LHCP 2017

Shanghai, China, May 15 - 20, 2017

Flavour Physics Reach after Upgrade

Olaf Steinkamp

on behalf of the LHCb collaboration

including beauty-ful results from ATLAS and CMS

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Flavour Physics

Study the properties of the three families of quarks and leptons and their interactions

Played a crucial role in establishing the Standard Model

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Search for signatures of physics
Beyond the Standard Model**

"Indirect Searches for New Physics"

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"Indirect Searches for New Physics"

**@ LHC: "Flavour Physics" ≈ mostly heavy quarks
"Searches for BSM physics" ≈ mostly *b* quarks**

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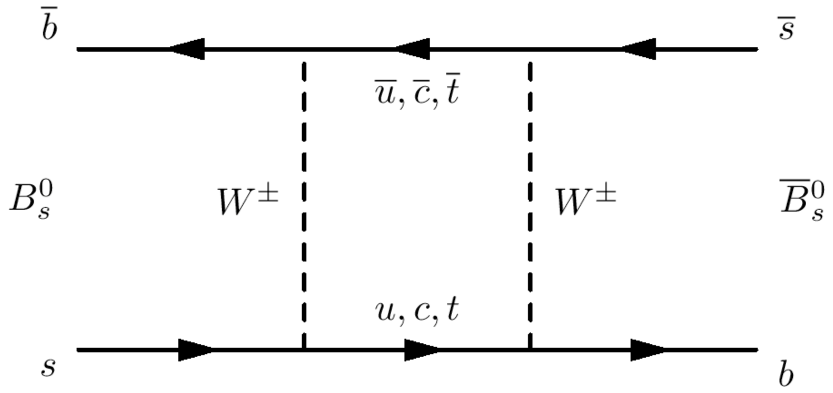
"Indirect Searches for New Physics"

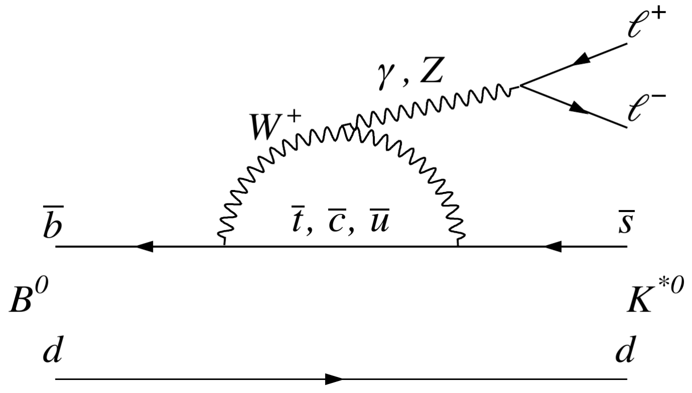
Many interesting and important measurements of SM physics,
but no time to discuss these here … sorry !!!

Indirect Searches For BSM Physics

Most BSM physics models predict additional heavy particles

→ Can cause additional amplitudes in processes with internal loops





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Most BSM physics models predict additional heavy particles

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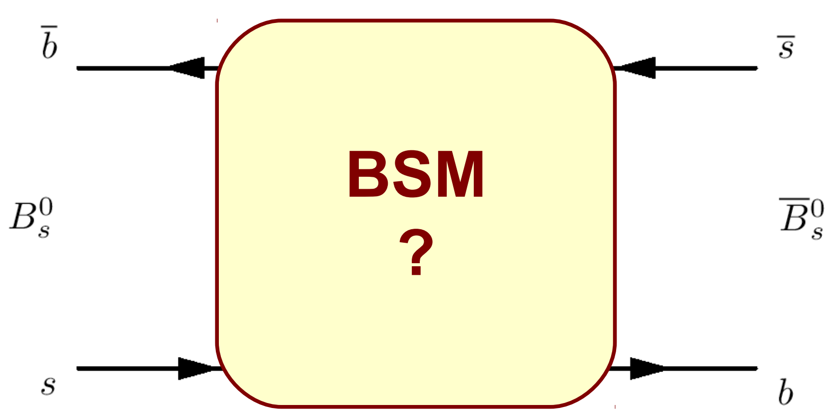
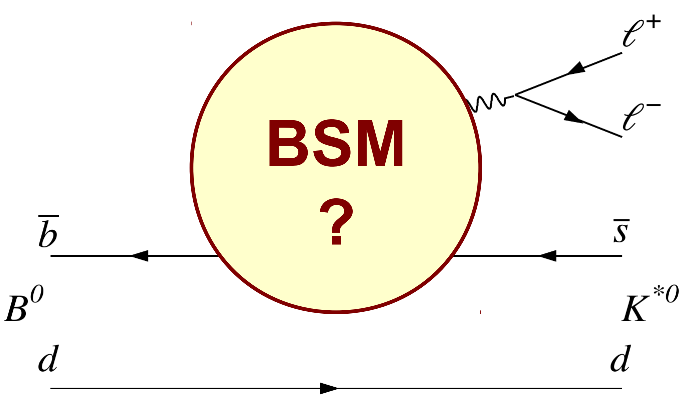
→ Can lead to sizeable modifications of observables

Rates, angular distributions, *CP* violating phases





Indirect Searches For BSM Physics

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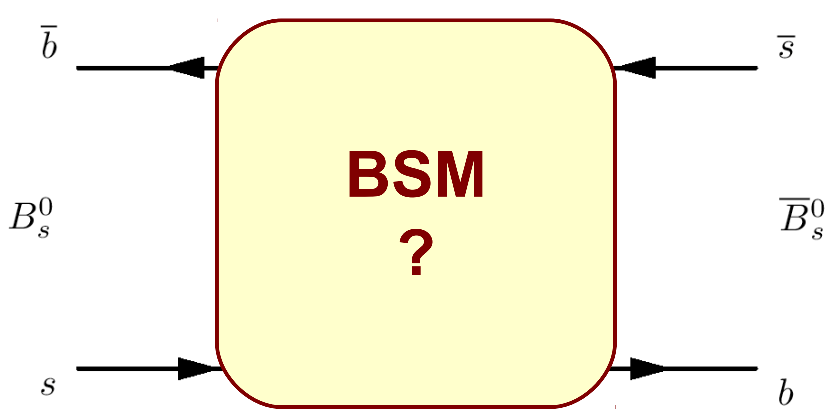
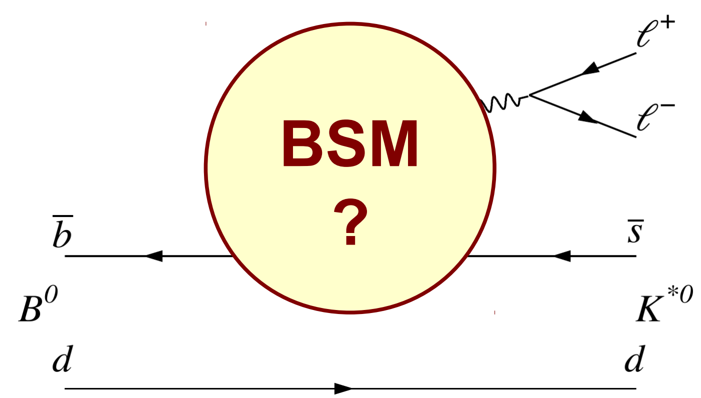
Rates, angular distributions, *CP* violating phases

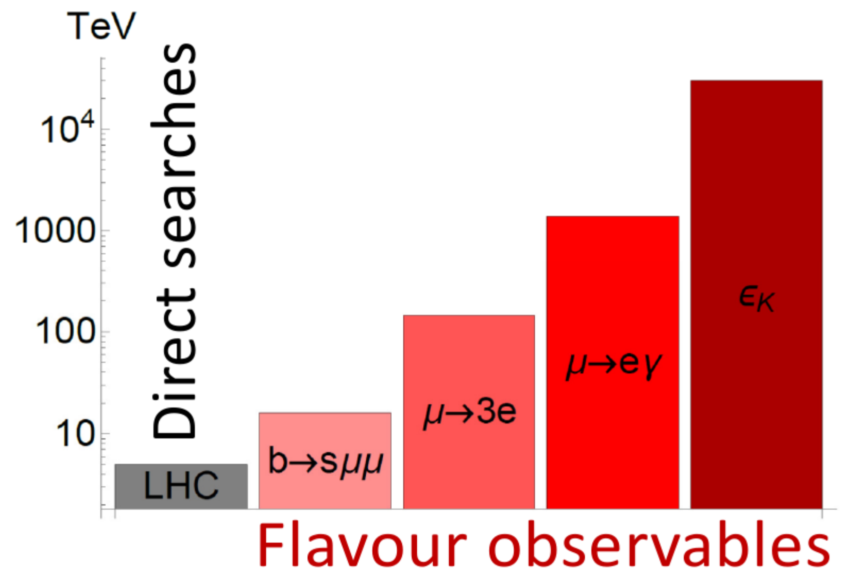
Goal: uncover deviations from Standard Model expectations by comparing <u>precise measurements</u> with <u>precise predictions</u>





Indirect Searches For BSM Physics

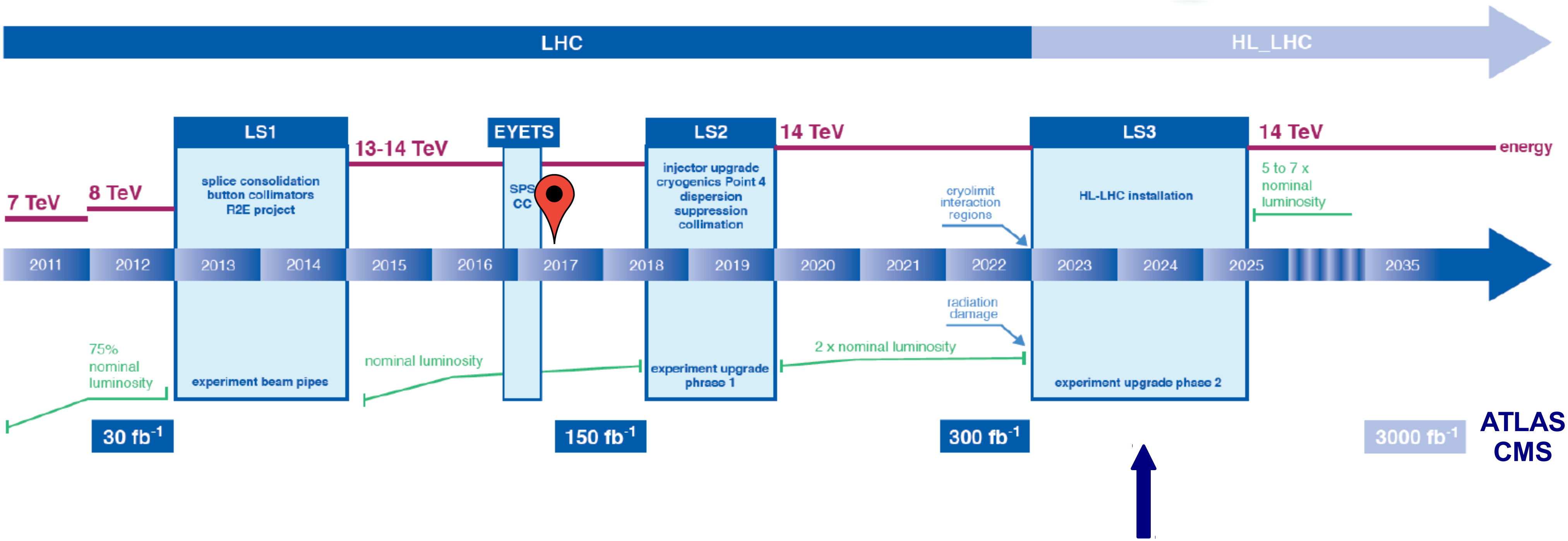
<u>Indirect searches</u> can be sensitive to <u>much higher mass scales</u> than direct searches for heavy particles



[A.Crivelin @ La Thuile 2017]

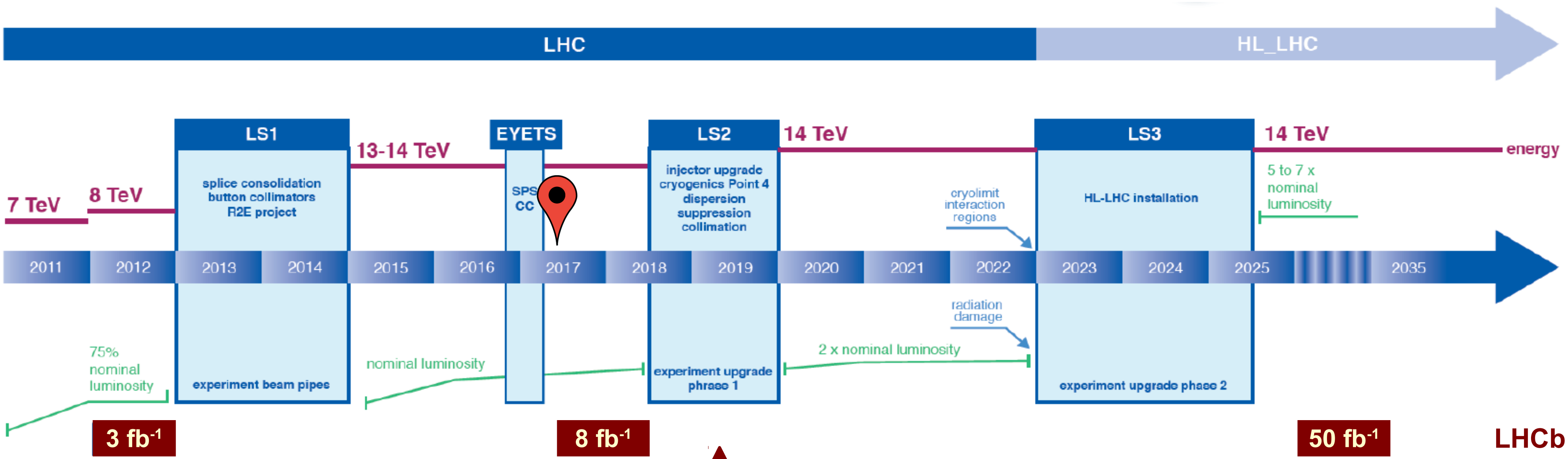
The <u>pattern of observed deviations</u> can hint at the <u>structure of the BSM physics</u> at work

Upgrade



ATLAS / CMS
HL-LHC upgrades

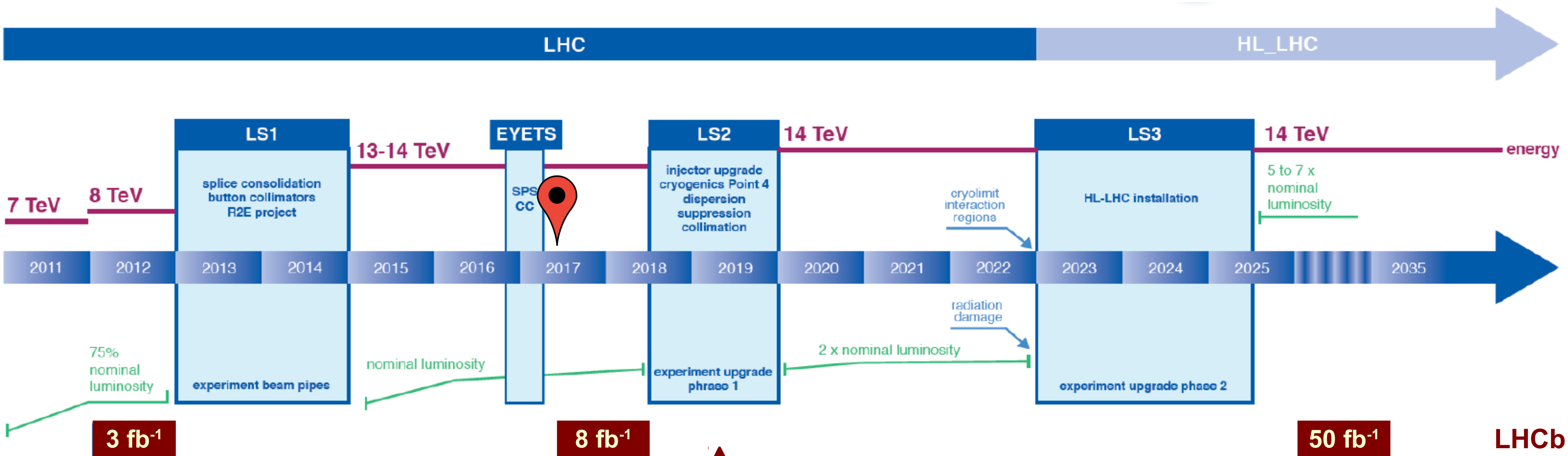
Upgrade



LHCb upgrade

Phase-2 upgrade
~ 2030 ?

Upgrade



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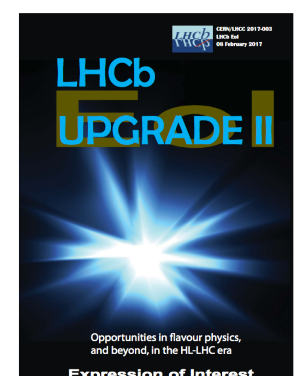
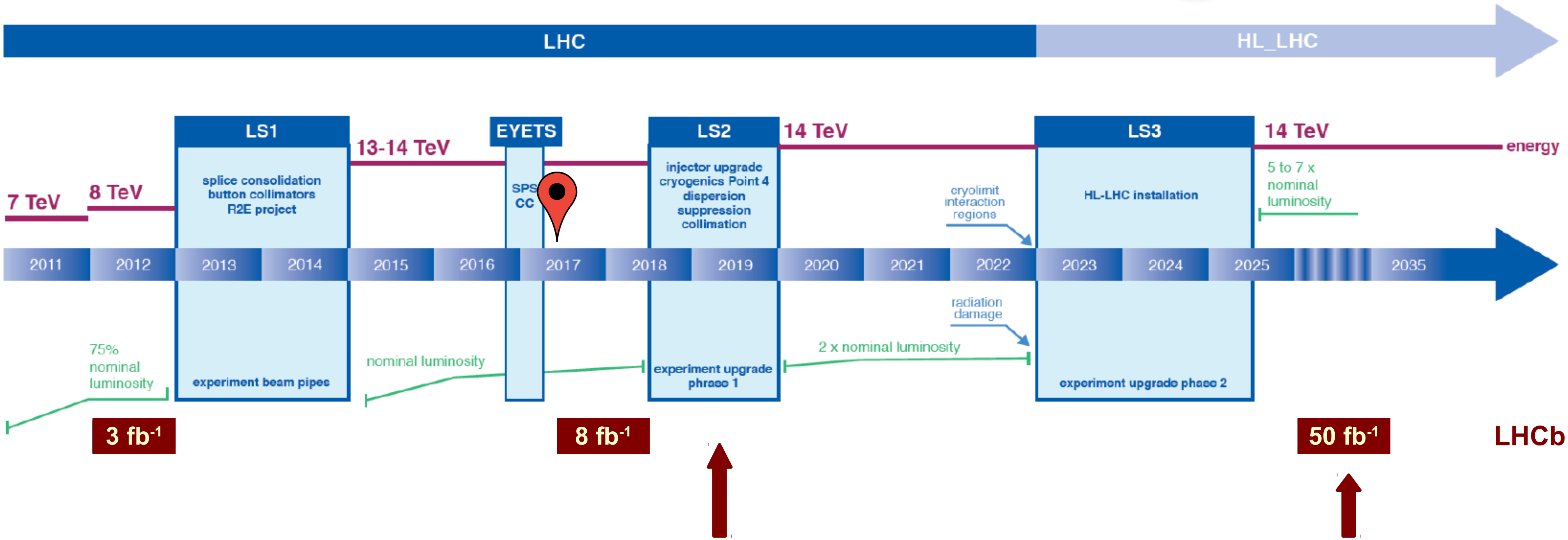


[CERN-LHCC-2017-003]

Upgrade



LHCb upgrade

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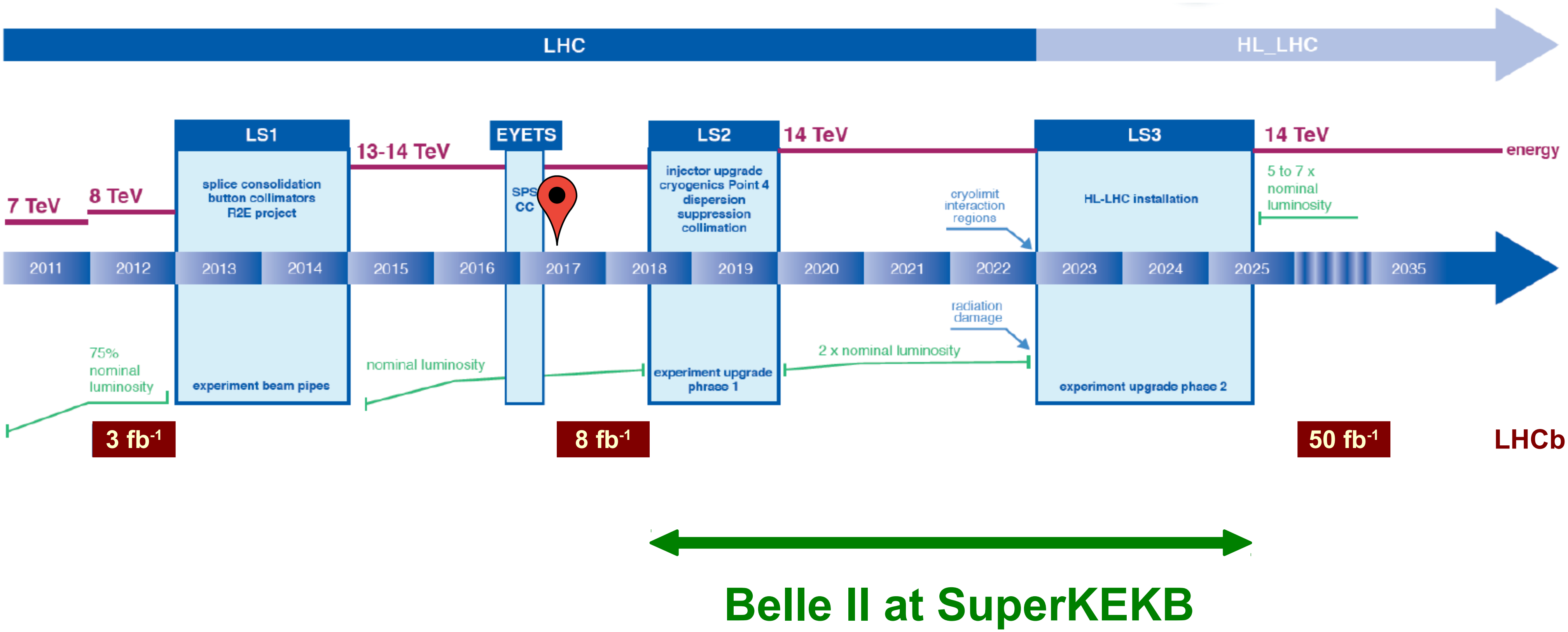
"After Upgrade" ≡ after LS2 (LHC Run 3 – 4)

Upgrade



$$e^+e^- \to \Upsilon(4s) \to B^0\overline{B}^0 \;/\; B^+B^-$$

collect 50 ab^{-1} by 2025

(50 × BaBar+Belle)

[arxiv:1011.0352]

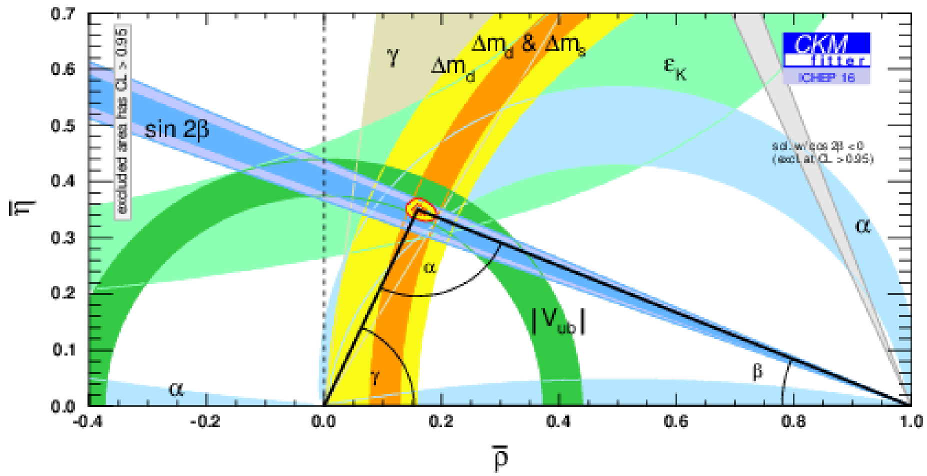
CKM angle γ

"Unitarity Triangle":

from unitarity condition of CKM matrix

All angles and sides related to observables

Over-constrained fits test Standard Model



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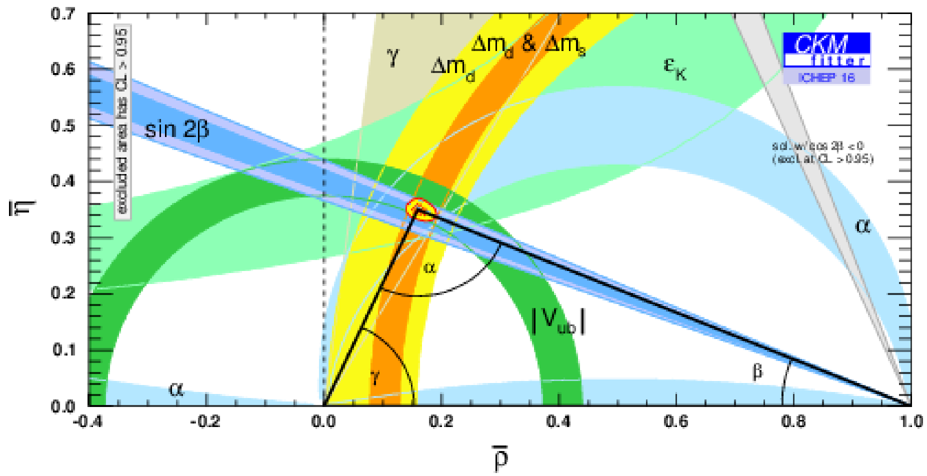

So far good consistency

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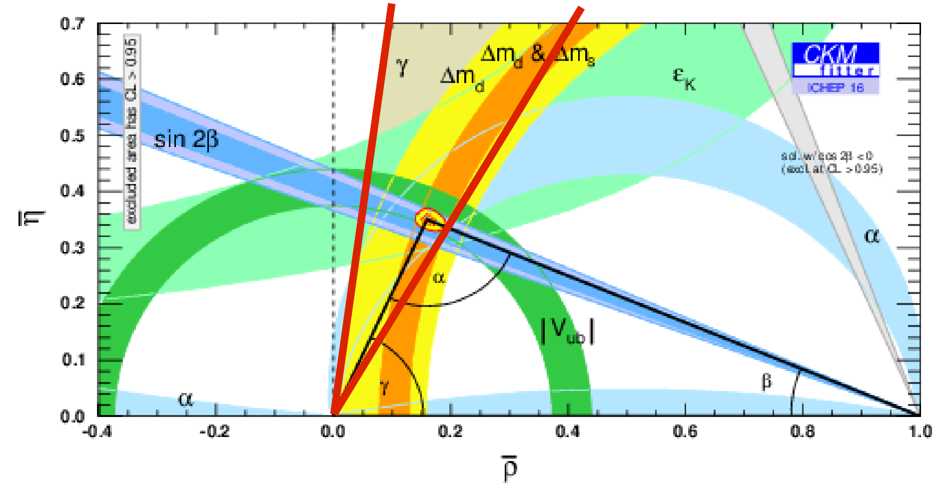

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Least well determined from direct measurements:

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

$$\gamma(\text{LHCb}) = \left(72.2^{+6.8}_{-7.3}\right)^{\circ}$$

[JHEP 12(2016)087]

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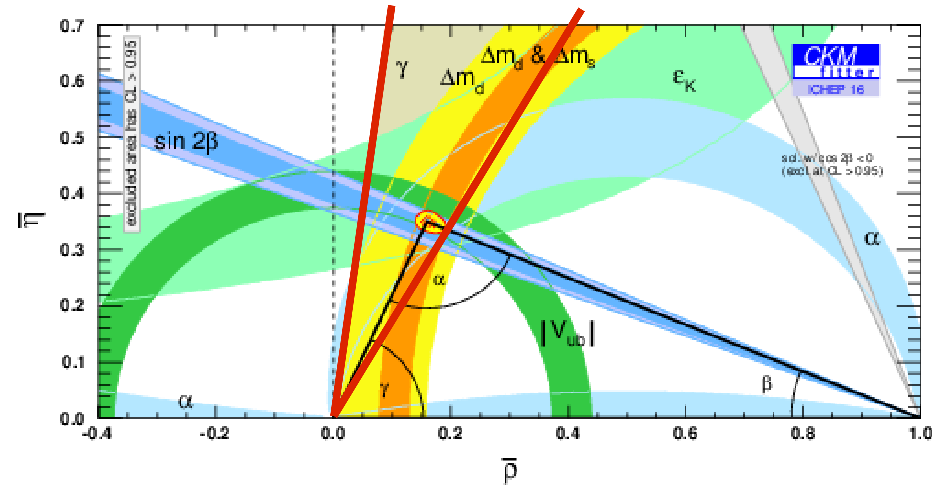
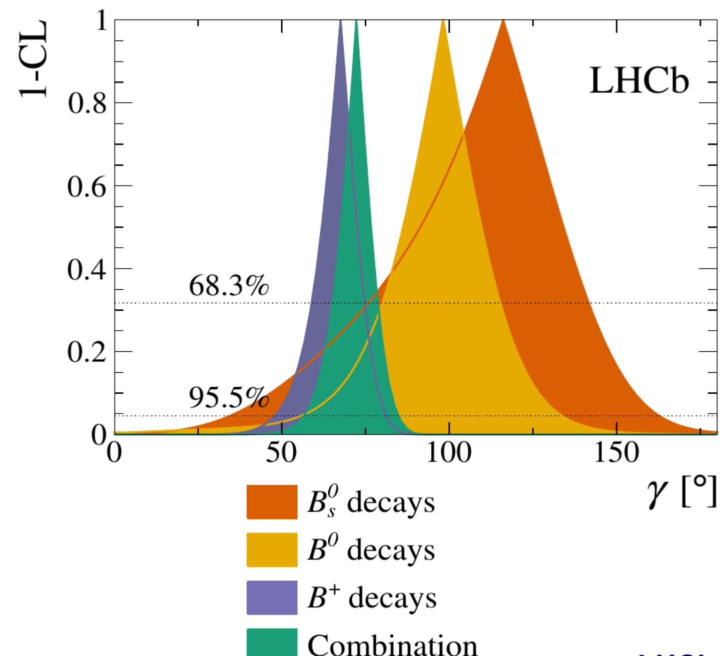


“Clean” measurements of γ from

Decay rates for tree decays
$B^{\pm} \to D K^{\pm}$ and $\overset{(-)}{B^0} \to D \overset{(-)}{K^{*0}}$

Time-dependent *CP* asymmetry in
$B_s^0 \to D_s^+ K^-$



LHCb
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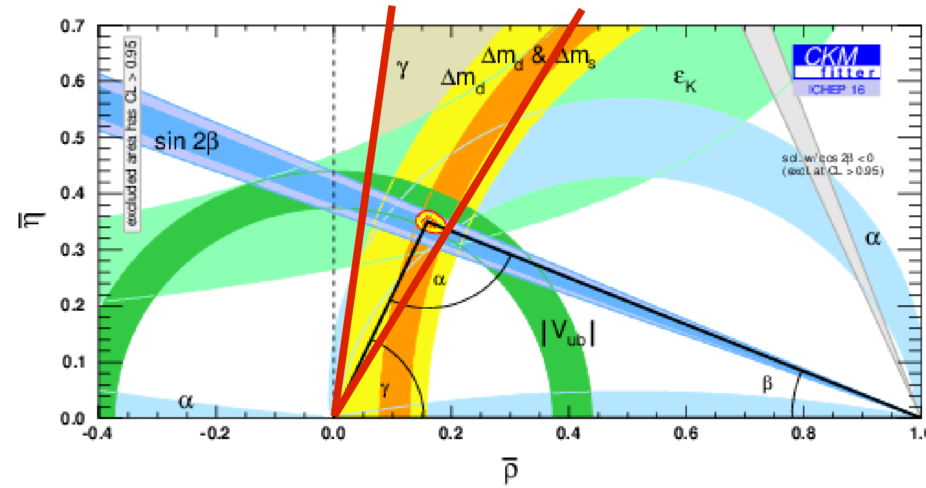

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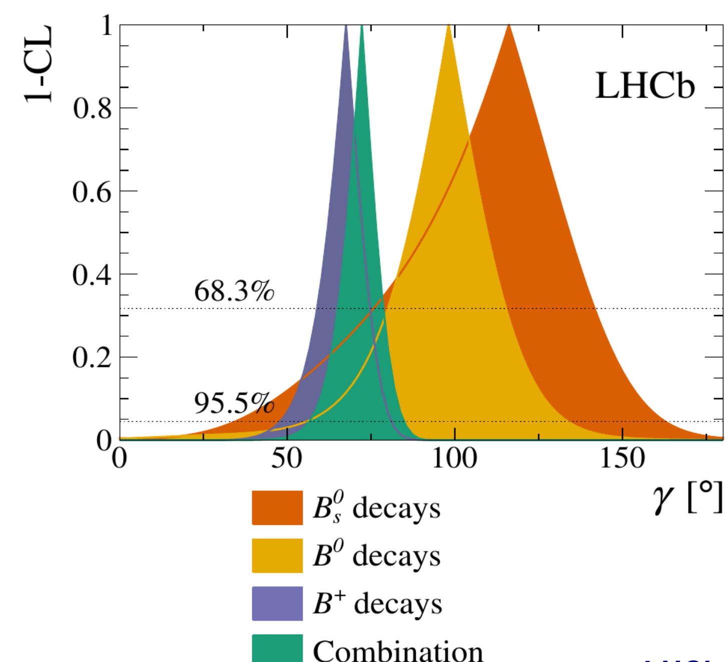
Small Branching Fractions:
Results limited
by statistical uncertainties



LHCb
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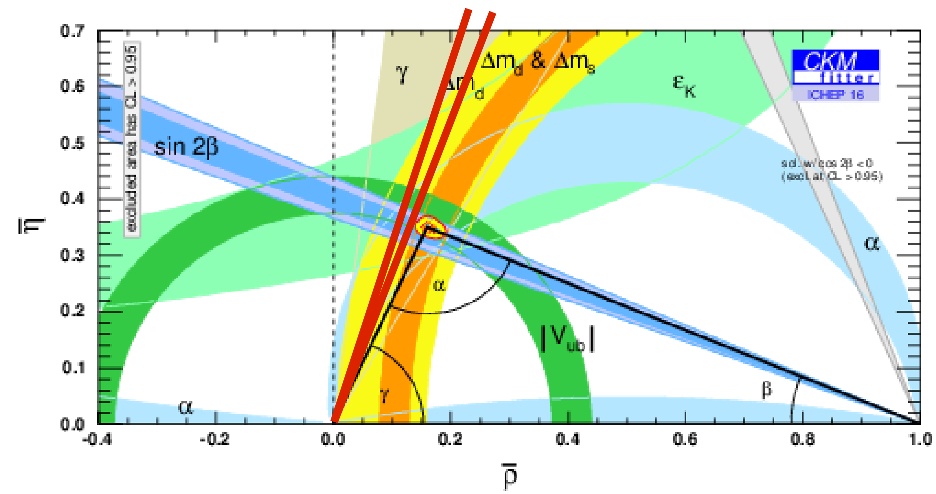
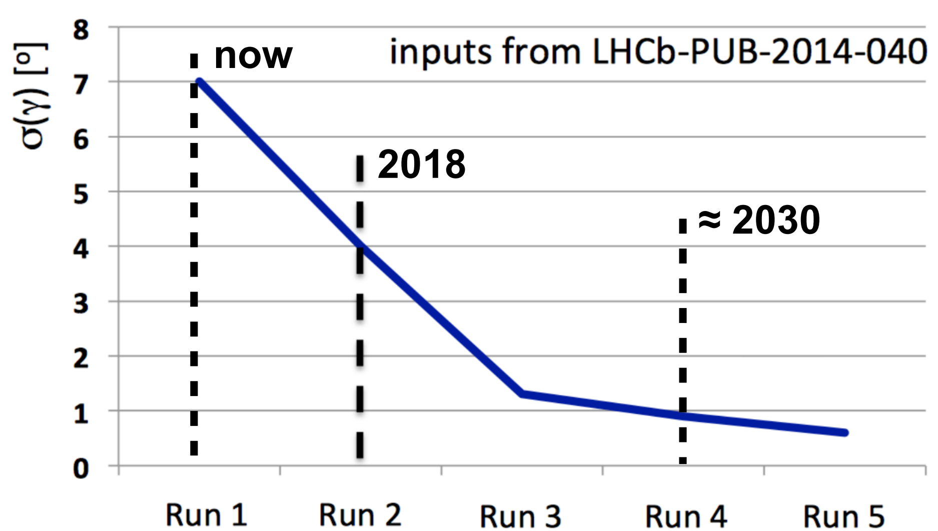


LHCb expect
σ (γ) < 1°
from 50 fb^{-1}

Belle II expect σ (γ) ≈ 1.5° from 50 ab^{-1}
(≈ 2025)

[Nucl.Part.Phys.Proc.263-264(2015)15]

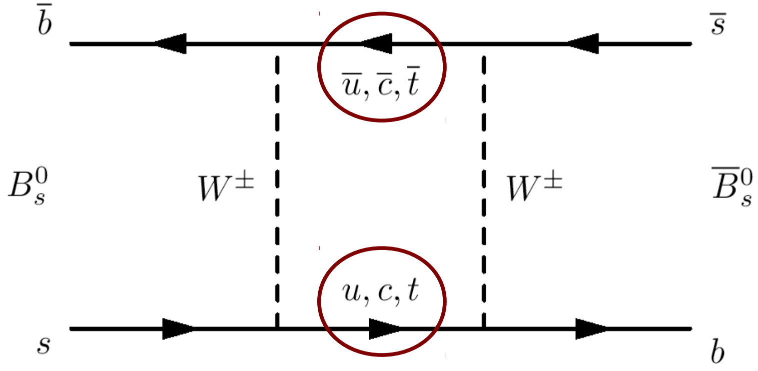


[LHCb-PUB-2014-040]

CP violation in $B_s^0 - \overline{B}_s^0$ mixing

_CP_ violation from interference of box diagrams with different CKM phases

probability $B_s^0 \to \overline{B}_s^0 \neq$ probability $\overline{B}_s^0 \to B_s^0$



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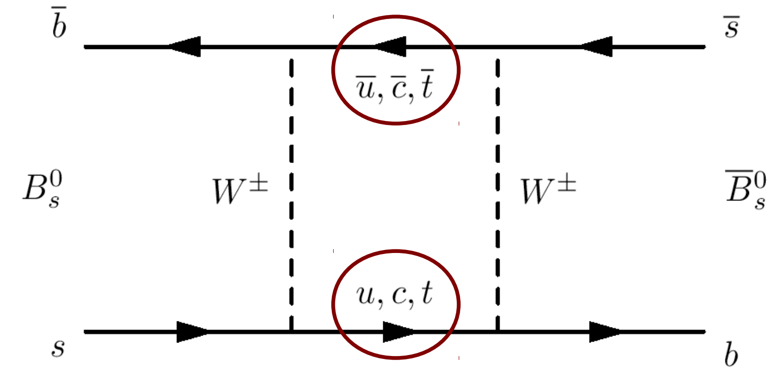

Can be measured in rate asymmetry for semi-leptonic decays

$$a_{sl}^s \equiv \frac{\Gamma(B_s^0 \to D_s^- \mu^+ X) - \Gamma(\overline{B}_s^0 \to D_s^+ \mu^- X)}{\Gamma(B_s^0 \to D_s^- \mu^+ X) + \Gamma(\overline{B}_s^0 \to D_s^+ \mu^- X)}$$

Predicted to be very small in the Standard Model

$$a_{sl}^s(\mathrm{SM}) = (1.9 \pm 0.3) \times 10^{-5}$$

A. Lenz
[arXiv:1205.1444]

Sensitive to possible BSM physics contributions in mixing

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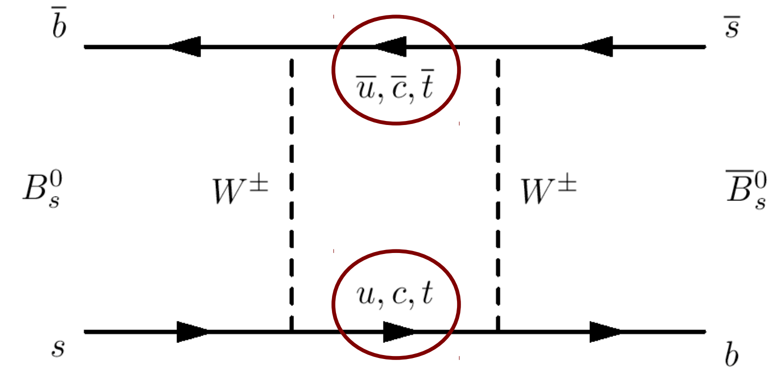
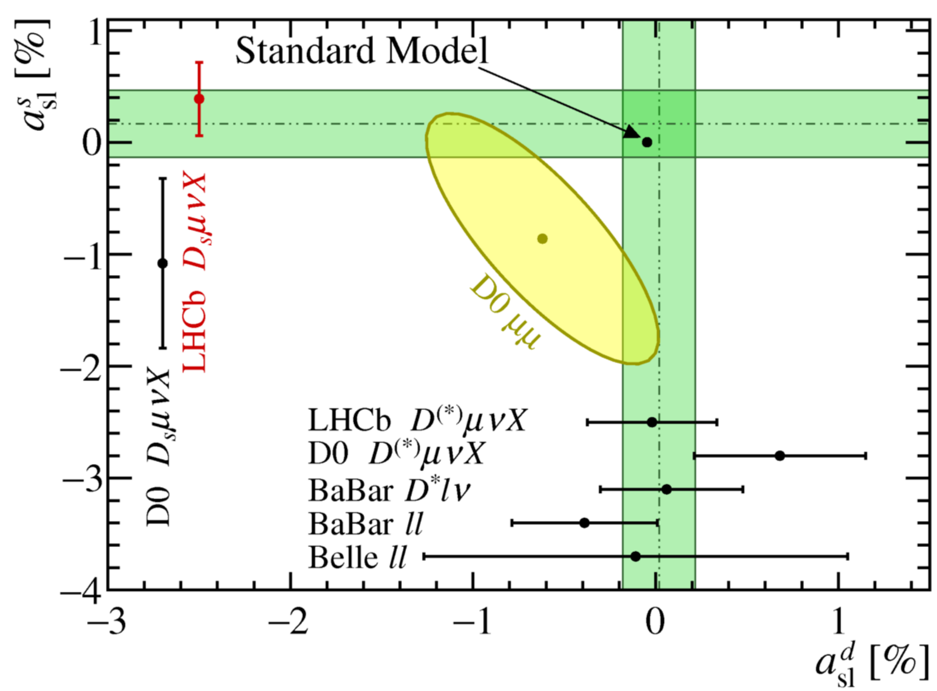


LHCb Run 1:

$$a_{sl}^{s}(\text{LHCb}) = (390 \pm 260 \pm 200) \times 10^{-5}$$

[PRL 117(2016)061803]

Systematics dominated by statistics in control samples



CP violation in $B_s^0 - \overline{B}_s^0$ mixing

***CP* violation from interference of box diagrams with different CKM phases**

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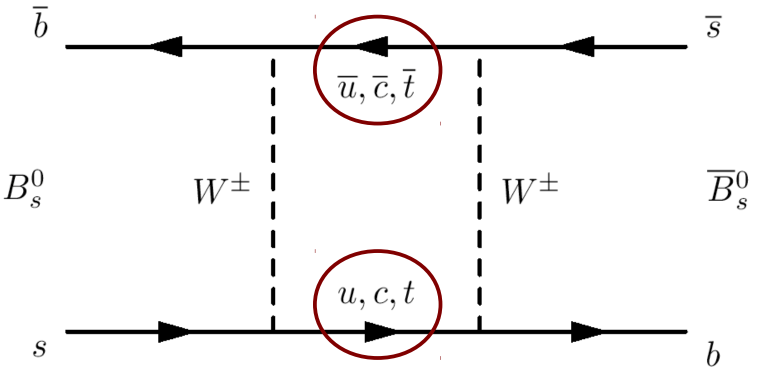
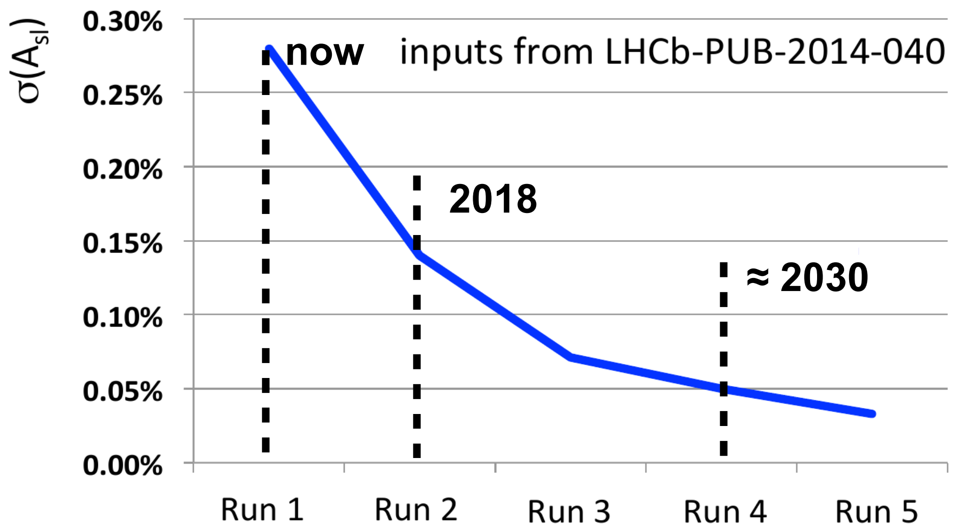


LHCb expect

$\sigma(a_{sl}^s) \approx 50 \times 10^{-5}$

from 50 fb^{-1}



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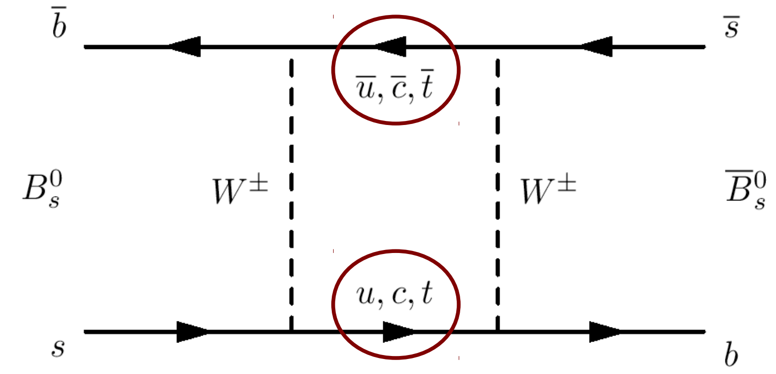

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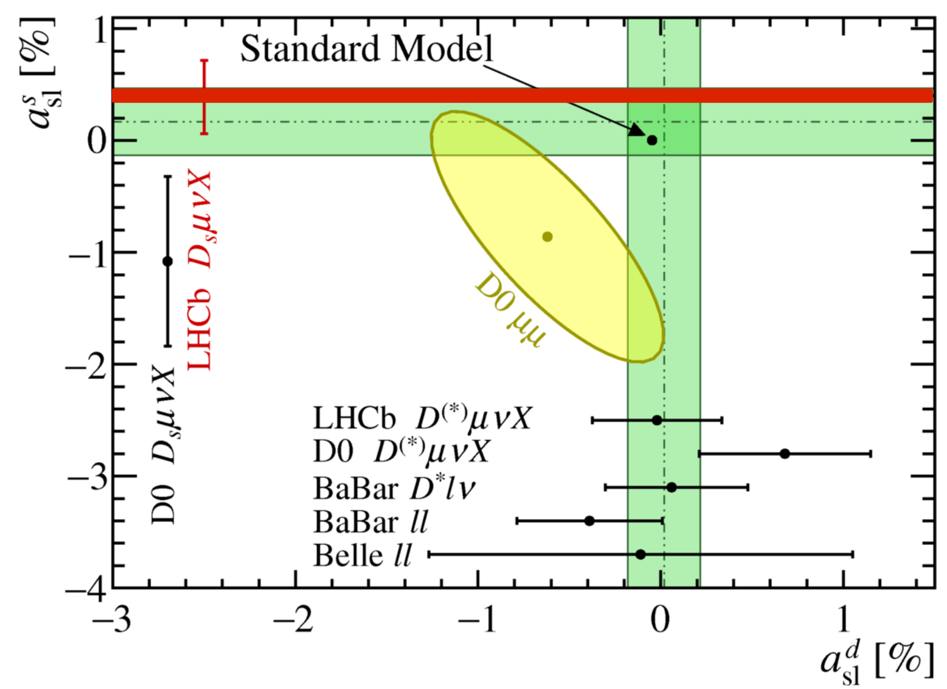
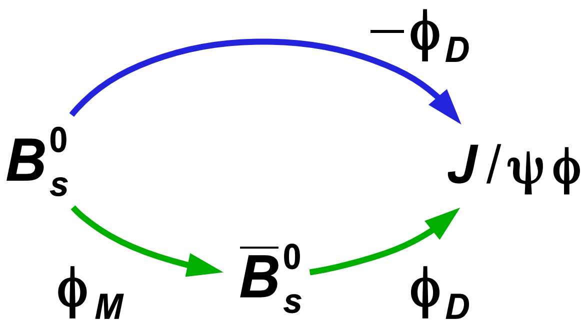


CP violation in $B_s^0 \rightarrow J/\psi\,\phi$

_CP_ violation through interference between mixing and decay amplitudes

_CP_ violating phase

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



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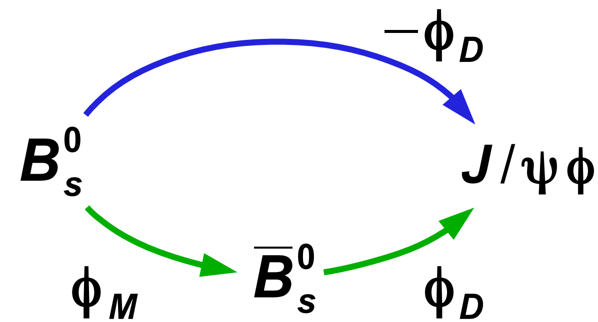


Predicted to be very small in the Standard Model:

$B_s^0 - \overline{B}_s^0$ mixing phase ϕ_M very small (as discussed above)

Decay amplitude dominated by a single tree diagram $\rightarrow$ ϕ_D very small

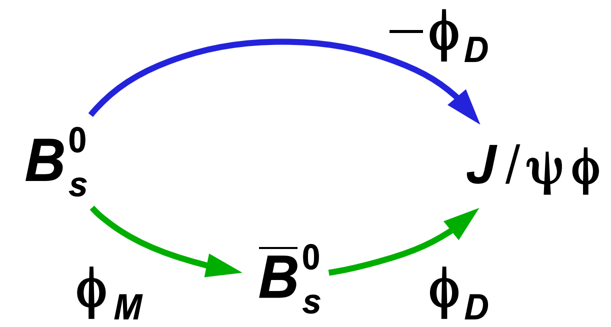
$$\phi_s(\text{SM}) = -38 \pm 1 \text{ mrad}$$

[CKMfitter]

Sensitive to possible contributions from BSM physics in $B_s^0 - \overline{B}_s^0$ mixing

CP violation in $B_s^0 \to J/\psi\,\phi$

_CP_ violation through interference between mixing and decay amplitudes



_CP_ violating phase

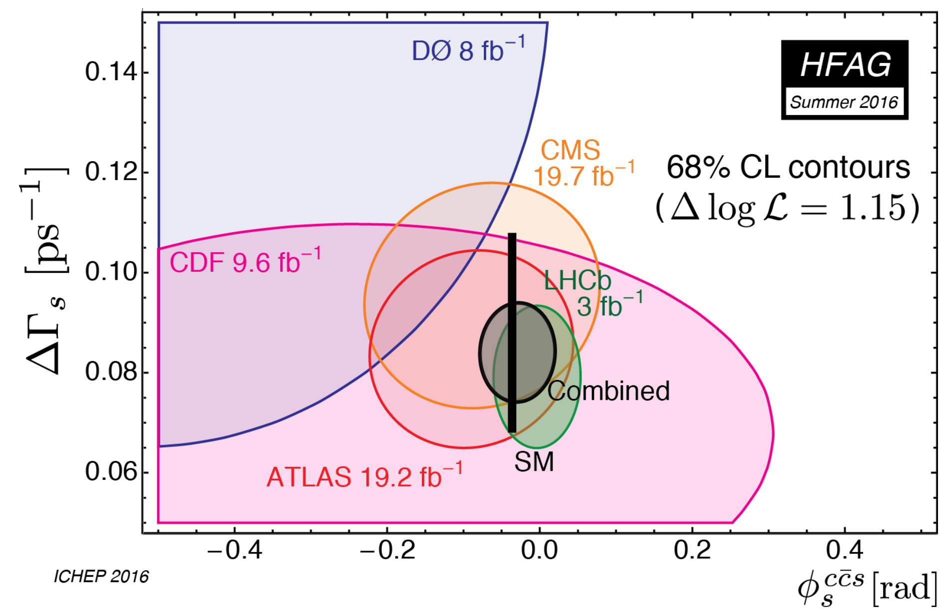
$$\phi_s = \phi_M - 2\phi_D$$

Run-1 measurements from ATLAS, CMS and LHCb

$$\phi_s(\text{LHCb}) = -10 \pm 39 \text{ mrad}$$

[PRL 114(2015)041801]

Limited by statistical uncertainty



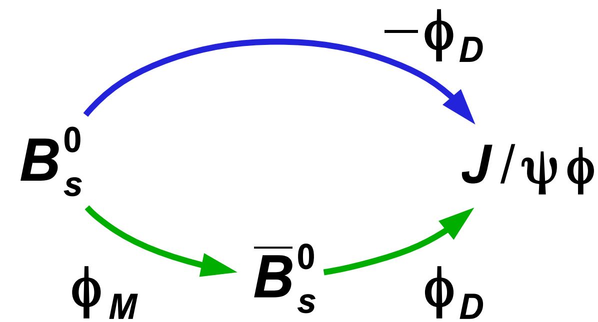
ATLAS [JHEP 08(2016)147]

CMS [PLB 757(2016)97]

[HFAG]

CP violation in $B_s^0 \to J/\psi\,\phi$

***CP* violation through interference between mixing and decay amplitudes**



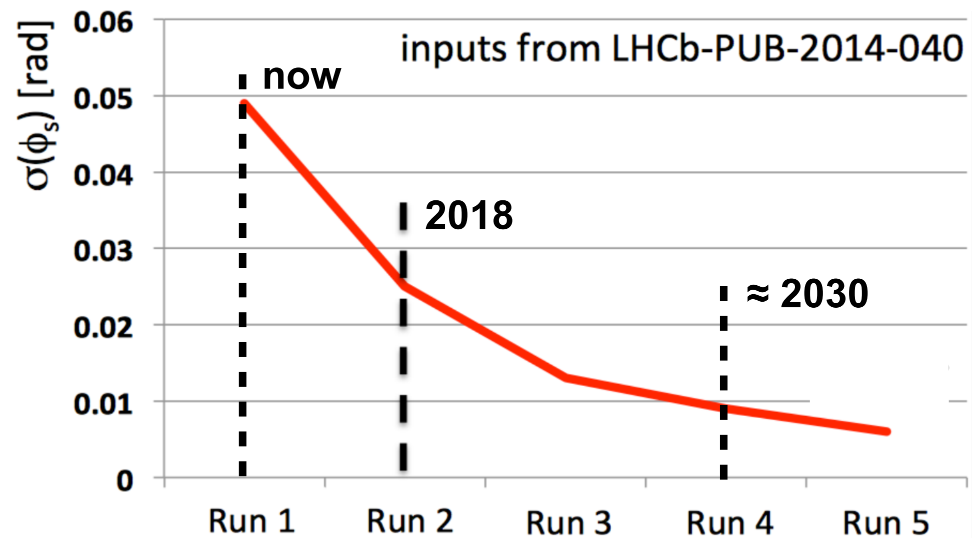
***CP* violating phase**

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

LHCb expect

$\sigma(\phi_s) < 10$ mrad

from 50 fb^{-1}



[LHCb-PUB-2014-040]

CP violation in $B_s^0 \to J/\psi\,\phi$

***CP* violation through interference between mixing and decay amplitudes**

***CP* violating phase**

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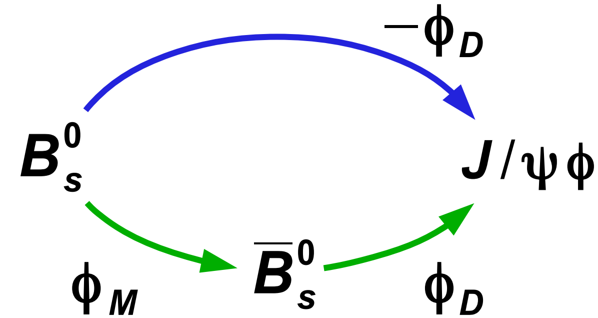

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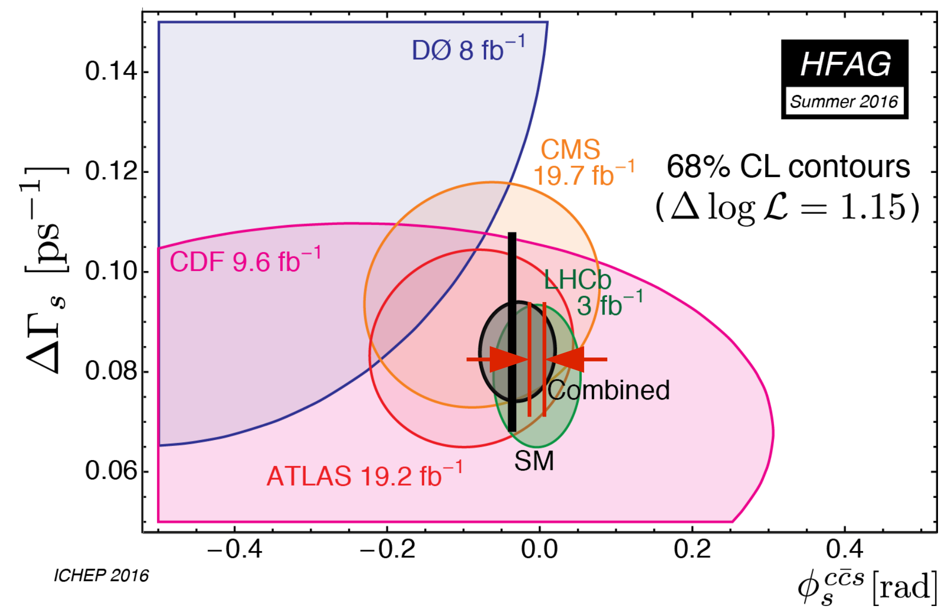
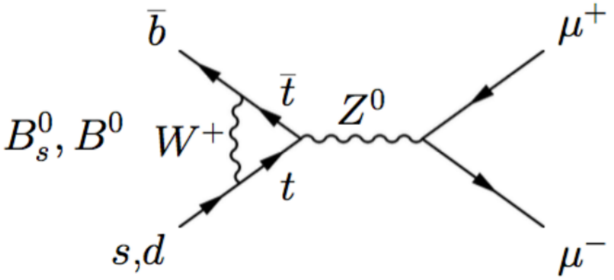


$B_s^0 \to \mu^+ \mu^-$

Flavour-changing neutral current + helicity suppressed



$$\mathrm{BF}_{\mathrm{SM}}\,(B_s^0 \to \mu^+ \mu^-) = (3.60 \pm 0.18) \times 10^{-9}$$

Bobeth et al. [PRL 112(2014)101801]

Altmannshofer et al. [arXiv:1702.05498]

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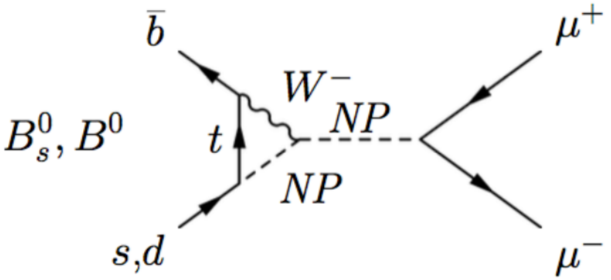
Large deviations possible in some BSM models



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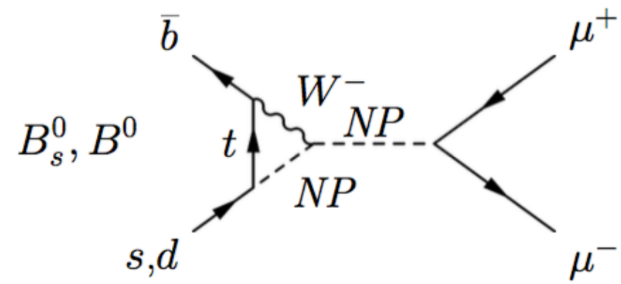
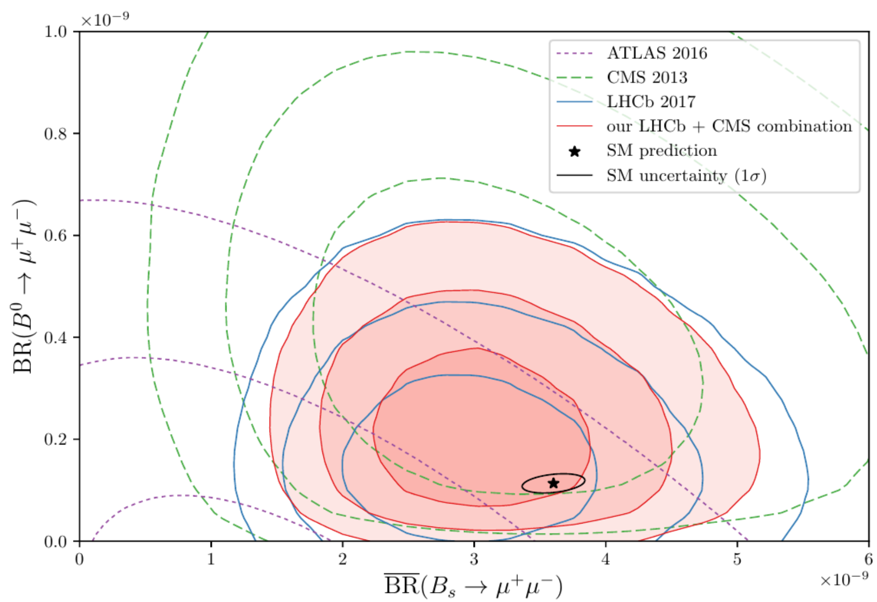


Measurements so far in agreement with SM predictions



CMS+LHCb, Run 1
[Nature 522(2015)68]
ATLAS
[EPJ C76(2016)513]
LHCb, Run 1+2
[arxiv:1703.05747]

plot from Altmannshofer et al.
[arXiv:1702.05498]

All limited by statistical uncertainties

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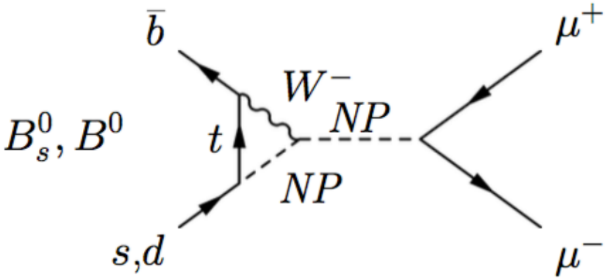

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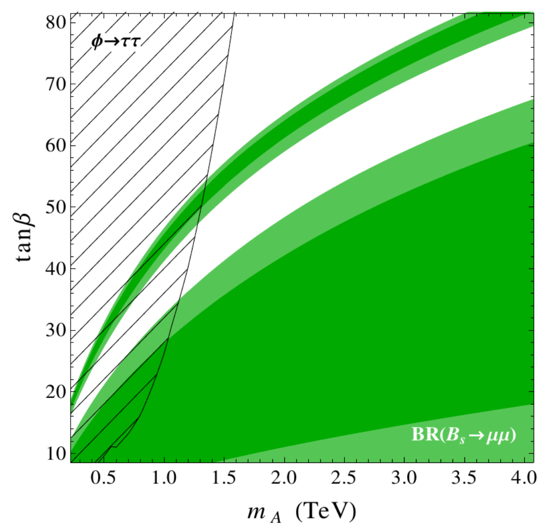
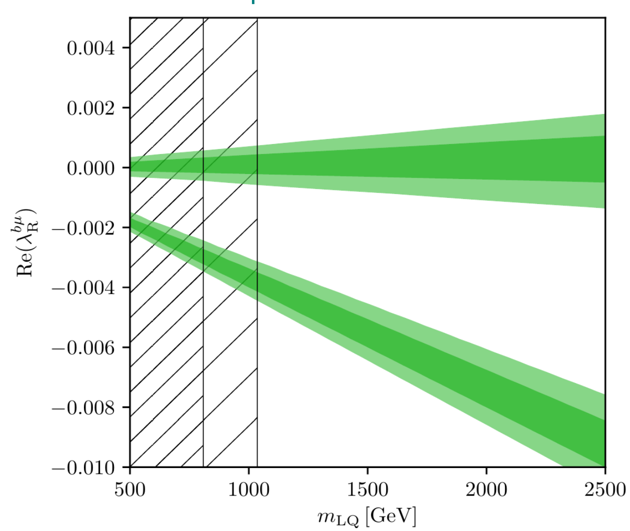
Large deviations possible in some BSM models

→ Constraints on BSM models, e.g.

MSSM



U_1 Leptoquark



Altmannshofer et al.
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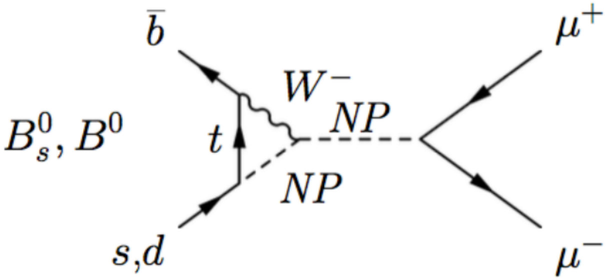


LHCb expect

$\sigma(BF)/BF = 5\ \%$

from 50 fb^{-1}

[LHCb-PUB-2014-040]

CMS expect

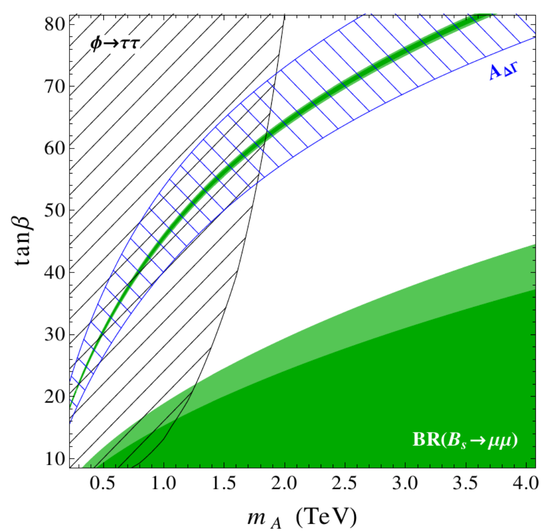
$\sigma(BF)/BF = 12\ \%$

from 300 fb^{-1}

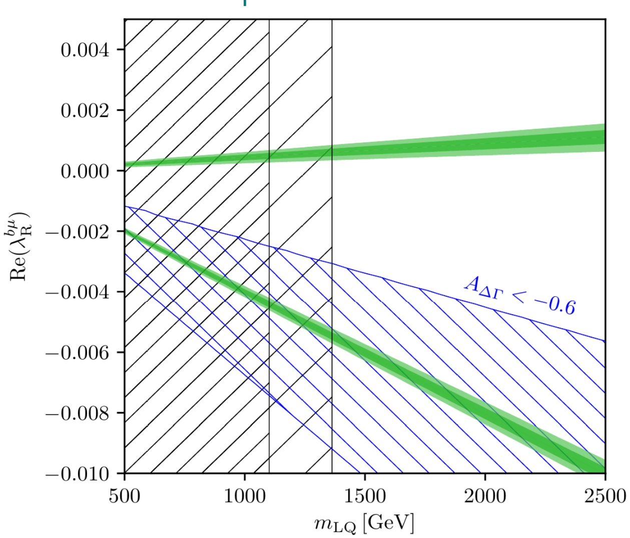
[CMS-PAS-FTR-13-022]

→ Constraints on BSM models, e.g.

MSSM



U_1 Leptoquark



Altmannshofer et al.

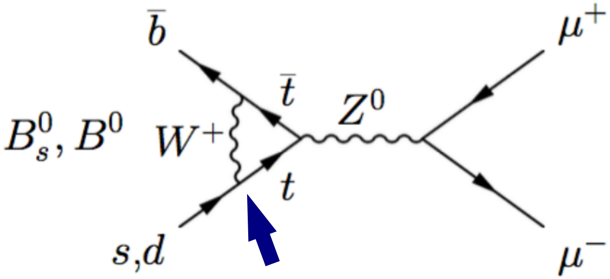
[arXiv:1702.05498]

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

Even stronger suppression due to $V_{td} < V_{ts}$

$$BF_{SM}(B^0 \to \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

Bobeth et al.
[PRL 112(2014)101801]



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

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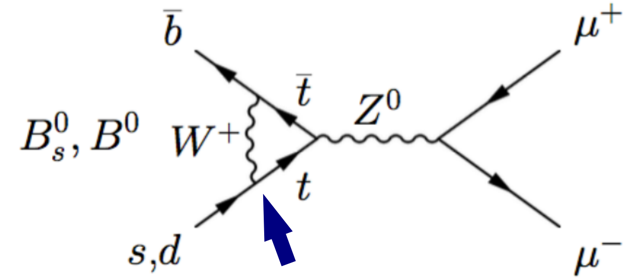


$$BF_{SM}\,(B^0 \to \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

Not observed yet

Goal for upgrade: measure the ratio of the Branching Fractions
(theory uncertainty ≈ 5 %)

LHCb expect

$$\sigma\left(\frac{BF\,(B^0 \to \mu^+ \mu^-)}{BF\,(B_s^0 \to \mu^+ \mu^-)}\right) \approx 40\,\%$$

from 50 fb^{-1}

[LHCb-PUB-2014-040]

CMS expect

$$\sigma\left(\frac{BF\,(B^0 \to \mu^+ \mu^-)}{BF\,(B_s^0 \to \mu^+ \mu^-)}\right) \approx 47\,\%$$

from 300 fb^{-1}

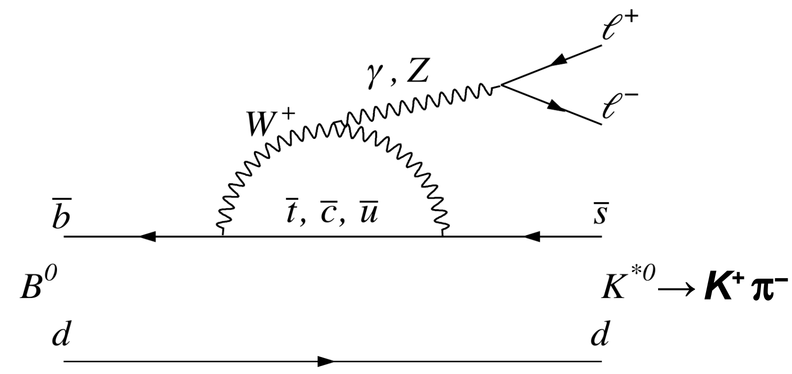
(21 % from 3000 fb^{-1})

[CMS-PAS-FTR-13-022]

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$

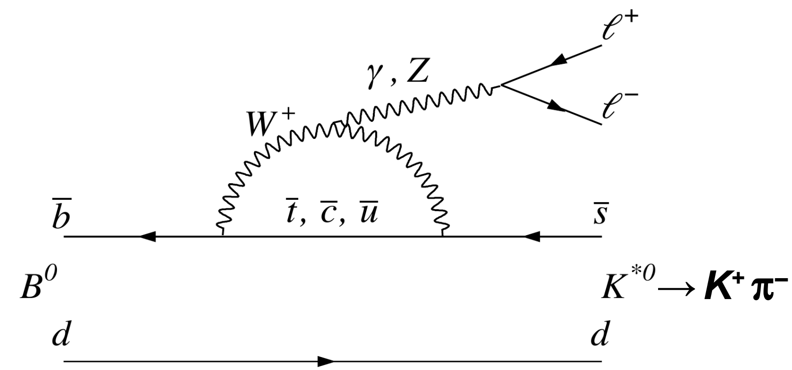
Flavour-Changing Neutral Current Decay

Angular distributions of final-state particles sensitive to possible contributions from BSM physics



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

Flavour-Changing Neutral Current Decay

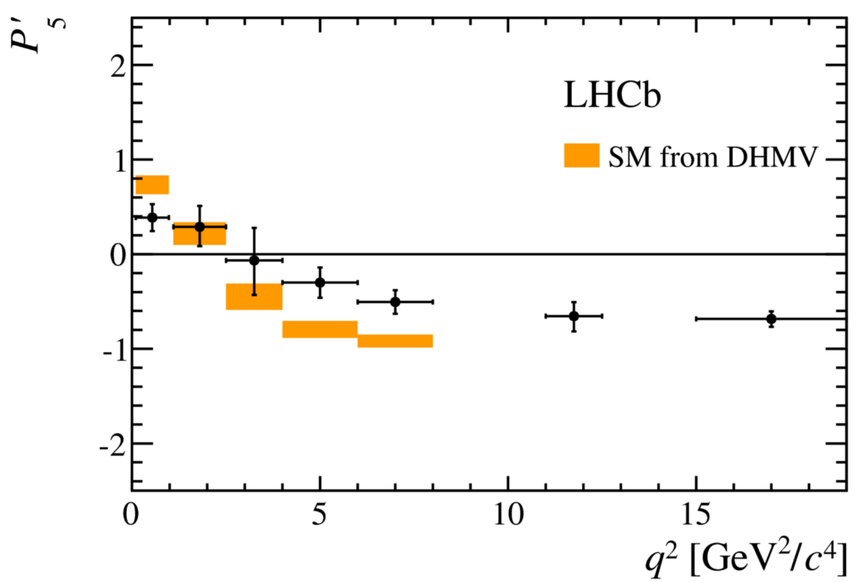


Angular distributions of final-state particles sensitive to possible contributions from BSM physics

Eight independent angular observables

LHCb find deviation in the central q^2 region for the observable P_5'

Local significance ≈ 3.6 σ from LHCb Run 1

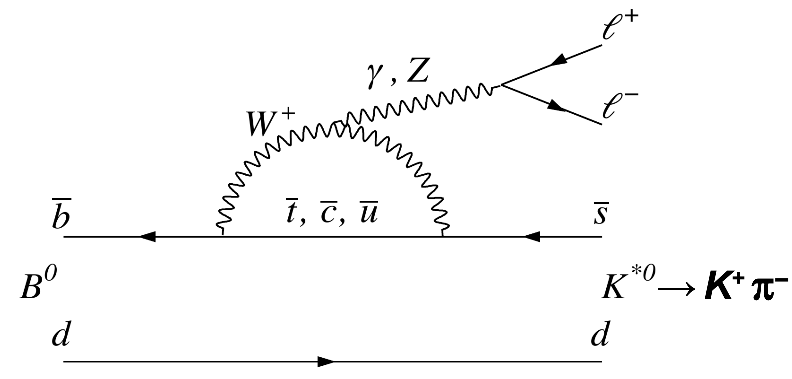


LHCb Run 1
[JHEP 02(2016)104]

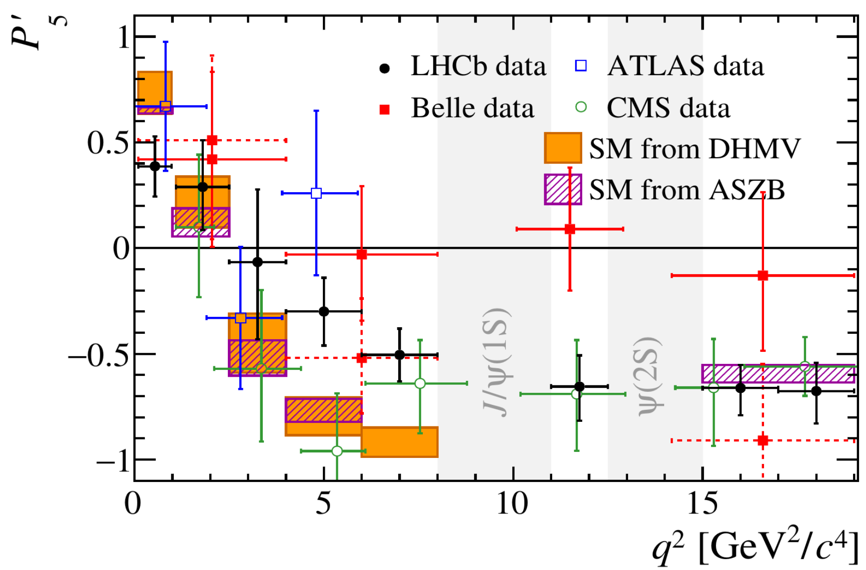
$B^0 \to K^{*0} \mu^+ \mu^-$

Flavour-Changing Neutral Current Decay

Angular distributions of final-state particles sensitive to possible contributions from BSM physics



ATLAS, CMS, Belle follow up, but uncertainties larger than in LHCb



LHCb Run 1 [JHEP 02(2016)104]

CMS Run 1 [CMS-PAS-BPH-15-008]

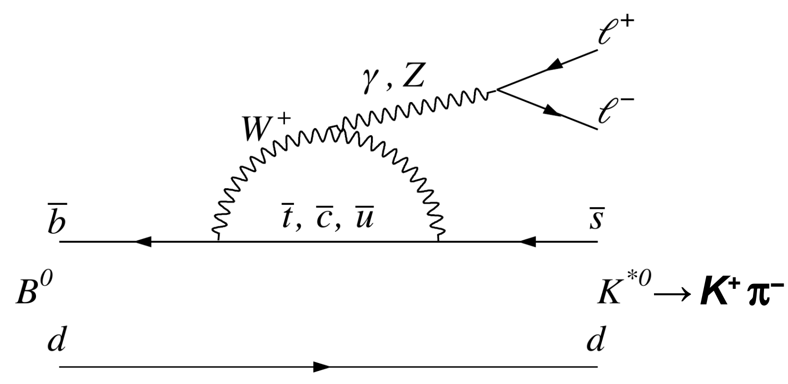
Belle [PRL 118(2017)111801]

ATLAS Run 1 [ATLAS-CONF-2017-023]

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$

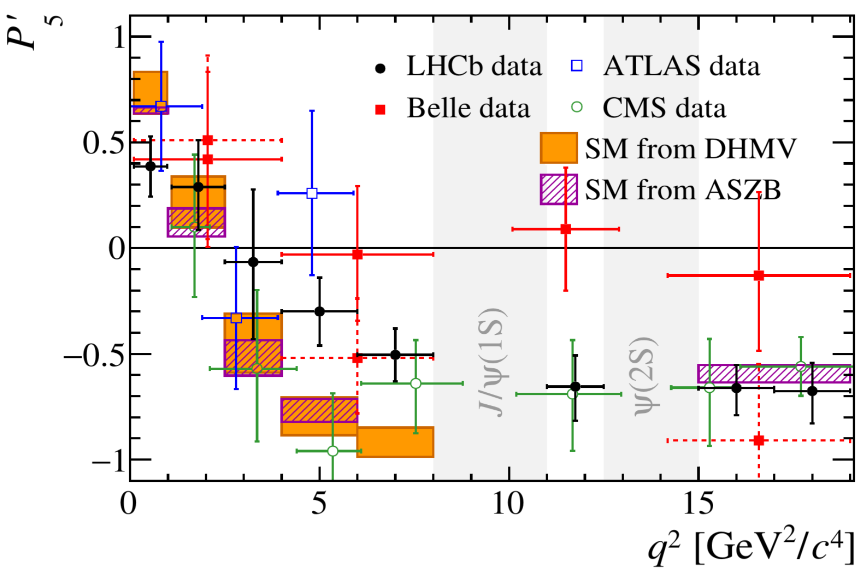
Flavour-Changing Neutral Current Decay

Angular distributions of final-state particles sensitive to possible contributions from BSM physics



ATLAS, CMS, Belle follow up, but uncertainties larger than in LHCb

LHCb expect to reduce uncertainties by ≈ factor 2 by the end of Run 2



LHCb Run 1 [JHEP 02(2016)104]

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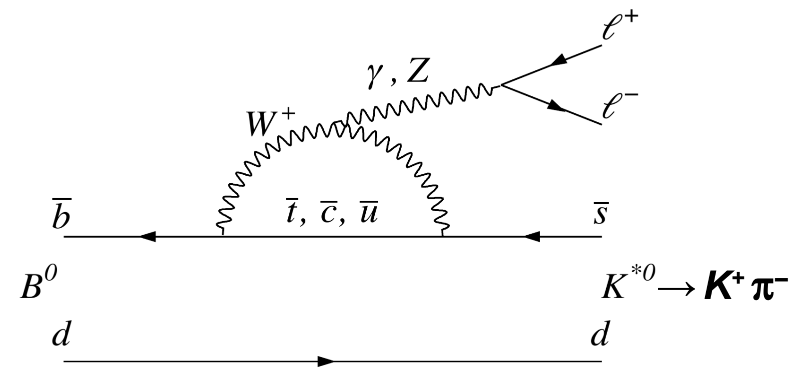
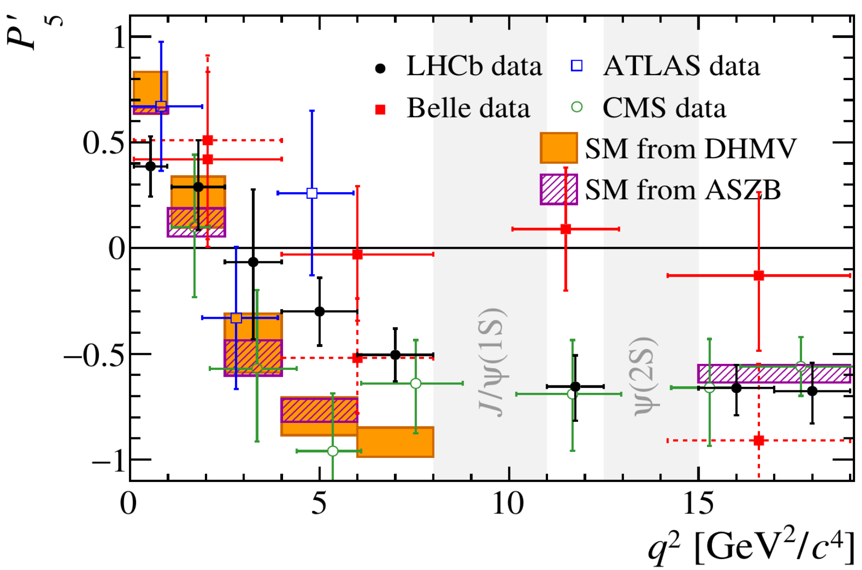


ATLAS, CMS, Belle follow up, but uncertainties larger than in LHCb

LHCb expect to reduce uncertainties by ≈ factor 2 by the end of Run 2

We should be able to know then, whether this is just another statistical fluctuation



LHCb Run 1 [JHEP 02(2016)104]

CMS Run 1 [CMS-PAS-BPH-15-008]

Belle [PRL 118(2017)111801]

ATLAS Run 1 [ATLAS-CONF-2017-023]

$B^0 \rightarrow K^{*0}\mu^+\mu^-$

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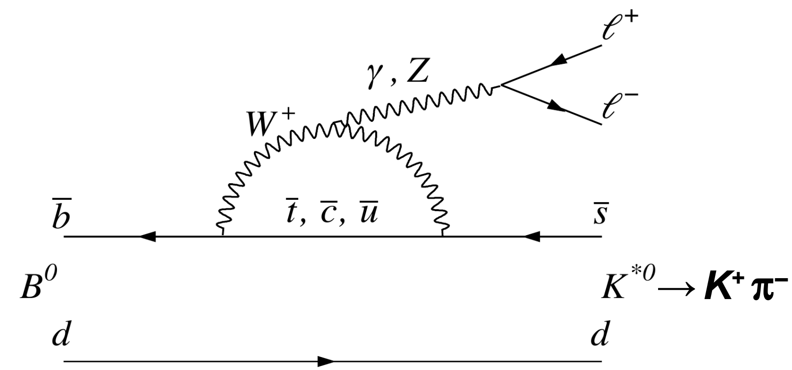
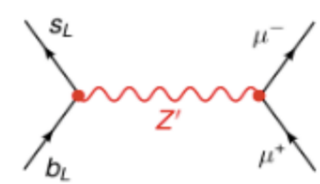
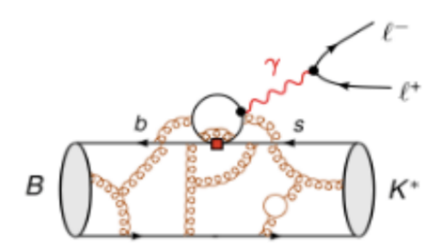


If the deviation is "real":

Optimist's view point



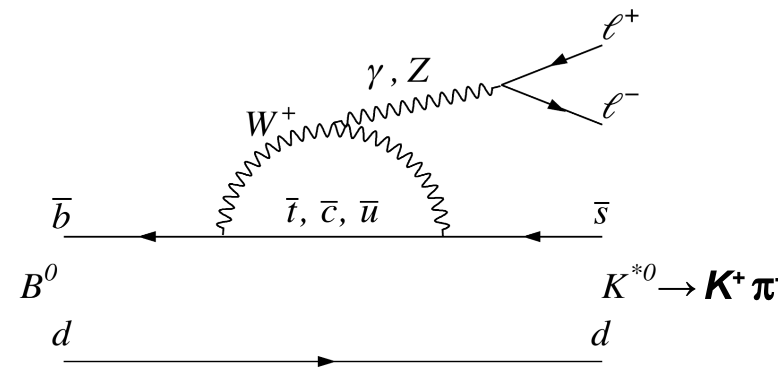
Pessimist's view point



$B^0 \rightarrow K^{*0} \mu^+ \mu^-$

Flavour-Changing Neutral Current Decay

Angular distributions of final-state particles sensitive to possible contributions from BSM physics

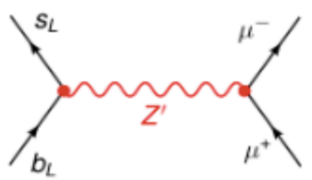


If the deviation is "real":

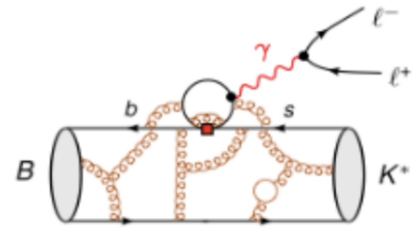
With 50 fb^{-1}, LHCb should be able to perform unbinned amplitude fits over the full q^2 range and distinguish between the two hypotheses

[N.Serra, priv.comm.]

Optimist's view point



Pessimist's view point



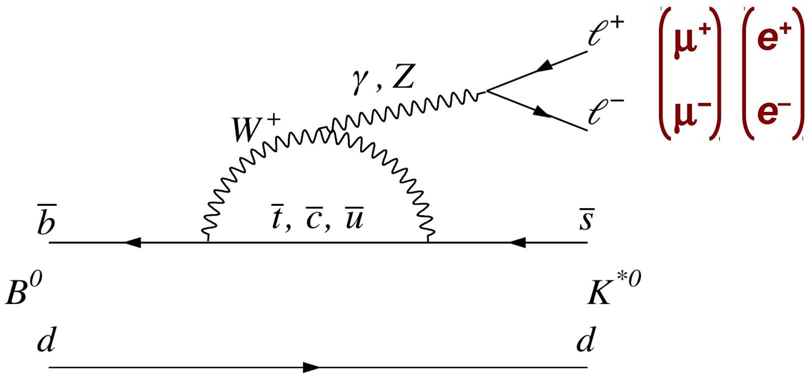
R_K, R_{K^*}

Testing Lepton Flavour Universality:

$$R \equiv \frac{\Gamma(b \to s\, \mu^+ \mu^-)}{\Gamma(b \to s\, e^+ e^-)}$$

expected to be very close to unity

(after phase-space correction**)**



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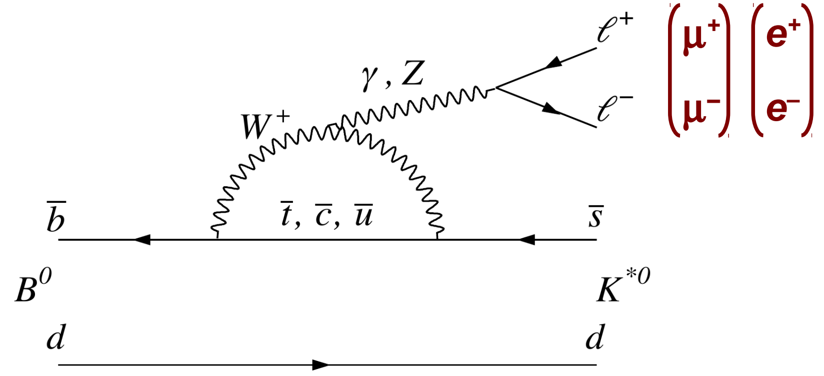
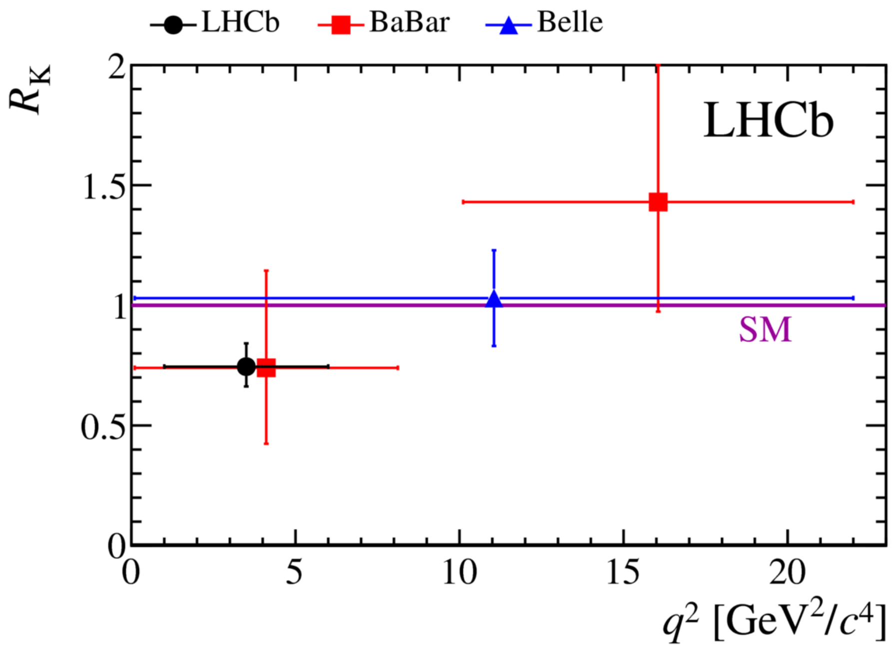


LHCb find 2.6 σ tension in central q^2 bin for

$$R_K \equiv \frac{\Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^+ \to K^+e^+e^-)}$$



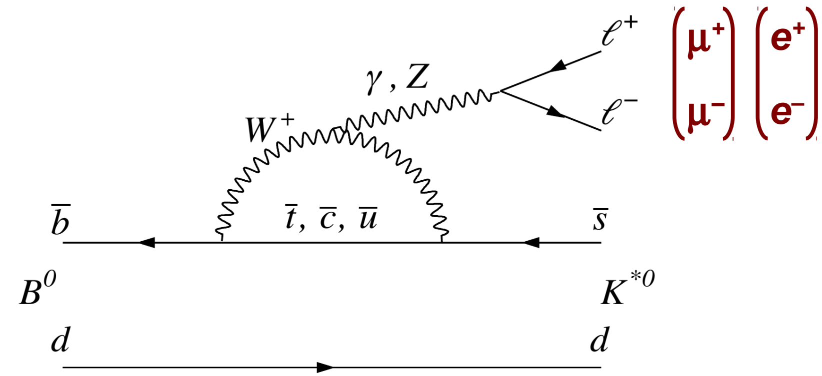
LHCb Run 1	BaBar	Belle
[PRL 113(2014)151601]	[PRD 86(2012)032012]	[PRL 103(2009)171801]

R_{K}, R_{K^*}

Testing Lepton Flavour Universality:

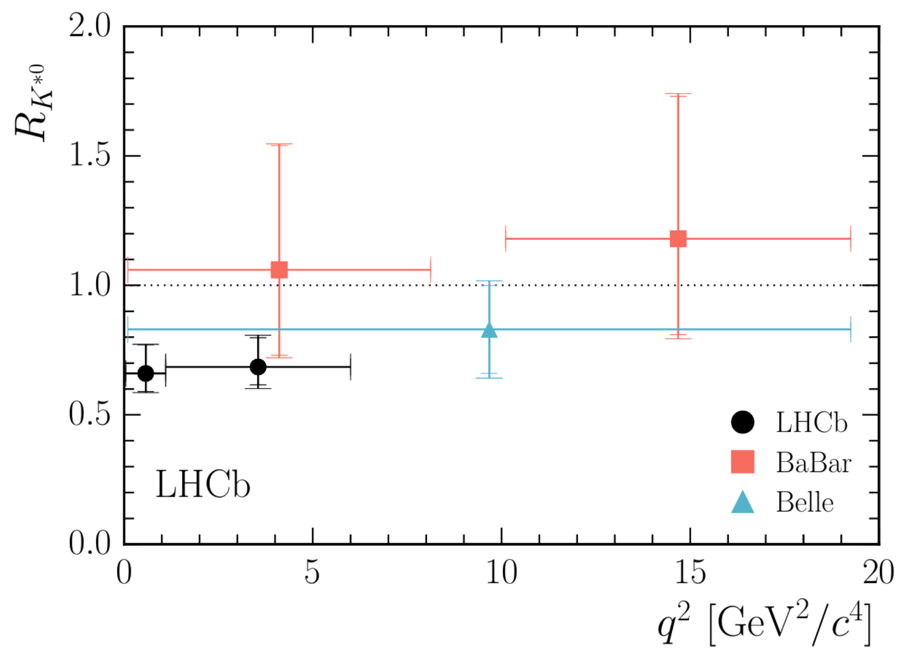
$$R \equiv \frac{\Gamma(b \to s\,\mu^+\mu^-)}{\Gamma(b \to s\,e^+e^-)}$$

expected to be very close to unity



LHCb find 2.2-2.5 σ tension in low and central q^2 bins for

$$R_{K^*} \equiv \frac{\Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{\Gamma(B^0 \to K^{*0}e^+e^-)}$$

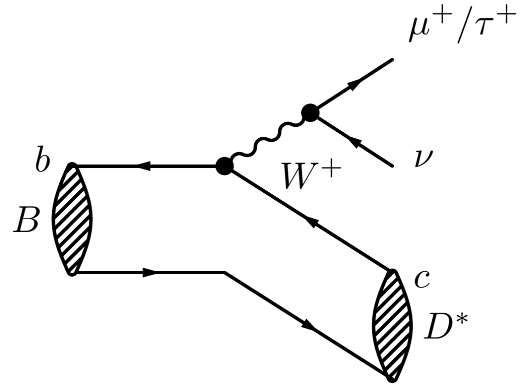


LHCb Run 1	**BaBar**	**Belle**
[arXiv:1705.05802]	[PRD 86(2012)032012]	[PRL 103(2009)171801]

$R(D^*)$ etc.

Another test of Lepton Flavour Universality:

$$R\left(D^{(*)}\right) \equiv \frac{\Gamma\left(B \to D^{(*)}\tau^+\nu_\tau\right)}{\Gamma\left(B \to D^{(*)}\mu^+\nu_\mu\right)}$$



$R(D^*)$ etc.

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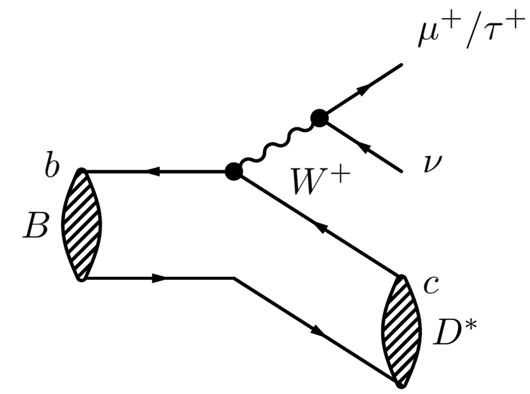
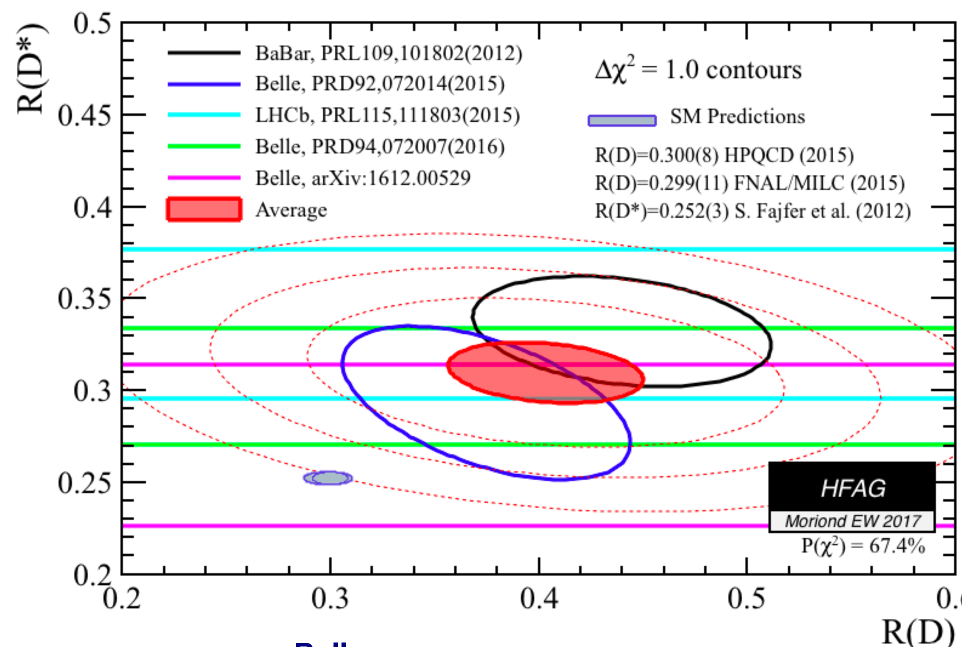


BaBar and Belle find both $R(D^*)$ and $R(D)$ larger than predicted

LHCb also find 2.1 σ tension for $R(D^*)$, using $\tau \to \mu\,\nu_\mu\,\nu_\tau$

LHCb Run 1
[PRL 115(2015)111803]



Belle
[PRD 92(2015)072014]
[PRD 94(2016)072007]
[arxiv:1612.00529]

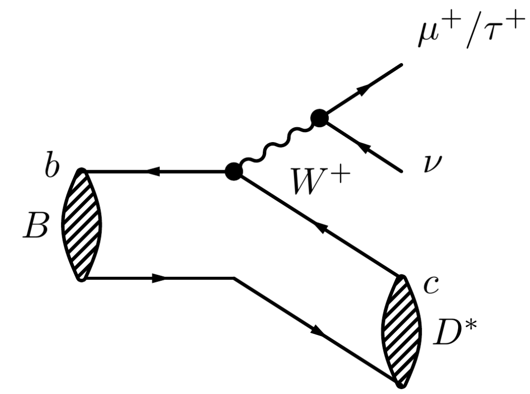
BaBar
[PRL 109(2012)101802]

$R(D^*)$, $R(D)$ combined: 3.9 σ tension

$R(D^*)$ etc.

Another test of Lepton Flavour Universality:

$$R\left(D^{(*)}\right) \equiv \frac{\Gamma\left(B \to D^{(*)}\tau^+\nu_\tau\right)}{\Gamma\left(B \to D^{(*)}\mu^+\nu_\mu\right)}$$

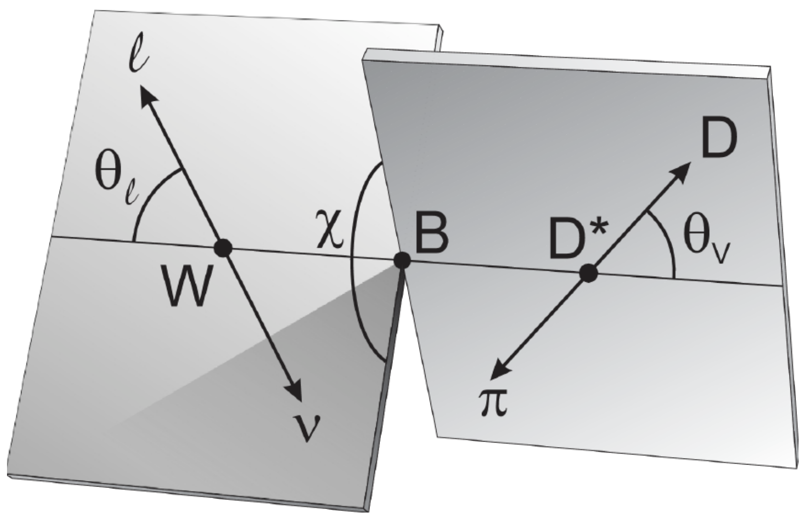


Other LHCb analyses underway, e.g.

$R(D^*)$ using $\tau \to \pi\pi\pi\nu_\tau$

$R(D)$, $R(D_s^{(*)})$, $R(J/\psi)$, $R(\Lambda_c)$

With upgrade statistics, might become sensitive to angular distributions



Summary

Holy Grail of Flavour Physics
=
"Indirect" Searches for BSM Physics

"Classic" benchmark observables
so far in agreement with SM predictions

Measurement uncertainties limited by statistics
and much larger than those on theory
→ Expect significant improvements from upgrades

Some intriguing deviations in observables testing
Lepton Flavour Universality

Again, measurements limited by statistical uncertainties
Upgrade statistics will help to show,
whether these are fluke coincidences
or part of a consistent pattern

Summary

Holy Grail of Flavour Physics

=

"Indirect" Searches for BSM Physics

These Indirect Searches need to be complemented by Direct Searches at the "Energy Frontier"

(e.g. $Z' \to \tau^+\tau^-$)

Close interaction between Experimentalists and Theorists is mandatory to derive consistent interpretation of data, to develop new observables

Again, measurements limited by statistical uncertainties
Upgrade statistics will help to show,
whether these are fluke coincidences
or part of a consistent pattern

Summary

What if, by the end of Run 2, …

… BSM signal is found in "direct searches"

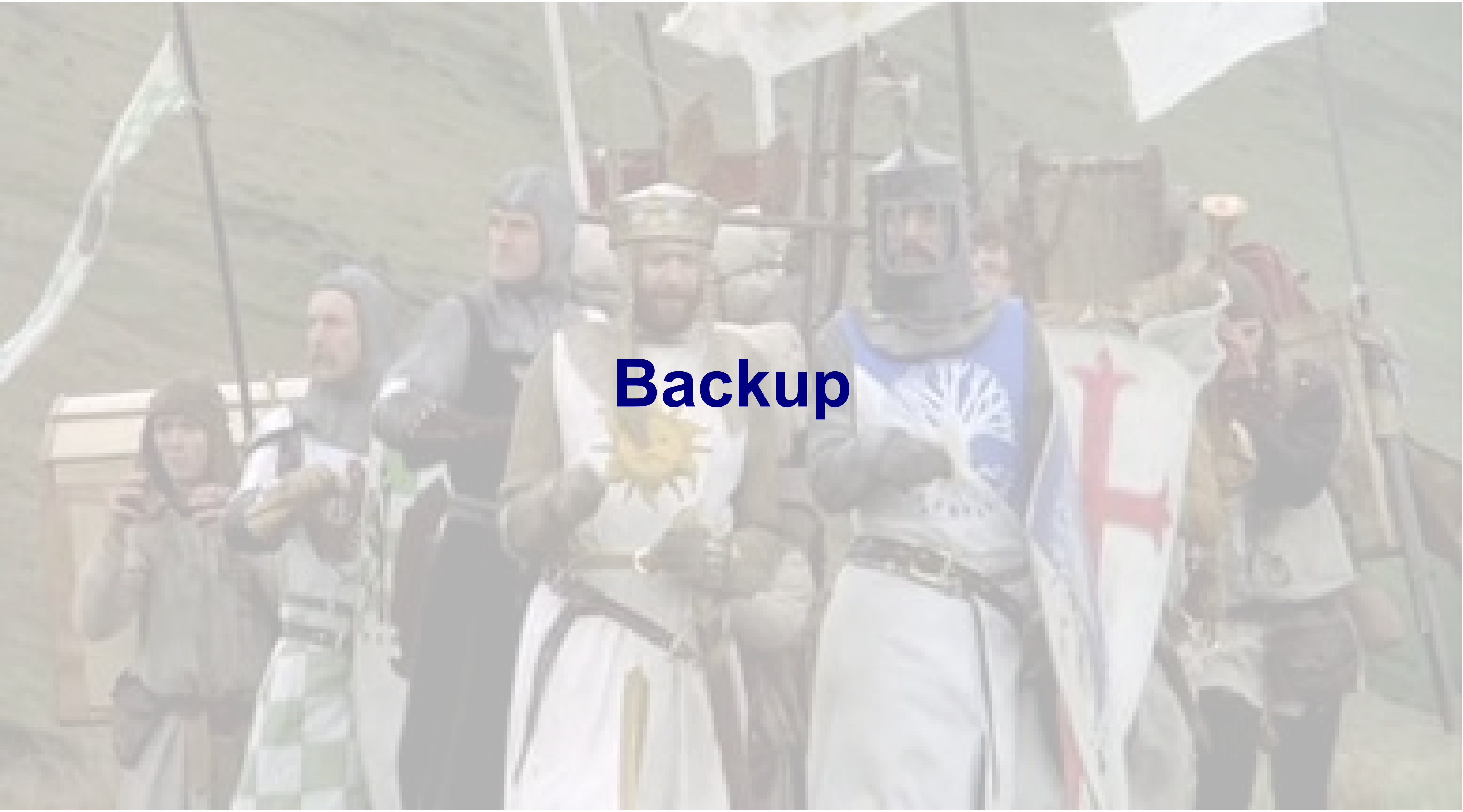
→ Precision measurements
to characterize the flavour structure of the BSM physics

… BSM signal is found in "indirect searches"

→ Follow-up measurements

… no clear signal for BSM physics found anywhere

→ Continue to push highest mass scales with
precision flavour measurements



Backup

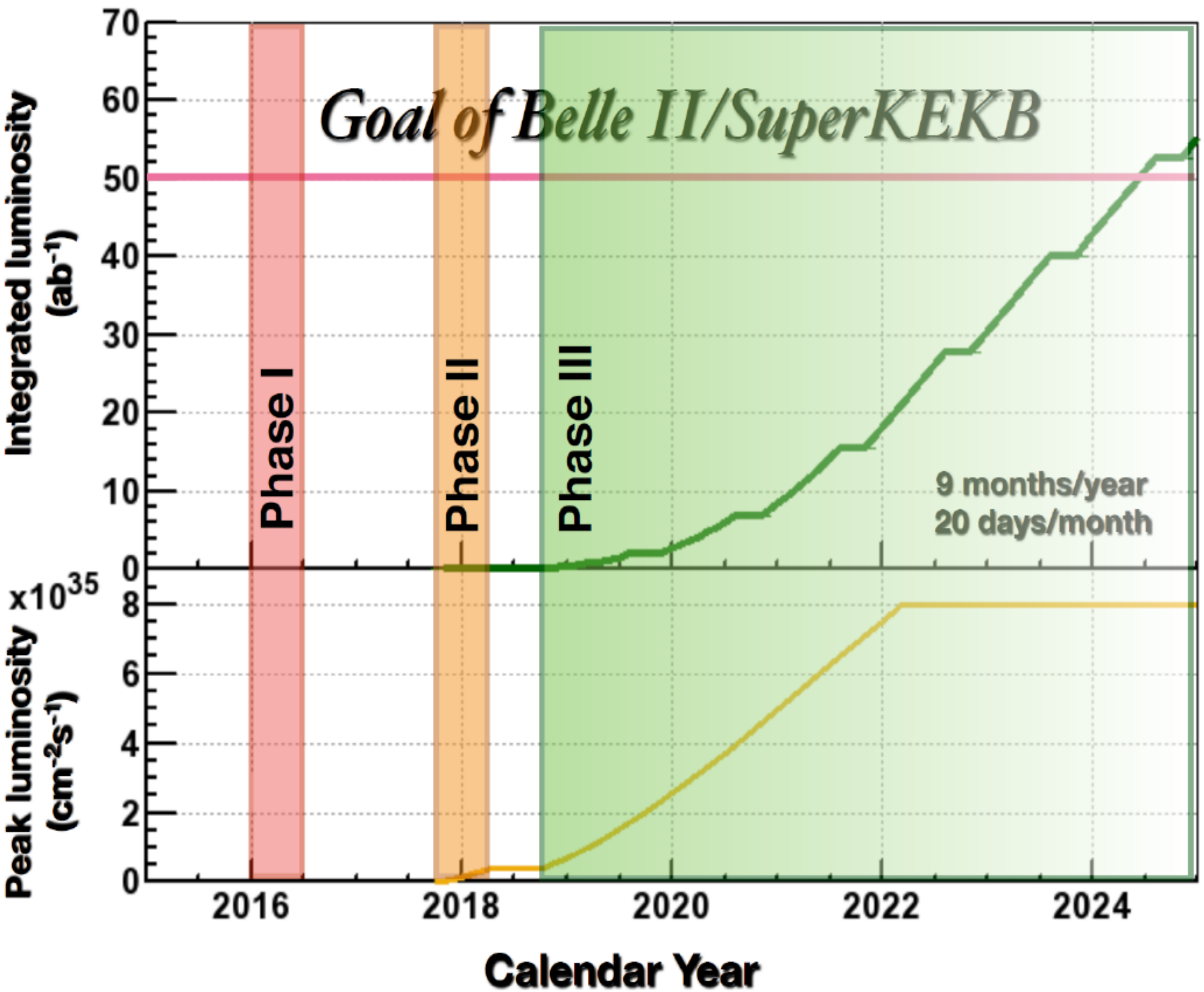
Prospects @ LHCb

Type	Observable	LHCb 2018	**Upgrade** (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s(B_s^0 \to J/\psi\phi)$	0.025	0.008	$\sim$0.003
	$2\beta_s(B_s^0 \to J/\psi f_0(980))$	0.045	0.014	$\sim$0.01
	a_{sl}^s	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\overline{K}^{*0})$	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	0.09	0.02	$<$0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.025	0.008	0.02
	$s_0 A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08	0.025	$\sim$0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	8 %	2.5 %	$\sim$10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$\sim$100 %	$\sim$35 %	$\sim$5 %
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	4°	0.9°	negligible
	$\gamma(B_s^0 \to D_s K)$	11°	2.0°	negligible
	$\beta(B^0 \to J/\psi K_S^0)$	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	0.65×10^{-3}	0.12×10^{-3}	–

Prospects LFU@LHCb

Observable	Run 1 result		8 fb^{-1}	50 fb^{-1}
Yield $B^0 \to K^{*0}\mu^+\mu^-$	2398 ± 57	[63]	9175	70480
Yield $B^0_s \to \phi\mu^+\mu^-$	432 ± 24	[64]	1653	12697
Yield $B^+ \to K^+\mu^+\mu^-$	4746 ± 81	[71]	18159	139491
Yield $B^+ \to \pi^+\mu^+\mu^-$	93 ± 12	[72]	355	2725
Yield $\Lambda^0_b \to \Lambda\mu^+\mu^-$	373 ± 25	[73]	1426	10957
Yield $B^+ \to K^+e^+e^-$ $(1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	254 ± 29	[65]	972	7465
$\mathrm{d}\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-, 1.0 < q^2 < 6\,\mathrm{GeV}^2/c^4)/\mathrm{d}q^2[10^{-9}\,\mathrm{GeV}^{-2}c^4]$	$0.91 \pm 0.21 \pm 0.03$	[72]	0.11	0.04
$\mathrm{d}\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-, 15 < q^2 < 22\,\mathrm{GeV}^2/c^4)/\mathrm{d}q^2[10^{-9}\,\mathrm{GeV}^{-2}c^4]$	$0.47 \pm 0.12 \pm 0.01$	[72]	0.06	0.02
$A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-, 1.1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	$-0.075 \pm 0.034 \pm 0.007$	[63]	0.017	0.006
$A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-, 15 < q^2 < 19\,\mathrm{GeV}^2/c^4)$	$0.355 \pm 0.027 \pm 0.009$	[63]	0.014	0.005
$S_5(B^0 \to K^{*0}\mu^+\mu^-, 1.1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	$-0.023 \pm 0.050 \pm 0.005$	[63]	0.026	0.009
$S_5(B^0 \to K^{*0}\mu^+\mu^-, 15 < q^2 < 19\,\mathrm{GeV}^2/c^4)$	$-0.325 \pm 0.037 \pm 0.009$	[63]	0.019	0.007
$S_5(B^0_s \to \overline{K}^{*0}\mu^+\mu^-, 1.1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	-		-	0.087
$S_5(B^0_s \to \overline{K}^{*0}\mu^+\mu^-, 15 < q^2 < 19\,\mathrm{GeV}^2/c^4)$	-		-	0.064
$\mathcal{R}_K(1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	$0.745 \pm 0.090 \pm 0.036$	[65]	0.046	0.017

Belle 2



Phase 1 (completed)

- Circulate beams (no collisions)

Phase 2 (2017-2018)

- First collisions
- Physics without vertex detector

Phase 3 (2018-2025)

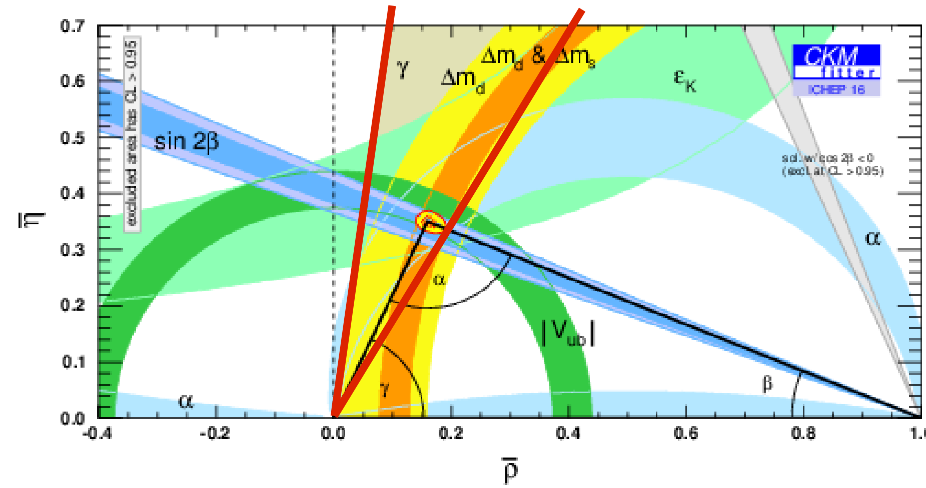
- Physics with full detector

CKM angle γ

"Unitarity Triangle":
from unitarity condition of CKM matrix

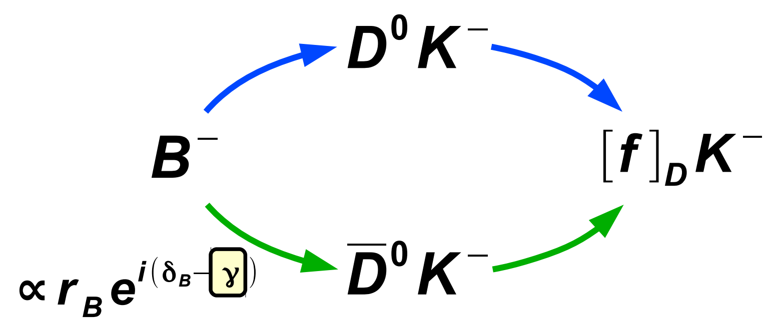
All angles and sides related to observables

Over-constrained fits test Standard Model

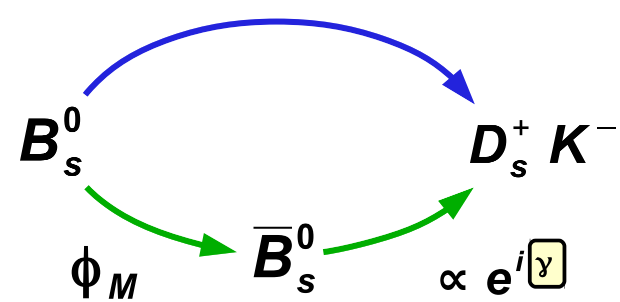


"Clean" measurements of γ through

Decay rates for tree decays
$B^{\pm} \to D K^{\pm}$ **and** $\overset{(-)}{B^0} \to D \overset{(-)}{K}{}^{*0}$



Time-dependent ***CP*** **asymmetry in**
$B_s^0 \to D_s^+ K^-$



Systematics a_{sl}^{s}

Source	Value	Statistical uncertainties	Systematic uncertainties	
$A_{\rm raw}$	0.11	0.09	0.02	
$-A_{\rm track}(K^+K^-)$	0.01	0.00	0.03	
$-A_{\rm track}(\pi^-\mu^+)$	0.01	0.05	0.04	
$-A_{\rm PID}$	−0.01	0.02	0.03	
$-A_{\rm trig}$(hardware)	0.03	0.02	0.02	
$-A_{\rm trig}$(software)	0.00	0.01	0.02	
$-f_{\rm bkg}\ A_{\rm bkg}$	0.02	–	0.03	+
$(1-f_{\rm bkg})a_{\rm sl}^s/2$	0.16	0.11	0.08	
$2/(1-f_{\rm bkg})$	2.45	–	0.18	×
$a_{\rm sl}^s$	0.39	0.26	0.20	

$$a_{sl}^{s} = \left(3.9 \pm 2.6 \pm 2.0\right) \times 10^{-3}$$

LHCb Run 1

[PRL 117(2016)061803]

Systematics ϕ_s

Source	Γ_s (ps^{-1})	$\Delta\Gamma_s$ (ps^{-1})	$\lvert A_\perp\rvert^2$	$\lvert A_0\rvert^2$	$\delta_\parallel$ (rad)	$\delta_\perp$ (rad)	ϕ_s (rad)	$\lvert\lambda\rvert$	Δm_s (ps^{-1})
Total statistical uncertainty	0.0027	0.0091	0.0049	0.0034	$^{+0.10}_{-0.17}$	$^{+0.14}_{-0.15}$	0.049	0.019	$^{+0.055}_{-0.057}$
Mass factorization	···	0.0007	0.0031	0.0064	0.05	0.05	0.002	0.001	0.004
Signal weights (statistical)	0.0001	0.0001	···	0.0001	···	···	···	···	···
b-hadron background	0.0001	0.0004	0.0004	0.0002	0.02	0.02	0.002	0.003	0.001
B_c^+ feed down	0.0005	···	···	···	···	···	···	···	···
Angular resolution bias	···	···	0.0006	0.0001	$^{+0.02}_{-0.03}$	0.01	···	···	···
Angular efficiency (reweighting)	0.0001	···	0.0011	0.0020	0.01	···	0.001	0.005	0.002
Angular efficiency (statistical)	0.0001	0.0002	0.0011	0.0004	0.02	0.01	0.004	0.002	0.001
Decay-time resolution	···	···	···	···	···	0.01	0.002	0.001	0.005
Trigger efficiency (statistical)	0.0011	0.0009	···	···	···	···	···	···	···
Track reconstruction (simulation)	0.0007	0.0029	0.0005	0.0006	$^{+0.01}_{-0.02}$	0.002	0.001	0.001	0.006
Track reconstruction (statistical)	0.0005	0.0002	···	···	···	···	···	···	0.001
Length and momentum scales	0.0002	···	···	···	···	···	···	···	0.005
S-P coupling factors	···	···	···	···	0.01	0.01	···	0.001	0.002
Fit bias	···	···	0.0005	···	···	0.01	···	0.001	···
Quadratic sum of systematics	0.0015	0.0032	0.0036	0.0067	$^{+0.06}_{-0.07}$	0.06	0.006	0.007	0.011

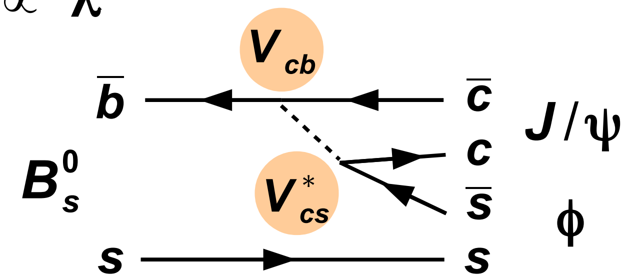
$$\phi_s = -\,0.010 \pm 0.039 \text{ rad}$$

LHCb Run 1

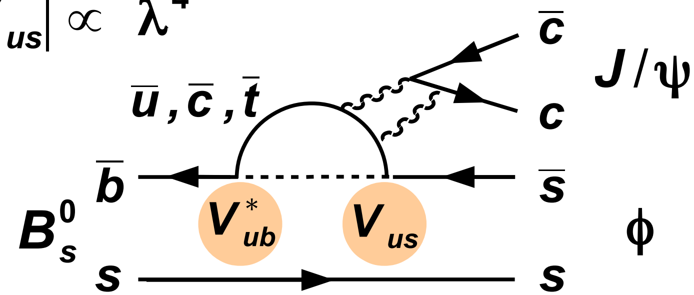
[PRL 114(2015)041801]

Penguin Pollution in J/ψ φ

$\left|V_{cb}V^*_{cs}\right| \propto \lambda^2$



$\left|V^*_{ub}V_{us}\right| \propto \lambda^4$

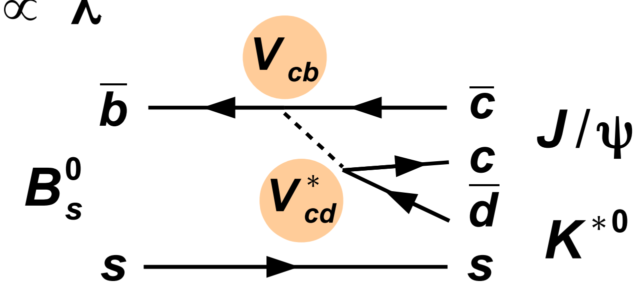


- penguin decay amplitude suppressed by smallness of CKM matrix element

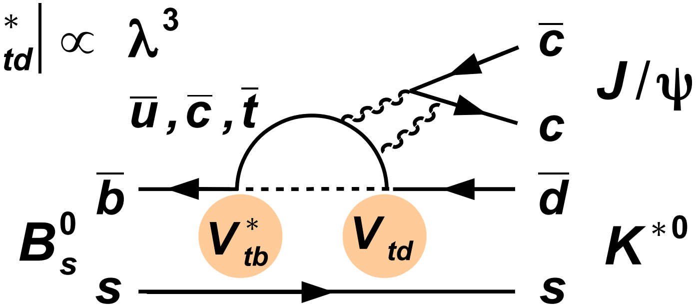
$$(\lambda = \sin\theta_C \approx 0.23)$$

- but effects from hadronic form factors not easy to estimate
- derive constraints on possible penguin pollution from $B_s^0 \to J/\psi\, \overline{K}^{*0}$ and $B^0 \to J/\psi\, \rho^0$, where penguin and tree amplitudes have similar magnitude

$\left|V_{cb}V^*_{cd}\right| \propto \lambda^3$



$\left|V_{tb}V^*_{td}\right| \propto \lambda^3$



- for $B^0 \to J/\psi\, \rho^0$, assume that effects from SU(3)-breaking can be neglected

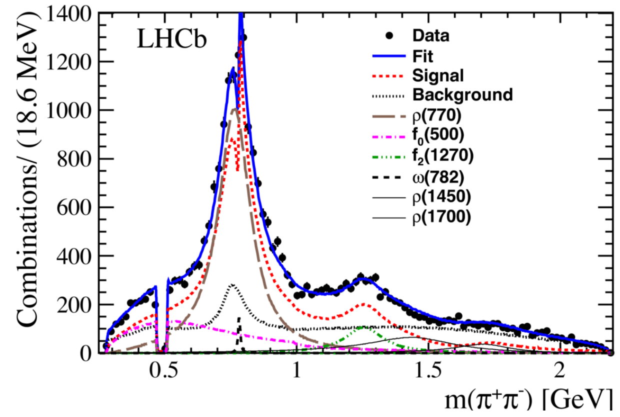
Penguin Pollution in J/ψ φ

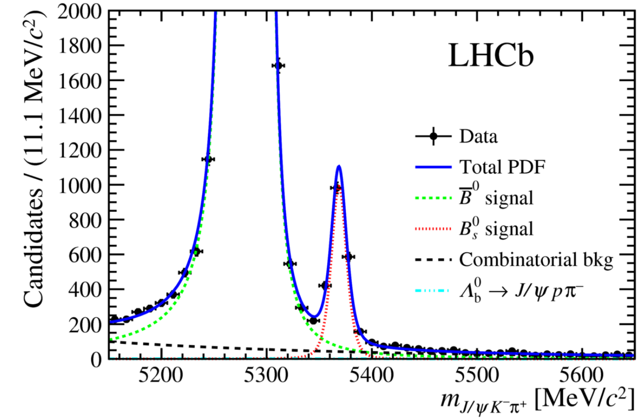
[PLB 742(2015)038]
[JHEP 11(2015)082]

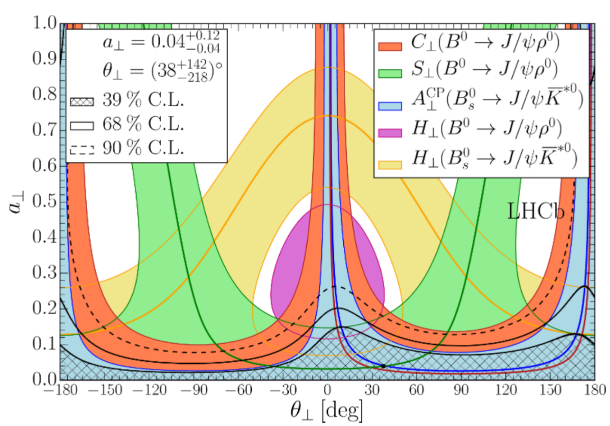
- 18'000 $B^0 \to J/\psi\, \pi^+ \pi^-$ and 1'800 $B_s^0 \to J/\psi\, \overline{K}^{*0}$ signal candidates from 3 fb^{-1}
- time-dependent angular analyses to extract polarisation fractions and *CP* asymmetries in each polarization state

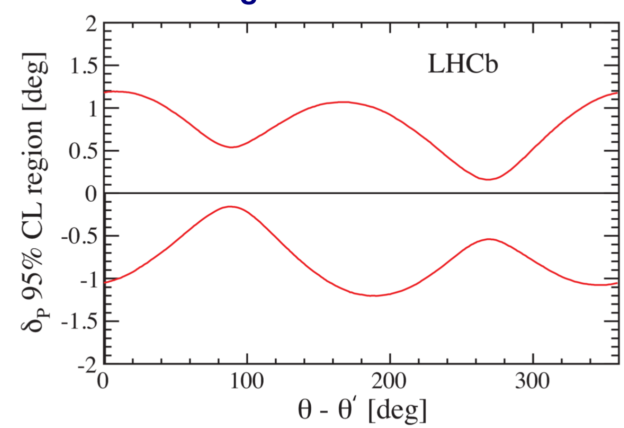
$$A_i^{CP} = -\frac{2 a_i \sin\theta_i \sin\gamma}{1 - 2 a_i \cos\theta_i \cos\gamma + a_i^2} \quad \left(i \in \{ 0, \parallel, \perp \} \right)$$

- derive constraints on fraction a_i and strong phase θ_i of penguin contributions
- translate into constraints on phase shift on ϕ_s







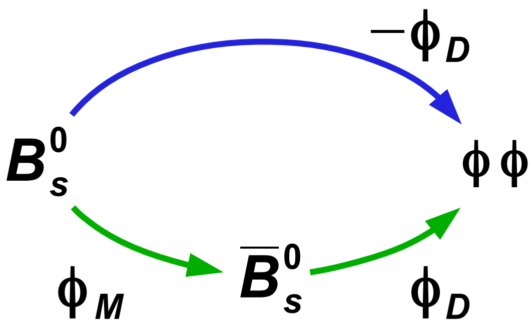


CP violation in $B_s^0 \rightarrow \phi\,\phi$

Similar to $B_s^0 \rightarrow J/\psi\,\phi$,

but decay amplitude dominated by

penguin diagram



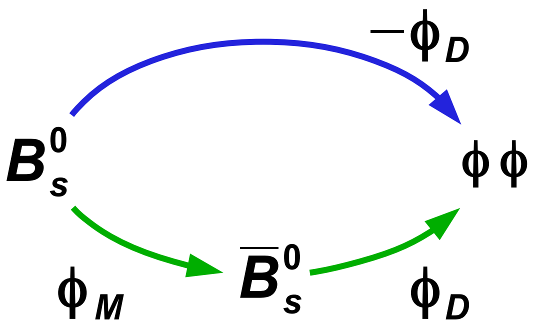
Sensitive to possible BSM contributions in decay

CP violation in $B_s^0 \to \phi\,\phi$

Similar to $B_s^0 \to J/\psi\,\phi$,

but decay amplitude dominated by

penguin diagram



Sensitive to possible BSM contributions in decay

LHCb Run-1 measurement:

$$\phi_s^{\phi\phi}(\text{LHCb}) = -\,0.17 \pm 0.15 \pm 0.03 \text{ rad}$$

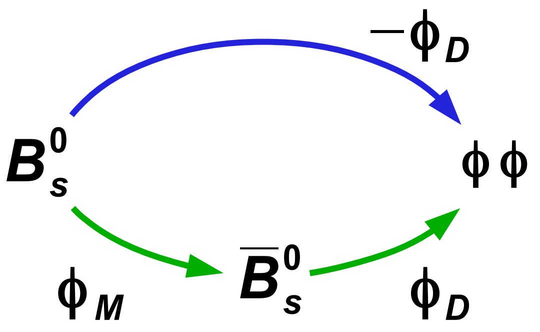
[PRD 90(2014)052011]

CP violation in $B_s^0 \to \phi\phi$

Similar to $B_s^0 \to J/\psi\,\phi$,

but decay amplitude dominated by penguin diagram

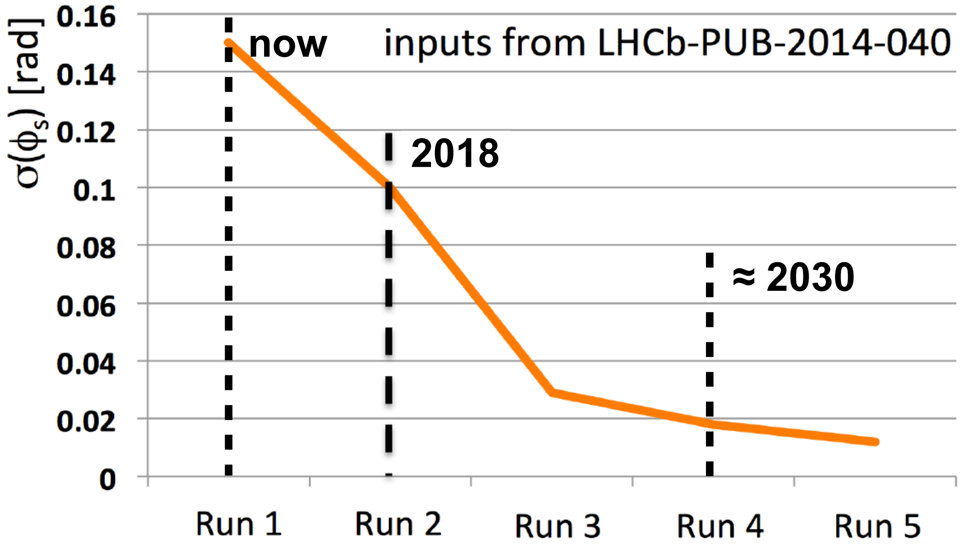
Sensitive to possible BSM contributions in decay



LHCb expect

$\sigma(\phi_s^{\phi\phi}) \approx 0.02$ rad

from 50 fb^{-1}



[LHCb-PUB-2014-040]

Systematics BF ($B_s^0 \to \mu^+ \mu^-$)

Measure BF relative to

$B^+ \to J/\psi\,(\mu^+\mu^-)\,K^+$ and $B^0 \to K^+\pi^-$

$$\mathrm{BF}\left(B_s^0 \to \mu^+\mu^-\right) = \mathrm{BF}(\mathrm{ref}) \times \frac{N\left(B_s^0 \to \mu^+\mu^-\right)}{N(\mathrm{ref})} \times \frac{f_{\mathrm{ref}}}{f_s} \times \frac{\epsilon(\mathrm{ref})}{\epsilon\left(B_s^0 \to \mu^+\mu^-\right)}$$

Systematic uncertainty dominated by relative uncertainty of ≈ 5.8 % on $f_s / f_{(u,d)}$

[LHCb-CONF-2013-011]

$$\mathrm{BF}\left(B_s^0 \to \mu^+\mu^-\right) = \left(3.0 \pm 0.6\,^{+0.3}_{-0.2}\right) \times 10^{-9}$$

LHCb Run 1+2

[arXiv:1703.05747]

Upgrade statistics will also give access to additional observables, e.g.

$$A_{\Delta\Gamma} \equiv \frac{\Gamma(B_s^H \to \mu^+\mu^-) - \Gamma(B_s^L \to \mu^+\mu^-)}{\Gamma(B_s^H \to \mu^+\mu^-) + \Gamma(B_s^L \to \mu^+\mu^-)}$$

Standard-Model:

$$A_{\Delta\Gamma}^{\mathrm{SM}} = 1$$

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

Upgrade statistics will also give access to additional observables, e.g.

$$A_{\Delta\Gamma} \equiv \frac{\Gamma(B_s^H \to \mu^+\mu^-) - \Gamma(B_s^L \to \mu^+\mu^-)}{\Gamma(B_s^H \to \mu^+\mu^-) + \Gamma(B_s^L \to \mu^+\mu^-)}$$

De Bruyn et al. [PRL 109(2012)041801]

Standard-Model:

$$A_{\Delta\Gamma}^{\mathrm{SM}} = 1$$

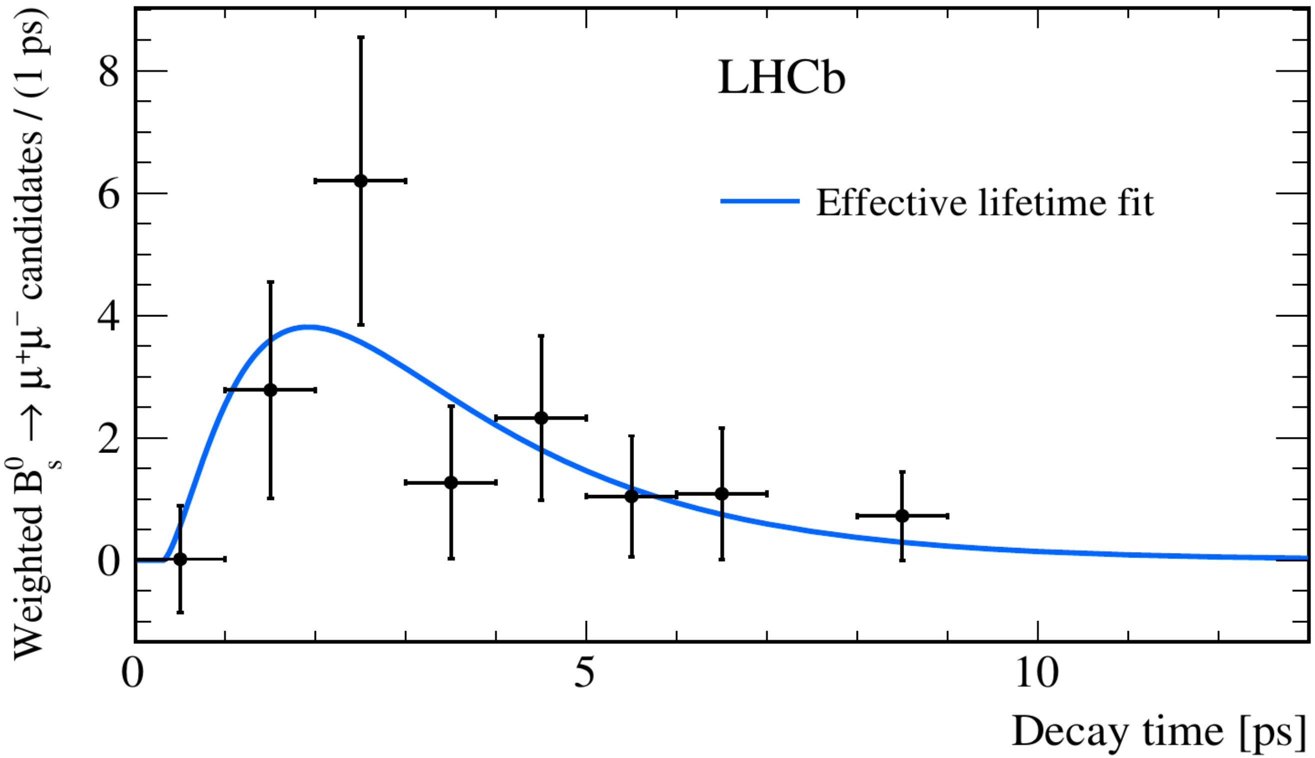
Extract $A_{\Delta\Gamma}$ from measurements of the "effective lifetime"

$$\tau_{\mathrm{eff}} \equiv \frac{\int t \times \left\langle \frac{d\Gamma}{dt}(B_s^0 \to \mu^+\mu^-) \right\rangle dt}{\int \left\langle \frac{d\Gamma}{dt}(B_s^0 \to \mu^+\mu^-) \right\rangle dt}$$

$$\Rightarrow \quad A_{\Delta\Gamma} = \frac{(1-y_s^2)\,\tau_{\mathrm{eff}} - (1+y_s^2)\,\tau_{B_s^0}}{y_s\,(2\tau_{B_s^0} - (1-y_s^2)\,\tau_{\mathrm{eff}})}$$

with $\tau_{B_s^0} \equiv \frac{1}{\Gamma_s}$ **and** $y_s \equiv \frac{\Delta\Gamma_s}{2\Gamma_s}$

$B_s^0 \rightarrow \mu^+ \mu^-$ effective lifetime



First proof-of-principle measurement by LHCb

$$\tau_{eff} = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$

LHCb Run1+2

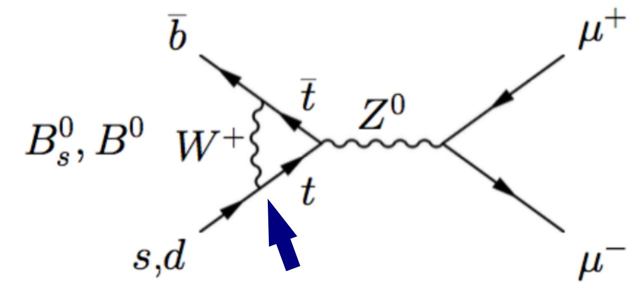
[arxiv:1703.05747]

Compatible with $A_{\Delta\Gamma} = 1$ at 1σ, with $A_{\Delta\Gamma} = -1$ at 1.4σ

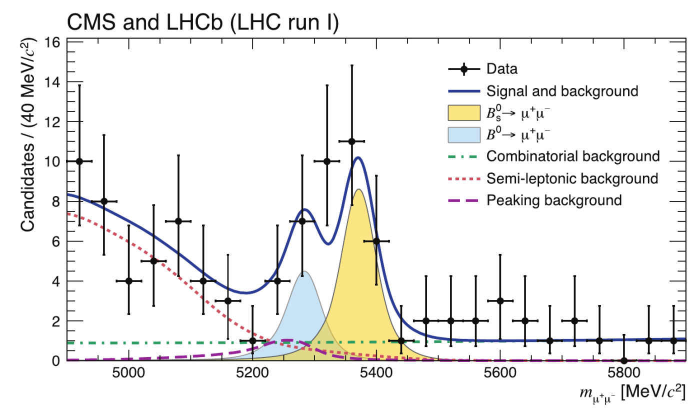
$B^0 \to \mu^+ \mu^-$

Even stronger suppression due to $V_{td} < V_{ts}$

$$BF_{SM} (B^0 \to \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

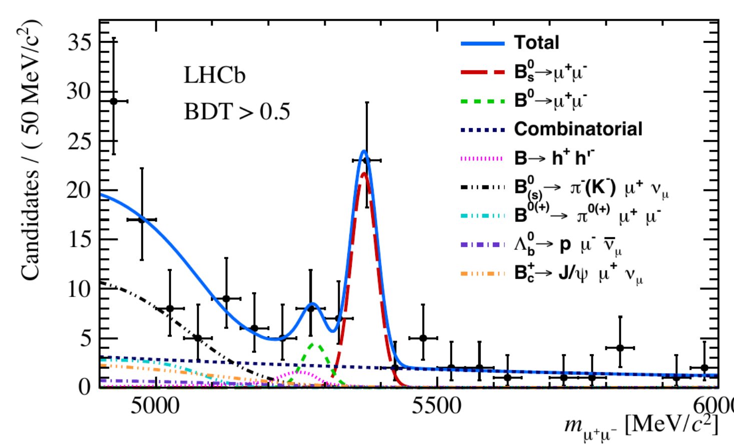


Not observed yet



3.0 σ significance
from LHCb+CMS Run 1

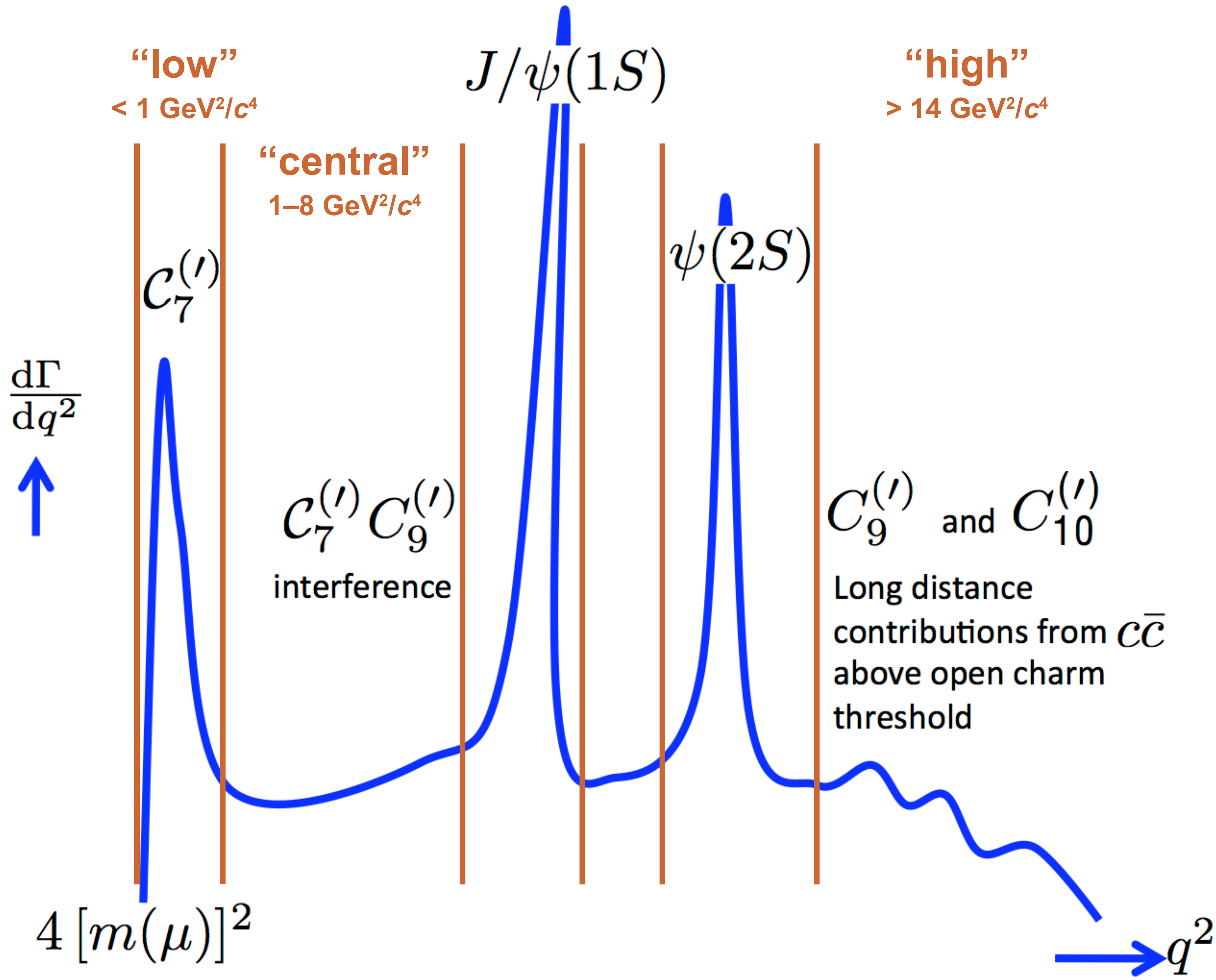
[Nature 522(2015)68]



1.9 σ significance
from LHCb Run 1+2

[arxiv:1703.05747]

q^2 Regions



"low"
< 1 GeV²/c⁴
"central"
1–8 GeV²/c⁴
$J/\psi(1S)$
$\psi(2S)$
"high"
> 14 GeV²/c⁴
$C_7^{(\prime)}$
$\frac{d\Gamma}{dq^2}$
$C_7^{(\prime)} C_9^{(\prime)}$
interference
$C_9^{(\prime)}$ and $C_{10}^{(\prime)}$
Long distance
contributions from $c\bar{c}$
above open charm
threshold
$4\,[m(\mu)]^2$
q^2

Systematics P_5'

Source	F_L	S_3–S_9	A_3–A_9	P_1–P_8'	q_0^2 GeV$^2/c^4$
Acceptance stat. uncertainty	< 0.01	< 0.01	< 0.01	< 0.01	0.01
Acceptance polynomial order	< 0.01	< 0.02	< 0.02	< 0.04	0.01–0.03
Data-simulation differences	0.01–0.02	< 0.01	< 0.01	< 0.01	< 0.02
Acceptance variation with q^2	< 0.01	< 0.01	< 0.01	< 0.01	—
$m(K^+\pi^-)$ model	< 0.01	< 0.01	< 0.01	< 0.03	< 0.01
Background model	< 0.01	< 0.01	< 0.01	< 0.02	0.01–0.05
Peaking backgrounds	< 0.01	< 0.01	< 0.01	< 0.01	0.01–0.04
$m(K^+\pi^-\mu^+\mu^-)$ model	< 0.01	< 0.01	< 0.01	< 0.02	< 0.01
Det. and prod. asymmetries	—	—	< 0.01	< 0.02	—

$$P_5' \left(1.1 < q^2 < 6\,\mathrm{GeV}^2/c^4\right) = -0.049\,^{+0.107}_{-0.108} \pm 0.014 \text{ rad}$$

LHCb Run 1
[JHEP 02(2016)104]

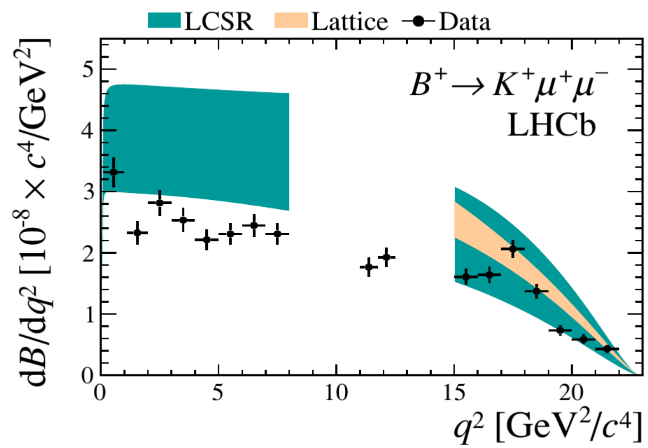
$b \to s \mu^+ \mu^-$ Branching Fractions

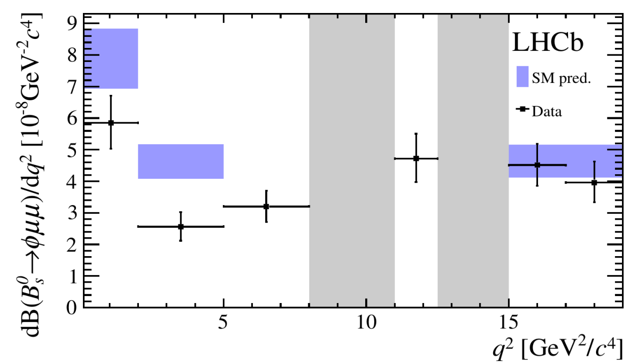
LHCb measure differential Branching Fractions as function of q^2: consistently lower than predicted in the central q^2 region?

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

LHCb Run 1

[JHEP 06(2014)133]





$B_s^0 \to \phi \mu^+ \mu^-$

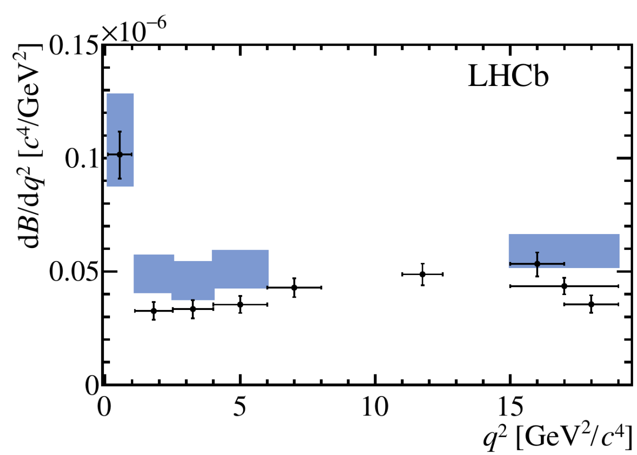
LHCb Run 1

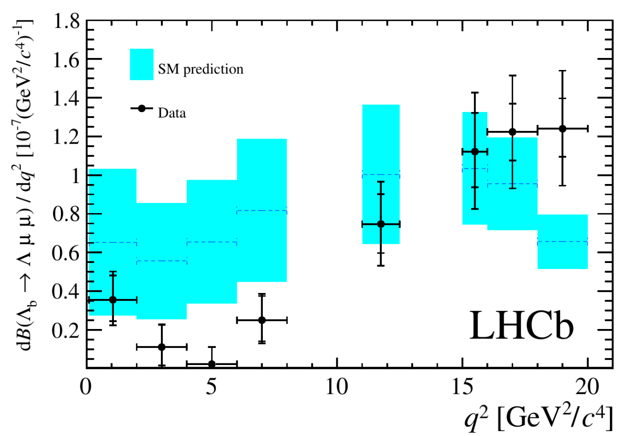
[JHEP 09(2015)179]

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

LHCb Run 1

[JHEP 04(2017)142]





$\Lambda_b \to \Lambda \mu^+ \mu^-$

LHCb Run 1

[JHEP 06(2015)115]

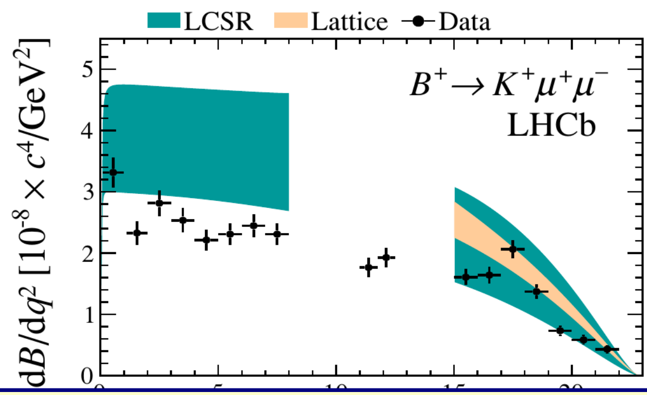
$b \to s \mu^+ \mu^-$ Branching Fractions

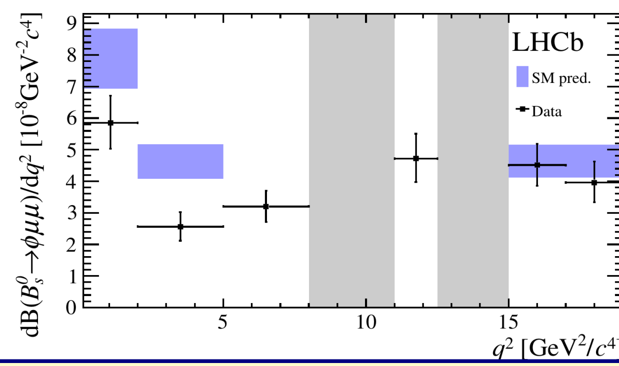
LHCb measure differential Branching Fractions as function of q^2: consistently lower than predicted in the central q^2 region?

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

LHCb Run 1

[JHEP 06(2014)133]





$B_s^0 \to \phi \mu^+ \mu^-$

LHCb Run 1

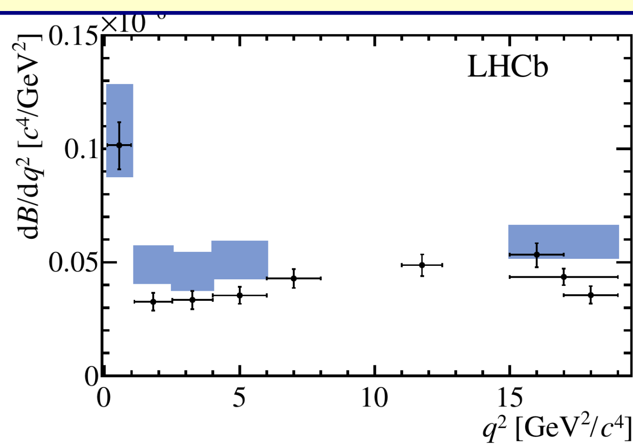
[JHEP 09(2015)179]

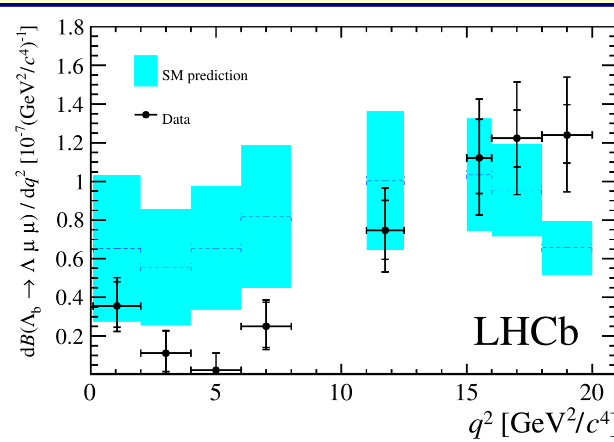
Significant theory uncertainties from hadronic form factors

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

LHCb Run 1

[JHEP 04(2017)142]





$\Lambda_b \to \Lambda \mu^+ \mu^-$

LHCb Run 1

[JHEP 06(2015)115]

Systematics R_K

The dominant sources of systematic uncertainty are due to the parametrization of the $B^+ \to J/\psi(\to e^+e^-)K^+$ mass distribution and the estimate of the trigger efficiencies that both contribute 3% to the value of R_K.

$$R_K\left(1 < q^2 < 6\,\mathrm{GeV}^2/c^4\right) = 0.745\,^{+0.090}_{-0.074} \pm 0.036$$

LHCb Run 1

[PRL 113(2014)151601]

Systematics R_{K^*}

	low-q^2			central-q^2		
Trigger category	L0E	L0H	L0I	L0E	L0H	L0I
Corrections to simulation	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
Kinematic selection	2.1	2.1	2.1	2.1	2.1	2.1
Residual background	–	–	–	5.0	5.0	5.0
Mass fits	1.4	2.1	2.5	2.0	0.9	1.0
Bin migration	1.0	1.0	1.0	1.6	1.6	1.6
$r_{J/\psi}$ flatness	1.6	1.4	1.7	0.7	2.1	0.7
Total	4.0	6.1	5.5	6.4	7.5	6.7

%

$$R_{K^*}\left(0.045 < q^2 < 1.1\,\mathrm{GeV}^2/c^4\right) = 0.660\,^{+0.11}_{-0.07} \pm 0.03$$

$$R_{K^*}\left(1.1 < q^2 < 6\,\mathrm{GeV}^2/c^4\right) = 0.685\,^{+0.11}_{-0.07} \pm 0.05$$

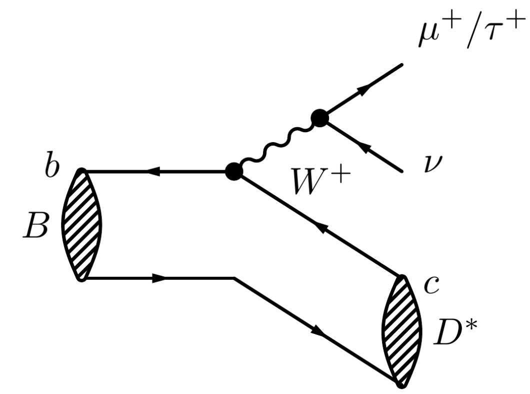
LHCb Run 1

[arXiv:1705.05802]

$R(D^*)$ etc.

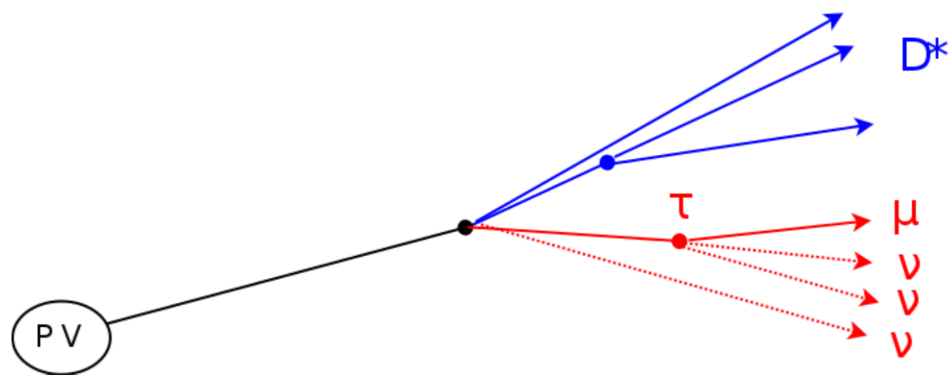
Another test of Lepton Flavour Universality:

$$R\left(D^{(*)}\right) \equiv \frac{\Gamma\left(B \to D^{(*)}\tau^+\nu_\tau\right)}{\Gamma\left(B \to D^{(*)}\mu^+\nu_\mu\right)}$$



Tree decays with BF of about a percent

But τ reconstruction challenging at hadron colliders



Systematics $R(D^*)$

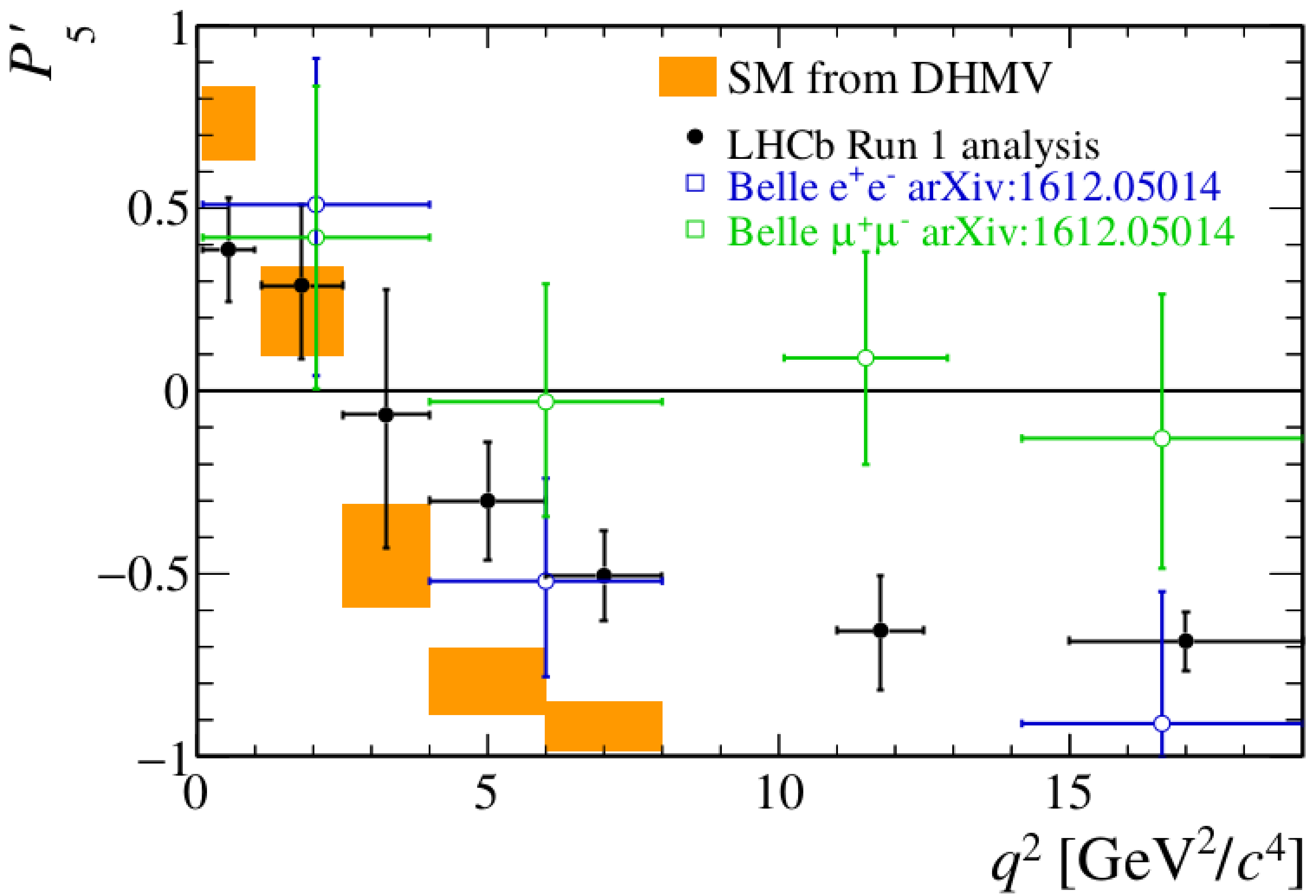
Model uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$

LHCb Run 1

[PRL 115(2015)111803]

$B^0 \to K^{*0} \ell^+ \ell^-$

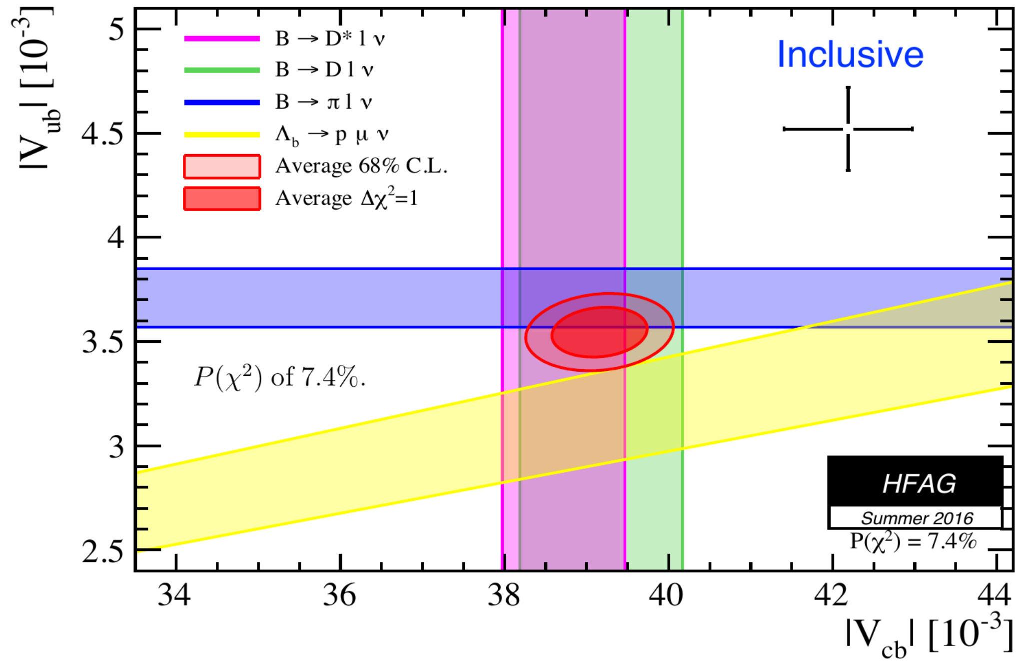


LHCb Run 1
[JHEP 02(2016)104]

Belle
[PRL 118(2017)111801]

V_{ub} and V_{cb}

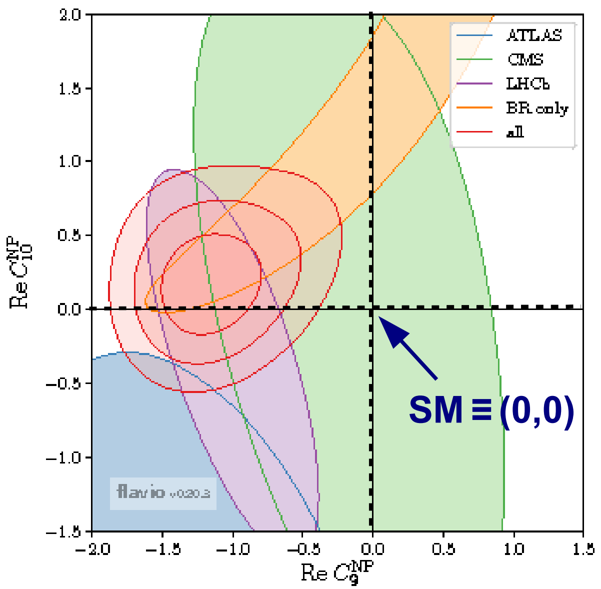
Long standing discrepancies between exclusive and inclusive determinations of V_{ub} and V_{cb}



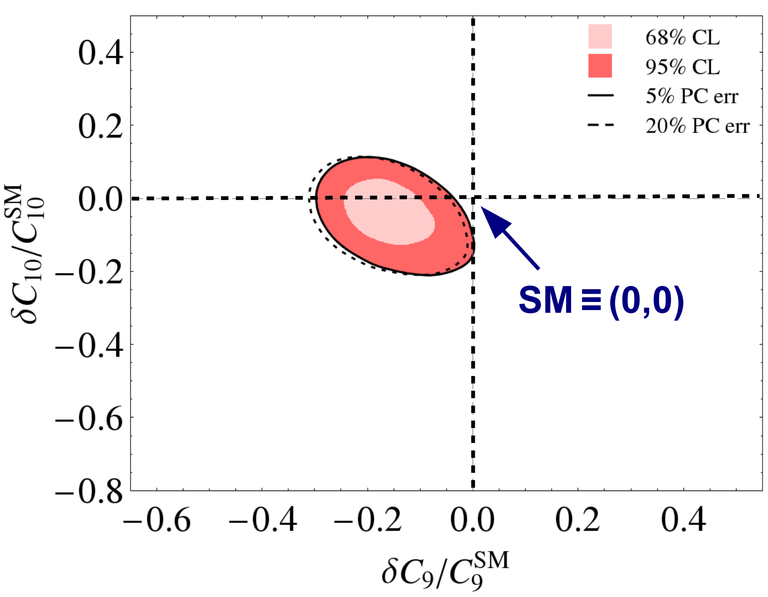
Inclusive analyses assume LFU to estimate backgrounds from BF ($b \to X_{u,c} \tau \nu_\tau$)

Taking central values from $R(D)$ and $R(D^*)$ measurements: BF ($b \to X_{u,c} \tau \nu_\tau$) ≈ 20 % larger than expected from LFU

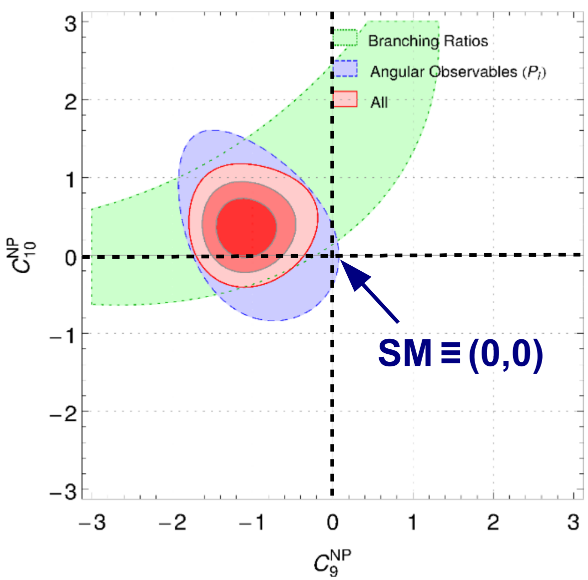
Global Fits



Altmannshofer et al.
[arxiv:1703.09189]



Mahmoudi et al.
[NPP Proc. 285-286(2017)39-44]



Descotes-Genon et al.
[JHEP 06(2016)092]

Taking into account up to 90 observables from different experiments, including $B \to \mu\mu$ and $b \to s\ell\ell$ transitions