Results from LHCb

XLII International Meeting on Fundamental Physics
27-31 January 2014 (Benasque)

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(LHCb Collaboration)

outlook

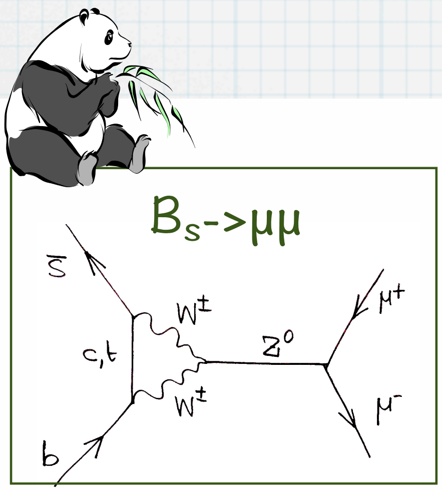
- LHCb and Flavor Physics
  - The Physics case
  - The LHCb detector
- CP Violation
  - Direct CP violation in $B_{(s)} \rightarrow hh$
  - γ measurements $B \rightarrow DK$
  - B_s oscillations
  - ϕ_s: $B_s \rightarrow J/\psi\phi$
- Rare decays (RD)
  - $B \rightarrow K^*\mu\mu$
  - $B_{(s)} \rightarrow \mu\mu$
- Conclusion

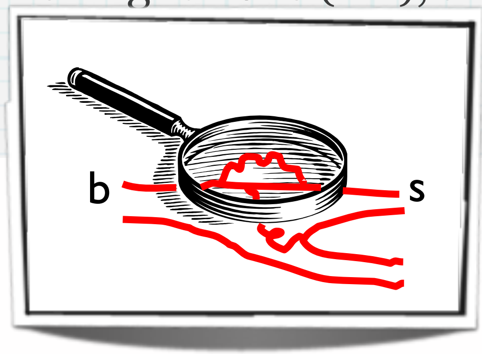
I. Physics case, the LHCb Detector

Physics case

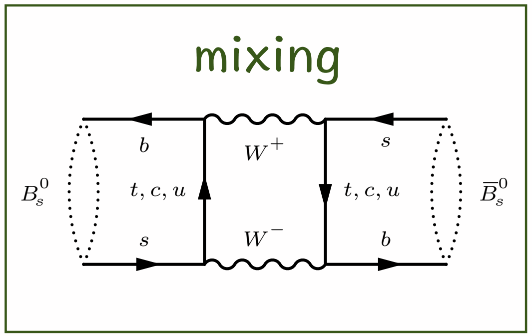
- **FCCC**: the Unitary Triangle: **γ**
- **FCNC**: Flavour Changing Neutral Currents: a search for New Physics **(NP)**
  - Forbidden at tree level. NP enters in loops and penguins!
  - **B** (D, K **decays**) controlled by SM CKM matrix with some precise SM predictions
    - Oscillation in $B_{(s)}$, CP violation, rare decays (RD)
    - Measure: Asymmetries, branching rations (BR), angular distributions

$\Delta F = 1$





$\Delta F = 2$



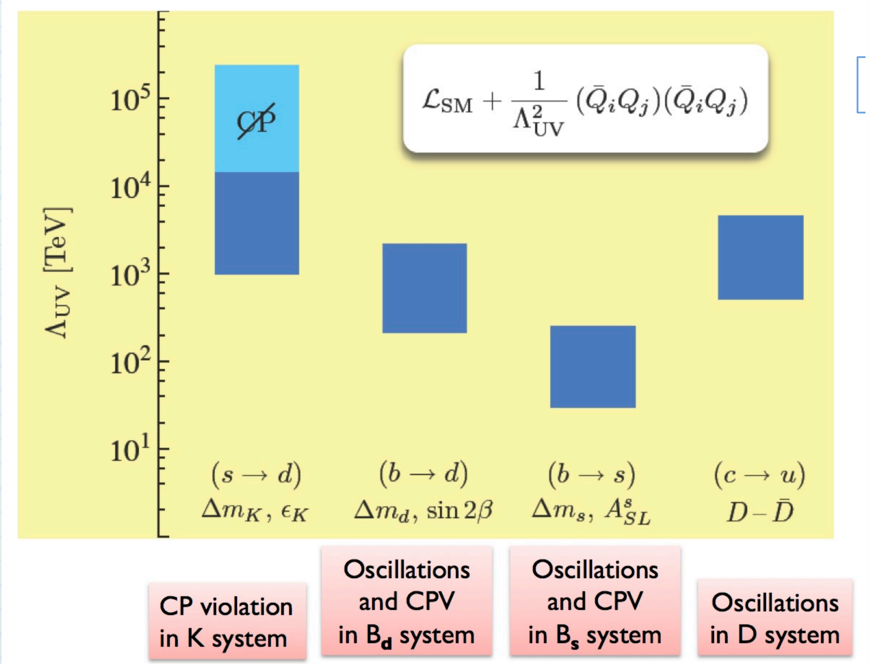
The Flavor puzzle!

- Flavor transitions can be parameterized in terms of operators, coupling and mass scale
- The Flavor puzzle: If NP is at 1 TeV the coupling should be small or if the couplings are *O(1)* the **NP is a higher scale than 1 Tev!** *or* the flavor structure of NP is 'aligned' with the flavour in SM (Minimum Flavor Violation **MFV**)

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

Operator	Bounds on Λ in TeV ($c_{\rm NP}=1$) Re	Im	Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar s_L \gamma^\mu d_L)^2$	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; $\lvert q/p\rvert, \phi_D$
$(\bar c_R\, u_L)(\bar c_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar b_L \gamma^\mu d_L)^2$	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 $c_{\rm NP}/\Lambda^2$.



(Fig. Neubert, EPS-HEP'11)

Isidori, Nir, Peres, arXiv:1002.900
Isidori arXiv:1302.0661

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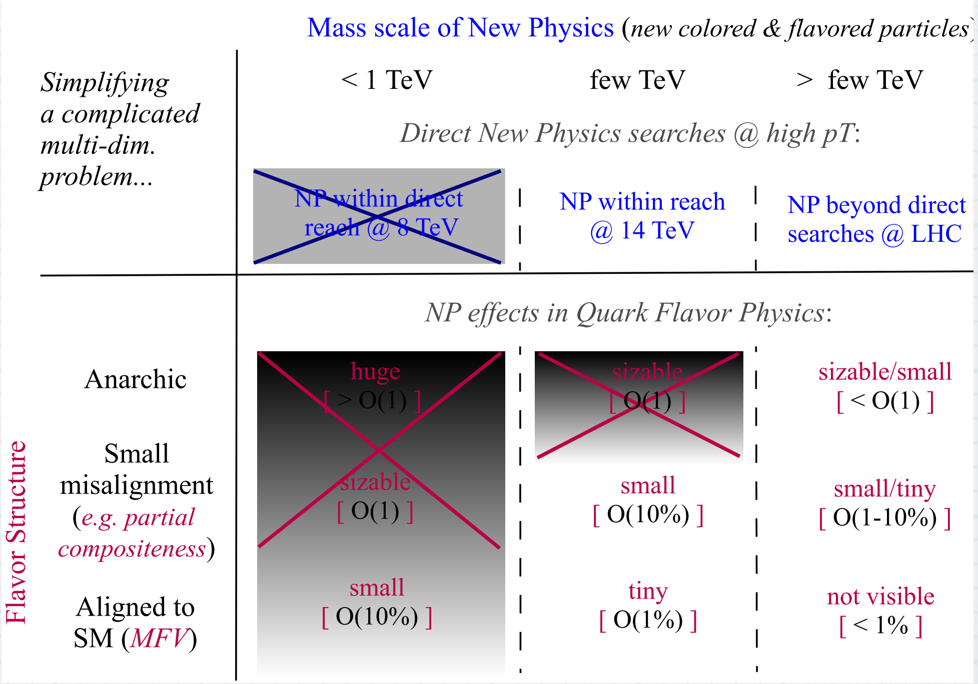
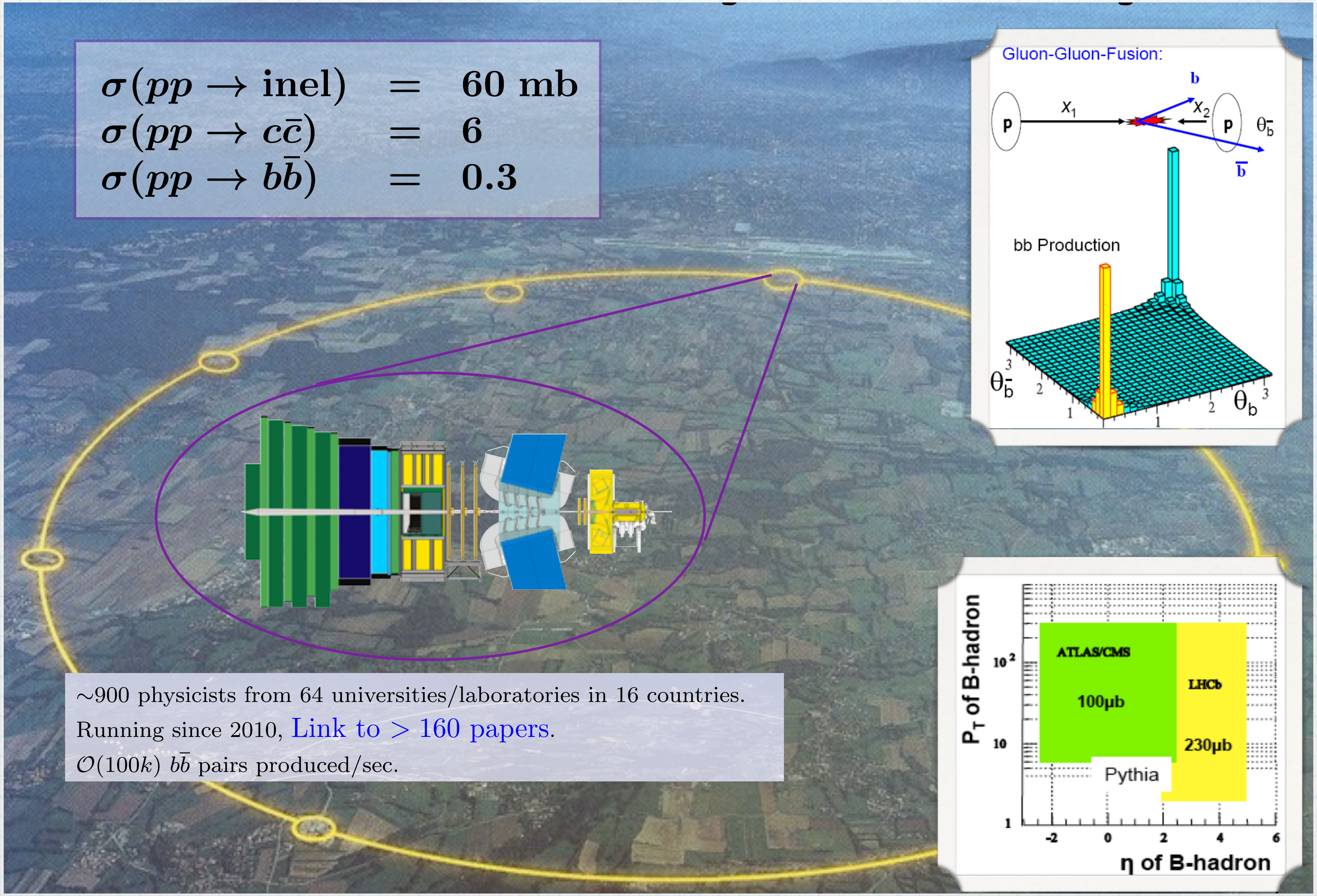


Isidori, 2013

LHC: a beauty and charm factory

- b hadrons in forward direcion, 2<η<5, and “low” P_T
- but in a ‘dirty’ hadronic emvironment

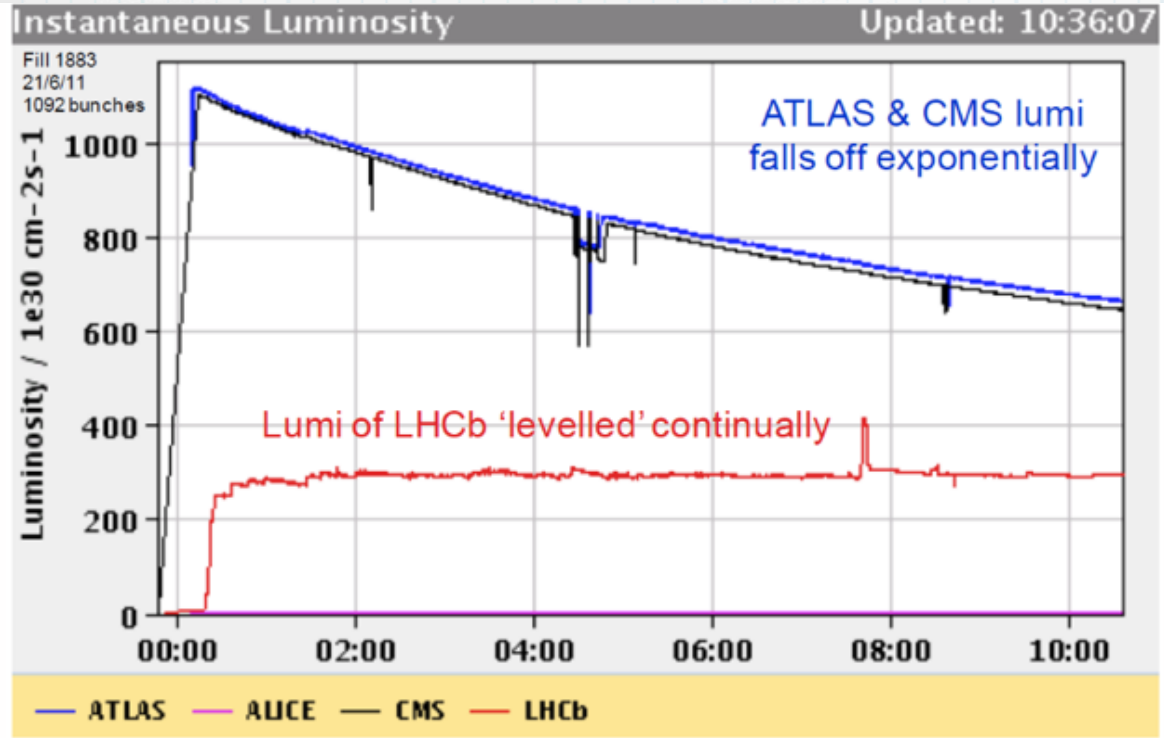
$$
\begin{aligned}
\sigma(pp \to \text{inel}) &= 60 \text{ mb} \\
\sigma(pp \to c\bar{c}) &= 6 \\
\sigma(pp \to b\bar{b}) &= 0.3
\end{aligned}
$$



~900 physicists from 64 universities/laboratories in 16 countries.
Running since 2010, Link to > 160 papers.
$\mathcal{O}(100k)$ $b\bar{b}$ pairs produced/sec.

LHCb: Leveling the luminosity

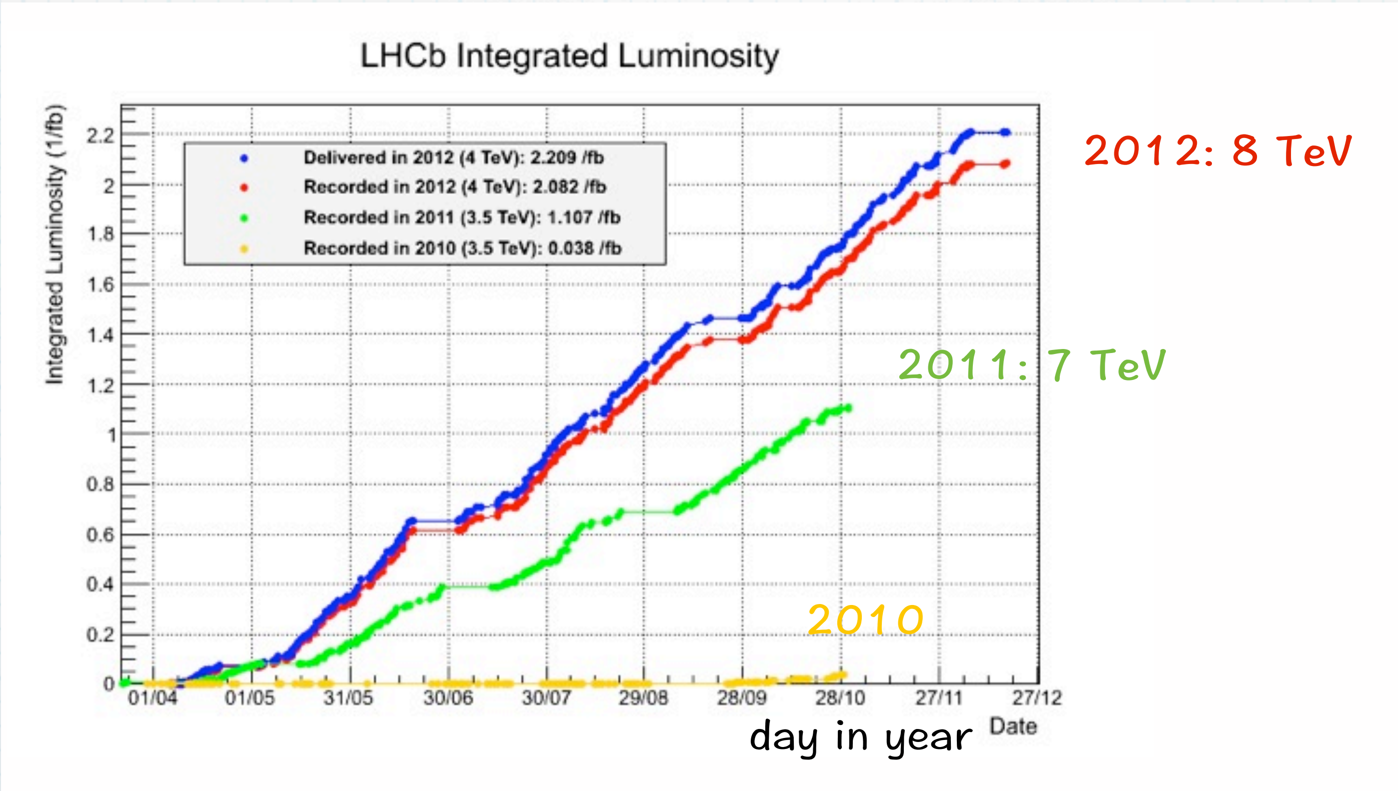
- ATLAS/CMS luminosity: ~25 primary interactions, LHCb can cope with ~2
  - Due to radiation, occupancy and PID performance
- ReduceD Instantaneous Luminosity: L ~ 2-4 10^{32} $cm^{-2}s^{-1}$
- Lateraly displaced from head on collision to reduce inst. luminosity



$$\langle \mathcal{L} \rangle_{2011} \sim 2.7 \times 10^{32} cm^{-2} s^{-1}$$
$$\langle \mathcal{L} \rangle_{2012} \sim 4.0 \times 10^{32} cm^{-2} s^{-1}$$

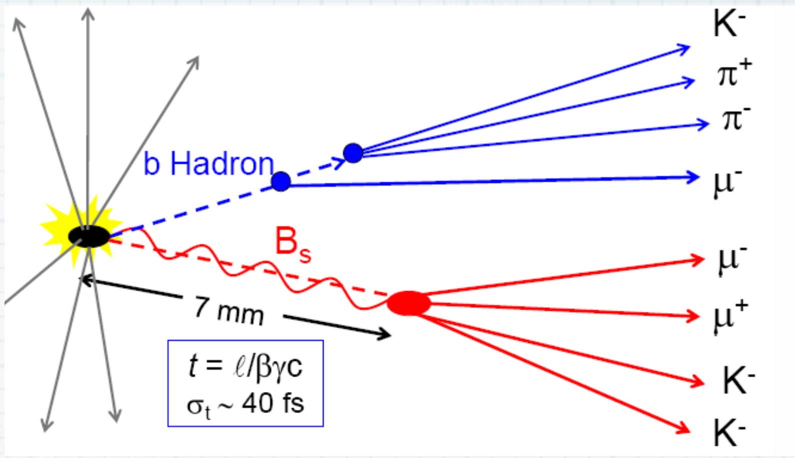
Luminosity

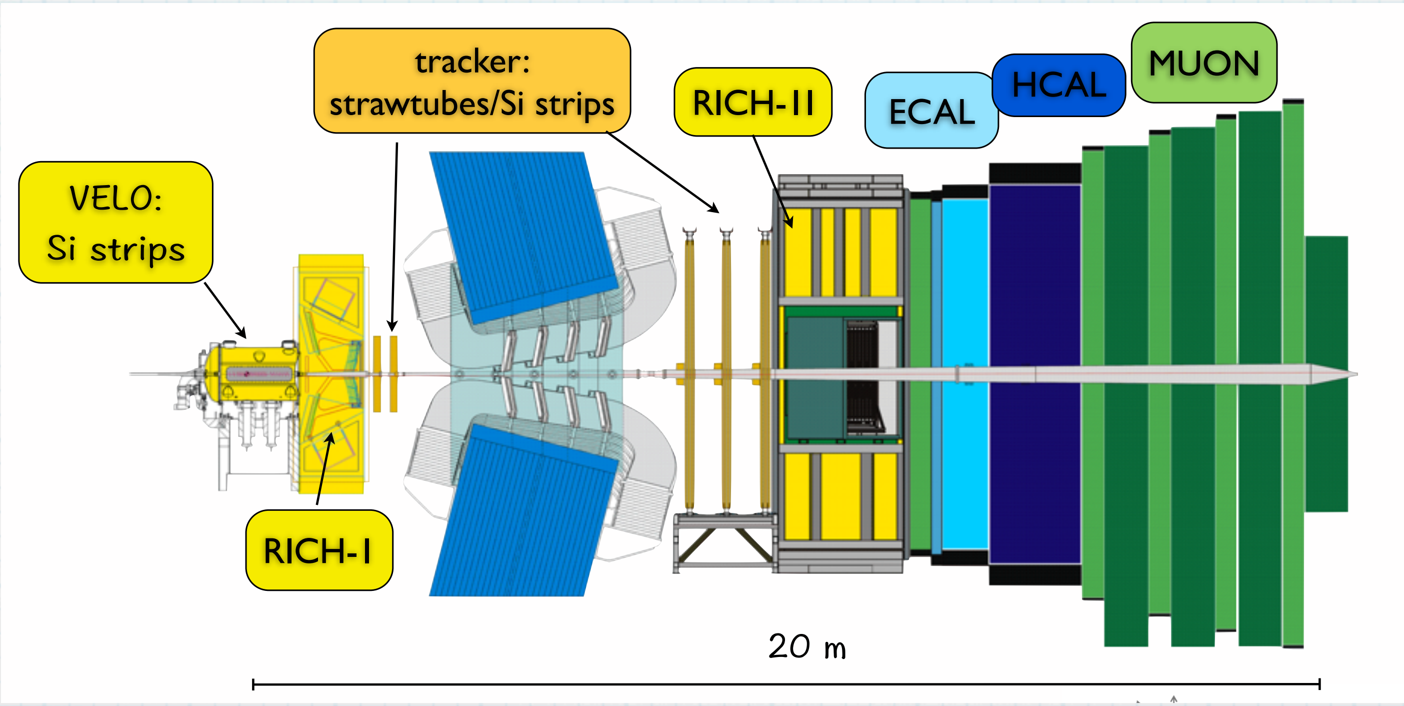
- Integrated Luminosity: **1 fb^{-1}(2011) 2 fb^{-1}(2012)**
  - efficiency >93%
- Relevant decays have small BR, with selection efficiencies, we expect $O(10^4)$ to few events per fb^{-1}!
- Most analysis use **1 fb^{-1}**, few with 3 fb^{-1}, expect most data analyzed in 2014!



Detector requirements

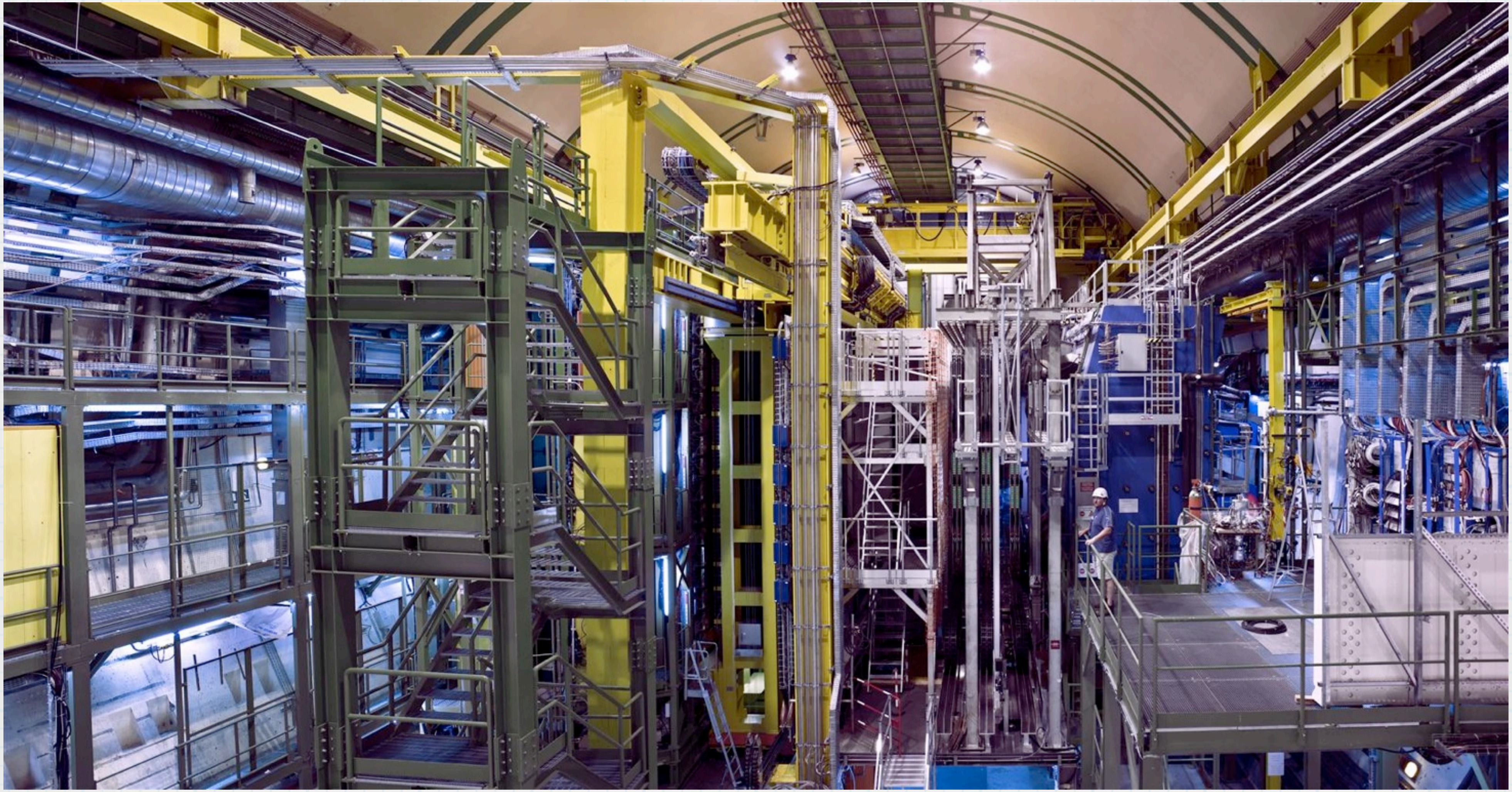
- Identify specific $B_{(s)}$ decays and separate them from background!
  - Good secondary vertex resolution
  - Good mass resolution, resolve $B_{(s)}$, $D_{(s)}$
  - Particle Identification (PID) $p/\pi/K/\mu/e$
  - Trigger on hadrons, μ, di-μ, e, γ





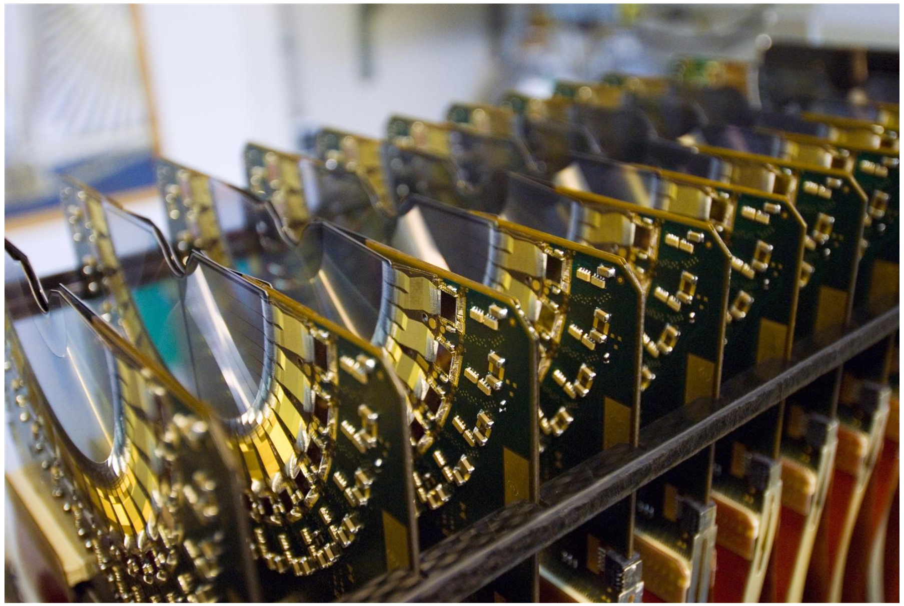
300 mrad

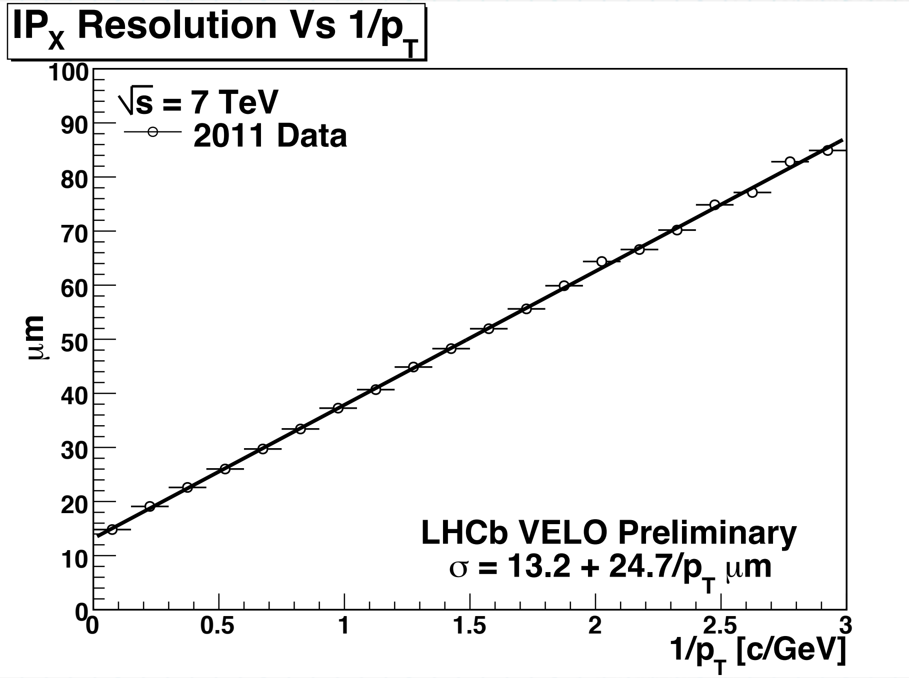
LHCb detector



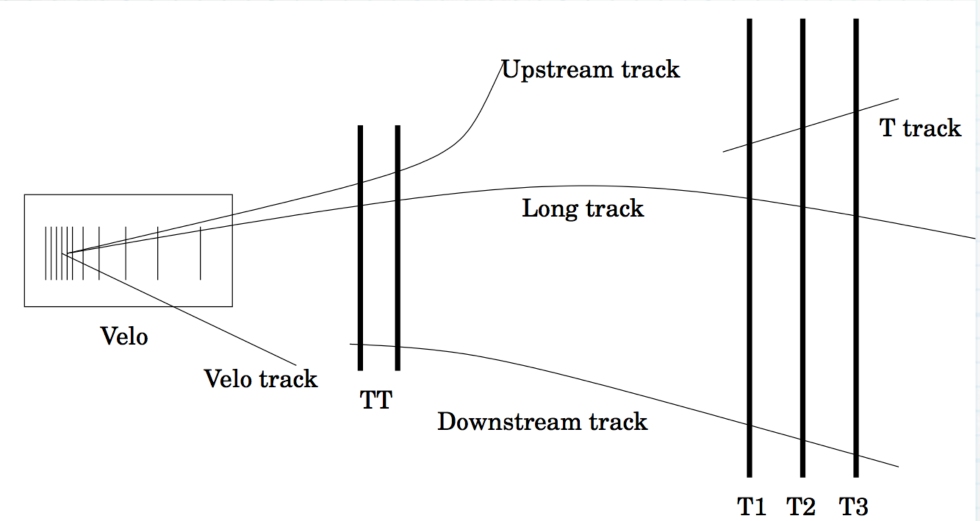
The Velo detector

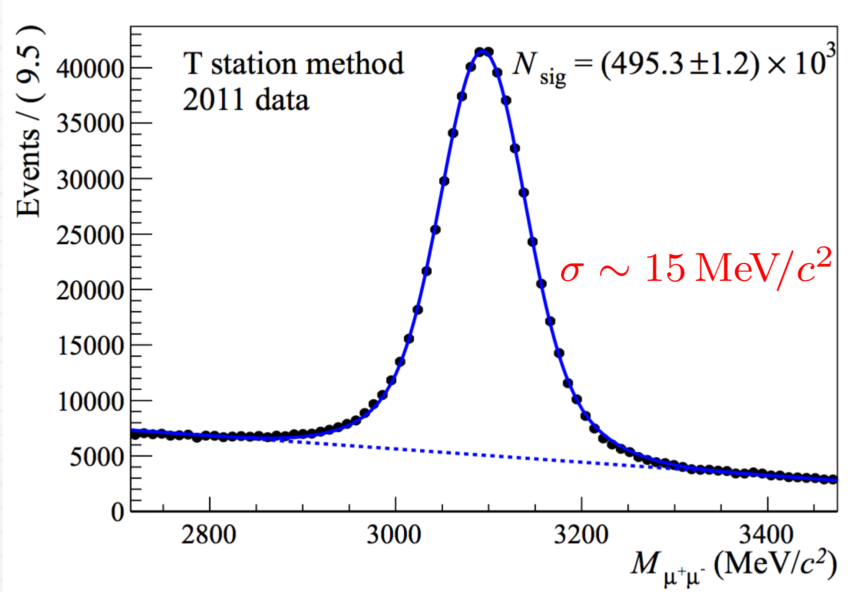
- Velo detector
  - Si strips (r,ϕ) sensors, in vacuum and RF foil
  - retractable: 8 mm from the beam line!
  - PV resolution: 13 μm (x,y), 69 μm (z)
    - proper time resolution σ_t~45 fs!
  - Impact parameter,IP, <20 μm (P_T>2 GeV)
- crucial:
  - Trigger (hadrons, single muon)
  - Secondary Vertices ($B_{(s)}$ decays)
  - Oscillation





The tracking system



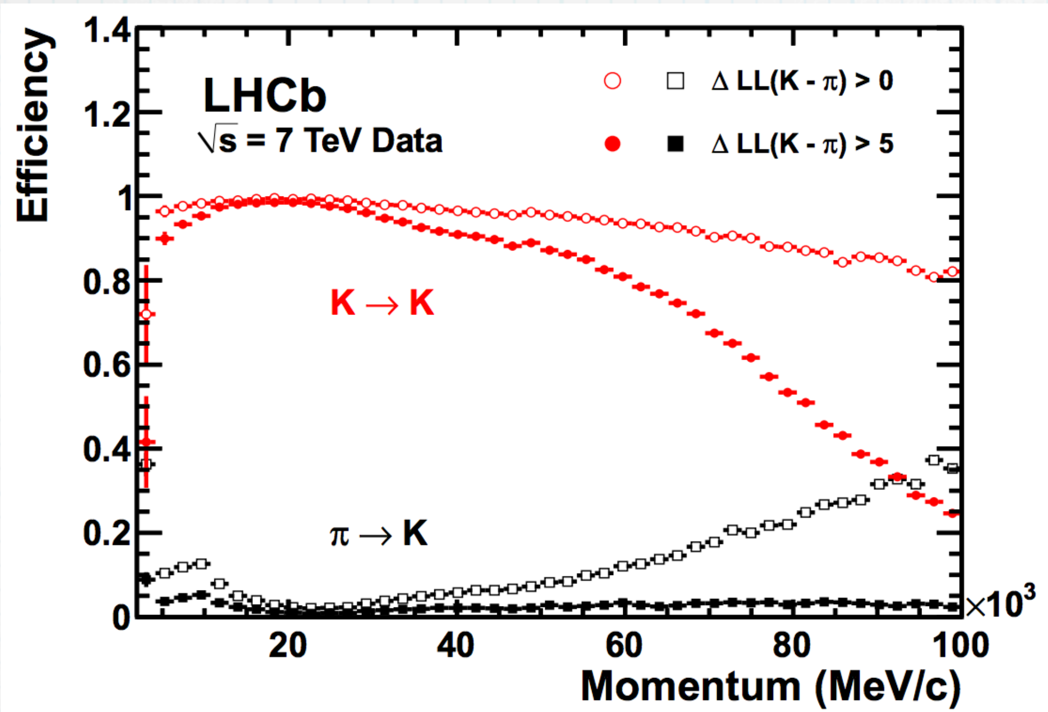


- Tracking system:
  - Velo+TT+T-stations
  - central: silicon strips, external: straw tubes
  - Aligned to 14 μm using $J/\psi \to \mu\mu$, $D^0 \to K\pi$
  - efficiency 98%
  - $\Delta p/p \simeq 0.5\%$

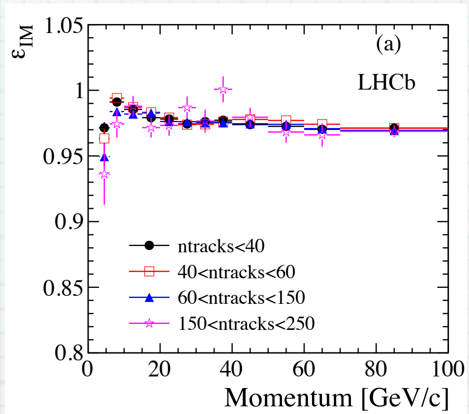
- Crucial:
  - trigger: large P_T and good χ^2
  - mass resolution:
    - $\sigma(B_{(s)} \to J/\psi X) \simeq 8$ MeV
    - $\sigma(B_{(s)} \to \mu\mu) \simeq 23$ MeV

PID

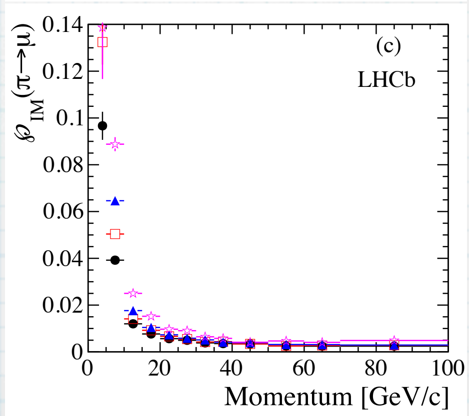
- **PID:**
  - Riches:Gas radiatios and aerogel, Photomultiplies tubes
  - Efficiency/Rejection using ΔLL
  - Calibrated with data: $J/\psi \to \mu\mu$, tag and probe, $D^{*-} \to D(K\pi)\pi^-$



- **Crucial:**
  - trigger: μ-ID (di-μ)
  - Separation of $B(s) \to hh'$ ($h=\pi,K$)
  - Separation $B^{\pm} \to DK^{\pm}$ from $B^{\pm} \to D\pi^{\pm}$
  - Rejection of bkg: $B^{(s)} \to \mu\mu$, due to $B \to hh'$, with h(h') misID by μ

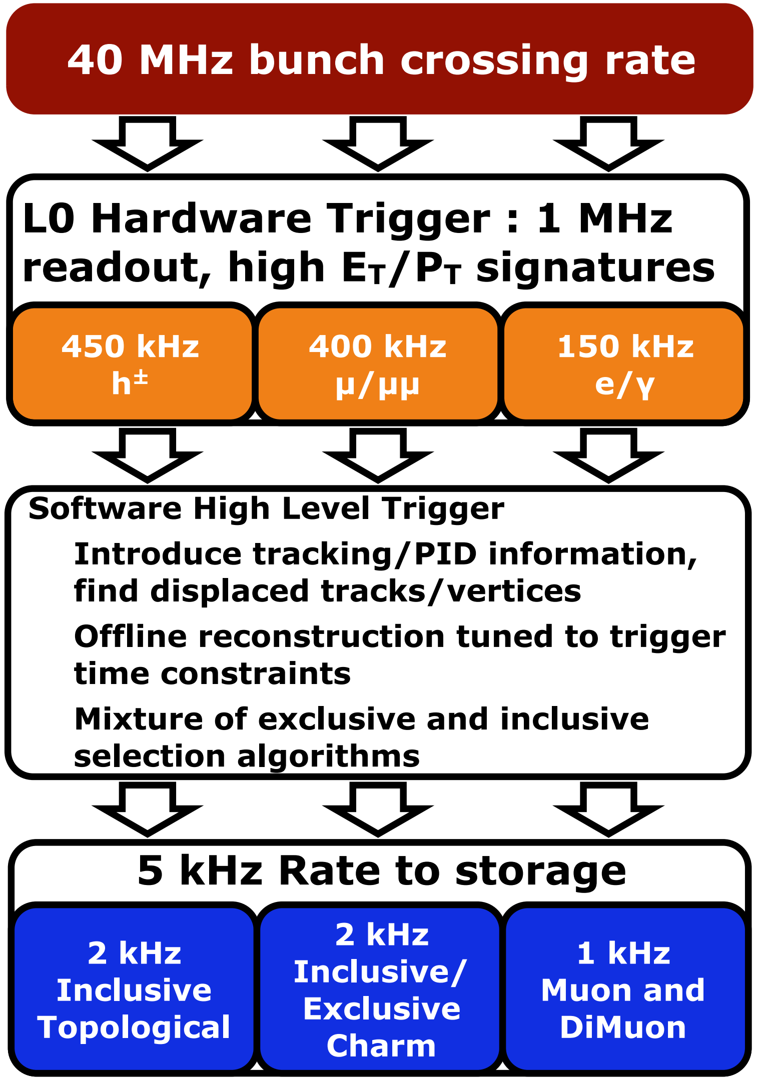


μ-ID

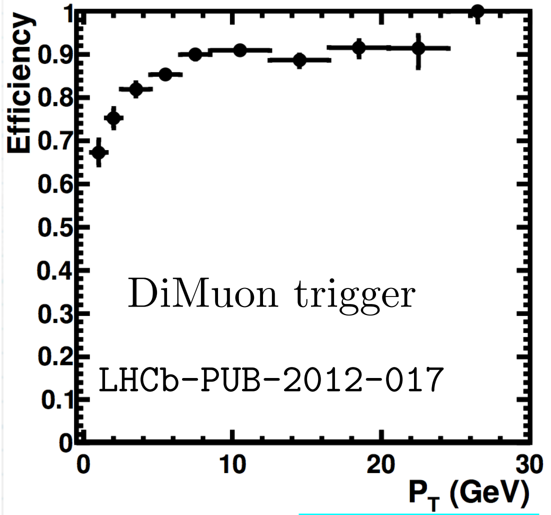


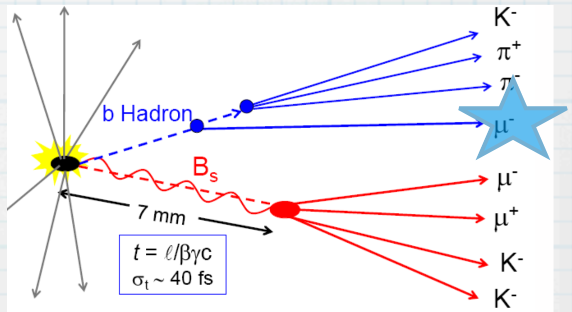
μ-misID

Trigger



- High efficiency, manageable data size
- Trigger on different B (D) decays:
  - Inclusive/Exclusive
- Handles:
  - P_T signals, IP tracks, displaced Secondary Vertices (SV), muons
  - Identify events **TOS** (Trigger on Signal)/**TIS** (Trigger Independent of Signal), => trigger efficiency!





Dimu eff

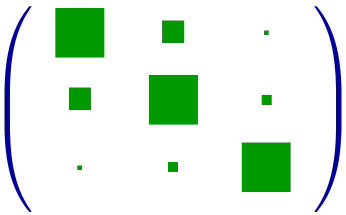
II. CP violation

Unitary Triangle

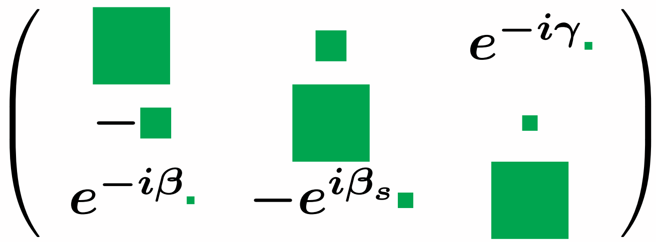
- 3 quarks families, a Unitary complex matrix (CKM)

CKM matrix

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

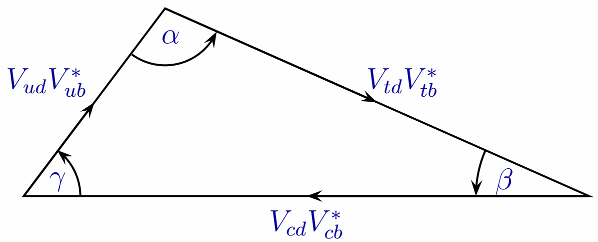


$$\boldsymbol{V} =$$



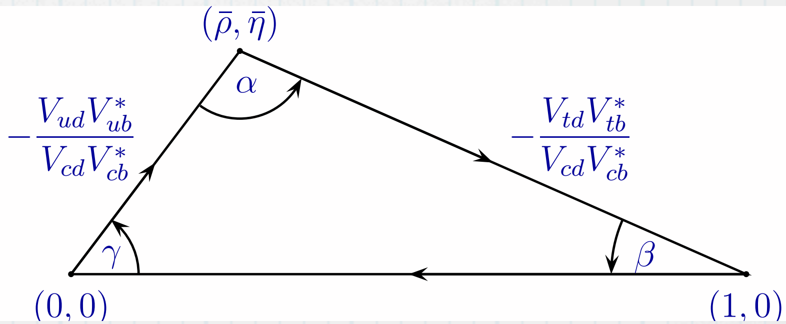
- Wolfestein parameterization

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

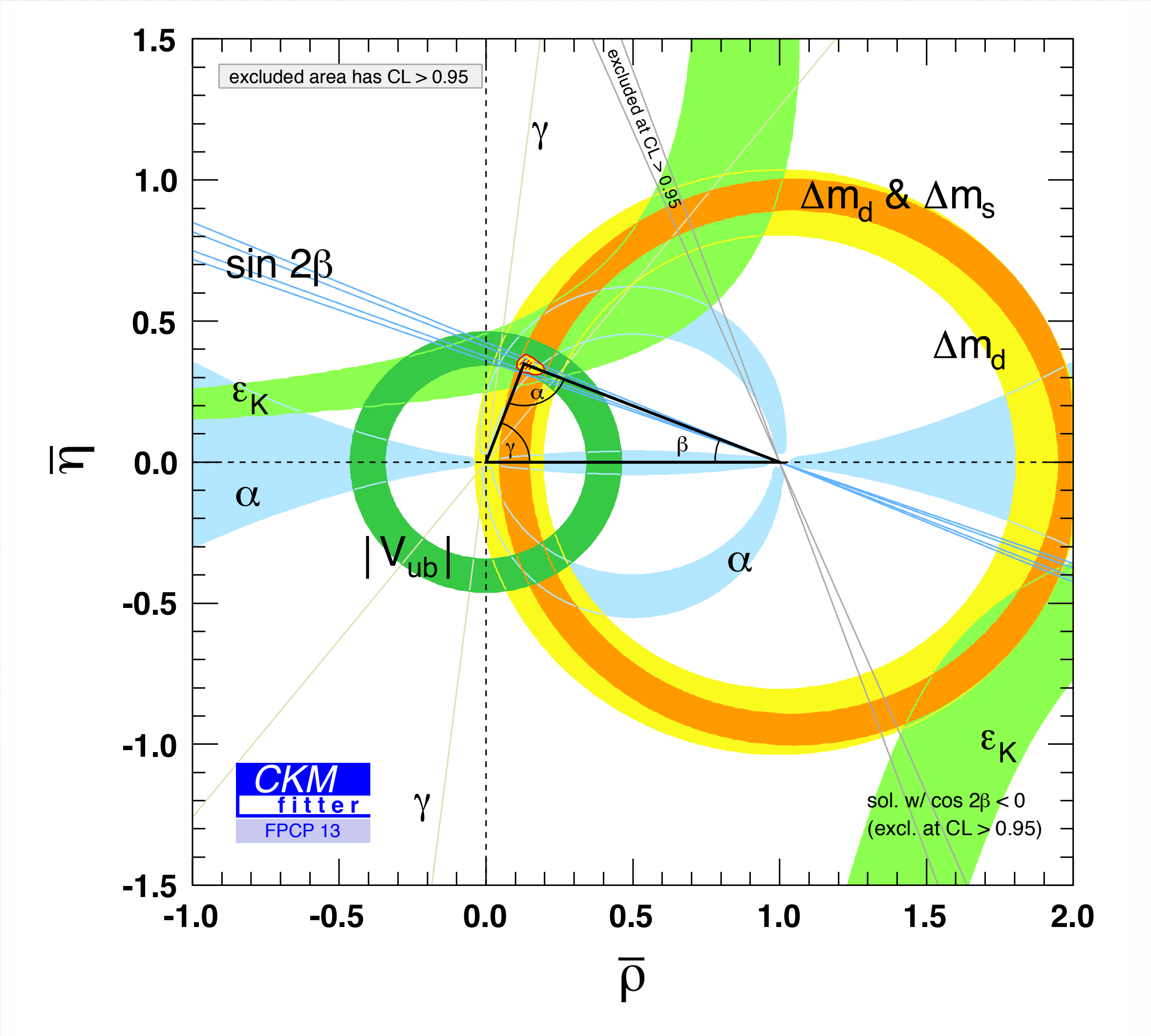


$$\alpha = \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] \quad \beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right] \quad \gamma = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

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



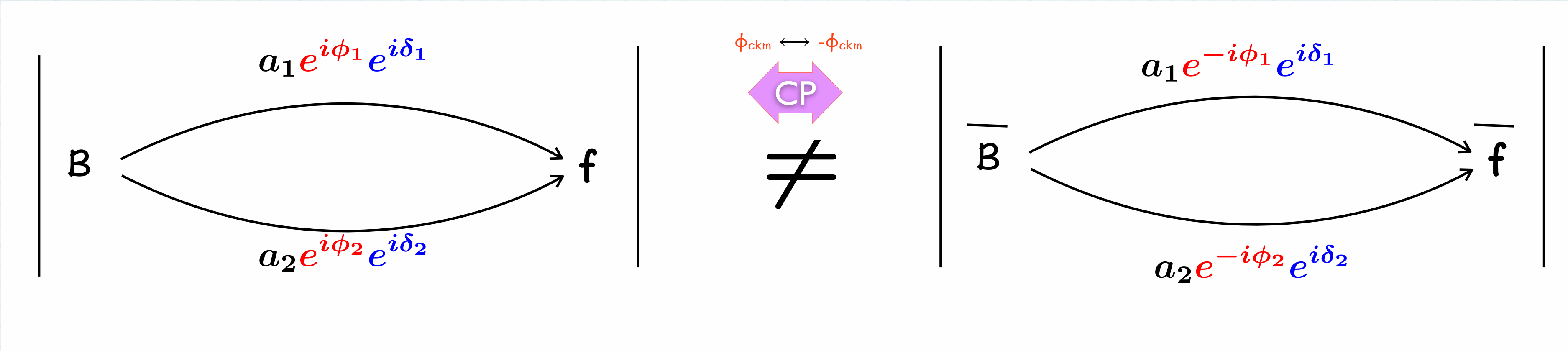
Status of UT



- CKM success!
- LHCb aims: direct measure γ ~4° precision (~10 fb^{-1})

Observing CP

- CP arises due to the interference of amplitudes with different phases

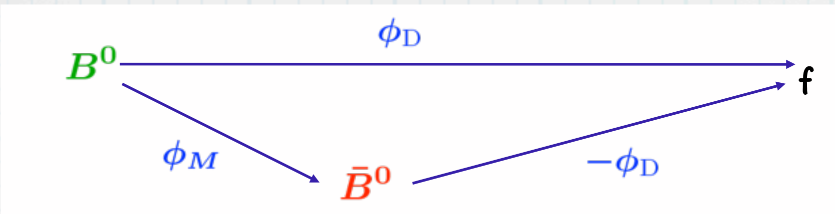


- Charge Asymmetry (direct):

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

- Time dependent Asymmetry (indirect):
  - same final state f

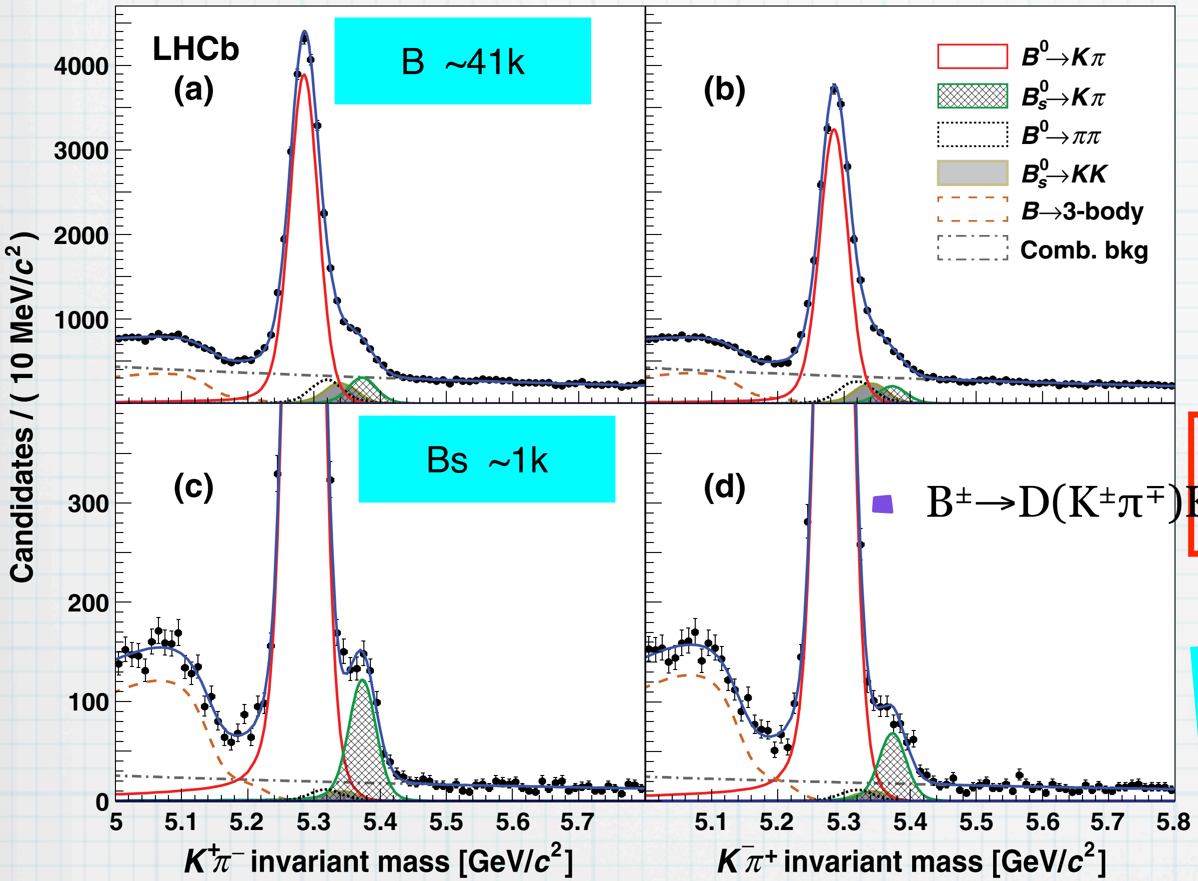
$$A(t) \equiv \frac{N(\overline{B}^0(t) \to f) - N(B^0(t) \to f)}{N(\overline{B}^0(t) \to f) + N(B^0(t) \to f)}$$



Direct CP - $B_{(s)} \to hh$

PRL 100 221601 (2013)/1fb^{-1}

- Large direct CP violation in $B_{(s)} \to hh$ ($h=K,\pi$) decays:



- $B^\pm \to D(K^\pm\pi^\mp)K^\pm$

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

$$A_{CP}(B^0 \to K^+\pi^-) = -0.080 \pm 0.007\,(\text{stat}) \pm 0.003\,(\text{syst}),$$
$$A_{CP}(B_s^0 \to K^-\pi^+) = 0.27 \pm 0.04\,(\text{stat}) \pm 0.01\,(\text{syst}).$$

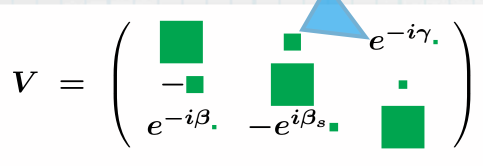
>5σ

first observation of direct CP in Bs!

- Must take into account detector and production asymmetries (data driven methods)
- difficult to relate to SM due to hadronic factors, but we can test a SM relation:

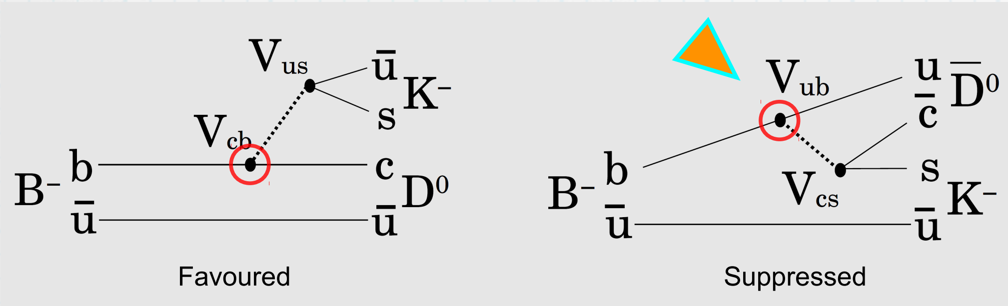
$$\frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B_s^0 \to K^-\pi^+)} + \frac{\mathcal{B}(B_s^0 \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)}\frac{\tau_d}{\tau_s} = 0$$

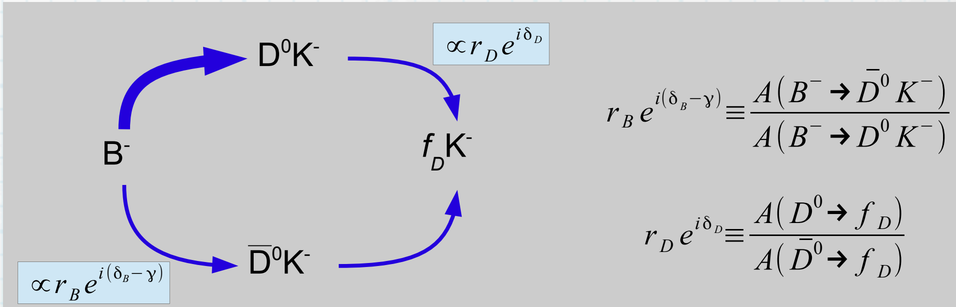
$$-0.02 \pm 0.05 \pm 0.04,$$



UT triangle: γ via trees!

- γ angle: (68±12)° (Morion12, no LHCb)!
- Measurable using $B^{\pm} \to DK^{\pm}$!
- Common final state *f*



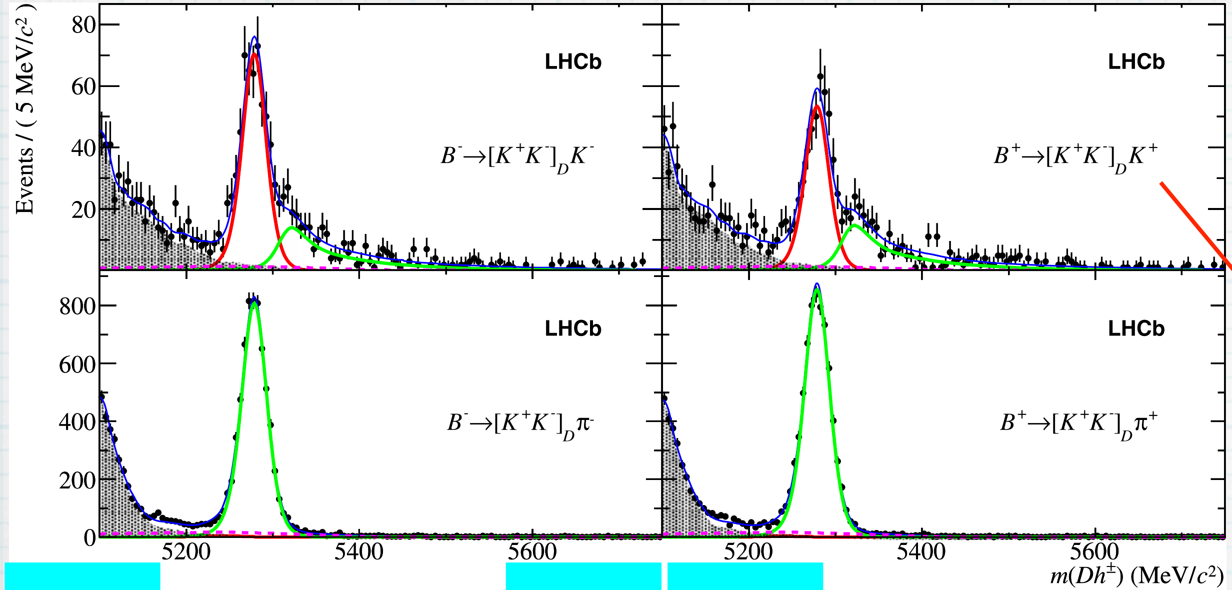


- Methods:
  - **GLW**: CP eigenstates (D→KK,ππ): large yield but small interference
  - **ADS**: suppressed D decays, $B^{\pm} \to D(\pi^{\pm}K^{\mp})K^{\pm}$ vs favored anti-D decays $B^{\pm} \to D(K^{\pm}\pi^{\mp})K^{\pm}$: small yield, but large interference
  - **GGSZ**: via Dalitz plot of $D \to K_S K^+ K^-, K_S \pi^+ \pi^-$
  - Hadronic parameter are a nuisance but can be deteminated from data

γ: B→D(hh)K

PLB 712 (2012) 203/1fb^{-1}

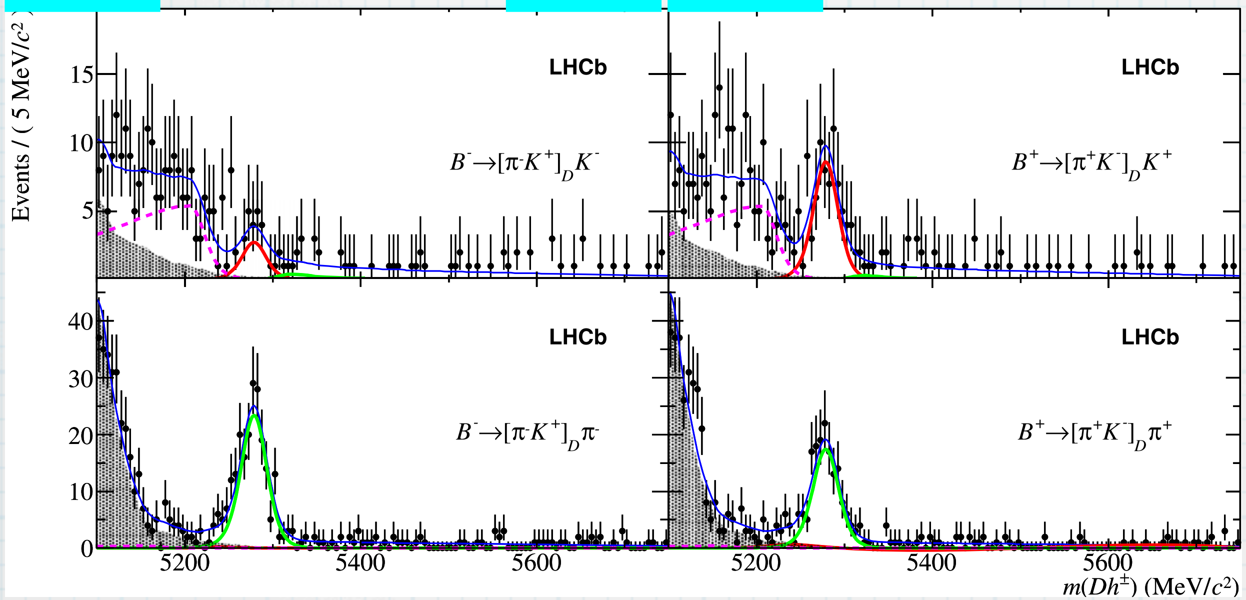
CP



$B^\pm$ mode	D mode	B^-	B^+
$DK^\pm$	$K^\pm\pi^\mp$	3170 ± 83	3142 ± 83
	$K^\pm K^\mp$	592 ± 40	439 ± 30
	$\pi^\pm\pi^\mp$	180 ± 22	137 ± 16
	$\pi^\pm K^\mp$	23 ± 7	73 ± 11
$D\pi^\pm$	$K^\pm\pi^\mp$	40 767 ± 310	40 774 ± 310
	$K^\pm K^\mp$	6539 ± 129	6804 ± 135
	$\pi^\pm\pi^\mp$	1969 ± 69	1973 ± 69
	$\pi^\pm K^\mp$	191 ± 16	143 ± 14

$$A_{CP+} = \langle A_K^{KK}, A_K^{\pi\pi} \rangle$$
$$= 0.145 \pm 0.032 \pm 0.010,$$

ADS B- B+



$$A_{\mathrm{ADS}(K)} = (R_K^- - R_K^+)/(R_K^- + R_K^+)$$
$$= -0.52 \pm 0.15 \pm 0.02,$$

4 σ (consistent BaBar, Belle, CDF)

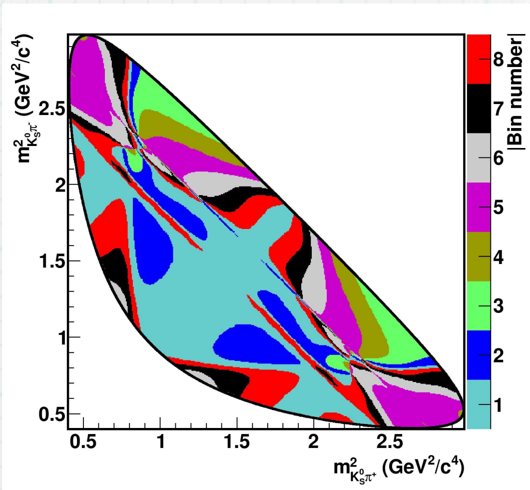
$$A_{\mathrm{ADS}(\pi)} = (R_\pi^- - R_\pi^+)/(R_\pi^- + R_\pi^+)$$
$$= 0.143 \pm 0.062 \pm 0.011,$$

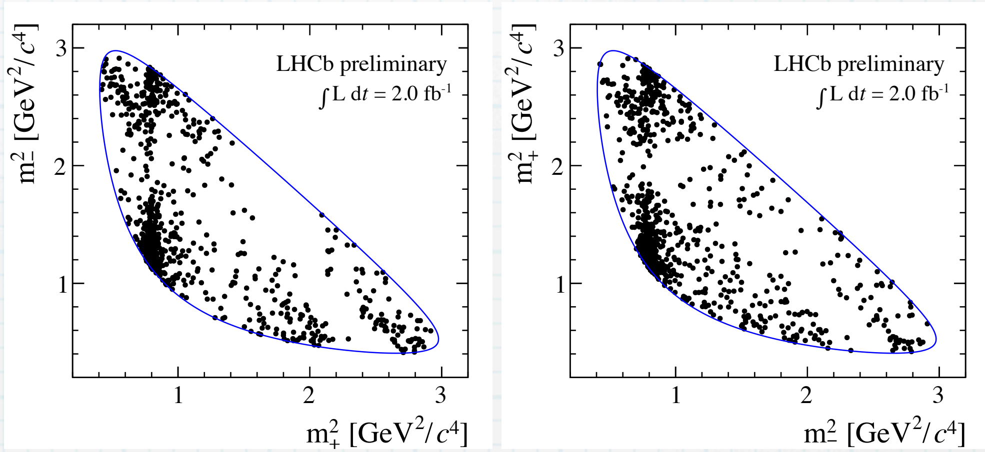
- Mass PDF: signal, π bachelor misID as K, partially reconstructed B→DX, combinatorial

γ: $B^\pm \to D(K_S KK, K_S\pi\pi)K^\pm$

PLB 718 (2012) 43/1fb^{-1}
LHCB-CONF-2013-004/+2fb^{-1}

- $B^\pm \to D(K_S KK, K_S\pi\pi)h^\pm$: CP conjugate decay
  - extract γ from the Asymmetry of $B^\pm$ in the Dalitz plot
  - hadronic phase change across the plane: Use of CLEO-c data

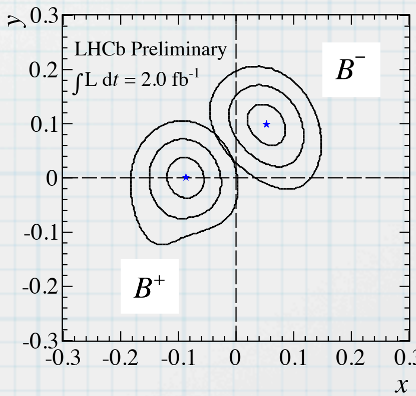




$$\Gamma_{\pm i}(B^-) = n^-(K_{\pm i} + r_B^2 K_{\mp i} + 2\sqrt{K_i K_{-i}}(x_- c_i \pm y_- s_i)),$$
$$\Gamma_{\pm i}(B^+) = n^+(K_{\mp i} + r_B^2 K_{\pm i} + 2\sqrt{K_i K_{-i}}(x_+ c_i \mp y_+ s_i)),$$

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

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



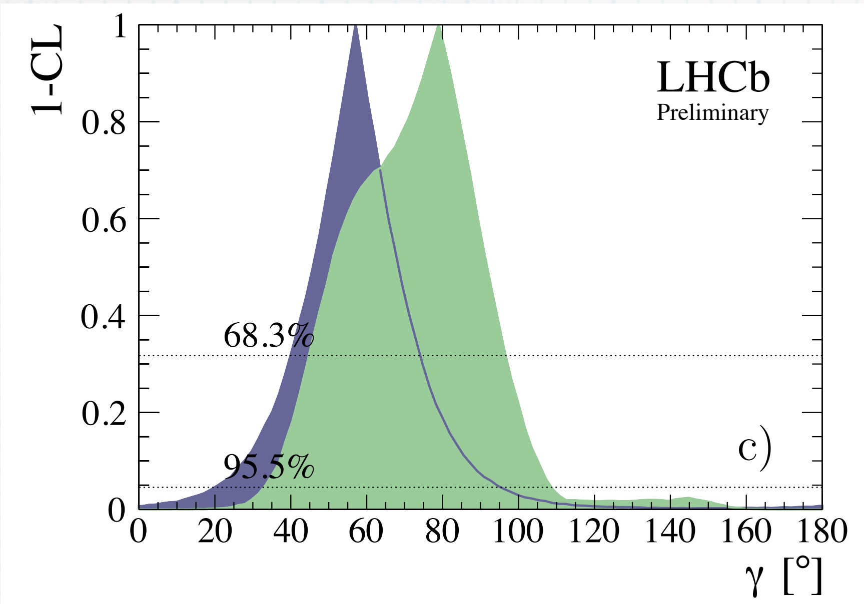
γ $(57 \pm 16)^\circ$

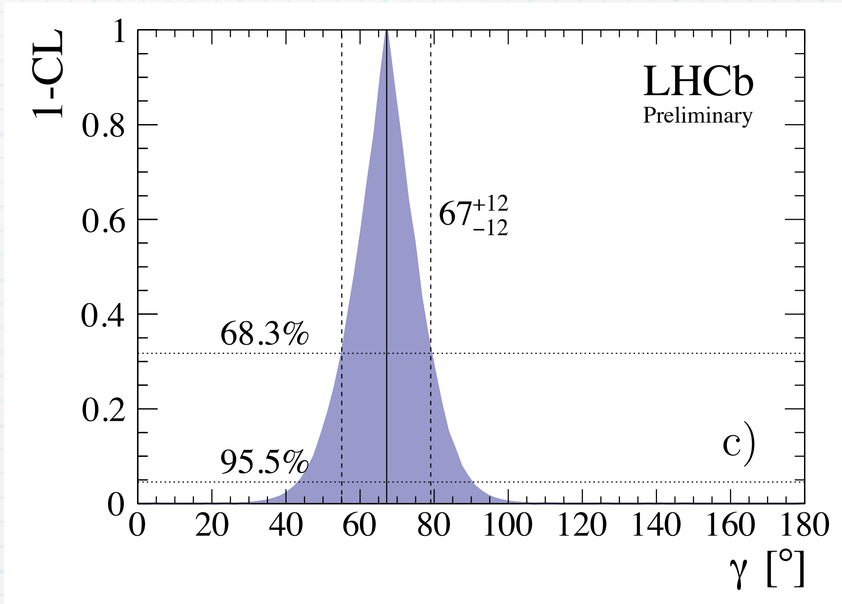
2fb^{-1}

γ: Combination

LHCB-CONF-2013-006/(1-3)fb^{-1}

- Combination $B^\pm \to DK^\pm$:
  - GLW/ADS 1fb^{-1} (still *2fb^{-1} to add!*) + GGSZ 3fb^{-1}
  - Combination with $B^\pm \to D\pi^\pm$ only 2011 data





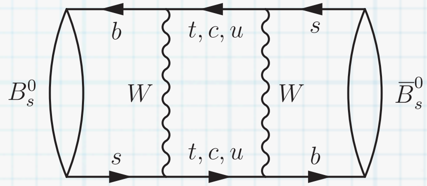
$$\gamma = (67 \pm 12)^\circ \text{ at } 68\% \text{ CL}\,.$$

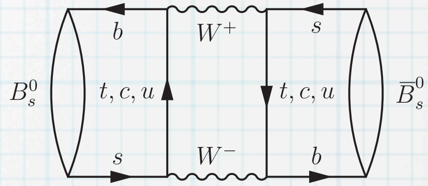
$\gamma = (68^{+8.0}_{-8.5})^\circ$ - FPCP'13 CKMfitter

most precise single experiment!
in agreement with BaBar/Belle

Δm_s: Bs oscillations

- B(s),D,K neutral mesons oscillate
  - via loop diagram, NP can enter in the loop!
  - Bs very rapid oscillation!
  - described by Schroedinger eq. with $B_{H/L}$ mass states
    - oscillation governed by Δm_s





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

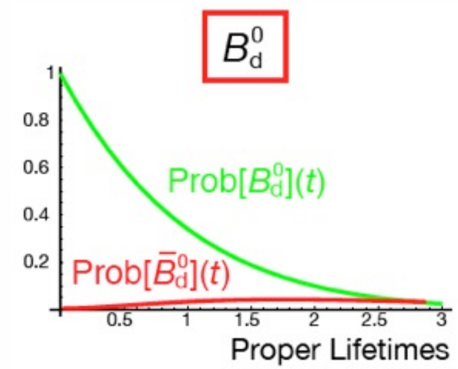
$$\Gamma \equiv \frac{\Gamma_H + \Gamma_L}{2} \qquad m \equiv \frac{m_H + m_L}{2}$$

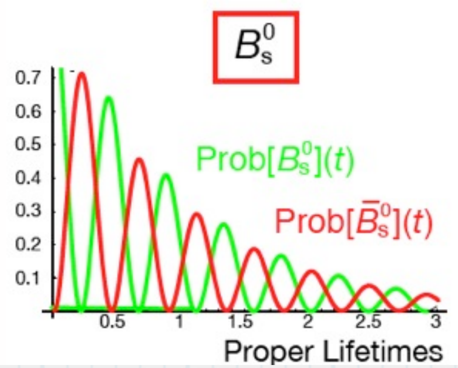
$$\Delta m \equiv m_H - m_L \simeq 2|M_{12}|$$

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

$$\Delta\Gamma \equiv \Gamma_L - \Gamma_H \simeq 2\,|\Gamma_{12}|\cos\phi_{12}$$

$$1 - \left|\frac{q}{p}\right|^2 = \frac{|\Gamma_{12}|}{|M_{12}|}\sin\phi_{12}$$



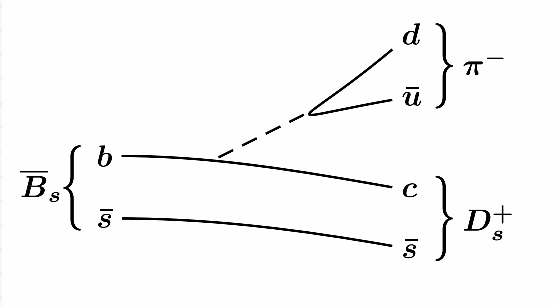


$$\boxed{\Delta m_s^{\mathrm{SM}} = 17.3 \pm 2.6} \quad \text{ps}$$

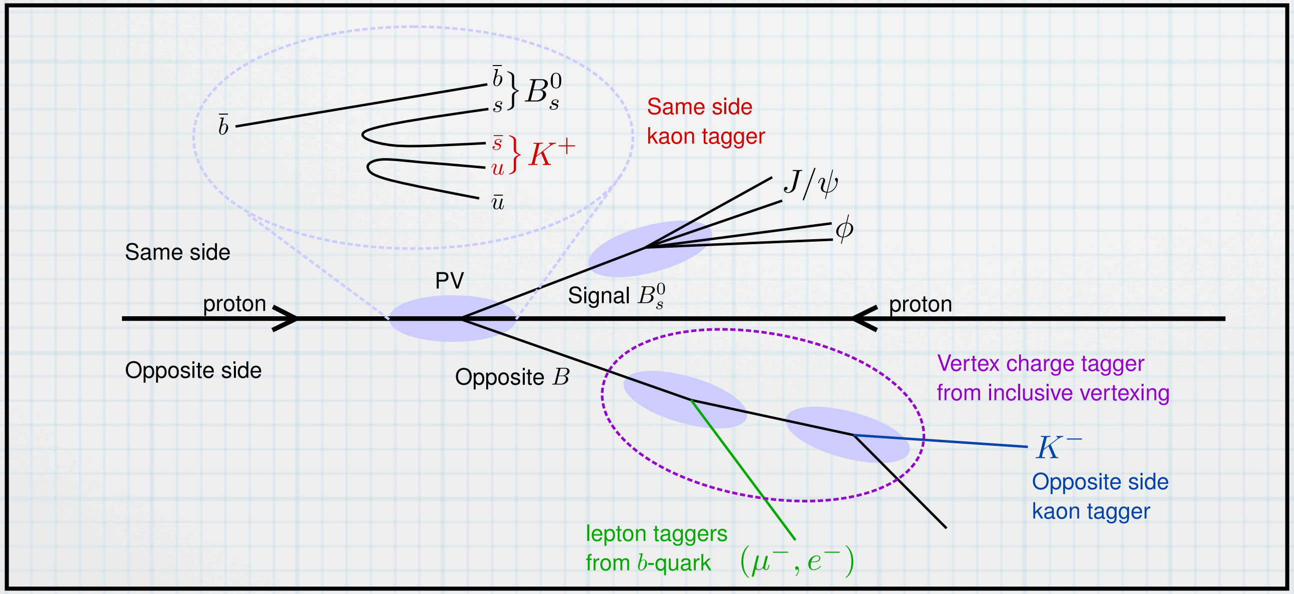
Δm_s: Bs oscillations

New J. Phys 15 (2013)/1fb^{-1}

- flavor specific decay: $B_s \to D_s^- \pi^+$
  - several $D_s^- \to h^+h^-h^-$ i.e $D_s^- \to \phi(K^+K^-)\pi^-$: ~34k events/fb^{-1}
  - proper time resolution $\sigma(t)$~44 fs, selection efficiency $\epsilon(t)$
  - use of flavour tagging to identify mix and unmixed decays:
    - OST: lepton, K or seconcary vertex charge: **$B^+ \to J/\psi K^+$**
    - SST: associated K
    - tagging efficiency, wrong tag probability, effective tagging 2.6±0.4 % (OST), 1.2±0.3% (SST)



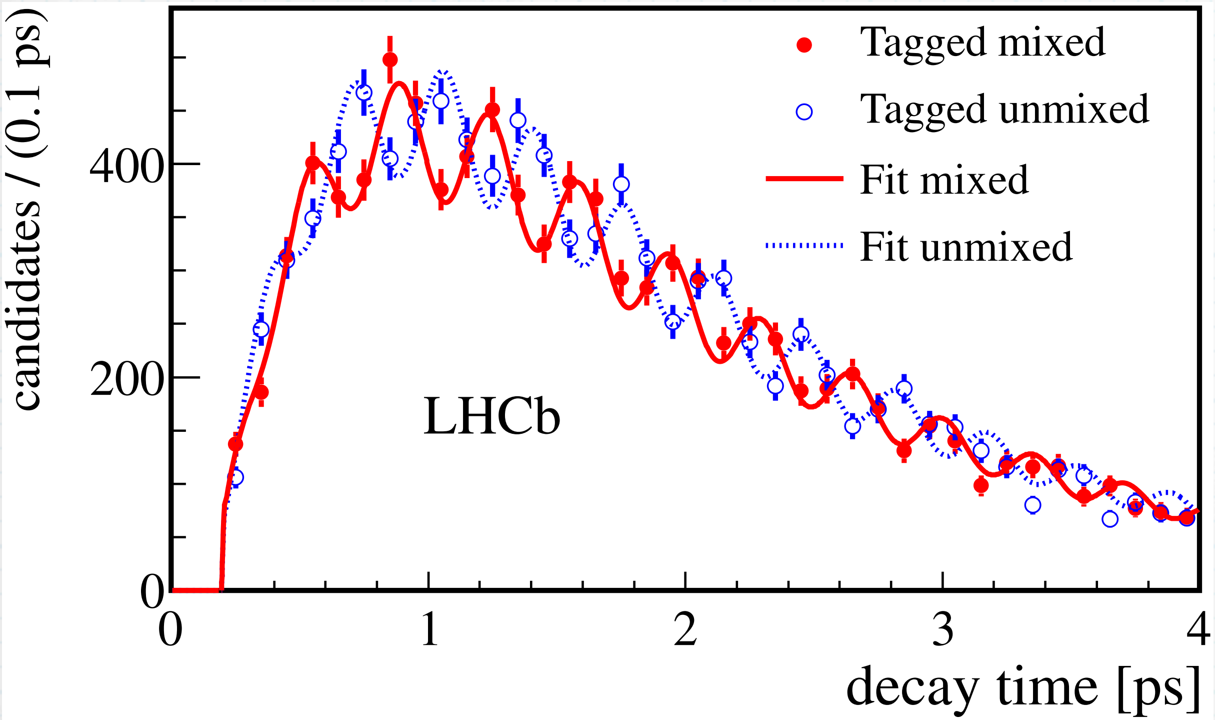
$$\boxed{t = \frac{Lm}{p},}$$



combine different taggers
optimize with simulation
calibrate with data

Δm_s: Bs oscillations

New J. Phys 15 (2013)/1fb-1



$\Delta\Gamma_s = 0.106 \pm 0.011 \pm 0.007\ \mathrm{ps}^{-1}$.

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

most precise measurement!
in agreement SM!

- fit to mass and proper time distribution PDF

$$\mathcal{P}_t(t|\sigma_t) \propto \left\{ \Gamma_s\, e^{-\Gamma_s t}\, \frac{1}{2}\left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + q\,[1 - 2\omega(\eta_{\mathrm{OST}}, \eta_{\mathrm{SST}})]\cos(\Delta m_s t)\right]\theta(t)\right\} \otimes G(t, S_{\sigma_t}\sigma_t)\,\mathcal{E}_t(t)\,\epsilon,$$

convolution t-resolution

q=0,1(unmix),-1(mix), ω (wrong tag), ϵ (tag eff)

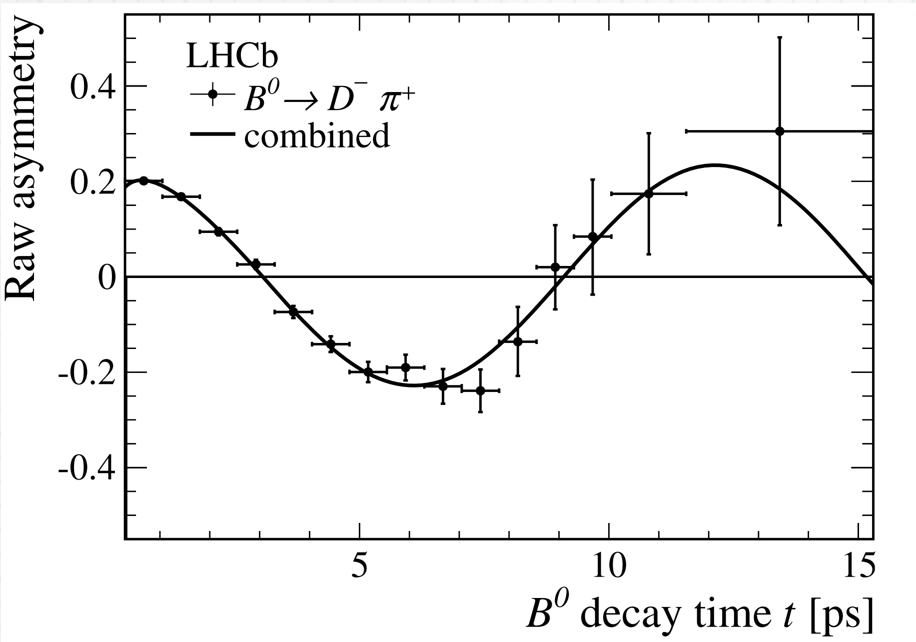
- syst: reference and scale of proper time

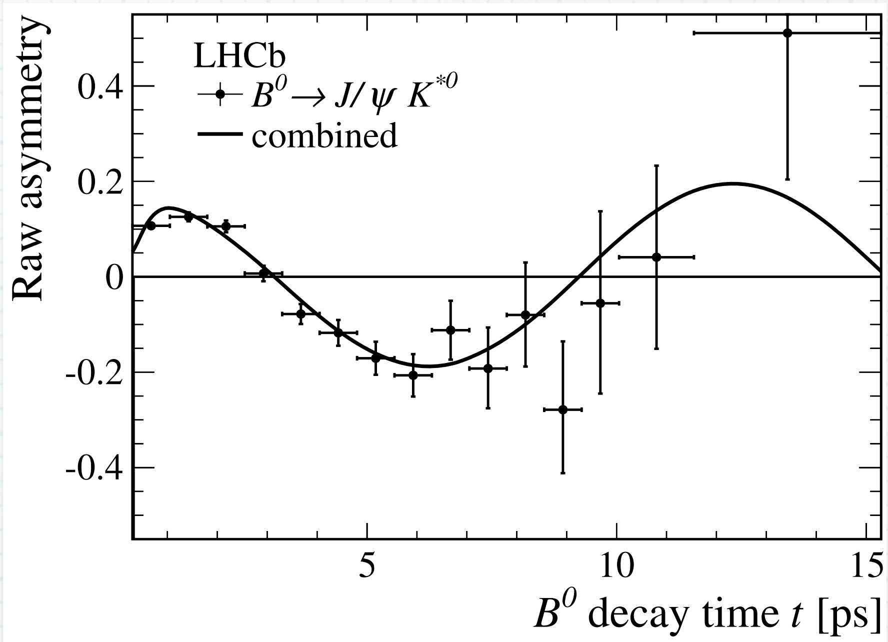
Δm : B oscillations

PLB 719 (2013) 318/1fb-1

- And the B oscillations:
  - using $B \to D^- \pi^+$, and $B \to J/\psi K^*$

$$\Delta m_d^{SM} = 0.555 \pm 0.073 \, \mathrm{ps}^{-1}$$





$$A_{mix}(t) = \frac{N(\text{unmixed}) - N(\text{mixed})}{N(\text{unmixed}) + N(\text{mixed})} \propto \frac{\cos(\Delta m_d t)}{\cosh(\Delta \Gamma_d t/2)}$$

$$\Delta m_d = 0.5156 \pm 0.0051 \, (\text{stat.}) \pm 0.0033 \, (\text{syst.}) \, \mathrm{ps}^{-1}.$$

most precise measurement!

in agreement SM!

CP semileptonic asymmetry

arXiv:1308.1048/1fb[-1]

- CP due to mixing
  - via flavor specific decays (semileptonic):
    - $B_s \to D_s^+ \mu\nu$, $D_s^+ \to \phi(K^+K^-)\pi^+$
  - ϕ^s_{12} is very small in SM ~0.2° but can be affected by NP!

$$a_{sl} \equiv 1 - \left|\frac{q}{p}\right|^2$$

$$a_{sl} \equiv \frac{\Gamma\left(\overline{B}(t) \to f\right) - \Gamma\left(B(t) \to \bar{f}\right)}{\Gamma\left(\overline{B}(t) \to f\right) + \Gamma\left(B(t) \to \bar{f}\right)} \simeq \frac{\Delta\Gamma}{\Delta M} \tan\phi_{12},$$

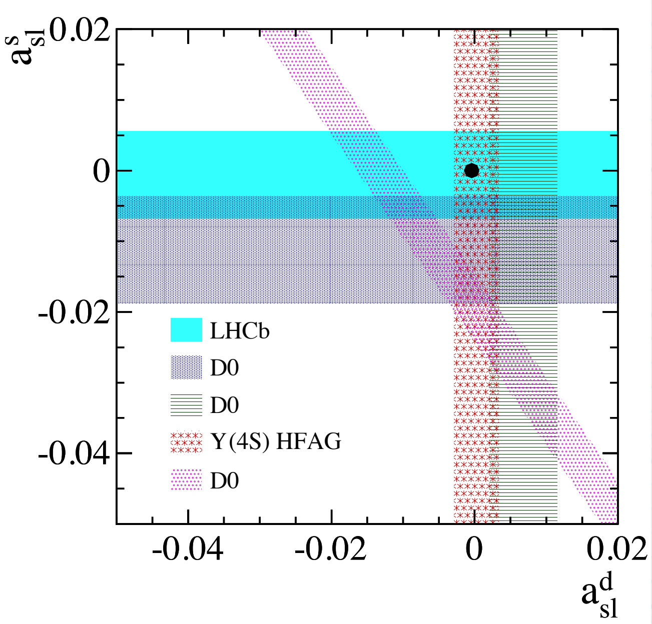
$$\phi_{12} \equiv \arg\left(-M_{12}/\Gamma_{12}\right)$$

$$a^s_{sl}(B^0_s) = (+1.9 \pm 0.3) \times 10^{-5}$$

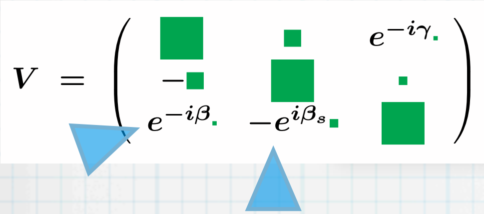
negiglible due to rapit oscillations

$$A_{meas} \equiv \frac{\Gamma[D_s^-\mu^+] - \Gamma[D_s^+\mu^-]}{\Gamma[D_s^-\mu^+] + \Gamma[D_s^+\mu^-]} = \frac{a^s_{sl}}{2} + \left[a_P - \frac{a^s_{sl}}{2}\right] \frac{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cos(\Delta M_s t)\epsilon(t)dt}{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cosh(\frac{\Delta\Gamma_s t}{2})\epsilon(t)dt},$$

- ~189k candidates
- Correct by detector asymmetries
  - J/ψ TIS, and tag-&-probe, $D^{*-} \to D(K\pi\pi\pi)\pi^-$
- Dominant syst. from stats of control sample

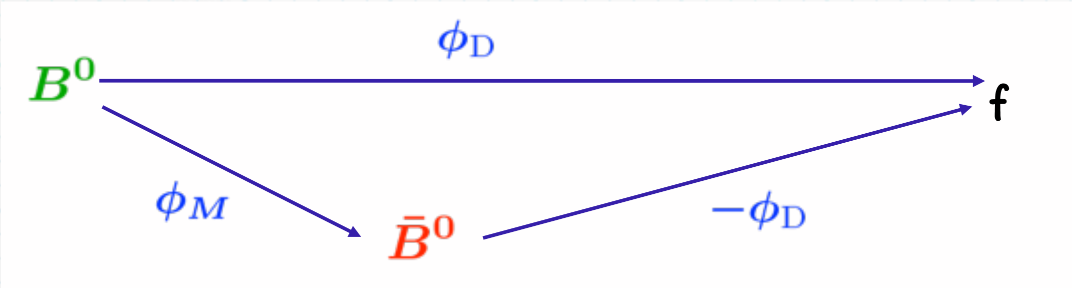


more precise measurement!
in agreement SM!
Not exclused not confirmed D0!



CP in interferance between mixing and decay

- Common CP final state accessible via mixing:
  - NP can enter in the ϕ_M phase!



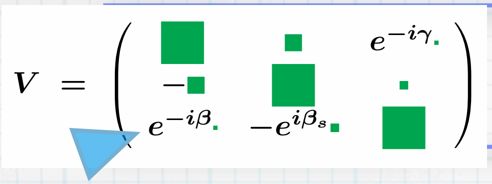
- time dependent asymmetry:
  - dilution due to tagging!

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

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

- Golden channels:

$$B_d \to \psi K_s : \quad \phi_{J/\psi K_s} = 2\beta \quad \stackrel{SM}{=} 50^\circ - 55^\circ$$
$$B_s \to \psi\phi : \quad \phi_{J/\psi\phi} = -2\beta_s \quad \stackrel{SM}{=} -2.1^\circ \pm 0.1^\circ$$



β: CP in B→J/ψK$_s$

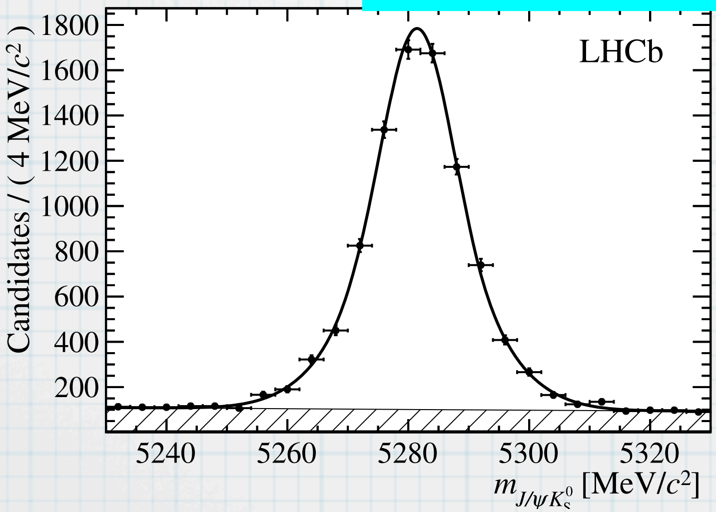
PLB 721 (2013) 24/1fb-1

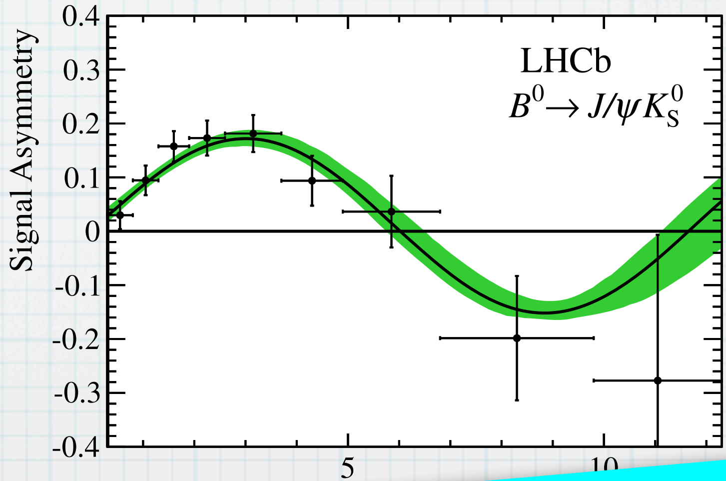
- reproduce B factories measurement!
- golden channel: B→J/ψKs
- time-dependent asymmetry
  - tagging OST: D (2.38±0.27)%
    - main syst, ϵ=(32.65±0.31)%, ω= 0.365±0.008
    - simultaneous fit to the different Γ(t)

$$\mathcal{A}_{J/\psi K_S^0}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to J/\psi K_S^0) - \Gamma(B^0(t) \to J/\psi K_S^0)}{\Gamma(\overline{B}^0(t) \to J/\psi K_S^0) + \Gamma(B^0(t) \to J/\psi K_S^0)} = S_{J/\psi K_S^0} \sin(\Delta m_d t) - C_{J/\psi K_S^0} \cos(\Delta m_d t).$$

$$S_{J/\psi K_S^0} = 0.73 \pm 0.07\,(\text{stat}) \pm 0.04\,(\text{syst}),$$
$$C_{J/\psi K_S^0} = 0.03 \pm 0.09\,(\text{stat}) \pm 0.01\,(\text{syst}),$$

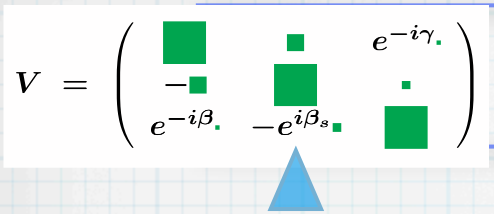
~8k flavor tagged





WA $S_{J/\psi K_S^0} = 0.679 \pm 0.020$

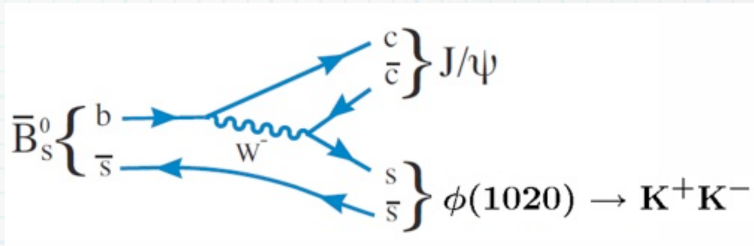
in agreement with World Average!

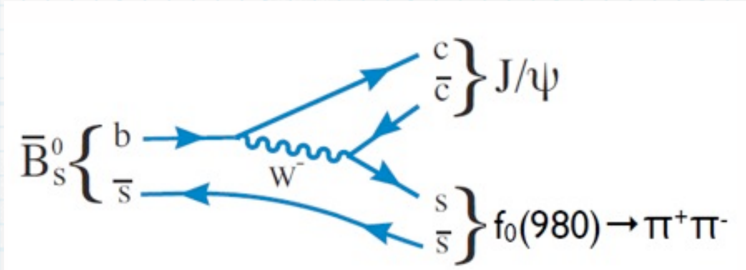


ϕ_s: $B_s \to J/\psi KK$, $B_s \to J/\psi\pi\pi$

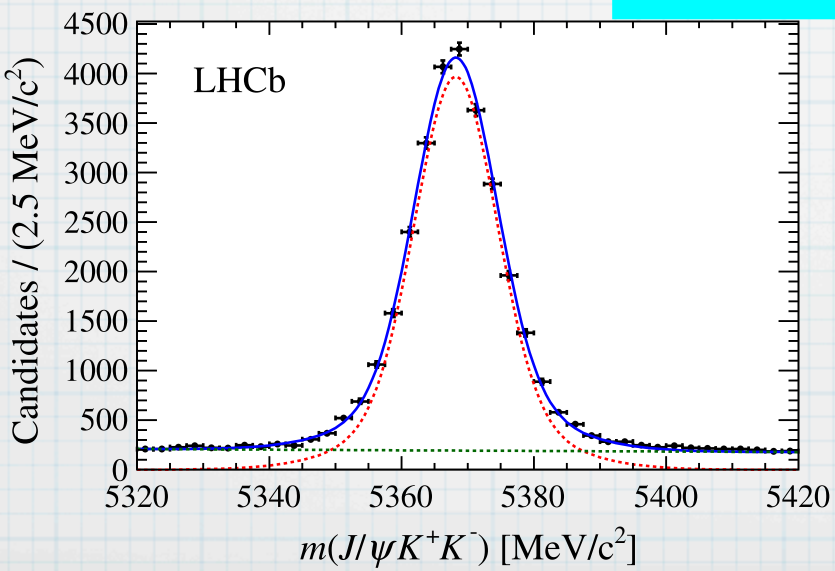
PRD 87, 112010 (2013)/1fb-1
PLB 713, 370 (2012)/1fb-1

- ϕ_s is $-2\beta_s$ in absence of NP!
- Golden channels:
  - $B_s \to J/\psi K^+K^-$, mostly $B_s \to J/\psi\phi(K^+K^-)$, vector-vector, separate via angular distributions CP even and odd components ⇒ **angular analysis**
  - $B_s \to J/\psi\pi^+\pi^-$, mostly $B_s \to J/\psi f_0(980)$, vector-pseudoscalar, CP odd component

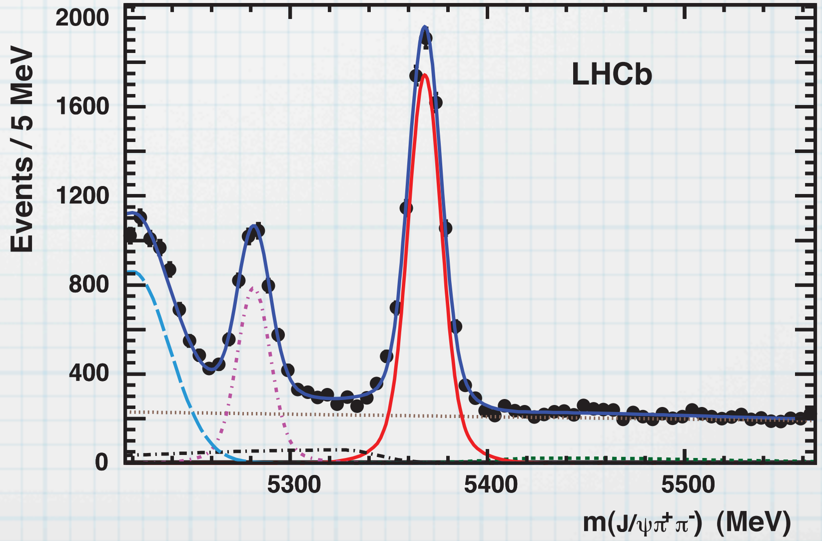




~27k candidates



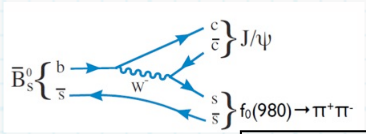
~7.4k candidates



ϕ_s: $B_s \to J/\psi KK$, $B_s \to J/\psi\pi\pi$

PRD 87, 112010 (2013)/1fb-1
PLB 713, 370 (2012)/1fb-1

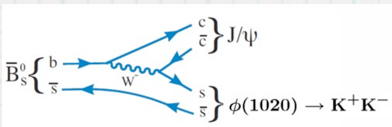
- time dependent decay rate!
- $J/\psi KK$, 4 amplitudes, angular analysis
  - angular acceptance using simulation
- ambiguity: $(\phi_s, \Delta\Gamma_s) \longleftrightarrow (\pi-\phi_s, -\Delta\Gamma_s)$
- requires tagging!
- proper time resolution: prompt candidates
- life time acceptance: $B^+ \to J/\psi K^+$ and simulation

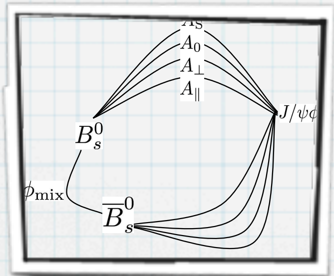


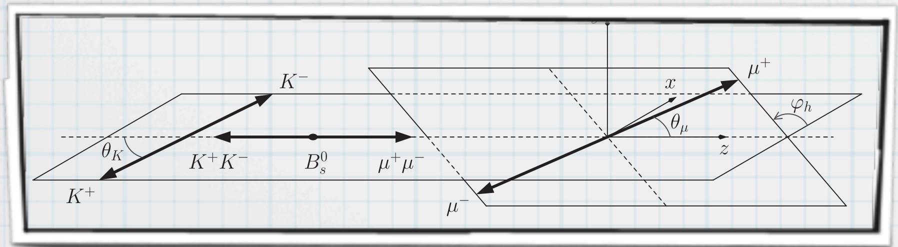
$$\Gamma(\overset{(-)}{B_s^0} \to f_-) = \mathcal{N} e^{-\Gamma_s t} \left\{ \frac{e^{\Delta\Gamma_s t/2}}{2}(1+\cos\phi_s) + \frac{e^{-\Delta\Gamma_s t/2}}{2}(1-\cos\phi_s) \pm \sin\phi_s \sin(\Delta m_s t) \right\},$$

$$\frac{d^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{dt\,d\Omega} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega).$$

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







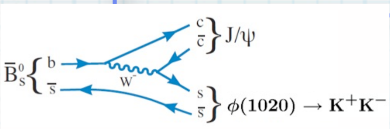
k	$f_k(\theta_\mu, \theta_K, \varphi_h)$	N_k	a_k	b_k	c_k	d_k
1	$2\cos^2\theta_K \sin^2\theta_\mu$	$\lvert A_0\rvert^2$	1	D	C	$-S$
2	$\sin^2\theta_K(1-\sin^2\theta_\mu \cos^2\varphi_h)$	$\lvert A_\parallel\rvert^2$	1	D	C	$-S$
3	$\sin^2\theta_K(1-\sin^2\theta_\mu \sin^2\varphi_h)$	$\lvert A_\perp\rvert^2$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

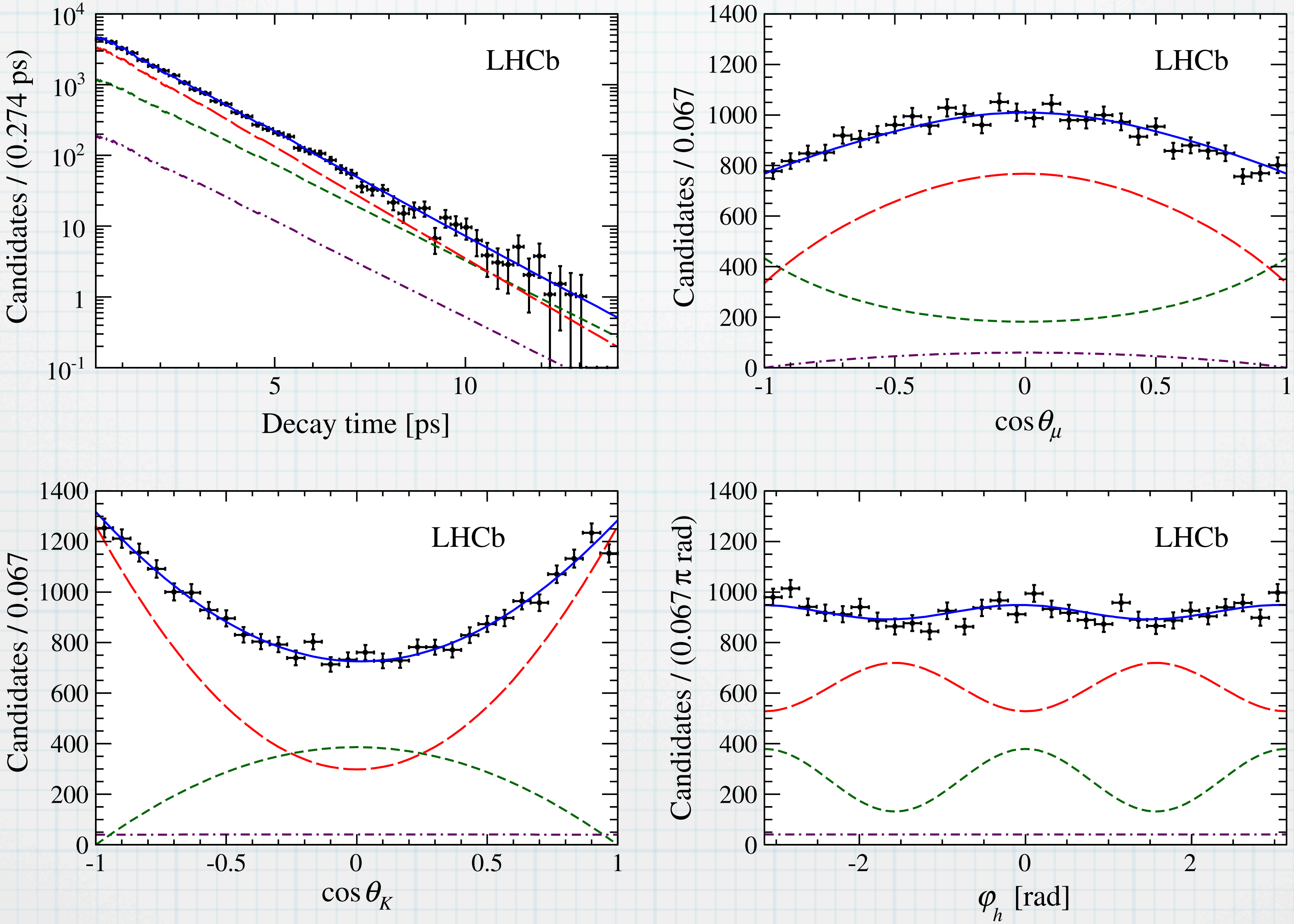
$$S \equiv -\frac{2|\lambda|\sin\phi_s}{1+|\lambda|^2}, \qquad D \equiv -\frac{2|\lambda|\cos\phi_s}{1+|\lambda|^2}.$$

$$\lambda_i \equiv \frac{q}{p}\frac{\bar{A}_i}{A_i},$$

ϕs: Bs→J/ψKK

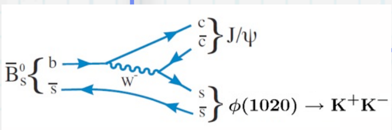
PRD 87, 112010 (2013)/1fb^{-1}



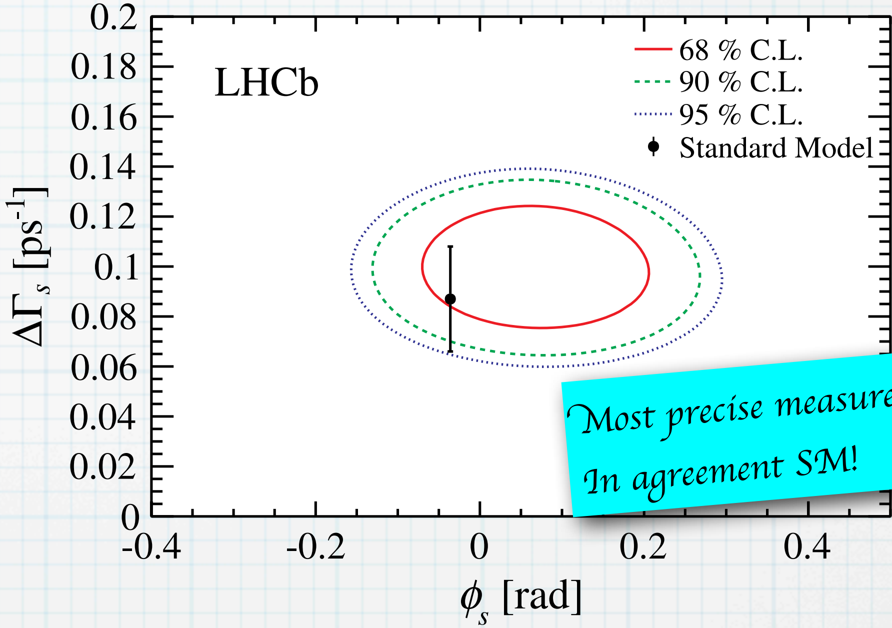


ϕ_s: $B_s \to J/\psi KK$

PRD 87, 112010 (2013)/1fb^{-1}



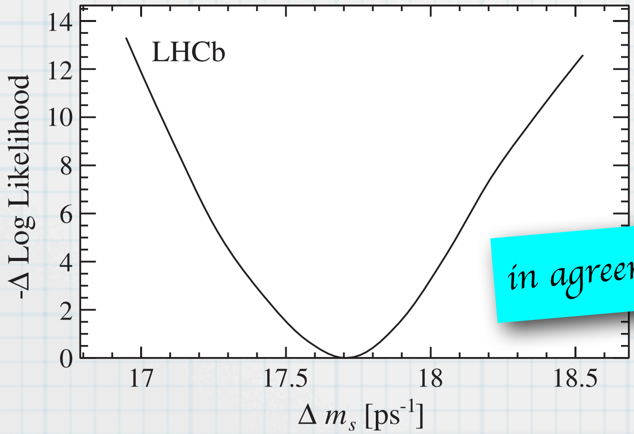
$$\begin{aligned}\phi_s &= 0.07 \pm 0.09 \ (\text{stat}) \pm 0.01 \ (\text{syst}) \ \text{rad}\\ \Gamma_s &= 0.663 \pm 0.005 \ (\text{stat}) \pm 0.006 \ (\text{syst}) \ \text{ps}^{-1}\\ \Delta\Gamma_s &= 0.100 \pm 0.016 \ (\text{stat}) \pm 0.003 \ (\text{syst}) \ \text{ps}^{-1}\end{aligned}$$



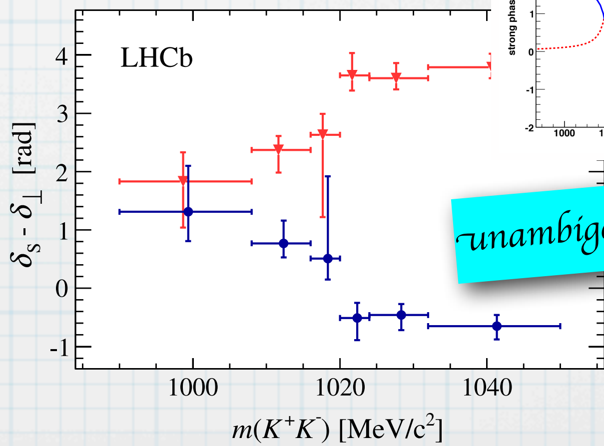
Most precise measurement!
In agreement SM!

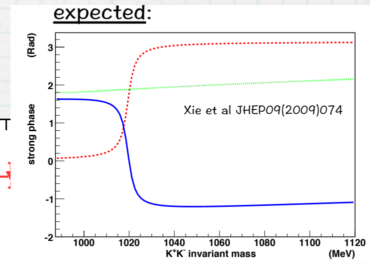
- Main syst: angular and life time acceptance
- Can extract Δms too!
- Can resolve ambiguity studing KK mass regions

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



in agreement with Bs→Dsπ!

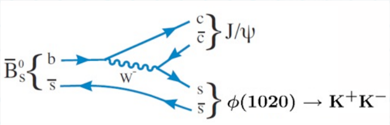


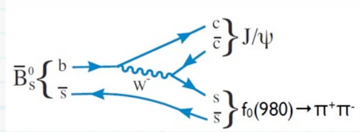


unambigous! $\Delta\Gamma s>0$

ϕ_s: $B_s \to J/\psi KK$, $B_s \to J/\psi\pi\pi$

PRD 87, 112010 (2013)/1fb^{-1}
PLB 713, 370 (2012)/1fb^{-1}



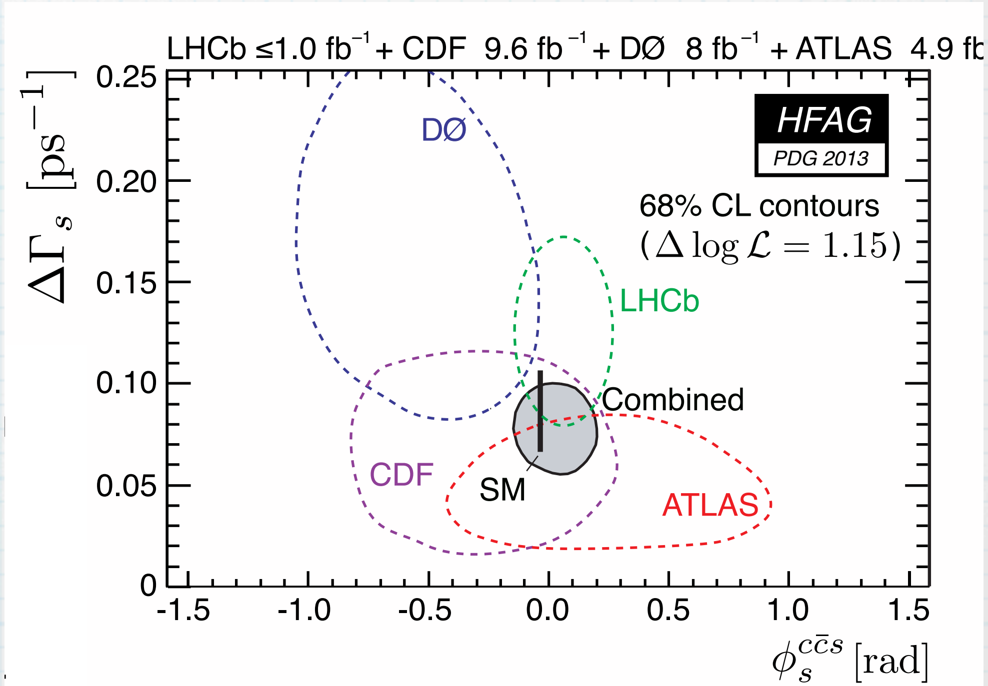


$$\phi_s = 0.07 \pm 0.09(\text{stat}) \pm 0.01(\text{syst})\ \text{rad},$$
$$\Gamma_s = 0.663 \pm 0.005(\text{stat}) \pm 0.006(\text{syst})\ \text{ps}^{-1},$$
$$\Delta\Gamma_s = 0.100 \pm 0.016(\text{stat}) \pm 0.003(\text{syst})\ \text{ps}^{-1}.$$

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

- combination

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



In agreement SM!

Charm: D^0 mixing

arXiv:1309.6534v2 (2013)/3fb^{-1}

- D^0 mix (similar mechanism, down quarks in the loops)! small rate.
- time dependent ratio: $D^{*+} \to D^0(K^-\pi^+)\pi^+_s$ (RS:CF), $D^{*+} \to D^{0-}(K^+\pi^-)\pi^+_s$ (WS:2CS or via oscillation)

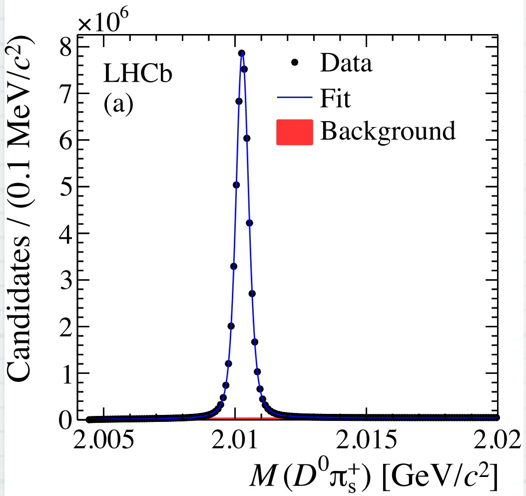
$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle,$$

$$x \equiv \Delta m/\Gamma \quad y \equiv \Delta\Gamma/2\Gamma$$

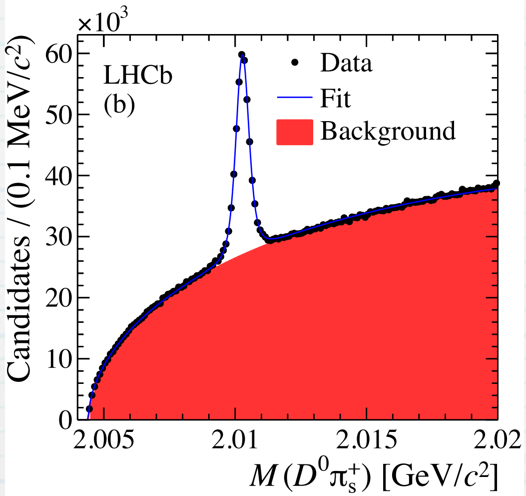
$O(10^{-2})$

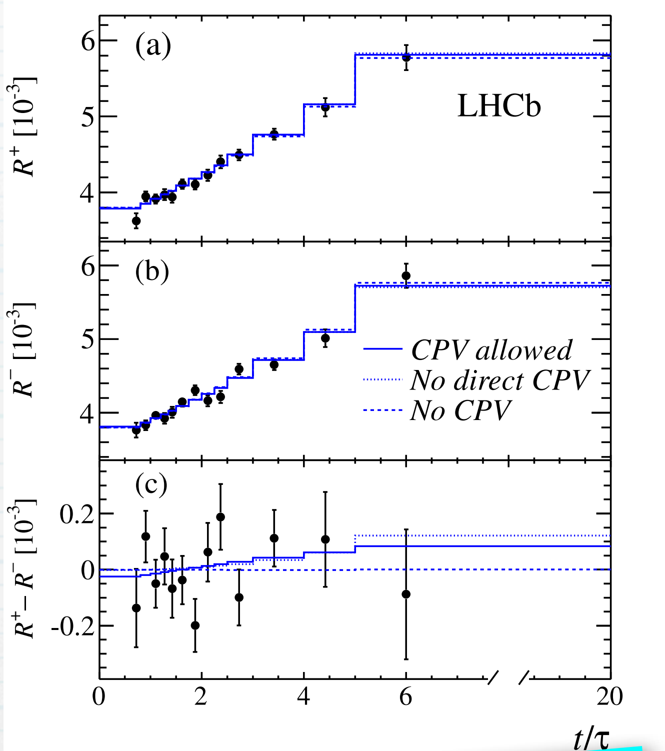
$$R(t) \approx R_D + \sqrt{R_D}\, y' \,\frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2,$$

RS~23M



WS ~0.1M





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

$$A_D = (-0.7 \pm 1.9)\%, \quad 0.75 < |q/p| < 1.24$$

68%C.L:

Oscillation established!

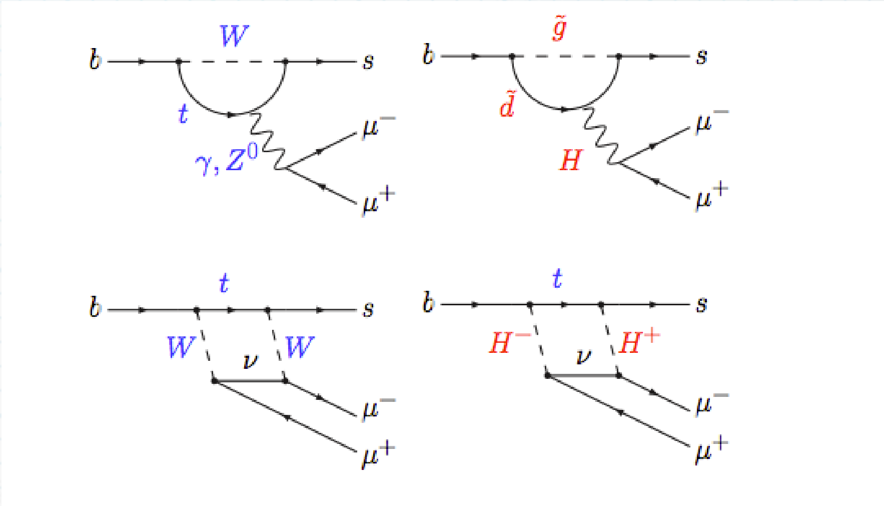
No evidence of direct or indirect CP violation!

III.Rare Decays

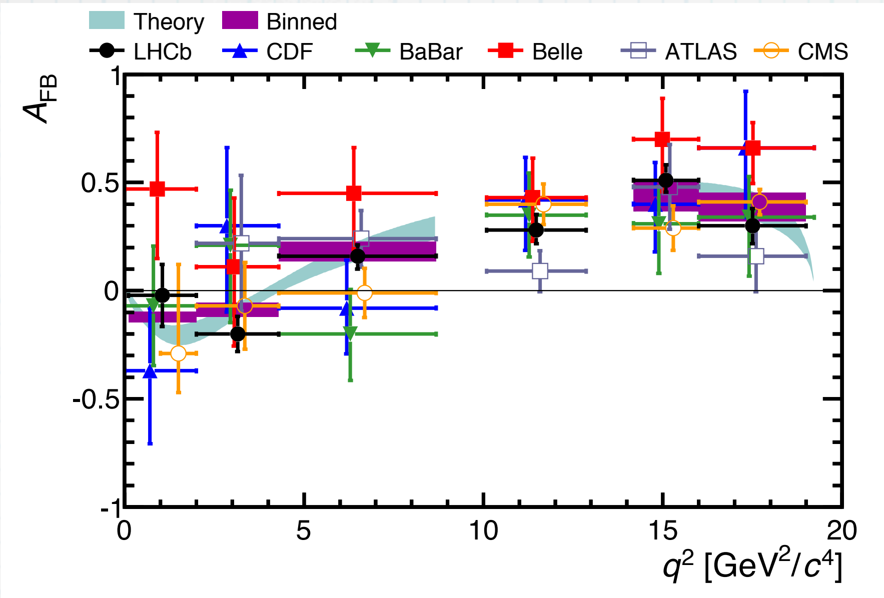
Angular analysis $B \to K^* \mu\mu$

JHEP 09 (2013) 131/1fb^{-1}

- In the SM, the γ/Z penguin introduces a forward/backward asymmetry (A_{FB}) of the muons
- SM prediction of the zero-crossing point of A_{FB}
  - SM $q^2_0 = (4.-4.3)\ \mathrm{GeV}^2/c^2$
- This Asymmetry and other observables (F_L,S_3) can be altered by the presence of NP
  - W. Coefficients involved: C_7,C_9,C_{10}
- LHCb measurement clarified the situation after BaBar, Belle, CDF results!



See: F. Kruger, J. Matias PR D71(2005);
J.Matias et al, JHEP, 1204:104,2012



$$A_{FB}\left(s = m^2_{\mu^+\mu^-}\right) = \frac{N_F - N_B}{N_F + N_B}$$

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

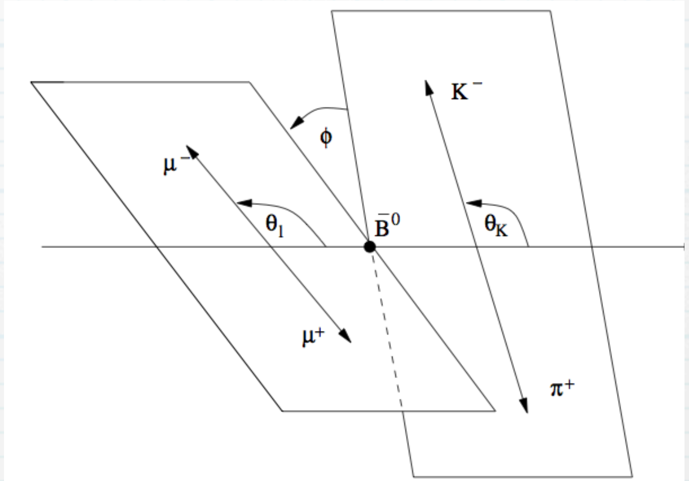
In agreement with SM!

Angular analysis $B \to K^*\mu\mu$

JHEP 09 (2013) 131/1fb-1

- The decay is described by 3 angles ($\theta_l, \theta_K, \varphi$) and the q^2 dimuon mass squared
  - Reduced expression of the angular distribution after φ folding:

$$
\begin{aligned}
\frac{1}{\Gamma}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\hat{\phi}\, dq^2} = \frac{9}{16\pi}\Big[& F_L \cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) \ + \\
& F_L \cos^2\theta_K (2\cos^2\theta_\ell - 1) \ + \\
& \frac{1}{4}(1-F_L)(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) \ + \\
& S_3 (1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} \ + \\
& \frac{4}{3} A_{FB} (1-\cos^2\theta_K)\cos\theta_\ell \ + \\
& A_{Im} (1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi} \ \Big]
\end{aligned}
$$

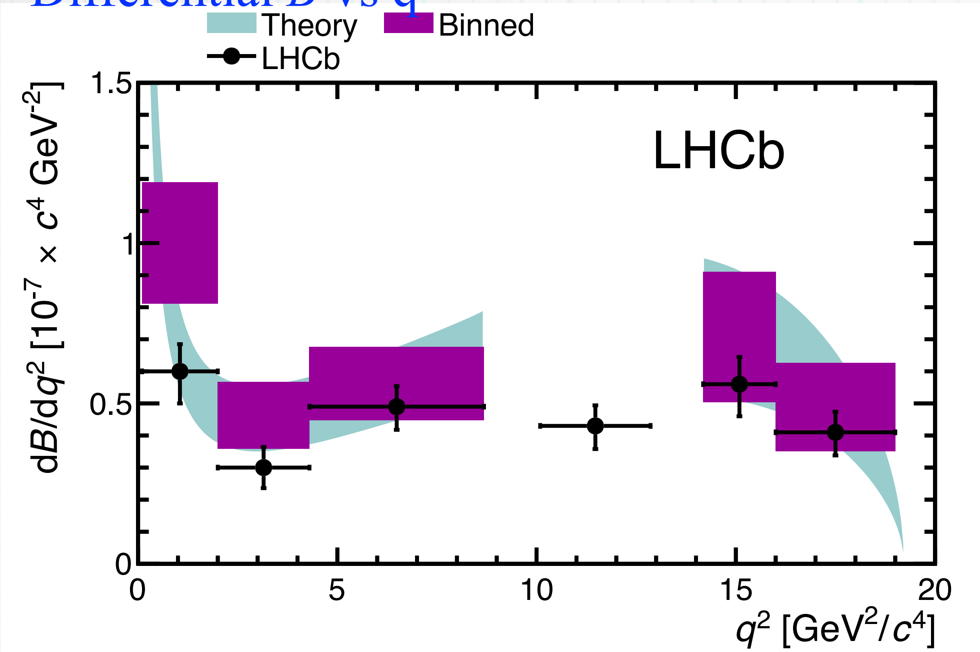


- Analysis:
  - BDT to suppress combinatorial bkg
  - Veto dimuon resonances J/ψ, $\psi(2S)$
  - Remove peaking background due to swap or misid, $B \to J/\psi K^*$, $B_s \to \phi(KK)\mu\mu$
  - Acceptance function from simulation but cross-checked with $B \to J/\psi K^*$
  - ~900 candidates
  - 3D fit in the angles (in bis q^2)
  - F_L, the longitudinal polarization of K^*
  - A_{FB}, the forward/backwark dimuon asymmetry

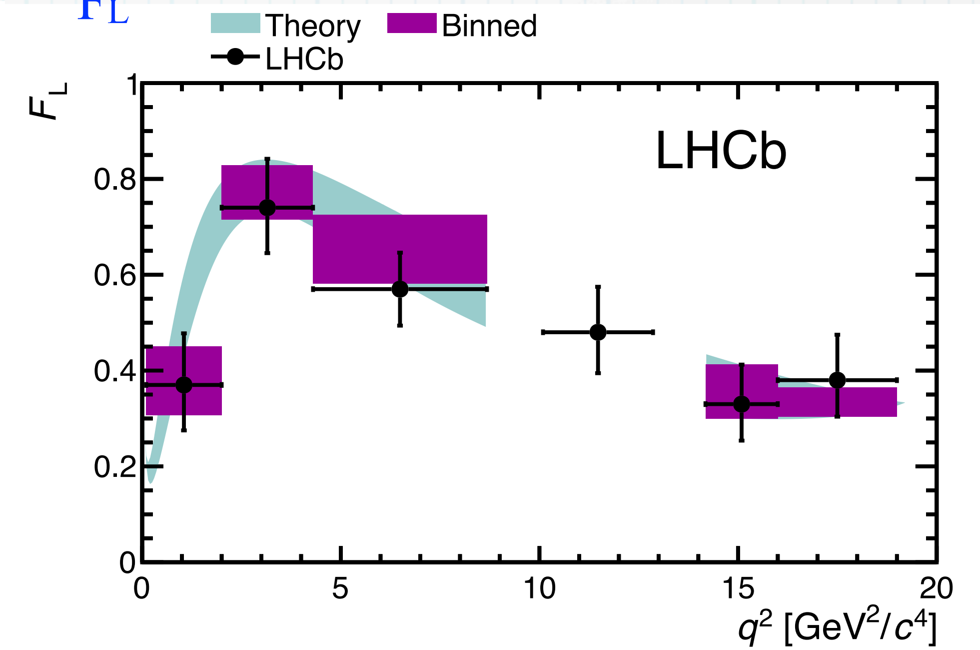
Angular analysis B→K*μμ

JHEP 09 (2013) 131/1fb-1

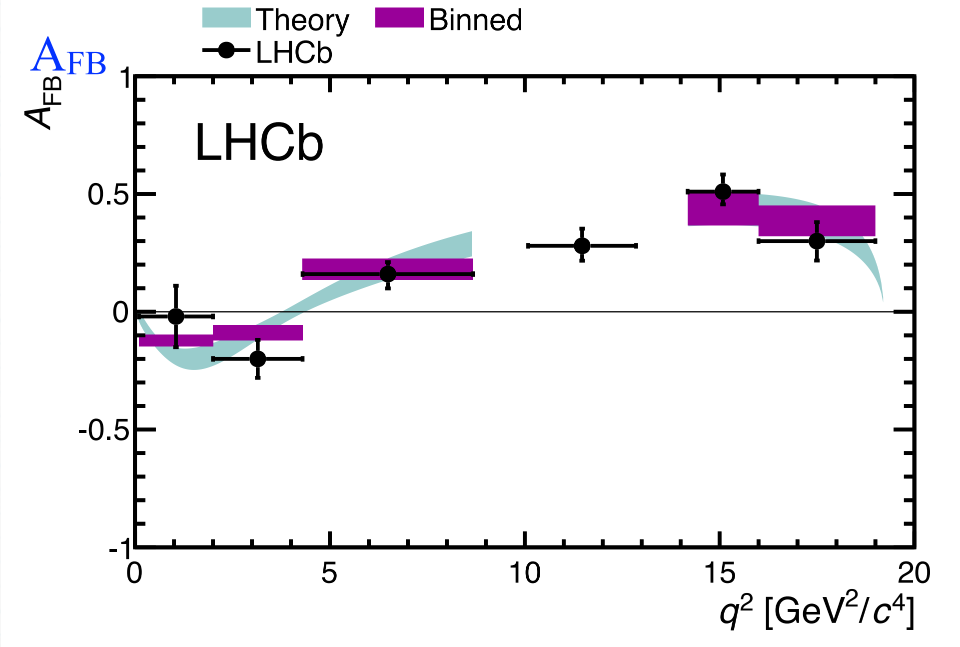
Differential B vs q^2



F_L



A_{FB}



In agreement with SM!

$$A_{FB} = -0.18^{+0.06+0.01}_{-0.06-0.02} \qquad (1 < q^2 < 6 GeV^2) \text{ LHCb}$$

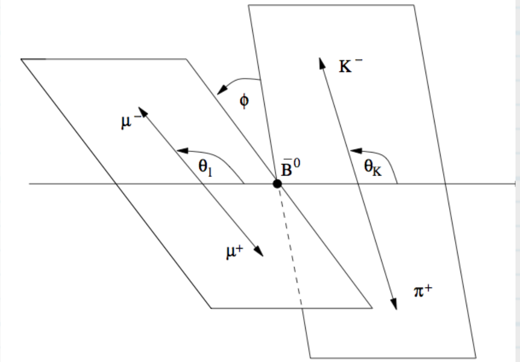
Angular analysis B→K*μμ

PRL 111 (2013) 191801/1fb^{-1}

- Angular analysis with **new observables**:
  - S_i are functions of Wilson coefficients and form-factors
  - P'_i observables reduce hadron form-factors uncertainties, are **complementary**!
  - using SM predictions [Descotes-Genon et al. JHEP 05 (2013) 137]

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

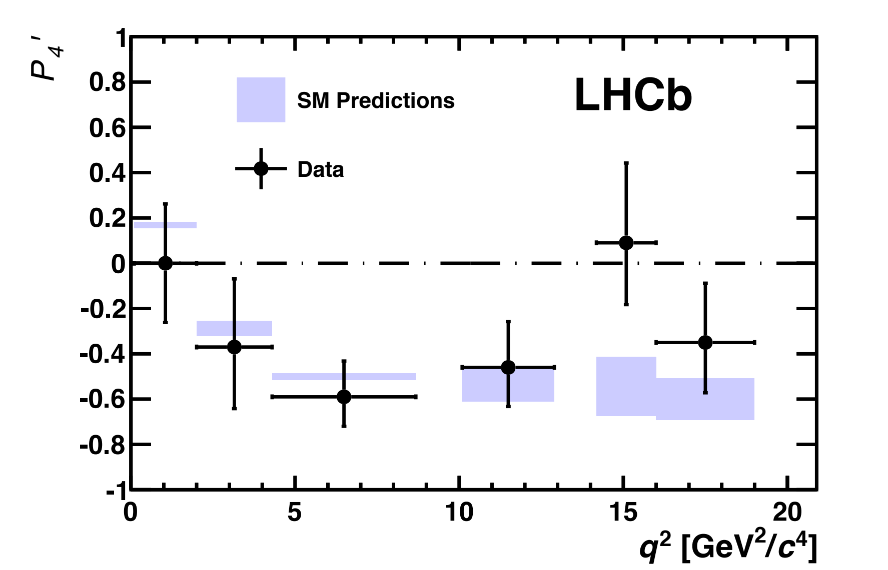
$$\begin{aligned}\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_K\,d\phi\,dq^2} = \frac{9}{32\pi}\Big[&\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K - F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell \\ &+ \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos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

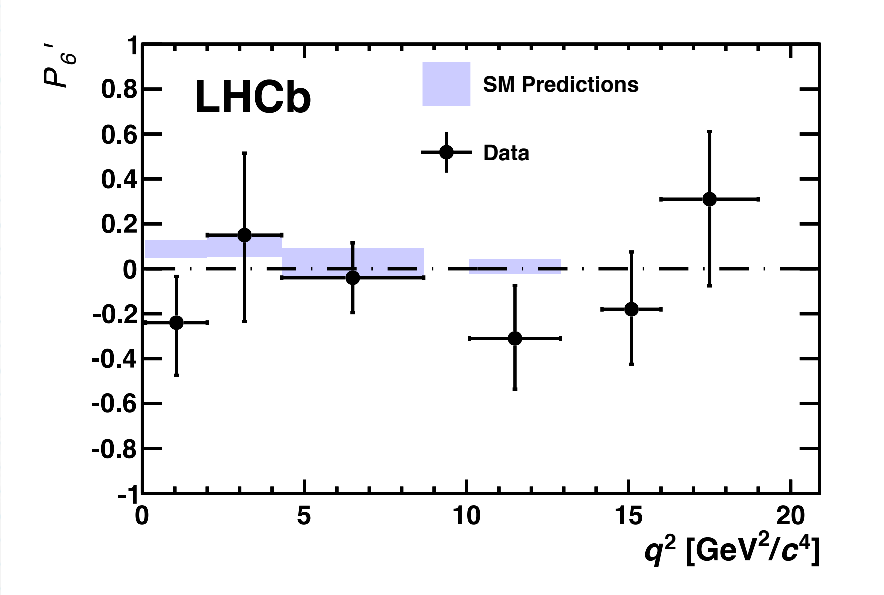


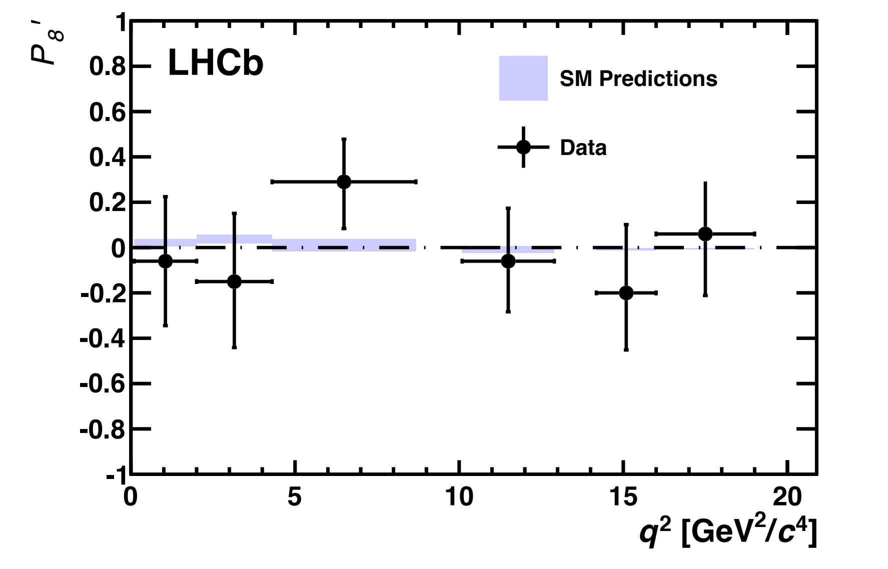
- Analysis:
  - BDT to suppress combinatorial bkg
  - Veto in dimuon resonances J/ψ, ψ(2S)
  - Veto peaking background due to swap or mis-id: B→J/ψK*, B_s→ϕ(KK)μμ
  - Acceptance function from simulation, but cross-checked with B→J/ψK*
  - mass from control channel and bkg distributions from upper side bands
  - Fit to the mass and angular distributions after unfolding ϕ
  - main systematic: background distributions, acceptance function and S-wave contribution

new angular analysis B→K*μμ

arXiv:1308.1707/1fb[-1]



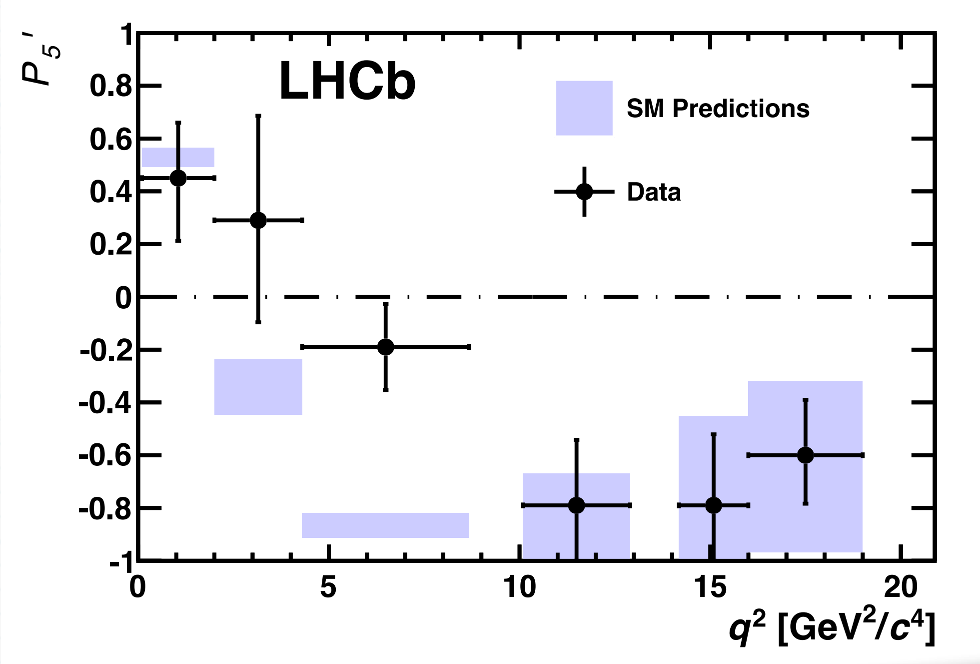




In agreement with SM!

new angular analysis $B \to K^* \mu\mu$

arXiv:1308.1707/1fb-1



all bins (24) in q^2 in agreement with SM except 1 (at 3.7 σ)!

- if all bins independent, the probability of have such deviation or greater is 0.5%
- it will imply a smaller value of C_9,C_7 with respect SM [arXiv:1308.101, arXiv:1307.5683]
- further theoretical and more data studies are needed to clarify the picture

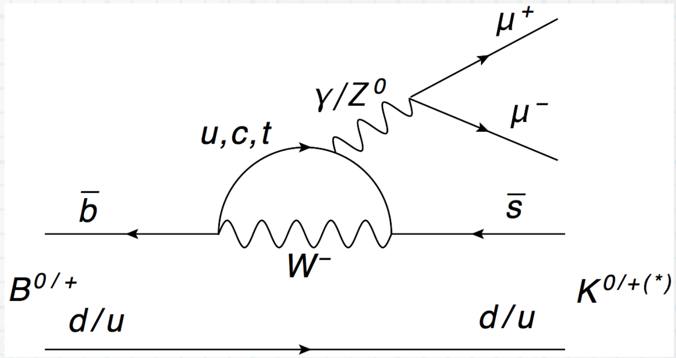
Isospin Analysis $B\to K^{(*)}\mu\mu$

JHEP 07 (2012) 133/1fb-1

- Isospin asymmetry:

See: T.Feldmann and J.Matias, JHEP, 01 (2002) 074

$$
\begin{aligned}
A_{\mathrm{I}} &= \frac{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)}{\Gamma(B^0 \to K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \to K^{(*)+}\mu^+\mu^-)} \\
&= \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)},
\end{aligned}
$$

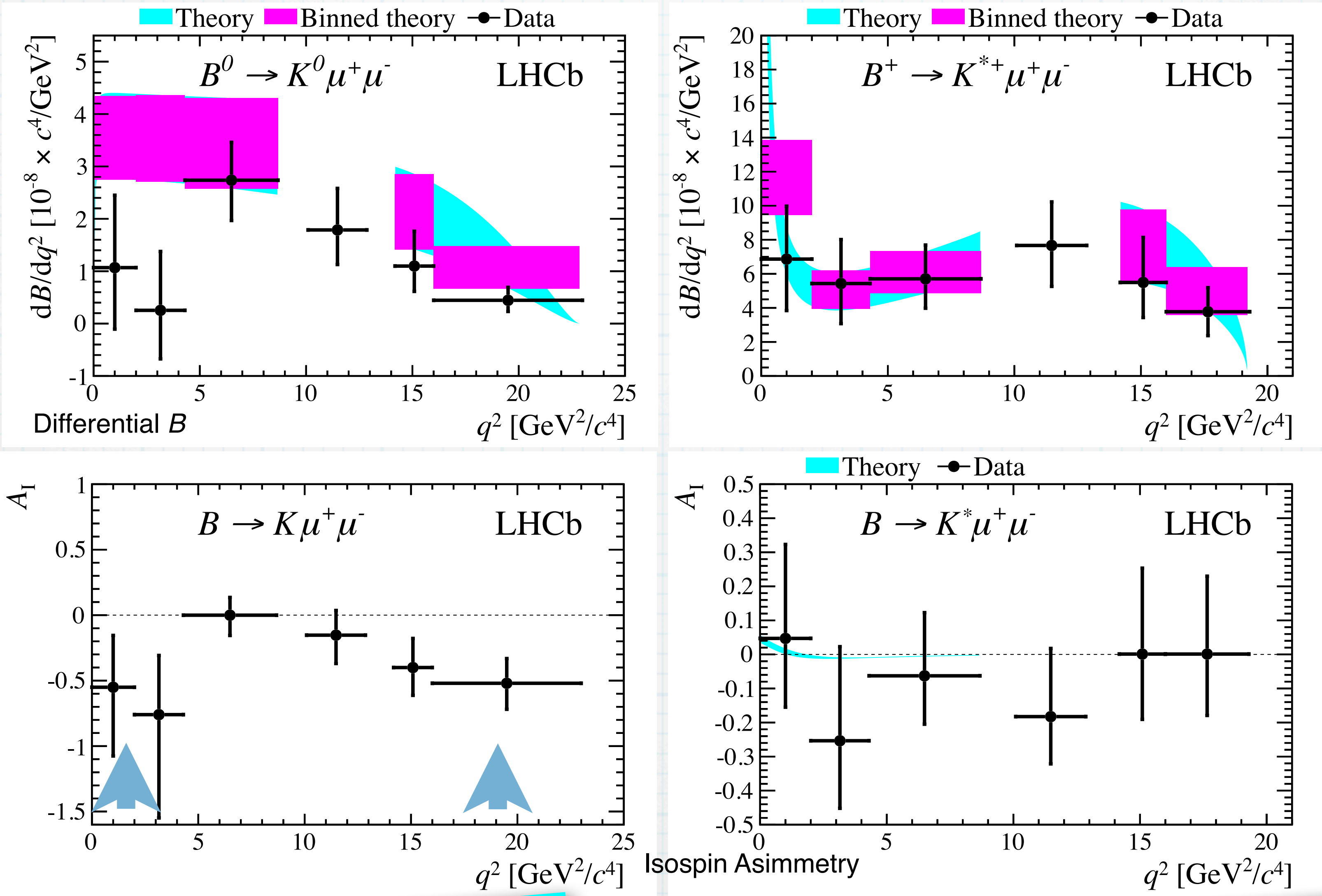


  - SM prediction is close to zero
- Measured by BaBar, Belle and CDF. Babar measurement of B with some tension (3.9σ)!

- SM *B* predictions suffer from hadron form factors uncertainties
- Measured Differential *B*:
  - $B^+\to K^{*+}(K_S\pi^+)\mu\mu$, $B\to K^*\mu\mu$,
  - $B\to K\mu\mu$, $B^+\to K^+\mu\mu$
- Use as normalization channel $B\to J/\psi(\mu\mu)K^*$; $B^+\to J/\psi(\mu\mu)K^+$

Isospin Analysis B→K$^{(*)}$μμ

JHEP 07 (2012) 133/1fb-1



Deviation from 0 at 4.4 σ !

but difficult to interpret!

In agreement with SM!

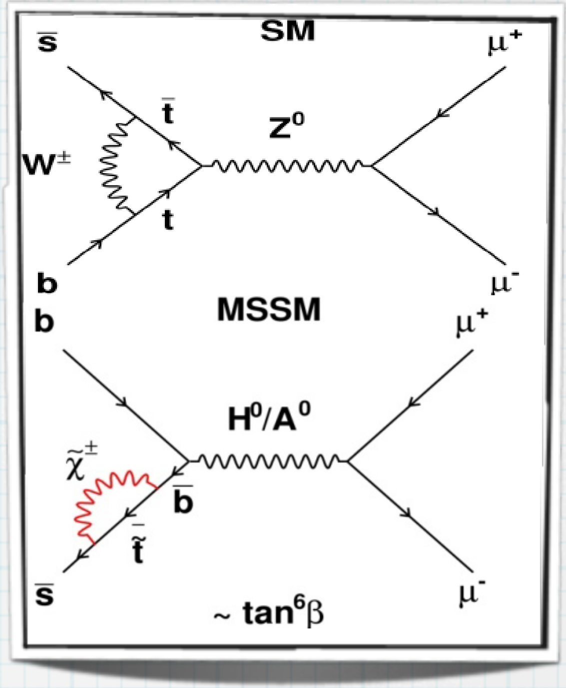
and with previous measurements!

Update of $B_{(s)} \to \mu\mu$ with $3fb^{-1}$

PRL 111 (2013) 101805/$3fb^{-1}$

- SM prediction (FCNC, helicity suppressed)
  - SM $\mathcal{B}(B_s \to \mu\mu) = (3.56 \pm 0.30)\ 10^{-9}$
  - SM $\mathcal{B}(B \to \mu\mu) = (1.07 \pm 0.10)\ 10^{-10}$
- Branching Ratio very sensitive to NP

arXiv:1208.0934
arXiv:1303.3820



- Analysis:
  - BTD to suppress combinatorial bkg ($bb \to X\mu\mu$)
  - Use PID to reduce peaking background and study of specific peaking backgrounds
  - Discrimination in 2D space:
    - BDT (kinematical & geometrical variables) & mass
  - Normalize to $B^+ \to J/\psi K^+$
  - Use CLs method to set a limit and a unbinned maximum likelihood fit to obtain ***B***

Update of $B_{(s)} \to \mu\mu$ with $3fb^{-1}$

PRL 111 (2013) 101805/3fb-1

- A multivariate discriminant BDT:

  kinematical and geometrical variables

  signal uniformly distributed [0,1]

  trained with MC

  estimated with data:

  signal $B \to hh$ trigger unbias

  background: $B_s \to \mu\mu$ sidebands

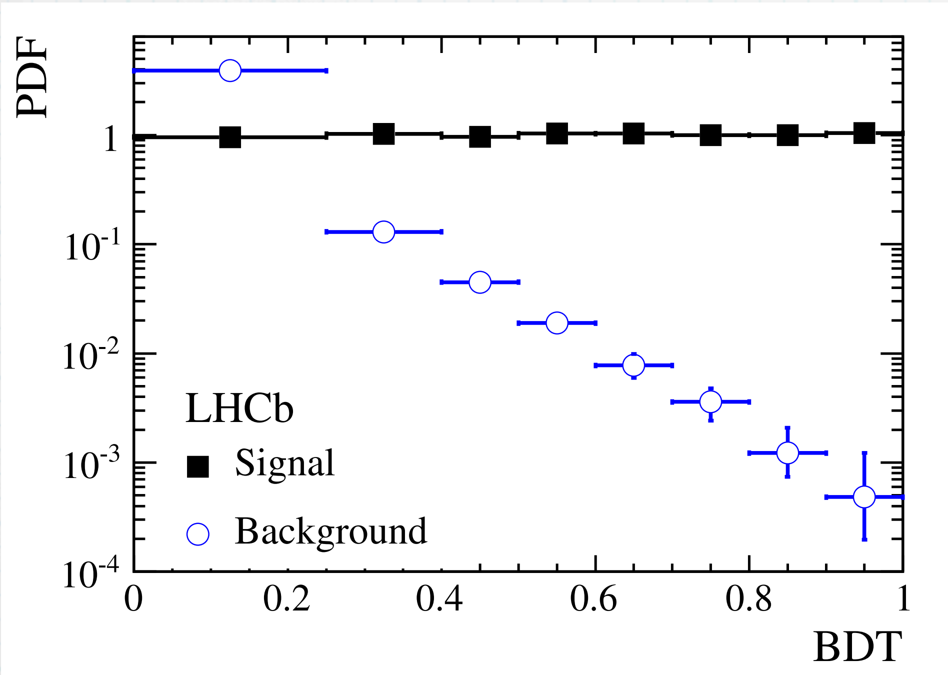
- Mass:

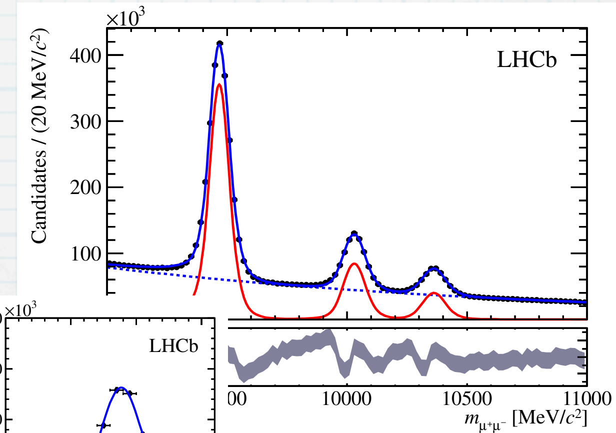
  signal: CB shape

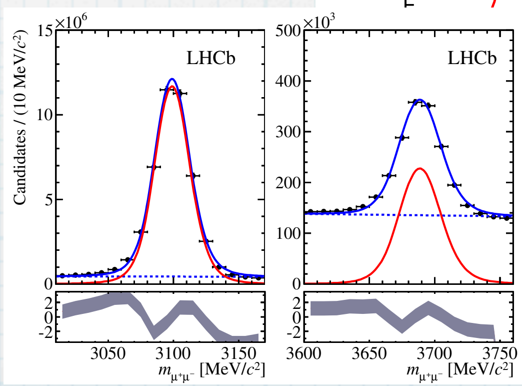
  central values $B \to hh$ fit

  resolution: interpolation between $\mu\mu$ resonances J/ψ, $\Psi(2S)$, $\Upsilon(1S,2S,3S)$

$\sigma(B_s) = 23.2 \pm 0.4$ MeV/c^2
$\sigma(B) = 22.8 \pm 0.4$ MeV/c^2





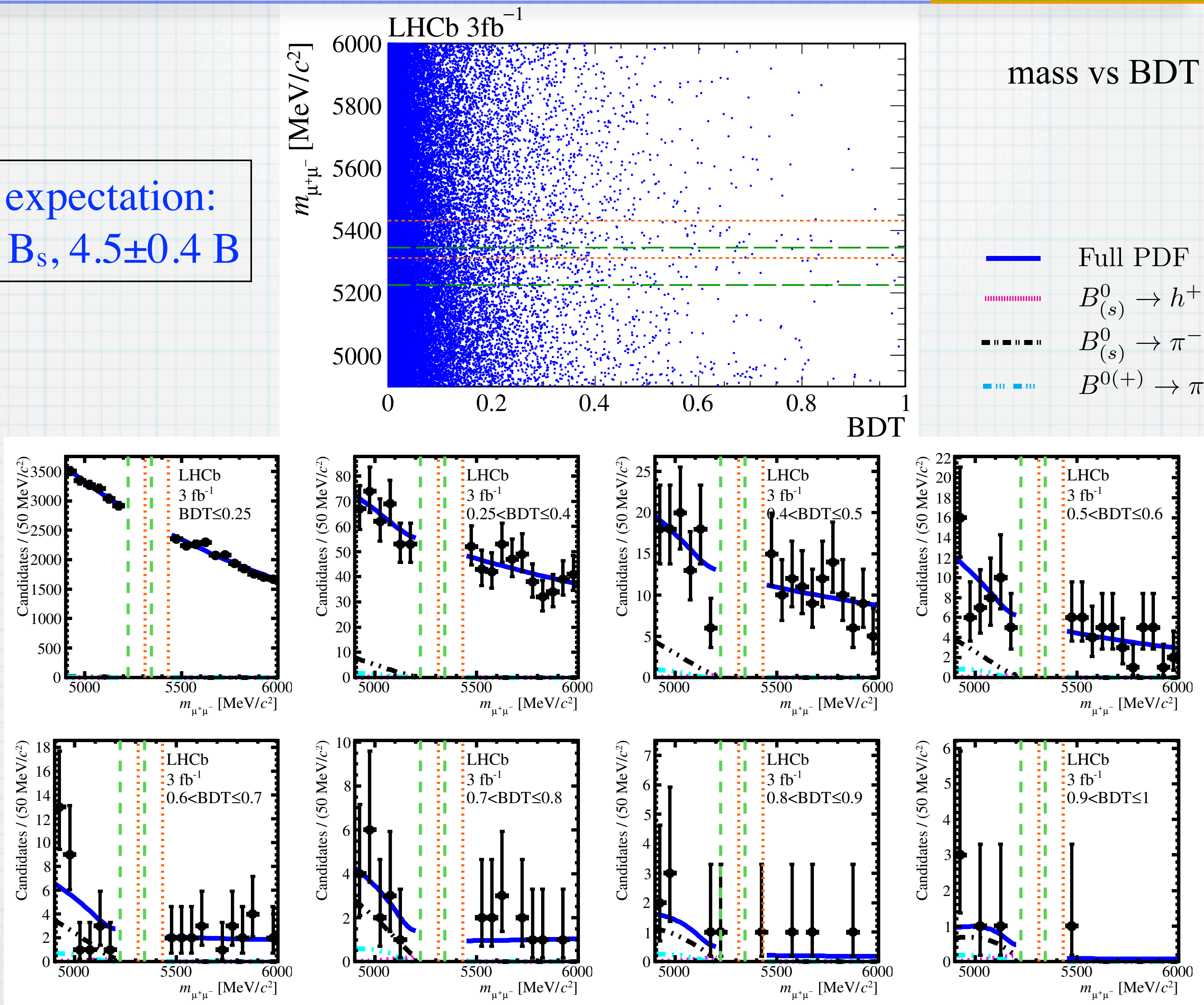


Update of $B_{(s)} \rightarrow \mu\mu$ with $3fb^{-1}$

PRL 111 (2013) 101805/$3fb^{-1}$

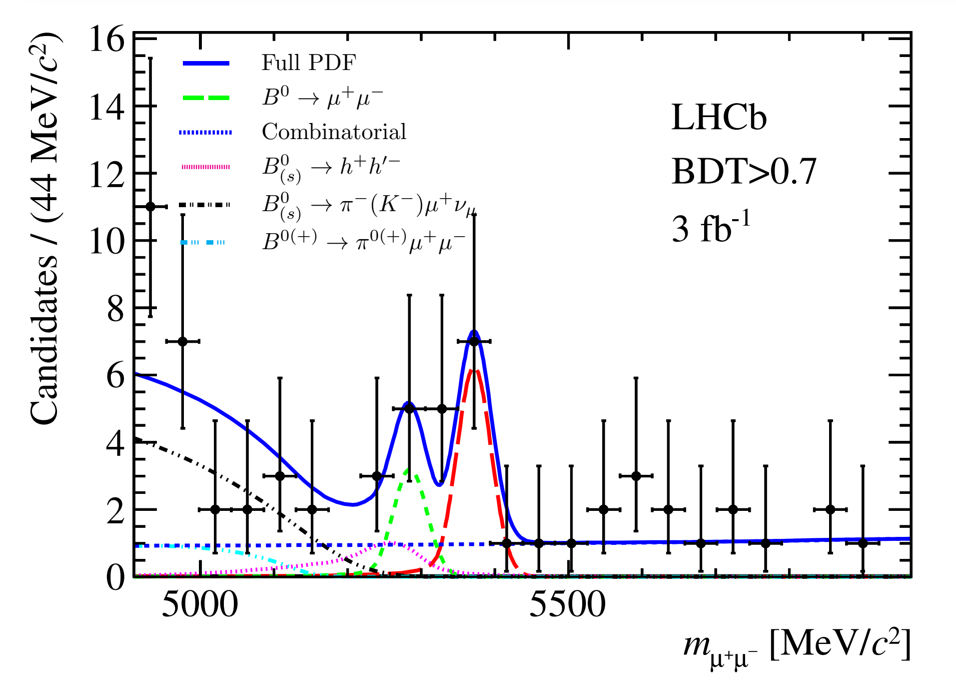
SM expectation:
49±4 B_s, 4.5±0.4 B

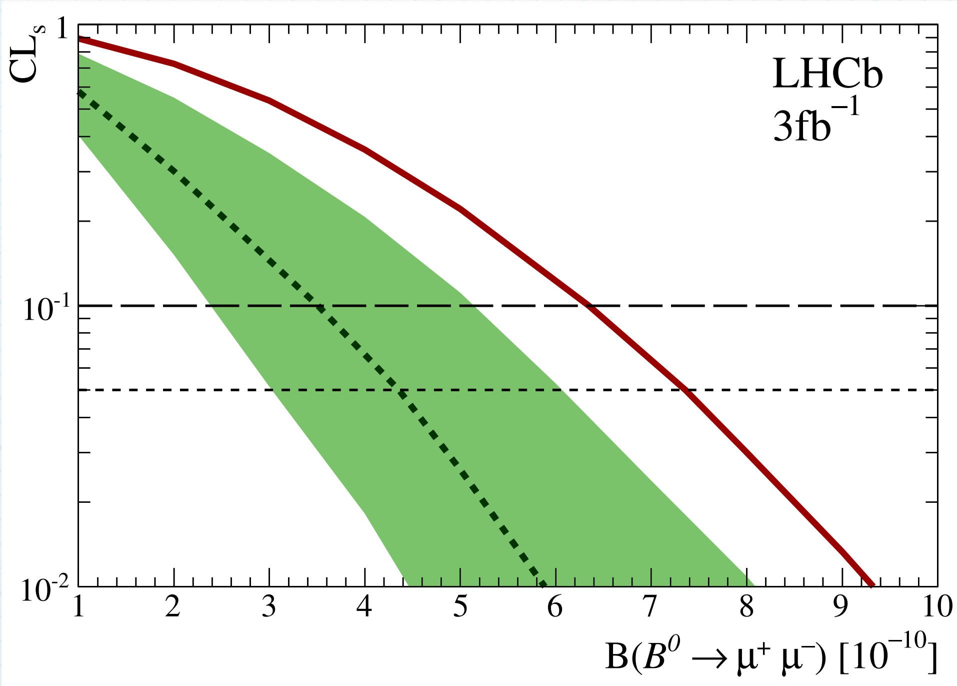
mass vs BDT data



Update of B(s)→μμ with 3fb-1

PRL 111 (2013) 101805/3fb-1





$\mathcal{B}$(B(s)) measurements

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

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7\,^{+2.4}_{-2.1}(\text{stat})\,^{+0.6}_{-0.4}(\text{syst})) \times 10^{-10}.$$

B limits

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

$\mathcal{B}_s$ significance 4 σ, $\mathcal{B}$ 2 σ!

In agreement with SM!

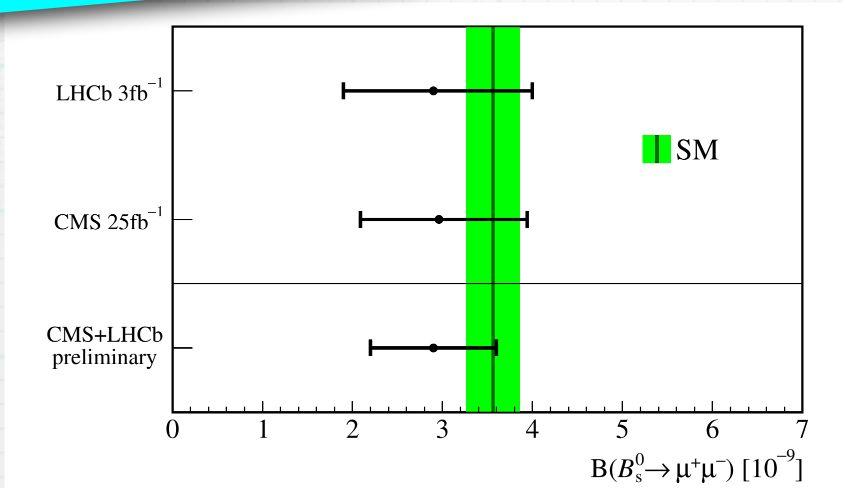
$B_{(s)} \to \mu\mu$ combination with CMS

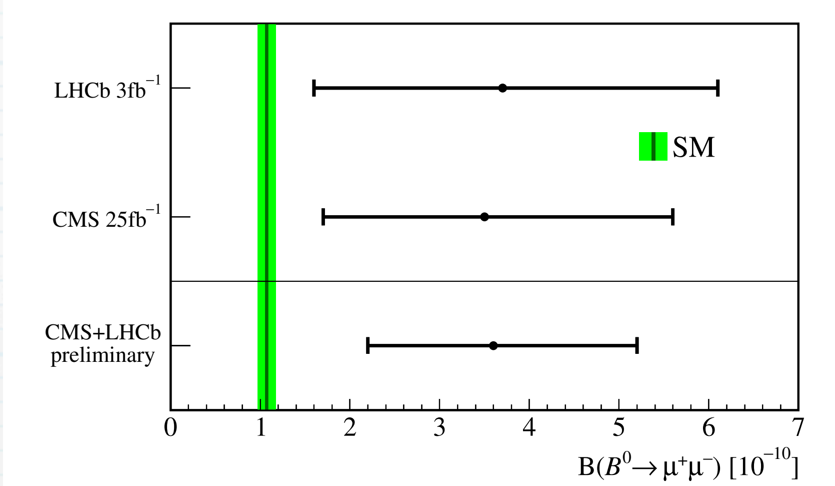
LHCb-CONF-2013-12/3fb^{-1}

- Combination with latest CMS result

Observation!

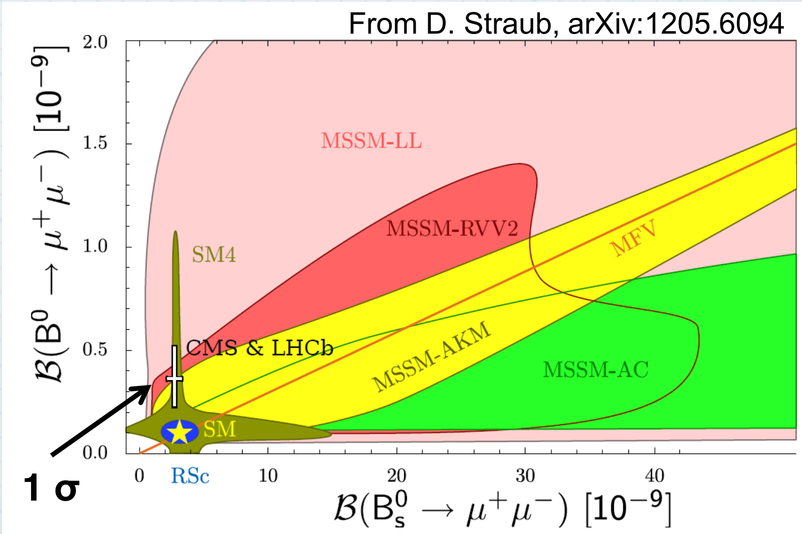
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.6\,^{+1.6}_{-1.4}\right) \times 10^{-10},$$





- strong constraint to models beyond SM

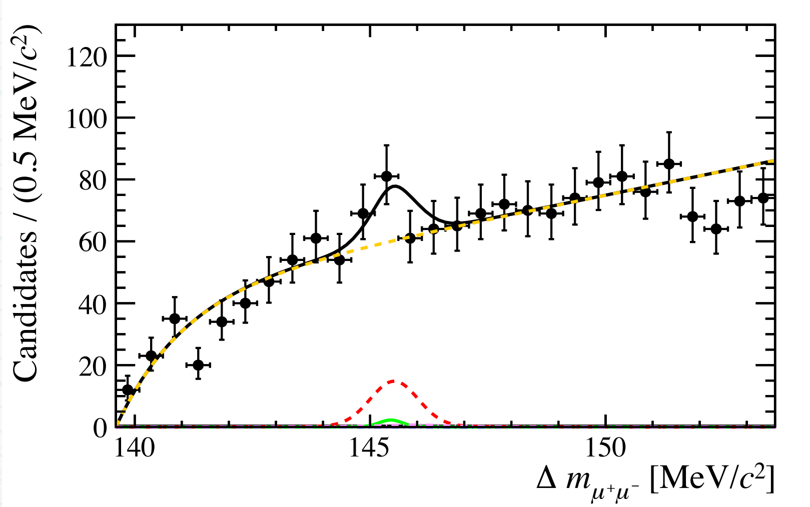
In agreement with SM!

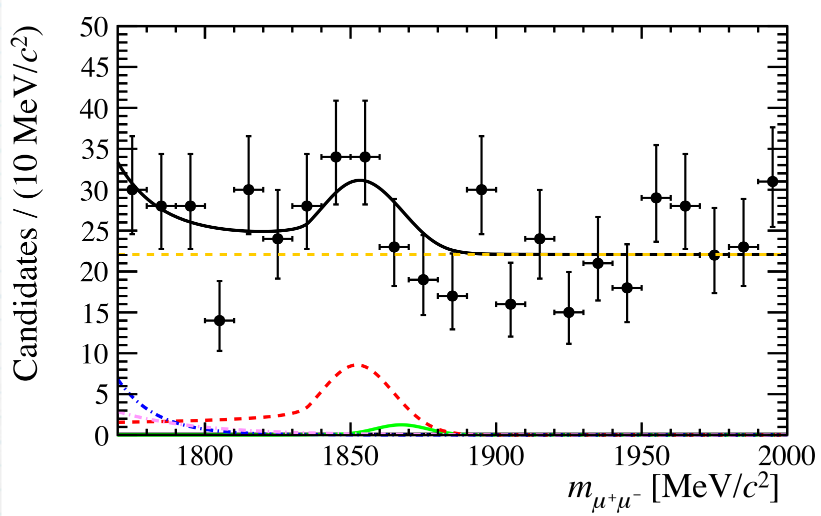


D→μμ

PLB 725 (2013) 15/0.9fb^{-1}

- SM: FCNC suppression driven by GIM mechanism
  - SM B(D→μμ): 10^{-13}-10^{-11}
- NP models can enhance B (R parity violating MSSM)
- Analysis:
  - Use $D^{*+}\to D^0(\mu\mu)\pi^+$
  - 2D fit to m(D^0), $\Delta m(D^{*+}-D^0)$
  - Background: combinatorial, D→ππ
  - Normalize to $D^-_s\to\phi(\mu\mu)\pi^-$





$$\mathcal{B}(D^0\to\mu^+\mu^-) < 6.2\ (7.6)\times 10^{-9} \quad \text{at 90\% (95\%) CL.}$$

best limit!

Conclusions

- LHC and LHCb performing beautifully
- LHCb has a rich Physics program:
  - Direct CP violation $B_{(s)} \to hh$
  - γ angle via trees: $B \to DK$
  - $B_s \to D\pi$ oscillations
  - ϕ_s angle: $Bs \to J/\psi\phi$
  - D^0 mixing!
  - $B \to K^*\mu\mu$ angular analysis
    - new observables! (one bin in 24 shows discrepancy)
  - $B_s \to \mu\mu$ signal (4σ) , limit on $B \to \mu\mu$
- Everything in agreement with SM, no NP found (yet)!
  - Stringent constraints in models that extend the SM
  - Now looking for NP smallish effects...
  - Most analysis with 3fb^{-1} expected by first half 2014

$\gamma = (67 \pm 12)^\circ$ at 68% CL .

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

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

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

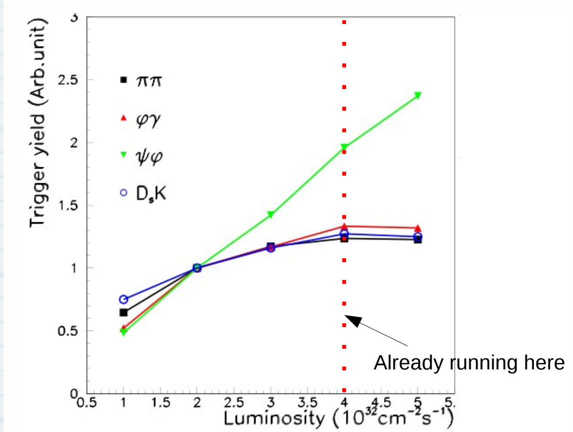
$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9\,^{+1.1}_{-1.0}(\text{stat})\,^{+0.3}_{-0.1}(\text{syst})) \times 10^{-9}$,

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 7.4 \times 10^{-10}$

in agreement with SM!
but more to come!

LHCb Upgrade

- Current limitation: trigger in hadronic channels!
- Upgrade LHCb:
  - Trigger (40 MHz), Velo, Tracking
- Current (~2 fb^{-1}/year): Upgrade 50 fb^{-1} (5x) data



Type	Observable	Current precision	LHCb 2018	Upgrade (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [138]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [214]	0.045	0.014	~ 0.01
	$a_{\rm sl}^s$	6.4×10^{-3} [43]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [43]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.08 [67]	0.025	0.008	0.02
	$s_0\,A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [67]	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.25 [76]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [85]	8 %	2.5 %	~ 10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	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	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–12° [244, 258]	4°	0.9°	negligible
	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K_S^0$)	0.8° [43]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

Extra

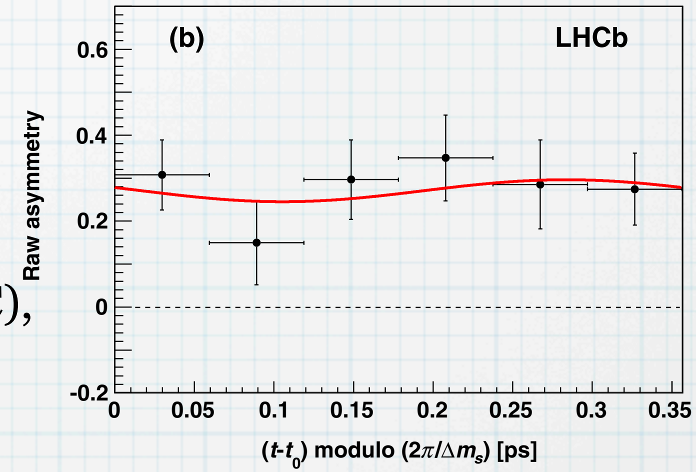
Direct CP - B(s)→hh

PRL 100 221601 (2013)/1fb^{-1}

- **Charge Asymmetry:**

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

- **selection:**
  - D distance/σ>2 to reduce bkg
  - Calibration Rich D*+→D(Kπ)π+ kinematically selected; reweighted to B(s) phase-space
- **Mass PDFs:**
  - signal: 2Gauss + tails, comb: exponential, x-feed (MC), partial B→Xhh (feno)
- **Detector and production asymmetries**
  - detector: using D*+→D(Kπ,KK)π+, A_{CP}(KK) external
  - production: amplitude of oscillation
- **Systematic:**
  - B (det. Asymm), Bs (signal model, comb bkg)



$$A_\Delta(B^0_{(s)} \to K\pi) = \zeta_{d(s)} A_D(K\pi) + \kappa_{d(s)} A_P(B^0_{(s)}),$$

$$A^*_{\rm raw}(K\pi) - A^*_{\rm raw}(KK) = A^*_D(K\pi) - A_{CP}(KK).$$

$$\mathcal{A}(t) \approx A_{CP} + A_D + A_P \cos(\Delta m_{d(s)} t);$$

Extra

Direct CP $B^{\pm} \to K^{\pm}h^{+}h^{-}$

PRL 100 221601 (2013)/1fb-1

- Charge Asymmetry:

$$A_{CP}(B^{\pm} \to f^{\pm}) = \Phi[\Gamma(B^{-} \to f^{-}), \Gamma(B^{+} \to f^{+})],$$

- selection:
  - D distance/σ>2 to reduce bkg, exclude D mass region
  - Calibration Rich $D^{*+} \to D(K\pi)\pi^{+}$ kinematically selected; reweighted to B(s) phase-space
- Mass PDFs:
  - signal: 2Gauss + tails, comb: exponential, partial $B \to Xhhhh$ (feno)
- Detector and production asymmetries
  - Only for K and B
  - use $B^{\pm} \to J/\psi K^{\pm}$, $A_{CP}(J/\psi K)$ word average

$$A_{CP} = A_{\text{raw}} - A_{\Delta}, \qquad A_{\Delta} = A_D(K^{\pm}) + A_P(B^{\pm}).$$

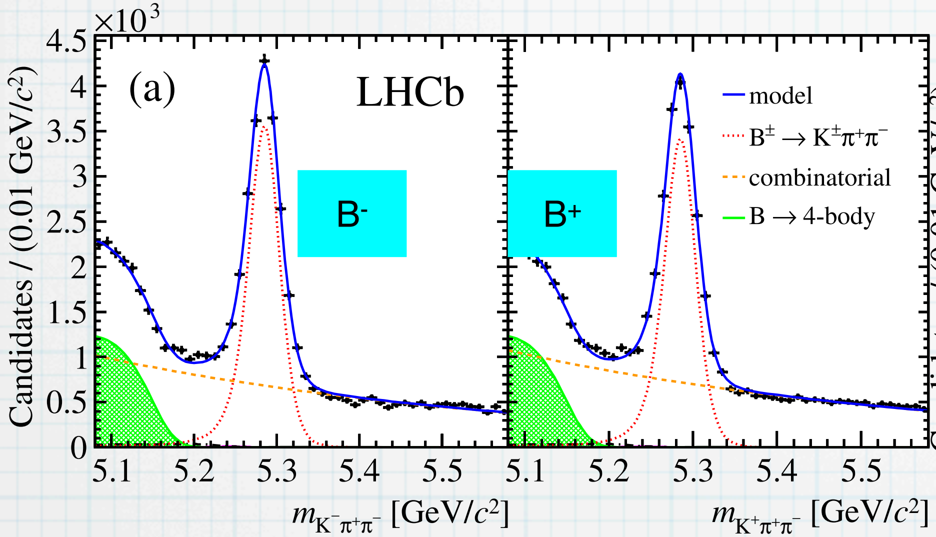
$$A_{\Delta} = A_{\text{raw}}(J/\psi K) - A_{CP}(J/\psi K),$$

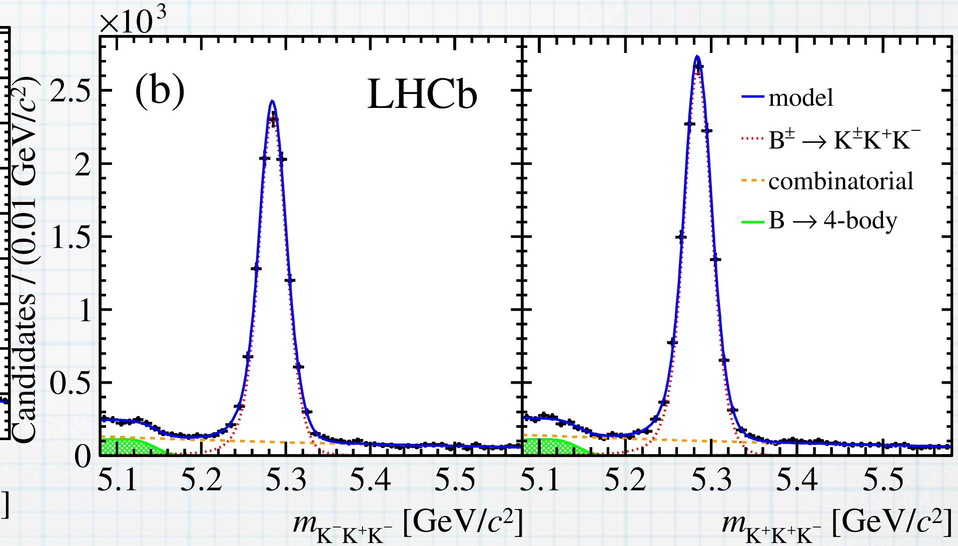
- Systematic:
  - trigger asymmetries (trigger response to K, diff decisions) and phase-space acceptance corrections (det eff data/MC)

Direct CP $B^{\pm}\to K^{\pm}h^{+}h^{-}$

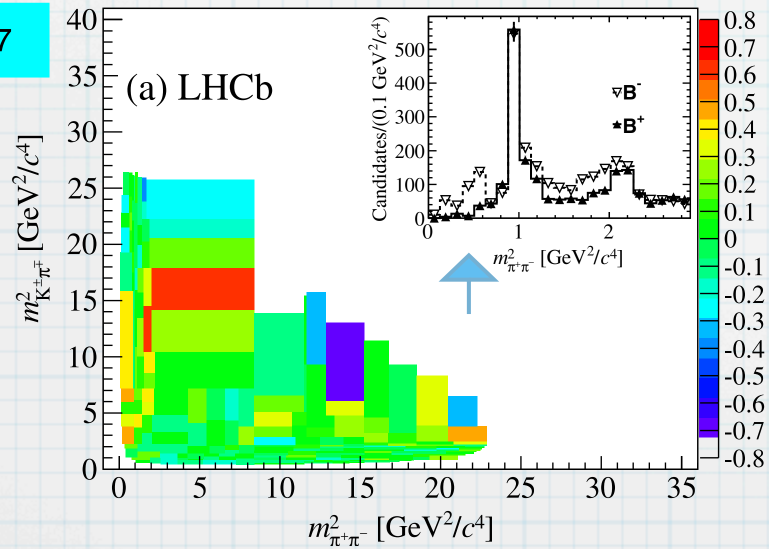
PRL 111 101801 (2013)/1fb^{-1}

- Direct CP in $B^{\pm}\to K^{\pm}\pi^{+}\pi^{-}$, $B^{\pm}\to K^{\pm}K^{+}K^{-}$

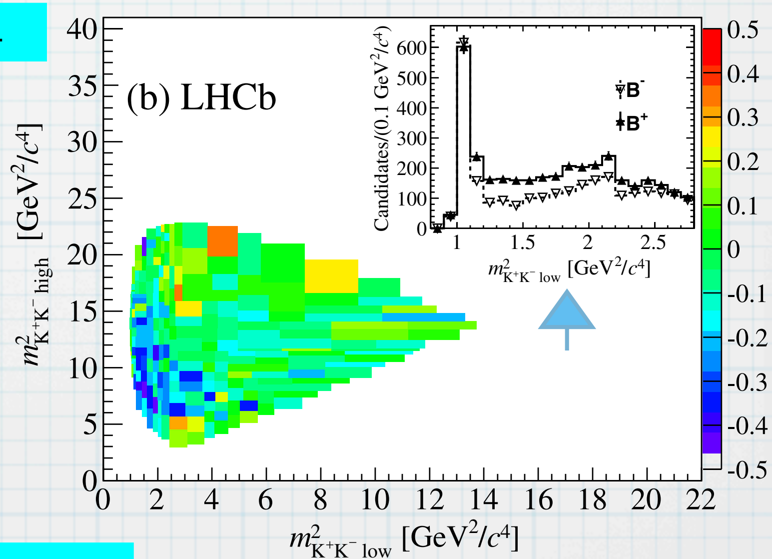




35901±327



22119±164



$$A_{CP}(B^{\pm}\to K^{\pm}\pi^{+}\pi^{-}) = 0.032 \pm 0.008 \pm 0.004 \pm 0.007,$$

$$A_{CP}(B^{\pm}\to K^{\pm}K^{+}K^{-}) = -0.043 \pm 0.009 \pm 0.003 \pm 0.007,$$

2.8σ
3.7σ

γ: B→D(hh)K

PLB 712 (2012) 203/1fb^{-1}

- GWL/ADS analysis with $B^\pm \to D(hh)K^\pm$ ($h=K^\pm,\pi^\pm$)
  - GWL $D \to KK,\pi\pi$
  - ADS $B^\pm \to D(\pi^\pm K^\mp)K^\pm$ (suppressed), $B^\pm \to D(K^\pm\pi^\mp)K^\pm$(favoured)
  - $B^\pm \to D(K^\pm\pi^\mp)\pi^\pm$ control sample (and reduced sensitivity)
- Observables: ratios and asymmetries

$$R^f_{K/\pi} = \frac{\Gamma(B^- \to [f]_D K^-) + \Gamma(B^+ \to [f]_D K^+)}{\Gamma(B^- \to [f]_D \pi^-) + \Gamma(B^+ \to [f]_D \pi^+)},$$

ratio K/π

$$A^f_h = \frac{\Gamma(B^- \to [f]_D h^-) - \Gamma(B^+ \to [f]_D h^+)}{\Gamma(B^- \to [f]_D h^-) + \Gamma(B^+ \to [f]_D h^+)},$$

Asymmetry -/+

$$R^\pm_h = \frac{\Gamma(B^\pm \to [\pi^\pm K^\mp]_D h^\pm)}{\Gamma(B^\pm \to [K^\pm \pi^\mp]_D h^\pm)}.$$

Ratio suppressed/favoured

- Selection:
  - mass D (25 MeV), D distance/σ, and BDT (B,D,tracks, isolation,…), trained MC
  - PID: DLL(K-π) separation, veto if mass in J/ψ, ψ(2S)
  - ADS modes suffers x-feed K↔π from favoured decays!
  - efficiency of PID calibrated using $D^{*+} \to D(K^-\pi^+)\pi^+$ and $B^\pm \to D(K^\pm\pi^\mp)\pi^\pm$ phase-space

γ: B→D(Kπππ)K

PLB 723 (2013) 44/1fb^{-1}

- **ADS modes:**
  - favoured: $B^\pm \to D(K^\pm\pi^\mp\pi^+\pi^-)h^\pm$, suppressed $B^\pm \to D(\pi^\pm K^\mp\pi^+\pi^-)h^\pm$
- **Observables**

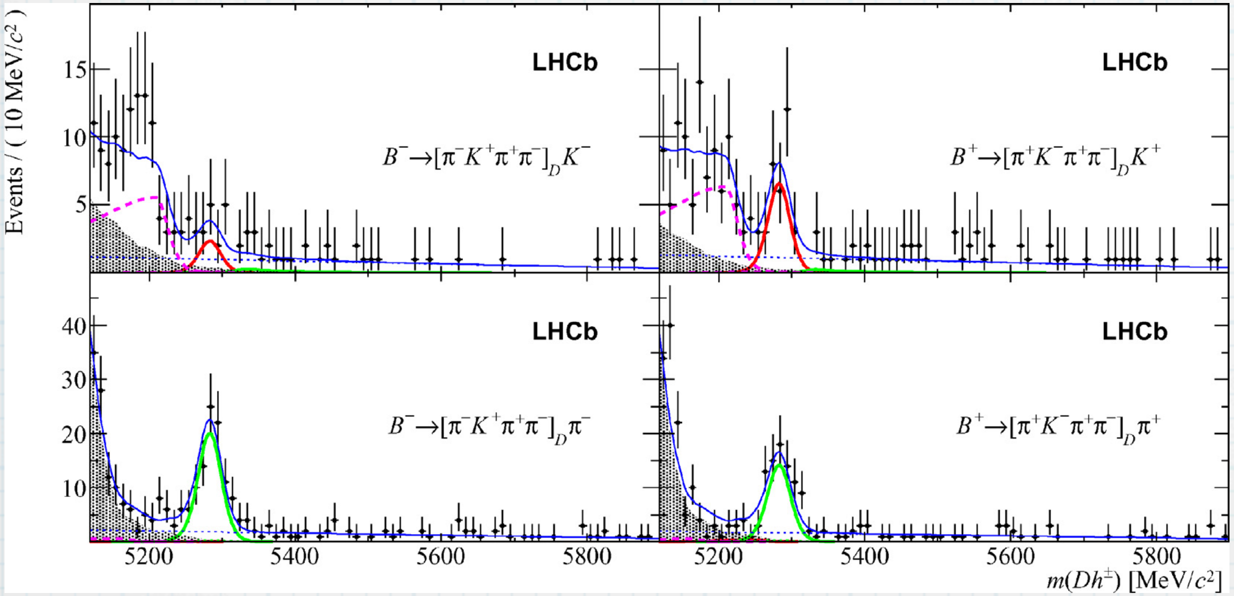
$$R_h^{K3\pi,\pm} \equiv \frac{\Gamma(B^\pm \to [\pi^\pm K^\mp \pi^+\pi^-]_D h^\pm)}{\Gamma(B^\pm \to [K^\pm \pi^\mp \pi^+\pi^-]_D h^\pm)}$$

ratio suppressed/favoured

$$R_h^{K3\pi,\pm} = (r_B^h)^2 + (r_D^{K3\pi})^2 + 2 r_B^h r_D^{K3\pi} \kappa_D^{K3\pi} \cos(\delta_B^h + \delta_D^{K3\pi} \pm \gamma).$$

$r_D^{K3\pi} \sim 0.06$ $\quad \kappa_D^{K3\pi} = 0.33^{+0.20}_{-0.23}$ $\quad \delta_D^{K3\pi} = (114^{+26}_{-23})^\circ$

CLEO-c



$$R_{ADS(K)}^{K3\pi} = \frac{R_K^{K3\pi,-} + R_K^{K3\pi,+}}{2} = 0.0124 \pm 0.0027,$$

$$R_{ADS(\pi)}^{K3\pi} = \frac{R_\pi^{K3\pi,-} + R_\pi^{K3\pi,+}}{2} = 0.0037 \pm 0.0004,$$

$$r_B^K = 0.097 \pm 0.011 \text{ [68.3\% CL]}$$

Mode	B^-	B^+
$[K\pi\pi\pi]_D\pi$	20,791 ± 232	21,054 ± 235
$[K\pi\pi\pi]_D K$	1567 ± 57	1660 ± 60
$[\pi K\pi\pi]_D\pi$	87 ± 11	68 ± 10
$[\pi K\pi\pi]_D K$	11 ± 5	29 ± 7

first observation of this decay!

Charm: CP direct D→hh

PLB 723 (2013) 33/1fb^{-1}
LHCB-CONF-2013-003 (2013)/1fb^{-1}

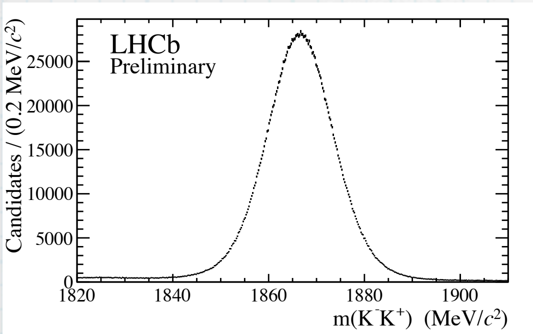
- D^0 reconstructed in large number at LHCb! (350 M/1fb-1) $\sigma_{cc} \sim 20\ \sigma_{bb}$!
- prompt and secondary charm production b→c
- Direct CP (f=K^-K^+,$\pi^+\pi^-$)
- D^0 tag: prompt: π^+_s charge: $D^{*+} \to D^0\pi^+_s$, secondary: μ charge: $B \to D^0 X \mu^- \nu$
- sample divided TOS/TIS for different kinematics, magnet up/down
- cancelation of production and detector asymmetries in the difference!

$$A_{\mathrm{raw}} = \frac{N(D^0 \to f) - N(\overline{D}^0 \to f)}{N(D^0 \to f) + N(\overline{D}^0 \to f)},$$

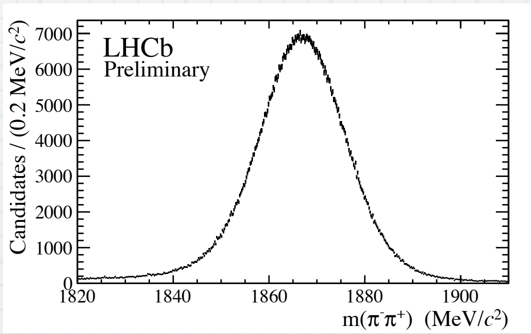
$$A_{\mathrm{raw}}(f) = A_{CP}(f) + A_{\mathrm{D}}(f) + A_{\mathrm{D}}(\pi^+_{\mathrm{s}}) + A_{\mathrm{P}}(D^{*+}).$$

$$\Delta A_{CP} = A_{\mathrm{raw}}(K^-K^+) - A_{\mathrm{raw}}(\pi^-\pi^+).$$

D0→K+K- ~2.2M/fb-1



D0→π+π- ~0.6M /1fb-1



- combined:

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

No evidence os CP violation!

prompt
$$\Delta A_{CP} = (-0.34 \pm 0.15\,(\mathrm{stat.}) \pm 0.10\,(\mathrm{syst.}))\,\%$$

semilept.
$$\Delta A_{CP} = (+0.49 \pm 0.30\,(\mathrm{stat.}) \pm 0.14\,(\mathrm{syst.}))\,\%$$

CP $B^+ \to K^+\mu\mu$, $B \to K^*\mu\mu$

PRL 110 (2013) 031801/1fb-1

- CP Asymmetry predicted to be small SM
- Use control channels to eliminate production and detection asymmetries

$$\mathcal{A}_{CP} = \frac{\Gamma(B^- \to K^-\mu^+\mu^-) - \Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^- \to K^-\mu^+\mu^-) + \Gamma(B^+ \to K^+\mu^+\mu^-)},$$

$$\mathcal{A}_{CP} = \frac{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-) - \Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-) + \Gamma(B^0 \to K^{*0}\mu^+\mu^-)},$$

$$\mathcal{A}_{\rm RAW}(B^+ \to K^+\mu^+\mu^-) = \mathcal{A}_{CP}(B^+ \to K^+\mu^+\mu^-) + \mathcal{A}_{\rm P} + \mathcal{A}_{\rm D},$$

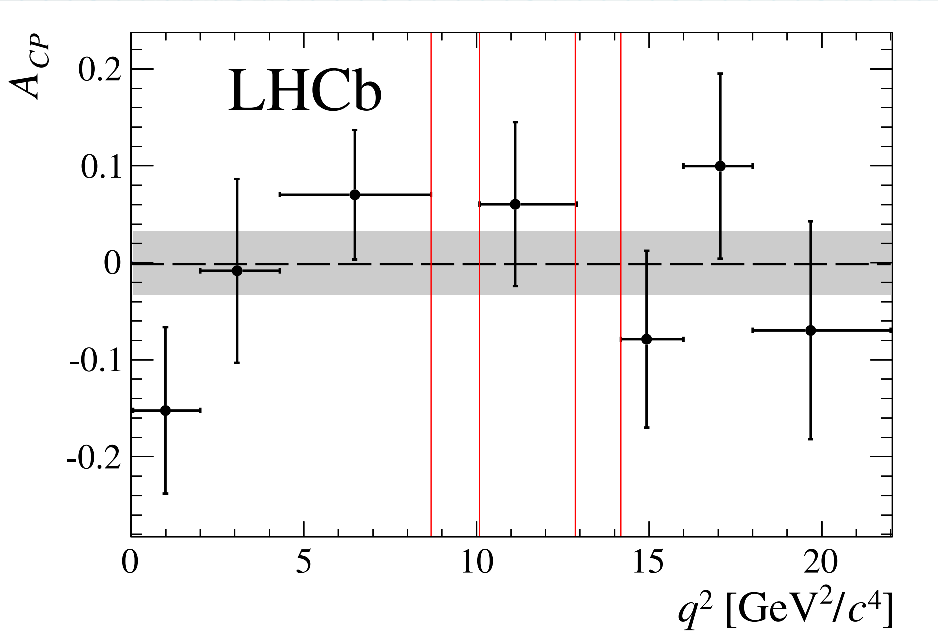
$$\mathcal{A}_{CP}(B^+ \to K^+\mu^+\mu^-) = \mathcal{A}_{\rm RAW}(B^+ \to K^+\mu^+\mu^-) - \mathcal{A}_{\rm RAW}(B^+ \to J/\psi K^+) + \mathcal{A}_{CP}(B^+ \to J/\psi K^+).$$

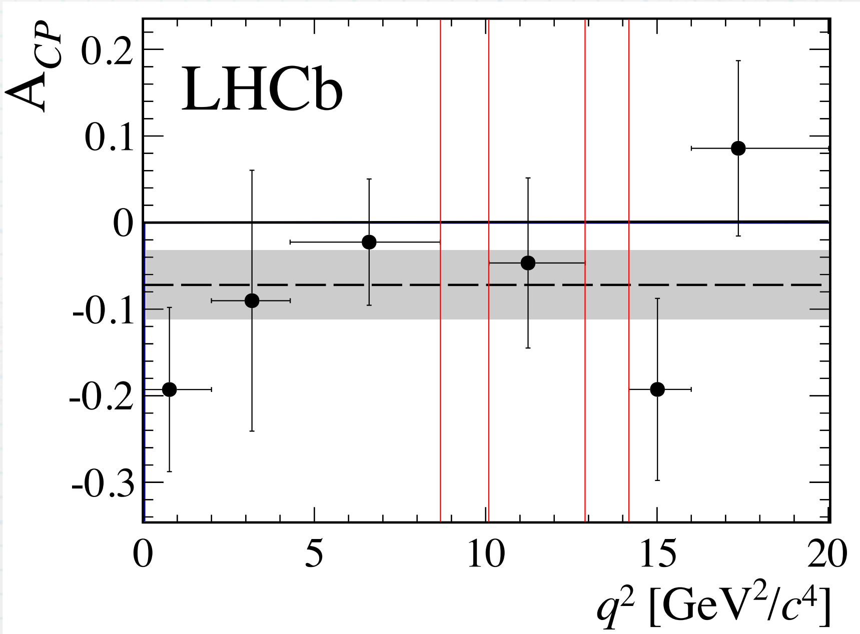
$$\mathcal{A}_{\rm RAW} = \mathcal{A}_{CP} + \kappa\mathcal{A}_P + \mathcal{A}_D,$$

$$\mathcal{A}_{CP} = \mathcal{A}_{\rm RAW}(B^0 \to K^{*0}\mu^+\mu^-) - \mathcal{A}_{\rm RAW}(B^0 \to J/\psi K^{*0}).$$

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

$$\mathcal{A}_{CP}(B^0 \to K^{*0}\mu^+\mu^-) = -0.072 \pm 0.040 \pm 0.005.$$

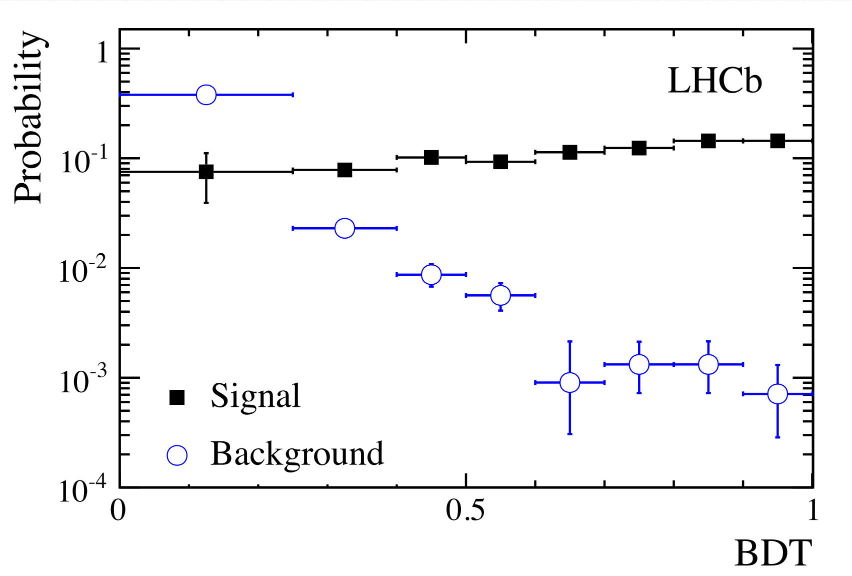


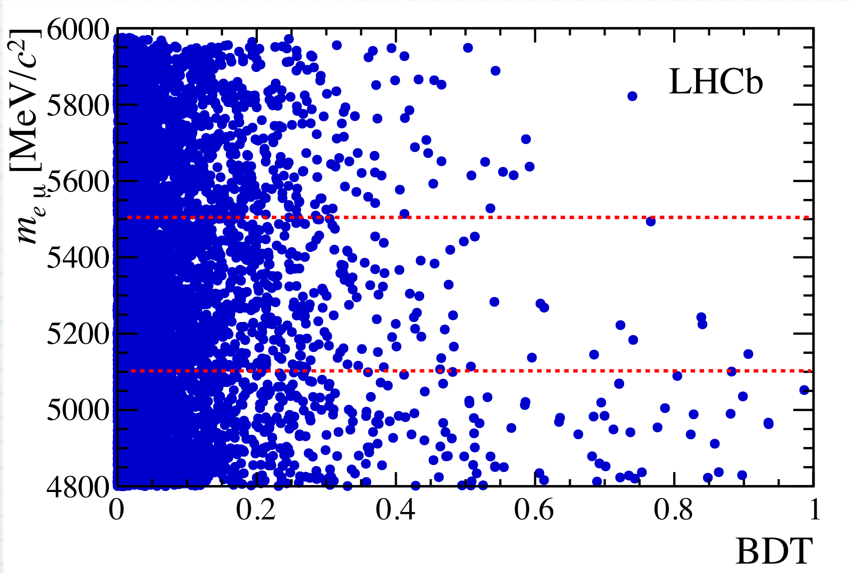


$B_{(s)} \rightarrow \mu e$

PRL 111 (2013) 141801/1fb^{-1}

- LFV process, sensible to NP, (i.e. leptoquarks)
- similar strategy to $B_s \rightarrow \mu\mu$
  - normalization and control channel B→hh'





Mode	Limit	90 % C.L.	95 % C.L.
$B_s^0 \to e^\pm\mu^\mp$	Expected	1.5×10^{-8}	1.8×10^{-8}
	Observed	1.1×10^{-8}	1.4×10^{-8}
$B^0 \to e^\pm\mu^\mp$	Expected	3.8×10^{-9}	4.8×10^{-9}
	Observed	2.8×10^{-9}	3.7×10^{-9}

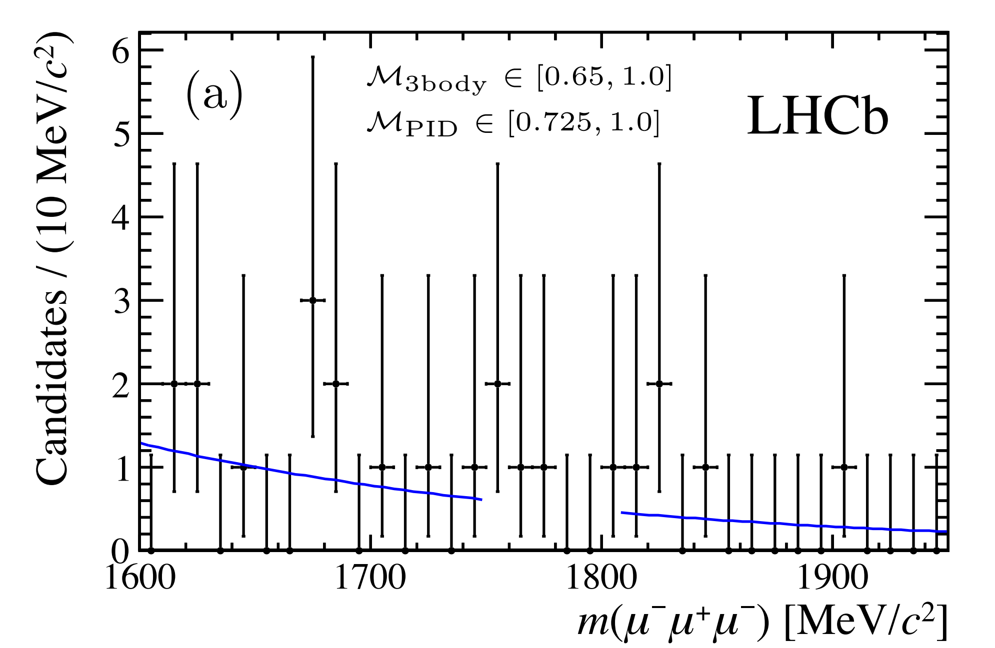
$m_{LQ}(B_s \to e^+\mu^-) > 107(101)\ TeV/c^2$ @ 90(95)%CL,

$m_{LQ}(B_d \to e^+\mu^-) > 135(126)\ TeV/c^2$ @ 90(95)%CL

$\tau \to \mu\mu\mu$

PLB 724 (2013) 36/1fb-1

- LFV process, sensible to NP,
- similar strategy to $B_s \to \mu\mu$
  - discrimination using BDT, mass and PID
  - combinatorial background $bb \to \mu\mu X$, $cc \to \mu\mu X$, $D^-_s \to \eta(\mu\mu\gamma)\mu\nu$
  - normalization and control channel: $D^-_s \to \phi(\mu\mu)\pi^-$



expected 90(95) % C.L.:

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 8.3\ (10.2) \times 10^{-8},$$

observed:

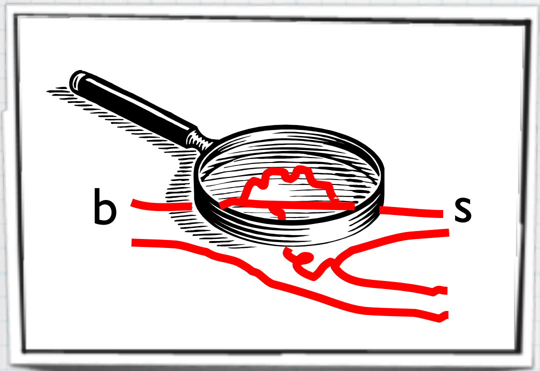
$$\boxed{\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 8.0\ (9.8) \times 10^{-8},}$$

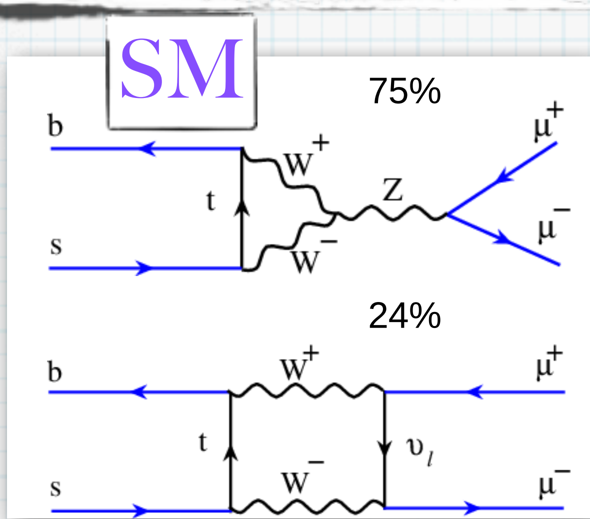
approaching Belle limits!

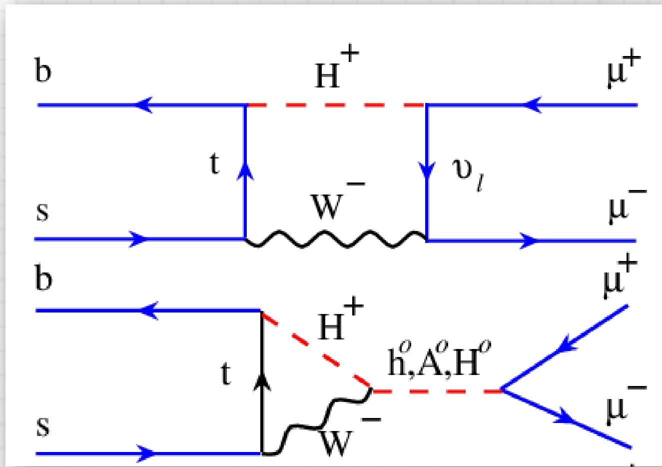
$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 2.1 \times 10^{-8} \text{ at } 90\%$$

Introduction

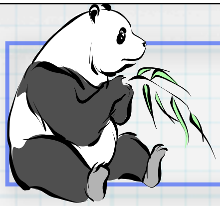
LHCb searches for NP in FCNC with B (and D) decays, new particles can enter in the loops and modify the SM prediction on some observables!







- Some **FCNC** processes have **precise SM prediction**
  - *Branching fractions* and *angular dependence*
- **Luck of NP**
  - *constrains models beyond SM*, set higher energy scale for NP
  - In a model independent interpretation, *constrains Wilson coefficients*

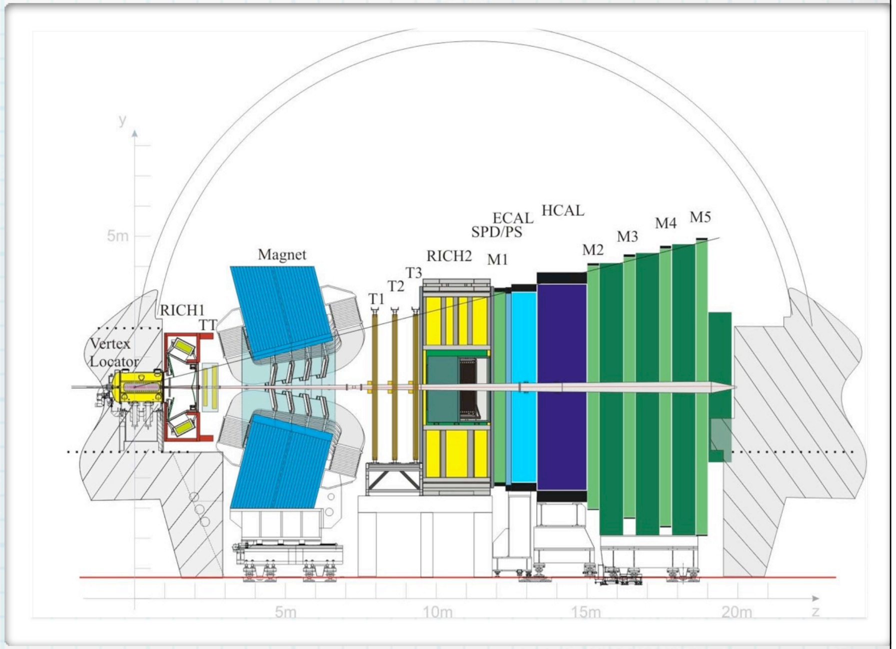


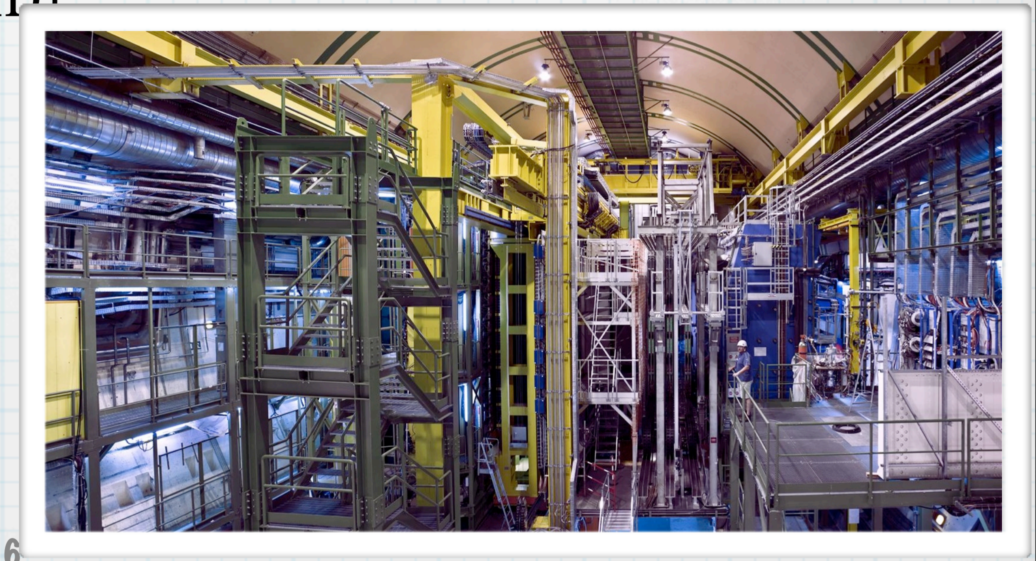
Rare Decays Analysis

- Very rare decays
  - **$B_{(s)} \to \mu\mu$** [3fb^{-1}/arXiv:1307.5024]
  - **$D \to \mu\mu$** [0.9fb^{-1}/arXiv:1305.5050]
  - $K_S \to \mu\mu$ [1fb^{-1}/arXiv:1209.4029]
  - $B \to 4\mu$ [1fb^{-1}/arXiv:1303.1092]
  - $B^+ \to \pi^+\mu\mu$ [1fb^{-1}/arXiv:1210.2645]
- Angular an isospin analysis
  - **$B \to K^*\mu\mu$** [1fb^{-1}/arXiv:1308.1707] [1fb^{-1}/arXiv:1304.6325]
  - $\Lambda_b \to \Lambda\mu\mu$ [1fb^{-1}/arXiv:1306.2577]
  - $B_s \to \phi\mu\mu$ [1fb^{-1}/arXiv:1305.2168]
  - **$B \to K^{(*)}\mu\mu$** [1fb^{-1}/arXiv:1205.3422]
    - $\psi(4160)$ [3fb^{-1}/arXiv:1307.7595]
- CP Asymmetries
  - $B \to K^*\mu\mu$ [1fb^{-1}/arXiv:1210.4492]
  - $B^+ \to K^+\mu\mu$ [1fb^{-1}/arXiv:1308.1340]
- No SM processes
  - $B^+ \to X\mu^-\mu^-$ [0.41fb^{-1}/arXiv:1201.5600]
  - **$B_{(s)} \to \mu e$** [1fb^{-1}/arXiv:1307.4889]
  - $\tau \to 3\mu$, $\tau \to p\mu\mu$ [1fb^{-1}/arXiv:1304.4518]
- Radiative decays
  - $B \to K^*\gamma, B_s \to \phi\gamma$ [1fb^{-1}/arXiv:1202.6267]

LHCb detector

- LHCb detector
  - single-arm spectrometer ($2<\eta<5$)
  - B, B_s, B^+,D,Λ_b, ... produced at LHCb
  - trigger on muons, electrons, hadrons with "low" P_T
    - efficiency on dimuon channels ~90%
  - precise vertex (IP ~20 μm at high P_T)
  - excellent momentum resolution $\Delta p/p \approx 0.5$ %
  - good particle ID (>97% μ-eff, 1-3% mis-ID)



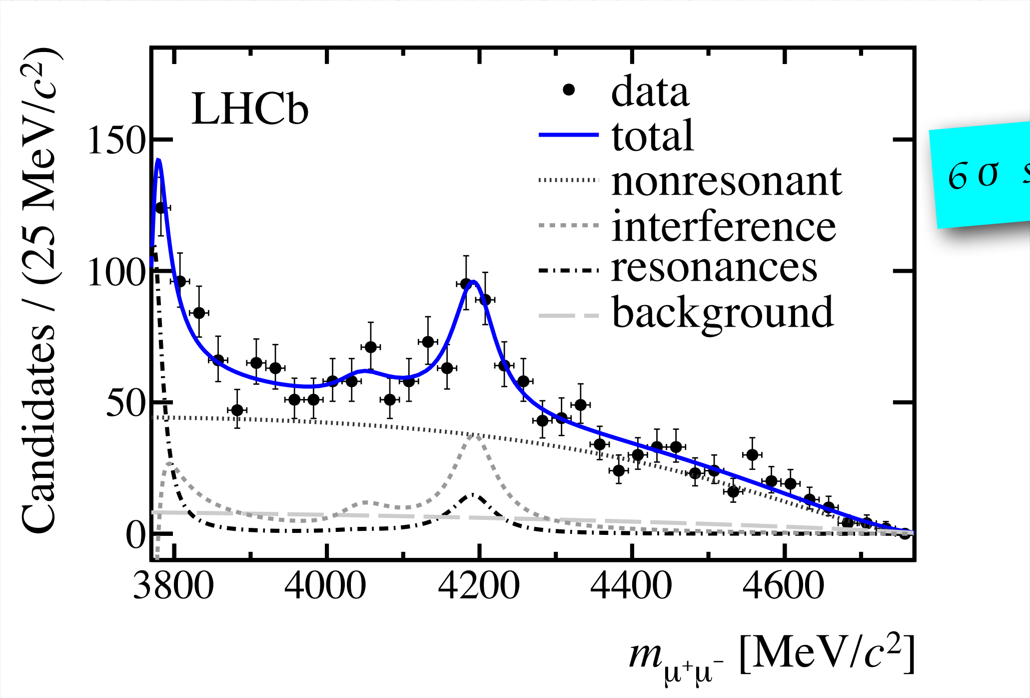


- LHCb operation
  - "beautifully"
  - operating @ 2 nominal luminosity
  - Integrated luminosity **3 fb^{-1}**
    - (2 fb^{-1} 8 TeV, 1 fb^{-1} 7 TeV)

A new resonance in $B^+ \to K^+ \mu\mu$

PRL 111 (2013) 112003/1fb^{-1}

ψ(3370) ψ(4160)



6 σ significance!

$\mathcal{B}[\times 10^{-9}]$	$3.9\,^{+0.7}_{-0.6}$
Mass $[\mathrm{MeV}/c^2]$	$4191\,^{+9}_{-8}$
Width $[\mathrm{MeV}/c^2]$	$65\,^{+22}_{-16}$

- A resonance structure at high q^2
- Consistent with ψ(4160) measured by BES
- Contribute to 20% of the total signal at high q^2
  - much larger than theoretical estimations