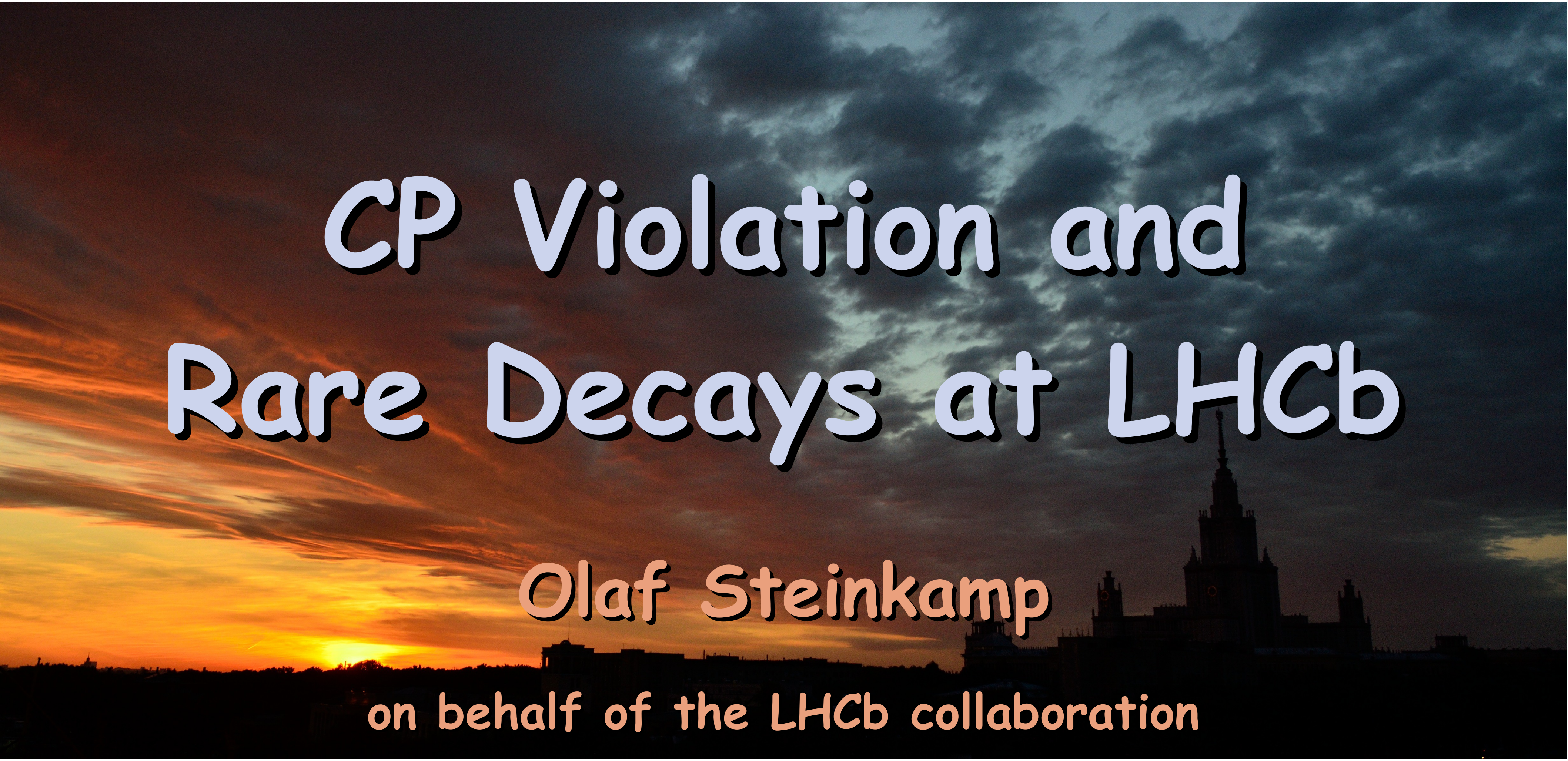
16th Lomonosov Conference

Moscow, Aug 22-28, 2013



CP Violation and Rare Decays at LHCb

Olaf Steinkamp

on behalf of the LHCb collaboration

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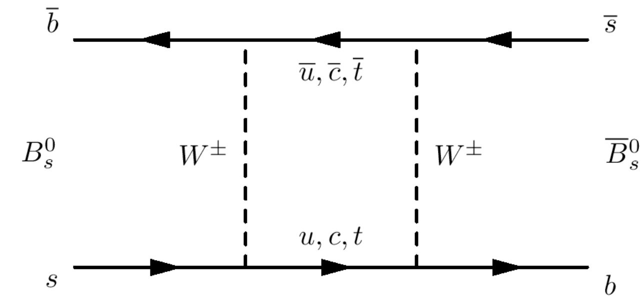
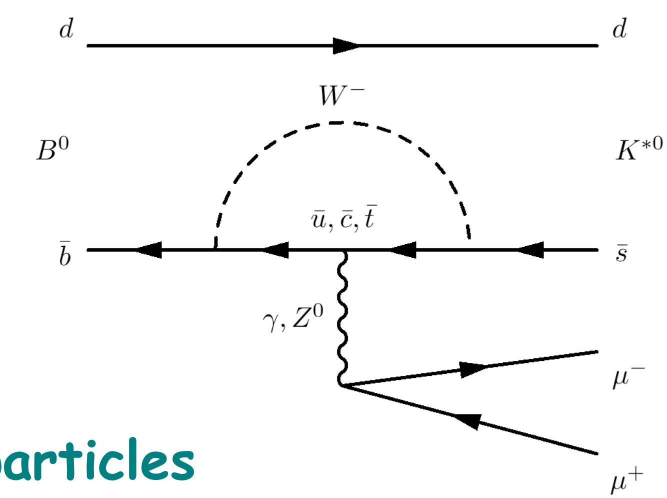
Universität Zürich[UZH]

Indirect Search For New Physics

- most New Physics models predict the existence of new heavy particles
  - these can enter in internal loops and have sizeable effect on observables
  - CP violating phases, rare FCNC decays



- B^0 and B^0_s systems are an ideal hunting ground
  - rich phenomenology, precise SM predictions
  - confront predictions with precision measurements ⇒ LHCb



- indirect searches for New Physics are sensitive to higher mass scales than direct searches for new particles
- the pattern of deviations can hint at the structure of the New Physics

> suppression of FCNC → prediction of charm quark
> CP violation in $K^0\overline{K}^0$ system → prediction of 3rd quark doublet

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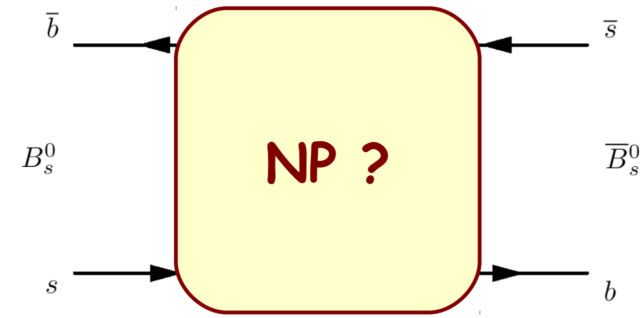

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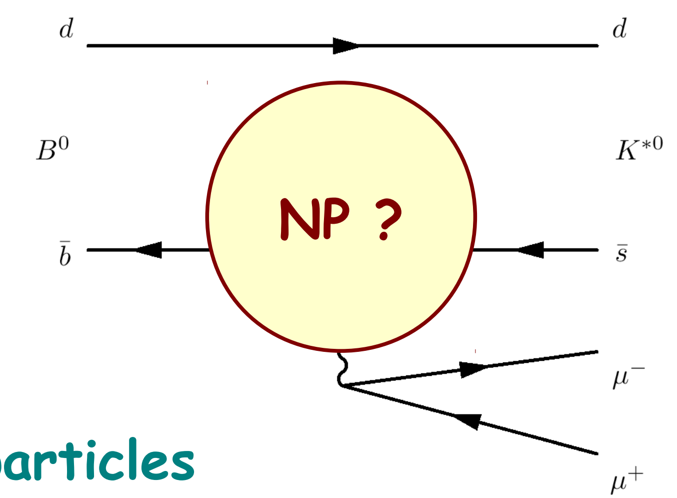

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suppression of FCNC → prediction of charm quark
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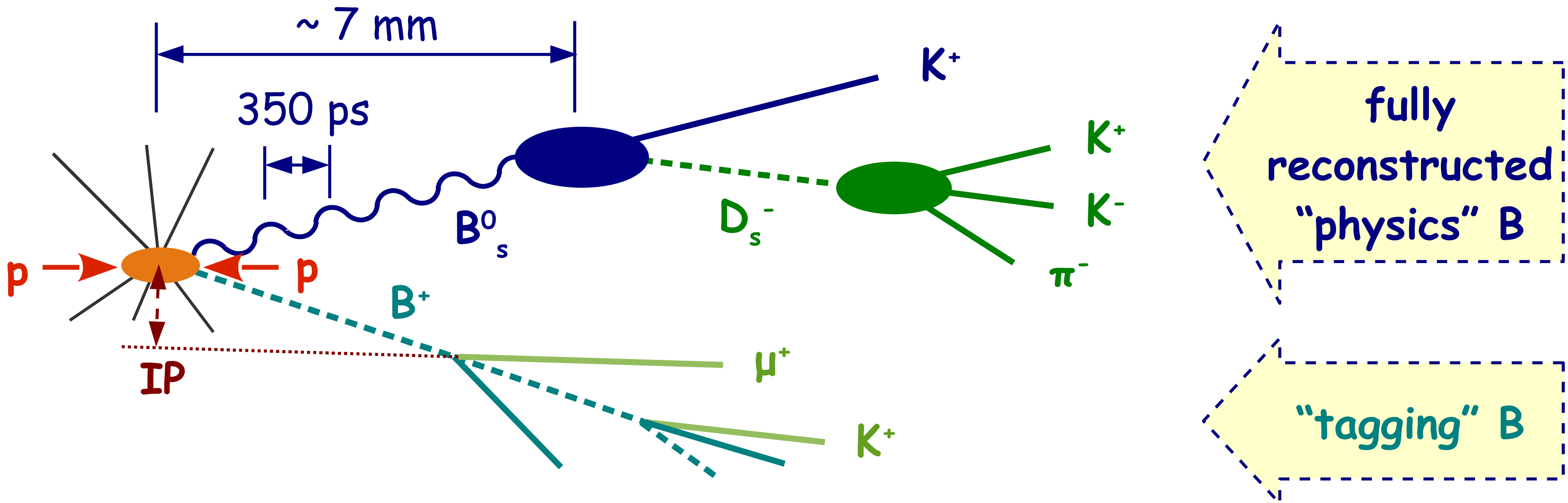
Key Requirements



- **impact parameter resolution**
  - identify secondary vertices
- **proper time resolution**
  - resolve fast B^0_s-$\overline{B}^0_s$ oscillations
- **momentum & invariant mass resolution**
  - against combinatorial backgrounds
- **large numbers of b hadrons (B^0, $B^\pm$, B^0_s, Λ_b)**
- **K/π separation**
  - against peaking backgrounds
  - flavour tagging
- **selective and efficient trigger, also for hadronic final states**

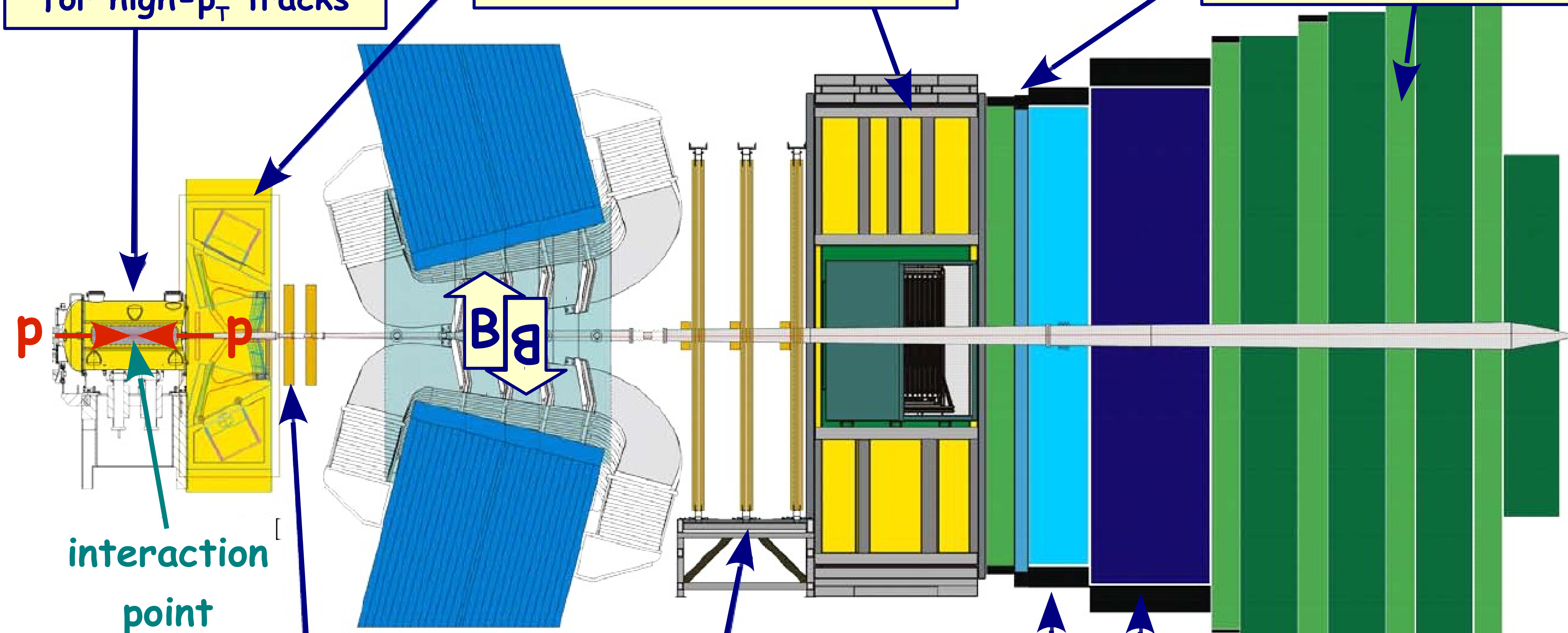
$\sigma(b\bar{b}) \approx 290\ \mu b$ @ 7 TeV
[PLB 694 (2010) 209]

LHCb Apparatus

VErtex LOcator
σ_{IP} ~ 20 μm
for high-p_T tracks

RICH detectors
$\varepsilon(K \to K)$ ~ 95 %
for 5 % $\pi \to K$ mis-id

Muon system
$\varepsilon(\mu \to \mu)$ ~ 97 %
for 1-3 % $\mu \to \pi$ mis-id



Acceptance
$2 < \eta < 5$

Tracking system
$\Delta p/p$ = 0.4 % @ 5 GeV/c to
0.6 % @ 100 GeV/c

Calorimeters
ECAL: σ_E/E ~ 1 % ⊗ 10 %/ $\sqrt{E}$ (GeV)

[JINST 3 (2008) S08005]

LHCb Appar us

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for high-p_T trac

RICH ctors

ε(K– %

for 5

Muon system

μ→μ) ~ 97 %

1-3 % μ→π mis-id

Important contributions from Russian groups:

PNPI, ITEP, MSU,

INR, Novosibirsk, IHEP

Acce

2 < η < 5

eV/c

.6 % 00 GeV/c

Calorimeters

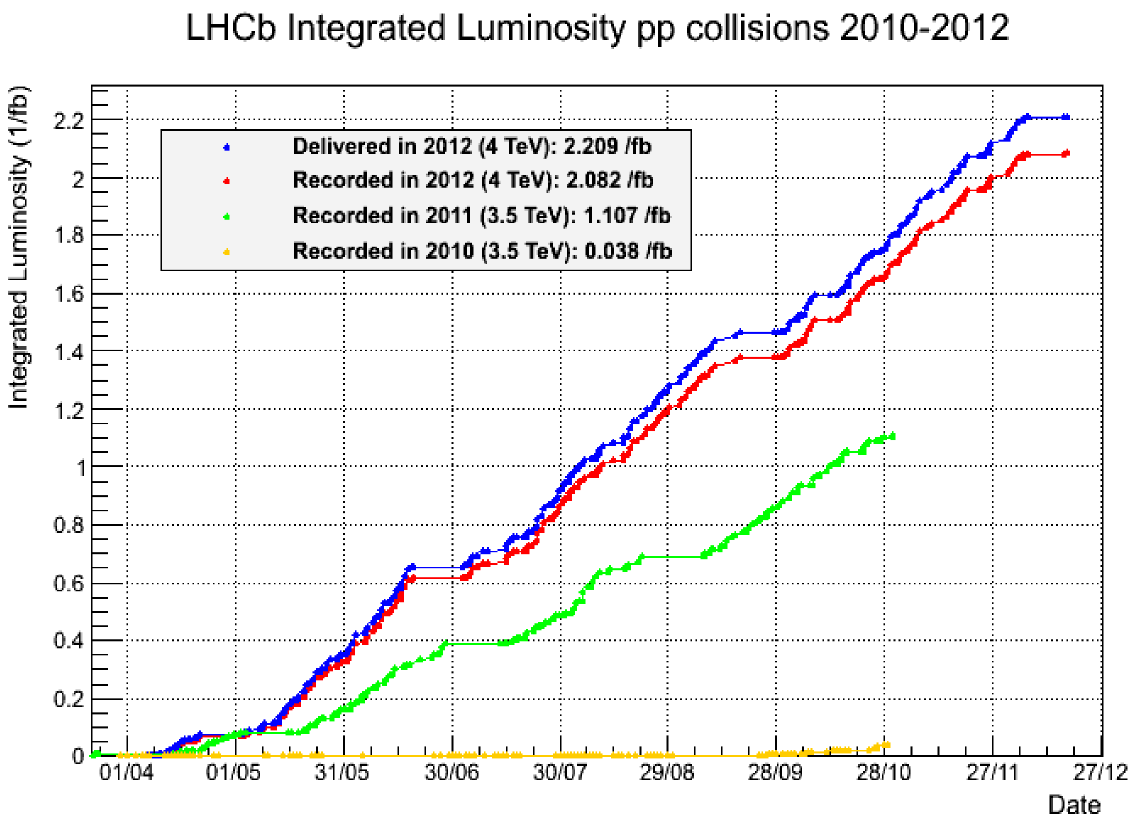
ECAL: σ_E/E ~ 1 % ⊗ 10 %/ √E (GeV)

[JINST 3 (2008) S08005]

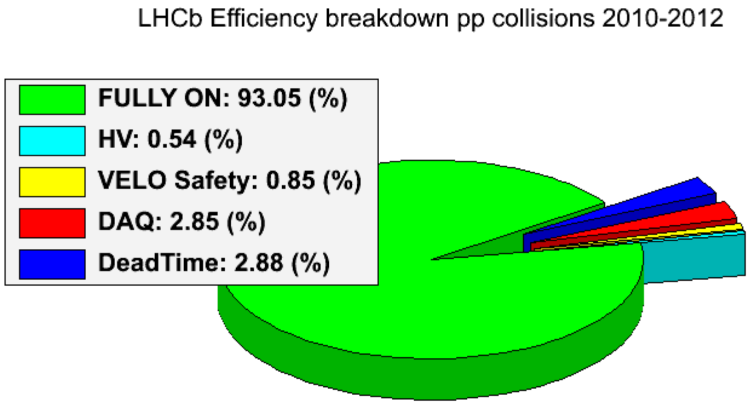
Data Taking

- 2011: 1.0 fb^{-1} at 7 TeV
- 2012: 2 fb^{-1} at 8 TeV

- 93 % data taking efficiency
- 99 % working detector channels
- 99 % of data good for analysis



unless mentioned explicitly,
all presented analyses are
based on the 2011 data set
= 1/3 of collected luminosity



Overview

- **Short introduction and motivation** ✔
- **CP violation**
  - CP phase ϕ_s from $B^0_s \rightarrow J/\psi\,\phi$
  - flavour-specific asymmetry in B^0_s decays
  - CKM phase γ from $B^\pm \rightarrow DK^\pm$ tree decays
  - CP violation in charmless B decays
- **Rare decays**
  - BR and CP violation in $B^\pm \rightarrow K^\pm \mu^+ \mu^-$
  - angular distributions in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
  - photon polarization in $B^\pm \rightarrow K^\pm \pi^+ \pi^- \gamma$
- **Conclusion and outlook: LHCb upgrade**

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sorry, no time to discuss interesting LHCb results on CPV and rare decays in the charm sector

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- **Conclusion and outlook: LHCb upgrade**

see Alexander's talk right after mine for $B^0_s \to \mu^+ \mu^-$ and other leptonic rare decays

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- **Conclusion and outlook: LHCb upgrade**

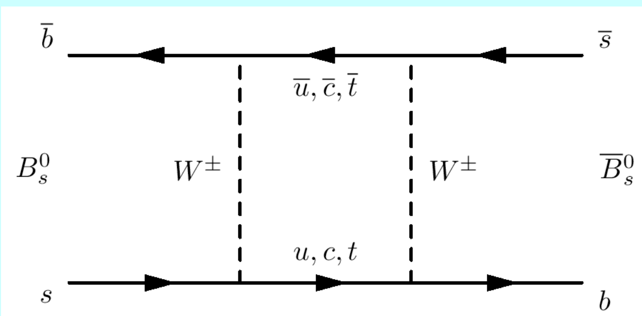
rich programme also in production & spectroscopy - some examples in Ivan's and Alexander's talks

CP Violation

Sources of CP Violation

CPV in mixing

("indirect CP violation")



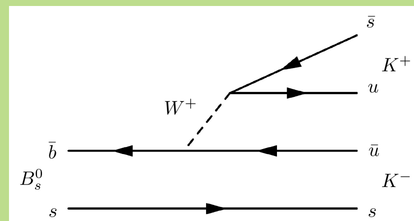
- interference of absorptive and dispersive part of mixing amplitude
- different mixing rate

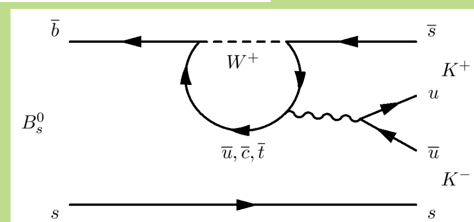
  $B \to \overline{B}$ vs $\overline{B} \to B$

- small in Standard Model

CPV in decay

("direct CP violation")



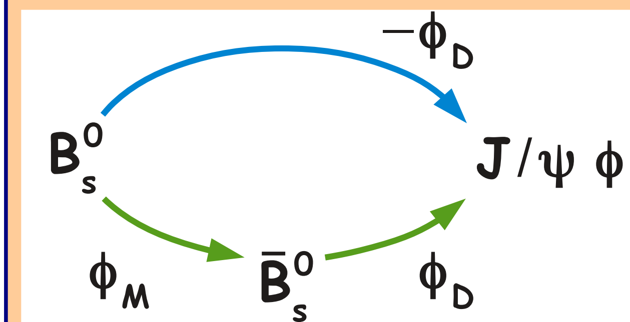


- interference of decay diagrams with different weak and strong phases
- different decay rates

  $B \to f$ vs $\overline{B} \to \overline{f}$

- beware of strong phases

CPV in interference of mixing and decay



- interference between direct decay and decay after mixing
- different decay rates

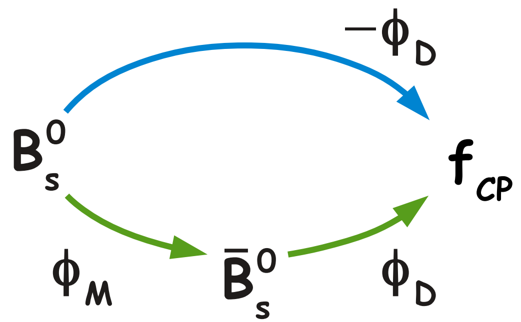
  $B \to f_{CP}$ vs $\overline{B} \to f_{CP}$

- "golden modes"

CP violating phase ϕ_s

- CP violation from interference between mixing and decay

$$\phi_s = \phi_M - 2\phi_D$$



- predicted to be very small in Standard Model

$$\phi_s = 0.0364 \pm 0.0016 \text{ rad}$$ [CKMfitter]

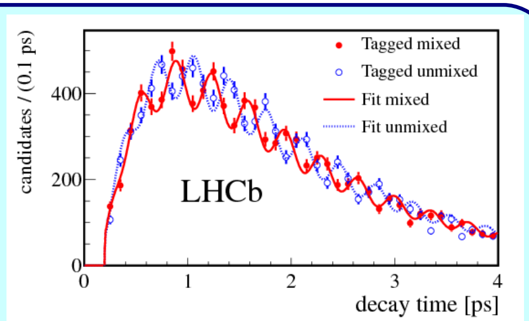
- sensitive to New Physics contributions in B^0_s-$\bar{B}^0_s$ mixing
- measure time-dependent asymmetry for decays to CP eigenstate f_{CP}

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

- use opposite-side and same-side tagging algorithms to infer initial flavour of B meson at production
- resolve fast B^0_s-$\bar{B}^0_s$ oscillations

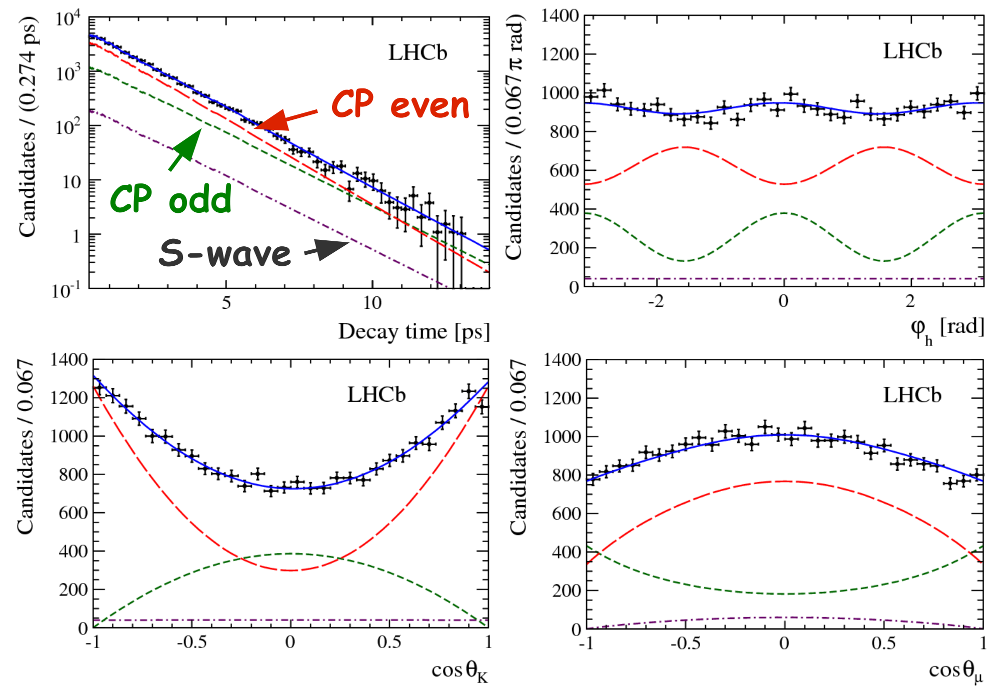
$B^0_s \to D^-_s \pi^+$

[arxiv:1304.4741]

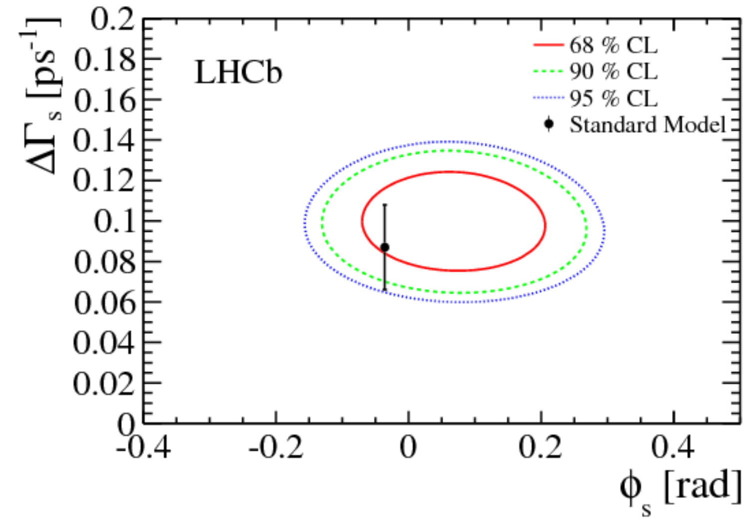


ϕ_s from $B^0_s \to J/\psi\,\phi$

- final state is mix of CP even and odd
  - 3 polarisation amplitudes, plus contribution from S-wave K^+K^-
  - time-dependent angular analysis to disentangle these and determine ϕ_s
- also determine lifetime difference $\Delta\Gamma_s$ between the two CP eigenstates



$$\phi_s = 0.07 \pm 0.09(\text{stat}) \pm 0.01(\text{syst})\ \text{rad}$$
$$\Delta\Gamma_s = 0.100 \pm 0.016(\text{stat}) \pm 0.003(\text{syst})\ \text{ps}^{-1}$$



- from combined analysis with $B^0_s \to J/\psi\,\pi^+\pi^-$:

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

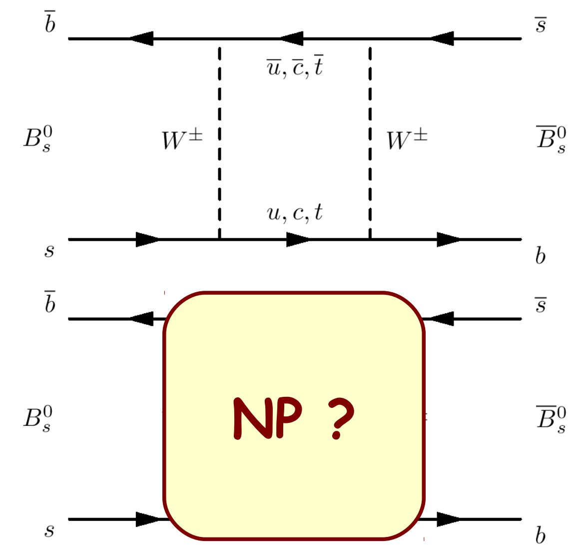
- excellent agreement with Standard Model

[PRD 87 (2013) 112010]

Flavour-Specific Asymmetry

- flavour-specific asymmetry

$$a_{sl}^{s} = \frac{\Gamma(\overline{B}_s^0(t) \to f) - \Gamma(B_s^0(t) \to \bar{f})}{\Gamma(\overline{B}_s^0(t) \to f) + \Gamma(B_s^0(t) \to \bar{f})}$$



- non-zero if CP violated in B^0_s-$\overline{B}^0_s$ mixing

$$\text{Prob}\,(B_s^0 \to \overline{B}_s^0) \neq \text{Prob}\,(\overline{B}_s^0 \to B_s^0)$$

- predicted to be very small in Standard Model

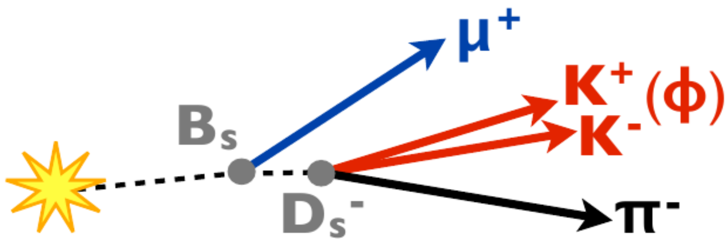
$$a_{sl}^{s} = (1.9 \pm 0.3) \times 10^{-5}$$

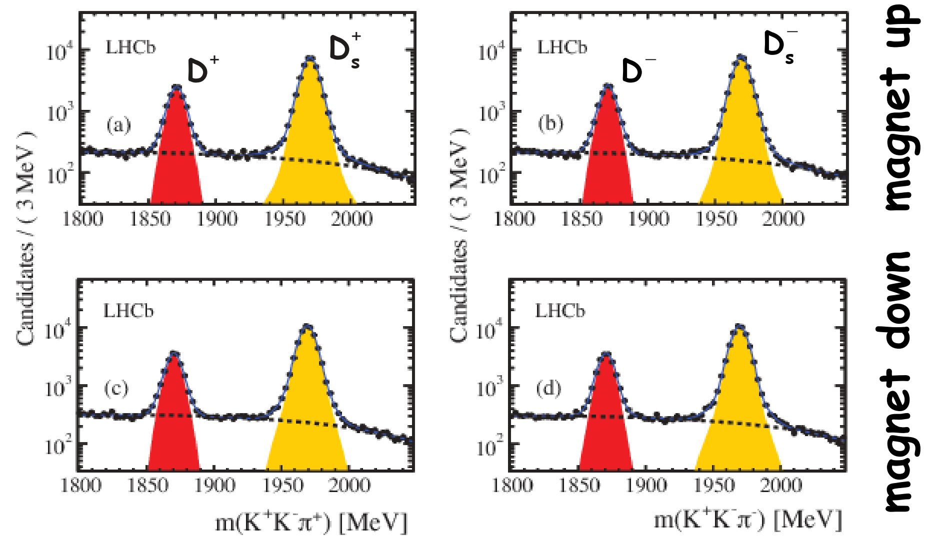
[A.Lenz, arXiv:1205.1444]

- sensitive to possible New Physics contributions in B^0_s-$\overline{B}^0_s$ mixing
- LHCb analyis uses $f = D_s^- \mu^+ X$ to measure time-integrated asymmetry
- production asymmetry $a_P \leq$ few %, washed out by rapid B^0_s-$\overline{B}^0_s$ oscillations

$$A_{raw} = \frac{N(D_s^-\mu^+) - N(D_s^+\mu^-)}{N(D_s^-\mu^+) + N(D_s^+\mu^-)} = \frac{a_{sl}^s}{2} + \left[a_P - \frac{a_{sl}^s}{2}\right] \times \underbrace{\frac{\int e^{-\Gamma_s t} \cos(\Delta m_s t)\,\varepsilon(t)\,dt}{\int e^{-\Gamma_s t} \cosh(\Delta \Gamma_s t/2)\,\varepsilon(t)\,dt}}_{=2\times10^{-3} \text{ for LHCb acceptance } \varepsilon(t)}$$

Flavour-Specific Asymmetry

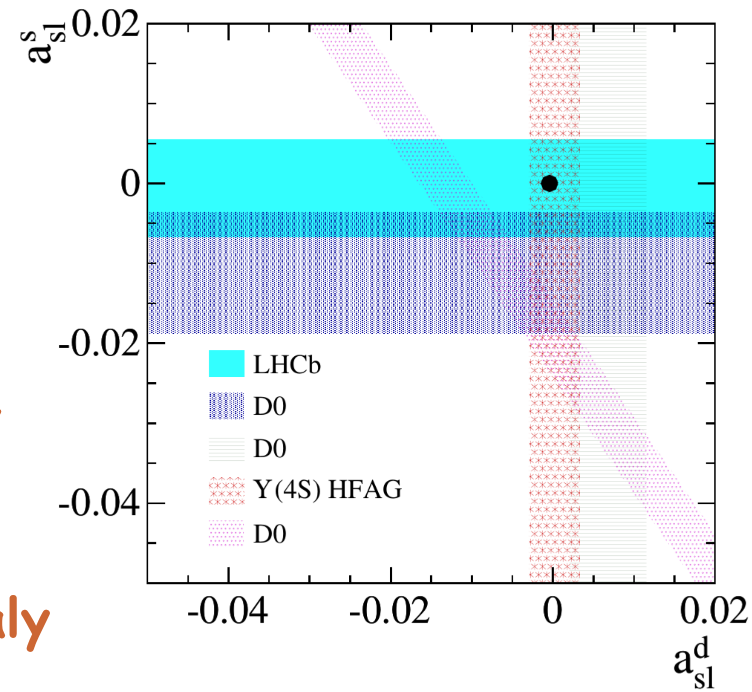




- detection asymmetries: measured from data using various control channels
- separately analyse two magnet polarities

$$a_{sl}^{s} = (-0.06 \pm 0.50\,(\text{stat}) \pm 0.36\,(\text{syst}))\ \%$$

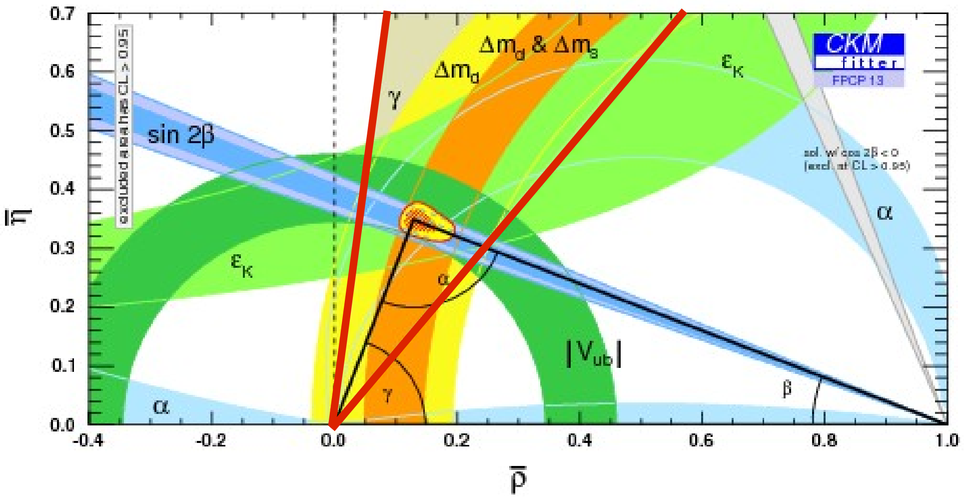
[arxiv:1308.1048]



- most precise measurement to date
  - main systematic: residual track reconstruction asymmetry
- excellent agreement with Standard Model
- no confirmation of D0 same-sign dilepton anomaly

CKM Angle γ from Tree Decays

- consistency of CKM fits establish Standard Model as dominant source of CP violation in quark sector
- need more precise measurements to test for possible subdominant contributions from New Physics



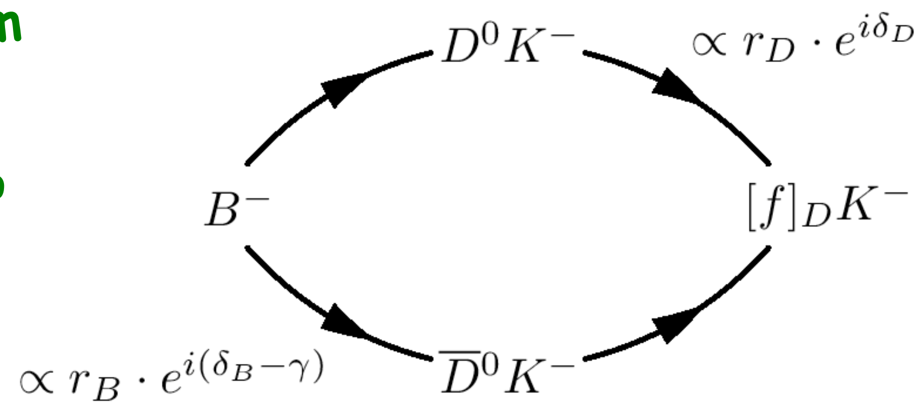
- angle γ still the least well constrained CKM parameter

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

$\gamma = \left(68.0\,^{+8.0}_{-8.5}\right)^\circ$ [CKMfitter]

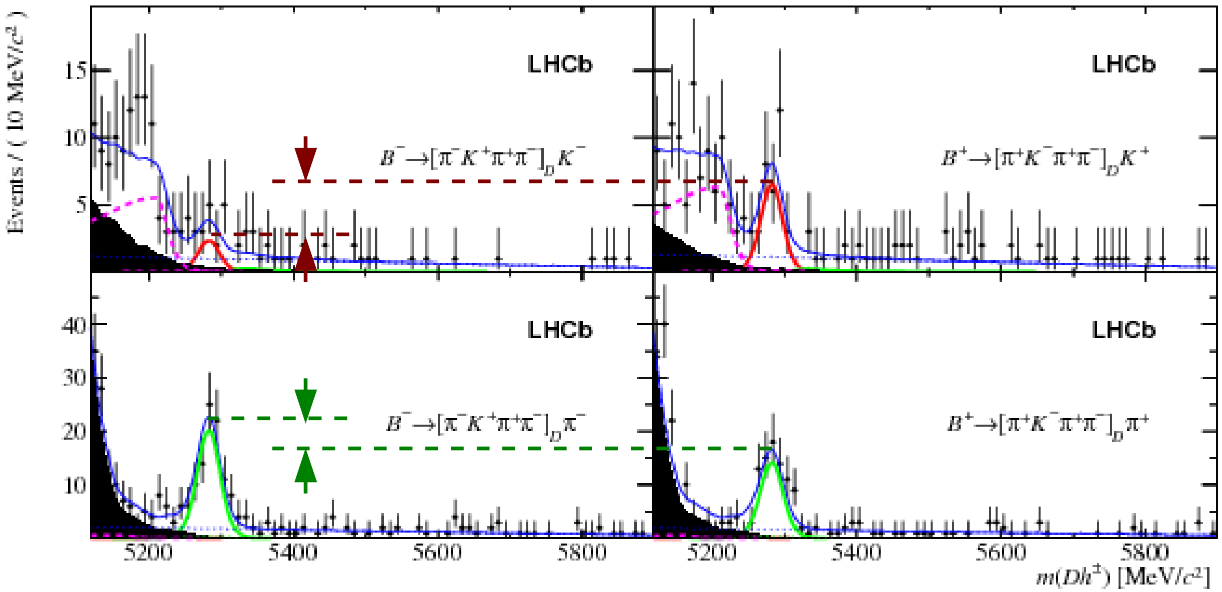
$\gamma = \left(70.8 \pm 7.8\right)^\circ$ [UTfit]

- theoretically "clean" determination from tree-level $B^\pm \to D\,K^\pm \to f_{[D]}\,K^\pm$ decays to final states $f_{[D]}$ accessible to D^0 and $\overline{D}^0$
- no loops → largely unaffected by possible effects from New Physics



CKM Angle γ from Tree Decays

- CP eigenstates $K^+K^-, \pi^+\pi^-$ ("GLW" [PLB 253 (1991) 483] [PLB 265 (1991) 172])
- quasi flavour-specific states $K^\pm\pi^\mp, K^\pm\pi^\mp\pi^\pm\pi^\mp$ ("ADS" [PRL 78 (1997) 3257] [PRD 63 (2001) 036005])
  - observables: ratios and asymmetries of B^+ and B^- decay rates



first observation of the suppressed ADS modes

$B^\pm \to [\pi^\pm K^\mp]_D h^\pm$

[PLB 713 (2012) 351]

$B^\pm \to [\pi^\pm K^\mp \pi^+ \pi^-]_D h^\pm$

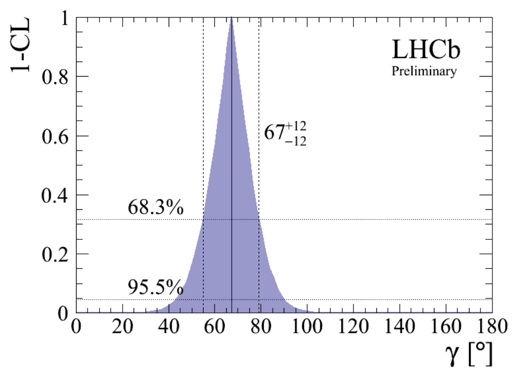
[PLB 723 (2013) 44]

- 3-body final states $K^0_s\pi^+\pi^-$, $K^0_sK^+K^-$ ("GGSZ" [PRD 68 (2003) 054018] [PRD 70 (2004) 072003])
  - compare interference patterns in Dalitz plots from B^+ and B^- decays

[PLB 718 (2012) 43] ← 1 fb^{-1} | 3 fb^{-1} → **[LHCb-CONF-2013-006]**

CKM Angle γ from Tree Decays

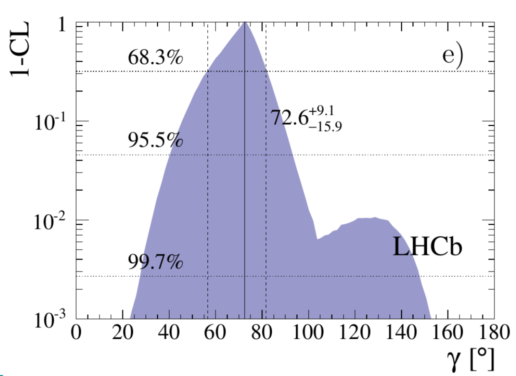
- preliminary γ measurement from combination of GLW/ADS and 3 fb^{-1} GGSZ
  - using input from CLEO-c to constrain strong phases in D decays



$$\gamma = 67 \pm 12\,°$$

[LHCb-CONF-2013-006]
PRELIMINARY

- published γ measurement using GLW/ADS and 1 fb^{-1} GGSZ result
  - includes also $B^{\pm} \to f_{[D]}\pi^{\pm}$ (less sensitivity due to smaller interference)
  - takes D^0-$\overline{D}^0$ mixing into account (small but not negligible in $B^{\pm} \to f_{[D]}\pi^{\pm}$)



$$\gamma = 72.6^{+9.1}_{-15.9}\,°$$

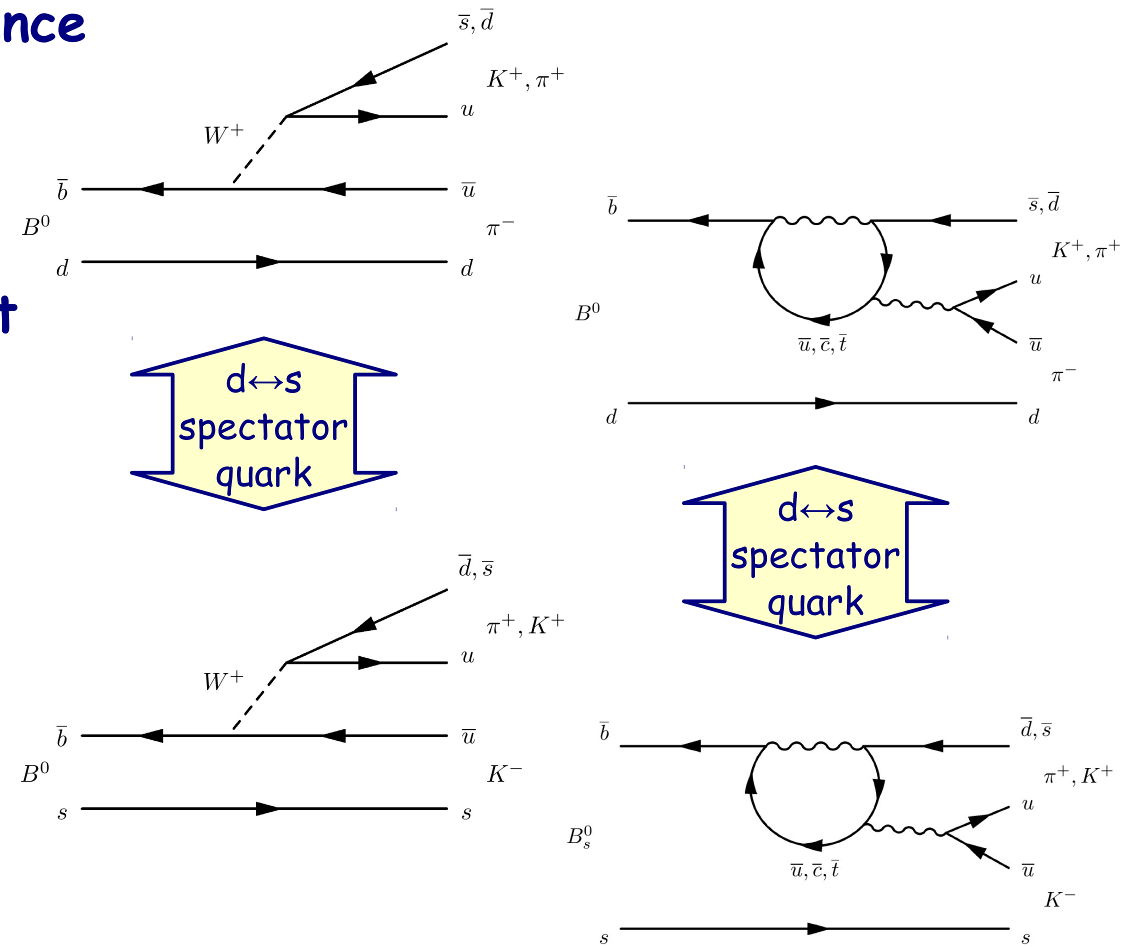
[arXiv:1305.2050]

- most precise γ measurements to date

CPV in 2-Body Charmless B decays

- direct CP violation from interference of b → u tree diagrams and b → s(d) penguin diagrams
- measures γ in Standard Model but sensitive to possible New Physics contribution in penguin loops
- exploit U-spin symmetry between B^0 and B^0_s decays to extract strong decay phases

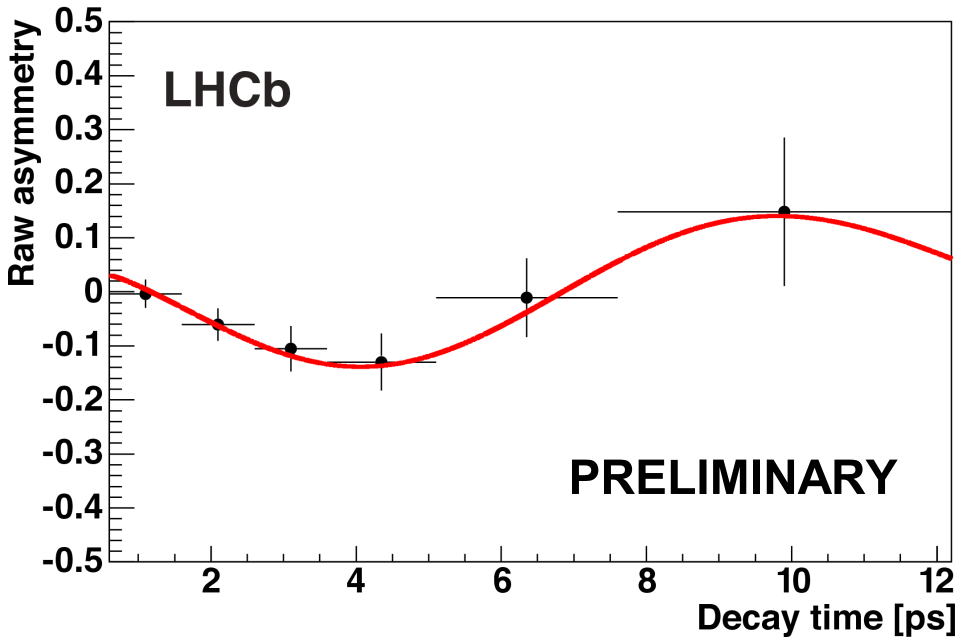
  [Fleischer, EPJC 52 (2007) 267]



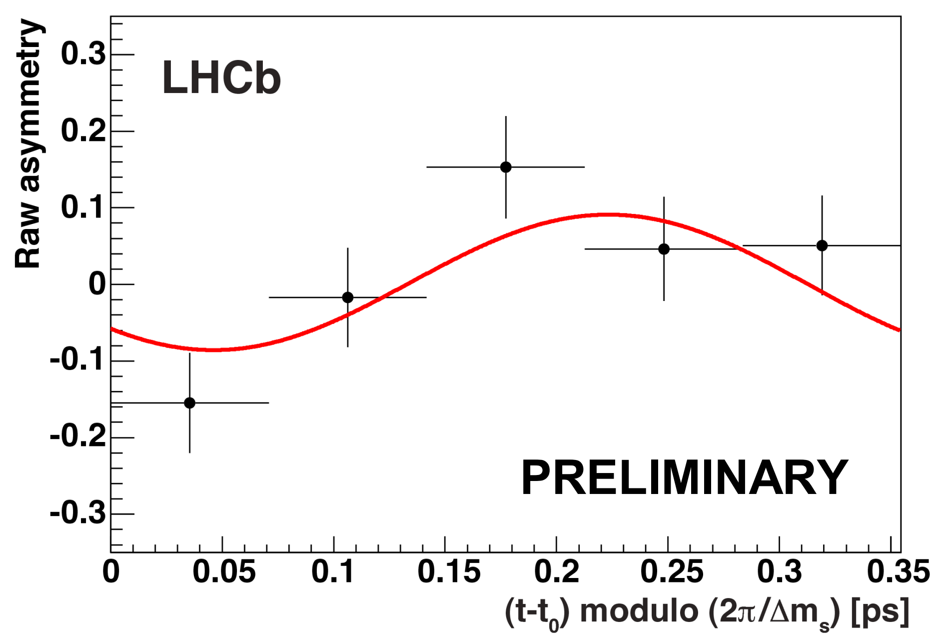
- two approaches:
  - time-dependent CP asymmetry in $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$
  - time-integrated CP asymmetry in $B^0 \to K^+\pi^-$ and $B^0_s \to \pi^+K^-$

CPV in 2-Body Charmless B decays

$B^0 \rightarrow \pi^+ \pi^-$



$B^0_s \rightarrow K^+ K^-$



$$C_{\pi\pi} = -0.38 \pm 0.15\,(\text{stat}) \pm 0.02\,(\text{syst})$$
$$S_{\pi\pi} = -0.71 \pm 0.13\,(\text{stat}) \pm 0.02\,(\text{syst})$$

$(C_{\pi\pi}, S_{\pi\pi}) \neq (0,0)$ at 5.6 σ

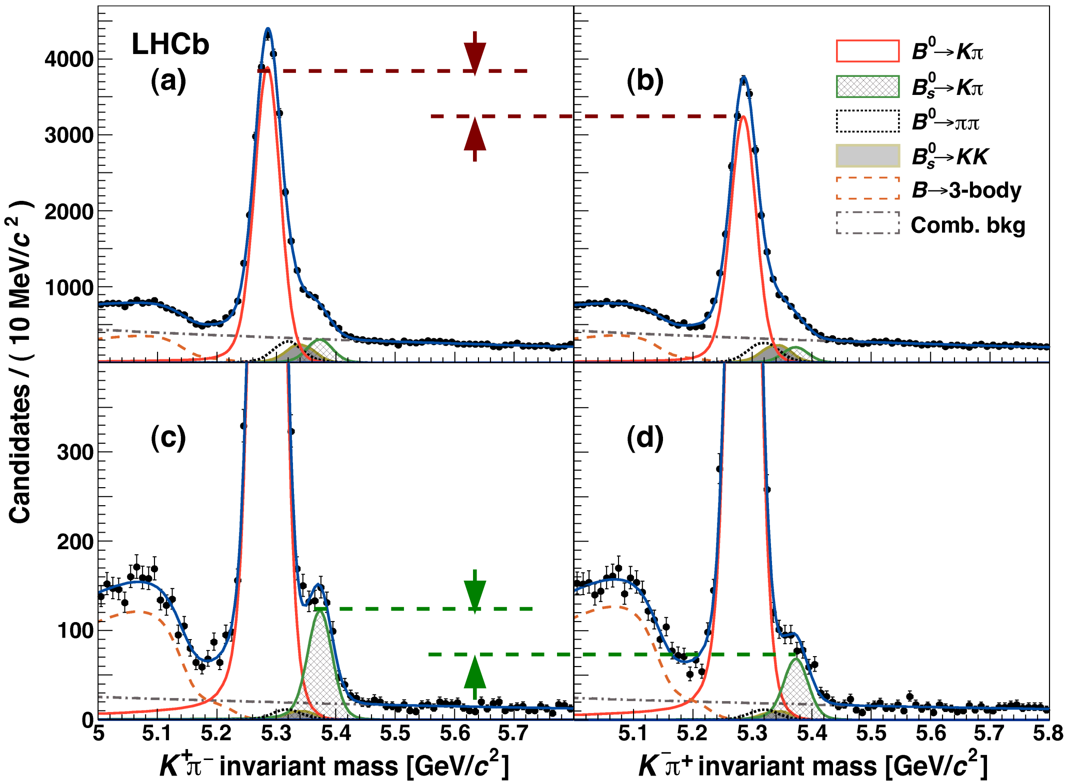
$$C_{KK} = 0.14 \pm 0.11\,(\text{stat}) \pm 0.03\,(\text{syst})$$
$$S_{KK} = 0.30 \pm 0.12\,(\text{stat}) \pm 0.04\,(\text{syst})$$

$(C_{KK}, S_{KK}) \neq (0,0)$ at 2.7 σ

[LHCb-PAPER 2013-040]

PRELIMINARY

CPV in 2-Body Charmless B decays



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

$$A_{CP} = -0.080 \pm 0.007\,(\text{stat}) \pm 0.003\,(\text{syst})$$

- most precise measurement to date

$B^0_s \to K^- \pi^+$

$$A_{CP} = 0.27 \pm 0.04\,(\text{stat}) \pm 0.01\,(\text{syst})$$

- first observation of CPV in B^0_s decays, significance $6.5\,\sigma$

[PRL 110 (2013) 221601]

- also: test of U-spin symmetry

$$\Delta = \frac{A_{CP}\left(B^0 \to K^+\pi^-\right)}{A_{CP}\left(B^0_s \to K^-\pi^+\right)} + \frac{BF\left(B^0_s \to K^-\pi^+\right)}{BF\left(B^0 \to K^+\pi^-\right)} \cdot \frac{\tau_d}{\tau_s} = 0$$

[Lipkin, PLB 621 (2005) 126]

- using LHCb measurements of BFs and world averages for lifetimes τ:

$$\Delta = -0.02 \pm 0.05\,(\text{stat}) \pm 0.04\,(\text{syst})$$


Rare Decays

Flavour Changing Neutral Currents

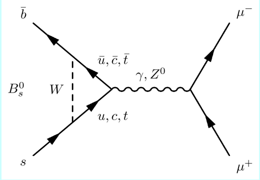
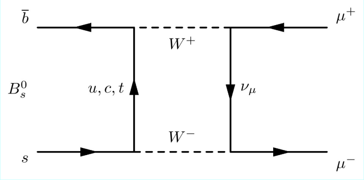
- $b \to s(d)$ transitions can only proceed through loops in Standard Model
- ideal hunting ground for possible contributions from New Physics

- Operator Product Expansion: describe decay by an effective Hamiltonian

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} \cdot V_{tb} V_{ts}^* \cdot \frac{e^2}{16\pi^2} \cdot \sum \left(C_i O_i + C_i' O_i' \right) + h.c.$$

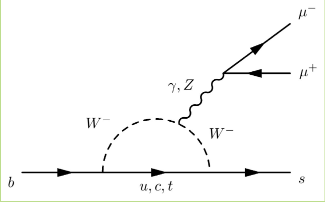
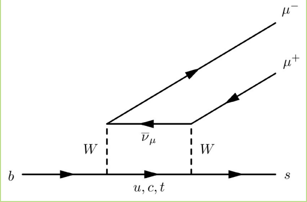
- New Physics can add new operators $O_i^{(\prime)}$ or change Wilson coefficients $C_i^{(\prime)}$

$B^0_{(s)} \to \mu^+ \mu^-$
branching fraction

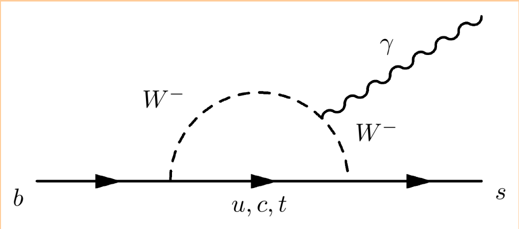
O_{10}

$b \to s \mu^+ \mu^-$
angular distributions

O_7, O_9, O_{10}

$b \to s \gamma$
photon polarization



O_7

Flavour Changing Neutral Currents

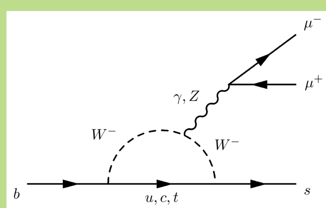
- $b \rightarrow s(d)$ transitions can only proceed through loops in Standard Model
- ideal hunting ground for possible contributions from New Physics
- Operator Product Expansion: describe decay by an effective Hamiltonian

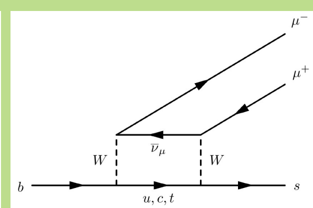
$$H_{eff} = -\frac{4G_F}{\sqrt{2}} \cdot V_{tb} V_{ts}^* \cdot \frac{e^2}{16\pi^2} \cdot \sum \left(C_i O_i + C_i' O_i' \right) + h.c.$$

- New Physics can add new operators $O_i^{(\prime)}$ or change Wilson coefficients $C_i^{(\prime)}$

Alexander's presentation in 5 minutes

$b \rightarrow s \mu^+ \mu^-$
angular distributions





O_7, O_9, O_{10}

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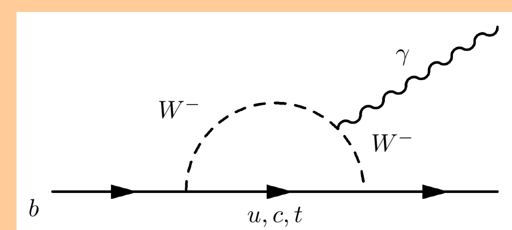


O_7

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

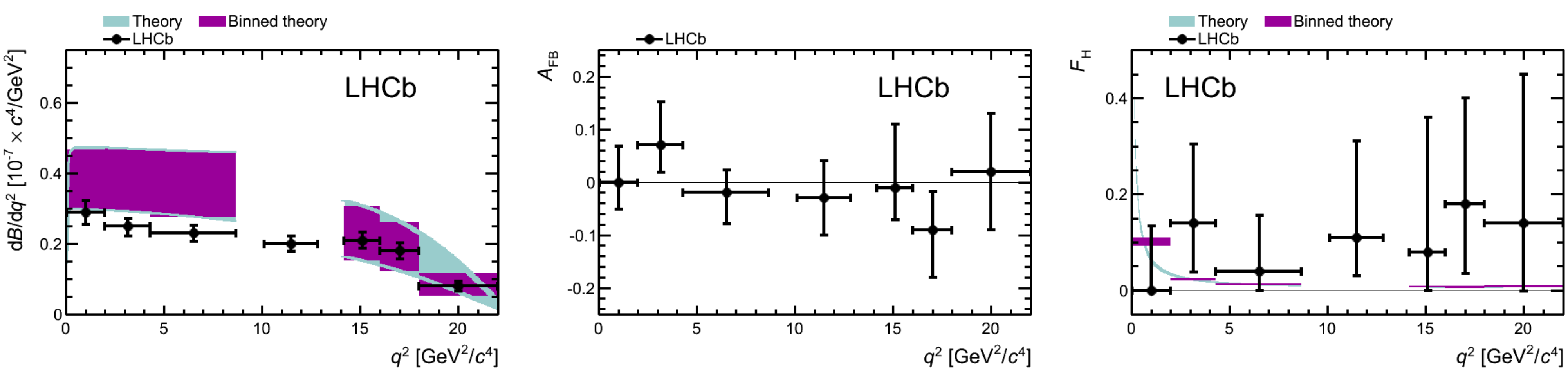
- decay fully described by $q^2 = m^2(\mu^+ \mu^-)$ and angle θ_l between μ^+ and K^+

$$\frac{1}{\Gamma}\frac{d^2\Gamma}{d\cos\theta_l \, dq^2} = \frac{3}{4}\left(1 - F_H\right)\cdot\left(1-\cos^2\theta_l\right) + \frac{1}{2}F_H + A_{FB}\cdot\cos\theta_l$$

- measure $d\Gamma/dq^2$, A_{FB} and F_H as a function of q^2
- exclude regions around J/ψ and $\psi(2s)$ resonances

serve as excellent calibration samples

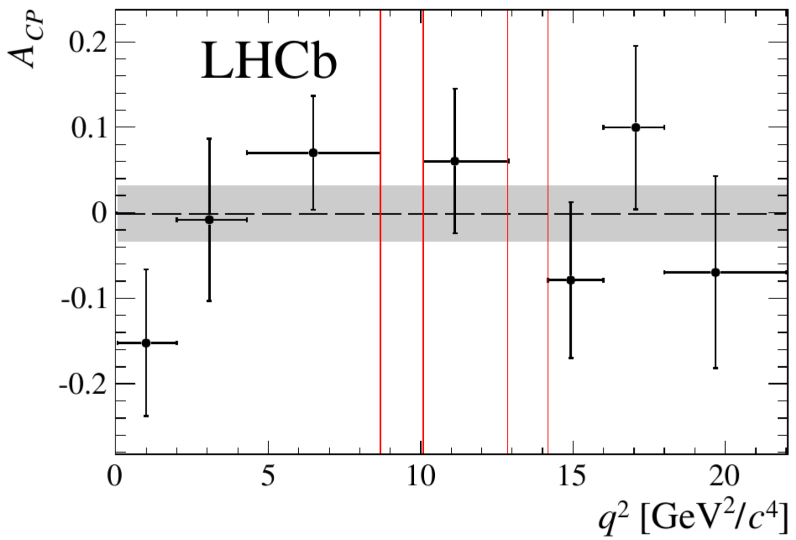
- results in good agreement with Standard Model predictions



[JHEP 02 (2013) 105]

[Bobeth et al., JHEP 01 (2012) 107]
[Bobeth et al., JHEP 07 (2011) 067]

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

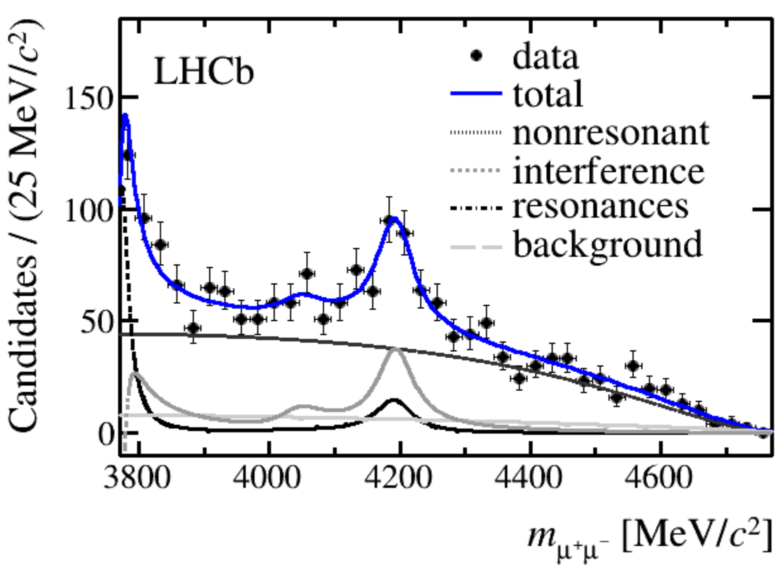


Measurement of the CP asymmetry

$$A_{CP} = 0.000 \pm 0.033(\text{stat}) \pm 0.005(\text{syst}) \pm 0.07(J/\psi\ K^{\pm})$$

- in agreement with SM prediction
- factor four improvement of current WA

[arxiv:1308:1340]



Observation of a $\mu^+ \mu^-$ resonance

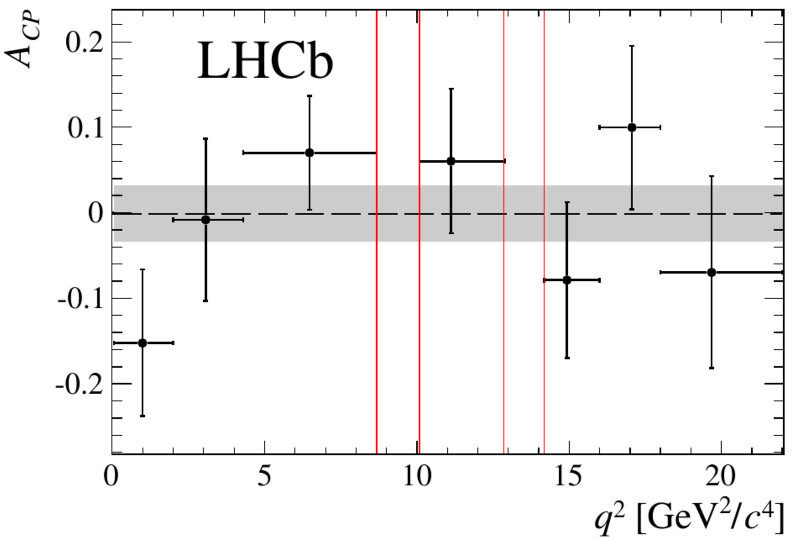
$$\text{mass} = 4191^{+9}_{-8}\ \text{MeV}/c^2\ \ ;\ \ \text{width} = 65^{+22}_{-16}\ \text{MeV}/c^2$$

- compatible with known $\psi(4160)$
- 20 % of $K^{\pm} \mu^+ \mu^-$ signal at low recoil

[arxiv:1307:7595]

- could effect angular distributions around $q^2 \sim 16$ GeV^2

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



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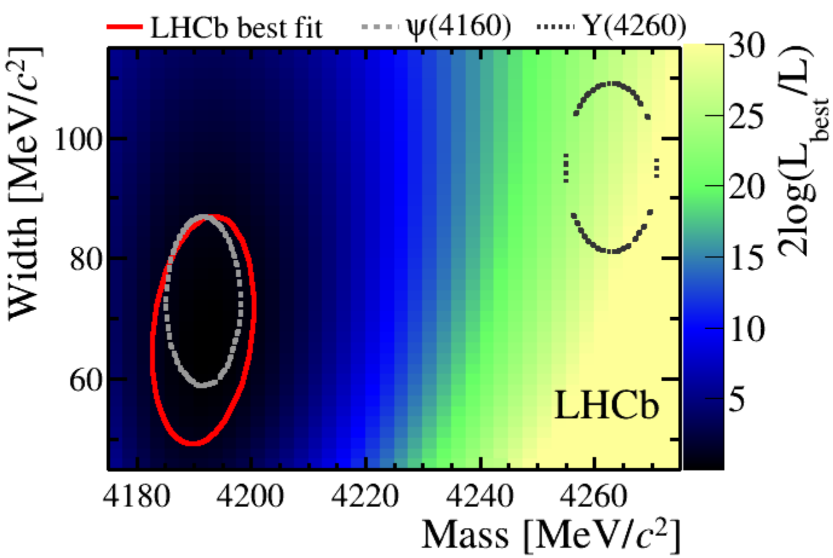

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[arxiv:1307:7595]

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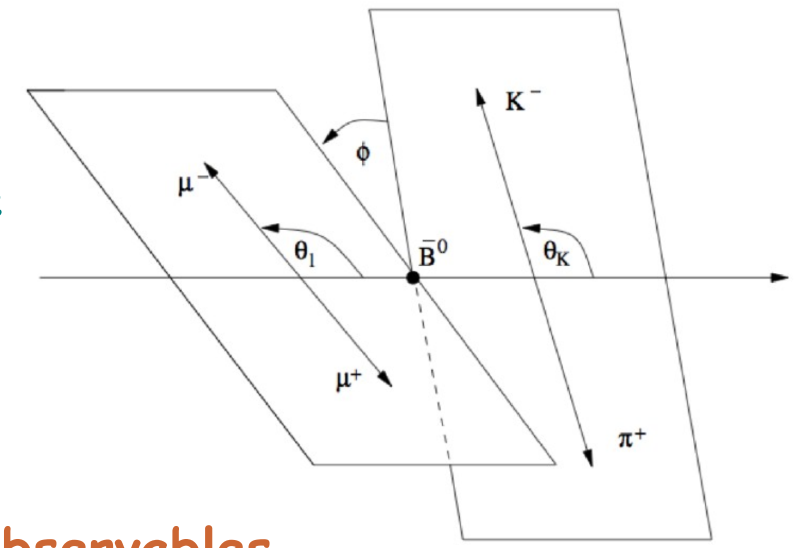
Angular Observables in $B^0 \to K^{*0} \mu^+ \mu^-$

- four final state particles → three angles, eight angular observables

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

- $F_L(q^2)$ and $S_j(q^2)$ are functions of the underlying Wilson coefficients
- clever combinations of F_L and S_j less sensitive to uncertainties from hadronic form factors

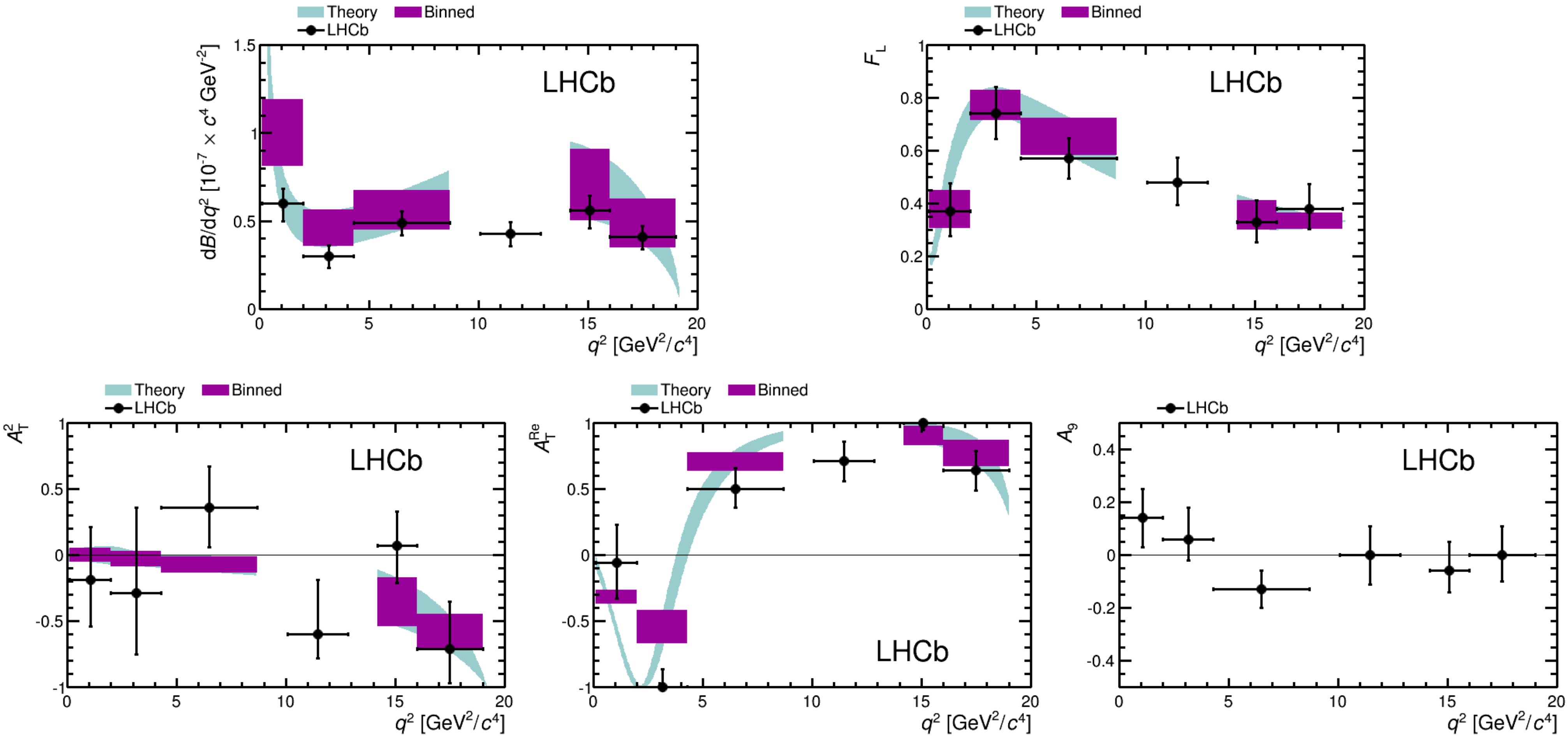


- "folding technique": exploit symmetries of sin and cos functions to extract subsets of the observables

  e.g. substitute $\phi \to \phi + \pi$ for $\phi < 0$ ⇒ terms for S_4, S_5, S_7, S_8 cancel

Angular Observables in $B^0 \to K^{*0} \mu^+ \mu^-$

- results in good agreement with Standard Model predictions

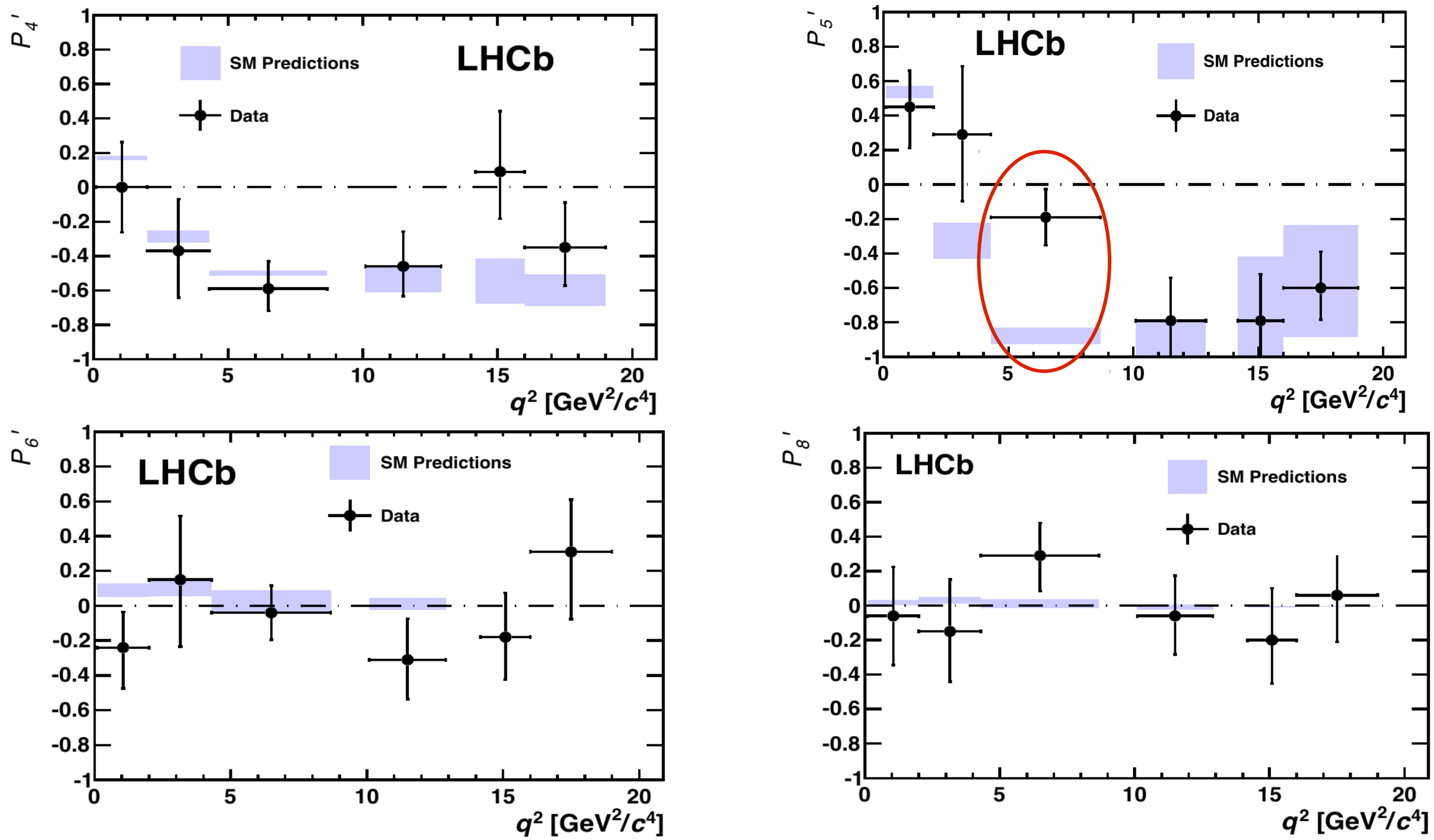


[arxiv:1304:6325]

[Bobeth et al., JHEP 07 (2011) 067]

Angular Observables in $B^0 \to K^{*0} \mu^+ \mu^-$

- different angular foldings → extract remaining four observables
- observe 3.7 σ discrepancy in one bin of the observable P_5'
  - probability for such a deviation in one out of 24 analysed bins is 0.5 %

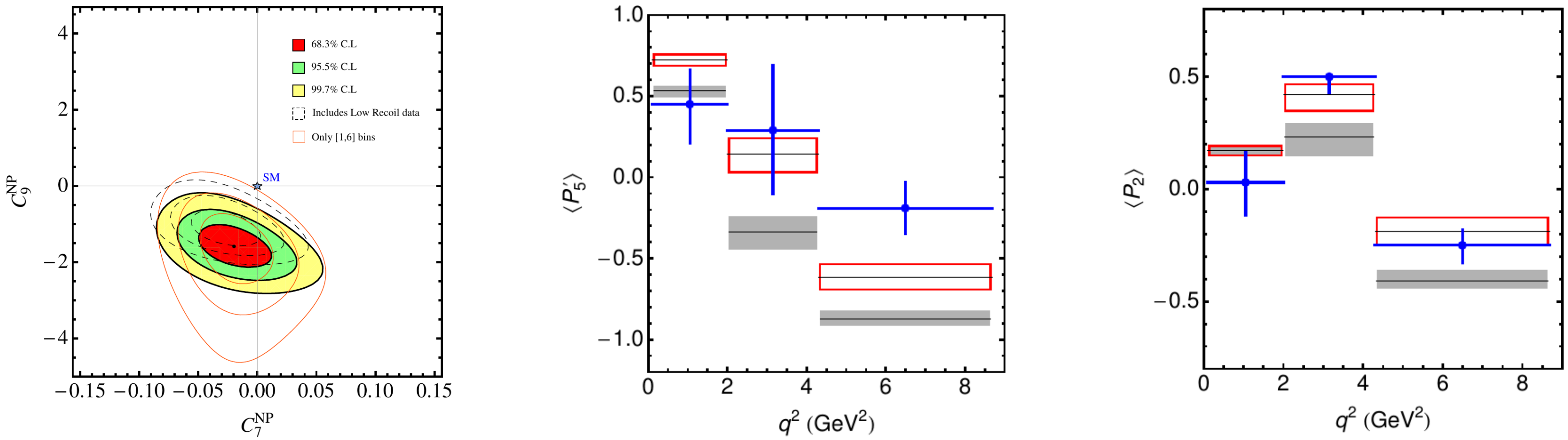


[arxiv:1308:1707]

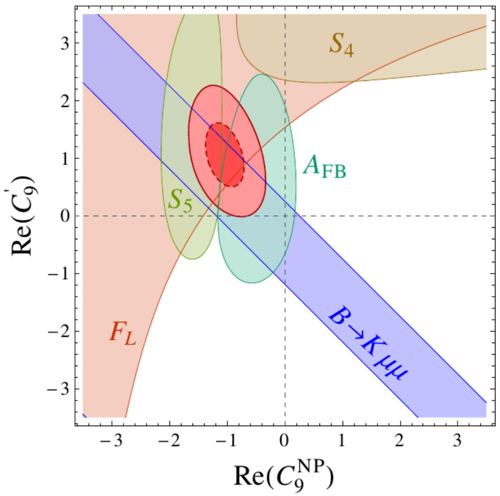
[Descotes-Genon et al, JHEP 05 (2013) 137]

Angular Observables in $B^0 \to K^{*0} \mu^+ \mu^-$

- Descotes-Genon et al. interpret discrepancy as possible sign for New Physics contribution in Wilson coefficient C_9 [arxiv:1307.5683]
- gives slight improvement also in other observables (e.g. $P_2 = -\frac{1}{2}A_T^{Re}$)



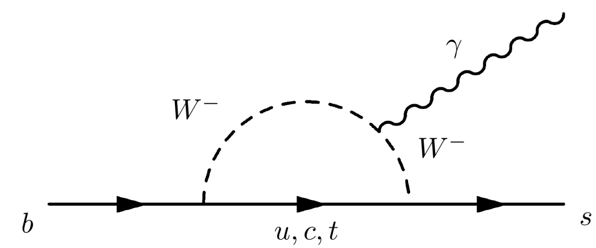
- Altmannshofer et al. combine LHCb results with other experiments [arxiv:1308.1501]
- best fit indicates New Physics contribution in Wilson coefficients C_9 and C_9' or C_{10}'



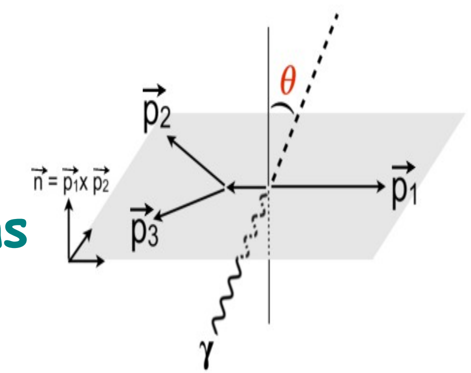
- looking forward to interesting discussions with theory community and to results from 2012 data

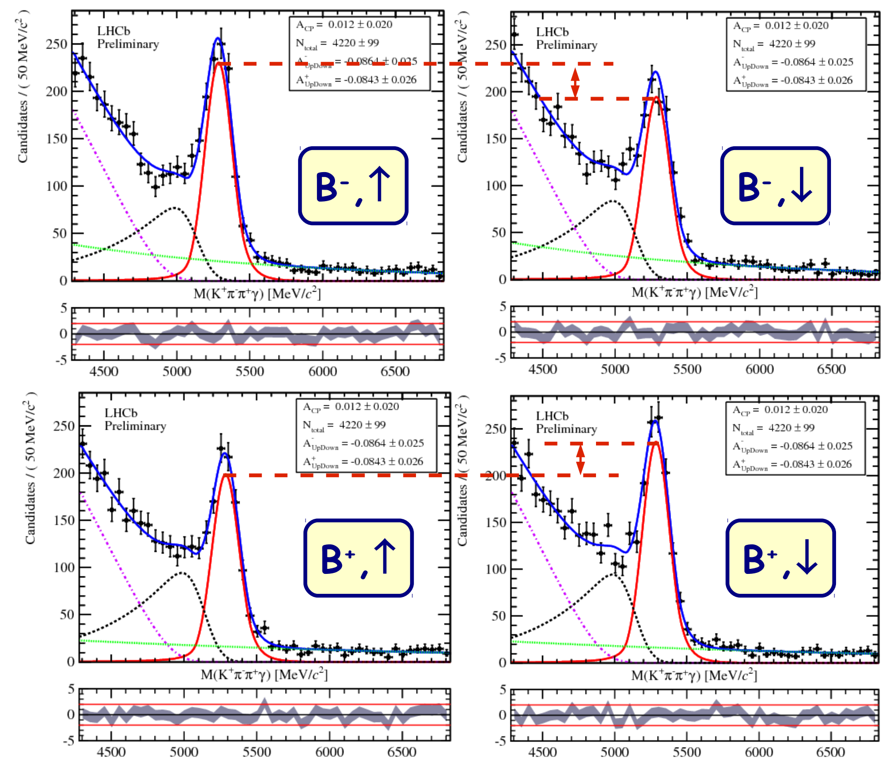
Radiative Decays $b \to s\gamma$

- another type of loop-mediated FCNC decays sensitive to New Physics
- in Standard Model, expect emitted photon to be close to 100 % left-handed polarized
- significant right-handed component possible in popular New Physics models



- photon polarization can in principle be extracted from angular distributions in $B^{\pm} \to K_{res}\,\gamma \to K^{\pm}\,\pi^{+}\,\pi^{-}\,\gamma$





- first measurement of up/down asymmetry "Wu's experiment with photons"
- using 2012 data set (2 fb^{-1})
- 4.6 σ evidence for non-zero polarization
- CP asymmetry consistent with zero

[LHCb-CONF-2013-009] PRELIMINARY


Conclusion and Outlook:
LHCb Upgrade

Outlook: LHCb Upgrade

- LHC and LHCb are a spectacular success
- so is the Standard Model … still
- current precision of measurements in flavour sector still leaves room for sub-dominant contributions from New Physics
- almost all LHCb results are completely dominated by statistical uncertainties
- leading systematic uncertainties will also decrease with increasing statistics

WANT MORE STATISTICS
⇒
THE LHCb UPGRADE !

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

[☆ all results except three presented just now used 2011 data set of 1.0 fb^{-1}]

- goal: reach measurement precision that matches theory uncertainties

[CERN-LHCC-2012-007]

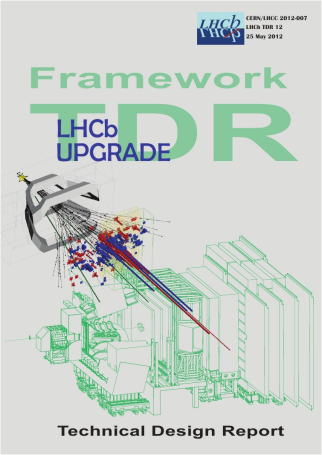
Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\rm fs}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [18]	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 penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [19, 20]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [18]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

LHCb Upgrade

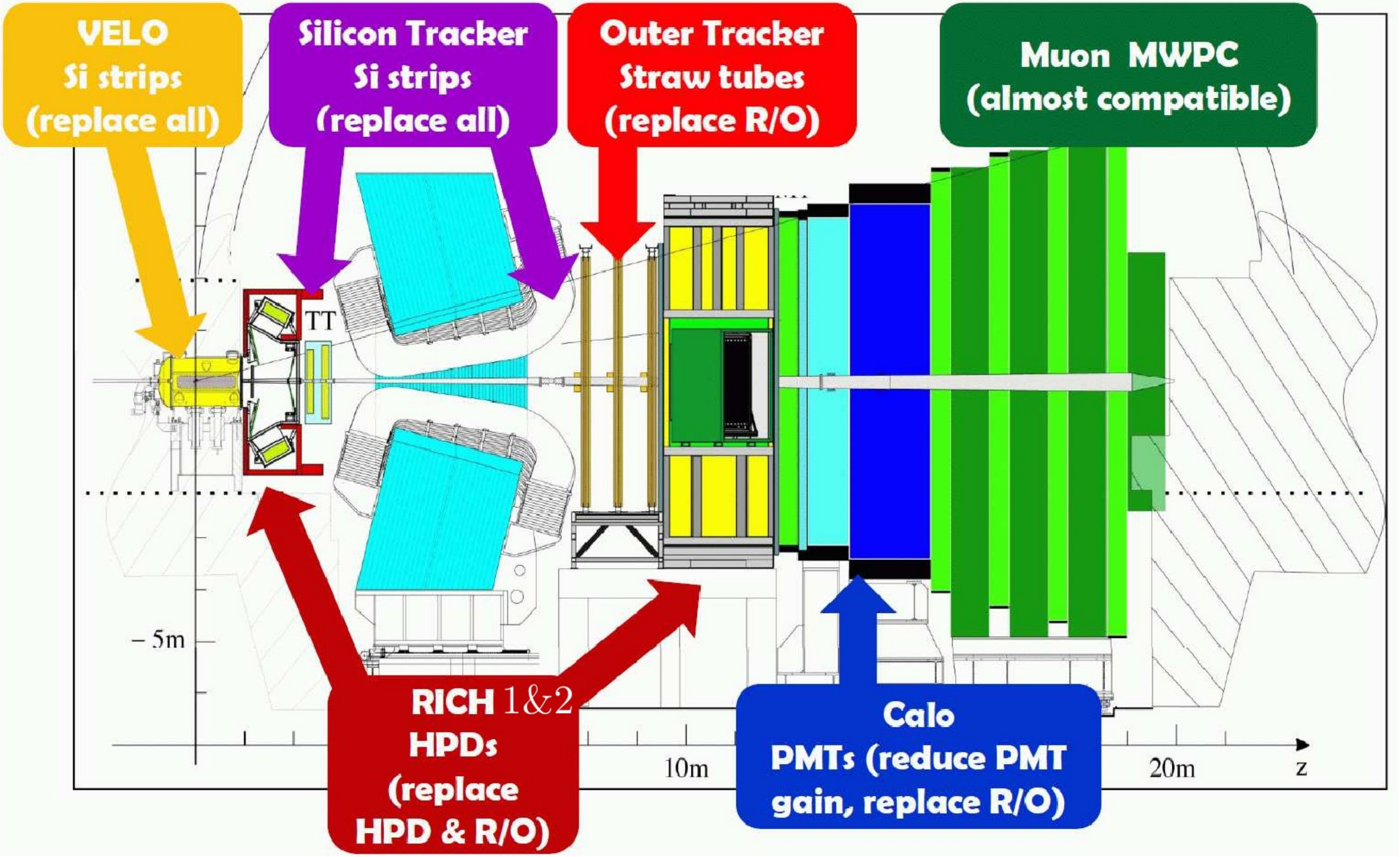
- two lines of attack
  - increase trigger efficiencies for hadronic final states
    - read out the full detector at the LHC bunch-crossing frequency
  - operate the detector at up to x 5 higher luminosity
    - new main tracker to cope with increase in particle densities

expected increase in yearly rate (compared to 2011):
x 10 for channels involving final-state muons
x 20 for channels to fully hadronic final states

- details are described in
  - Letter of Intent [CERN-LHCC-2011-001]
  - Framework TDR [CERN-LHCC-2012-007]
- endorsed by the LHCC



LHCb Upgrade



- **2013:** technology choices, preparation of sub-system TDRs
- **2014:** funding, procurements
- **2015-2019:** construction and installation

- CP violating phases and rare FCNC decays provide a sensitive probe for New Physics – up to higher mass scales than direct searches

- LHC and LHCb are a spectacular success
  - number of submitted papers approaching 150 – already 59 in 2013

- results are in excellent agreement with Standard Model predictions
  - severe constraints on New Physics models

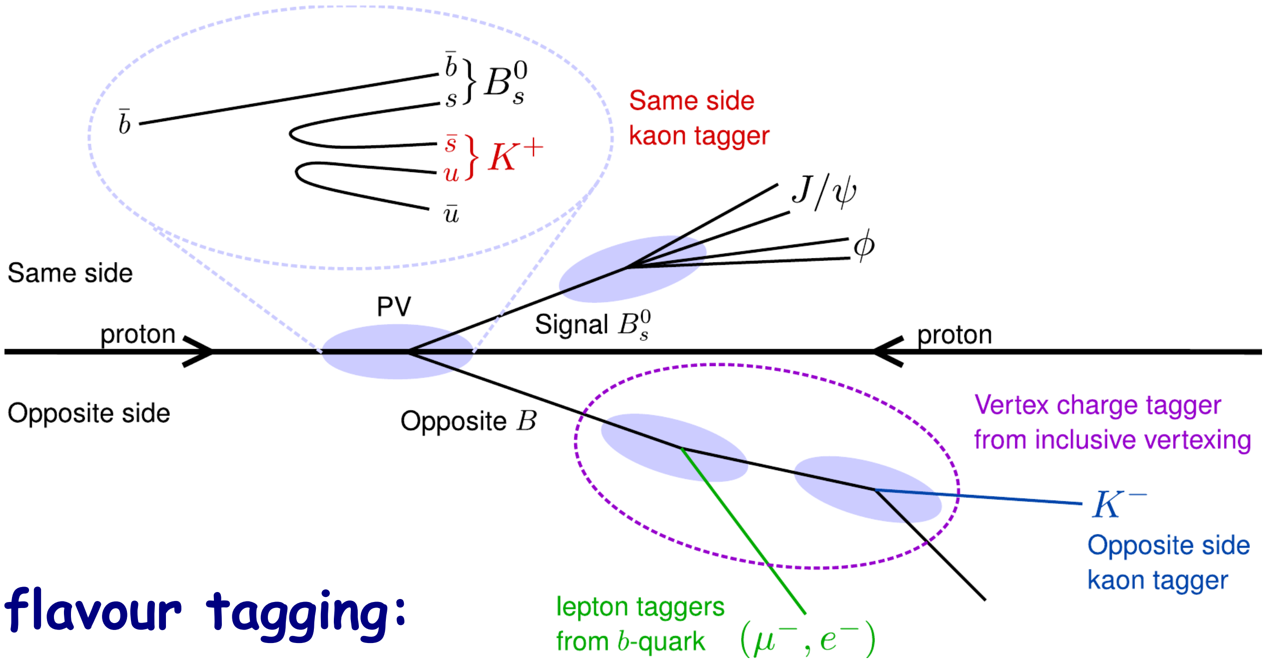
- … except for an intriguing deviation in angular distribution of $B^0 \to K^{*0} \mu^+ \mu^-$
  - looking forward to stimulating discussions with theorists and to results from analysis of 2012 data

- LHCb upgrade is on its way for 2018/19
  - factor 20 compared to 2011 in rate for hadronic final states

Stay tuned … exciting times are ahead.

Backup

Flavour Tagging



- **opposite-side flavour tagging:**
  imply B^0_s flavour at production
  from decay properties of the associated b hadron produced
  - **neural net algorithm using charge of lepton, kaon, inclusive vertex**
- **calibrated on flavour-specific decays such as $B^\pm \to J/\psi\, K^\pm$**
- **effective tagging power:**

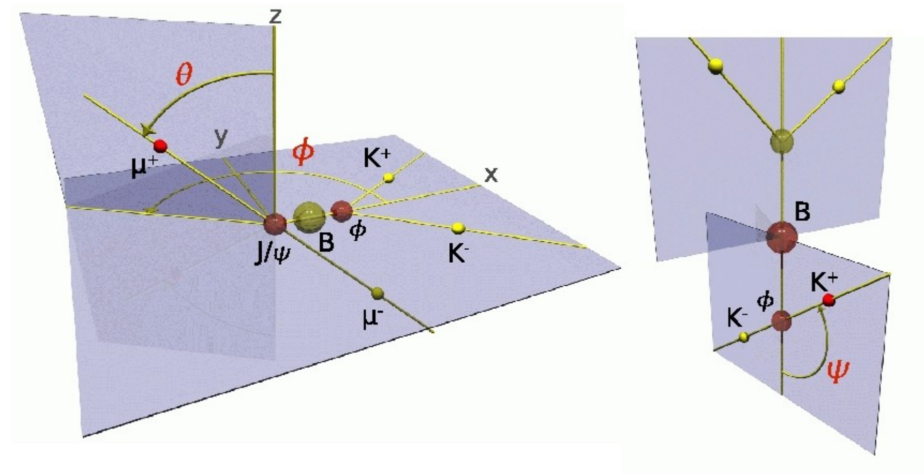
$$\varepsilon_{tag} \times (1 - 2\,\overline{\omega}_{tag})^2 = (2.35 \pm 0.06(stat))\ \%$$

[LHCb-CONF-2012-026]
preliminary

Angular Analysis in $B^0_s \to J/\psi\,\phi$

- **time-dependent angular fit using transversity angles**

  $\Omega = (\theta=\theta_\mu,\ \phi=\phi_\mu,\ \psi=\theta_K)$



- **full fit function:**

$$\frac{d^4\Gamma(B^0_s \to J/\psi\,\phi)}{dt\,d\Omega} \propto \sum_{k=1}^{10} h_k(t)\,f_k(\Omega)$$

$$h_k(t) = N_k e^{-Gt}\left[a_k \cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)\right]$$

k	$f_k(\theta_\mu,\theta_K,\phi_h)$	N_k	a_k	b_k	c_k	d_k
1	$2\cos^2\theta_K \sin^2\theta_\mu$	$\lvert A_0(0)\rvert^2$	1	D	C	$-S$
2	$\sin^2\theta_K\left(1-\sin^2\theta_\mu\cos^2\phi_h\right)$	$\lvert A_\parallel(0)\rvert^2$	1	D	C	$-S$
3	$\sin^2\theta_K\left(1-\sin^2\theta_\mu\sin^2\phi_h\right)$	$\lvert A_\perp(0)\rvert^2$	1	$-D$	C	S
4	$\sin^2\theta_K \sin^2\theta_\mu \sin 2\phi_h$	$\lvert A_\parallel(0)A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{2}\sqrt{2}\sin 2\theta_K \sin 2\theta_\mu \cos\phi_h$	$\lvert A_0(0)A_\parallel(0)\rvert$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$-\frac{1}{2}\sqrt{2}\sin 2\theta_K \sin 2\theta_\mu \sin\phi_h$	$\lvert A_0(0)A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}\sin^2\theta_\mu$	$\lvert A_s(0)\rvert^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\theta_K \sin 2\theta_\mu \cos\phi_h$	$\lvert A_s(0)A_\parallel(0)\rvert$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$-\frac{1}{3}\sqrt{6}\sin\theta_K \sin 2\theta_\mu \sin\phi_h$	$\lvert A_s(0)A_\perp(0)\rvert$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\theta_K \sin^2\theta_\mu$	$\lvert A_s(0)A_0(0)\rvert$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

- **physics parameters:**

  $S \approx \boxed{-\sin\phi_s}\ ;\ D \approx \boxed{-\cos\phi_s}\ ;\ \Delta m_s\ ;\ \Delta\Gamma_s\ ;\ |A_\perp|\ ;\ |A_\parallel|\ ;\ |A_0|\ ;\ \delta_\perp\ ;\ \delta_\parallel\ ;\ \delta_0$

- **two-fold ambiguity in solution: fit function invariant under transformation**

  $(\phi_s, \Delta\Gamma_s, \delta_\parallel, \delta_\perp) \leftrightarrow (\pi-\phi_s, -\Delta\Gamma_s, 2\pi-\delta_\parallel, -\delta_\perp)$

Sign of $\Delta\Gamma_s$

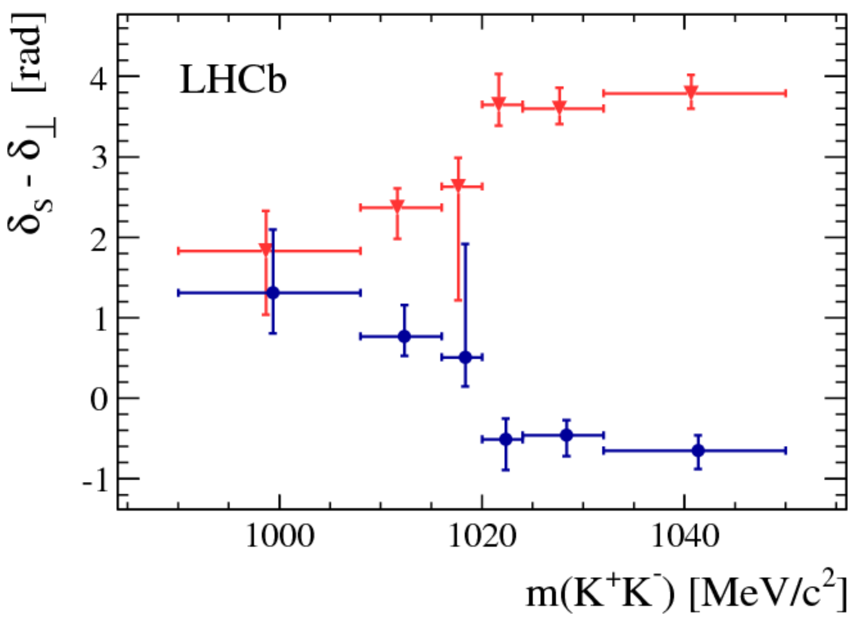
- two-fold ambiguity of fit function

$$(\phi_s, \Delta\Gamma_s, \delta_\parallel, \delta_\perp) \leftrightarrow (\pi-\phi_s, -\Delta\Gamma_s, 2\pi-\delta_\parallel, -\delta_\perp)$$

("solution I") ("solution II")

- resolve this by looking at the strong phase difference $\delta_{s\perp} = \delta_s - \delta_\perp$ between K^+K^- P-wave and S-wave amplitudes as a function of $m(K^+K^-)$ around the $\phi(1020)$
- method explained in [PRL 108 (2012) 241801]
  - P-wave: going through $\phi(1020)$ resonance → expect rapid positive phase shift
  - S-wave: non-resonant + tail from $f_0(980)$ → expect no significant variation of phase
- determine $\delta_{s\perp}$ in six K^+K^- mass bins

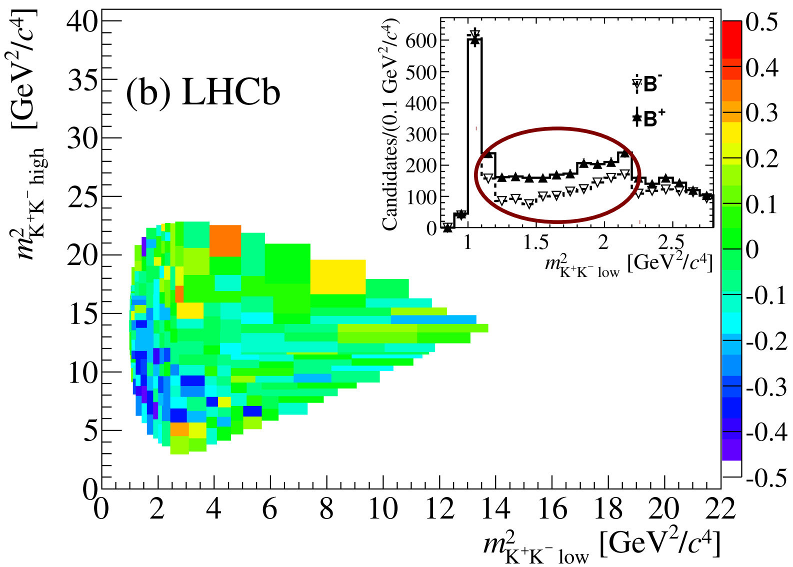
solution corresponding to $\Delta\Gamma_s > 0$ (blue points) matches expectation



[PRD 87 (2013) 112010]

CPV in 3-Body Charmless B decays

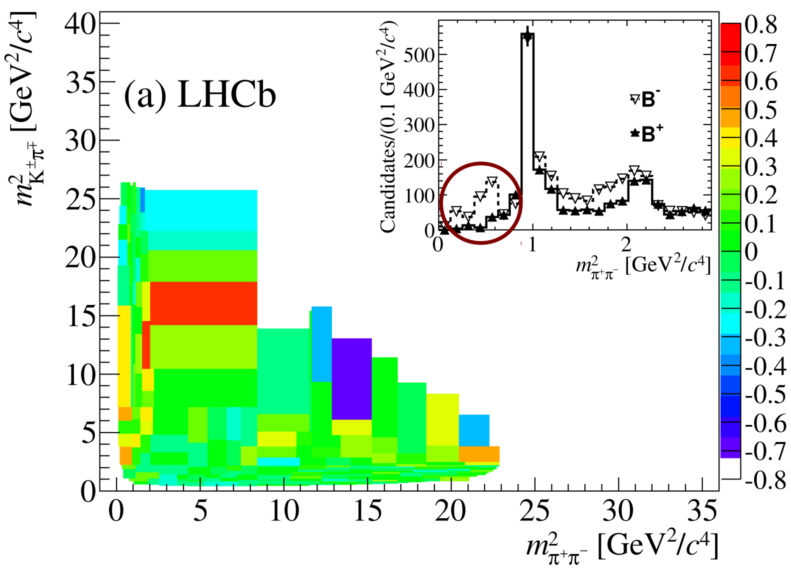
- study time-integrated CP asymmetry in bins of the Dalitz plot



$B^{\pm} \rightarrow K^{\pm} K^{+} K^{-}$

- large local asymmetry, not aligned with a resonance
- integrated over Dalitz plot:

$$A_{CP} = -0.043 \pm 0.009(\text{stat}) \pm 0.003(\text{syst}) \pm 0.07(J/\psi\, K^{\pm})$$



$B^{\pm} \rightarrow K^{\pm} \pi^{+} \pi^{-}$

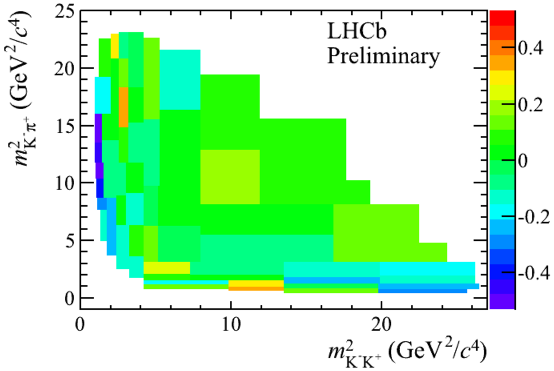
- large local asymmetry at ρ^0 resonance
- integrated over Dalitz plot:

$$A_{CP} = 0.032 \pm 0.008(\text{stat}) \pm 0.004(\text{syst}) \pm 0.07(J/\psi\, K^{\pm})$$

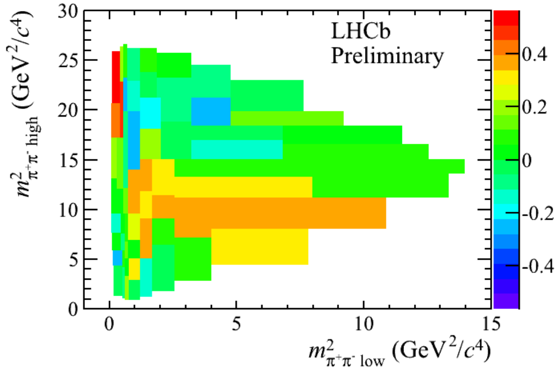
[arxiv:1306:1246]

Other 3-Body Charmless B decays

$B^{\pm} \to \pi^{\pm} K^{+} K^{-}$



$B^{\pm} \to \pi^{\pm} \pi^{+} \pi^{-}$

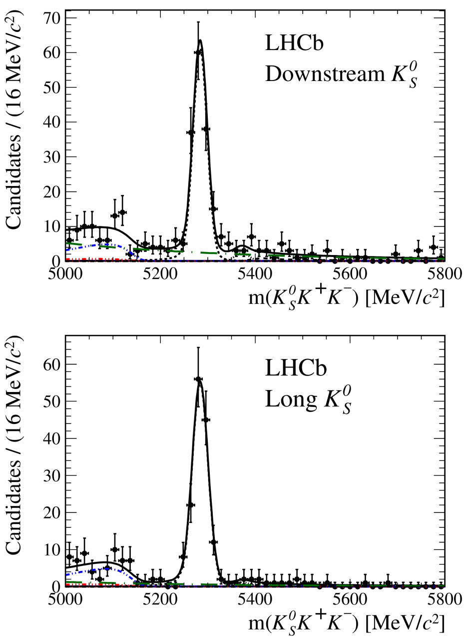


- large local asymmetries, not aligned with resonances

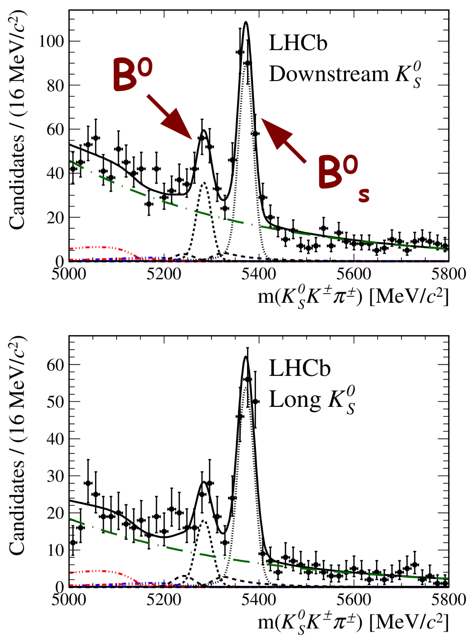
[LHCb-CONF-2012-028]

PRELIMINARY

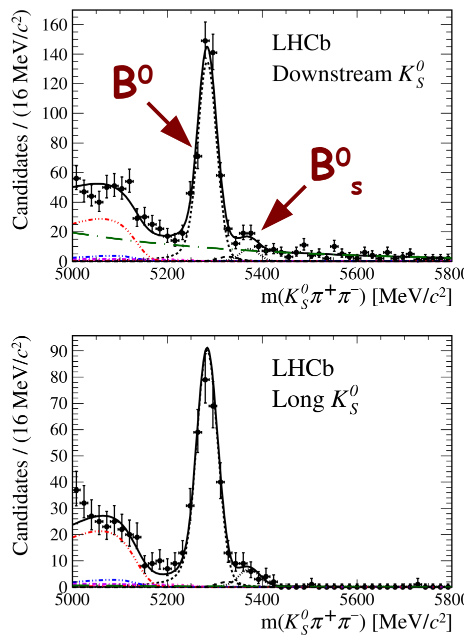
$B^0_{(s)} \to K^0_S K^{+} K^{-}$



$B^0_{(s)} \to K^0_S K^{\pm} \pi^{\mp}$



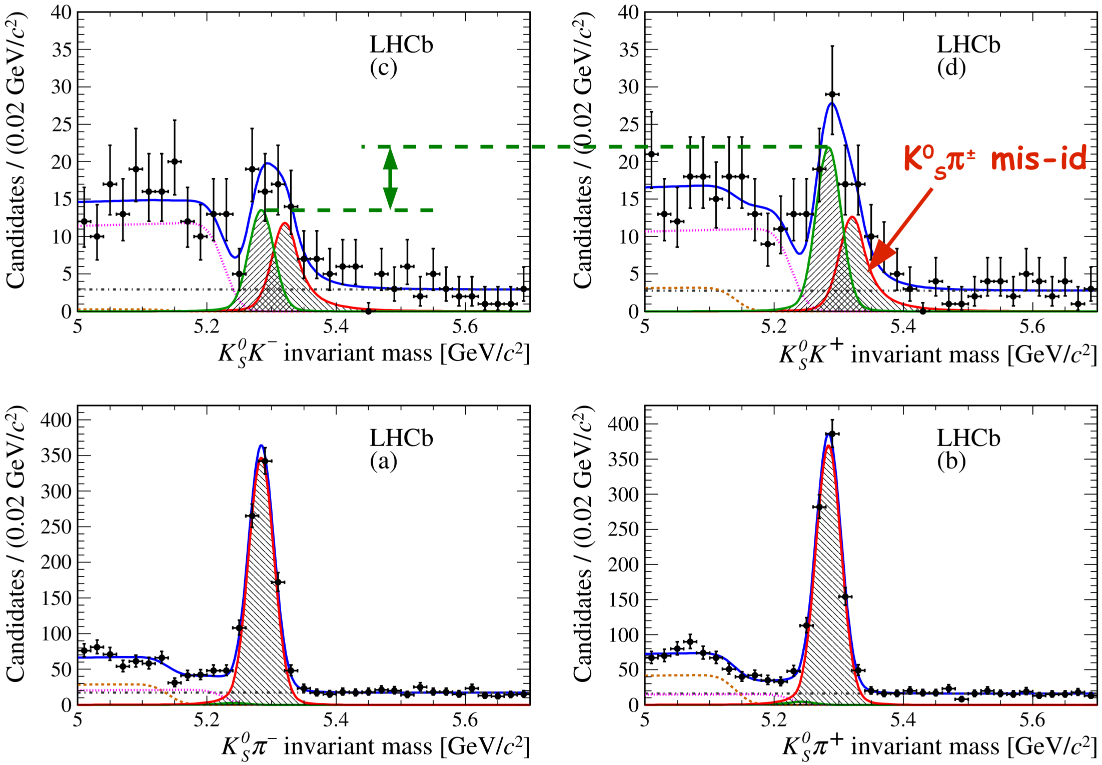
$B^0_{(s)} \to K^0_S \pi^{+} \pi^{-}$



- first observations of $B^0_s \to K^0_S K^{\pm} \pi^{\mp}$ and of $B^0_s \to K^0_S \pi^{+} \pi^{-}$ (5.9 σ)

[arxiv:1307:7648]

Other 2-Body Charmless B decays



$B^\pm \to K^0{}_S K^\pm$

$$A_{CP} = -0.21 \pm 0.14\,(\text{stat}) \pm 0.01\,(\text{syst})$$

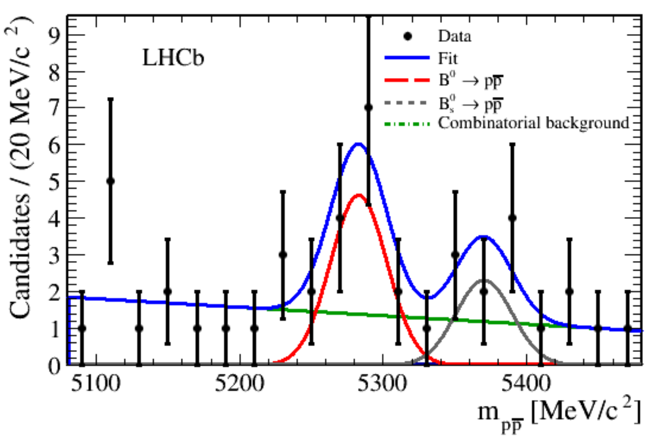
- best single measurement to date

$B^\pm \to K^0{}_S \pi^\pm$

$$A_{CP} = -0.022 \pm 0.025\,(\text{stat}) \pm 0.010\,(\text{syst})$$

[arxiv:1308:1277]

(using the full 3 fb^{-1})

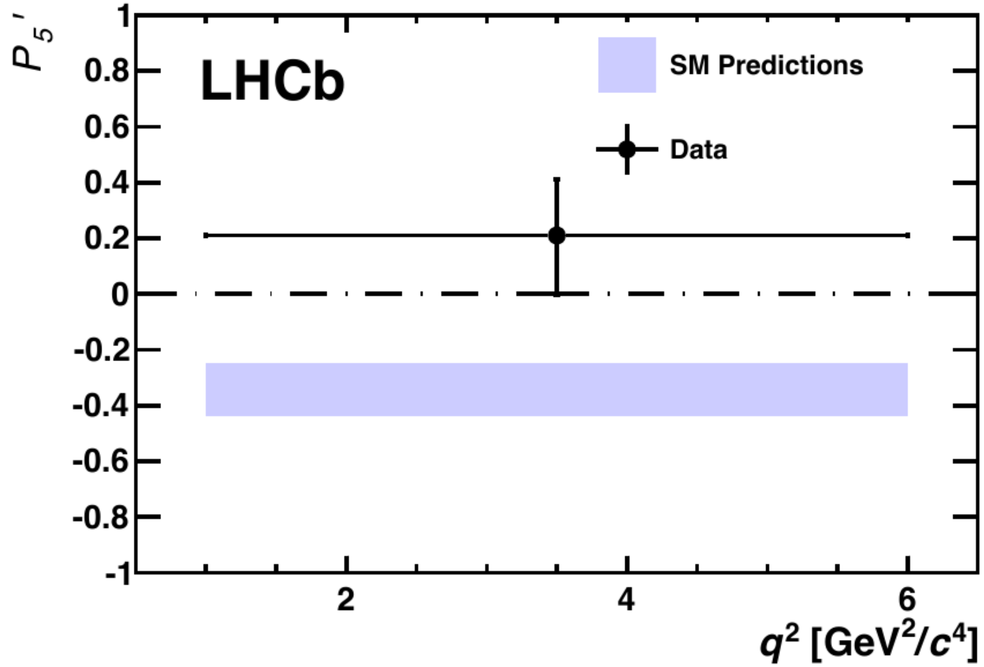


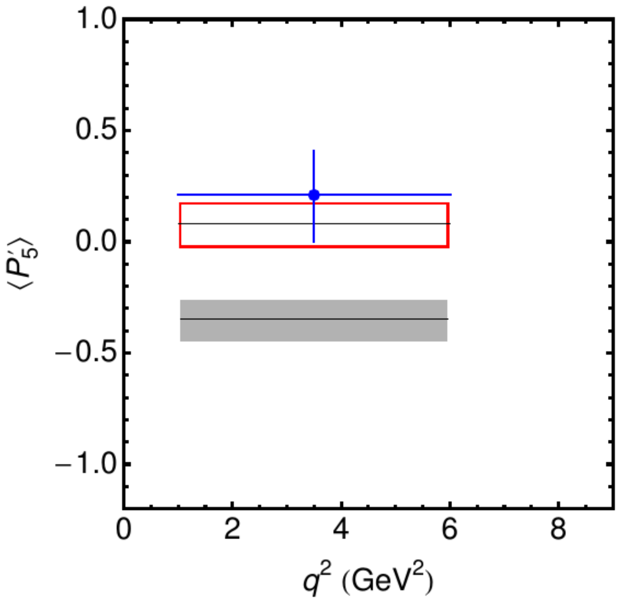
$B^0 \to p\,\bar{p}$: first evidence (3.3 σ)

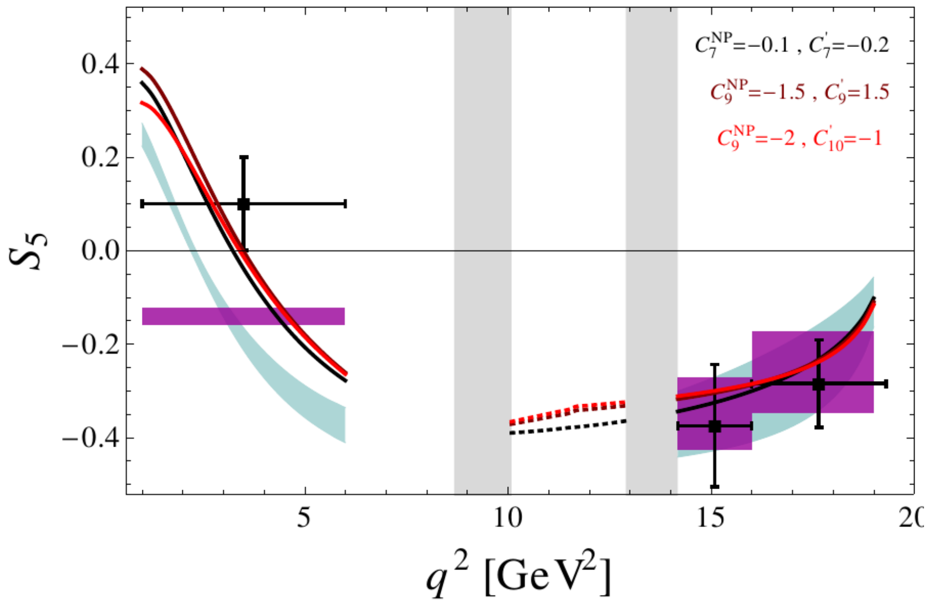
$$BF\,(B^0 \to p\,\bar{p}) = (1.47^{+1.09\,+0.69}_{-0.81\,-0.18}) \times 10^{-8} \text{ at } 90\% \text{ C.L.}$$

[arxiv:1308:0961]

P5' in 1-6 GeV²/c⁴



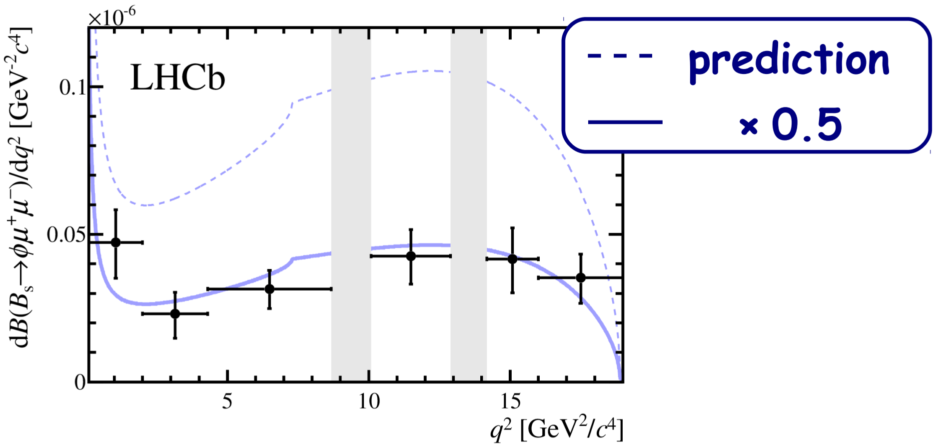


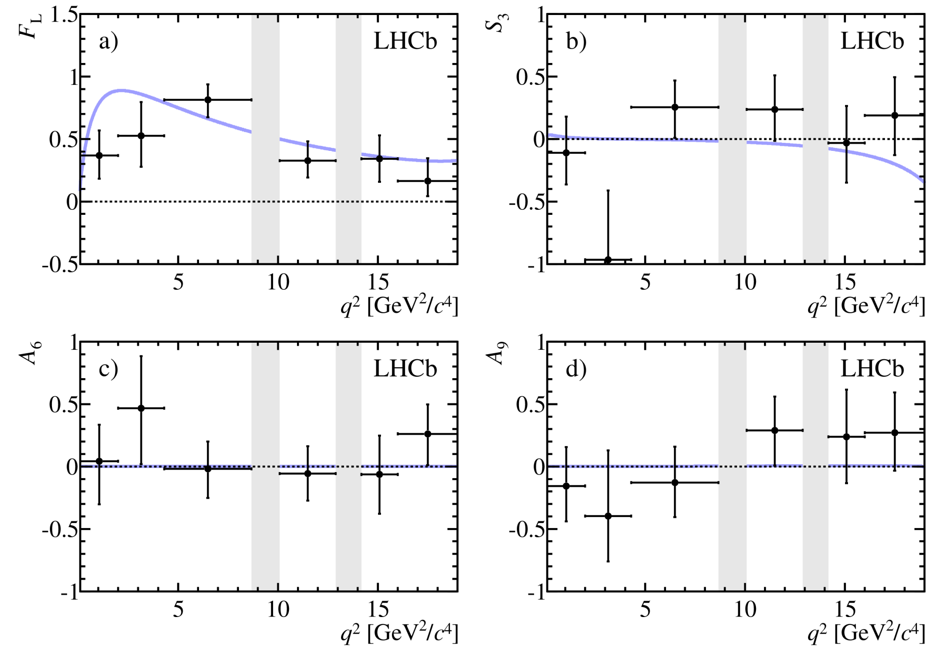


Other $b \to s \mu^+ \mu^-$ Decays

$B^0_s \to \phi \mu^+ \mu^-$ differential BF and angular observables **[JHEP 07 (2013) 084]**

- angular observables in good agreement with Standard Model prediction
- BF smaller than predicted, shape as function of q^2 agrees with prediction

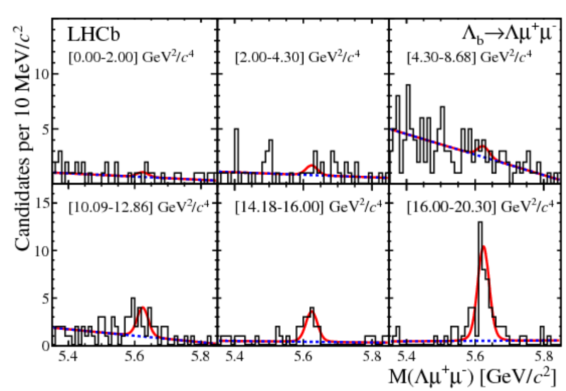


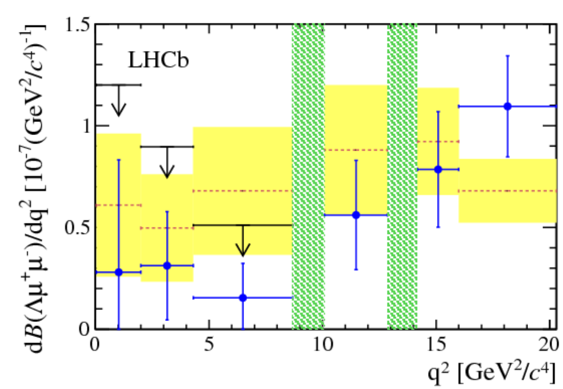


$\Lambda_b \to \Lambda \mu^+ \mu^-$ differential BF

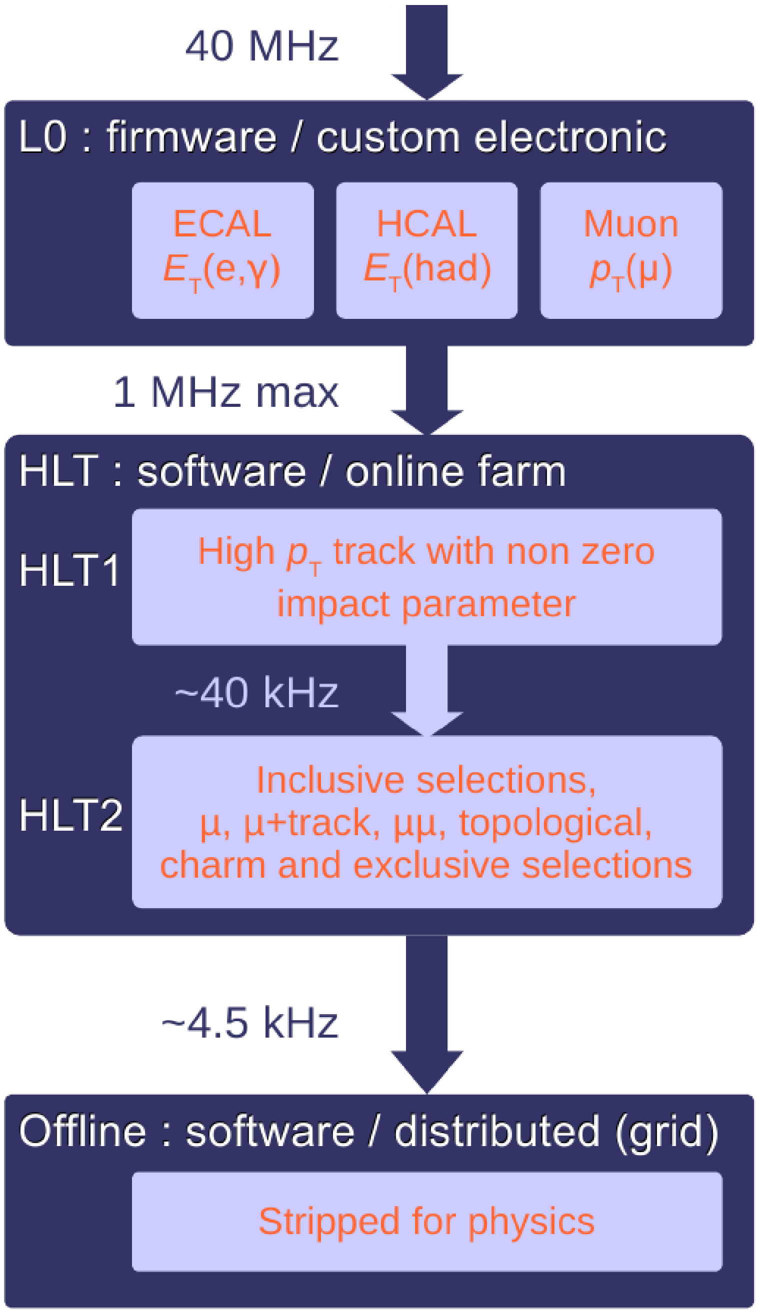
- agreement with SM prediction but uncertainties still large

[arxiv:1306:2577]





Reminder: Current LHCb Trigger



Hardware level (L0):

- maximum output rate 1 MHz
- typical thresholds 2012:

  $E_T(e/\gamma) > 2.7$ GeV

  $E_T(h) > 3.6$ GeV

  $p_T(\mu) > 1.4$ GeV

Software level (HLT):

~ 30000 tasks in parallel on ~ 1500 nodes

Combined efficiency (L0+HLT):

~ 90 % for di-muon channels

~ 30 % for multi-body hadronic final states

Offline processing:

~ 10^{10} events, 700 TB recorded per year