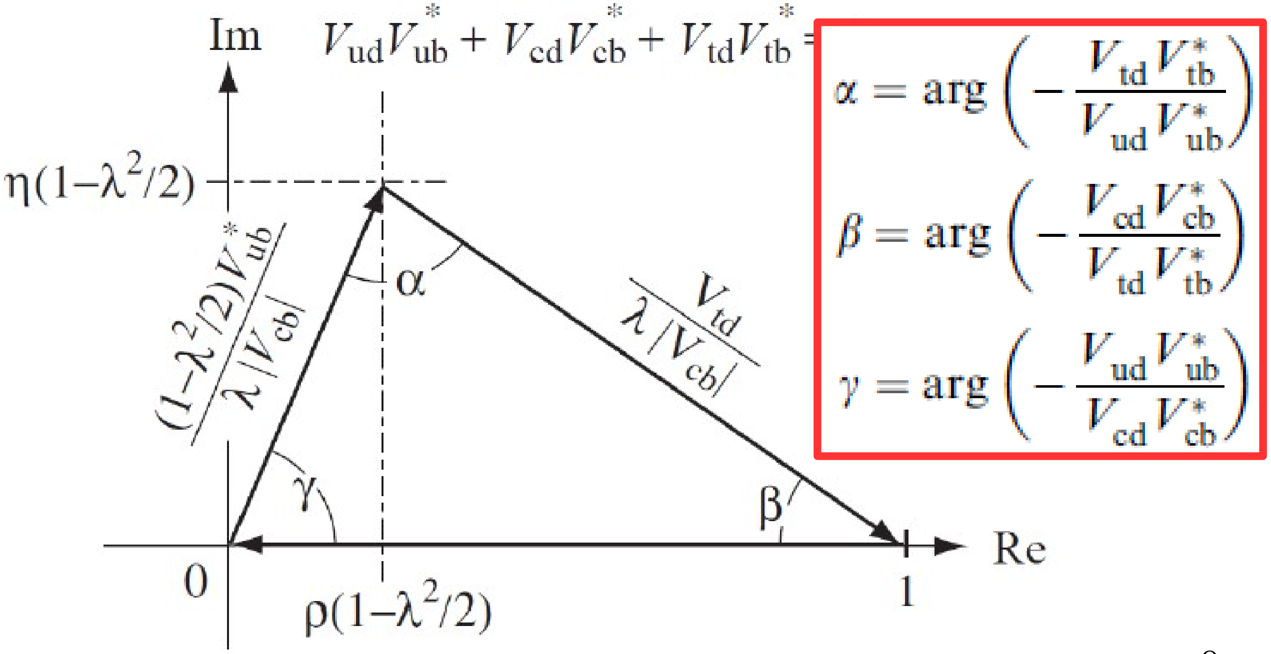
$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0\,,$$
$$V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0\,,$$
$$V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0\,,$$
$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0\,,$$
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0\,,$$
$$V_{us}V_{ub}^*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

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

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

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

- **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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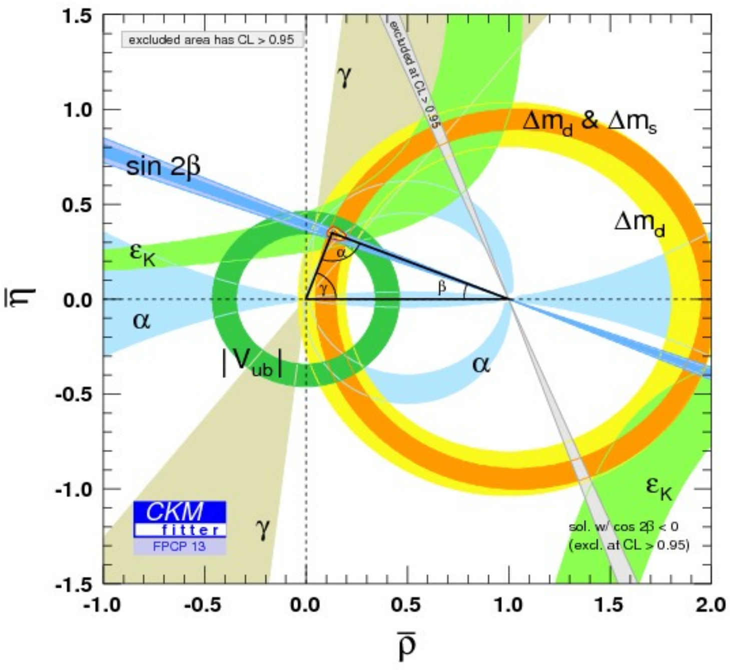
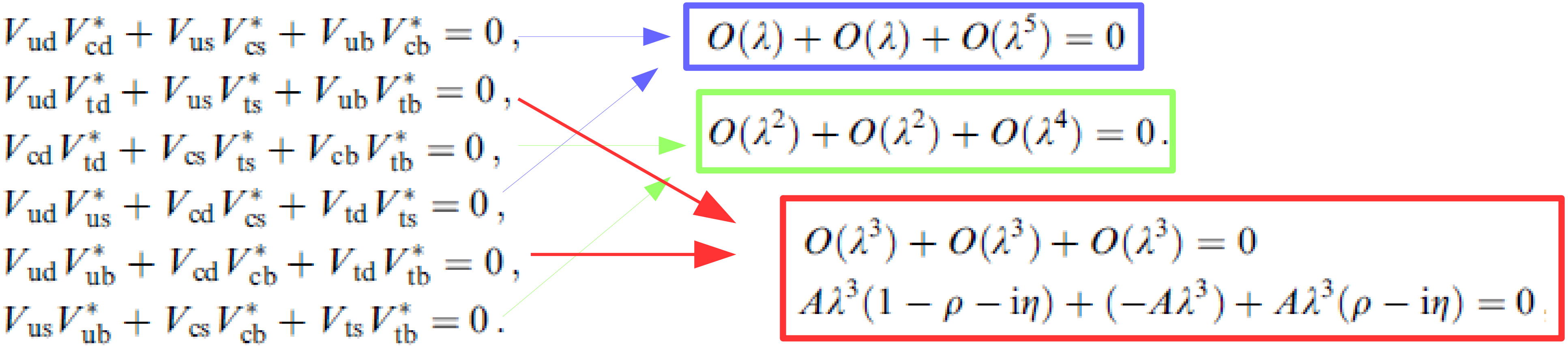
$$\boxed{\begin{array}{l} O(\lambda^3) + O(\lambda^3) + O(\lambda^3) = 0 \\ A\lambda^3(1-\rho-i\eta) + (-A\lambda^3) + A\lambda^3(\rho - i\eta) = 0 \end{array}}$$



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

- **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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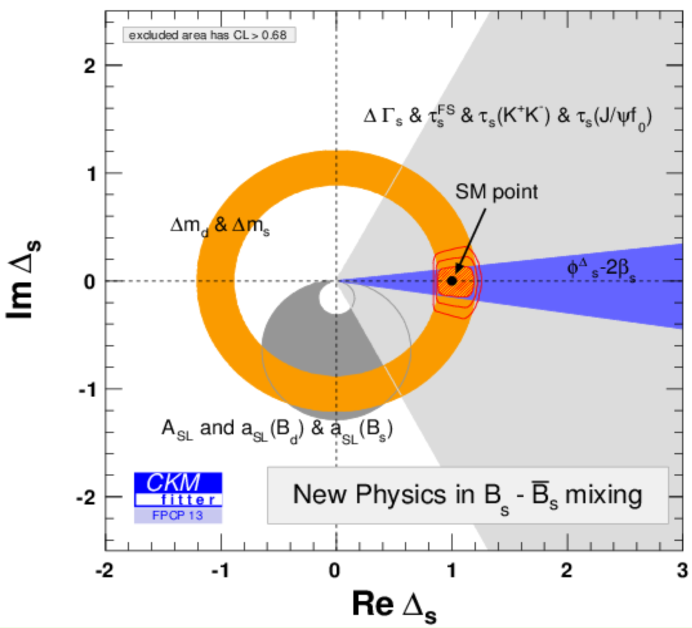


- **Other triangles are also very important**
- **In this talk I will show LHCb results on φs**
- **Note: Another consequence of V_{CKM} unitarity is that squares of elements in raws and columns must be equal to one. [see for example RPP 73, 046301]**

NP and flavour symmetry; Wilson's coefficients

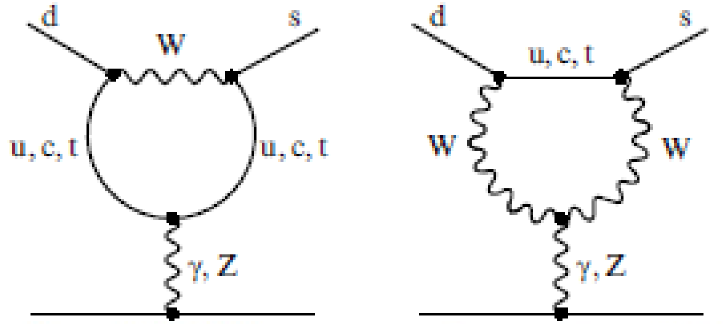
- **Progress of theory calculations allows to take into account QCD corrections needed for SM FCNC implementation to decays. (Calculation of C_i in SM as well as quite precise predictions for certain processes)**
- **$H_{\rm eff}$ is an effective way to test different classes of possible NPs, because 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

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

Example



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

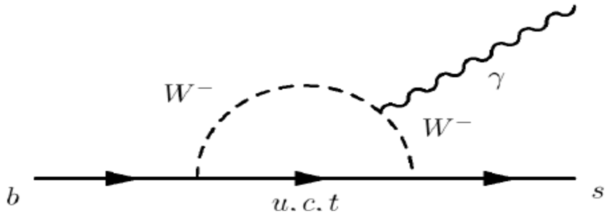
- **If NP contains additional FV sources of C_i become complex as well as new CPV effects might appear!**

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

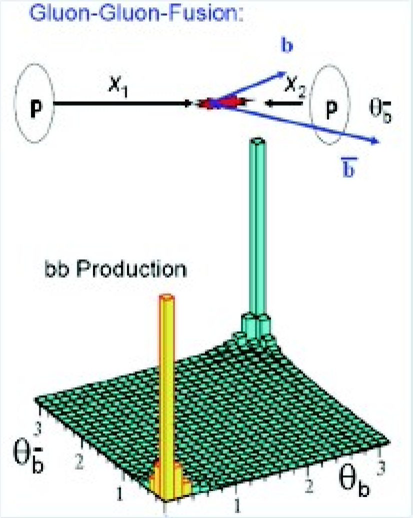
Example #3: ARGUS collaboration report large B-mixing

Suggest large mass of top quark

~8 years *t* has been discovered at Tevatron

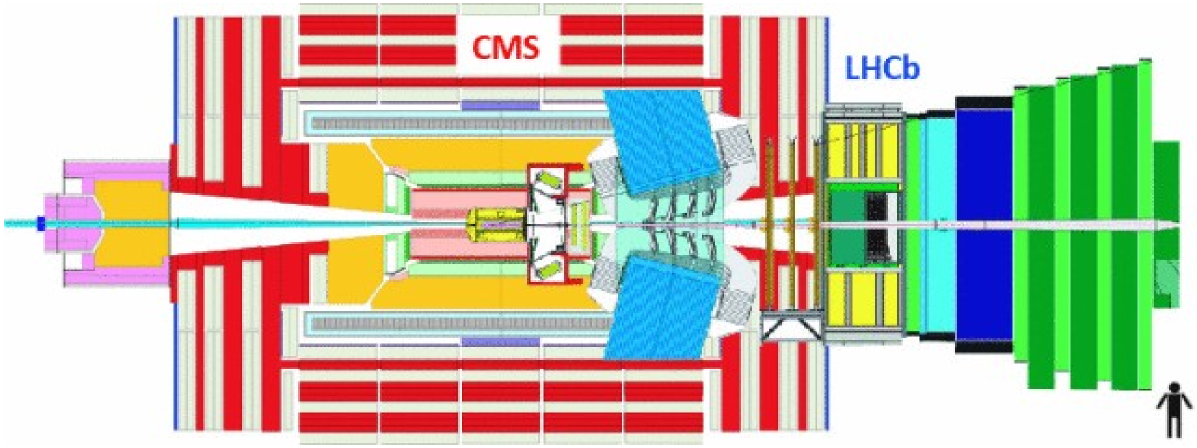
LHCb features

Beauty and charm production

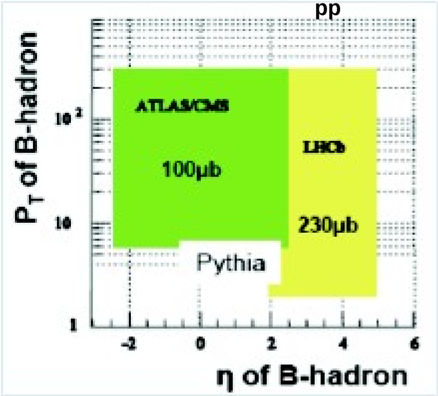


- **LHCb: forward spectrometer** 2 < η < 5

  (ATLAS & CMS: |η|<2.5)



$\sqrt{s}_{pp}$ = 14 TeV



- In LHCb acceptance (*pp*-collisions √s = 7TeV)

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

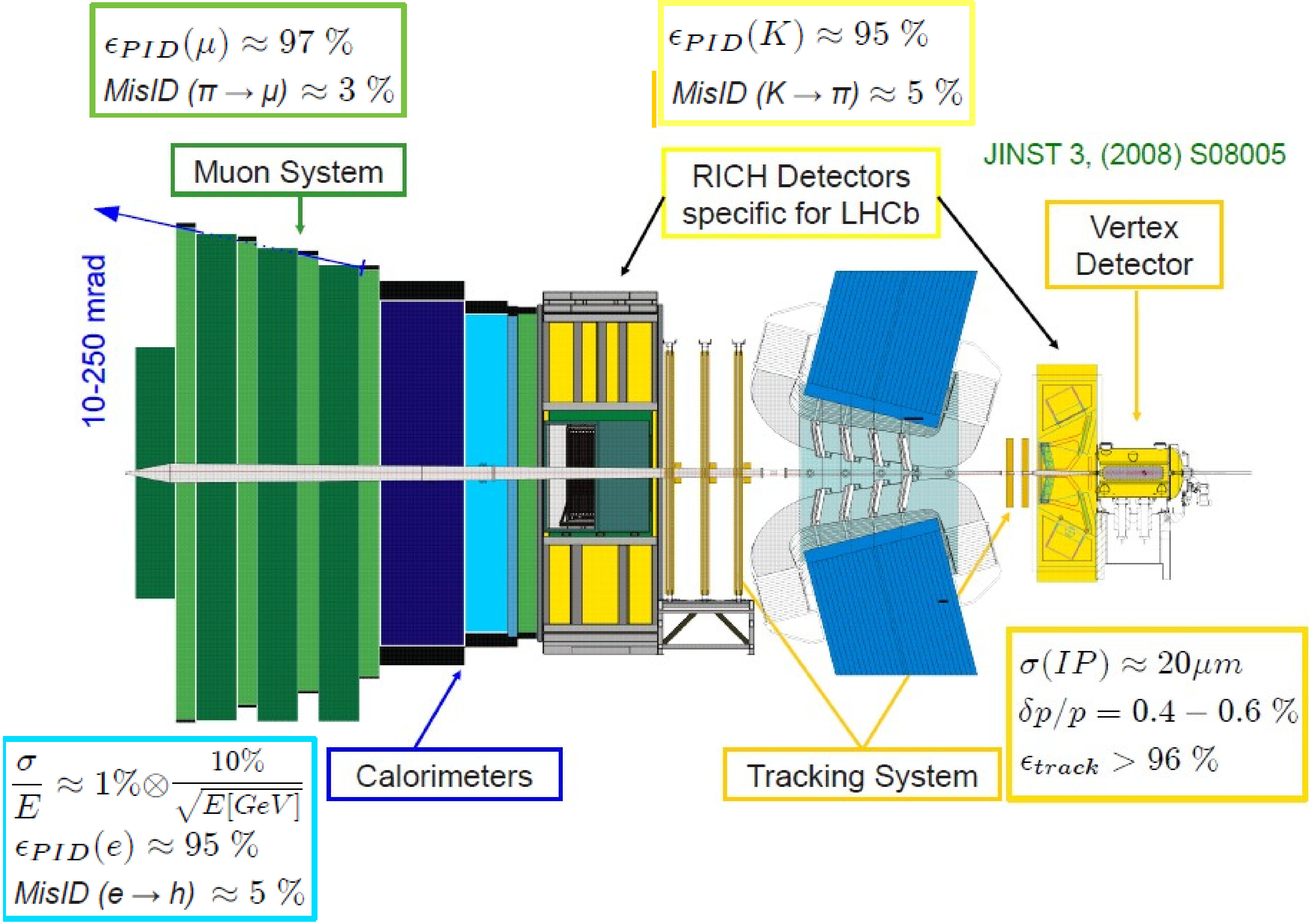
Phys.Lett.B694 (2010) 209-216

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

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

JINST 3, (2008) S08005

Muon System

RICH Detectors specific for LHCb

Vertex Detector

10-250 mrad

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

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

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

Calorimeters

Tracking System

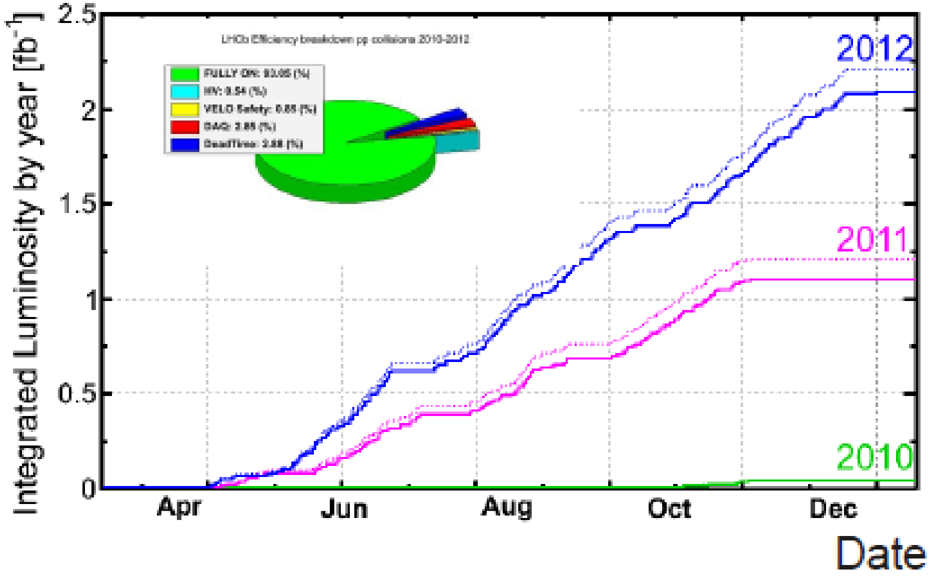
$\sigma(IP) \approx 20\mu m$

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

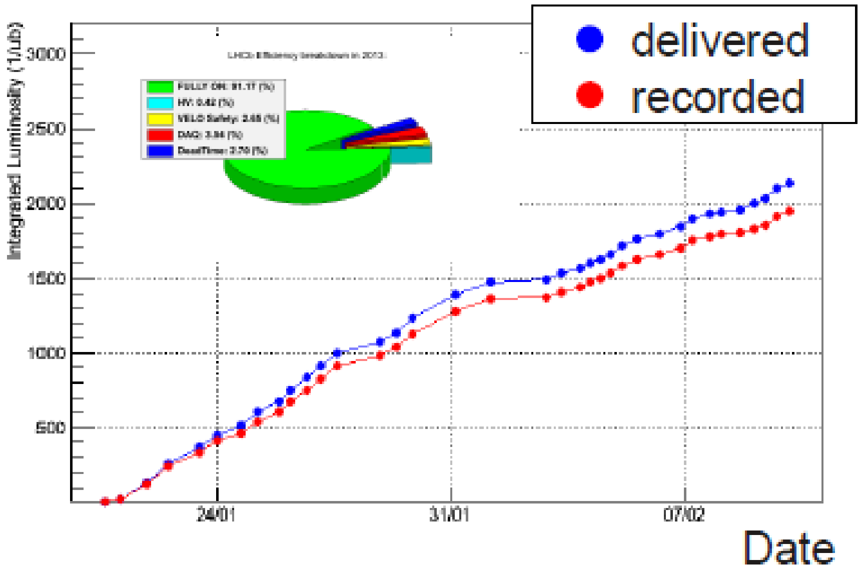
$\epsilon_{track} > 96\ \%$

Operation in 2010/12

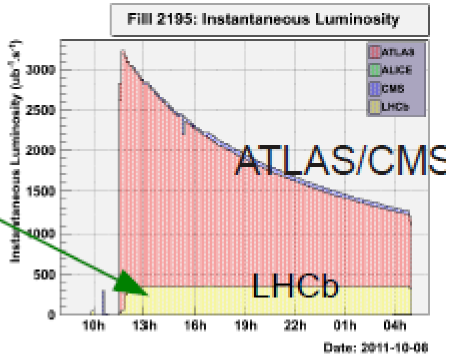
pp-collisions at $\sqrt{s}$ = 7 & 8 TeV (2011-12)



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



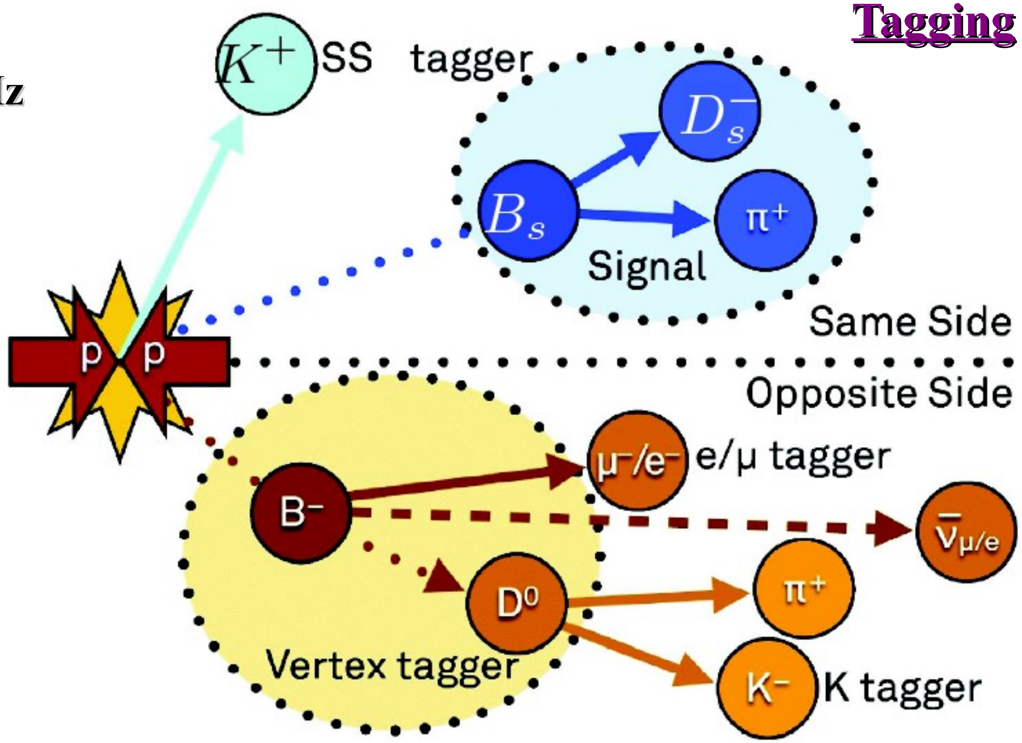
- LHCb operates with high efficiency
- Take data at constant instantaneous luminosity rate: $\mathcal{L} \approx 4 \times 10^{32}\, cm^{-2} s^{-1}$
  (factor 2 larger than design luminosity)
- Visible pp interactions per bunch crossing μ = 1.7 (50 ns bunch spacing)



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

LHCb data analysis

Tagging



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.*

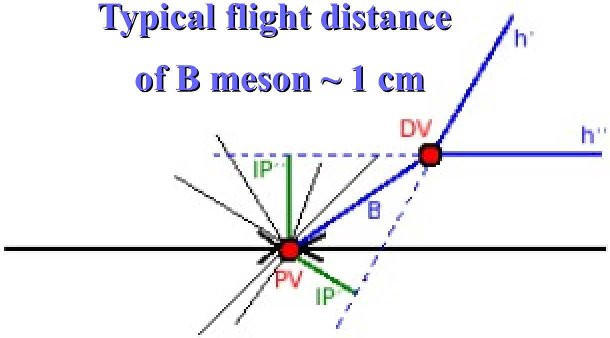
Optimization of selection
Using MC
Using small sample of real data

Angular analysis++

Check for systematics

And a lot of other checks!

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, Δm_s; Γ_s, $\Delta\Gamma$, ϕ_s ; CKM γ determination
3) Mixing and CPV in the D systems
 Mixing observ., $\Delta A(CP)$

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: $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi f(980)$

4) CKM angle γ

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

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

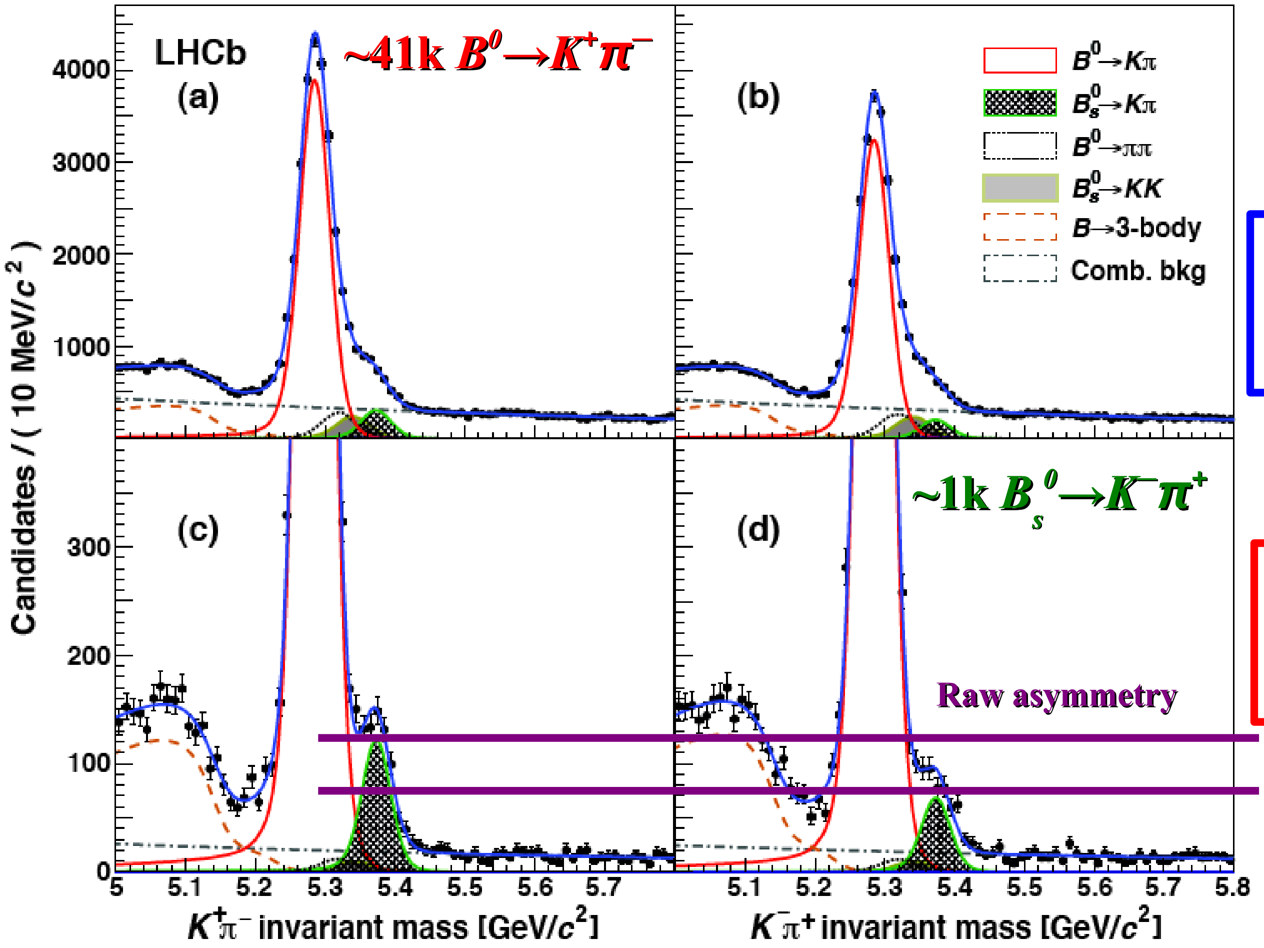
1 fb^{-1} dataset, PRL 110, 221601

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

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

Detection asymmetry

Production asymmetry



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

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

Raw asymmetry

Oscillation considered in the analysis!

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

$= -0.080 \pm 0.007_{\text{stat}} \pm 0.003_{\text{syst}}$

World best precision

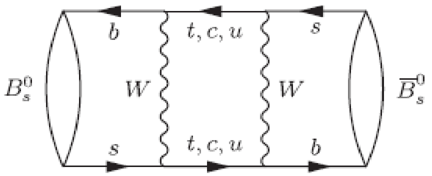
$A_{CP}(B_s^0 \to K^-\pi^+) =$

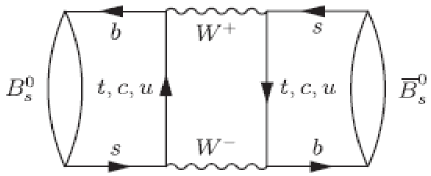
$= 0.27 \pm 0.04_{\text{stat}} \pm 0.01_{\text{syst}}$

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

Oscillation frequency for B_s

Corresponding SM box-diagrams





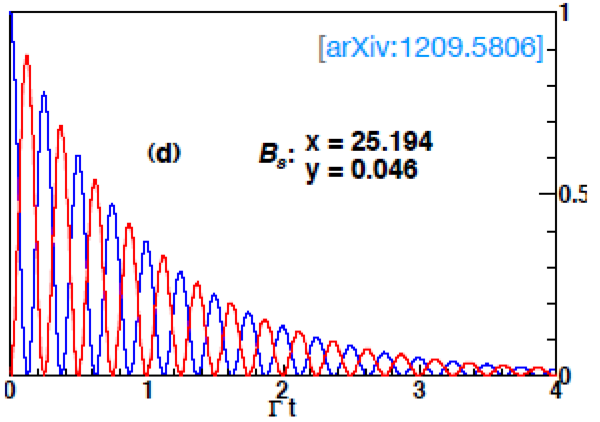
B_s: Fast oscillations

Excellent time resolution required!

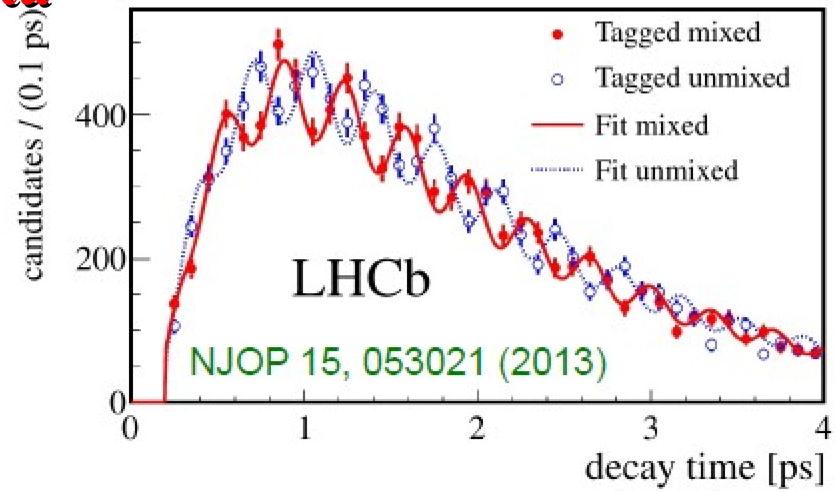
$$\Gamma = (\Gamma_L + \Gamma_H) / 2;$$

$$\Delta m_s = M_H - M_L$$

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



Data



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

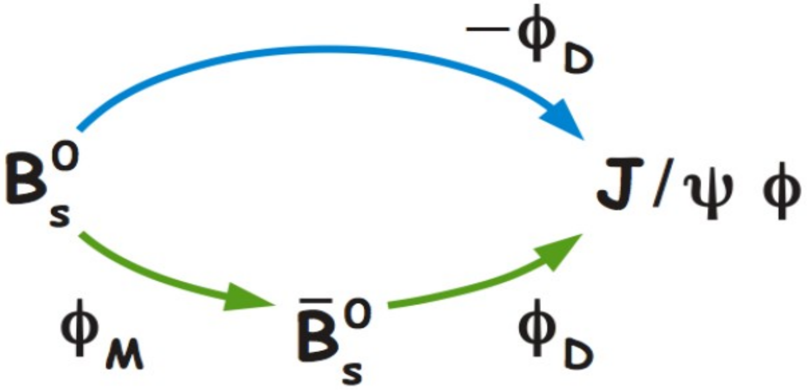
Also measured in semileptonic decays [arXiv:1308.1302] !

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]

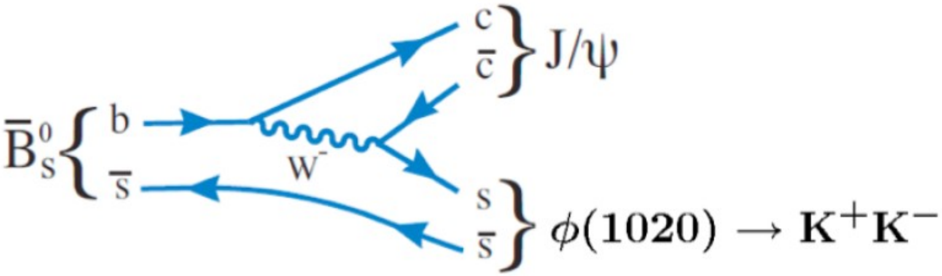
$$\boxed{\phi_s^{SM} = -2\beta_s = (-0.0363 \pm 0.0016)\,\mathrm{rad}}$$



- **Observable very sensitive to NP !**

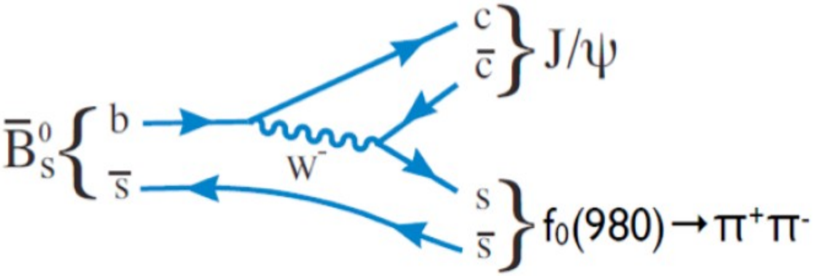
- LHCb measured it in two modes (1 fb^{-1} dataset)

  [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

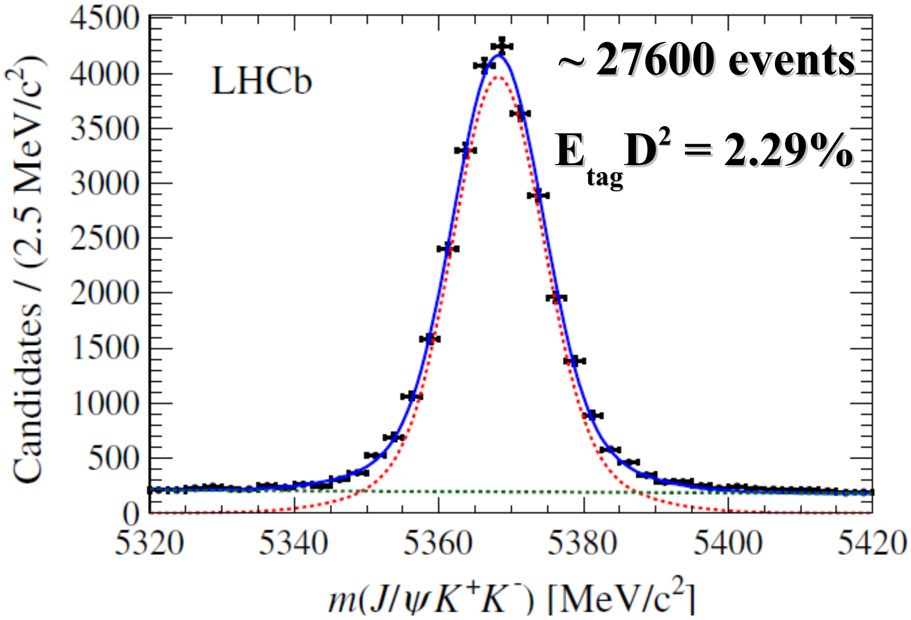
$B^0_s \to J/\psi\phi$

- **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**

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

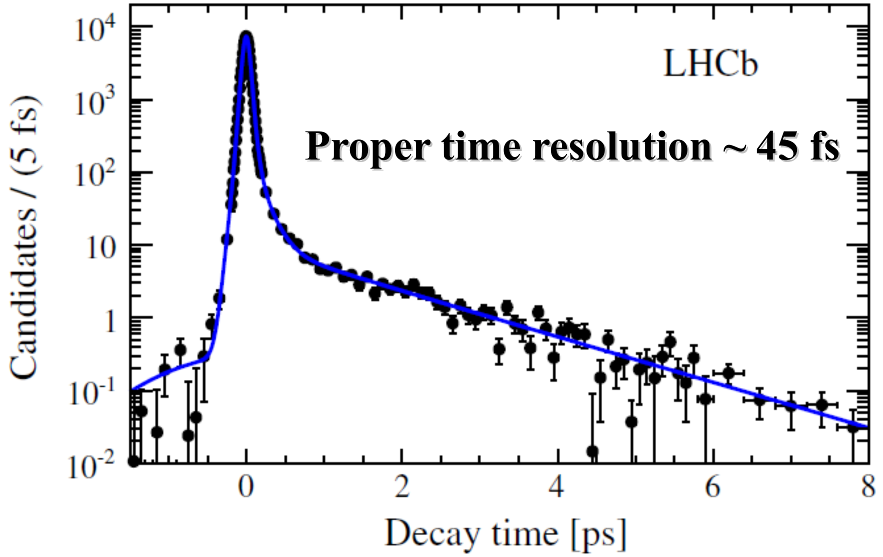
$$\Gamma_s = 0.663 \pm 0.005(\text{stat}) \pm 0.006(\text{syst})\ \text{ps}^{-1}$$

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



~ 27600 events

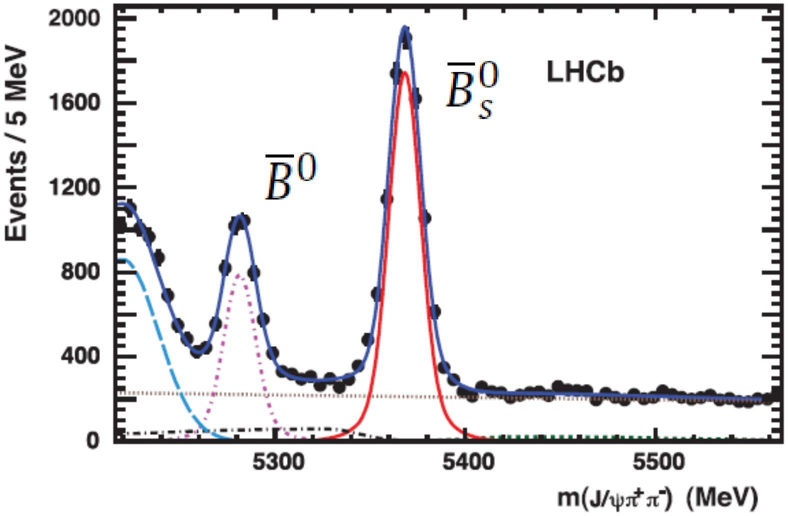
$E_{tag}D^2$ = 2.29%

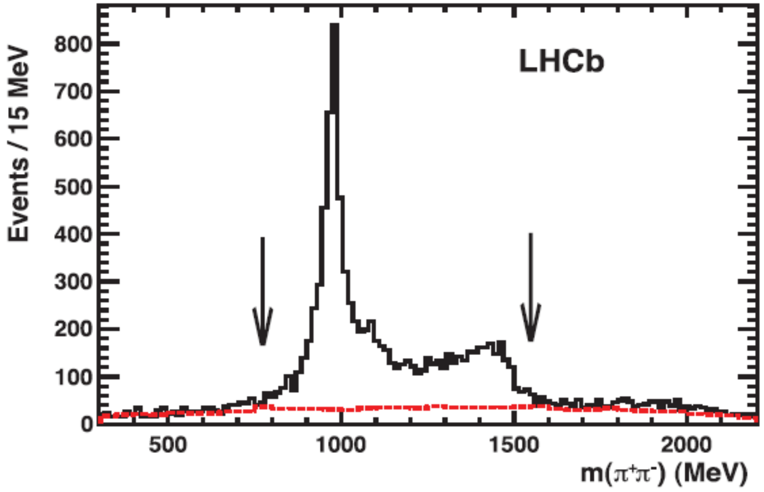


Proper time resolution ~ 45 fs

[PRD 87, 112010]

Mixing induced CP violation in B_s





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

- 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 $J/\psi\,\pi^+\pi^-$

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

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

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

Consistent with SM prediction!

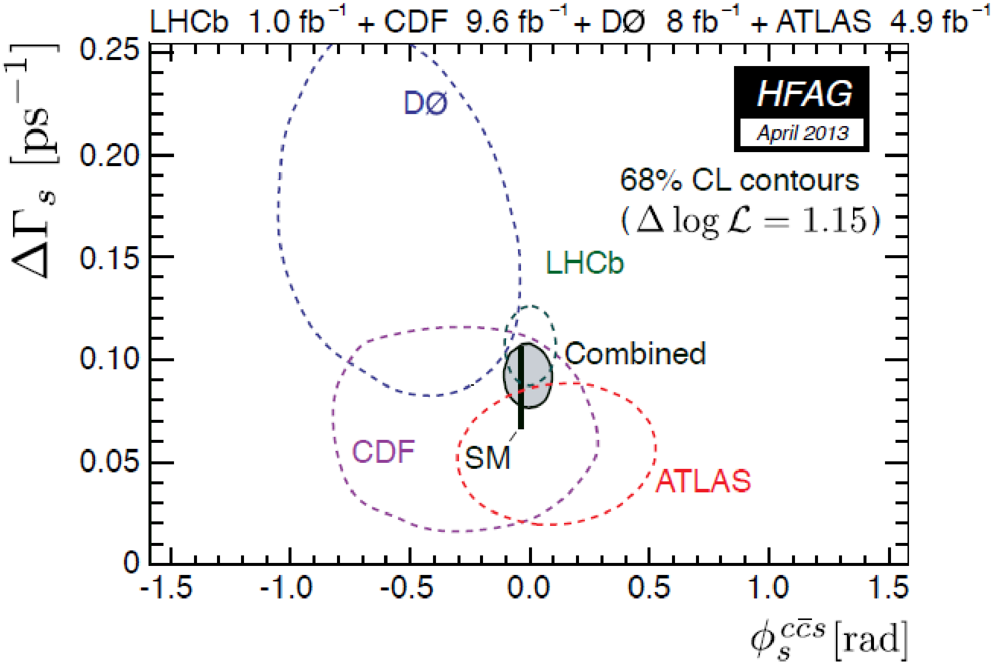
[PRD 87, 112010]

Constrain on NP parameters

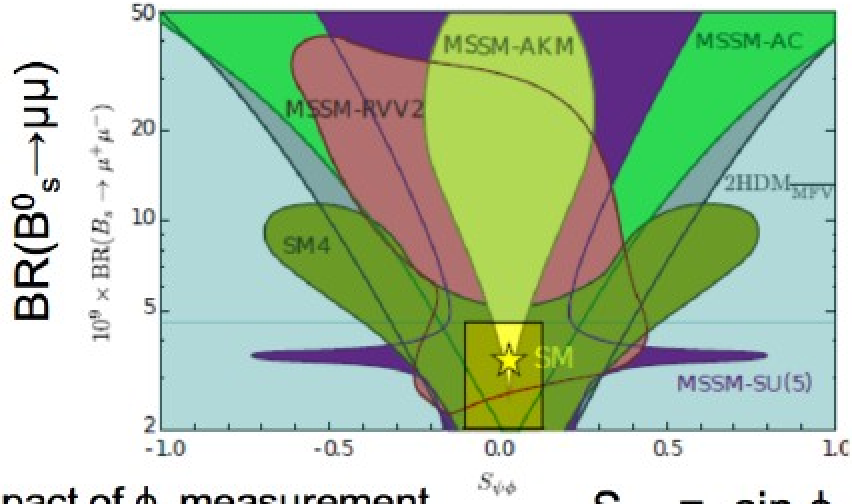
Consistent with SM prediction

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.

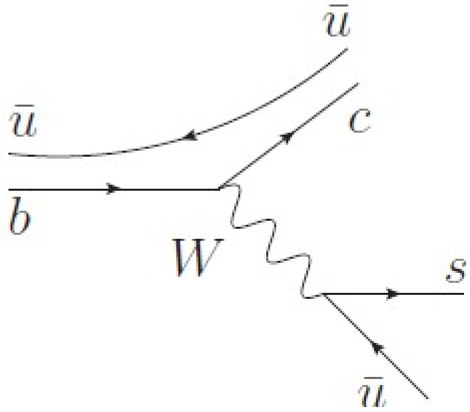
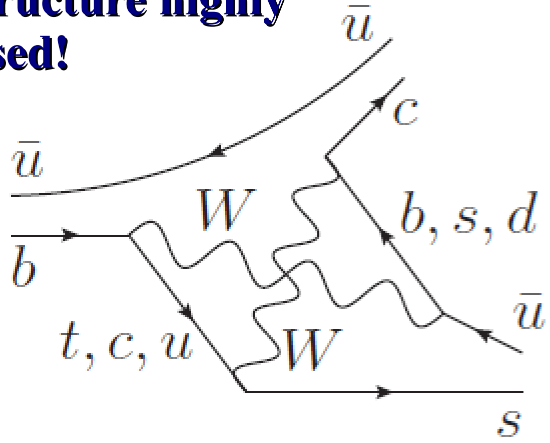


Diagram with other CKM structure highly suppressed!



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

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)]

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

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

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

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

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)]

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

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

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

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

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

Strong phase varies over the 3-body phase space.

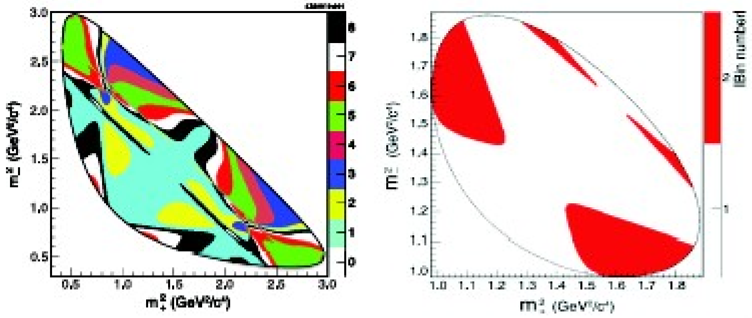
$$x_\pm = r_B \cos(\delta_B \pm \gamma) \quad y_\pm = r_B \sin(\delta_B \pm \gamma)$$

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

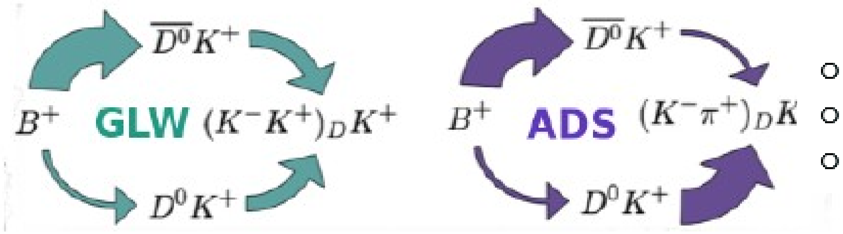
$$N^-_{\pm i} = h_{B^-}[K_{\pm i} + (x_-^2 + y_-^2)K_{\mp i} + 2\sqrt{K_i K_{-i}}(x_- c_{\pm i} \pm y_- s_{\pm i})]$$

Binned Dalitz plot phase variation measured by CLEO-c :

CLEO, Phys. Rev. D 82 (2010) 112006

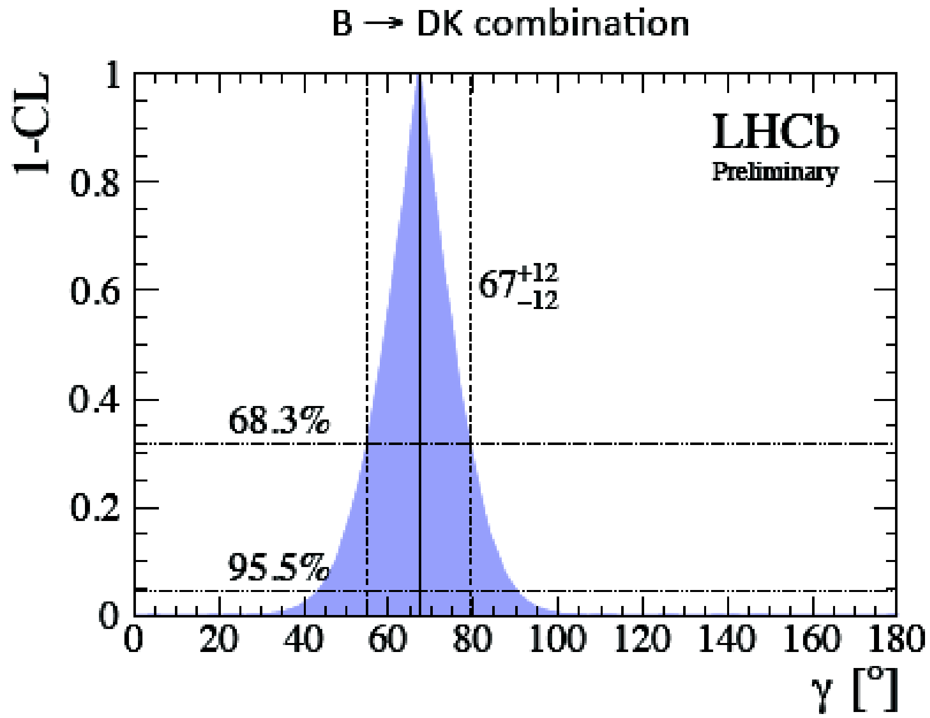


Result on CKM γ



- **(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

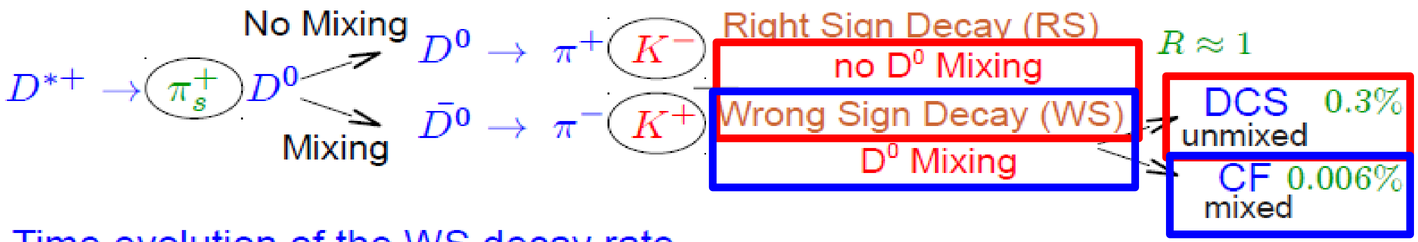
- Well defined m and Γ
- Define the mixing parameters

Mixing determines the time evolution of the flavor eigenstates

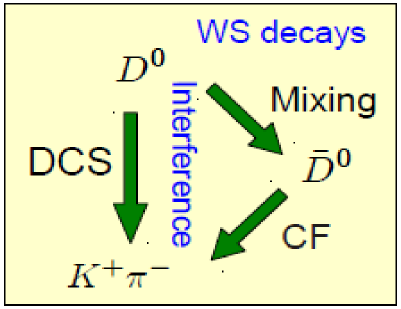
$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

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

- Event classes - flavour tagging at production and decay



- 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 ($D^0 \to K\pi$)

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

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

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

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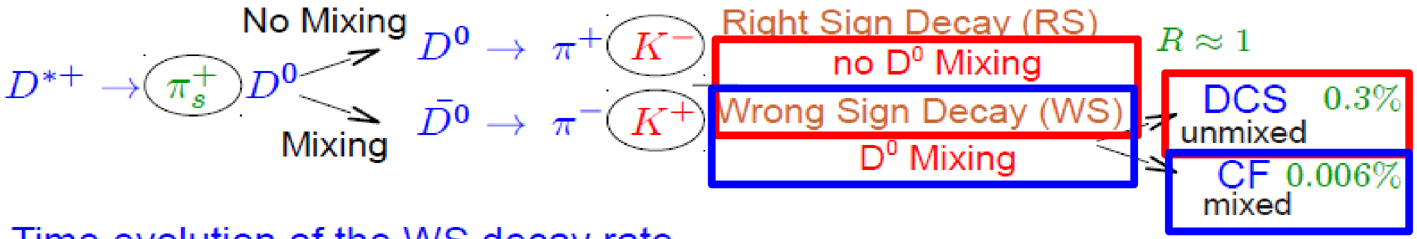

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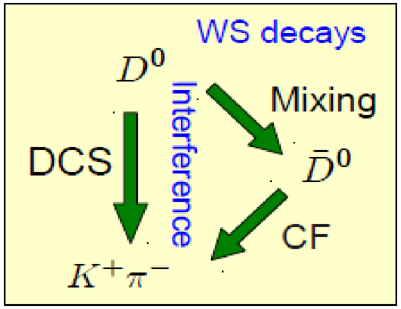

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$$y'^2 + x'^2 = x^2 + y^2$$

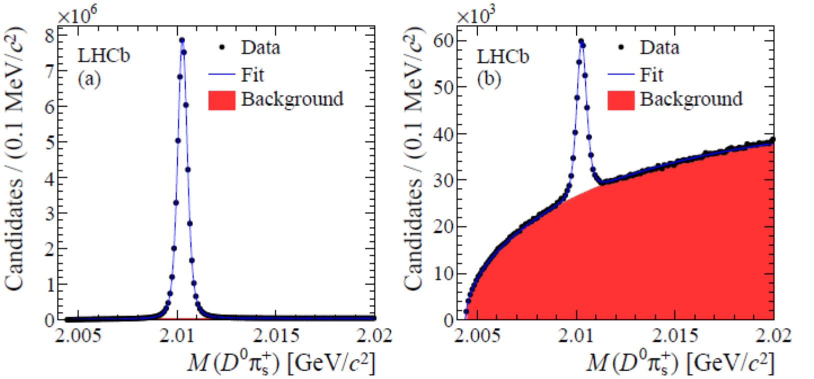
LHCb already reported about first observation of *D⁰* mixing (by single experiment, 9σ) **PRL 110, 101802**

Newest results on D^0 mixing (and CPV)

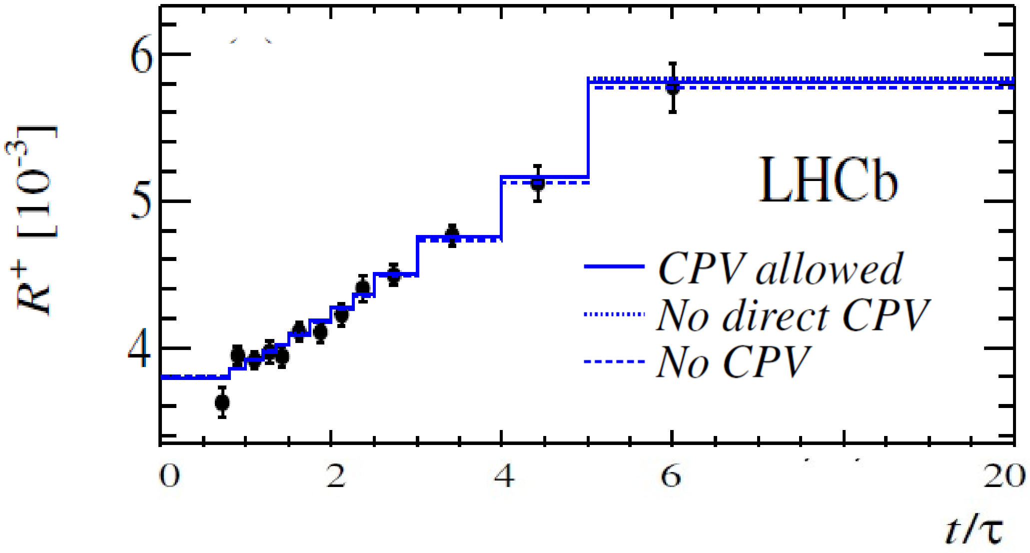
Wrong-sign-to-Right-sign ratio:

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

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



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



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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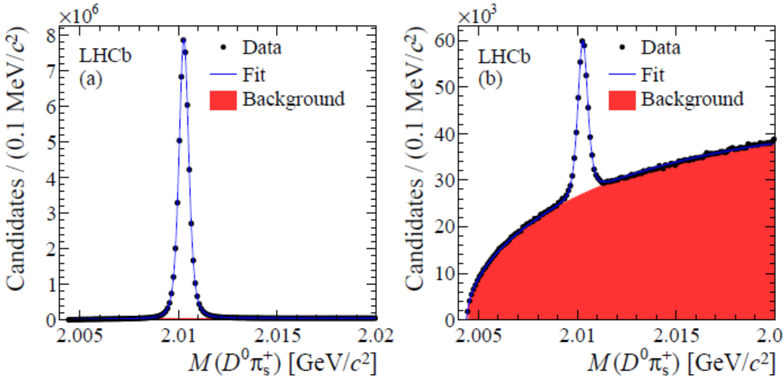

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World-best result!

Fit with CPV assumptions has been also done

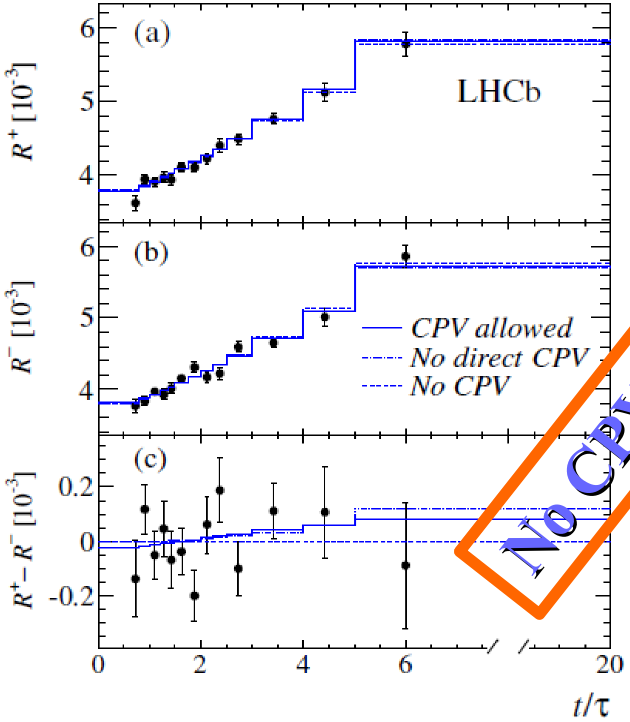
Direct CPV:

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

Mixing-Induced CPV:

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

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



No CPV effects found!

[arXiv:1309.6534]

Newest results on D^0 mixing (and CPV)

arXiv:1309.6534

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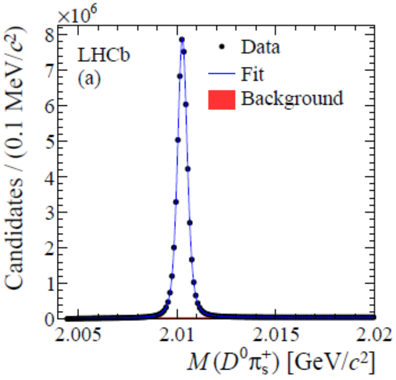
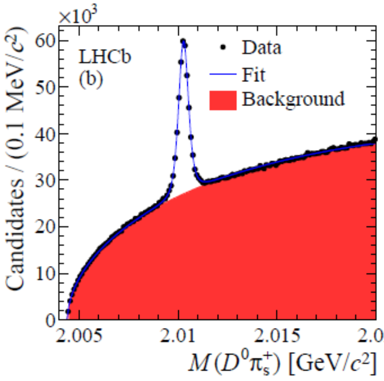
$$R(t) \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2$$

RS: 230 × WS ev. **WS:** 2.3×10^5 ev.





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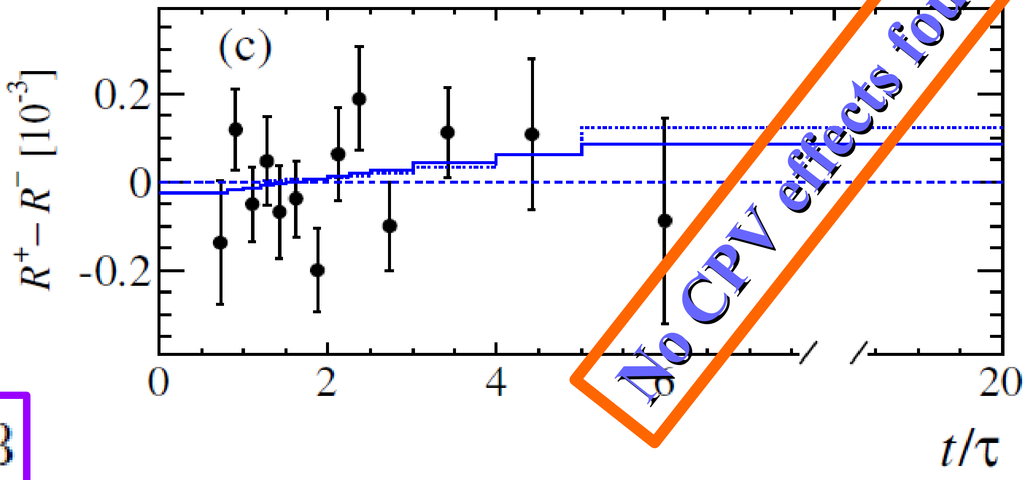

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χ^2/ndf		$86.4/101$

World-strongest constraints!

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

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

World-best result!

[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

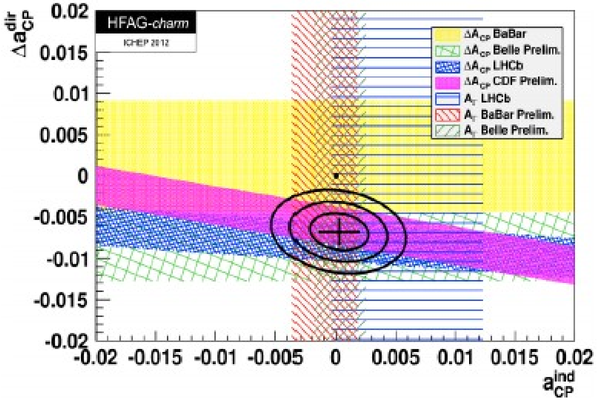
$$\begin{aligned}\Delta A_{CP} &= A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)\\ &= [a_{CP}^{dir}(K^+K^-) - a_{CP}^{dir}(\pi^+\pi^-)] + \frac{\Delta < t >}{\tau}a_{CP}^{ind}\end{aligned}$$

With $0.6\,\mathrm{fb}^{-1}$ 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}

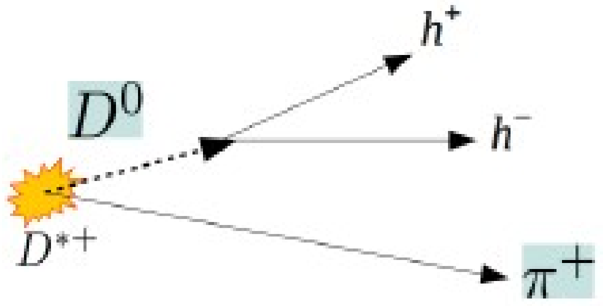
Access via asymmetry measurement

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

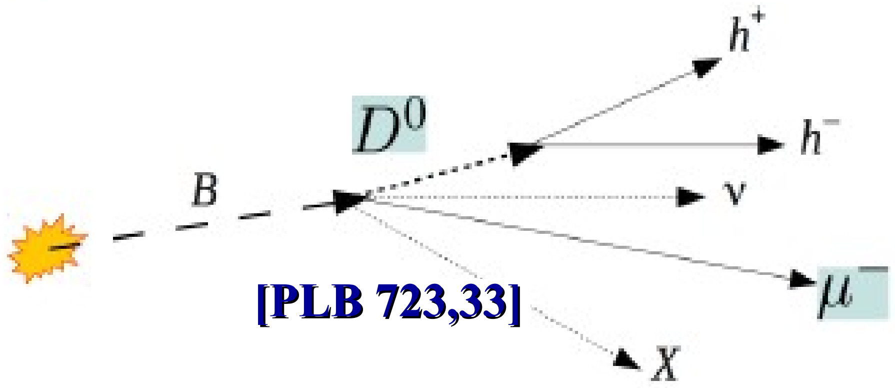
LHCb measured **time integrated difference of asymmetries**

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

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]

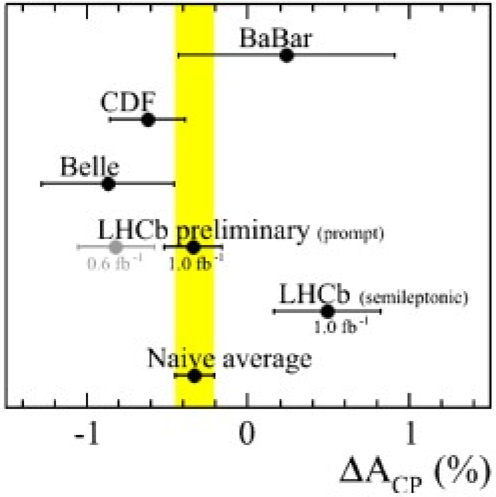
- D^* tagged sample (preliminary)

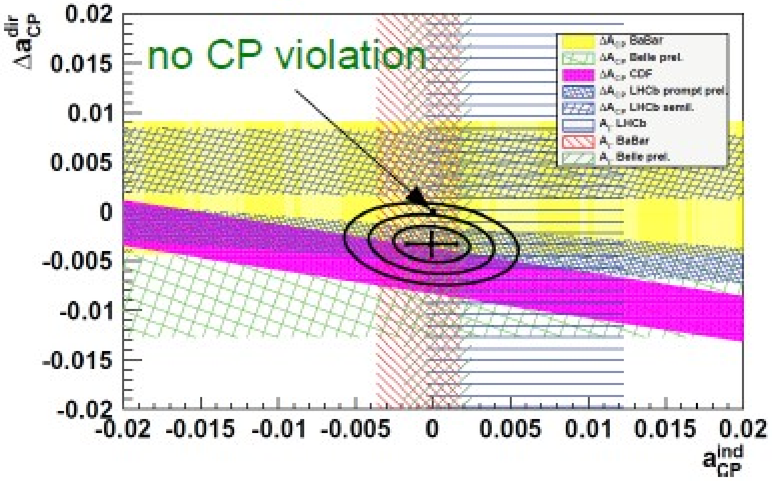
$$\Delta A_{CP} = (-0.34 \pm 0.15\,(stat) \pm 0.10\,(sys))\ \%$$

- 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:

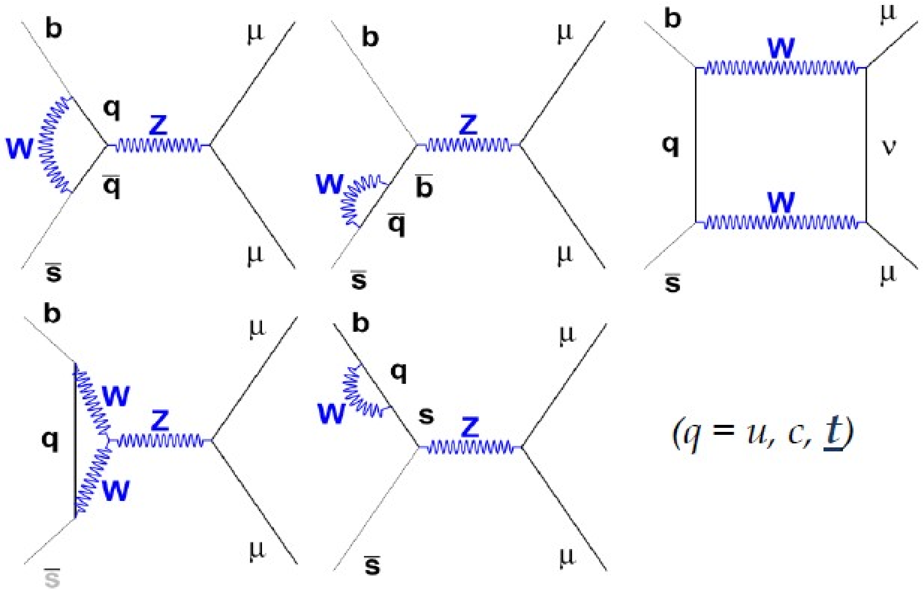
$$a_{CP}^{ind} = (-0.010 \pm 0.162)\ \%$$

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

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



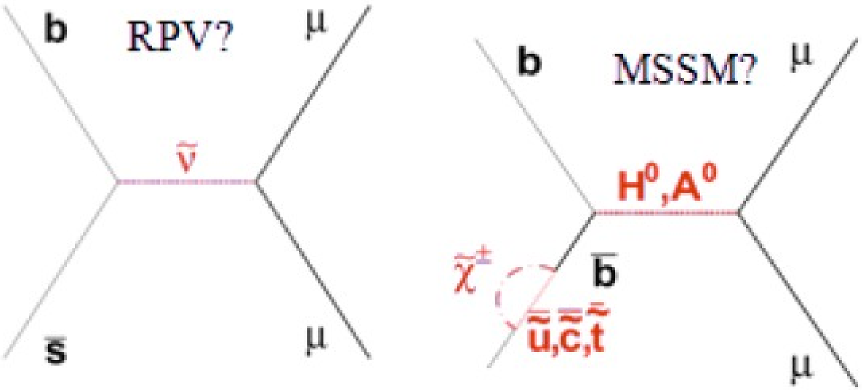
$(q = u, c, \underline{t})$

Helicity suppressed in SM [arXiv 1303.3820]

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

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

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



5% precision SM calculations!

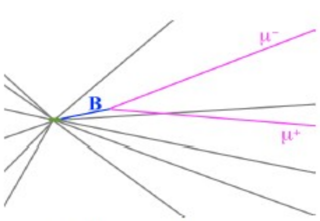
Sensitive to new scalar, pseudoscalar, axial-vector particles in loops

In MSSM:

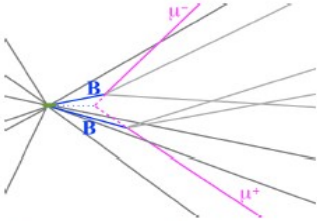
$$c_{S,P}^{MSSM\,2} \propto \frac{m_b^2 m_\mu^2 \tan^6\beta}{M_A^4}$$

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$_{inv}$)



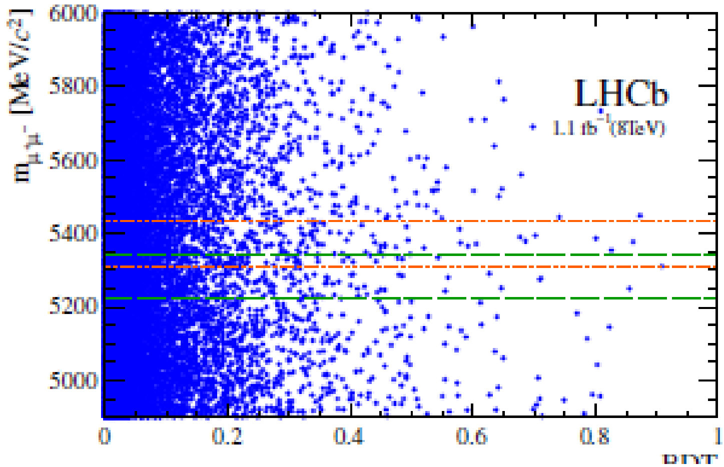
(a) $B^0_{d,s} \to \mu^+\mu^-$ signal

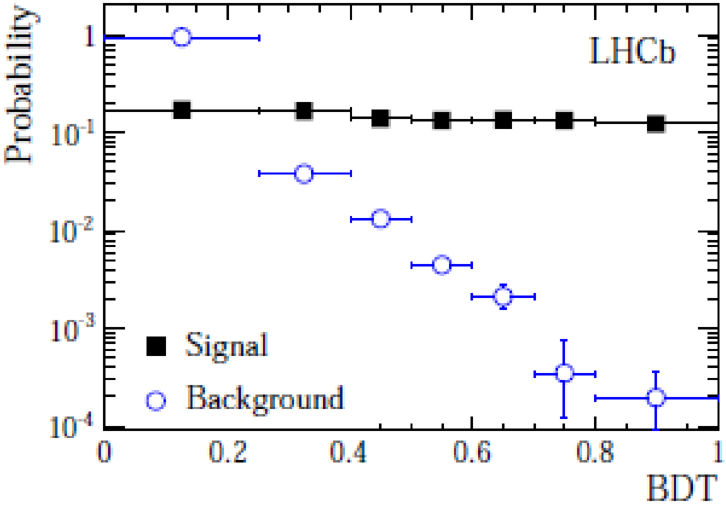


(b) $bb \to \mu^+\mu^- X$ background

- 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.

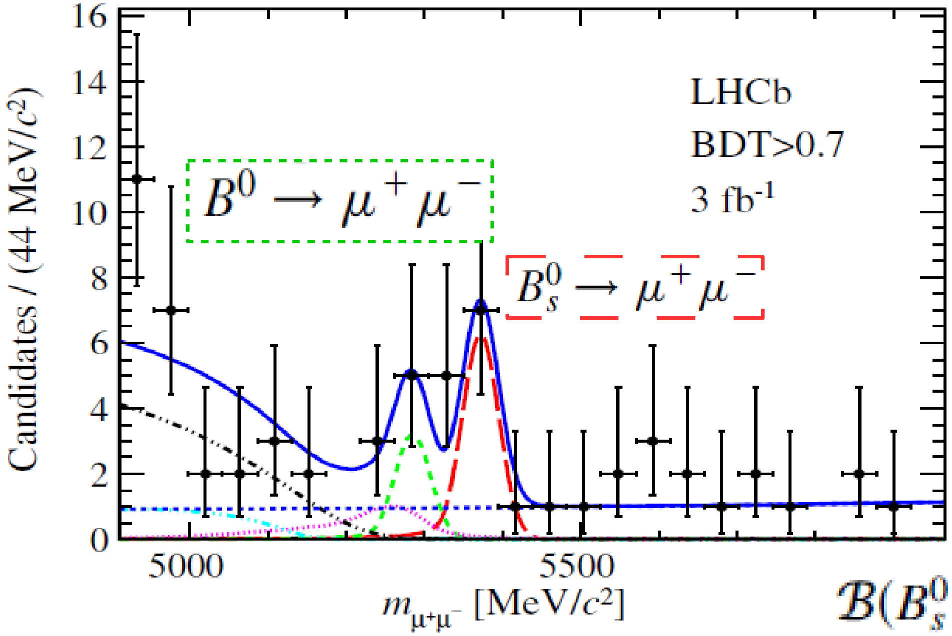
PRL 110, 021801





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
$B_s^0 \to K^-\mu^+\nu_\mu$	10 ± 4	21
$B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$	28 ± 8	15
$\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$	70 ± 30	11

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

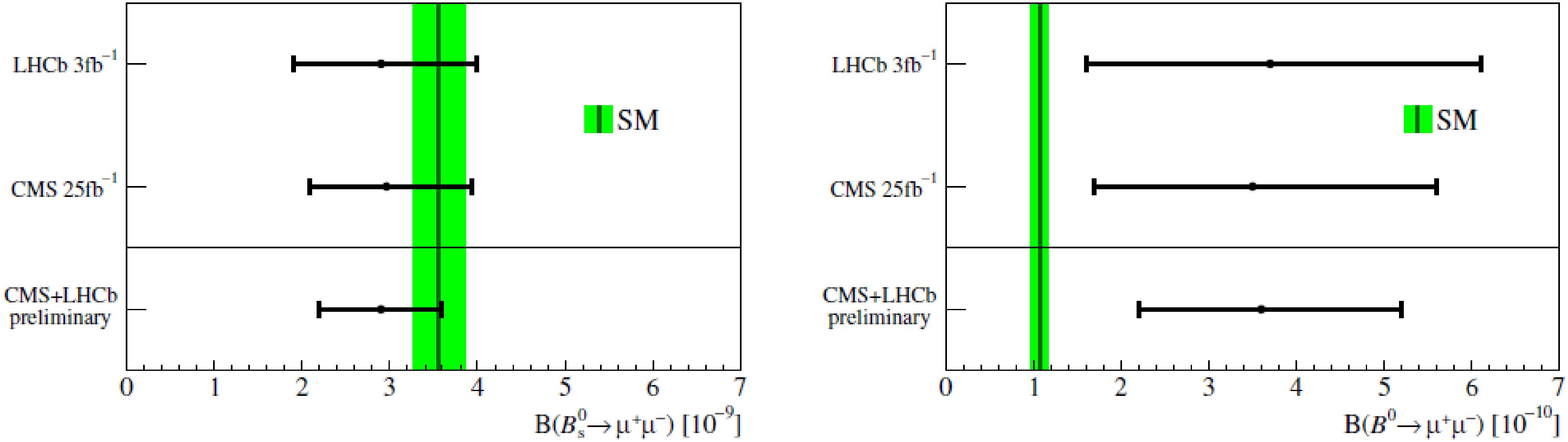
Statistical significance 4σ for B_s^0 signal!

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



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

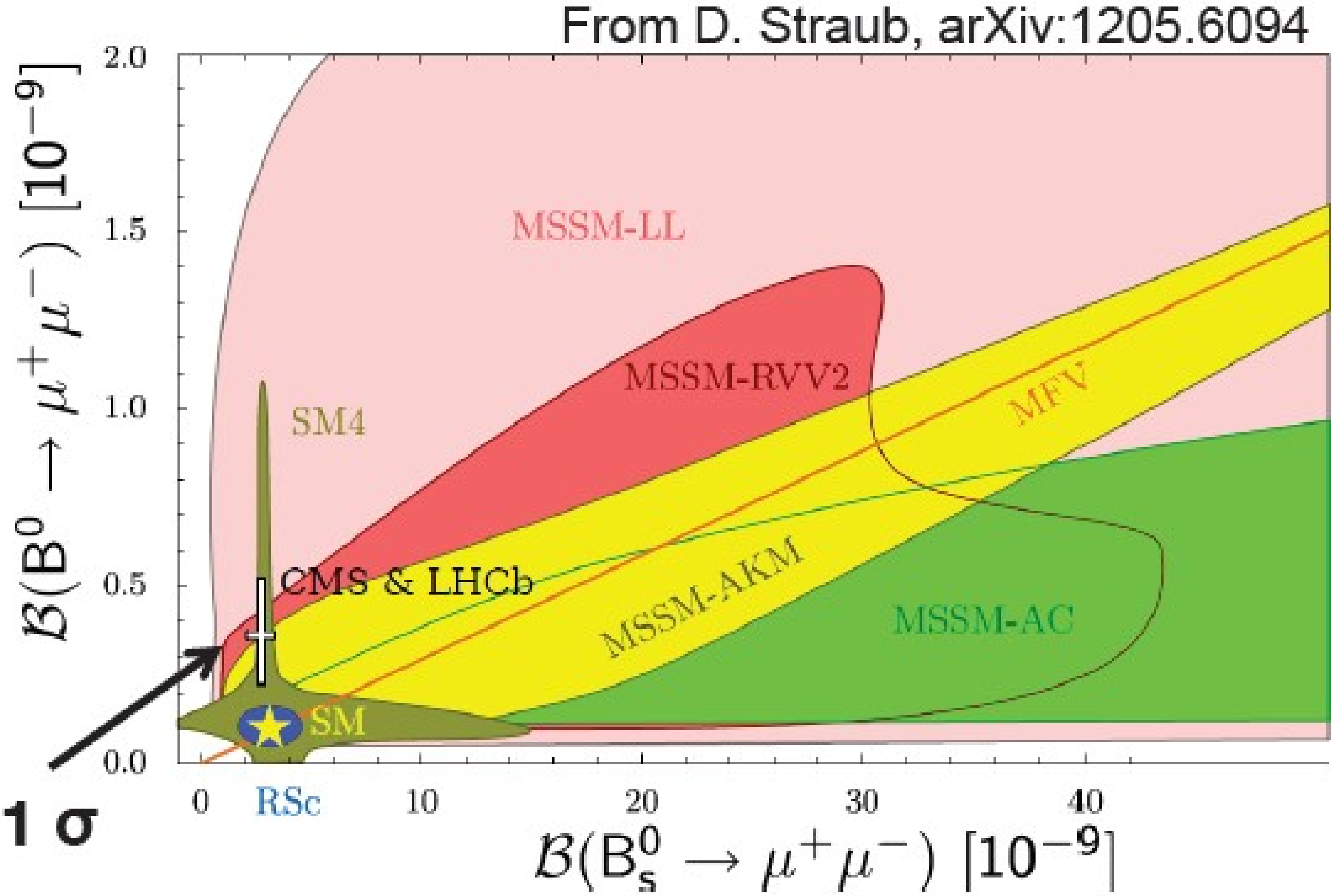
First evidence of the decay!

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

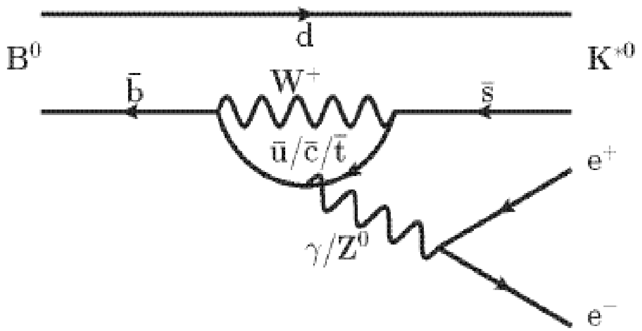
Result vs NP

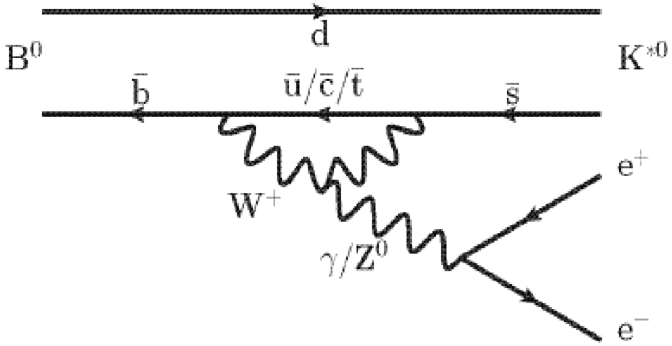
Any model that violates flavour via (pseudo)scalar is constrained.

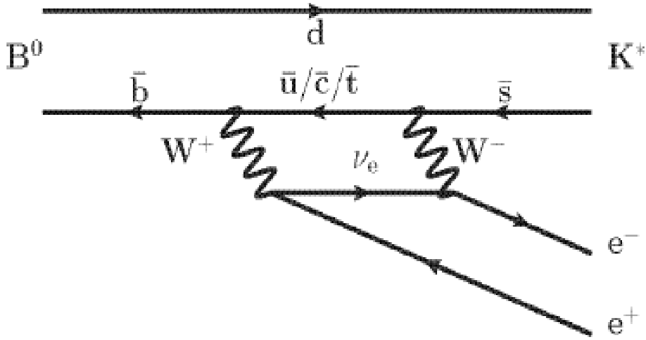
High *tanβ* SUSY too



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







FCNC processes with **a lot of observables**

Clear experimental signatures with low background

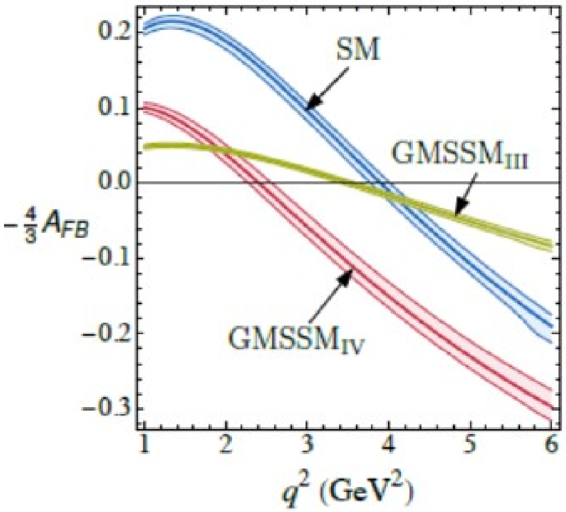
Well developed SM calculations

NP can be found in

- Rates
- Angular distributions
- Asymmetries

<u>As an example</u> zero-crossing point at forward-backward asymmetry for $B^0 \rightarrow K^*\mu^+\mu^-$ 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

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

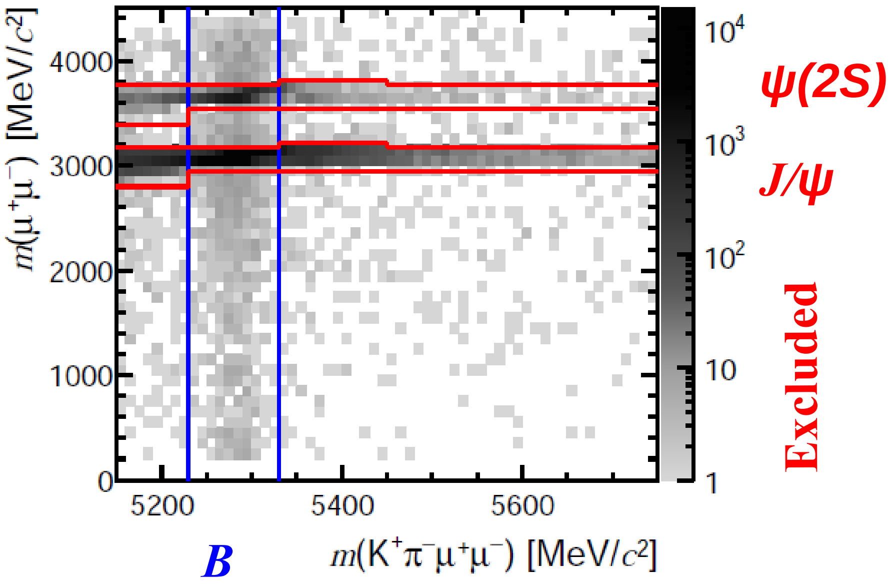
– $B^0 \to K^* \mu^+ \mu^-$	**JHEP8(2013)131 / 1308.1340**	**1st multiD angular analysis**
– $B^0 \to K \mu^+ \mu^-$	PRL 110, 031801	CP asymmetry
– $B^+ \to K^+ \mu^+ \mu^-$	1308.1707 / 1308.1340	ψ(4160) / CP asymmetry
– $B^0 \to \varphi^* \mu^+ \mu^-$	arXiv:1305.2168	1st angular analysis
– $B^0 \to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

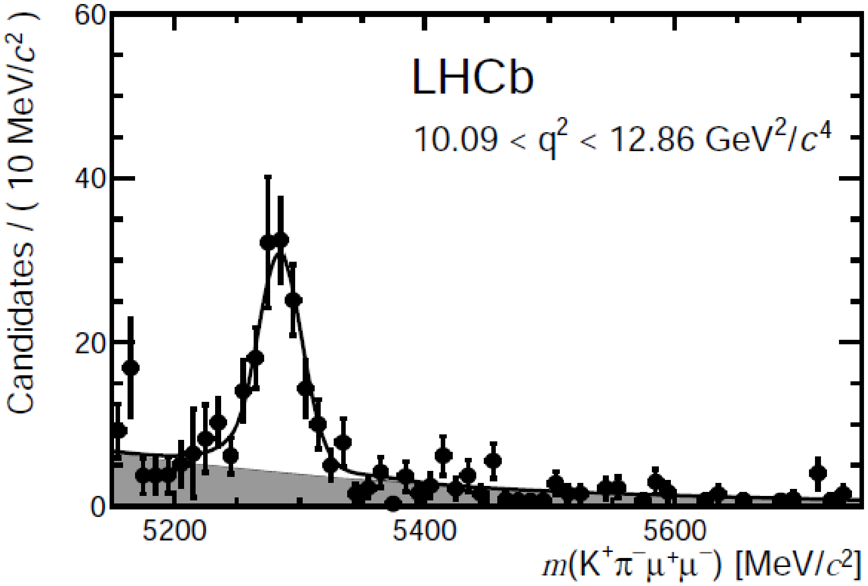
$c \to u l^+ l^-$

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

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

[arXiv:1304.6325]





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

- **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)

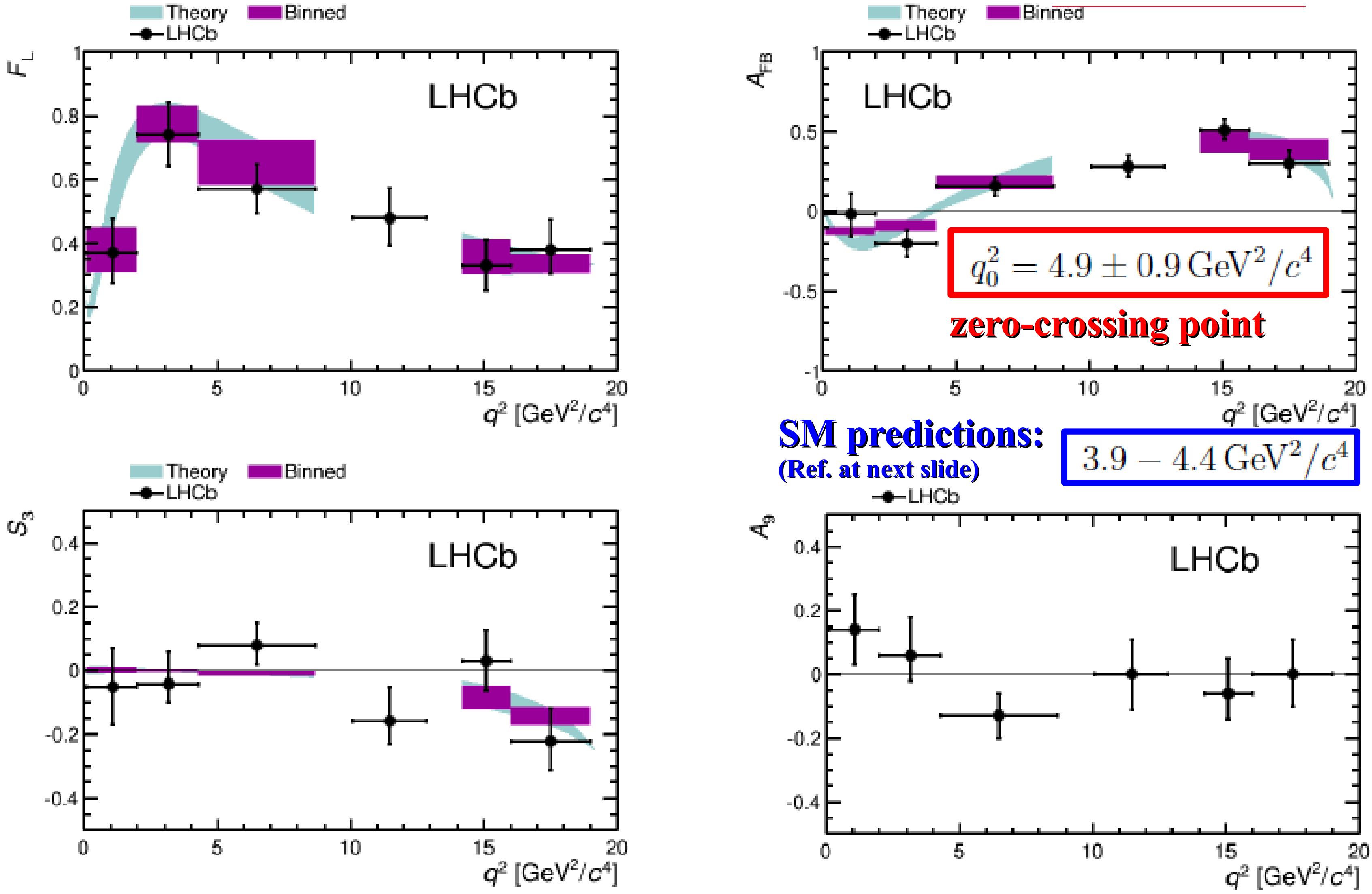
First multi-dimensional angular analysis

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}} \propto$$

$$\Big[F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) -$$
$$F_L\cos^2\theta_K(2\cos^2\theta_\ell - 1) +$$
$$\frac{1}{4}(1-F_L)(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) +$$
$$S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} +$$
$$\frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell +$$
$$A_9(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi}\Big]$$

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

JHEP 08 (2013) 131



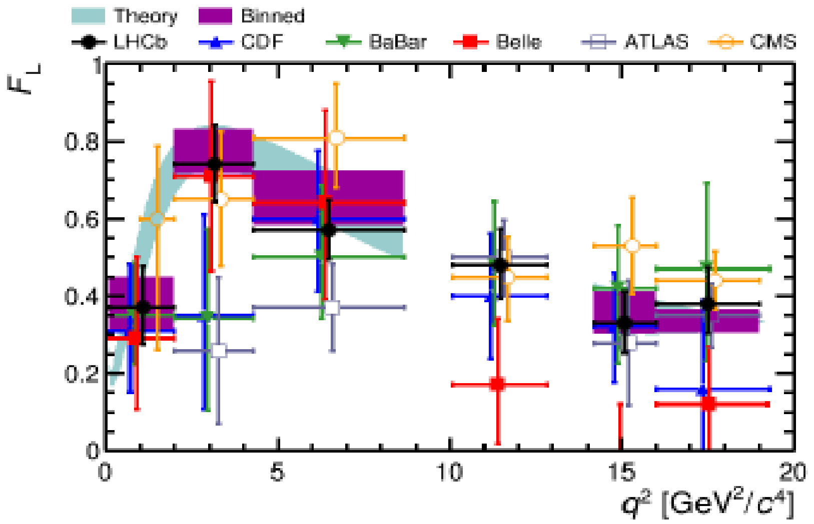
$$\boxed{q_0^2 = 4.9 \pm 0.9\,\mathrm{GeV}^2/c^4}$$

zero-crossing point

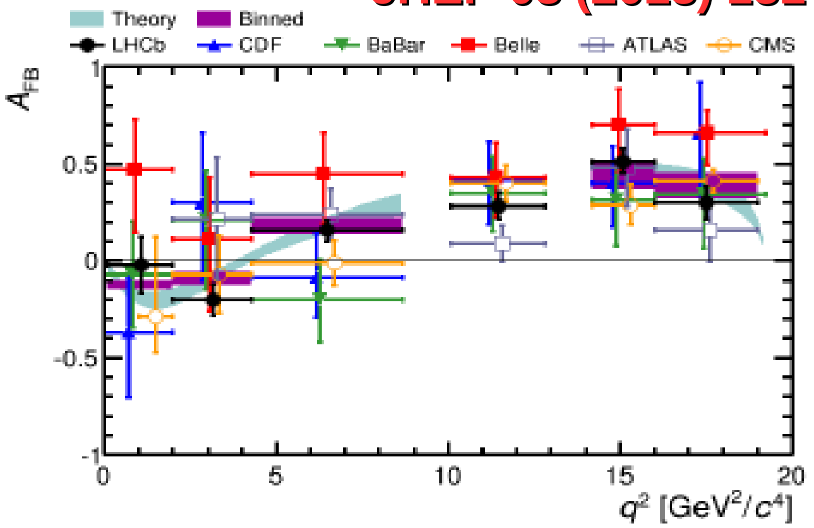
SM predictions:
(Ref. at next slide)

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

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



JHEP 08 (2013) 131

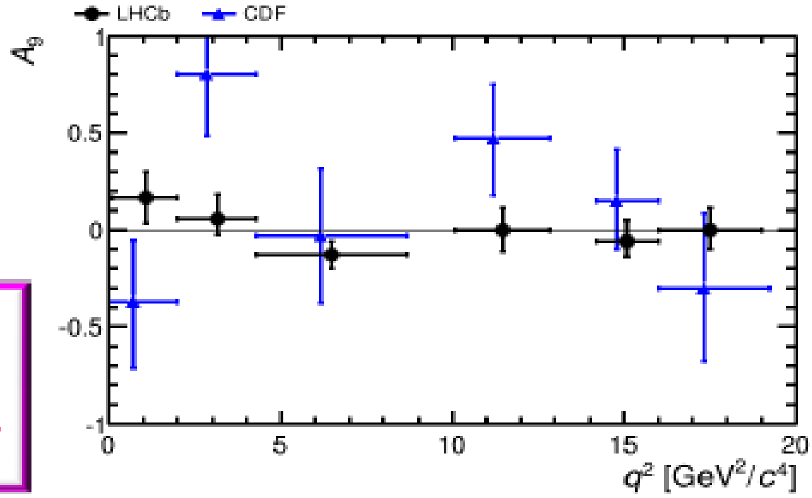


All experiments consistent with SM

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

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

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

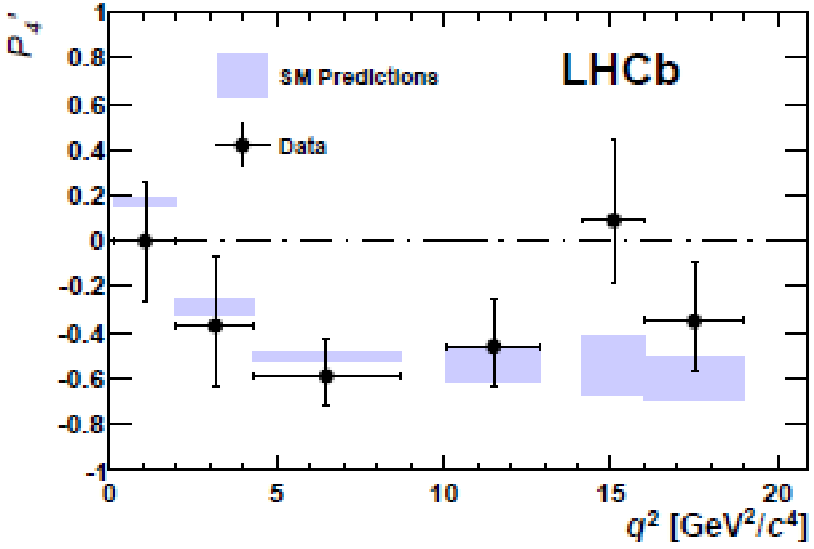
Further analysis of $B \rightarrow K^{*}\mu^{+}\mu^{-}$

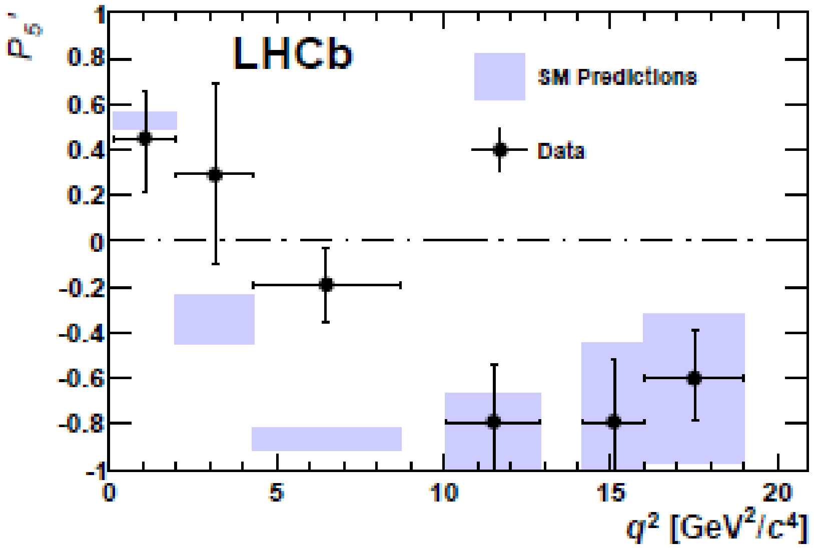
$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$-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

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

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

[arXiv:1308.1707]





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

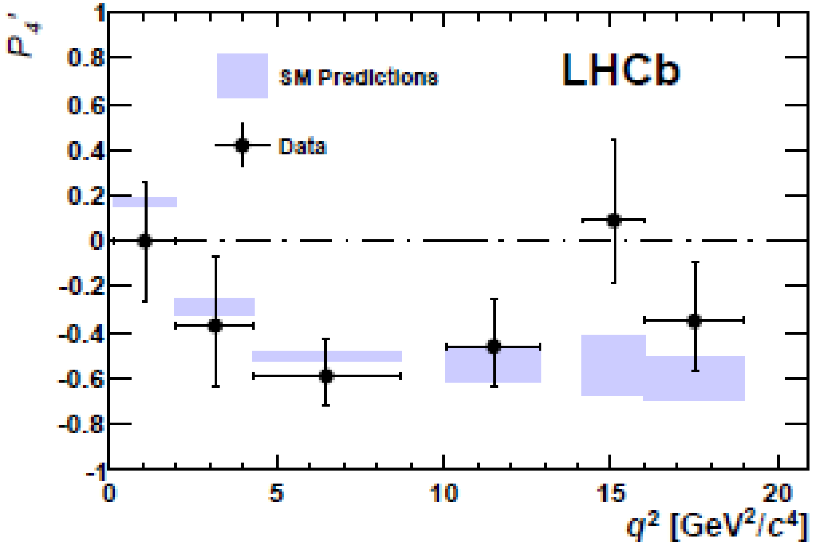
$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\left[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell \right.$$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

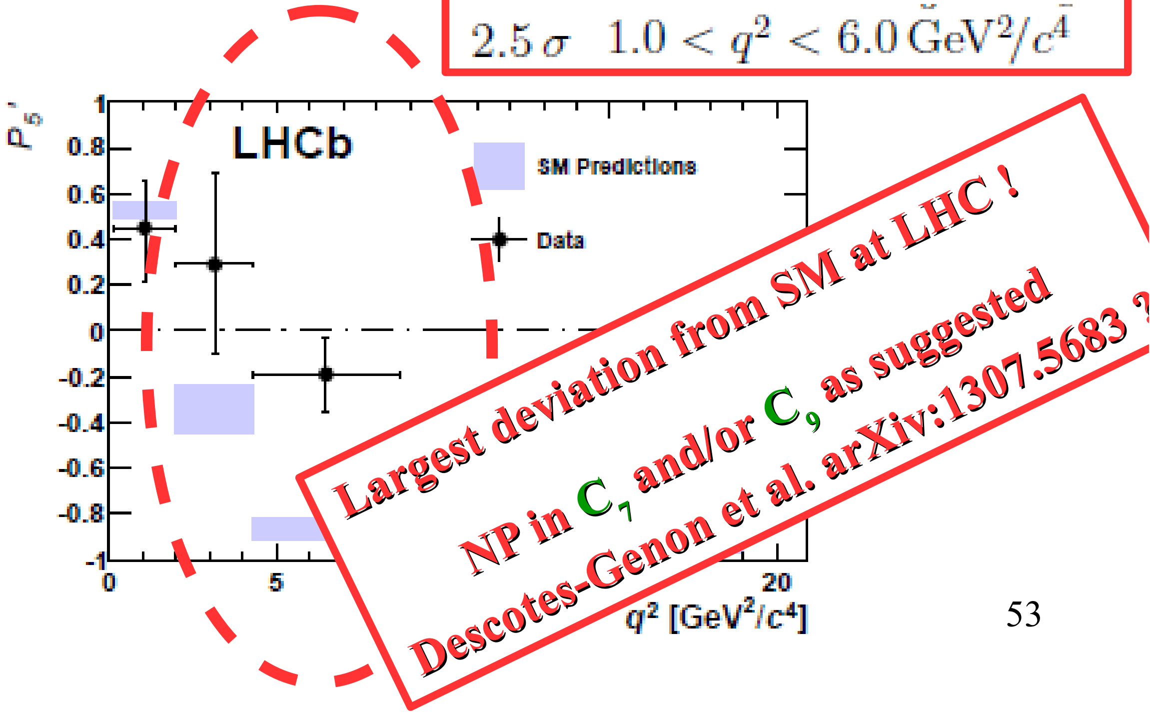
$$\boxed{P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}.}$$

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

[arXiv:1308.1707]

$$\boxed{\begin{array}{ll} 3.7\,\sigma & 4.30 < q^2 < 8.68\,\mathrm{GeV}^2/c^4 \\ 2.5\,\sigma & 1.0 < q^2 < 6.0\,\mathrm{GeV}^2/c^4 \end{array}}$$





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**)

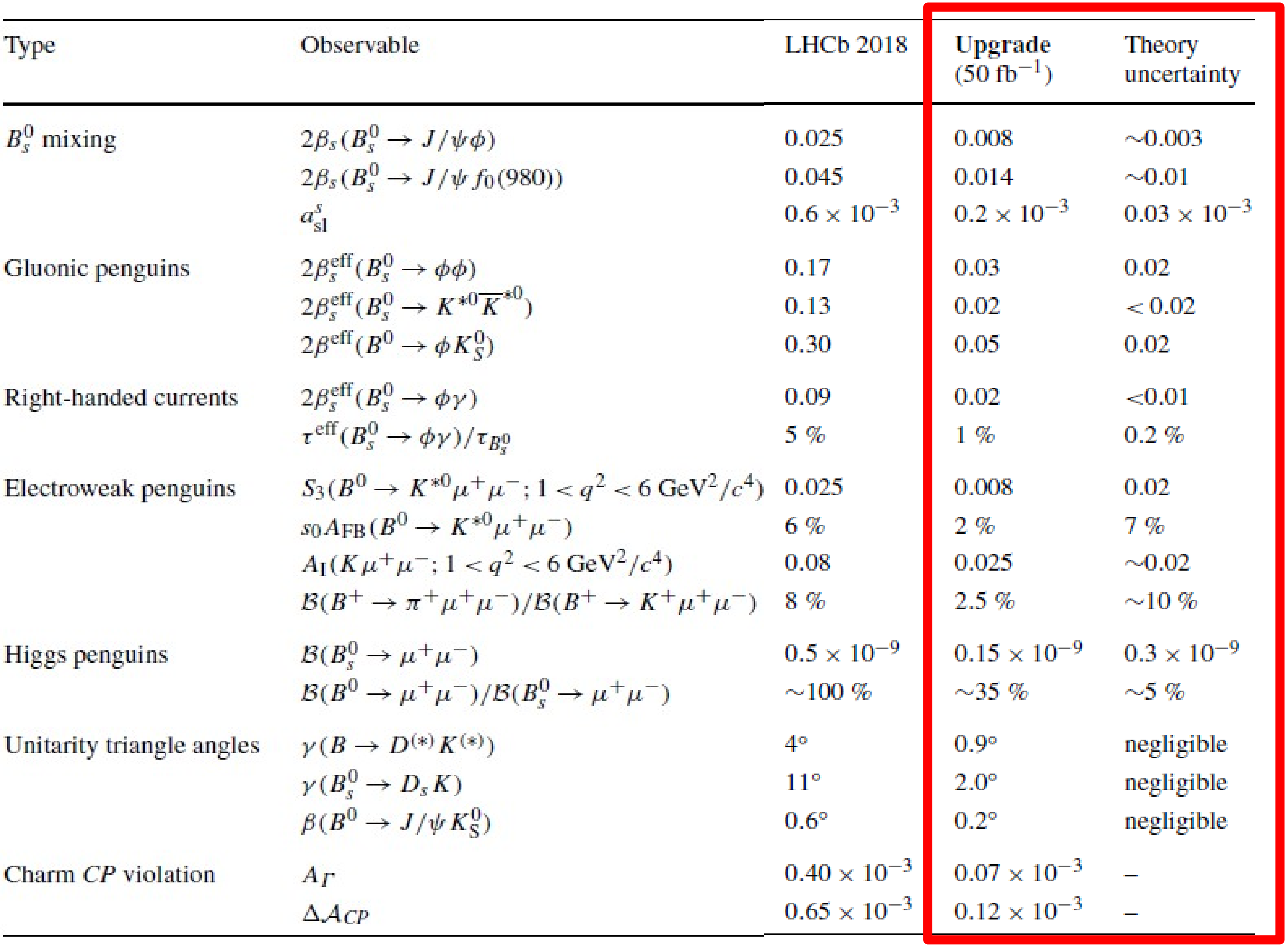
OUTLOOK:

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}***



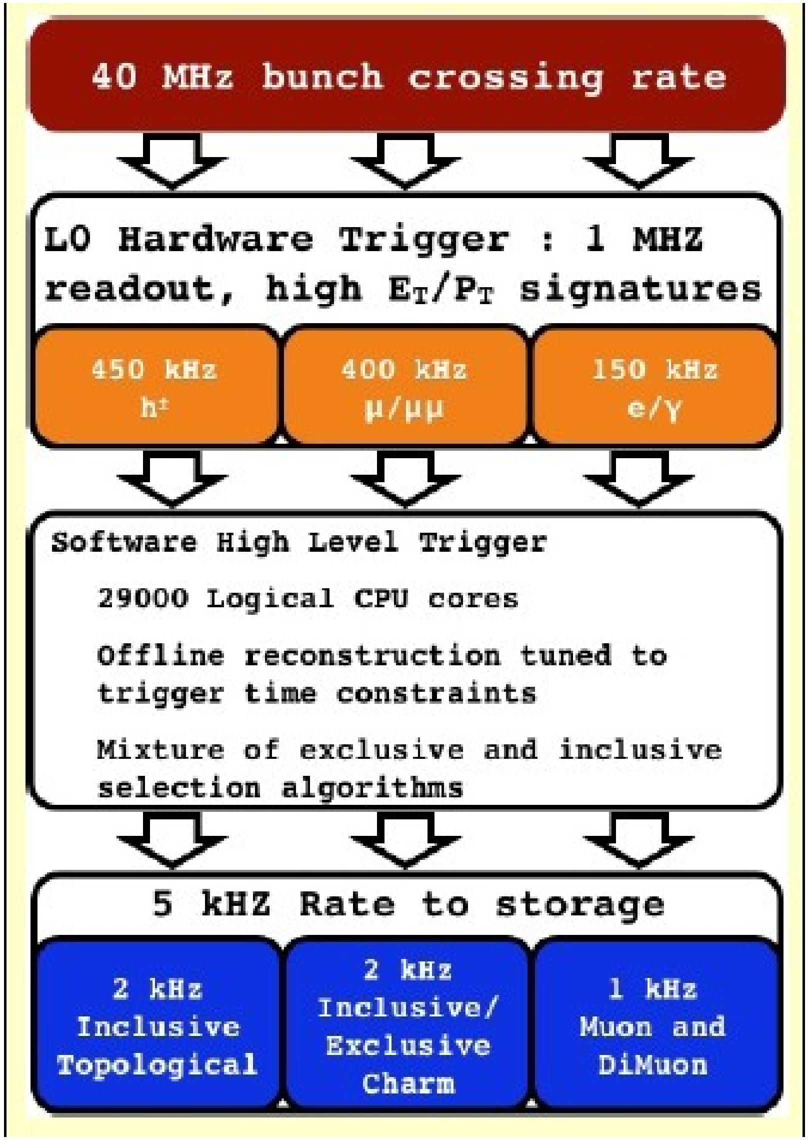
Type	Observable	LHCb 2018	Upgrade (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s(B_s^0 \to J/\psi\phi)$	0.025	0.008	$\sim$0.003
	$2\beta_s(B_s^0 \to J/\psi\, f_0(980))$	0.045	0.014	$\sim$0.01
	$a_{\rm sl}^s$	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	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

Thank you for your attention!

Spare slides

LHCb trigger



40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHZ readout, high E_T/P_T signatures

450 kHz $h^\pm$

400 kHz $\mu/\mu\mu$

150 kHz e/γ

Software High Level Trigger

29000 Logical CPU cores

Offline reconstruction tuned to trigger time constraints

Mixture of exclusive and inclusive selection algorithms

5 kHZ Rate to storage

2 kHz Inclusive Topological

2 kHz Inclusive/ Exclusive Charm

1 kHz Muon and DiMuon

Goal: To select interesting beauty and charm decays while maintaining the managable data rates

Level 0:

- Largest p_T (E) used
- Typical thresholds 1.5 – 3.5 GeV/c

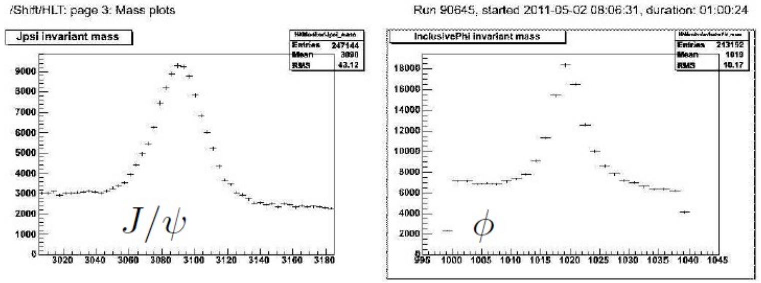
Software HLT1:

- Partial event reconstruction
- Selection based on p_T, IP

Software HLT2:

- Full event reconstruction
- Mass cuts

On-line charm and strange signals
Data quality from sig-to-bkg ratio.

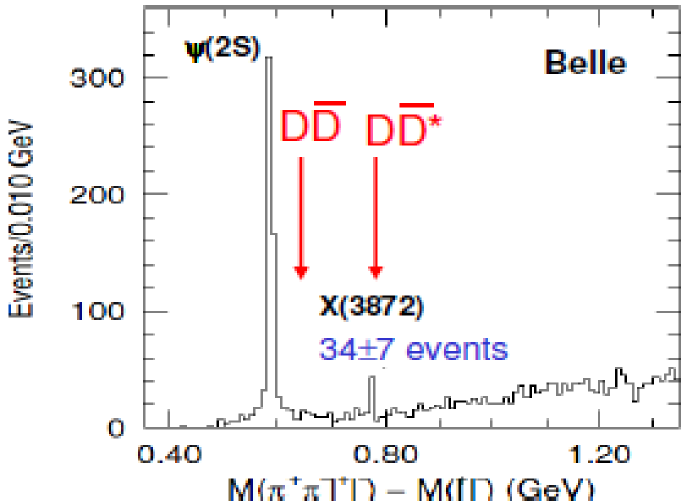


X(3872) quantum numbers

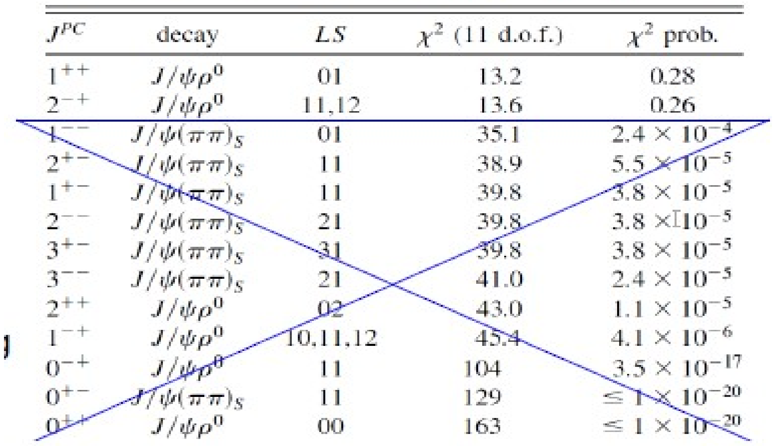
Discovered by Belle in 2003 at e^+e^-

- It is extremely narrow. Only upper limits on its width (<1.2 MeV) None of the known $c\bar{c}$ states above $D\bar{D}$ threshold is so narrow
  - This automatically eliminates all $c\bar{c}$ excitations which can decay to $D\bar{D}$
- Its mass is not near any of the predicted $c\bar{c}$ masses. Closest predicted $c\bar{c}$ states which could be narrow: $2^3P_{1}{}^{++}$, $1^1D_{2}{}^{-+}$
- Its mass is nearly equal $m(D^0)+m(D^{0*})$:
  - It is loosely bound $D^0\bar{D}^{0*}=(c\bar{u})(\bar{c}u)$ molecule or $(c\bar{c}u\bar{u})$ tetraquark? Both models require $J^{PC}=1^{++}$

PRL 91, 262001 (2003) 152 M BB



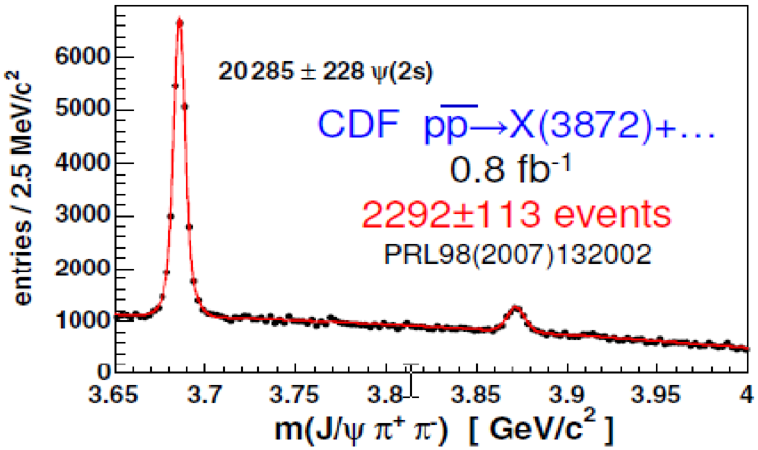
CDF's binned 3D angular χ^2 fit:



J^{PC}	decay	LS	χ^2 (11 d.o.f.)	χ^2 prob.
1^{++}	$J/\psi\rho^0$	01	13.2	0.28
2^{-+}	$J/\psi\rho^0$	11,12	13.6	0.26
1^{--}	$J/\psi(\pi\pi)_S$	01	35.1	2.4×10^{-4}
2^{+-}	$J/\psi(\pi\pi)_S$	11	38.9	5.5×10^{-5}
1^{+-}	$J/\psi(\pi\pi)_S$	11	39.8	3.8×10^{-5}
2^{--}	$J/\psi(\pi\pi)_S$	21	39.8	3.8×10^{-5}
3^{+-}	$J/\psi(\pi\pi)_S$	31	39.8	3.8×10^{-5}
3^{--}	$J/\psi(\pi\pi)_S$	21	41.0	2.4×10^{-5}
2^{++}	$J/\psi\rho^0$	02	43.0	1.1×10^{-5}
1^{-+}	$J/\psi\rho^0$	10,11,12	45.4	4.1×10^{-6}
0^{-+}	$J/\psi\rho^0$	11	104	3.5×10^{-17}
0^{+-}	$J/\psi(\pi\pi)_S$	11	129	$\leq 1 \times 10^{-20}$
0^{++}	$J/\psi\rho^0$	00	163	$\leq 1 \times 10^{-20}$

Cannot distinguish between 1^{++} and 2^{-+}
All other ruled out.

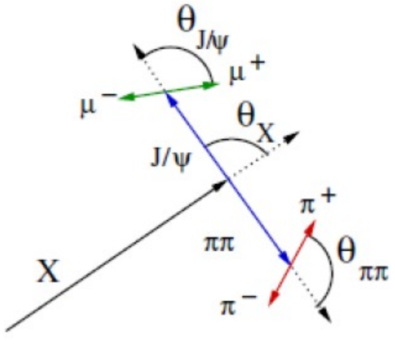
Previous angular analysis - CDF

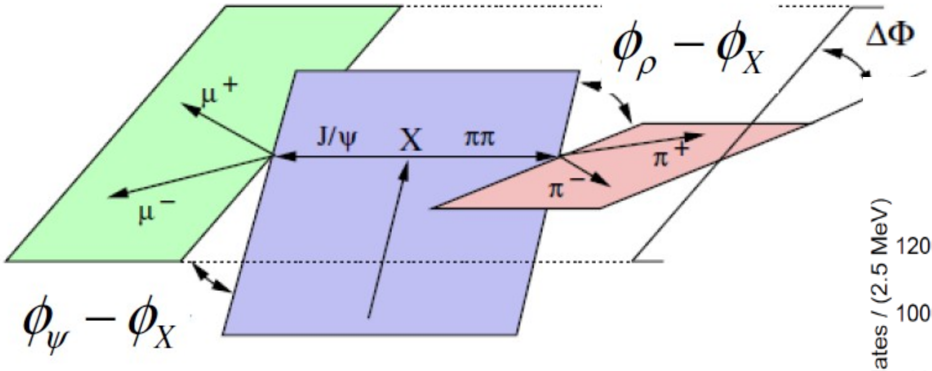


X(3872) quantum numbers

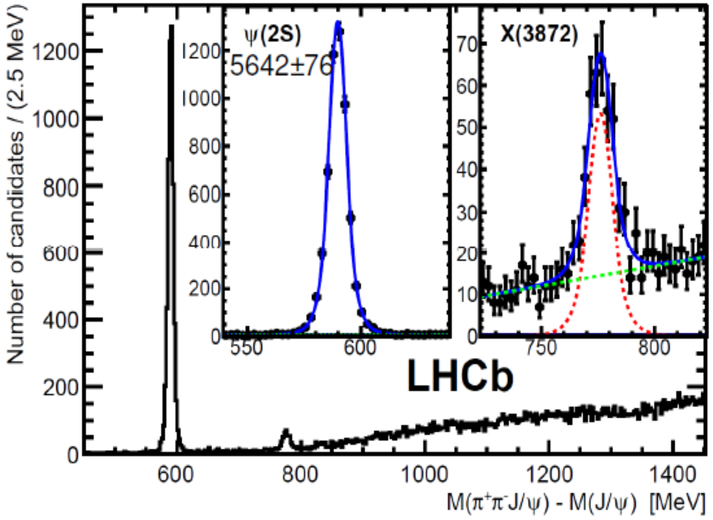
$B^+ \to X(3872) K^+$, $X(3872) \to J/\psi\, \rho$, $J/\psi \to l^+ l^-$, $\rho \to \pi^+ \pi^-$

$$P(\Omega \mid J_X, A^{J_X}_{\lambda_\psi,\lambda_\rho}) \propto \sum_{\Delta\lambda_\mu=-1,1} \left| \sum_{\lambda_\psi=-1,0,1} \sum_{\lambda_\rho=-1,0,1} A^{J_X}_{\lambda_\psi,\lambda_\rho} d^{J_X}_{0,\lambda_\psi-\lambda_\rho}(\theta_X) d^1_{\lambda_\psi,\Delta\lambda_\mu}(\theta_\psi) e^{i\lambda_\psi(\phi_\psi-\phi_X)} d^1_{-\lambda_\rho,0}(\theta_\rho) e^{i\lambda_\rho(\phi_X-\phi_\rho)} \right|^2$$





arXiv:1302.6269
Accepted by PRL



LHCb:

1fb^{-1} sample

313±26 ev.

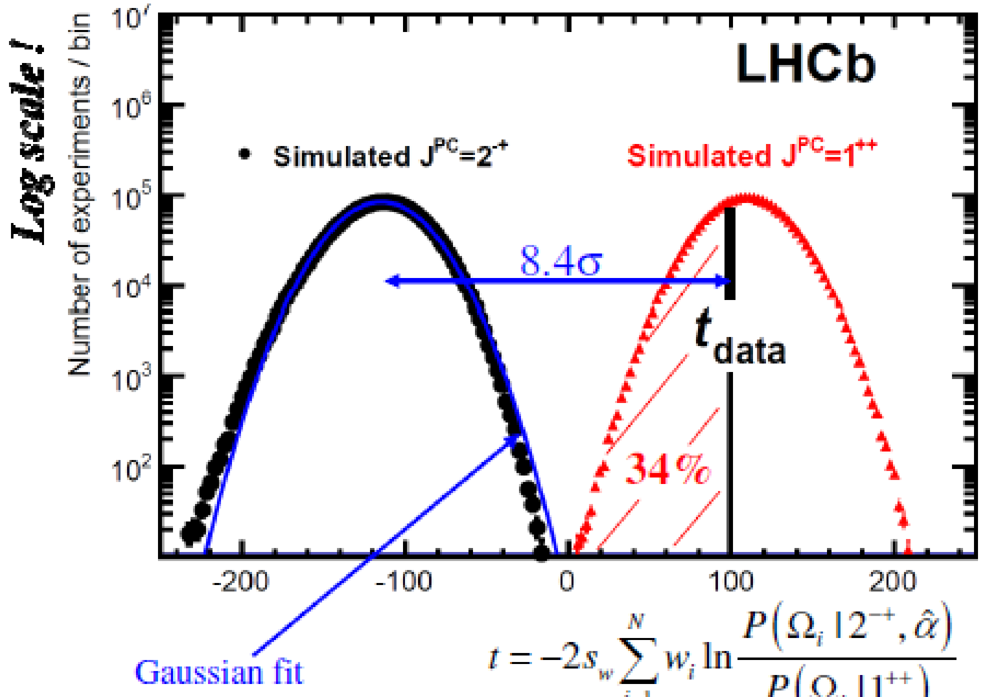
5D analysis

Unbinned data

Likelihood ratio test

X(3872) quantum numbers

$P(t|J_X^P)$



$$t = -2 s_w \sum_{i=1}^{N} w_i \ln \frac{P(\Omega_i \mid 2^{-+}, \hat{\alpha})}{P(\Omega_i \mid 1^{++})}$$

arXiv: 1302.6269
Accepted by PRL

- The Gaussian approximation conservative since the actual distribution to the left of the Gaussian fit.
  - The 2^{-+} hypothesis is ruled out at 8.4σ (>8 after systematics)
- 1^{++} C.L. is high (34%).

The state $\eta_{c2}(1^1D_2)$ is excluded, favour unconventional interpretations $\chi_{c1}(2^3P_1)$, $D^{*0}\bar{D}^0$ molecule, tetra quarks or charmonium-molecules

D meson mass measurement

Interpreting X(3872) as $D^{*0}D^0$ molecule E_B is determined by D mass measurements: $E_B = 0.16 \pm 0.26\, MeV/c^2$

➢ Mass measurements in the D system arXiv: 1304.6865 $(\int \mathcal{L} = 1 fb^{-1})$

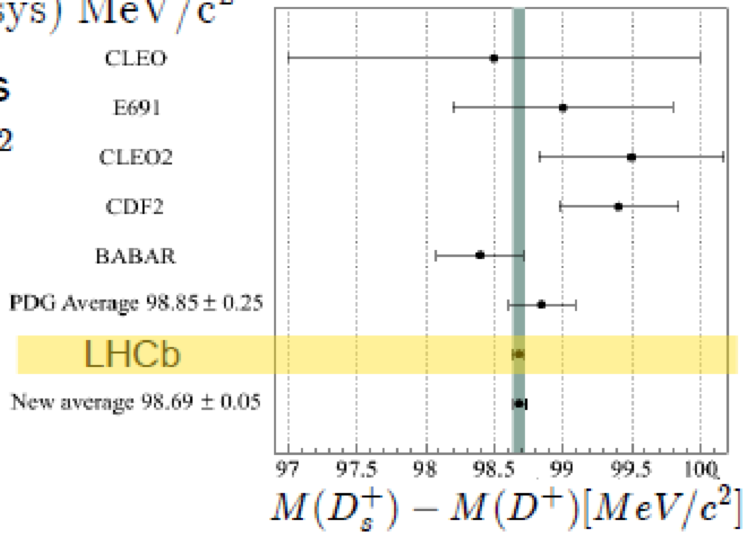
- Determine D^0 mass in $D^0 \to K^+K^-K^-\pi^+$
  $M(D^0) = 1864.75 \pm 0.15(\mathrm{stat}) \pm 0.11(\mathrm{sys})\ \mathrm{MeV/c^2}$
- Mass difference measurements
  $M(D^+) - M(D^0) = 4.76 \pm 0.12(\mathrm{stat}) \pm 0.07(\mathrm{sys})\ \mathrm{MeV/c^2}$
  $M(D_s^+) - M(D^+) = 98.68 \pm 0.03(\mathrm{stat}) \pm 0.04(\mathrm{sys})\ \mathrm{MeV/c^2}$

  Derive a significantly more precise D_s^+ mass
  $M(D_s^+) = 19684.19 \pm 0.20 \pm 0.14 \pm 0.08\ MeV/c^2$

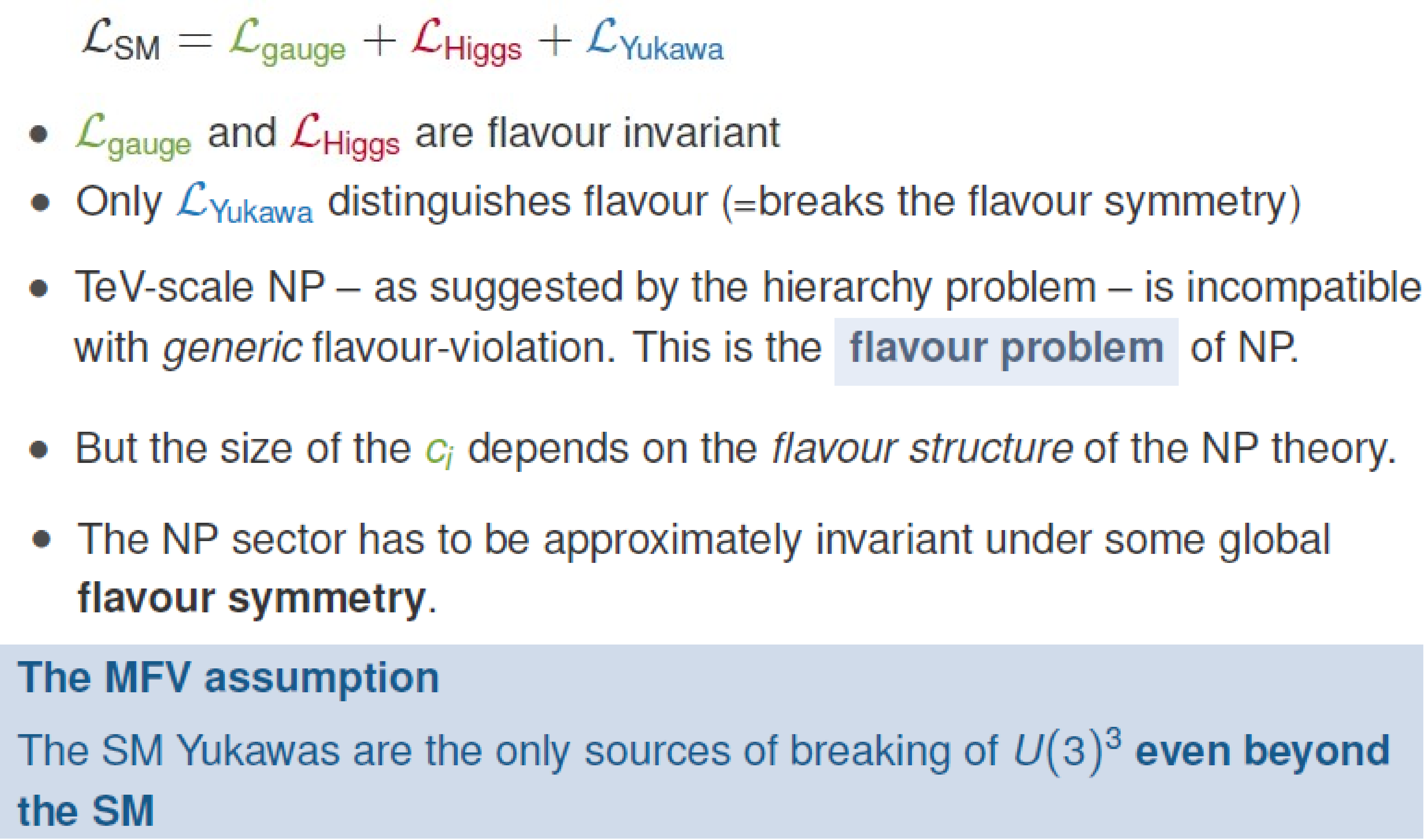
- Dominant syst. uncertainty on the mass is due to the momentum scale of 0.03 %

  D^0 mass : $0.09\ \mathrm{MeV/c^2}$
  mass difference : $0.04\ \mathrm{MeV/c^2}$

arXiv: 1304.6865



Flavour symmetry of SM



$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

- $\mathcal{L}_{\text{gauge}}$ and $\mathcal{L}_{\text{Higgs}}$ are flavour invariant
- Only $\mathcal{L}_{\text{Yukawa}}$ distinguishes flavour (=breaks the flavour symmetry)
- TeV-scale NP – as suggested by the hierarchy problem – is incompatible with *generic* flavour-violation. This is the **flavour problem** of NP.
- But the size of the c_i depends on the *flavour structure* of the NP theory.
- The NP sector has to be approximately invariant under some global **flavour symmetry**.

The MFV assumption

The SM Yukawas are the only sources of breaking of $U(3)^3$ **even beyond the SM**

Consequences of MFV

All FCNC amplitudes are governed by the **same** CKM factors as in the SM

- NP effects in $b \to s$, $b \to d$ and $s \to d$ transitions are perfectly **correlated**
- Ratios such as

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

  are **not modified** and consitute a test of the MFV paradigm

- CP violating phase aligned with the SM ⇒ CP asymmetries mostly **SM-like**

Effective Hamiltonian and Wilson's coefficients

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

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

Current-current operators

$$O_1 = (\bar{s}\gamma^\mu T^a P_L c) \otimes (\bar{c}\gamma_\mu T^a P_L b) \qquad O_2 = (\bar{s}\gamma^\mu P_L c) \otimes (\bar{c}\gamma_\mu P_L b)$$

QCD penguin operators

$$O_3 = (\bar{s}\gamma^\mu P_L b) \otimes \sum_q (\bar{q}\gamma_\mu q) \qquad O_4 = (\bar{s}\gamma^\mu T^a P_L b) \otimes \sum_q (\bar{q}\gamma_\mu T^a q)$$

$$O_5 = (\bar{s}\gamma^\mu \gamma^\nu \gamma^\rho P_L b) \otimes \sum_q (\bar{q}\gamma_\mu\gamma_\nu\gamma_\rho q) \qquad O_6 = (\bar{s}\gamma^\mu \gamma^\nu \gamma^\rho T^a P_L b) \otimes \sum_q (\bar{q}\gamma_\mu\gamma_\nu\gamma_\rho T$$

Scalar operators

$$O_S = \frac{m_b}{m_{B_s}}(\bar{s}_L b_R)(\bar{\ell}\ell) \qquad O_P = \frac{m_b}{m_{B_s}}(\bar{s}_L b_R)(\bar{\ell}\gamma_5\ell)$$

Dipole operators

$$O_7 = \frac{m_b}{e}(\bar{s}_L \sigma_{\mu\nu} b_R)F^{\mu\nu} \qquad O_8 = \frac{g_s m_b}{e^2}(\bar{s}_L \sigma_{\mu\nu} T^a b_R)G^{\mu\nu\, a}$$

Semileptonic operators

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

$$O_\nu = (\bar{s}_L \gamma_\mu b_L)(\bar{\nu}_L \gamma^\mu \nu_L)$$

NB: in MFV, all Wilson coefficients C_i are **real**, dimensionless numbers

C_{1-6} dominated by QCD contributions and hardly sensitive to NP!

$C_{7-10,\nu}$ are generated in the SM and **sensitive** to many **NP** models

$C_{S,P}$ **vanish** in the SM but can be sizable in models with extended Higgs sector

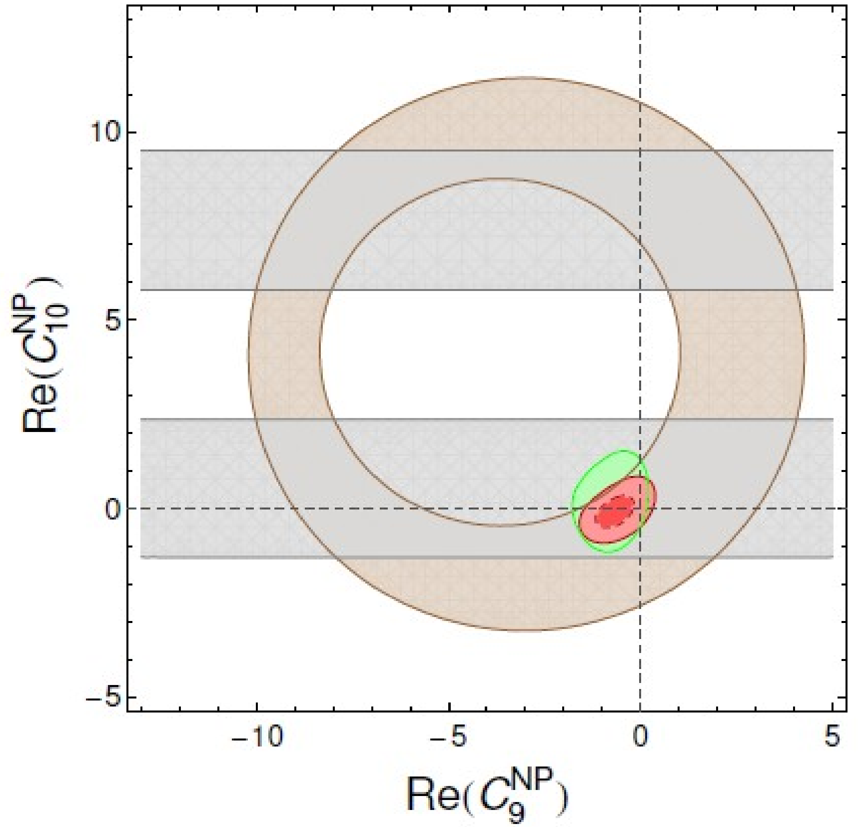
Effective Hamiltonian and Wilson coefficients

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

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

$b \to s$		
γ	$B \to X_s\gamma$ $B \to K^*\gamma$	$O_{7,8}$
$\ell^+\ell^-$	$B \to K\ell^+\ell^-$ $B \to K^*\ell^+\ell^-$ $B \to X_s\ell^+\ell^-$	$O_{7,8}, O_9, O_{10}$
	$B_s \to \mu^+\mu^-$	$O_{10}, O_{S,P}$
$\nu\bar{\nu}$	$B \to X_s\nu\bar{\nu}$ $B \to K\nu\bar{\nu}$ $B \to K^*\nu\bar{\nu}$	O_ν

$B \to X_s\mu\mu$, $B \to K^*\mu\mu$ and $B_s \to \mu\mu$



Beyond MFV

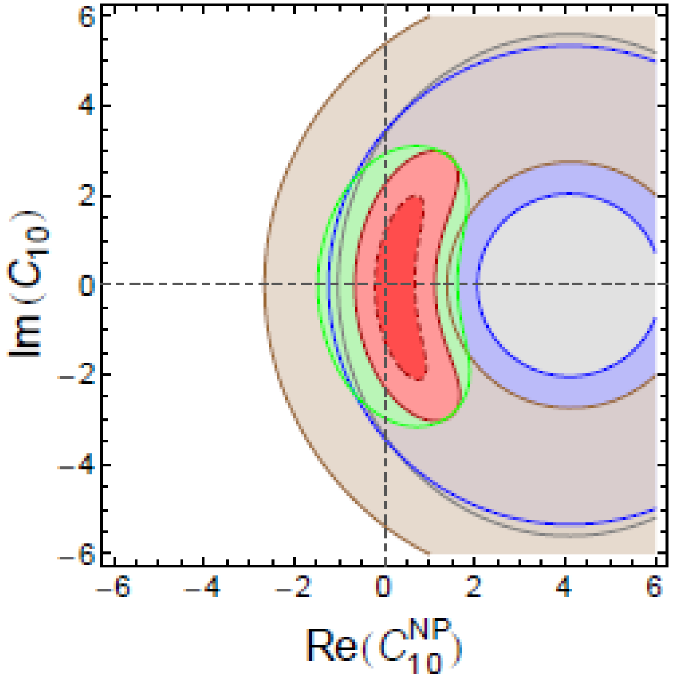
$\Delta F = 1$ operators in the SM and in MFV

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

In $U(2)^3$, no new operators beyond MFV are generated, but Wilson coefficients are now **complex numbers**!

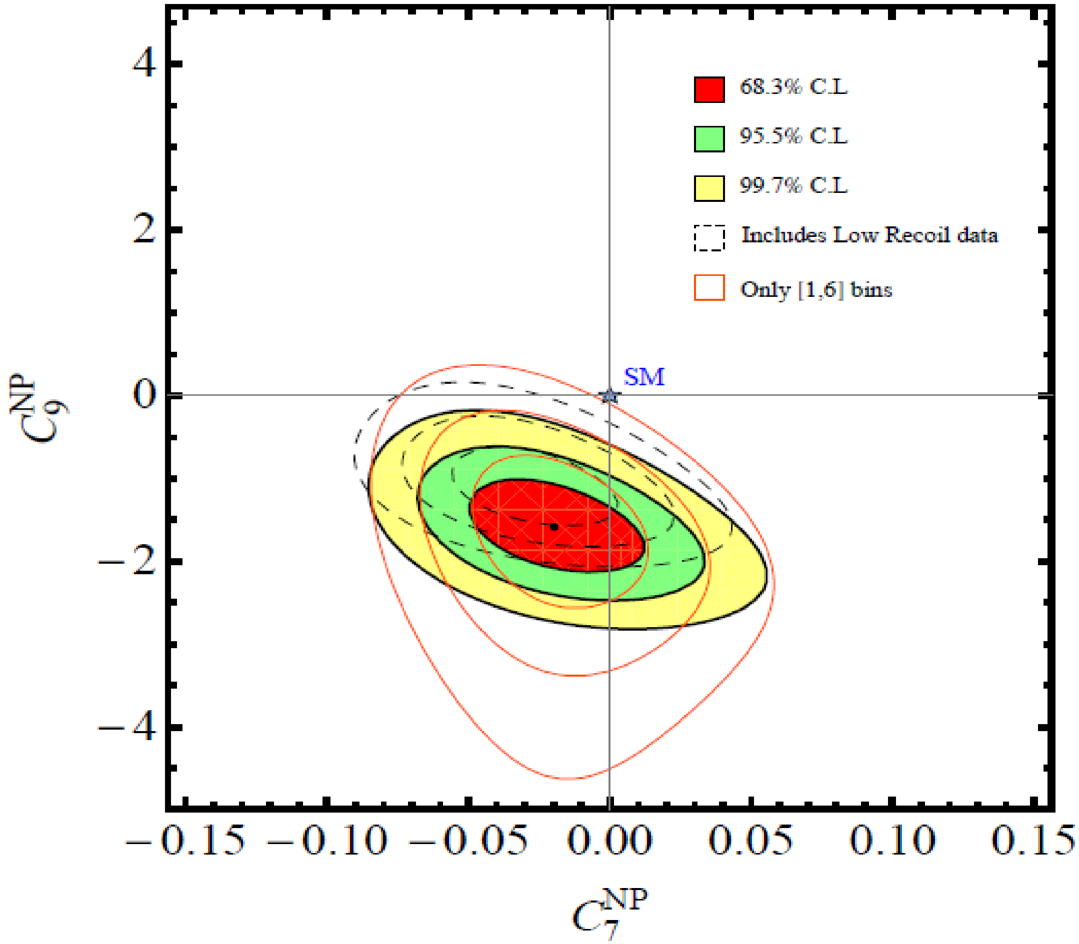
- Correlation between B and K decays **broken**
- New **CPV phase** in B decays

$B \to X_s\gamma$, $B \to (K, K^*, X_s)\mu\mu$ and $B_s \to \mu\mu$



LHCb result on $B \to K^*\mu^+\mu^-$ *pull "theory trigger"*

- **Of course this is only evidence, which must be supported by further experimental analysis**
- **But everybody can start to think the pointer to which direction of NP it is.**
- **Here is an example of such studies arXiv:1307.5683 [this is not LHCb result]**
- **Combination with another world data gives 4.5σ deviation respect to SM**
- **Possible large NP in C_9.**



Fit to $(\mathcal{C}_7^{NP}, \mathcal{C}_9^{NP})$, using the three large-recoil bins for $B \to K^*\mu^+\mu^-$ observables, together with $B \to X_s\gamma$, $B \to X_s\mu^+\mu^-$, $B \to K^*\gamma$ and $B_s \to \mu^+\mu^-$.