“Flavour in the era of the LHC”

(or, more honestly: a subset of highlights from LHCb)

Workshop on High Energy Physics Phenomenology

12-21st December, 2013, Puri, India

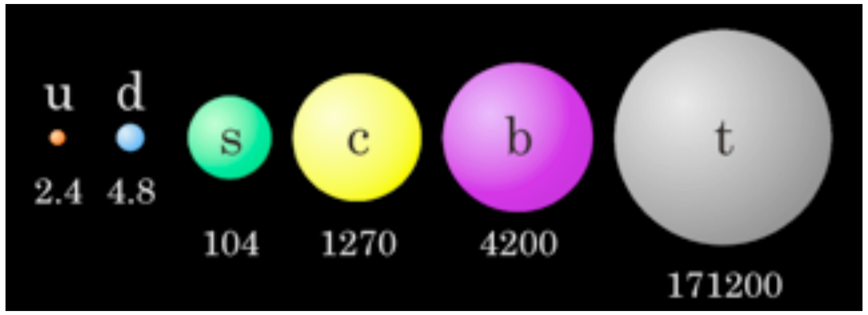
Wouter Hulsbergen (Nikhef, Amsterdam)
on behalf of the LHCb collaboration

Motivation

- SM explains fermion masses and quark flavour transitions via Yukawa couplings

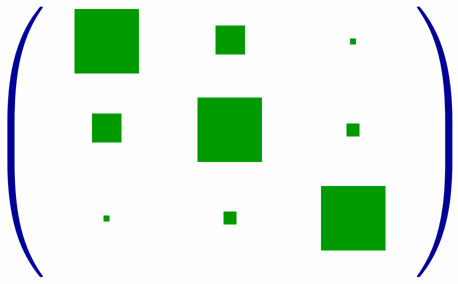
$$\boxed{-\mathcal{L}^{\rm SM}_{\rm Yukawa} = Y_d^{ij}\bar{Q}^i_L\phi D^j_R + Y_u^{ij}\bar{Q}^i_L\tilde{\phi}U^j_R + Y_e^{ij}\bar{L}^i_L\phi E^j_R + \text{h.c.}}$$

quark (and lepton) masses



CKM matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim$$



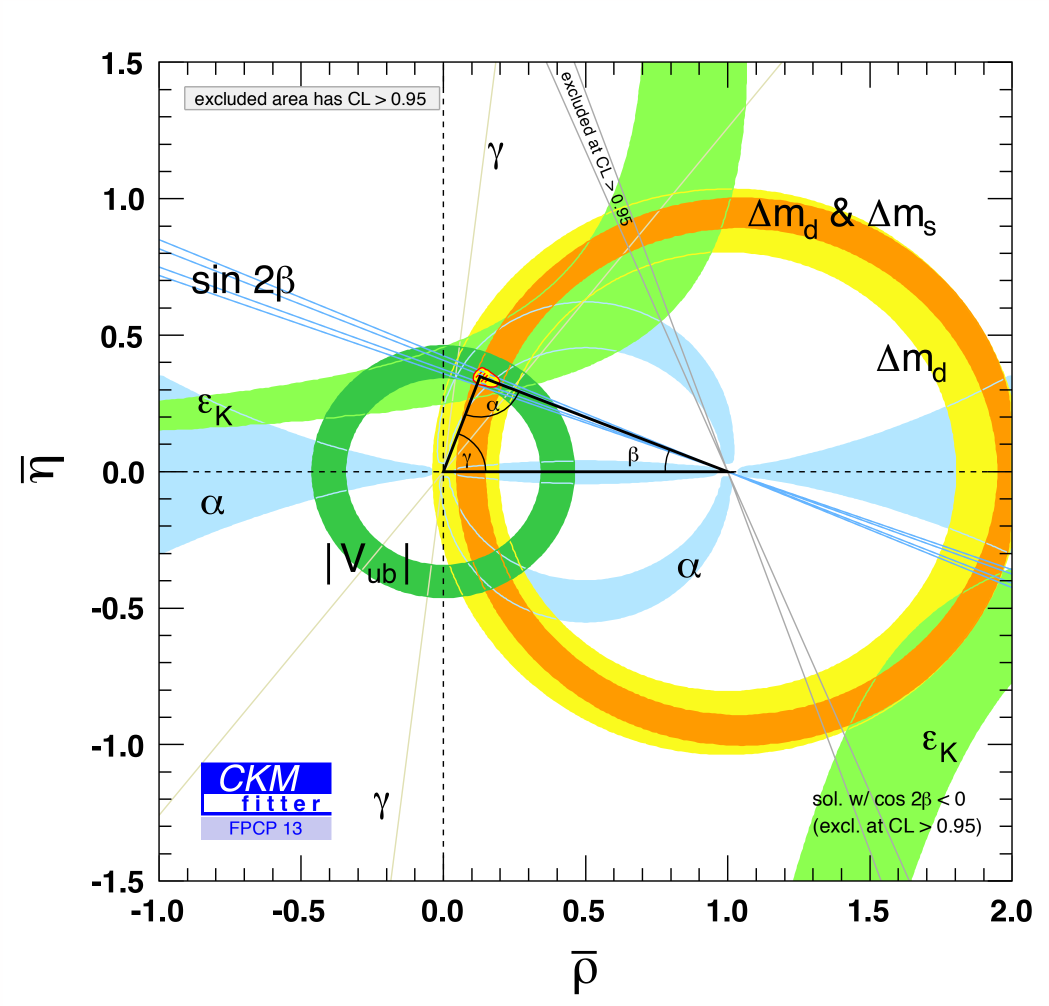
- many parameters (10 out of 19 SM parameters are in quark sector!)
- rich phenomenology
  - meta-stable baryons with many decay modes, some very rare ...
  - neutral meson mixing, CP violation, ...

Motivation

- SM explains fermion masses and quark flavour transitions via Yukawa couplings

$$-\mathcal{L}^{\rm SM}_{\rm Yukawa} = Y_d^{ij}\bar{Q}_L^i\phi D_R^j + Y_u^{ij}\bar{Q}_L^i\tilde{\phi}U_R^j + Y_e^{ij}\bar{L}_L^i\phi E_R^j + \text{h.c.}$$

- extremely successful ...



$$V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0$$

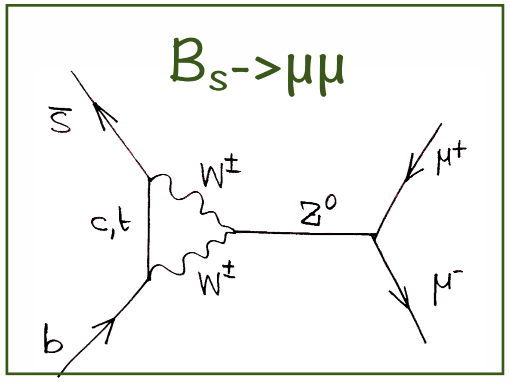
... but puzzling

- why the large hierarchy in masses and couplings?
- if due to symmetry, then what breaks it?
- if there is NP at the TeV scale, then why don't we see it?

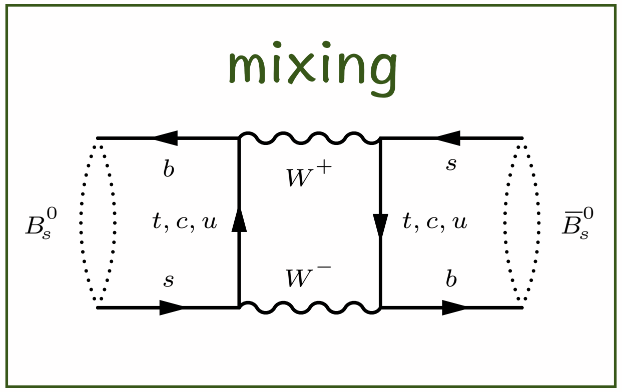
The NP flavour problem

- flavour transitions probes high mass scales in quantum loops, e.g. in FCNC

$\Delta F = 1$



$\Delta F = 2$



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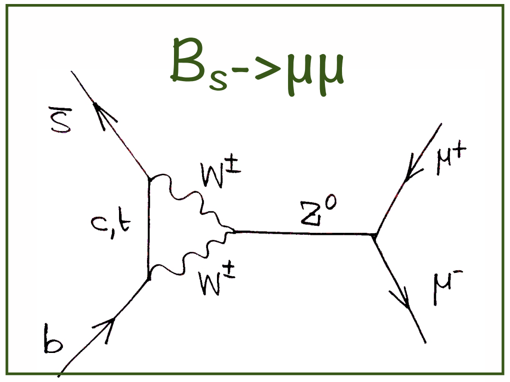

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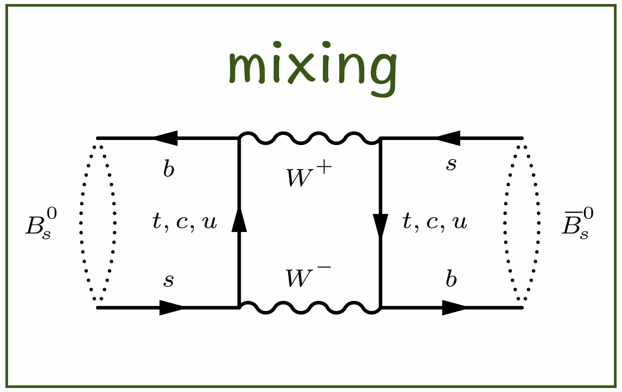
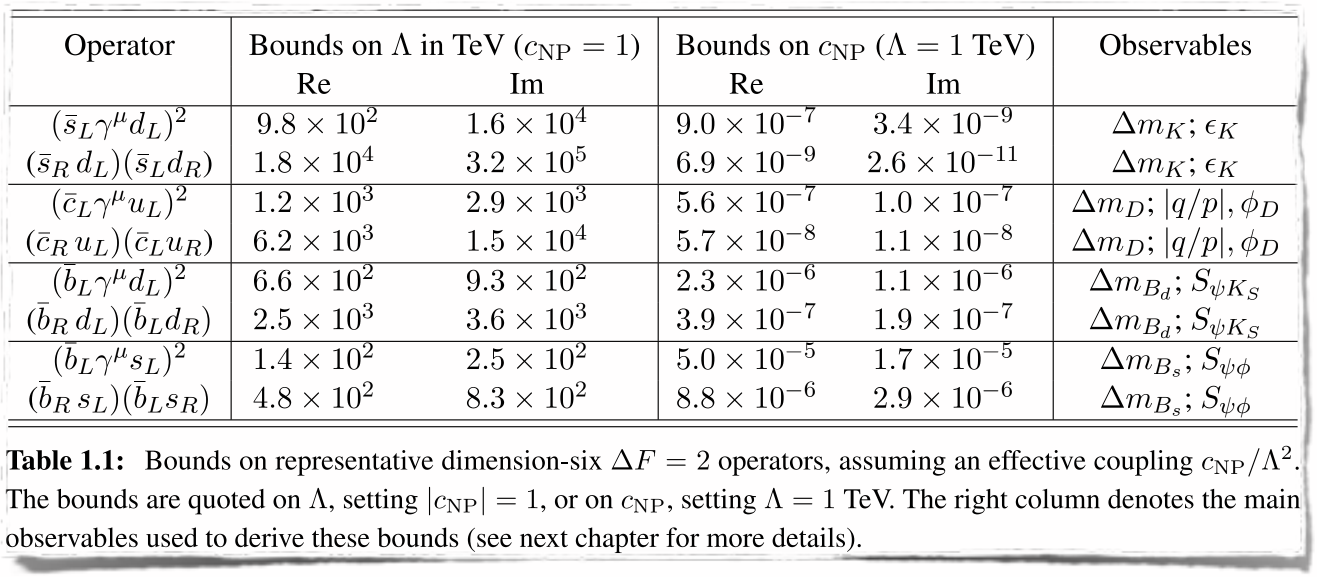


- parameterize in terms of operators, couplings and mass scales

$$\mathcal{A}(f_i \to f_j + X) = \mathcal{A}_0 \left[\frac{c_{\rm SM}}{M_W^2} + \frac{c_{\rm NP}}{\Lambda^2} \right]$$



Operator	Bounds on Λ in TeV ($c_{\rm NP} = 1$)		Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\|q/p\|, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\|q/p\|, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

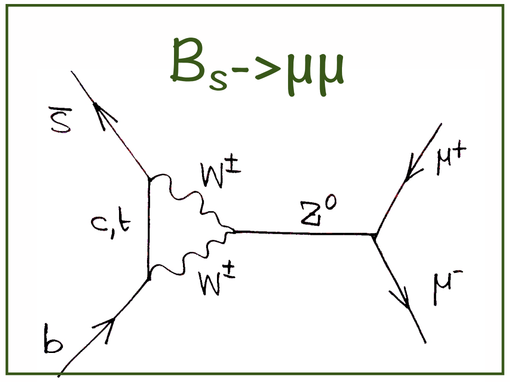
Table 1.1: Bounds on representative dimension-six $\Delta F = 2$ operators, assuming an effective coupling $c_{\rm NP}/\Lambda^2$. The bounds are quoted on Λ, setting $|c_{\rm NP}| = 1$, or on $c_{\rm NP}$, setting $\Lambda = 1$ TeV. The right column denotes the main observables used to derive these bounds (see next chapter for more details).

Isidori, Nir, Perez, Ann. Rev. Nucl. Part. Sci. 60 (2010) 355 [arXiv:1002.0900],
Isidori, arXiv:1302.0661

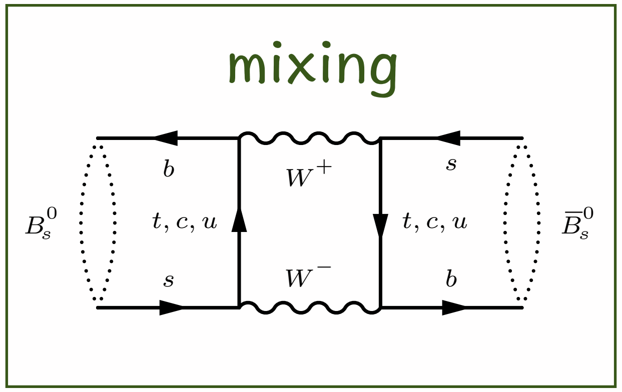
The NP flavour problem

- flavour transitions probes high mass scales in quantum loops, e.g. in FCNC

ΔF = 1


B_s->μμ

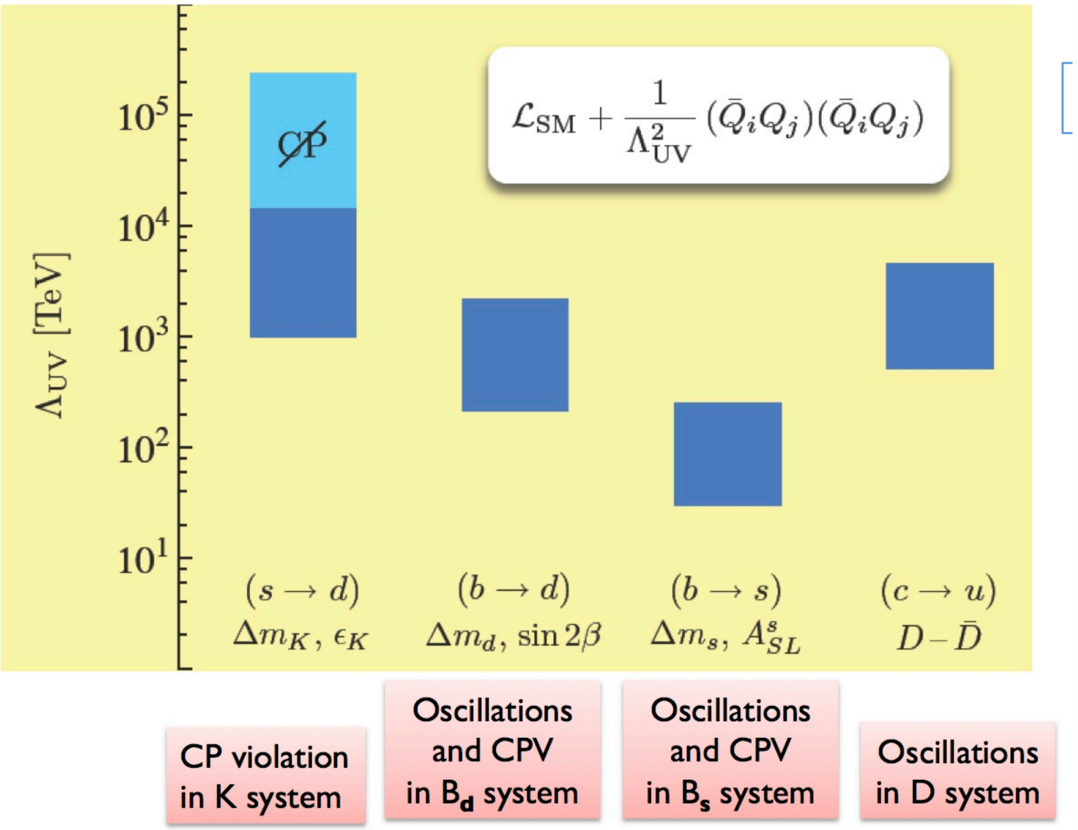
ΔF = 2


mixing

- parameterize in terms of operators, couplings and mass scales

$$\mathcal{A}(f_i \to f_j + X) = \mathcal{A}_0 \left[\frac{c_{\rm SM}}{M_W^2} + \frac{c_{\rm NP}}{\Lambda^2} \right]$$

- NP models with generic flavour structure at 1 TeV are ruled out
- either NP scale is much higher, or couplings are small. why?

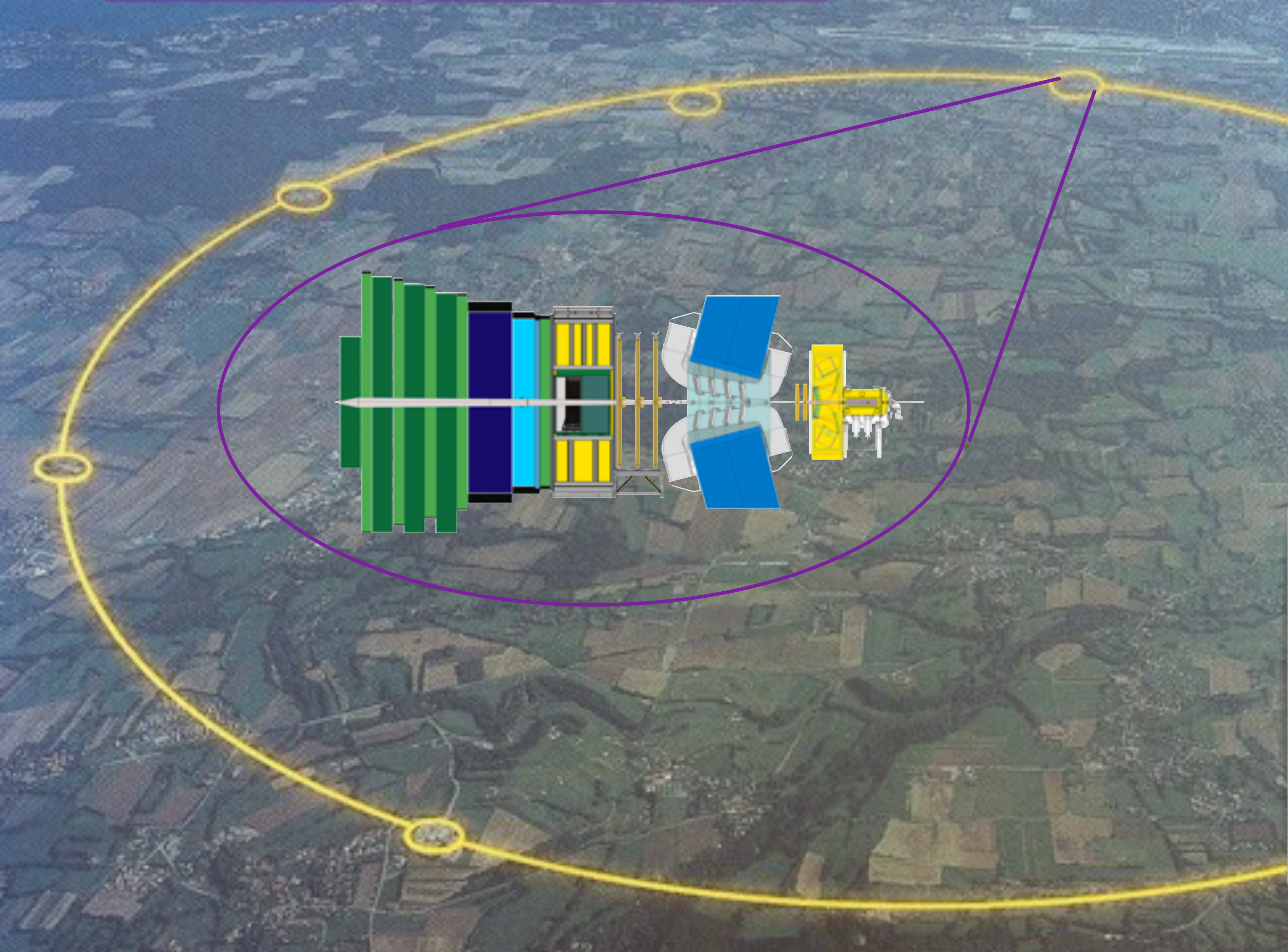


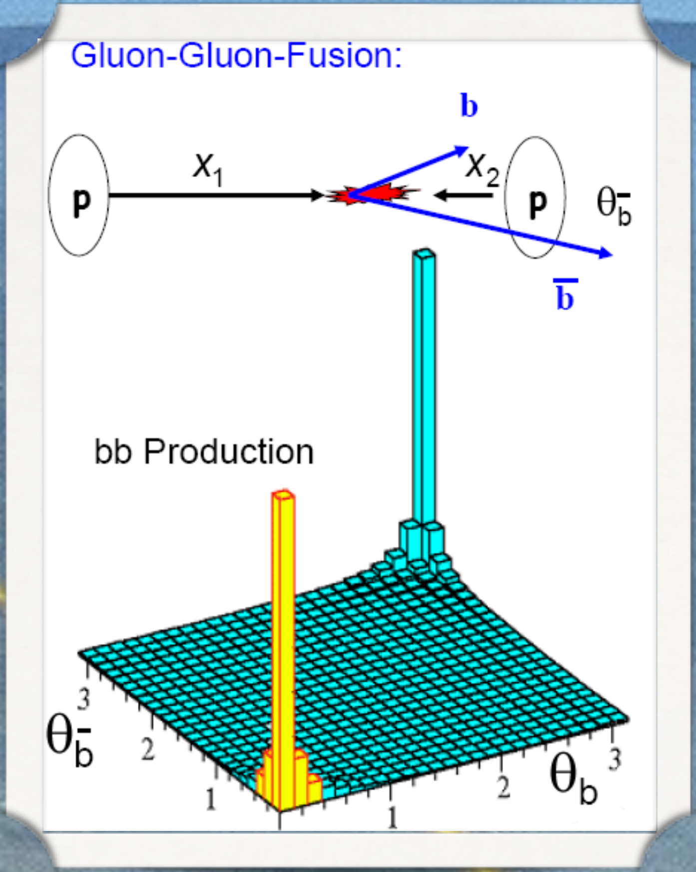
(Fig. Neubert, EPS-HEP'11)

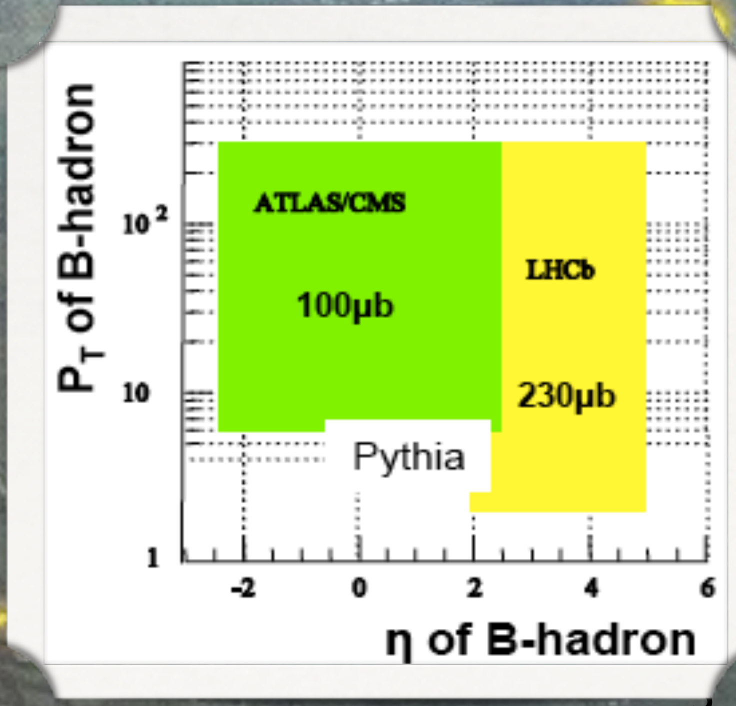
Isidori, Nir, Perez, Ann. Rev. Nucl. Part. Sci. 60 (2010) 355 [arXiv:1002.0900],
Isidori, arXiv:1302.0661

The LHC: a hadronic beauty and charm factory

$$\begin{aligned} \sigma(pp \to \text{inel}) &= 60 \text{ mb} \\ \sigma(pp \to c\bar{c}) &= 6 \\ \sigma(pp \to b\bar{b}) &= 0.3 \end{aligned}$$

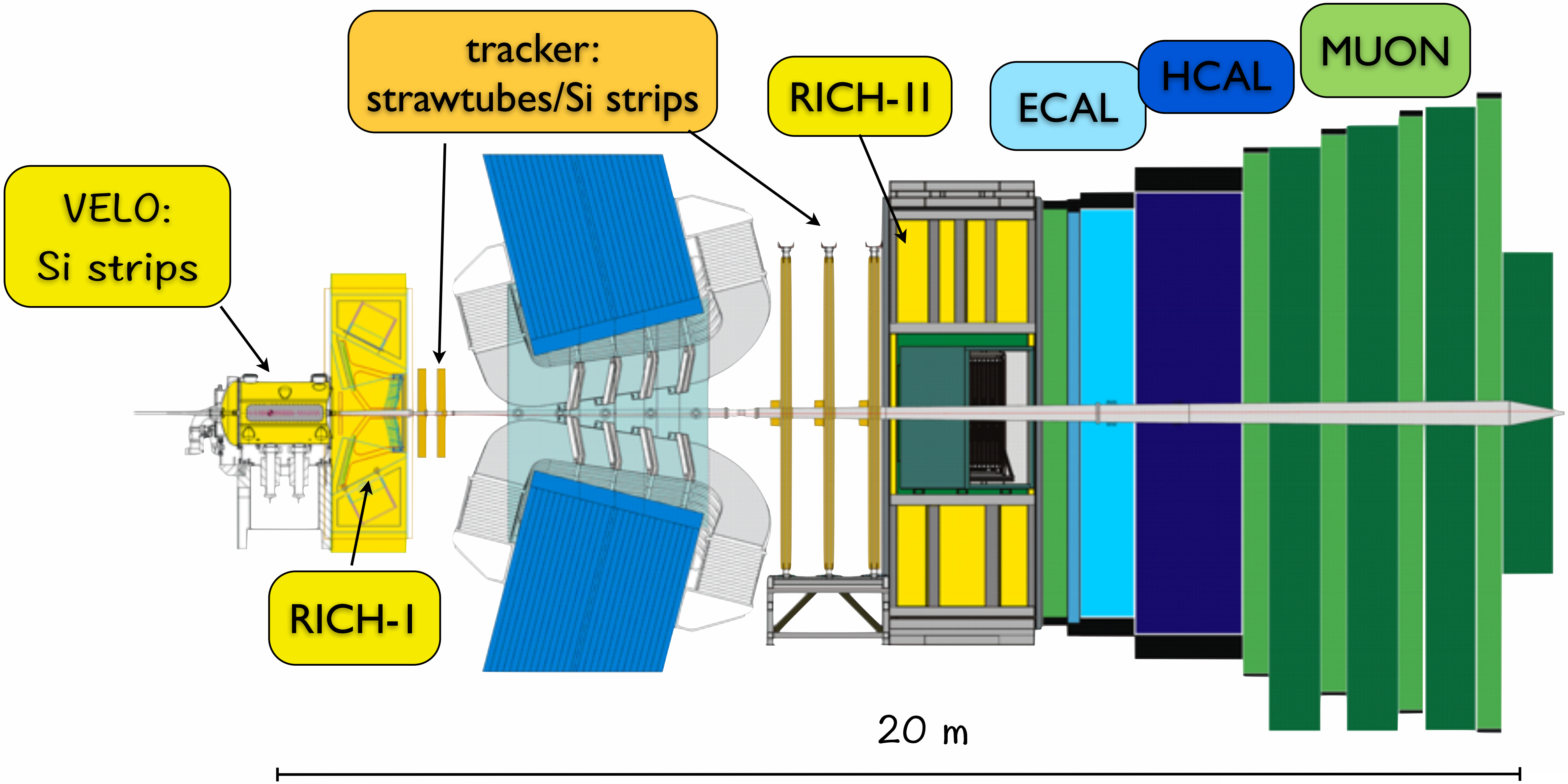






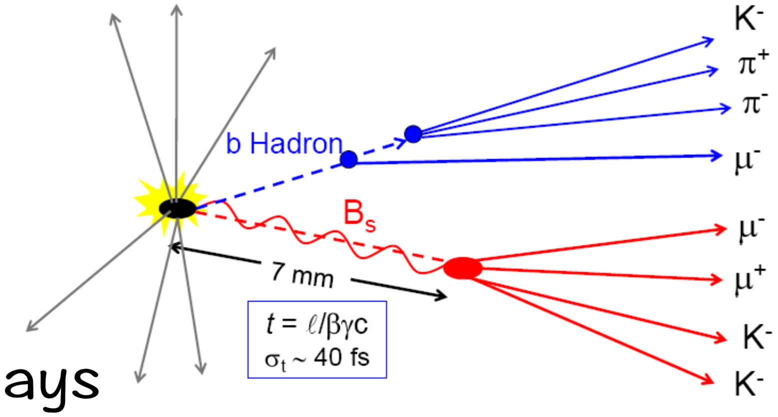
The LHCb experiment

The LHCb Detector
JINST 3 (2008) S08005



Requirements dictated by flavour physics:

- vertex resolution: resolve B_s oscillations
- excellent p/π/K/μ/e separation: flavour tagging; rare decays
- momentum resolution: resolve B/B_s,D/D_s, etc



The LHCb trigger

JINST 8 (2013) P04022

Challenge:

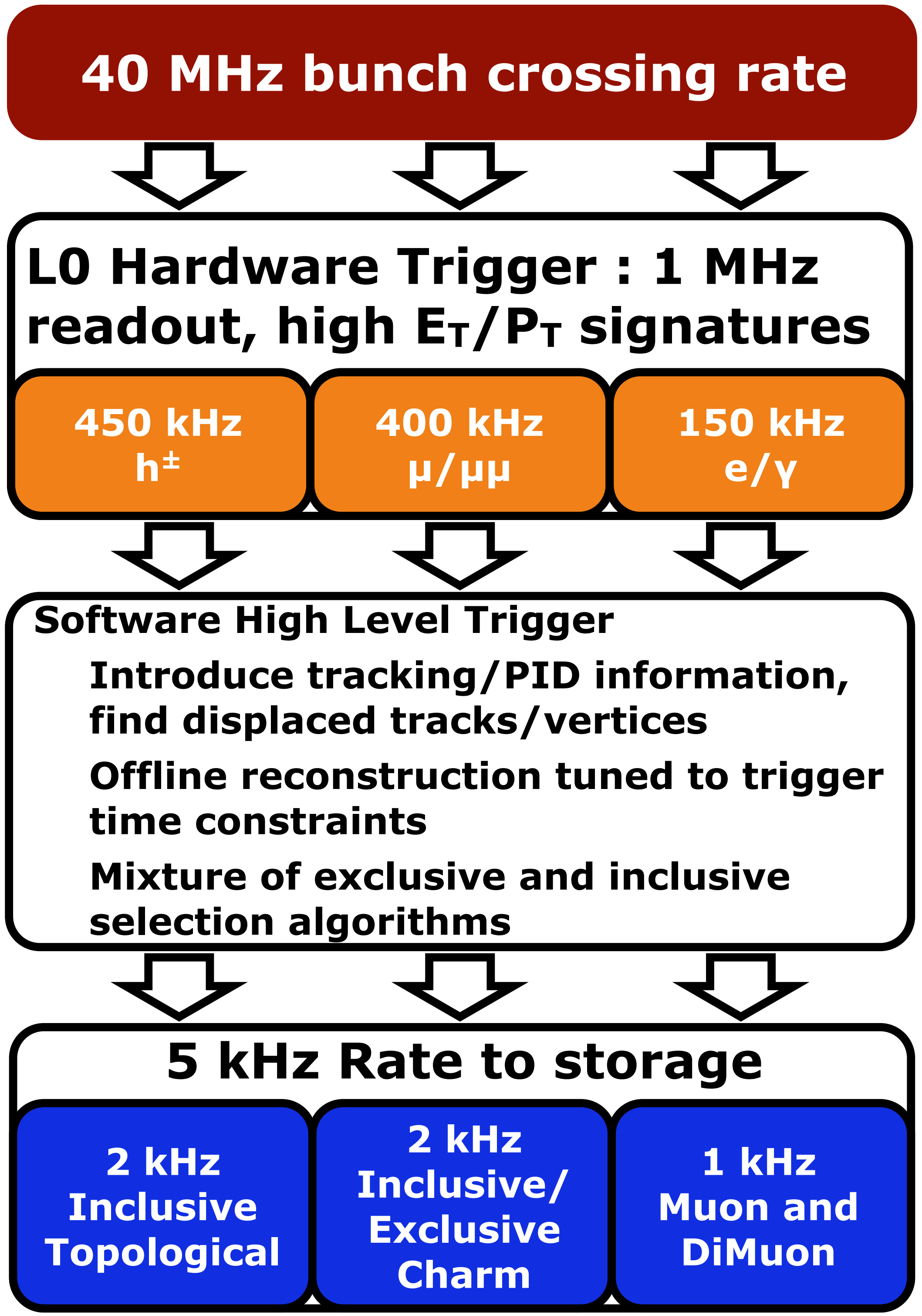
- high efficiency for manageable data rates

Main backgrounds:

- minimum bias
- less interesting charm and beauty decays

Handles:

- high pT signals (hadrons, electrons, muons)
- displaced vertices



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

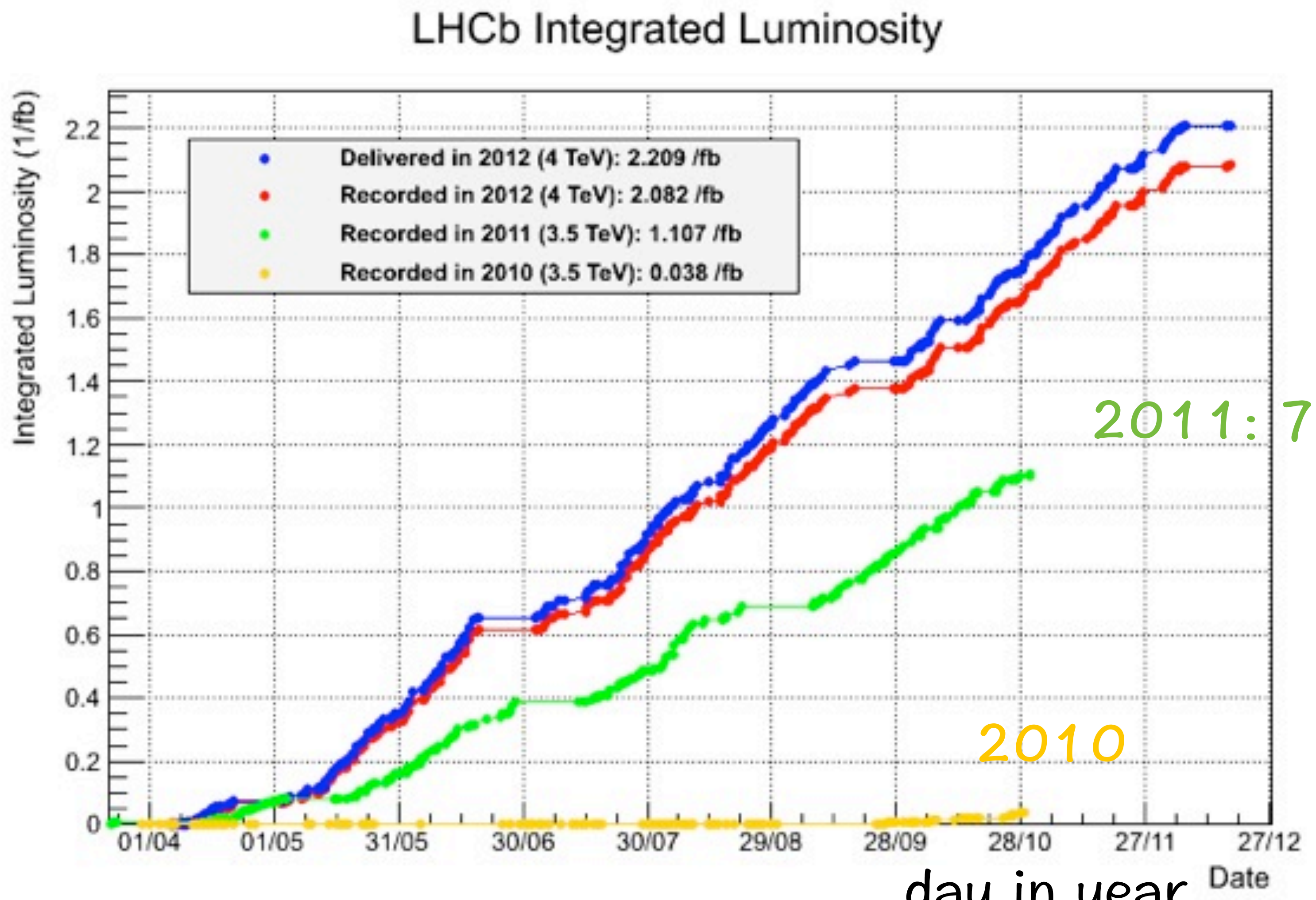
Software High Level Trigger

- Introduce tracking/PID information, find displaced tracks/vertices
- 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

The LHCb data set



2012: 8 TeV

2011: 7 TeV

2010

day in year

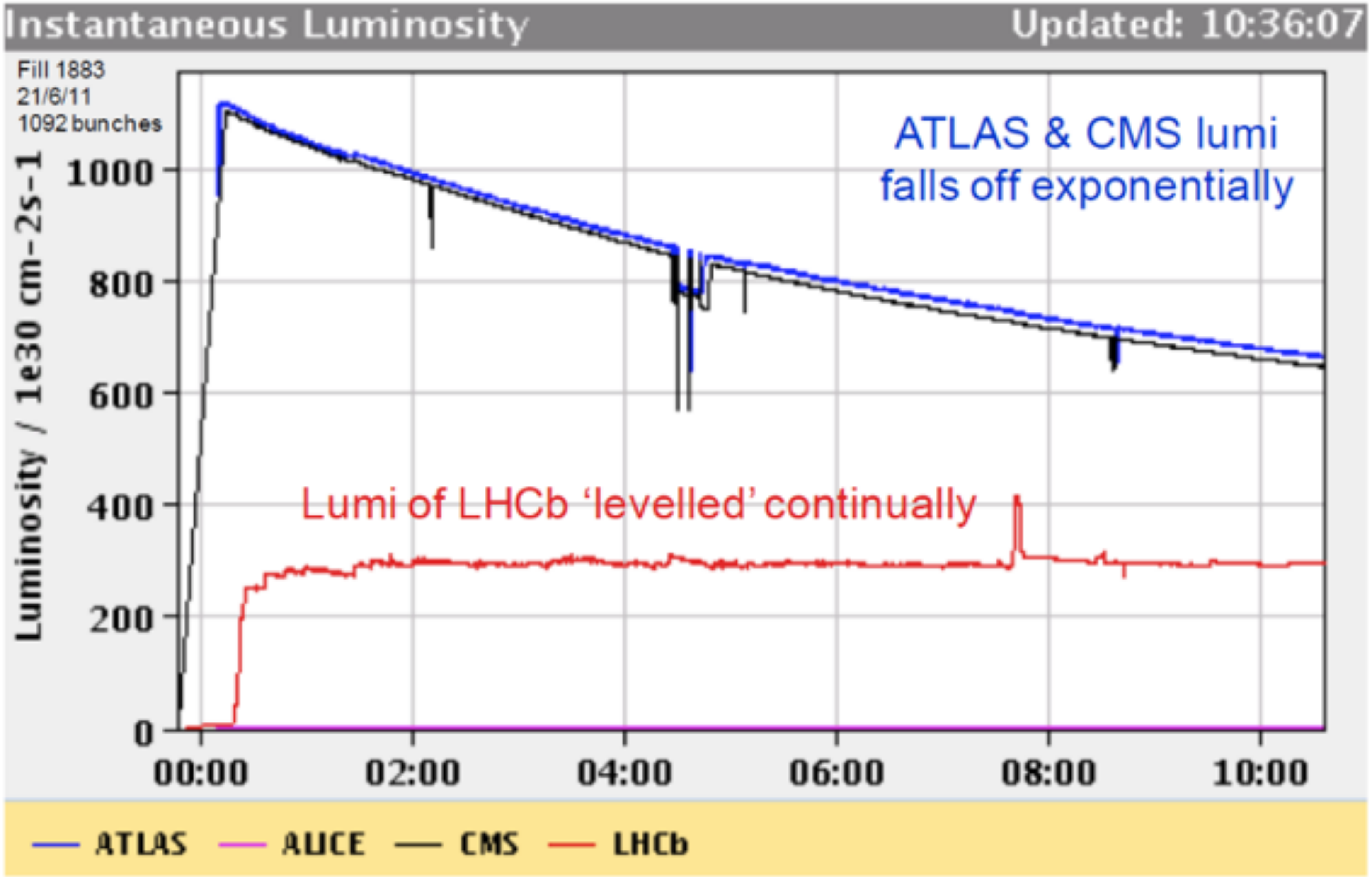
LHC is currently shut down to prepare for 13 TeV running

most analyses reported in this talk used 2011 dataset (1/fb) only

... many 2012 (2/fb) results will come in spring

running strategy: reduce pile-up

- LHCb tracking/PID performance sensitive to pile-up
- beams at LHCb displaced from head-on to reduce instantaneous luminosity



optimal L_{inst}:

$2\text{-}4 \times 10^{32}$ /cm^2/s

→ LHCb collects less luminosity than CMS and ATLAS, but at much lower pile-up

LHCb Physics

LHCb physics menu (link)

- charm and beauty: cross-sections, spectroscopy, lifetimes, CP violation, mixing, rare decays, states, ...
- electroweak production: Z, W, jets, ...
- heavy ions: e.g. J/ψ in pA collisions
- ...

>160 publications ... (link)

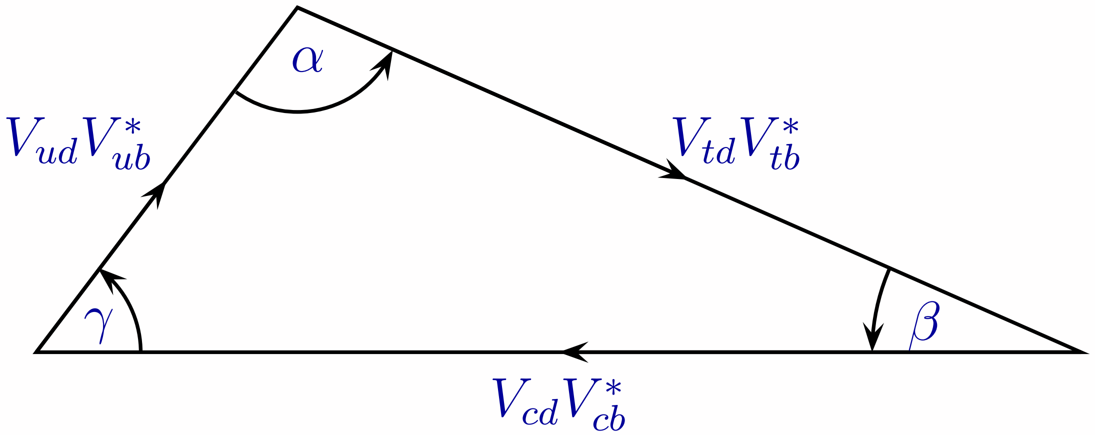
Selected results for this talk

- gamma: the least well known angle of the CKM matrix
- mixing and time-dependent CP violation in the B_s system
- rare decays: B_s->$\mu^+\mu^-$ and B_s->$K^{*0}\mu^+\mu^-$

The unitarity triangle

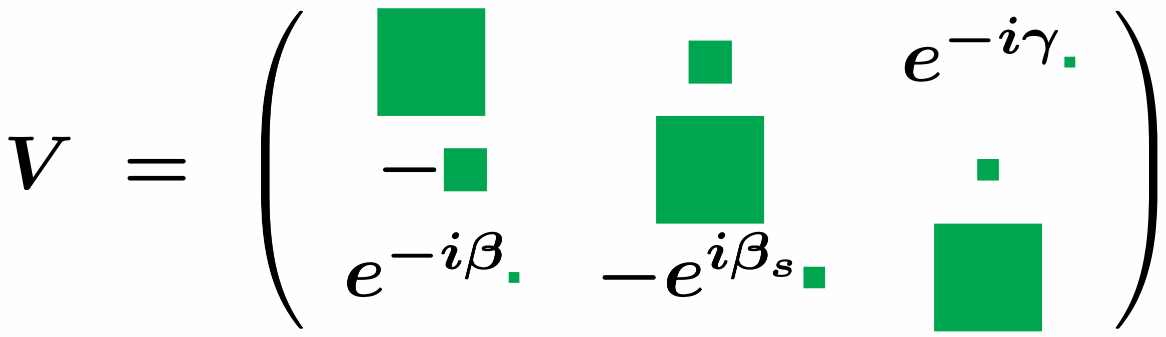
- CKM matrix is unitary and has only 4 independent physical parameters
- unitarity constraints expressed as ‘triangles’ in complex plane, e.g.

$$V_{ub}^* V_{ud} \;+\; V_{cb}^* V_{cd} + V_{tb}^* V_{td} \;=\; 0 \quad \Rightarrow$$



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

In Wolfenstein phase convention:



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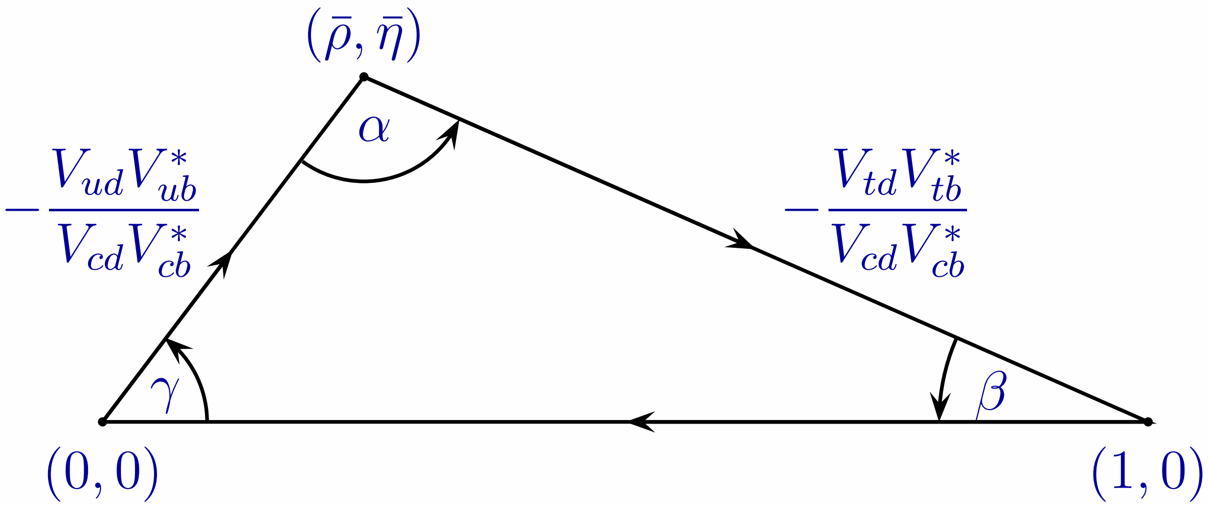
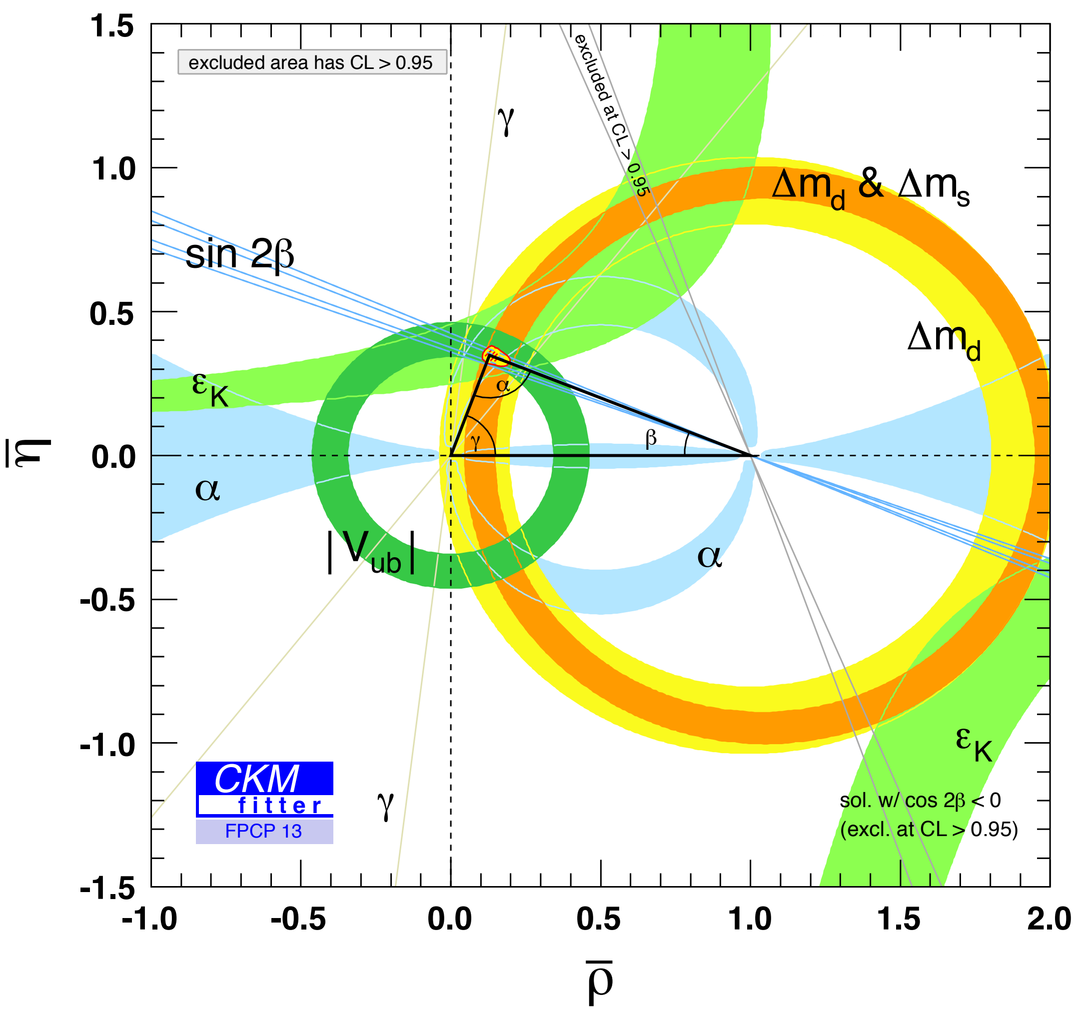
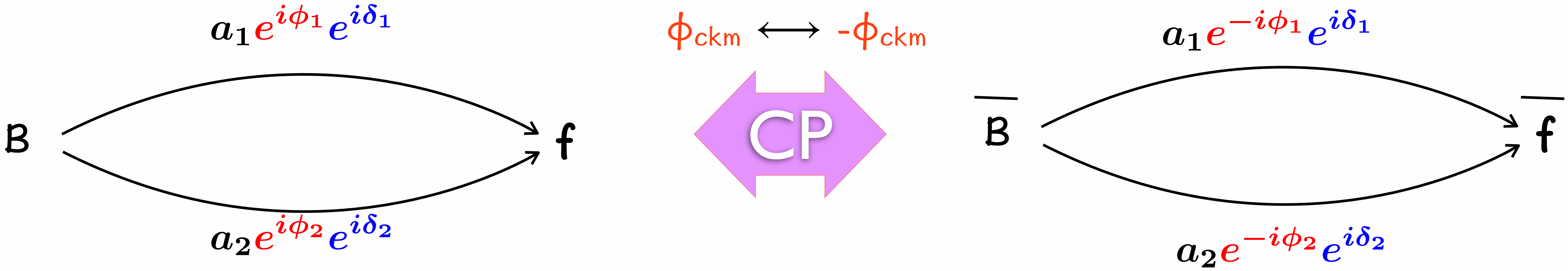




- angle γ has largest exp. uncertainty
- can be constrained with B->DK decays

Observing CP violation

- CPV arises due to interfering amplitudes with different CKM phases



$a_1 e^{i\phi_1} e^{i\delta_1}$

B

f

$a_2 e^{i\phi_2} e^{i\delta_2}$

$\phi_{\text{ckm}} \longleftrightarrow -\phi_{\text{ckm}}$

CP

$a_1 e^{-i\phi_1} e^{i\delta_1}$

$\overline{\text{B}}$

$\overline{\text{f}}$

$a_2 e^{-i\phi_2} e^{i\delta_2}$

Observing CP violation

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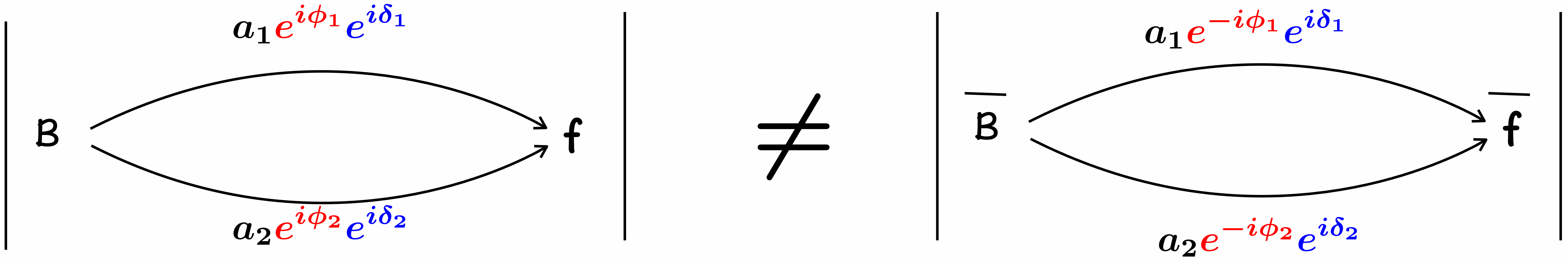

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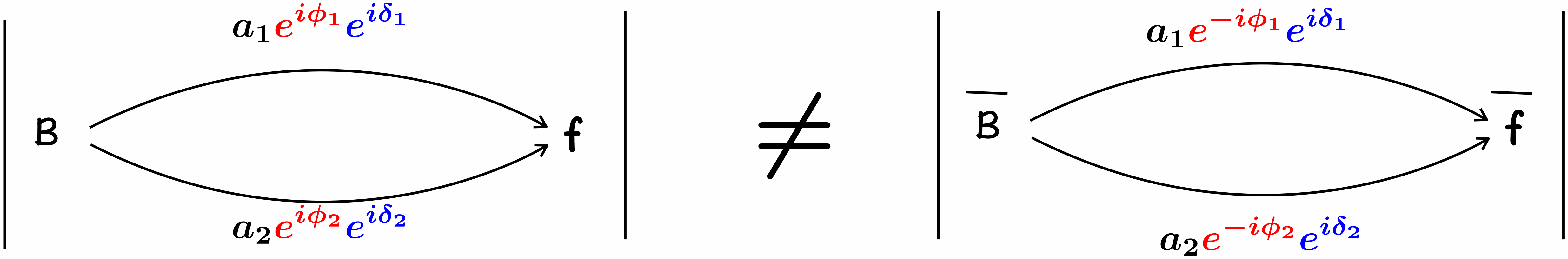


- two types of phenomena

1. charge asymmetry (direct CPV)

$$\boxed{A_f^{\mathrm{ch}} \equiv \frac{N(B \to f) - N(\overline{B} \to \bar{f})}{N(B \to f) + N(\overline{B} \to \bar{f})}}$$

2. time-dependent asymmetry (indirect CPV)
   arises of if B0 and B0-bar have common final state

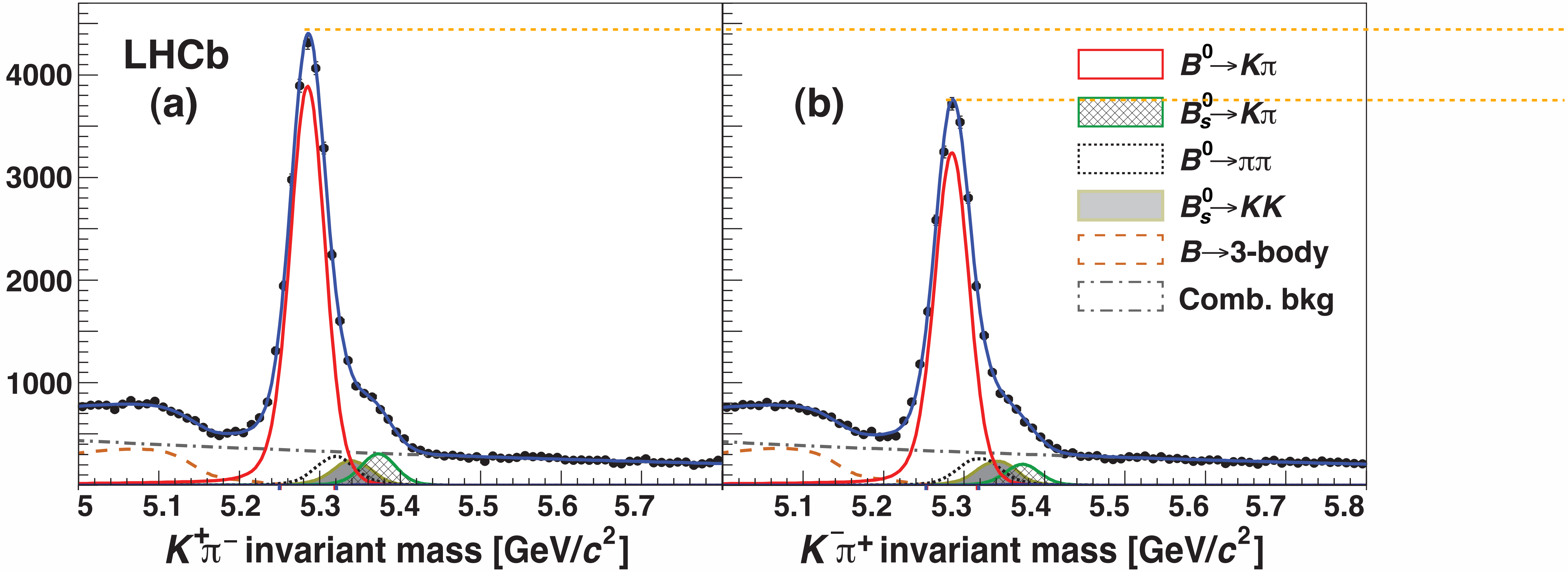
$$\boxed{A(t) \equiv \frac{N(\overline{B}^0(t) \to f) - N(B^0(t) \to f)}{N(\overline{B}^0(t) \to f) + N(B^0(t) \to f)}}$$

Large direct CP violation exists in ...

arXiv:1304.6173,PRL.110, 221601(2013)

... two-body decays of B^0 mesons

41000 Bd->Kπ candidates in 1/fb



$$A_{CP}(B^0\to K^+\pi^-) = -0.080 \pm 0.007\,(\text{stat}) \pm 0.003\,(\text{syst})$$

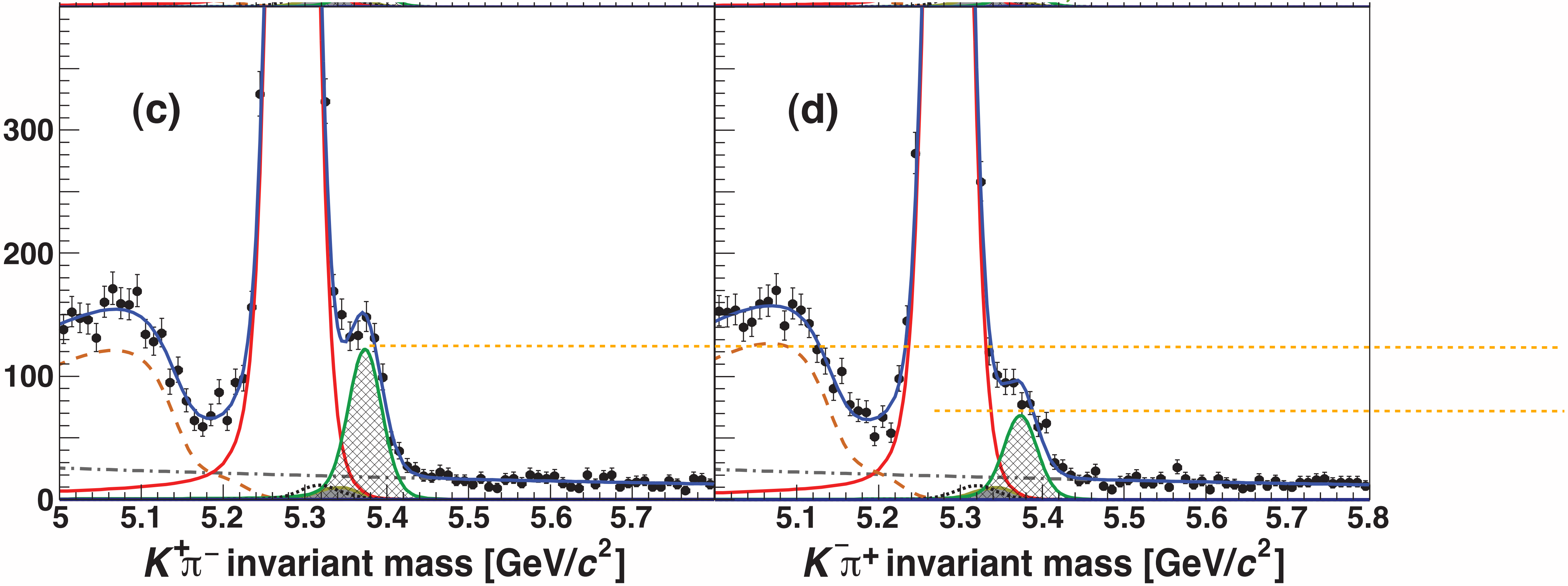
(in agreement with Belle and Babar, but with smaller uncertainty)

Large direct CP violation exists in ...

arXiv:1304.6173,PRL.110, 221601(2013)

... two-body decays of B_s mesons

1065 ± 55 Bs->Kπ candidates in 1/fb



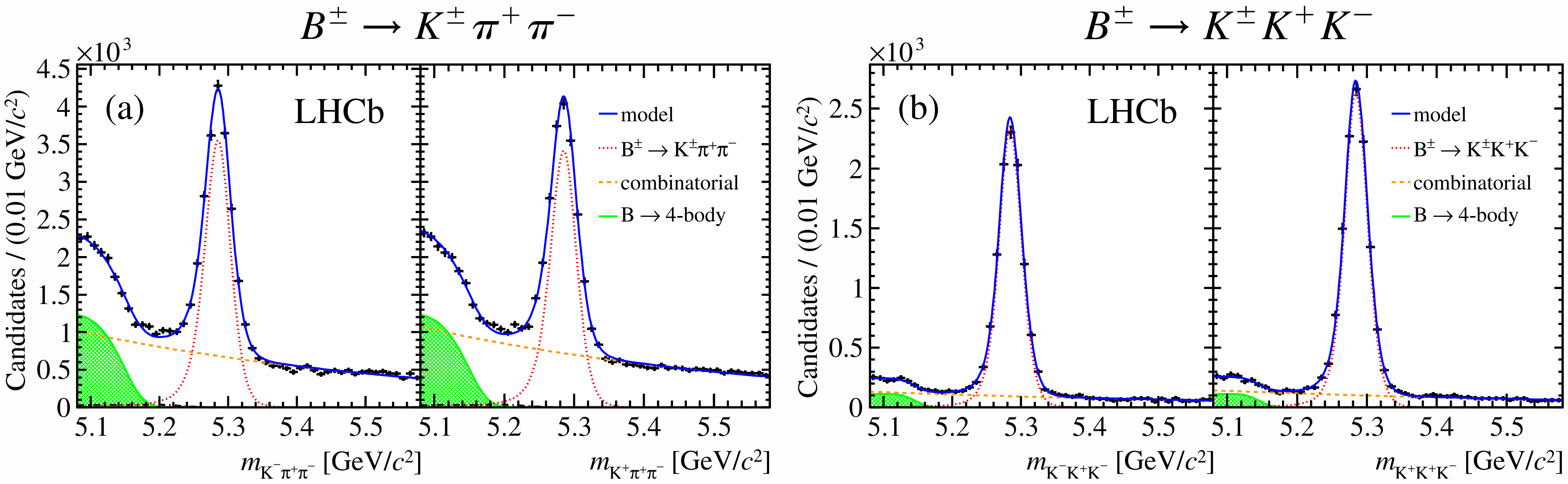
$$A_{CP}(B_s^0 \to K^- \pi^+) = 0.27 \pm 0.04\,(\mathrm{stat}) \pm 0.01\,(\mathrm{syst}).$$

(first observation of direct CPV in Bs decays)

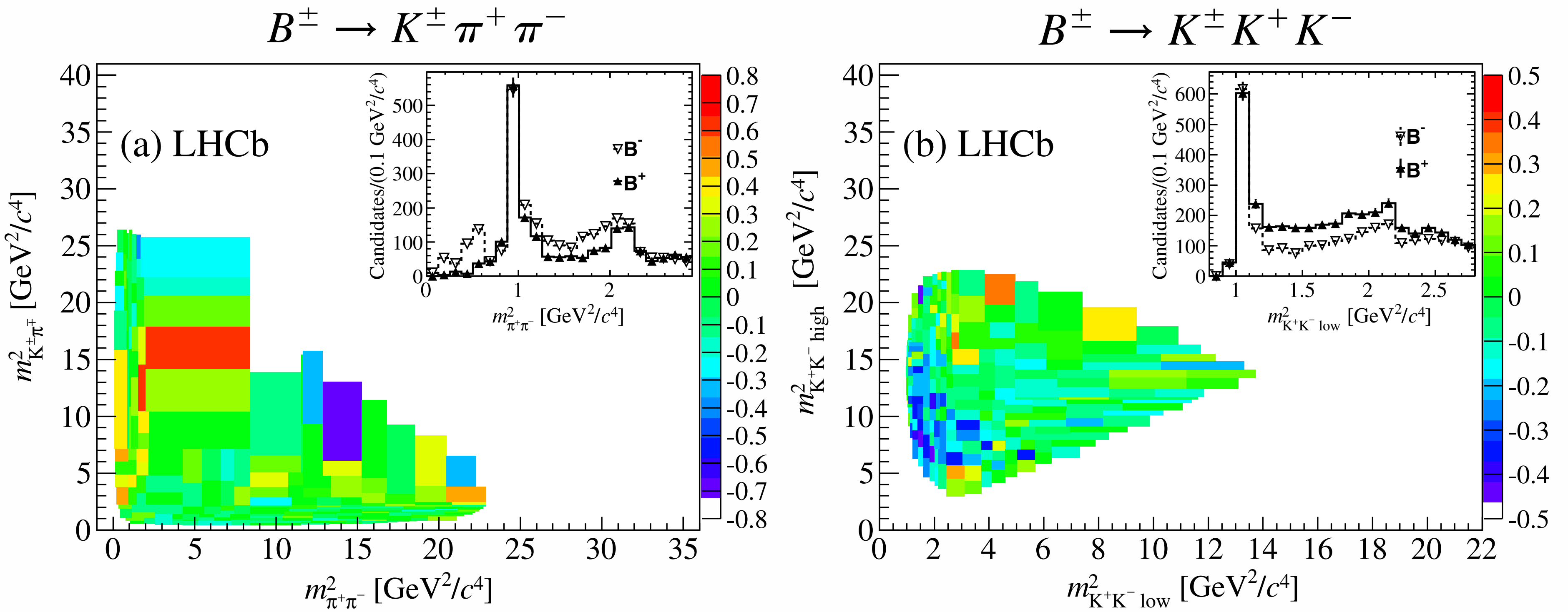
Large direct CP violation exists ...

arXiv:1306.1246, PRL 111, 101801 (2013)

... and in 3-body B^+ decays



over 50% in some parts of the Dalitz plane?!

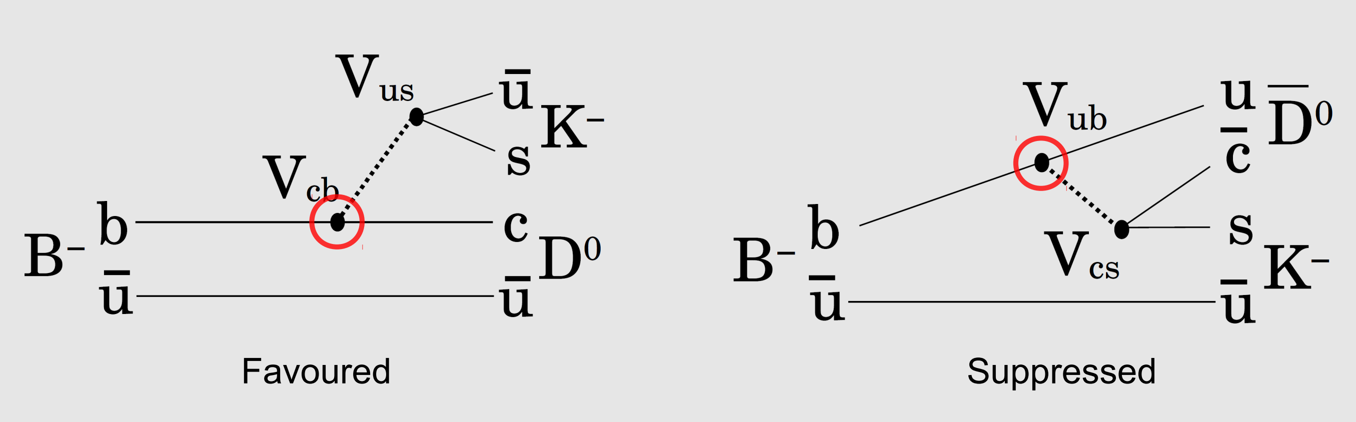


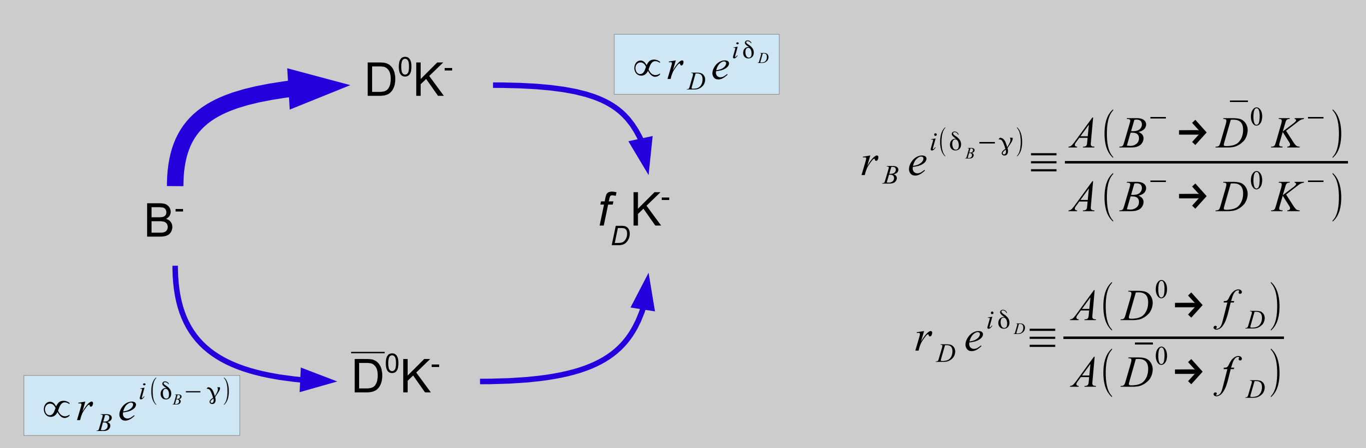
Evidence for "compound" CPV?

(Cheng, Chua and Soni, PRD 71, 014030 (2005))

Measurement of ‘gamma’

- CP violation in $B^\pm \to D^0 K^\pm$ occurs via ‘tree-level’ diagrams: small theoretical uncertainty, no ‘background’ from NP
- interfering amplitudes





$$r_B e^{i(\delta_B-\gamma)} \equiv \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)}$$

$$r_D e^{i\delta_D} \equiv \frac{A(D^0 \to f_D)}{A(\bar{D}^0 \to f_D)}$$

‘hadronic’ parameters are a nuisance but can be extracted from the data

- need common final state for D^0 and anti-D^0
  - GLW: CP eigenstate ($D^0 \to \pi\pi$, KK)
  - ADS: suppressed D^0 with favoured anti-D^0 decay
  - GGSZ: Dalitz analysis of $K_s^0K^+K^-$ or $K_s^0\pi^+\pi^-$

[Gronau-London-Wyler] PLB 253,483(1991), PLB 265,172 1991)
[Atwood-Dunietz-Soni] PRL 78,257(1997), PRD 63,036005(2001)
[Giri-Grossman-Soffer-Zupan] PRD 68,054018(2003)

ADS/GWL in B->[πK]K/π and B->[πKππ] K/π

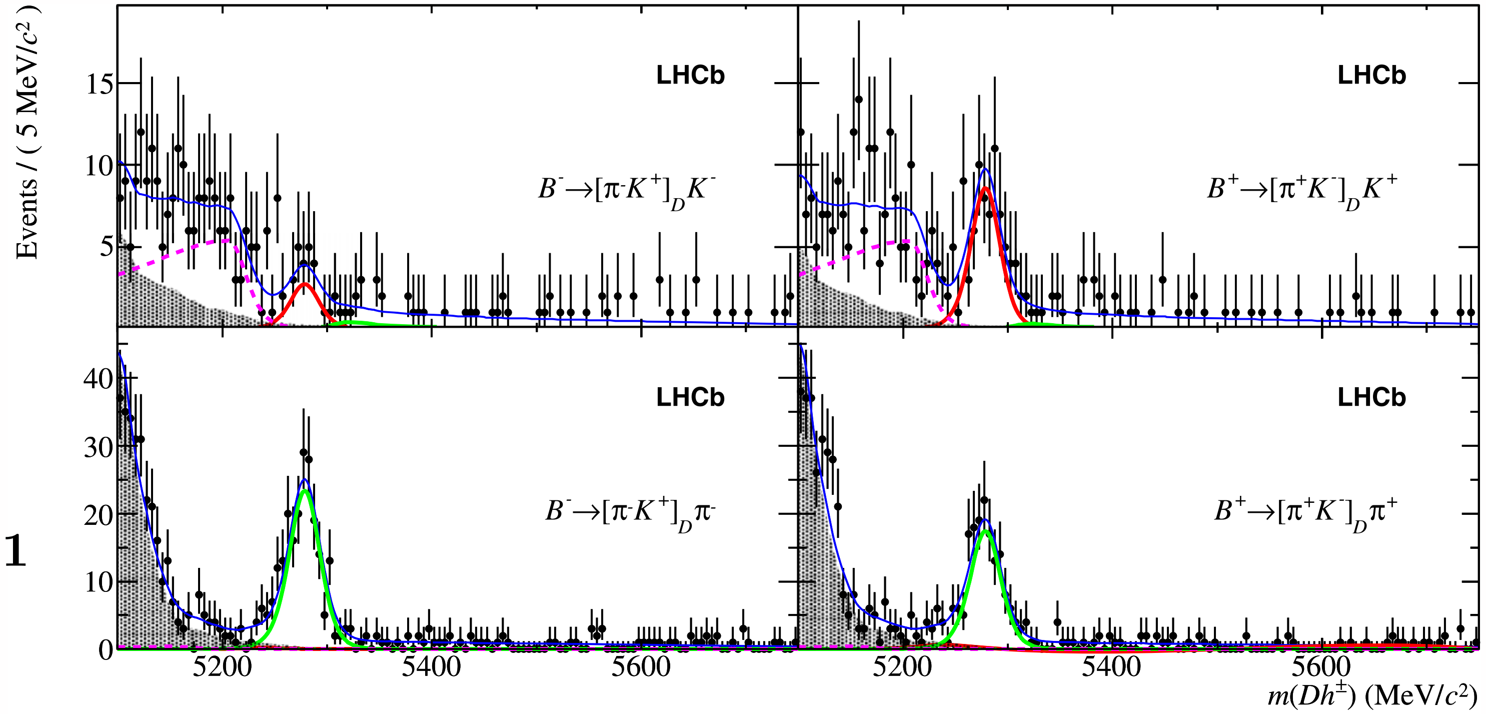
Several modes explored ....

1/fb: arXiv:1203.3662, PLB 712 (2012), 203

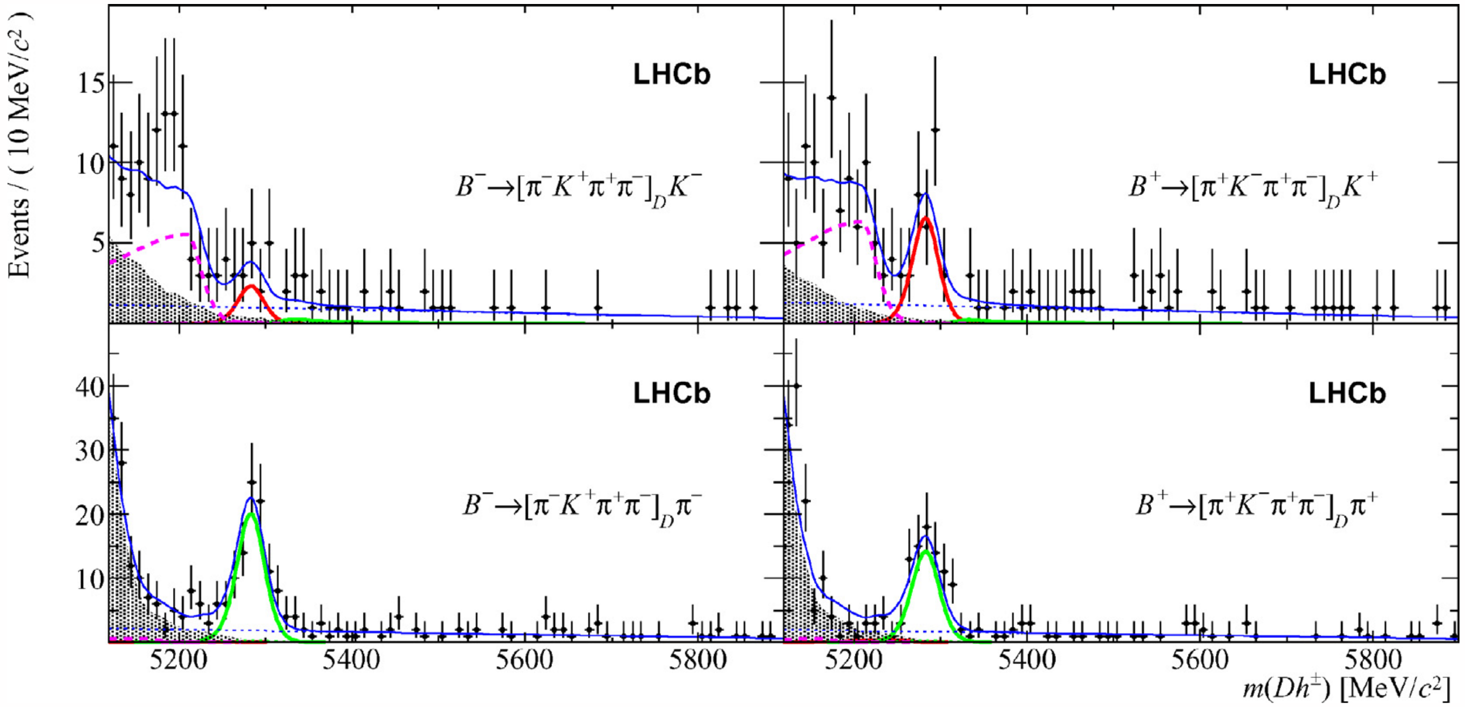
- First observation of ADS mode $B^+ \to D^0(\pi^+K^-)K^+$ (10σ)
- clear CP asymmetries:

$$A_{\mathrm{ADS}}(D^0(\pi^-K^+)K^-) = -0.52 \pm 0.15 \pm 0.02$$

$$A_{\mathrm{ADS}}(D^0(\pi^-K^+)\pi^-) = -0.143 \pm 0.062 \pm 0.11$$



1/fb: arXiv:1303.4646, PLB 723 (2013) 44



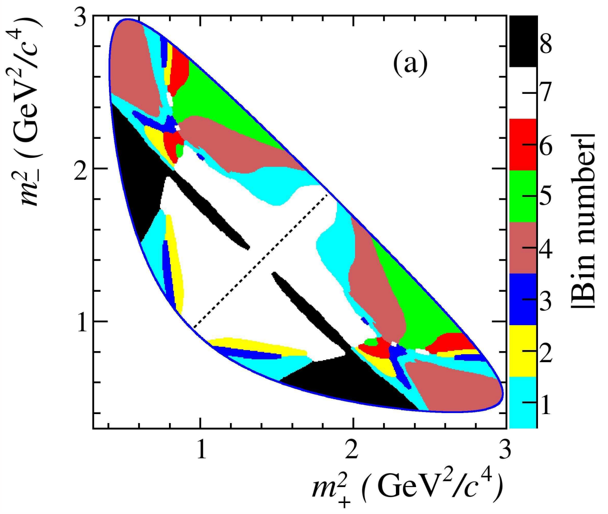
- First observation of ADS modes with $D^0 \to \pi K\pi\pi$, both in B->DK and B->πK

GGSZ: B->Dπ/K with D->KsKK or D->$K_s\pi\pi$

1/fb: PLB 718(2012)43

2/fb: LHCb-CONF-2013-004

- CP conjugate three body decay: extract gamma from asymmetry of B+ and B- yield across Dalitz plane
- strong phase changes across D^0 Dalitz plane: use CLEO data (PRD82(2010)112006) to constrain the phase



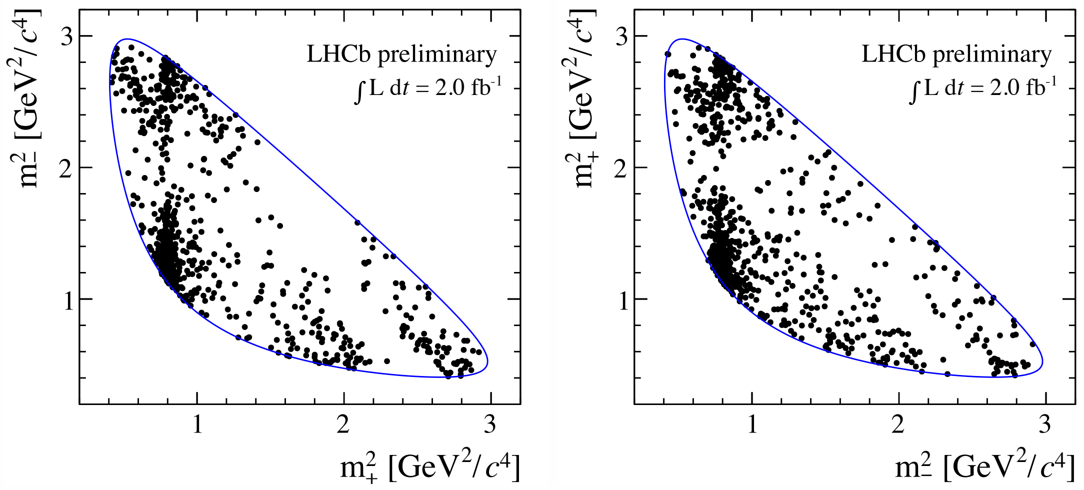


Figure 4: Dalitz plots for $B^\pm \to (K^0_S\pi^+\pi^-)_D K^\pm$ decays; (left) B^+, (right) B^-.

- extract two parameters that are function of gamma:

$$x_\pm \equiv r_B\cos(\delta_B \pm \gamma), \qquad y_\pm \equiv r_B\sin(\delta_B \pm \gamma).$$

- result (2012, 2/fb):

$$\begin{aligned}
x_+ &= (-8.7 \pm 3.1 \pm 1.6 \pm 0.6) \times 10^{-2}\\
x_- &= \quad (5.3 \pm 3.2 \pm 0.9 \pm 0.9) \times 10^{-2}\\
y_+ &= \quad (0.1 \pm 3.6 \pm 1.4 \pm 1.9) \times 10^{-2}\\
y_- &= \quad (9.9 \pm 3.6 \pm 2.2 \pm 1.6) \times 10^{-2}
\end{aligned}$$

stat. LHC-syst. CLEO-syst.

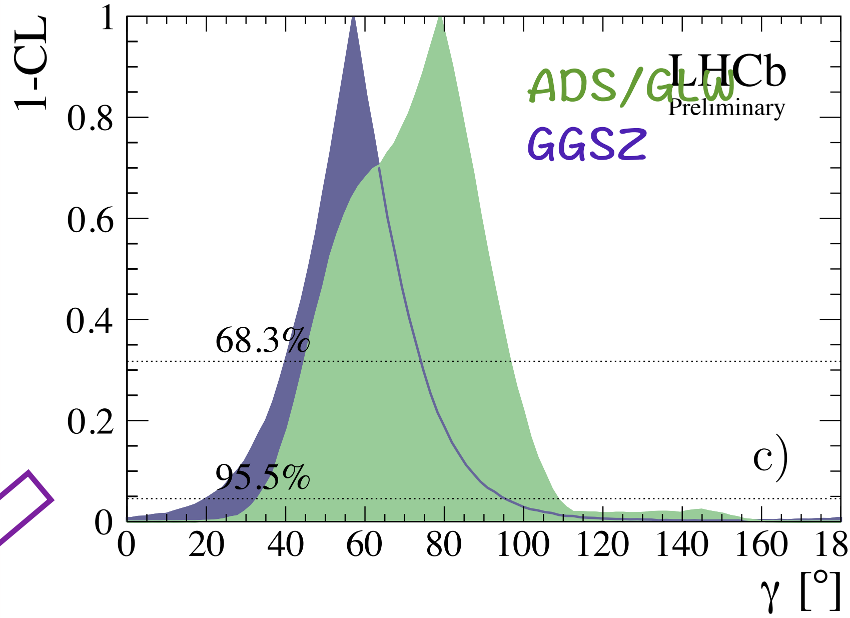
gamma: combination of LHCb measurements

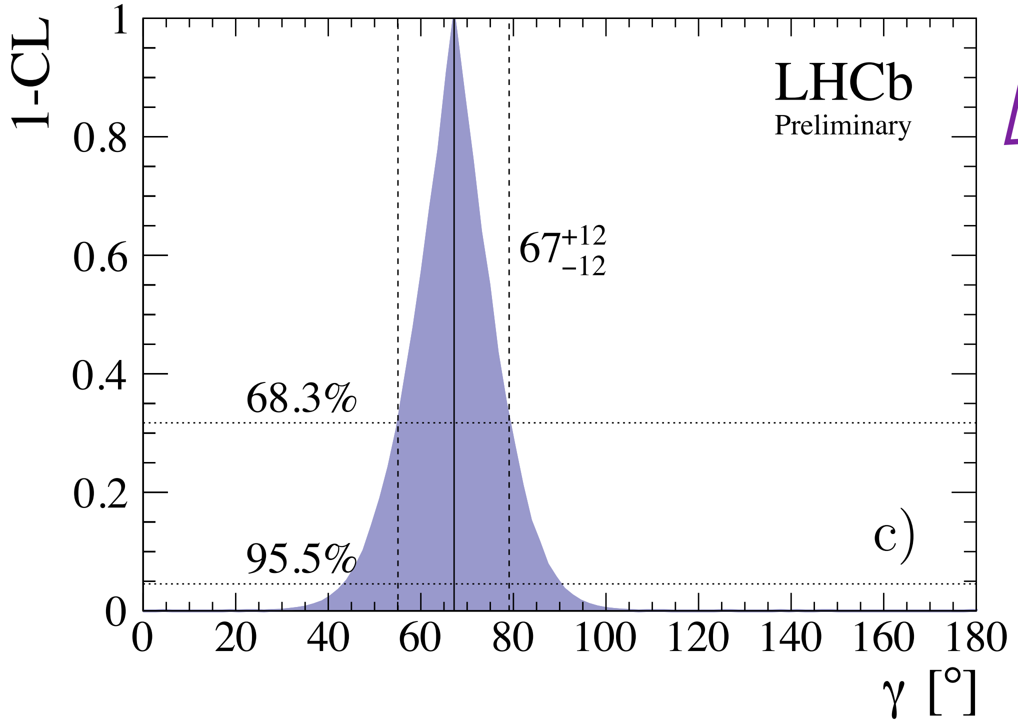
- LHCb B->DK results combined to extract single confidence interval

Combination uses

- ADS/GLW: 1/fb (2011)
- GGSZ: 3/fb (2011 + 2012)

LHCB-CONF-2013-006 (prel.)





- result: $\gamma = (67 \pm 12)^\circ$ preliminary

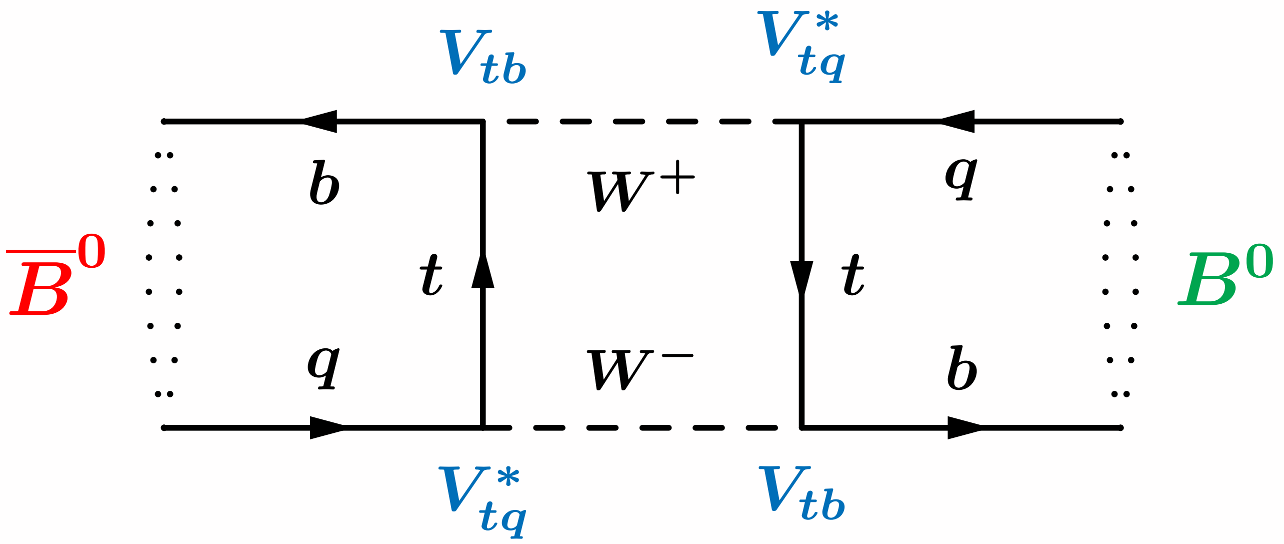
- most precise value from single experiment
- in good agreement with Belle and Babar

- sensitivity to gamma will improve further when ADS/GWL extended to 3/fb
- combination with B->Dπ exists, but only for 2011 data

arXiv:1305.2050,PLB726(2013)151

Neutral meson mixing

- neutral meson flavour states mix via this weak interaction loop diagram

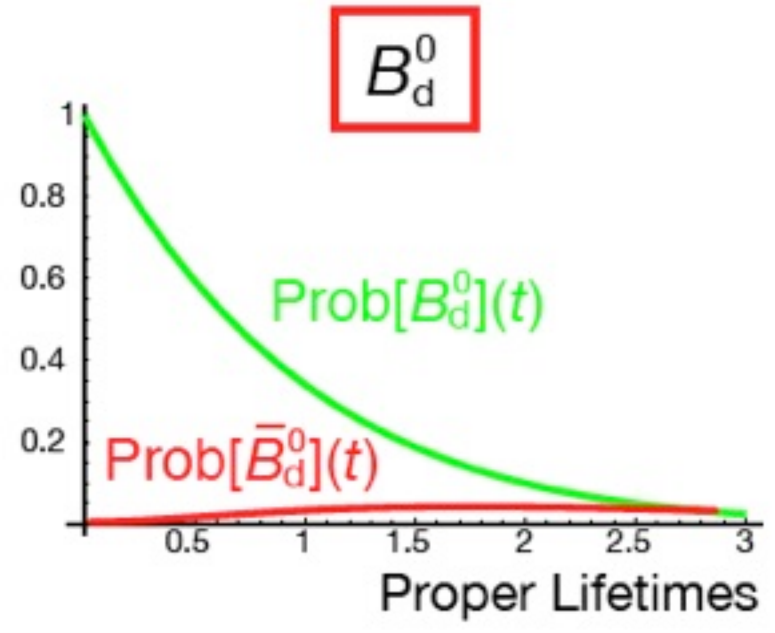


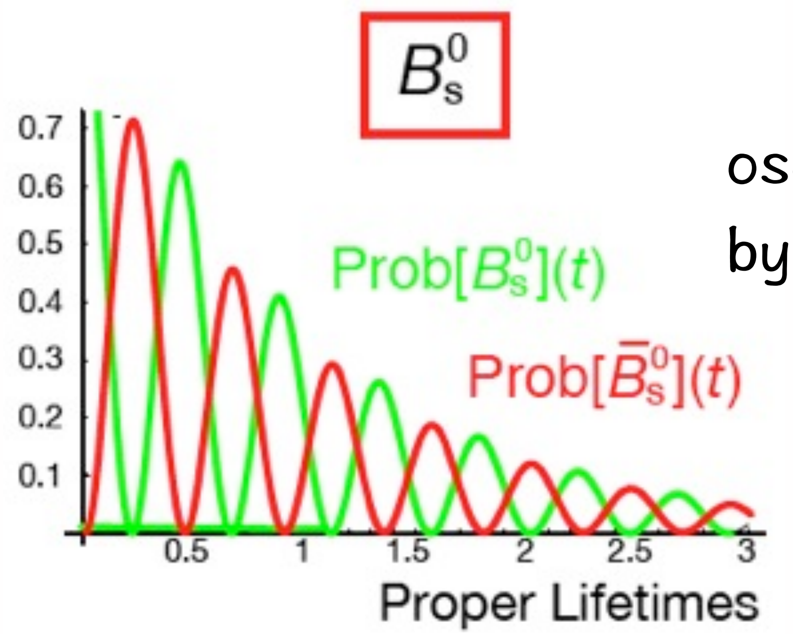
2nd order weak process

very sensitive to BSM contributions

- heavy (H) and light (L) mass eigenstates are mixture of flavour eigenstates

$$
\begin{aligned}
|B_L\rangle &= p\,|B^0\rangle + q\,|\overline{B}^0\rangle \\
|B_H\rangle &= p\,|B^0\rangle - q\,|\overline{B}^0\rangle
\end{aligned}
$$





oscillation frequency governed by mass difference

Neutral meson mixing

- mixing and decay described by Schroedinger equation

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\langle B^0|B(t)\rangle\\ \langle \overline{B}^0|B(t)\rangle\end{pmatrix}=\begin{pmatrix}M_{11}-\frac{i}{2}\Gamma_{11} & M_{12}-\frac{i}{2}\Gamma_{12}\\ M_{21}-\frac{i}{2}\Gamma_{21} & M_{22}-\frac{i}{2}\Gamma_{22}\end{pmatrix}\begin{pmatrix}\langle B^0|B(t)\rangle\\ \langle \overline{B}^0|B(t)\rangle\end{pmatrix}$$

- phenomenology described in terms of 5 observables

$$\boxed{m\equiv\frac{m_H+m_L}{2}}\qquad\boxed{\Gamma\equiv\frac{\Gamma_H+\Gamma_L}{2}}\qquad\boxed{\Delta m\equiv m_H-m_L\simeq 2|M_{12}|}$$

$$\boxed{\Delta\Gamma\equiv\Gamma_L-\Gamma_H\simeq 2\,|\Gamma_{12}|\cos\phi_{12}}\qquad\boxed{1-\left|\frac{q}{p}\right|^2=\frac{|\Gamma_{12}|}{|M_{12}|}\sin\phi_{12}}$$

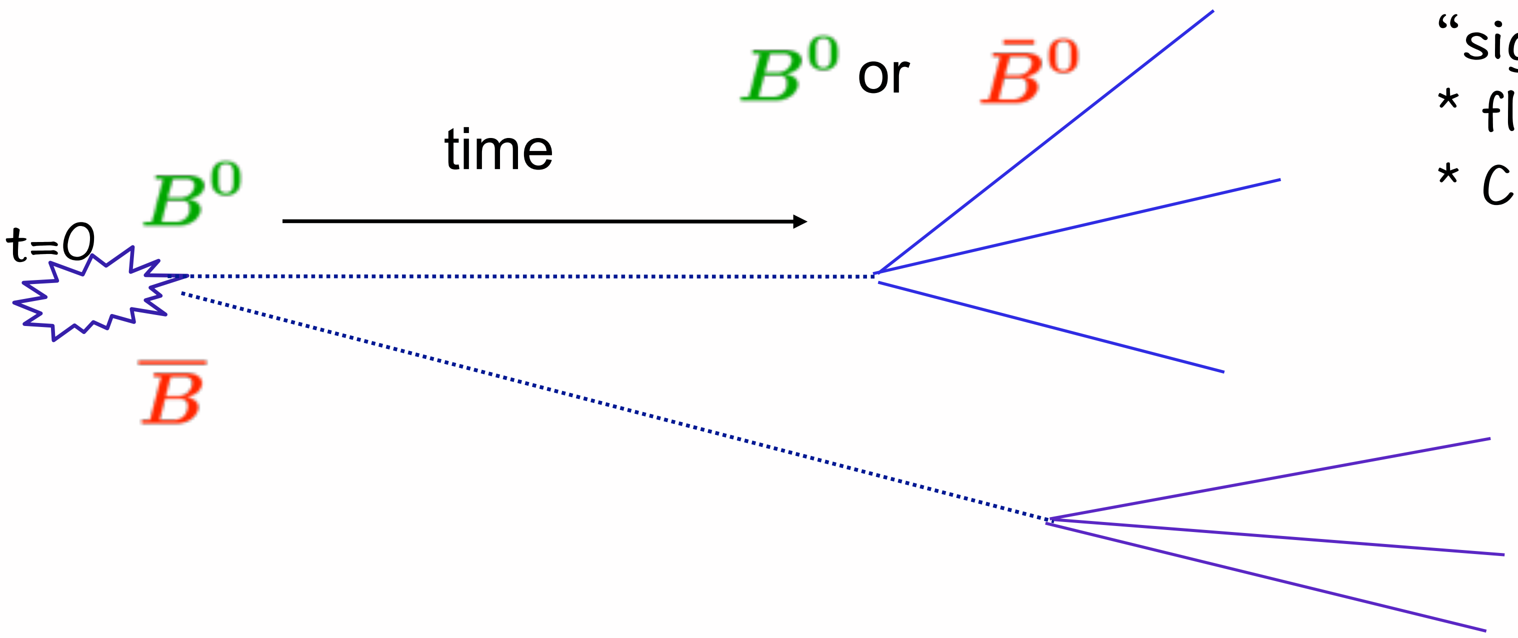
CP violation, small in SM

clean predictions in SM

- M_{12} and Γ_{12}: mixing amplitudes via off-shell and on-shell states, respectively
- CP violating phase ϕ_{12} is their relative phase: $\boldsymbol{\phi_{12}\equiv\arg\left(-M_{12}/\Gamma_{12}\right)}$
  - in SM close to zero both in Bs and Bd system

Experimental observables in B mixing

- decay time allows to observe time-evolution

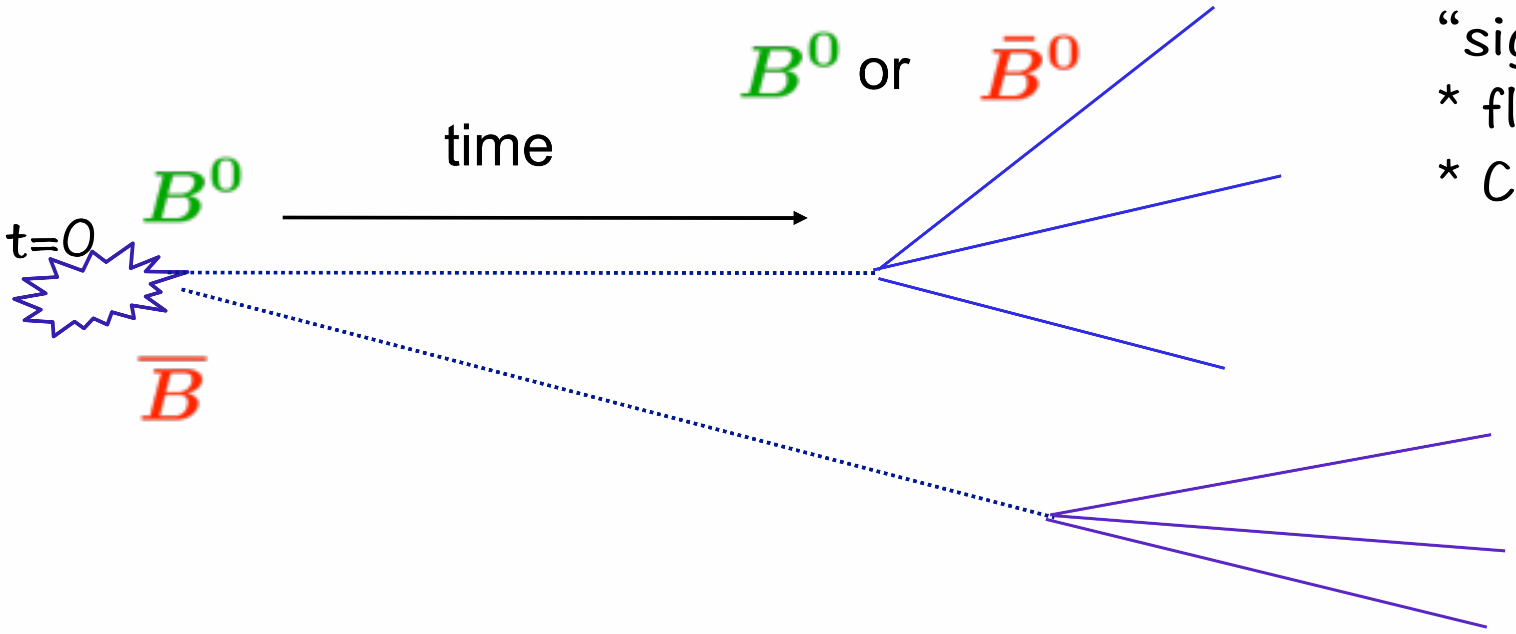


"signal B":
* flavour specific decays
* CP eigenstates

"tagging B": determines flavour of signal B at t=0

Experimental observables in B mixing

- decay time allows to observe time-evolution



"signal B":
* flavour specific decays
* CP eigenstates

"tagging B": determines flavour of signal B at t=0

- four types of observables

1. oscillations:

$$A^{\mathrm{mix}}(t) = \frac{N^{B^0\overline{B}^0|\overline{B}^0B^0} - N^{B^0B^0|\overline{B}^0\overline{B}^0}}{N^{B^0\overline{B}^0|\overline{B}^0B^0} + N^{B^0B^0|\overline{B}^0\overline{B}^0}} = \cos(\Delta m_q t)$$

2. CPV in mixing:

$$a_{fs} \equiv \frac{N^{B^0B^0} - N^{\overline{B}^0\overline{B}^0}}{N^{B^0B^0} + N^{\overline{B}^0\overline{B}^0}} = \frac{1-|q/p|^4}{1+|q/p|^4}$$

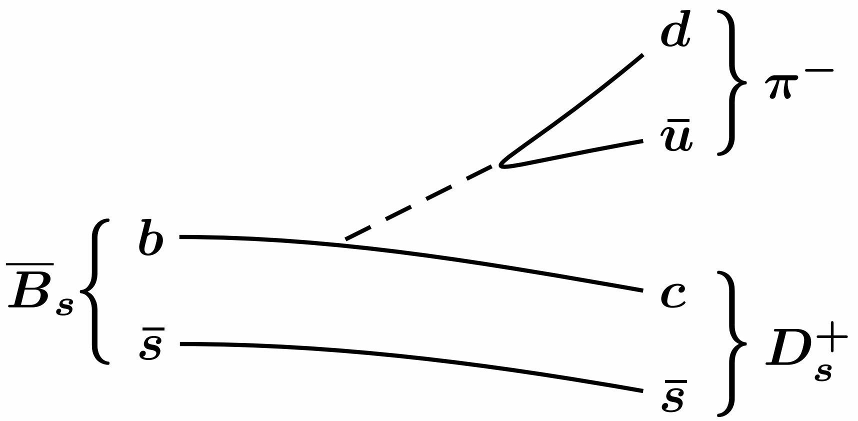
3. CPV in interference between mixing and decay (time-dependent CPV)

4. lifetimes

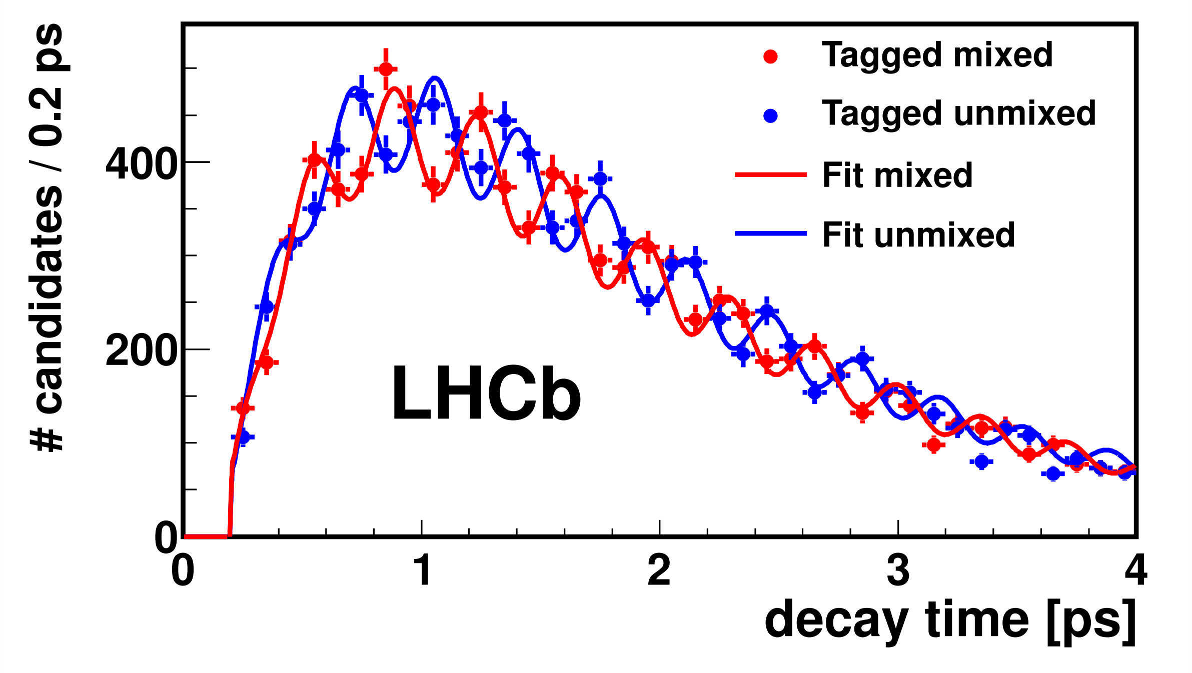
Mixing frequency

arXiv:1304.4741, New J. Phys. 15 (2013) 053021

- most easy mode: $B_s \rightarrow D_s^- \pi^+$



~34k signal events in 1.0/fb



opposite side tagger: Eur.Phys.J. C72(2012) 2022

same side tagger: LHCb-CONF-2012-033

$$N_{\pm}(t) \;\propto\; \mathrm{eff}(t) \;\times\; e^{-\Gamma t} \;\times\; \left(1 \pm D \cos(\Delta m\, t)\right)$$

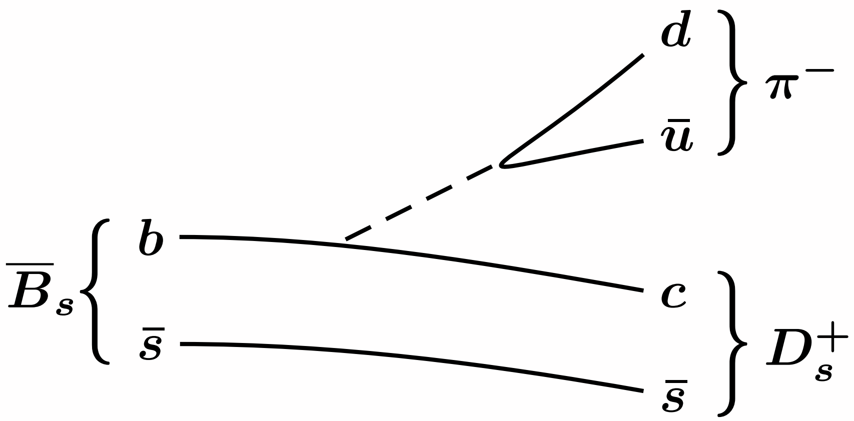
experimental 'dilution':
- wrong flavour tagging
- decay time resolution

decay time efficiency

Mixing frequency

arXiv:1304.4741, New J. Phys. 15 (2013) 053021

- most easy mode: $B_s \rightarrow D_s^- \pi^+$



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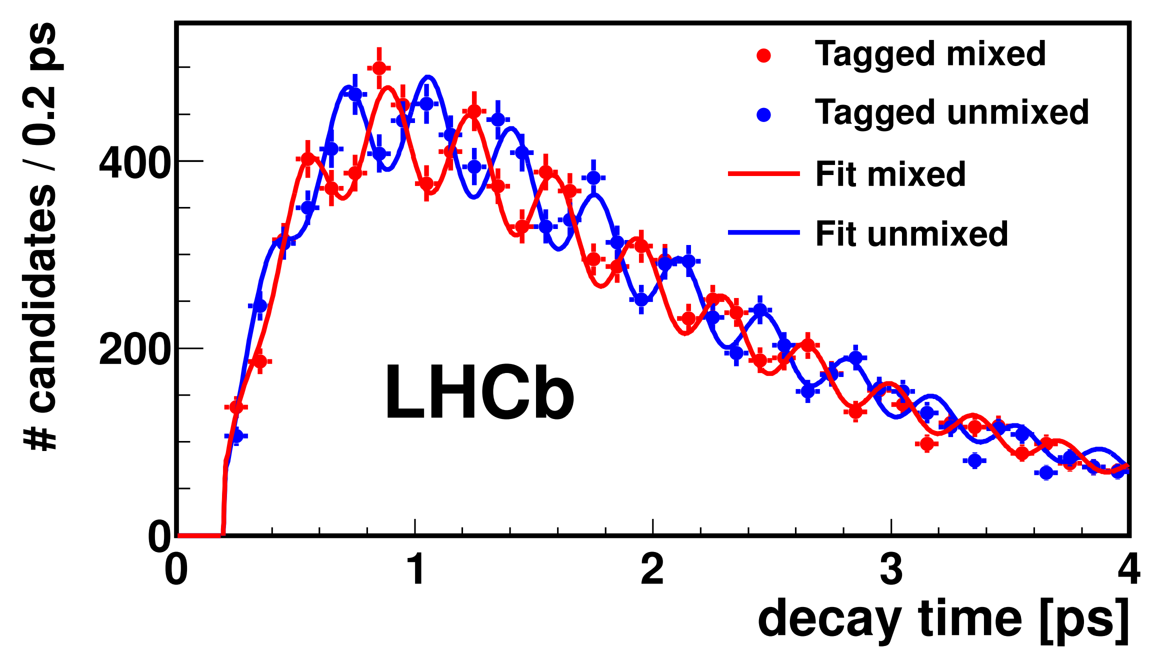

opposite side tagger: Eur.Phys.J. C72(2012) 2022

same side tagger: LHCb-CONF-2012-033

$$N_\pm(t) \;\propto\; \mathrm{eff}(t) \;\times\; e^{-\Gamma t} \;\times\; \left(1 \;\pm\; D\; \cos\left(\Delta m\, t\right)\right)$$

- result (arXiv:1304.4741):

$$\boxed{\Delta m_s \;=\; 17.768 \pm 0.023\,(\mathrm{stat}) \pm 0.006\,(\mathrm{syst})}$$

- world's most precise measurement
- compatible with SM prediction

$\Delta m_s^{\mathrm{SM}} \;=\; 17.3 \pm 2.6$ (Lenz and Nierste, 2011)

Time-dependent CP violation

- common final state f : mixing induced CPV

$$\begin{tikzcd}
B^0 \arrow[rr, "\phi_D"] \arrow[dr, "\phi_M"'] & & f \\
& \bar{B}^0 \arrow[ur, "-\phi_D"'] &
\end{tikzcd}$$

- if f is CP eigenstate, time dependent CP violation with pattern

$$A_{\mathrm{CP}}(t) \equiv \frac{N(\overline{B} \to f) - N(B \to f)}{N(\overline{B} \to f) + N(B \to f)} = D \quad \eta_f^{\mathrm{CP}} \quad \sin\phi_f \quad \sin(\Delta m\, t)$$

$$\phi_f = \phi_M - 2\phi_D$$

$$\eta_f^{\mathrm{CP}} = \pm 1$$

experimental dilution

flavour ‘tag’ at t=0

Time-dependent CP violation

- common final state f : mixing induced CPV

$$\begin{tikzcd}
B^0 \arrow[rr, "\phi_{\mathrm{D}}"] \arrow[dr, "\phi_M"'] & & f \\
& \bar{B}^0 \arrow[ur, "-\phi_{\mathrm{D}}"'] &
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$$A_{\mathrm{CP}}(t) \equiv \frac{N(\overline{B} \to f) - N(B \to f)}{N(\overline{B} \to f) + N(B \to f)} = D \;\; \eta_f^{\mathrm{CP}} \;\; \sin\phi_f \;\; \sin(\Delta m\, t)$$

$$\phi_f = \phi_M - 2\phi_D$$

- 'golden' modes:

$$B_d \to \psi K_s : \quad \phi_{J/\psi K_s} = 2\beta \quad \overset{SM}{=} 50^\circ - 55^\circ$$

$$B_s \to \psi\phi : \quad \phi_{J/\psi\phi} = -2\beta_s \quad \overset{SM}{=} -2.1^\circ \pm 0.1^\circ$$

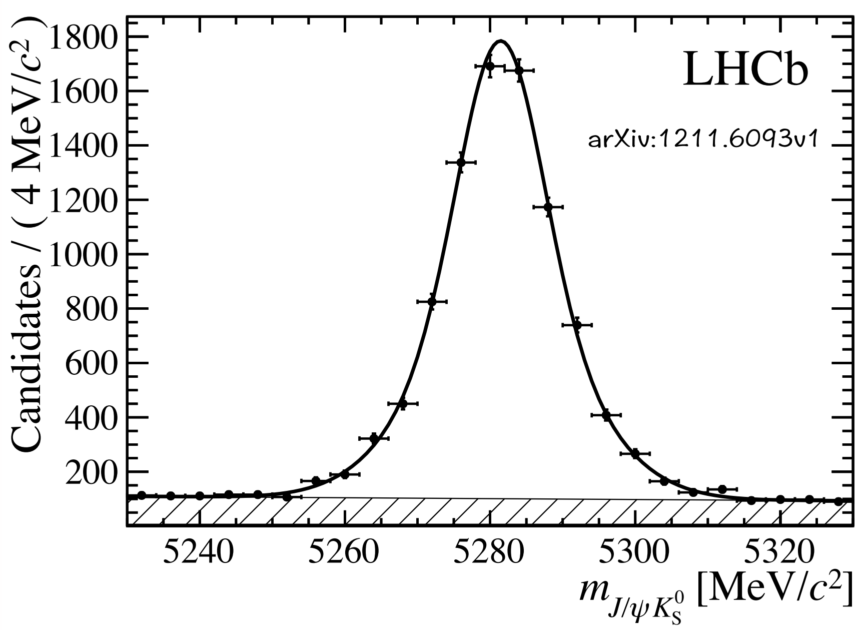
(SM predictions from CKMFitter, PRD83,036004 and UFTit 2010)

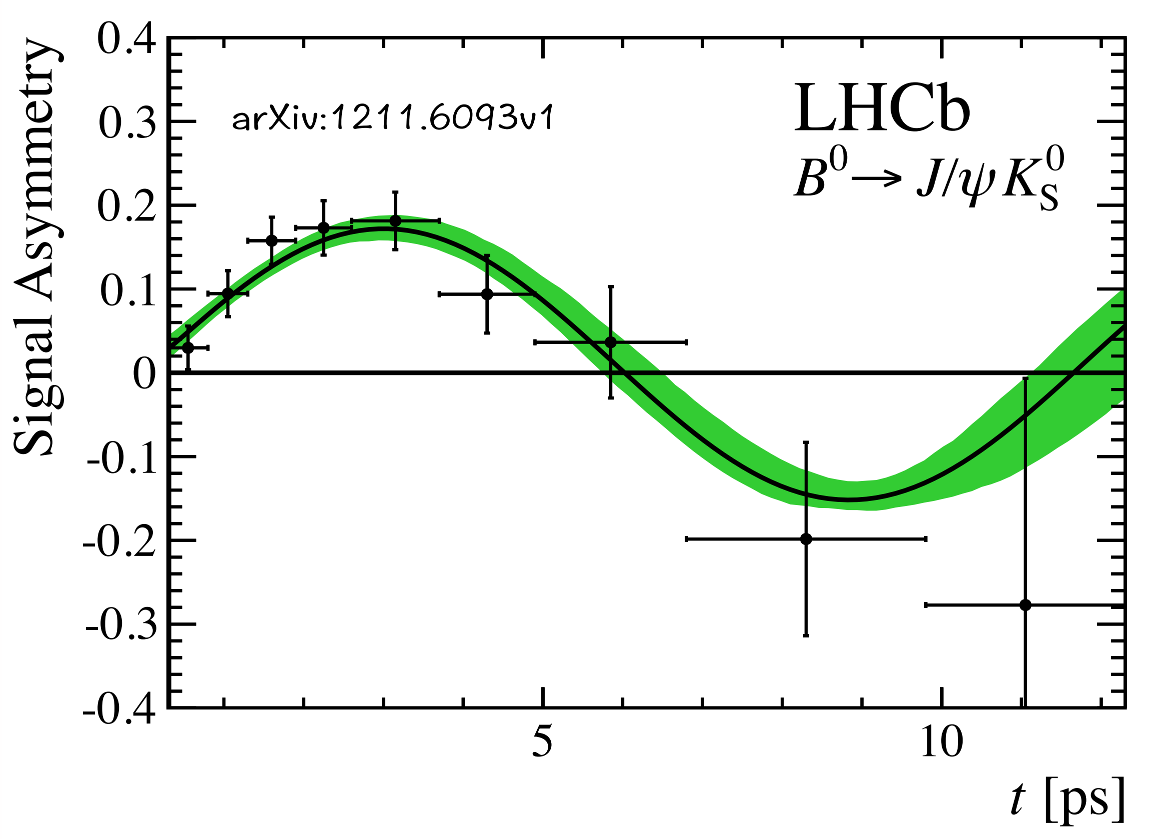
- new phase in mixing ⇒ $\phi_f = \phi_f^{\mathrm{SM}} + \delta\phi_M^{\mathrm{NP}}$

$B_d \to J/\psi\ K_s$ at LHCb

arXiv:1211.6093, PLB 721 (2013) 24-31

- important test: can we reproduce B-factory results?
- LHCb has ~8200 B_d->$J/\psi\ K_s$ candidates in 1.0/fb





$$A_{\rm CP}(t) = D \sin 2\beta \sin(\Delta m\, t)$$

$$D_{\rm tag} = 0.270 \pm 0.015$$

$$\epsilon_{\rm tag} = (2.4 \pm 0.3)\%$$

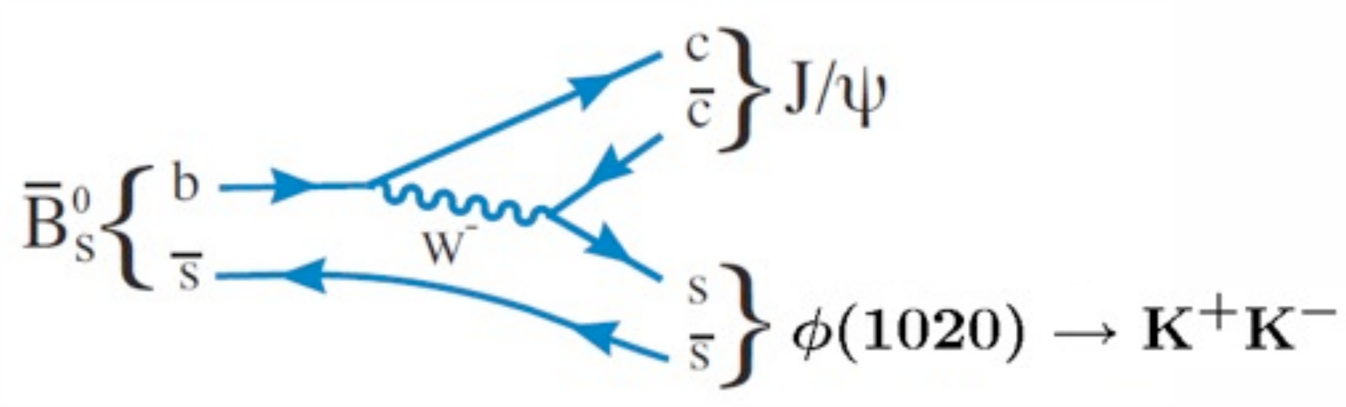
- result (1.0/fb, arXiv:1211.6093):

$$\boxed{S_{J/\psi\, K_S^0} = 0.73 \pm 0.07\,({\rm stat}) \pm 0.04\,({\rm syst}),}$$

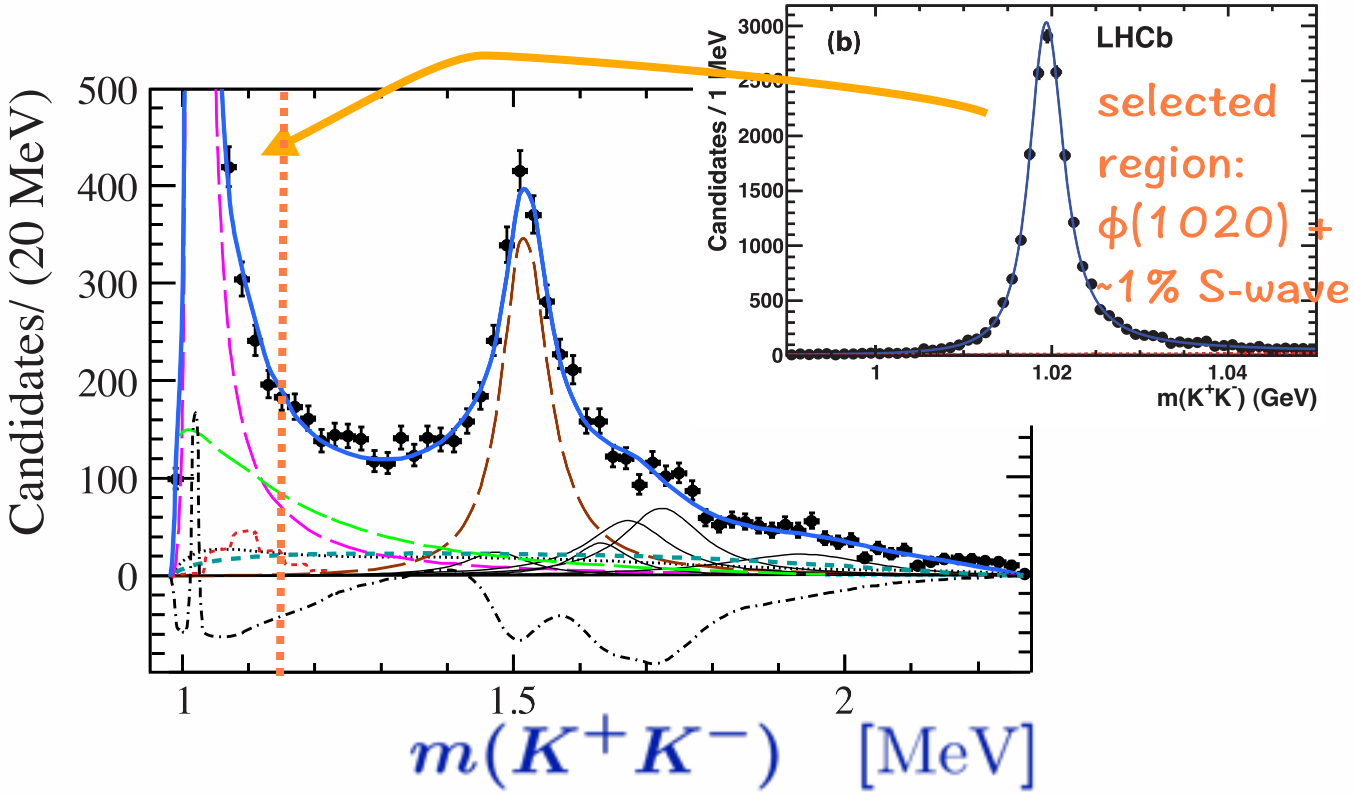
- in good agreement with WA: $\sin 2\beta^{\rm WA} = 0.679 \pm 0.020$

ϕ_s at LHCb

- two most interesting modes:

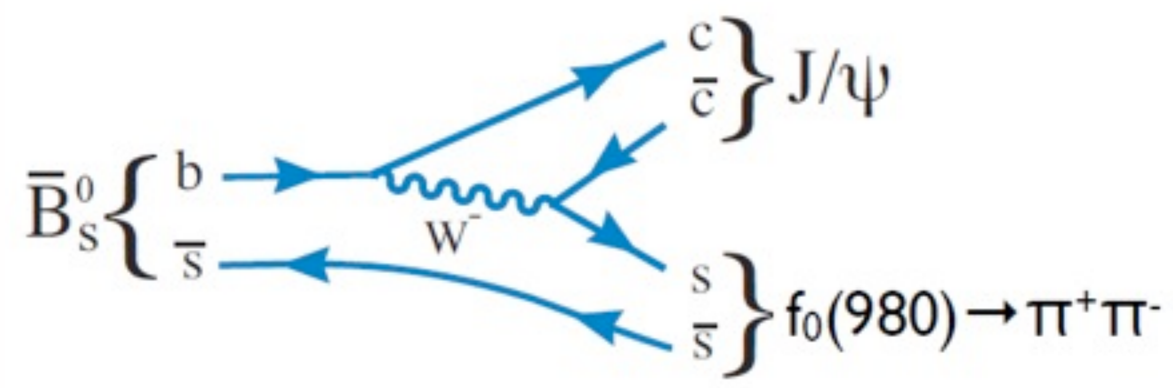


- narrow φ resonance --> clean
- vector-vector final state

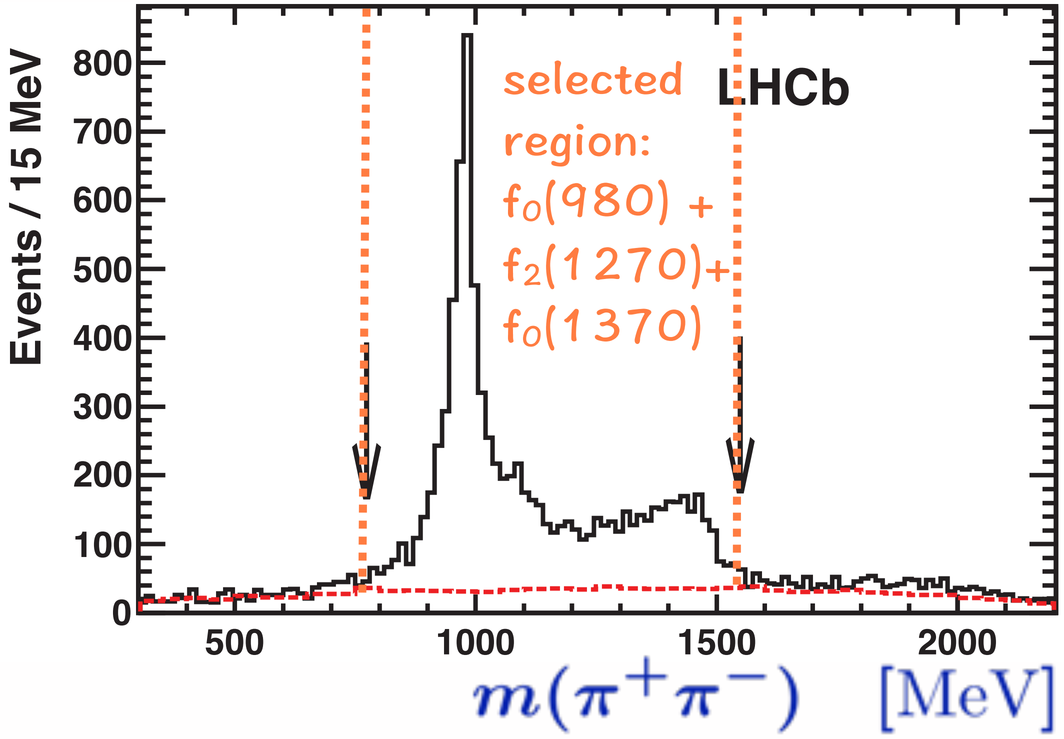


selected region: $\phi(1020)$ + ~1% S-wave

Dalitz analysis: LHCb-PAPER-2012-040, arXiv:1302.1213 (accepted by PRD)



- yield about 1/3 of $B_s \to J/\psi\,\varphi$
- vector-pseudo-scalar final state

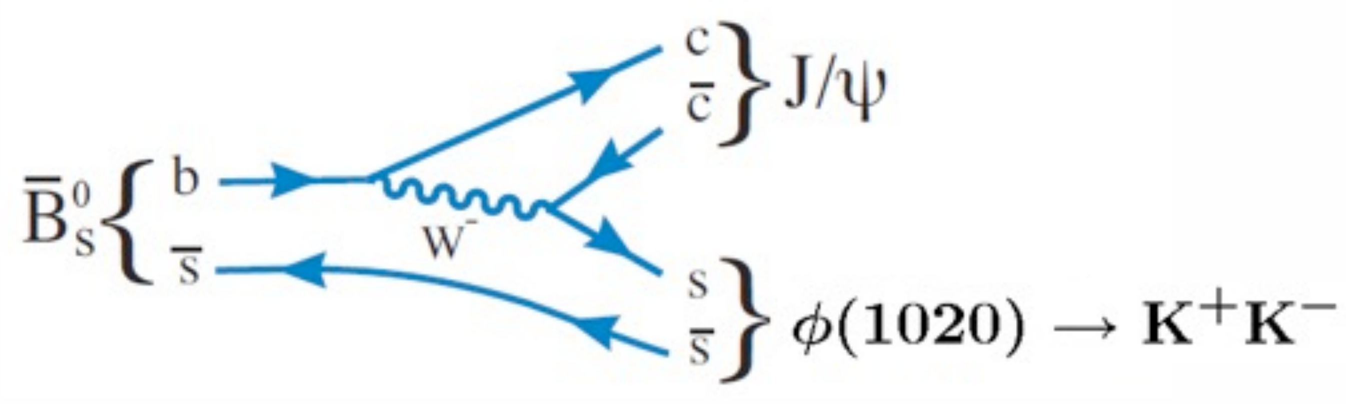


selected region: $f_0(980)$ + $f_2(1270)$+ $f_0(1370)$

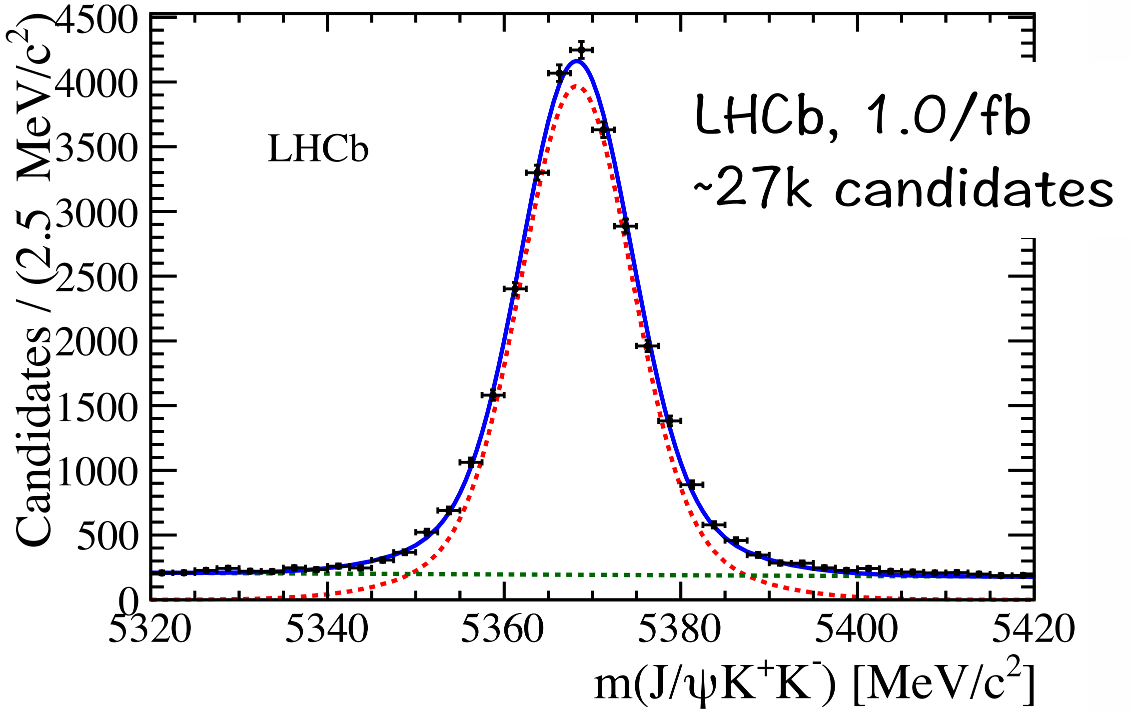
Dalitz analysis: LHCb-PAPER-2012-005, PRD86(2012)052006

ϕ_s at LHCb

- two most interesting modes:

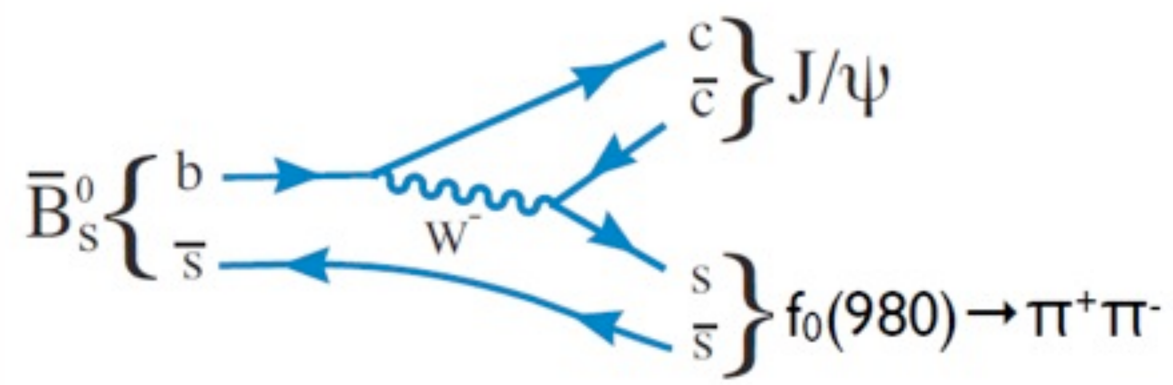


- narrow φ resonance --> clean
- vector-vector final state

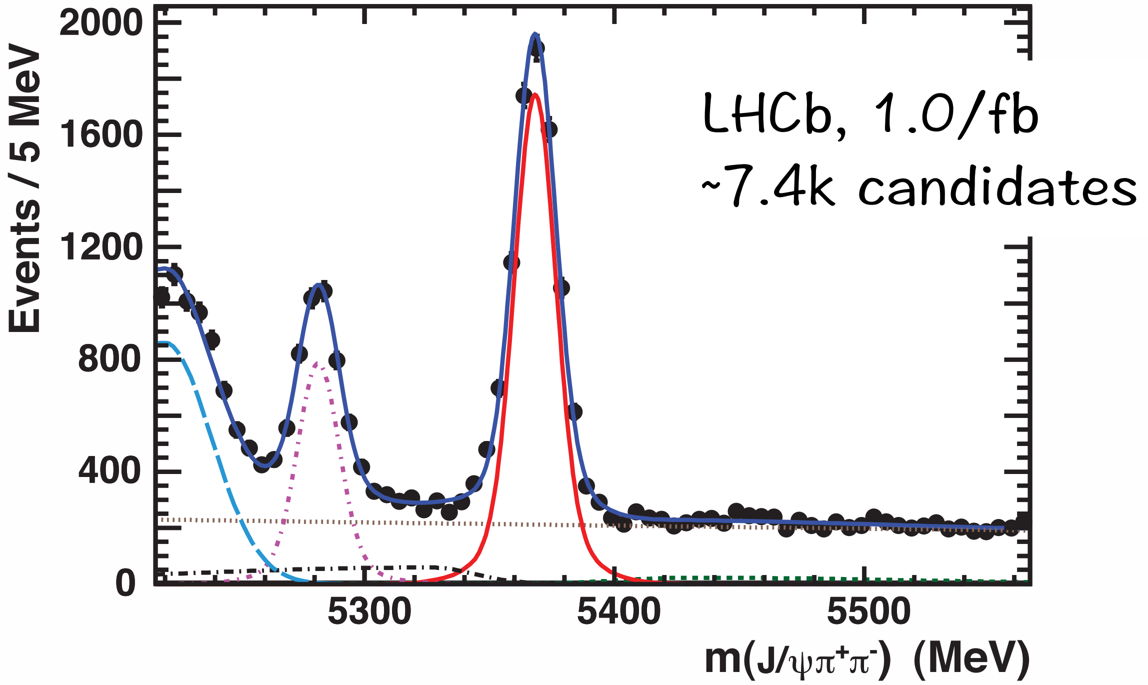


LHCb, 1.0/fb
~27k candidates

LHCb-PAPER-2013-002



- yield about 1/3 of $B_s \to J/\psi\,\varphi$
- vector-pseudo-scalar final state



LHCb, 1.0/fb
~7.4k candidates

LHCb-PAPER-2012-006,
Phys. Lett. B713 (2012) 378

Time-dependent CPV

- common final state f : mixing induced CPV

$$\begin{tikzcd} B^0 \arrow[rr, "\phi_{\mathrm{D}}"] \arrow[dr, "\phi_M"'] & & f \\ & \bar{B}^0 \arrow[ur, "-\phi_{\mathrm{D}}"'] & \end{tikzcd}$$

- if f is CP eigenstate, time dependent CP violation with pattern

$$A_{\mathrm{CP}}(t) \equiv \frac{N(\overline{B} \to f) - N(B \to f)}{N(\overline{B} \to f) + N(B \to f)} = D \;\; \eta_f^{\mathrm{CP}} \;\; \sin\phi_f \;\; \sin(\Delta m\, t)$$

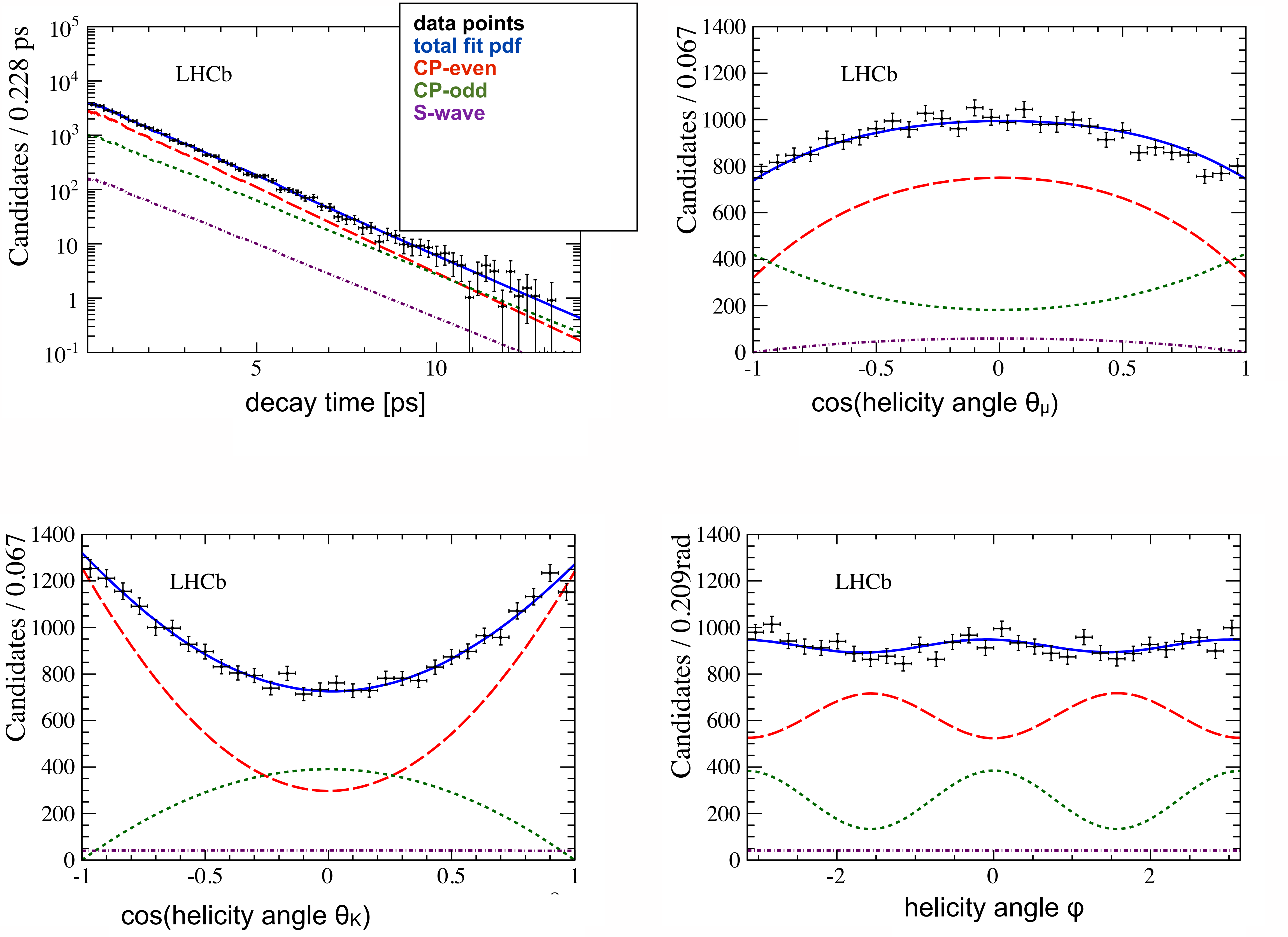
- CP eigenvalue: $\eta_f^{\mathrm{CP}} = (-1)^L$
  - Bs->J/ψ $f_{0,2}$: CP-odd (see also LHCb-PAPER-2012-005)
  - Bs->J/ψϕ : mixture of CP-odd and CP-even

    ➔ needs 'angular analysis': include 4-body decay-angles in fit

- ambiguity: $(\phi_s, \Delta\Gamma_s) \longleftrightarrow (\pi - \phi_s, -\Delta\Gamma_s)$

MLL fit for $B_s \to J/\psi\,\varphi$

arXiv:1304.2600, Phys. Rev. D 87, 112010 (2013)



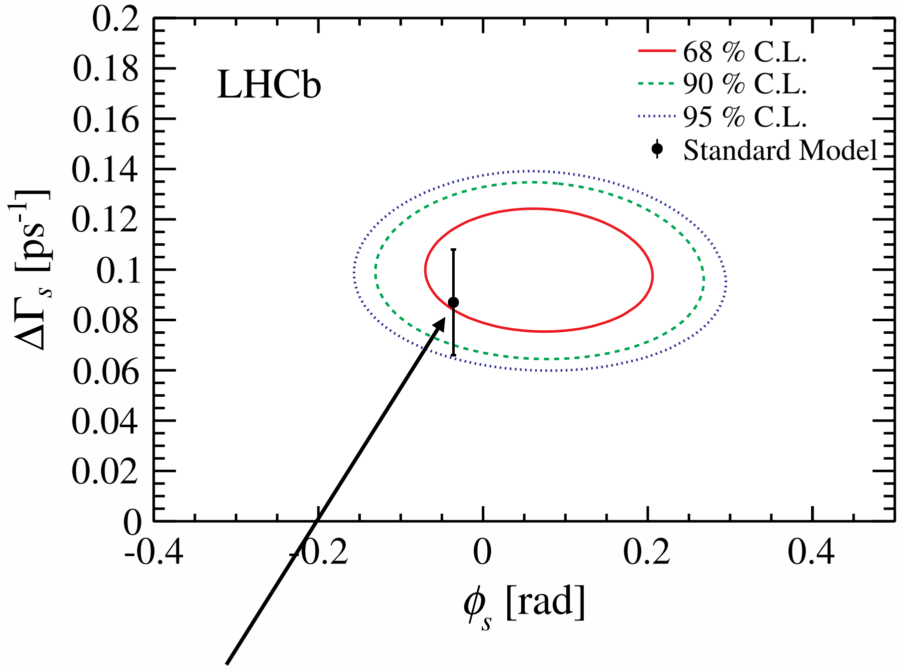
Fit results

arXiv:1304.2600, Phys. Rev. D 87, 112010 (2013)

- result for mixing parameters of J/psiKK fit

$$
\boxed{\begin{aligned}
\phi_s &= 0.07 \quad \pm 0.09 \quad (\text{stat}) \pm 0.01 \quad (\text{syst})\ \text{rad} \\
\Gamma_s &= 0.663 \pm 0.005\ (\text{stat}) \pm 0.006\ (\text{syst})\ \text{ps}^{-1} \\
\Delta\Gamma_s &= 0.100 \pm 0.016\ (\text{stat}) \pm 0.003\ (\text{syst})\ \text{ps}^{-1}
\end{aligned}}
$$

dominant systematics: angular and decay time acceptance



SM: Lenz and Nierste, arXiv: 1102.4274,
CKM fitter, arXiv:1106.4041

Fit results

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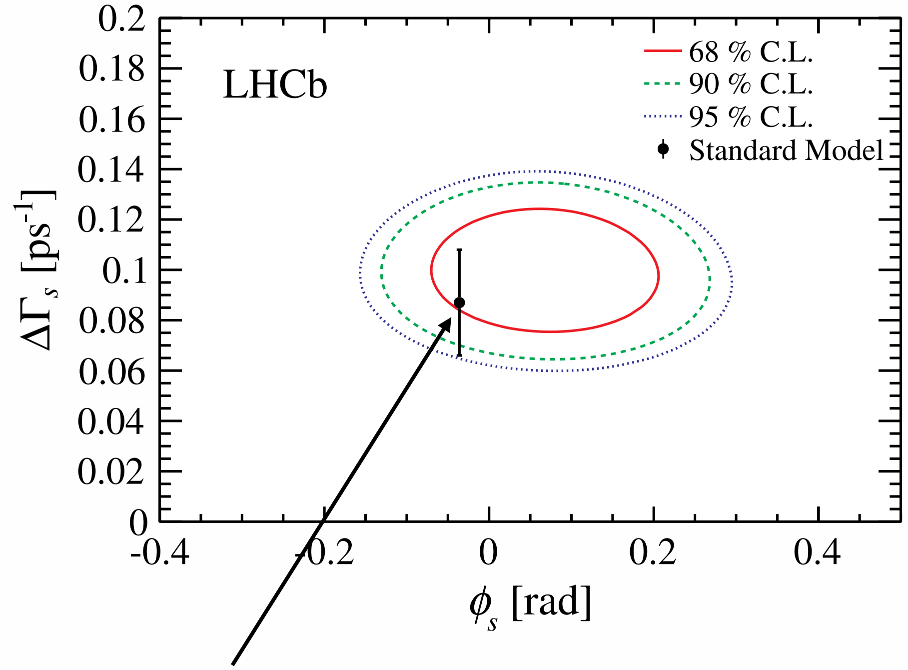
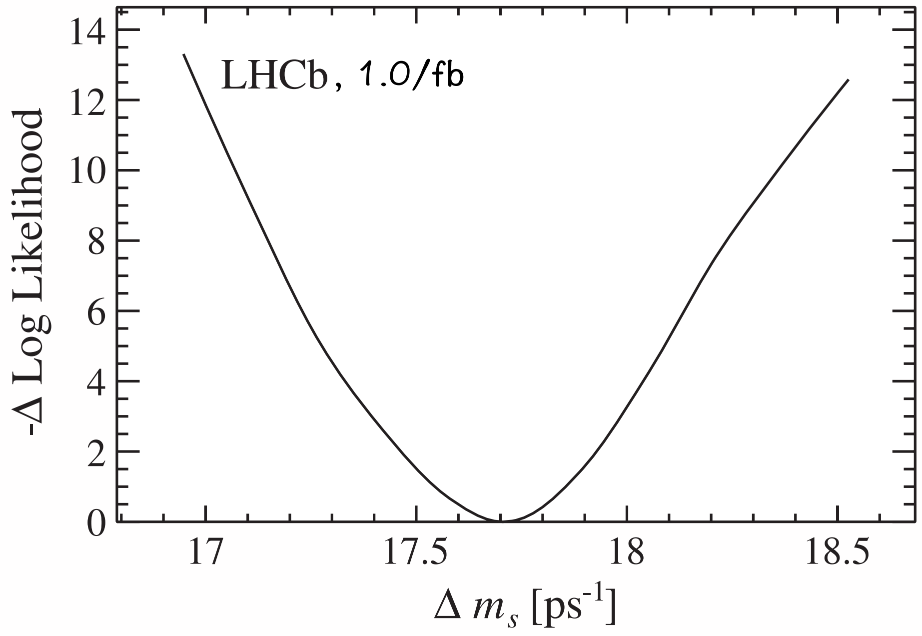
dominant systematics: angular and decay time acceptance



SM: Lenz and Nierste, arXiv: 1102.4274, CKM fitter, arXiv:1106.4041

- data now contains enough information to constrain also oscillation frequency



$$\boxed{\Delta m_s = 17.70 \pm 0.10\ (\text{stat}) \pm 0.01\ (\text{syst})\ \text{ps}^{-1}}$$

in perfect agreement with $B_s \to D_s\pi$

(and as good as Δm_s WA before start of LHC!)

Fit results

arXiv:1304.2600, Phys. Rev. D 87, 112010 (2013)

- result for mixing parameters of J/psiKK fit

$$\boxed{\begin{aligned}\phi_s &= 0.07 \pm 0.09\ (\mathrm{stat}) \pm 0.01\ (\mathrm{syst})\ \mathrm{rad}\\ \Gamma_s &= 0.663 \pm 0.005\ (\mathrm{stat}) \pm 0.006\ (\mathrm{syst})\ \mathrm{ps}^{-1}\\ \Delta\Gamma_s &= 0.100 \pm 0.016\ (\mathrm{stat}) \pm 0.003\ (\mathrm{syst})\ \mathrm{ps}^{-1}\end{aligned}}$$

dominant systematics: angular and decay time acceptance

- result for J/ψ $\pi^+\pi^-$ fit

$$\boxed{\phi_s = -0.14^{+0.17}_{-0.16} \pm 0.01\,\mathrm{rad}}$$

Phys. Lett. B713 (2012) 378
+ update in PRD87,112010 (2013)

- combination

$$\boxed{\begin{aligned}\phi_s &= 0.01 \pm 0.07\ (\mathrm{stat}) \pm 0.01\ (\mathrm{syst})\ \mathrm{rad},\\ \Gamma_s &= 0.661 \pm 0.004\ (\mathrm{stat}) \pm 0.006\ (\mathrm{syst})\ \mathrm{ps}^{-1},\\ \Delta\Gamma_s &= 0.106 \pm 0.011\ (\mathrm{stat}) \pm 0.007\ (\mathrm{syst})\ \mathrm{ps}^{-1}.\end{aligned}}$$

Fit results

arXiv:1304.2600, Phys. Rev. D 87, 112010 (2013)

- result for mixing parameters of J/psiKK fit

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dominant systematics: angular and decay time acceptance

- result for $J/\psi\ \pi^+\pi^-$ fit

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Phys. Lett. B713 (2012) 378
+ update in PRD87,112010 (2013)

- combination

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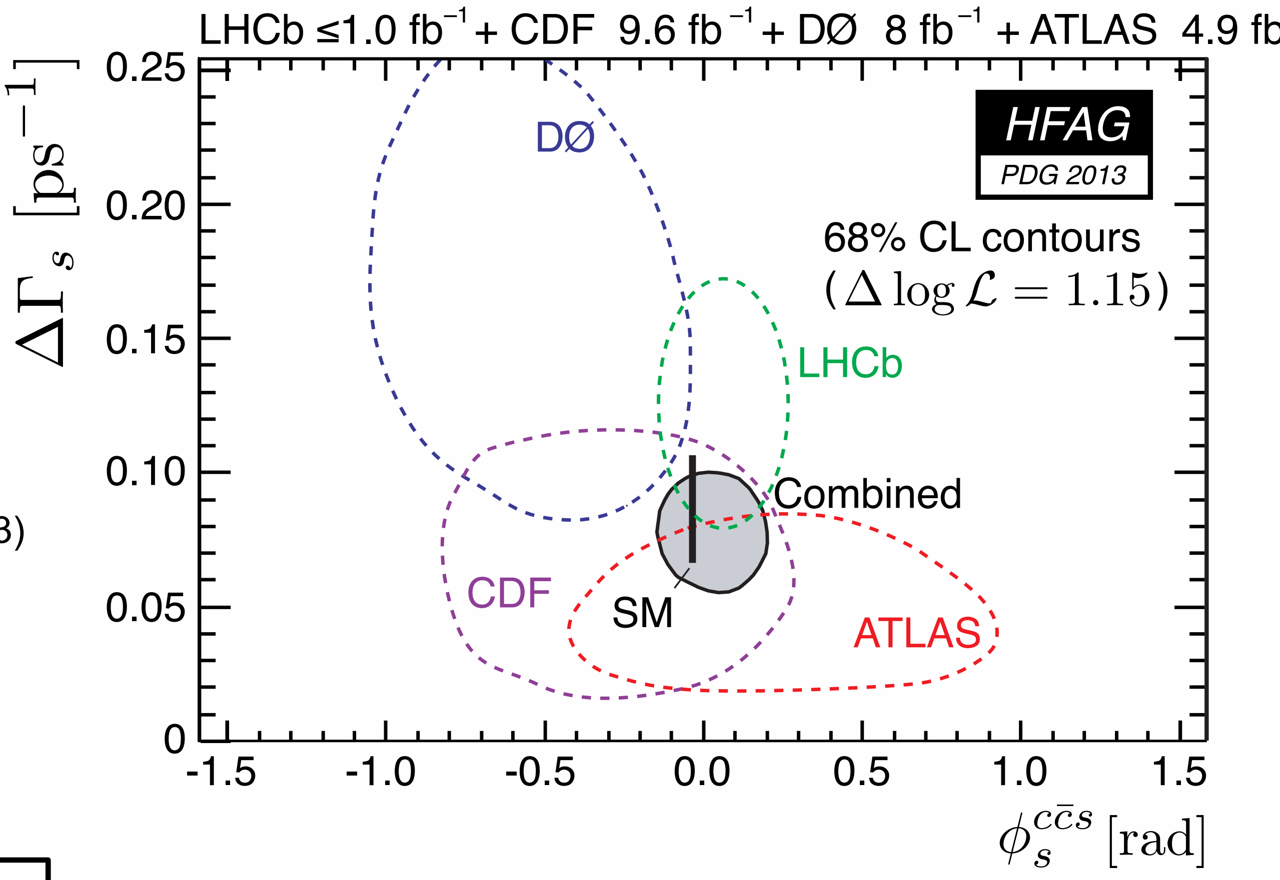


A closer look at lifetimes

- entangled states, with different lifetimes? you bet!

$$\tau^{\rm eff}_{KK} = 1.455 \pm 0.046\ ({\rm stat}) \pm 0.006\ ({\rm syst})\ {\rm ps}$$

arXiv:1207.5993, PLB 716 (2012) 393-400

$$\tau^{\rm eff}_{D_s^- D_s^+} = 1.379 \pm 0.026\ ({\rm stat}) \pm 0.017\ ({\rm syst})\ {\rm ps}$$

arXiv:1312.1217, subm. to PRL

$$\tau^{\rm eff}_{J/\psi\,\pi^+\pi^-} = 1.652 \pm 0.024\ ({\rm stat}) \pm 0.024\ ({\rm syst})\ {\rm ps}$$

arXiv:1304.2600, PRD 87, 112010 (2013)

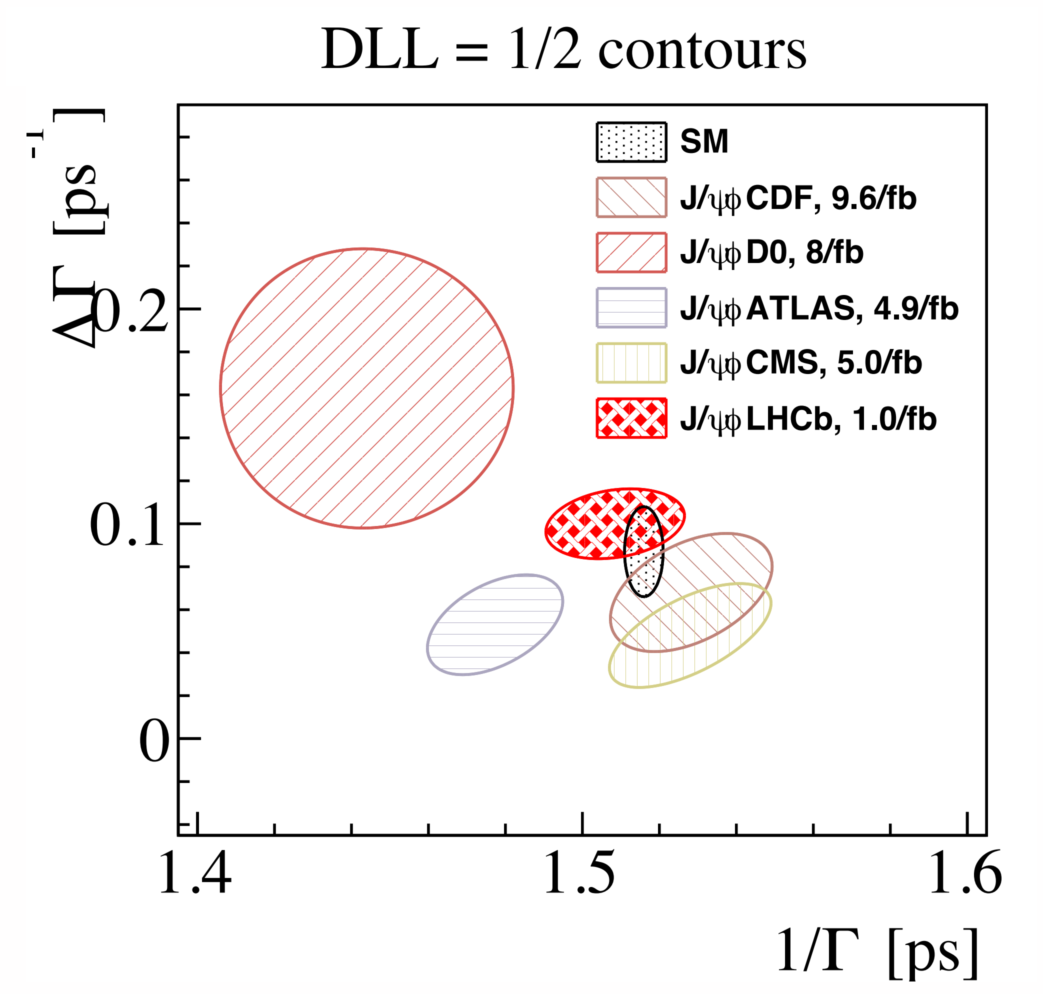
$$\tau^{\rm eff}_{J/\psi K^0_s} = 1.75 \pm 0.12\ ({\rm stat}) \pm 0.07\ ({\rm syst})\ {\rm ps}$$

arXiv:1304.4500, Nucl. Phys. B 873 (2013) 275

- states with different CP-content are sensitive to different combinations of Γ and ΔΓ (and ϕ_s)

(see also Fleischer and Knegjens, Eur.Phys.J. C71 (2011) 1789)

A closer look at lifetimes



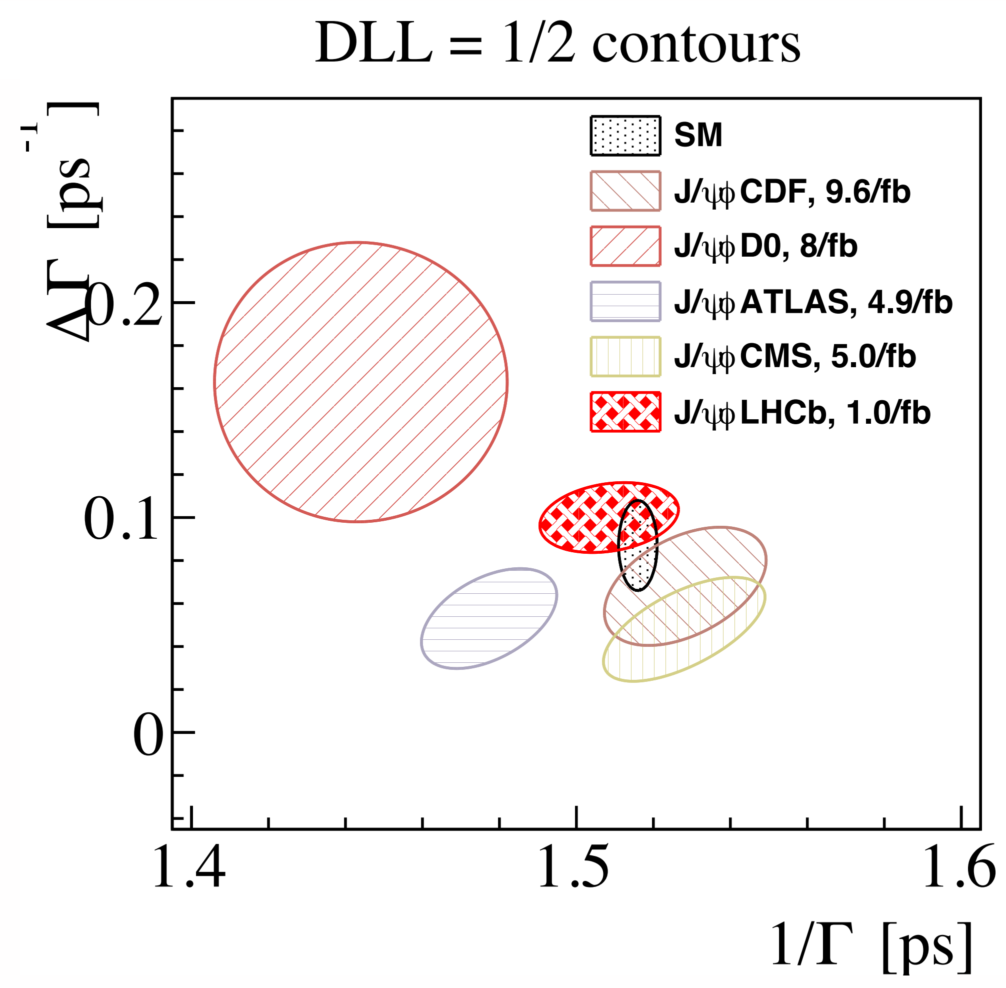
CDF: Phys. Rev. Lett 109, 171802 (2012)
D0: Phys. Rev. D **85**, 032006 (2012),
ATLAS: JHEP 12 (2012) 072
CMS: CMS-PAS-BPH-11-006

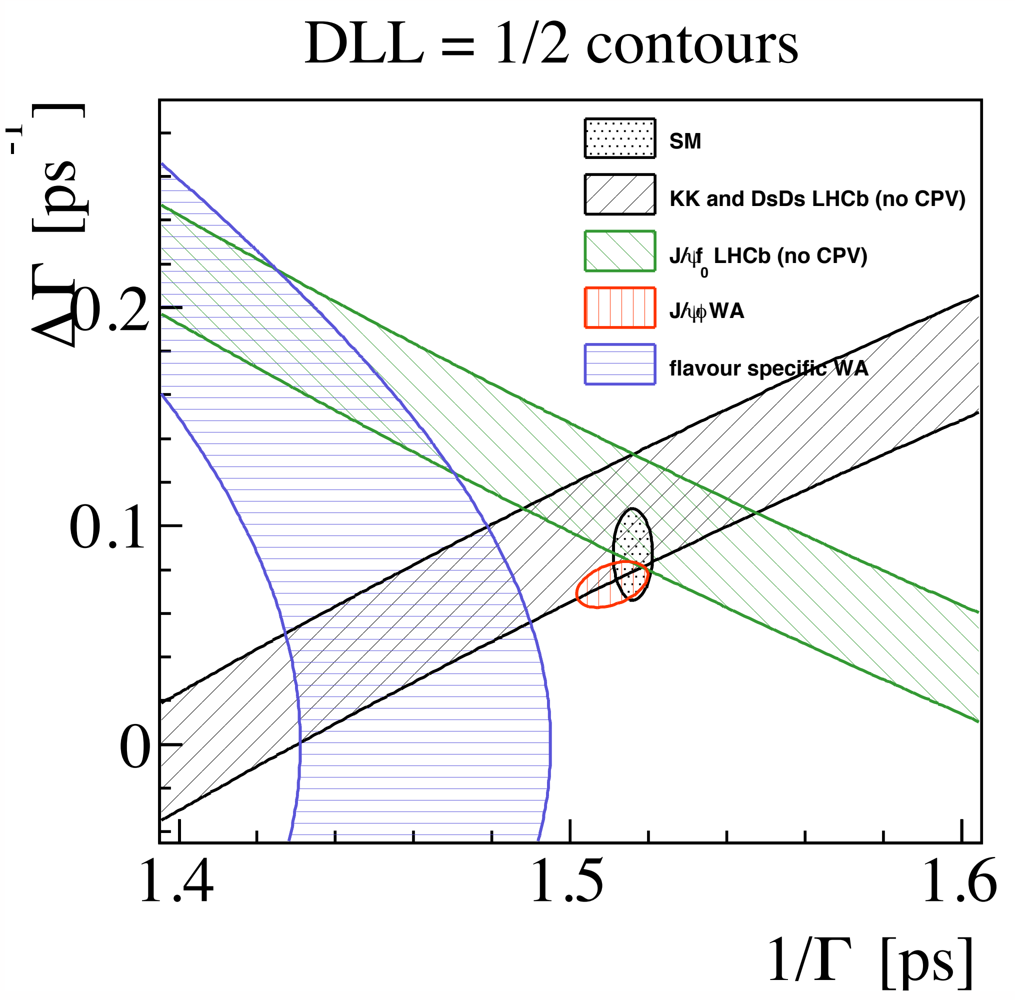
latest SM prediction: Lenz and Nierste, arXiv: 1102.4274

(Γ_s prediction uses $\tau_{B_d}^{\mathrm{WA}}$ and $-4 \cdot 10^{-4} < \dfrac{\tau_{B_s}}{\tau_{B_d}} - 1 < 0$)

- everything in agreement with mixing model and SM+HQE predictions

A closer look at lifetimes





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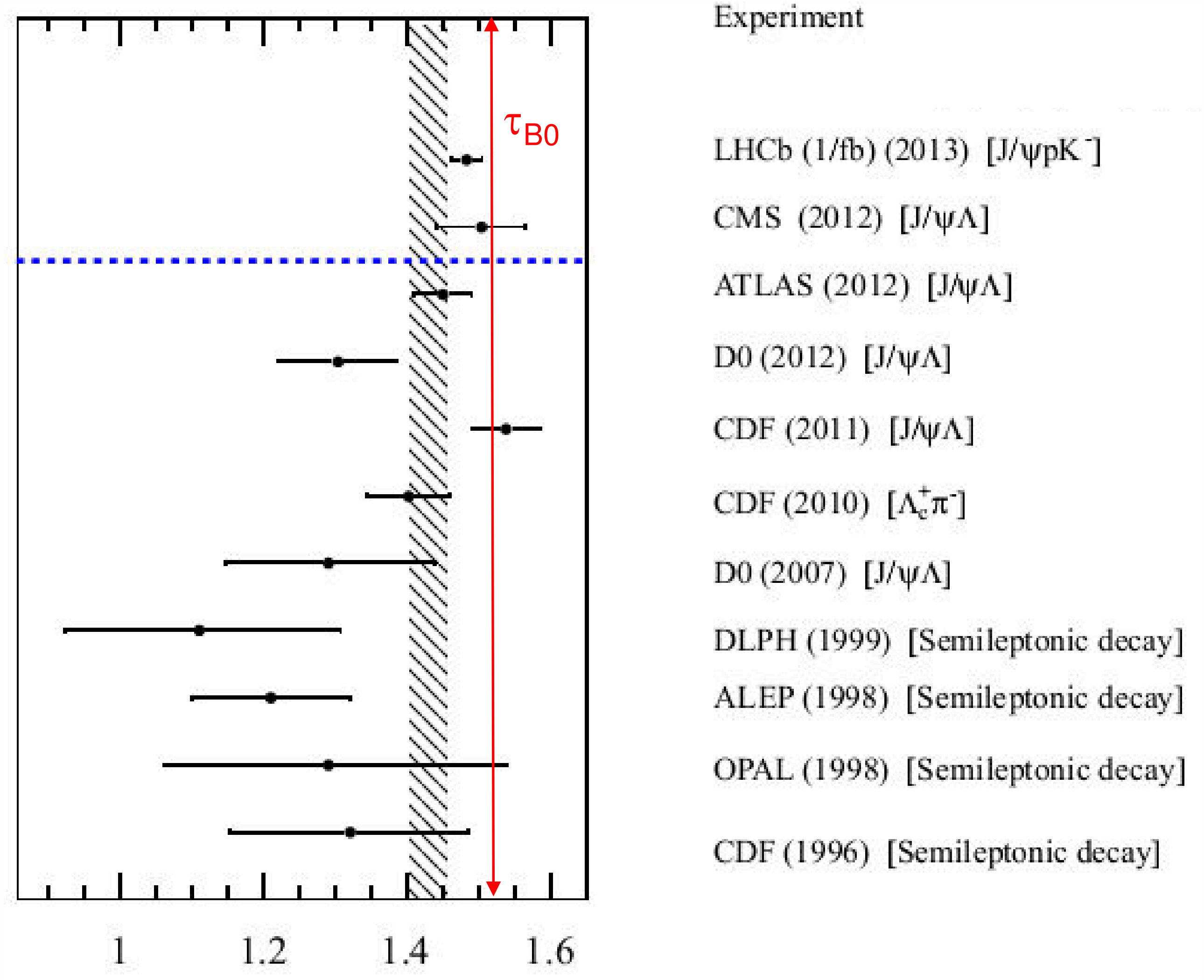
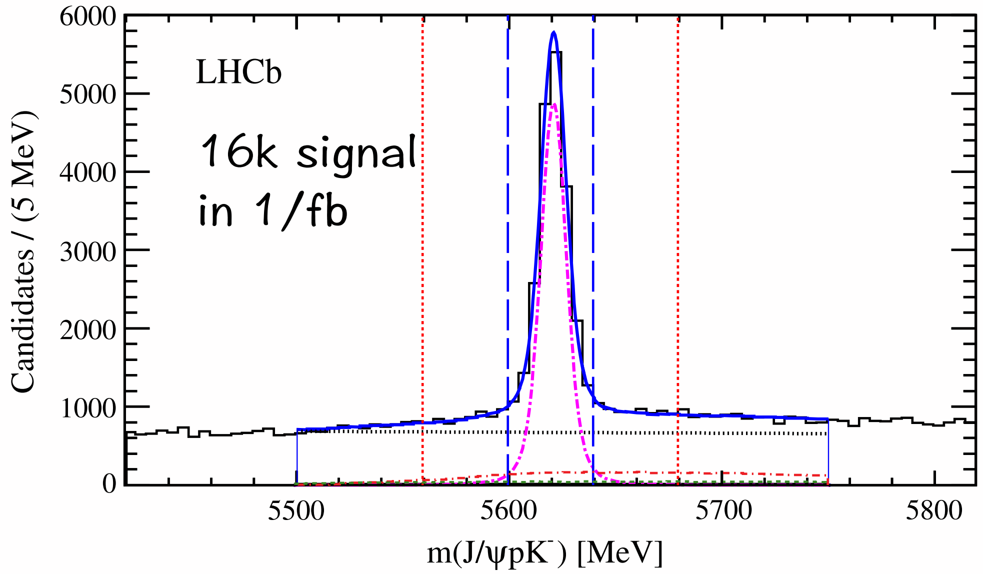
- everything in agreement with mixing model and SM+HQE predictions

Λ_b baryon lifetime

arXiv:1307.2476,
PRL 111 (2013) 102003

- clean prediction from HQE: $\tau(\Lambda_b) / \tau(B^0) = 1$ +/- few %
- long standing controversy: experiments measured 'too small' $\tau(\Lambda_b)$





- most recent LHCb measurement, using 16k $\Lambda_b \to J/\psi\, p\, K$ in 1/fb:

$$\boxed{\frac{\tau_{\Lambda_b^0}}{\tau_{B^0}} = \mathbf{0.976 \pm 0.012 \pm 0.006}}$$

- ... in good agreement with expectation

CPV in mixing

- CPV in mixing: $\boldsymbol{a_{\mathrm{sl}} \equiv 1 - \left|\frac{q}{p}\right|^2 = \frac{|\Gamma_{12}|}{|M_{12}|} \sin\phi_{12}}$
- very small in SM: $a_{\mathrm{sl}}^{\mathrm{SM}}(B_d) = (-4.1 \pm 0.6) \cdot 10^{-4}$ and $a_{\mathrm{sl}}^{\mathrm{SM}}(B_s) = (1.9 \pm 0.3) \cdot 10^{-5}$

(Lenz and Nierste,2011)

- LHCb: measure time-integrated rate asymmetry in $\boldsymbol{B_s \to D_s^- X \mu^+ \nu}$

$$A = \frac{N(D_s^-\mu^+) - N(D_s^+\mu^-)}{N(D_s^-\mu^+) + N(D_s^+\mu^-)} = \frac{1}{2}a_{\mathrm{sl}} - \left(a_{\mathrm{prod}} - \frac{1}{2}a_{\mathrm{sl}}\right) \frac{\int_0^\infty \mathrm{d}t\, e^{-\Gamma_s t}\cos(\Delta m_s t)}{\int_0^\infty \mathrm{d}t\, e^{-\Gamma_s t}\cosh(\frac{1}{2}\Delta\Gamma_s t)}$$

dilution factor from oscillations ~0.2%

production asymmetry: ~0.01

CPV in mixing

- CPV in mixing: $\boldsymbol{a_{\rm sl} \equiv 1 - \left|\frac{q}{p}\right|^2 = \frac{|\Gamma_{12}|}{|M_{12}|} \sin\phi_{12}}$
- very small in SM: $a_{\rm sl}^{\rm SM}(B_d) = (-4.1 \pm 0.6)\cdot 10^{-4}$ and $a_{\rm sl}^{\rm SM}(B_s) = (1.9 \pm 0.3)\cdot 10^{-5}$ (Lenz and Nierste,2011)
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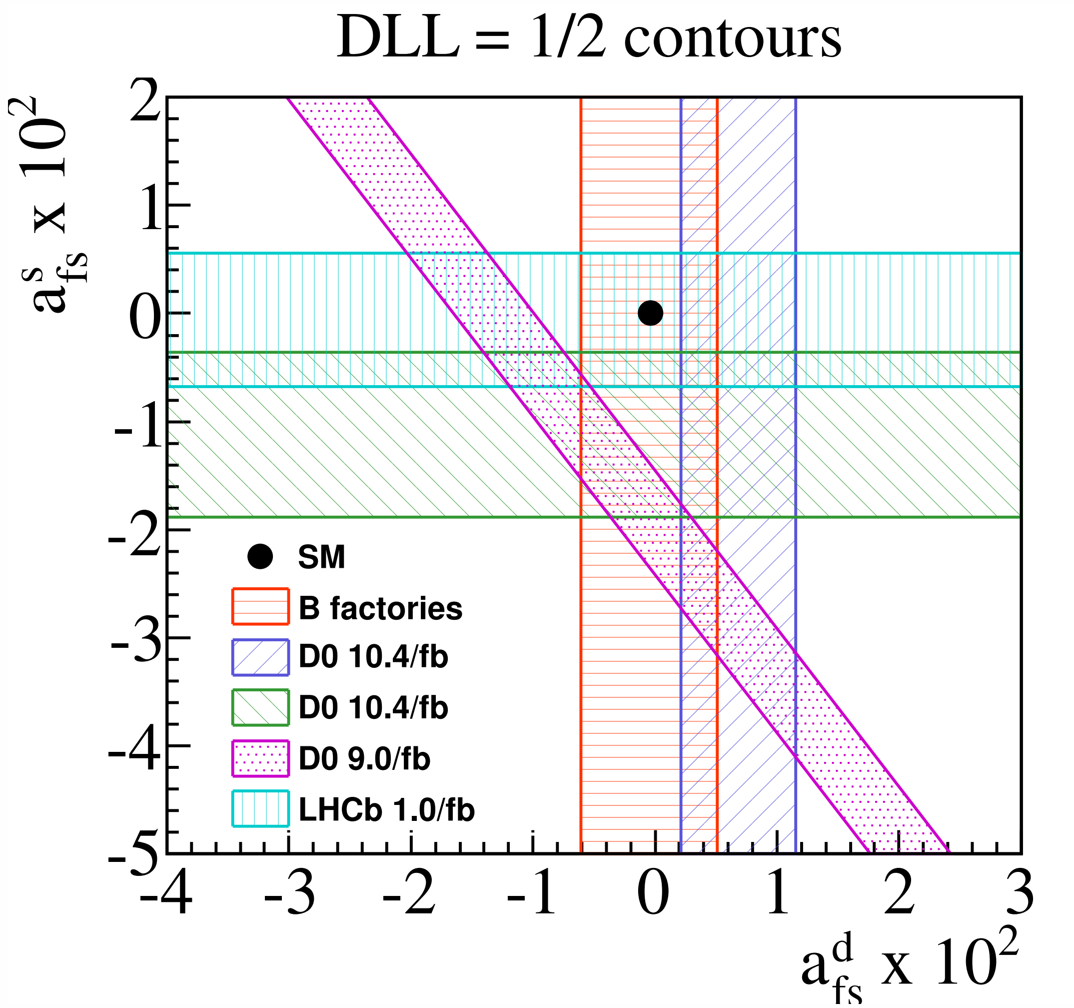
- result (1.0/fb, arxiv:1308:1048, subm. to PLB)

$$\boxed{a_{\rm sl}^s = (-0.06 \pm 0.50 \pm 0.36)\%.}$$

current systematics dominated by statistical uncertainty on efficiency ratio



B_s->μμ and B_d->μμ

Very rare decays in SM:

- no tree-level FCNC
- helicity suppression
- CKM suppresion

... none of which is necessarily true in NP!

Precise SM predictions

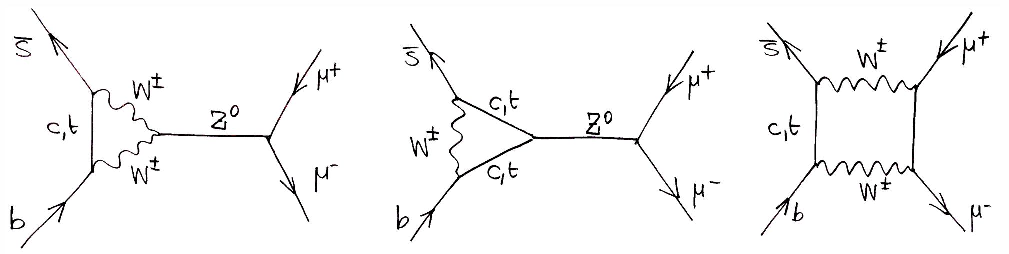
- $Br(B_d\text{->}\mu\mu) = (1.1 \pm 0.2)\ 10^{-10}$
- $Br(B_s\text{->}\mu\mu) = (3.5 \pm 0.2)\ 10^{-9}$

Buras et al, EPJ C72 (2012) 2172; see also PRL109 (2012) 041801

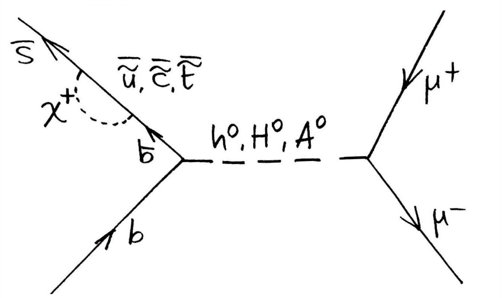
Strong enhancement in e.g. MSSM: Br ∝ $\tan^6\beta$

Previously known as the “golden channel” for NP discovery ... more recently named the “SUSY killer”!

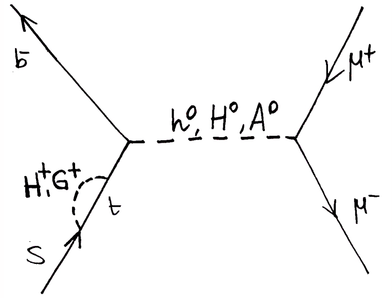
SM



MSSM

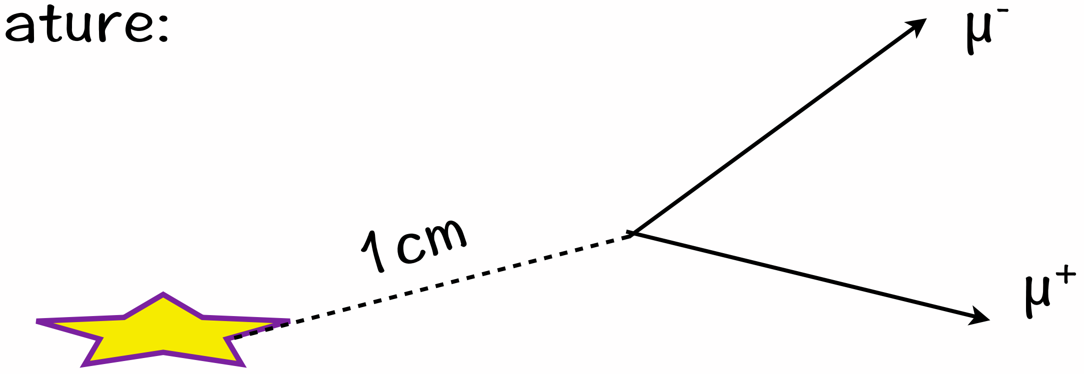


2HDM-II

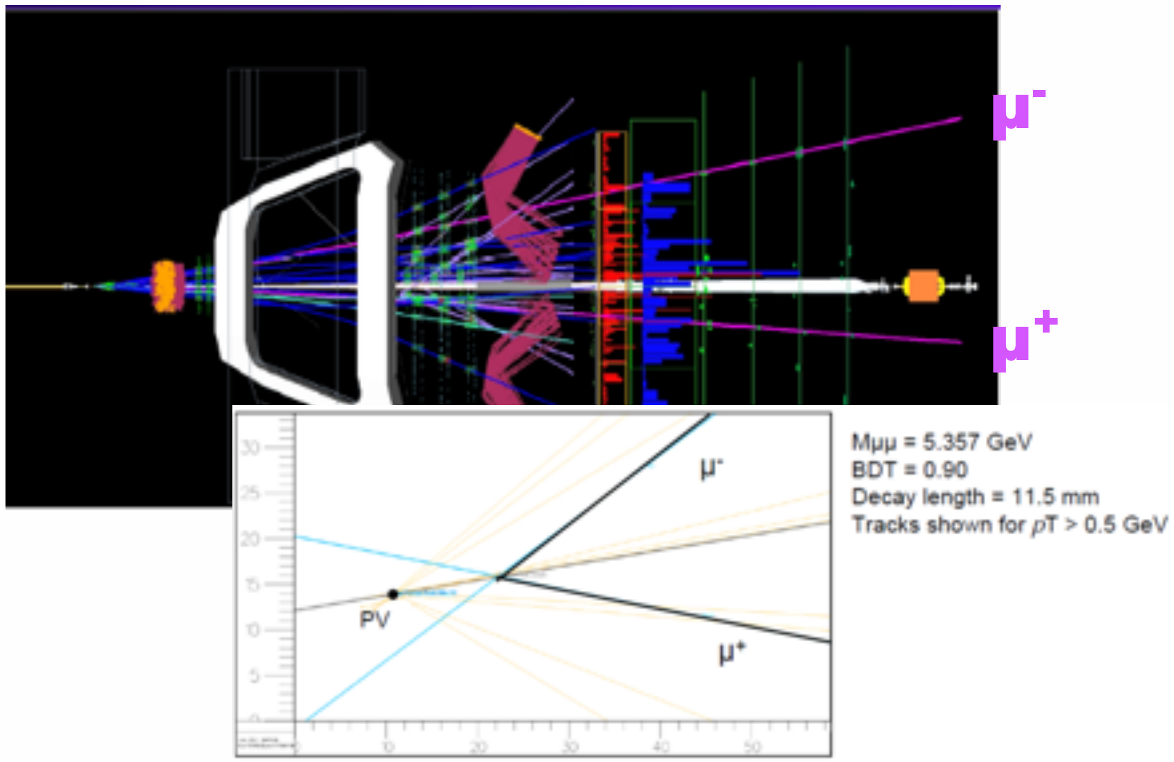


The quest for B_q->μμ

Signature:

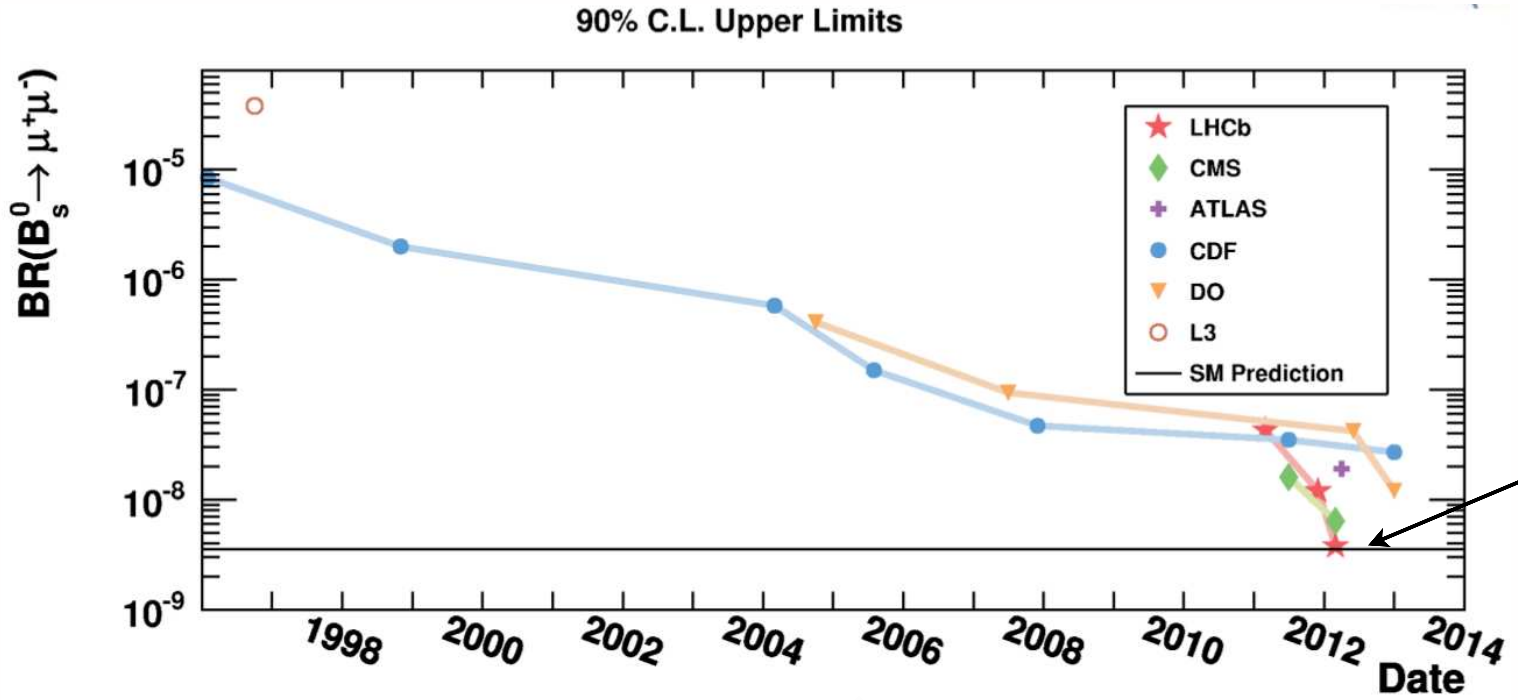


Actual candidate in LHCb data



Complicated measurement: large backgrounds from B->hh and double B->Xμ

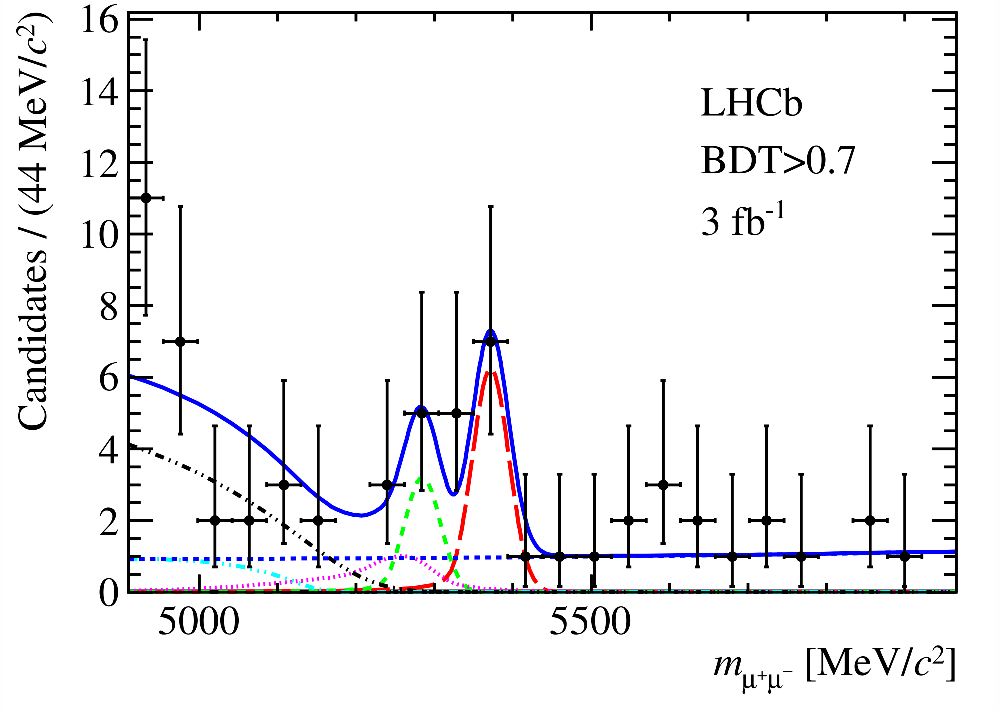
Searches started as early as 1984 (CLEO)!
Evolution of limit as function of time:



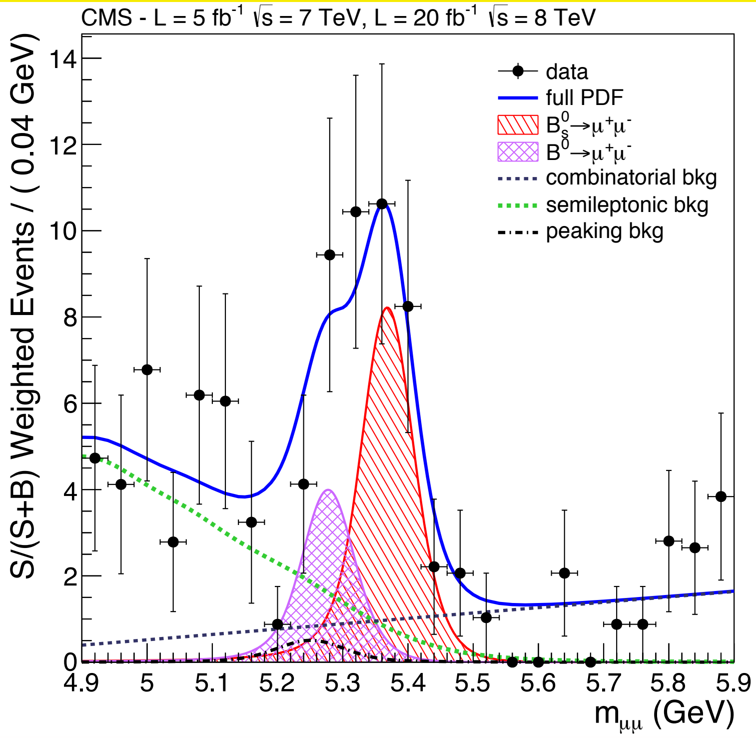
first hints by LHCb and CMS

EPS2013: LHCb/CMS joint discovery of B_s->$\mu^+\mu^-$

LHCb: arXiv:1307.5024, PRL.111.101805 (2013)



CMS: arXiv:1307.5025, PRL. 111.101804 (2013)



$$\mathcal{B}(B^0_s\to\mu^+\mu^-) = (2.9\,^{+1.1}_{-1.0})\times10^{-9},$$
$$\mathcal{B}(B^0\to\mu^+\mu^-) = (3.7\,^{+2.4}_{-2.1})\times10^{-10}$$

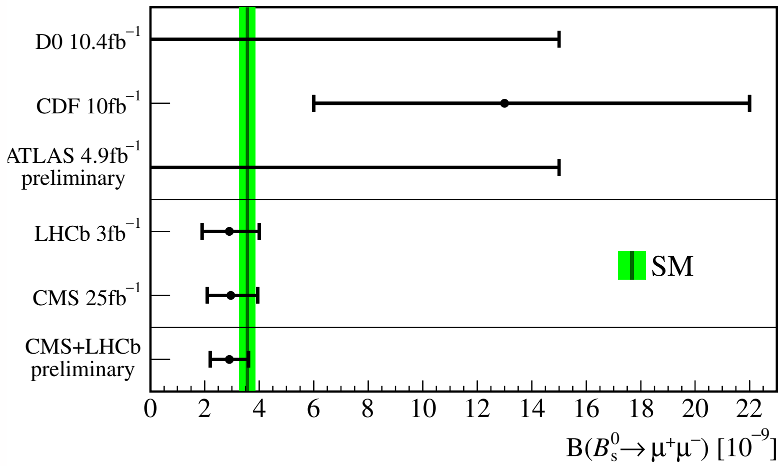
--> 4.0σ

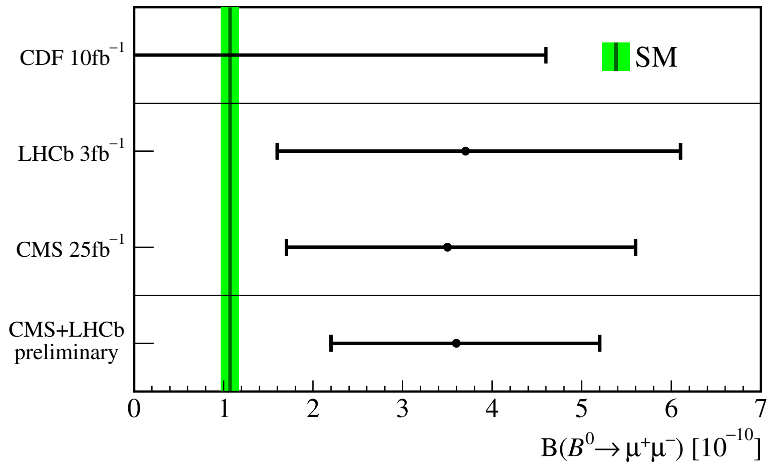
$$\mathcal{B}(B^0_s\to\mu^+\mu^-) = (3.0\,^{+1.0}_{-0.9})\times10^{-9},$$
$$\mathcal{B}(B^0\to\mu^+\mu^-) = (3.5\,^{+2.1}_{-1.8})\times10^{-10}$$

--> 4.3σ

combination: BR($B_s\to\mu^+\mu^-$) = $(2.9\pm0.7)\times10^{-9}$

BR($B^0\to\mu^+\mu^-$) = $3.6^{+1.6}_{-1.4}\times10^{-10}$





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

Other weak decays to μμ ...

D^0->μμ

arXiv:1305.5059, PLB 725 (2013) 15-24

SM:

short-distance: ~< 10^{-18}

long-distance: < 6×10^{-11}

LHCb, 0.9/fb: $\boxed{\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2\ (7.6) \times 10^{-9}}$

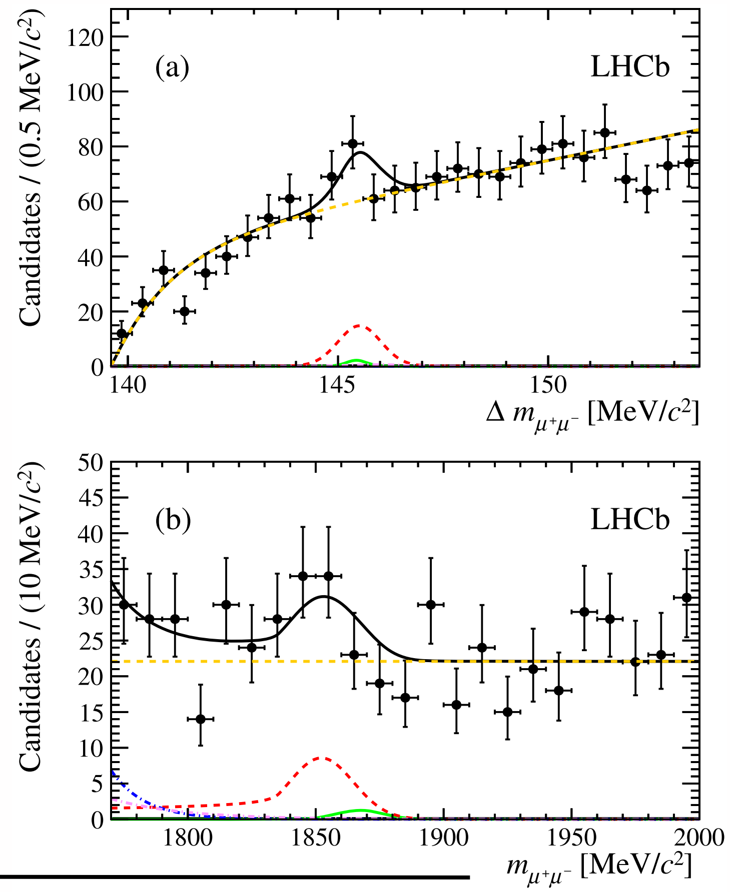
at 90 (95)% CL

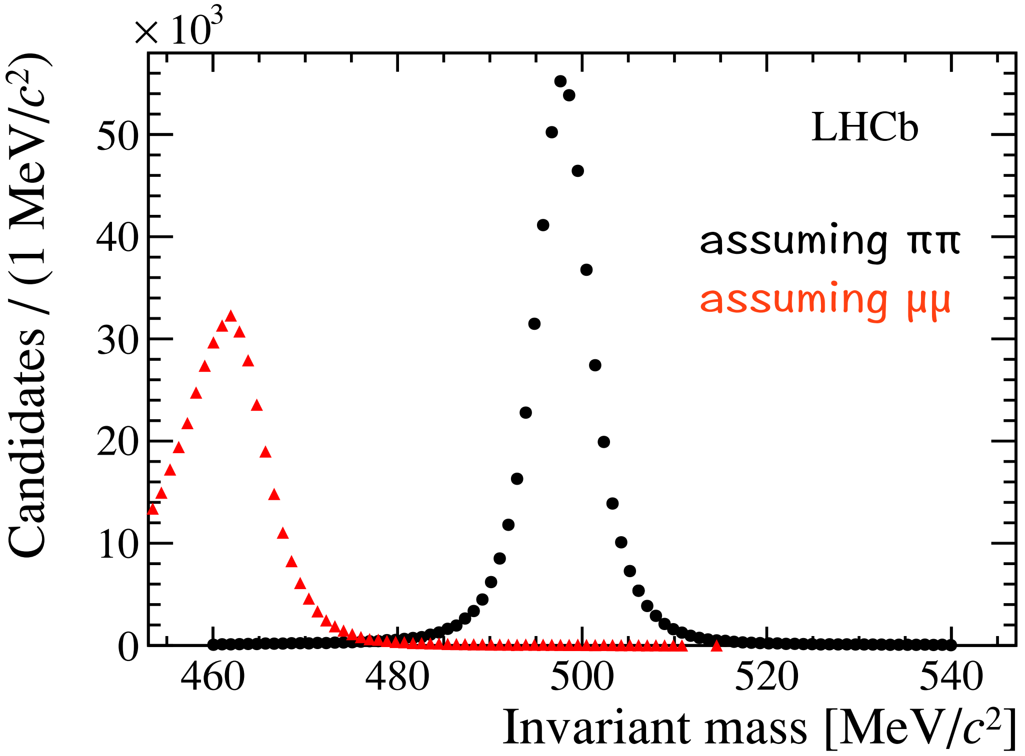
combin.

D^0->Kπ

D^0->ππ

D^0->μμ





K_S->μμ

1/fb: arXiv:1209.4029, JHEP 01 (2013) 090

SM: $\mathcal{B}(K_S^0 \to \mu^+\mu^-) = (5.0 \pm 1.5) \times 10^{-12}$

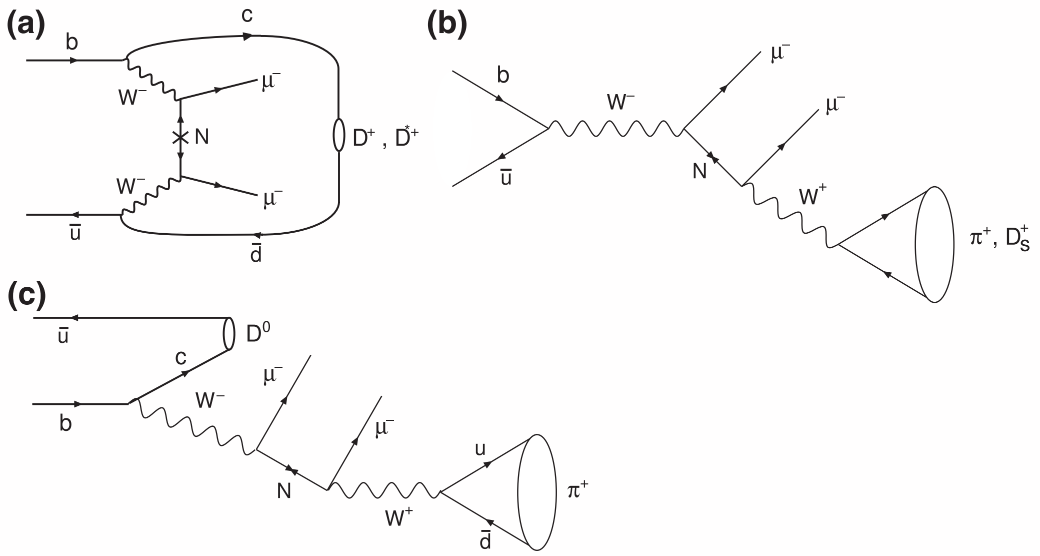
1/fb, number Ks in acceptance: ~10^13

LHCb, 1/fb: $\boxed{\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 11(9) \times 10^{-9}}$

at 95 (90)% CL

arXiv:1201.5600, PRD 85 (2012) 112004

And more exotic signals with two muons ...



- B final states with like-sign muons are sensitive to `medium-heavy' majorana neutrino N
- 5 decays analyzes in LHCb

$$\left.\begin{array}{ll} B^- & \to D^+\mu^-\mu^- \\ B^- & \to D^{*+}\mu^-\mu^- \end{array}\right\} \text{via virtual N}$$

$$\left.\begin{array}{ll} B^- & \to \pi^+\mu^-\mu^- \\ B^- & \to D_s^{*+}\mu^-\mu^- \\ B^- & \to D^0\pi^+\mu^-\mu^- \end{array}\right\} \text{also via on-shell N}$$

- results, using 0.4/fb of LHCb data

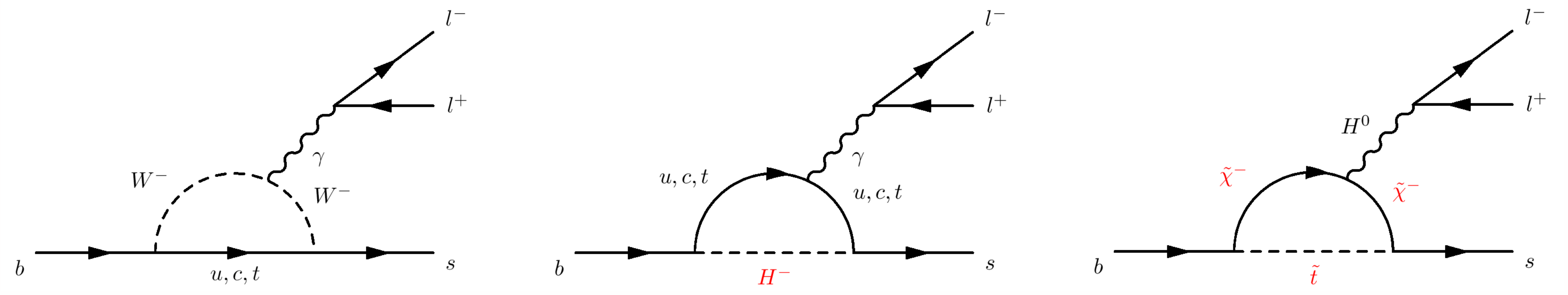
Mode	$\mathcal{B}$ upper limit	Approximate limits as function of M_N
$D^+\mu^-\mu^-$	6.9×10^{-7}	
$D^{*+}\mu^-\mu^-$	2.4×10^{-6}	
$\pi^+\mu^-\mu^-$	1.3×10^{-8}	$(0.4-1.0)\times10^{-8}$
$D_s^+\mu^-\mu^-$	5.8×10^{-7}	$(1.5-8.0)\times10^{-7}$
$D^0\pi^+\mu^-\mu^-$	1.5×10^{-6}	$(0.3-1.5)\times10^{-6}$

nothing seen ...

... yet!

B -> K(*) $\mu^+\mu^-$

- another example if a b->s transition (FCNC): very sensitive to NP



- many observables rates, angular distributions, CP/isospin asymmetries
  - clean theoretical predictions
  - clean experimental signature

- theoretical framework: Operator Product Expansion

$$\boxed{H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \Big[\ \underbrace{C_i(\mu)O_i(\mu)}_{\text{left-handed part}} + \underbrace{C'_i(\mu)O'_i(\mu)}_{\text{right-handed part suppressed in SM}}\ \Big]}$$

$i = 1,2$	Tree
$i = 3-6,8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9,10$	Electroweak penguin
$i = S$	Higgs (scalar) penguin
$i = P$	Pseudoscalar penguin

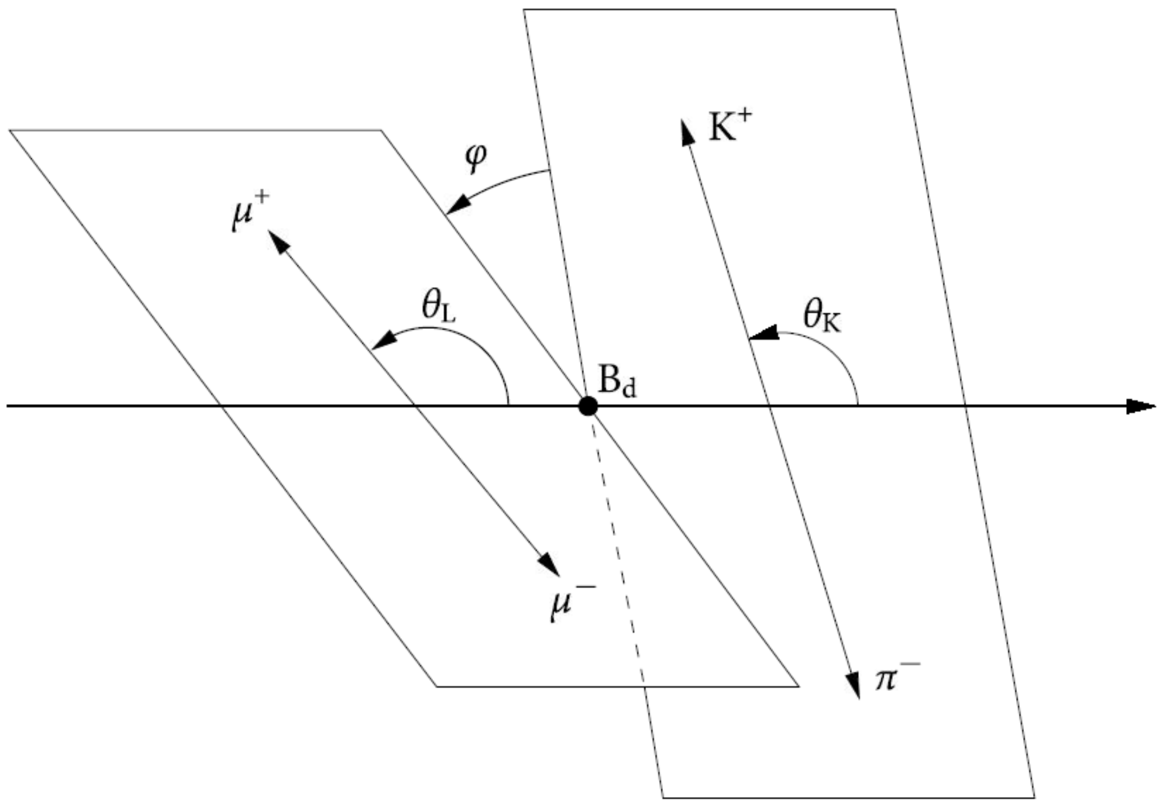
Angular analysis of B_d->$K^{*0}\mu^+\mu^-$

generic parameterization of CP-averaged angular distribution:

$$\begin{aligned}\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\theta_l\, d\theta_K\, d\varphi\, dq^2} = \frac{9}{32\pi}\Big[&\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_l\\ &- F_L\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\varphi\\ &+ S_4\sin 2\theta_K\sin 2\theta_l\cos\varphi + S_5\sin 2\theta_K\sin\theta_l\cos\varphi\\ &+ \boxed{S_6^s}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\varphi\\ &+ S_8\sin 2\theta_K\sin 2\theta_l\sin\varphi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\varphi\Big]\end{aligned}$$

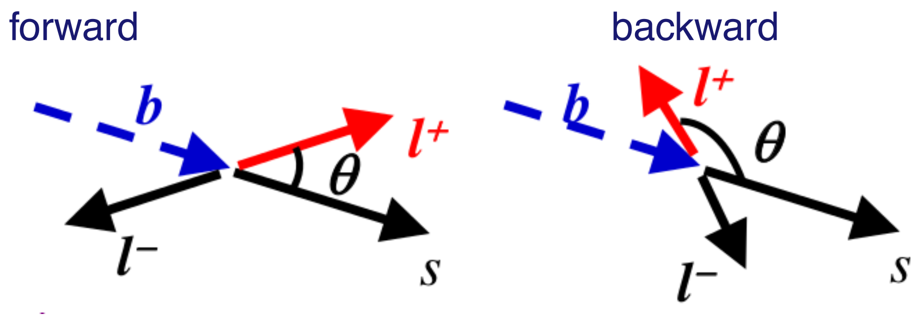
Altmannshofer et al, JHEP 01 (2009) 019

q^2 = dimuon invariant mass^2



Most well known observables:

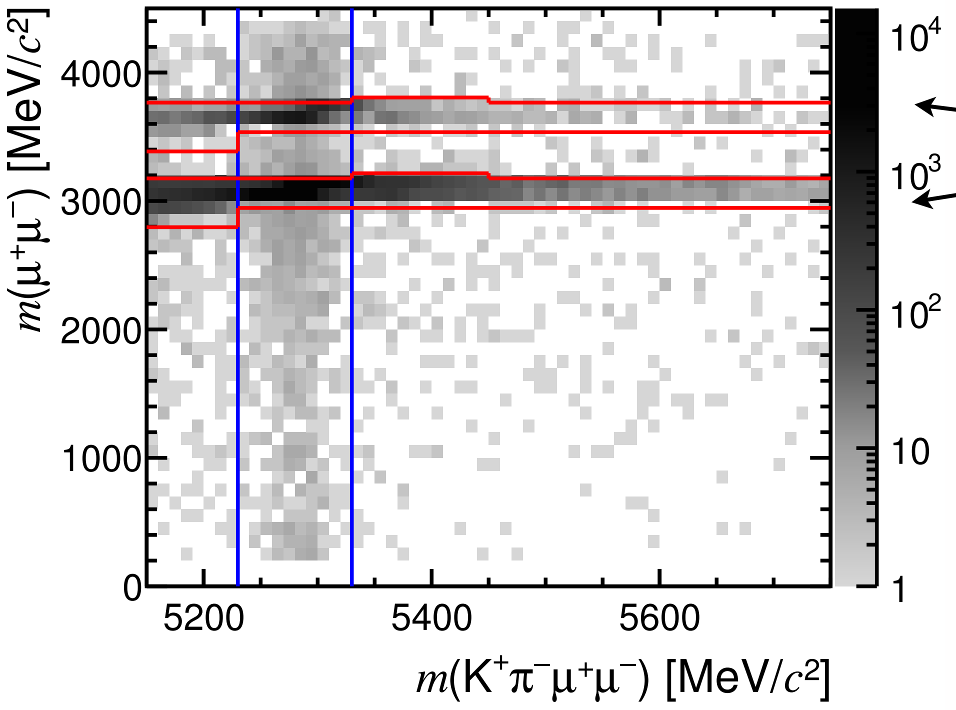
- muon forward backward asymmetry $A_{FB} = 4/3\ S_6^s$



- K* longitudinal polarization fraction, F_L

$B_d \to K^{*0}\mu^+\mu^-$ at LHCb

arXiv:1304.6325, JHEP 08 (2013) 131

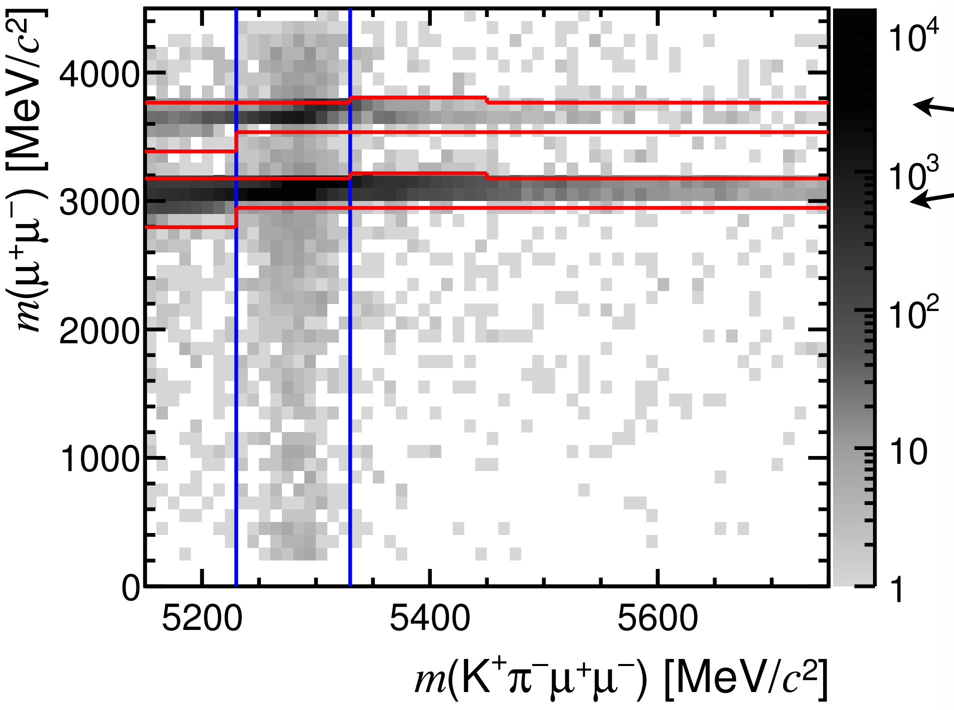


vetoed regions for $B \to \psi K^{*0}$

used to calibrate acceptance and normalize decay rates

B_d->$K^{*0}\mu^+\mu^-$ at LHCb

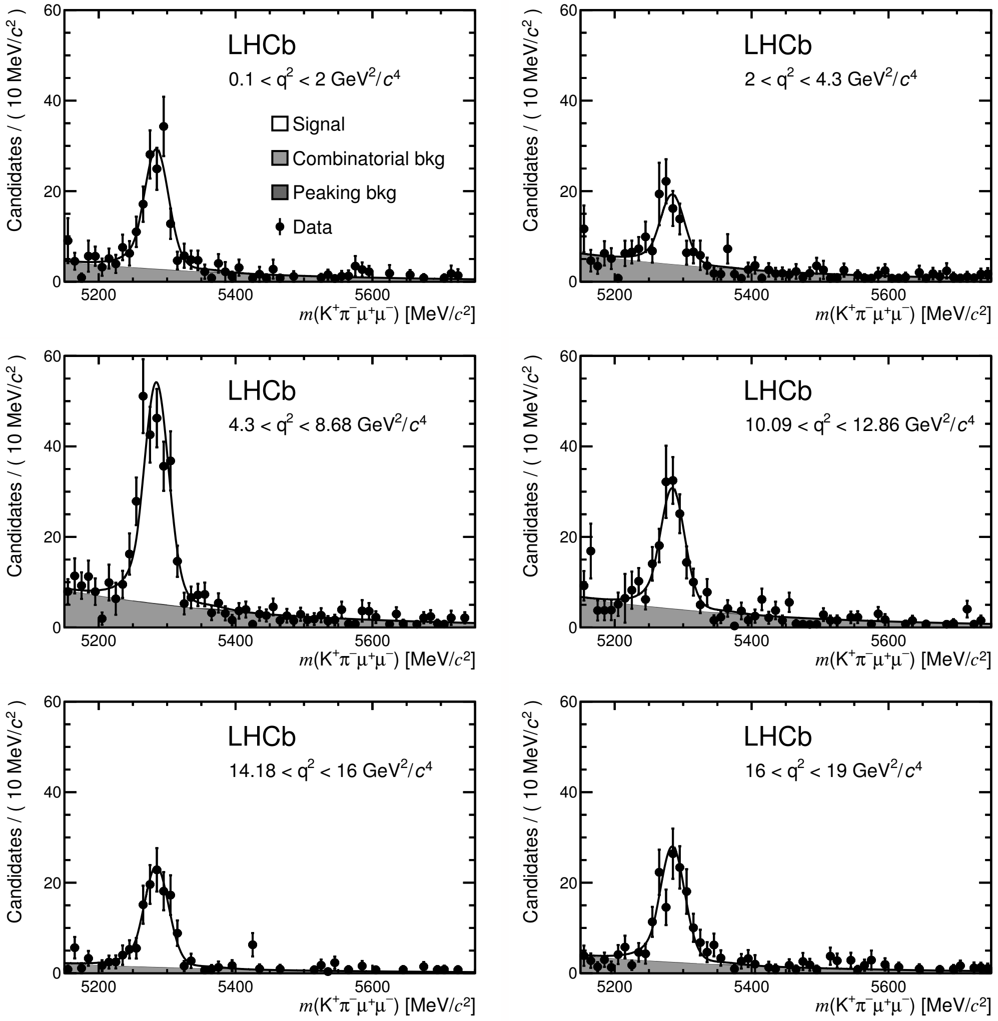
arXiv:1304.6325, JHEP 08 (2013) 131

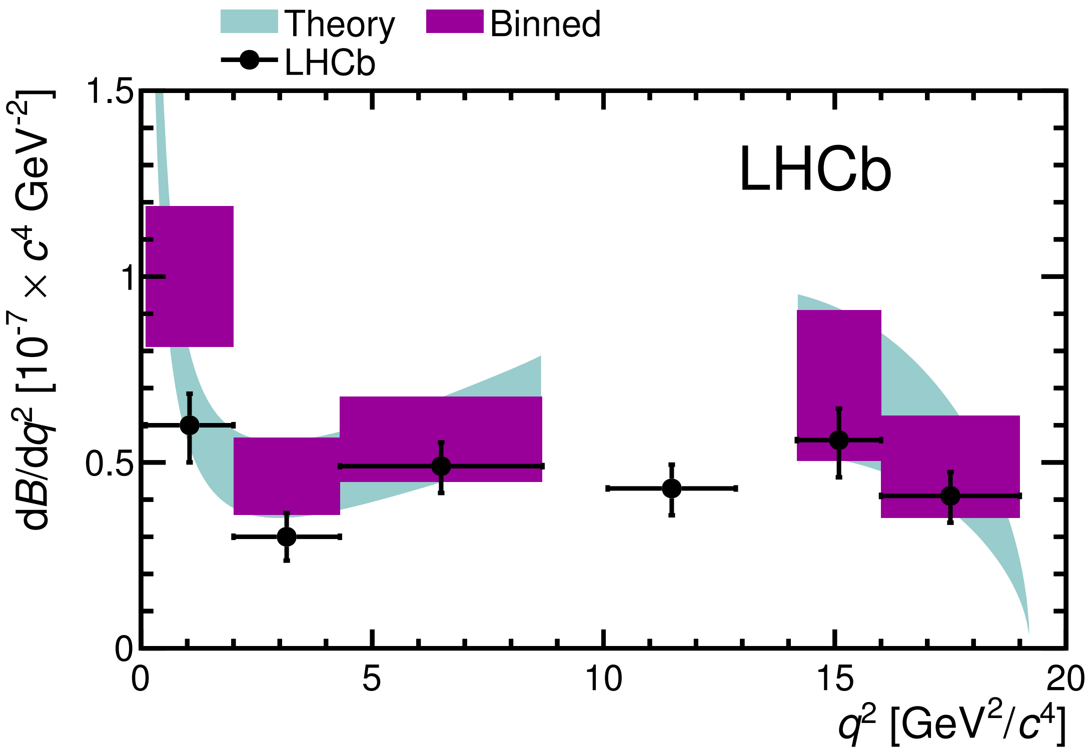


vetoed regions for B->ψK^{*0}

used to calibrate acceptance and normalize decay rates

B candidate mass in bins of q^2
(in total: 883±34 candidates in 1/fb)

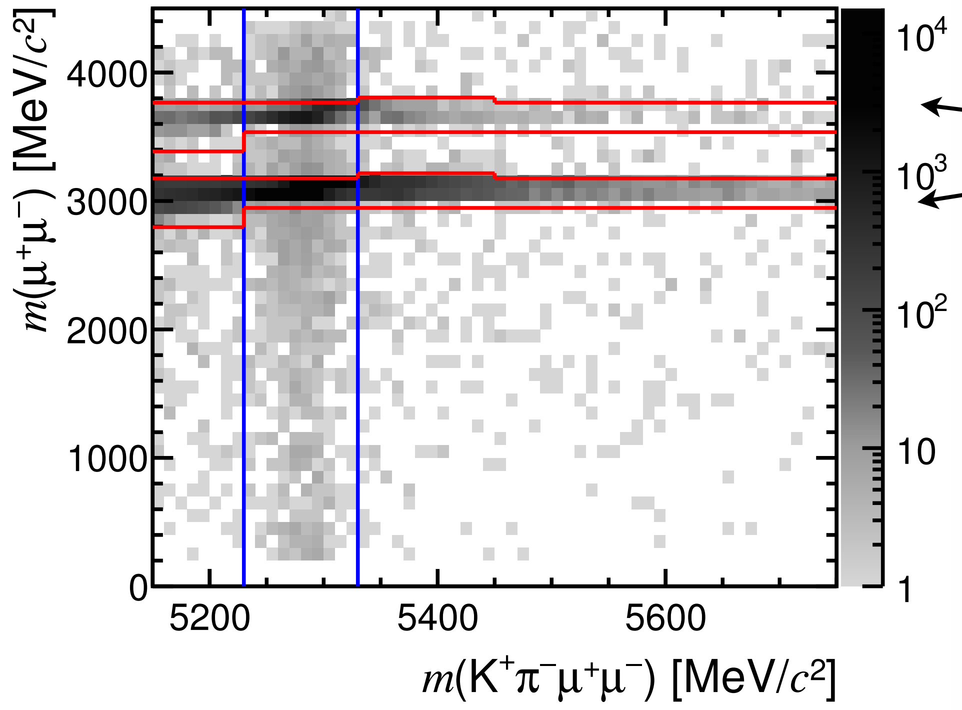




good agreement between data and predictions?

$B_d \to K^{*0}\mu^+\mu^-$ at LHCb

arXiv:1304.6325, JHEP 08 (2013) 131



vetoed regions for $B \to \psi K^{*0}$

used to calibrate acceptance and normalize decay rates

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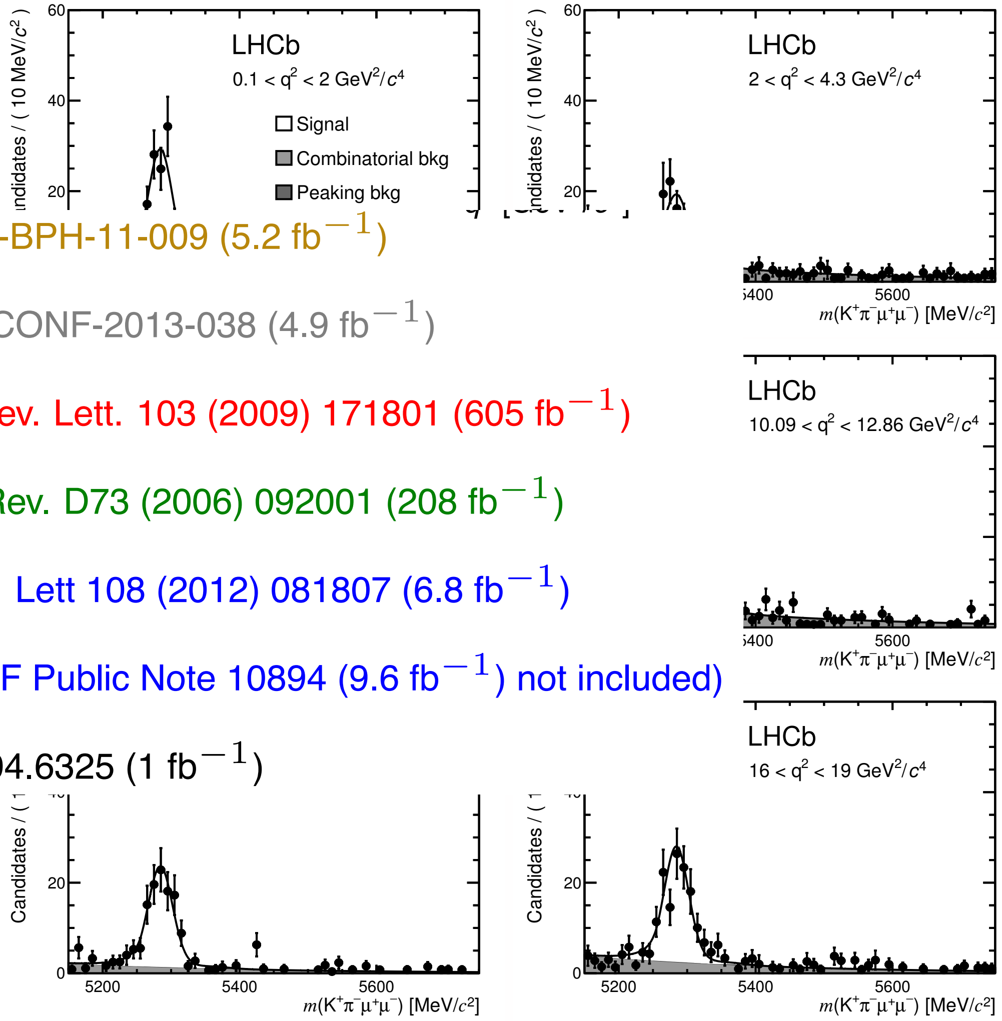
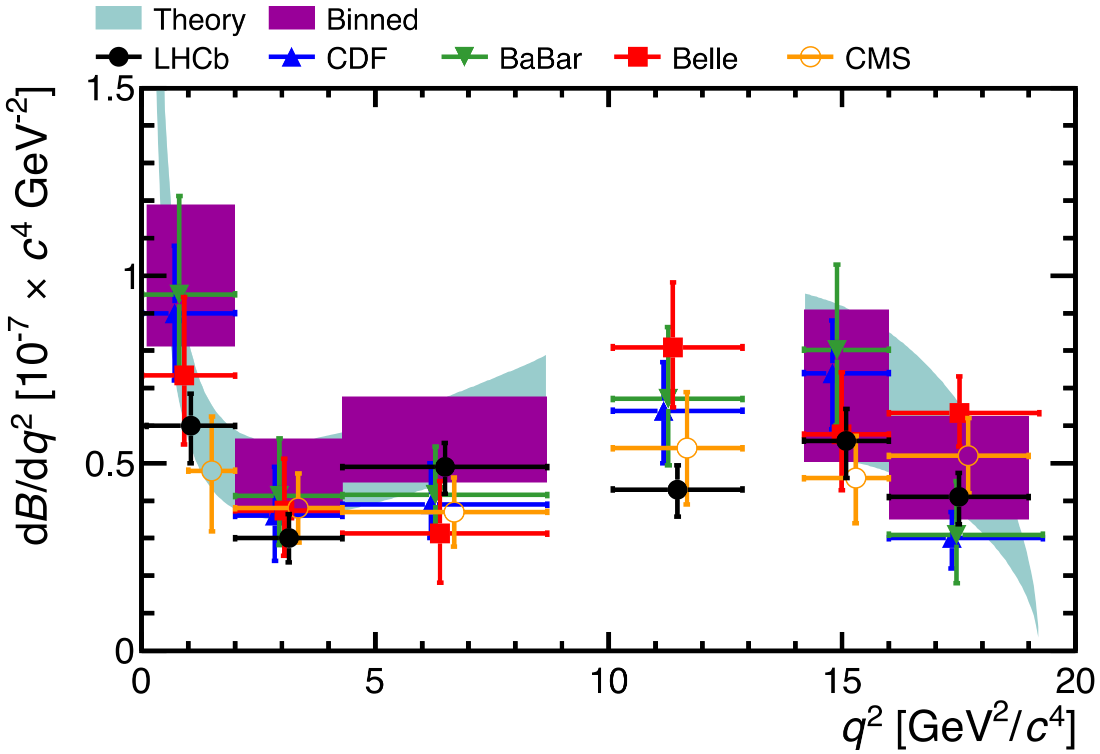
(in total: 883±34 candidates in 1/fb)





CMS: CMS-PAS-BPH-11-009 (5.2 fb^{-1})

ATLAS: ATLAS-CONF-2013-038 (4.9 fb^{-1})

BELLE: Phys. Rev. Lett. 103 (2009) 171801 (605 fb^{-1})

BABAR: Phys. Rev. D73 (2006) 092001 (208 fb^{-1})

CDF: Phys. Rev. Lett 108 (2012) 081807 (6.8 fb^{-1})

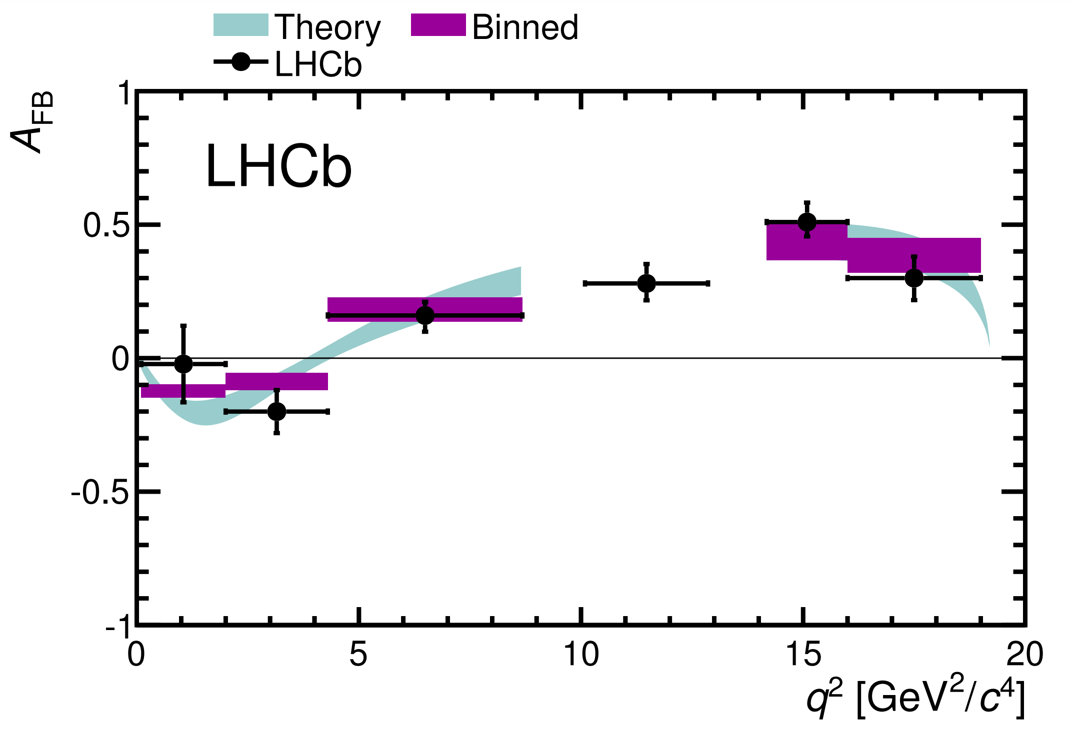
(results from CDF Public Note 10894 (9.6 fb^{-1}) not included)

LHCb: arXiv:1304.6325 (1 fb^{-1})

good agreement between data and predictions?

Angular analysis at LHCb

arXiv:1304.6325, JHEP 08 (2013) 131



'zero crossing point'

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

agrees well with SM prediction:

$$\boldsymbol{q^2_{0,\mathrm{SM}}} \;\in\; \mathbf{[3.9, 4.4]\ GeV/}\boldsymbol{c^2}$$

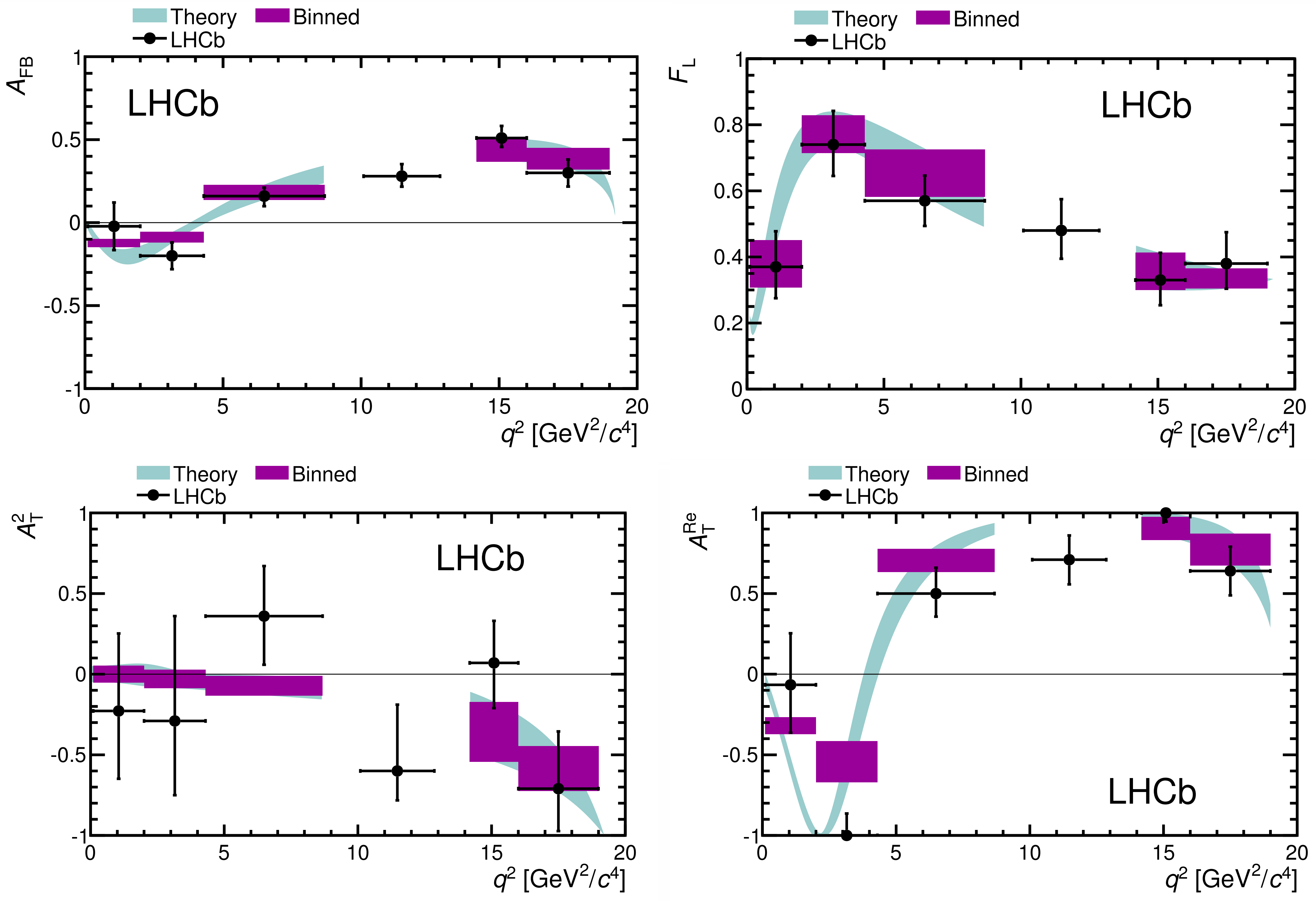
C. Bobeth, G. Hiller, D. van Dyk and C. Wacker, *The decay $B \to K\ell^+\ell^-$ at low hadronic recoil and model-independent $\Delta B = 1$ constraints*, *JHEP* **01** (2012) 107 [arXiv:1111.2558] [INSPIRE].

M. Beneke, T. Feldmann and D. Seidel, *Exclusive radiative and electroweak $b \to d$ and $b \to s$ penguin decays at NLO*, *Eur. Phys. J.* **C 41** (2005) 173 [hep-ph/0412400] [INSPIRE].

A. Ali, G. Kramer and G.-h. Zhu, *$B \to K^+\ell^+\ell^-$ decay in soft-collinear effective theory*, *Eur. Phys. J.* **C 47** (2006) 625 [hep-ph/0601034] [INSPIRE].

Angular analysis at LHCb

arXiv:1304.6325, JHEP 08 (2013) 131



- good agreement with predictions ....
  ... but theory errors large due to 'hadronic form factors'

--> look at ratios of observables to reduce form factors uncertainties

Angular analysis at LHCb

arXiv:1304.6325, JHEP 08 (2013) 131

arXiv:1308.1707, PR 111 (2013) 191801

- at low q^2, ratios $P'_{i=4,5,6,8} = \frac{S_{i=4,5,7,8}}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}}$ largely free of FF uncertainties, while sensitivity to NP remains (Descotes-Genon, Hurth, Matias, Virto, arXiv:1303.5794)
- P6’ and P8’ close to SM predictions, which are close to zero for all q^2
- P4’ and P5’ have less trivial structure:

Angular analysis at LHCb

arXiv:1304.6325, JHEP 08 (2013) 131

arXiv:1308.1707, PR 111 (2013) 191801

- at low q^2, ratios $P'_{i=4,5,6,8} = \frac{S_{i=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$ largely free of FF uncertainties, while sensitivity to NP remains (Descotes-Genon, Hurth, Matias, Virto, arXiv:1303.5794)
- P6' and P8' close to SM predictions, which are close to zero for all q^2
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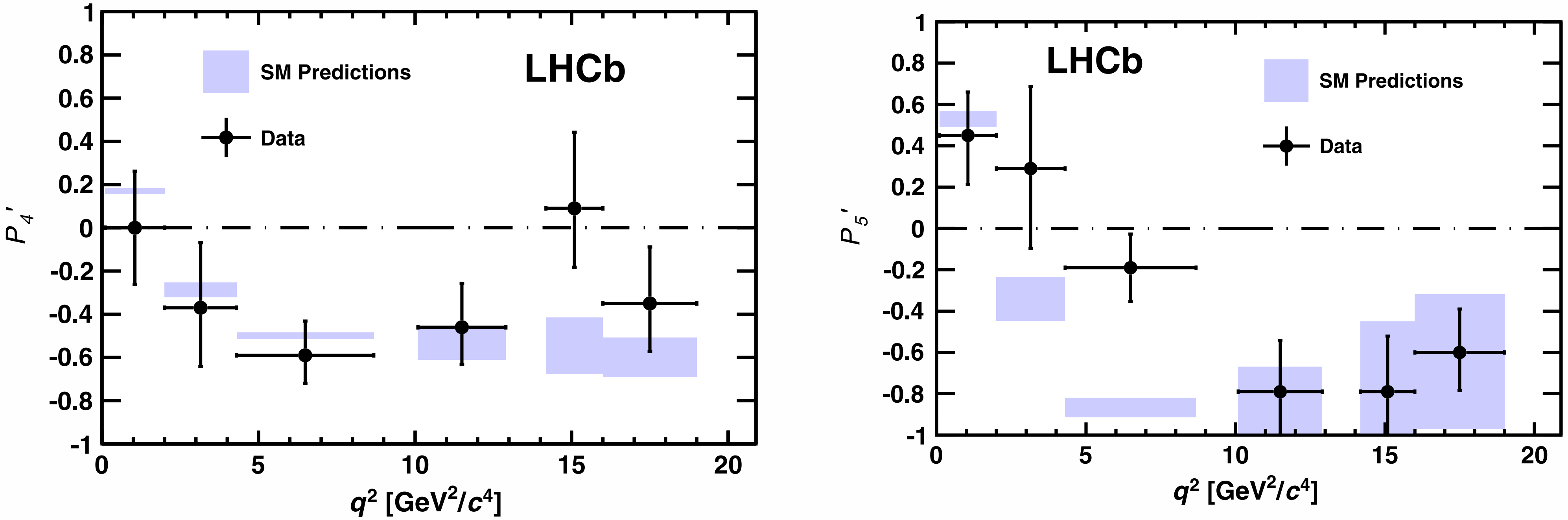


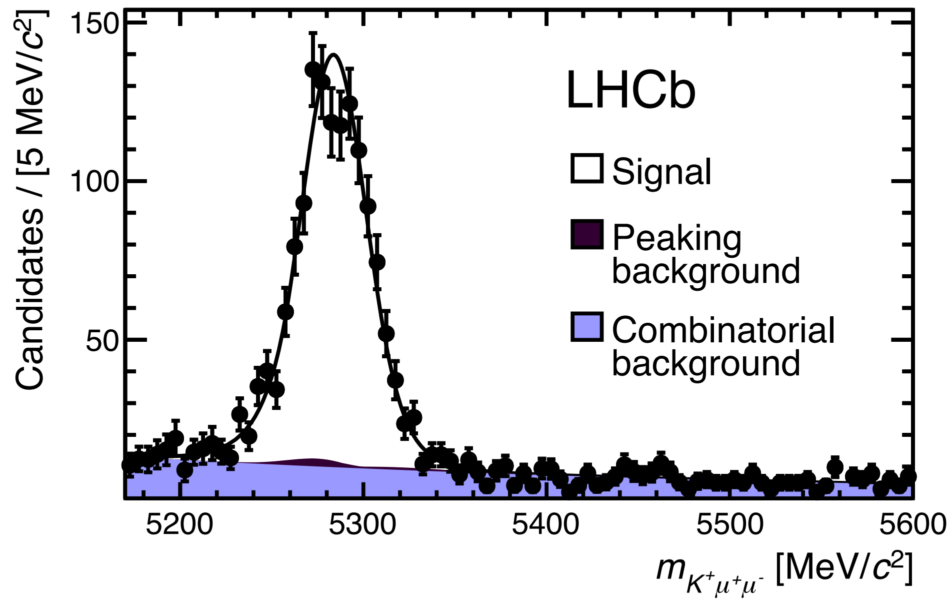
- note the tension in P5': 3.7σ (1 out of 24 bins: global significance 2.8σ)
  - change in C9? (Descotes, Matias, Virto, arXiv:1307.5683) by a Z'? (Gauld et al, arXiv:1308.1959; Buras and Girrbach, arXiv:1309.2466)
  - or more mundane effects of QCD, 'non-factorizable form factors'?

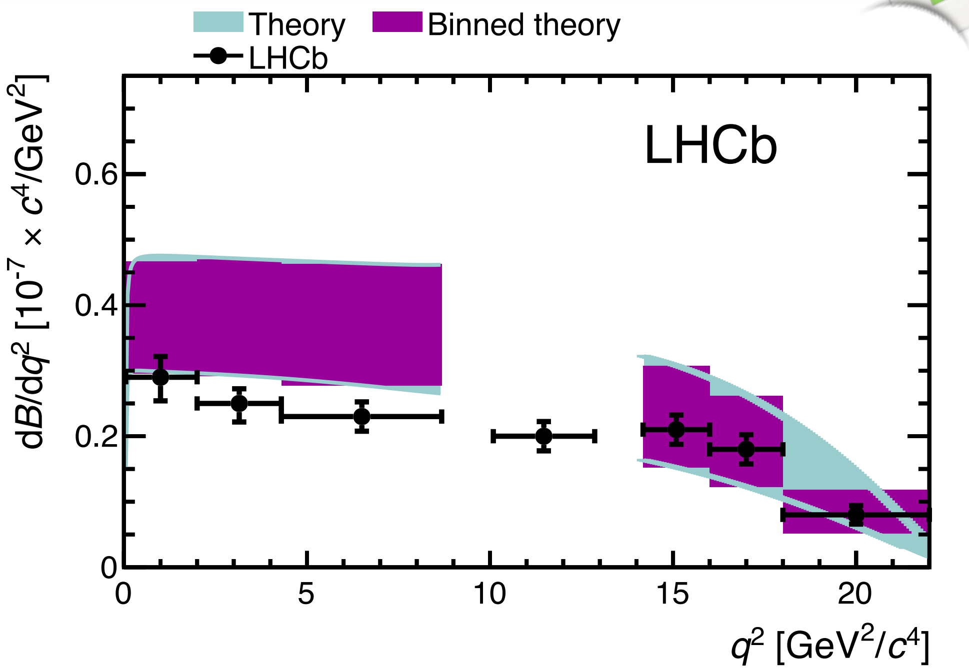
B^+ -> $K^+\mu^+\mu^-$ at LHCb

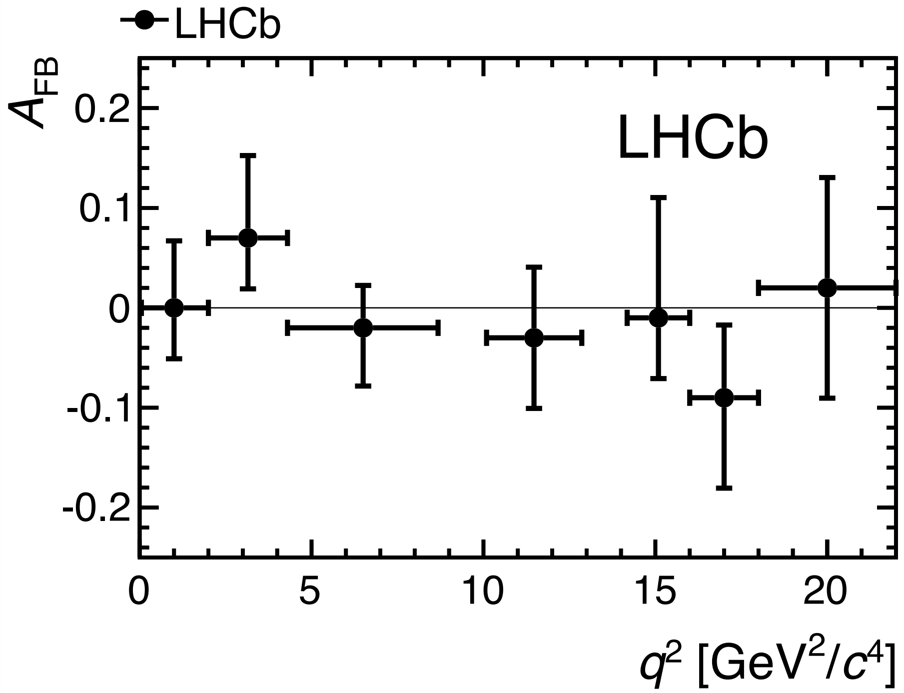
- B^+ -> $K^+\mu^+\mu^-$ also extensively studied at LHCb
  - differential distributions (1/fb) arXiv:1209.4284,JHEP02(2013)105

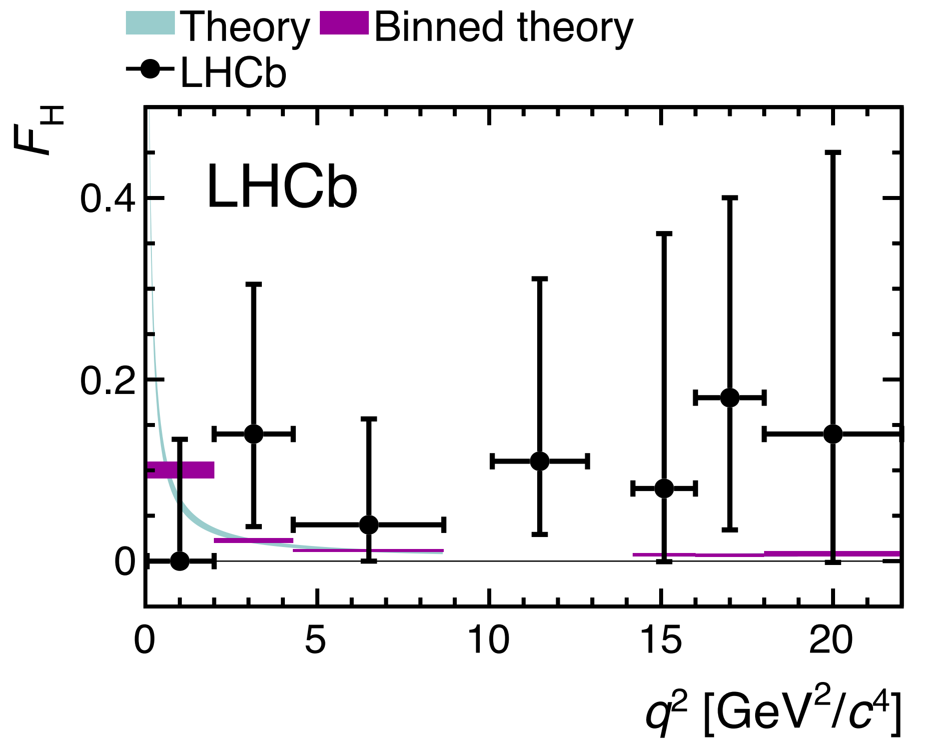
no surprises

1240 candidates in 1/fb





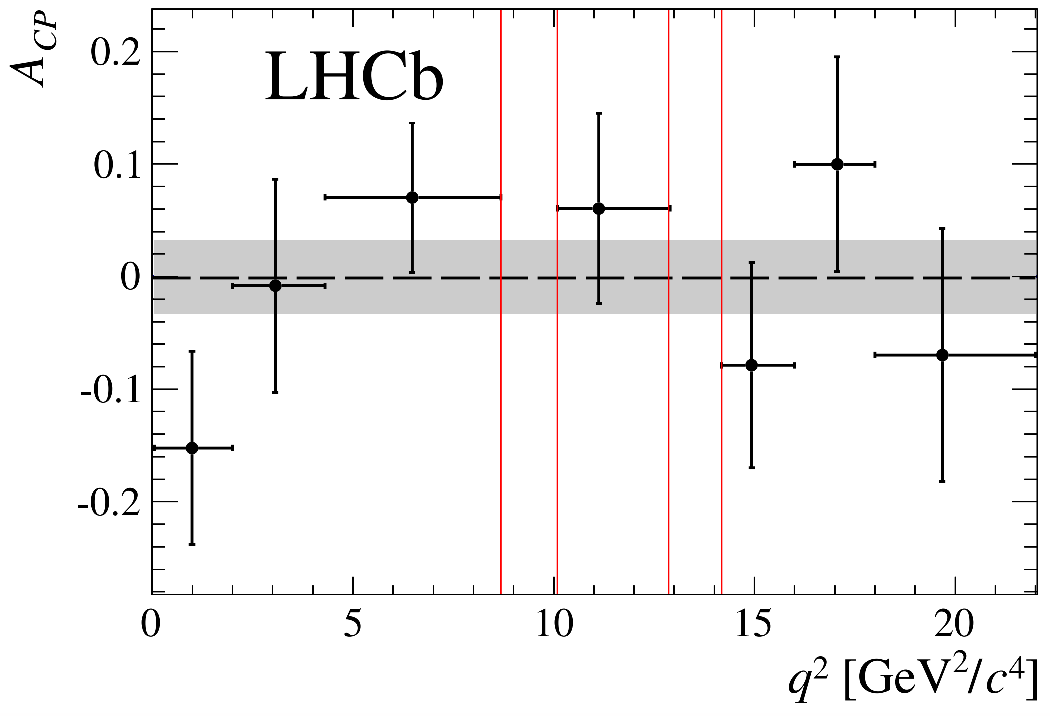




$B^+ \to K^+\mu^+\mu^-$ at LHCb

- $B^+ \to K^+\mu^+\mu^-$ also extensively studied at LHCb
  - differential distributions (1/fb) arXiv:1209.4284,JHEP02(2013)105
  - CP asymmetry (1/fb) arXiv:1308.1340, PRL 111, 151801 (2013)

no surprises



efficiency-corrected q2 average

$$\mathcal{A}_{CP} = 0.000 \pm 0.033(\text{stat.}) \pm 0.005(\text{syst.}) \pm 0.007(J/\psi K).$$

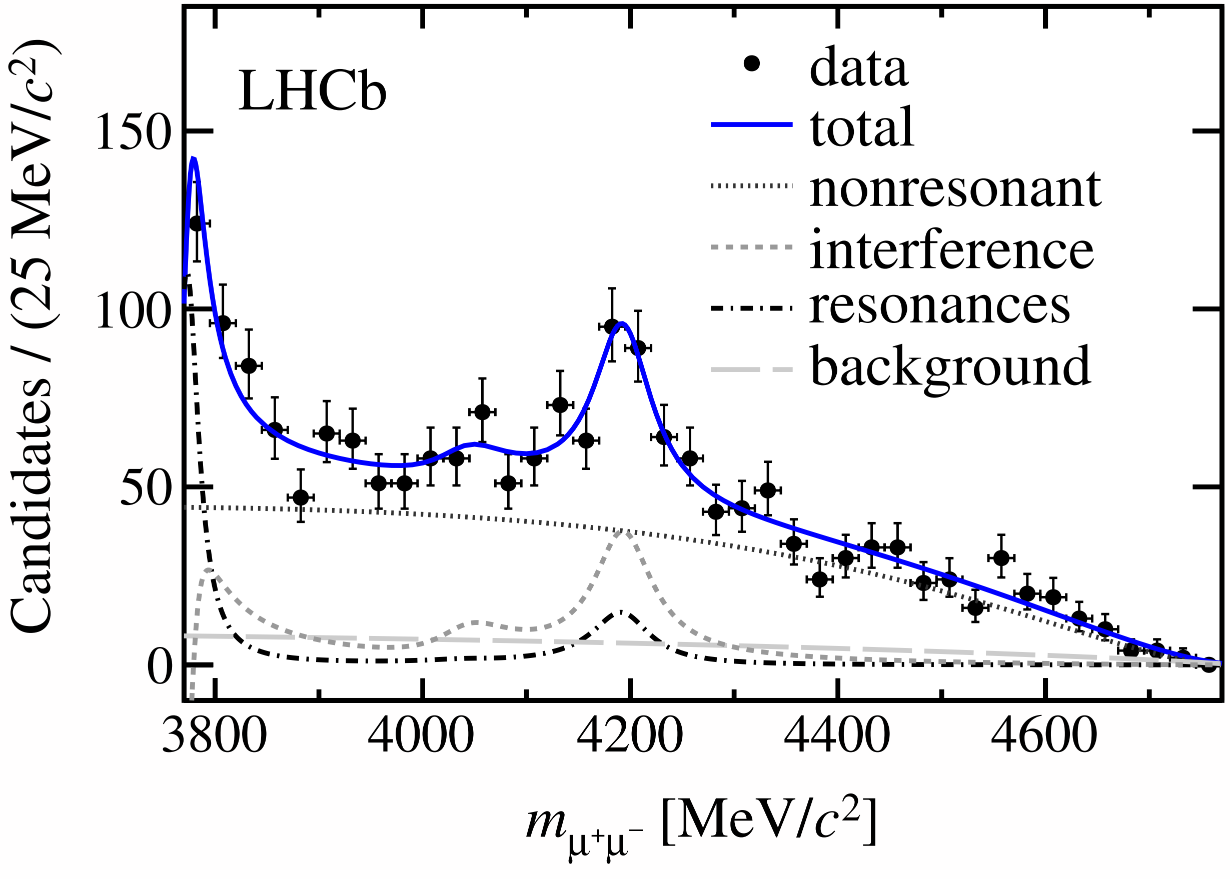
consistent with SM ...

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

- $B^+ \to K^+\mu^+\mu^-$ also extensively studied at LHCb
  - differential distributions (1/fb) arXiv:1209.4284,JHEP02(2013)105
  - CP asymmetry (1/fb) arXiv:1308.1340, PRL 111, 151801 (2013)
  - resonance structure (3/fb) arXiv:1307.7595, PRL 111, 112003 (2013)

surprise!

830 B+->K+μμ candidates



- $\mu^+\mu^-$ resonance 'at low recoil' (high-q^2)
- significance > 6σ
- consistent with ψ(4160) found by BES

	Unconstrained	$\psi(4160)$
$\mathcal{B}[\times 10^{-9}]$	$3.9\,^{+0.7}_{-0.6}$	$3.5\,^{+0.9}_{-0.8}$
Mass [MeV/c^2]	$4191\,^{+9}_{-8}$	4190 ± 5
Width [MeV/c^2]	$65\,^{+22}_{-16}$	66 ± 12
Phase [rad]	-1.7 ± 0.3	-1.8 ± 0.3

Q: what does this mean for reliability of predictions in $B^{*0} \to K^{*0}\mu\mu$ at high q^2?

isospin asymmetries

arXiv:1205.3422,
JHEP 07(2012)133

isospin asymmetry:

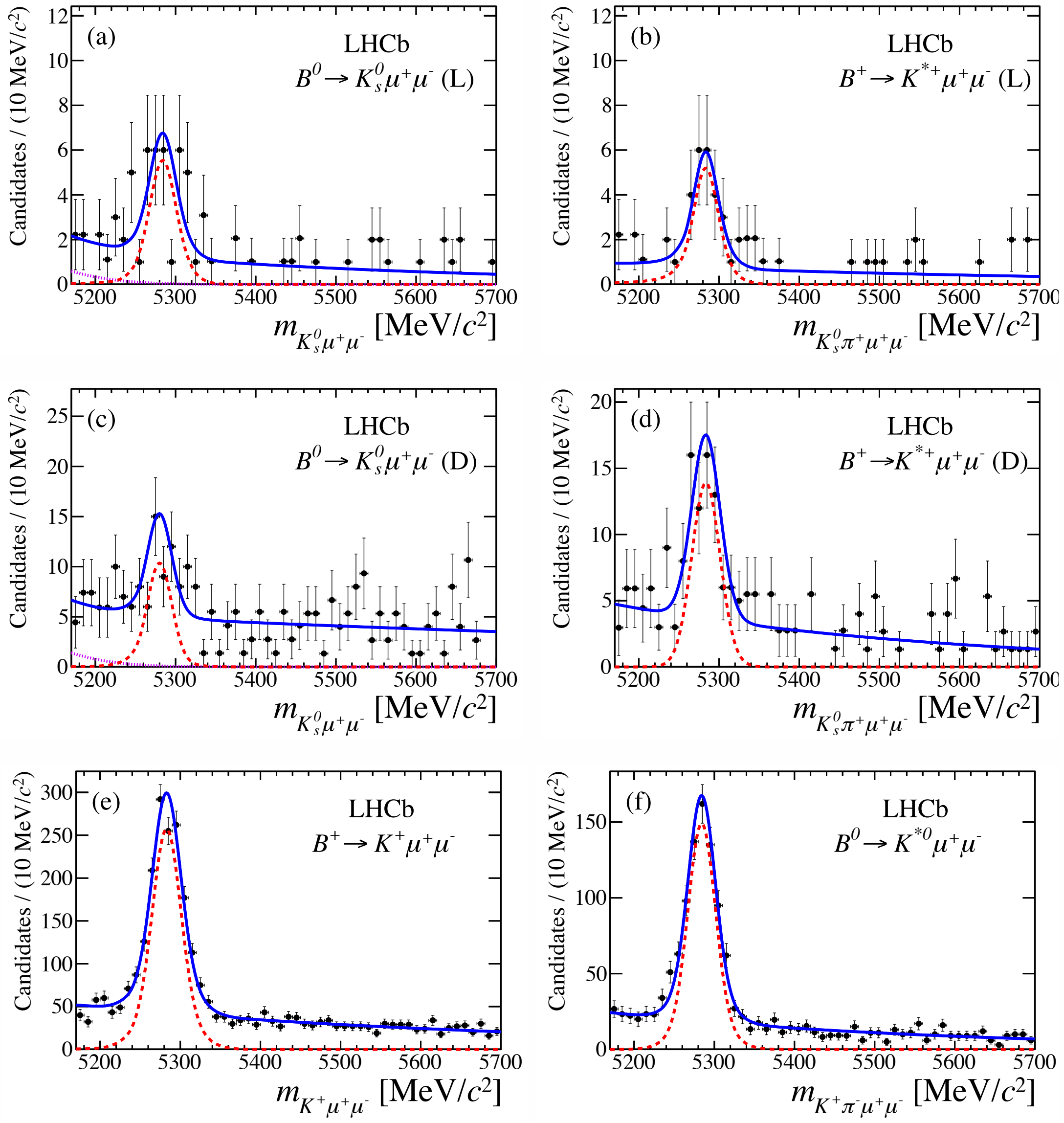
$$A_\mathrm{I} = \frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}$$

predicted to be close to zero in SM

LHCb measurement on 1/fb using final states with charged particles only:

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

$$B^0 \to K^{*0}\mu^+\mu^- \to K^+\pi^-\mu^+\mu^-$$
$$B^+ \to K^{*+}\mu^+\mu^- \to K^0_s\pi^+\mu^+\mu^-$$



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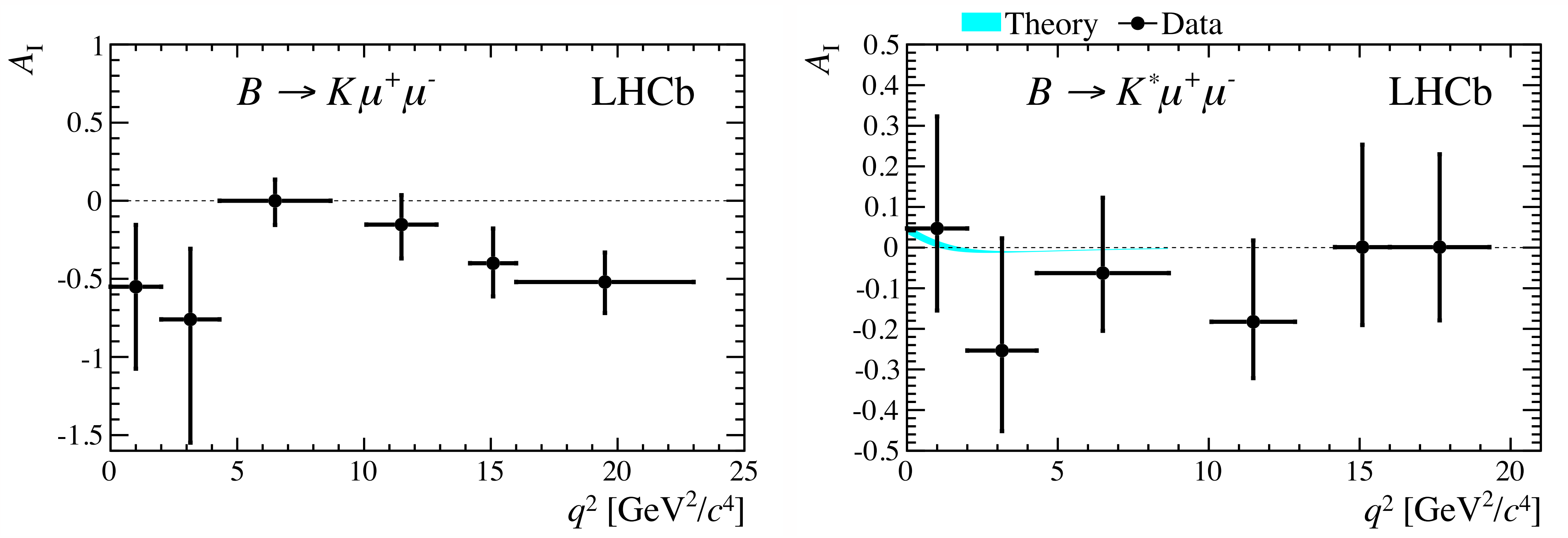


Both consistent with previous measurements (Babar, Belle, CDF) ... but Kμμ has a 4.4σ devation from zero?!

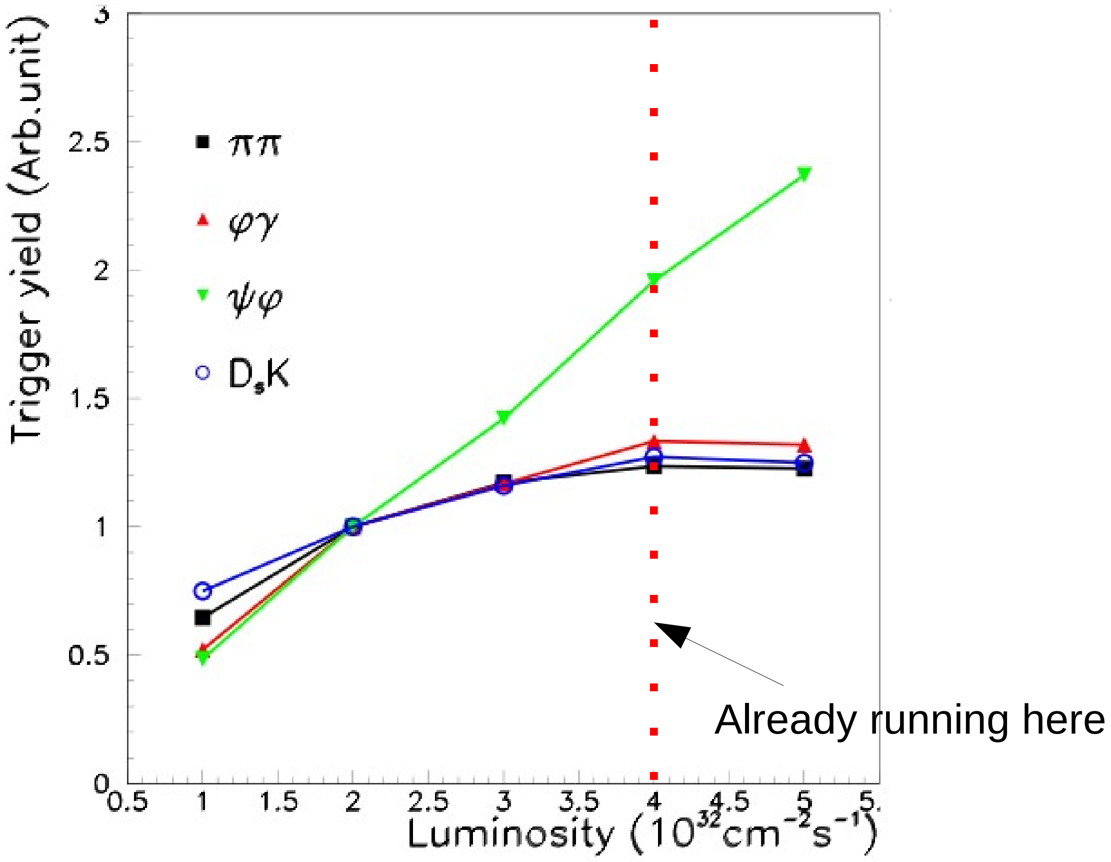
More $B \to X\mu\mu$ and $B \to X\gamma$

Similar physics, omitted due to lack of time ...

$B_s \to \phi\mu\mu$	arXiv:1305.2168, JHEP. 07 (2013) 084
$\Lambda_b \to \Lambda\mu\mu$	arXiv:1306.2577, PLB 725 (2013) 25
$B^+ \to \pi^+\mu^+\mu^-$	arXiv:1210.2645, JHEP. 12 (2012) 125
$B^+ \to K\pi\pi\gamma$ (photon polarization)	LHCb-CONF-2013-009
$B^0 \to K^*\gamma$ and $B_s \to \phi\gamma$	arXiv:1209.0313, Nucl. Phys. B 867 (2012) 1

LHCb future

- 2010-2012: collected about 3/fb at effective L_{inst} up to $4\text{x}10^{32}$ /cm^2/s
- 2015-2017: collect another ~5/fb at similar lumi
- 2017-2018: LHC LS2 ... then what?



- current L0 output rate cannot exceed ~1 MHz
- to keep rate limited, cut hard on hadron pT
- with current detector, no gain in hadronic event yields from increased lumi!

- LHCb upgrade: prepare detector for L_{inst} ~ $20\text{x}10^{32}$ /cm^2/s
  - read out full detector at 40 MHz
  - full software trigger with momentum/vertex reconstruction
  - velo pixel detector, Si and scintillating fibre tracker, new RICH, ...

Summary

- flavour physics at the LHC works!
  - large yields, clean signals (cleaner than expected by many of us!)
  - many important new results

- the Standard Model has survived ... so far

- exciting prospects for the future
  - 2015-2017: double (triple?) existing dataset
  - 2017-2019: LS2, upgrade installation
  - 2019- ...: collect ~50/fb, with up to 2x more efficient trigger

backup

Mixing in the D^0 system

1/fb: arXiv:1211.1230, PRL 110.101802 (2013)

3/fb: arXiv:1309.6534, subm. to PRL

- in D^0 system flavour can be tagged via D*:

right sign: $D^{*+} \to \pi^+ D^0 \to \pi^+ (K^- \pi^+)_{D^0}$

wrong sign: $D^{*+} \to \pi^+ D^0 \to \pi^+ (K^+ \pi^-)_{D^0}$

- mixing probed with time-dependence of $R = \frac{N(\text{wrong})}{N(\text{right})}$

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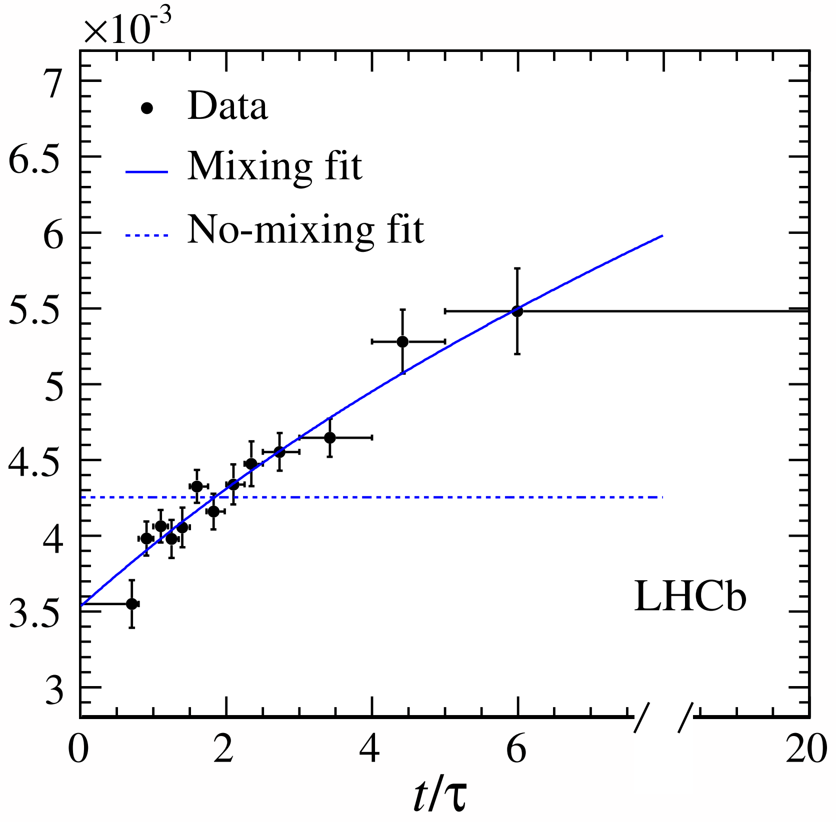

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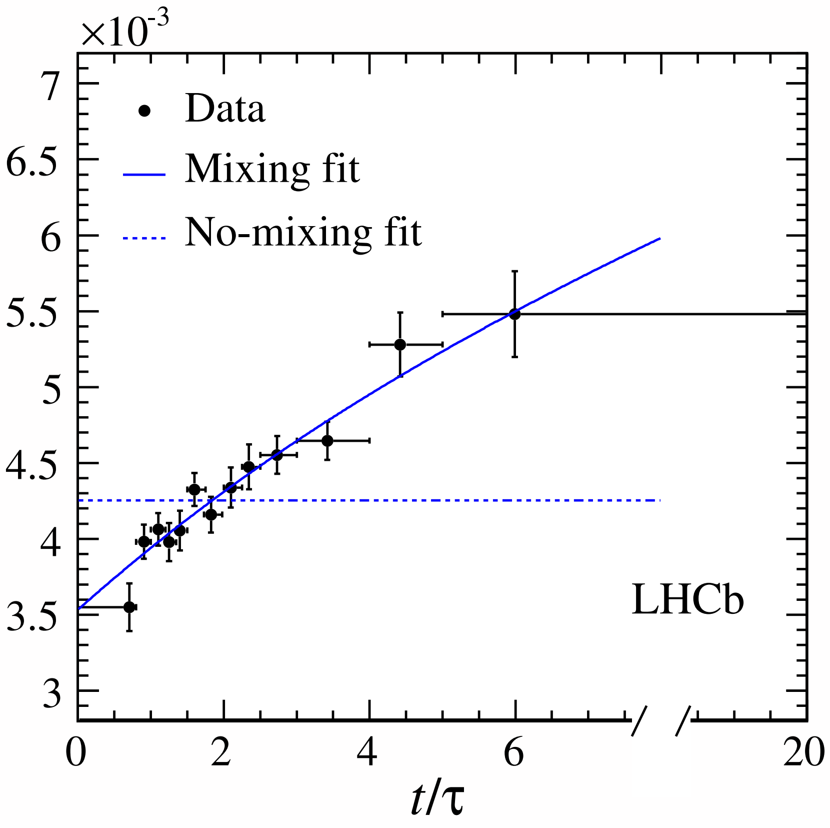
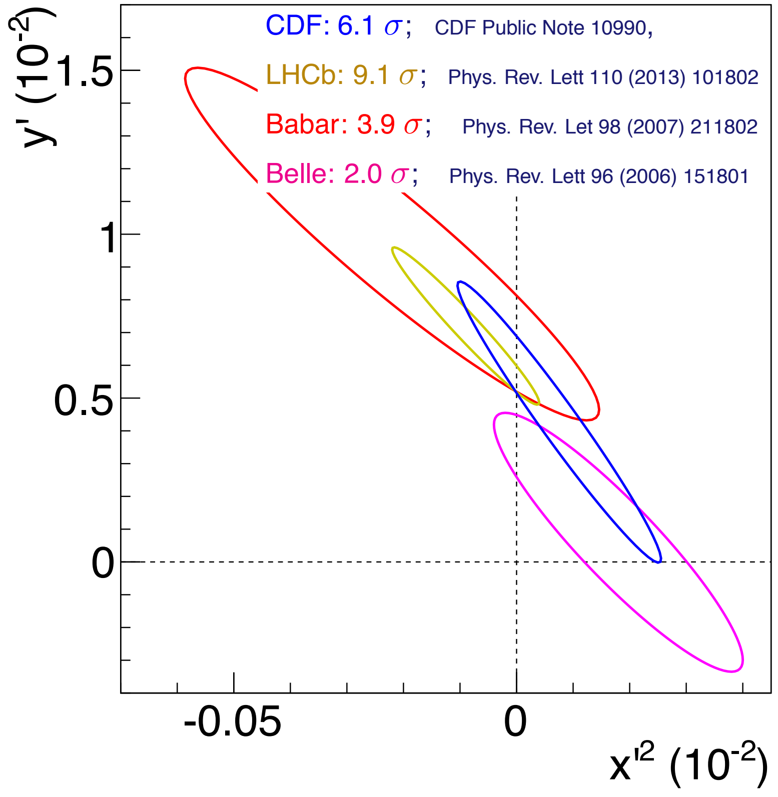
- mixing probed with time-dependence of $R = \dfrac{N(\text{wrong})}{N(\text{right})}$

$$R(t) \equiv \frac{N_{\text{ws}}(t)}{N_{\text{rs}}(t)} \approx R_D + \sqrt{R_D}\, y'\, t + \frac{1}{4}\,(x' + y')\, t^2$$





CDF: 6.1 σ; CDF Public Note 10990,

LHCb: 9.1 σ; Phys. Rev. Lett 110 (2013) 101802

Babar: 3.9 σ; Phys. Rev. Let 98 (2007) 211802

Belle: 2.0 σ; Phys. Rev. Lett 96 (2006) 151801

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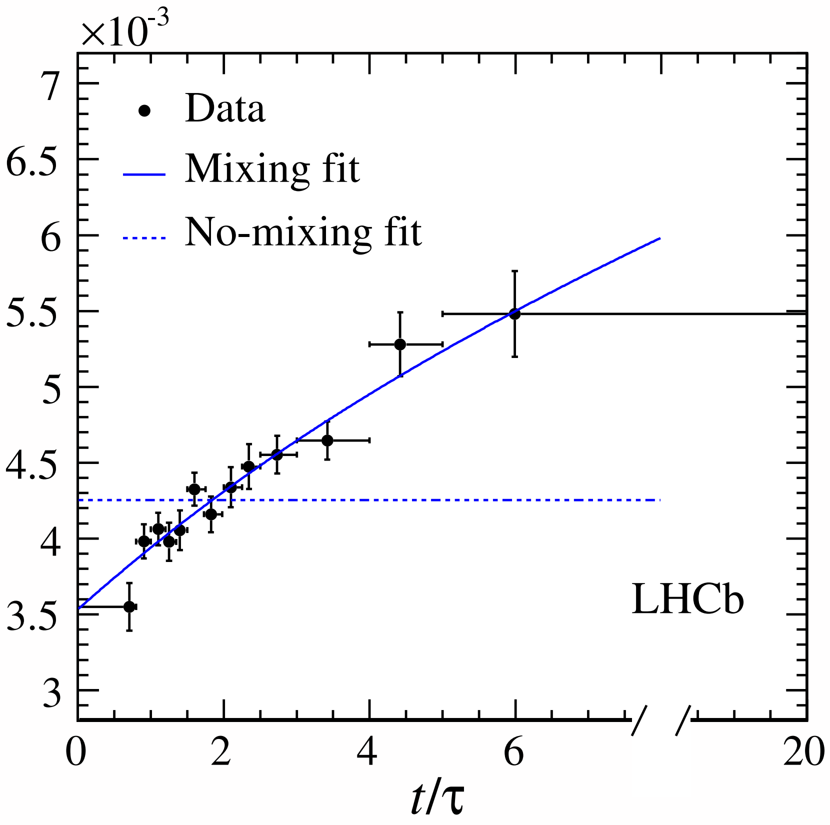
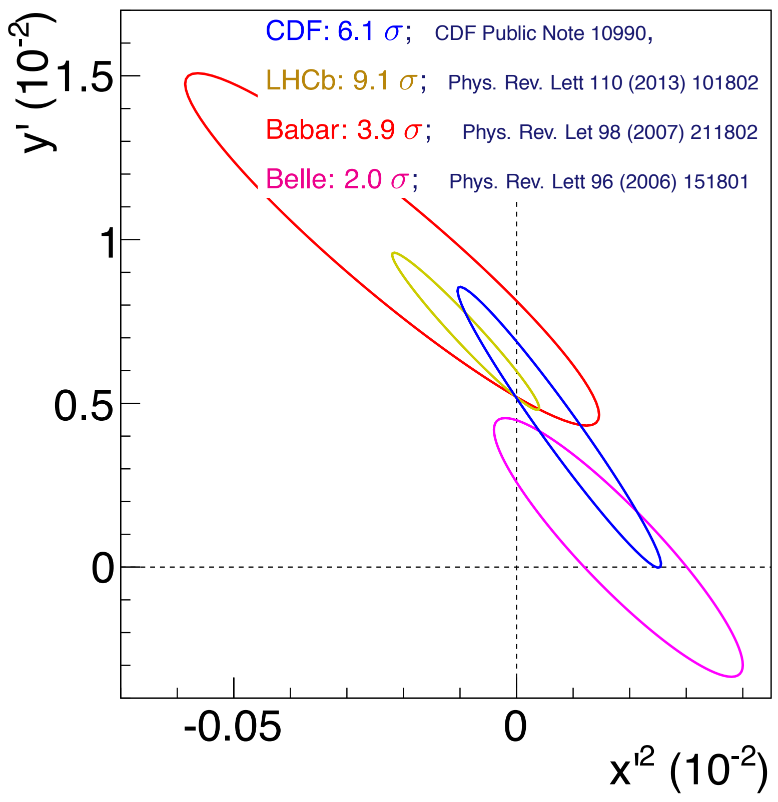




- D^0 mixing now firmly established:

$$x'^2 = (5.5 \pm 4.9) \times 10^{-5},\ y' = (4.8 \pm 1.0) \times 10^{-3}$$

- latest LHCb analysis (3/fb) also measures CPV in decay and mixing:

$$A_D \equiv (R_D^+ - R_D^-)/(R_D^+ - R_D^-) = (-0.7 \pm 1.9)\%$$

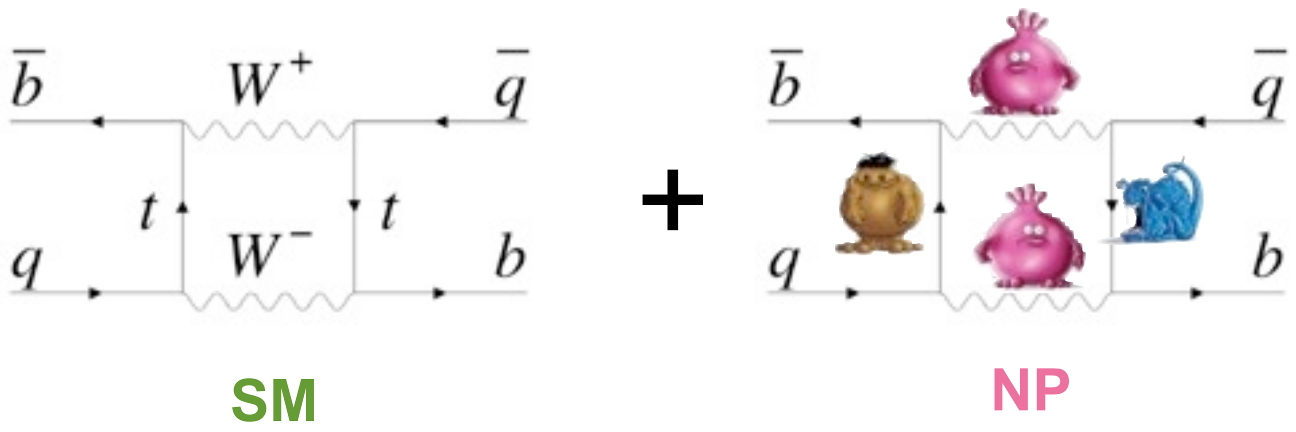
$$|q/p| = 1.00 \pm 0.25$$

⇨ no sign of CPV

- related: measurement of indirect CPV using effective lifetimes in KK and ππ: arXiv:1310.7201, acc. PRL

Constraints on M_{12}

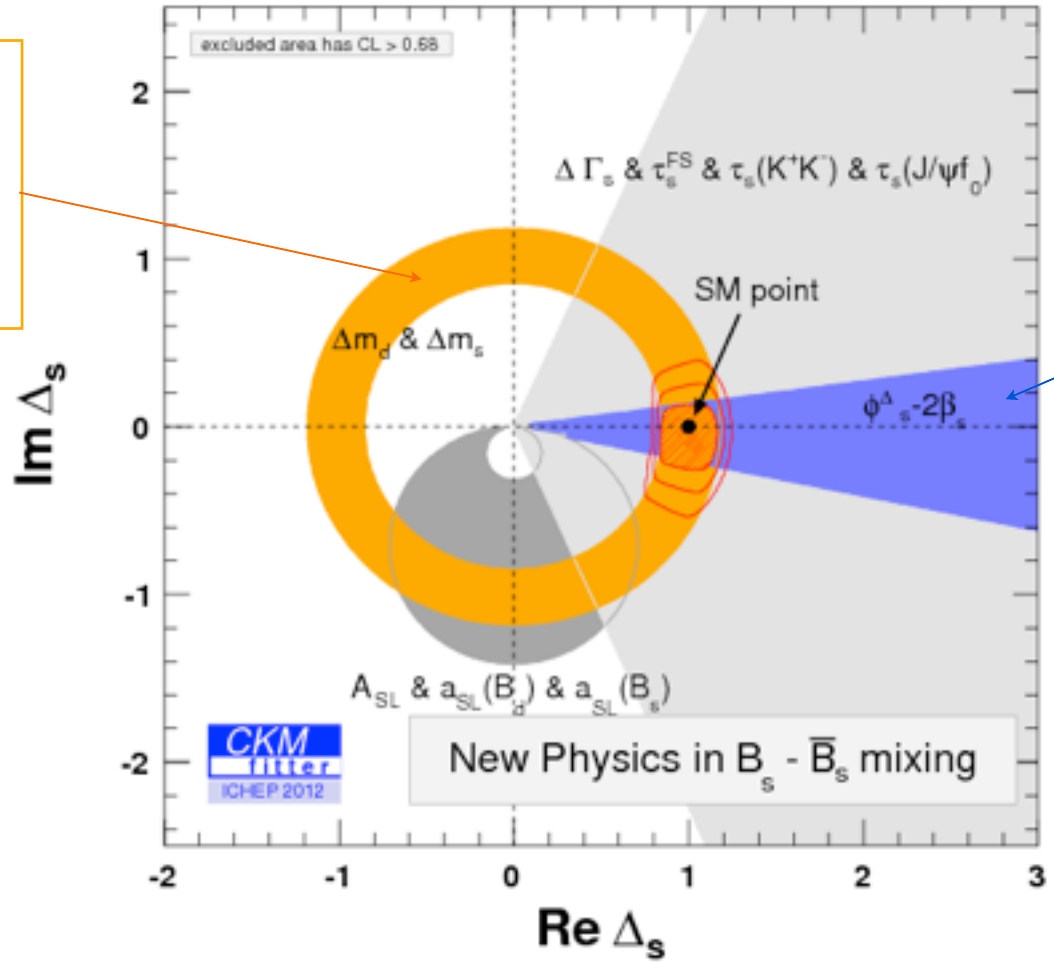
- suppose new physics affects M_{12}



$$M_{12,q} = \Delta_q \cdot M_{12,q}^{\mathrm{SM}}$$

- constraints from mixing measurements

constraint from oscillation frequencies, theory limited



constraint from indirect CP violation, statistically limited

From Lenz, Nierste and CKMFitter, arXiv:1203.0238

The future of gamma: B_s->D_sK

- extract ‘sin(2beta_s - gamma)’ from amplitudes of oscillations in $B_s^0 \to D_s^\mp K^\pm$

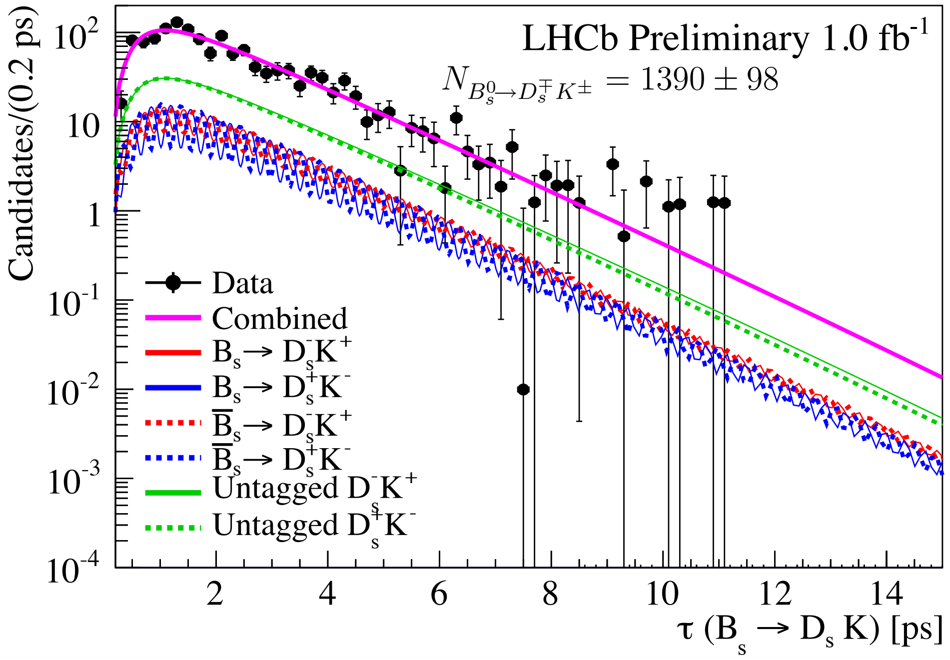
$$\begin{aligned}\frac{d\Gamma_{B_s^0\to f}(t)}{dt} = \frac{1}{2}|A_f|^2(1+|\lambda_f|^2)e^{-\Gamma_s t} & \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - D_f \sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right. \\ & \left. + C_f\cos\left(\Delta m_s t\right) - S_f \sin\left(\Delta m_s t\right)\right],\end{aligned}$$

$$C = \frac{1-r_{D_sK}^2}{1+r_{D_sK}^2}\,,$$

$$D_f = \frac{2r_{D_sK}\cos(\Delta-(\gamma-2\beta_s))}{1+r_{D_sK}^2}\,,\quad D_{\bar f} = \frac{2r_{D_sK}\cos(\Delta+(\gamma-2\beta_s))}{1+r_{D_sK}^2}\,;$$

$$S_f = \frac{2r_{D_sK}\sin(\Delta-(\gamma-2\beta_s))}{1+r_{D_sK}^2}\,,\quad S_{\bar f} = \frac{2r_{D_sK}\sin(\Delta+(\gamma-2\beta_s))}{1+r_{D_sK}^2}\,.$$

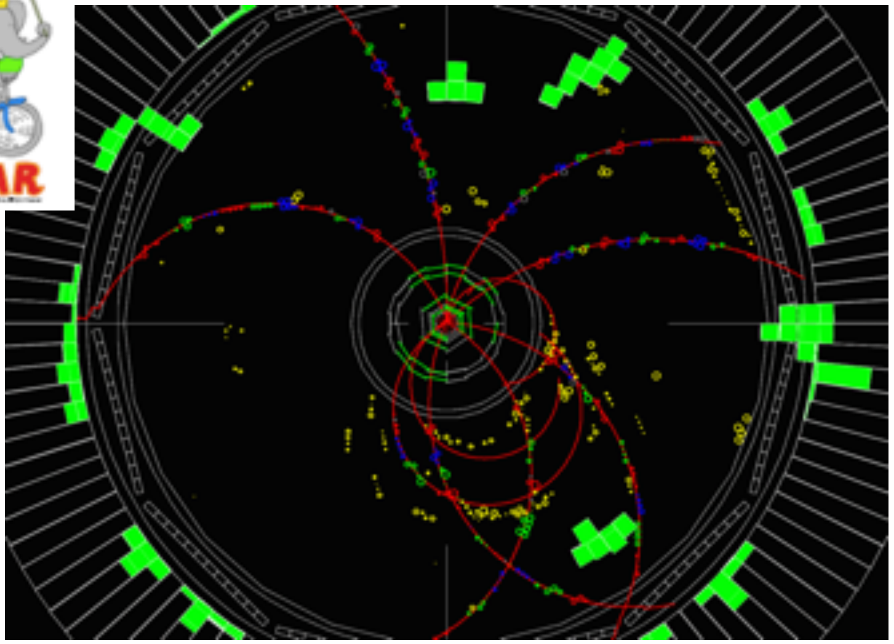
- small theory uncertainties, but requires flavour tagging (see later)
- first results on 2011 data (LHCb-CONF-2012-029)



$$\begin{aligned} C &= 1.01 \pm 0.50 \pm 0.23\,, \\ S_f &= -1.25 \pm 0.56 \pm 0.24\,, \\ S_{\bar f} &= 0.08 \pm 0.68 \pm 0.28\,, \\ D_f &= -1.33 \pm 0.60 \pm 0.26\,, \\ D_{\bar f} &= -0.81 \pm 0.56 \pm 0.26\,, \end{aligned}$$

- first constraints of gamma expected from 3/fb analysis (in progress)
- systematics limited by lifetimes, mixing and tagging calibration: will all improve with more LHCb data

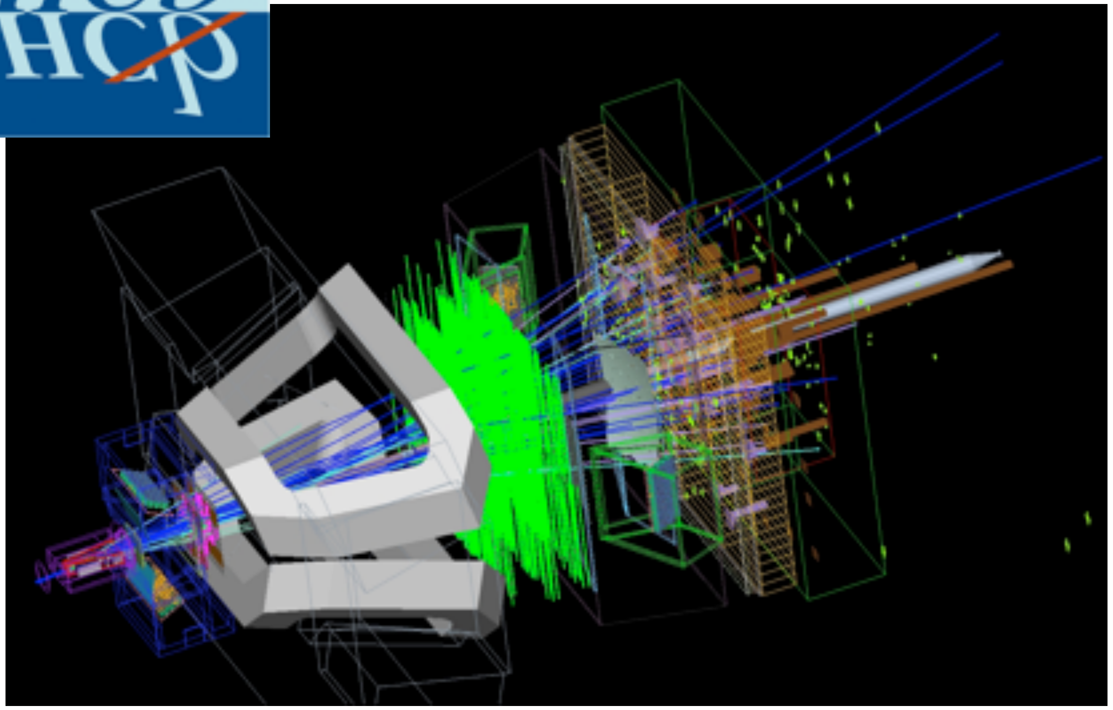
The price to pay ...



~10 b-bbar events / s
O(20) particles/event

full event reconstruction

typical B->X efficiency ~ 30%
Qtag ~ 30%
σ(t) ~ 0.6 ps



50000 b-bbar events / s
O(200) particles/event

typical B->X efficiency 1%
Qtag ~ 2-4%
σ(t) ~ 0.05 ps

good with muons, reasonably good with hadrons, but not so good with photons and flavour tagging

ambiguity resolution

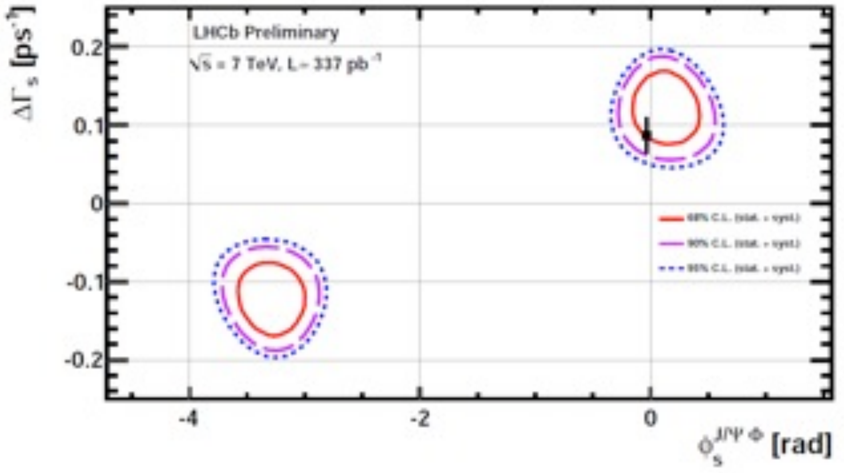
arXiv:1304.2600, Phys. Rev. D 87, 112010 (2013)

- ambiguity:

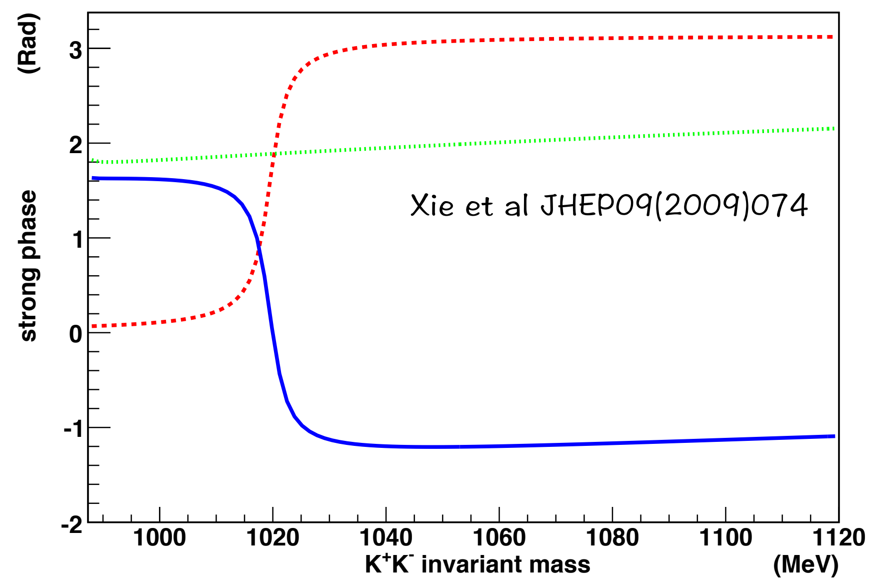
$$(\phi_s, \Delta\Gamma_s, \delta_0, \delta_\parallel, \delta_\perp, \delta_\mathrm{S}) \mapsto (\pi - \phi_s, -\Delta\Gamma_s, -\delta_0, -\delta_\parallel, \pi - \delta_\perp, -\delta_\mathrm{S})$$

- solution: measure phase difference between S and P-wave in bins of mass (Xie, e.a. 2009)

(note: plot for first 0.37/fb only)



expected:

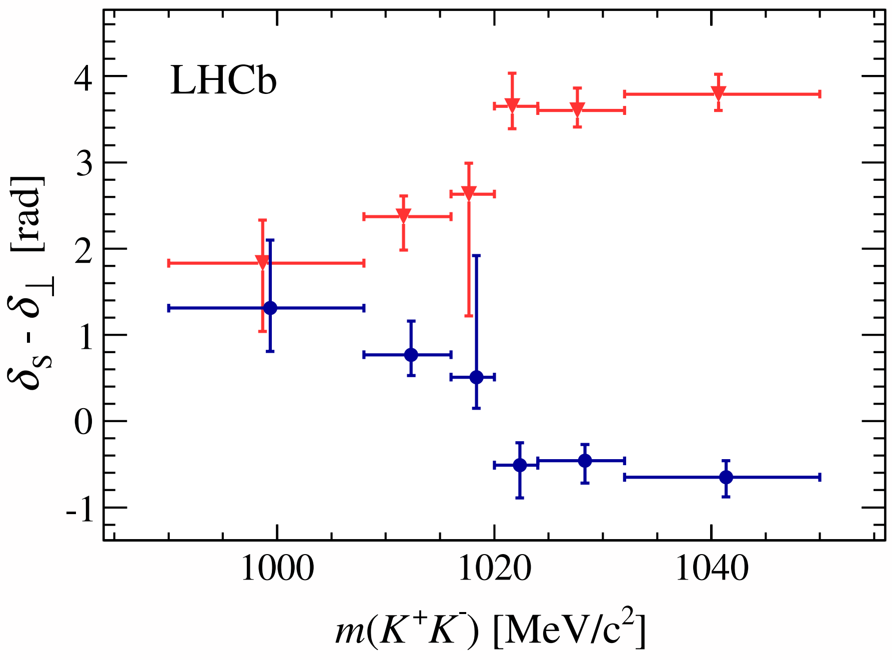


P-wave: relativistic Breit wigner

S-wave: not well known, but mild variation with mKK

difference

observed:



$\Delta\Gamma < 0$

$\Delta\Gamma > 0$

- unambiguous!
  only ΔΓ>0 solution fits
  expected pattern

B_s -> φμμ

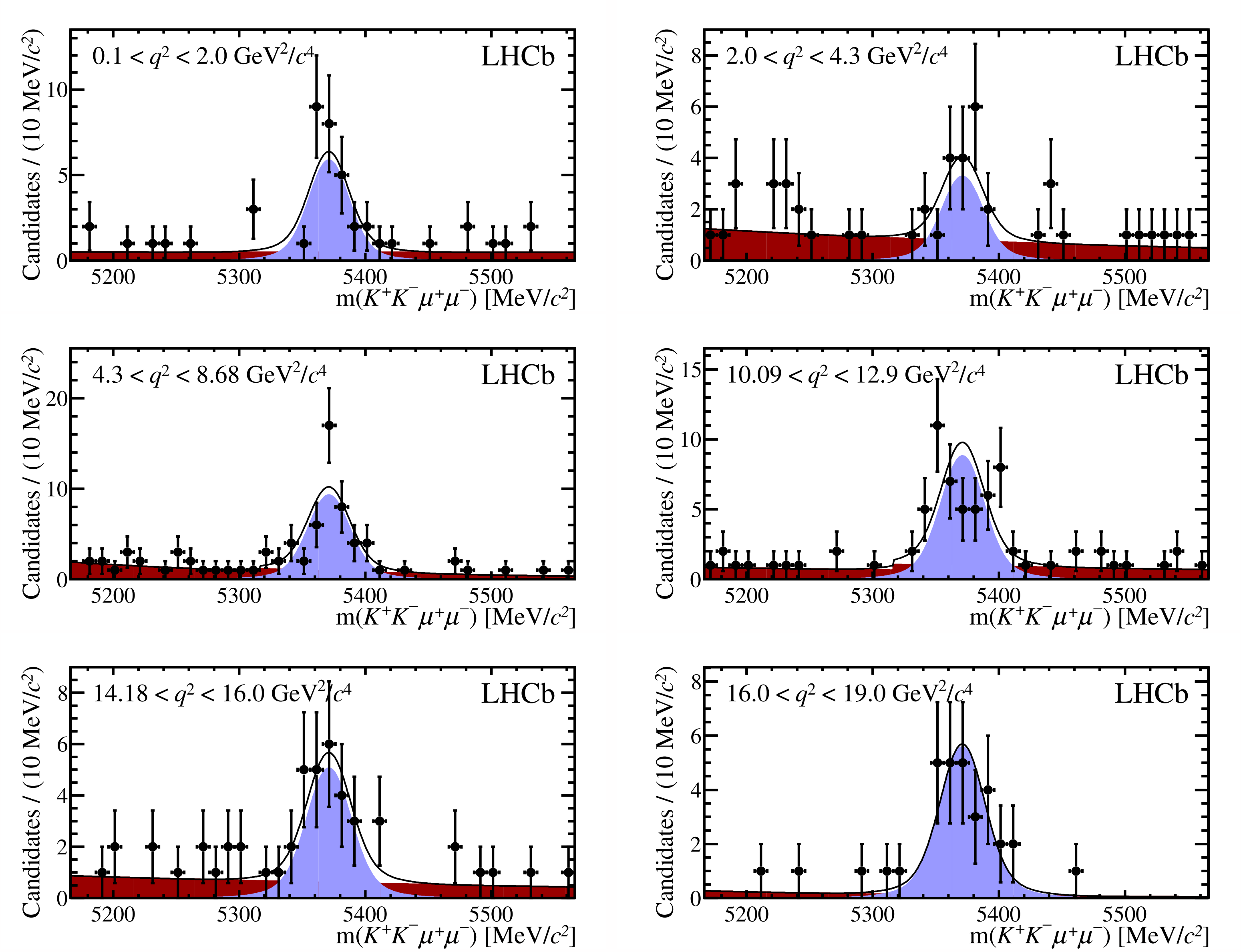
arXiv:1305.2168, JHEP. 07 (2013) 084

---

174 +/- 15 candidates in 1/fb

integrated BF: $\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-) = \left(7.07\,^{+0.64}_{-0.59} \pm 0.17 \pm 0.71\right) \times 10^{-7}$

error on BF(J/ψφ)

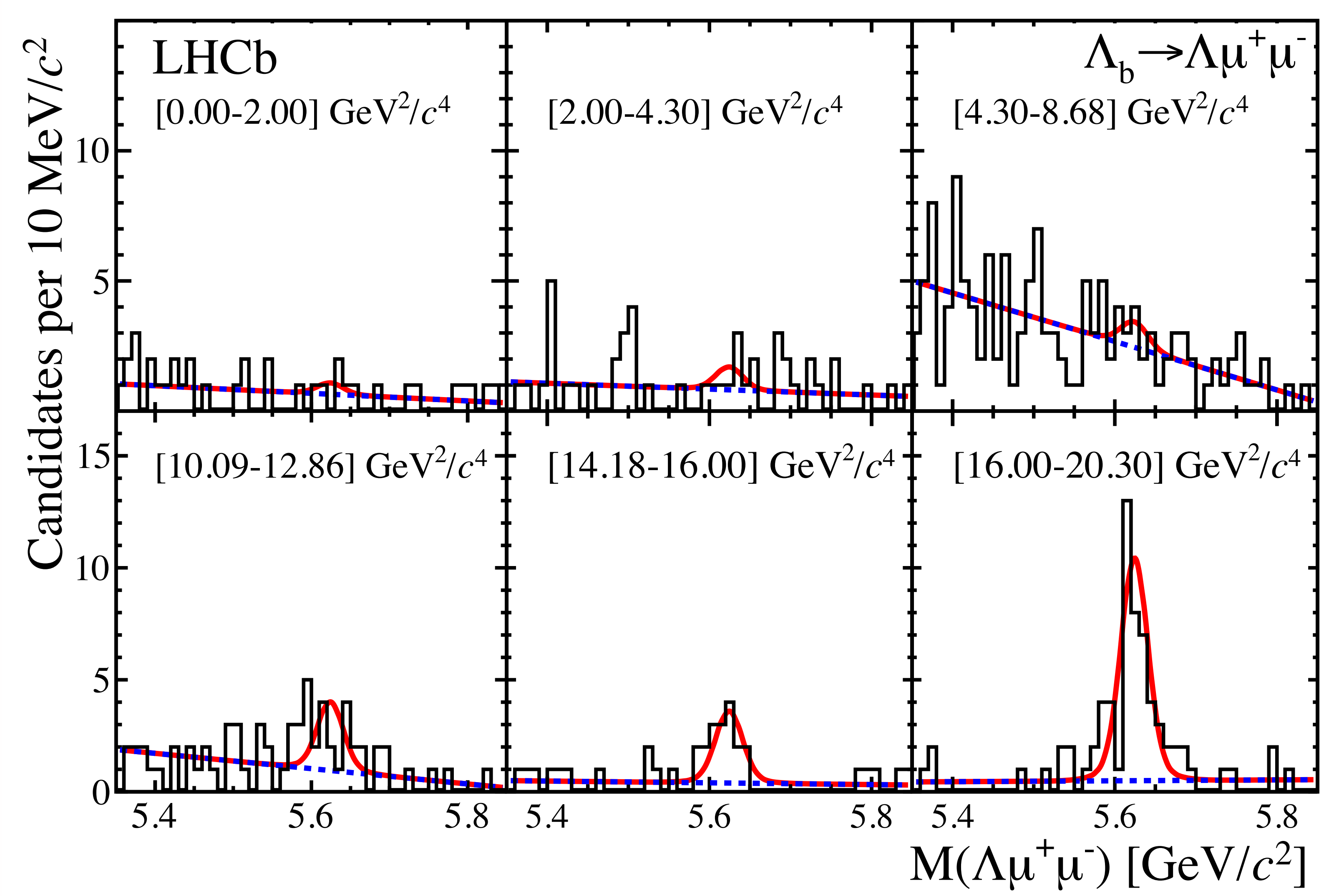


Λ_b -> $\Lambda\mu\mu$

arXiv:1306.2577, PLB 725 (2013) 25

78 +/- 12 events in 1/fb

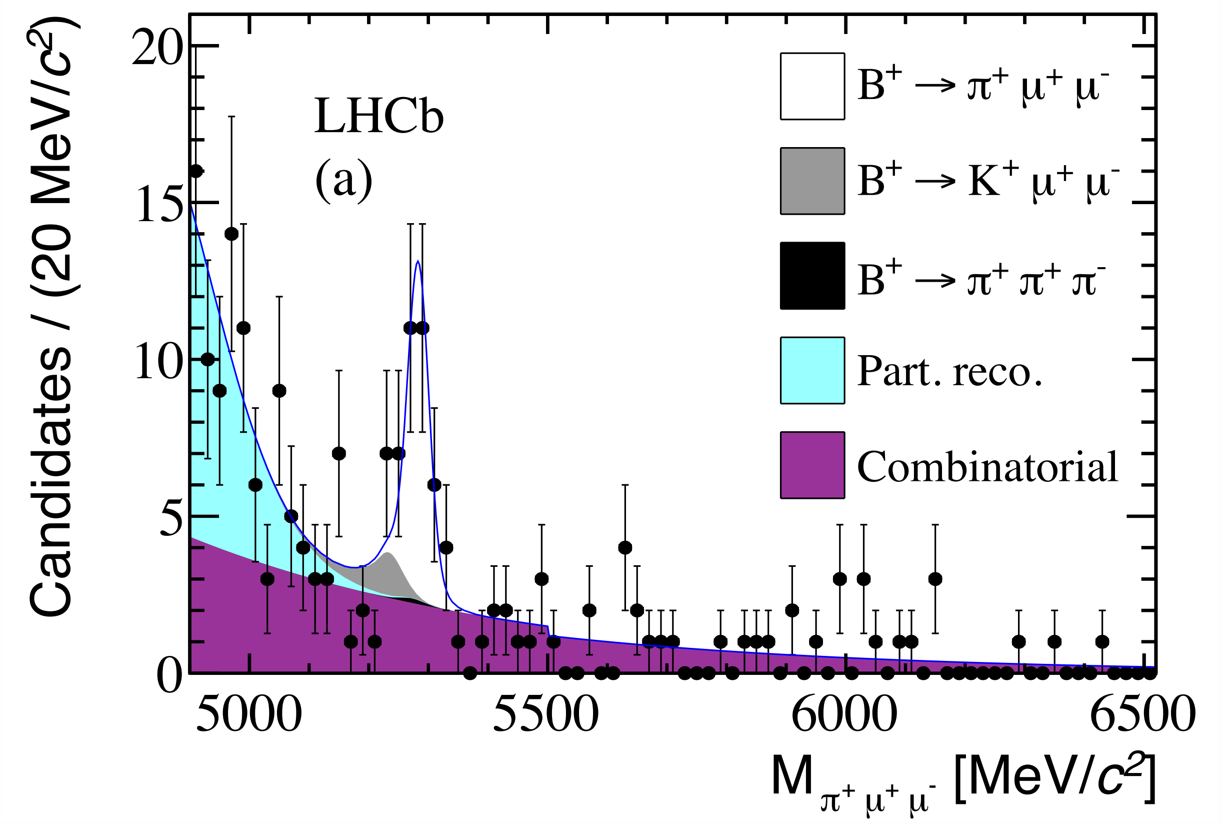
integrated BF: $\mathcal{B}(\Lambda_b^0 \to \Lambda\mu^+\mu^-) = (0.96 \pm 0.16\,(\mathrm{stat}) \pm 0.13\,(\mathrm{syst}) \pm 0.21\,(\mathrm{norm})) \times 10^{-6}$



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

arXiv:1210.2645, JHEP. 12 (2012) 125

about 25 +/- 7 events in 1/fb



$$\frac{\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)} = 0.053 \pm 0.014\,(\text{stat.}) \pm 0.001\,(\text{syst.})\,.$$

$$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) = (2.3 \pm 0.6\,(\text{stat.}) \pm 0.1\,(\text{syst.})) \times 10^{-8}\,.$$

my very naive estimate of the B->ρμμ yield:

25 x 883 / 1240 = 17 events / fb ?

(that's why nobody looked yet)

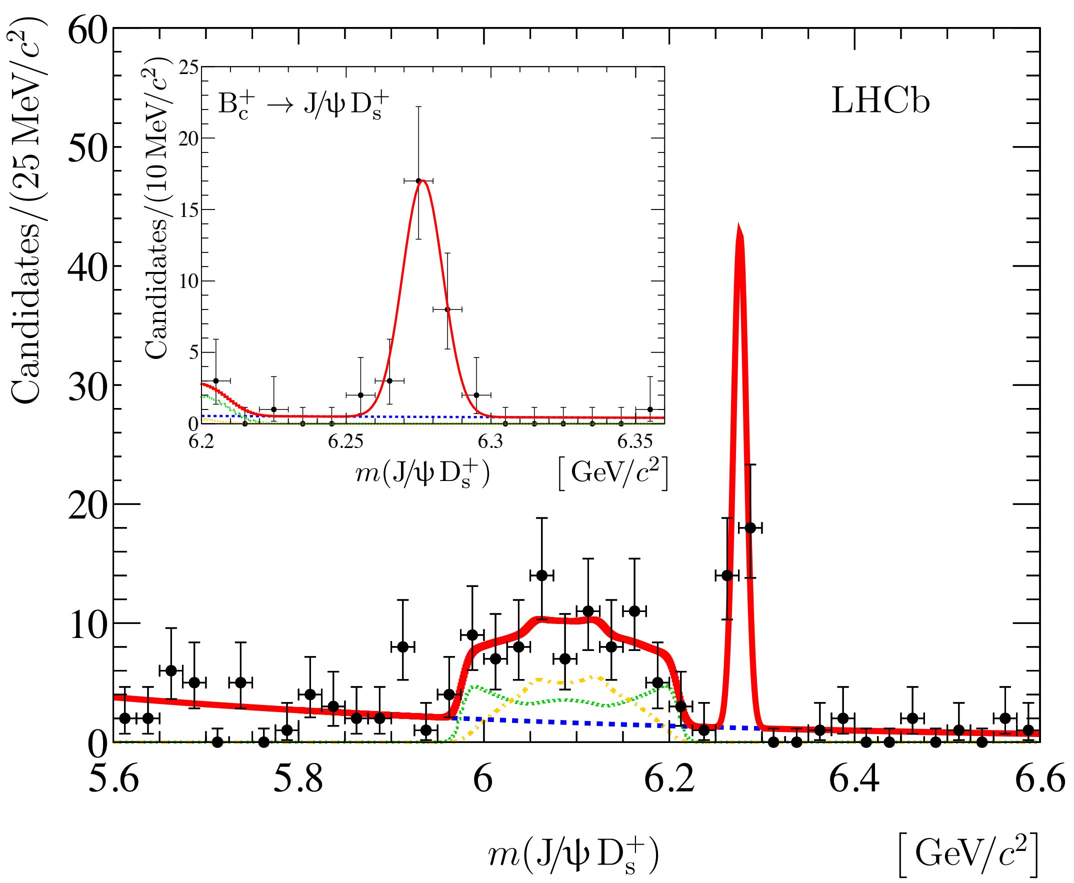
can LHCb do B_c -> D_s μμ ?

well ... we have just seen Bc -> J/ψ Ds$^{(*)}$

arXiv:1304.4530,
PRD 87 (2013) 112012

N(Bc -> J/ψ Ds) = 28.9 +/- 5.6

N(Bc -> J/ψ Ds*) = 68.5 +/- ?

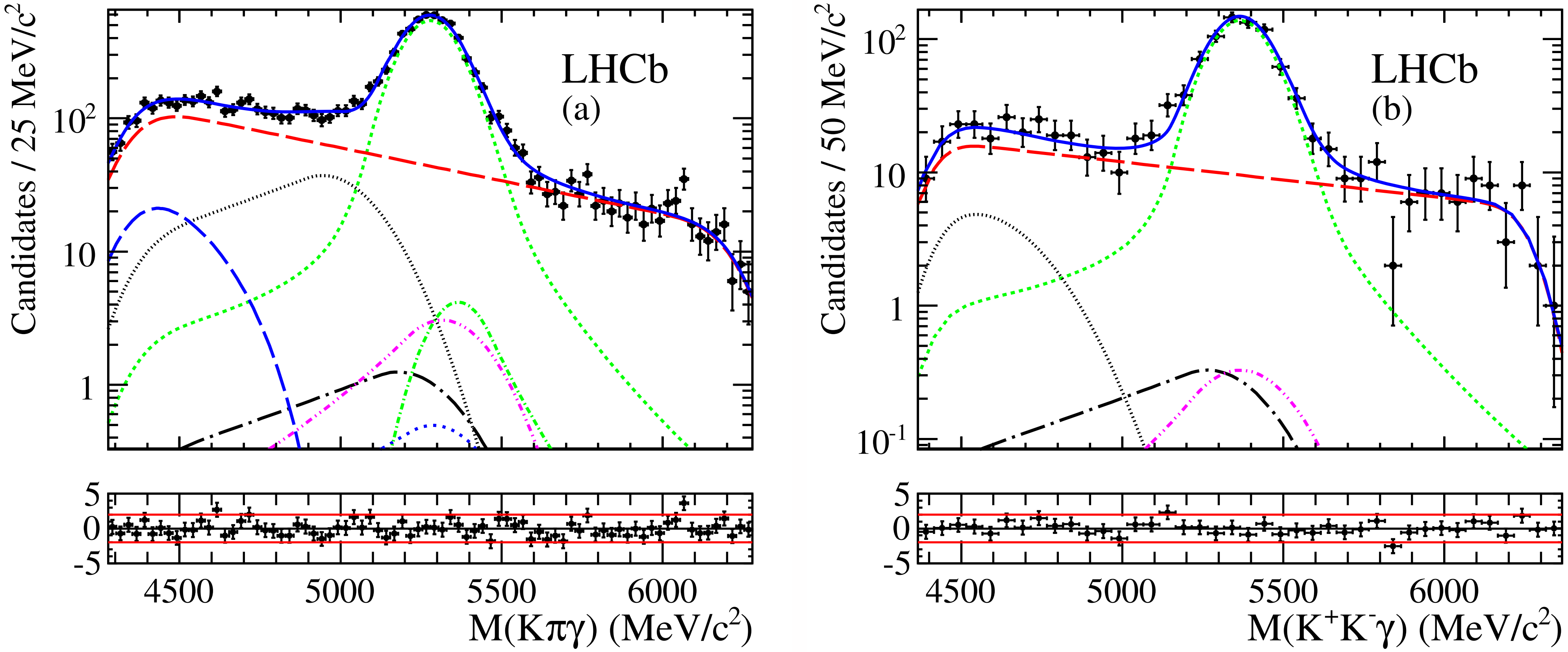


draw you own conclusion ...

$B^0 \to K^*\gamma$ and $B_s \to \phi\gamma$

arXiv:1209.0313, Nucl. Phys. B 867 (2012) 1-18

measurements of BF ratios and direct CP asymmetry in 1/fb:



5279±93 $B^0 \to K^*\gamma$

691±36 $B_s \to \phi\gamma$

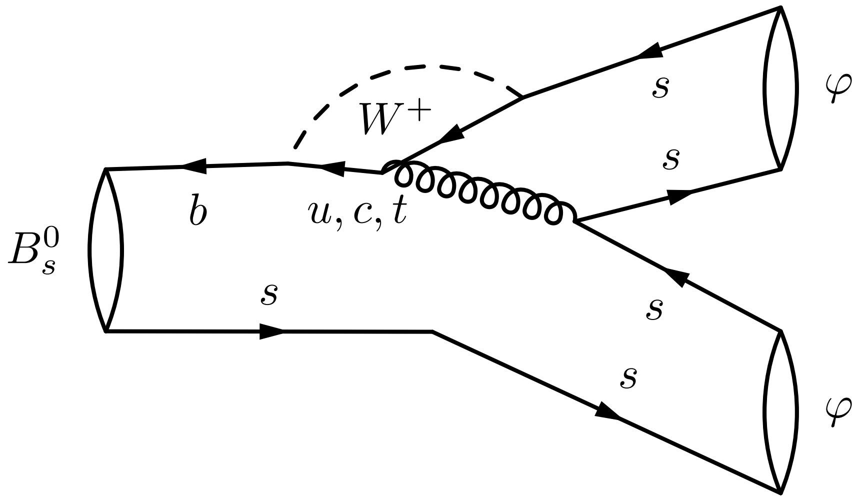
$$\frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B_s^0 \to \phi\gamma)} = 1.23 \pm 0.06\,(\text{stat.}) \pm 0.04\,(\text{syst.}) \pm 0.10\,(f_s/f_d),$$

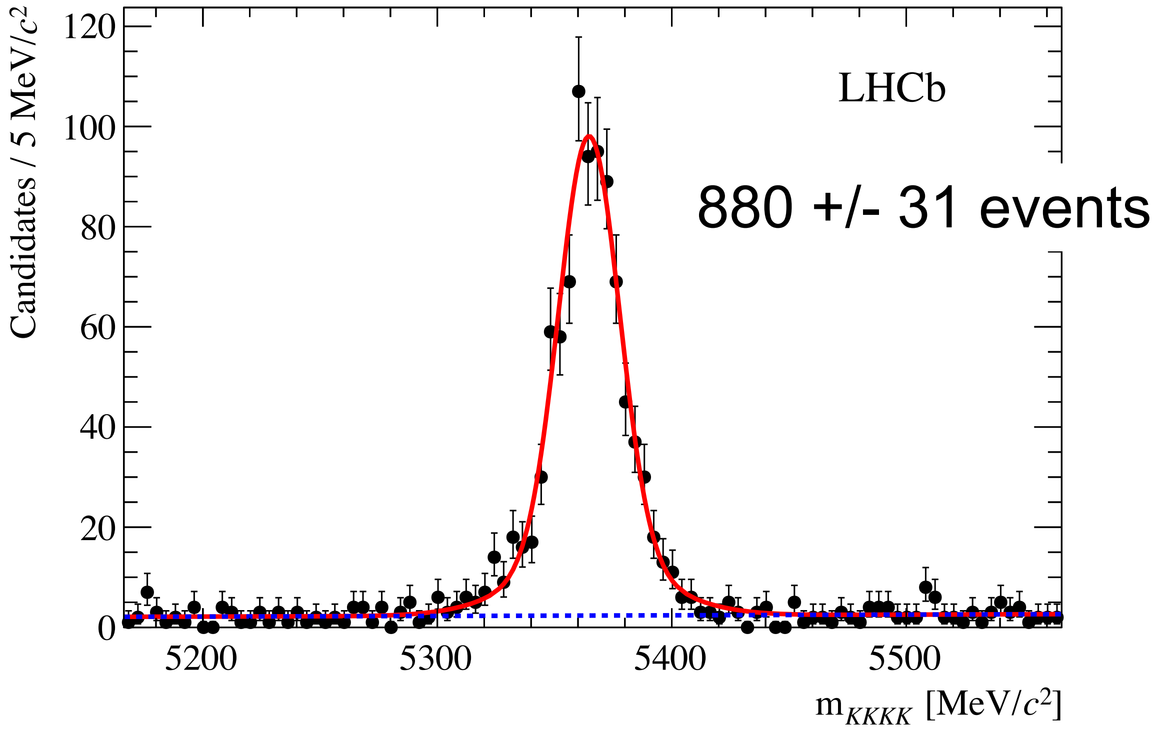
$$\mathcal{A}_{CP}\big(B^0 \to K^{*0}\gamma\big) = \big(0.8 \pm 1.7\,(\text{stat.}) \pm 0.9\,(\text{syst.})\big)\%.$$

note: with 3/fb should have enough events for
tagged time-dependent CPV analysis in $B_s \to \phi\gamma$

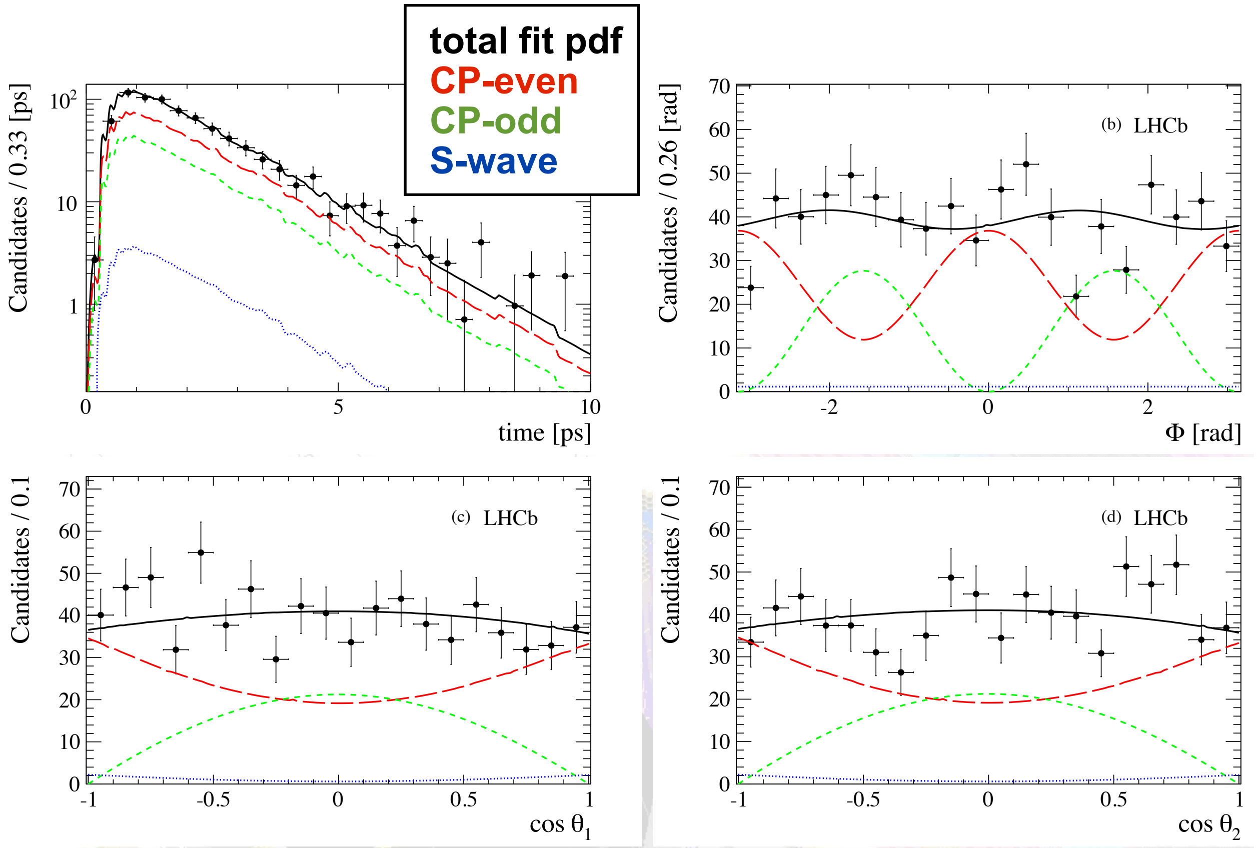
Bs->φφ

- ‘golden penguin’ mode: similar CKM phases as J/ψφ, but only penguin amplitude
- expect very small CPV phase in SM: $\phi_s^{s\bar{s}s} \approx 0.01$
  [see e.g. Bartsch, Buchalla, and Kraus, 2008]
- requires very similar tagged time-dependent angular analysis





880 +/- 31 events



total fit pdf
CP-even
CP-odd
S-wave

Bs->φφ

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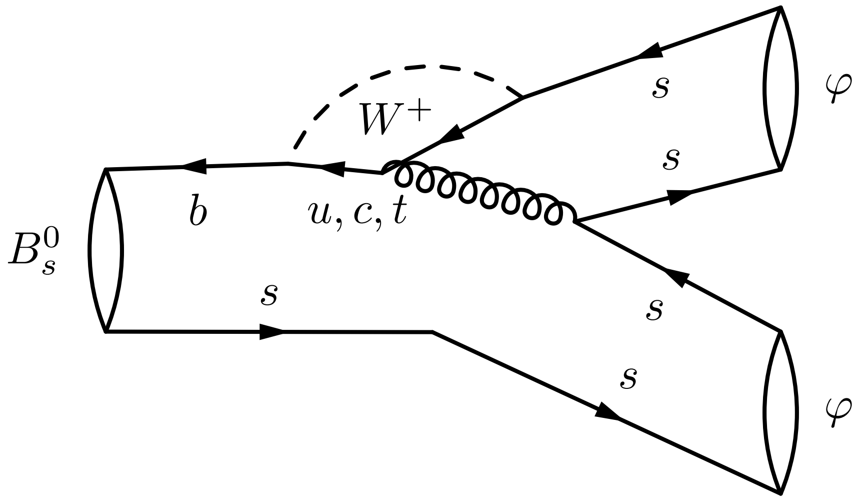
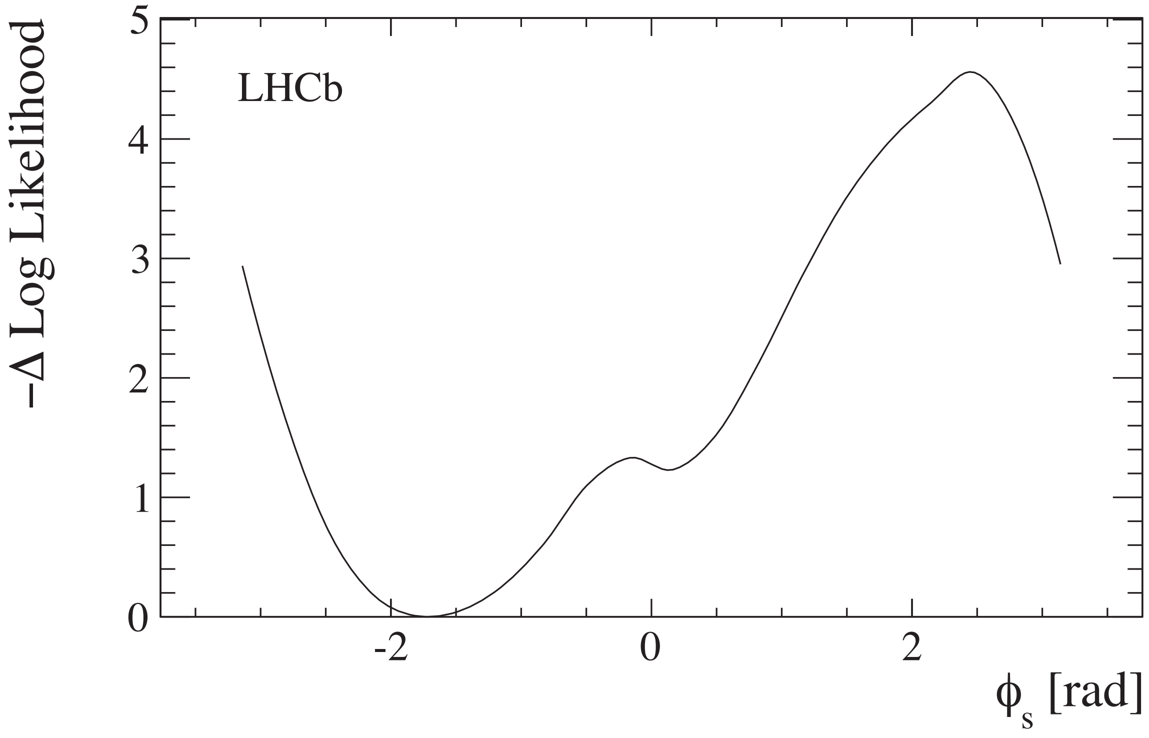


- result for the CPV phase



LHCb-PAPER-2013-007, *preliminary*

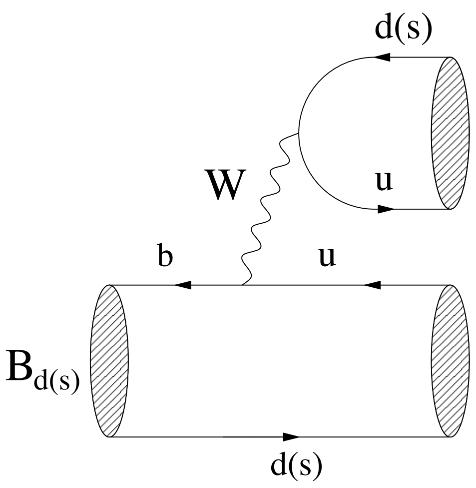
$\boldsymbol{\phi_s^{s\bar{s}s} \in [-2.46, -0.76]}$ at 68% CL

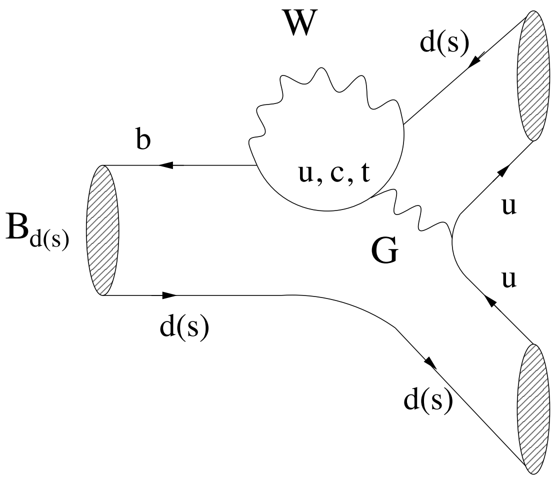
First measurement of B_s mixing phase in a pure penguin decay

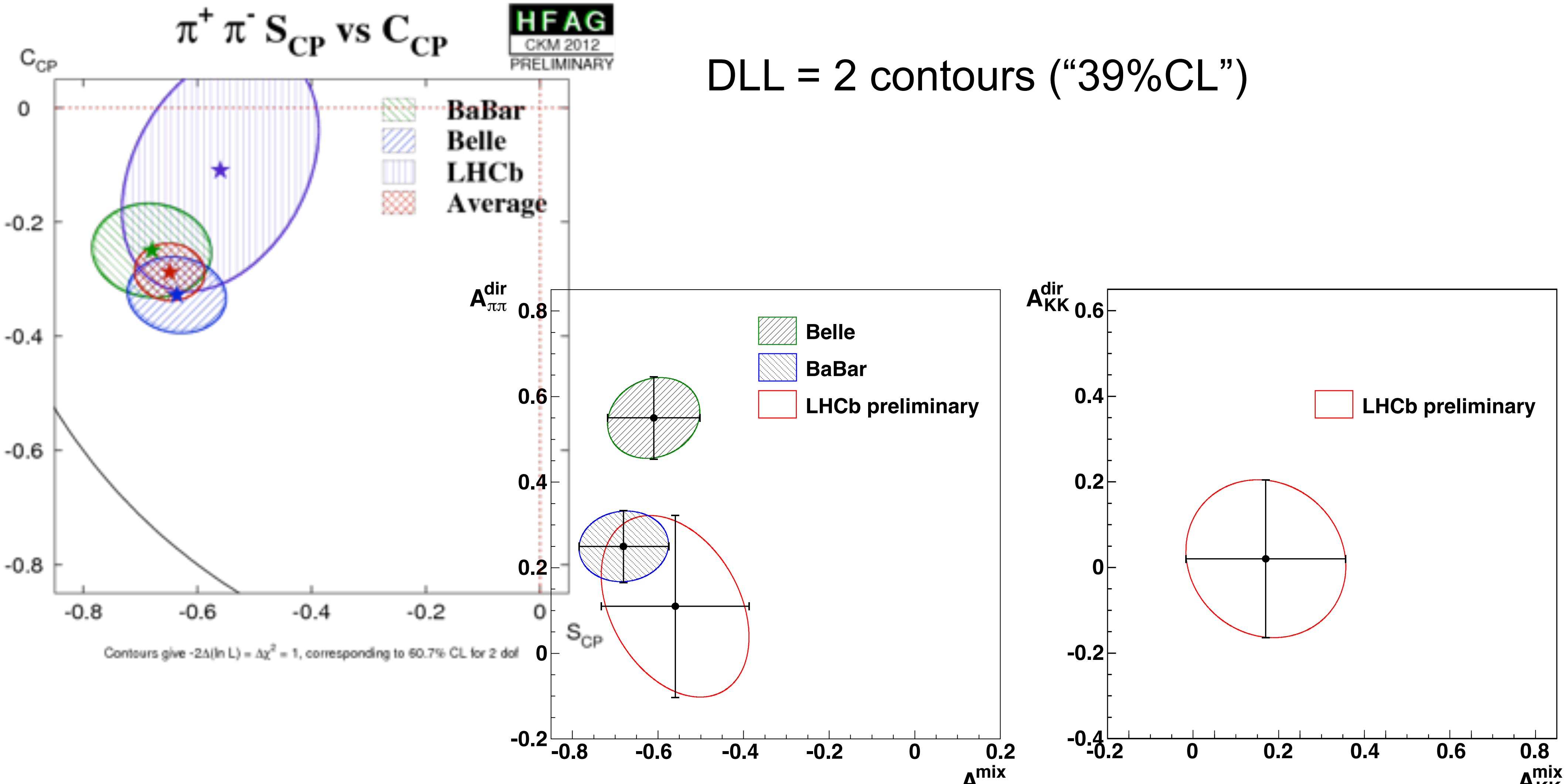
Bs->K+K- and Bd->pi+pi-

LHCb-CONF-2012-007

two amplitudes, with different weak phases: also expect large direct CPV (C!=0)







DLL = 2 contours (“39%CL”)