CERN-FERMILAB HADRON COLLIDER PHYSICS Summer School 2013

Heavy Flavour Experiment Lecture 2

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30. & 31. August 2013

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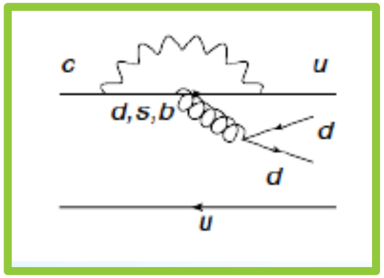
Experimentelle Physik V
Teilchenphysik

Contents

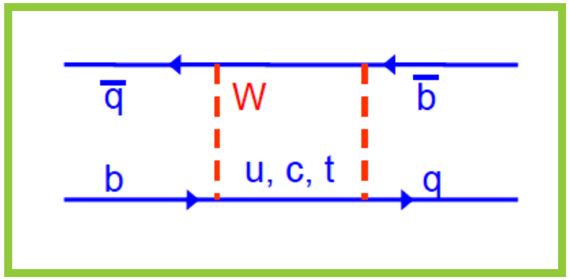
- Lecture 1:
  - Introduction to “heavy flavour physics”
  - The Experiments:
    Flavour physics at e^+e^- and at hadron colliders
  - Precision measurements of the quark mixing matrix

- Lecture 2:
  - “Golden modes for New physics searches” – loop zoology

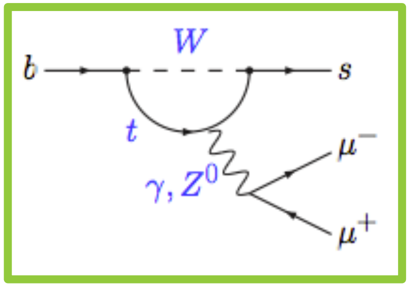
- Map of flavour transitions and types of loop processes



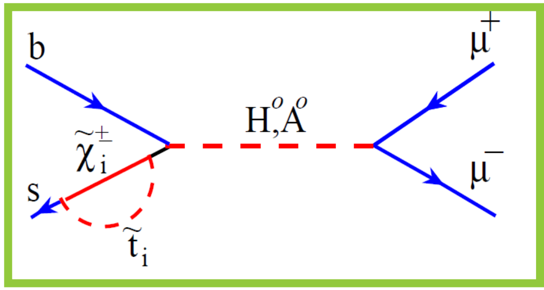
QCD penguin



ΔF=2 box



EW penguin



Higgs penguin

	$b \to s$	$b \to d$	$c \to u$	$s \to d$
QCD penguin	$A_{CP}(B_s \to hhh)$	$A_{CP}(B^0 \to hhh)$	**$\Delta a_{CP}(D \to hh)$**	$K \to \pi^0 ll$ $\varepsilon' / \varepsilon$
ΔF=2 box	ΔM_{Bs} **$A_{CP}(B_s \to J/\psi\phi)$**	ΔM_{Bd} $A_{CP}(B^0 \to J/\psi K_s)$	x,y, q/p	ΔM_K ε_K
EW penguin	**$B \to K^{(*)}\mu\mu$** $B \to X_s\gamma$	$B \to \pi\mu\mu$ $B \to X\gamma$	$D \to X_u l\, l$	$K \to \pi^0 ll$ $K \to \pi^\pm \nu\nu$
Higgs penguin	**$B_s \to \mu\mu$**	**$B^0 \to \mu\mu$**	$D \to \mu\mu$	$K^0 \to \mu\mu$

1)

QCD penguins

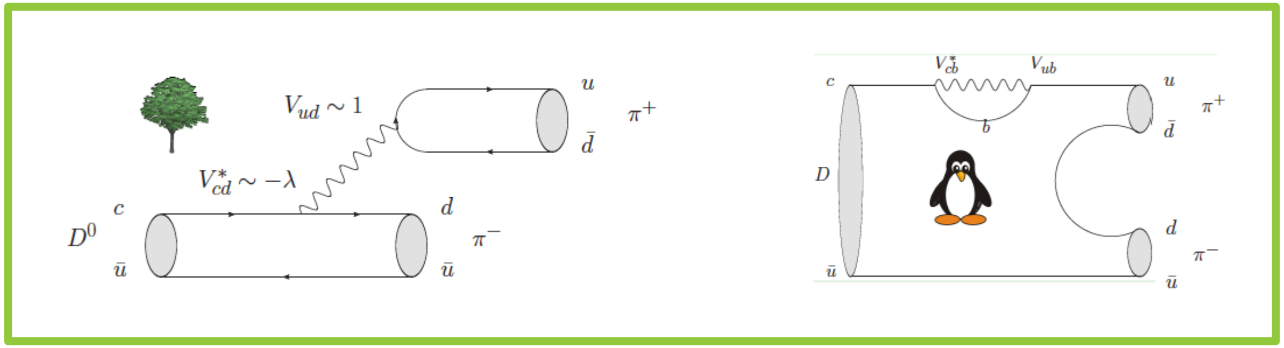
or

Search for CP violation in charm decays

CP violation in charm

- Generally, 3 types of CP violation
  a) In decay (direct CPV)
  b) In mixing
  c) In interference between mixing and decay

- No evidence yet on CP violation in b) or c)
  Could there be large **direct CP violation** in charm penguin decays?



- **A priory**, consensus was "no"
  – CP violation O(1%) would be "sign for NP"

CP violation in charm: ΔA_{CP}

$$A_{\mathrm{raw}}(f) = \boxed{A_{CP}(f)} + \boxed{A_{\mathrm{D}}(f)} + \boxed{A_{\mathrm{P}}(D^{*+})}$$

- Physical CP asymmetry (very small)
- Detection asymmetry
- Production asymmetry

(Detection and production asymmetry:) large O(1%)

CP violation in charm: ΔA_{CP}

$$A_{\rm raw}(f) = \boxed{A_{CP}(f)} + \boxed{A_{\rm D}(f)} + \boxed{A_{\rm P}(D^{*+})}$$

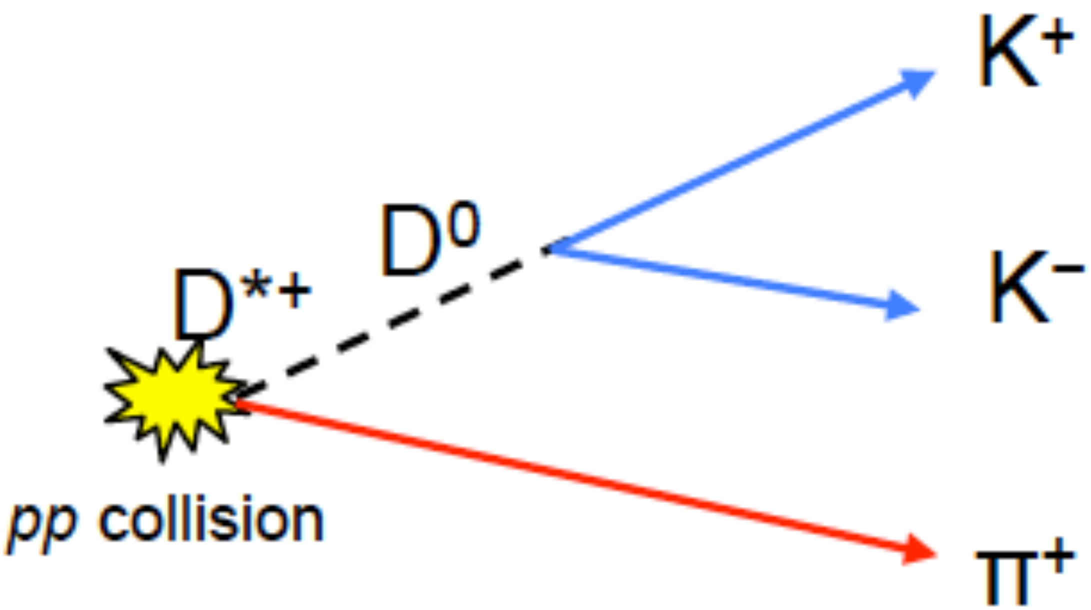
- Physical CP asymmetry (very small)
- Detection asymmetry, cancels for $D^0 \to \pi\pi$, KK
- Production asymmetry

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

w/ U-spin symmetry: $A_{CP}(K^-K^+) = -A_{CP}(\pi^-\pi^+)$

Measure CP violation: $D^{*+} \rightarrow D^0 \pi^+$

- LHCb performed two independent measurements
  - "D* tagged": $D^{*\pm} \rightarrow D^0 (\rightarrow K^+K^-$ or $\pi^+\pi^-) \pi^\pm$
    → pion charge determines D^0 production flavour



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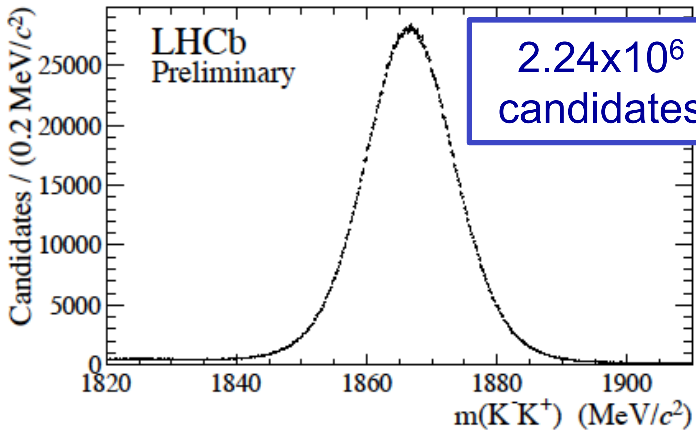
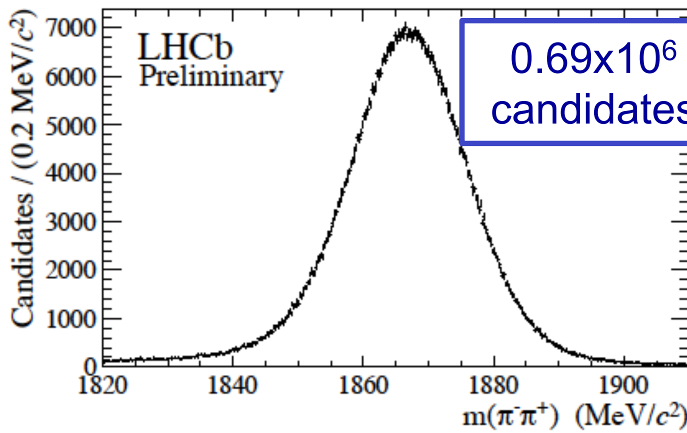
$D^0 \rightarrow K^+K^-$



2.24x10^6 candidates

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



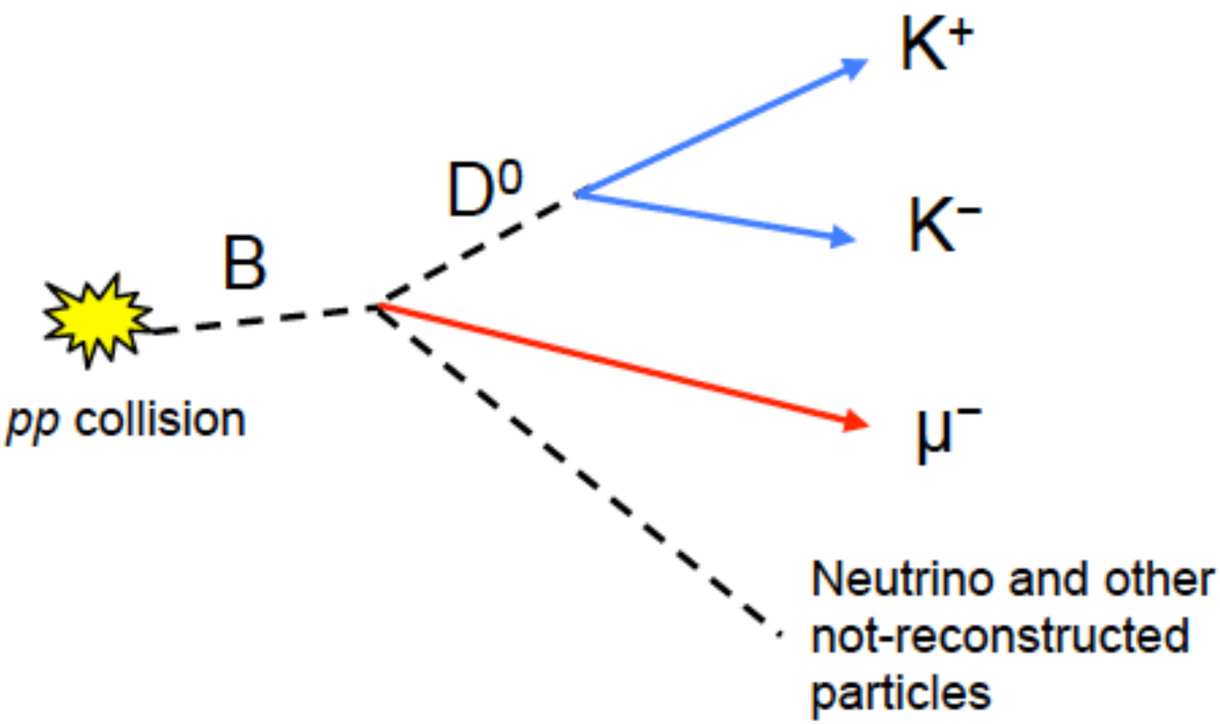
0.69x10^6 candidates

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

[LHCb-CONF-2013-003]

Measure CP violation: $B \rightarrow D^0 \mu^+ X$

- LHCb performed two (experimentally orthogonal) measurements
  - "D* tagged": $D^{*\pm} \rightarrow D^0 (\rightarrow K^+K^- \text{ or } \pi^+\pi^-)\ \pi^\pm$
  - "Muon tagged": $B^\pm \rightarrow D^0 (\rightarrow K^+K^- \text{ or } \pi^+\pi^-)\ \mu^\pm \nu X$
    $\rightarrow$ muon charge determines D^0 production flavour



Measure CP violation: $B \rightarrow D^0 \mu^+ X$

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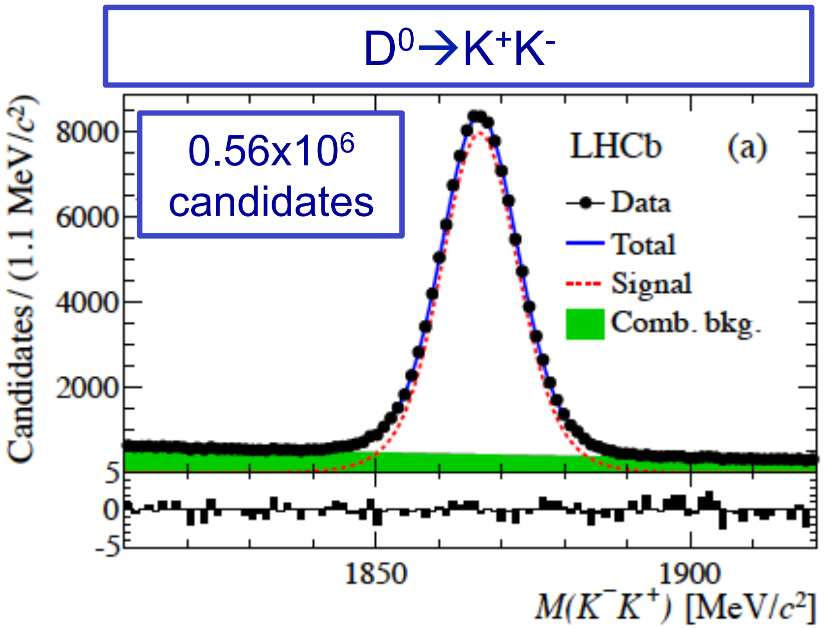
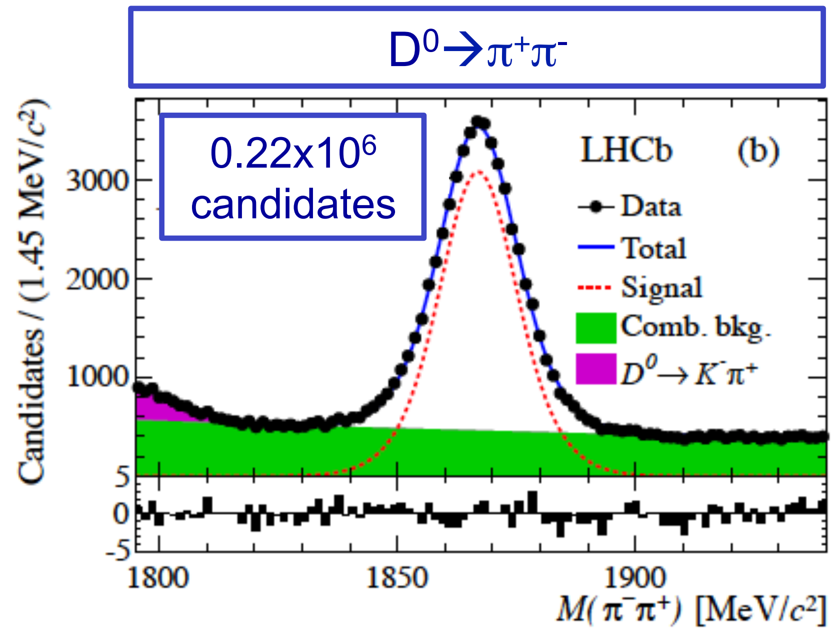




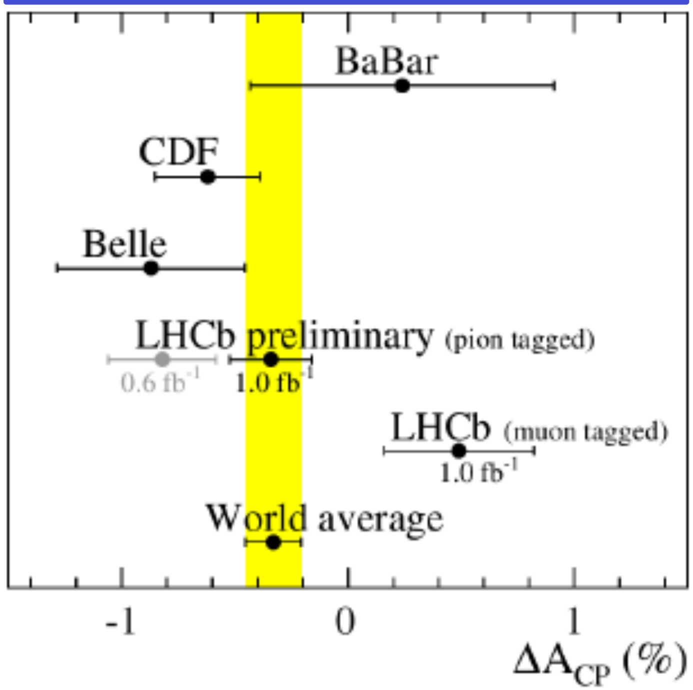
$$\Delta A_{CP} = [+0.49 \pm 0.30\ (\mathrm{stat}) \pm 0.14\ (\mathrm{syst})]\%$$

[arXiv:1303.2614]

Measure CP violation: B→$D^0 \mu^+ X$

- LHCb performed two (experimentally orthogonal) measurements
  - "D* tagged": $D^{*\pm} \to D^0 (\to K^+K^-$ or $\pi^+\pi^-) \pi^\pm$
  - "Muon tagged": $B^\pm \to D^0 (\to K^+K^-$ or $\pi^+\pi^-) \mu^\pm \nu X$

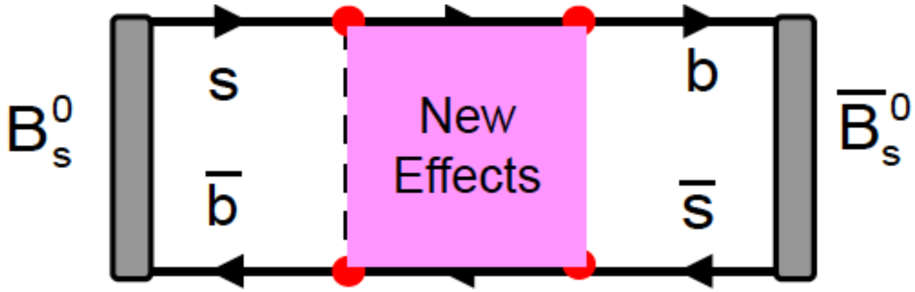
ΔA_{CP}: world average



LHCb results dominated by statistics. Situation should become more clear with the analysis of the full 3/fb

$\Delta F=2$ boxes: CP violating phase in B_s mixing

B_s mixing and CP violation



$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \left(\mathbf{M} + i\frac{\mathbf{\Gamma}}{2} \right) \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$

Flavor states B_s & $\bar{B}_s$ $\neq$ mass states B_H & B_L

<u>Observables:</u>

Δm_s = Mixing frequency = mass difference between B_H and B_L

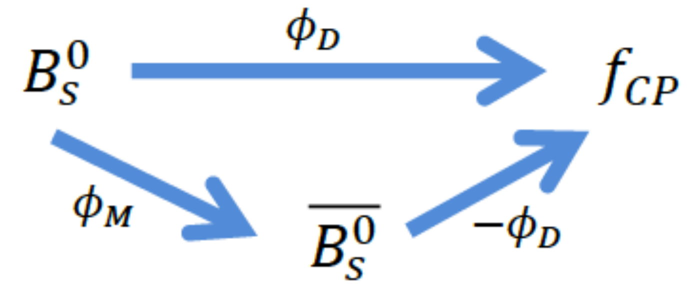
$\Delta\Gamma_s$ = Decay width (lifetime) difference between B_H and B_L

ϕ_s = Phase: $A_{mix} = |A_{mix}|\, e^{-i\phi_s}$ $\rightarrow$ $\not{CP}$

B_s mixing and CP violation

Interference between mixing and decay:
→ measure relative phase ϕ_s

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



CP asymmetry (for CP eigenstates):

$$A_{CP}(t) = \frac{\Gamma\left(\overline{B_s^0}(t) \to f_{CP}\right) - \Gamma\left(B_s^0(t) \to f_{CP}\right)}{\Gamma\left(\overline{B_s^0}(t) \to f_{CP}\right) + \Gamma\left(B_s^0(t) \to f_{CP}\right)} = -\eta_{CP}\sin(\phi_s)\sin(\Delta m_s t)$$

Standard Model prediction: $\phi_s^{SM} = -0.036 \pm 0.002$ rad

CKM-Fitter (*Phys. Rev. D 84 (2011), 033005*)

CPV phase very small → basically a NULL test

B_s mixing and CP violation

Interference between mixing and decay:
→ measure relative phase ϕ_s

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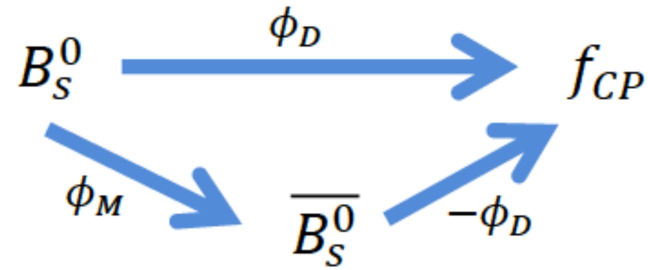

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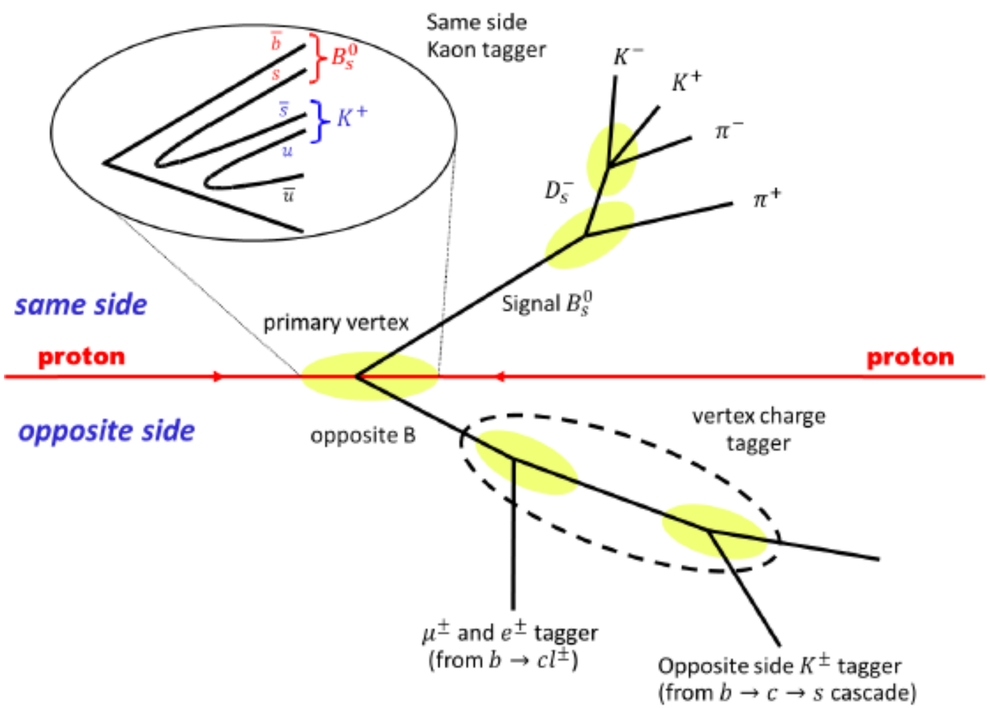
Need excellent Flavour tagging
→ tagging power

time-dependent analysis
& fast $B_s^0 - \overline{B_s^0}$ oscillation
→ need excellent decay time resolution

Detour: Flavour tagging at hadron colliders

Tagging efficiency	Mistag probability	Dilution
$\varepsilon = \frac{\#\, tagged\ candidates}{\#\, all\ candidates}$	$\omega = \frac{\#\, tagged\ wrong}{\#\, tagged}$	$D = (1 - 2\omega)$



- Opposite side taggers
  - Partially reconstruct second b in event → conclude on production flavour
- Same sign taggers
  - Exploit hadronization remnants
- Combine all taggers
  - Combined tagging power:
    LHCb: $\varepsilon D^2 \sim 3.5\%$
    ATLAS: ~ 1.5%
    B-factories ~ 30%

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

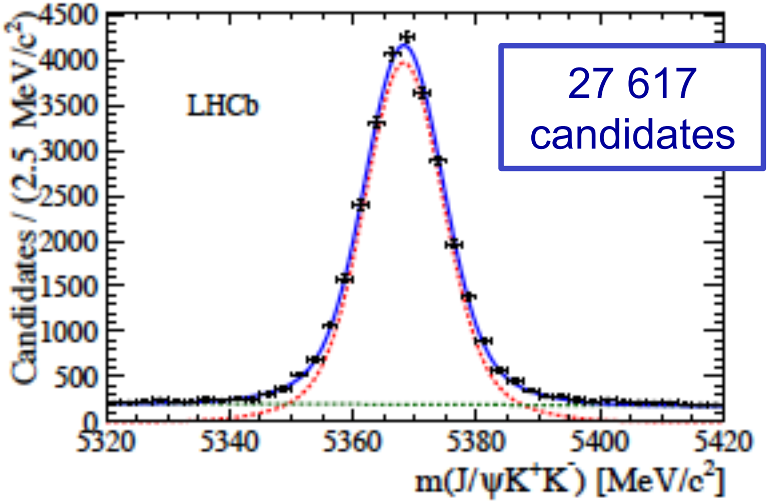
B_s : $J^P = 0^{-1}$ (pseudo scalar)

J/ψ: : $J^{CP} = 1^{-1-1}$ (vector)

ϕ: : $J^{CP} = 1^{-1-1}$ (vector)

Angular momentum conservation:

0 = J $(J/\psi\phi)$ = $|\vec{S} + \vec{L}|; \rightarrow$ L = 0,1,2



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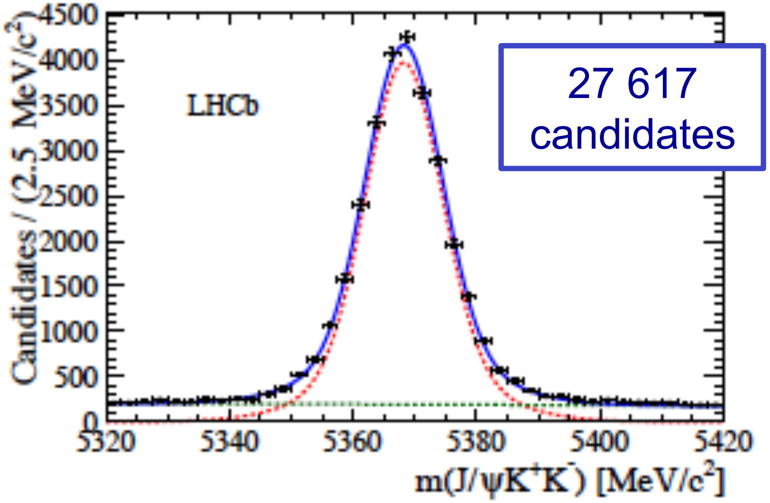

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L = 0,2 $\rightarrow$ CP even final state

L = 1 $\rightarrow$ CP odd final state

Final state no CP eigenstate but linear combination!

Angular analysis, to separate CP even/odd contributions.

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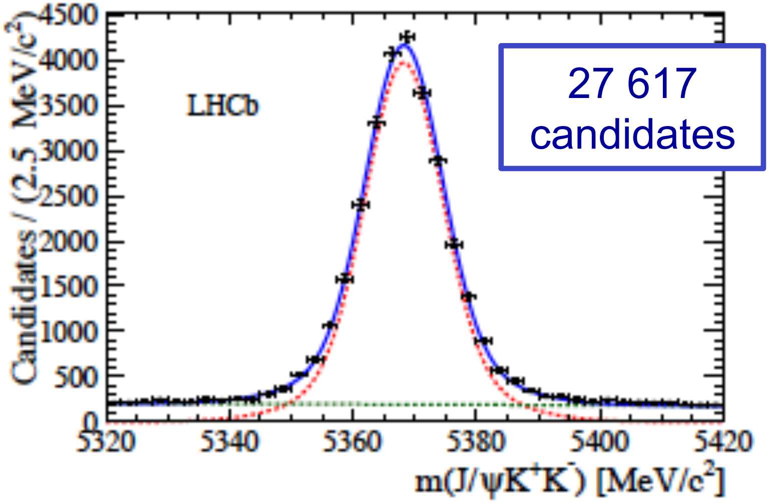

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Final state no CP eigenstate but linear combination!

Angular analysis, to separate CP even/odd contributions.

Need to measure three decay amplitudes and two strong phases

Additionally: $\Delta\Gamma$ not negligible

➔ need to consider time evolution of Γ_H and Γ_L

Results of the B_s mixing phase

Most precise analysis:
combined 1/fb analysis of $B_s \to J/\psi\phi$ and $B_s \to J/\psi\pi\pi$ by LHCb

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

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

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

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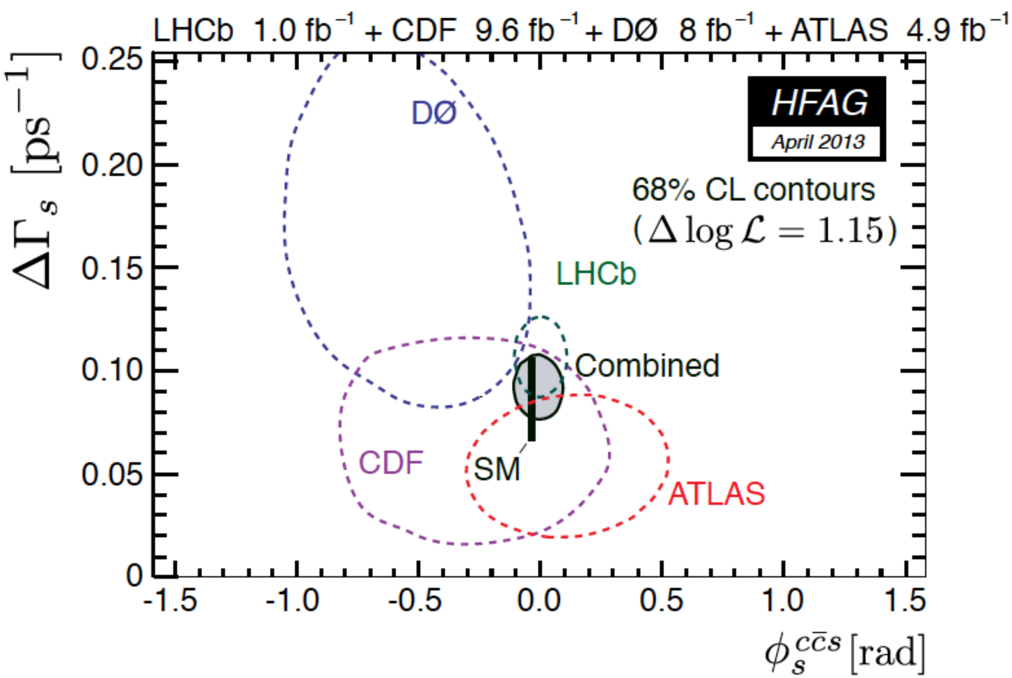
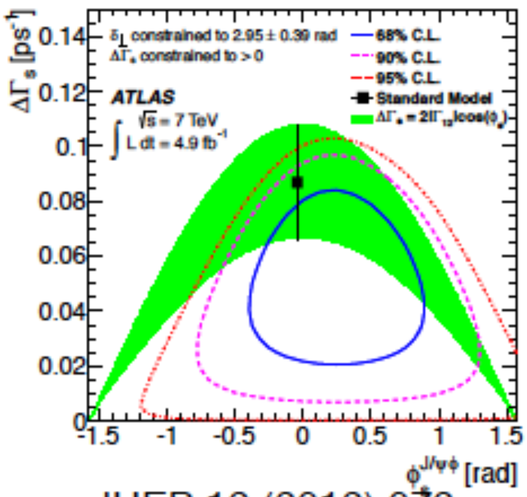


Detour: The importance of flavour tagging

ATLAS untagged result

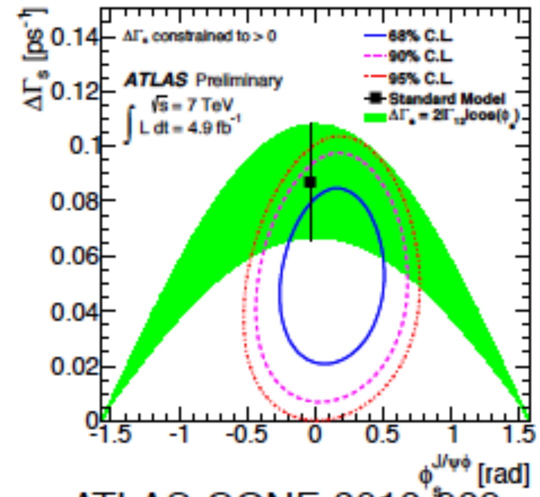


JHEP 12 (2012) 072

uncertainty on ϕ_s

improved by 40%

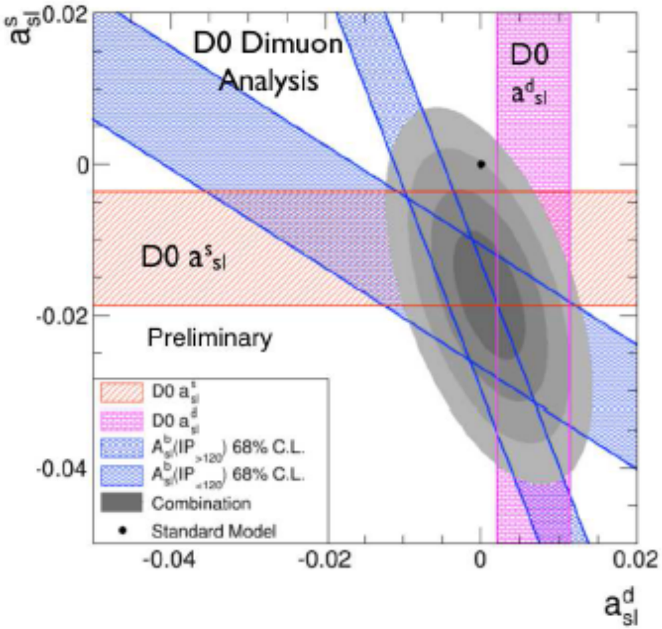
ATLAS tagged result



ATLAS-CONF-2013-039

The ATLAS collaboration managed to improve their sensitivity by 40% with the inclusion of flavour tagging (εD^2=1.45%, cf. ~3.5% @ LHCb)

CPV in mixing I



semileptonic (untagged) asymmetry:

$$a_{sl}^{s} \propto \frac{N(\mu^+ D_s^{(*)-}) - N(\mu^- D_s^{(*)+})}{N(\mu^+ D_s^{(*)-}) + N(\mu^- D_s^{(*)+})}$$

$$a_{sl}^{d} \propto \frac{N(\mu^+ D^{(*)-}) - N(\mu^- D^{(*)+})}{N(\mu^+ D^{(*)-}) + N(\mu^- D^{(*)+})}$$

assuming no production asymmetry and

no CP in semileptonic decays

PRD 86, 072009 (2012), PRL, 10, 011801 (2013),
PRD 84, 052007 (2011)

D0 only results:

A_{CP} = (-0.276 $\pm$ 0.067 $\pm$ 0.063)% (9.0 fb^{-1})

3.9 σ compatible with SM

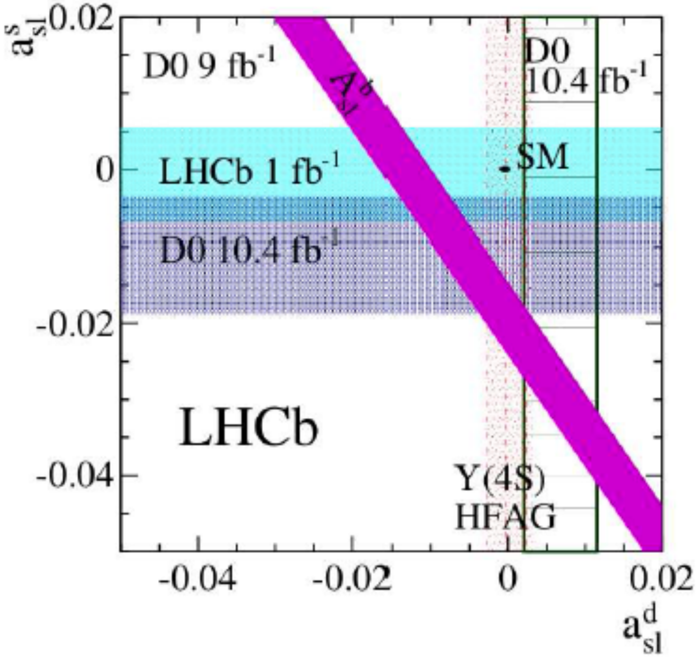
ϕ_s, a_{sl} as well not compatible in NP models ...

LHCb: pp collider $\rightarrow$ production asymmetry

$$A_{meas} = \frac{N(D_q^- \mu^+) - N(D_q^+ \mu^-)}{N(D_q^- \mu^+) + N(D_q^+ \mu^-)} = \frac{a_{sl}^q}{2} + [a_{prod} - \frac{a_{sl}^q}{2}]\kappa_q$$

due to fast B_s oscillation time integrated a_{sl}^s measurement possible ($\kappa_s = 0.2\%$)

however for a_{sl}^d time dependent analysis required ($\kappa_d \sim 30\%$)



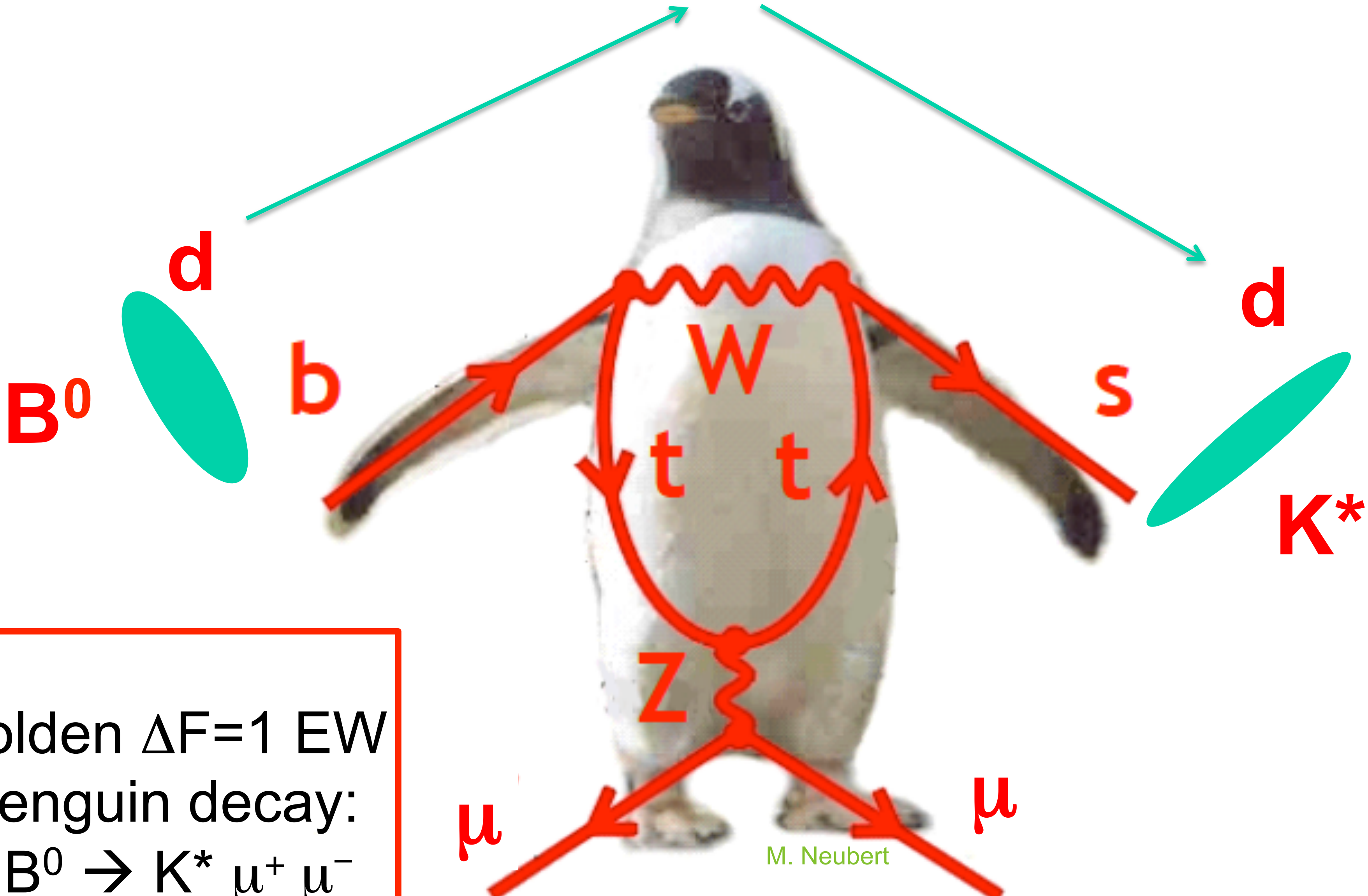
a_{sl}^s = (-0.06 $\pm$ 0.50 $\pm$ 0.36)%

LHCb-PAPER-2013-033-001

single most precise result on a_{sl}^d using partial reconstructed $B \rightarrow D^* \ell \nu$ + kaon tags:

a_{sl}^d = (0.06 $\pm$ 0.16$^{+0.36}_{-0.32}$)%

Babar: arXiv:1305.1575



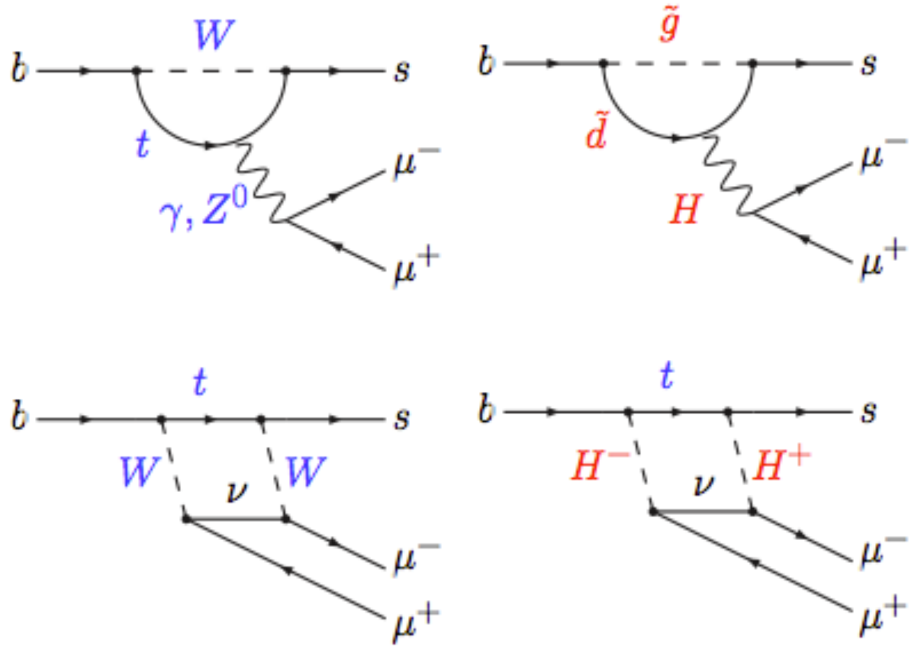
Golden ΔF=1 EW penguin decay: $B^0 \rightarrow K^* \mu^+ \mu^-$

General description of Hamiltonian (see D. Straub):

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

$i = 1,2$	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

b→s transitions are sensitive to: $O_7^{(')}$, $O_9^{(')}$, $O_{10}^{(')}$



$B^0 \to K^* \mu^+\mu^-$ is the most prominent channel (large statistics & flavour specific)

Studies with rarer $B_s \to \phi\, \mu^+\mu^-$, $\Lambda_b^0 \to \Lambda\, \mu^+\mu^-$, .. have started

Experimental overview of b→sll

- Large variety of different final states accessible
- Decays defined in terms of decay angles and $q^2 = m_{\mu\mu}^2$
  - typically, angular analyses are performed in 6-7 bins of q^2
  - No measurements can be made near the J/ψ and $Y(2S)$ resonances

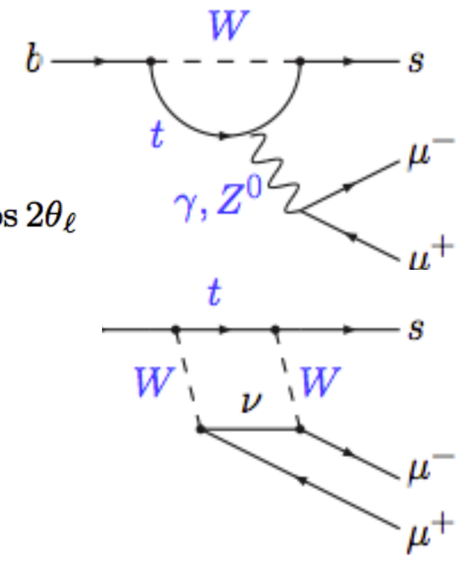
# of evts	BaBar 2012 471 M $\bar{B}B$	Belle 2009 605 fb^{-1}	CDF 2011 9.6 fb^{-1}	LHCb 2011/12 1 fb^{-1}	ATLAS 2012 5/fb	CMS 2012 5/fb
$B^0 \to K^{*0} \ell\bar{\ell}$	$137 \pm 44^\dagger$	$247 \pm 54^\dagger$	288 ± 20	900 ± 34	466±34	415±29
$B^+ \to K^{*+} \ell\bar{\ell}$			24 ± 6	76 ± 16		
$B^+ \to K^+ \ell\bar{\ell}$	$153 \pm 41^\dagger$	$162 \pm 38^\dagger$	319 ± 23	1232 ± 40		
$B^0 \to K^0_S \ell\bar{\ell}$			32 ± 8	60 ± 19		
$B_s \to \phi \ell\bar{\ell}$			62 ± 9	77 ± 10		
$\Lambda_b \to \Lambda \ell\bar{\ell}$			51 ± 7			
$B^+ \to \pi^+ \ell\bar{\ell}$		limit		25 ± 7		

ATLAS (preliminary) [ATLAS-CONF-2013-038]
CMS (preliminary) [CMS-BPH-11-009]

Babar arXiv:1204.3933
Belle arXiv:0904.0770
CDF arXiv:1107.3753 + 1108.0695 + ICHEP 2012
LHCb LHCb-CONF-2012-008 (-003, -006), arXiv:1205.3422 + 1209.4284 + 1210.4492 + 1211.2674

$B^0 \to K^* \mu^+ \mu^-$ - Angular Analysis

- $B^0 \to K^* \mu^+ \mu^-$ full decay rate is given as



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

Experiments typically measure sub-set of these observables by integrating out some parts

classical observable
measured for the FIRST time by LHCb

$B^0 \to K^* \mu^+ \mu^-$ - Angular Analysis

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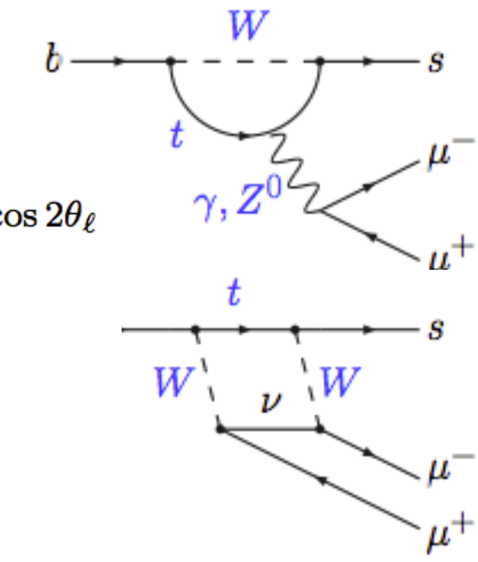
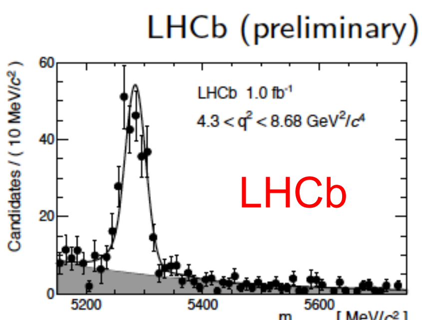
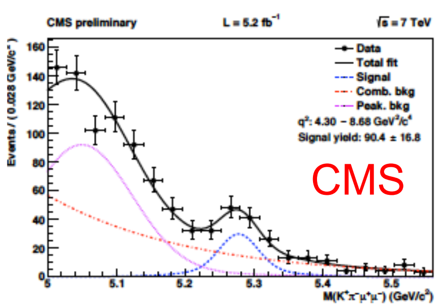


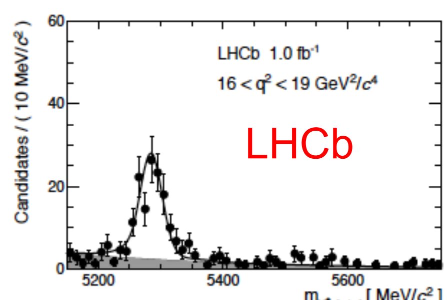
$$
\begin{aligned}
\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[& \frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell \\
& - F_L\cos^2\theta_K\cos 2\theta_\ell + \\
& S_3\sin^2\theta_K\sin^2\theta_\ell\cos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

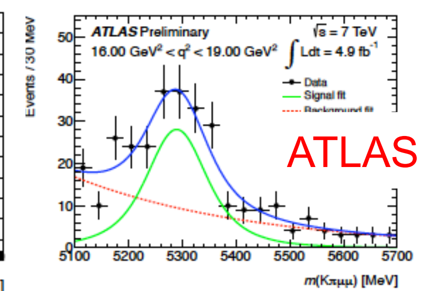
Example mass:
mid-q^2 ($4.3 < q^2 < 8.7$)





Example mass:
high-q^2 ($16 < q^2 < 19$)





~Largest sample: 1000 events (LHCb) → not enough for a full fit

Simplifying the analysis

By exploiting symmetries:
this form can be reduced to …

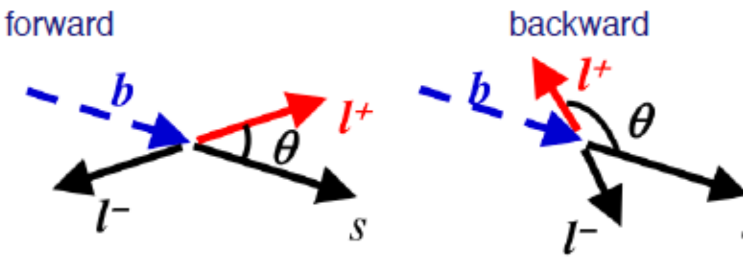
$$\hat{\phi} = \begin{cases} \phi + \pi & \text{if } \phi < 0 \\ \phi & \text{otherwise} \end{cases}$$

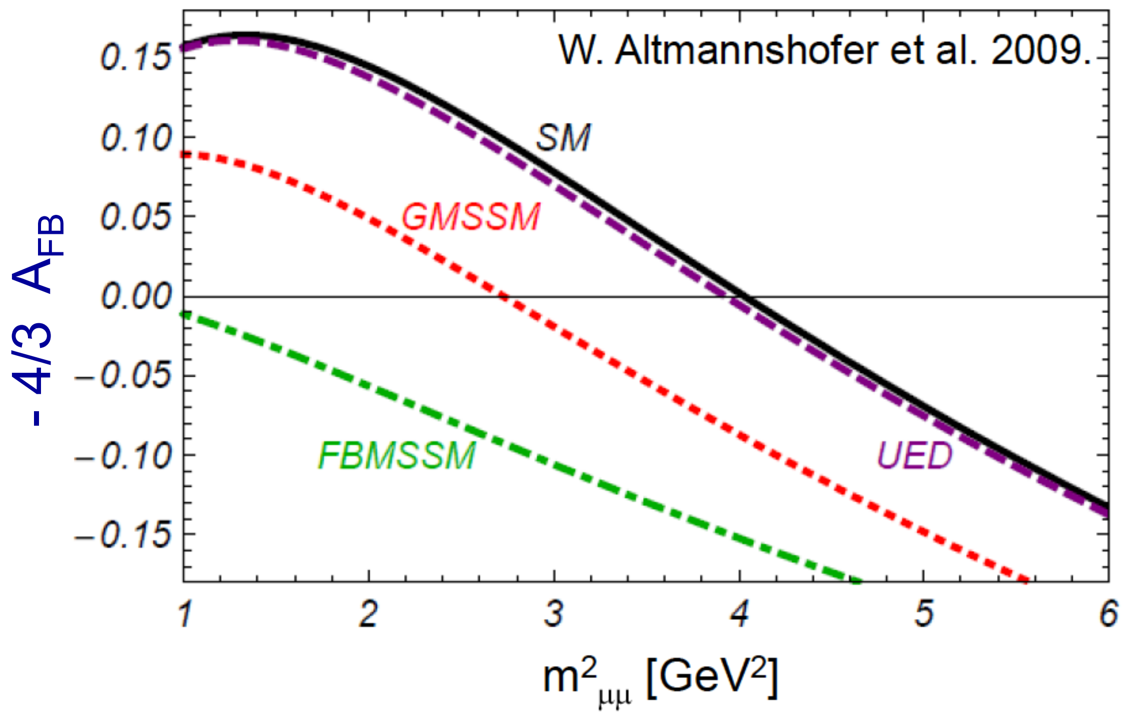
$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}} = \frac{9}{16\pi}\Big[F_\mathrm{L}\cos^2\theta_K + \frac{3}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K) - F_\mathrm{L}\cos^2\theta_K(2\cos^2\theta_\ell - 1) + \frac{1}{4}(1-F_\mathrm{L})(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) + S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} + \frac{4}{3}A_\mathrm{FB}(1-\cos^2\theta_K)\cos\theta_\ell + A_9(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi}\Big]$$

- Simpler expression remains, sensitive to F_L, **A_{FB}**, S_3, A_9
  - Lost sensitivity to terms 4, 5 ,7 and 9

One very famous variable:

$$A_{FB} \propto -Re[(2C_7^{eff} + \frac{q^2}{m_b^2} C_9^{eff}) C_{10}]$$





Particularly interesting: zero crossing point of A_{FB}

q_0= 4.0-4.3 GeV^2

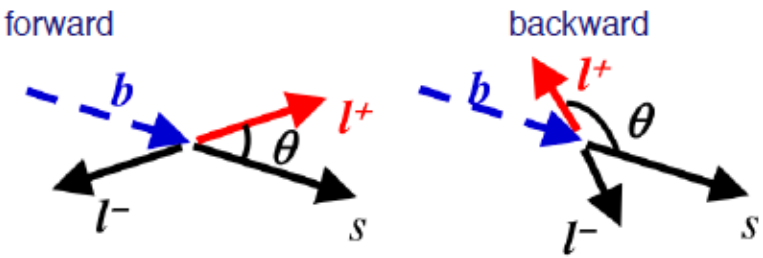
(~independent from hadronic uncertainties)

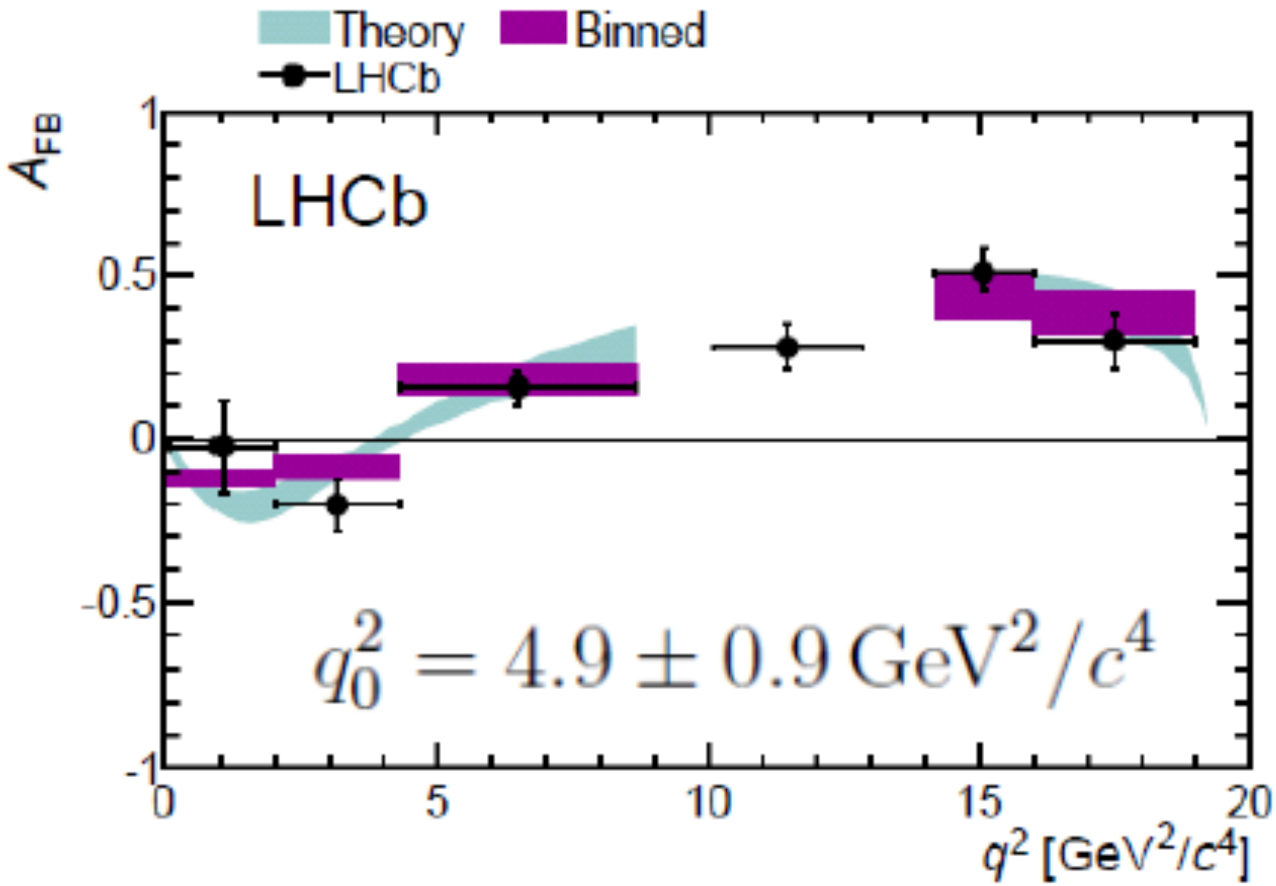
[Eur. Phys. J C 41 (2005) 173-188]

FBMSSM Flavor Blind MSSM
GMSSM: Non Minimal Flavor Violating MSSM
UED: One universal extra dimension

One very famous variable:

$$A_{FB} \propto -Re[(2C_7^{eff} + \frac{q^2}{m_b^2} C_9^{eff}) C_{10}]$$



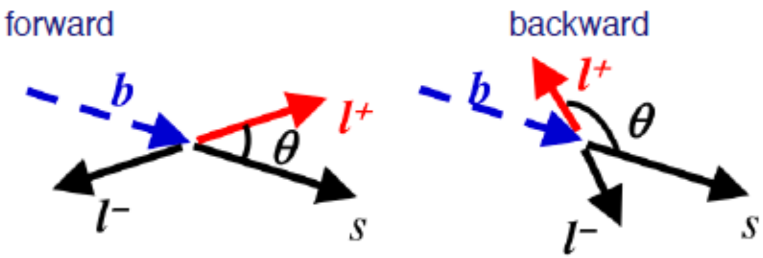


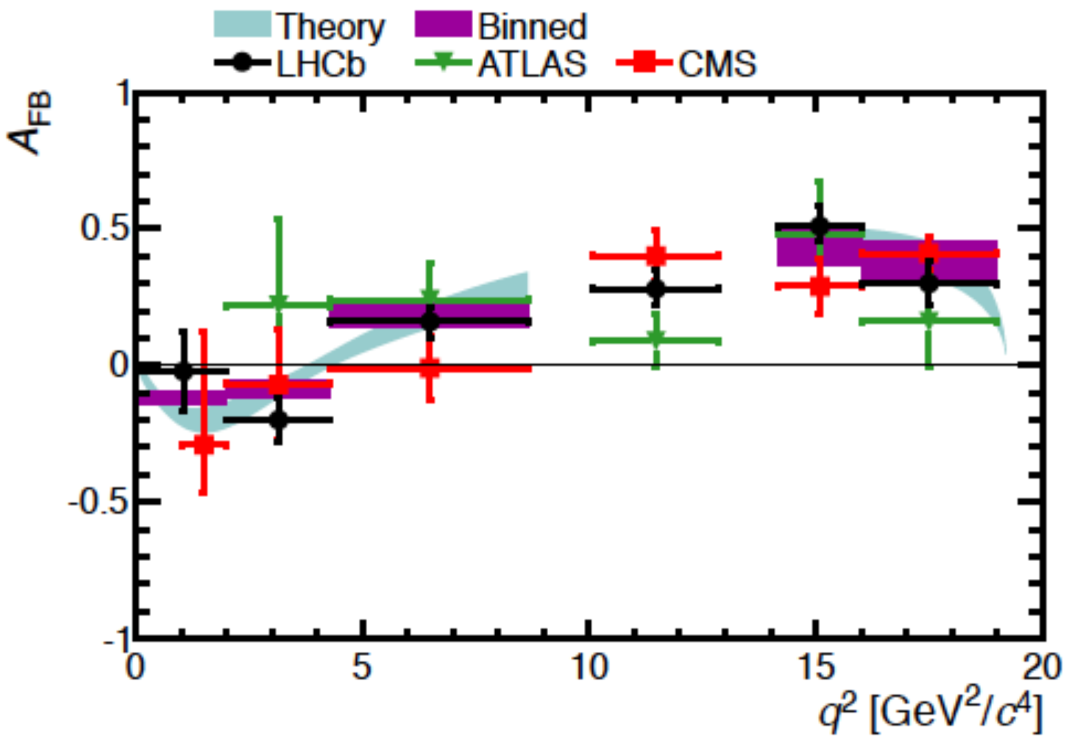
LHCb 2012:
First measurement of zero-crossing point:
q_0=4.9±0.9 GeV^2/c^4

Forward-backward Asymmetry

One very famous variable:

$$A_{FB} \propto -Re[(2C_7^{eff} + \frac{q^2}{m_b^2} C_9^{eff}) C_{10}]$$





LHCb 2012:
First measurement of zero-crossing point:
$q_0 = 4.9 \pm 0.9$ GeV^2/c^4

Generally **very good agreement with SM** in the observables F_L, A_{FB}, S_3, A_9

$B^0 \rightarrow K^* \mu^+ \mu^-$: Alternative transformation

- Earlier we lost sensitivity to 4 terms to simplify the fit
- Now: extract the observables related to those terms!

- To extract these observables, apply different transforms, e.g.

P'_4, S_4:

$$\begin{cases} \phi \rightarrow -\phi & \text{for } \phi < 0 \\ \phi \rightarrow \pi - \phi & \text{for } \theta_\ell > \pi/2 \\ \theta_\ell \rightarrow \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2 \end{cases}$$

P'_5, S_5:

$$\begin{cases} \phi \rightarrow -\phi & \text{for } \phi < 0 \\ \theta_\ell \rightarrow \pi - \theta_\ell & \text{for } \theta_\ell > \pi/2 \end{cases}$$

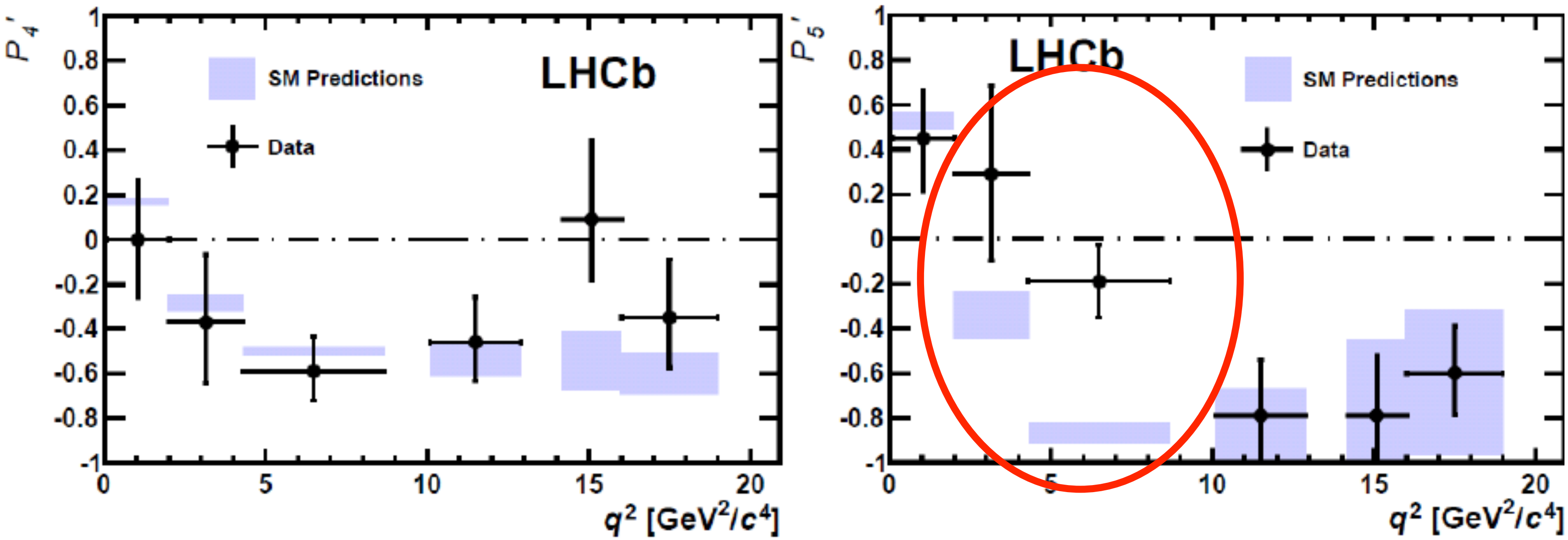
S_4, S_5 → Standard Observables

P'_4, P'_5 → Theoretically cleaner observables

- Plus observables for the 7[th] and 8[th] terms

$B^0 \rightarrow K^* \mu^+ \mu^-$: Alternative analysis

- Extract four “transverse” observables:



- **Local fluctuation in P_5’ is 3.7σ from the SM prediction**

  → is the “look elsewhere effect” applicable here?
  → Discussion session

- **Significantly more data on tape already**
  - **LHCb has three times this data on tape**
  - **CMS + ATLAS can also measure P5’**

Full angular analysis needed & planned

The interpretation of the anomaly …

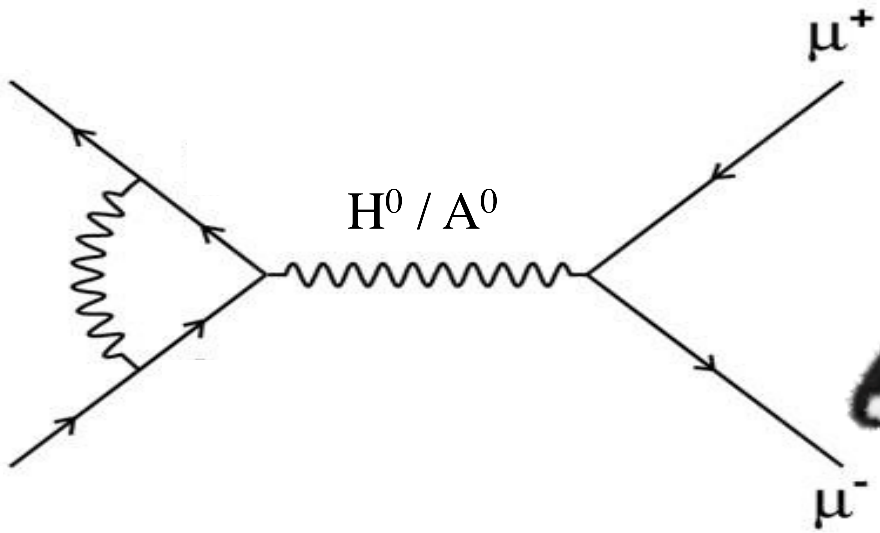
… has just started.

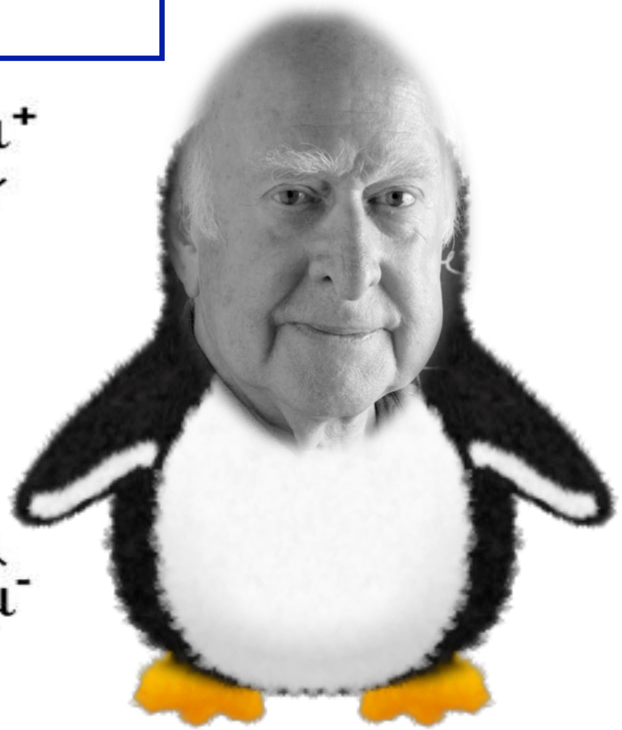
- Interesting local discrepancy in P_5'
  - few others tension less significant in other observables
- Possibly due to:
  - statistical fluctuation
  - SM theoretical prediction not fully correct
    (QCD effects not fully understood???)
  - New Physics:
    different value for some Wilson coefficients, ex: C_9, or C_9 and C_9',
    including the possibility of Z' particle with a mass around few TeV

Descotes-Genon, Matias, Virto arXiv:1307.5683
Gauld, Goertz, Haisch arXiv:1308.1959
Altmannshofer, Straub arXiv:1308.1501

$\Delta F=1$ Higgs penguins

K_s, D^0, B_0, B_s



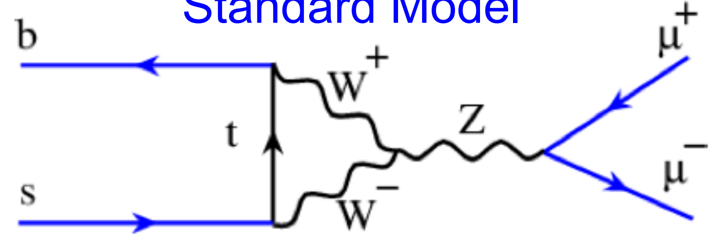


Theory prediction: Standard Model

decay	SM
$B_s \rightarrow \mu^+\mu^-$	$3.5 \pm 0.3 \times 10^{-9}$
$B^0 \rightarrow \mu^+\mu^-$	$1.1 \pm 0.1 \times 10^{-10}$

SM: Buras, Isidori et al: arXiv:1208.0934
Mixing effects: Fleischer et al, arXiv:1204.1737

Standard Model

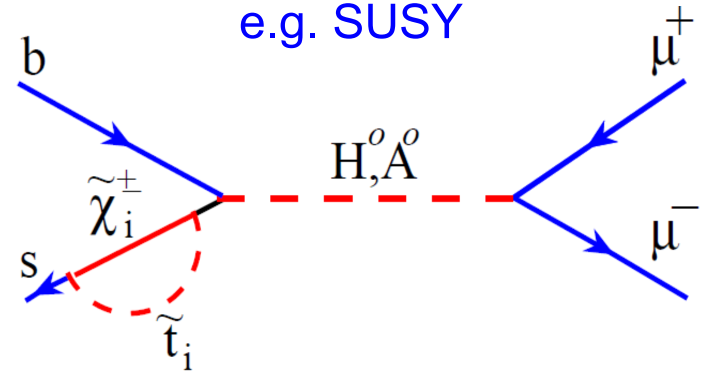


Left handed couplings
→ helicity suppressed

Discovery channel for New Phenomena

➔ Very **sensitive to an extended scalar sector** (e.g. extended Higgs sectors, SUSY, etc.)

e.g. SUSY



First search by CLEO in 1984:

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1

Two-body decays of *B* mesons

B. Search for exclusive $\bar{B}^0$ decays into two charged leptons

Our search for the $\pi^+\pi^-$ final state is not sensitive to the mass of the final-state particles, provided that they are light, since the mass enters only in the energy constraint. Therefore, the upper limit of 0.05% applies for any final-state particles with a pion mass or less. When the final-state particles are leptons the limits are improved by using the lepton identification capabilities of the CLEO detector.[14] For the decay $\bar{B}^0 \to \mu^+\mu^-$, we improve our limit by requiring that both muons penetrate the iron and produce signals in drift chambers. We find no such events. After correcting for detection efficiency (33%), we set an upper limit of 0.02% at 90% confidence for this decay. We im-

The Experimental Quest for $B \to \mu^+\mu^-$

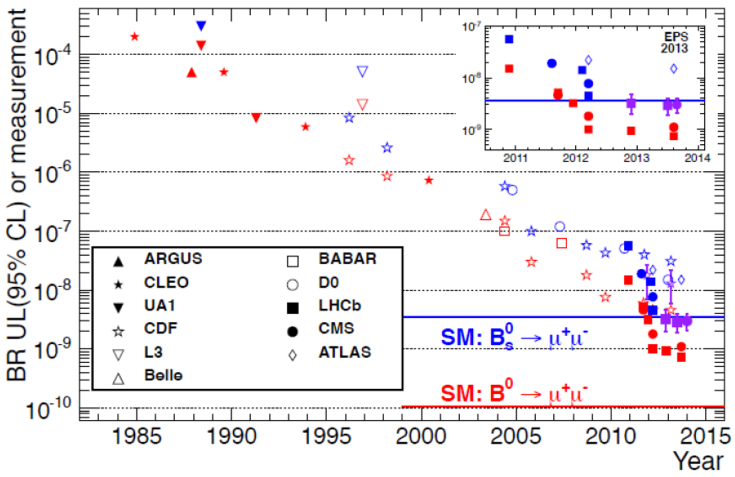
LHCb: Phys Rev Lett 110 (2013) 021801 (2.1 fb^{-1})

CMS: J. High Energy Phys 04 (2012) 033 (5.0 fb^{-1})

ATLAS: ATLAS-CONF-2013-076 (5.0 fb^{-1})

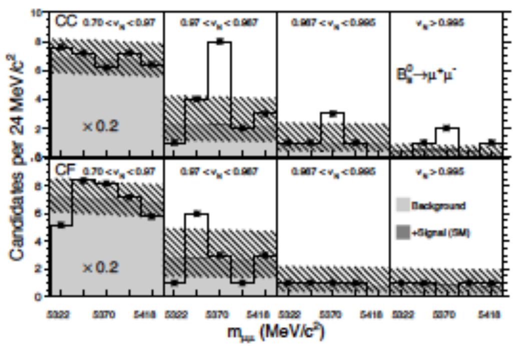
CDF: Phys. Rev. D 87, 072003 (2013) (9.7 fb^{-1})

D0: Phys. Rev. D87 07.2006 (2013) (10.4 fb^{-1})



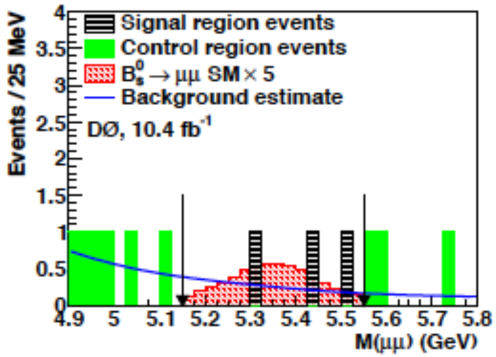
CC: two central muons

CF: one forward muon



95% CL:

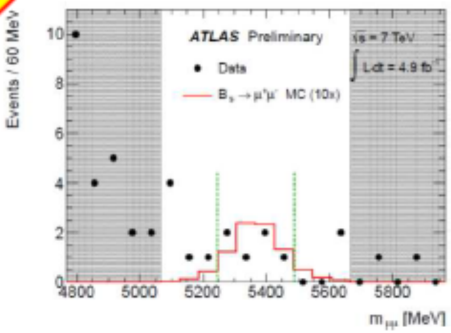
$$\text{BR}(B_s \to \mu^+\mu^-) < 3.1 \times 10^{-8}$$



95% CL:

$$\text{BR}(B_s \to \mu^+\mu^-) < 1.5 \times 10^{-8}$$

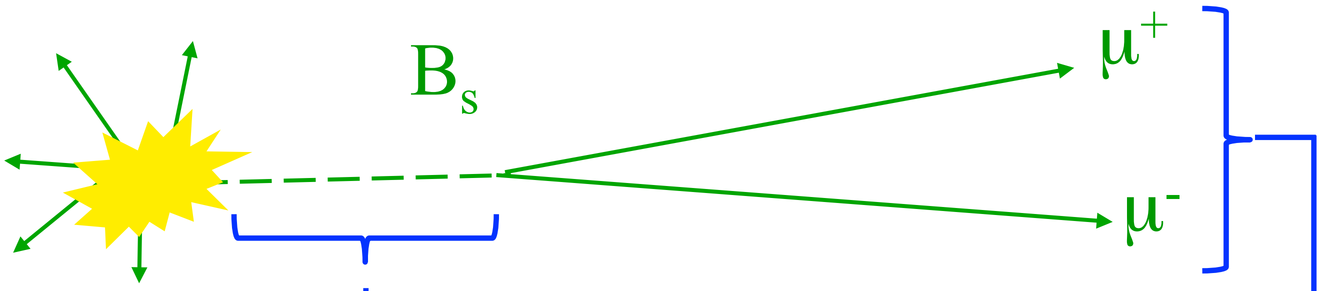
new @ EPS2013



95% CL:

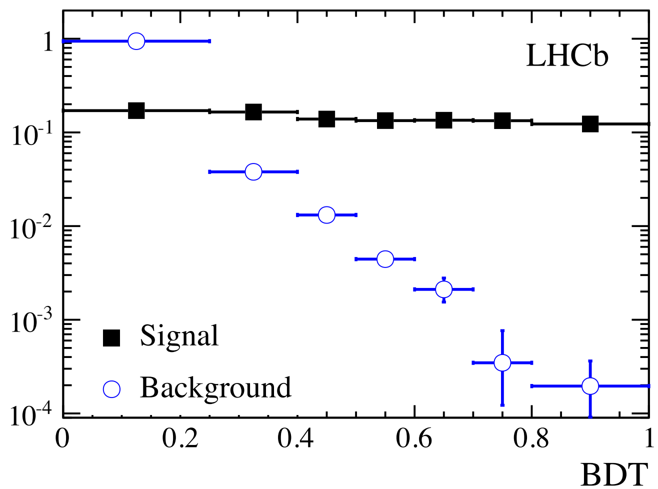
$$\text{BR}(B_s \to \mu^+\mu^-) < 1.5 \times 10^{-8}$$

Search strategy: Example LHCb

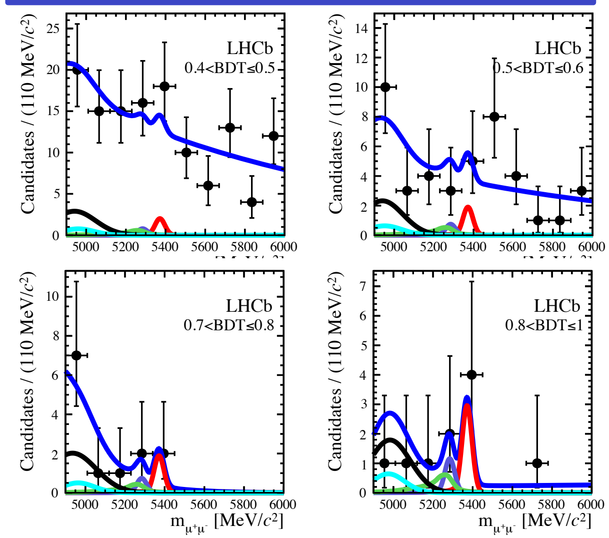


Classification of events

BDT (topology, kinematics)



Invariant mass



Measurement of exclusion limits or decay rates

New results for $B \to \mu^+\mu^-$

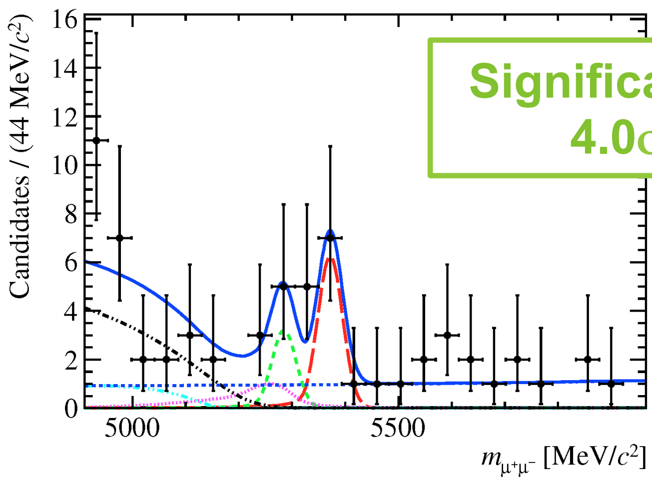
- **Nov 2012: LHCb found the first evidence for $B_s \to \mu^+\mu^-$ using $2.1 fb^{-1}$**

New results for $B \rightarrow \mu^+\mu^-$

- **Nov 2012: LHCb found the first evidence for $B_s \rightarrow \mu^+\mu^-$ using $2.1 fb^{-1}$**

- Update: full dataset: $3fb^{-1}$
  - Improved BDT
  - Expected sensitivity: 5.0σ

arXiv:1307.5024



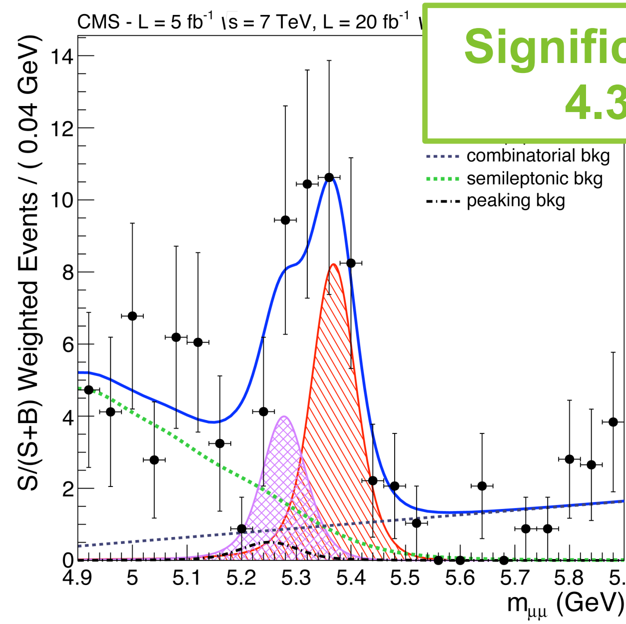
Significance: 4.0σ

$$BR(B_s \rightarrow \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}) \times 10^{-9}$$

$$BR(B^0 \rightarrow \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}) \times 10^{-9}$$

$$BR(B^0 \rightarrow \mu^+\mu^-) < 0.7 \times 10^{-9} @95\%CL$$

- Update to $25fb^{-1}$
  - Cut based → BDT based
  - Improved variables
  - Expected sensitivity: 4.8σ



Significance: 4.3σ

arXiv:1307.5025

$$BR(B_s \rightarrow \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$$

$$BR(B^0 \rightarrow \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-9}$$

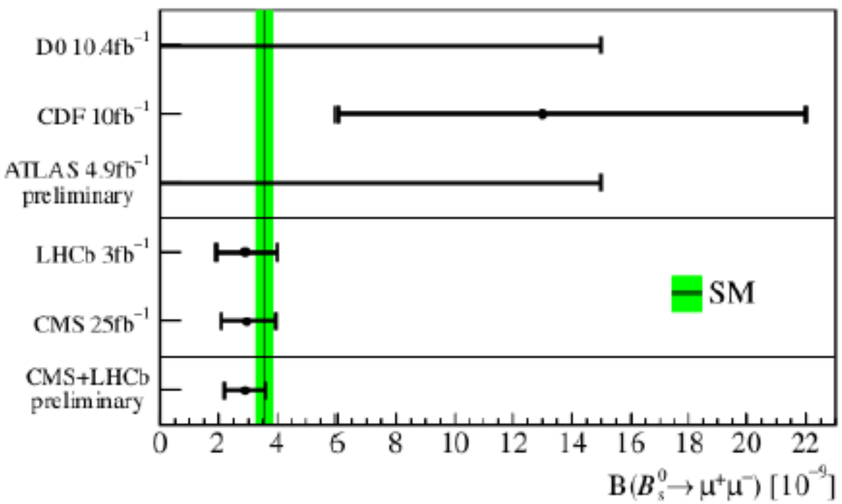
$$BR(B^0 \rightarrow \mu^+\mu^-) < 1.1 \times 10^{-9} @95\%CL$$

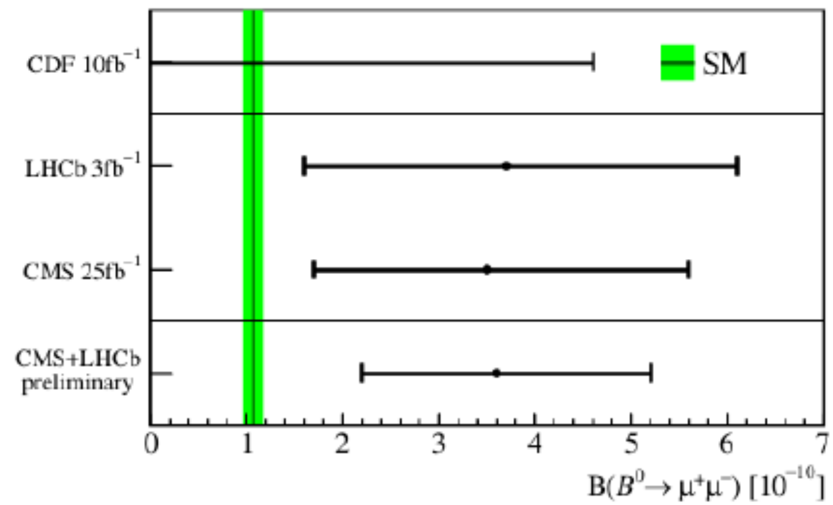
Observation:

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

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

[see here [**arXiv:1307.2448**] for speculations about enhanced BR(B_0)]

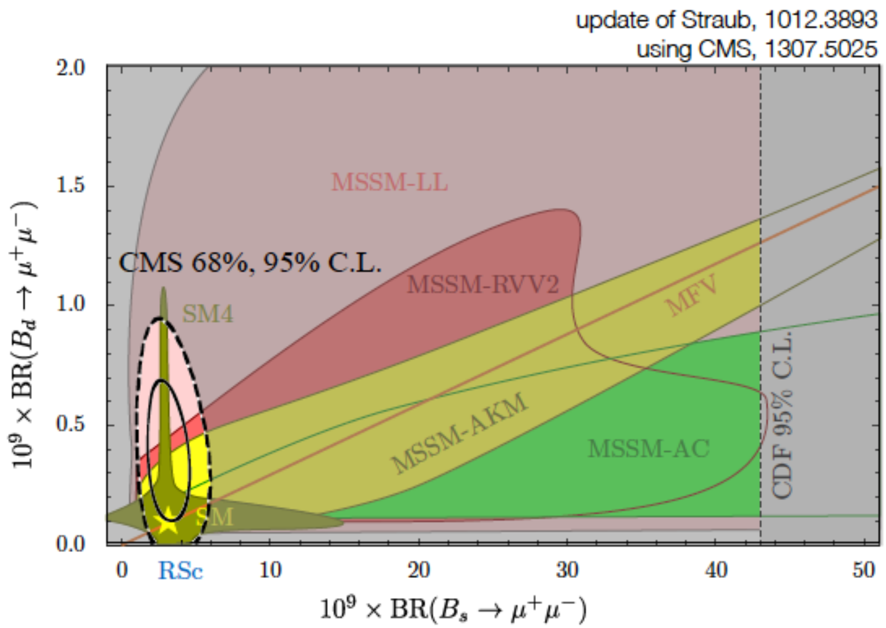




LHCb-CONF-2013-012, CMS-PAS-BPH-13-007

Implications of $B_s \to \mu^+\mu^-$

Allowed parameter space 2011:



Strong constraints on many new physics models

→ together with direct searches: „Constrained MSSM" models (almost) excluded

- Future key measurements:
  - **ratio of decay rates** of $B^0 \to \mu^+\mu^-$ / $B_s \to \mu^+\mu^-$
    →allows, e.g., test of „Minimal Flavour Violation" hypothesis
  - **Lifetime of $B_s \to \mu^+\mu^-$**
    → new, theoretically clean observable that is largely unconstrained

Summary

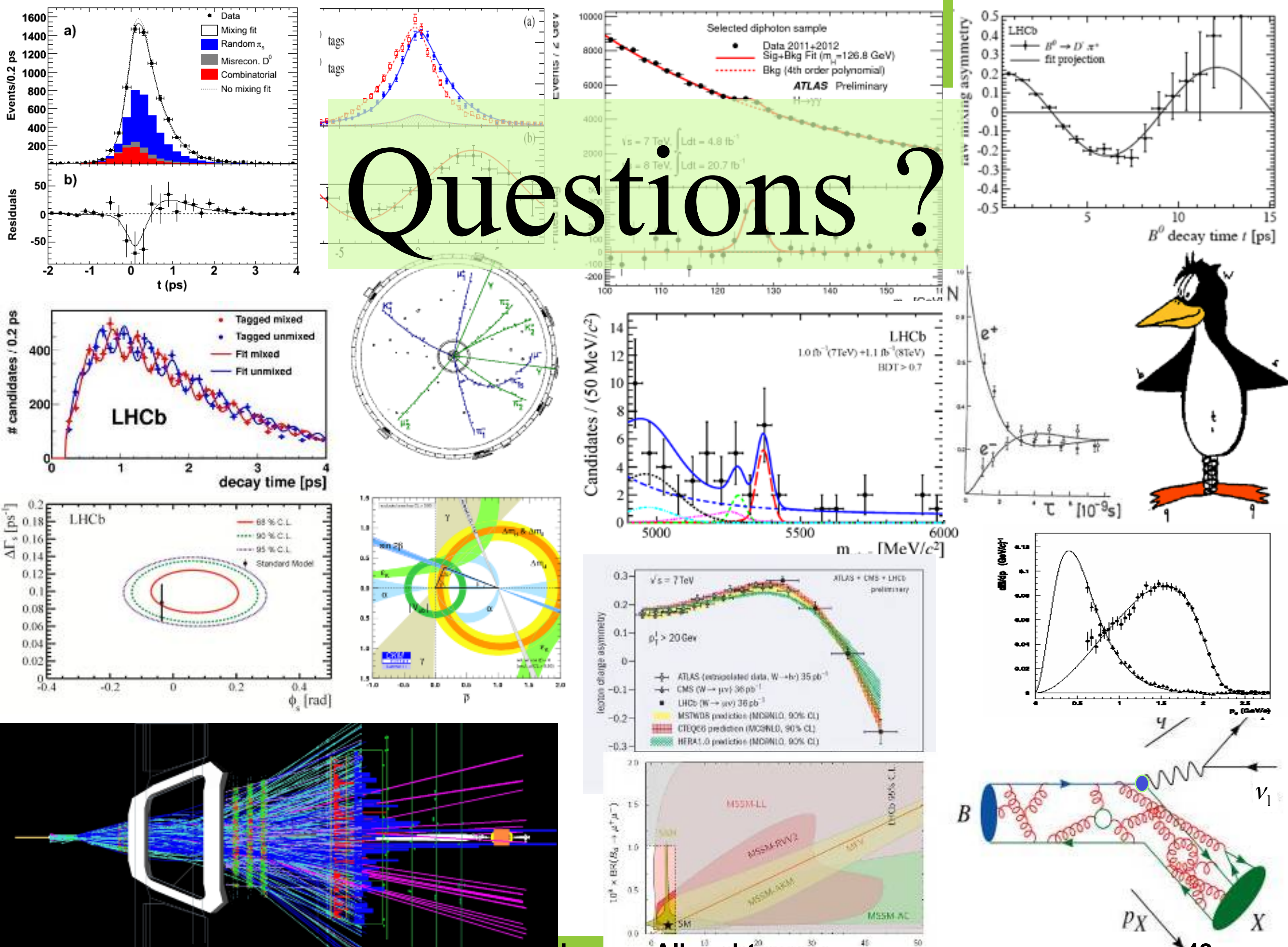
- **Interest in flavour measurements stronger than ever**

- Most generally, the agreement with the SM is excellent
  - Large NP contributions O(SM) ruled out in many cases

- However, interesting anomalies start to emerge
  - Assumptions are carefully re-assessed on the TH side
  - Measurements need to be confirmed

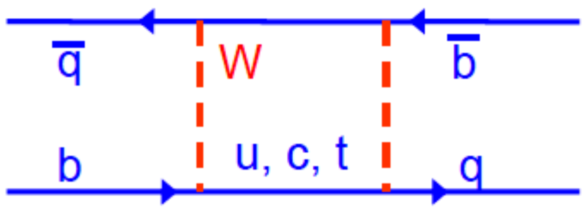
- The search has just started
  - With LHCb with (1+2)/fb at 7 and 8 TeV
    → not all recorded data is analyzed
  - ATLAS and CMS have an growing heavy flavour programme
  - Bright (near) future with Belle-II, LHC 2015++, LHCb-upgrade, …

Questions ?



Data
Mixing fit
Misrecon. D
Combinatorial
No mixing fit
Events/0.2 ps
Residuals
t (ps)
Selected diphoton sample
Data 2011+2012
Bkg (4th order polynomial)
ATLAS Preliminary
LHCb
fit projection
raw mixing asymmetry
decay time t [ps]
Tagged mixed
Tagged unmixed
Fit mixed
Fit unmixed
candidates / 0.2 ps
decay time [ps]
Candidates / (50 MeV/c²)
BDT > 0.7
68 % C.L.
90 % C.L.
95 % C.L.
Standard Model
lepton charge asymmetry
MSSM-LL
MSSM-RVV2
MSSM-AKM
MSSM-AC
MFV
SM

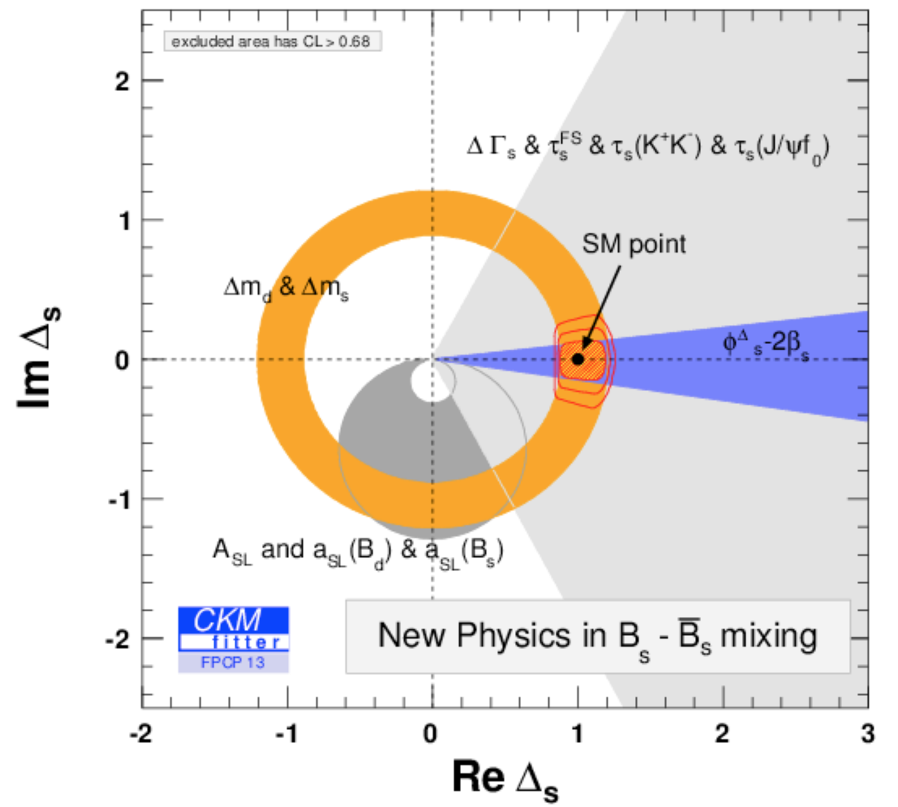
B_s:



$$\mathcal{A}_{mix} = \mathcal{A}_{mix}^{SM} + \mathcal{A}_{mix}^{NP} = \mathcal{A}_{mix}^{SM} \times \Delta$$

$$\Delta_s = |\Delta_s| e^{i\phi_s^{NP}}$$

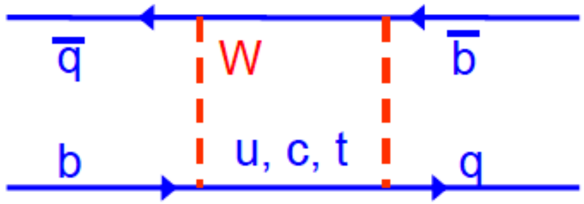
$$\Delta_d = |\Delta_d| e^{i\phi_d^{NP}}$$



Perfect agreement
→ within experimental precision, no hint for New Physics

Status of $B_{s,d}$ mixing and New Physics

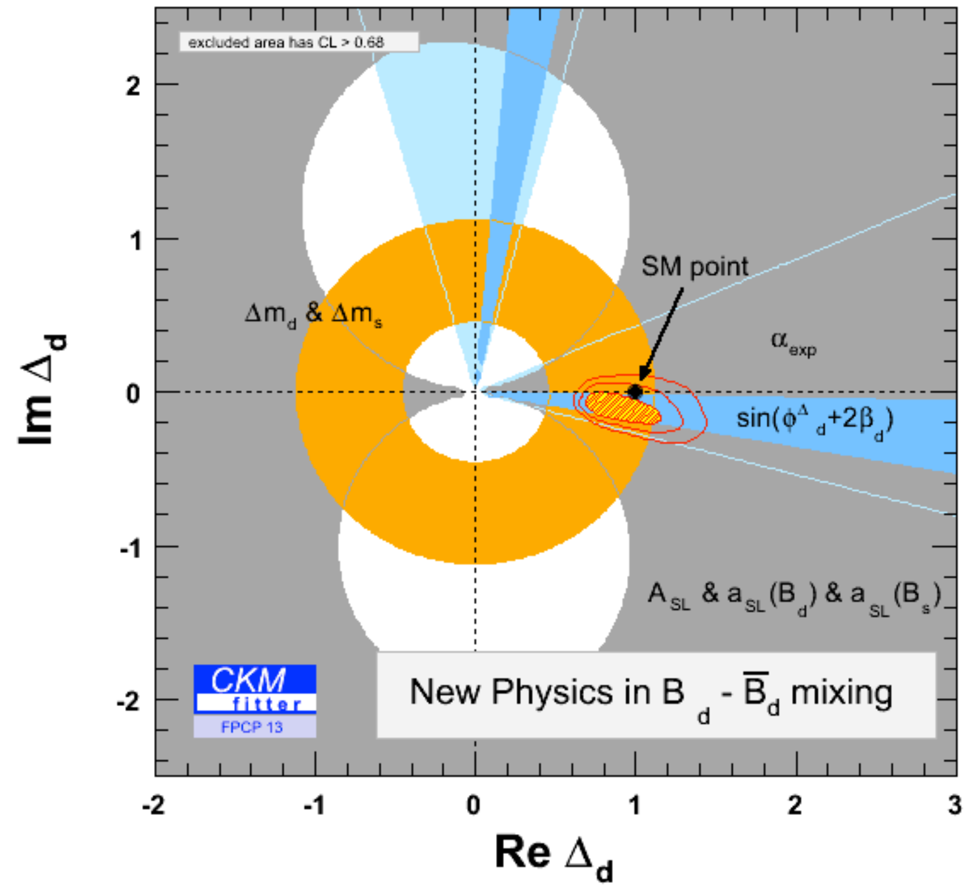
B^0:



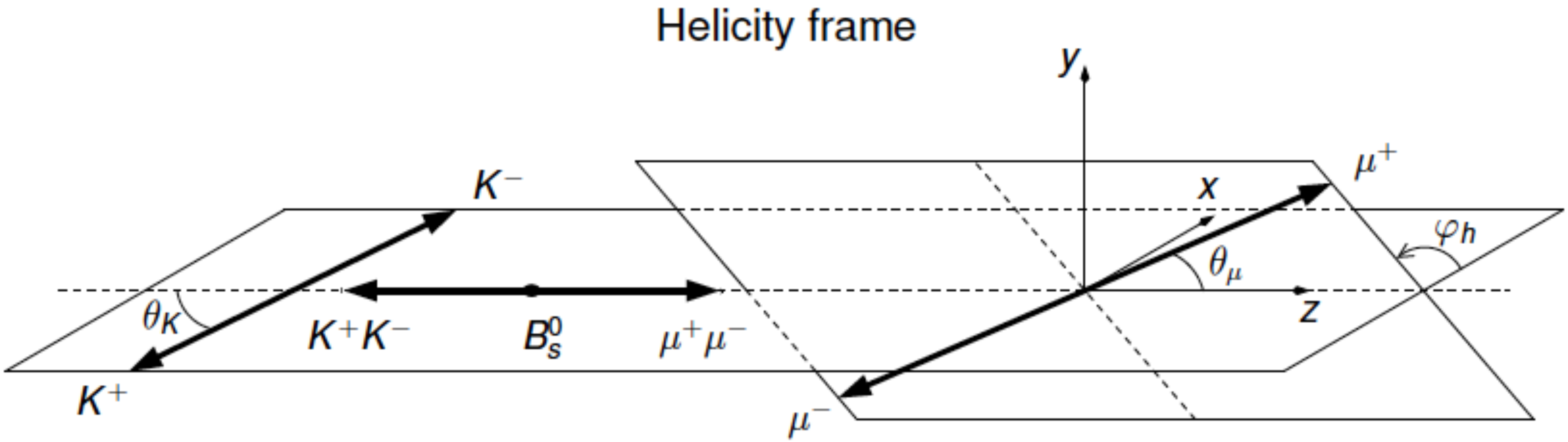
$$\mathcal{A}_{mix} = \mathcal{A}_{mix}^{SM} + \mathcal{A}_{mix}^{NP} = \mathcal{A}_{mix}^{SM} \times \Delta$$

$$\Delta_s = |\Delta_s| e^{i\phi_s^{NP}}$$

$$\Delta_d = |\Delta_d| e^{i\phi_d^{NP}}$$

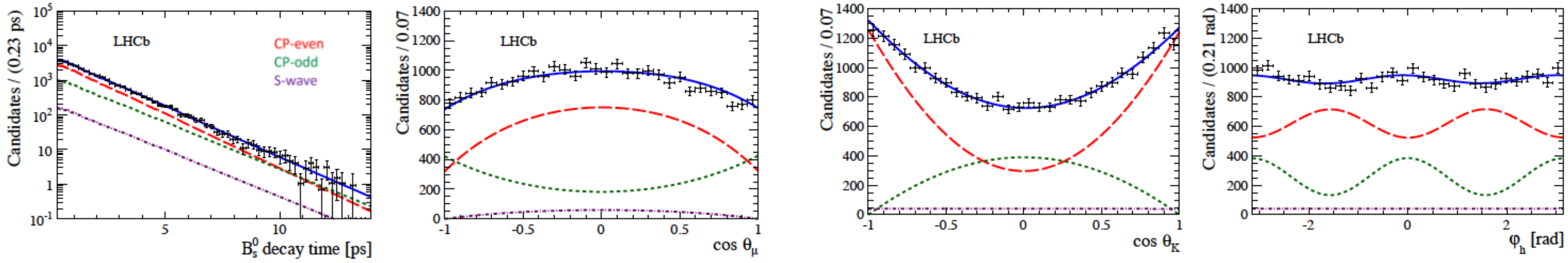


1.5σ "tension"
→ need more data



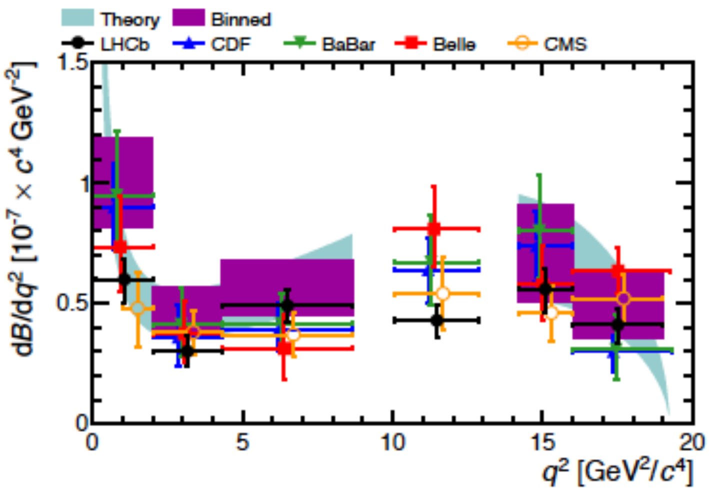
Fit differential decay rates (for B_s^0 and $\overline{B}_s^0$):

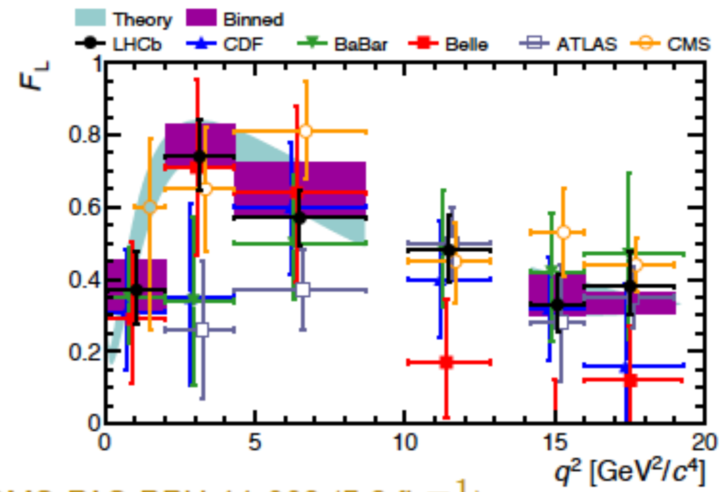
$$\frac{\mathrm{d}^4\Gamma(B_s^0 \to J/\psi\phi)}{\mathrm{d}t\,\mathrm{d}\cos\theta_\mu\,\mathrm{d}\varphi_h\,\mathrm{d}\cos\theta_K} = f(\phi_s, \Delta\Gamma_s, \Gamma_s, \Delta m_s, |A_\perp|, |A_\parallel|, |A_S|, \delta_\perp, \delta_\parallel, \ldots)$$

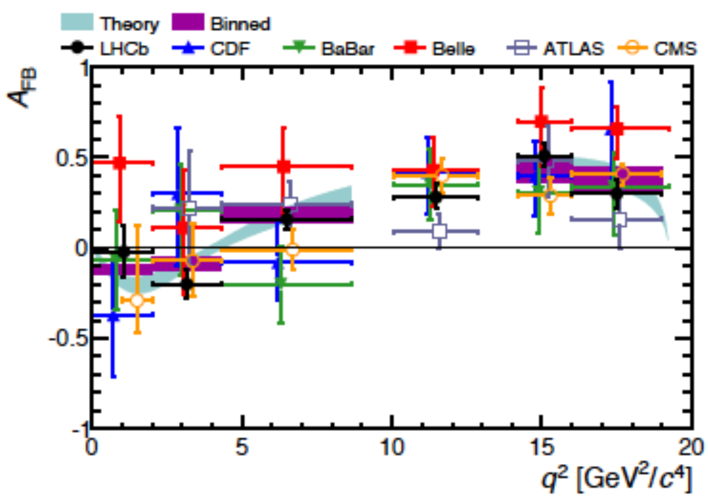


$B^0 \rightarrow K^* \mu^+ \mu^-$ - Angular Distributions

Some example distributions:







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})

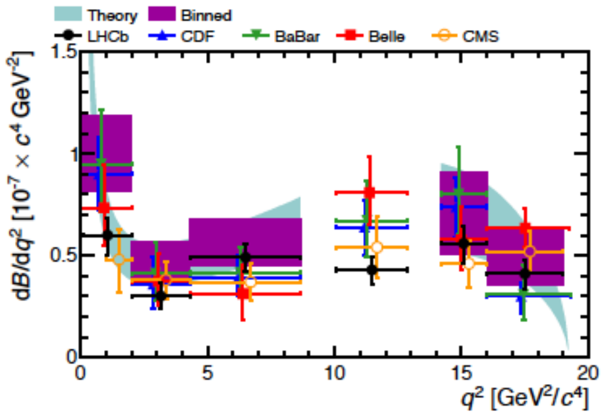
CDF: Phys. Rev. Lett 108 (2012) 081807 (6.8 fb^{-1})

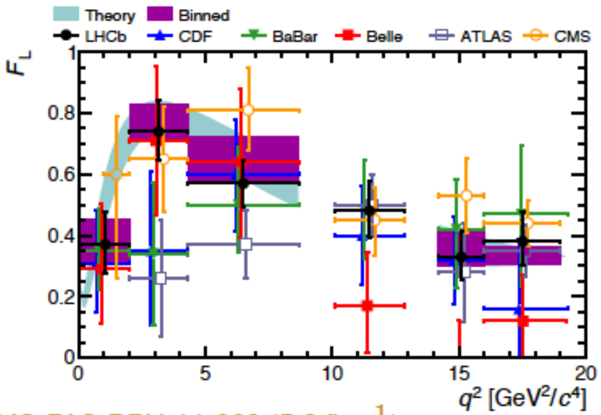
(results from CDF Public Note 10894 (9.6 fb^{-1}) not included)

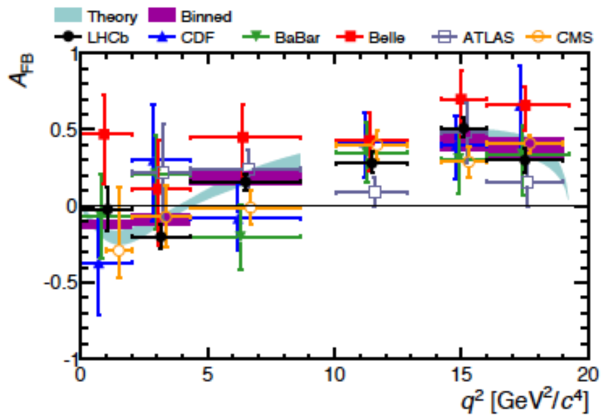
LHCb: arXiv:1304.6325 (1 fb^{-1})

$B^0 \rightarrow K^* \mu^+\mu^-$ - Angular Distributions

Some example distributions:







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})

Generally very good agreement in these “classical observables”
→ bounds on the New Physics scale between 0.5 and ~15TeV are set

New observables in $B^0 \rightarrow K^* \mu^+\mu^-$

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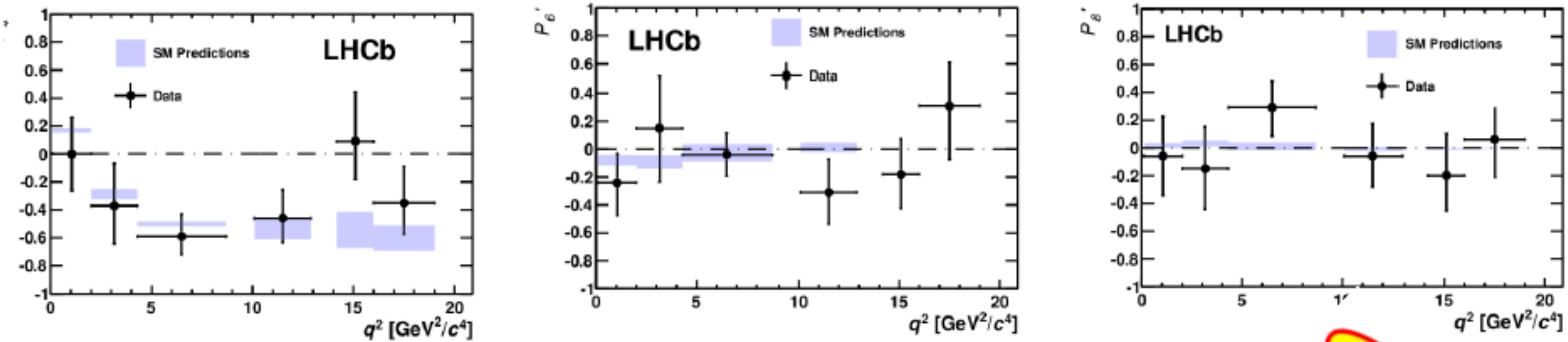
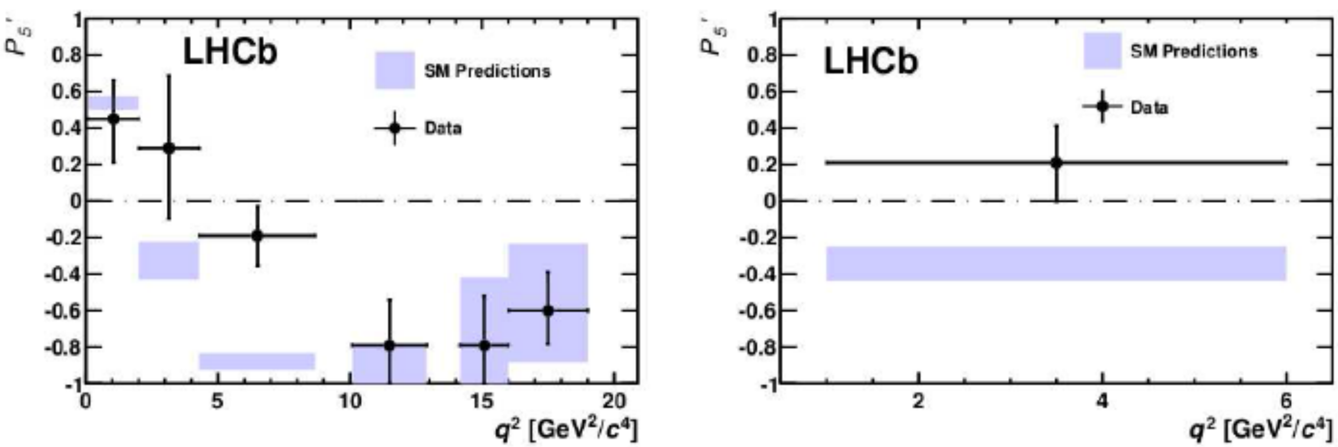
Very good agreement in P_4', P_6', P_8'



some tension in P_5' (3.7 σ):



new @ EPS2013

Discussion at EPS resulted in an article: Descotes, Matias, Virto arXiv:1307.5683

0.5% probability to see such a deviation with 24 independent measurements.