LHCb upgrade: physics perspectives

(or anatomy of the LHCb upgrade)

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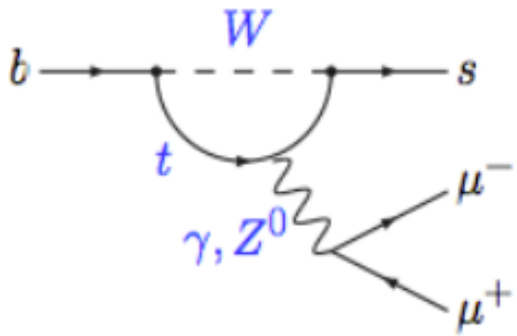
The landscape of flavour physics towards the high intensity era, Pisa 9-10 December 2014

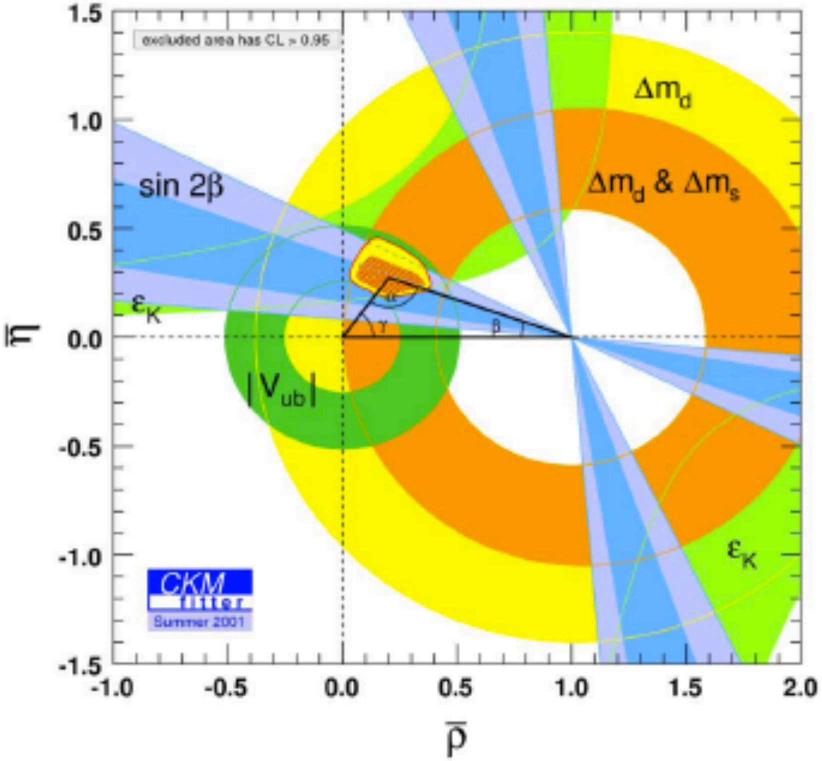
The mission of a flavor physicist

To look for New Physics in [mostly FCNC] B, K, charm decays (and cLFV decays) that can be sensitive to quantum corrections from degrees of freedom **at** and **above** the electroweak scale.

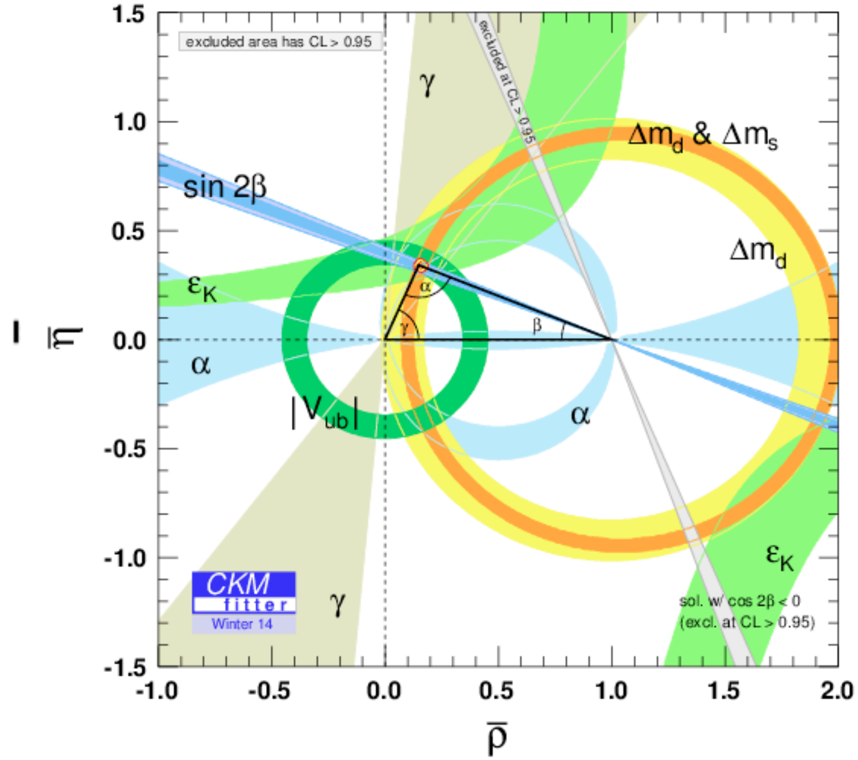


The success of the CKM picture is impressive….

EPS 2001



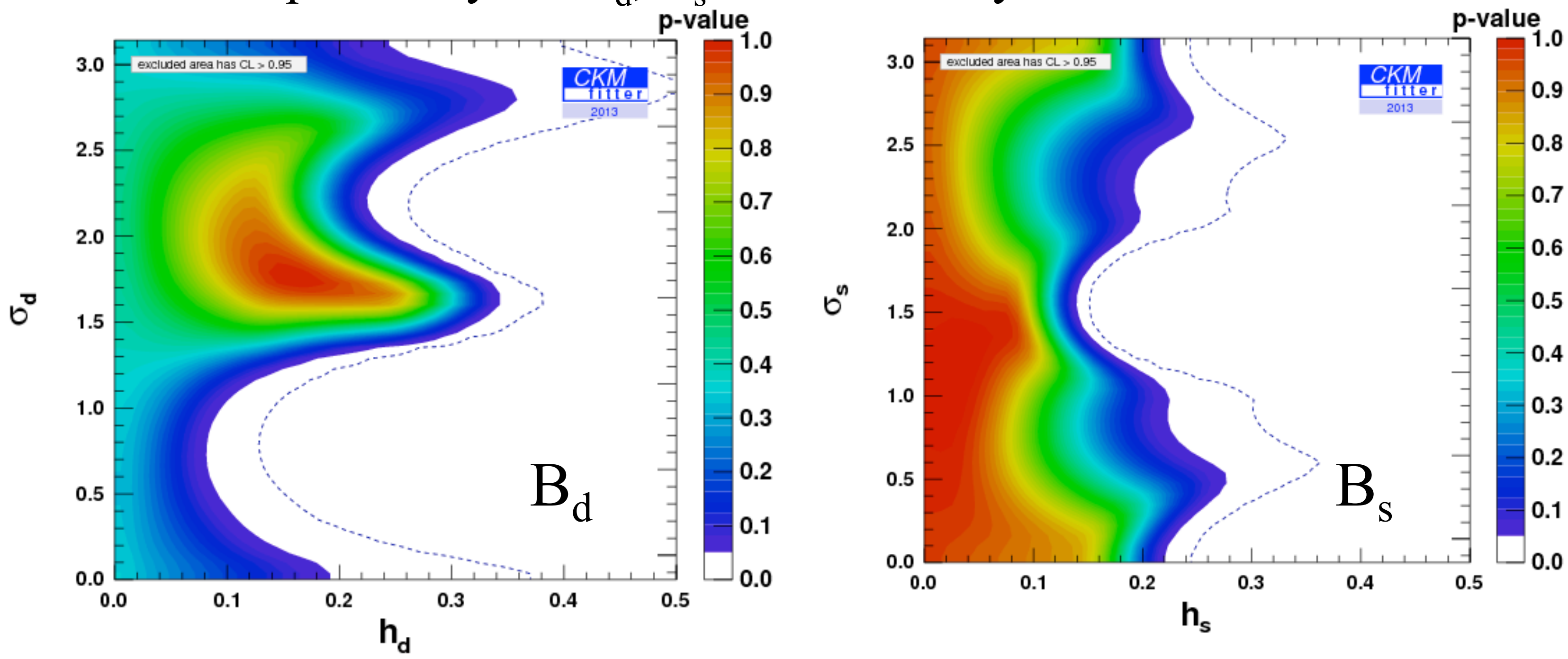
Moriond 2014



But how well do we know CKM? Assume ΔF=2 transitions

arXiv: 1309.2203 (CKMFitter)

consider NP in $\mathbf{M_{12}^{q} = M_{12}^{SM,q}(1+ h_q e^{2i\sigma_q})}$
independently for B_d, B_s with arbitrary flavour structure.



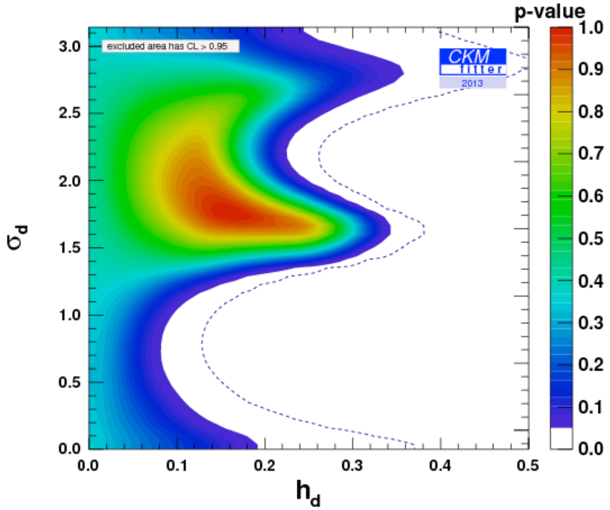
Current status: in most flavor-changing neutral-current processes,
NP can still contribute at least at the level of **~20-30%** with respect to the SM

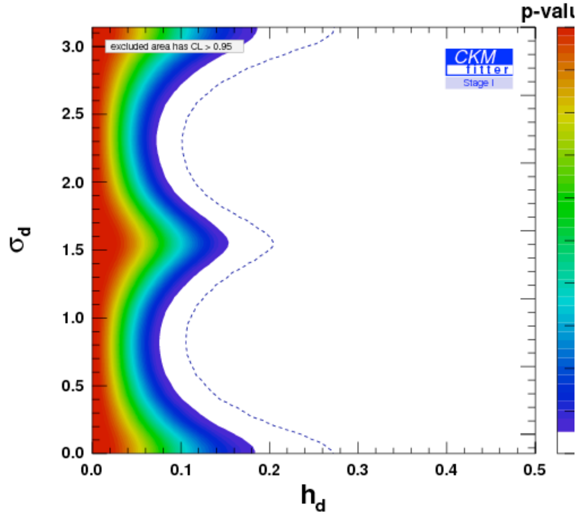
2013

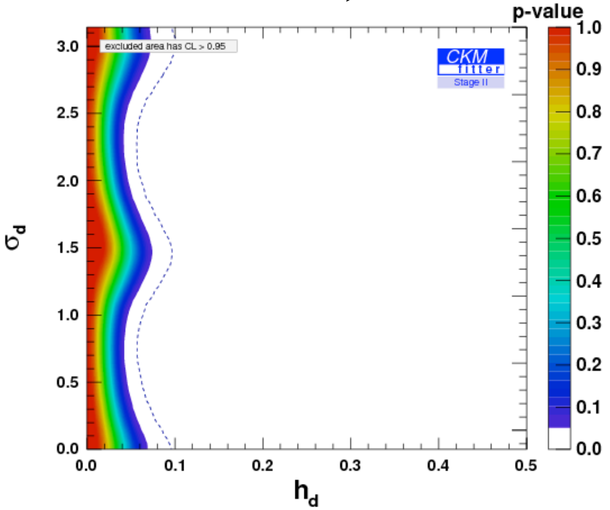
2018+:
LHCb 7 fb^{-1}, Belle II: 5 ab^{-1}

2028+:
50 fb^{-1} LHCb, 50 ab^{-1} BelleII

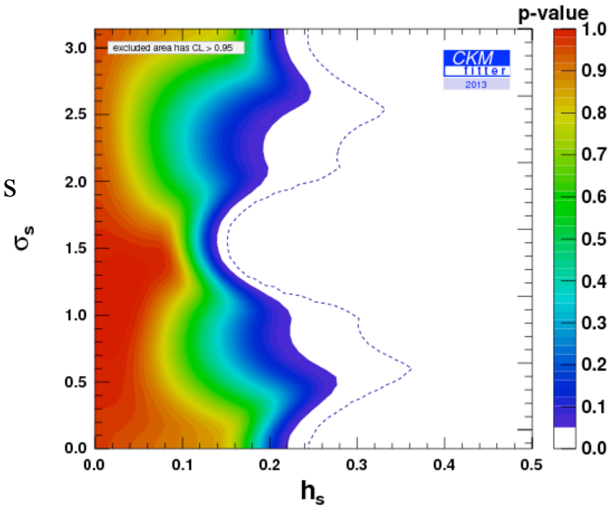
B_d

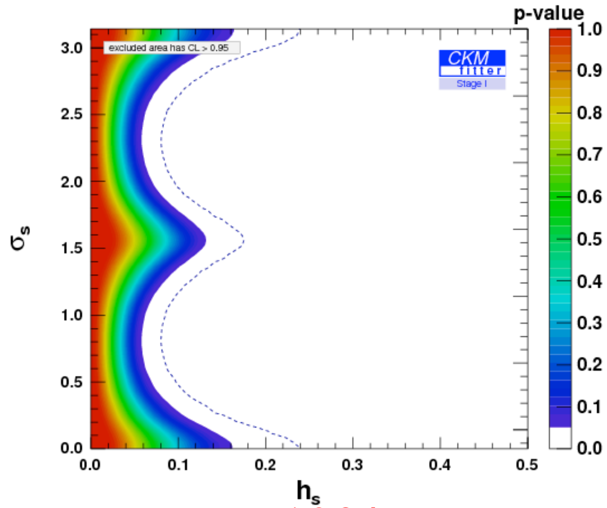


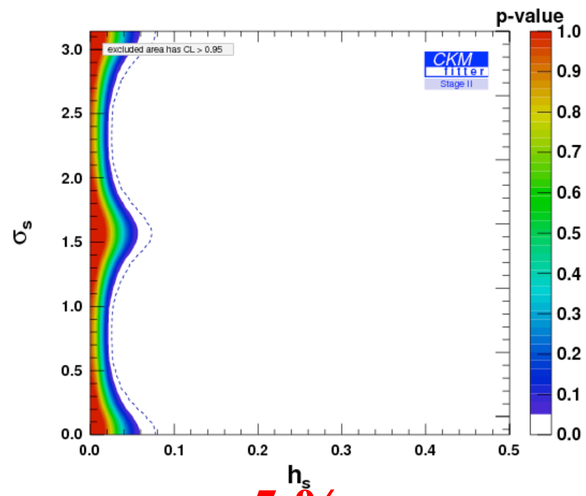




B_s



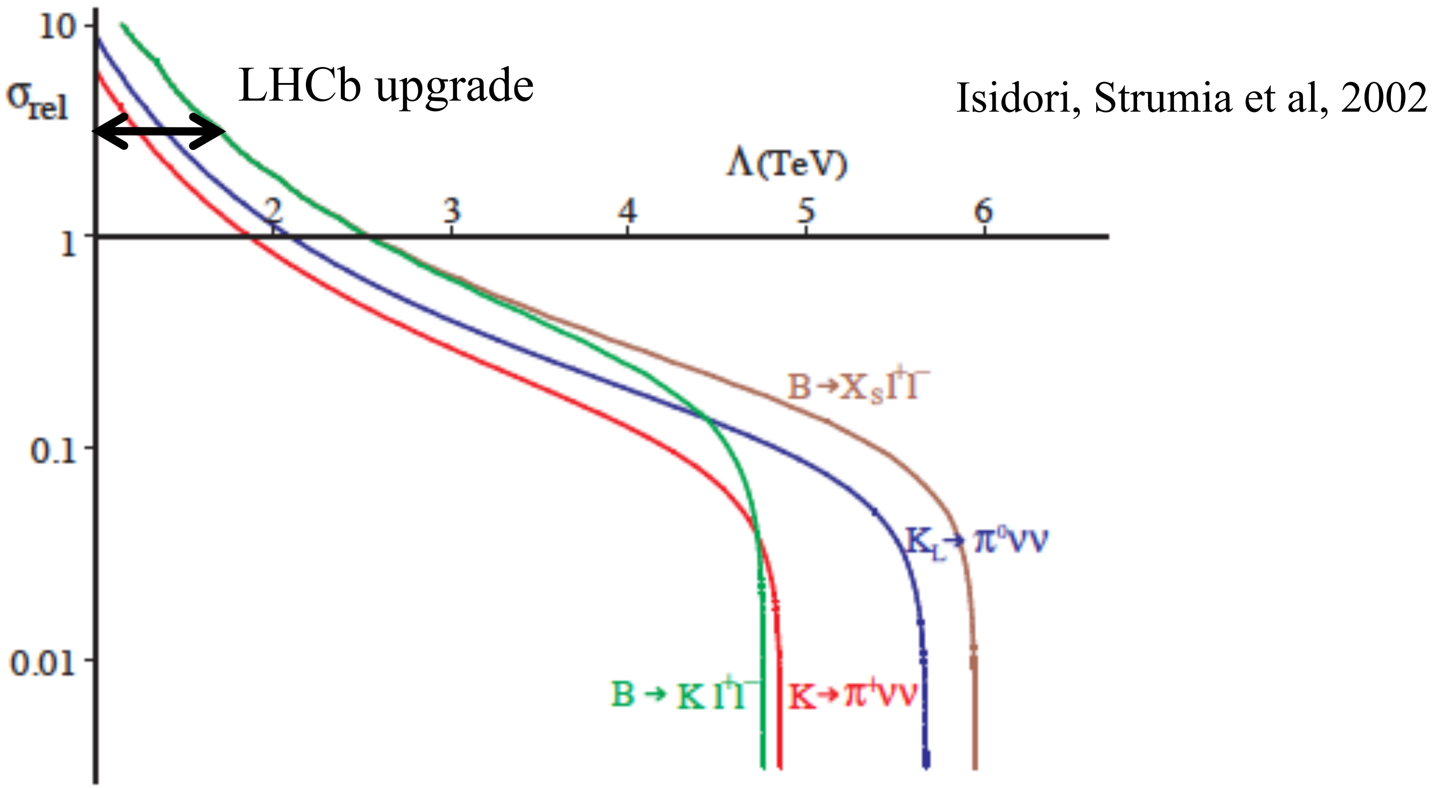




~ 20-25% **~ 10%** **~ 5 %**

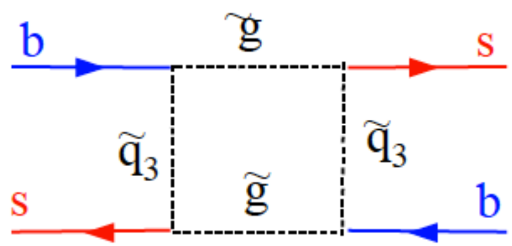
arXiv: 1309.2203 (CKMFitter)

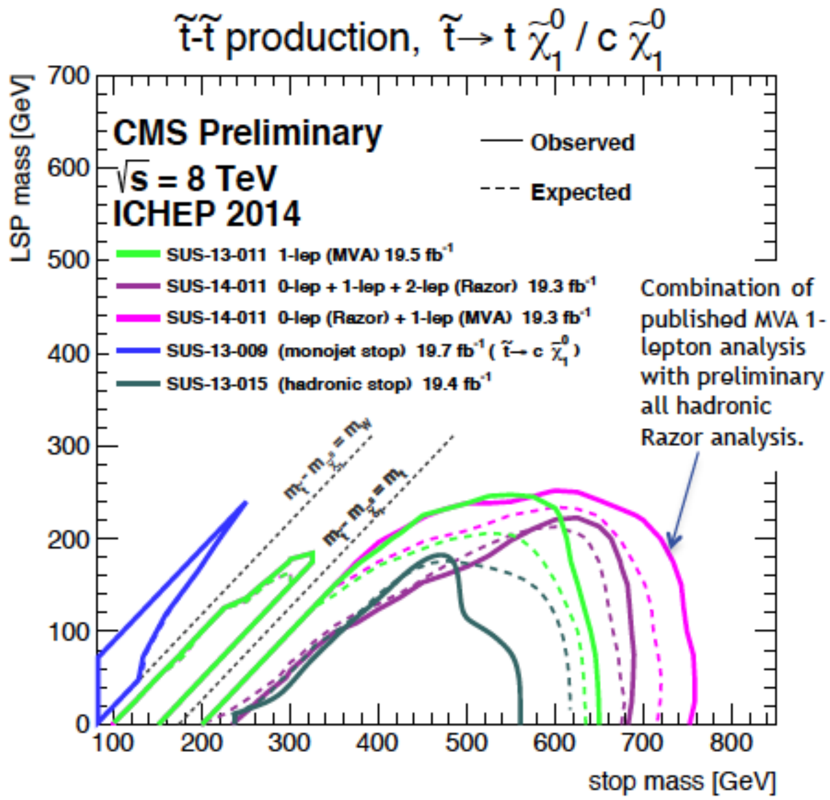
CKMFitter, 1309.2203: a knowledge of CKM at ~5-10% (2028+) could probe new particles with CKM-like couplings with masses, M,
→ in the **10-20 TeV range** if they contribute at tree level (i.e., $\Lambda \sim M$),
→ in the **1-2 TeV** range if they enter with loop suppression

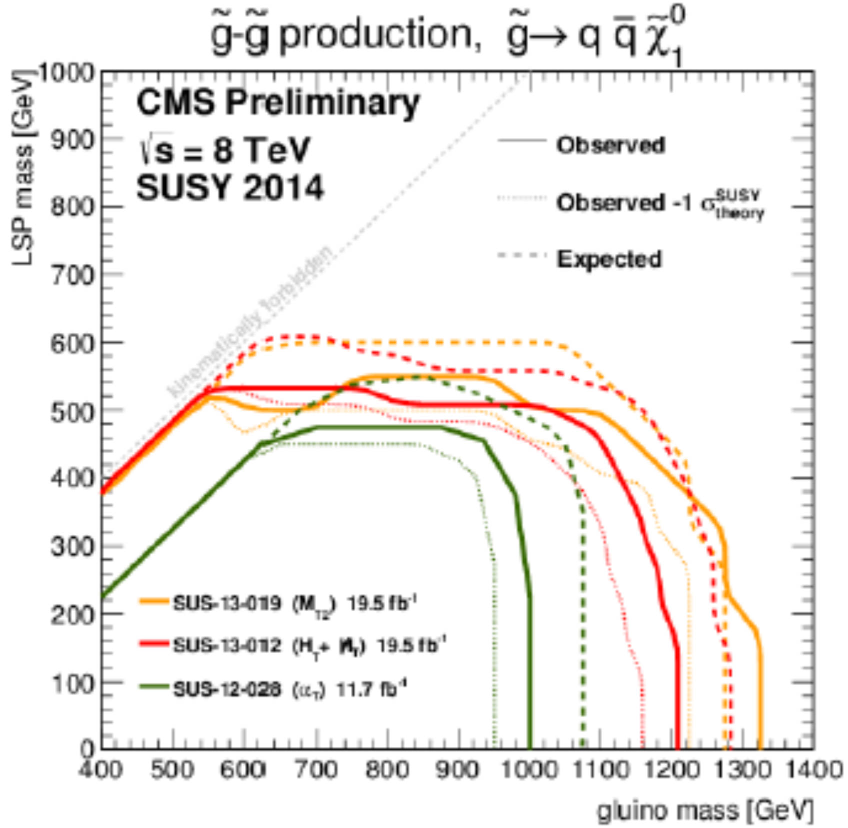


.. And are in the **ballpark of the gluino masses** explored at LHC @14 TeV

Stop & gluino searches at CMS
[Flaecher, SUSY 2014]

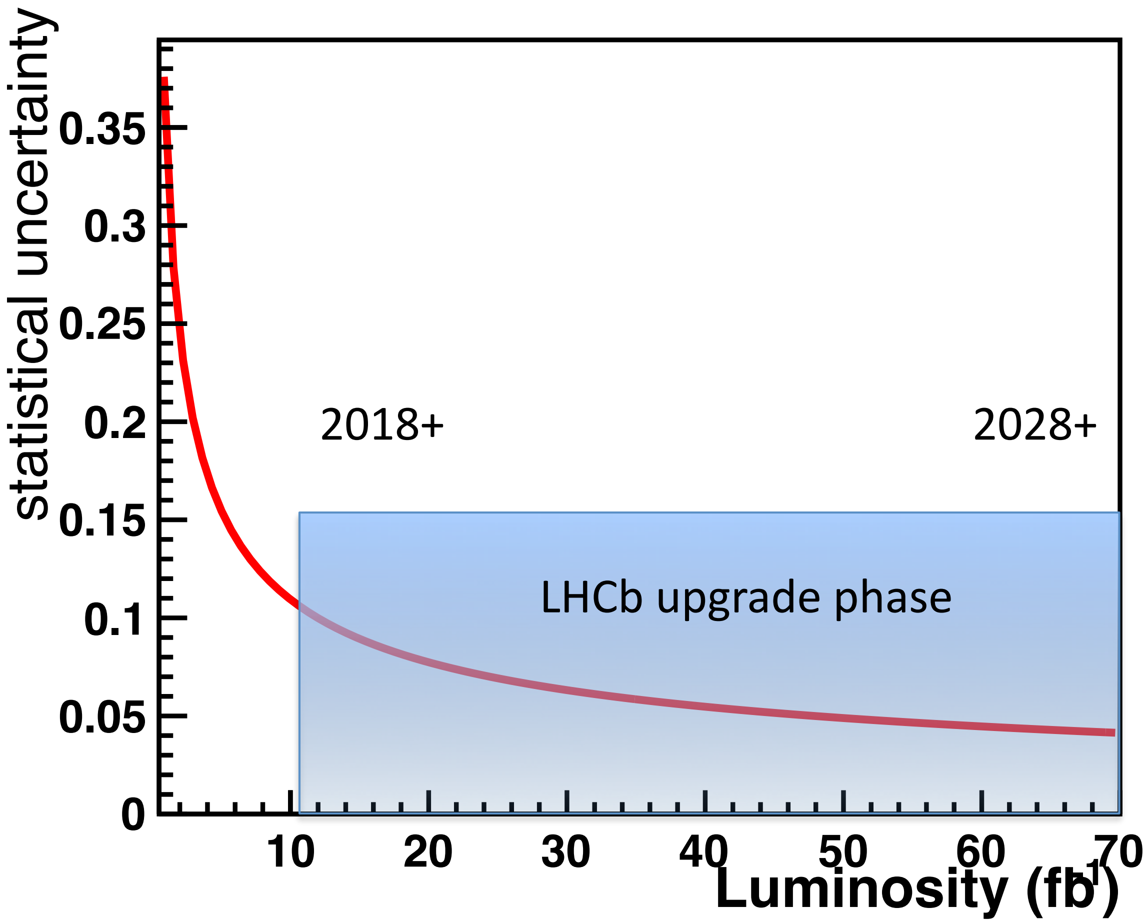






[stop mass already excluded at 700-800 GeV, gluino at 1.2 TeV]

For statistically limited measurements, the sensitivity to the NP mass grows as $1/\sqrt{\sigma}$ → as $1/N^{1/4}$ → Luminosity matters !

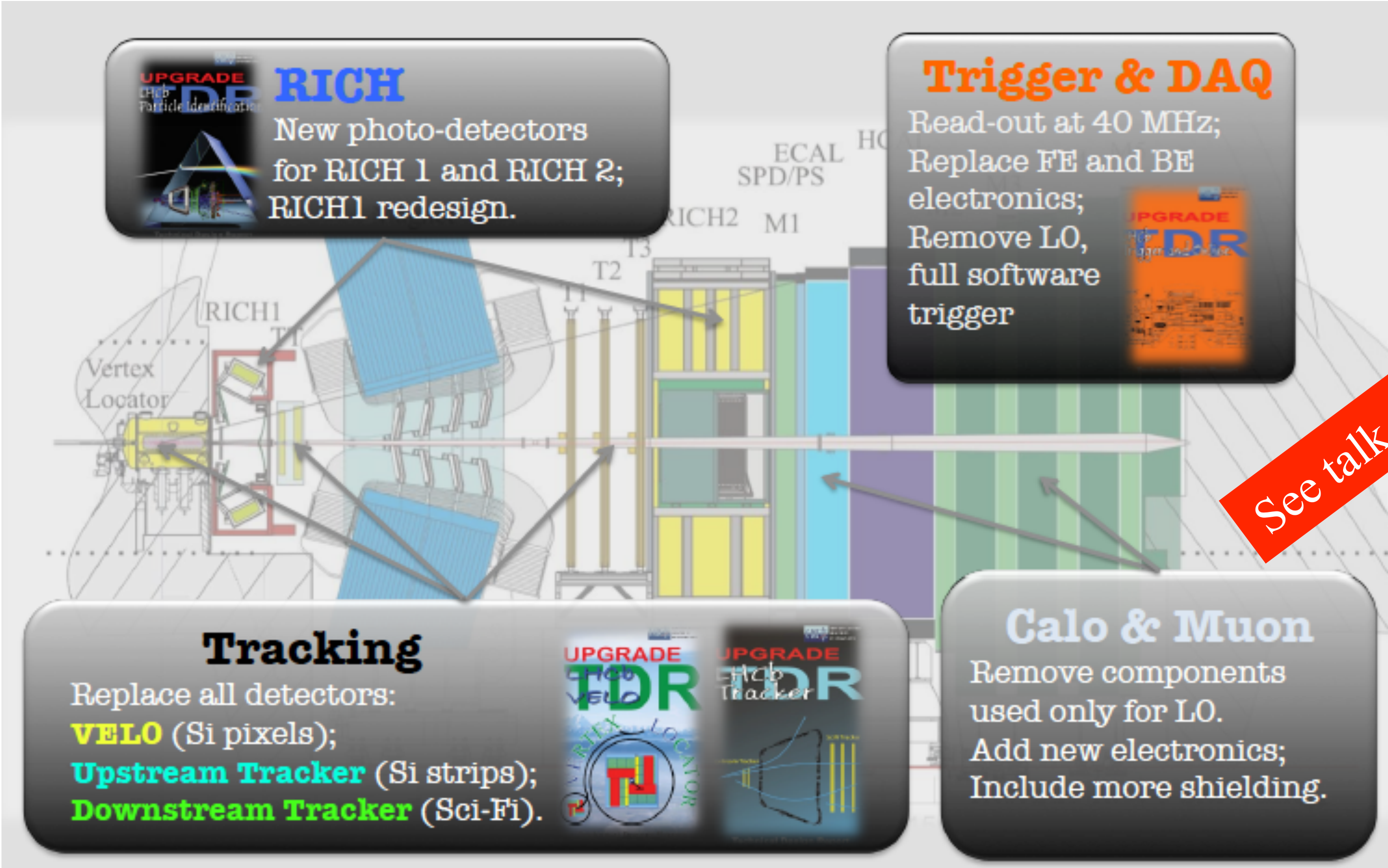


This is why we need to upgrade the detector…..

	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2020-22)	Run 4 (2025-28)	Run 5+ (2030+)
ATLAS, CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	⟶	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}

2018++: x 4

2030++: L x 20



See talk of A. Cardini

Type	Observable	LHC Run 1	LHCb 2018	LHCb upgrade	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\, \phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2%
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

Extrapolations assume:

- Scaling of accuracy with √L
- gain x2 for L0 removal for fully hadronic b-decays (a bit more for fully hadronic charm decays)
- same HLT efficiency, reconstruction, stripping, selection, PID efficiencies as in Run I
- same background contamination as in Run I.

Are we going to be dominated by systematic uncertainties?

LHCb (naïve) sensitivities in Run I, Run II and upgrade

Type	Observable	LHC Run 1	LHCb 2018	LHCb upgrade	Theory
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Right-handed	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
currents	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2 %
Electroweak	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
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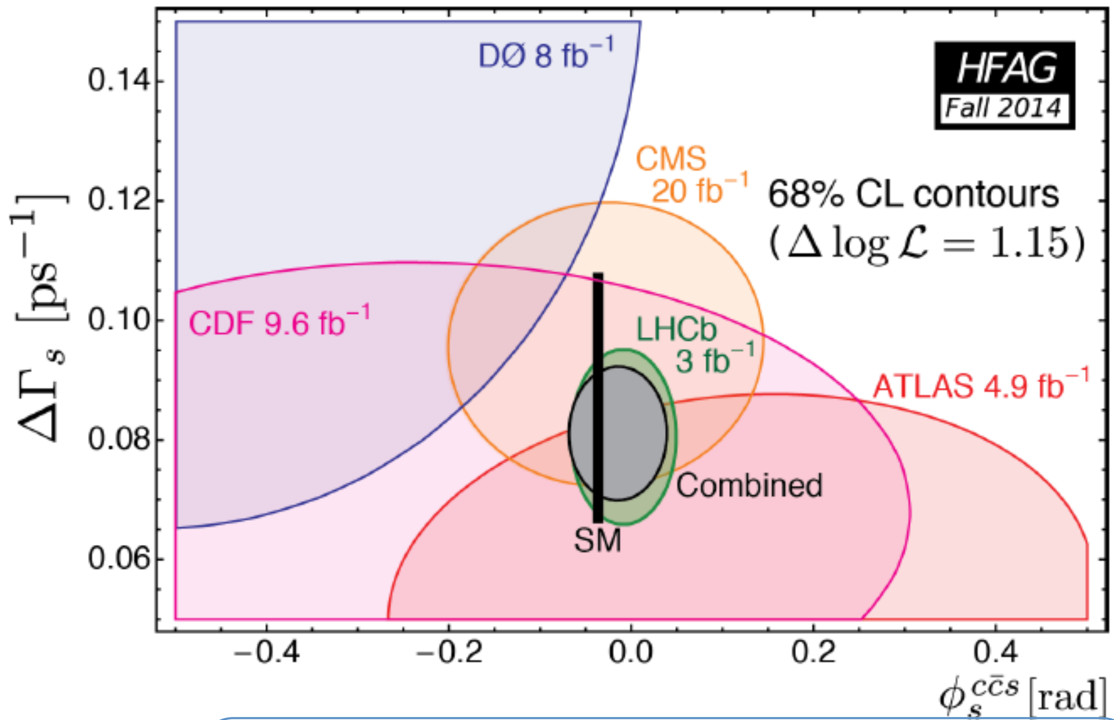
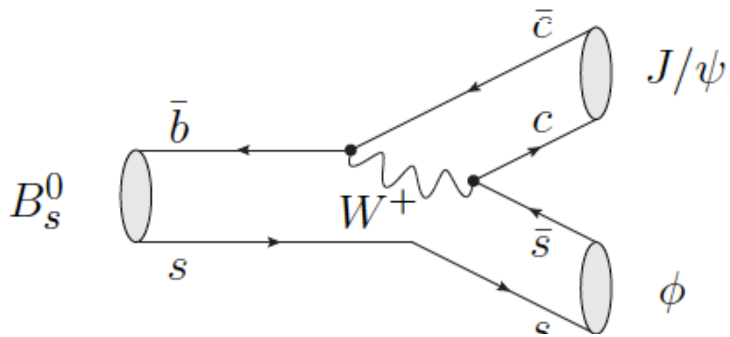
Unitarity	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
triangle	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	negligible
angles	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
CP violation	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

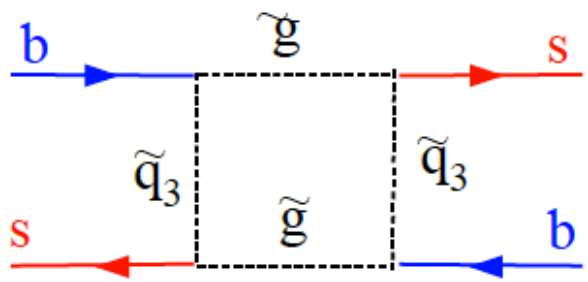
A closer look to ΔF=2 transitions

Mixing-induced CP violating phase ϕ_s: $B_s \to J/\psi KK$ & $B_s \to J/\psi\pi\pi$

LHCb, 3 fb-1, arXiv 1411.3104







World average: -15± 36 mrad
LHCb only: -10 ± 40 mrad
SM : 36 ± 2 mrad (Phys. Rev. D 84 (2011) 033005)

	$B_s^0 \to J/\psi K^+K^-$	$B_s^0 \to J/\psi \pi^+\pi^-$	Combined
ϕ_s[rad]	$-0.058 \pm 0.049 \pm 0.006$	$0.070 \pm 0.068 \pm 0.008$	-0.010 ± 0.039
$\lvert\lambda\rvert$	$0.964 \pm 0.019 \pm 0.007$	$0.89 \pm 0.05 \pm 0.01$	0.957 ± 0.017

Fully dominated by statistical uncertainty (x8 syst. uncertainty)

Breakdown of systematic uncertainties for ϕ_s in $B_s \rightarrow J/\psi KK$

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}]
Nominal stat. uncertainty	0.0027	$^{+0.0089}_{-0.0092}$	$^{+0.0050}_{-0.0048}$	$^{+0.0035}_{-0.0033}$	$^{+0.10}_{-0.17}$	$^{+0.14}_{-0.15}$	$^{+0.049}_{-0.050}$	0.019	$^{+0.055}_{-0.057}$
Angular resolution (scale factor)	1.001	1.003	1.007	1.002	1.013	1.009	1.003	1.003	1.006
Total stat. uncertainty	0.0027	$^{+0.0089}_{-0.0092}$	$^{+0.0050}_{-0.0048}$	$^{+0.0035}_{-0.0033}$	$^{+0.10}_{-0.17}$	$^{+0.14}_{-0.15}$	$^{+0.049}_{-0.050}$	0.019	$^{+0.055}_{-0.057}$
Mass factorisation	–	0.0007	0.0031	0.0064	0.050	0.05	0.002	0.001	0.004
sWeights (stat.)	0.0001	0.0008	–	0.0001	0.002	0.001	–	–	–
Resonant bkg	0.0001	0.0004	0.0004	0.0002	0.02	0.02	0.002	0.003	0.001
Ang. acc. (reweighting)	0.0001	–	0.0011	0.0020	0.01	–	0.001	0.005	0.002
Ang. acc. (stat.)	0.0001	0.0002	0.0011	0.0004	0.02	0.01	0.004	0.002	0.001
Time resolution	–	–	–	–	–	0.01	0.002	0.001	0.005
Trigger efficiency (stat.)	0.0011	0.0009	–	–	–	–	–	–	–
Track reconstruction (simul.)	0.0007	0.0029	0.0005	0.0006	0.01	0.001	0.001	0.001	0.006
Track reconstruction (stat.)	0.0005	0.0002	–	–	–	–	–	–	0.001
Length and mom. scales	0.0002	–	–	–	–	–	–	–	0.005
C_{SP} factors	–	–	–	–	0.01	0.01	–	0.001	0.002
Angular resolution bias	–	–	0.0006	0.0001	$^{+0.02}_{-0.03}$	0.01	–	–	–
B_c^+ background	0.0005	–	–	–	–	–	–	–	–
Fit bias	–	–	0.0005	–	–	0.01	–	0.001	–
Quadratic sum of syst.	0.0015	0.0033	0.0036	0.0067	$^{+0.063}_{-0.069}$	0.058	0.0055	0.0066	0.011
Total uncertainties	0.0031	0.0097	0.0061	0.0075	$^{+0.12}_{-0.18}$	$^{+0.15}_{-0.16}$	0.049	0.020	$^{+0.056}_{-0.058}$

Dominant systematic uncertainties:

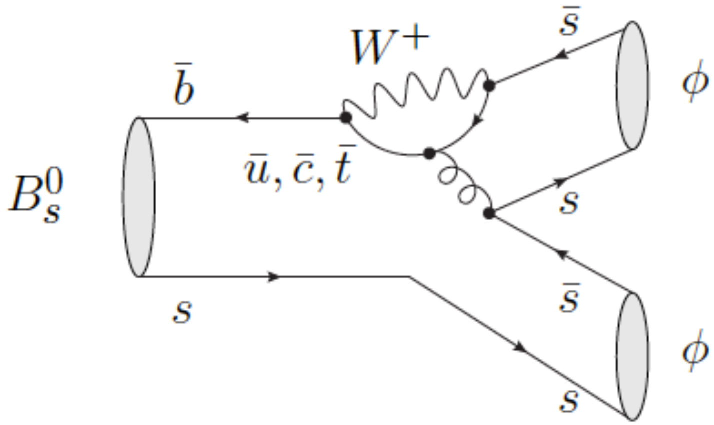
- ϕs: angular acceptance (MC stat dominated)
- Γs, $\Delta\Gamma$s: correction for VELO acceptance (tracking reconstruction) and trigger efficiency

→ This should be solved with the upgraded VELO and with the fully lifetime unbiased software trigger foreseen in the upgrade.

CPV phase in $B_s \to \phi\phi$:
[Phys. Rev. D20 (2014) 052011]

$B_s \to \phi\phi$ is a FCNC gluonic penguin decay:

- sensitive to CPV phase due to interference between mixing and decay
- phase close to zero in SM (upper limit: 0.02)
- sizeable enhancements due to NP are possible [hep-ph/0007328, arXiv:1212.6486v1].



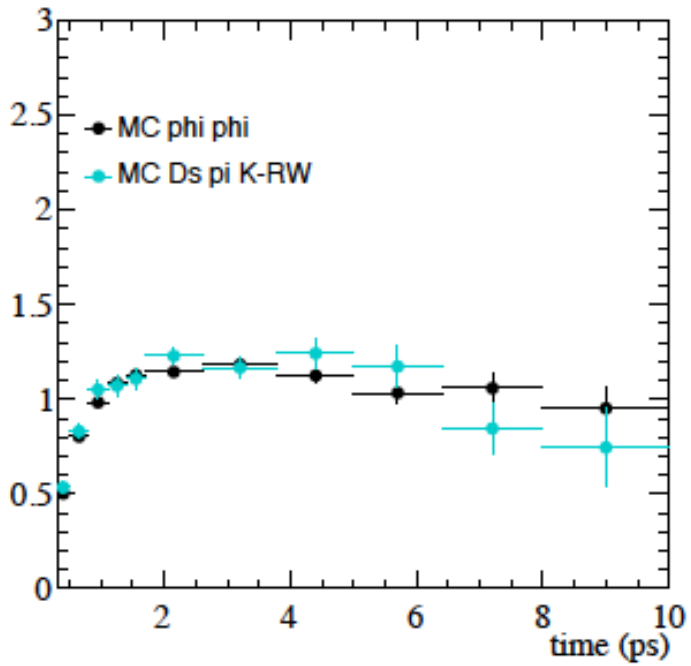
Result based on 3 fb^{-1}:

$$\phi_s = -0.17 \pm 0.15(stat) \pm 0.03(syst) \text{ rad}$$
$$|\lambda| = 1.04 \pm 0.07 \pm 0.03(syst)$$

Agreement with prediction, no evidence of CPV in decay or mixing

CPV phase in $B_s \rightarrow \phi\phi$:

[Phys. Rev. D20 (2014) 052011]



Parameter	Value	Stat. error	Syst. error
$\phi^{s\bar{s}s\bar{s}}$ rad	-0.17	0.15	0.03
λ	1.04	0.07	0.03
$\|A_0\|^2$	0.364	0.012	0.009
$\|A_\perp\|^2$	0.305	0.013	0.005
δ_1 rad	0.13	0.23	0.05
δ_2 rad	2.67	0.23	0.07
A_U	-0.003	0.017	0.006
A_V	-0.017	0.017	0.006

Systematic uncertainty dominated by the knowledge of the **angular acceptances** and **time acceptance** :

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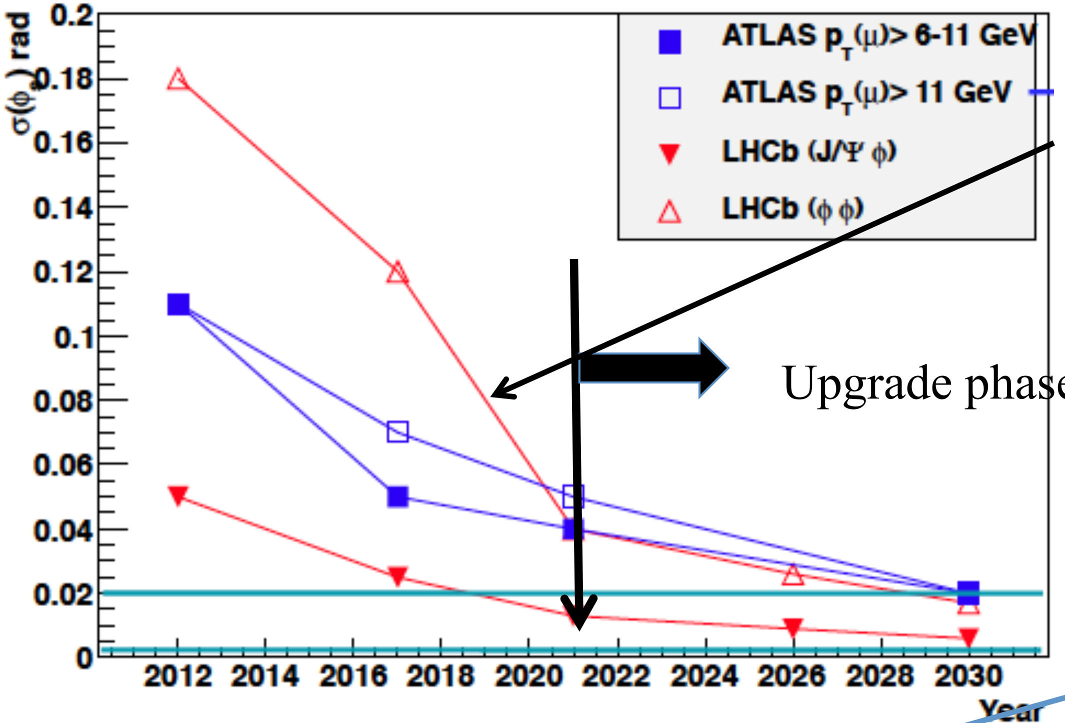
ϕ_s projections



Large enhancement of the yield expected for removal of the L0 trigger for Bs→φφ

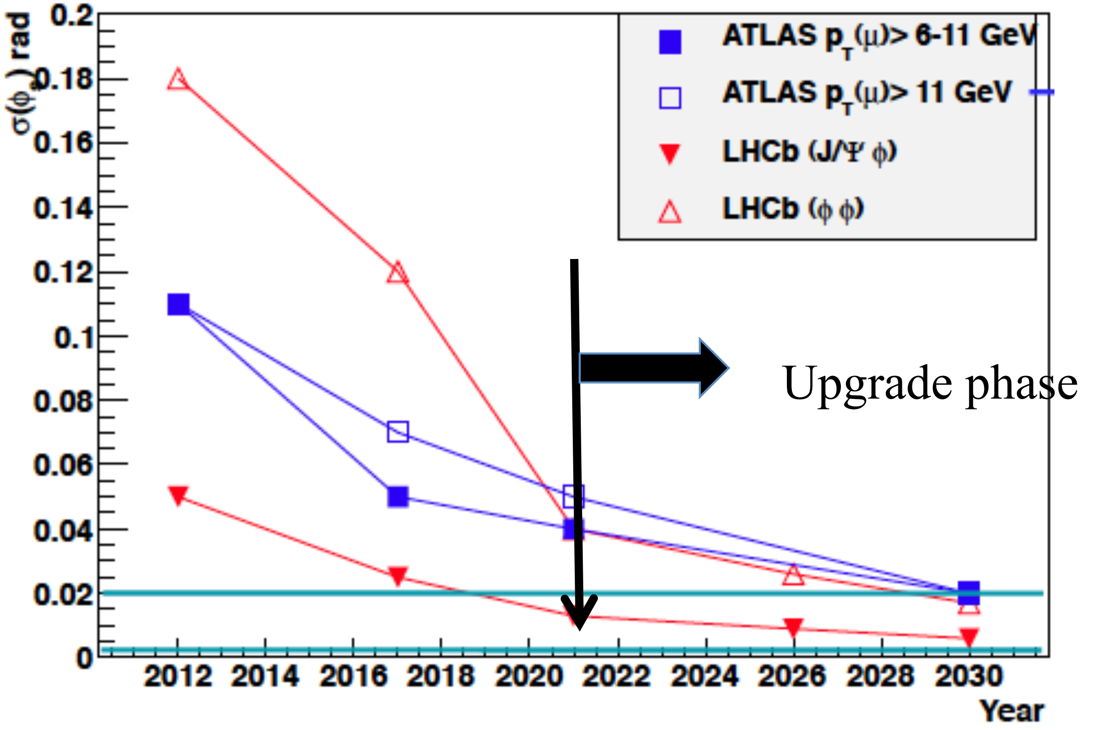
20-30% relative accuracy

	Run 1 (2010-12)	Run 2 (2015-17)	Upgrade 2030)	Theory
	3fb^{-1}	8fb^{-1}	50fb^{-1}	
$B_s^0 \to J/\psi K^+K^-$	0.05	0.025	0.009	$\sim$ 0.003
$B_s^0 \to J/\psi \pi^+\pi^-$	0.09	0.05	0.016	$\sim$ 0.001
$B_s^0 \to \phi\phi$	0.18	0.12	0.026	0.02

SM : 36 ± 2 mrad

A crucial ingredient is (and will be) the tagging efficiency and its knowledge
Crucial to control the penguin pollution [control modes rely on assumptions on SU(3) breaking corrections].

ϕ_s projections



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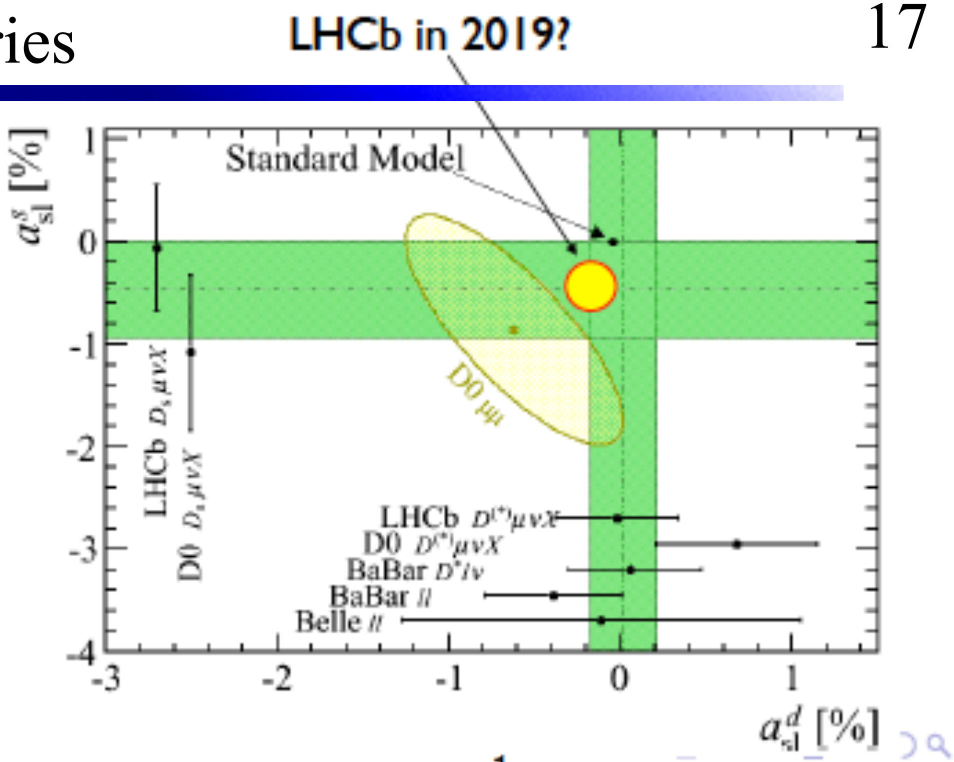
SM : 36 ± 2 mrad

$$\boxed{\frac{\Gamma(K_L^0 \to \pi^0 \nu\bar{\nu})}{\Gamma(K^+ \to \pi^+ \nu\bar{\nu})} = r_{is} \sin^2(\beta - \beta_s)}$$

will the kaon measurements be at the same level?

Mixing in Semi-leptonic asymmetries



$$a_{\rm sl} = \frac{\Gamma(\overline{B} \to B \to f) - \Gamma(B \to \overline{B} \to f)}{\Gamma(\overline{B} \to B \to f) + \Gamma(B \to \overline{B} \to f)}$$

- SM predictions [arXiv:1102.4274] are:
- $a^d_{\rm sl}$ (SM) $= (-4.1 \pm 0.6) \times 10^{-4}$
- $a^s_{\rm sl}$ (SM) $= (1.9 \pm 0.3) \times 10^{-5}$

So far, measured a^d_{sl} with $3\,{\rm fb}^{-1}$ [arXiv:1409.8586] and a^s_{sl} with $1\,{\rm fb}^{-1}$ [arXiv:1308.1048].

$$\boxed{\begin{aligned} a^d_{sl} &= -0.02 \pm 0.19(\text{stat}) \pm 0.30(\text{syst})\% \\ a^s_{sl} &= -0.06 \pm 0.50(\text{stat}) \pm 0.36(\text{syst})\% \end{aligned}}$$

Both consistent with SM

Here the systematic uncertainties matter!
Dominant systematics: detection asymmetry
Second dominant systematic for Bd is the B^+ production asymmetry

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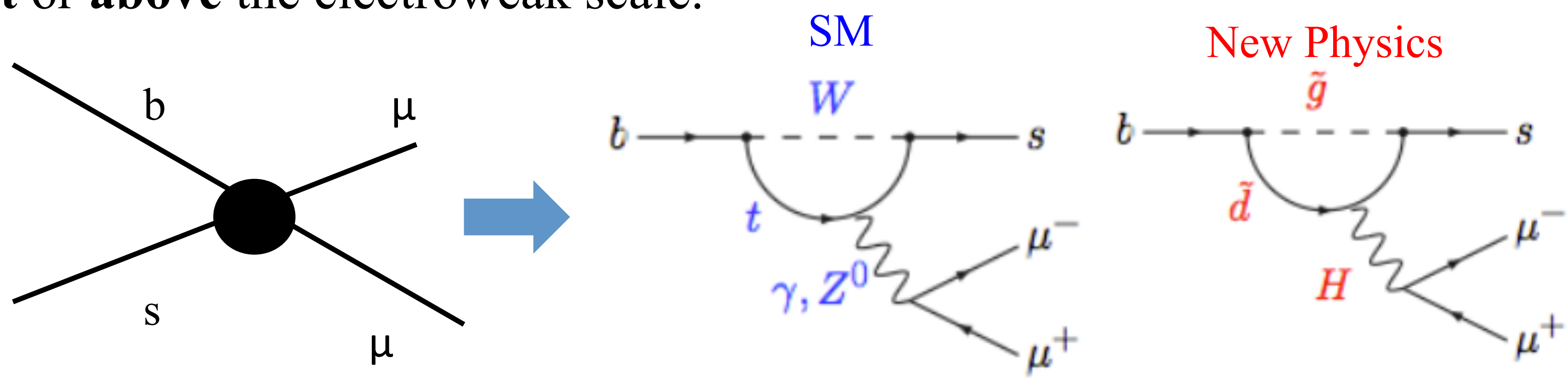
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\,A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	negligible
	$\beta(B^0 \to J/\psi\,K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

Let's move into the realm of the rare decays…

Rare decays: the beauty of EW- & Higgs- penguins

FCNC decays are an infinite source of information as they are sensitive to quantum corrections from degrees of freedom **at** or **above** the electroweak scale.



NP can modify the Wilson coefficients (C_i) affecting observable quantities as angular distributions in $B \to K^{(*)}\mu\mu$ decays (C_7,C_9,C_{10}), branching fractions in $B \to \mu\mu$ decays (C_s, C_p) and photon polarization (C'_7)

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

$i = 1,2$	Tree
$i = 3-6,8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9,10$	Electroweak penguin
$i = S$	Higgs (scalar) penguin
$i = P$	Pseudoscalar penguin

Constraints on New Physics from rare decays are looser than mixing

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

$i = 1,2$	Tree
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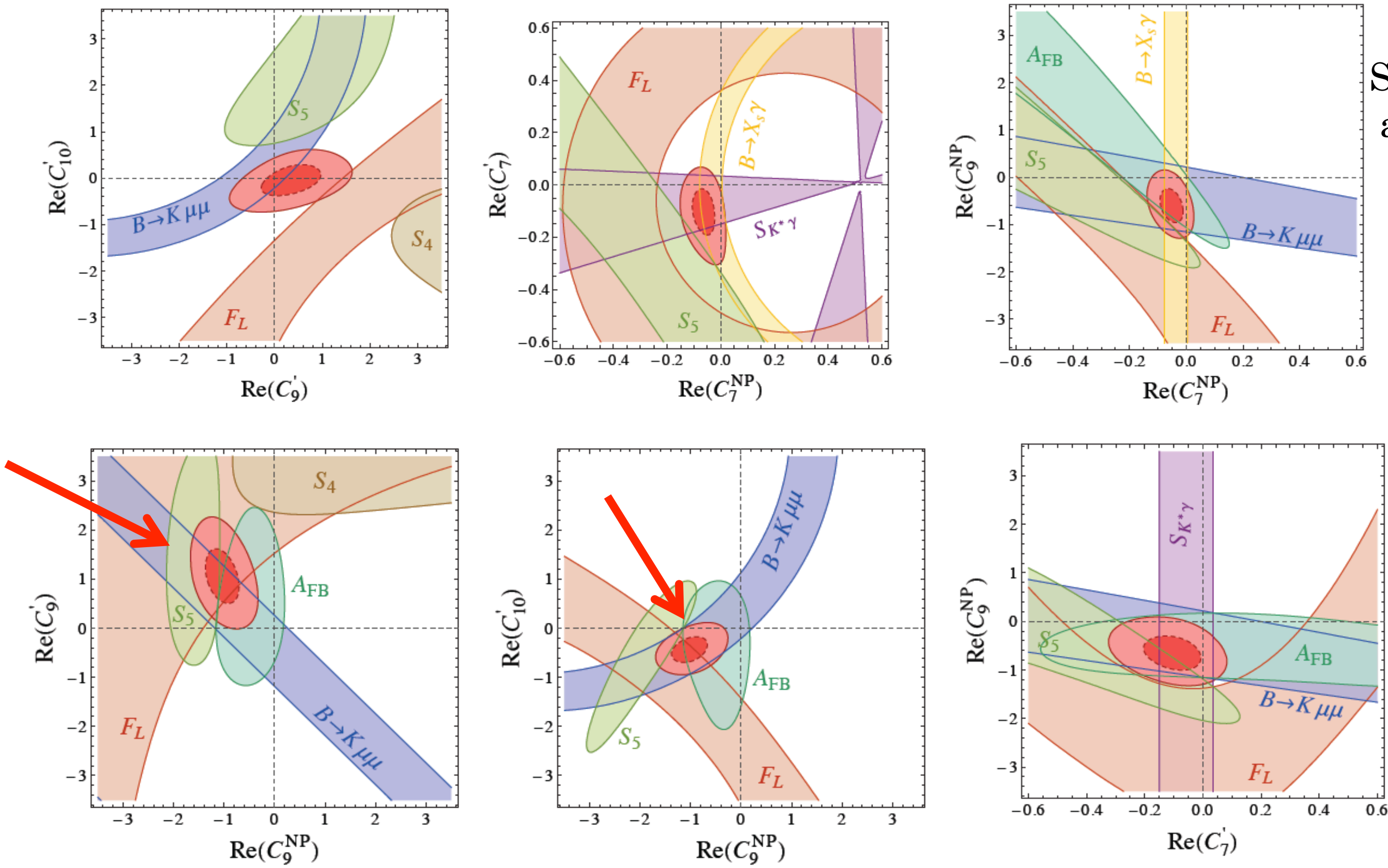
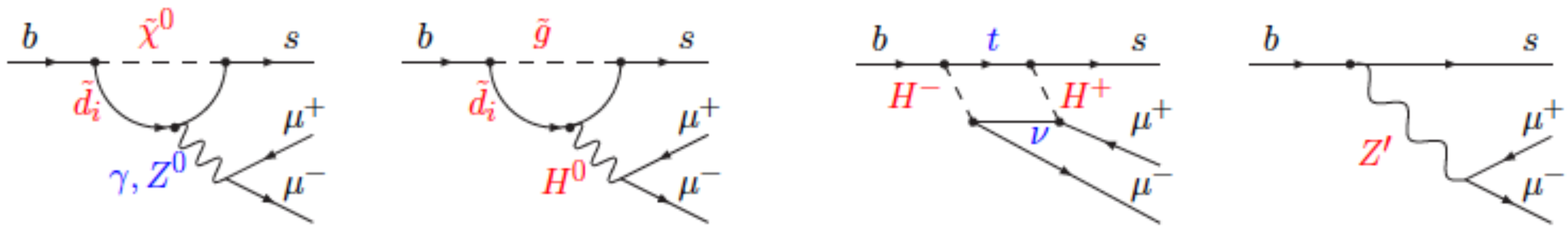


Straub, Altmannshofer arXiv:1308.1501

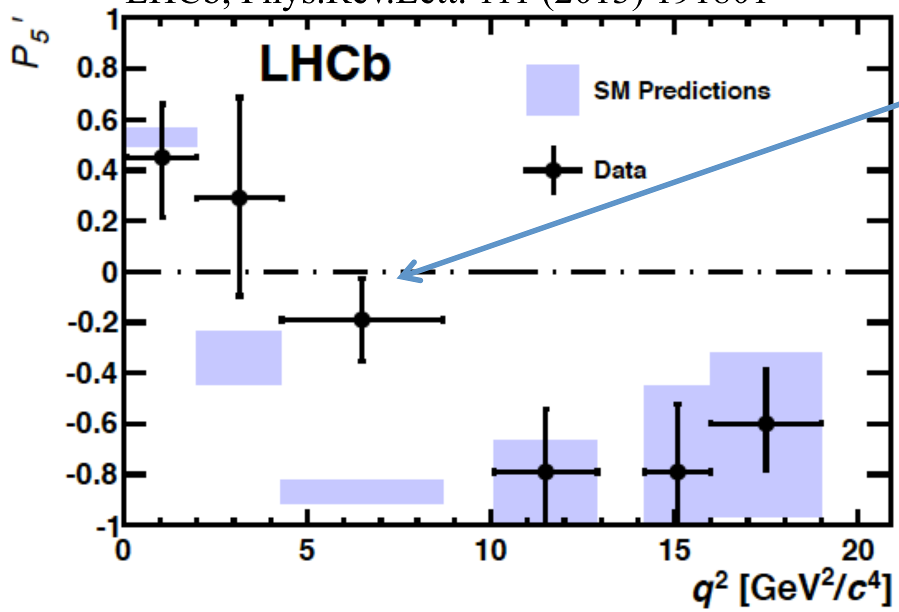
The C_i^{NP} are all compatible with zero (so far) but one $C_9^{(NP)}$

Puzzling deviations: P'_5 in $B_d \to K^*\mu\mu$

In 2013, the observation by LHCb of a tension with the SM in $B \to K^*\mu\mu$ angular Observables has received considerable attention from theorists and it was shown that the tension could be softened by assuming the presence of new physics (NP).



LHCb, Phys.Rev.Lett. 111 (2013) 191801



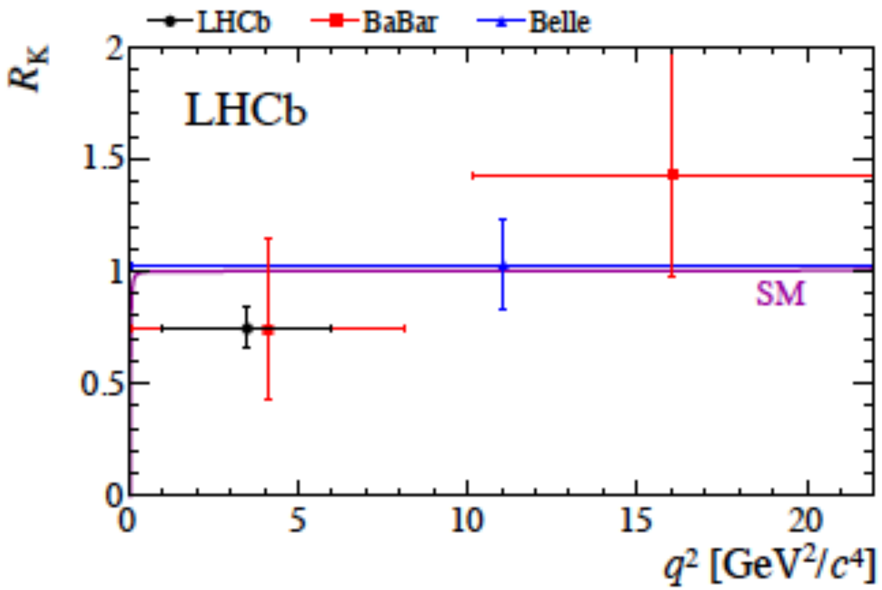
-3.7 σ discrepancy in the reqion $4.3 < q^2 < 8.68$ GeV^2/c^4

Can be explained by a negative NP contribution to the Wilson coefficient C_9, namely $C_9 = C_9(SM) - 1.5$

Descotes-Genon, Virto, Matias PRD 88 (2013) 074002
D. Van Dyck, C. Bobeth, F. Beaujean arXiv 1310.2478
Altmannshofer, Straub (arXiv 1308.1501)

Puzzling deviations: $R_k = BR(B^+ \rightarrow K^+\mu^+\mu^-)/BR(B^+ \rightarrow K^+e^+e^-)$

In 2014, another tension with the SM has been observed by LHCb, namely a suppression of the ratio R_K of $B^+ \rightarrow K^+\mu\mu$ and $B^+ \rightarrow K^+ e e$ branching ratios at low dilepton invariant mass → test of lepton universality



LHCb, PRL 113 (2014) 151601
Belle, PRL 103 (2009) 171801
Babar, PRD 86 (2012) 032012

In 3 fb^{-1} LHCb measures:

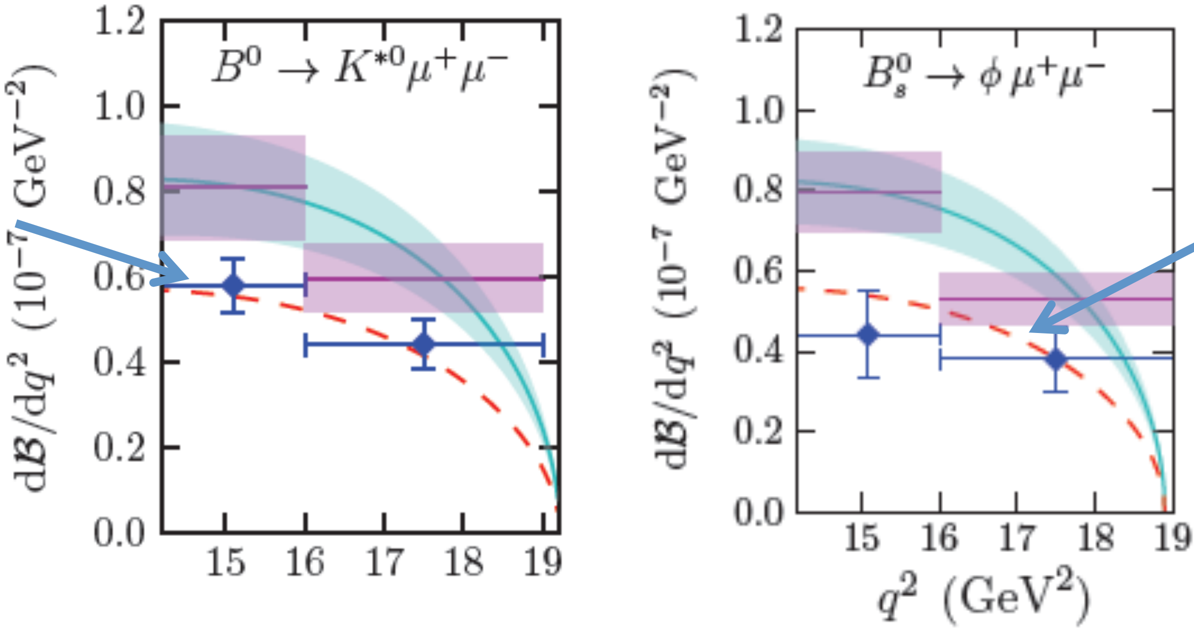
$$R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat})\,^{+0.036}_{-0.036}\,(\text{syst})$$

which is consistent with SM at 2.6 σ

Puzzling deviations: BR($B_d \to K^*\mu\mu$) and BR ($B_s \to \phi\mu\mu$)

Finally, also branching ratio measurements of $B_d \to K^*\mu\mu$ and $B_s \to \phi\mu\mu$ decays published recently seem to be too low compared to the SM predictions when using state-of-the art form factors from lattice QCD or light-cone sum rules (LCSR).

Zwicky et al,Phys.Rev. D71 (2005) 014029,
Horgan et al., Phys.Rev. D89 (2014) 094501
Horgan et al., Phys. Rev. Lett. 112 (2014) 212003



Average from LHCb, CDF, CMS and ATLAS

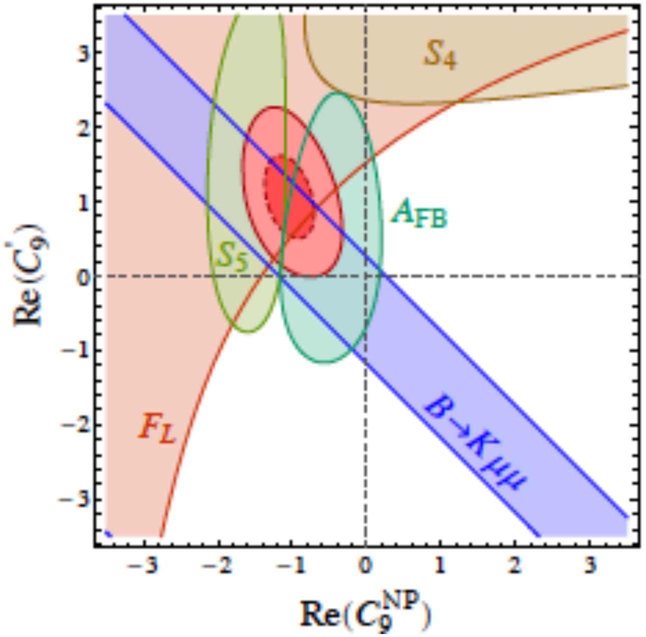
Average from LHCb, CDF

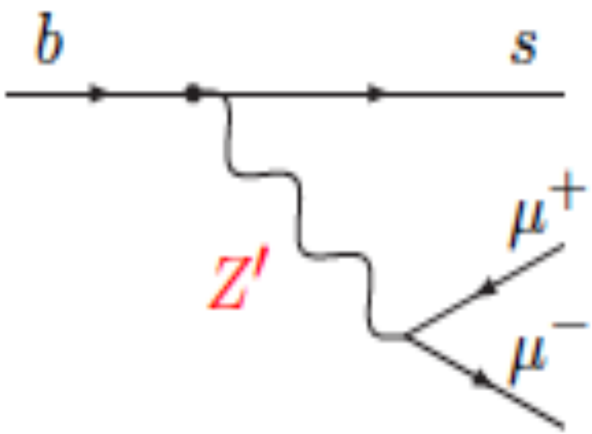
LHCb: JHEP 1406 (2014) 133, JHEP 1308 (2013)131, JHEP 1307 (2013) 084
CDF: Public note 10894, CMS: arXiv: 1308.3409 ATLAS: ATLAS-CONF-2013-038

Interpretation

Assuming new physics in B →K$^{(*)}$μμ only, a consistent description of these anomalies seems possible:

G. Hiller and M. Schmaltz, PRD90 (2014) 054014
D. Ghosh et al., arXiv:1408.4097 [hep-ph].
T. Hurth at al., arXiv:1410.4545 [hep-ph].
S. L. Glashow et al., arXiv:1411.0565 [hep-ph].





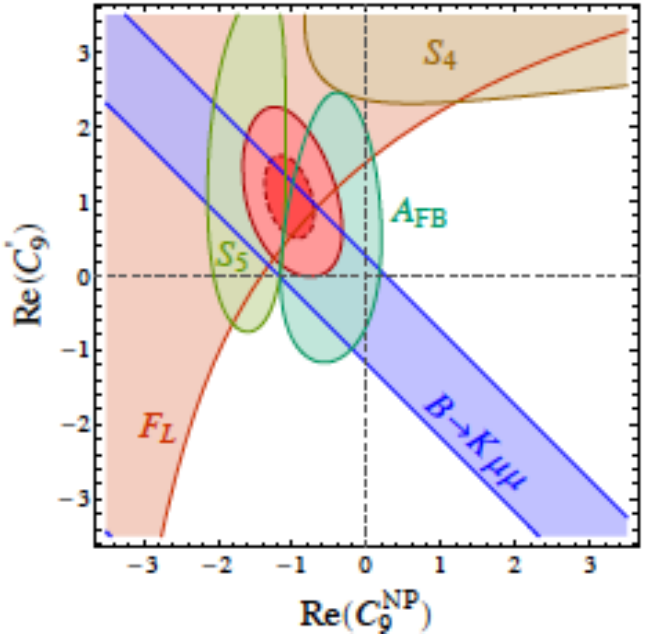
Difficult to explain data in SUSY scenarios
or using partial compositeness (why only $C_9^{(')}$?)
Data can be described using **Z' with flavour violating couplings**, but mass must be o(**7 TeV**)
to avoid direct limits and limits from mixing (Δms).

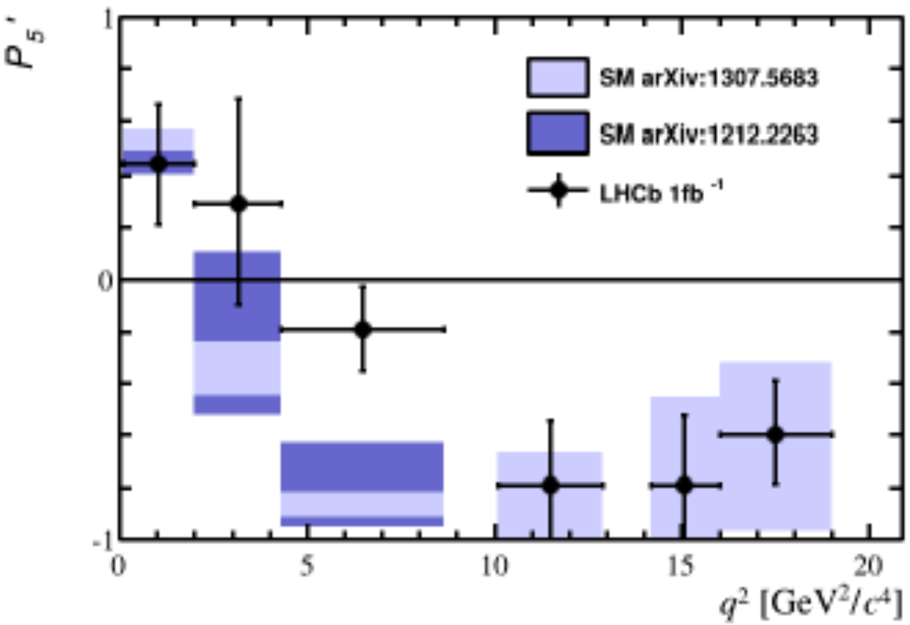
PS: NA62 will probe the same underlying physics with K → πνν decays

Interpretation

Assuming new physics in $B \rightarrow K^{(*)}\mu\mu$ only, a consistent description of these anomalies seems possible:

G. Hiller and M. Schmaltz, PRD90 (2014) 054014
D. Ghosh et al., arXiv:1408.4097 [hep-ph].
T. Hurth at al., arXiv:1410.4545 [hep-ph].
S. L. Glashow et al., arXiv:1411.0565 [hep-ph].



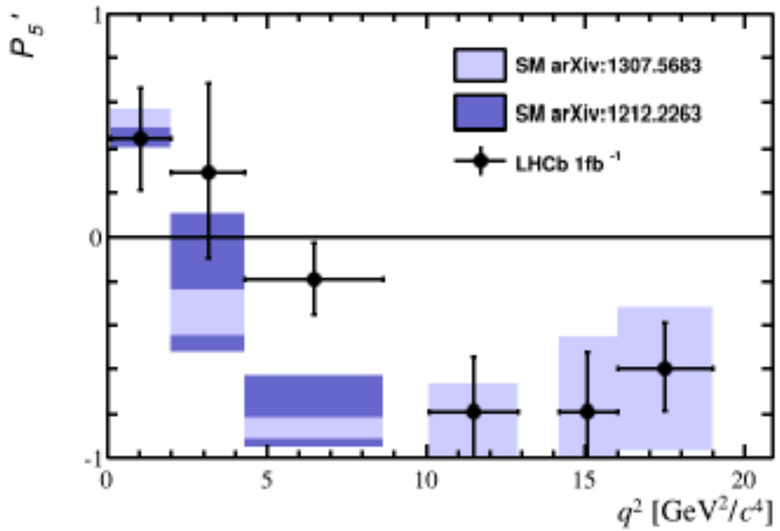


However, while R_K is theoretically extremely clean, predicted to be 1 to an excellent accuracy in the SM, the **other observables are plagued by sizable hadronic uncertainties**, [different treatments of (factorisable/non-factorisable) corrections can give large variation of P'_5]

Rare decays with ew-penguins: prospects

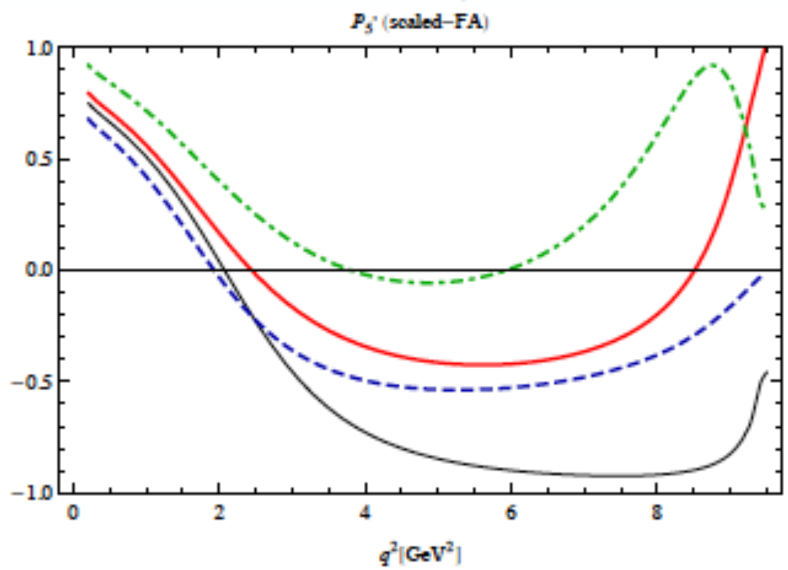
	$3\,\mathrm{fb}^{-1}$ (7+8 TeV)	2015	Run II	Upgrade
$B^0 \to K^{*0}\mu^+\mu^-$	2.6k†	$1.4 - 2.1$k	8.5k	34 k
$B^+ \to K^+\mu^+\mu^-$	4746 ± 81	$2.6 - 3.9$k	15.4k	61.6 k
$B^+ \to \pi^+\mu^+\mu^-$	100	$50 - 80$	320	1280
$B^+ \to K^+e^+e^-$ $(1 < q^2 < 6)$	256^{+25}_{-23}	$140 - 210$	830	3320

†with enlarged q^2 windows for $3\,\mathrm{fb}^{-1}$ analysis



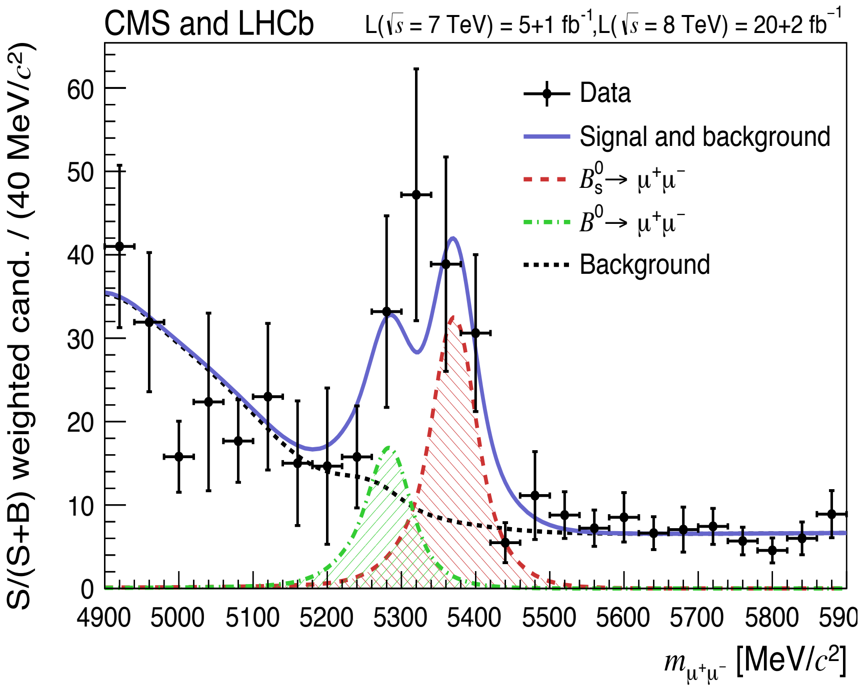
By 2028 the statistical uncertainty on each point will be reduced by a factor 3-4

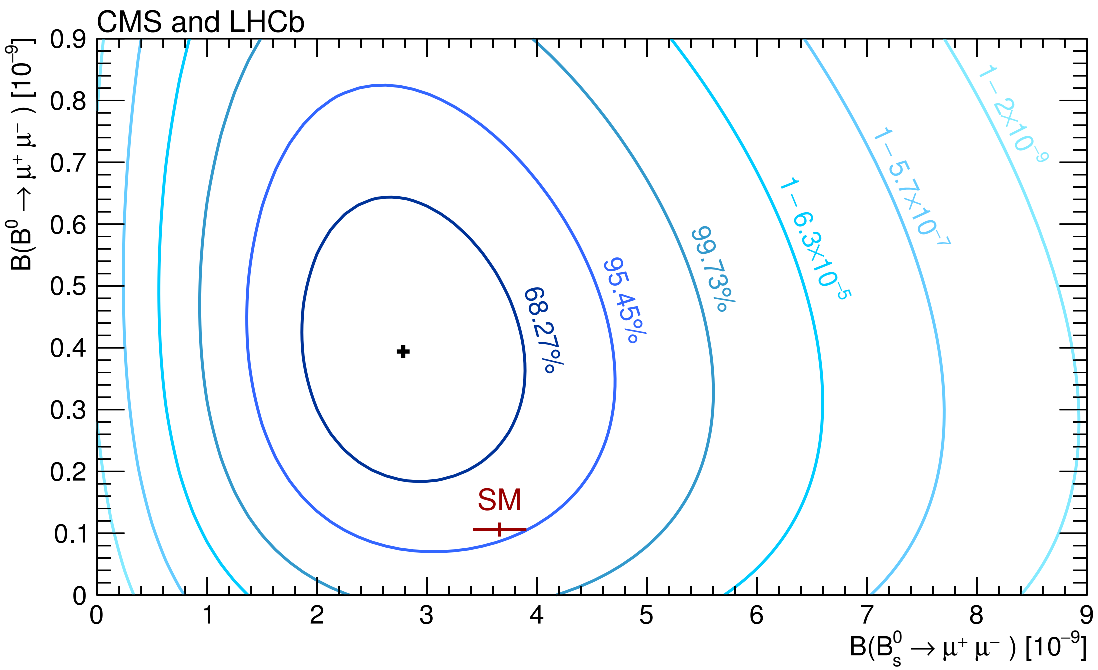
Zwicky & Lyon in [arXiv:1406.0566]

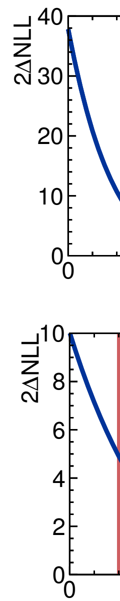


Will we be able to control the hadronic uncertainties at the same level?

Another puzzling deviation: BR($B_d \to \mu^+\mu^-$)







LHCb and CMS, arXiv:1411.4413

BR(Bd) = $(3.94\,^{+1.58}_{-1.41}\,^{+0.31}_{-0.24}) \times 10^{-10}$ 6.2σ observed (7.6σ expected)

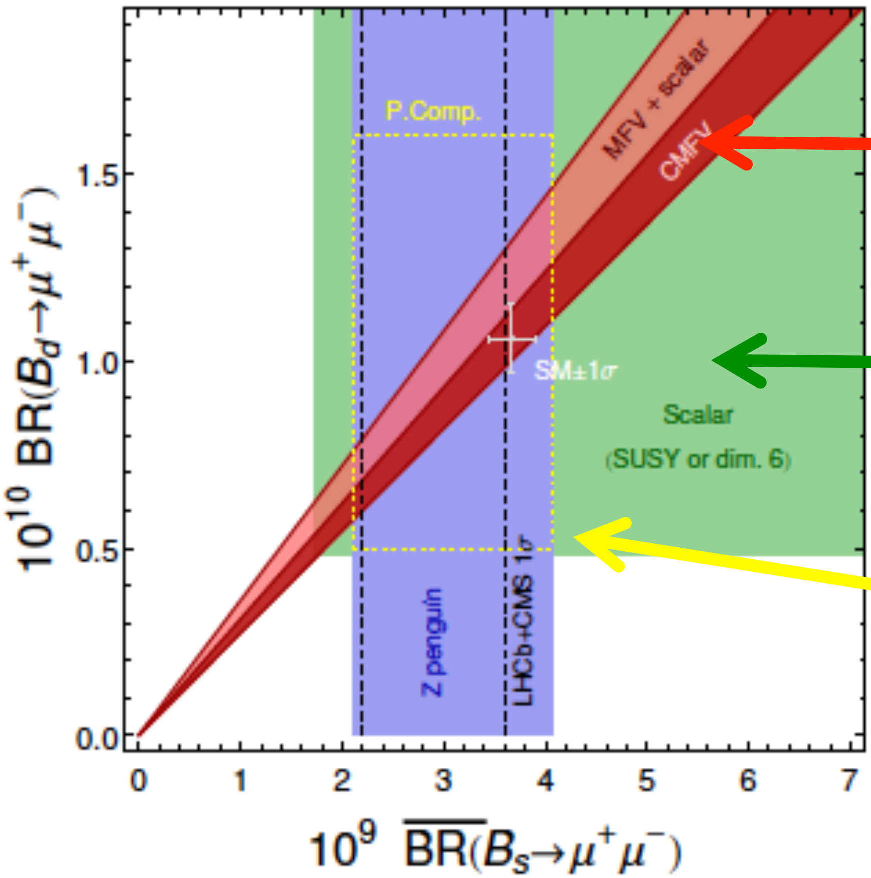
BR(Bs) = $(2.79\,^{+0.66}_{-0.60}\,^{+0.26}_{-0.19}) \times 10^{-9}$ 3.2σ observed (0.8σ expected)

BR($B_s^0 \to \mu^+\mu^-$) = (3.66 ± 0.23) x 10^{-9}
BR($B^0 \to \mu^+\mu^-$) = (1.06 ± 0.09) x 10^{-10}
← Theory: Bobeth et al, Phys. Rev. Lett. 112 (2014) 101801

Compatibility with the SM predictions: 2.2 σ for B^0 and 1.2 σ for B_s

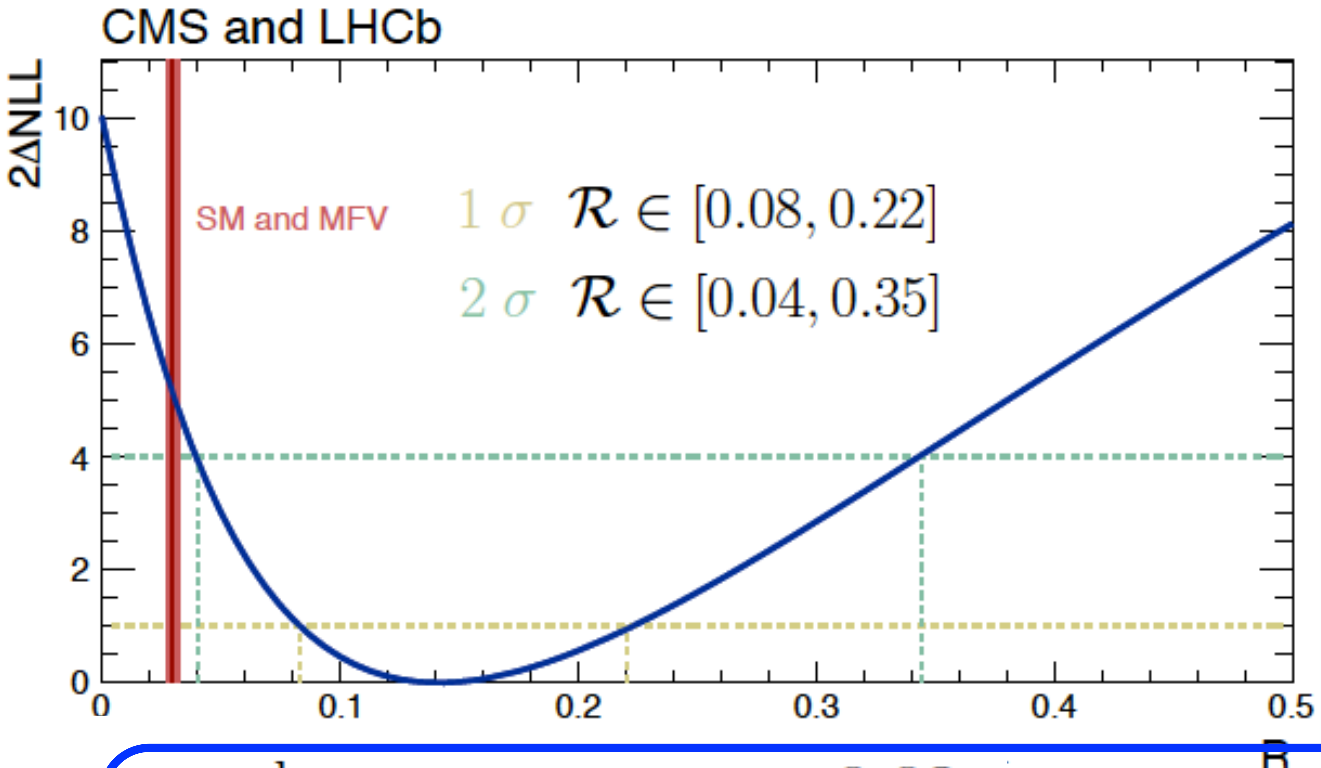
BR($B_d \to \mu^+\mu^-$) and BR($B_d \to \mu^+\mu^-$) in a model independent approach:

LHCb+CMS Bd
result out of scale



- $B_s \to \mu\mu$ vs. $B_d \to \mu\mu$: powerful test of Minimal Flavour Violation
- Beyond MFV: scalar operators (e.g. SUSY) unconstrained by other processes
- Z penguins beyond MFV: size constrained by $b \to s\ell^+\ell^-$ processes (notably $B \to K^*\mu^+\mu^-$)

$R = BR(B^0 \to \mu^+\mu^-)/BR(B_s^0 \to \mu^+\mu^-)$

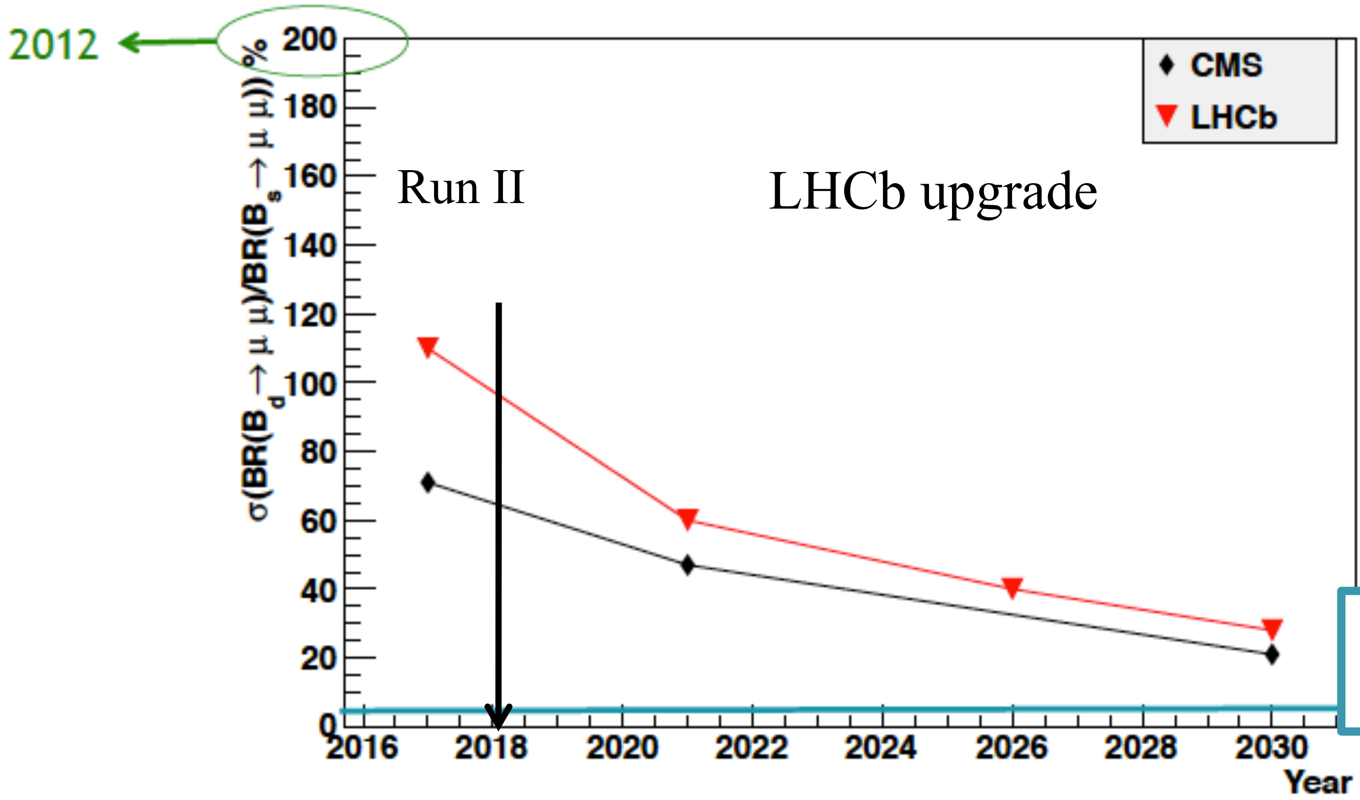


$$\mathcal{R} = 0.14^{+0.08}_{-0.06}$$

R (theory) = $0.0295^{+0.0028}_{-0.0025}$ (+8.7% - 7.7%)

Compatibility with the SM at 2.3 σ (including theoretical uncertainty)

Expected precision on R = $BR(B^0 \to \mu^+\mu^-)/BR(B_s^0 \to \mu^+\mu^-)$



σ_{theory} likely at 1-2 % level in 2030

Main limiting factor will be the control of the peaking backgrounds
(pure particle identification problem)

Are these extrapolations reliable ?

→ a look into the past (LHCb roadmap document, 2009)
→ a look into the future (LHCb upgrade TDRs, 2014)

A look into the past:

"Roadmap document": LHCb sensitivities pre data taking

Let's compare with the current results:

For φ_s from $B_s^0 \to J/\psi\,\phi$:

ROADMAP (2 fb^{-1} AT 14 TEV):

Expected 117 000 decays, B/S$\sim$ 2.1,

$\epsilon_{\text{tag}}(1-2\omega)^2 = 4.5\%$ and

$\sigma(\varphi_s) \sim 0.03$

DATA: We see 96 000 decays, B/S$\sim$ 5,

$\epsilon_{\text{tag}}(1-2\omega)^2 = 3.7\%$ and

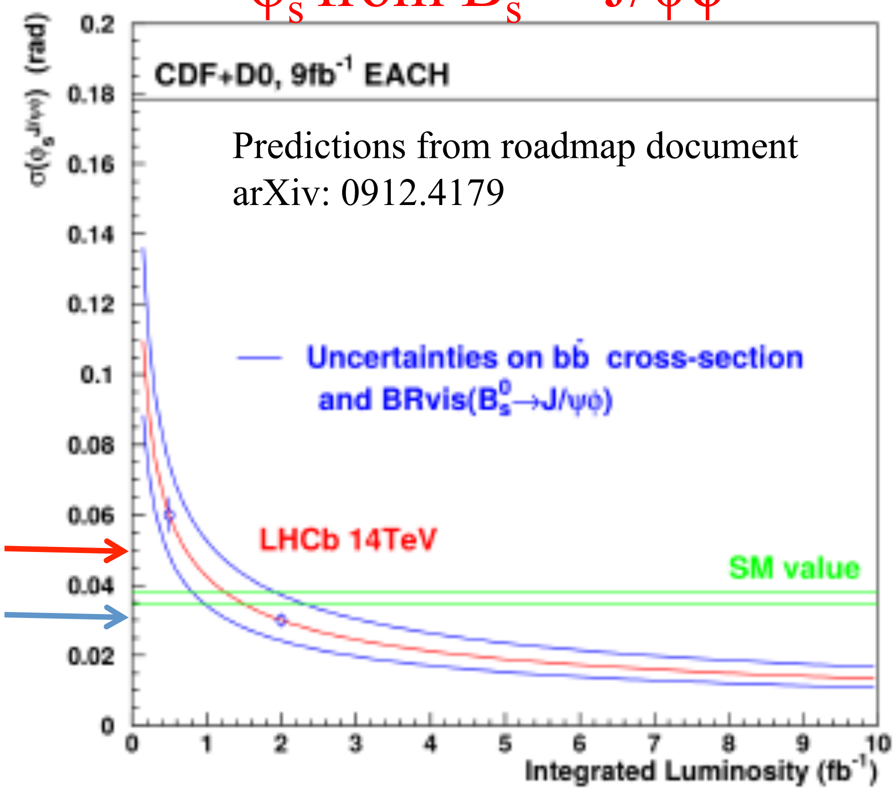
$\sigma(\varphi_s) \sim 0.049$

→ Not there yet

φ_s from $B_s \to J/\psi\phi$

data

MC



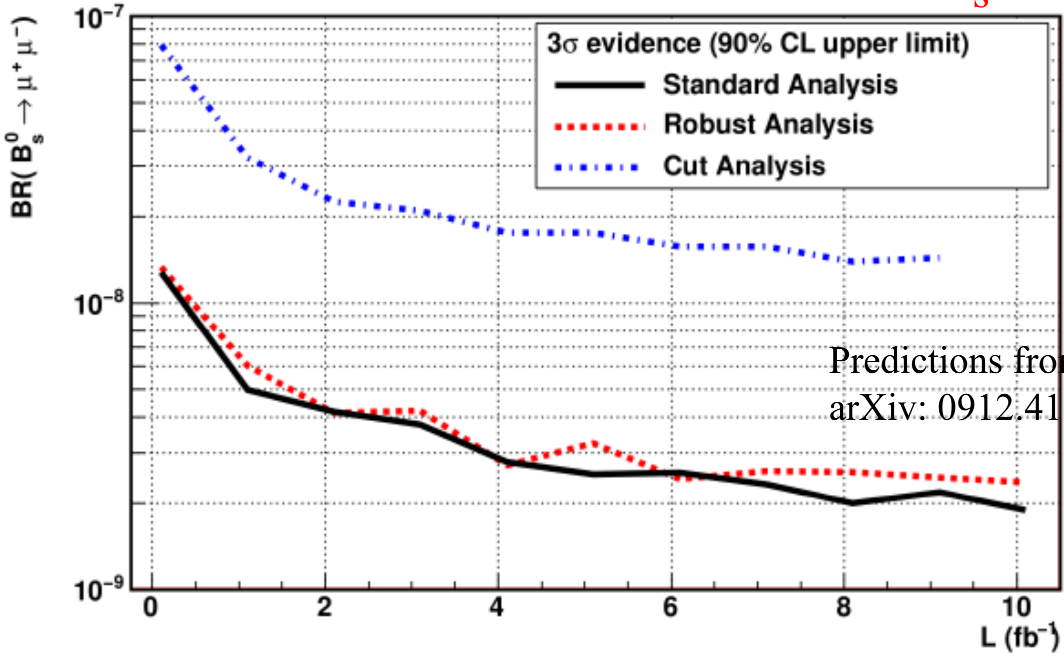
Slightly worse.

A look into the past:

“Roadmap document”: LHCb sensitivities pre data taking

Let’s compare with the current results:

3σ evidence for $B_s \rightarrow \mu\mu$



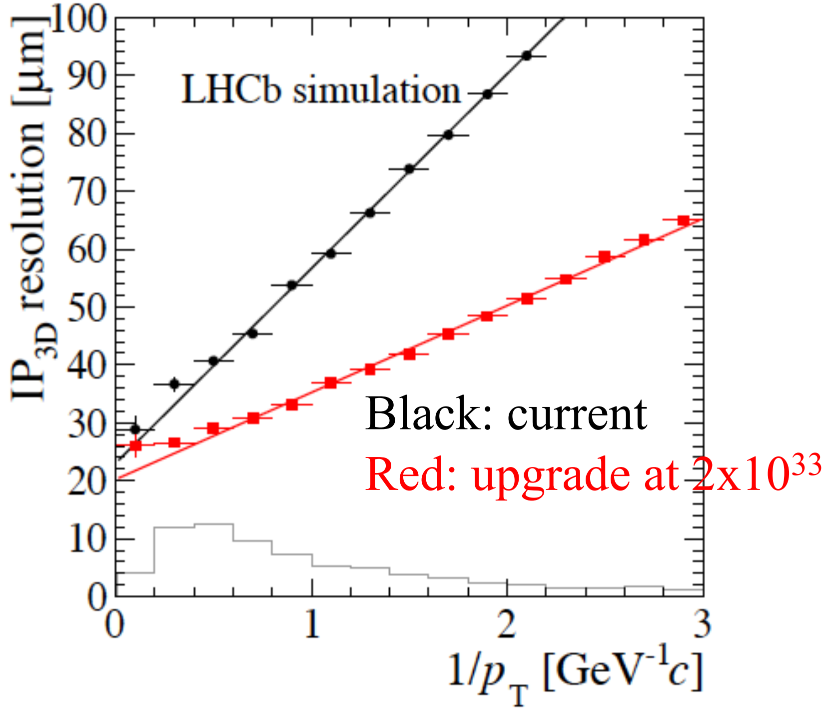
Predictions from roadmap document
arXiv: 0912.4179

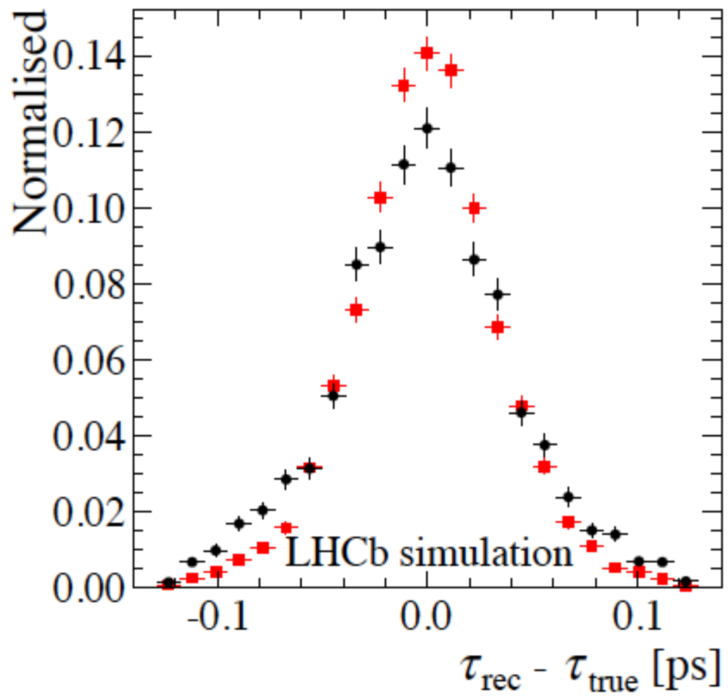
Roadmap: Expect 3 σ with 3 fb^{-1} @ 14 TeV
Data: We got 3σ with 2.1 fb^{-1} @ 7-8 TeV

Better.

A look into the future: performance of the upgraded VELO

VELO TDR, CERN-LHCC-2013-021





Much better IP resolution:

-Intercept is the RF foil thickness,

- slope is due to multiple scattering

Similar time resolution (~ 50 fs)

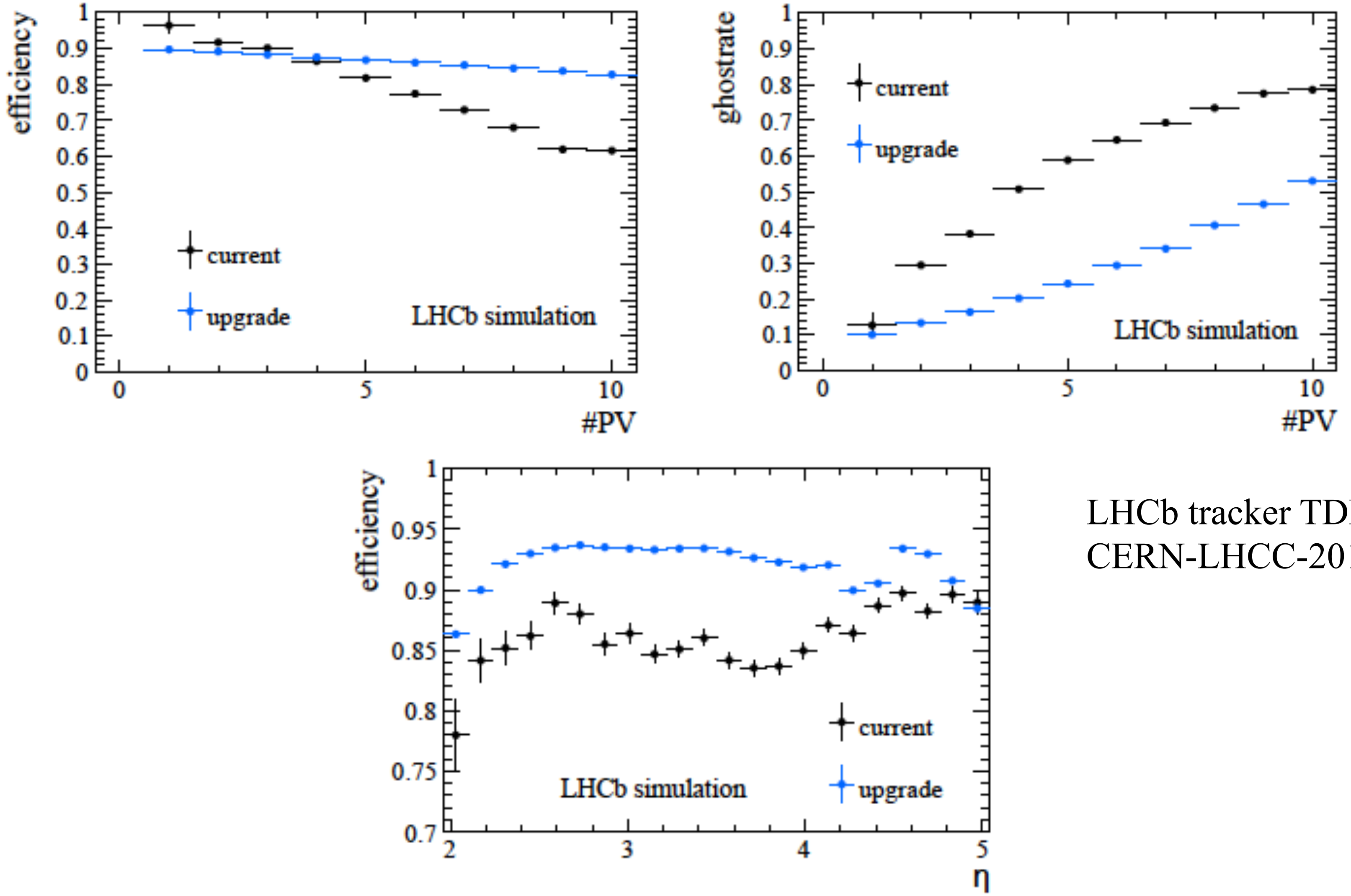
- important for the dilution factor

$D = \exp(-\sigma^2_t\, \Delta m^2/2)$ for B_s CP asymmetries

The upgraded VELO will be a major asset for the LHCb upgrade

A look into the future: performance of the upgraded SciFi tracker

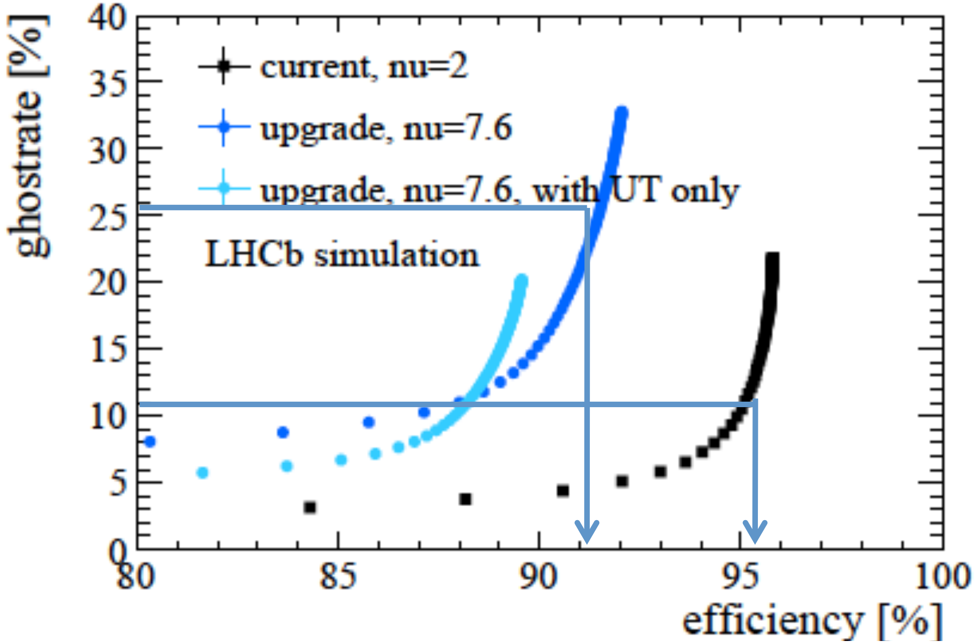
The current tracker would never be able to stand in the upgrade conditions….



LHCb tracker TDR
CERN-LHCC-2014-001

A look into the future: performance of the upgraded SciFi tracker

….However the upgrade tracker in the upgrade conditions will have worse performance than the current tracker in the current conditions

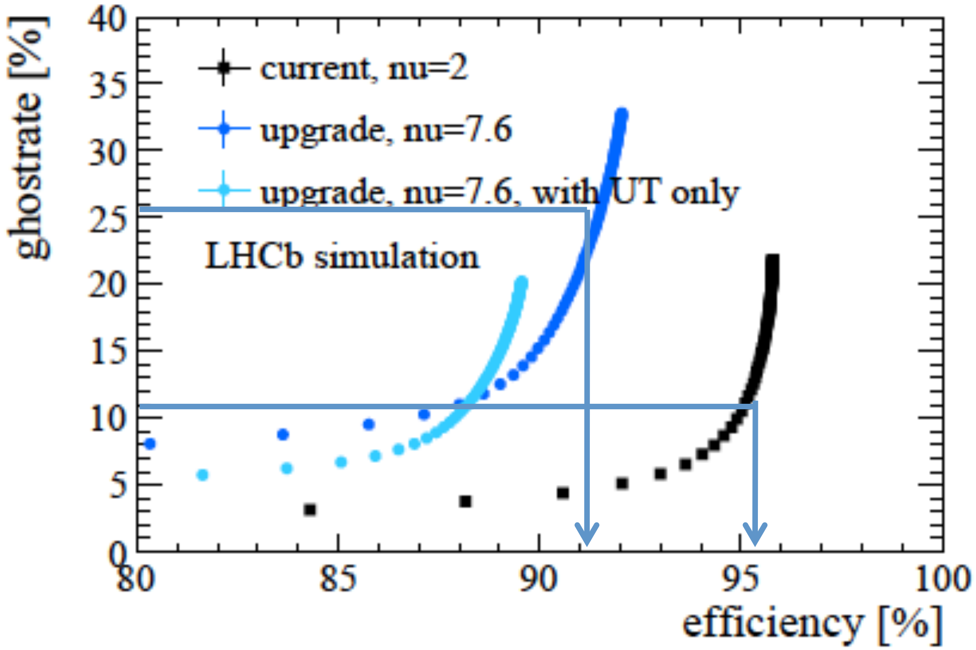


LHCb tracker TDR
CERN-LHCC-2014-001

	Current LHCb [%]	Upgrade LHCb [%]	
	$\nu = 2$	$\nu = 3.8$	$\nu = 7.6$
Ghost rate	13.1	14.7	25.5
Reconstruction efficiency			
long	90.9	86.9	84.5
→ long, $p > 5\,\mathrm{GeV}/c$	95.4	92.9	91.5
b-hadron daughters	93.9	91.9	90.6
→ b-hadron daughters, $p > 5\,\mathrm{GeV}/c$	96.1	95.1	94.2

A look into the future: performance of the upgraded SciFi tracker

….However the upgrade tracker in the upgrade conditions will have worse performance than the current tracker in the current conditions



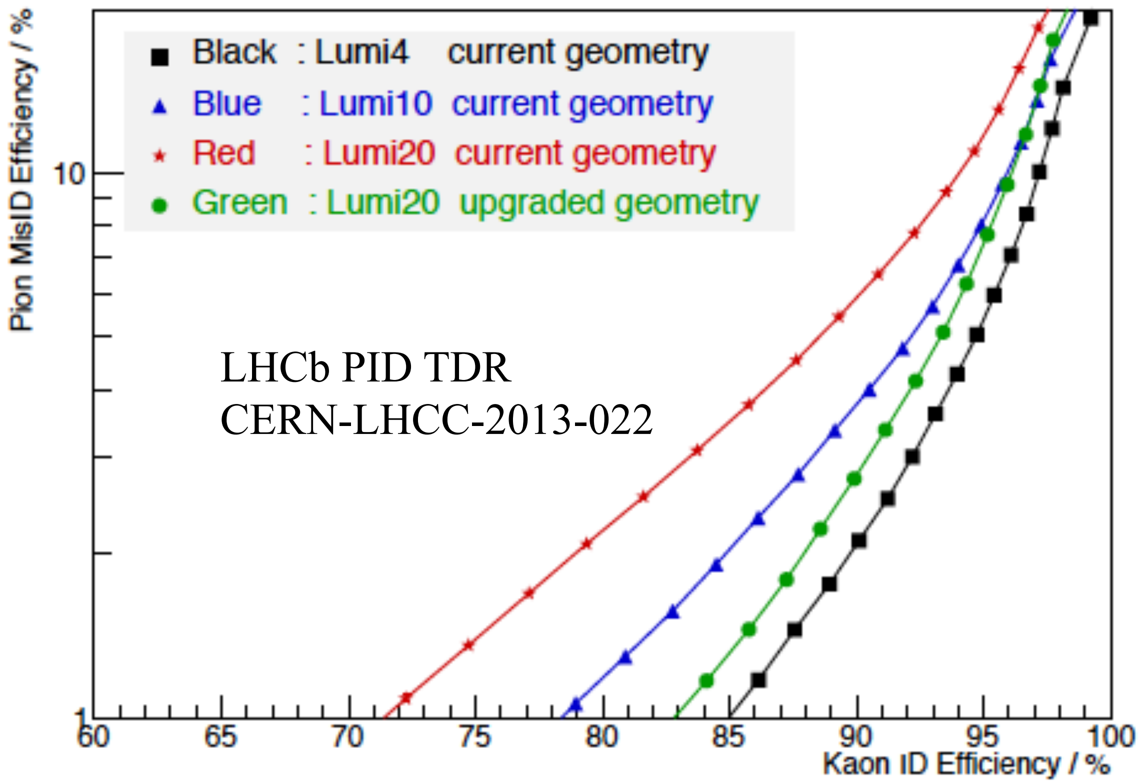
LHCb tracker TDR
CERN-LHCC-2014-001

Long tracks, p>5 GeV:
→ loss of 4% (5-6%) for double (same) ghost rate for generic long tracks (charm, strange..)
→ loss of 2% (3-4%) for double (same) ghost rate for long tracks from b decays (high pt)

Hence: loss of 8-16% in four body decays ($B_d \to K^* \mu\mu$, $B_s \to J/\psi\, \phi$, $B_s \to \phi\phi$, etc.)

A look into the future: performance of the upgraded RICH system

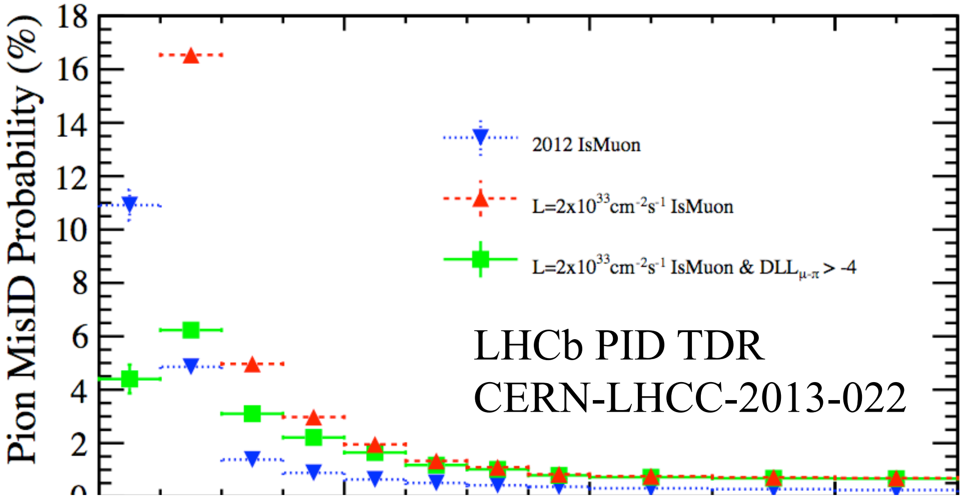
Upgraded RICH system in principle is able to recover the performance of Run I

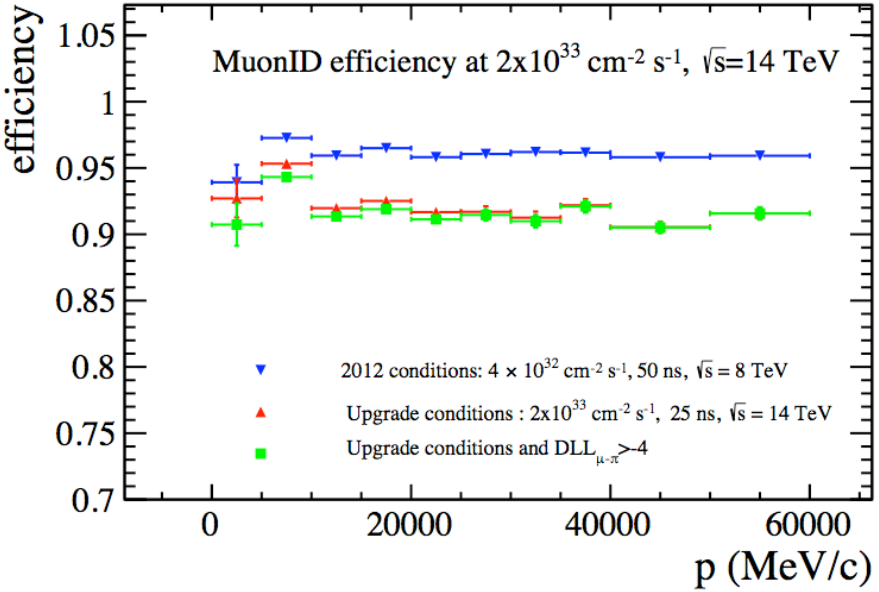


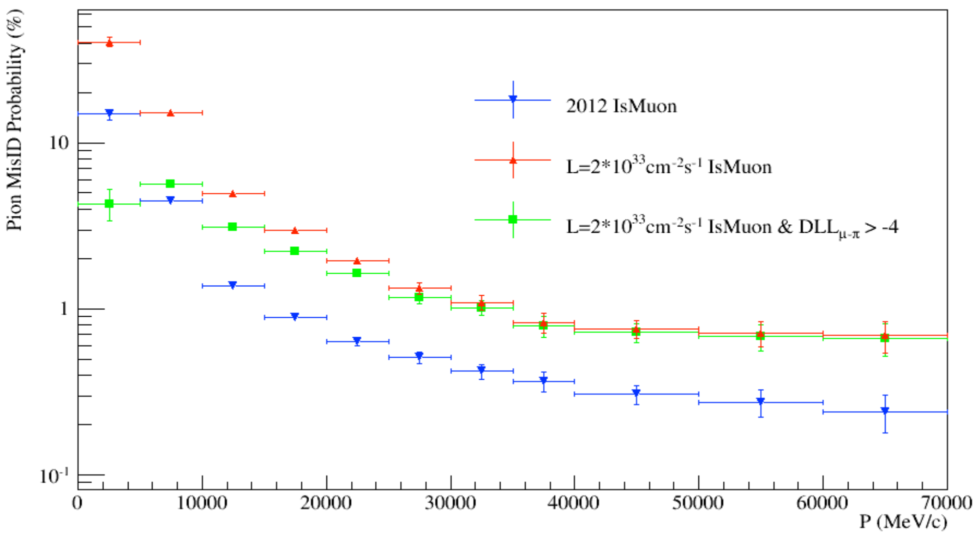
[However any increase of hits multiplicity with respect to current simulation can change the results – and we know that the LHCb MC is not tuned (we measured +40% hits in calorimeters with respect to simulation in Run I)]

A look into the future: performance of the MUON system

MuonID performance: pion misidentification and muon efficiency in the upgrade





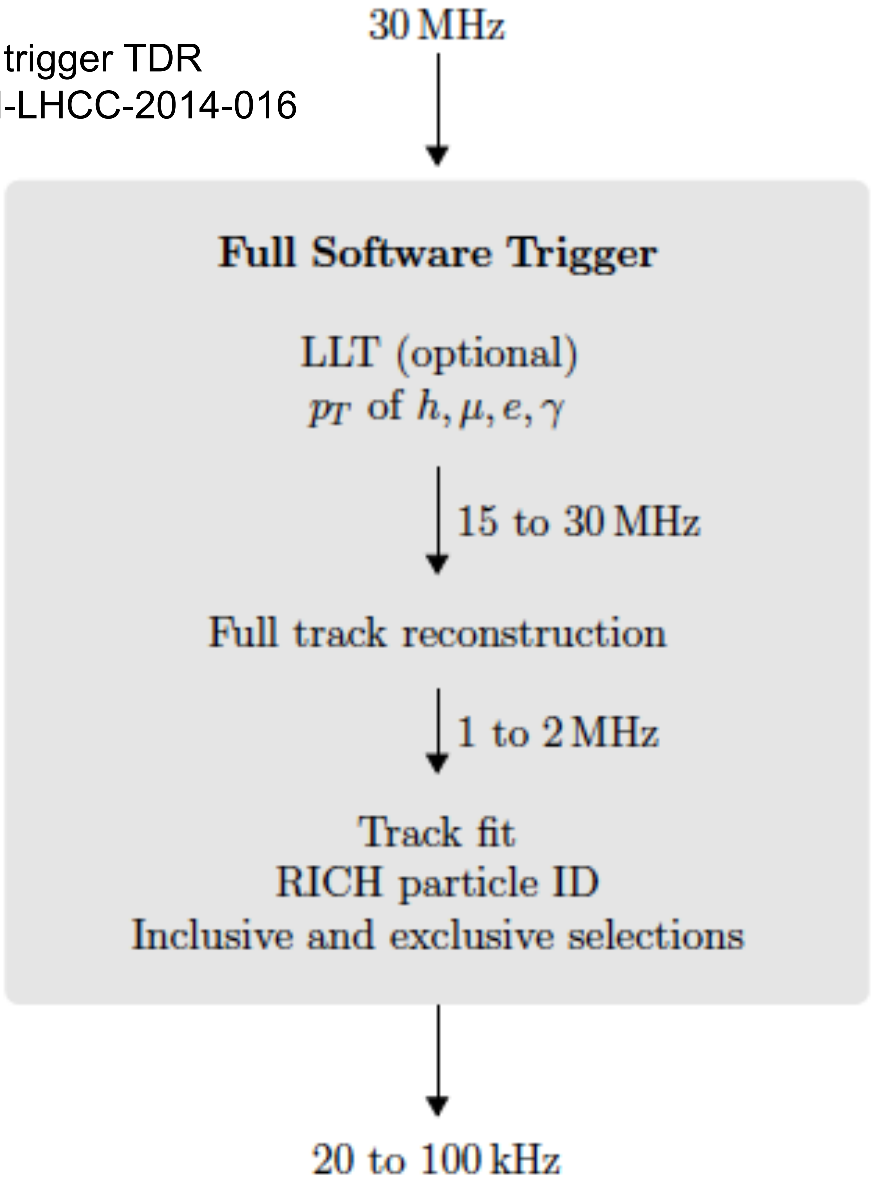


Extrapolations from data hence more reliable:
- 5 % efficiency/ track
- x 2 more background/per track

But no safety factor included.

The upgrade trigger: the name of the game

LHCb trigger TDR
CERN-LHCC-2014-016



The numbers from the LHC:
30 MHz of primary interactions, pile-up=7.6
3 b's, 12 c's and 41 s per 100 BX

Output rate:
270 (b), 800 (c), 260 (s) kHz of events
in LHCb acceptance with mild cuts
(p_T>2 GeV, tau>0.2 ps)

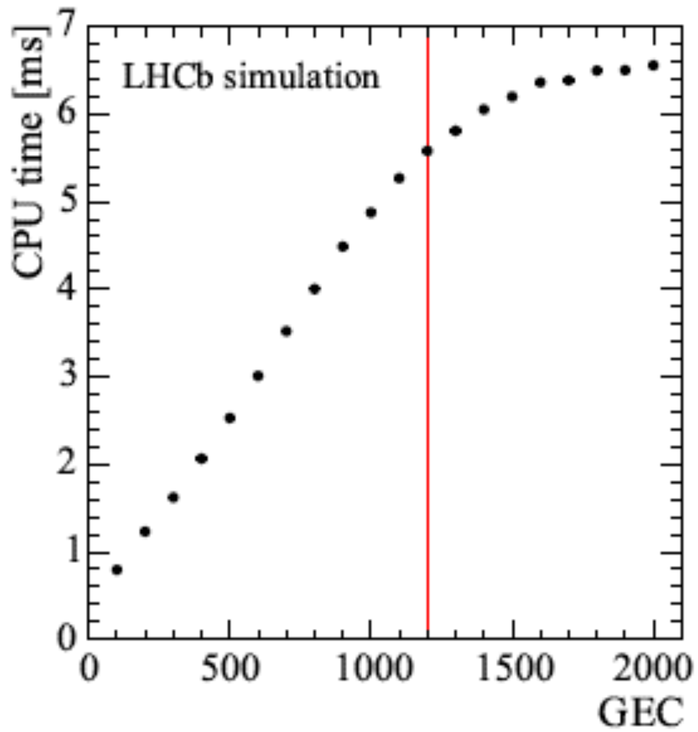
The numbers from the upgrade:
money secured to build a farm:
- 13 ms /event @ 30 MHz time budget
- 20 kHz, 2 GB/s output rate

A very challenging project

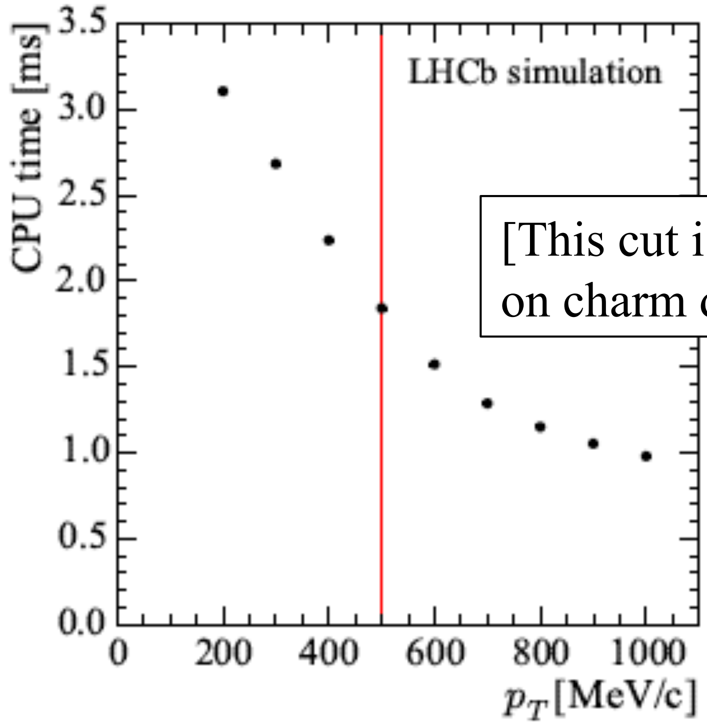
The upgraded trigger: the name of the game

Time budget: 13 ms/event [(*)] @ 30 MHz
Tracking possible only applying global event cuts and p_T cuts:

LHCb trigger TDR
CERN-LHCC-2014-016



(a) Trigger time versus GEC



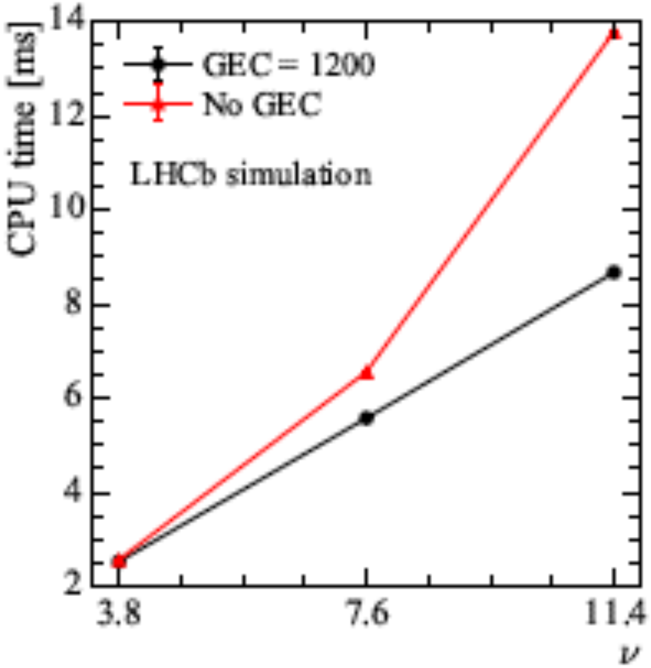
(b) Forward tracking time versus p_T

[This cut is 60% efficient on charm decays]

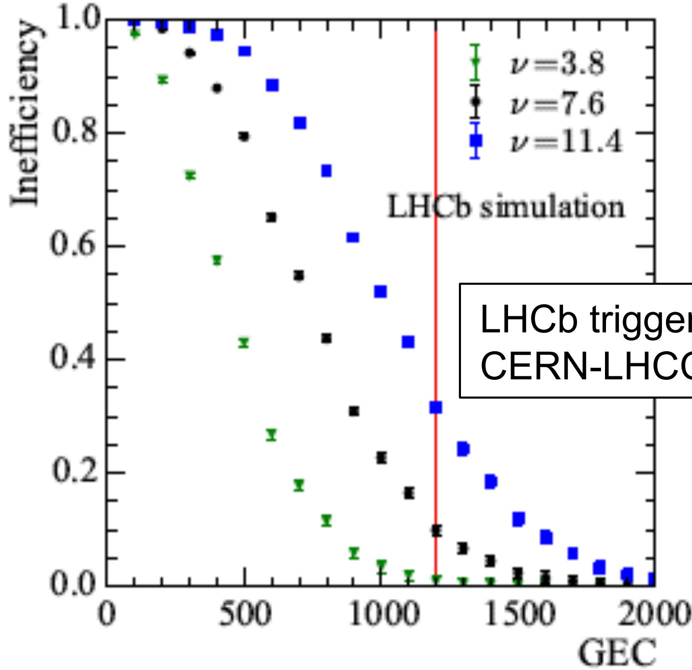
[(*) this budget has been estimated assuming that the memory bandwidth grows such That the individual instances of HLT code do not influence each other performance.]

The upgraded trigger: the name of the game

Time budget: 13 ms/event @ 30 MHz



(a) Total timing



(b) $B_s^0 \to \phi\phi$

LHCb trigger TDR
CERN-LHCC-2014-016

[Assuming a more realistic MC with 30% more hits the time to build up the tracks almost saturate the available total time budget. A Global event cut allows to recover a reasonable CPU time but cuts away 30% of Bs → ϕϕ.]

The upgraded trigger: the name of the game

Bandwidth: 20 kHz, 2 GB/sec

LHCb trigger TDR
CERN-LHCC-2014-016

Selection	Output Rate (kHz)		
Topological	10	20	50
Lifetime unbiased	1	4	5
Exclusive beauty	ϵ	1	3
Inclusive di-muon	–	–	2
Charm	9	20	40
Total	20	50	100
Bandwidth [GBs^{-1}]	2	5	10

With 20 kHz, 2 GB/sec:
- topological trigger (only b-decays, lifetime biased selection)
- handful of lifetime unbiased selections (only b-decays)
- exclusive: only $Bs \rightarrow \mu\mu$, $Bs \rightarrow \phi\phi$,
- charm: almost nothing fits in 9 kHz

($D^0 \rightarrow KK$: 2 kHz, $D^0 \rightarrow K\pi$: 20 kHz, $D^0 \rightarrow \pi\pi$ +Cabibbo-suppressed modes: 40 kHz; $D^0 \rightarrow Ks\,\pi\pi$: 9 kHz)

In order to cover the same physics program as in Run I we need
either to increase the offline resources or to reduce the event size or to park the data

Conclusions

Flavour physics has been, is and will always be a strategic asset in the quest for new physics… However :

- only a few “hints” of deviations from SM predictions observed so far ;
- sensitivity on NP mass scale reachable with LHCb upgrade (2028) is in the same ball park as direct searches at LHC @ 14 TeV (if we assume MFV) and grows (very) slowly with L

Hence:

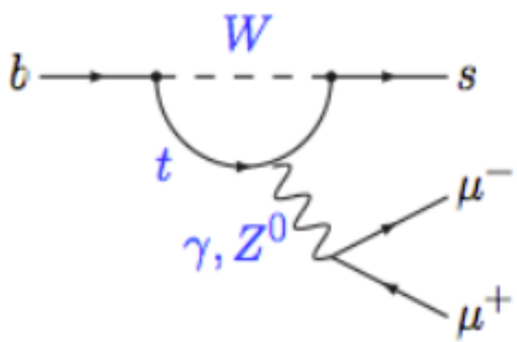
To do a sizeable step forward in the flavour sector we need high luminosity, highly performing detectors, deep control of systematic uncertainties and reliable theory predictions…

Will the LHCb-upgrade able to keep its promises?

Rendez-vous in 2023 for the answer…

Back to the beginning: the mission of a flavor physicist

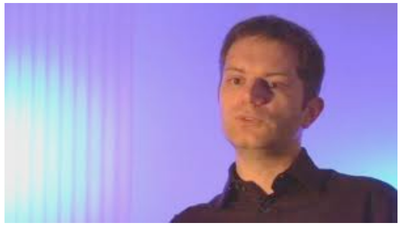
To look for New Physics in FCNC B, K, charm decays (and cLFV decays) that can be sensitive to quantum corrections from degrees of freedom **at** and **above** the electroweak scale.



...but if there was nothing between the EW and Planck scales?

……To be continued…..

SPARES



Higgs and naturalness

"Given the absence of unambiguous signal of new physics and the compatibility of the Higgs properties with the SM predictions **some doubts arose about the relevance of the naturalness argument** as an organizing principle at higher energies."

C. Grosjean, Future circular collider kick-off meeting, Geneva, February 12-14

"With a mass of the Higgs boson of ~126 GeV the **Standard Model could be a self-consistent stable or meta-stable weakly coupled effective field theory** up to very high scales (possibly up to the Planck scale) **without adding new particles**.*"*

N. Arkani-Hamed, Future circular collider kick-off meeting, Geneva, February 12-14

……To be continued…..

Sin2β^{eff} from $B^0 \rightarrow J/\psi\, \pi^+\pi^-$

LHCb-PAPER-2014-058
arXiv:1411.1634

$$2\beta^{J/\psi\,\rho} = 2\beta^{\rm eff} = (41.7 \pm 9.6^{+2.8}_{-6.3})^\circ$$
$$\Delta 2\beta_f = 2\beta^{J/\psi\,\rho} - 2\beta^{J/\psi\,K^0_S} = (-0.9 \pm 9.7^{+2.8}_{-6.3})^\circ$$

Sets limits on the penguin contribution to ϕ_s in $B_s^0 \rightarrow J/\psi h^+h^-$

[−1.05°, 1.18°] at 95% CL, *

assuming approximate SU(3) symmetry. The limits depends on the difference of strong phases and relative magnitudes between tree and penguin amplitudes, but do not exceed ±1.8°.

Effect of penguin contributions in $B^0 \rightarrow J/\psi K_S^0$ should be limited to similar values.

*N.B. Currently, $\sigma(2\beta) = \pm 1.6^\circ$ and $\sigma(\phi_s) = \pm 2^\circ$ [HFAG].

arXiv: 1309.2203 (CKMFitter)

Inputs for CKMfitter results on NP

	2003	2013	Stage I		Stage II	
$\lvert V_{ud}\rvert$	0.9738 ± 0.0004	$0.97425 \pm 0 \pm 0.00022$	id		id	
$\lvert V_{us}\rvert$ $(K_{\ell 3})$	$0.2228 \pm 0.0039 \pm 0.0018$	$0.2258 \pm 0.0008 \pm 0.0012$	0.22494 ± 0.0006		id	
$\lvert \epsilon_K \rvert$	$(2.282 \pm 0.017) \times 10^{-3}$	$(2.228 \pm 0.011) \times 10^{-3}$	id		id	
Δm_d [ps^{-1}]	0.502 ± 0.006	0.507 ± 0.004	id		id	
Δm_s [ps^{-1}]	> 14.5 [95% CL]	17.768 ± 0.024	id		id	
$\lvert V_{cb}\rvert \times 10^3$ $(b \to c\ell\bar{\nu})$	$41.6 \pm 0.58 \pm 0.8$	$41.15 \pm 0.33 \pm 0.59$	42.3 ± 0.4	[17]	42.3 ± 0.3	[17]
$\lvert V_{ub}\rvert \times 10^3$ $(b \to u\ell\bar{\nu})$	$3.90 \pm 0.08 \pm 0.68$	$3.75 \pm 0.14 \pm 0.26$	3.56 ± 0.10	[17]	3.56 ± 0.08	[17]
$\sin 2\beta$	0.726 ± 0.037	0.679 ± 0.020	0.679 ± 0.016	[17]	0.679 ± 0.008	[17]
α (mod π)	—	$(85.4^{+4.0}_{-3.8})^\circ$	$(91.5 \pm 2)^\circ$	[17]	$(91.5 \pm 1)^\circ$	[17]
γ (mod π)	—	$(68.0^{+8.0}_{-8.5})^\circ$	$(67.1 \pm 4)^\circ$	[17, 18]	$(67.1 \pm 1)^\circ$	[17, 18]
β_s	—	$0.0065^{+0.0450}_{-0.0415}$	0.0178 ± 0.012	[18]	0.0178 ± 0.004	[18]
$\mathcal{B}(B \to \tau\nu) \times 10^4$	—	1.15 ± 0.23	0.83 ± 0.10	[17]	0.83 ± 0.05	[17]
$\mathcal{B}(B \to \mu\nu) \times 10^7$	—	—	3.7 ± 0.9	[17]	3.7 ± 0.2	[17]
$A^d_{\rm SL} \times 10^4$	10 ± 140	23 ± 26	-7 ± 15	[17]	-7 ± 10	[17]
$A^s_{\rm SL} \times 10^4$	—	-22 ± 52	0.3 ± 6.0	[18]	0.3 ± 2.0	[18]
$\bar{m}_c$	$1.2 \pm 0 \pm 0.2$	$1.286 \pm 0.013 \pm 0.040$	1.286 ± 0.020		1.286 ± 0.010	
$\bar{m}_t$	167.0 ± 5.0	$165.8 \pm 0.54 \pm 0.72$	id		id	
$\alpha_s(m_Z)$	$0.1172 \pm 0 \pm 0.0020$	$0.1184 \pm 0 \pm 0.0007$	id		id	
B_K	$0.86 \pm 0.06 \pm 0.14$	$0.7615 \pm 0.0026 \pm 0.0137$	0.774 ± 0.007	[19, 20]	0.774 ± 0.004	[19, 20]
f_{B_s} [GeV]	$0.217 \pm 0.012 \pm 0.011$	$0.2256 \pm 0.0012 \pm 0.0054$	0.232 ± 0.002	[19, 20]	0.232 ± 0.001	[19, 20]
B_{B_s}	1.37 ± 0.14	$1.326 \pm 0.016 \pm 0.040$	1.214 ± 0.060	[19, 20]	1.214 ± 0.010	[19, 20]
f_{B_s}/f_{B_d}	$1.21 \pm 0.05 \pm 0.01$	$1.198 \pm 0.008 \pm 0.025$	1.205 ± 0.010	[19, 20]	1.205 ± 0.005	[19, 20]
B_{B_s}/B_{B_d}	1.00 ± 0.02	$1.036 \pm 0.013 \pm 0.023$	1.055 ± 0.010	[19, 20]	1.055 ± 0.005	[19, 20]
$\tilde{B}_{B_s}/\tilde{B}_{B_d}$	—	$1.01 \pm 0 \pm 0.03$	1.03 ± 0.02		id	
$\tilde{B}_{B_s}$	—	$0.91 \pm 0.03 \pm 0.12$	0.87 ± 0.06		id	

TABLE I. Central values and uncertainties used in our analysis (see definitions in Ref. [10]). The entries "id" refer to the value in the same row in the previous column. The 2003 and 2013 values correspond to Lepton-Photon 2003 and FPCP 2013 conferences [4]. The assumptions entering the Stage I and Stage II estimates are described in the text.

Theory predictions: error budget

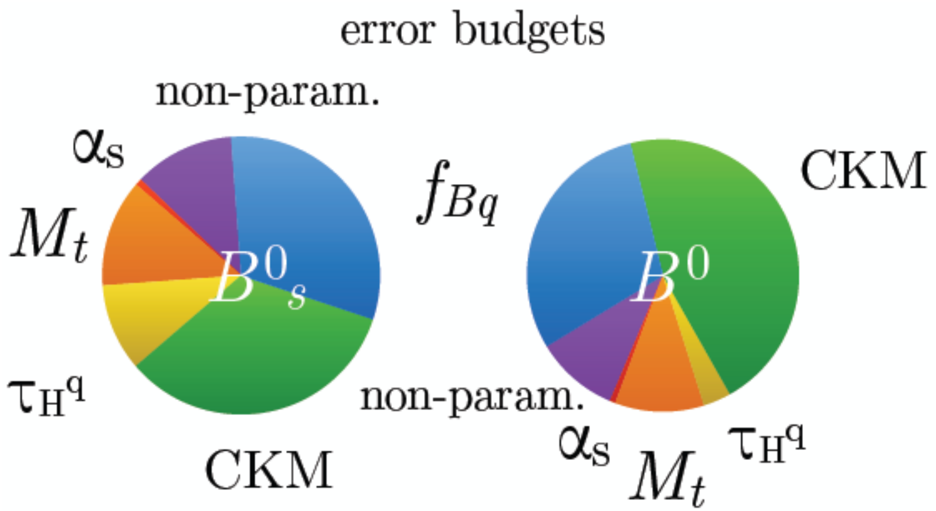
$BR(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$ (6.3%)
$BR(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$ (8.5%)

Bobeth et al. '13

$B_s^0 \to \mu^+\mu^-$	f_{B_s}	CKM	τ_H^s	M_t	α_s	other param.	**non-param.**	$\sum$
	4.0%	4.3%	1.3%	1.6%	0.1%	< 0.1%	1.5%	6.4%
$B^0 \to \mu^+\mu^-$	f_{B_d}	CKM	τ_H^s	M_t	α_s	other param.	**non-param.**	$\sum$
	4.5%	6.9%	0.5%	1.6%	0.1%	< 0.1%	1.5%	8.5%

- $f_{B_s} = 227.4(4.5)$ MeV
  [FLAG '13, arXiv:1310.8555]
- V_{cb} from recent inclusive fit
  [Gambino, Schwanda '13, arXiv:1307.4551]

- $f_{B_d} = 190.5(4.2)$ MeV
  [FLAG '13, arXiv:1310.8555]



The uncertainty of CKM matrix elements is now larger than the uncertainty on $f_{Bs,d}$

Theory predictions: error budget

$BR(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$ (6.4%)
$BR(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$ (8.5%)

$B_s^0 \to \mu^+\mu^-$	f_{B_s}	CKM	τ_H^s	M_t	α_s	other param.	**non-param.**	$\sum$
	4.0%	4.3%	1.3%	1.6%	0.1%	< 0.1%	1.5%	6.4%
$B^0 \to \mu^+\mu^-$	f_{B_d}	CKM	τ_H^s	M_t	α_s	other param.	**non-param.**	$\sum$
	4.5%	6.9%	0.5%	1.6%	0.1%	< 0.1%	1.5%	8.5%

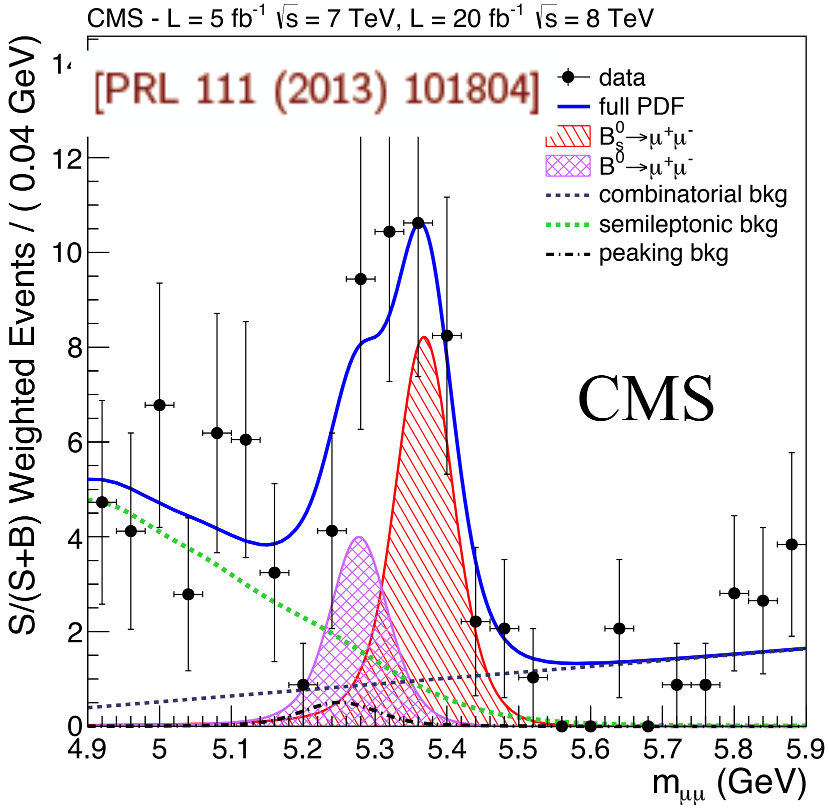
$R = BR(B^0 \to \mu^+\mu)/ BR(B_s^0 \to \mu^+\mu) = 0.0295^{+0.0028}_{-0.0025}$ (+8.7% - 7.7%)

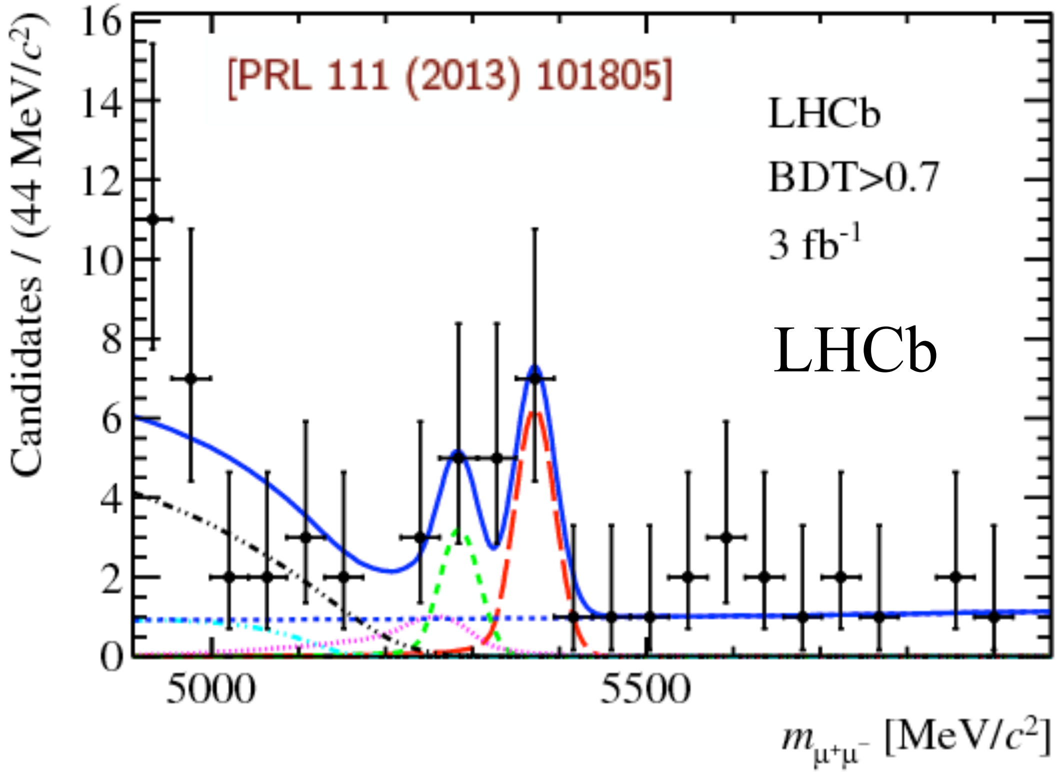
The theoretical uncertainty on R is due:

- 8 % uncertainty from CKM elements ;
- 3.7 % uncertainty from f_{Bs}/f_{Bd}
- 1.4 % uncertainty on the B_s lifetime

These uncertainties do not cancel in the ratio.

CMS and LHCb results: pre-combination





$BR(B_s^0 \to \mu^+\mu^-) = (3.0\ ^{+1.0}_{-0.9})\ 10^{-9}$ (4.3 σ)
$BR(B^0 \to \mu^+\mu^-) = (3.5\ ^{+2.1}_{-1.98})\ 10^{-10}$ (2.0 σ)

$BR(B_s^0 \to \mu^+\mu^-) = (2.9\ ^{+1.1}_{-1.9})\ 10^{-9}$ (4.0 σ)
$BR(B^0 \to \mu^+\mu^-) = (3.7\ ^{+2.4}_{-2.1})\ 10^{-10}$ (2.0 σ)

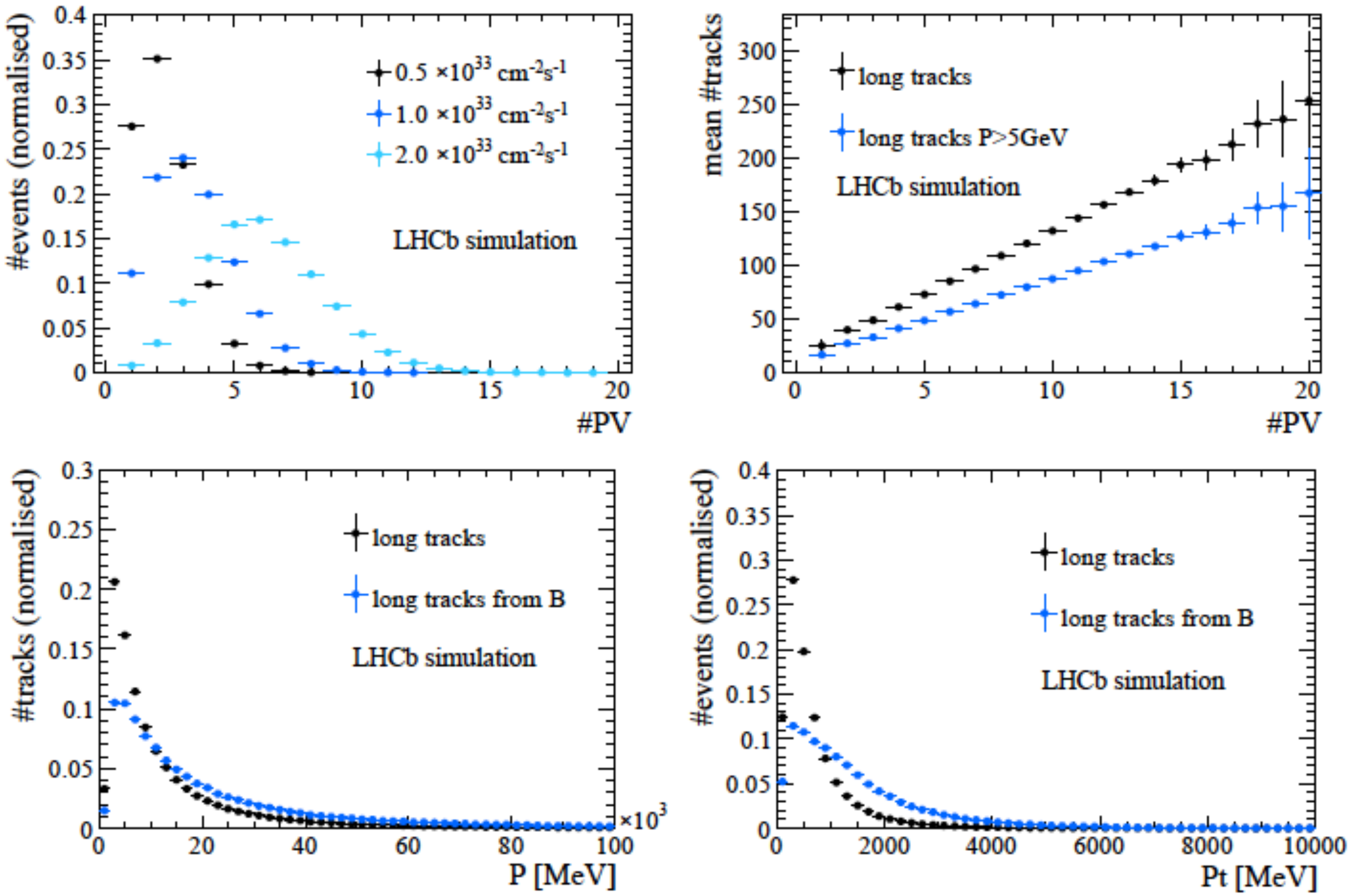


Figure 4.2: Top left: Number of primary vertices for simulated data samples generated with $\nu = 2$, $\nu = 3.8$ and $\nu = 7.6$. Top right: Number of reconstructible long tracks per primary vertex in an event. Bottom row: Momentum and transverse momentum distributions for all long reconstructible particles in $B_s \to \phi\phi$ events at $\sqrt{s} = 14\,\mathrm{TeV}$.

LHC schedule beyond LS1

LS2 starting in 2018 (July) => 18 months + 3 months BC
LS3 LHC: starting in 2023 => 30 months + 3 months BC
Injectors: in 2024 => 13 months + 3 months BC

	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2020-22)	Run 4 (2025-28)	Run 5+ (2030+)
ATLAS, CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	$\longrightarrow$	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}

How the accuracy on flavour observables translates into M(NP) limits ?

General decomposition of flavor-violating observables

$$A = A_0 \left[c_{SM} \frac{1}{M_W^2} + c_{NP} \frac{1}{M_{NP}^2} \right]$$

Isidori @ ECFA'14

trivial kinematical factors

(dimensionless) effective couplings

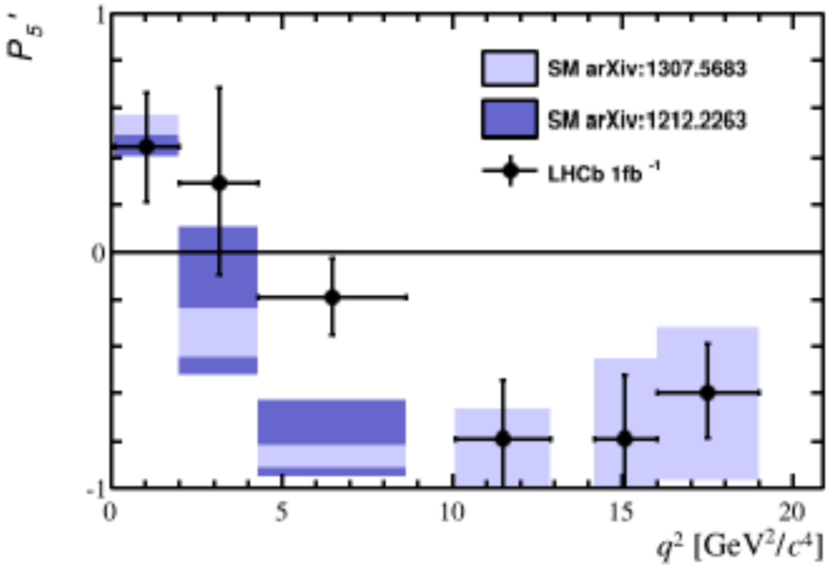
effective mass (scale) of NP

E.g.: If $c_{NP} \sim c_{SM}$ [*electroweak-MFV-like*] => 10% precision ↔ $M_{NP} \sim 250$ GeV

Decreasing the error to 2% (~30 x statistics) => 250 GeV → 600 GeV
$\sigma(c_{NP}) \rightarrow 0.2 \times \sigma(c_{NP})$

Form-factor uncertainties

- Decay amplitudes depend on 7 $B \to K^*$ form-factors:
  - A_0, A_1, A_2, T_1, T_2, T_3 and V.
- Can be reduced to two soft form-factors ($\xi_{\parallel}(q^2)$ and $\xi_{\perp}(q^2)$) at low q^2
  - Valid up-to $\mathcal{O}(\Lambda/m_B)$, usually assumed to be $\mathcal{O}(10\%)$.
- Form observables where $\xi_{\parallel}$ and $\xi_{\perp}$ cancel, e.g. P_5'.

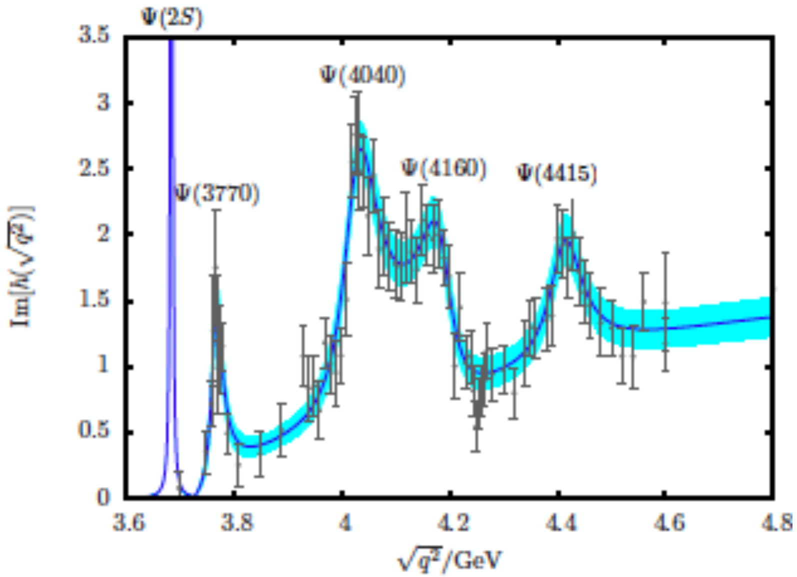


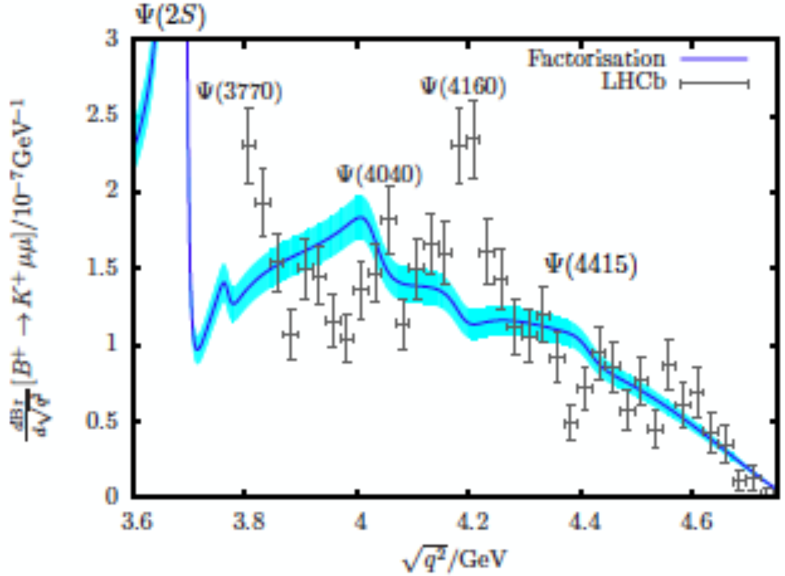
- Unfortunately different treatments of (factorisable + non-factorisable) corrections can give large variation of P_5'.

$\rightsquigarrow$ Try to constrain the form-factors from the data itself.

$c\bar{c}$ contributions

- In [Phys. Rev. Lett. 111 (2013) 112003] we showed that there are large $c\bar{c}$ contributions above the $\psi(2S)$ e.g. from $\psi(4160)$. Some debate about whether the level of these was compatible with OPE.
- Zwicky & Lyon in [arXiv:1406.0566] show that the LHCb data can not be explained by naive factorisation, i.e. by taking the vacuum polarisation from BES II.





$c\bar{c}$ contributions

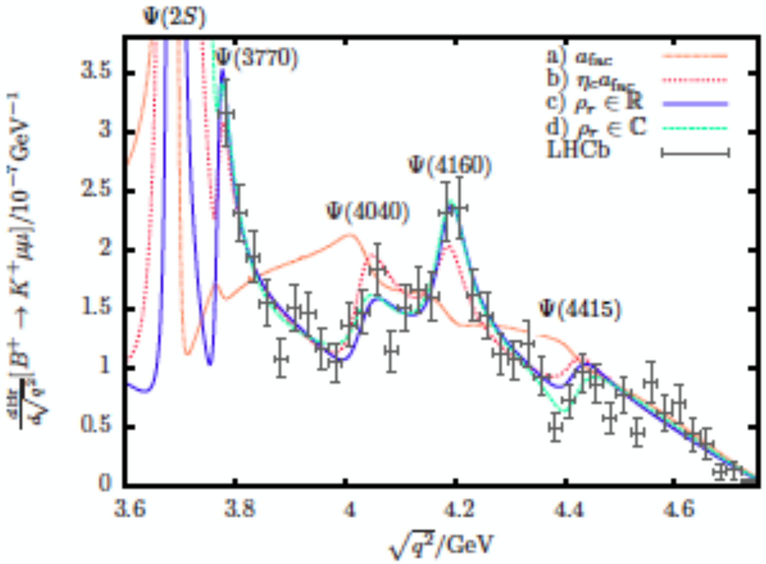
- To fit the data, Zwicky & Lyon try global scaling η_c and a per-resonance scaling ρ_c.

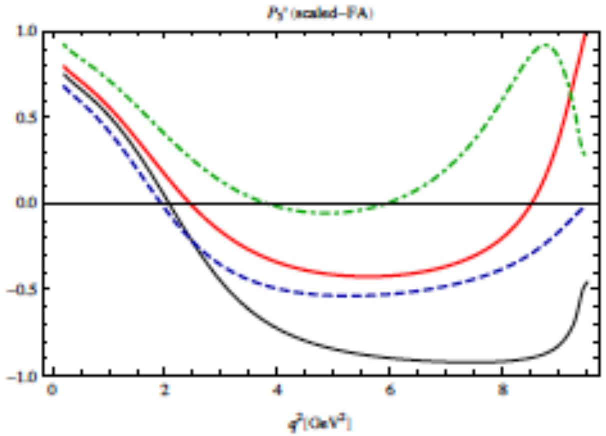
⇝ Data best described by large non-factorisable correction (350% !).

- Receive virtual $c\bar{c}$ contributions to C_9^{eff} below the J/ψ,

$$C_9^{\text{eff}} = C_9 + a \cdot \eta_c \cdot h_c(q^2) \quad .$$

⇝ Can also see large impact on observables at low q^2 (depending on C_7 interference) by applying a left- and right-handed scale factor.





$\eta_c = (1, 0)$, $\eta_c = (-1.25, -1.25)$,

$\eta_c = (0, -2.5)$, $\eta_c = (-2.5, 0)$