Heavy Flavour Experiment
Lecture 2

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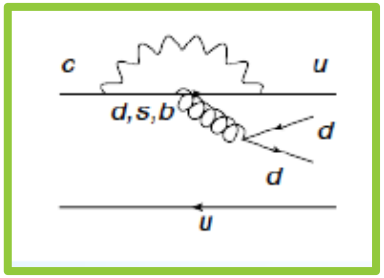
Contents

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

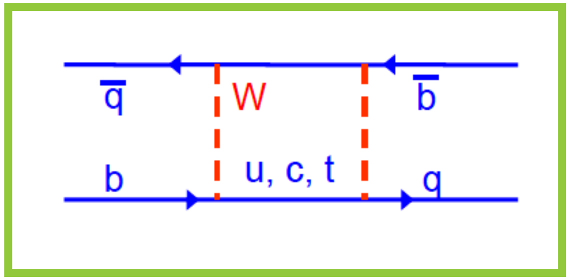
- Lecture 2:
  - “Golden modes for New physics searches” – loop zoology

Loop zoology – map of this talk

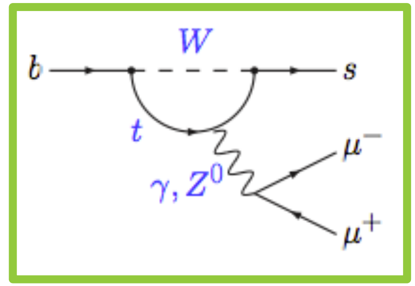
- Map of flavour transitions and types of loop processes



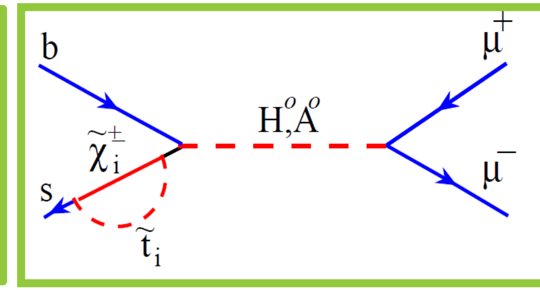
QCD penguin



ΔF=2 box



EW penguin

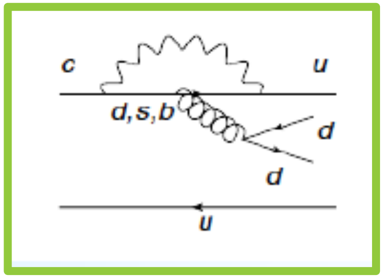


Higgs penguin

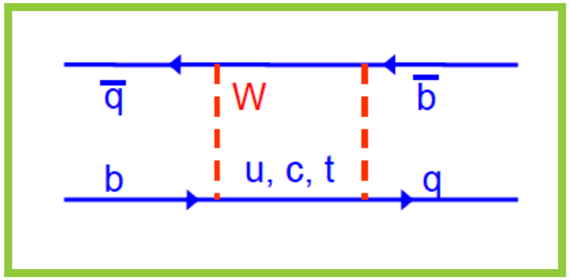
	$b \to s$	$b \to d$	$c \to u$	$s \to d$
QCD penguin	$A_{CP}(B_s \to hhh)$	$A_{CP}(B^0 \to hhh)$	**$\Delta a_{CP}(D \to hh)$**	$K \to \pi^0 ll$ ε'/ε
ΔF=2 box	ΔM_{Bs} **$A_{CP}(B_s \to J/\psi\phi)$**	ΔM_{Bd} $A_{CP}(B^0 \to J/\psi K_s)$	x,y, q/p	ΔM_K ε_K
EW penguin	**$B \to K^{(*)}\mu\mu$** $B \to X_s\gamma$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

Loop zoology – map of this talk

- Map of flavour transitions and types of loop processes



QCD penguin



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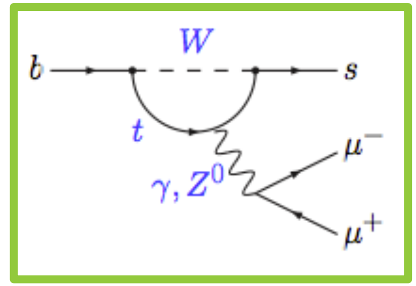
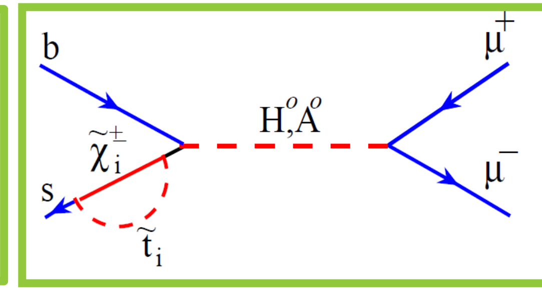


EW penguin



Higgs penguin

	$b \to s$	$b \to d$	$c \to u$	$s \to d$
QCD penguin	$A_{CP}(B_s \to hhh)$	$A_{CP}(B^0 \to hhh)$	$\Delta a_{CP}(D \to hh)$	$K \to \pi^0 ll$ ε'/ε
ΔF	[illegible]	[illegible]$\psi K_s)$	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	$B_s \to \mu\mu$	$B^0 \to \mu\mu$	$D \to \mu\mu$	$K^0 \to \mu\mu$

Detailed discussion tomorrow by Michel & Danny

1)

QCD penguins

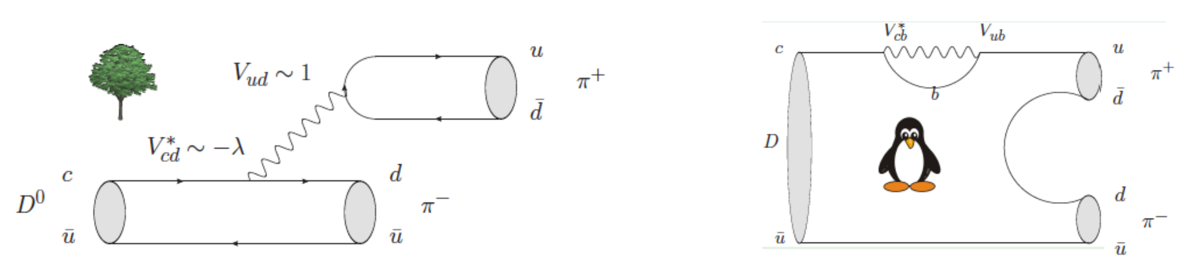
or

Search for CP violation in charm decays

CP violation in charm

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

- Charm: 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 "clear sign for NP"

CP violation in charm: ΔA_{CP}

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

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

} large O(1%)

CP violation in charm: ΔA_{CP}

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

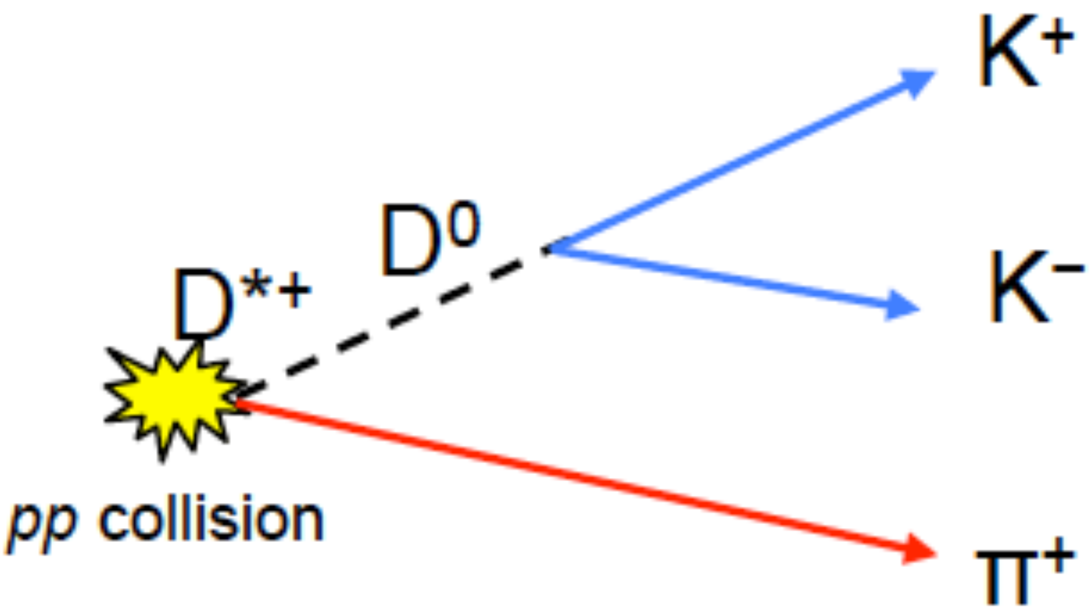
- Physical CP asymmetry (very small)
- Detection asymmetry, cancels for $D^0 \to \pi\pi$, KK
- Production asymmetry

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

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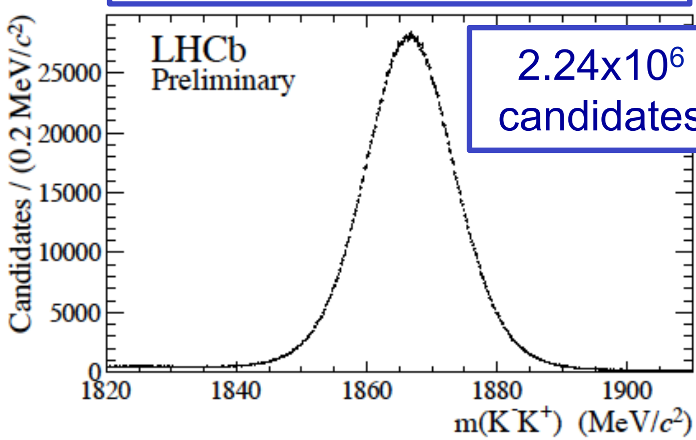
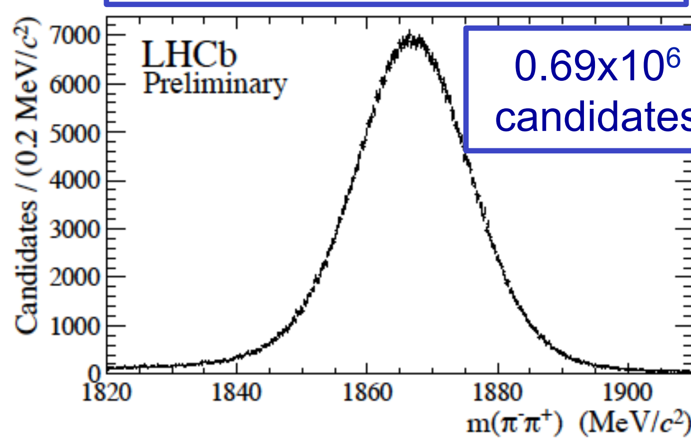
$D^0 \to K^+K^-$



2.24x10^6 candidates

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



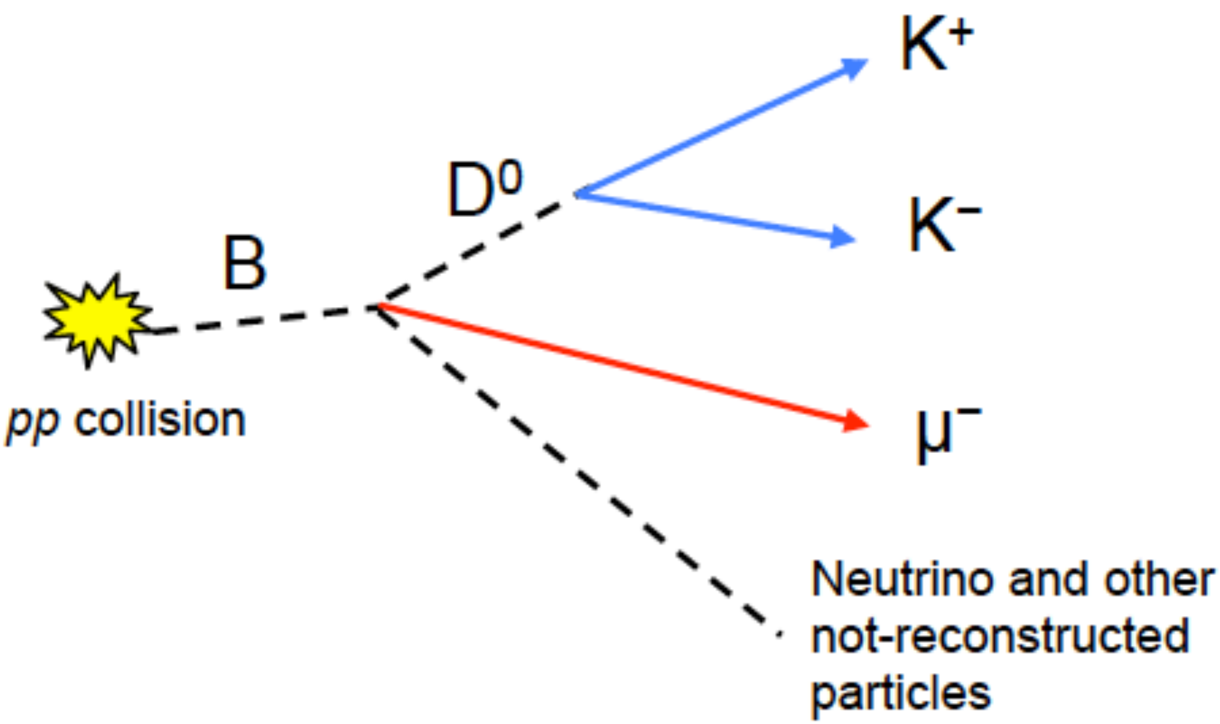
0.69x10^6 candidates

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

[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": $B^\pm \rightarrow D^0 (\rightarrow K^+K^- \text{ or } \pi^+\pi^-) \mu^\pm \nu X$
    → muon charge determines D^0 production flavour



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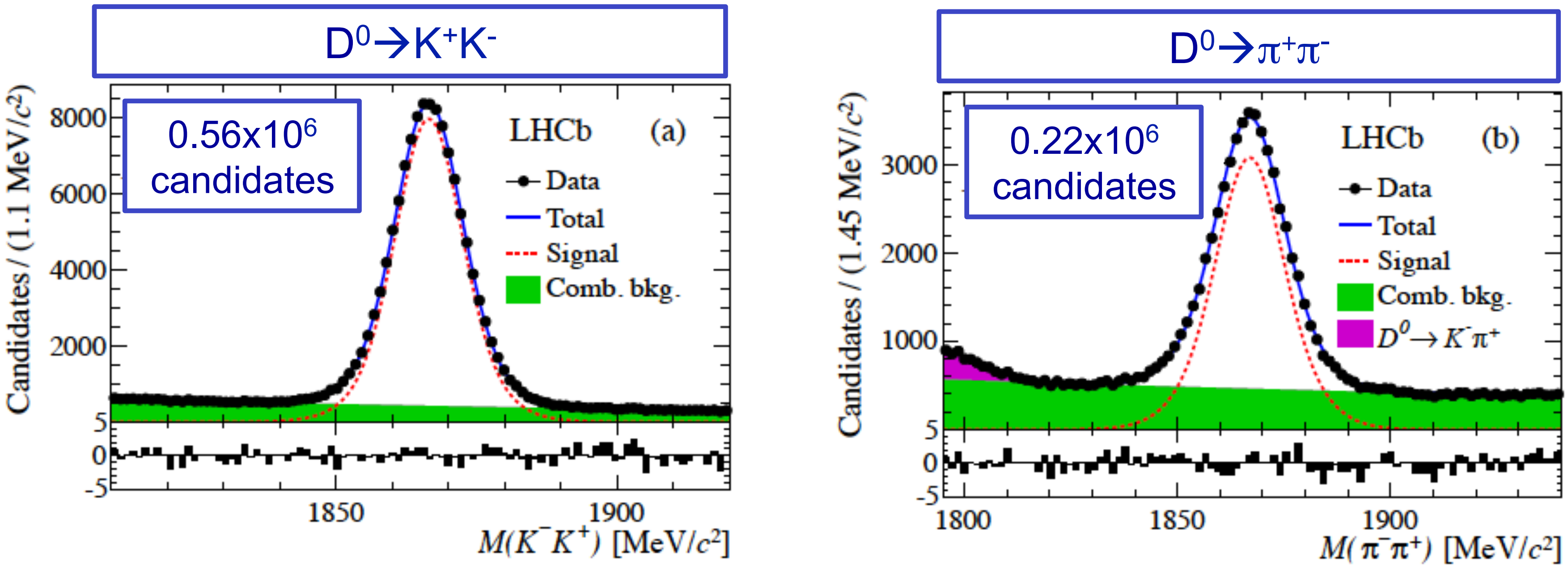

$$\Delta A_{CP} = [+0.49 \pm 0.30\ (\text{stat}) \pm 0.14\ (\text{syst})]\%$$

[arXiv:1303.2614]

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

- LHCb performed two (experimentally orthogonal) measurements
  - "D* tagged": $D^{*\pm} \rightarrow D^0 (\rightarrow K^+K^-$ or $\pi^+\pi^-) \pi^\pm$
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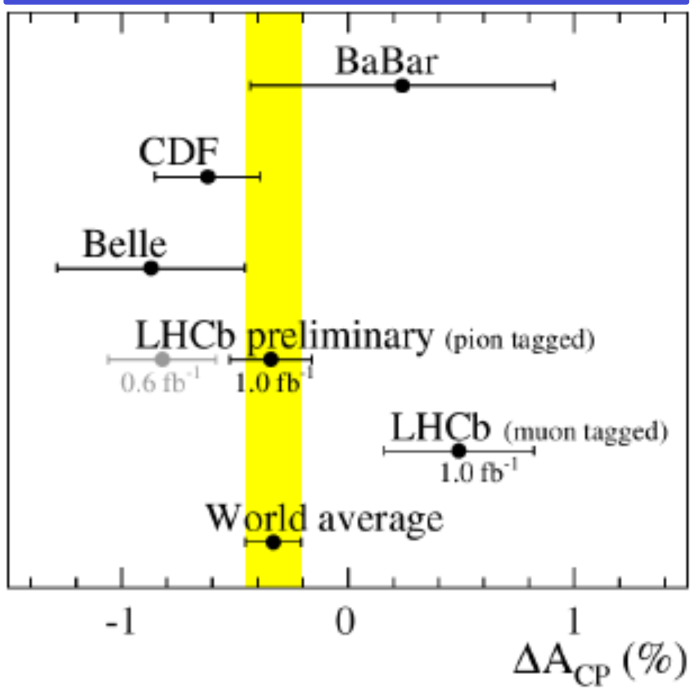
ΔA_{CP}: world average



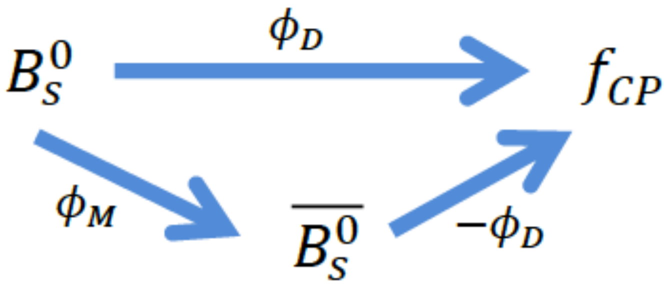
LHCb results dominated by statistics. Situation should become more clear with the analysis of the full 3/fb

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

B_s mixing and CP violation

Interference between mixing and decay:
→ measure relative phase ϕ_s

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



CP asymmetry (for CP eigenstates):

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

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:
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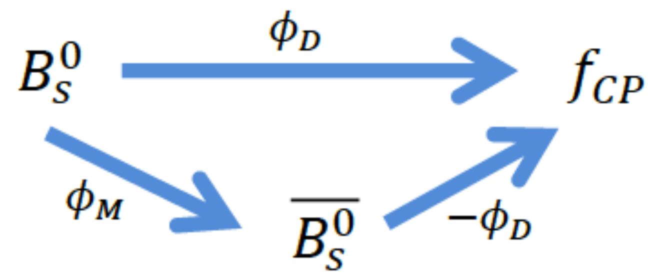

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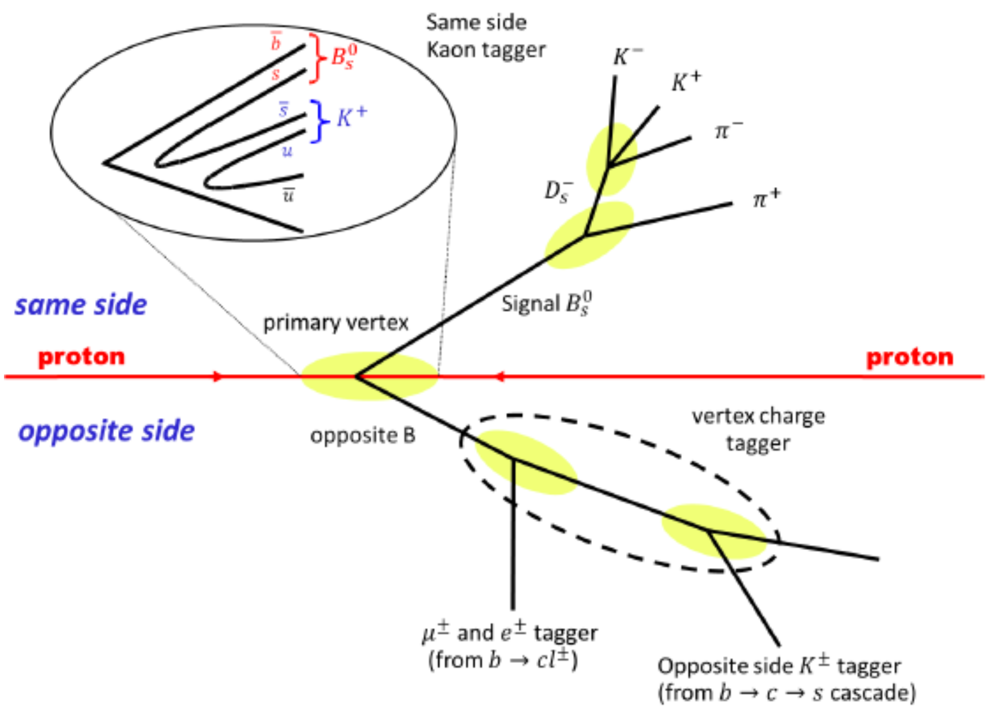
Need excellent Flavour tagging
→ tagging power

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 $B_s \rightarrow J/\psi\phi$

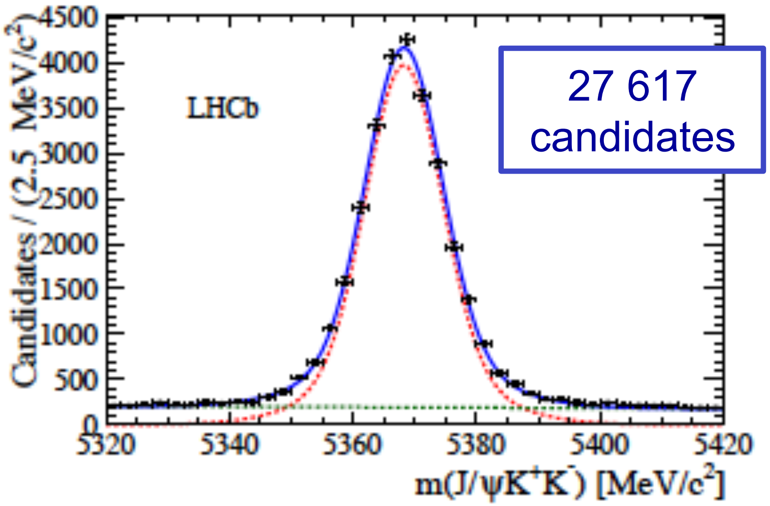
B_s : $J^P = 0^{-1}$ (pseudo scalar)

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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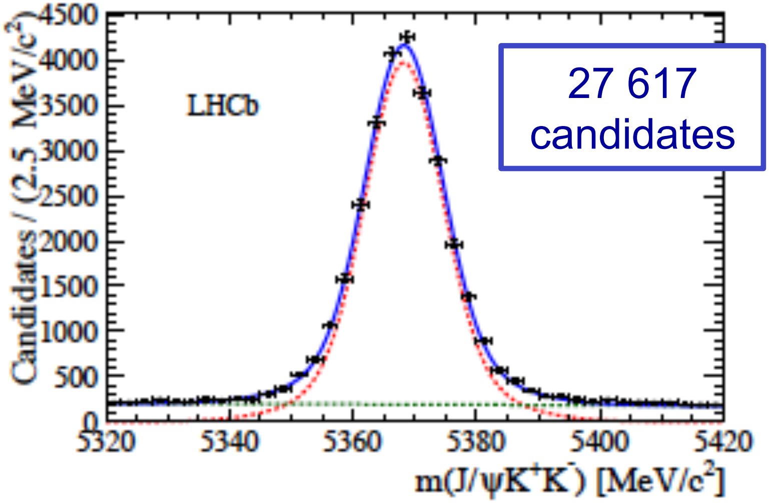

Angular momentum conservation:

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

L = 1 $\longrightarrow$ CP odd final state

Final state no CP eigenstate but linear combination!

Angular analysis, to separate CP even/odd contributions.

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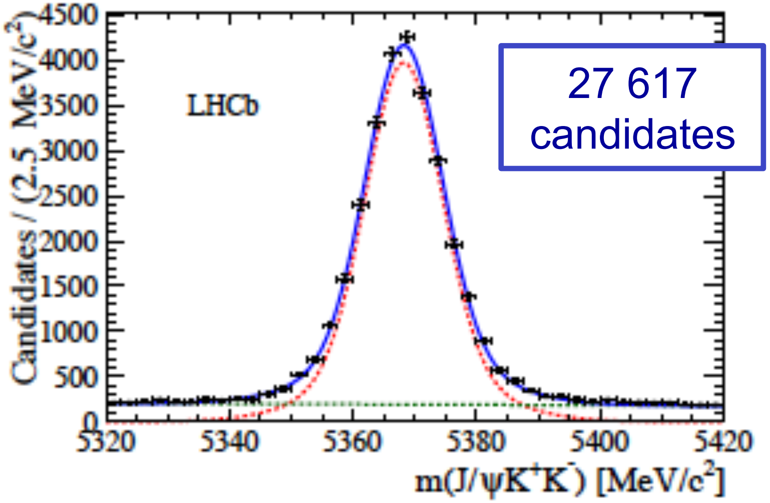

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Angular analysis, to separate CP even/odd contributions.

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 $B_s \rightarrow J/\psi\phi$ and $B_s \rightarrow J/\psi\pi\pi$ by LHCb

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

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

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

Results of the B_s mixing phase

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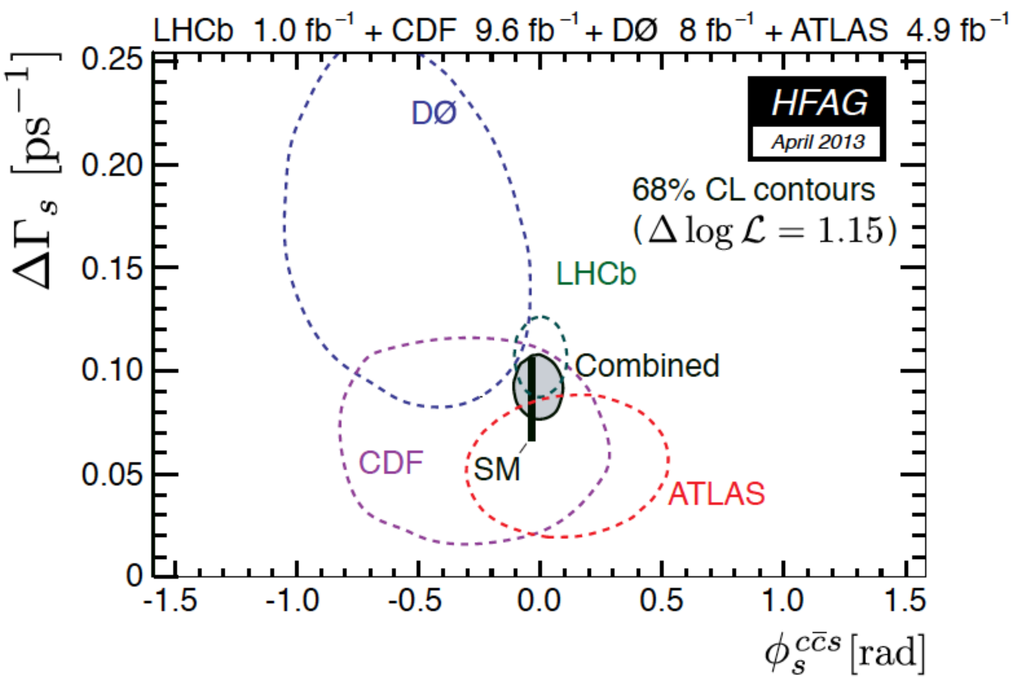
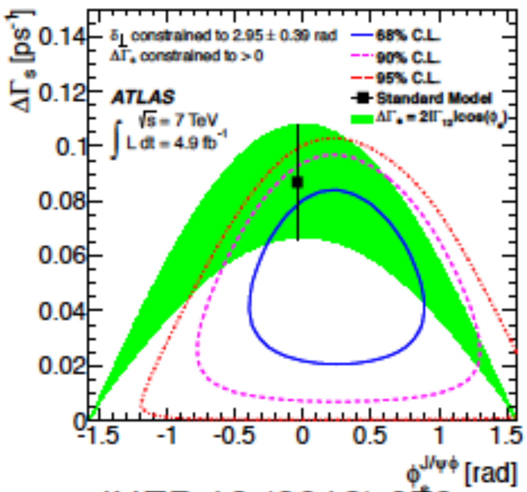


Detour: The importance of flavour tagging

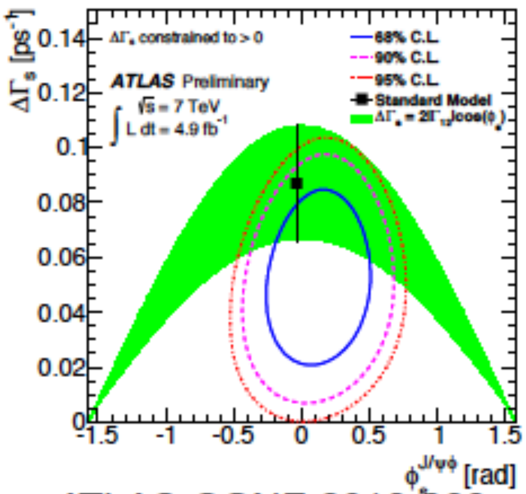
ATLAS untagged result



JHEP 12 (2012) 072

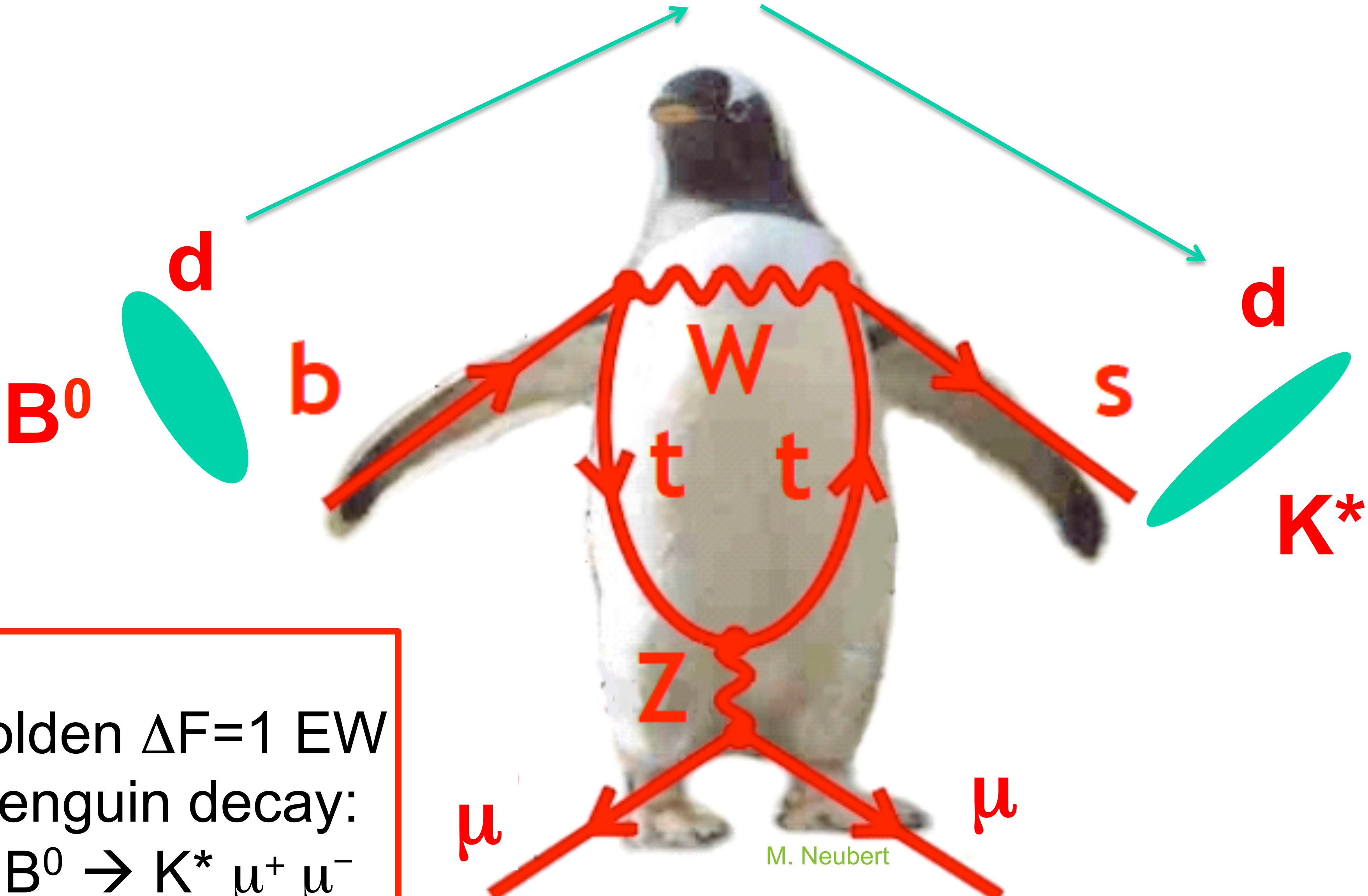
uncertainty on ϕ_s improved by 40%

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)



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

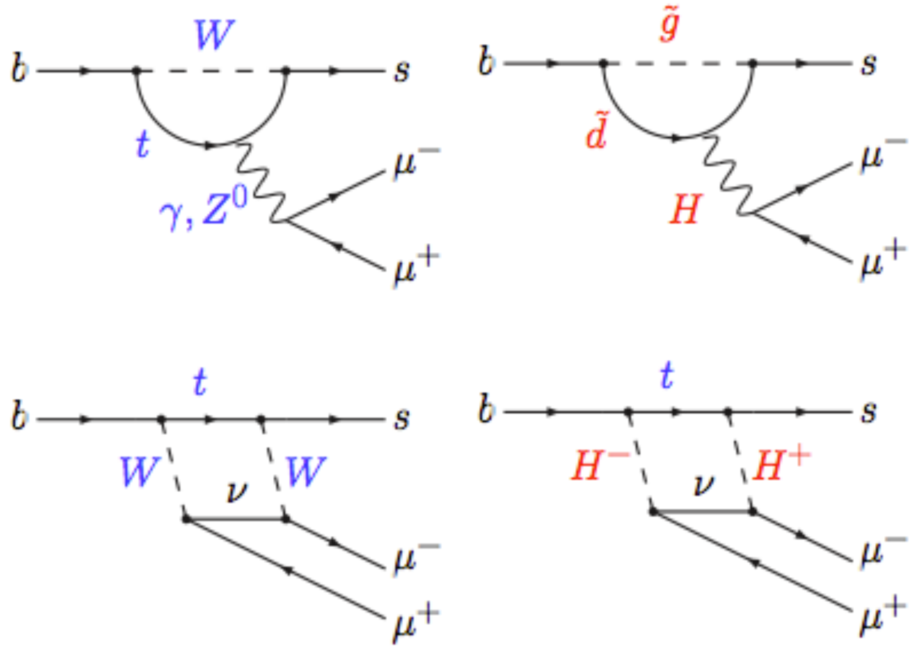
b → s transitions

General description of Hamiltonian (see T. Feldmann):

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

$i = 1,2$	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: $O_7^{(\prime)}$, $O_9^{(\prime)}$, $O_{10}^{(\prime)}$



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

Studies with rarer $B_s \rightarrow \phi\ \mu^+\mu^-$, $\Lambda_b^0 \rightarrow \Lambda\ \mu^+\mu^-$, .. 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 $\psi(2S)$ 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		

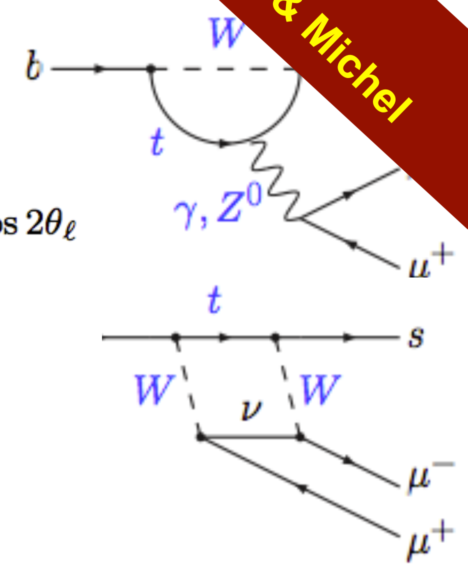
Babar arXiv:1204.3933
Belle arXiv:0904.0770
CDF arXiv:1107.3753 + 1108.0695 + ICHEP 2012
LHCb LHCb-CONF-2012-008 (-003, -006), arXiv:1205.3422 + 1209.4284 + 1210.4492 + 1211.2674

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

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

See Danny & Michel

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



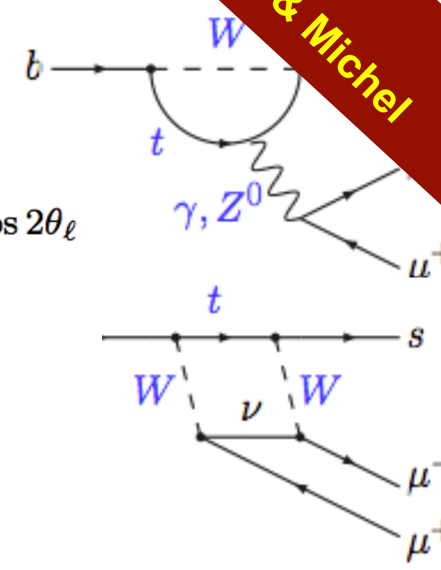
$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell +$$
$$S_3\sin^2\theta_K\sin^2\theta_\ell\cos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

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

classical observable
measured for the FIRST time by LHCb

See Danny & Michel

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



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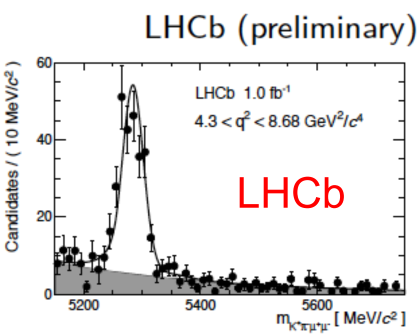
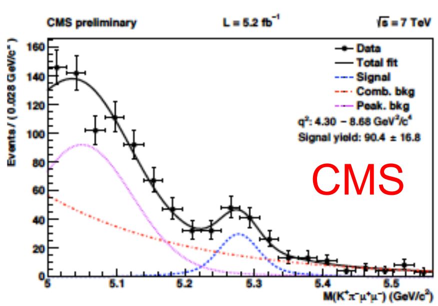
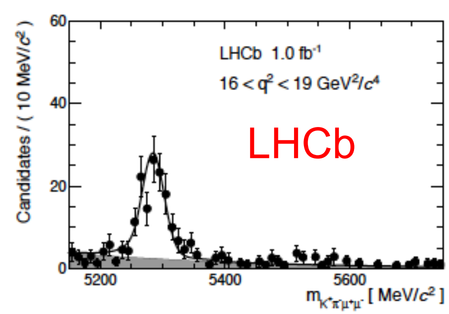
$$- F_L\cos^2\theta_K\cos 2\theta_\ell +$$
$$S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi +$$
$$S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6^s\sin^2\theta_K\cos\theta_\ell +$$
$$S_7\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

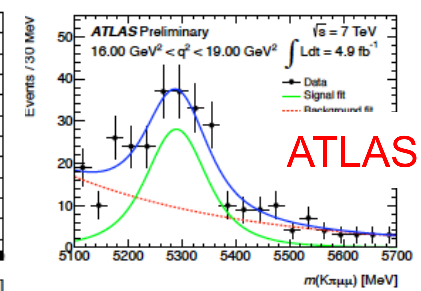
Example mass:
mid-q^2 ($4.3 < q^2 < 8.7$)





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





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

Simplifying the analysis

See Danny & Michel

By exploiting symmetries:
this form can be reduced to …

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

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

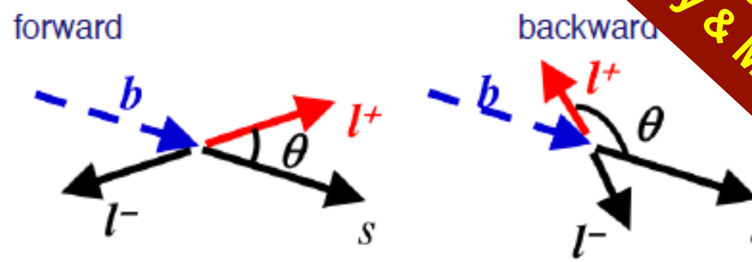
- Simpler expression remains, sensitive to F_L, A_{FB}, S_3, A_9
  - Lost sensitivity to terms 4, 5 ,7 and 9

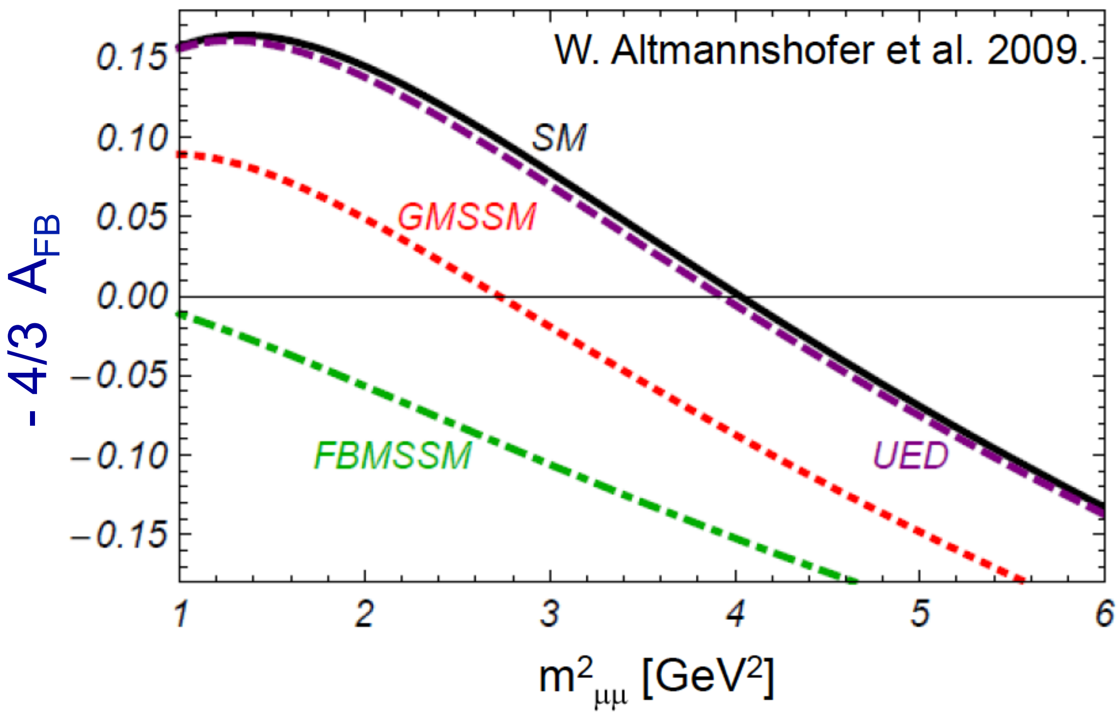
Forward-backward Asymmetry

See Danny & Michel

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

Forward-backward Asymmetry

See Danny & Michel

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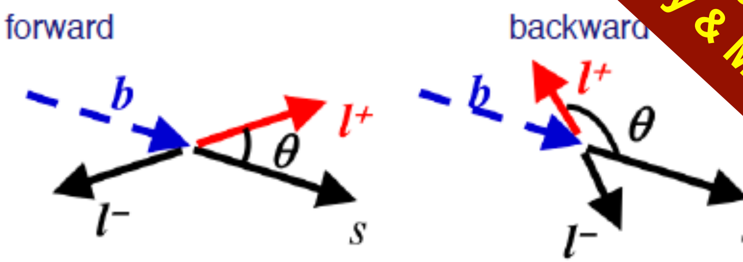
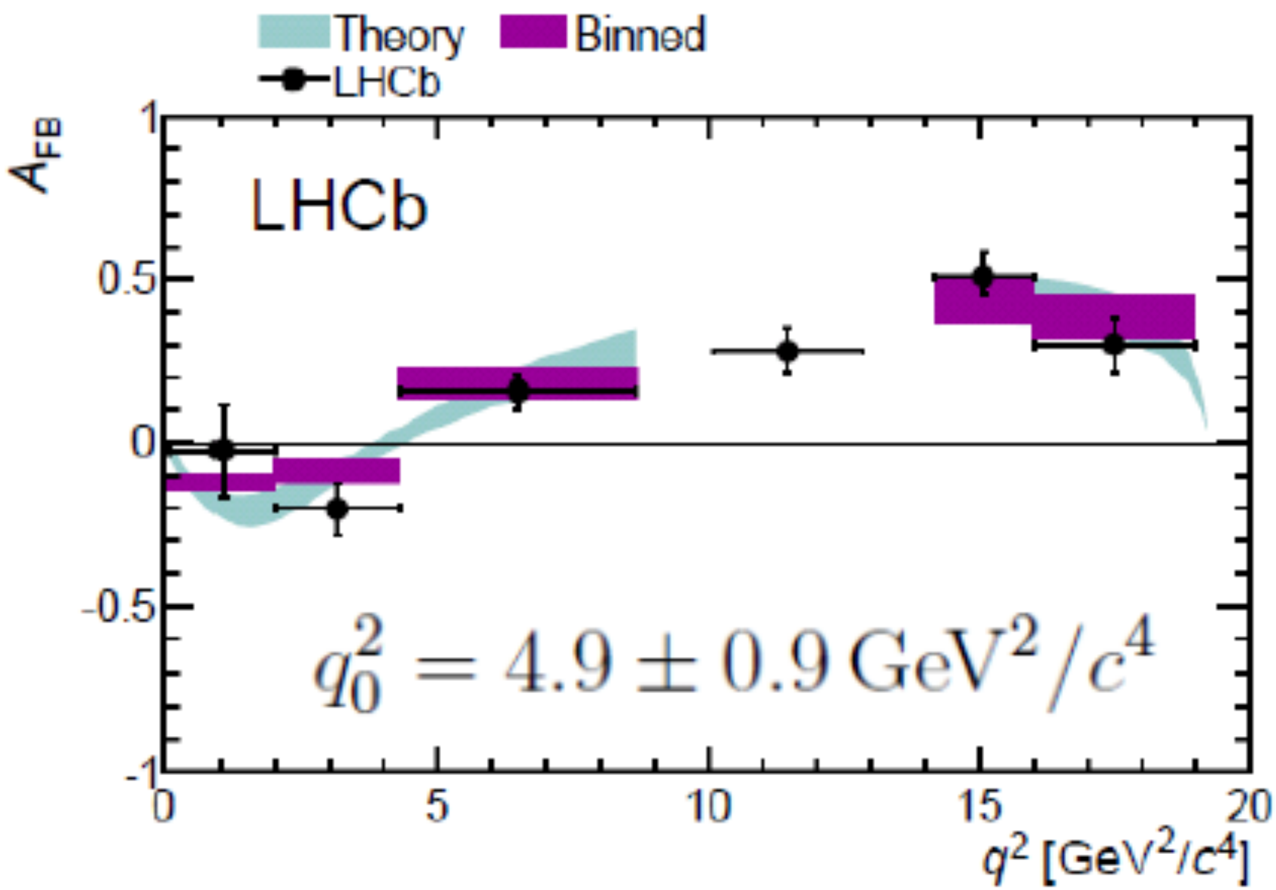
$$A_{FB} \propto -Re[(2C_7^{eff} + \frac{q^2}{m_b^2} C_9^{eff}) C_{10}]$$





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

Forward-backward Asymmetry

See Danny & Michel

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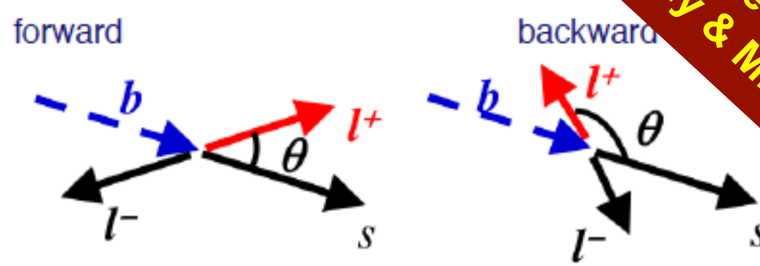
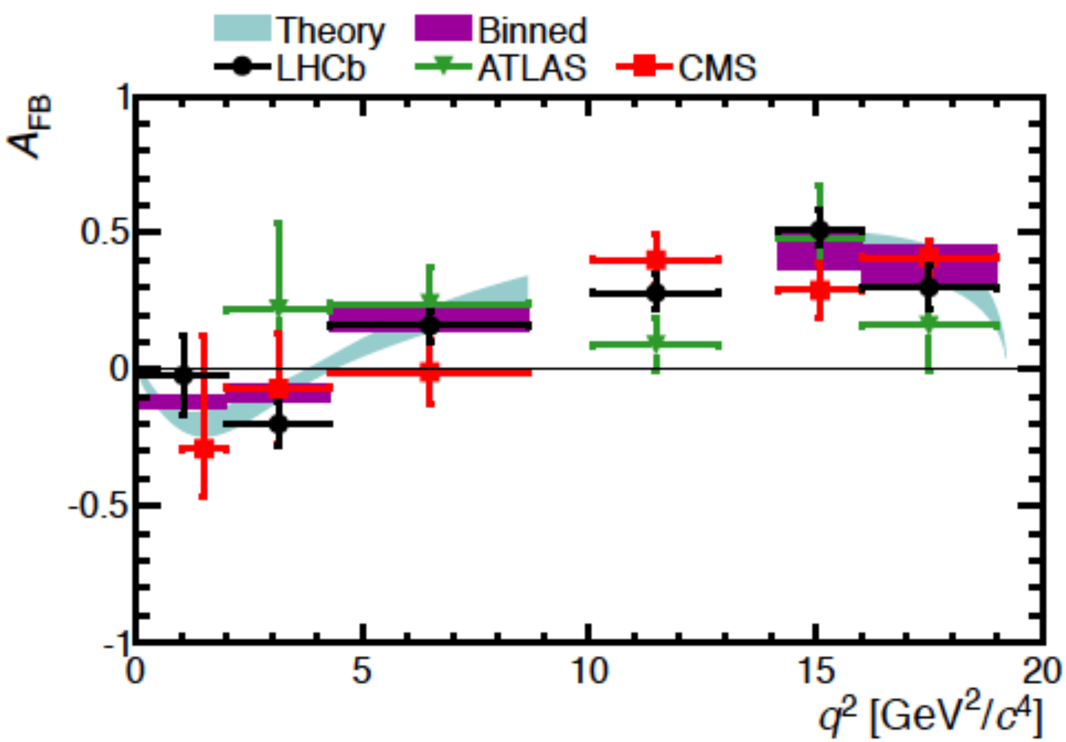




LHCb 2012:
First measurement of zero-crossing point:
q_0=4.9±0.9 GeV^2/c^4

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

$B^0 \to K^* \mu^+ \mu^-$: Alternative transformati

See Danny & Michel

- 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:

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

P'_5, S_5:

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

S_4, S_5 → Standard Observables

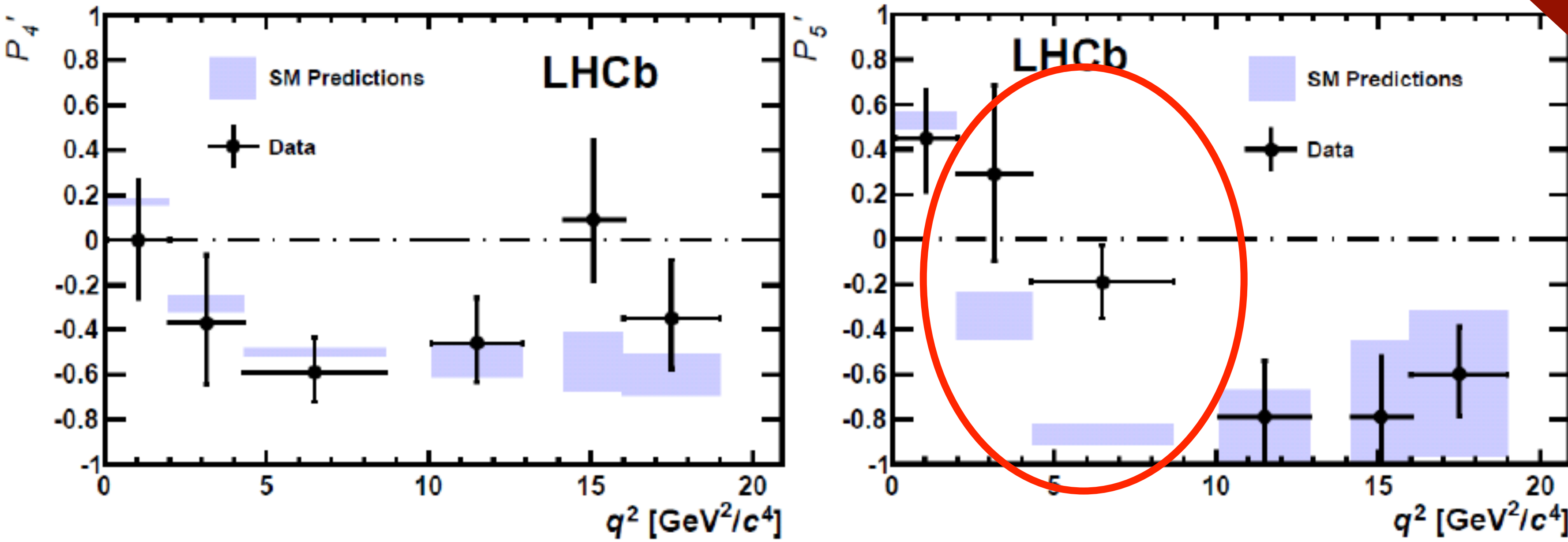
P'_4, P'_5 → Theoretically cleaner observables

- Plus observables for the 7$^{\text{th}}$ and 8$^{\text{th}}$ terms

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

See Danny & Michel

- 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 …

See Danny & Michel

… has just started.

- Interesting local discrepancy in P_5'
  - few others tension less significant in other observables

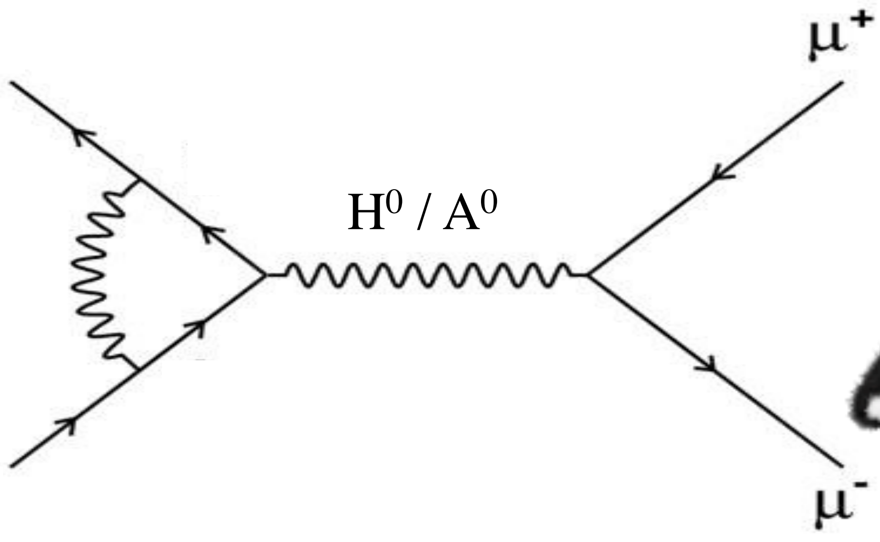
- Possibly due to:
  - statistical fluctuation
  - SM theoretical prediction not fully correct (QCD effects not fully understood???)
  - New Physics:
    different value for some Wilson coefficients, ex: C_9, or C_9 and C_9', including the possibility of Z' particle with a mass around few TeV

D. vanDyk et al, 1310.2478

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

$\Delta F=1$ Higgs penguins

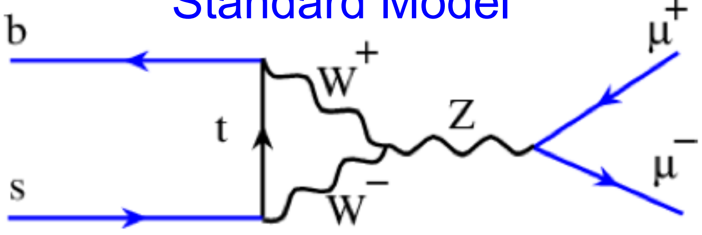
K_s, D^0, B_0, B_s



Golden channel: $B_{s,d} \to \mu^+\mu^-$

Theory prediction: Standard Model

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

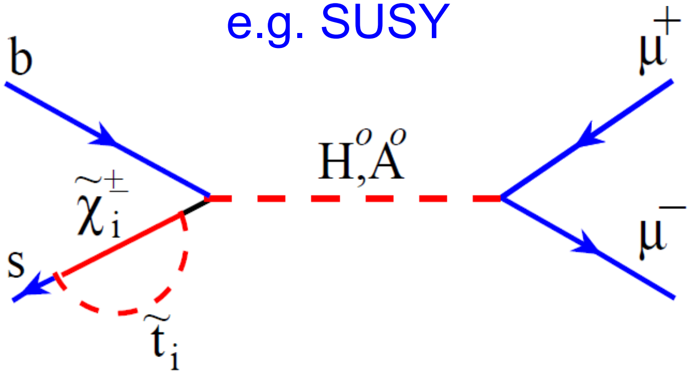


SM: Buras, Isidori et al: arXiv:1208.0934
Mixing effects: Fleischer et al, arXiv:1204.1737

Left handed couplings
→ helicity suppressed

Discovery channel for New Phenomena

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



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

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 $\bar{B}^0 \rightarrow \mu^+\mu^-$, 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→ $\mu^+\mu^-$

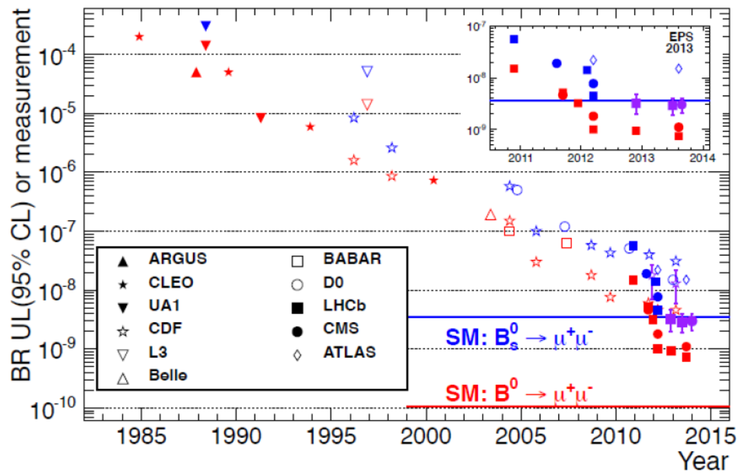
LHCb: Phys Rev Lett 110 (2013) 021801 (2.1 fb^{-1})

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

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

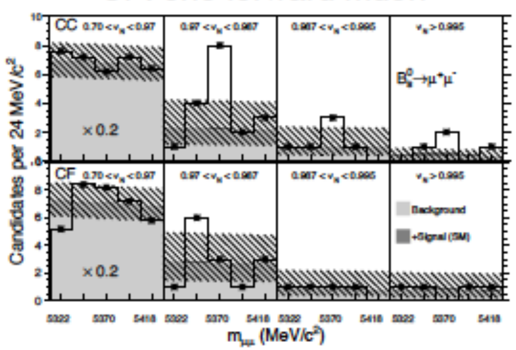
CDF: Phys. Rev. D 87, 072003 (2013) (9.7 fb^{-1})

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



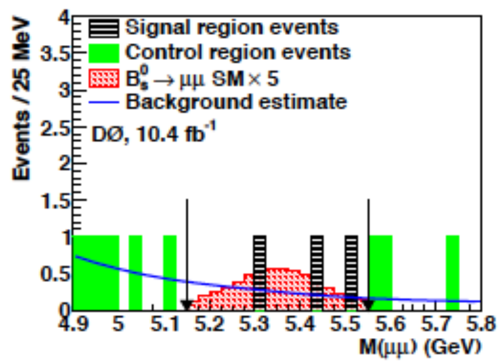
CC: two central muons

CF: one forward muon



95% CL:

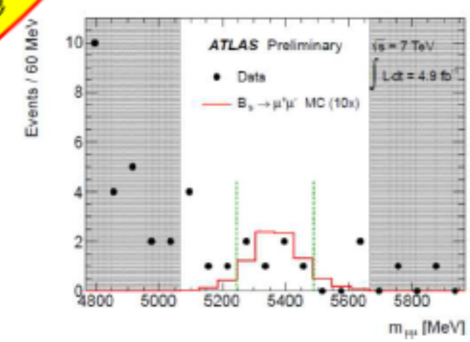
$\mathrm{BR}(B_s \to \mu^+\mu^-) < 3.1 \times 10^{-8}$



95% CL:

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

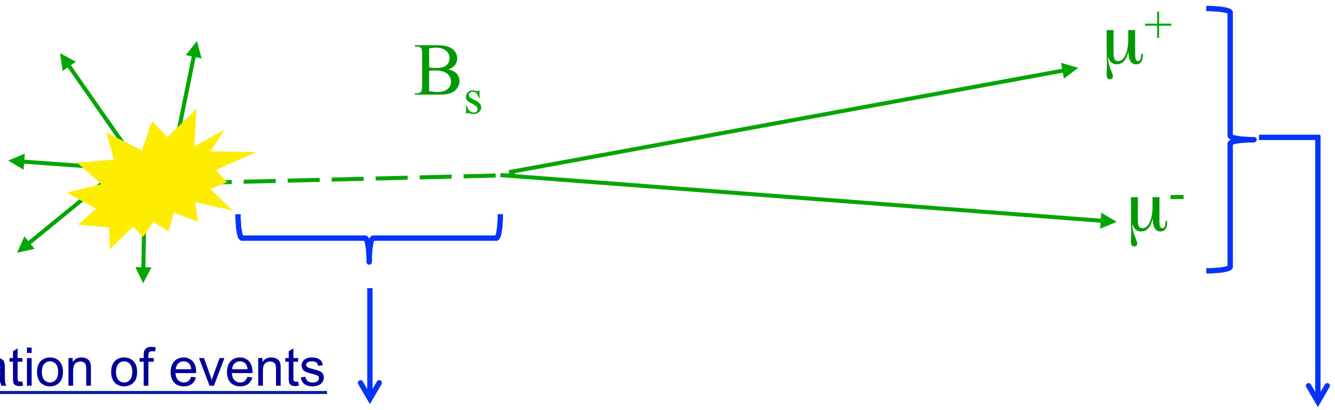
new @ EPS2013



95% CL:

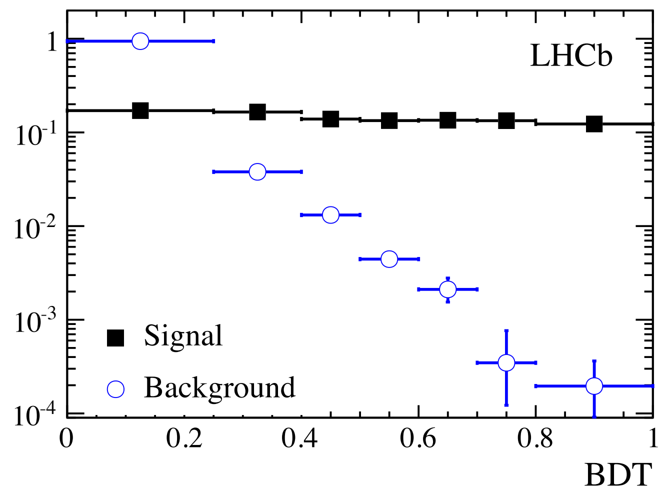
$\mathrm{BR}(B_s \to \mu^+\mu^-) < 1.5 \times 10^{-8}$

Search strategy: Example LHCb

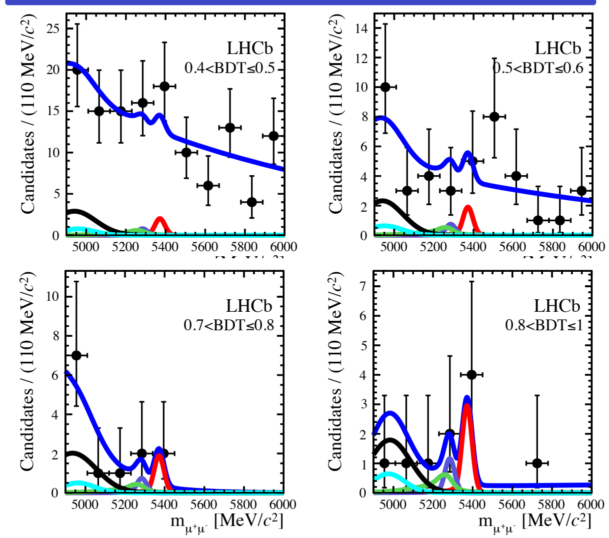


Classification of events

BDT (topology, kinematics)



Invariant mass



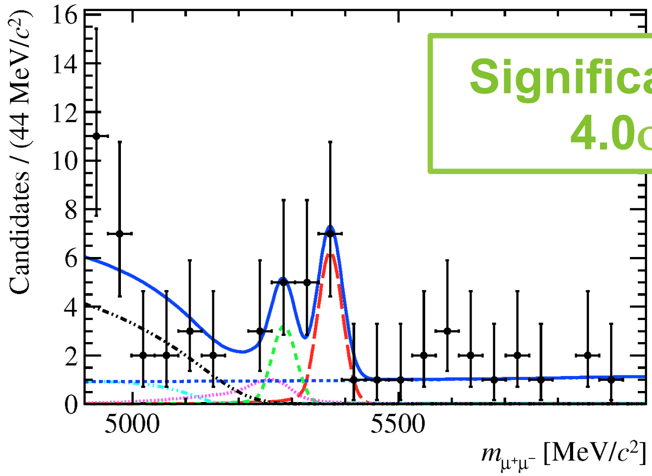
Measurement of exclusion limits or decay rates

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

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

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

- **Nov 2012: LHCb found the first evidence for $B_s \to \mu^+\mu^-$ using 2.1fb^{-1}**
- Update: full dataset: 3fb^{-1}
  - Improved BDT
  - Expected sensitivity: 5.0σ



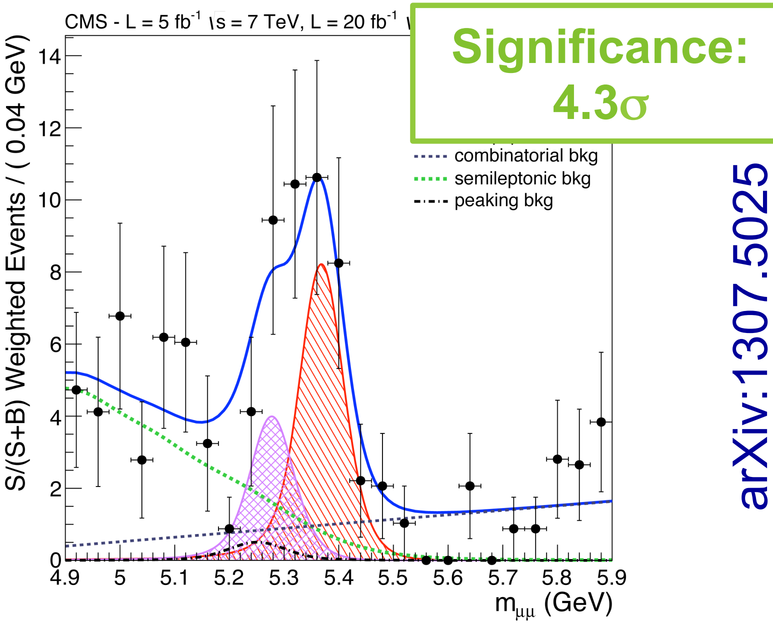
arXiv:1307.5024

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

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

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

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



arXiv:1307.5025

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

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

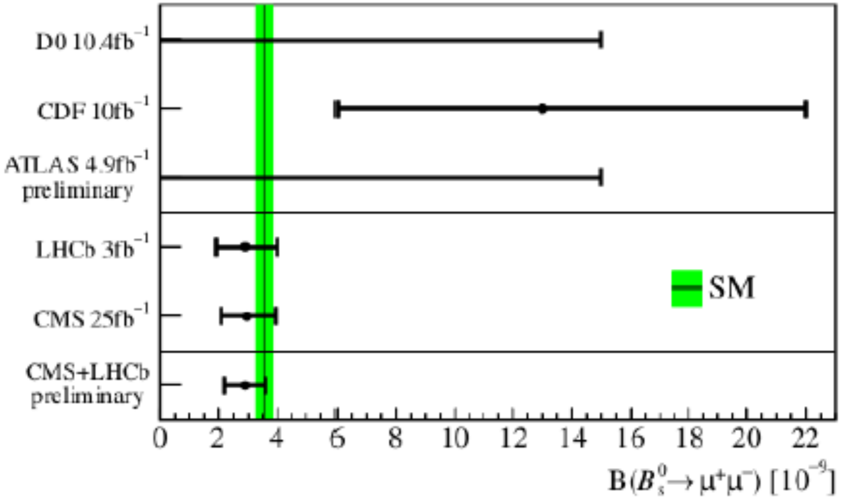
$$BR(B^0 \to \mu^+\mu^-) < 1.1 \times 10^{-9} @95\%CL$$

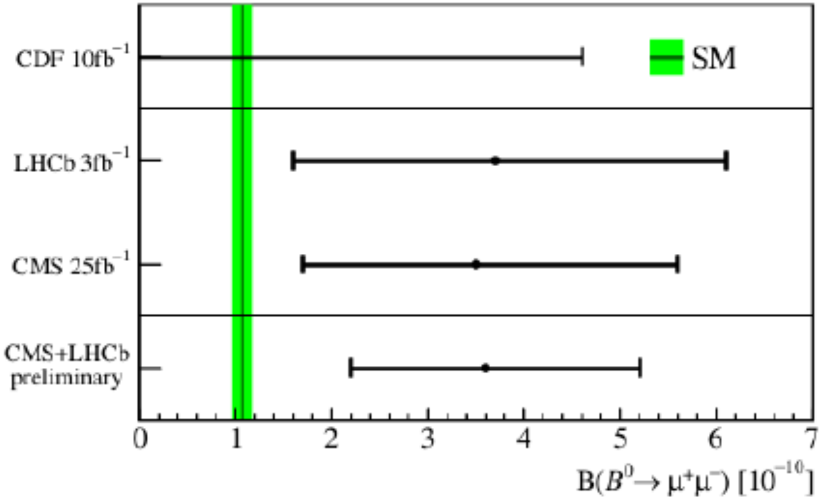
Observation:

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

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

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

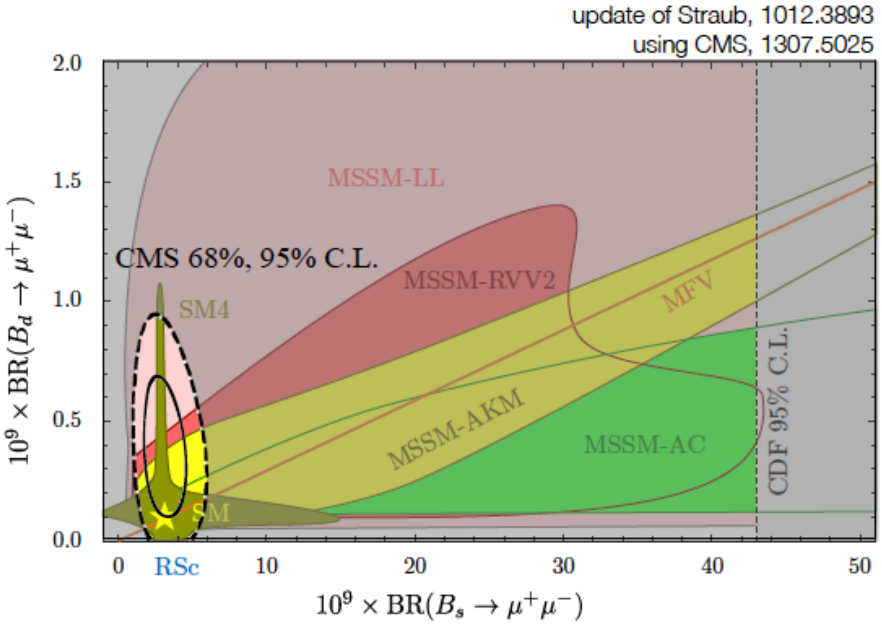




LHCb-CONF-2013-012, CMS-PAS-BPH-13-007

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

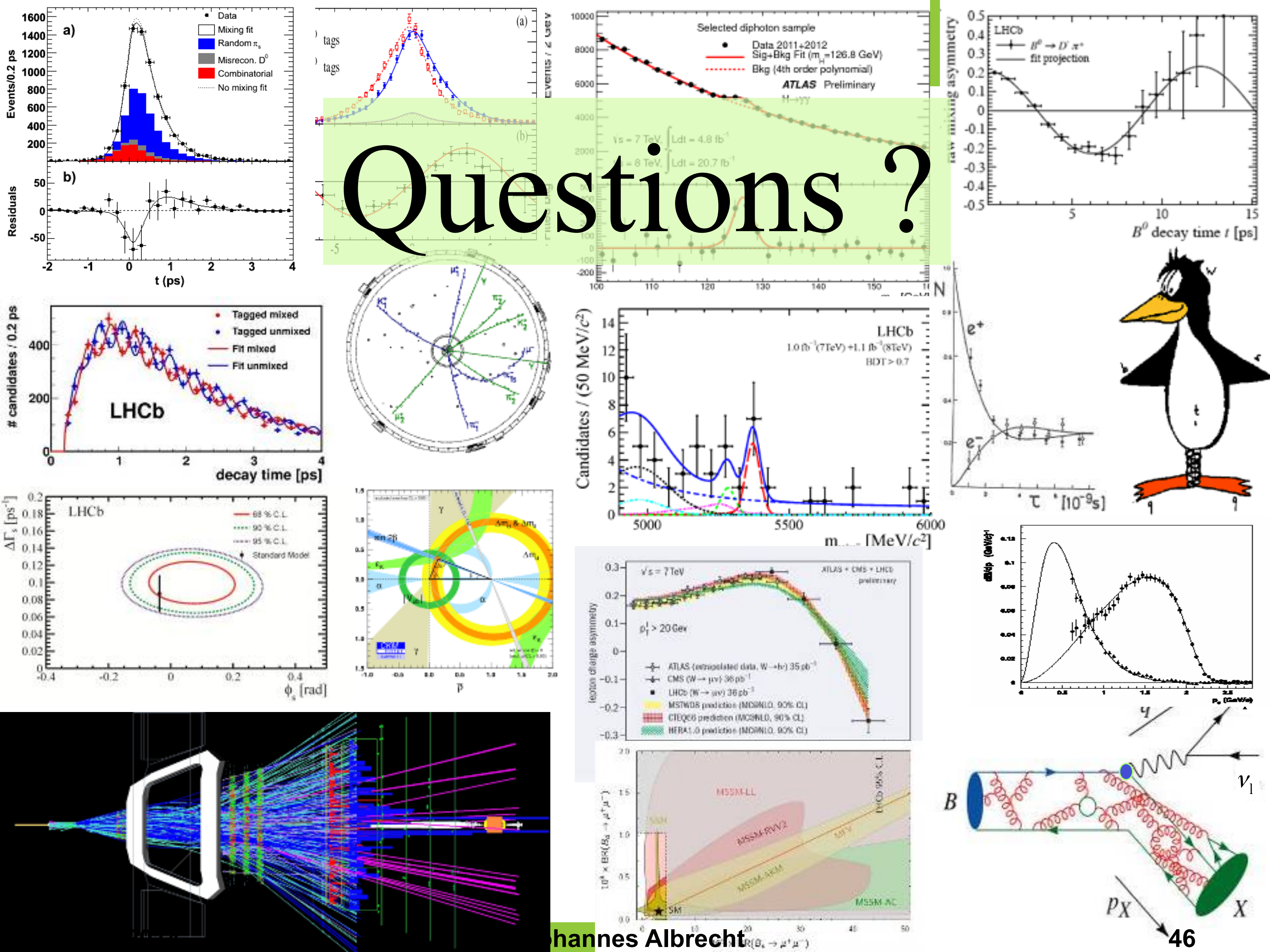
Summary

- **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

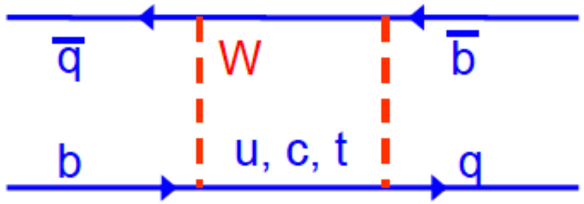
- However, interesting anomalies start to emerge
  - Assumptions are carefully re-assessed on the TH side
  - Measurements need to be confirmed

- 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, …


a)
Data
Mixing fit
Random π_s
Misrecon. D^0
Combinatorial
No mixing fit
Events/0.2 ps
b)
Residuals
t (ps)
Selected diphoton sample
Data 2011+2012
Sig+Bkg Fit (m_H=126.8 GeV)
Bkg (4th order polynomial)
ATLAS Preliminary
LHCb
$B^0 \to D^- \pi^+$
fit projection
B^0 decay time t [ps]
Tagged mixed
Tagged unmixed
Fit mixed
Fit unmixed
candidates / 0.2 ps
decay time [ps]
Candidates / (50 MeV/c^2)
BDT > 0.7
τ [10^{-9}s]
$\Delta\Gamma_s$ [ps^{-1}]
68 % C.L.
90 % C.L.
95 % C.L.
Standard Model
ϕ_s [rad]
$\sqrt{s}$ = 7 TeV
p_T^l > 20 GeV
lepton charge asymmetry
MSSM-LL
MSSM-RVV2
MSSM-AKM
MSSM-AC
MFV
SM
B
X
p_X
ν_l

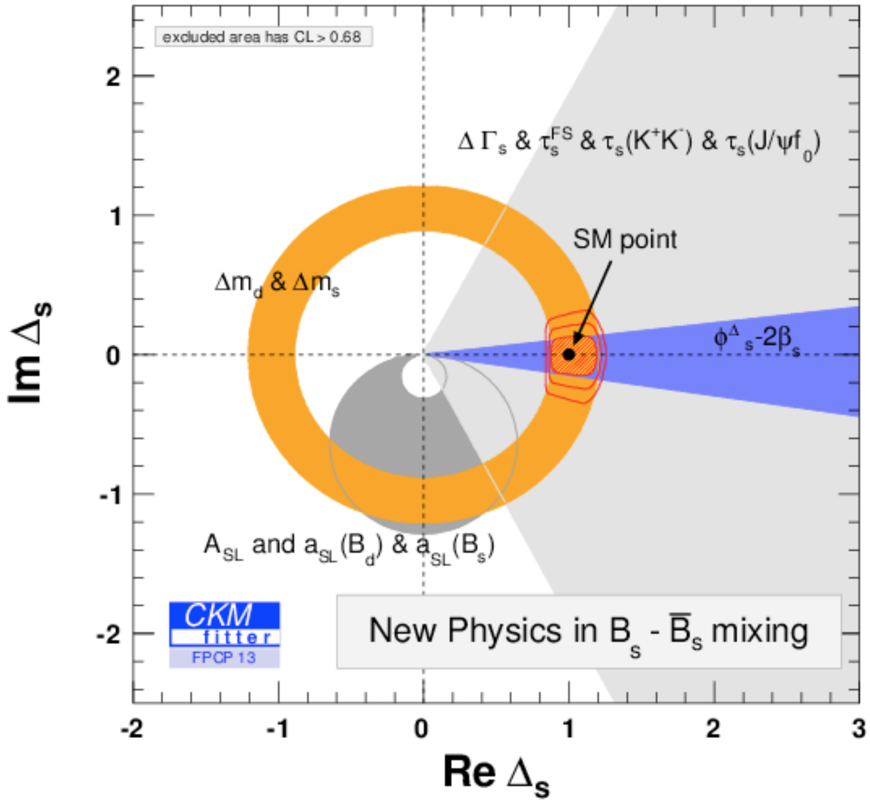
Questions ?

B_s:



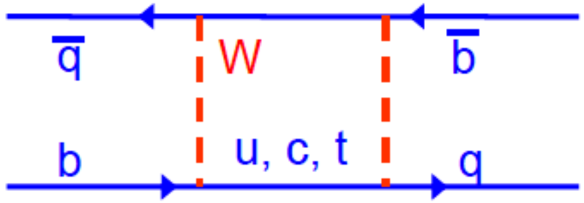
$$\mathcal{A}_{mix} = \mathcal{A}^{SM}_{mix} + \mathcal{A}^{NP}_{mix} = \mathcal{A}^{SM}_{mix} \times \Delta$$

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



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

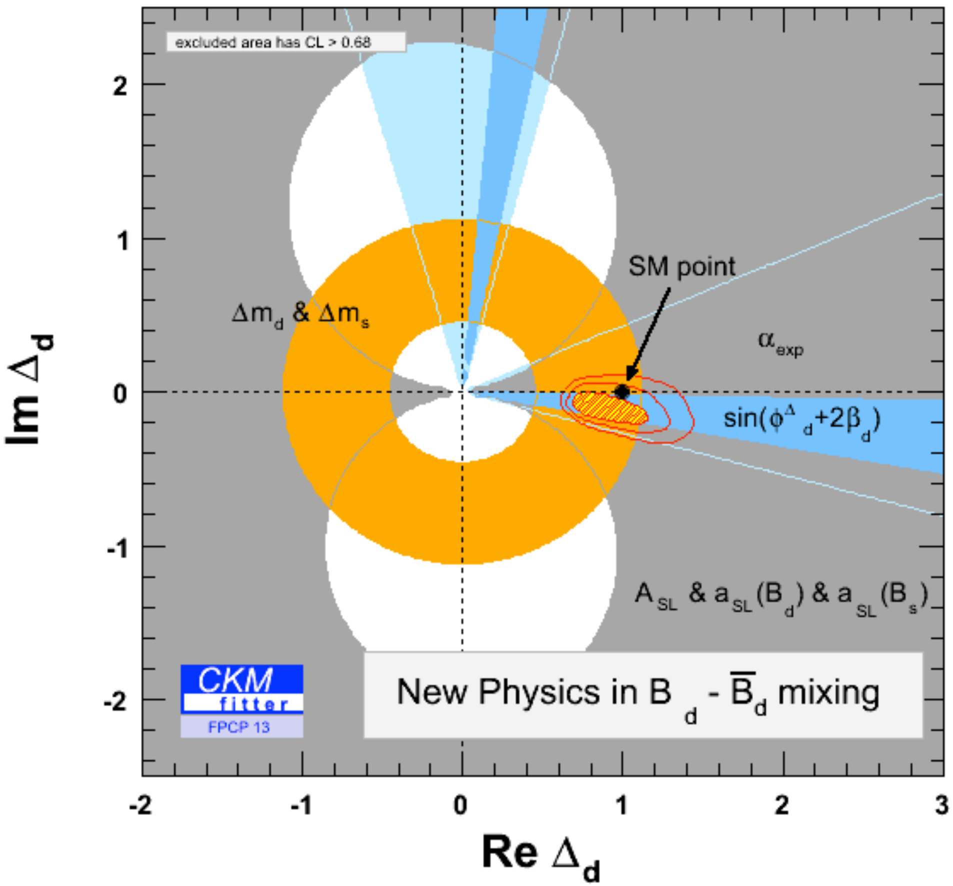
B^0:



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

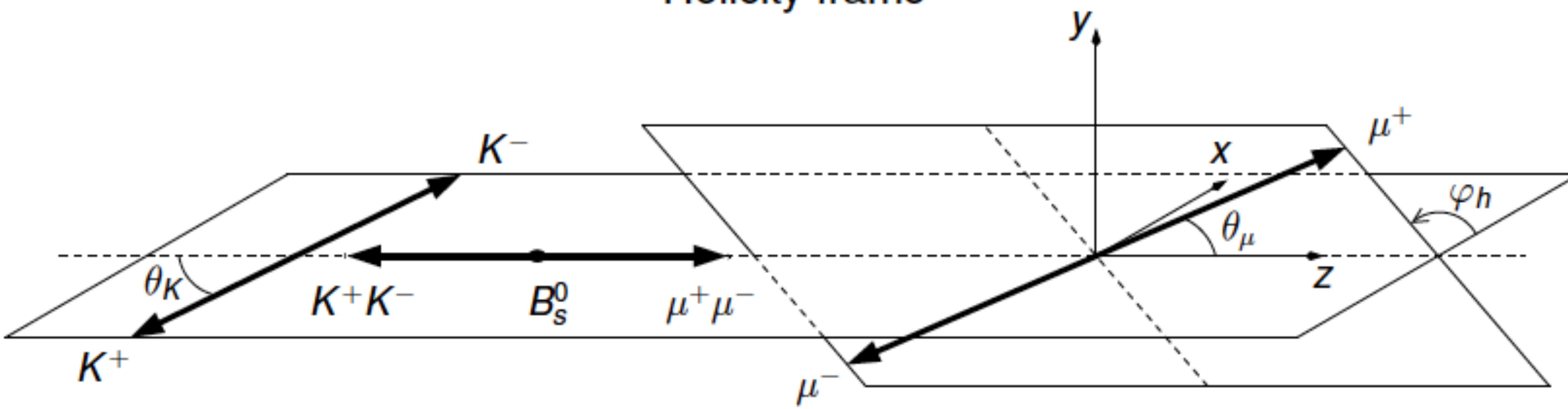
$$\Delta_s = |\Delta_s| e^{i\phi_s^{NP}}$$

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



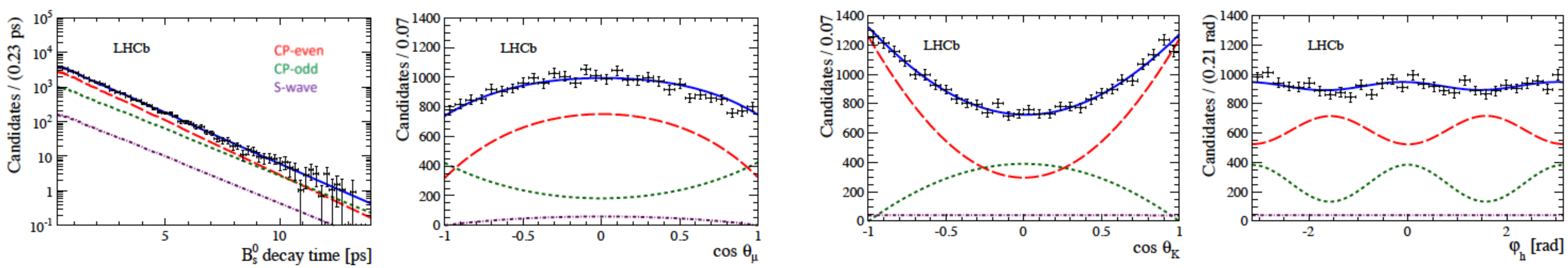
1.5σ "tension"
→ need more data

Helicity frame



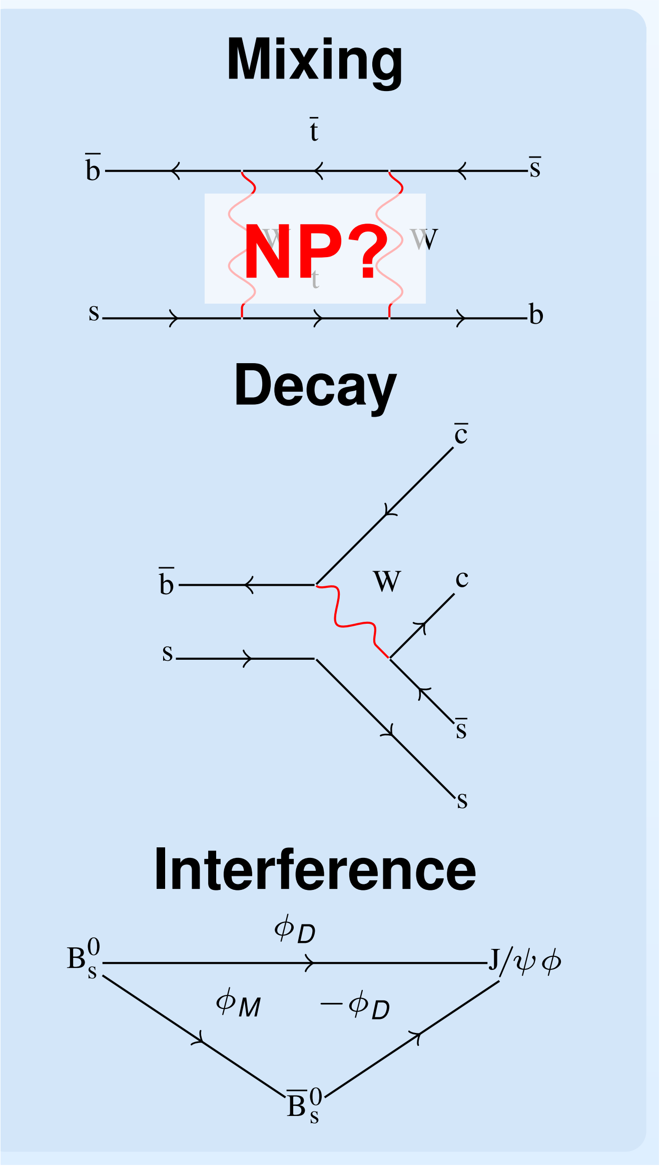
Fit differential decay rates (for B_s^0 and $\overline{B}_s^0$):

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




ANTIMATTER'S GONE MISSING...
WHEN DID THIS HAPPEN, SIR?
ABOUT 15 BILLION YEARS AGO...
LOST-PROPERTY OFFICE
CERN

CP violation in B_s mixing



- Interference between mixing and decay leads to CPV phase $\phi_s = \phi_M - 2\phi_D$
- Precise SM calculation for ϕ_s possible (small penguin contribution)

  $$\phi_s^{SM} = -0.0363 \pm 0.0016 \text{rad}$$

  CKMFitter, hep-ph:0406184

- Additional contributions from New Physics possible

  $$\phi_s = \phi_s^{SM} + \phi_s^{NP}$$

- Requires time dependent, flavour tagged angular analysis

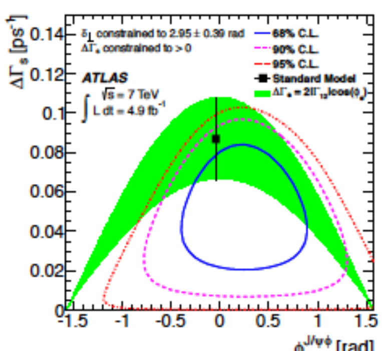
Summary of $B_s \rightarrow J/\psi\phi$ measurements

	CDF	D0	LHCb	ATLAS	CMS*)
$\int \mathcal{L}$ [fb^{-1}]	9.6	8.0	1.0	4.9	5.0
# $B_s \rightarrow J/\psi KK(f_0)$	11k	5.6k	27.6k (7.4k)	22.7k	14.5k
ϵD^2 OS [%]	1.39 ± 0.05	2.48 ± 0.22	2.29±0.22	1.45±0.05	-
ϵD^2 SS [%]	3.5±1.4	-	0.89±0.18	-	-
σ_t [fs]	100	100	48	100	-
Reference	PRL 109(2012) 171802	PRD85(2012) 032006	PRD87(2013) 112010	ATLAS-CONF-2013.029	CMS-PAS BPH-11-006

* CMS: $\Delta\Gamma$ only: 0.048±0.024±0.003 ps^{-1}

The importance of Flavour tagging

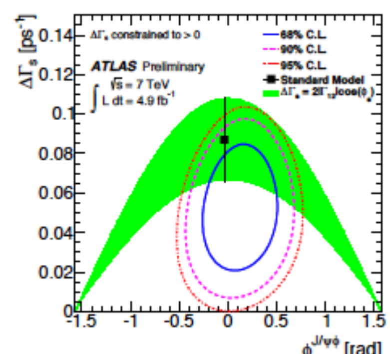
ATLAS untagged result



JHEP 12 (2012) 072

uncertainty on ϕ_s improved by 40%

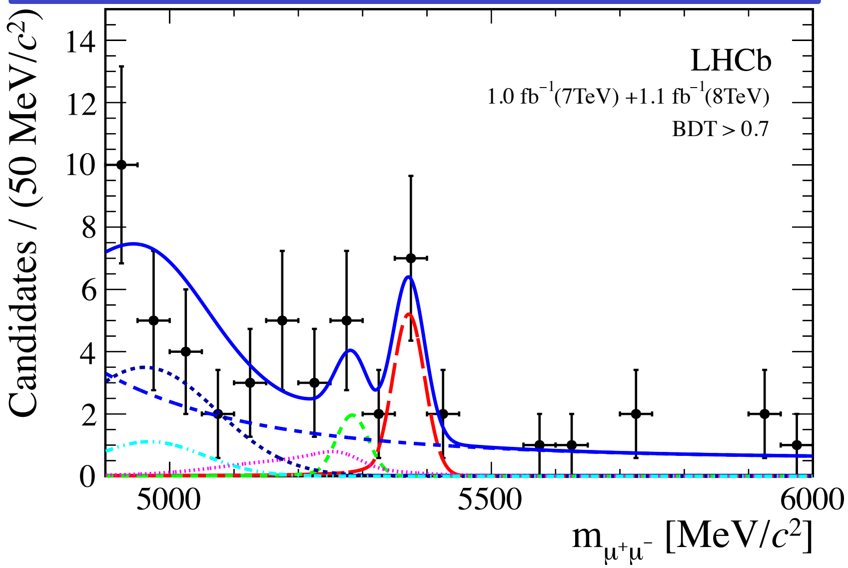
ATLAS tagged result



ATLAS-CONF-2013-039

Evidence for $B_s \to \mu^+\mu^-$

Signal region: $B_s \to \mu^+\mu^-$



Highlight after 25 years of searches (Argus 1987)

PRL 110 (2013) 021801

- New analysis: **3.5σ evidence for decay $B_s \to \mu^+\mu^-$** (HCP 12)

- First branching fraction measured:

$$BR(B_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$

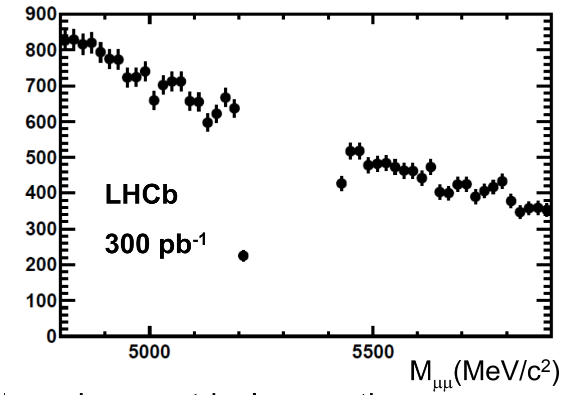
HCP2012

In good agreement with SM, but 40% uncertainty

- Limits obtained by other experiments:
  - CMS ($5fb^{-1}$): BR < 7.7×10^{-9} (sensitivity ~ LHCb with 2011+2012 dataset)
  - ATLAS ($2.4fb^{-1}$): BR < 22×10^{-9}
  - CDF ($10fb^{-1}$): BR < 31×10^{-9} , D0 ($10.4fb^{-1}$): BR < 15×10^{-9}

LHCb analysis strategy

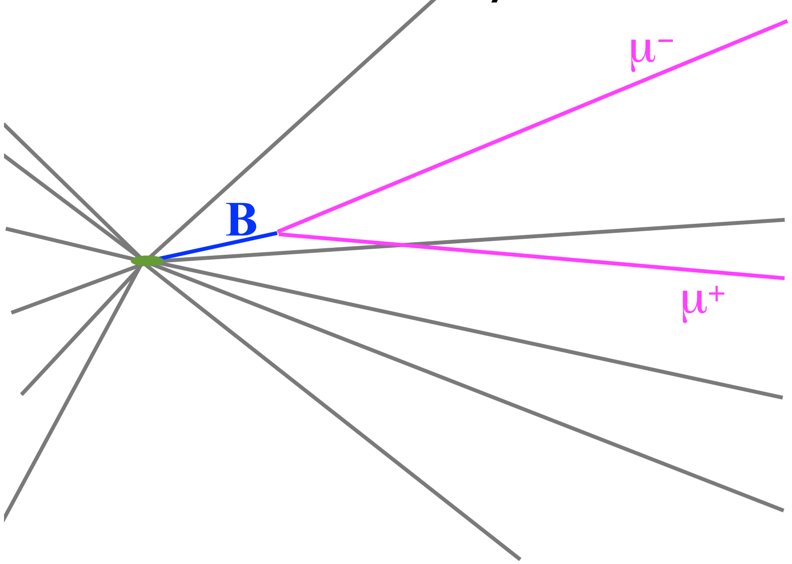
- **Selection**
  - Muon based triggers
  - Soft selection to reduce size of dataset
  - Similar to control channels
  - BDT based preselection for signal & control channels



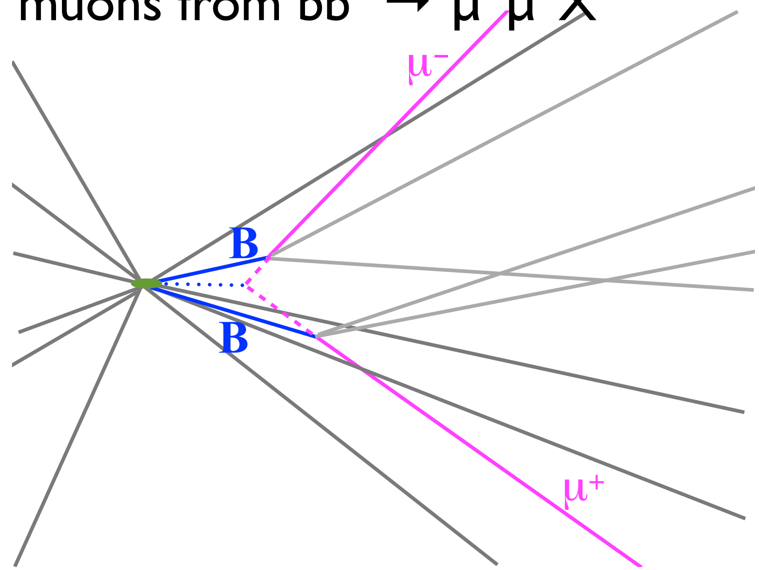
- **Signal and background likelihoods**
  - Multivariate classifier combining topological and kinematic information (BDT)
  - Invariant mass
- **Normalization**
  - Convert number of observed events in branching fraction by normalizing with channels of known BR
- **Extraction of the limit**
  - Extract observation / exclusion measurement using the CLs method
  - Determine branching fraction with unbinned ML fit

Signal discrimination

signal: 2 muons from a single well reconstructed secondary vertex



dominant background: two real muons from $b\bar{b} \rightarrow \mu^+\mu^-X$



Discrimination is achieved by a BDT with 9 input variables

B candidate:

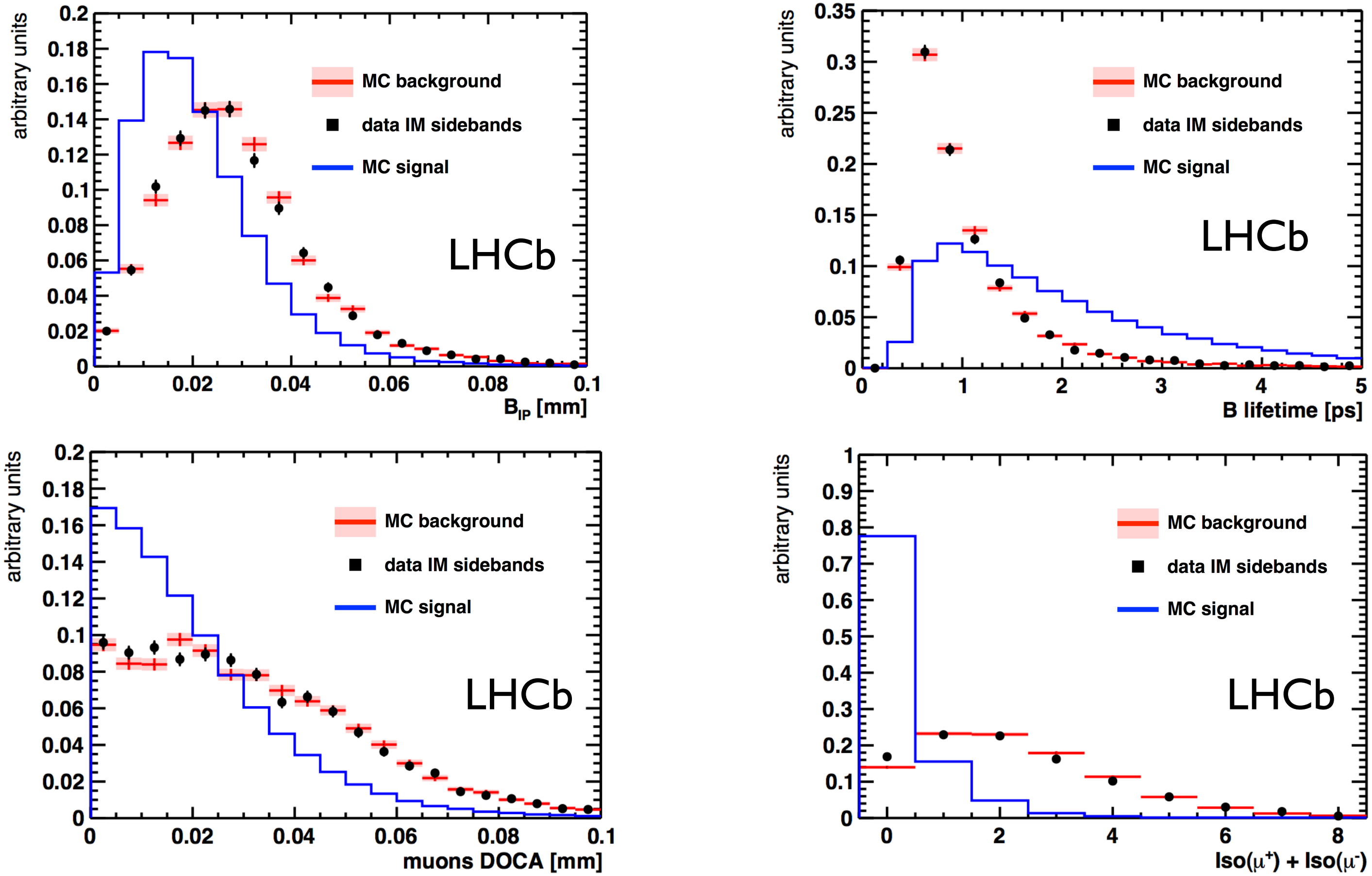
- proper time
- impact parameter
- transverse momentum
- B isolation

muons:

- min p_T
- min IP significance
- distance of closest approach
- muon isolation,
- polarization angle

this choice of variables avoids correlation with invariant mass

Signal discrimination: BDT input



Optimization and training on MC $B^0_s \rightarrow \mu^+\mu^-$ signal and $b\bar{b} \rightarrow \mu^+\mu^- X$ background
Same definition of BDT is used for 7 TeV and 8 TeV data, since most of the input variables are in very good agreement (checked on $B^\pm \rightarrow J/\psi K^\pm$)

Signal discrimination: BDT response

BDT output defined to be flat for signal, and peaked at zero for background

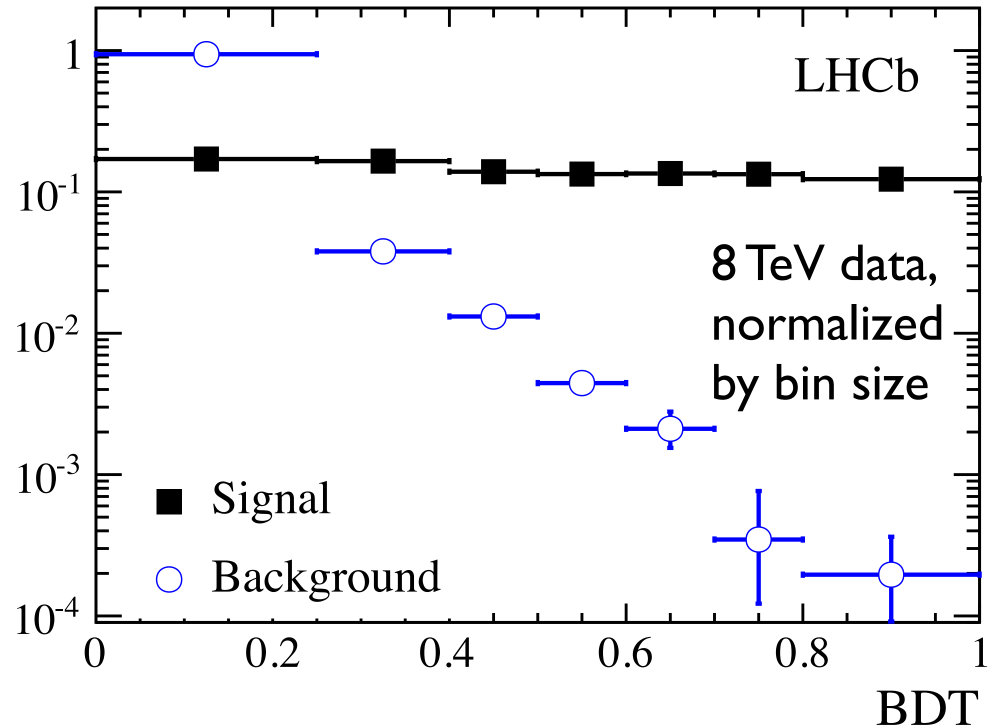
Signal BDT shape from $B^0_{(s)} \to h^+h'^-$ events, which have same topology as the signal (use sample triggered independent of the signal, to avoid bias)

Background BDT shape is evaluated on the dimuon mass sidebands

Analysis is performed in BDT bins

- BDT binning optimized on 7 TeV data → 8 bins

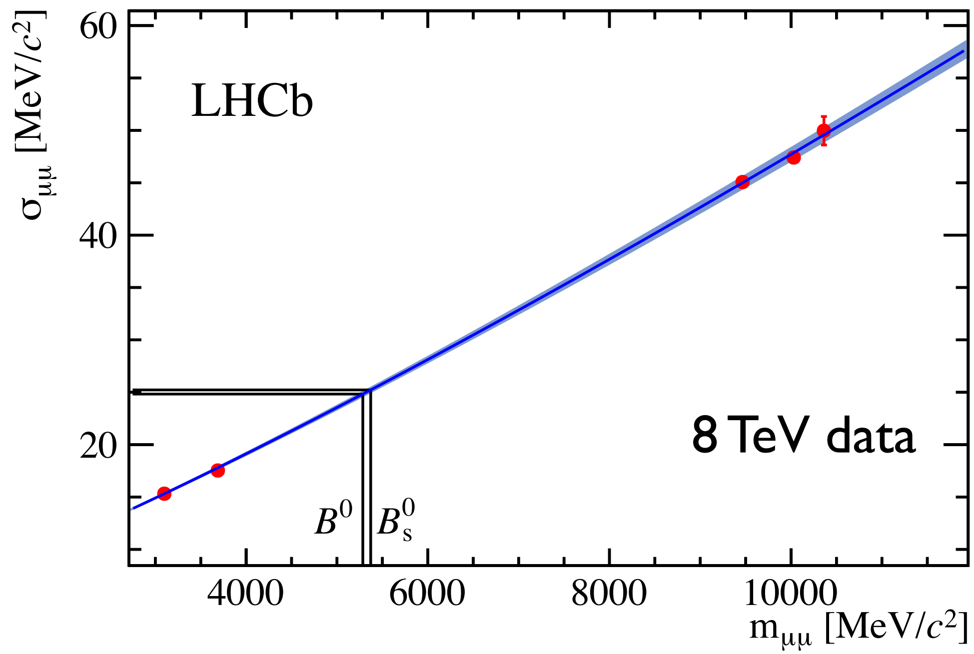
- For 8 TeV data we merged the two most sensitive bins (BDT>0.8), since we had no events on the mass sidebands: 8 TeV data → 7 bins



Two independent methods

1) Interpolation of dimuon resonances:
J/ψ and $\psi(2S)$,
$\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$

2) From $B^0_{(s)} \rightarrow h^+h'^-$



Results are in agreement:

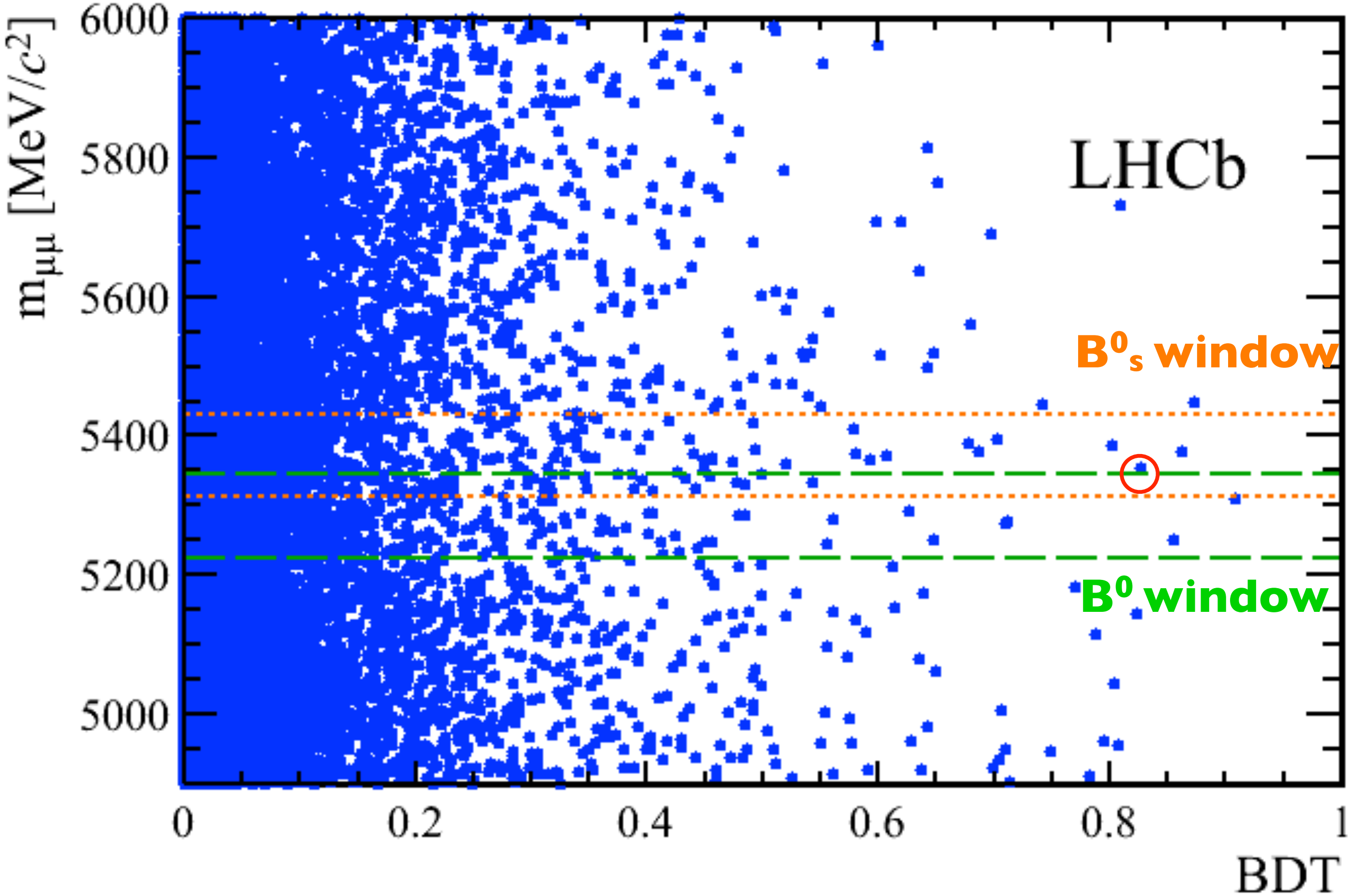
$$\sigma_{B^0} = (24.63 \pm 0.13_{\rm stat} \pm 0.36_{\rm syst})\ {\rm MeV}/c^2$$
$$\sigma_{B^0_s} = (25.04 \pm 0.18_{\rm stat} \pm 0.36_{\rm syst})\ {\rm MeV}/c^2$$

8 TeV data:

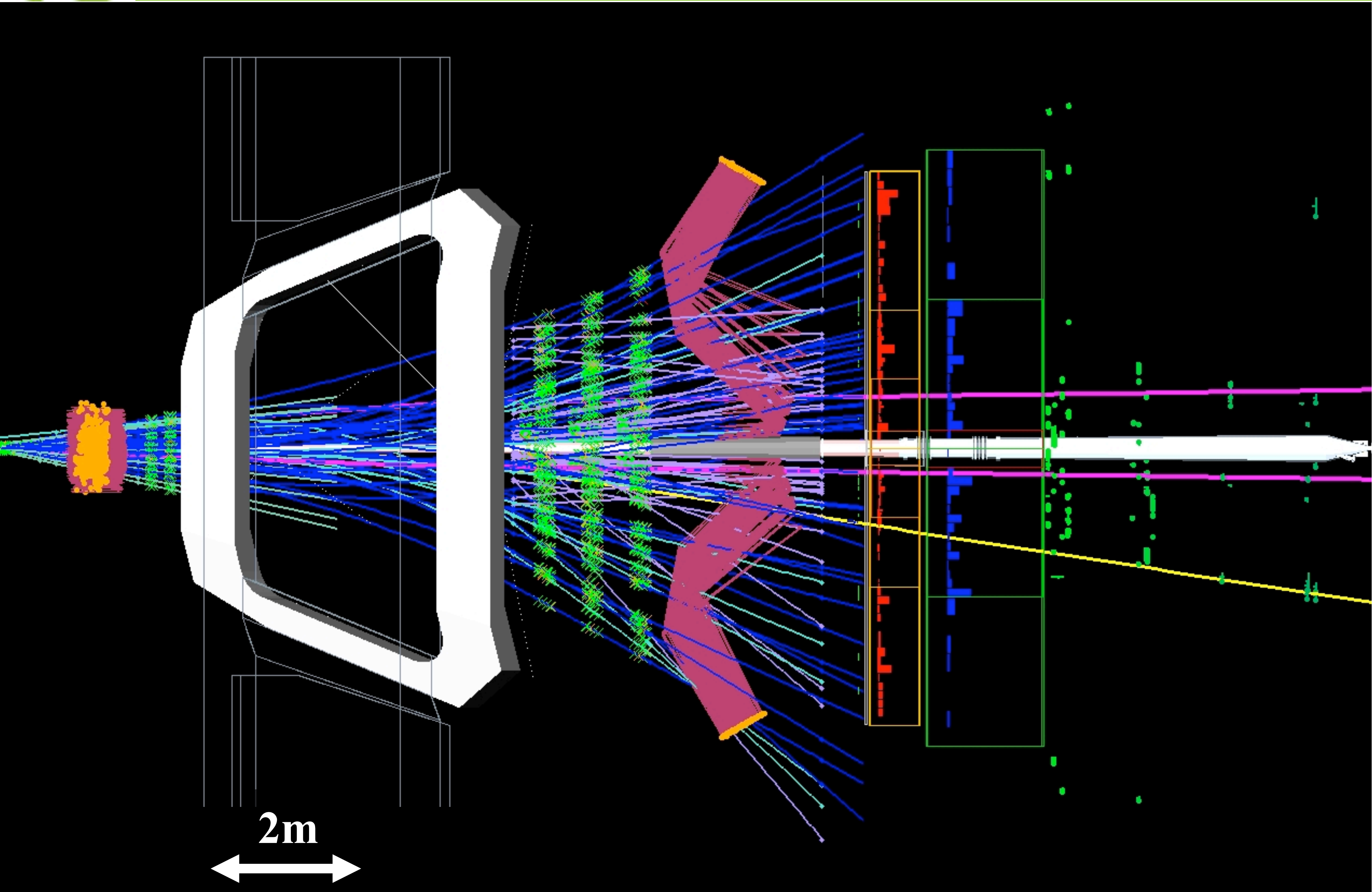
~1% difference observed between 7 TeV and 8 TeV data

For the signal mass pdf we use a Crystal Ball: transition point of the radiative tail from simulated events smeared to reproduce the measured resolution

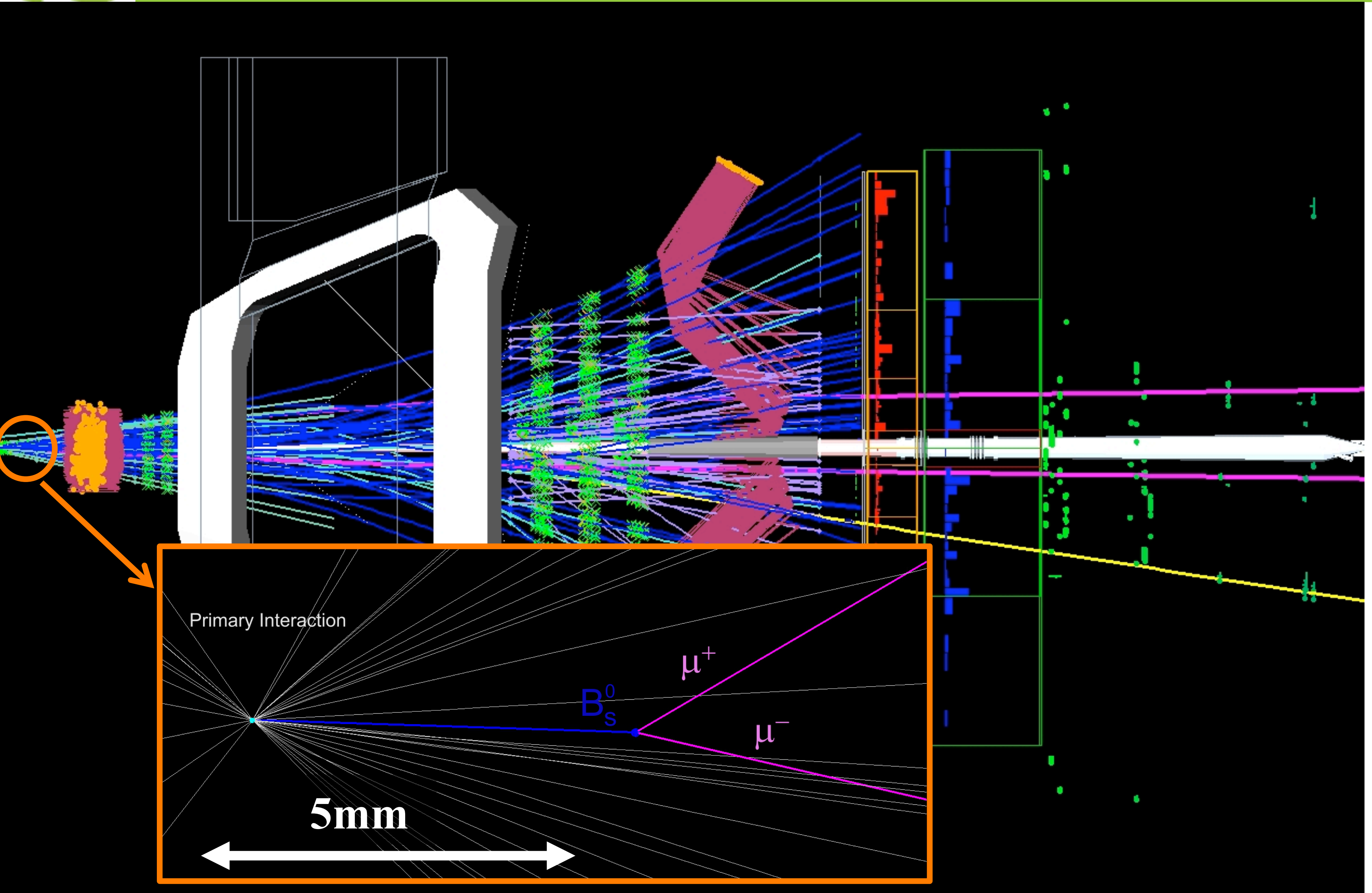
8 TeV data


LHCb
B^0_s window
B^0 window
$m_{\mu\mu}$ [MeV/c^2]
6000
5800
5600
5400
5200
5000
0
0.2
0.4
0.6
0.8
1
BDT

High likelihood event I



High likelihood event (zoom)



Normalization to channels with known BR

$$BR = BR_{cal} \cdot \frac{\varepsilon_{cal}^{Rec} \cdot \varepsilon_{cal}^{Sel} \cdot \varepsilon_{cal}^{Trig}}{\varepsilon_{Bs}^{Rec} \cdot \varepsilon_{Bs}^{Sel} \cdot \varepsilon_{Bs}^{Trig}} \cdot \frac{f_{cal}}{f_{B_s}} \cdot \frac{N_{B\to\mu\mu}}{N_{cal}} = \alpha \cdot N_{B\to\mu\mu}$$

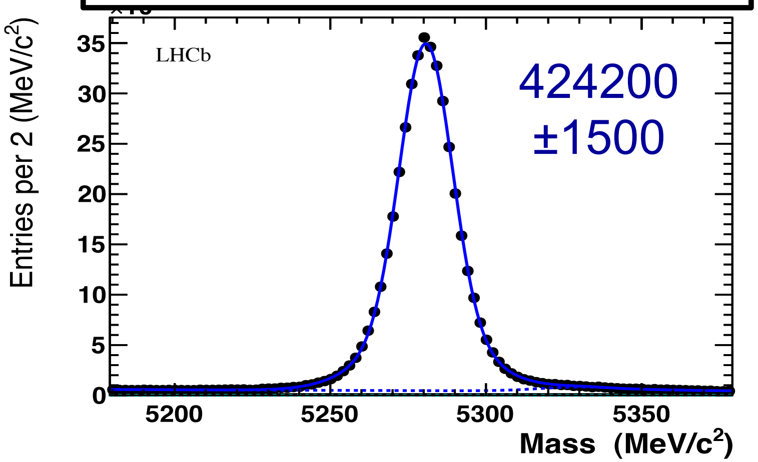
Evaluated from MC, cross checked with data

Measured in data

Ratio of probability for a b-quark to hadronize into a given meson

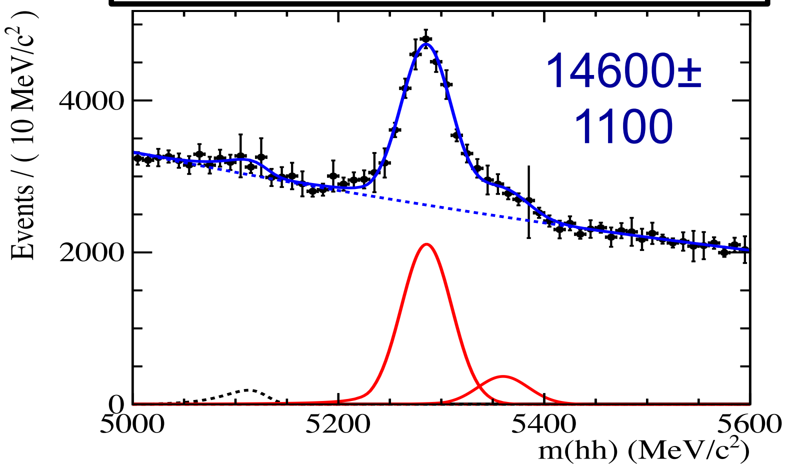
(more next slide)

$B^\pm \to J/\psi K^\pm$



wrt signal: similar trigger, one more track

Trigger unbiased $B \to h^+ h'^-$



wrt signal: different trigger, same topology

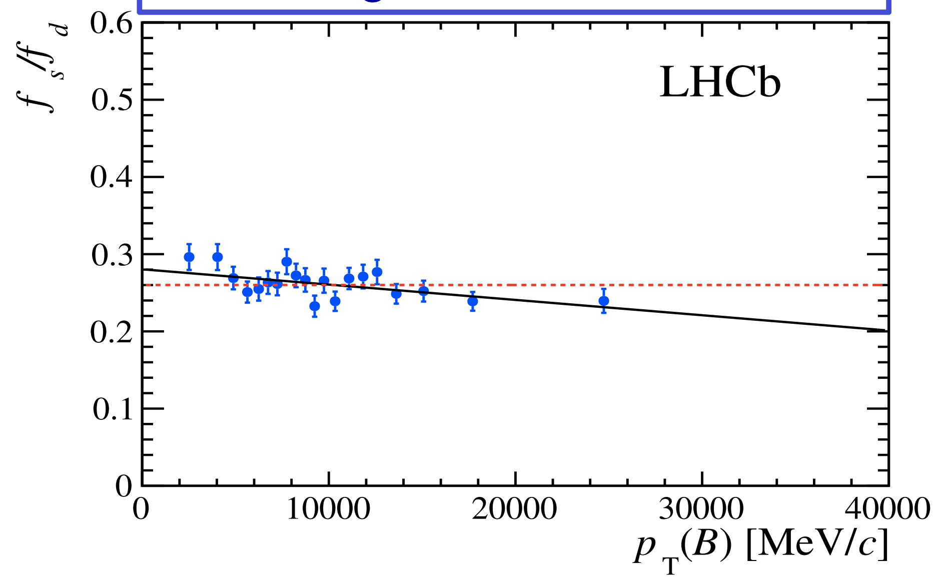
b fragmentation f_d/f_s (updated)

- LHCb has measured the fraction of $b \rightarrow B_s$ in two ways:
  - Ratio of $B_s \rightarrow D_s \mu X$ to $B \rightarrow D^+ \mu X$ [PRD85 (2012) 032008]
  - Ratio of $B_s \rightarrow D_s \pi^+$ to $B \rightarrow D^+ K$ and $B^0 \rightarrow D^+ \pi^+$ (**newly updated: $1 fb^{-1}$ @ 7 TeV**)
- Combined result $$\frac{f_s}{f_d} = 0.256 \pm 0.020$$

[LHCb-PAPER-2012-037] in preparation

- Found to be dependent of p_T
  - For the p_T values involved: effect smaller than 0.02 → negligible
- Stability 7 vs 8 TeV checked
  - $B^+ \rightarrow J/\psi K^+ / B_s \rightarrow J/\psi \phi$ ratio stable

B fragmentation Vs PT



Normalization to channels with known BR

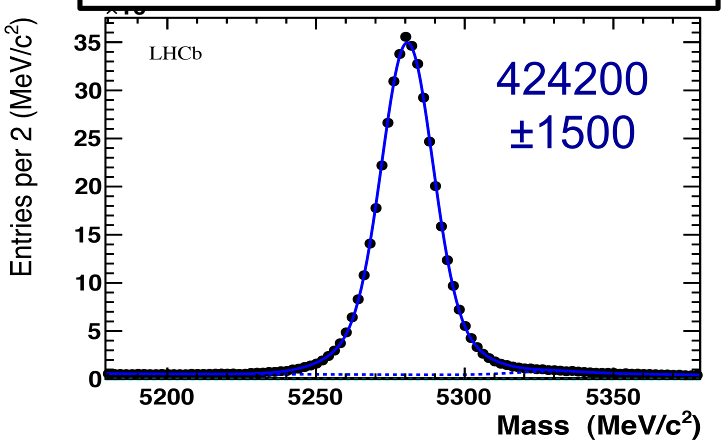
$$BR = BR_{cal} \cdot \frac{\varepsilon_{cal}^{Rec} \cdot \varepsilon_{cal}^{Sel}}{\varepsilon_{Bs}^{Rec} \cdot \varepsilon_{Bs}^{Sel}} \cdot \frac{\varepsilon_{cal}^{Trig}}{\varepsilon_{Bs}^{Trig}} \cdot \frac{f_{cal}}{f_{B_s}} \cdot \frac{N_{B\to\mu\mu}}{N_{cal}} = \alpha \cdot N_{B\to\mu\mu}$$

Evaluated from MC, cross checked with data

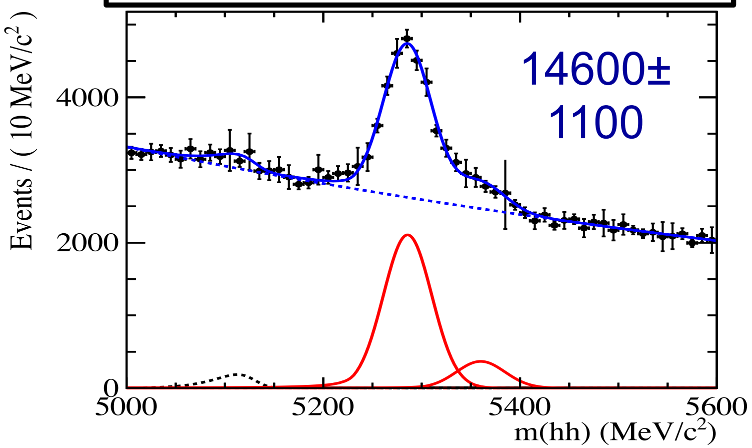
Measured in data

Ratio of probability for a b-quark to hadronize into a given meson

B±→J/ψK±



Trigger unbiased B→h⁺h'⁻



normalization factors from $B^\pm \to J/\psi K^\pm$ and $B \to h^+h'^-$ agree
→ take weighted average

$$\alpha(B_s \to \mu^+\mu^-) = (2.52 \pm 0.23) \times 10^{-10}$$
$$\alpha(B^0 \to \mu^+\mu^-) = (6.45 \pm 0.30) \times 10^{-11}$$

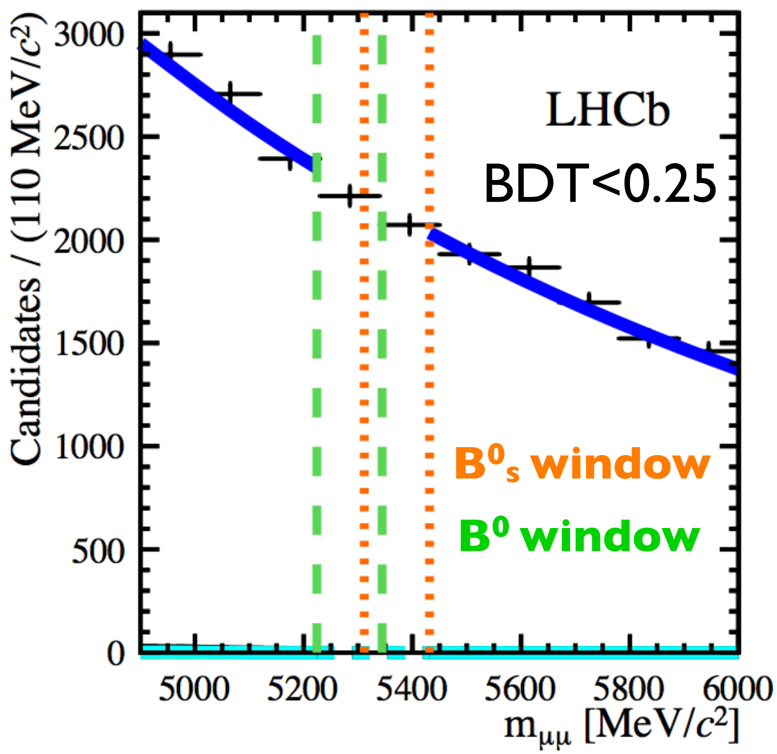
Background sources

The main background source in the $B^0_s \to \mu^+\mu^-$ signal window, $m(B^0_s)\pm60$ MeV/c^2, is combinatorial from $b\bar{b} \to \mu^+\mu^-X$

For CLs computation, the expected background yield in the signal region is evaluated from a fit to the mass sidebands, for each BDT bin separately

An exponential shape is assumed

For BDT values <0.5 this is by far the dominant bkg source in the mass range [4900-6000] MeV/c^2

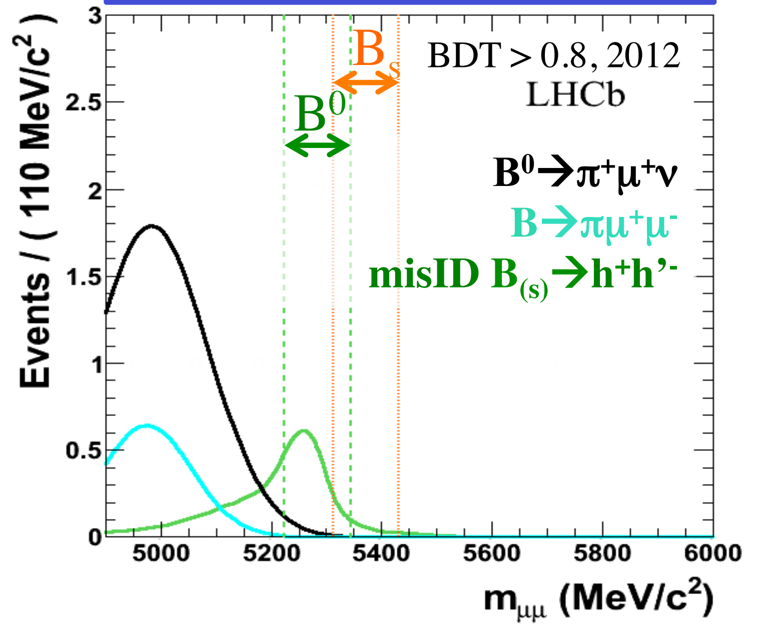


Peaking backgrounds

- Improvement of combinatorial background interpolation by inclusion of backgrounds from exclusive decays in the fit
  - Contribution in signal window: only $B_{(s)} \to h^+h'^-$ (identical treatment as 2011)
  - Mass shape different from exponential → bias the background interpolation (new):
    - $B^0 \to \pi^+\mu^-\nu$
    - $B^+ \to \pi^+\mu^+\mu^-$, $B^0 \to \pi^0\mu^+\mu^-$ (considered together)

    Both have a negligible contribution in the B^0 and B_s mass windows
- Exclusive background parameters used as priors in the fit (allowed to vary within 1σ)
  - Yield from relative normalization to $B^+ \to J/\psi K^+$
  - Mass and BDT shape from full MC
- Background systematic reduced (2011 was comparison exp-double exp)

Exclusive backgrounds

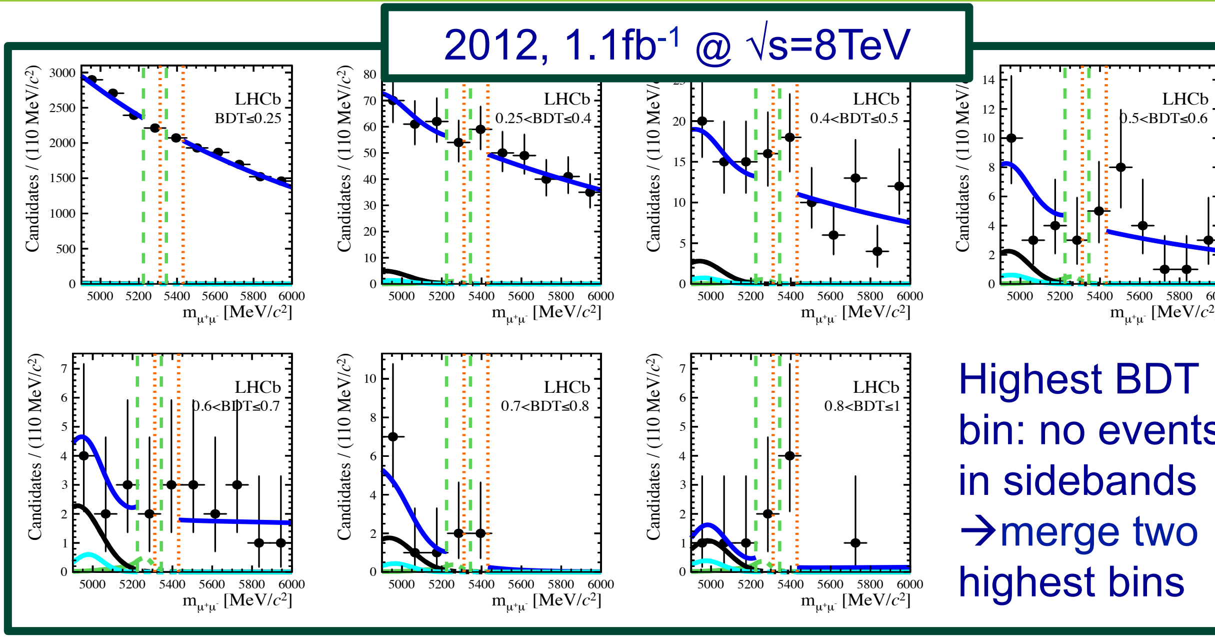


Expected events in [4.9 - 6] GeV, BDT > 0.8

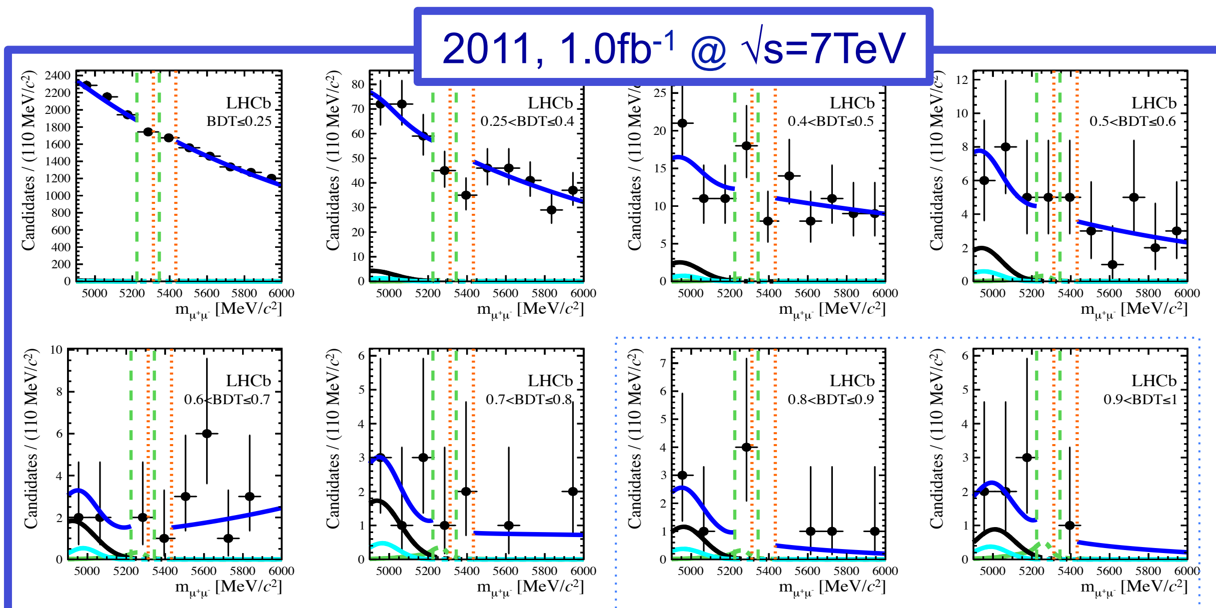
$B^0 \to \pi^-\mu^+\nu_\mu$	4.04 ± 0.28
$B^0_{(s)} \to h^+h^-$ misID	1.37 ± 0.11
$B^{+(0)} \to \pi^{+(0)}\mu^+\mu^-$	1.32 ± 0.39

Observed pattern of events

- Mass sideband fit to extrapolate background
  - Combinatorial background and
    - **$B^0 \rightarrow \pi^+\mu^+\nu$**
    - **$B \rightarrow \pi\mu^+\mu^-$**
    - **$B_{(s)} \rightarrow h^+h'^-$(misID)**

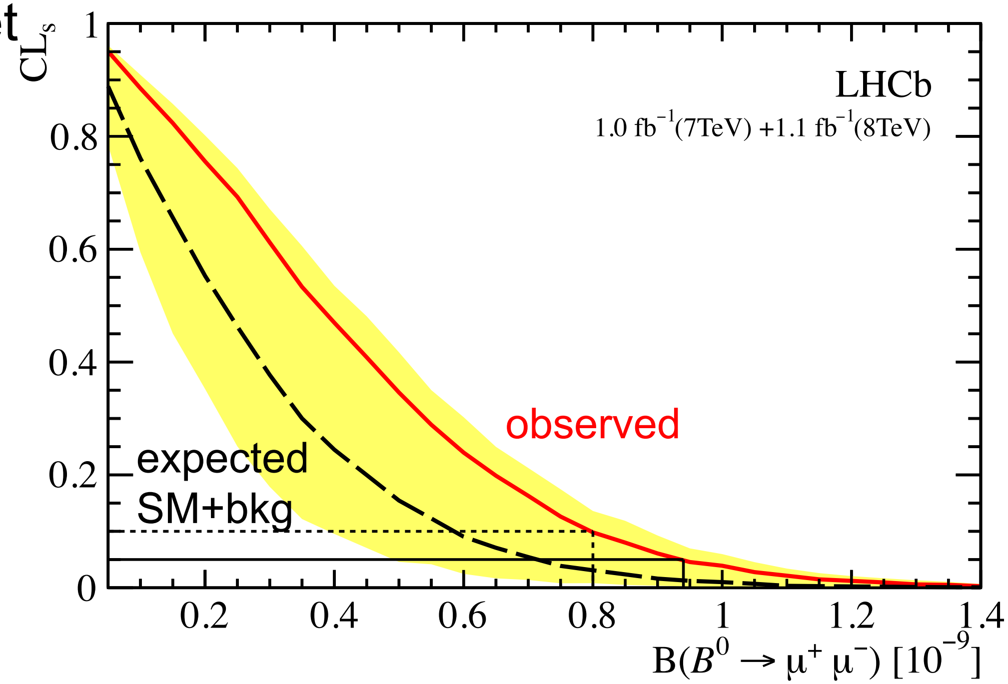


- Same fit has been repeated on 2011
  - Combinatorial component reduced in high BDT bins
  - Impact on published results evaluated



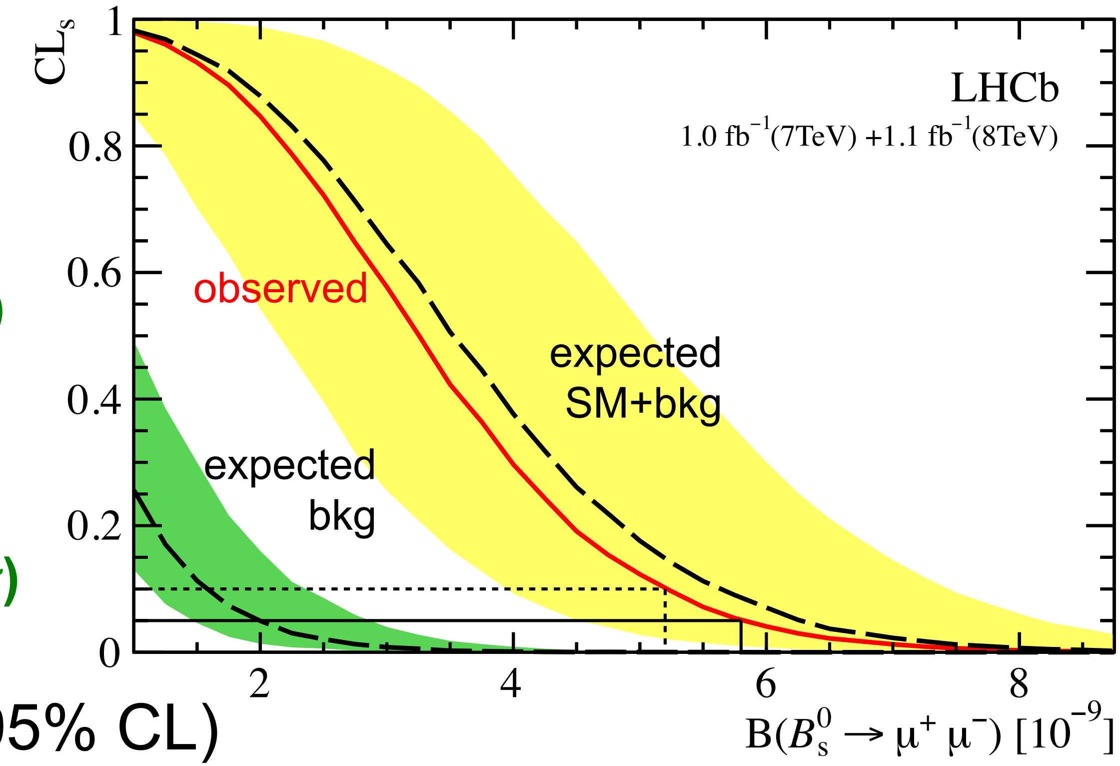
Results for $B^0 \to \mu^+\mu^-$

- Evaluate compatibility with background only and signal+background hypotheses (CLs method)
  - Combined 2011+2012 dataset used
  - bkg only p-value: 11%
  - Upper exclusion limit $BR(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10}$ @95% CL
    world best single experiment



$B^0 \to \mu^+\mu^-$	expected (bkg)	expected (SM+bkg)	observed	1-CLb
2012	9.6×10^{-10}	10.5×10^{-10}	12.5×10^{-10}	0.16
2011+2012	6.0×10^{-10}	7.1×10^{-10}	**9.4×10^{-10}**	**0.11**

- Evaluate compatibility with background only and background+signal hypotheses (CLs method)
  - **2011+2012: bkg only p-value: 5×10^{-4} (corresponds to 3.5σ)**
  - **2012 alone bkg only p-value: 9×10^{-4} (corresponds to $3.3\ \sigma$)**



- Double sided limit (@95% CL)

$$1.1\times10^{-9} < BR(B_s \rightarrow \mu^+\mu^-) < 6.4\times10^{-9}$$

- **This is the first evidence of the decay $B_s \rightarrow \mu^+\mu^-$!**

Branching fraction fit

- Unbinned maximum likelihood fit to the mass spectra
  - 8 BDT bins of 7 TeV and 7 BDT bins of 8 TeV data are treated simultaneously
  - mass range [4900-6000] MeV/c^2

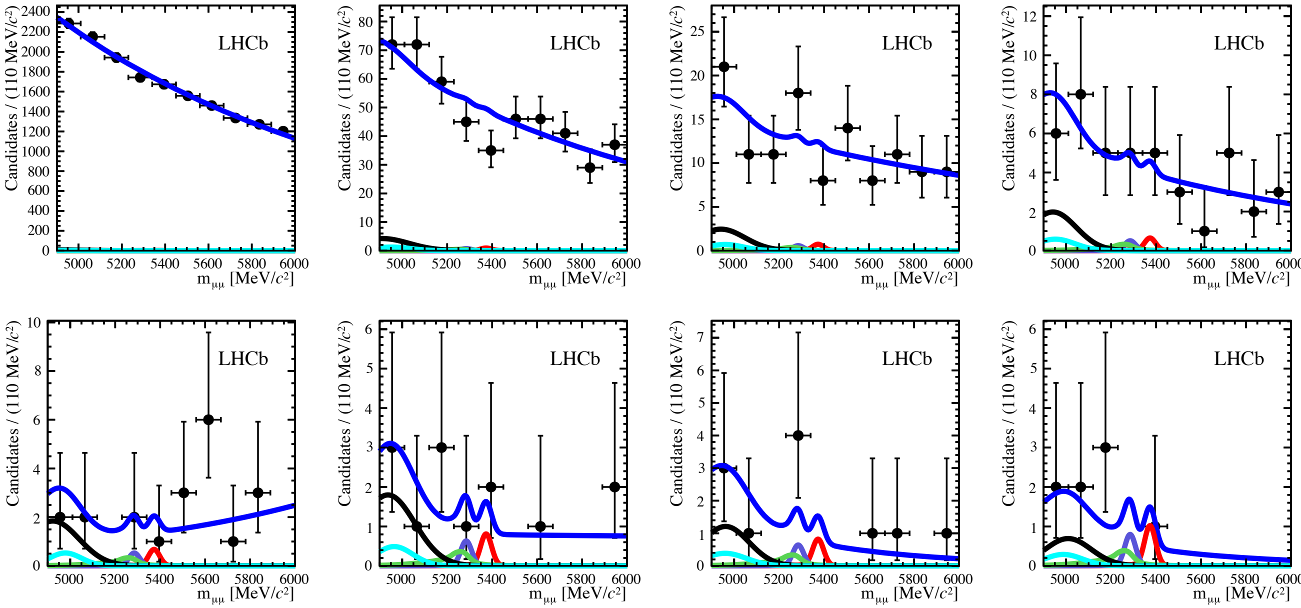
- Free parameters: $\mathcal{B}(B^0_s \to \mu^+\mu^-)$, $\mathcal{B}(B^0 \to \mu^+\mu^-)$ and combinatorial background

- The signal yield in each BDT bin is constrained to the expectation from $B^0_{(s)} \to h^+h'^-$ calibration

- The yields and pdf's for all of the relevant exclusive backgrounds are constrained to their expectations

- Additional systematic studies on background composition/parameterization:
  - add the $B^0_s \to K^-\mu^+\nu_\mu$ component to the exclusive bakground
  - change the combinatorial pdf from single to double exponential, to account for possible residual contributions from Λ^0_b and B^+_c decays
  - the syst error induced on $\mathcal{B}(B^0_s \to \mu^+\mu^-)$ is $\pm 0.2 \times 10^{-9}$

Fit projections



7 TeV data,
8 BDT bins

$B^0_s \to \mu^+\mu^-$

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

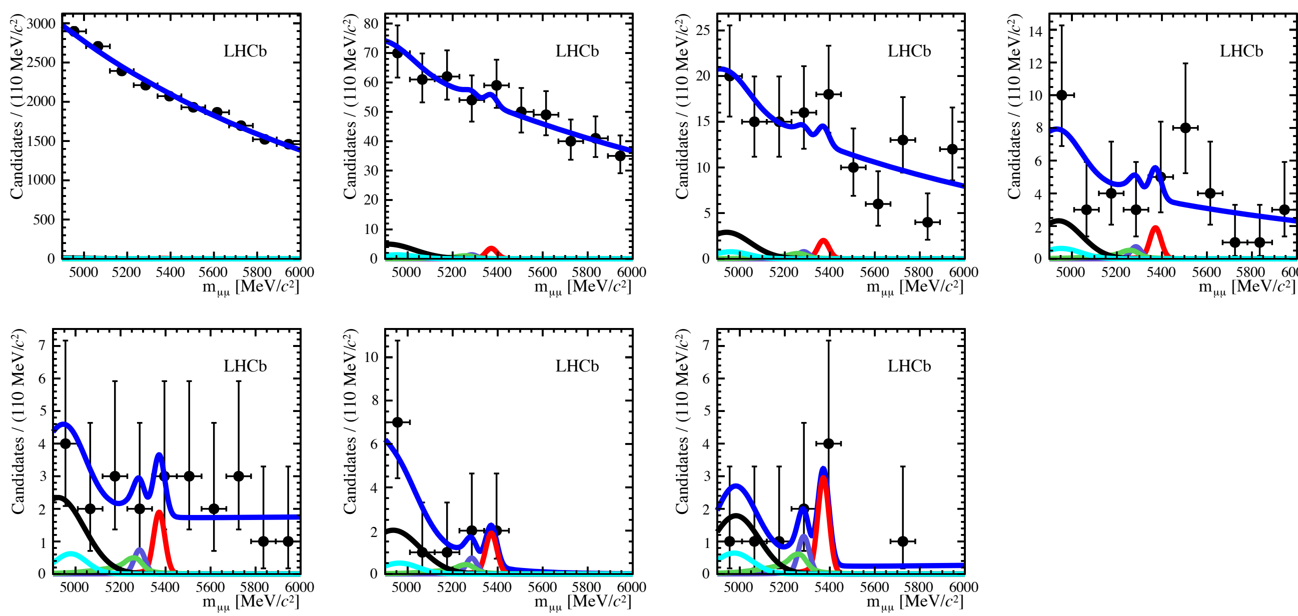
$B^0_{(s)} \to h^+h'^-$

$B^0 \to \pi^-\mu^+\nu_\mu$

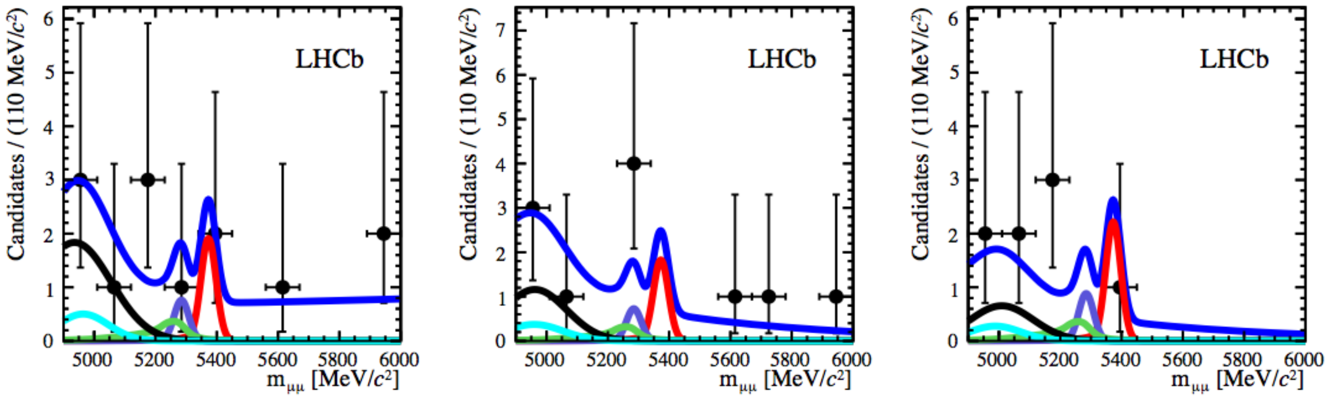
$B^{\pm,0} \to \pi^{\pm,0}\mu^+\mu^-$

total

8 TeV data,
7 BDT bins

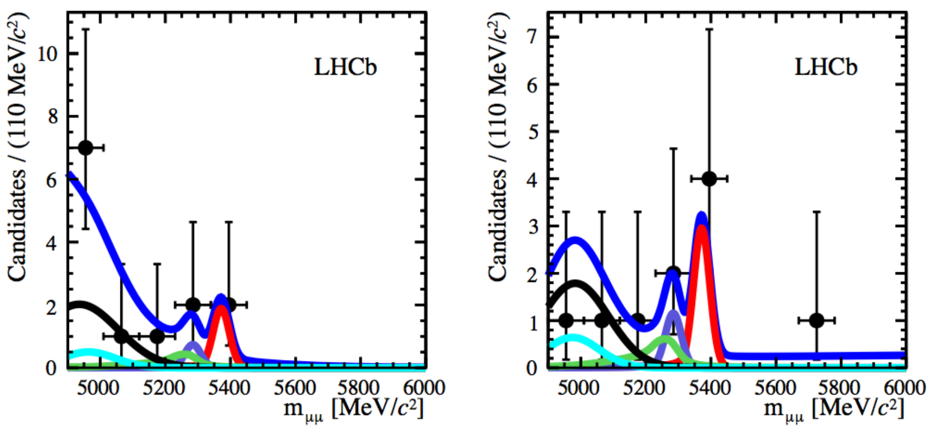


Fit projections: zoom



7 TeV data,
BDT >0.7

$B^0_s \to \mu^+\mu^-$
$B^0 \to \mu^+\mu^-$
$B^0_{(s)} \to h^+h'^-$
$B^0 \to \pi^-\mu^+\nu_\mu$
$B^{\pm,0} \to \pi^{\pm,0}\mu^+\mu^-$
total



8 TeV data,
BDT>0.7

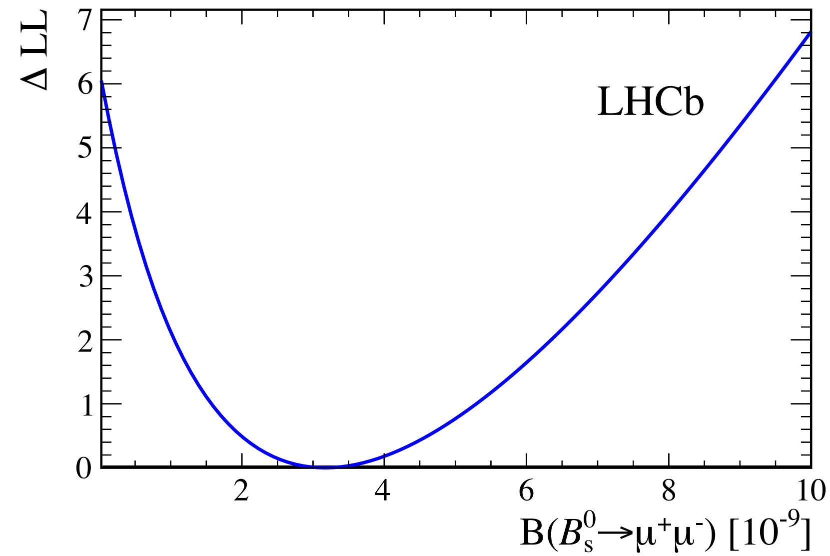
results from 7 TeV and 8 TeV are compatible at ~1.5σ

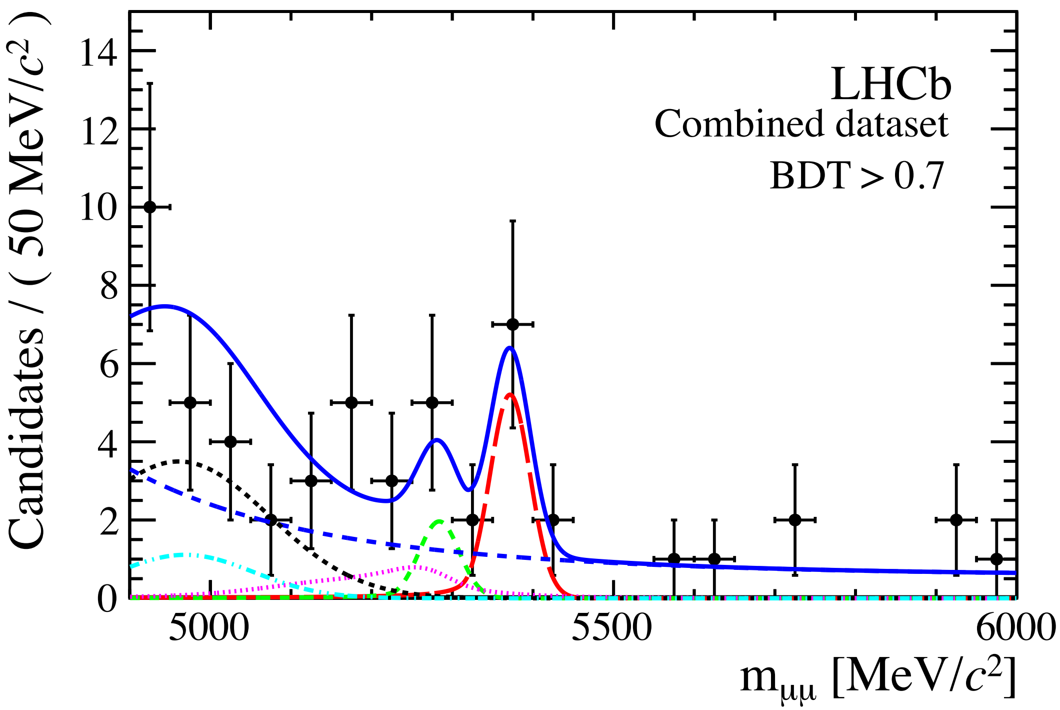
$B_s \to \mu^+\mu^-$: branching fraction

7 TeV (1 fb^{-1}) + 8 TeV (1.1 fb^{-1}):

$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$

SM expectation: $(3.54 \pm 0.30) \times 10^{-9}$





sum of BDT>0.7

- $B^0_s \to \mu^+\mu^-$
- $B^0 \to \mu^+\mu^-$
- $B^0_{(s)} \to h^+h'^-$
- $B^0 \to \pi^-\mu^+\nu_\mu$
- $B^{\pm,0} \to \pi^{\pm,0}\mu^+\mu^-$
- $bb \to \mu^+\mu^- X$ (dashed)
- total (solid)

Precise predictions

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

Slide shown to the CERN Scientific Policy Committee in December 2007

❑ "F… select

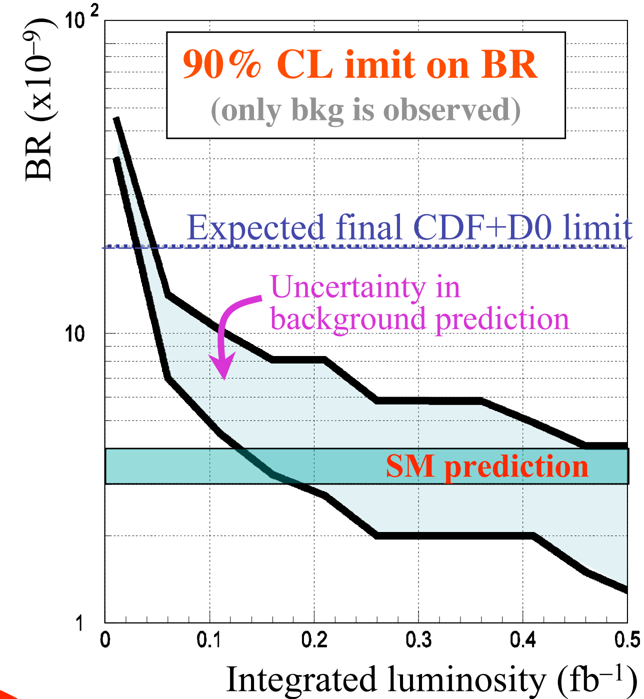
… s

… is b→μ, b→μ

- specific background dominated by $B_c \to J/\psi(\mu\mu)\mu\nu$

— Exploit good detector performance:

- muon ID
- vertexing (topology)
- mass resolution (18 MeV/c²)



0.05 fb^{-1} ⇒ overtake CDF+D0
0.5 fb^{-1} ⇒ exclude BR values down to SM
2 fb^{-1} ⇒ 3σ evidence of SM signal
6 fb^{-1} ⇒ 5σ observation of SM signal

LHCb's best NP discovery potential with the very early data !

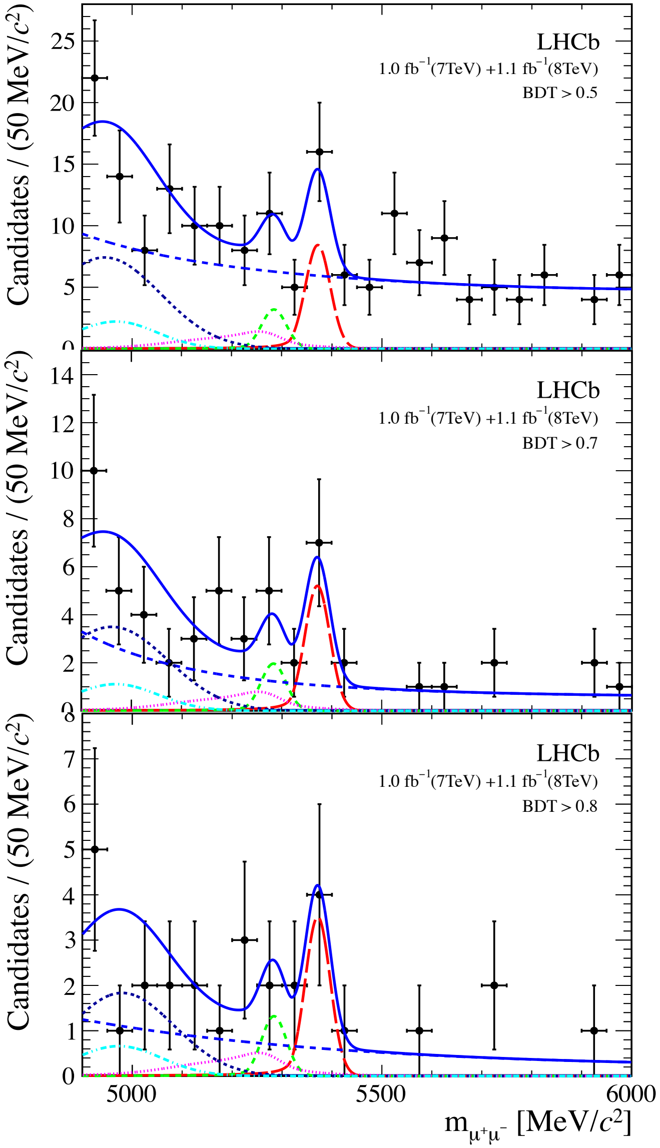
SPC meeting O. Schneider, Dec 10, 2007 16

Conclusions

- Combined analysis on 1.0fb^{-1} @ √s=7TeV and 1.1fb^{-1} @ √s=8TeV
- Upper exclusion limit @ 95% CL BR($B^0 \to \mu^+\mu^-$) < 9.4 x 10^{-10}
  worlds best single experiment limit
- **Excess of $B_s \to \mu^+\mu^-$ candidates with a signal significance of to 3.5 standard deviations (bkg only p-value: 5 x 10^{-4})**
- The branching fraction is measured as

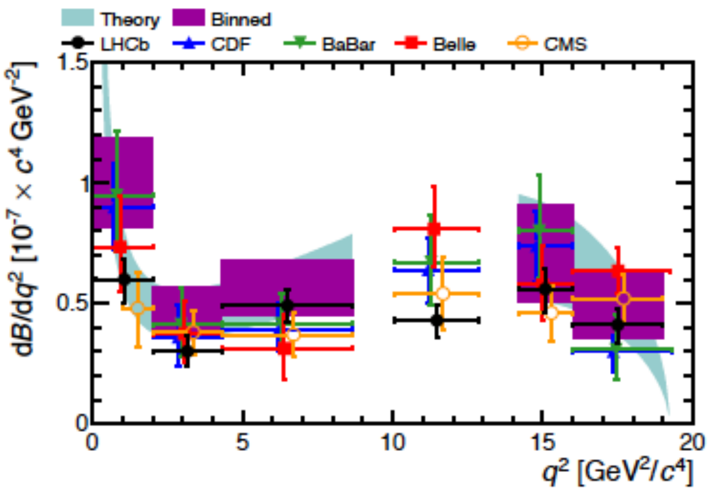
$$BR(B_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$

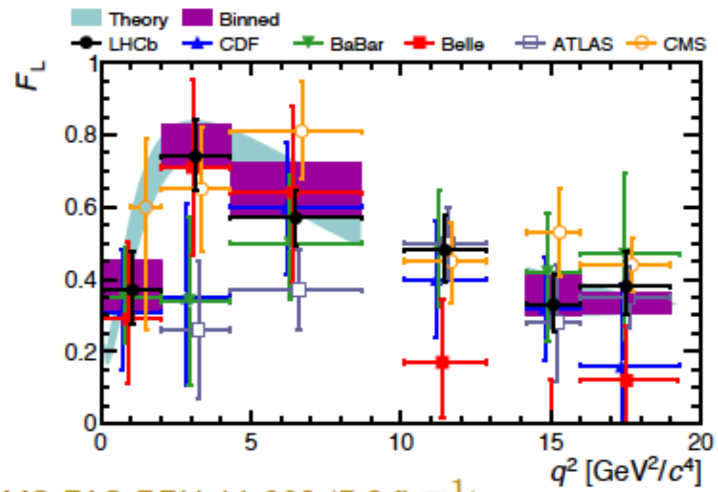
$B_s \to \mu^+\mu^-$ emerging

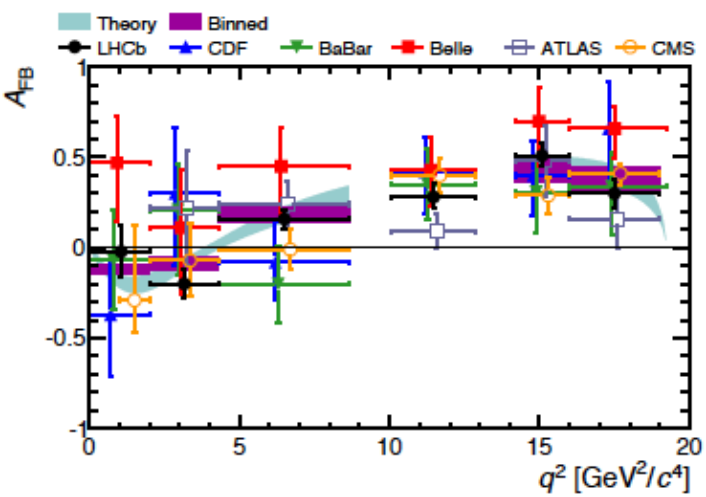


$B^0 \rightarrow K^* \mu^+ \mu^-$ - Angular Distributions

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})

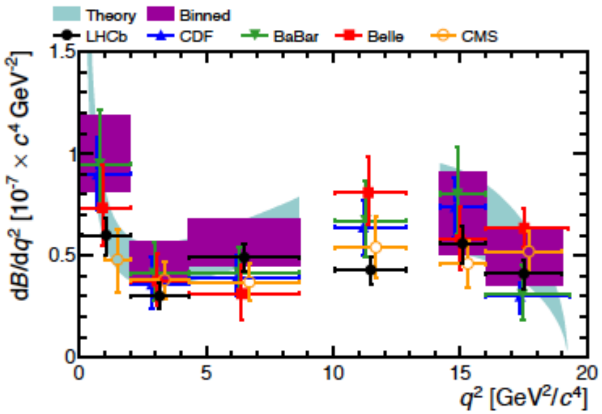
CDF: Phys. Rev. Lett 108 (2012) 081807 (6.8 fb^{-1})

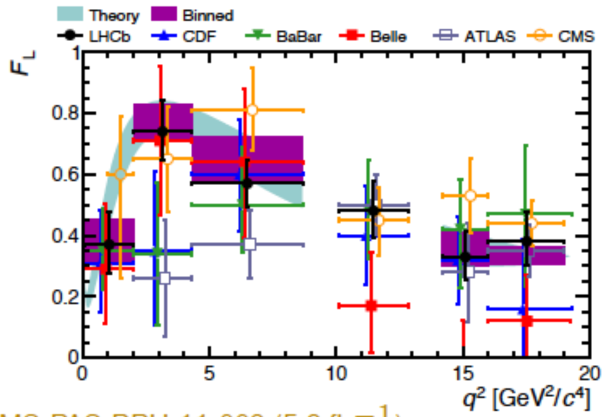
(results from CDF Public Note 10894 (9.6 fb^{-1}) not included)

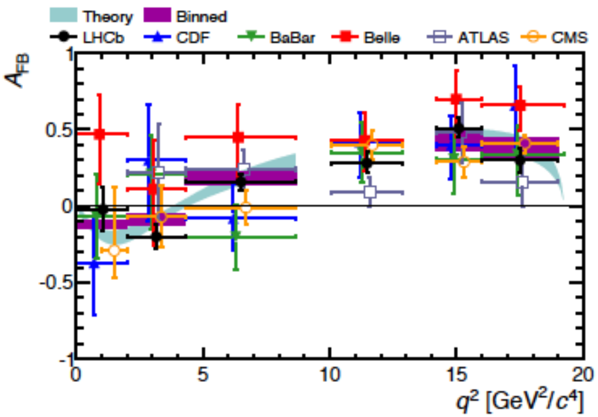
LHCb: arXiv:1304.6325 (1 fb^{-1})

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

Some example distributions:







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

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(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

Observables with limited dependence on form-factor uncertainty have been proposed by several authors:

Kruger-Matias (2005), Matias et al. (2012), Egede-Matias-Hurth-Ramon-Reece (2008), Bobeth-Hiller-Van Dyk (2010-11), Beciveric-Schneider (2012)

N.D.: There are other observables which are combination of those presented here

$$A_{\mathrm{T}}^{(2)} = \frac{2S_3}{(1-F_L)}$$

$$A_{\mathrm{T}}^{Re} = \frac{S_6}{(1-F_L)}$$

$$P'_4 = \frac{S_4}{\sqrt{(1-F_L)F_L}}$$

$$P'_5 = \frac{S_5}{\sqrt{(1-F_L)F_L}}$$

$$P'_6 = \frac{S_7}{\sqrt{(1-F_L)F_L}}$$

$$P'_8 = \frac{S_8}{\sqrt{(1-F_L)F_L}}$$

$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_{\mathrm{L}})A_{\mathrm{T}}^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi +$$
$$\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}P'_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}P'_5\sin 2\theta_K\sin\theta_\ell\cos\phi +$$
$$(1-F_{\mathrm{L}})A_{Re}^{\mathrm{T}}\sin^2\theta_K\cos\theta_\ell + \sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}P'_6\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}P'_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

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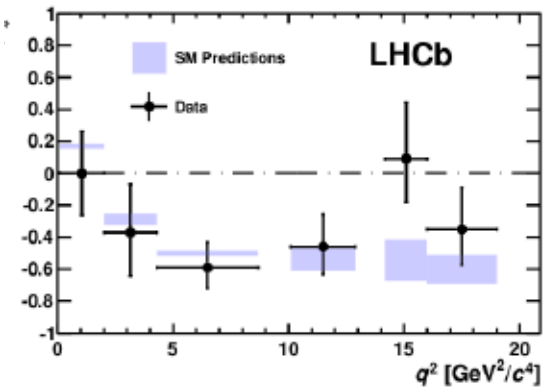
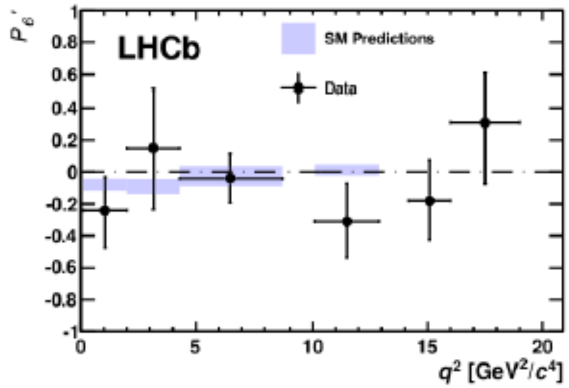
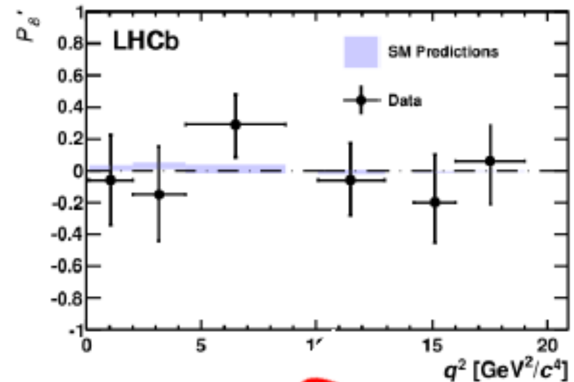
Very good agreement in P_4', P_6', P_8'

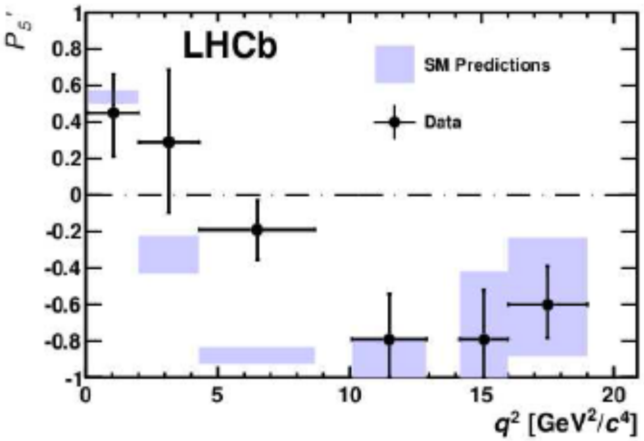


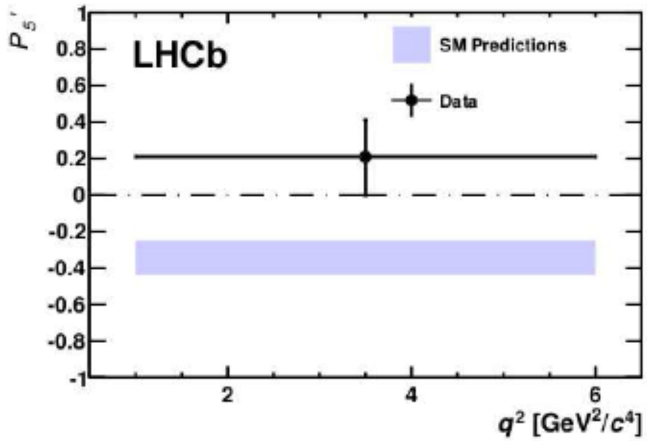




new @ EPS2013

some tension in P_5' (3.7 σ):





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.