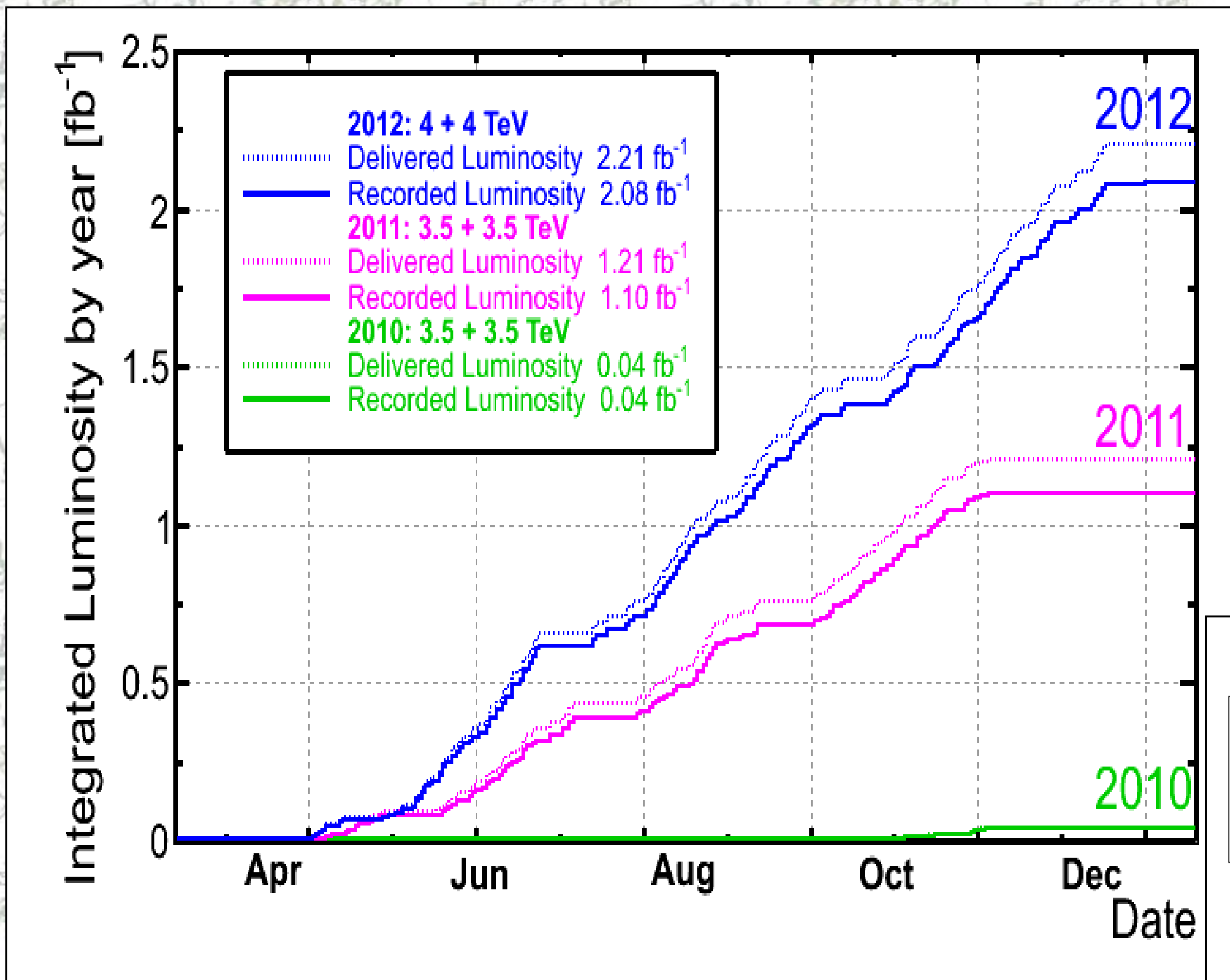
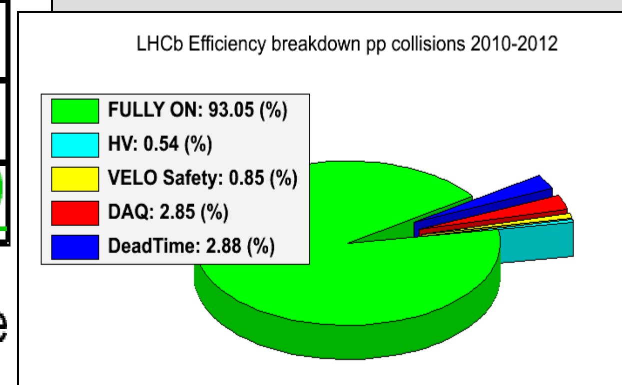
Последние результаты эксперимента LHCb

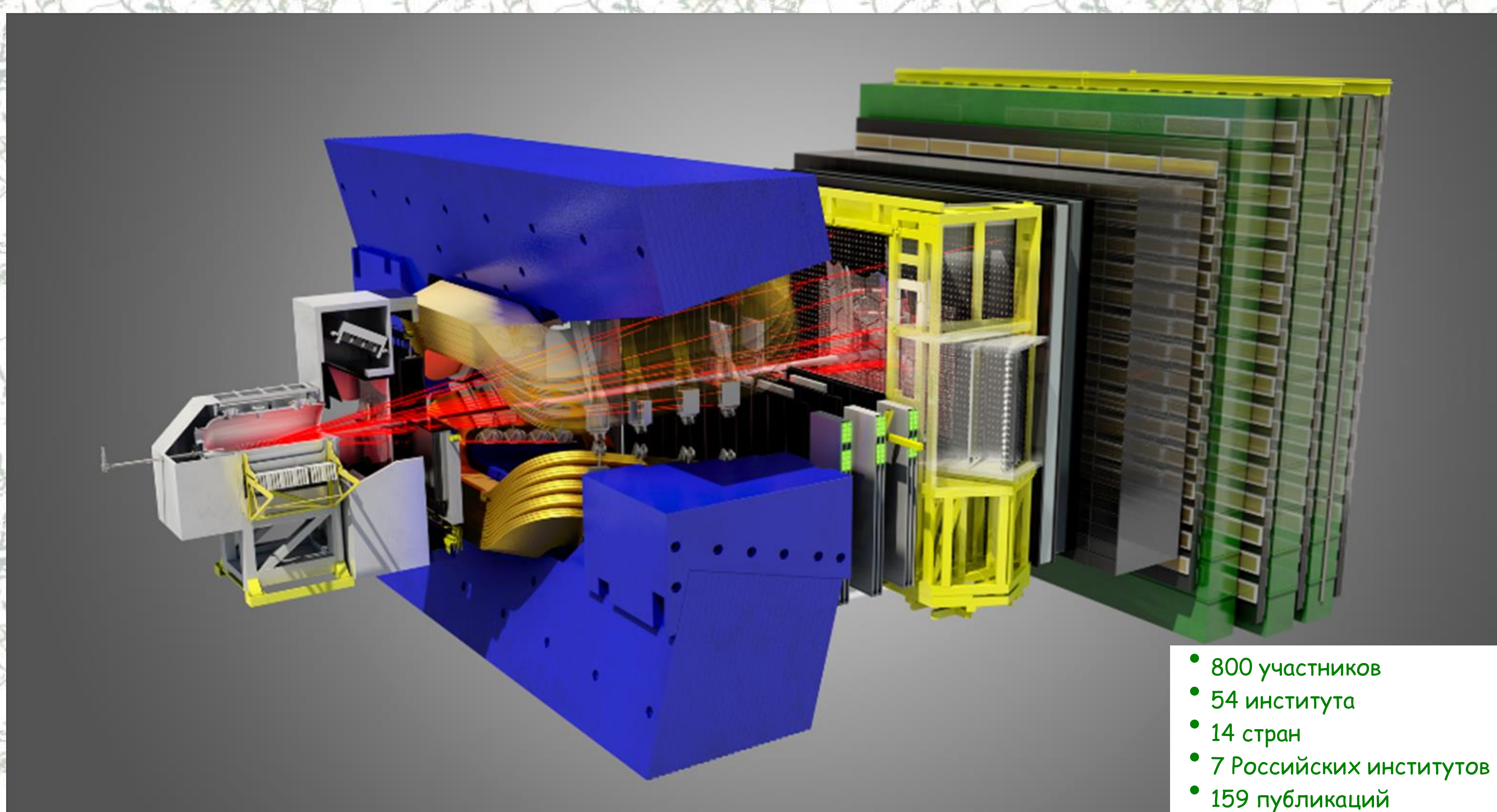
Иван Беляев (ИТЭФ, Москва)



+ pp @ 900GeV
+ pp @2.76TeV
+ pPb & Pbp



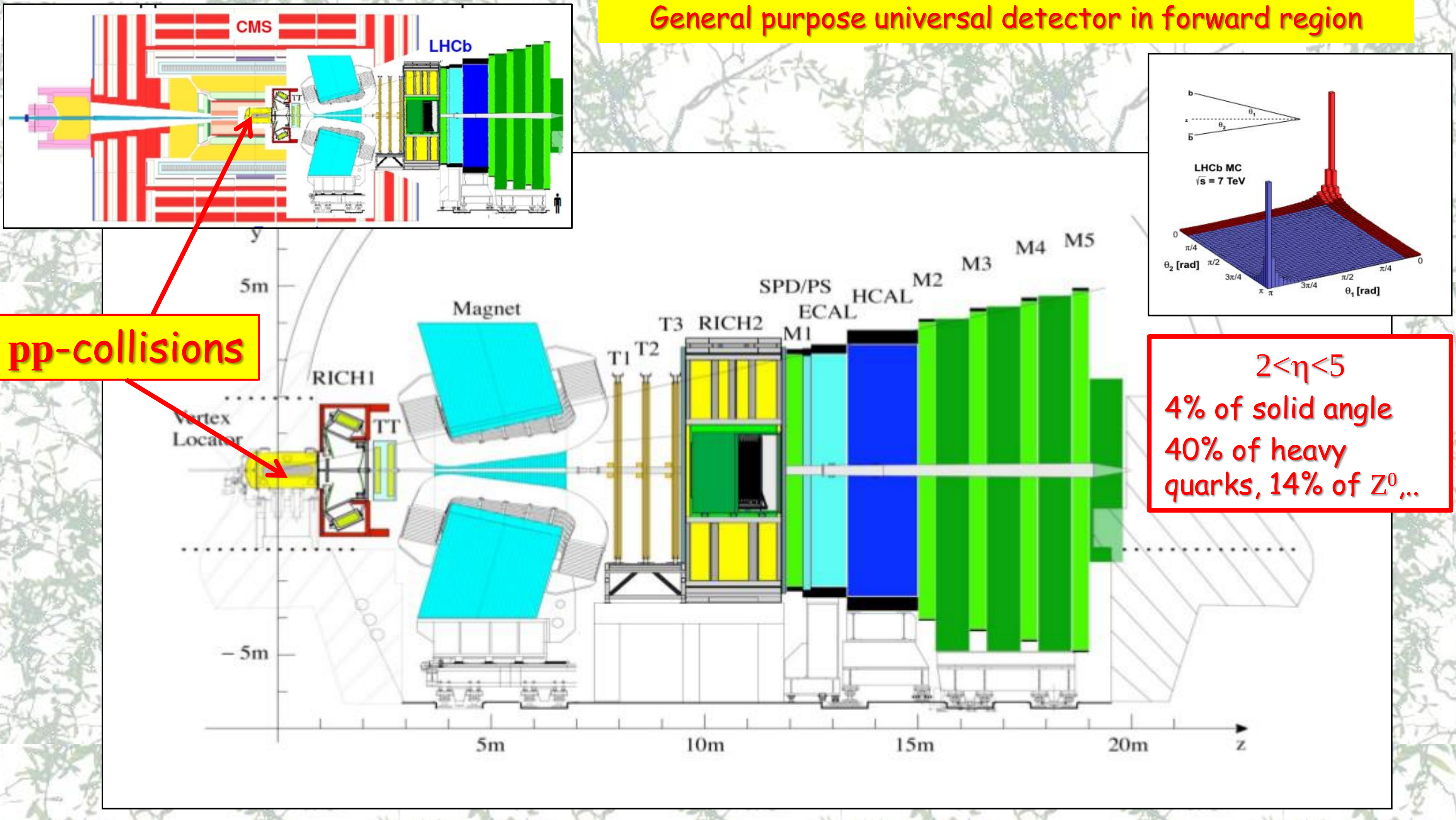
Эксперимент LHCb



- 800 участников
- 54 института
- 14 стран
- 7 Российских институтов
- 159 публикаций

LHCb: beauty detector

General purpose universal detector in forward region



$2<\eta<5$

4% of solid angle

40% of heavy quarks, 14% of Z^0,..

159 публикаций

- Распады прелестных частиц

Изначальная цель эксперимента

  - Редкие распады и CP-нарушение

Универсальный детектор!

- Распады очарованных частиц
  - CP-нарушение, смешивание, редкие распады
- Рожденние электрослабых бозонов
- КХД: Кварконии, B_c, перелестные барионы, экзотика, ассоциативное рождение, фрагментация, струи …
- Эксклюзивное рождение
- … и многое-многое другое

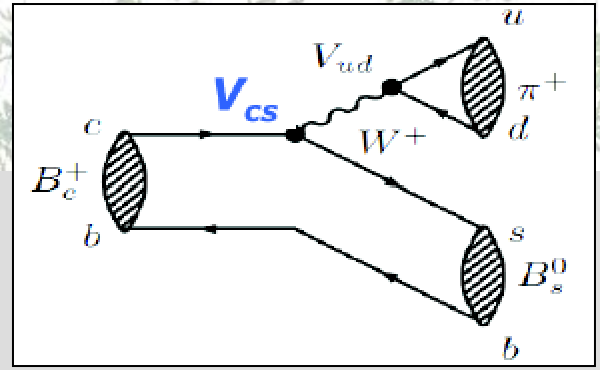
Спектроскопия

- Изучение D^{**} и D_J
- X(3872)
- ψ(4160) в распадах B
- Прелестные барионы
- Возбужденные B_s
- Рождение χ_{cJ}
  - Включая распады B
- Изучение распадов и свойств B_c

1. Observation of the decay $B_c^+ \to J/\Psi K^+ K^- \pi^+$ arXiv:1309.0587
2. Observation of the decay $B_c^+ \to B_s^0 \pi^+$ arXiv:1308.4544
3. First observation of the decay $B_c^+ \to J/\Psi K^+$ arXiv:1306.6723
4. Observation of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\Psi D_s^{+*}$ PRD87 (2013) 112012
5. Observation of the decay $B_c^+ \to \Psi(2S)\pi^+$ PRD87 (2013) 071103
6. Measurements of B_c^+ production and mass with the $B_c^+ \to J/\Psi K^+$ decay PRL109 (2013) 232001
7. First observation of the decay $B_c^+ \to J/\Psi \pi^+ \pi^- \pi^+$ PRL 108 (2012) 251802

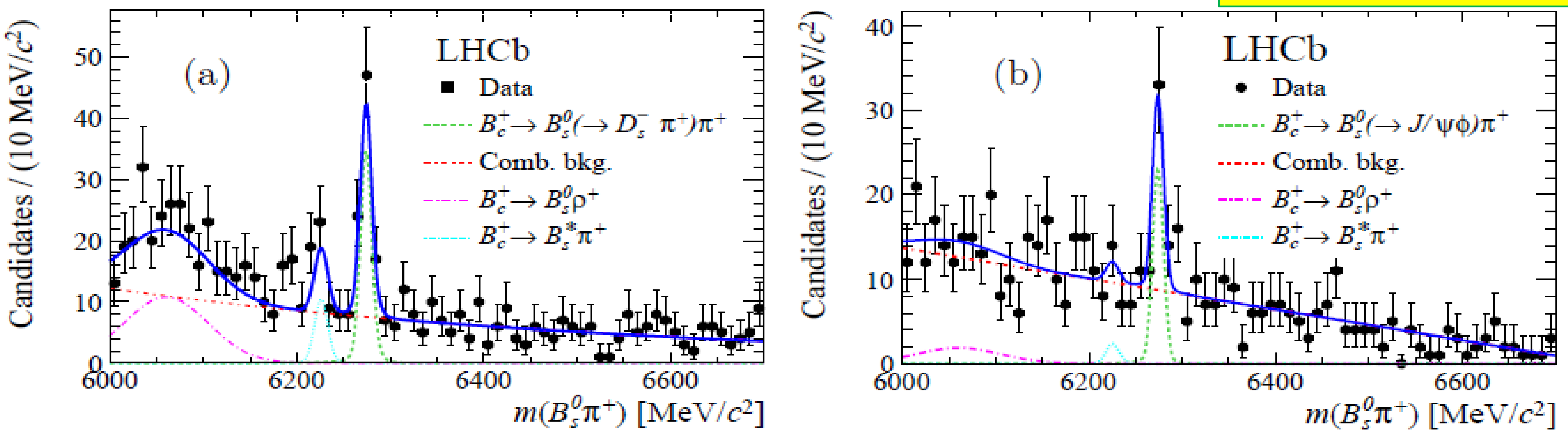
$B_c \to B_s \pi$

- Первый распад B-адрона с b-кварком в конечном сосстоянии



$$\frac{\sigma(B_c^+)}{\sigma(B_s^0)} \times \mathcal{B}(B_c^+ \to B_s^0 \pi^+) = \left(2.37 \pm 0.31\,(\text{stat}) \pm 0.11\,(\text{syst})\,^{+0.17}_{-0.13}\,(\tau_{B_c^+})\right) \times 10^{-3},$$

arXiv:1308.4544



Время жизни Λ_b бариона

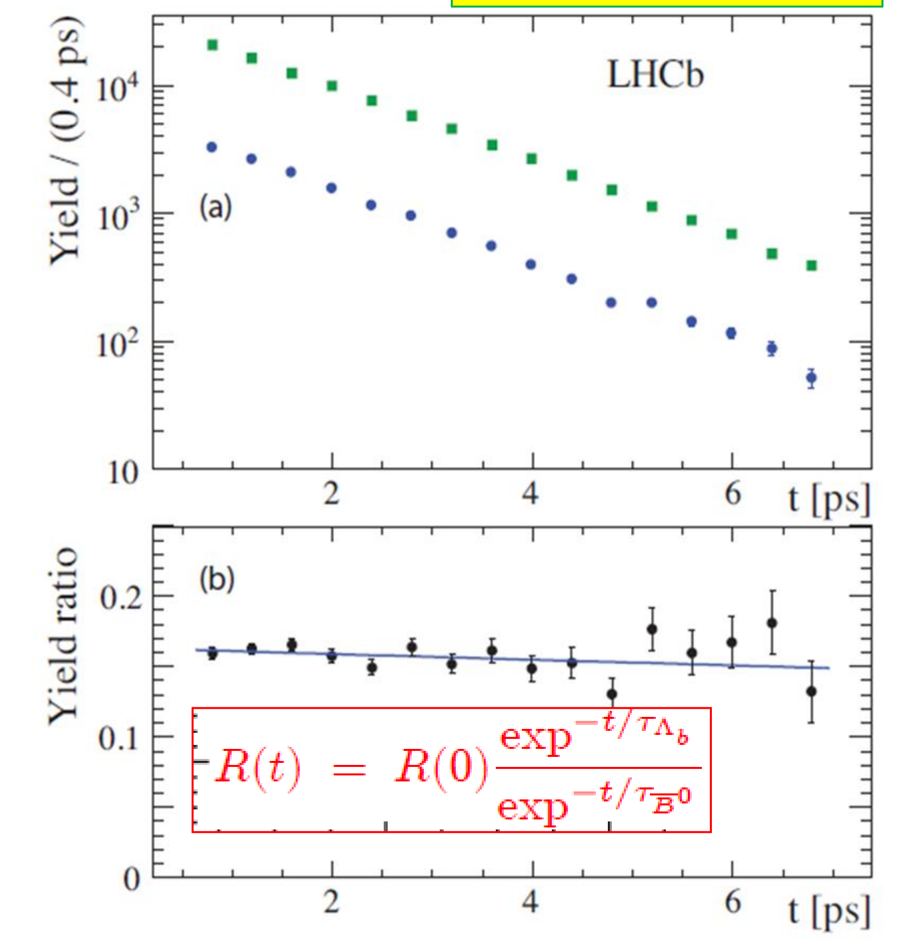
- Теория:
  - времена жизхни всех прелестных частиц примерно равны
- Метод:

$\Lambda_b \to J/\psi p K$ vs $B^0 \to J/\psi K\pi$

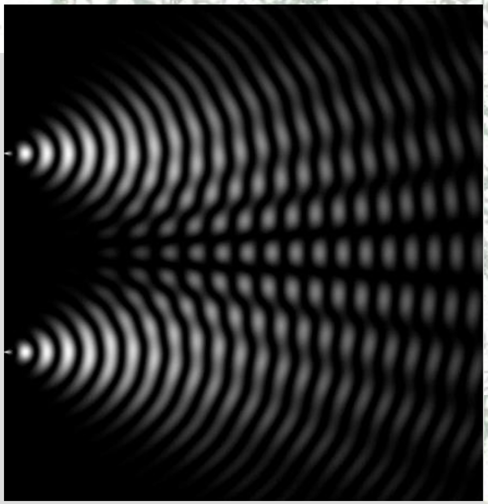
$$\frac{\tau_{\Lambda_b^0}}{\tau_{\overline{B}^0}} = \frac{1}{1+\tau_{\overline{B}^0}\Delta_{\Lambda B}} = 0.976 \pm 0.012 \pm 0.006,$$

$$\tau_{\Lambda_b^0} = 1.482 \pm 0.018 \pm 0.012 \text{ ps.}$$

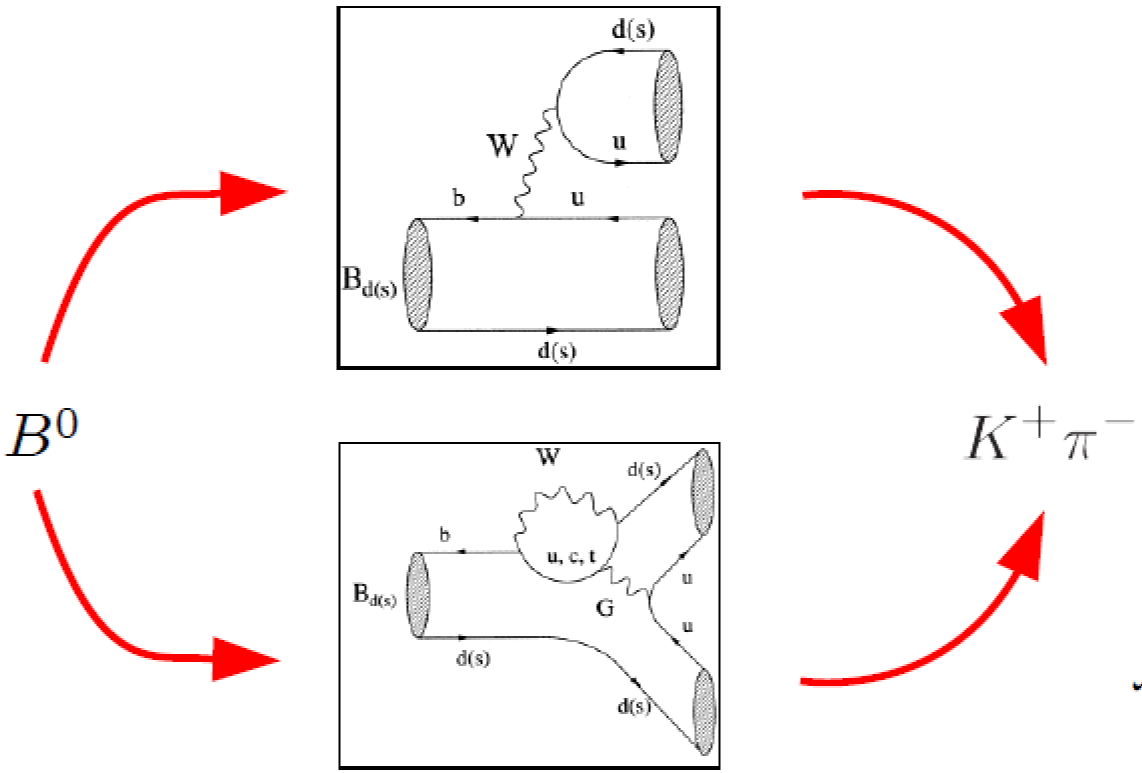
arXiv:1307.2476



$$R(t) = R(0)\frac{\exp^{-t/\tau_{\Lambda_b}}}{\exp^{-t/\tau_{\overline{B}^0}}}$$



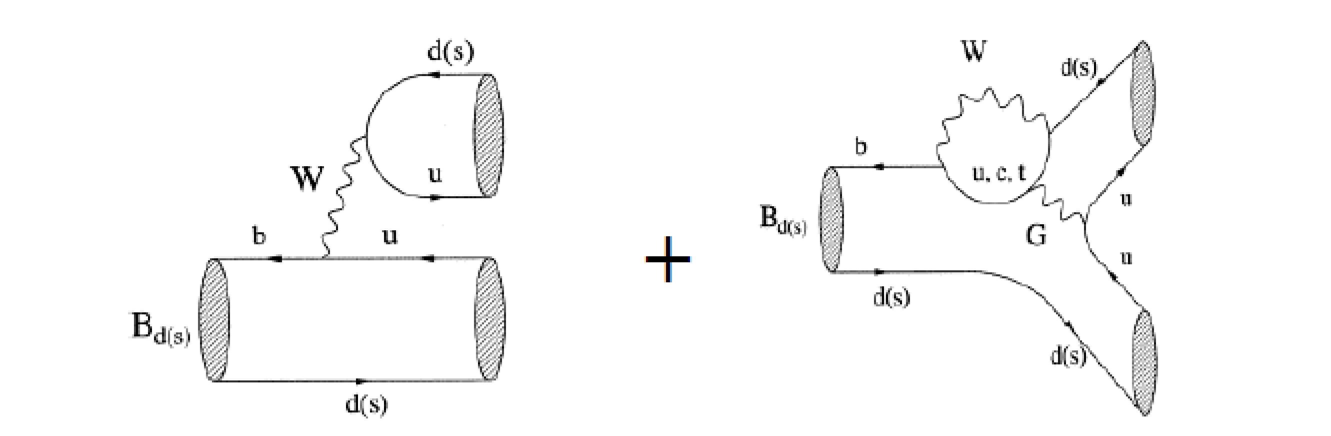
- CP нарушение в интреференции



$$\mathcal{A}_{cp} = \frac{\Gamma(B \to f) - \Gamma(\overline{B} \to \overline{f})}{\Gamma(B \to f) + \Gamma(\overline{B} \to \overline{f})}$$

Direct CPV $P(B \to f) \neq P(\overline{B} \to \overline{f})$

- Bs K-p+ & B0 K+p-



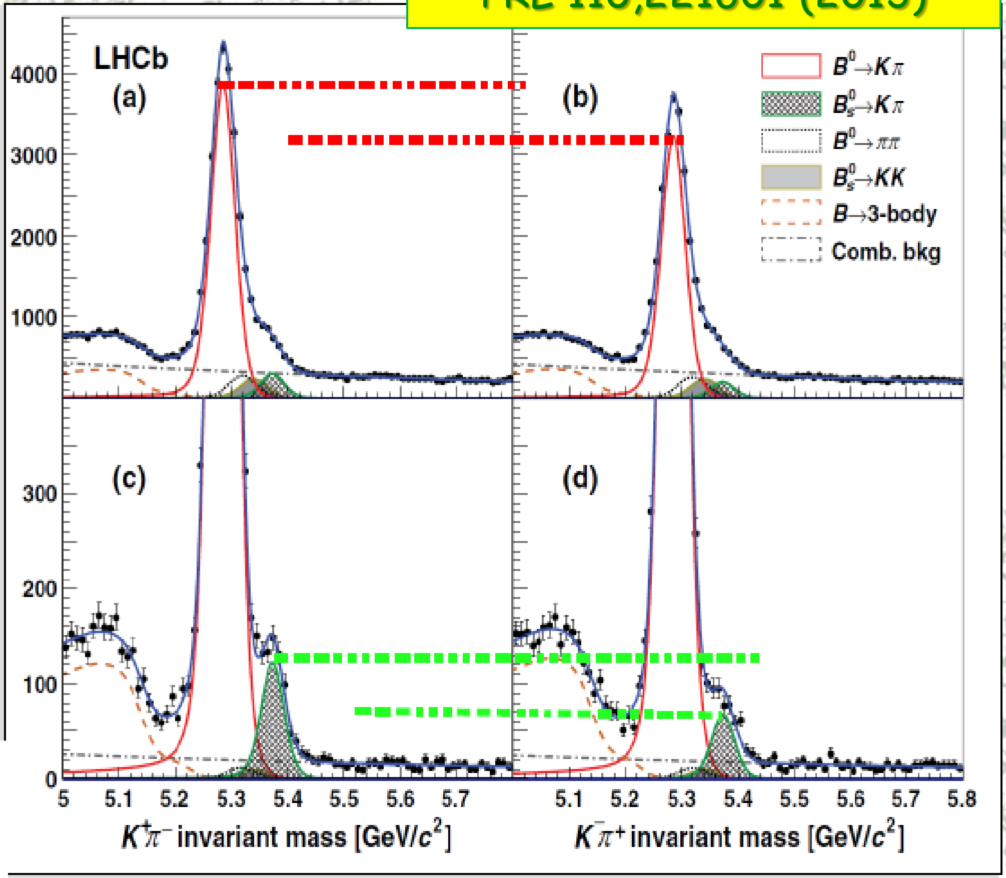
- Разные CKM факторые: разные ширины и CP
- НО в СМ:

Lipkin, EPJC9, 443 (1999)

$$\Delta = \frac{\mathcal{A}_{CP}(B^0_d \to K^+\pi^-)}{\mathcal{A}_{CP}(B^0_s \to K^-\pi^+)} + \frac{\mathcal{B}(B^0_s \to K^+\pi^-)}{\mathcal{B}(B^0_d \to K^-\pi^+)}\frac{\tau_d}{\tau_s} = 0$$

CP нарушение не мало!

PRL 110,221601 (2013)



$A_{CP}(B_d \to K^+\pi^-)$ = -0.08 +/- 0.007(stat) +/- 0.003(syst)

$A_{CP}(B_s \to K^-\pi^+)$ = 0.27 +/- 0.04(stat) +/- 0.01(syst)

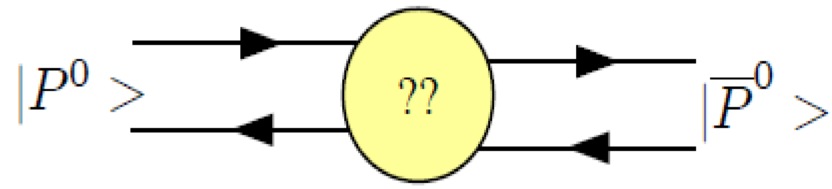
First observation of CPV in B_s system!

Δ = -0.02 +/- 0.05 +/- 0.04

Смешивание и CP-нарушение при смешивании

$$P(B \to \overline{B}) \neq P(\overline{B} \to B)$$

$$i\frac{\partial}{\partial t}\begin{pmatrix} P^0(t) \\ \bar{P}^0(t) \end{pmatrix} = \left[M - \frac{i}{2}\Gamma\right]\begin{pmatrix} P^0(t) \\ \bar{P}^0(t) \end{pmatrix}$$



$$\begin{aligned} |P_L(t)> &= p|P^0> + q|\overline{P}^0> \\ |P_H(t)> &= p|P^0> - q|\overline{P}^0> \end{aligned}$$

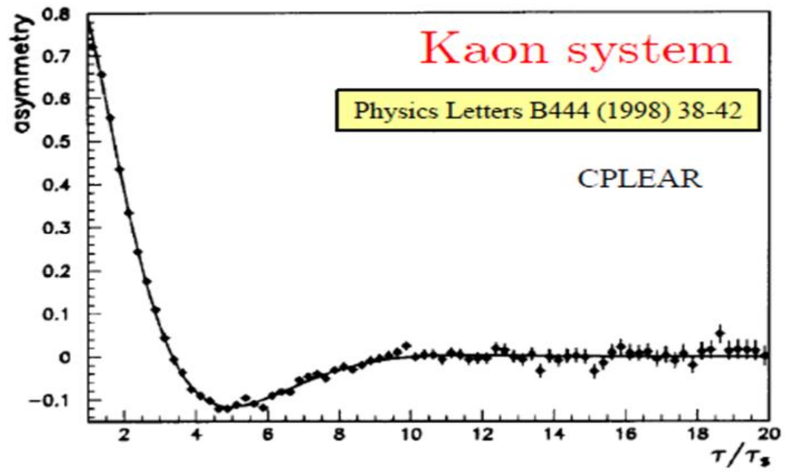
3 physical quantities describing mixing:

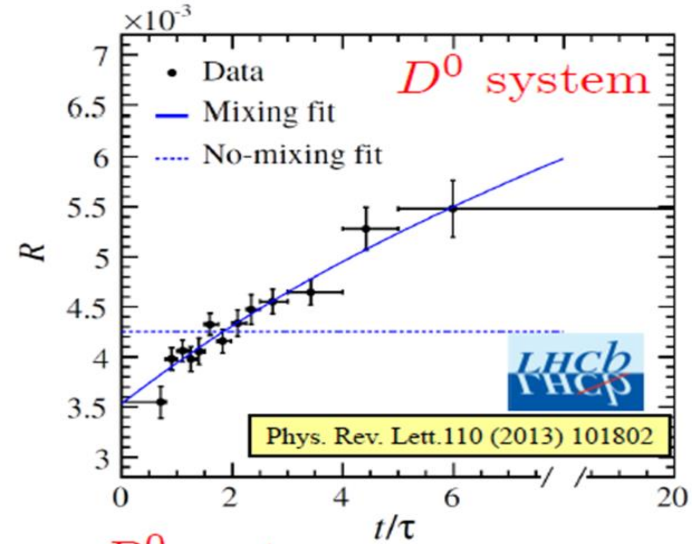
$$|M_{12}|, \quad |\Gamma_{12}|, \quad \phi = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

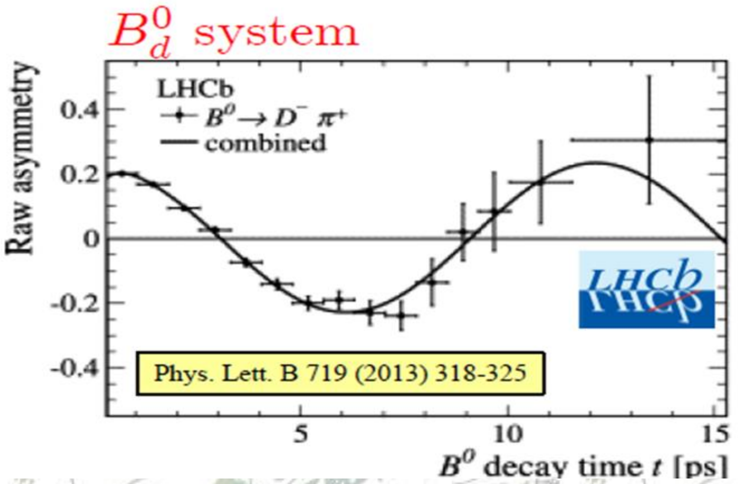
or

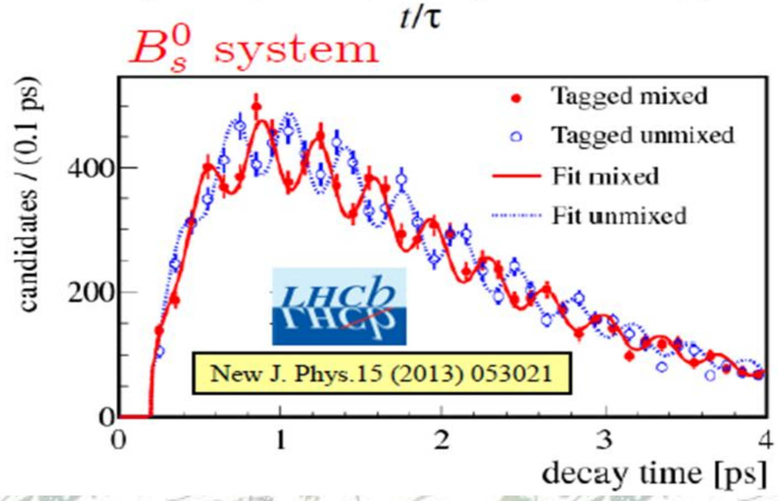
$$\Delta m = m_H - m_L = 2|M_{12}|, \quad \Delta\Gamma = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|\cos\phi, \quad \phi$$

Смешивание нейтральных мезонов



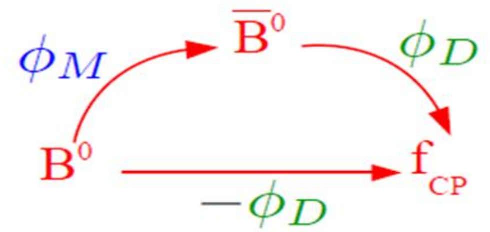






CP-нарущение в интерференции

- For CP eigenstates f_{CP} interference between mixing (ϕ_M) and decay (ϕ_D) is possible.



- CP asymmetry given by

$$A_{CP} = \frac{\Gamma(B_s^0 \to f_{CP}, t) - \Gamma(\overline{B}_s^0 \to f_{CP}, t)}{\Gamma(B_s^0 \to f_{CP}, t) + \Gamma(\overline{B}_s^0 \to f_{CP}, t)} = -\eta_f \sin(\phi_s)\sin(\Delta m_s t)$$

with $\phi_M = \arg M_{12}$

$$\phi_s = \phi_M - 2\phi_D \quad \text{and} \quad \eta_f : \text{CP eigenvalue of } f_{CP}$$

ϕ_s depends on final state:

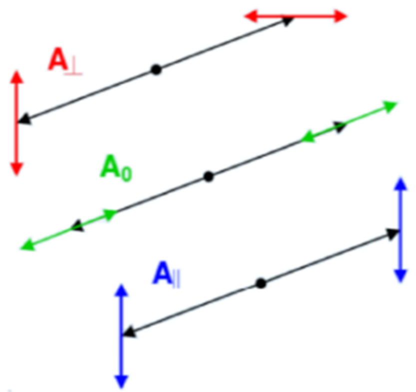
	SM prediction	LHCb measurements
$b \to c\bar{c}s$	$\phi_s^{c\bar{c}s} = -0.036 \pm 0.002$ rad Phys. Rev. D 84, 03305 (2011)	$B_s^0 \to J/\Psi\phi$ $B_s^0 \to J/\Psi\pi\pi$ Phys. Rev. D 87 112010 (2013)
$b \to s\bar{s}s$	$\phi_s^{s\bar{s}s} = 0.0 \pm 0.2$ rad Phys. Rev. D 80, 114026 (2009)	$B_s^0 \to \phi\phi$ PRL 110, 241802 (2013)

$B_s \to J/\psi\ \phi$

$$B_s^0 \to J/\Psi(\to \mu^+\mu^-)\Phi(\to K^+K^-)$$

Pseudoscalar to vector mesons ($J^{PC} = 1^{--}$):

$$L = 0, 2: \quad \Rightarrow \mathrm{CP} = (-1)^L = +1$$
$$L = 1: \quad \Rightarrow \mathrm{CP} = (-1)^L = -1$$



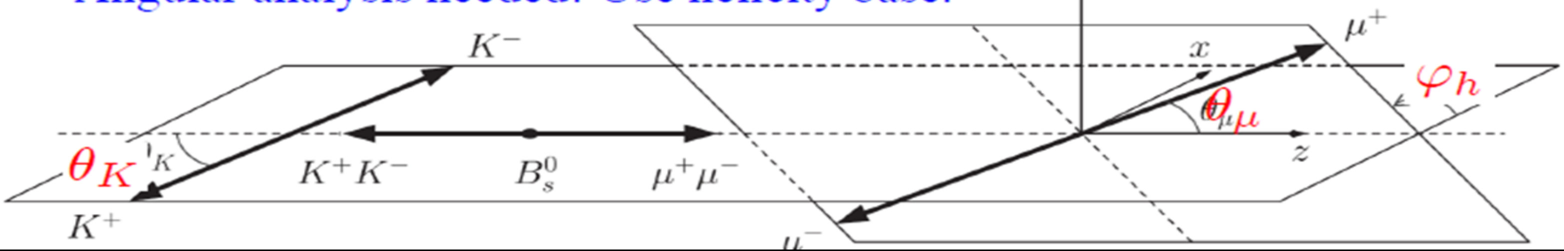
3 polarization amplitudes and phases needed:

- $|A_0|^2, |A_{||}^2|, \delta_0, \delta_{||}$ (CP even)
- $|A_\perp^2|, \delta_\perp$ (CP odd)

Additional S-wave component included in fit:

- $|A_s|^2, \delta_s$ (CP odd)

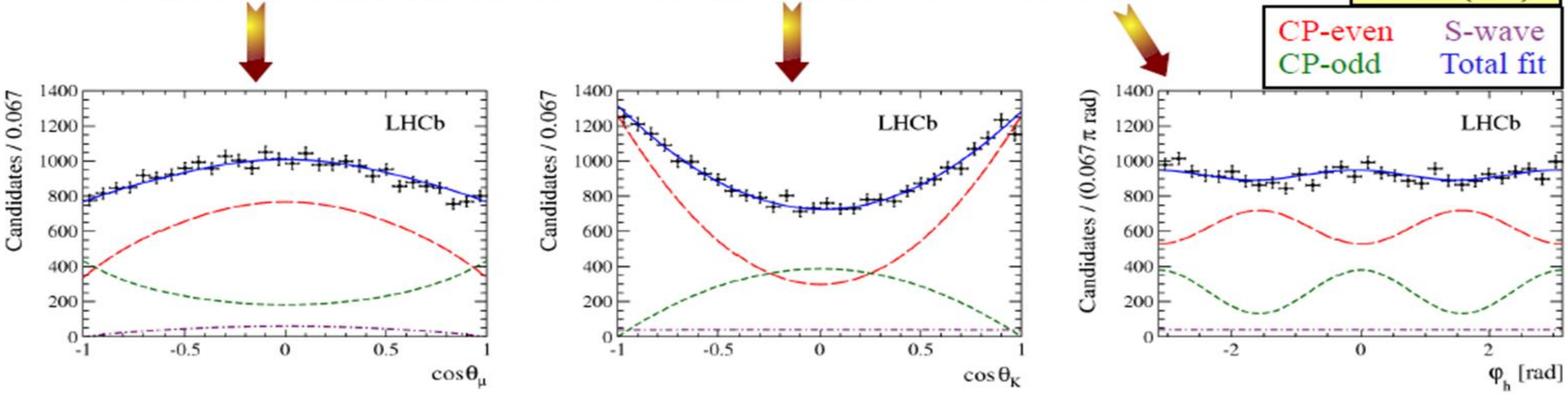
Angular analysis needed! Use helicity base.



$B_s \to J/\psi\ \phi$

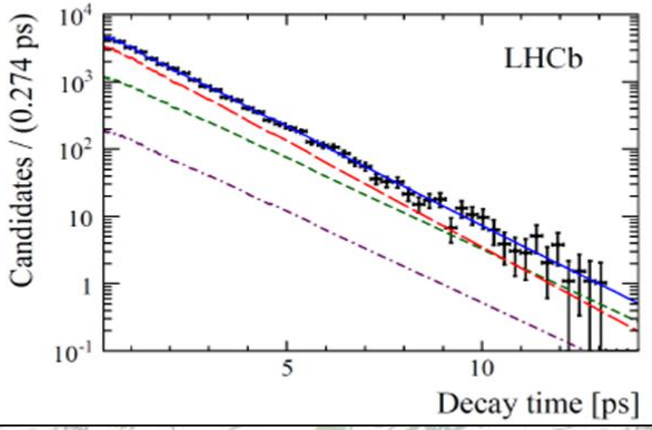
Clear seperation of CP even and CP odd component by unbinned maximum likelihood fit in angular distributions

Phys. Rev. D 87 112010 (2013)



Allows to determine different lifetimes for CP odd and CP even components:

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \approx \Gamma_{CP\ odd} - \Gamma_{CP\ even}$$



$B_s \rightarrow J/\psi\ \phi$

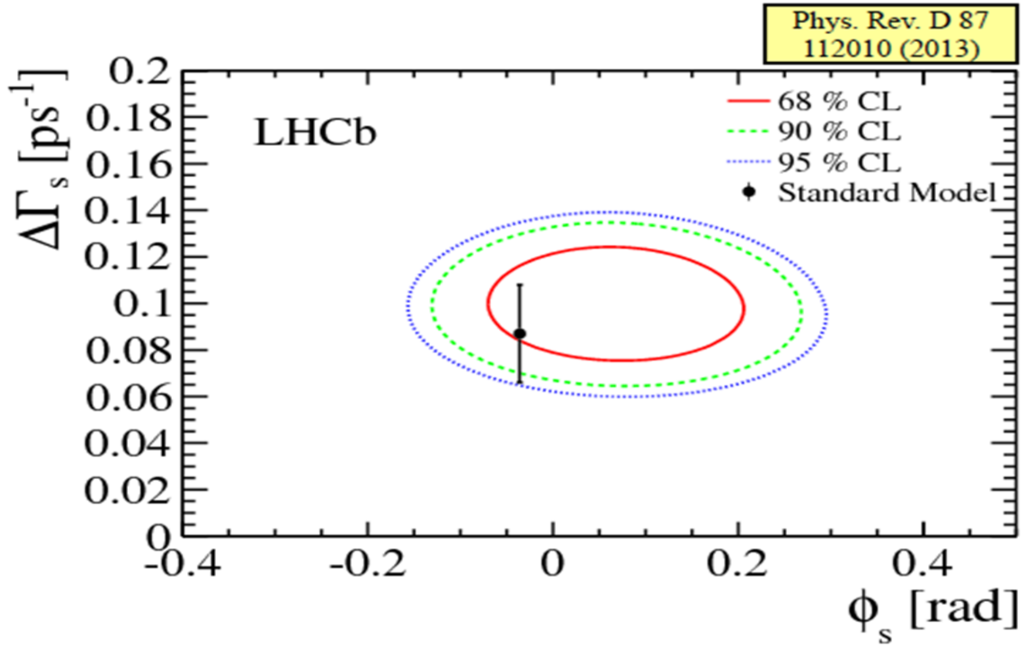
Results from $B_s \rightarrow J/\Psi\Phi$:

$$\phi_s^{c\bar{c}s} = (0.07 \pm 0.09(\text{stat}) \pm 0.01(\text{sys}))\ \text{rad}$$

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

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

Sign of $\Delta\Gamma$ measured from phase dependence of δ_s on $m_{K^+K^-}$ to be "+" !



CP-нарушение в очарованном секторе

- Ожидается (в СМ) малым $O(10^{-4})$
- Наблюдаемые:
  - Временная эволюция $D^0 \to K^+\pi^-$
  - $A_{CP}(D^0 \to K^-\pi^+)$
  - Асимметрия эффективных времен жизни

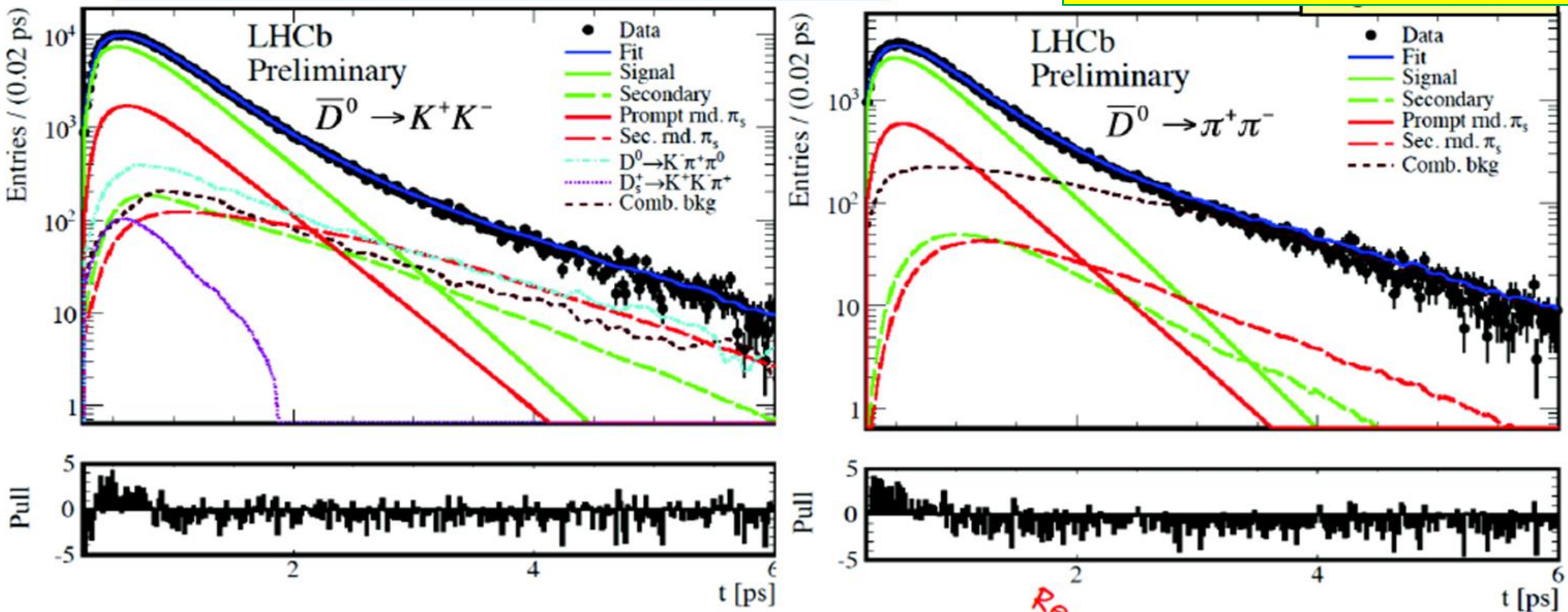
$$A_\Gamma = \frac{\tau(\overline{D}^0 \to f) - \tau(D^0 \to f)}{\tau(\overline{D}^0 \to f) + \tau(D^0 \to f)}$$

  - Асимметрия между K^+K^- и $\pi^+\pi^-$

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \approx \Delta A_{dir}\left(1 + y_{CP}\frac{<t>}{\tau}\right) + \Delta A_{ind}\frac{\Delta <t>}{\tau}$$

A_Γ

LHCb –PAPER-2013-054



Results consistent with CP conservation as expected in SM

Results:

$$A_\Gamma(KK) = (-0.35 \pm 0.62_{stat}) \cdot 10^{-3}$$

$$A_\Gamma(\pi\pi) = (0.35 \pm 1.06_{stat}) \cdot 10^{-3}$$

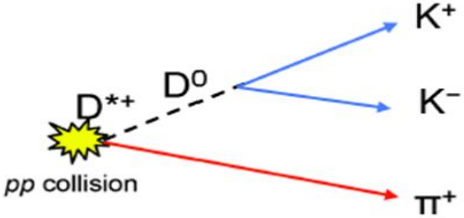
ΔA_{CP}

Two analysis, with largely independent systematics:

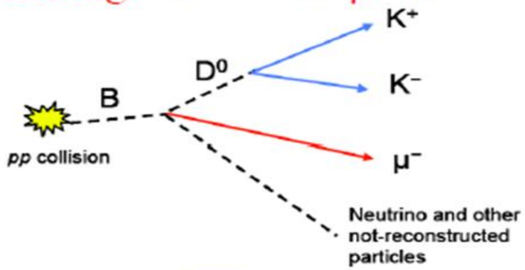
LHCb-CONF-2013-003

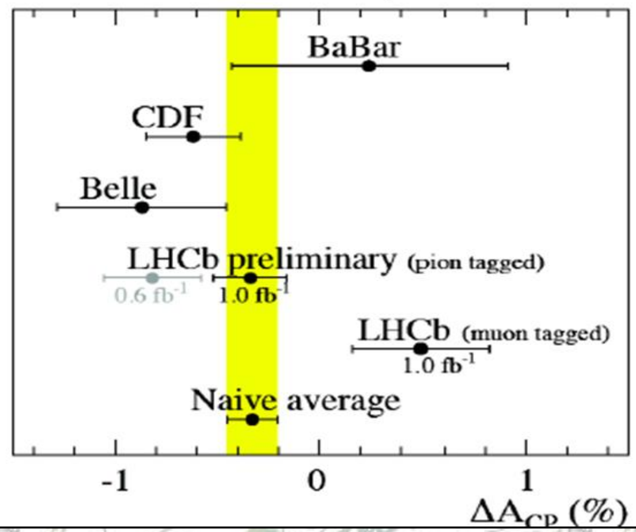
Phys. Lett. B 723 (2013) 33-43

Soft pion tag: $D^{*+} \rightarrow D^0\pi^+$



Muon tag: $B^- \rightarrow D^0\mu^- X$





Prompt analysis:
(Soft pion tag)

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

Semi-leptonic analysis:
(Muon tag:)

$$\Delta A_{CP} = (0.49 \pm 0.30(\text{stat} \pm 0.14(syst))\%$$

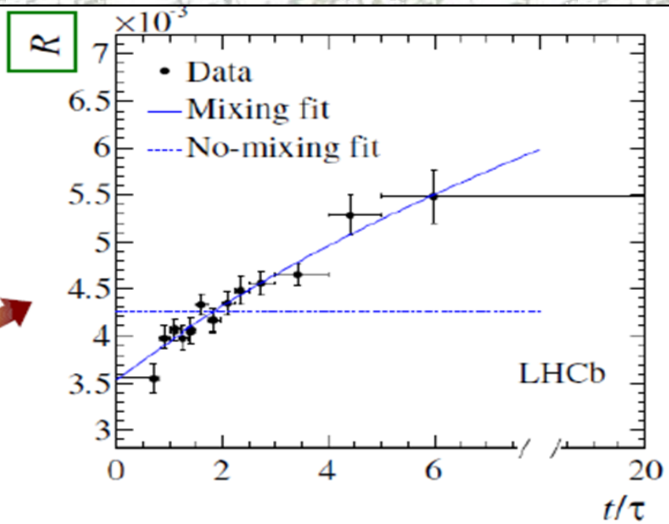
$D^0 \to K^+\pi^-$

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)}$$

WS: DCS $D^0 \to K^-\pi^+$

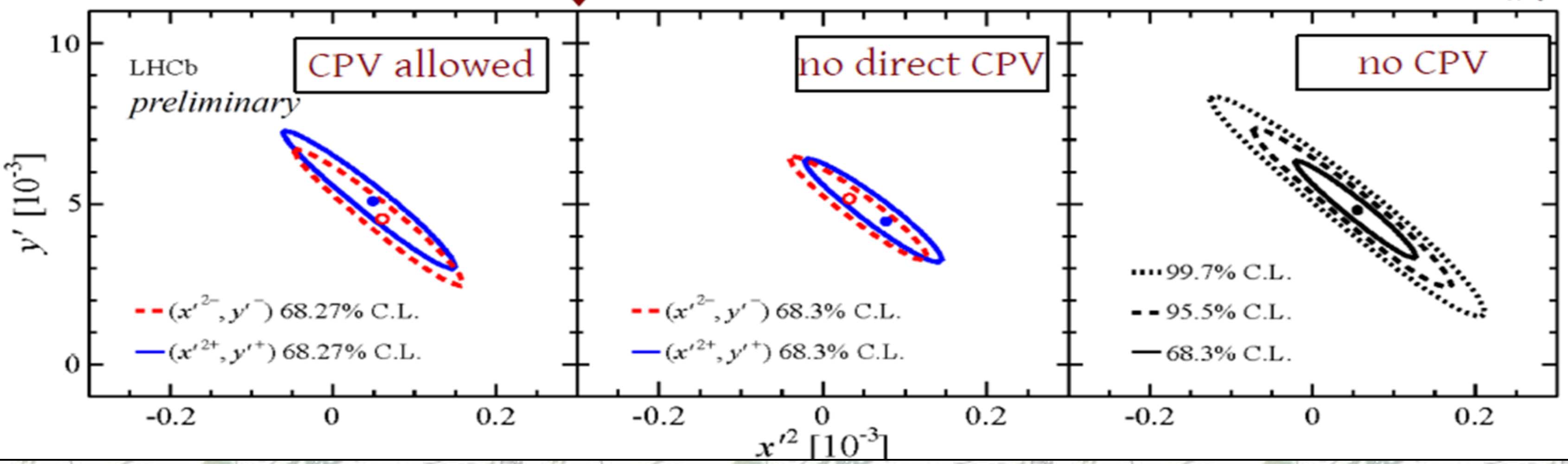
RS: CF $D^0 \mapsto K^-\pi^+$

Use π_s^+ in $D^{*+} \to D^0(K^-\pi^+)\pi_s^+$ to tag initial flavor of D^0



No mixing scenario excluded at 9.1σ…

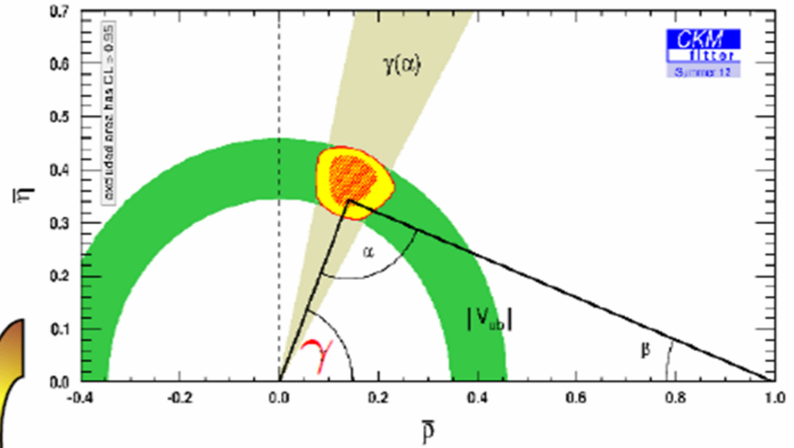
…but consistent with CP conservation



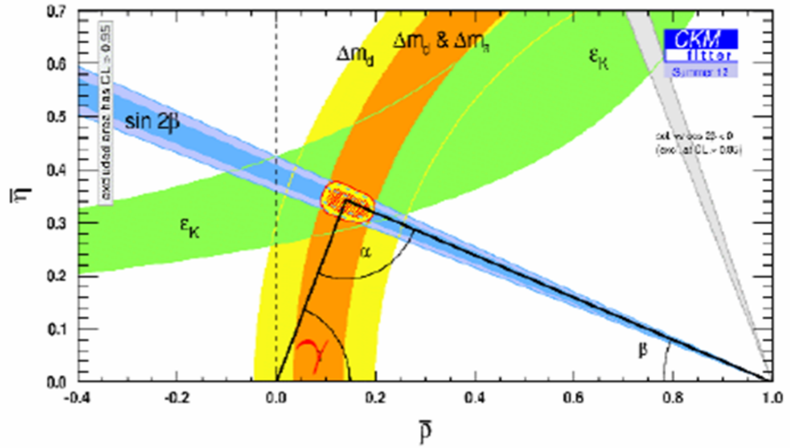
Угол γ в треугольнике унитарности

CKM angle $\gamma = arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ can be measured from:

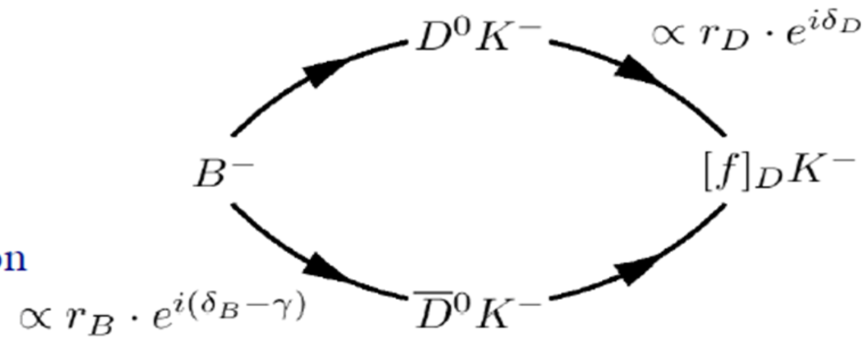
trees: largely unaffected by NP



loops: sensitive to NP



- tree-level decay $B^{\pm} \to DK^{\pm} \to f_{[D]}K^{\pm}$ allows theoretically clean determination
- Comparison with measurements from loop-dominated decays gives information about NP



Наблюдаемые

Gronau, London, Wyler (GLW)	Atwood, Dunietz, Soni (ADS)	Giri, Grossmann, Soffer, Zupan(GGSZ)
CP eigenstates	quasi flavor-specific states	self-conjuagated Dalitz modes
PLB253 (1991) 483 PLB 265 (1991) 172	PRL 78 (1997) 3257 PRD 63 (2001) 036005	PLB253 (1991) 483 PLB 265 (1991) 172
$B^\pm \to D(KK)\, K^\pm$ $B^\pm \to D(\pi\pi)\, K^\pm$ $B^\pm \to D(KK)\, \pi^\pm$ $B^\pm \to D(\pi\pi)\, \pi^\pm$ $B^\pm \to D(K\pi\pi\pi)\, K^\pm$ $B^\pm \to D(K\pi\pi\pi)\, \pi^\pm$	$B^\pm \to D(K^+\pi^-)\, K^\pm$ $B^\pm \to D(\pi^+K^-)\, K^\pm$ $B^\pm \to D(K^+\pi^-)\, \pi^\pm$ $B^\pm \to D(\pi^+K^-)\, \pi^\pm$	$B^\pm \to D(K_s^0\pi^+\pi^-)K^\pm$ $B^\pm \to D(K_s^0K^+K^-)K^\pm$

LHCb (first four GLW modes)

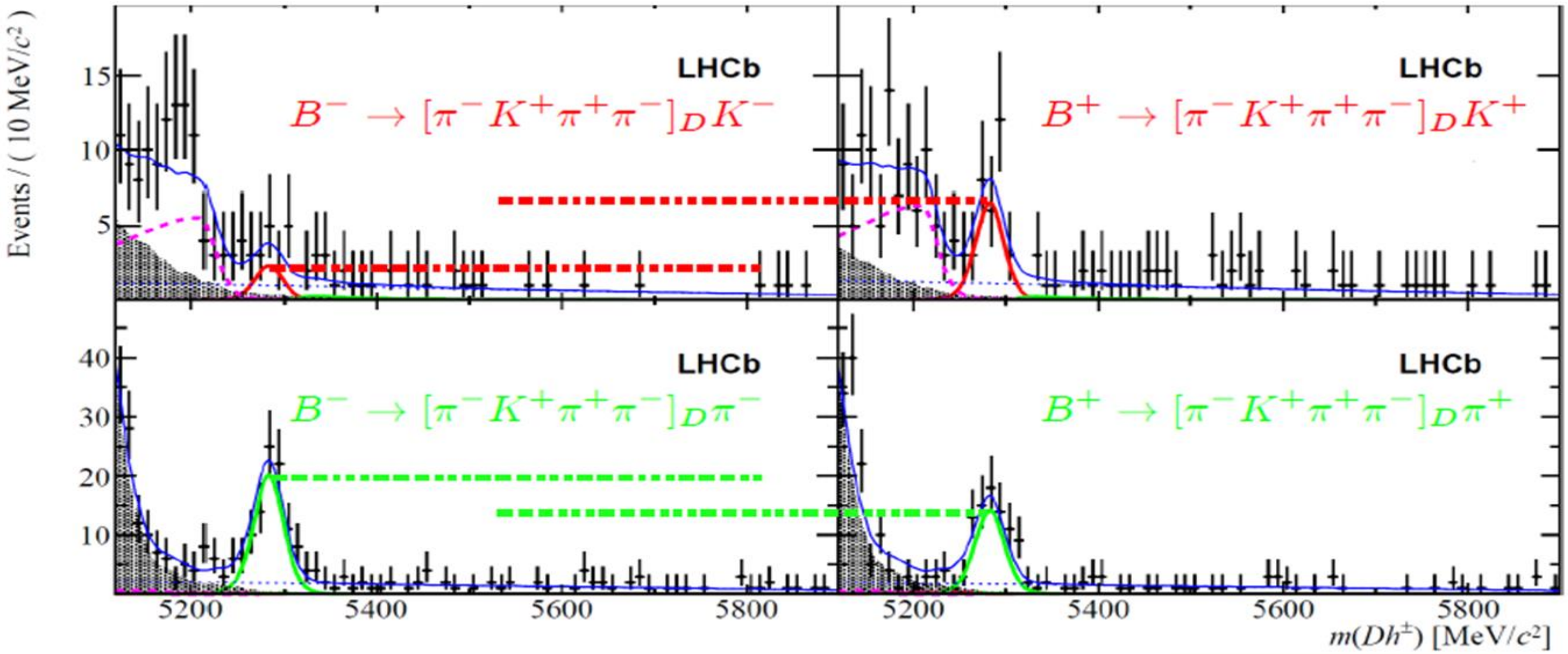
Observables:

Time integrated ratios and asymmetries of B^+ and B^- decay rates

Observables:

Interference patterns in Dalitz plots from B^+ and B^- decays

Измерения: $B^+ \to [\pi^+ K^- \pi^- \pi^+]_D h^+$ (ADS)



PLB 723(2013)44-53

First observation of suppressed ADS modes:

$B+ \to [\pi^+ K^- \pi^+ \pi^-]_D K^+$ 5.1σ significance for CP asymmetry

$B^+ \to [\pi^- K^+ \pi^+ \pi^-]_D \pi^+$ >10σ significance for CP asymmetry

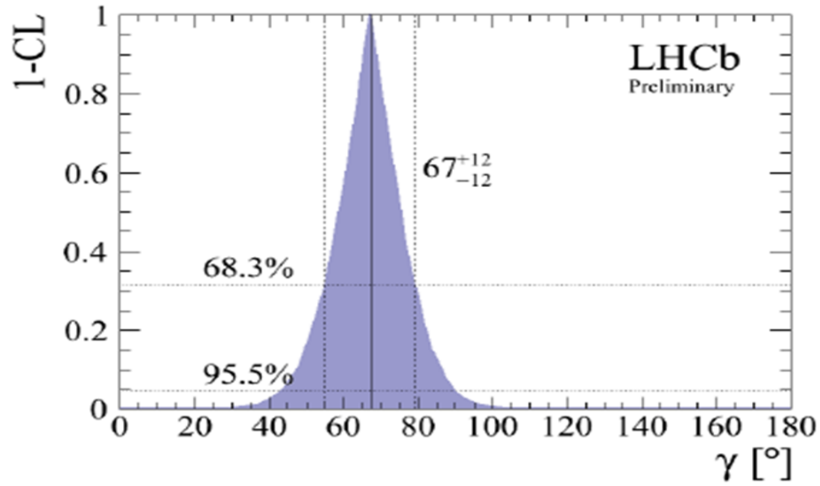
Измерение γ

LHCb:

- preliminary result from combination of GLS/ADS and GGSZ
- in total 25 observables! LHCb-CONF-2013-006

$$\gamma = (67 \pm 12)^\circ$$

- input from CLEO-c used to constrain strong phases in D decays



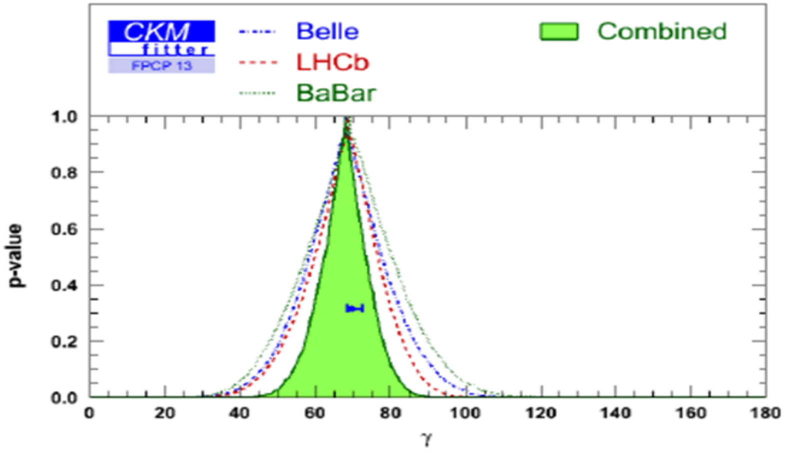
CKMfitter:

- constraints on γ combining results from D(*)K(*) decays (GLW+ADS) and Dalitz analyses (GGSZ)

$$\gamma = (68^{+8.0}_{-8.5}))$$

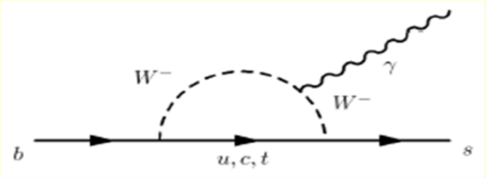
- prediction from global CKM fit (not including these measurements)

$$\gamma = (69.7^{+1.3}_{-2.8}))$$

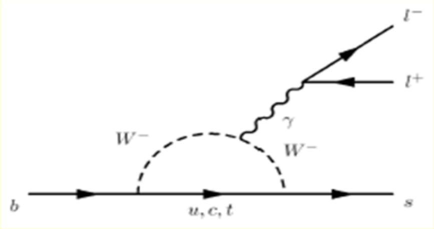


b→sγ & b→sμμ

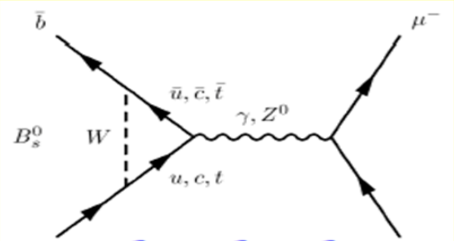
α_{QED} suppression   helicity suppression



$\mathcal{C}_7$



$\mathcal{C}_7,\ \mathcal{C}_9,\ \mathcal{C}_{10}$



$\mathcal{C}_{10},\ \mathcal{C}_S,\ \mathcal{C}_P$

LHCB-CONF-2013-009

Example	$B^+ \to K^+\pi^-\pi^+\gamma$ $B_s^0 \to \Phi\gamma$	$B^0 \to K^{*0}\mu^+\mu^-$	$B_{s(d)} \to \mu^+\mu^-$
Observable	γ polarisation	angular distruibution	branching fraction

Effective Hamiltonian in OPE: $\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \Sigma_{i=1}^{10} \left(\mathcal{C}_i\mathcal{O}_i + \mathcal{C}_i'\mathcal{O}_i'\right) + h.c.$

$\mathcal{C}_i$: Wilson coefficients

$\mathcal{O}_i$: local operators

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

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- **SM prediction**

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.23 \pm 0.27) \times 10^{-9}$$
$$\mathcal{B}(B_d \to \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$$

taking into account $\Delta\Gamma_s \neq 0$: $\mathcal{B}(B_s \to \mu^+\mu^-) = (3.56 \pm 0.18) \times 10^{-9}$

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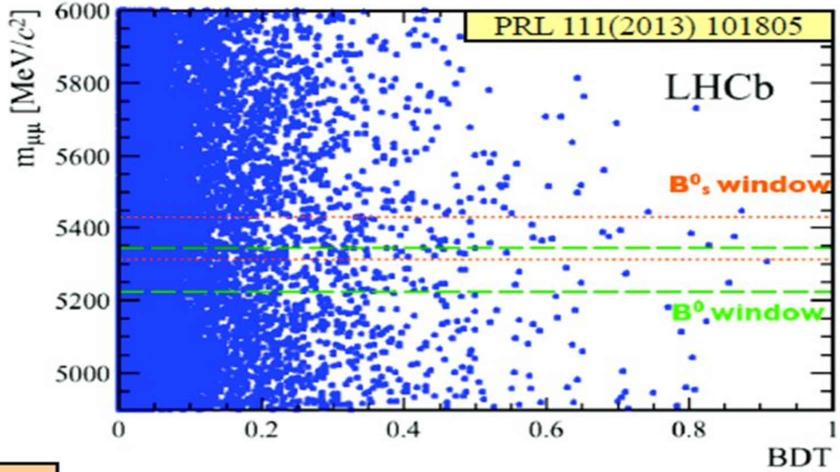
- **Analysis strategy**
  - Classification of candidates in 2D space of $m(\mu^+\mu^-)$ and a Boosted Decision Tree variable
  - Normalise using control channels

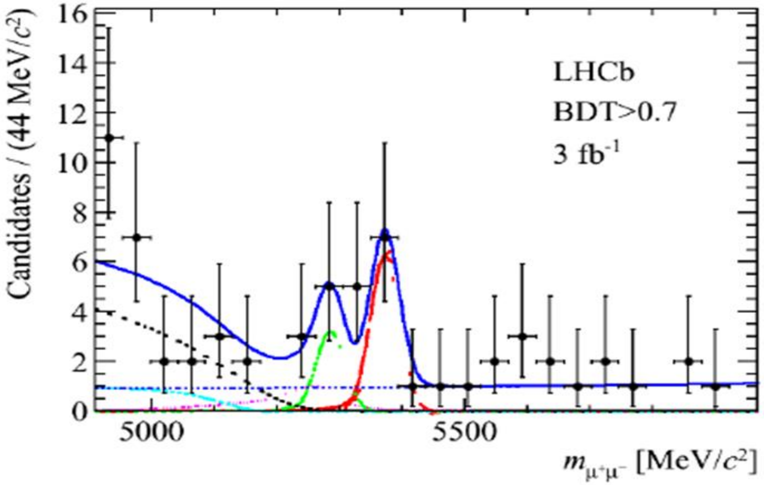
$$\mathcal{B}_{sig} = \mathcal{B}_{cal} \times \frac{\epsilon^{rec}_{cal}\epsilon^{sec}_{cal}}{\epsilon^{rec}_{sig}\epsilon^{sel}_{sig}} \times \frac{\epsilon^{trig}_{cal}}{\epsilon^{trig}_{sig}} \times \frac{f_{cal}}{f_{sig}} \times \frac{N_{sig}}{N_{cal}}$$

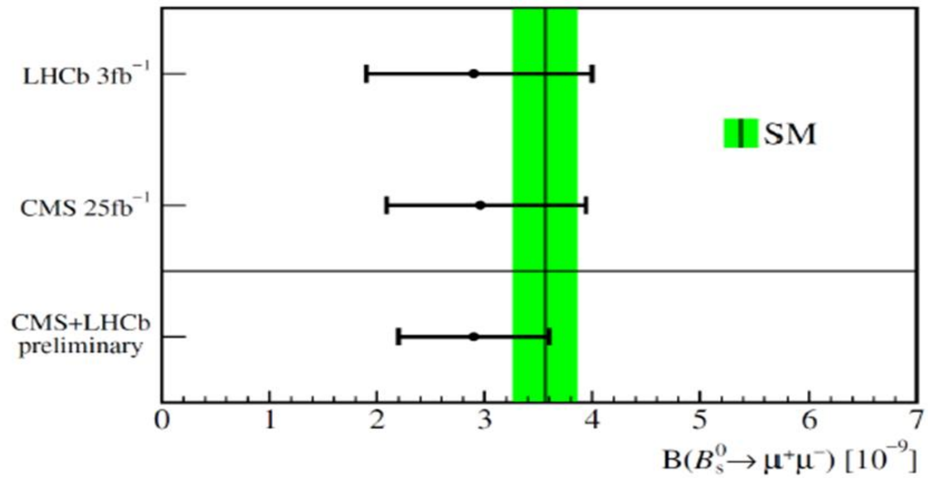
from MC checked on data	from data	hadronization fraction ratio



Combines information from several variables:
e.g. B decay vertex quality, B isolation
Kinematic variables, decay topology

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





Results: PRL 111(2013) 101805

Signal significance: 4σ

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

$$\mathcal{B}(B_d \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}(\text{stat})^{+0.6}_{-0.4}(\text{syst})) \times 10^{-9}$$

$< 7.4 \times 10^{-10}$ at 95% CL

Prel. combination with CMS: CMS-PAS-BPH-13-007 LHCb-CONF-2013-012

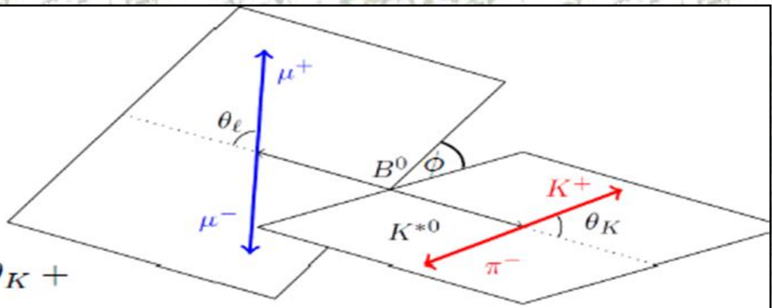
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

$$\mathcal{B}(B_d^0 \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-9}$$

$> 5\sigma$ observation

Угловой анализ $B\to K^{*0}\mu^+\mu^-$

- final state with four particles



$$\frac{1}{d\Gamma/dq^2}\frac{d\Gamma^4}{d\cos\theta_l d\cos\theta_K} = \frac{9}{32\pi}[\; S_1^s \sin^2\theta_K + S_1^c\cos^2\theta_K + S_2^s\sin^2\theta_K\cos 2\theta_l + S_2^c\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi + S_6\sin^2\theta_K\cos\theta_l\;;+ S_7\sin 2\theta_K\sin\theta_l\sin\phi + S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi]$$

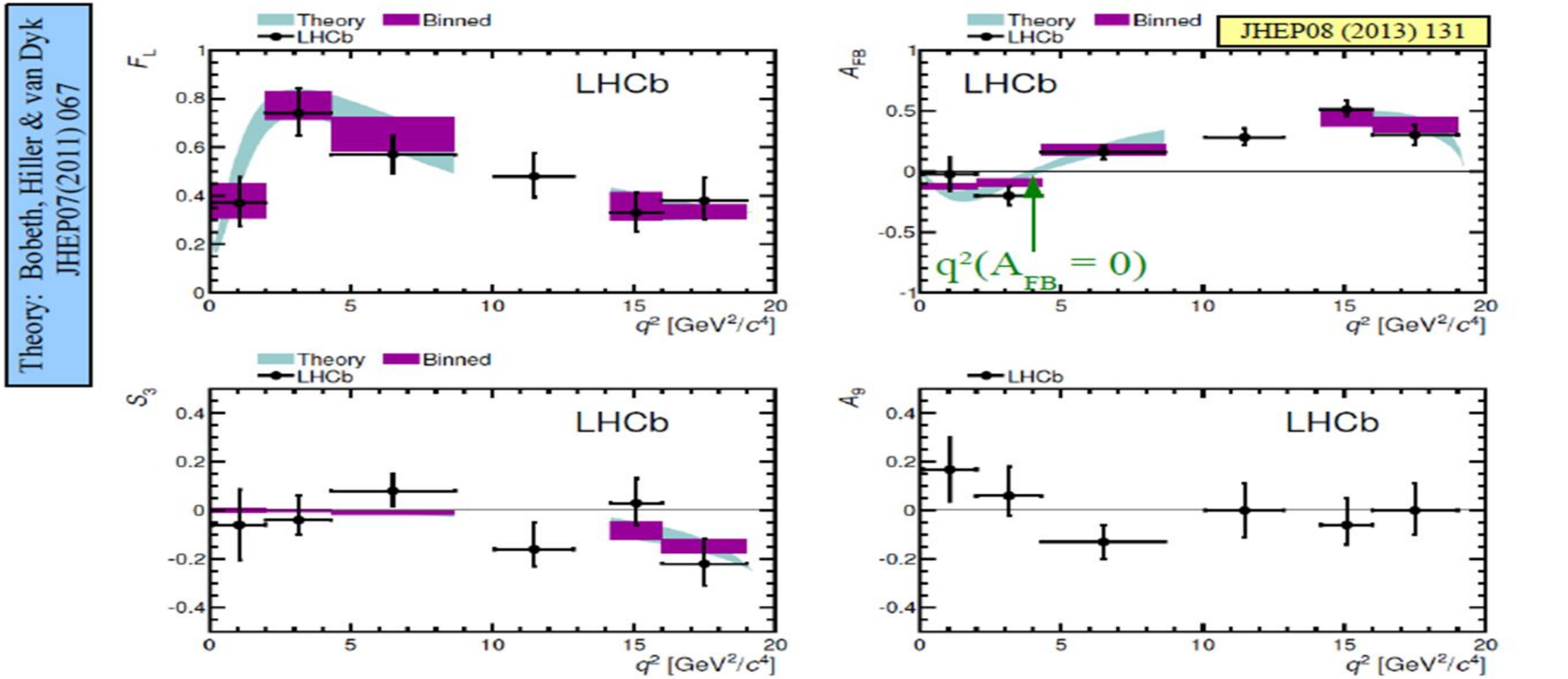
- $S_i(q^2)$ depend on Wilson coefficients.
- apply clever 'folding techniques' to extract variables sensitive to New Physics:

F_L :	fraction of K^*0 polarisation
S_3 :	$\propto K^{*0}$ transverse polarisation asymmetry
A_{FB} :	FB Asymmetry of the di-muon system
A_9 :	CP Asymmetry for S_9

$$P_{3,4,5,6} = \frac{S_{3,4,5,6}}{\sqrt{F_L(1-F_L)}}$$

In the large recoil limit (low q^2) $P_{3,4,5,6}$ are largely free from form factor uncertainities.
→ JHEP05 (2013) 137

Угловой анализ $B \to K^{*0}\mu^+\mu^-$

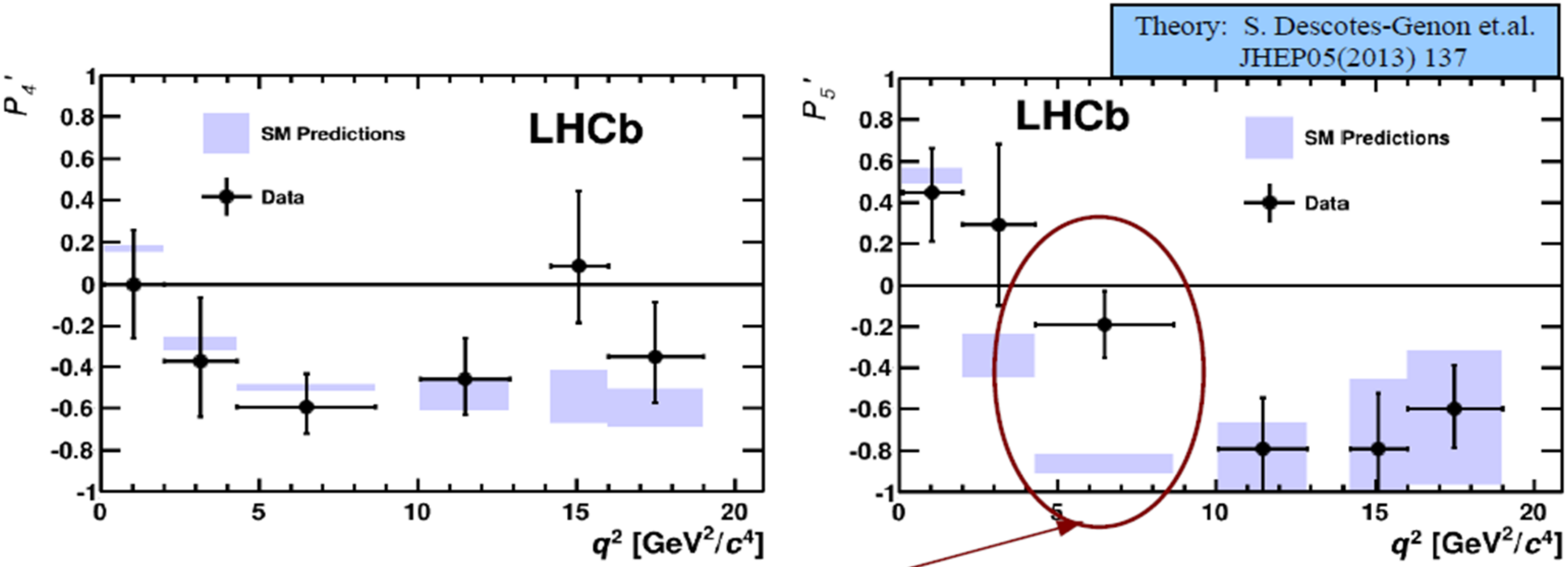


Measurements in good agreement with Standard Model predictions

First determination of well predicted A_{FB} zero-crossing point:

$q^2(A_{FB} = 0) = (4.9 \pm 0.9)\ \mathrm{GeV}^2/c^4$

Угловой анализ $B \to K^{*0}\mu^+\mu^-$



- 3.7σ discrepancy in 1 / 24 bins.
- triggered discussion on possible NP contribution to Wilson coefficients

LHCb: будущее

- Сейчас: 3фб$^{-1}$
  - Значительная часть представленных резльтатов на 1фб$^{-1}$
  - Во всех результатх статистическая ощибка доминирует
- Upgrage: 5фб$^{-1}$/год !
  - Существенное улучшение триггерной эффективности
  - Работа на светимости в 5 раз больше
  - Изменения в детекторе

2010	0.037 fb^{-1} @ 7 TeV
2011	1 fb^{-1} @ 7 TeV
☆ 2012	2 fb^{-1} @ 8 TeV
2013 2014	LHC LS1
2015 2016 2017	5 fb^{-1} @ 13 TeV
2018 2019	LHC LS2, LHCb upgrade
2020 2021 2022	5 fb^{-1} per year

Заключение

LHCb experiment is in a good shape now and we look forward with the great optimism