Recent results in flavor physics

Johannes Albrecht (TU Dortmund)

DPG Hauptvortrag, 08. März 2013

Emmy Noether-Programm
Deutsche Forschungsgemeinschaft
DFG

Indirect searches for new phenomena

Flavour Physics

Direct searches

Production and measurement of new particles

→ Limit given by available energy

→ O(1TeV) testable

Indirect searches

Measurement of new particles in quantum fluctuations

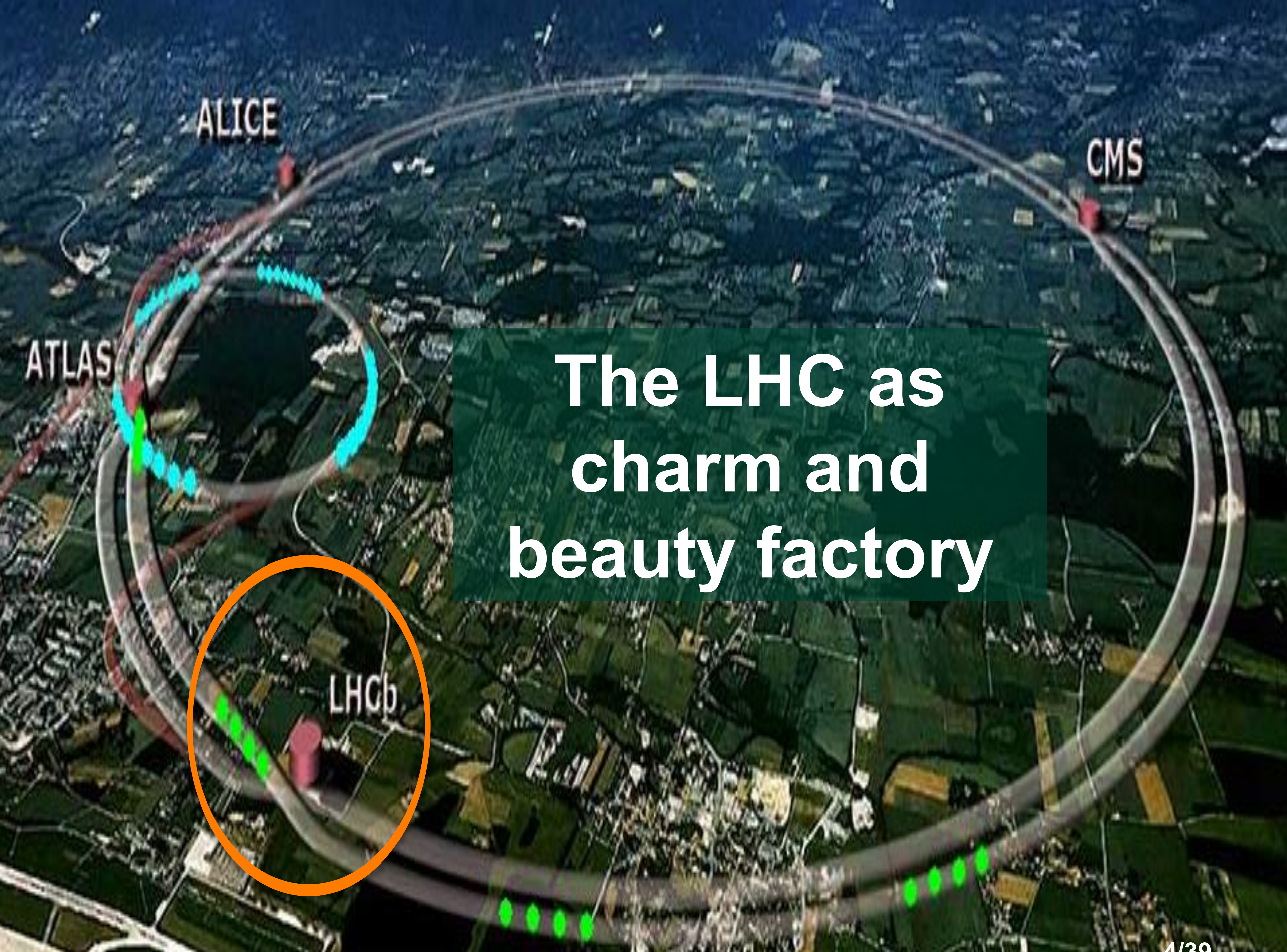
→ Limit given by precision

→ O(100) TeV testable

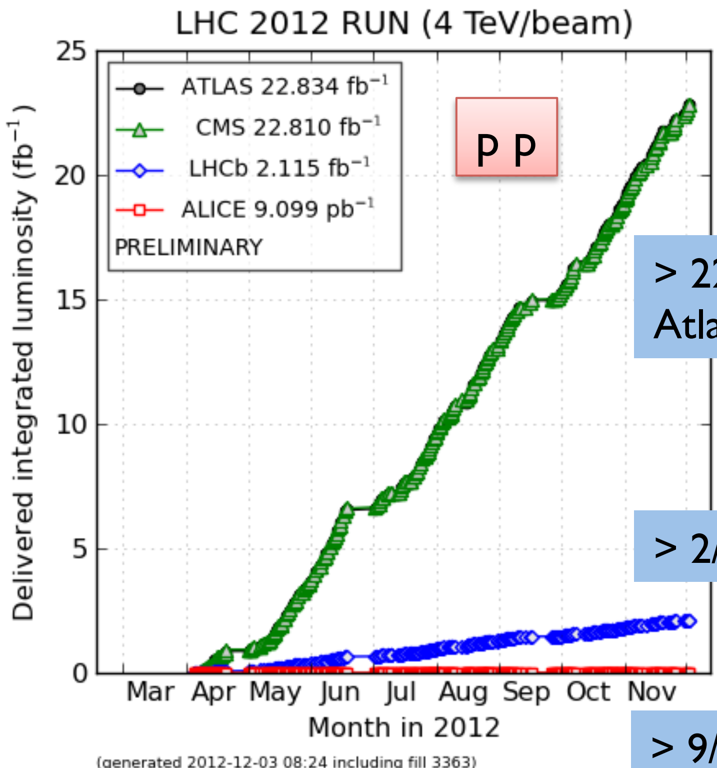
Outline

- Flavour physics == physics with heavy flavour decays
- Beauty physics
  - Beauty hadron production
  - Precision measurements of CP violation
  - Rare decays
- Charm & Kaon physics
  - Mixing and CP violation in charm decays
  - Rare charm decays
  - Lepton universality in Kaon decays
- Future flavour facilities
- This talk covers only few selected highlights

The LHC as charm and beauty factory



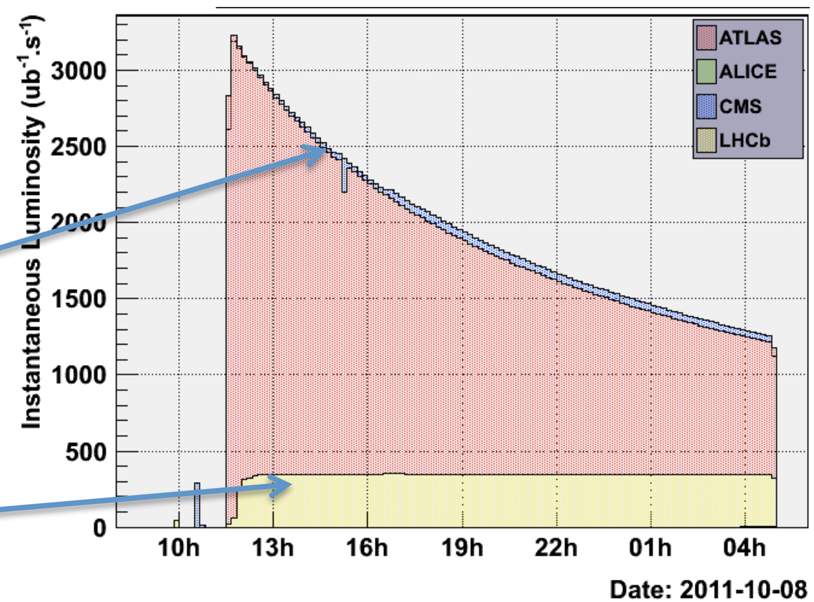
LHC performance in 2012



> 22/fb Atlas, CMS

> 2/fb LHCb

> 9/pb Alice

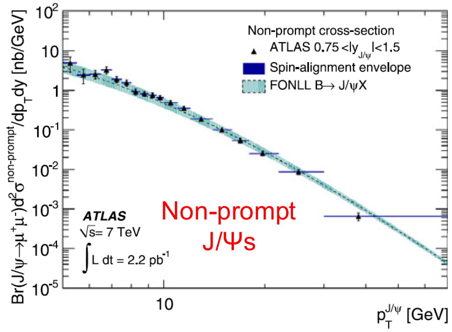


Pb-Pb runs / ALICE, ATLAS, CMS
p-Pb runs / all the experiments

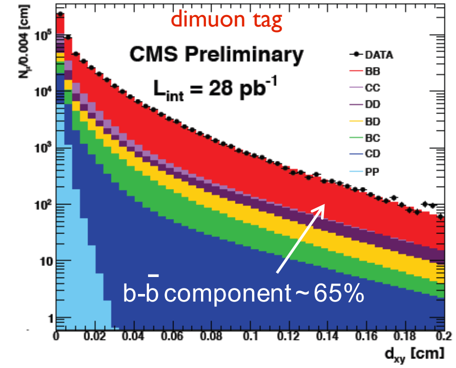
- Luminosity levelling: stable running and trigger conditions for LHCb even with LHC running at high luminosity ($L_{LHCb} = 4 \times 10^{32} cm^{-2} s^{-1}$)
- Plans for 2015
  - $\sqrt{s}$ = 13 TeV (HF cross section x2)
  - Bunch spacing 25ns (smaller pileup)

B production @ $\sqrt{s}$=7TeV

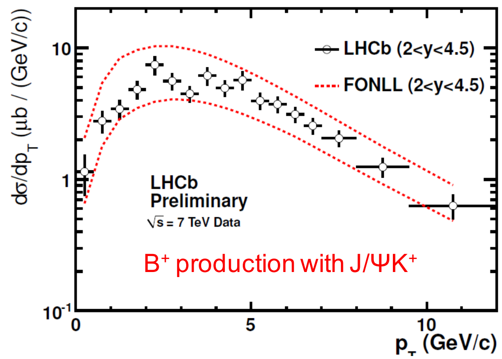
- Many methods used:
  1. (Di)Lepton tags (ATLAS[ATLAS-CONF-2011-057],CMS [CMS-PAS-BPH-10-015]),
  2. D+μ tag (LHCb[PLB694 (2010)209]),
  3. Secondary vertex tagged jets (ATLAS [ATLAS-CONF-2011-056], CMS [CMS-PAS-BPH-10-009])
  4. Detached J/ψ (ATLAS [Nucl.Phys.B850(2011)387], CMS [EPJ. C71(2011)1575], LHCb [EPJC71 (2011)1645]),
  5. Fully reconstructed J/ψX (LHCb[LHCb-CONF-2011-033],CMS [PRL.106:112001,2011 ,PRL 106, 252001 (2011), arXiv:1106.4048])
- All measurements reasonably well described by theory (FONLL, MC@NLO) -- quite an achievement!



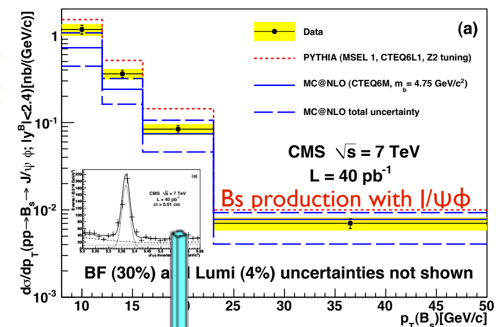
ATLAS, Nucl. Phys. B 850 (2011) 387

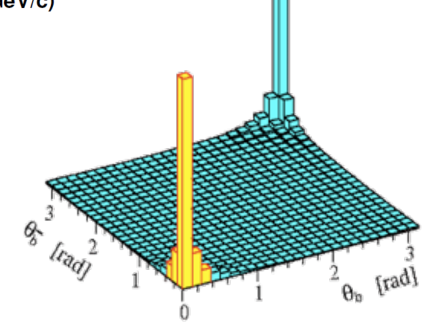


$$\sigma(pp \to b\bar{b}X \to \mu\mu Y) = 26.18 \pm 0.14\ (\text{stat.})$$



LHCb-CONF-2011-033





	L(fb^{-1})	σ_{acc}(μb)	bb / 10^{11}
ATLAS / CMS	27	75	2.7
LHCb	3	75	0.3
CDF / D0	9.5	2.8	0.03
Belle + BaBar	832+426	0.0011	0.001

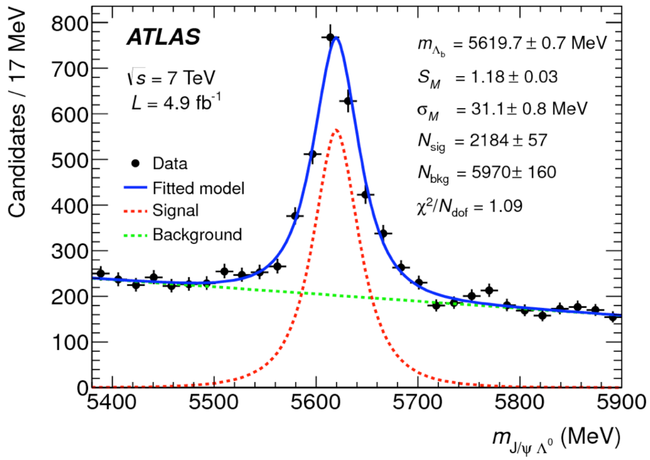
(1): CMS: p_t>5 GeV/c, |y|<2.2

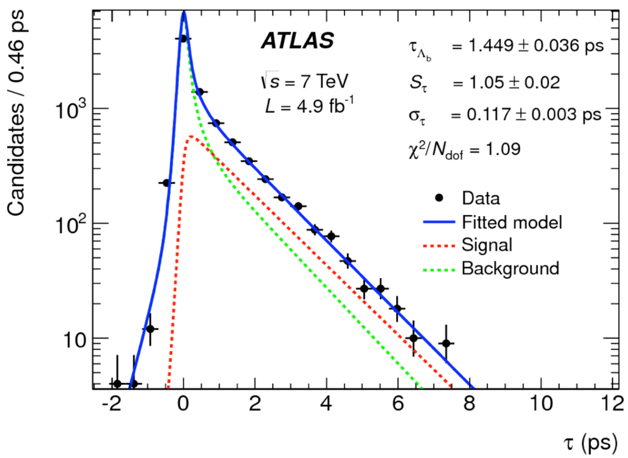
(2): LHCb: 2<η<6

(3): CDF: p_t>6 GeV/c, |y|<1 [PRD 75, 012010]

Beauty hadron production – Λ_b mass and lifetime

Summer 2012 ATLAS
Phys. Rev. D 87, 032002 (2013)





- ATLAS 2011 full data set (4.9fb^{-1})
  - using ***fully reconstructed*** $\boldsymbol{\Lambda_b \to \Lambda\, J/\psi \to (p\pi)(\mu\mu)}$ ***decay***

$m(\Lambda_b)$ = 5619.7 ± 0.7(stat) ± 1.1(syst) MeV
$\tau(\Lambda_b)$ = 1.449 ± 0.036(stat) ± 0.017(syst) ps

Fall 2012 CMS | CMS BPH-11-013

$\tau(\Lambda_b)$ = 1.503 ± 0.052(stat) ± 0.031(syst) ps

- $\boldsymbol{X(3872)}$ discovered by Belle ~10 years ago
  - Still unclear what X(3872) is
  - Knowledge of quantum numbers crucial for understanding its nature
    - $J^{PC} = 1^{++}$: DDbar molecule? Tetra quarks? $\chi_{c1}(2^3P_1)$?
    - $J^{PC} = 2^{-+}$: $\eta_{c2}(1^1D_2)$?

- Measure decay $B^+ \to X(3872) K^+$

New @ LaThuile

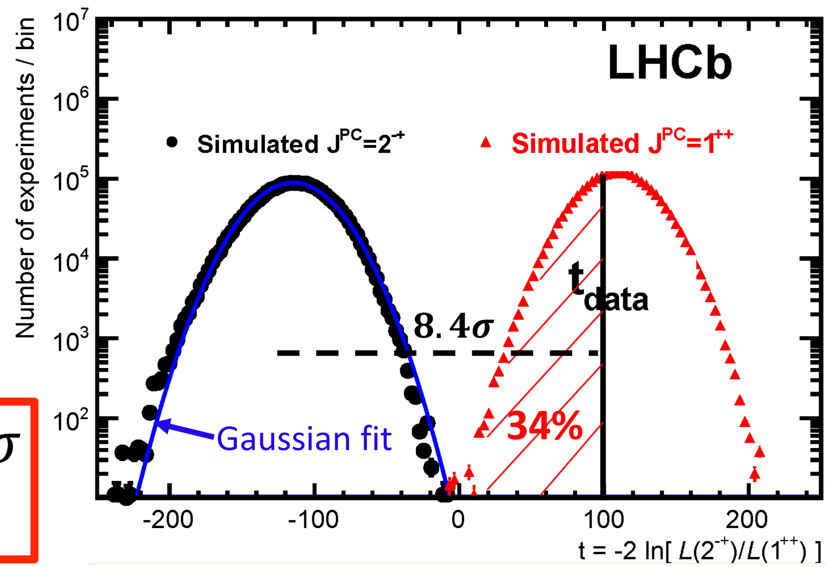
LHCb-PAPER-2013-001

- Discriminate between quantum numbers by using the 5-D angular correlations

$B^+ \to \psi(2S)K^+ \quad : N_{sig} = 5642 \pm 76$

$B^+ \to X(3872)K^+ : N_{sig} = 313 \pm 26$

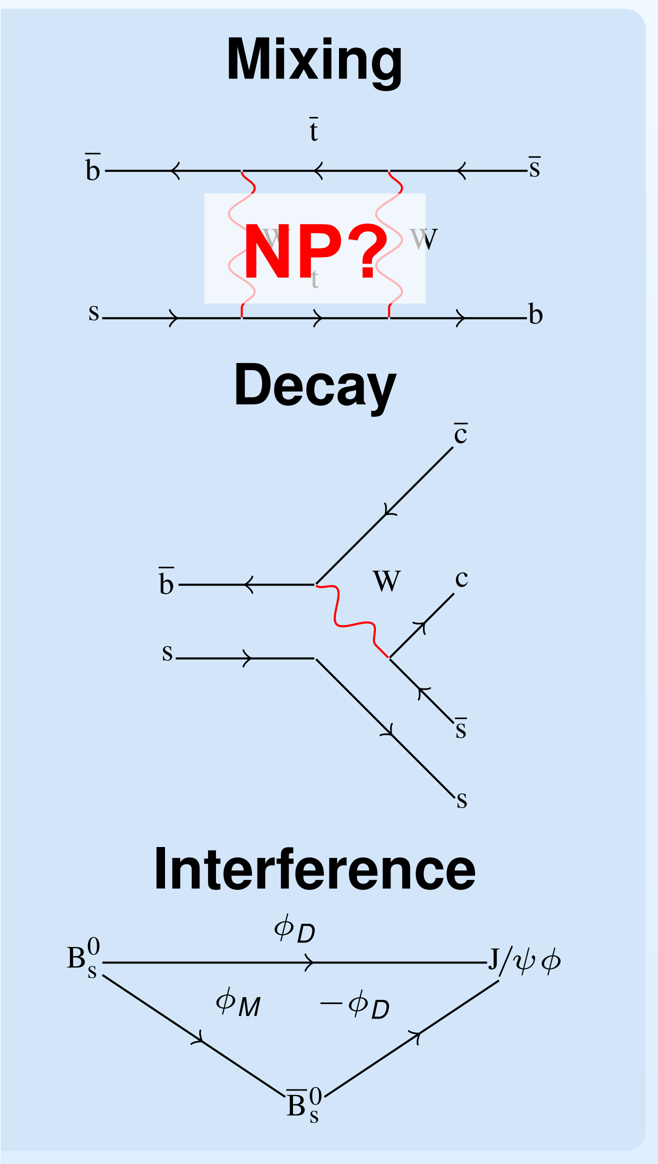
2^{-+} rejected with a significance of 8.4σ
1^{++} p-value is high (34%)



Precision measurements of CP violation in beauty decays

ϕ_s and γ

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

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

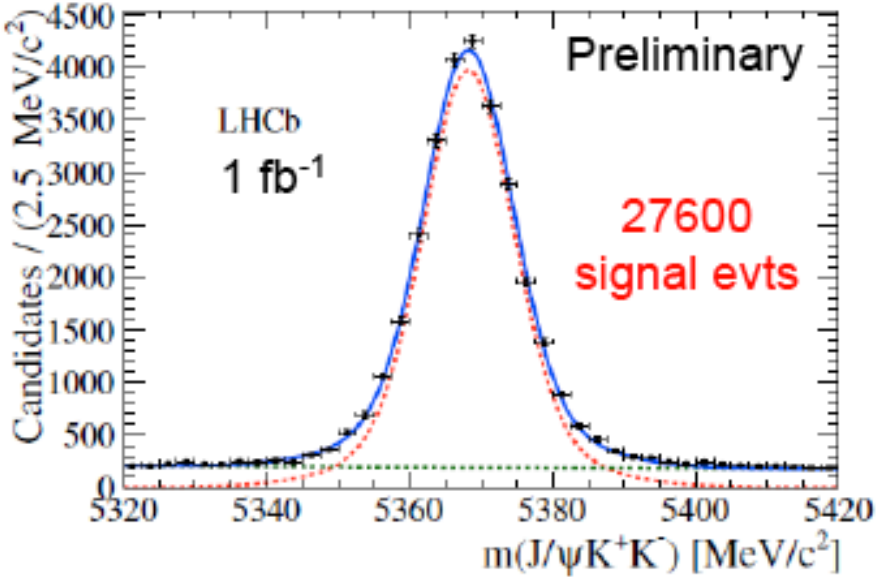
- Requires time dependent, flavour tagged angular analysis

CP violation in $B_s \to J/\psi\phi$

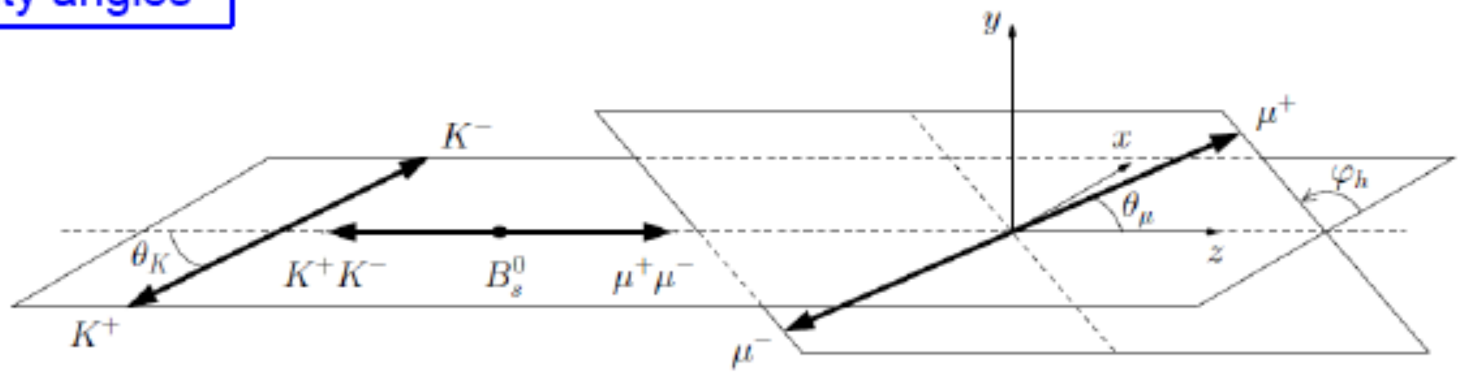
New @ LaTheuile

LHCb-Paper-2013-002
to be submitted to PRD

- experimentally clean
- VV final state: angular analysis to separate CP even/odd components
- Use helicity frame to describe decay angles ($\cos\theta_K$, $\cos\theta_\mu$, ϕ_h)
- Non-resonant KK (s-wave) comp.: CP odd



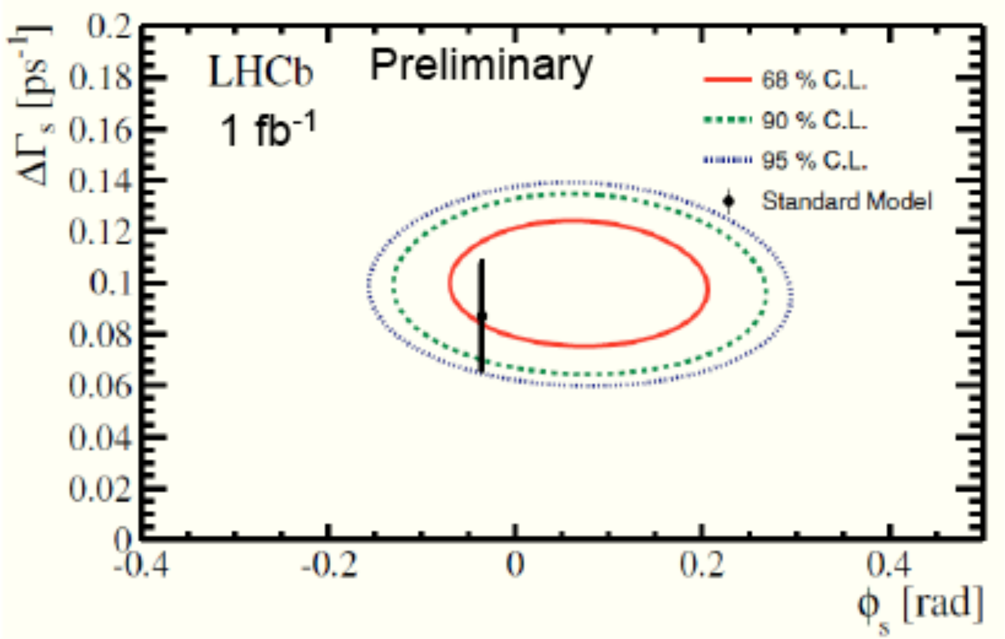
Helicity angles



LHCb: CP violation in $B_s \to J/\psi\phi$

New @ LaThuile

LHCb-Paper-2013-002
to be submitted to PRD



(stat. error only)

$B_s \to J/\psi\phi$

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

Preliminary

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

Systematics - ϕ_s : Angular accept. ; $\Delta\Gamma$: Bckg + t accept.

LHCb: CP violation in $B_s \to J/\psi\pi^+\pi^-$

$B_s \to J/\psi\ \pi\pi$ is (pure) CP odd state
$\to$ no angular analysis

Repeat analysis of *PL B713* but using OST and SSKT information.
(~7420 signal events)

Constrain Γ and $\Delta\Gamma$ to the $J/\psi\phi$ result:

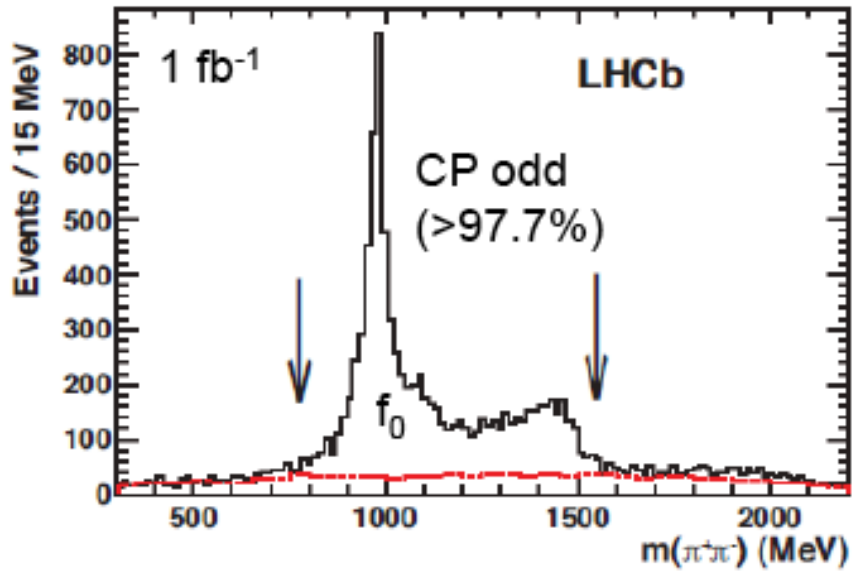
$$\phi_s = -0.14^{+0.17}_{-0.16} \pm 0.01\,\mathrm{rad}$$

new

LHCb-Paper-2013-002

Preliminary

Phys.Lett. B713 (2012) 378-386



LHCb: CP violation in $B_s \to J/\psi\pi^+\pi^-$

$B_s \to J/\psi\ \pi\pi$ is (pure) CP odd state
$\to$ no angular analysis

Repeat analysis of *PL B713* but using OST and SSKT information.
(~7420 signal events)

Constrain Γ and $\Delta\Gamma$ to the $J/\psi\phi$ result:

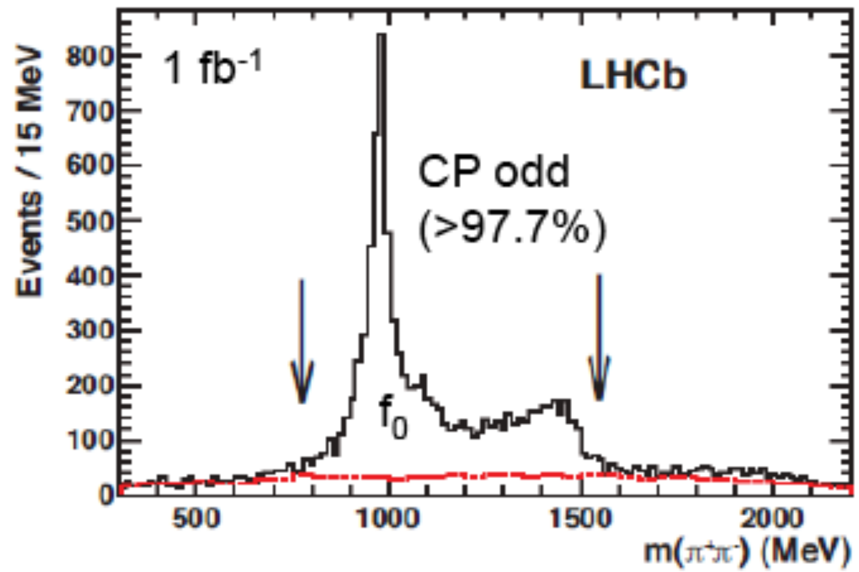
$$\phi_s = -0.14^{+0.17}_{-0.16} \pm 0.01\,\mathrm{rad}$$

new

Preliminary

LHCb-Paper-2013-002

Phys.Lett. B713 (2012) 378-386



New @ LaThuile

Simultaneous fit of $B_s \to J/\psi\ \pi\pi$ and $B_s \to J/\psi\phi$

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

new

Preliminary

LHCb-Paper-2013-002

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

ATLAS: CP violation in $B_s \rightarrow J/\psi\phi$

Summer 2012 ATLAS

JHEP 12 (2012) 072

- ATLAS performed an untagged measurement
  - $\Delta\Gamma_s$ measured with interesting precision
  - ϕ_s has significant penalty

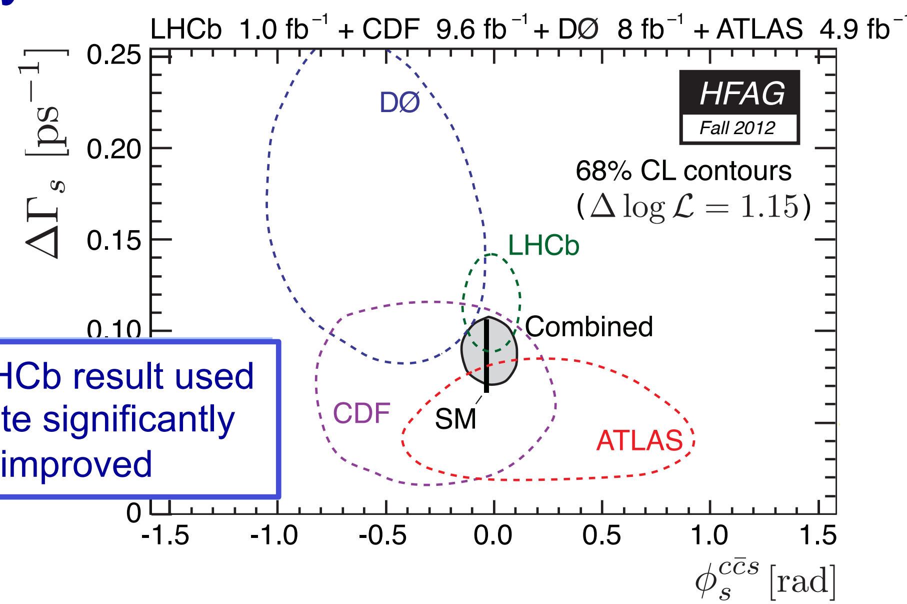
$B_s \rightarrow J/\psi\phi$

$$\phi_s = 0.22 \pm 0.41 \text{ (stat.)} \pm 0.10 \text{ (syst.) rad}$$
$$\Delta\Gamma_s = 0.053 \pm 0.021 \text{ (stat.)} \pm 0.010 \text{ (syst.) ps}^{-1}$$
$$\Gamma_s = 0.677 \pm 0.007 \text{ (stat.)} \pm 0.004 \text{ (syst.) ps}^{-1}$$

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

- Comparison of $B_s \rightarrow J/\psi\phi$ analyses

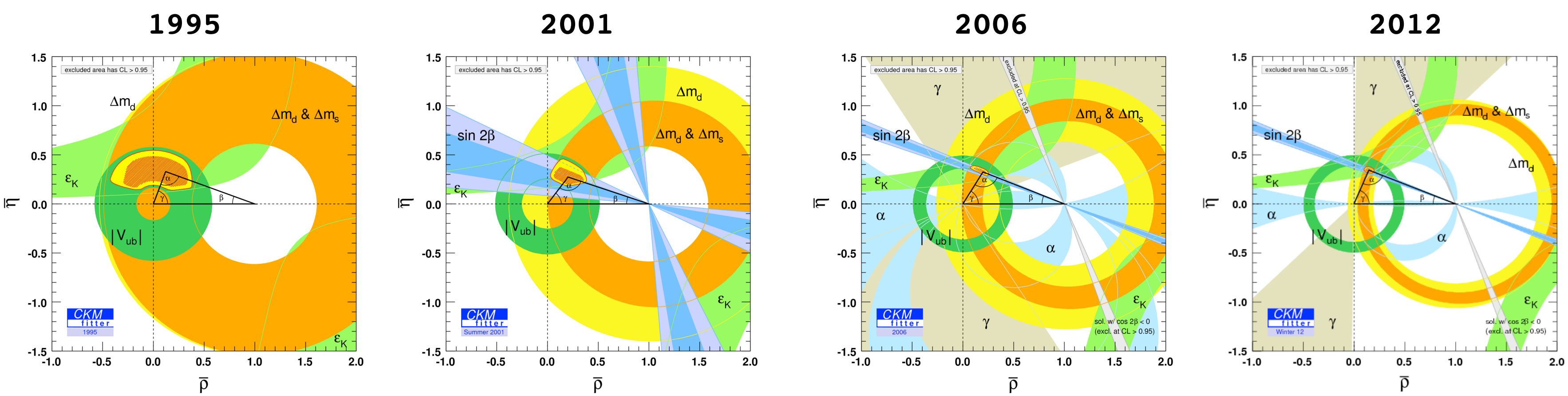
	Signal Events	Resolution	Tagging
ATLAS	22.5k	~ 100 fs	No
LHCb	21k	~ 50 fs	Yes
CDF	11.5k	~ 100 fs	Yes
DØ	6.5k	~ 100 fs	Yes



Old LHCb result used update significantly improved

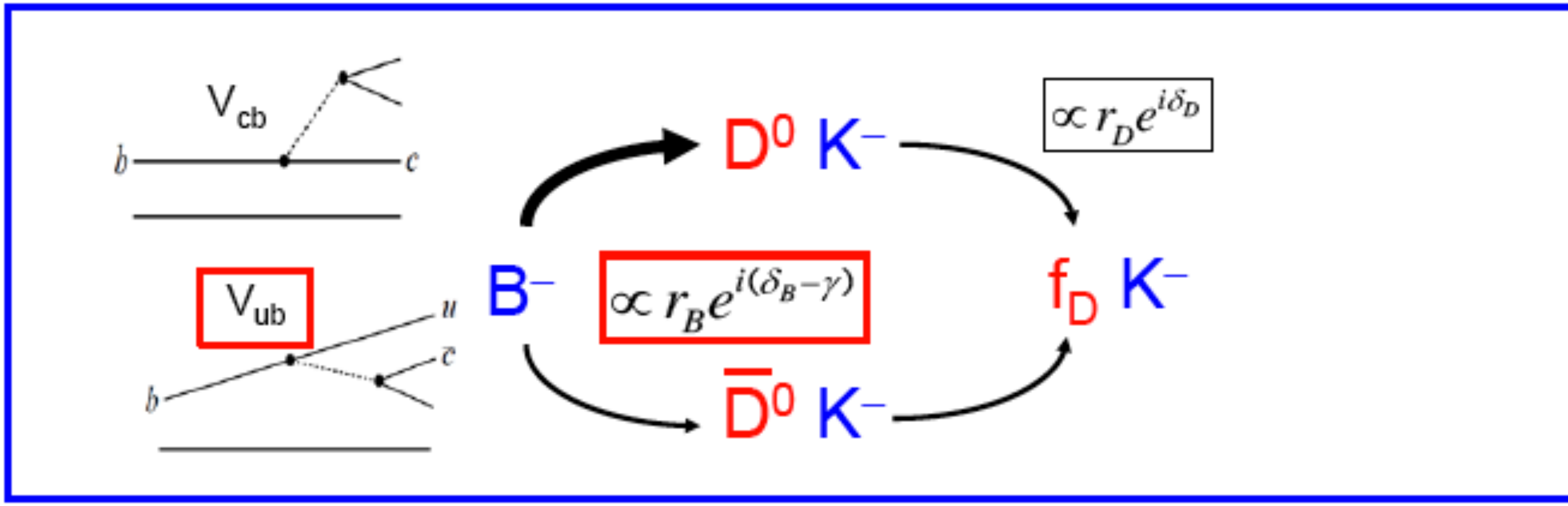
CKM angle γ

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



Inconsistencies in CKM triangle might reveal new phenomena

Determination of γ from B→DK decays



Gronau, London, Wyler (GLW)

f_D = KK, ππ (CP state)

LHCb:
- $B^\pm \to D(KK)\,K^\pm$
- $B^\pm \to D(\pi\pi)\,K^\pm$
- $B^\pm \to D(KK)\,\pi^\pm$
- $B^\pm \to D(\pi\pi)\,\pi^\pm$

Phys. Lett. B 712 (2012) 203.

Atwood, Dunietz, Soni (ADS)

f_D = Kπ and πK

LHCb:
- $B^\pm \to D(\pi^+K^-)\,K^\pm$
- $B^\pm \to D(K^+\pi^-)\,K^\pm$
- $B^\pm \to D(\pi^+K^-)\,\pi^\pm$
- $B^\pm \to D(K^+\pi^-)\,\pi^\pm$

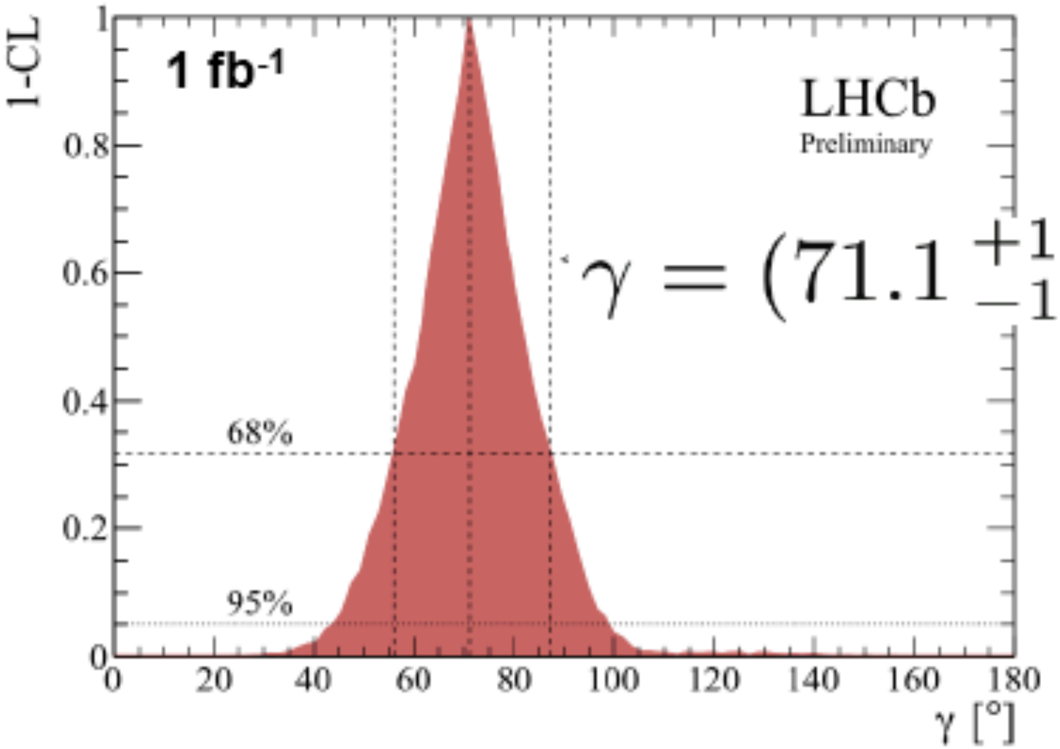
Phys. Lett. B 712 (2012) 203.

Giri, Grossman, Soffer, Zupan (GGSZ)

Self conjugated Dalitz modes

LHCB-CONF-2012-032

CKM 2012



$$\gamma = (71.1\,^{+16.6}_{-15.7})^\circ$$

For comparision:

BaBar : $\langle\gamma\rangle = 69\,^{+17}_{-16}\,(^\circ)$

Belle : $\langle\gamma\rangle = 68\,^{+15}_{-14}\,(^\circ)$

Eingeladener Vortrag: M. Karbach T7.3

Rare beauty decays

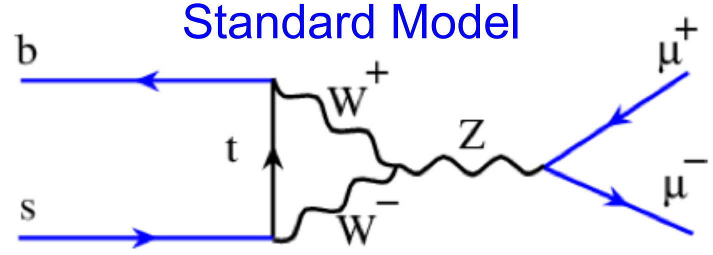
1) $B_{s,d} \rightarrow \mu^+\mu^-$
2) $b \rightarrow s\, \ell^+\ell^-$
3) $B \rightarrow \tau\, \nu$ and $B \rightarrow D^{(*)}\, \tau\, \nu$

Theory prediction: Standard Model

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

Review experiment: **J.A.**: MPL A27 1330028 (2012)
SM: Buras, Isidori: arXiv:1208.0934

Standard Model

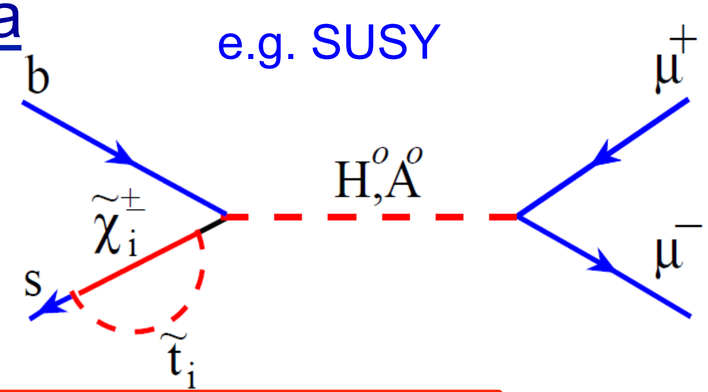


Left handed couplings
→ helicity suppressed

Discovery channel for New Phenomena

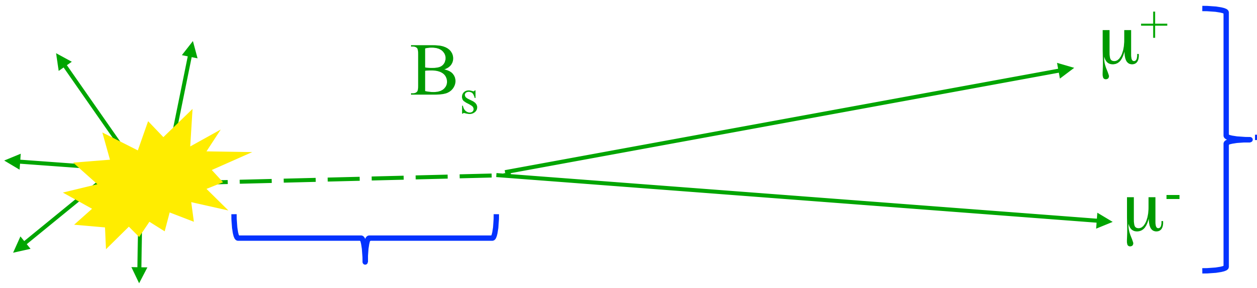
- → Very **sensitive to new particles** and their couplings (e.g. in extended Higgs sectors, SUSY, etc.)

e.g. SUSY



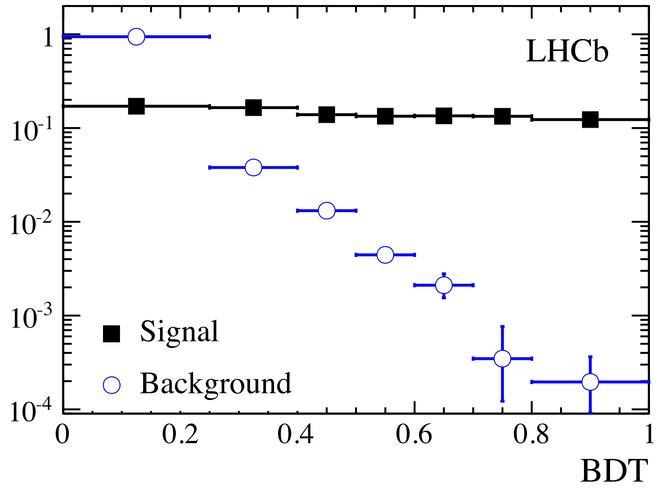
Precise measurement of these decays is one of the main goals of the LHCb experiment

Search strategy

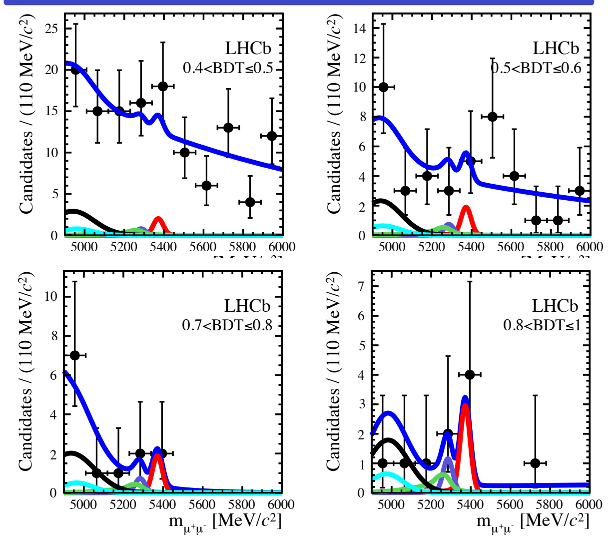


Classification of events

BDT (topology, kinematics)

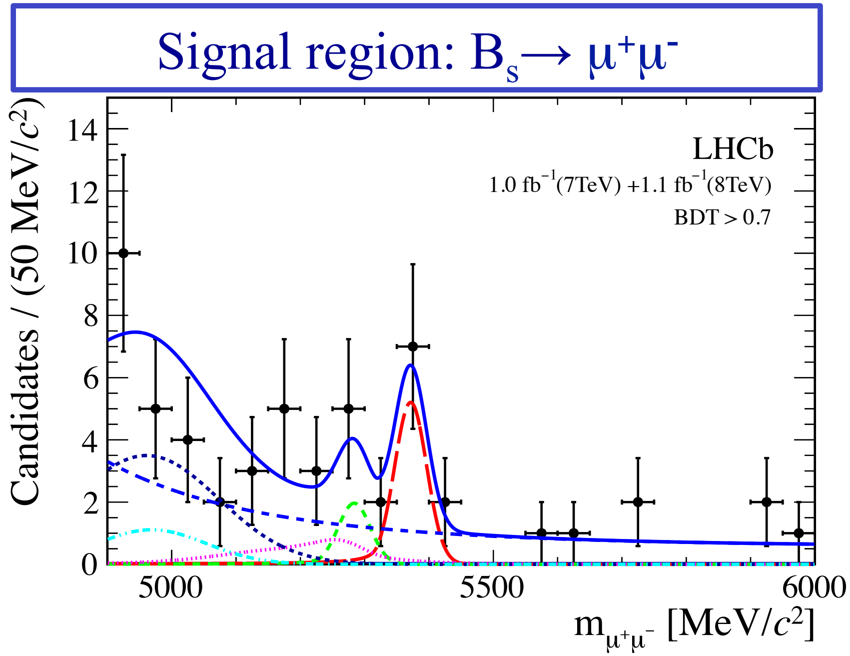


Invariant mass



Measurement of exclusion limits or decay rates

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



Highlight after 25 years of searches (Argus 1987)

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

PRL 110 (2013) 021801

- First branching fraction measured:

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

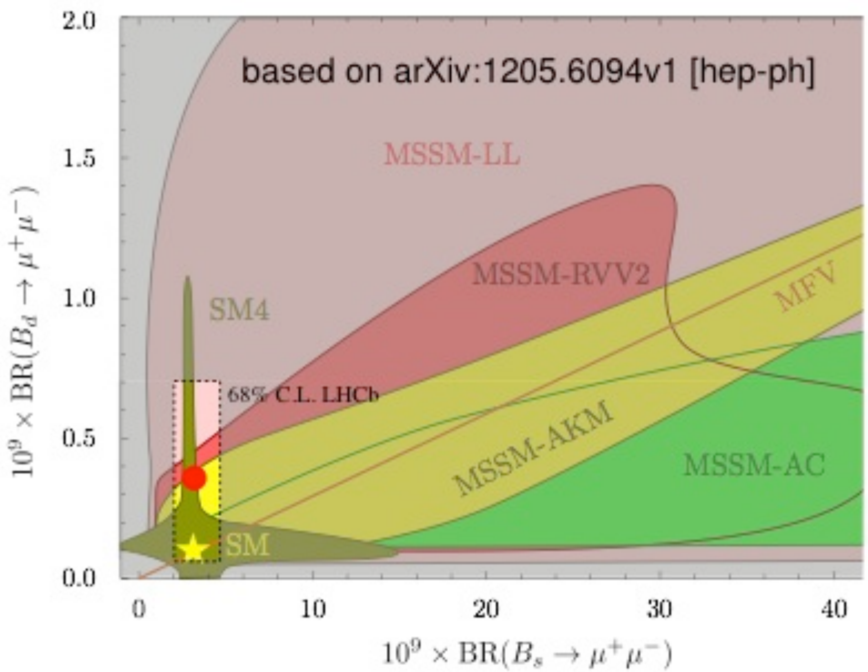
HCP2012

In good agreement with SM, but 40% uncertainty

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

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

Allowed parameter space 2011:

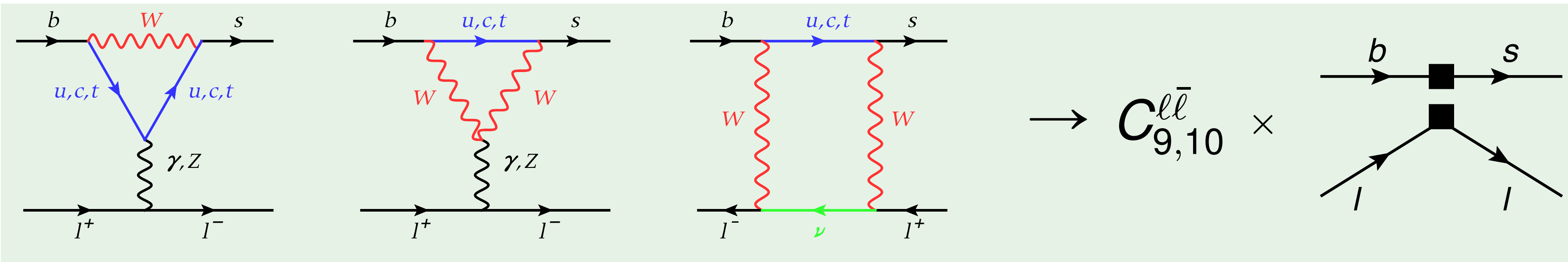


Strong constraints on many new physics models

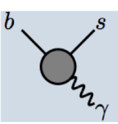
→ together with direct searches: „Constrained SUSY" models (almost) excluded

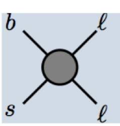
- Future key measurement: **ratio of decay rates** of $B^0 \to \mu^+\mu^- / B_s \to \mu^+\mu^-$
  - Allows test of a new category of scenarios
    → e.g. hypothesis of „Minimal Flavour Violation"

- $b \to s\, \ell^+\ell^-$ decays allow precise tests of Lorentz structure
  - Sensitive to new phenomena via non-standard couplings
  - Best described with effective field theory



Operator $\mathcal{O}_i$	$B \to K^{*0}\gamma$	$B \to K^{*0}\mu^+\mu^-$	$B \to \mu^+\mu^-$
$\mathcal{O}_7 \sim m_b(\bar{s}_L \sigma_{\mu\nu} b_R) F_{\mu\nu}$	✓	✓	
$\mathcal{O}_9 \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_V$		✓	
$\mathcal{O}_{10} \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_A$		✓	✓
$\mathcal{O}_{S,P} \sim (\bar{s}b)_{S+P}(\bar{\ell}\ell)_{S,P}$			✓





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

$O_{9,10}$, $O_{S,P}$, $O_{T,T5}$

SM:

- $O_{S,P} \sim 0$
- Helicity flipped operators O_i' suppressed by m_s/m_b

Experimental data: $b \to s \ell^+ \ell^-$ – number of events

# 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}
$B^0 \to K^{*0} \ell\bar{\ell}$	$137 \pm 44^\dagger$	$247 \pm 54^\dagger$	288 ± 20	900 ± 34
$B^+ \to K^{*+} \ell\bar{\ell}$			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
$B_s \to \mu\bar{\mu}$				emerging
$\Lambda_b \to \Lambda \ell\bar{\ell}$			51 ± 7	
$B^+ \to \pi^+ \ell\bar{\ell}$		limit		25 ± 7

- CP-averaged results
- vetoed q^2 region around J/ψ and ψ' resonances
- † unknown mixture of B^0 and $B^\pm$

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

Outlook / Prospects

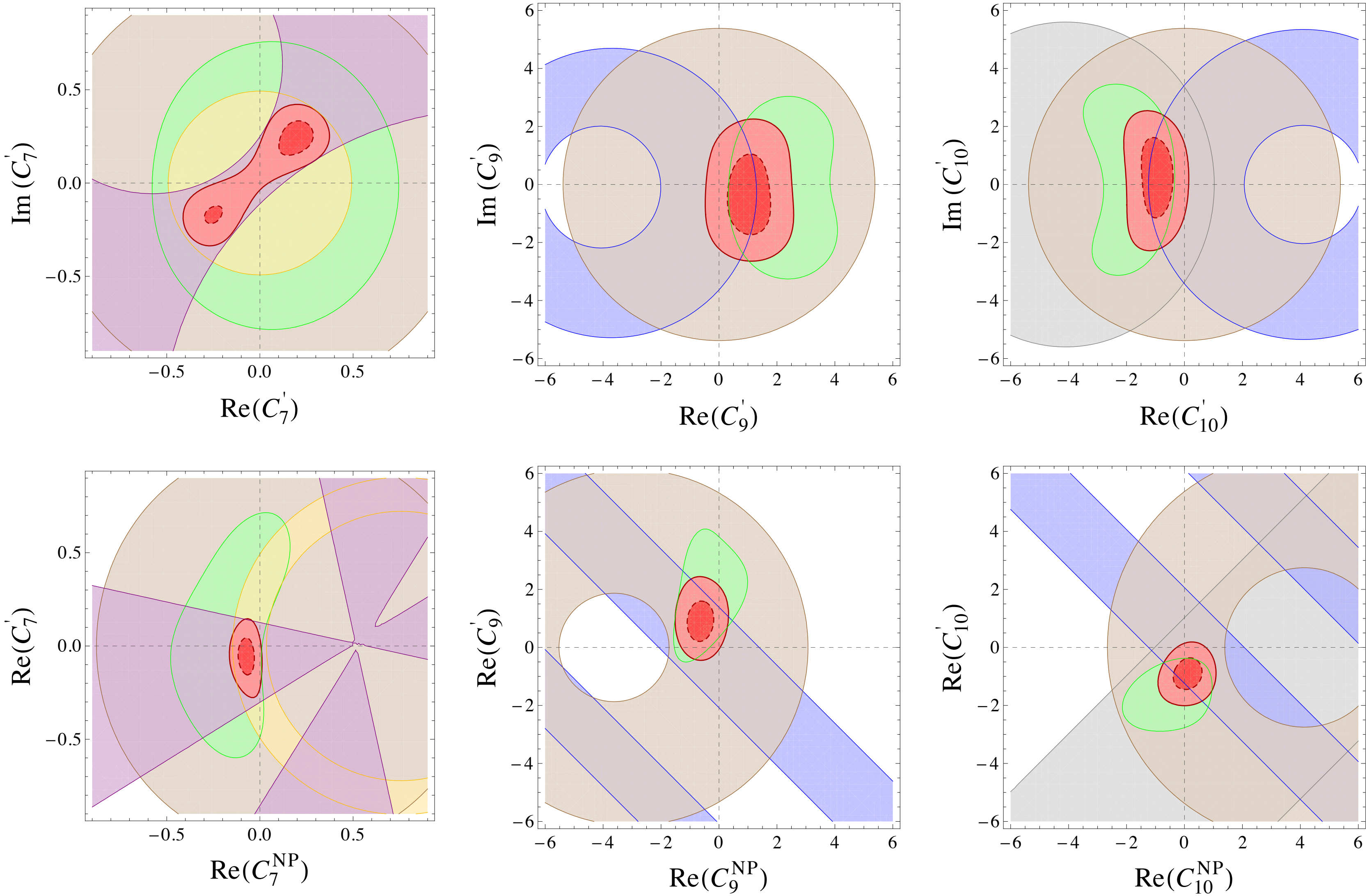
Belle	reprocessed all data 711 fb^{-1} → final analysis ?
LHCb	end of 2012 additional $\gtrsim 2$ fb^{-1} and $(5-7)$ fb^{-1} by the end of 2017
ATLAS / CMS	pursue also analysis of $B \to K^* \mu\bar{\mu}$ and $B \to K \mu\bar{\mu}$
Belle II / ~~SuperB~~	expects about (10-15) K events $B \to K^* \ell\bar{\ell}$ ($\gtrsim$ 2020) [A.J.Bevan arXiv:1110.3901]

C. Bobeth, HCP 12

Constraints on Wilson coefficients

W. Altmannshofer et al. [arXiv:1206.0273]

$b \to s\gamma$, $b \to s\ell^+\ell^-$, $A_{CP}(b \to s\gamma)$, $S_{K^*\gamma}$, $B^+ \to K^+\mu^+\mu^-$, $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-$



Constraints on mass scale of New Particles

Can turn constraints on Wilson coefficients in $\Delta F = 1$ $b \to s$ into constraints on the mass-scale of NP:

- Tree level contribution with $\mathcal{O}(1)$ couplings:

$$\mathcal{L}_{\text{NP}} \sim \frac{1}{\Lambda_{NP}^2} \mathcal{O}_{\text{NP}}$$

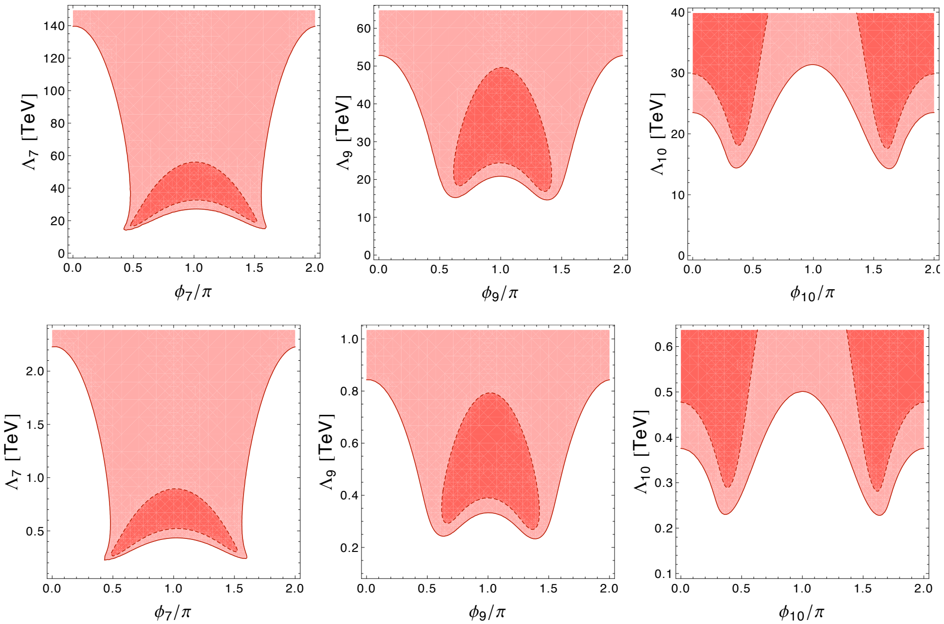
$\rightarrow$ $\Lambda_{\text{NP}} > \mathcal{O}(15\,\text{TeV}) - \mathcal{O}(140\,\text{TeV})$

- Loop and CKM suppressed:

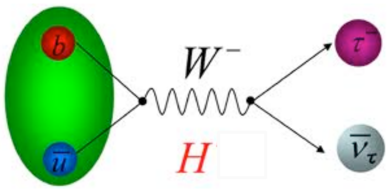
$$\mathcal{L}_{\text{NP}} \sim \frac{V_{tb} V_{ts}^*}{(4\pi)^2} \frac{1}{\Lambda_{NP}^2} \mathcal{O}_{\text{NP}}$$

$\rightarrow$ $\Lambda_{\text{NP}} > \mathcal{O}(300\,\text{GeV}) \to \mathcal{O}(2\,\text{TeV})$

W. Altmannshofer et al. [arXiv:1206.0273]



Branching fraction of $B^- \to \tau^- \nu$

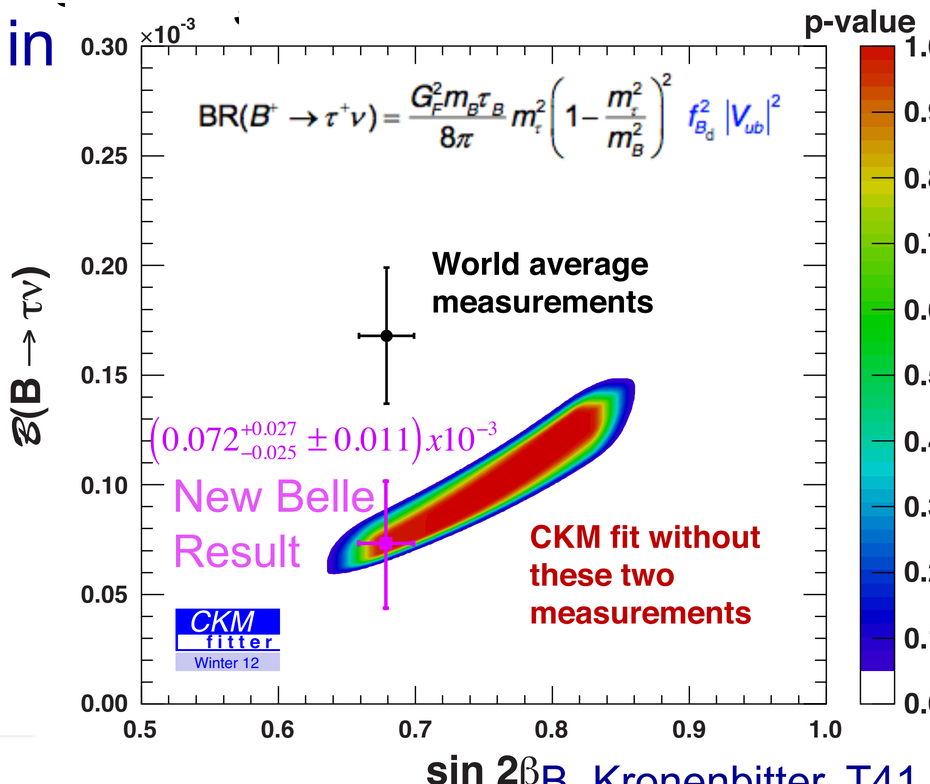


Can be new particles instead of W^- but why not also in $D^+_{(s)} \to \ell^+ \nu$?

- $B^- \to \tau^- \nu$, tree level decay
  - Sensitive to charged Higgs

- Previous measurements not in good agreement with SM prediction based on CKM fit

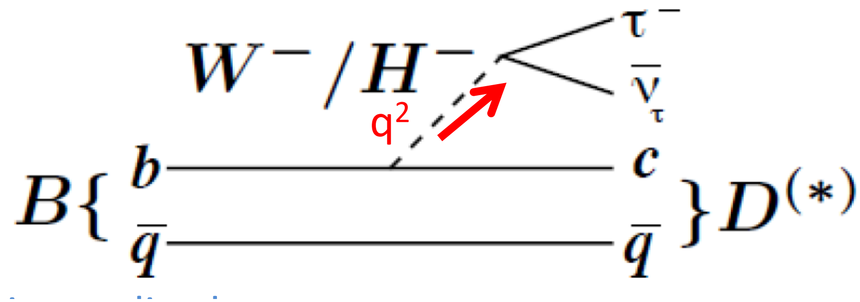
- Belle result (ICHEP 12):
  - BR ($B^- \to \tau^- \nu$) = $(0.072^{+0.027}_{-0.025} \pm 0.011) \times 10^{-3}$
  - BR factor 2 below previous world average
  - Consistent with CKM fit



B. Kronenbitter, T41.2
J. Hasenbusch, T41.4

Branching fraction of $B \to D^{(*)} \tau^- \nu$

- Tree level decay, NP sensitivity very similar to $B^- \to \tau^- \nu$

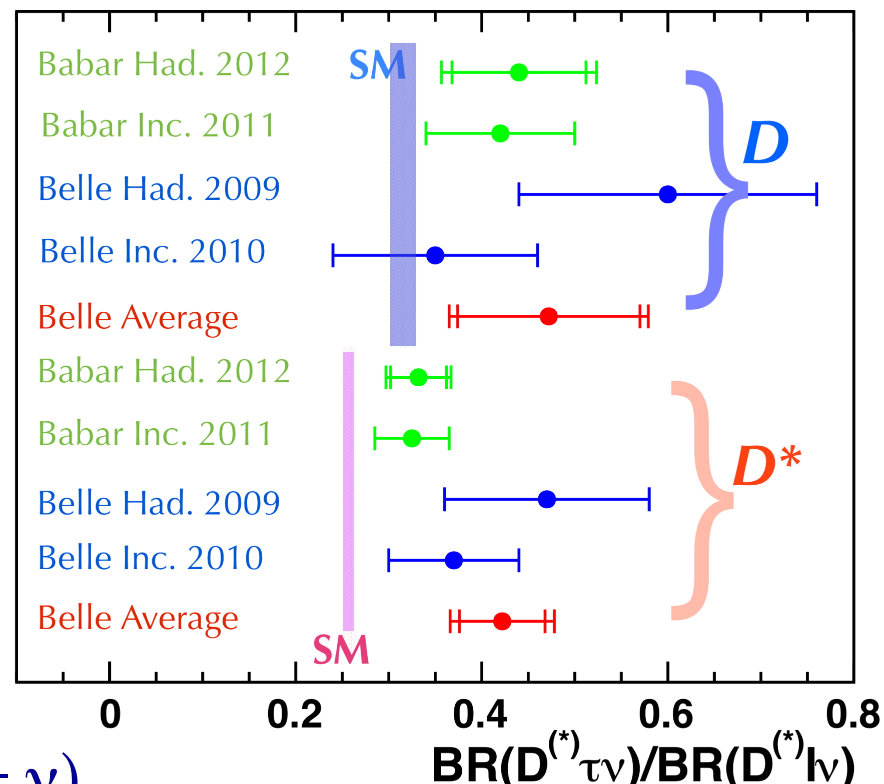


- Test SM by measuring the ratios

$$R(D) = \frac{BR(\overline{B} \to D\tau\upsilon)}{BR(\overline{B} \to D\ell\upsilon)}$$

and $$R(D^*) = \frac{BR(\overline{B} \to D^*\tau\upsilon)}{BR(\overline{B} \to D^*\ell\upsilon)}$$

M. Huschle, T40.4



- BaBar: 3.4σ tension to SM
- Belle supports tension, update expected soon
- Interesting to compare $BR(B \to \tau^- \nu)$ and $BR(B \to D^{(*)} \tau^- \nu)$

Beauty physics ≠ flavour physics

$5 \neq 5$

<u>Charm physics</u>

1) ΔA_{CP}
2) Observation of charm mixing
3) $D^0 \rightarrow \mu^+\mu^-$

<u>Kaon physics</u>

1) Lepton universality

CP violation in charm decays

Updates for D* tagged and new muon tagged analysis VERY soon

- Very small (<0.1%) CPV predicted in charm decays
  - Hard to calculate reliably
- Experimentally clean observable:

$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$

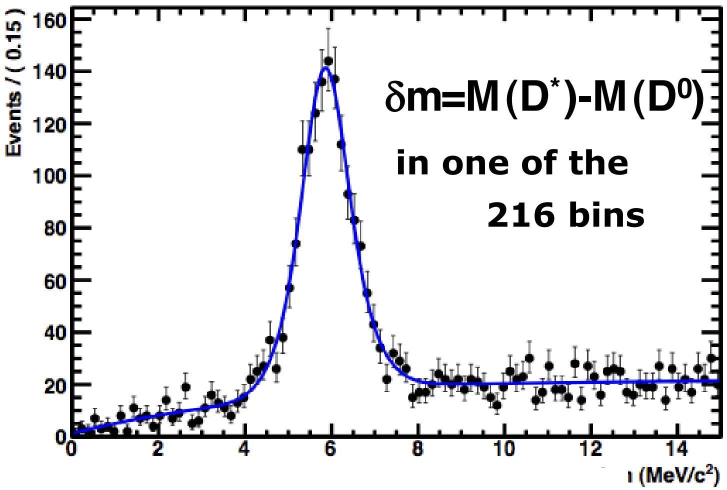
0.6 fb^{-1}

PRL viewpoint

Phys.Rev.Lett. 108 (2012) 111602

LHCb measurement with $D^* \to D\pi$

Big surprise in 2011



$$\Delta A_{CP} = (-0.82 \pm 0.21_{stat} \pm 0.11)\%$$

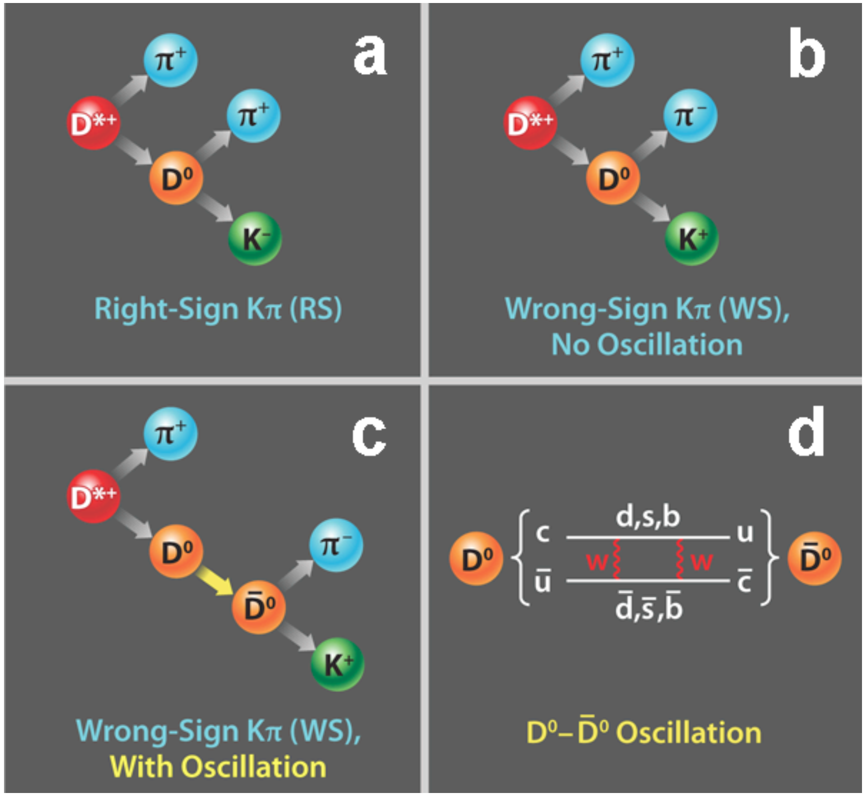
3.5 σ from no CPV.

Watch out for updates

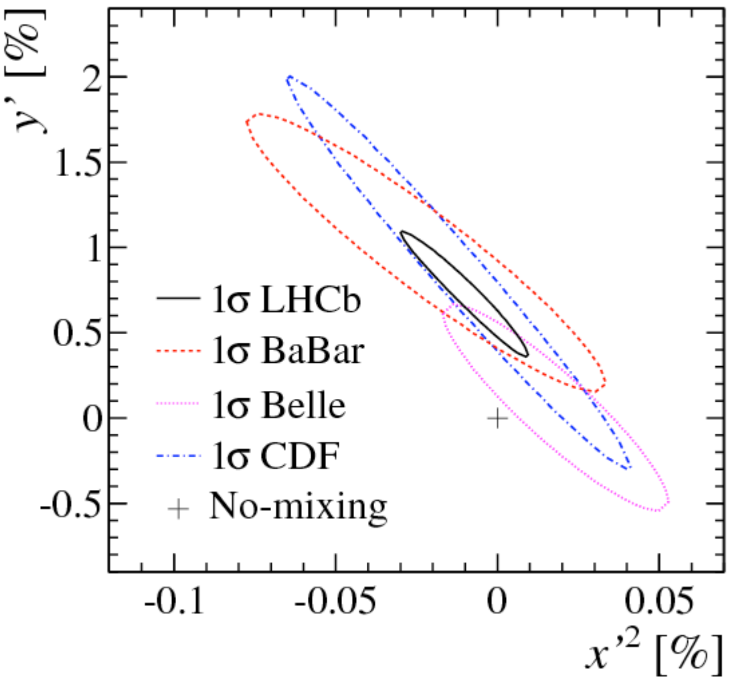
S. Stahl,. T42.3

Observation of charm mixing

- Charm mixing can be measured in the ratio of right sign vs wrong sign $D^0 \rightarrow K\pi$ decays



HCP2012



- LHCb has established mixing at 9.1σ
  - First observation of charm mixing by a single experiment

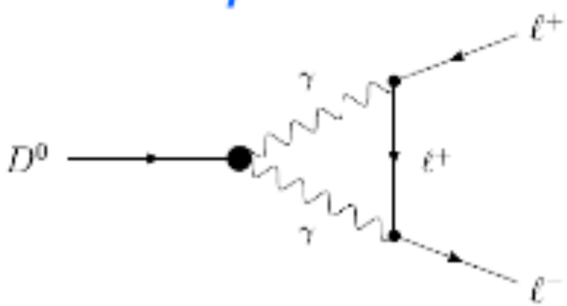
LHCb $1fb^{-1}$
PRL110 101802 (2013)
PRL viewpoint

Rare charm decays: $D^0 \to \mu^+\mu^-$

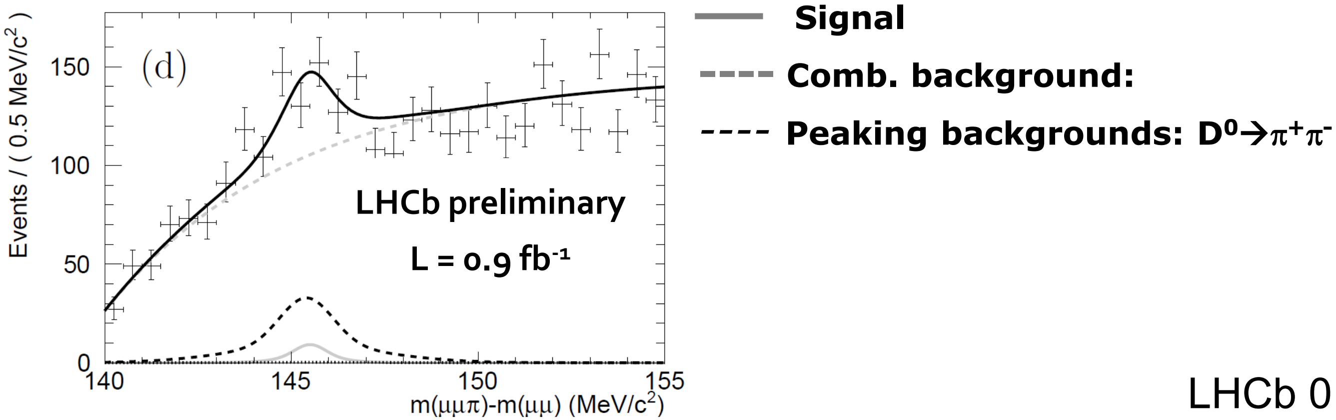
- $D^0 \to \mu^+\mu^-$ decays
  - Very strong GIM suppression
  - SM: $10^{-13} < B(D^0 \to \mu^+\mu^-) < 6 \times 10^{-11}$

    [G. Burdman et al., PR D66 (2002)]

2-photon



- LHCb Measurement



LHCb 0.9fb^{-1}, preliminary

➔ $$BR(D^0 \to \mu^+\mu^-) < 1.3 \times 10^{-8} @ 95\%\ CL$$

CERN-LHCb-CONF-2012-005

➔ **~10 times better than Belle's limit.**

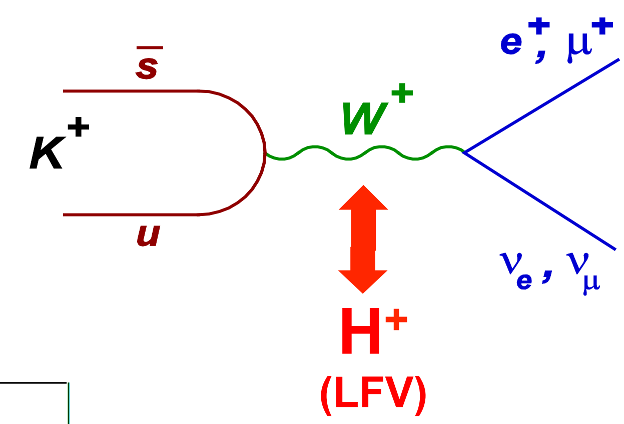
(Phys. Rev. D81 (2010) 091102, arXiv:1003.2345)

➔ **Still orders of magnitude above SM, paper with improved analysis in preparation**

Lepton universality in Kaon decays: R_K

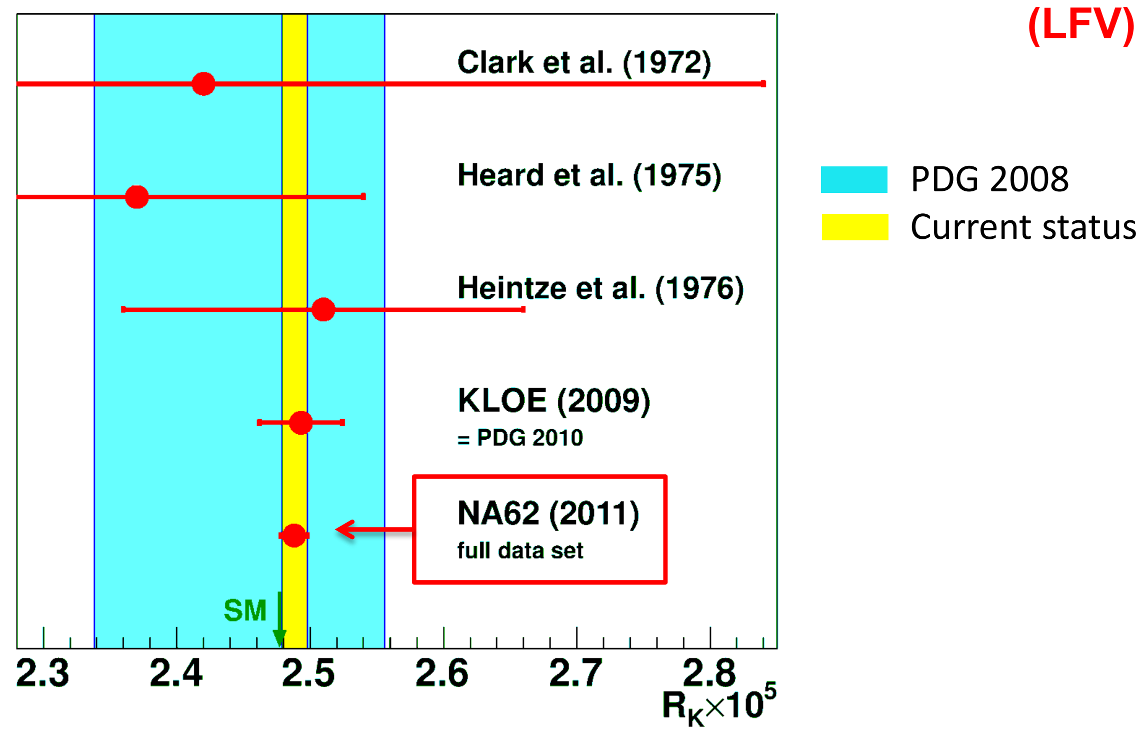
- NA62 recently published the final measurement of R_K

$$R_K = \frac{\Gamma(K^\pm \to e^\pm \upsilon)}{\Gamma(K^\pm \to \mu^\pm \upsilon)}$$



- Sensitive to LFV couplings

Discrete2012

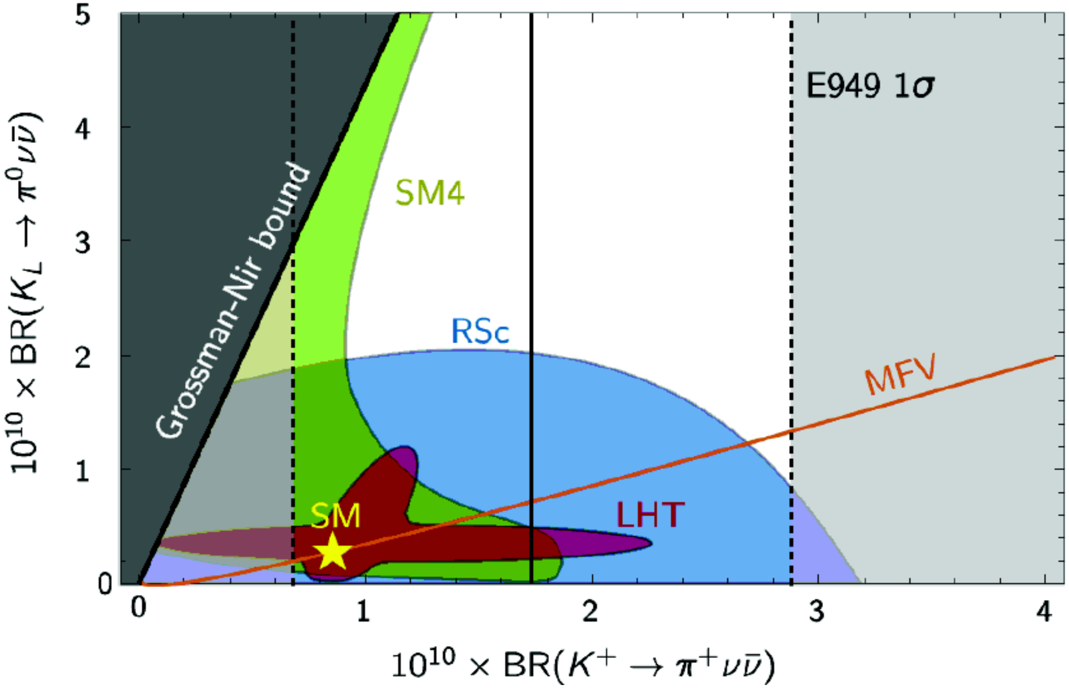


Current world average: $R_K = (2.488 \pm 0.009) \times 10^{-5}$


The Future
NEXT EXIT

Near future: Na62 and $K^+ \rightarrow \pi^+ \nu\nu$

A. Winhart, T42.1



- E949 result based on 7 events:

  $Br(K^+ \rightarrow \pi^+ \nu\nu) = (1.73^{+1.15}_{-1.05}) \cdot 10^{-10}$ SM: BR ~ 8×10^{-11}

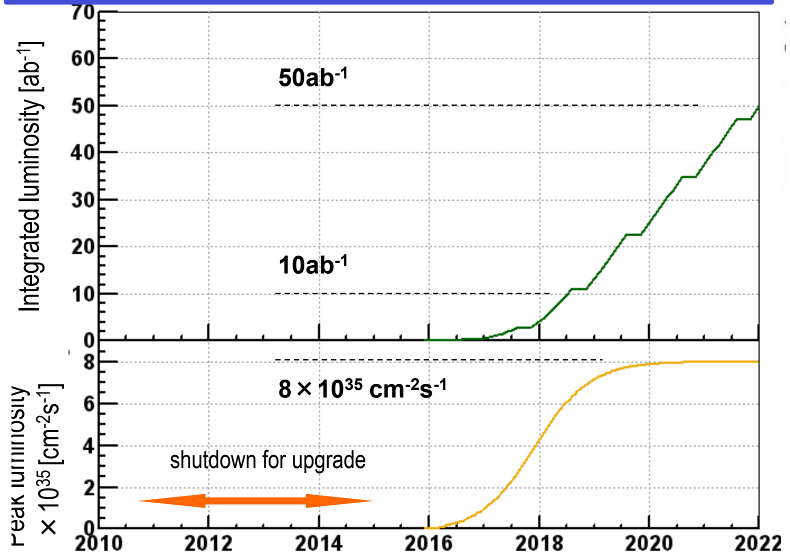
- $K^+ \rightarrow \pi^+ \nu\nu$ sensitive to NP contribution

NA62 plans to restart with the LHC 2015 and will collect O(100) $K^+ \rightarrow \pi^+ \nu\nu$ decays in 2 years and will perform a 10% measurement of V_{td}

Near future: (super) B-factories & LHC

- BaBar & Belle are analysing final dataset
  - Re-reconstruction with significantly increased the efficiencies
- Belle II is in preparation, commissioning scheduled for 2014

Belle II timeline



- LHC data from 2011+2012 not fully analysed
  - Most LHCb results use 1/3 of collected dataset
  - Similar situation for ATLAS & CMS heavy flavour measurements
- LHC will restart in 2015 with $\sqrt{s}$=13TeV
  - Heavy flavour cross section x 2
  - LHCb plans detector upgrade for 2018

2018-2022: LHCb Physics with $50fb^{-1}$

Essential features:

- Full software trigger: will readout into DAQ all subdetectors at 40 MHz (c.f. 1 MHz at present). This will improve efficiency compared with current hardware trigger, giving factor of two improvement for hadronic final states
- Increase operational luminosity to 10^{33} $cm^{-2}s^{-1}$ (and a possibility to raise still further to 2 x 10^{33} $cm^{-2}s^{-1}$)

Annual yields in muonic final states will increase 10x w.r.t. 2011, and 20x for hadronic decays. Aim to collect 50 fb^{-1}.

Type	Observable	Current precision	LHCb 2018	LHCb $50fb^{-1}$
(pseudo)- scalar	$BR(B_s \to \mu^+\mu^-)$	1.5 10^{-9}	0.5 10^{-9}	0.15 10^{-9}
MFV	$BR(B_s \to \mu^+\mu^-)$/ $BR(B_d \to \mu^+\mu^-)$	-	100%	35%
B_s mixing	$2\beta_s$	0.1	0.025	0.008
EW penguins	s_0 A_{FB}	25%	6%	2%
	A_L	0.25	0.08	0.025
UT triangle	γ	~12°	~4°	<1°

Summary

- No compelling evidence for physics beyond the SM yet
  - Heavy Flavour is very sensitive to new effects at high mass scales
  - All NP theories must satisfy stringent experimental constraints
- Experiments have not confirmed effects with marginal statistical significance (however, some remain)
  - Will some stand when precision improves?
- We are looking forward to new flavour physics discoveries
  - from the LHC & its upgrades
  - From Belle II and Na62
  - Or other experiments (BESIII, MEG, ….)

Thanks

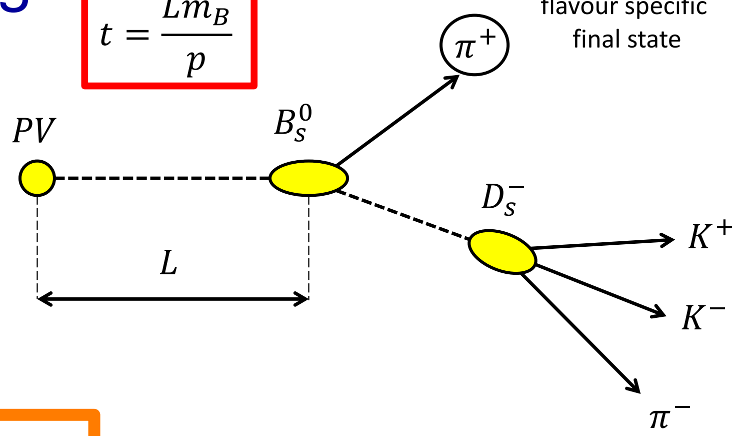
- Thanks for suggestions and information
  - Stephanie Hansmann-Menzemer
  - Ulrich Uwer
  - Rainer Wanke
  - Wolfgang Walkowiak
  - Jochen Dingfelder
  - Thomas Kuhr
  - Soeren Lange
  - Christoph Bobeth


STOP

Precision measurement of B_s mixing

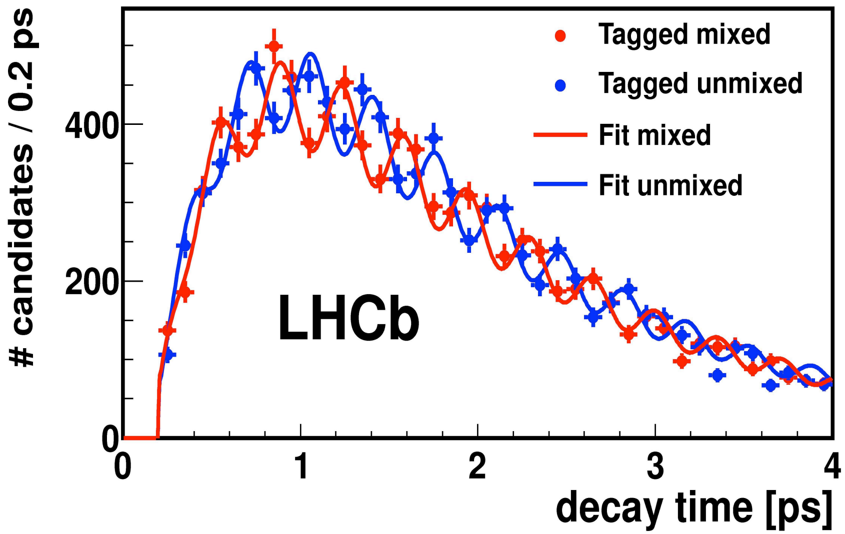
- Precision measurements of B_s mixing
  - Decay time dependent analysis of $B_s \rightarrow D_s\pi$ decays
  - Dominant systematics: decay length & momentum scale

$$t = \frac{Lm_B}{p}$$



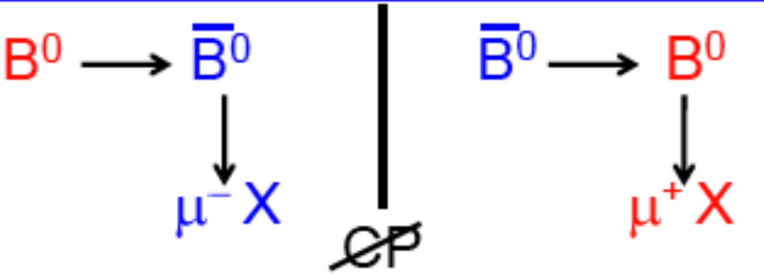
New @ MEW, preliminary

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



CP violation in B_s mixing

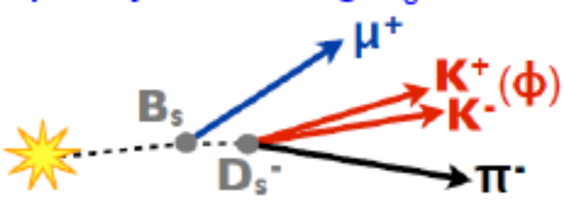
LHCb-CONF-2012-022



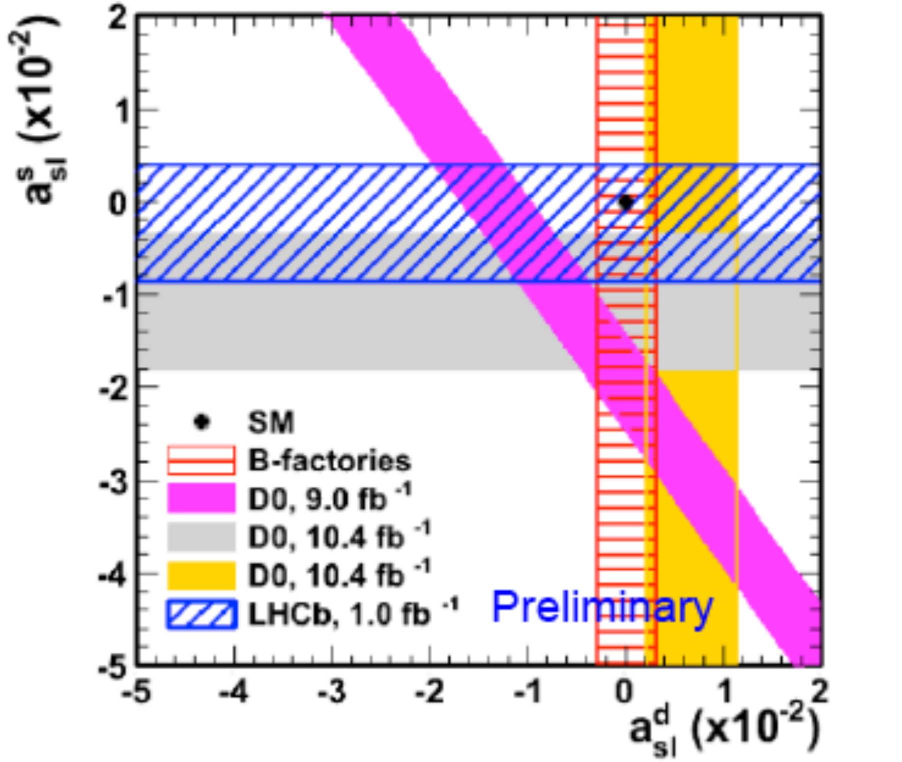
$$a_{sl}^{q} \equiv \frac{\Gamma(\overline{B}_q^0 \to \mu^+ X) - \Gamma(B_q^0 \to \mu^- X)}{\Gamma(\overline{B}_q^0 \to \mu^+ X) + \Gamma(B_q^0 \to \mu^- X)}$$

Problem: Production asymmetry at LHC

⇒ Use quickly oscillating B_s mesons only



$$\frac{a_{\rm sl}^{s}}{2} = \frac{N(D_s^- \mu^+) - N(D_s^+ \mu^-)}{N(D_s^- \mu^+) + N(D_s^+ \mu^-)}$$



$$a_{\rm sl}^{s} = (-0.24 \pm 0.54 \pm 0.33)\%$$

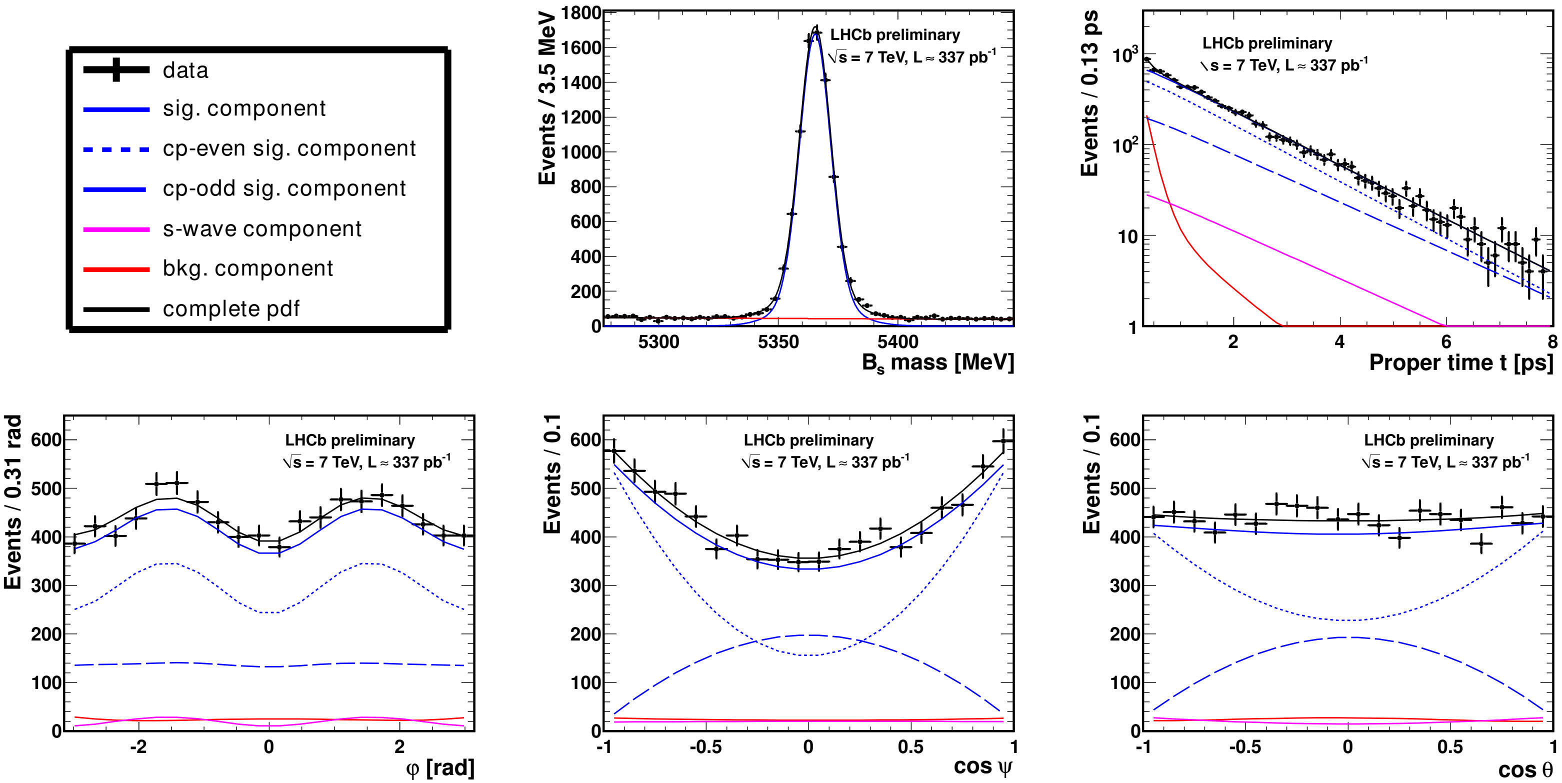
Main syst.: L0 μ-trigger efficiency

Consistent with Standard Model

$a_{\rm sl}^{s} = (1.9 \pm 0.3) \times 10^{-5}$ *(A.Lenz)*

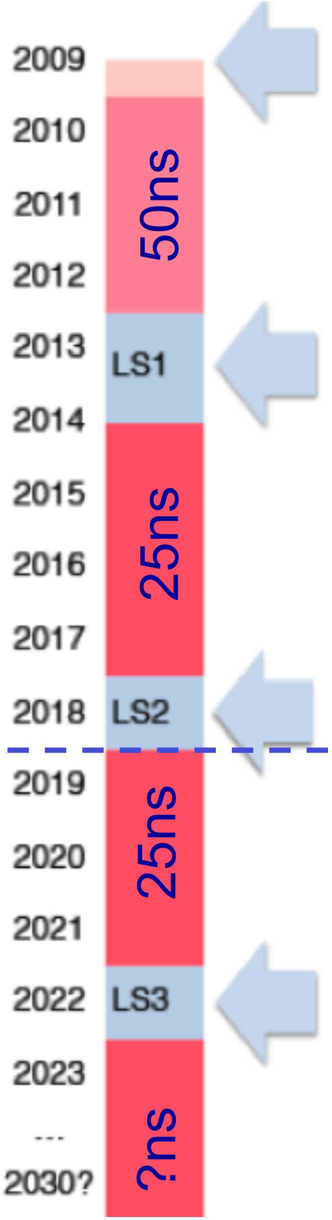
$B_s \to J/\psi\phi$: Angular analysis ML fit

- Maximum likelihood fit with 10 physics parameters
  - 7 angular amplitudes and phases
  - Γ_s , $\Delta\Gamma_s$, ϕ_s
- Proper time calibrated with prompt J/ψ: $\sigma(t)$~50ps
- Used Opposite sign flavour tagging, εD^2=(2.08±0.41)%



Goodness of fit: p-value=44%

LHC(b) long term plan



$\int L\,dt$

✧ LHC startup, $\sqrt{s}$ = 900 GeV

$\sqrt{s}$=7/8TeV; L_{LHCb}= 3-4x10^{32} $cm^{-2}s^{-1}$
→ ~1.5fb^{-1}/year

2.5/fb

Go to design energy, nominal luminosity

$\sqrt{s}$=13/14TeV; L_{LHCb}= 4x10^{32} $cm^{-2}s^{-1}$
→ 1.5-2fb^{-1}/year

5-7/fb

Injector and LHC Phase-1 upgrade to full design luminosity

$\sqrt{s}$=14TeV; L_{LHCb}= 1-2x10^{33} $cm^{-2}s^{-1}$
→ >5fb^{-1}/year

50/fb

HL-LHC Phase-2 upgrade, IR, crab cavities?

$\sqrt{s}$=14TeV; L_{LHCb}= ~2x10^{33} $cm^{-2}s^{-1}$

Search for $K_s \rightarrow \mu^+\mu^-$: analysis

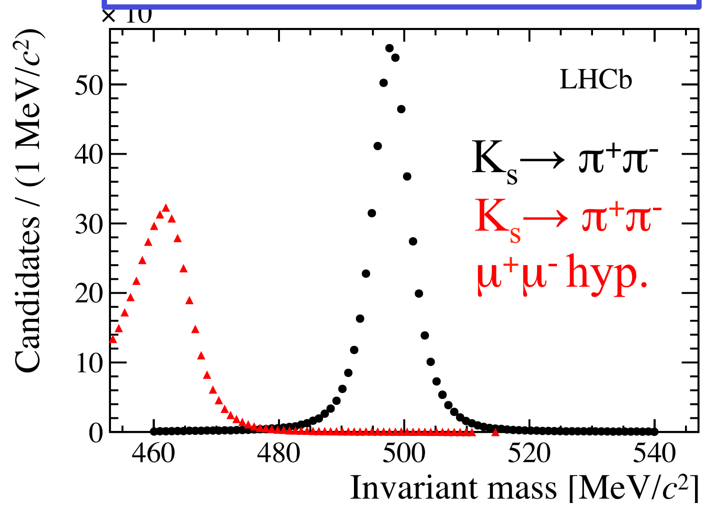
- Yet unobserved FCNC decay, SM prediction:

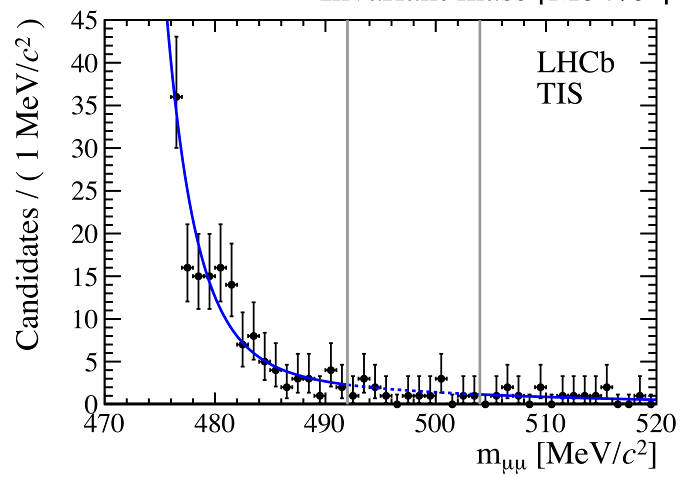
$$\mathcal{B}(K^0_S \rightarrow \mu^+\mu^-) = (5.0 \pm 1.5) \times 10^{-12}$$

Nucl. Phys. B366 (1991) 189, JHEP 0401 (2004) 009

- $K_s \rightarrow \mu^+\mu^-$ sensitive to light scalars
- Previous best limit from 1973
  - BR($K_s \rightarrow \mu^+\mu^-$) < 3.2 x 10^{-7}
    PLB44 (1973) 217
- LHCb analysis (~10^{13} K_s / fb^{-1}):
  - Excellent mass resolution enables to separate the $K_s \rightarrow \pi^+\pi^-$ misID peak
  - Discrimination through a BDT (geometric and kinematic), trained and calibrated on data
    - Signal proxy: $K_s \rightarrow \pi^+\pi^-$
    - Background from upper mass sideband
  - Normalization $K_s \rightarrow \pi^+\pi^-$

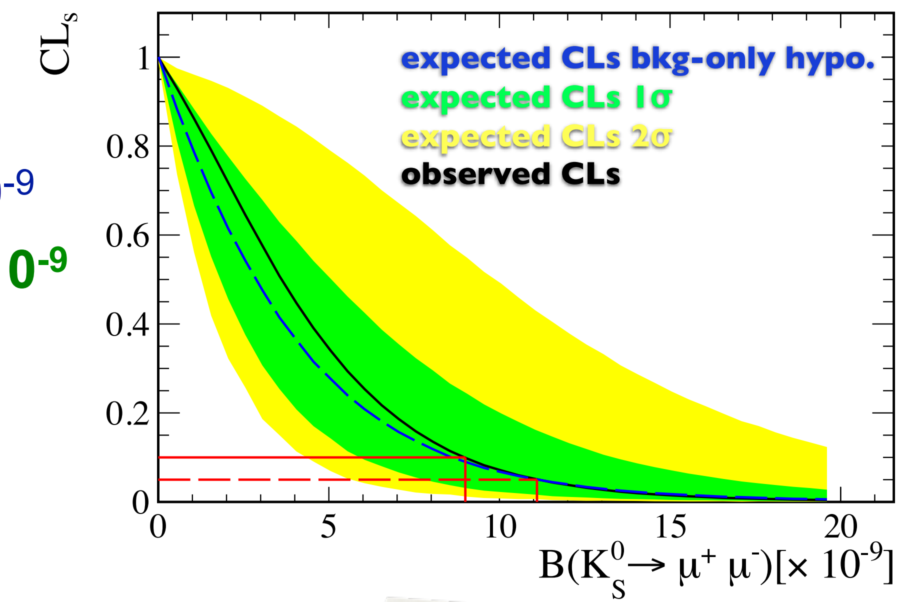
$K_s \rightarrow \pi^+\pi^-$





Search for $K_s \to \mu^+\mu^-$: results

- Limits from CLs:
  - expected: BR($K_s \to \mu^+\mu^-$) < 11 x 10^{-9}
  - **observed: BR($K_s \to \mu^+\mu^-$) < 11 x 10^{-9}**



- These limits improve the existing worlds best limits by a factor 35

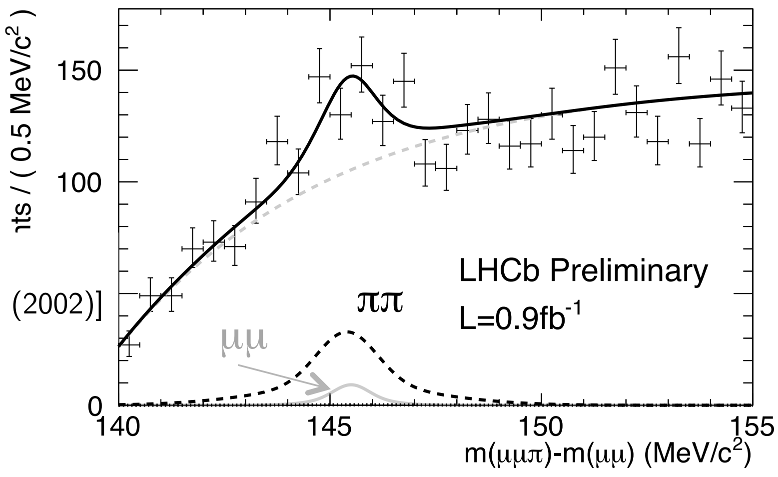
- 2011 trigger was not optimized for $K_s \to \mu^+\mu^-$
  → 2012 is, good prospects for this analysis

Search for $D^0 \rightarrow \mu^+\mu^-$

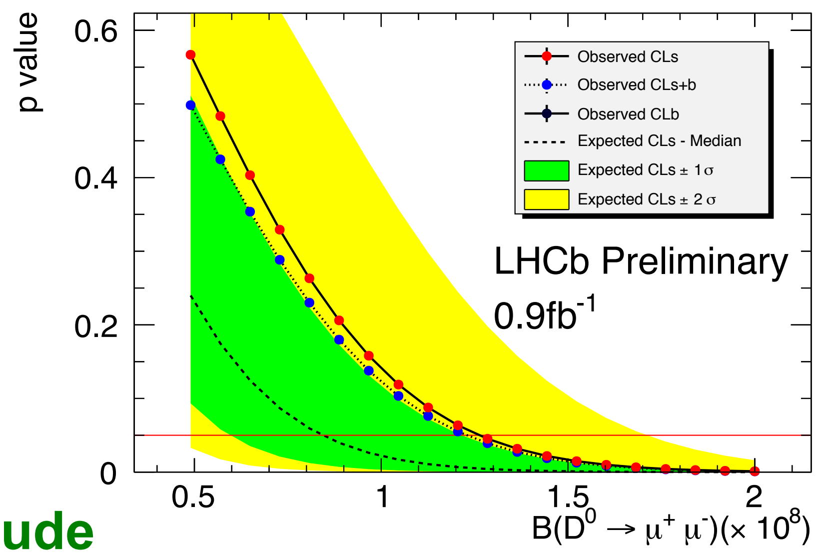
- Only Higgs penguin sensitive to up-type quarks
- SM is dominated by long distance contribution

$$10^{-13} < B(D^0 \rightarrow \mu^+\mu^-) < 6 \times 10^{-11}$$

[G. Burdman et al., PR D66 (2002)]



- NP up to 10^{-9}, e.g. RPV SUSY
- LHCb analysis:
  - D* tagged sample of $D^{*+} \rightarrow D^0(\rightarrow \mu^+\mu^-)\,\pi^+$
  - BDT used to reduce combinatorial bkg from b and c decays
  - Yield from 2D fit to m(D0), $\Delta m(D^{*+}-D^0)$
  - Normalization to $D^0 \rightarrow \pi^+\pi^-$



- **Upper exclusion limit(preliminary) 1.3×10^{-8} @ 95% CL worlds best by ~one order of magnitude**

- Major differences from 2006 analysis
  - Reprocessing of full Belle data set (2011)
    - → Improved detection efficiencies of low p_T tracks and neutral particles
  - Added 322M more $B\bar{B}$ data in addition to previous 449M
  - New sophisticated hadronic tagging algorithm
    - → Based on neural net & Bayesian interpretation
    - → More B/D decay modes included for the tag
  - Signal extraction by 2D fit to (E_{ECL}, M_{miss}^2)
    - → Improved handling of peaking backgrounds

Definition of variables

$$M^2_{miss} = (E_{CM} - E_{B_{tag}} - E_{B_{sig}})^2 - (P_{B_{tag}} - P_{B_{sig}})^2$$

E and $P_{B_{tag}}$: Energy and momentum of the tagged-B

E and $P_{B_{sig}}$: Energy and momentum of signal side B particles

E_{ECL} = Extra energy in ECL aside from those contributed via tagged-B and signal-B constituents

τ-decays used

$\tau^- \to e^- \bar{\nu}_e \nu_\tau$

$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$

$\tau^- \to \pi^- \nu_\tau$

$\tau^- \to \rho^- \nu_\tau$

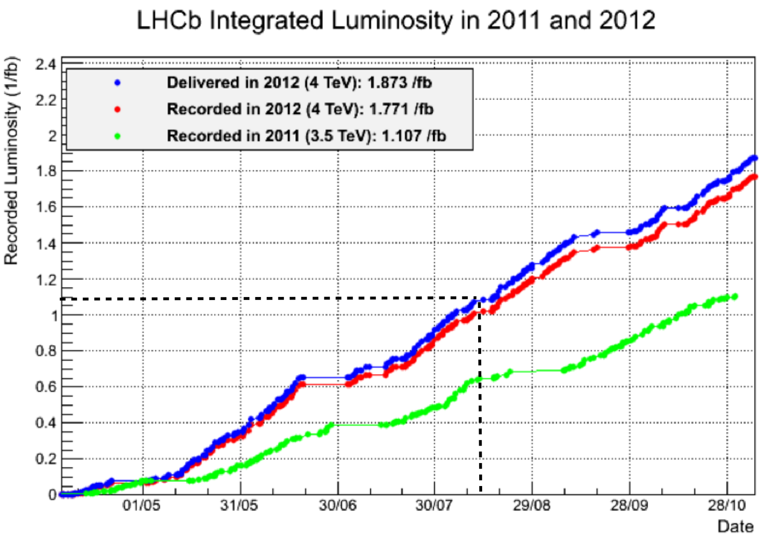
New results on the search for $B_s \to \mu^+\mu^-$ from LHCb

Johannes Albrecht (CERN & TU Dortmund)
on behalf of the LHCb Collaboration

Hadron Collider Physics Symposium 2012
November 12 - 16, 2012
Kyoto, Japan

Datasets

- Combined analysis of the following datasets:
  - 1.1fb^{-1} of data at $\sqrt{s}$=8TeV (2012) increased $b\bar{b}$-production cross section
  - 1.0fb^{-1} of data at $\sqrt{s}$=7TeV (2011)



the sample was fully available mid-september

- First analysis of the data recorded in 2011 published **PRL108(2012)231801**
  - Measurement presented here is similar to this previous analysis
  - improvements over the previous publication are implemented

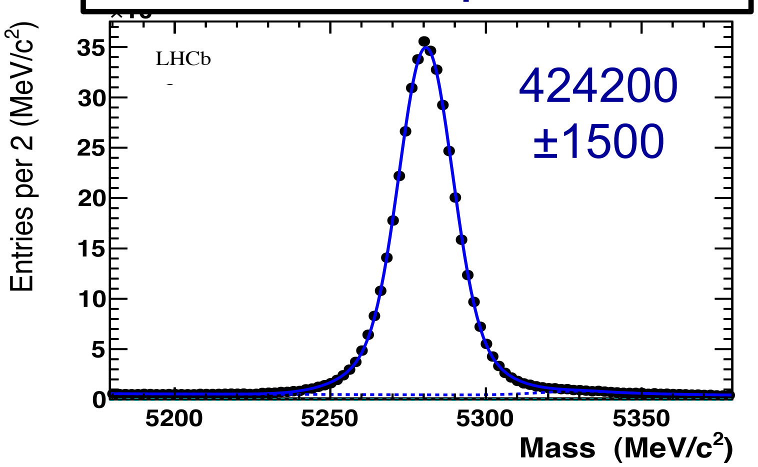
- Full 2011 data set reanalysed
  → It supersedes the previous publication

- **Selection**
  - Soft selection to reduce size of dataset, similar to control channels unchanged to previous analyses
- **Normalization**
  - Convert number of observed events in branching fraction by normalizing to $B^{\pm} \to J/\psi K^{\pm}$ and $B \to K^{+}\pi^{,-}$

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

from MC data checked | from data | fraction $b \to B_s$ (updated, next slide)

B±→J/ψK±



Normalization factors

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

Slightly lower than in 2011 measurement due to higher $\mathcal{L}$ and x-section

b fragmentation f_d/f_s (updated)

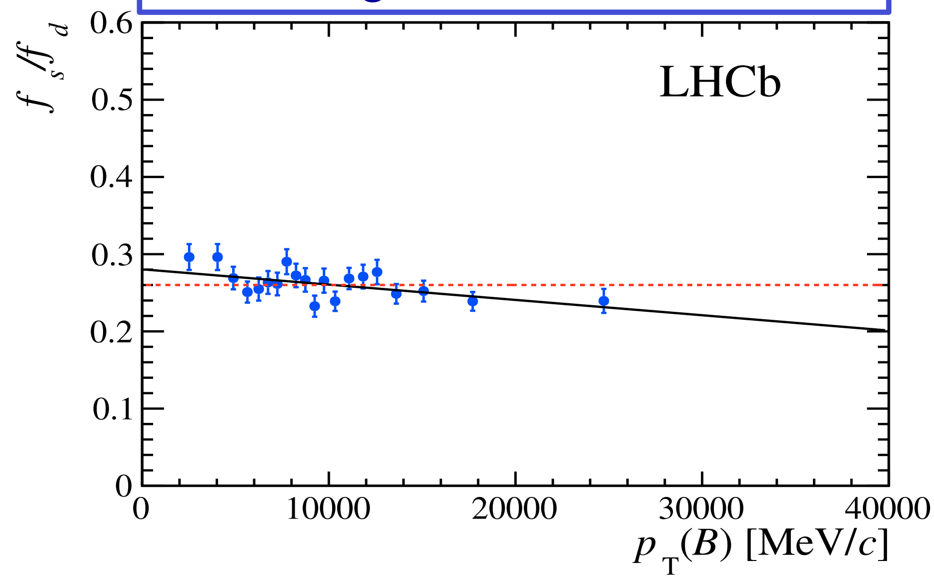
- LHCb has measured the fraction of $b \rightarrow B_s$ in two ways:
  - Ratio of $B_s \rightarrow D_s \mu X$ to $B \rightarrow D^+ \mu X$ **[PRD85 (2012) 032008]**
  - Ratio of $B_s \rightarrow D_s \pi^+$ to $B \rightarrow D^+ K$ and $B^0 \rightarrow D^+ \pi^+$ (**newly updated: $1 fb^{-1}$ @ 7 TeV**)

- 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

B fragmentation Vs PT



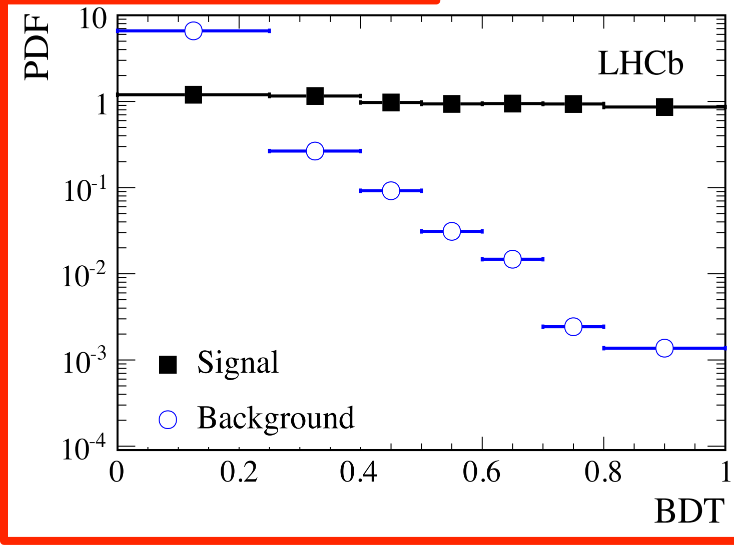
- Stability 7 vs 8 TeV checked
  - $B^+ \rightarrow J/\psi K^+ / B_s \rightarrow J/\psi \phi$ ratio stable

LHCb analysis II

- **Signal likelihood**
  - BDT for signal classification (unchanged to previous analysis)
    - Signal PDF calibrated with $B_{(s)} \rightarrow h^+h'^-$
    - Compared to 2011 analysis, BDT shape moved to slightly lower values
  - Invariant mass, resolution:
    - $\sigma(B^0 \rightarrow \mu\mu)$ = 24.63 ± 0.38$^{stat+syst}$ MeV/c^2
    - $\sigma(B_s \rightarrow \mu\mu)$ = 25.04 ± 0.40$^{stat+syst}$ MeV/c^2

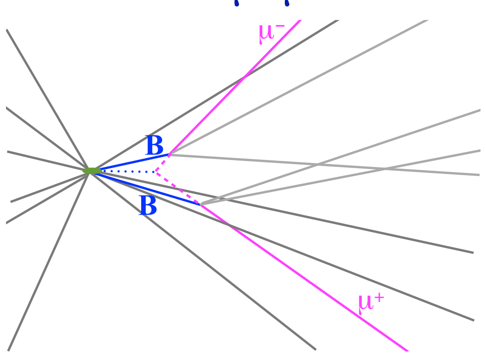
    → Well comparable to 2011 analysis

Calibrated BDT



- **Background likelihood:**
  - Main background: combinatorial from $bb \rightarrow \mu^+\mu^- X$
    → background extrapolated from sideband
  - Improved description of peaking background below signal window (see next slide)

$bb \rightarrow \mu^+\mu^- X$



- Extraction of the result
  - Extract observation / exclusion measurement using the CLs method
  - Determine branching fraction with unbinned ML fit

Peaking backgrounds

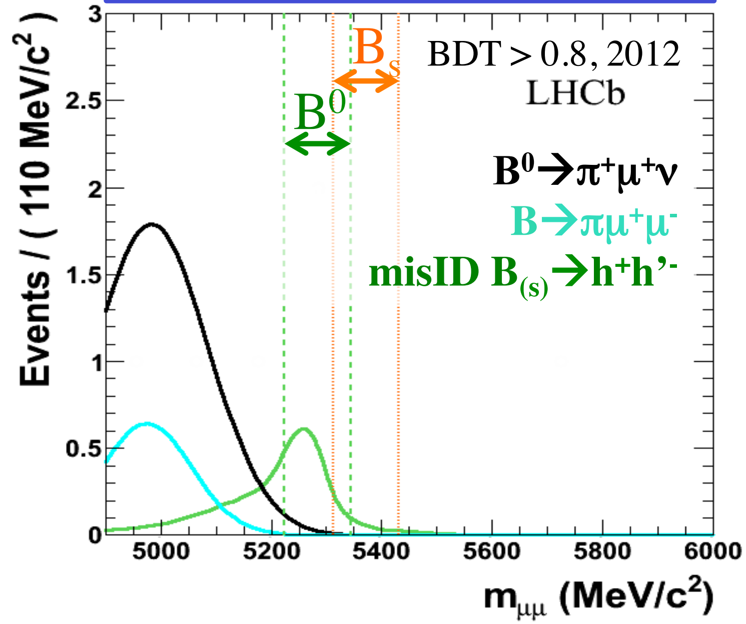
- Improvement of combinatorial background interpolation by inclusion of backgrounds from exclusive decays in the fit
  - Contribution in signal window: only $B_{(s)} \to h^+h'^-$ (identical treatment as 2011)
  - Mass shape different from exponential → bias the background interpolation (new):
    - $B^0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

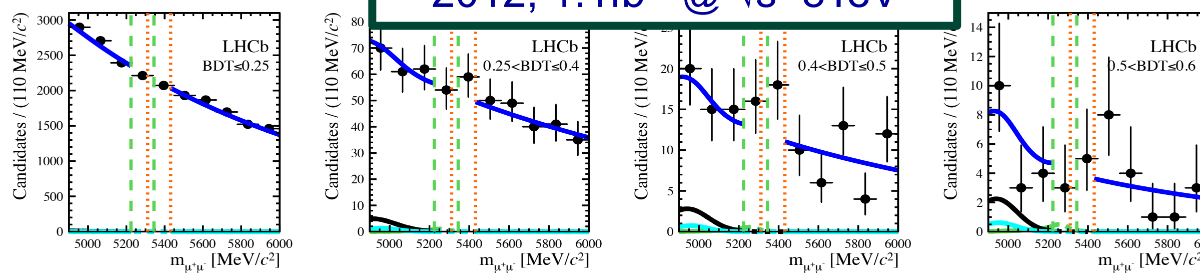
- Mass sideband fit to extrapolate background
  - Combinatorial background and

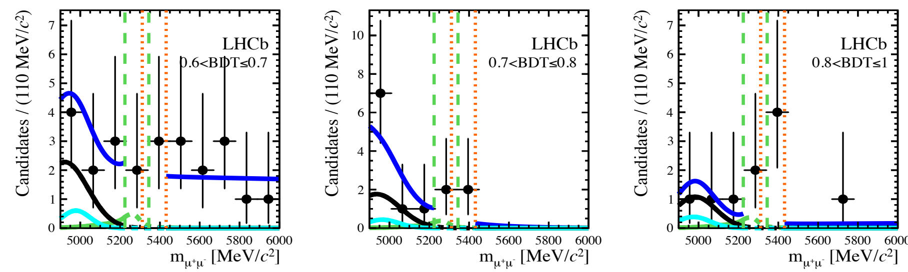
    $B^0 \rightarrow \pi^+\mu^+\nu$

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

    $B_{(s)} \rightarrow h^+h'^-$(misID)

2012, 1.1fb^{-1} @ √s=8TeV

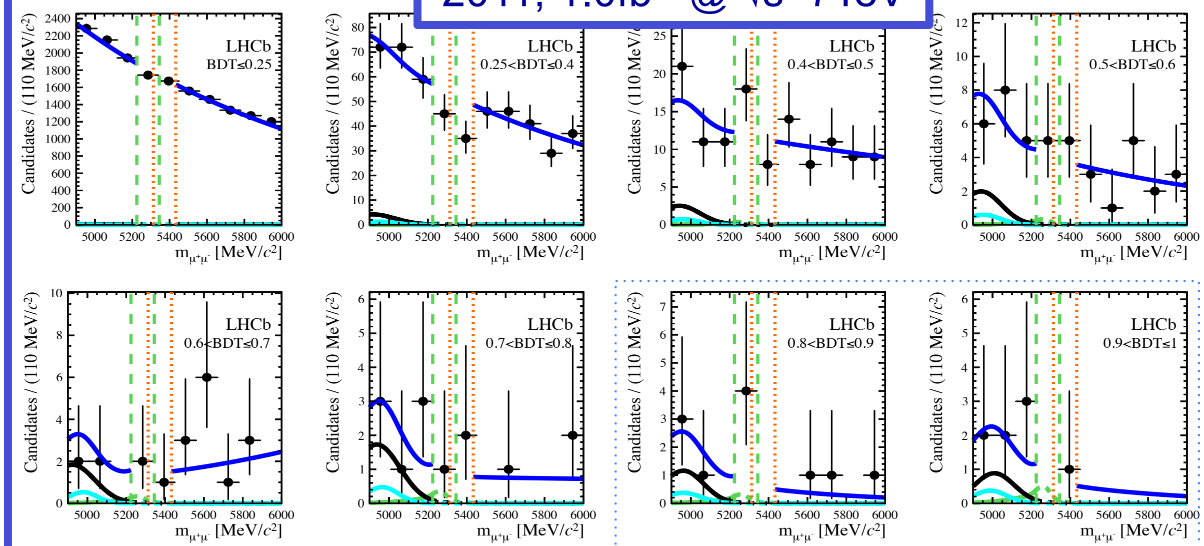




Highest BDT bin: no events in sidebands → merge two highest bins

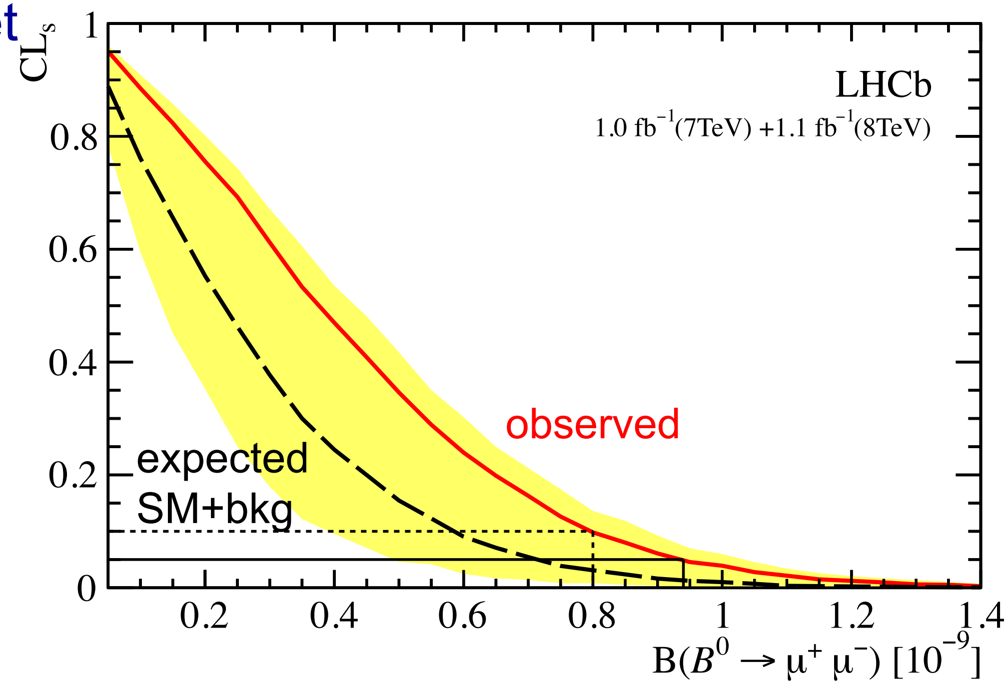
- Same fit has been repeated on 2011
  - Combinatorial component reduced in high BDT bins
  - Impact on published results evaluated

2011, 1.0fb^{-1} @ √s=7TeV



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

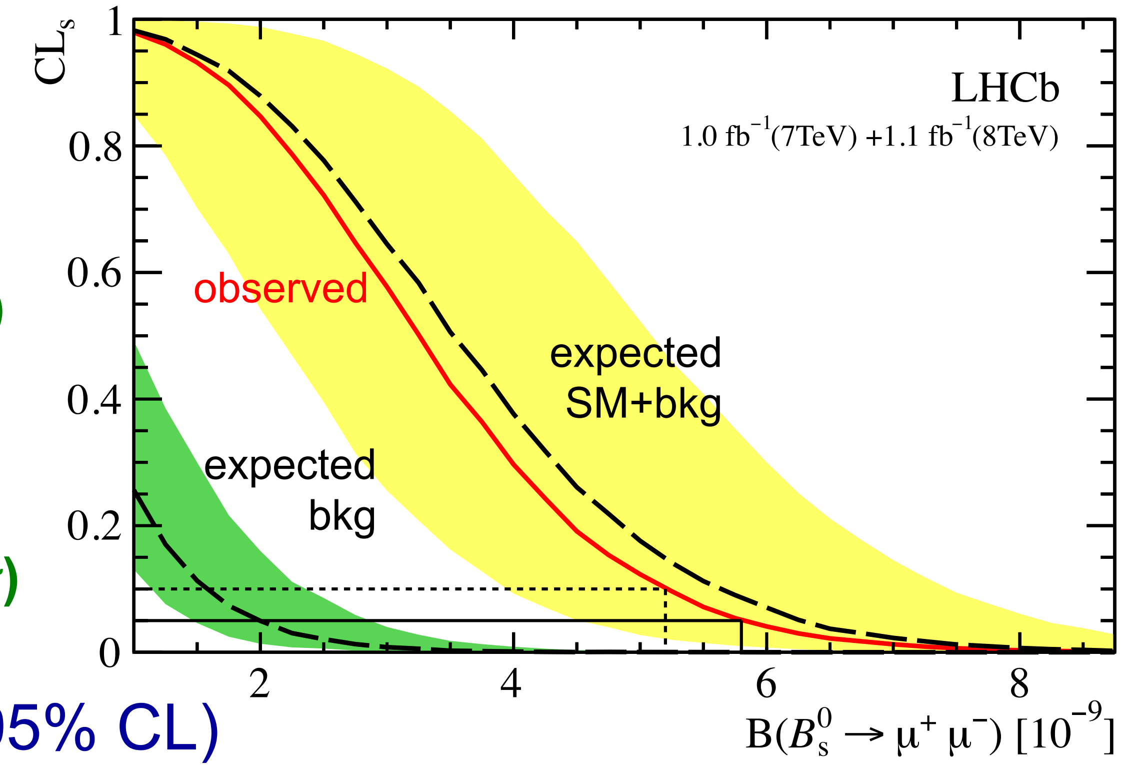
- Evaluate compatibility with background only and signal+background hypotheses (CLs method)
  - Combined 2011+2012 dataset used
  - bkg only p-value: 11%
  - Upper exclusion limit $BR(B^0 \rightarrow \mu^+\mu^-) < 9.4 \times 10^{-10}$ @95% CL
    world best single experiment



$B^0 \rightarrow \mu^+\mu^-$	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**

Results for $B_s \to \mu^+\mu^-$: Limits and significance

- 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 $3.3\ \sigma$)**



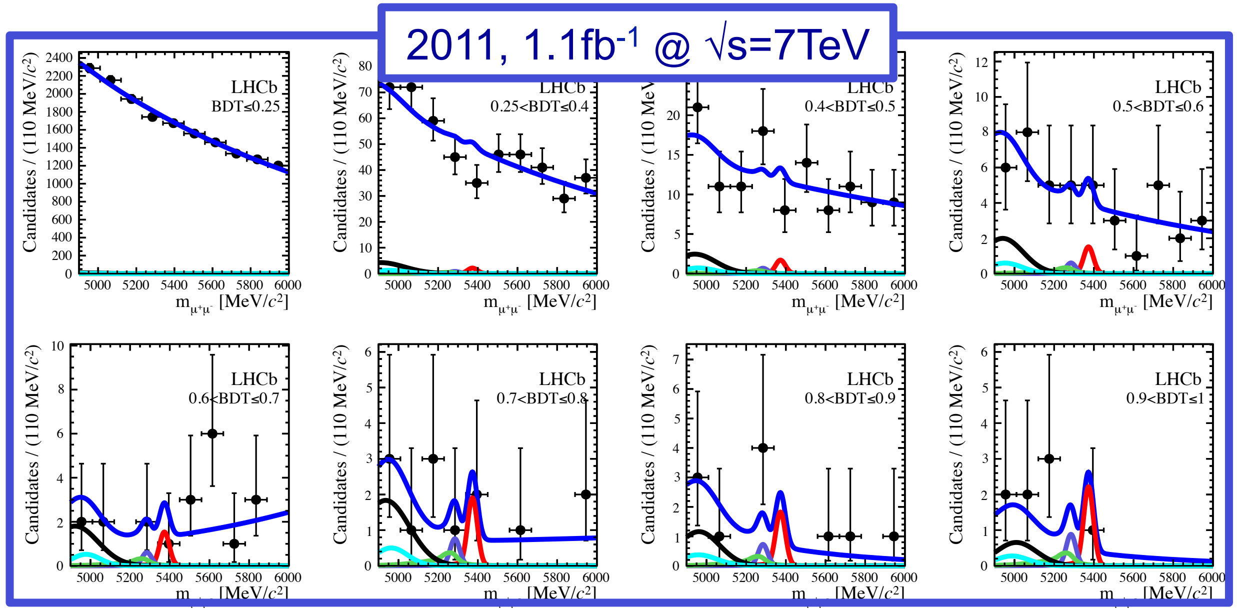
- Double sided limit (@95% CL)

$$1.1 \times 10^{-9} < BR(B_s \to \mu^+\mu^-) < 6.4 \times 10^{-9}$$

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

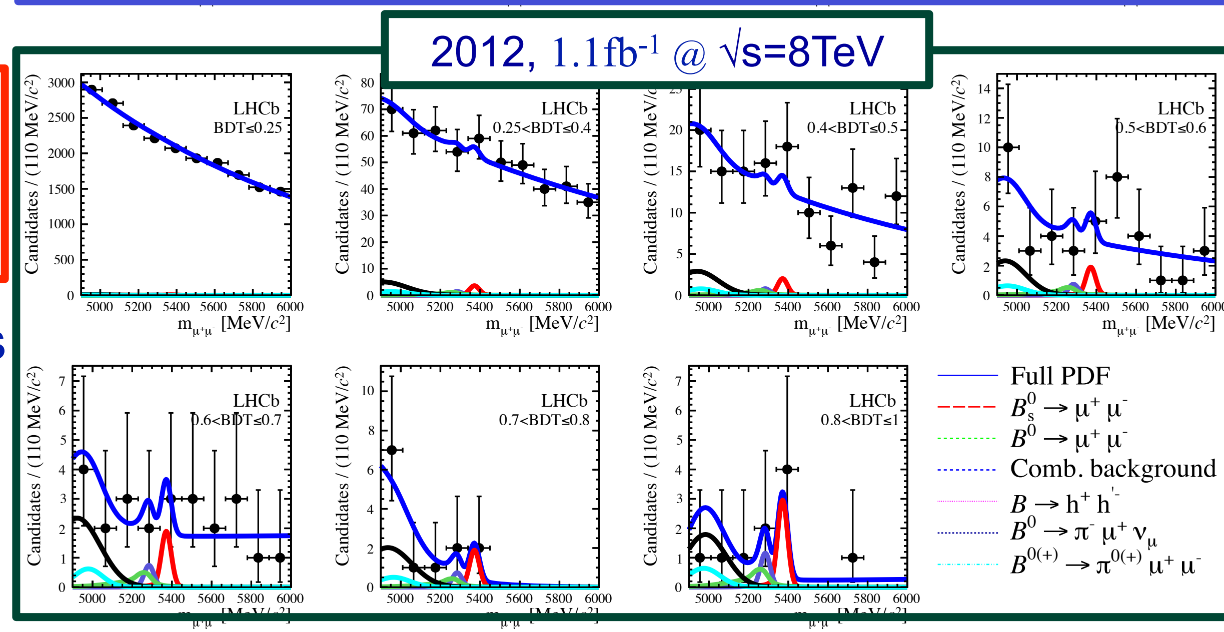
Results for $B_s \to \mu^+\mu^-$: BR fit

- Simultaneous unbinned likelihood fit to 15 BDT bins of 2011 + 2012
  - Combinatorial bkg, B_s and B^0 yield fully free
  - Exclusive backgrounds inserted as Gaussian constraints



- Fit result:

$$BR(B_s \to \mu^+\mu^-) = 3.2^{+1.4}_{-1.2}(stat)^{+0.5}_{-0.3}(syst)\times 10^{-9}$$



- Systematic Uncertainties
  - Change bkg model
  - Fix all Gaussian constraints

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