

# *Flavor at the HL-LHC*

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UNIFI & INFN-Pisa

on behalf of ATLAS, CMS, LHCb



LHCP 2016  
Lund, 12-18 June 2016

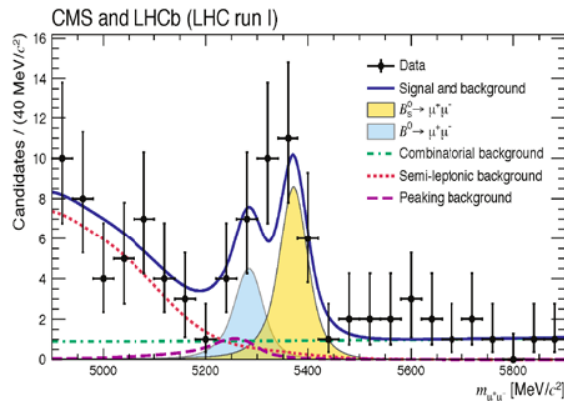


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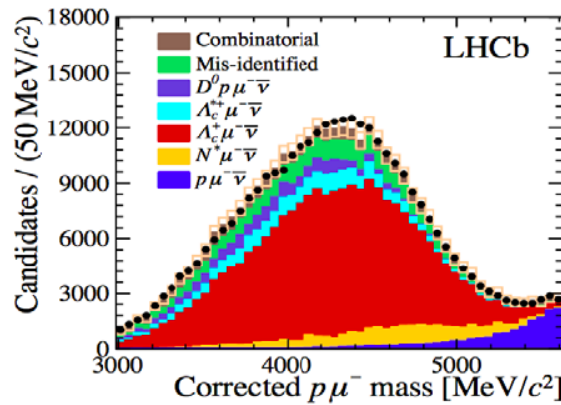


# LHC start has been so favourable...

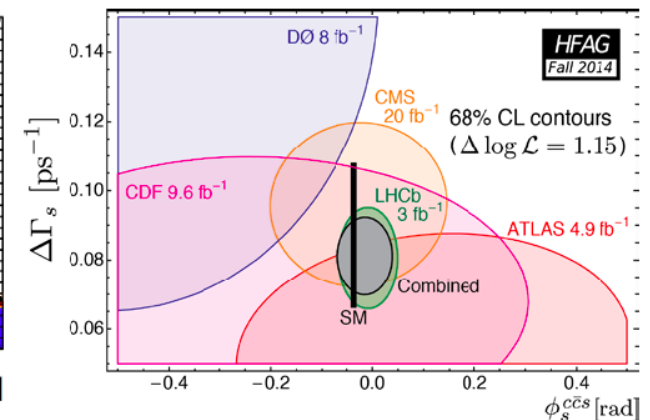
Observation of  $B_s \rightarrow \mu\mu$



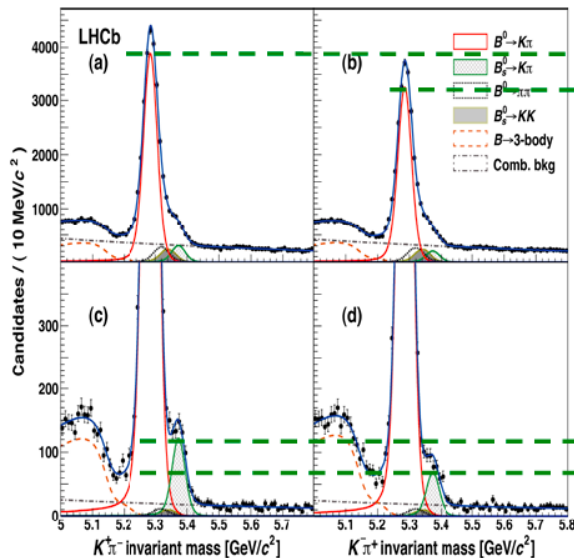
Measurement of  $V_{ub}$  in  $\Lambda_b \rightarrow p\mu\nu$



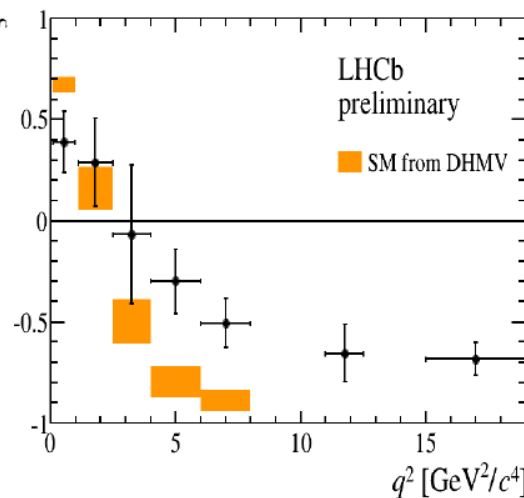
Best measurement of  $\phi_s$  in  $B_s \rightarrow J/\psi\phi$



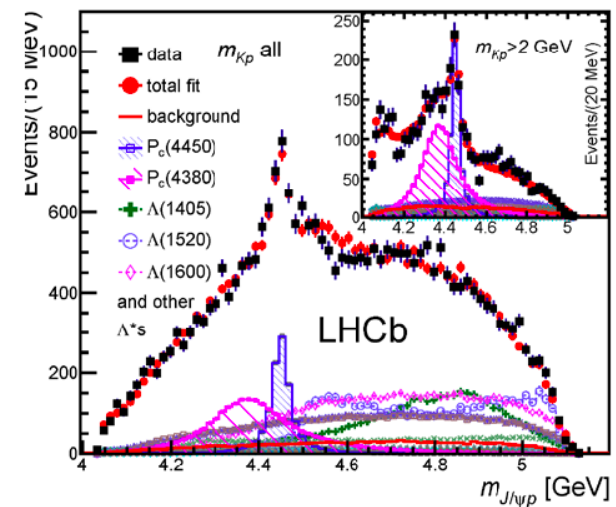
Observation of direct CP violation



Angular analysis in  $B^0 \rightarrow K^{*0}\mu\mu$

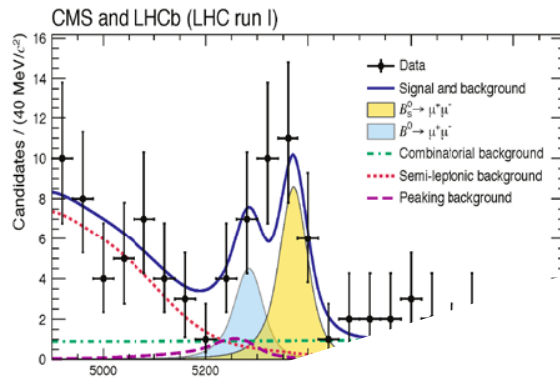


Observation of pentaquarks

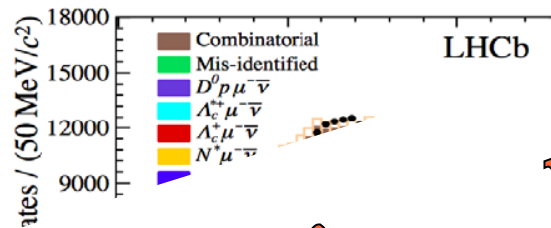


# LHC start has been so favourable...

## Observation of $B_s \rightarrow \mu\mu$



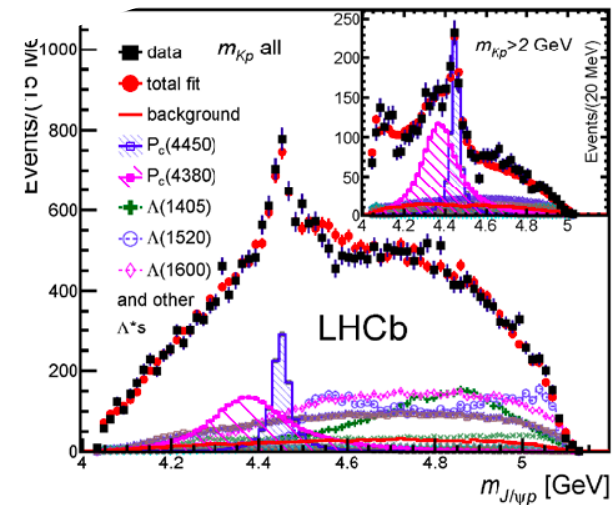
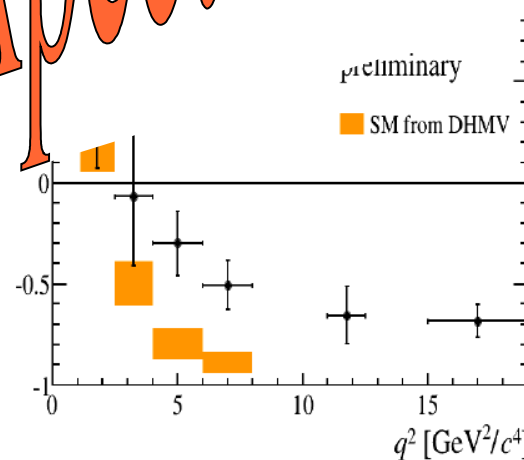
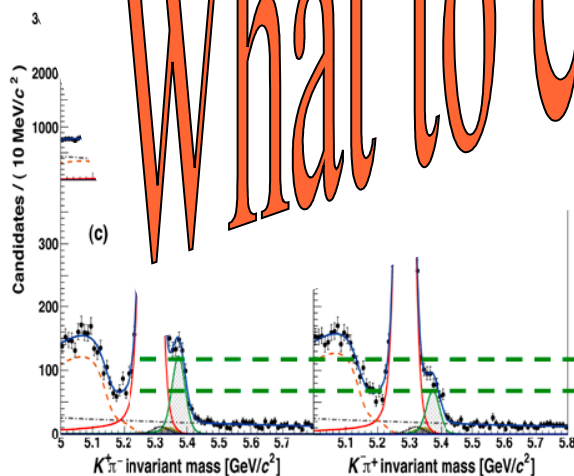
## Measurement of $V_{ub}$ in $\Lambda_b \rightarrow p\mu\nu$



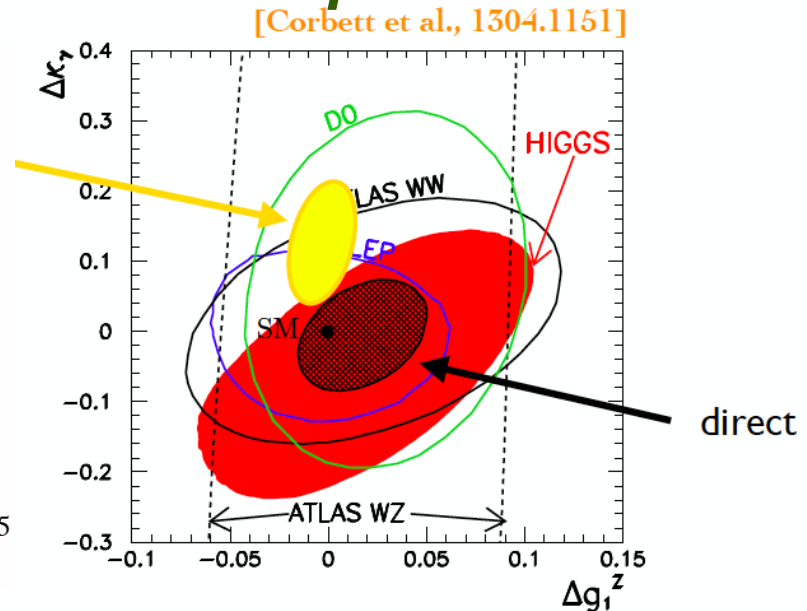
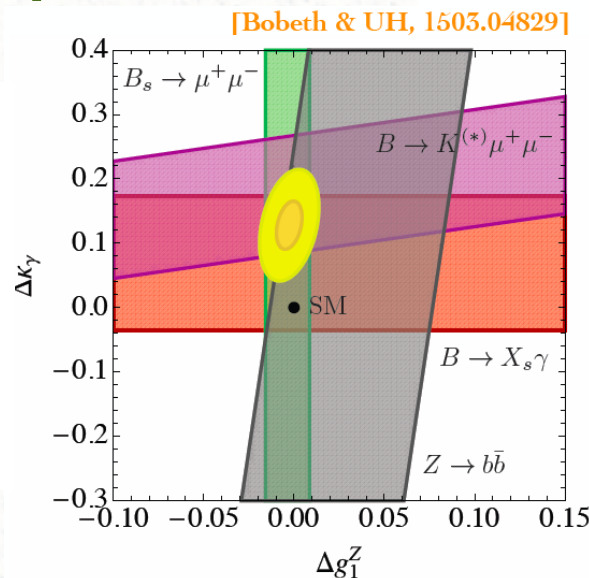
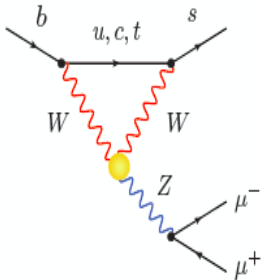
## Best measurement of $\alpha_s$ from $J/\psi \phi$



What to expect from HL-LHC?



# Not just 'stamp collecting': Flavor probes fundamental processes

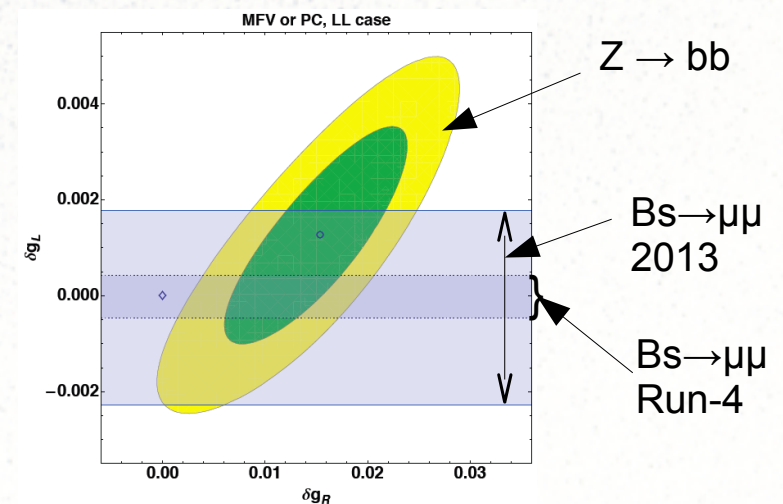


1) TGC coupling on 2 of 3 parameters competitive with Hi-Pt

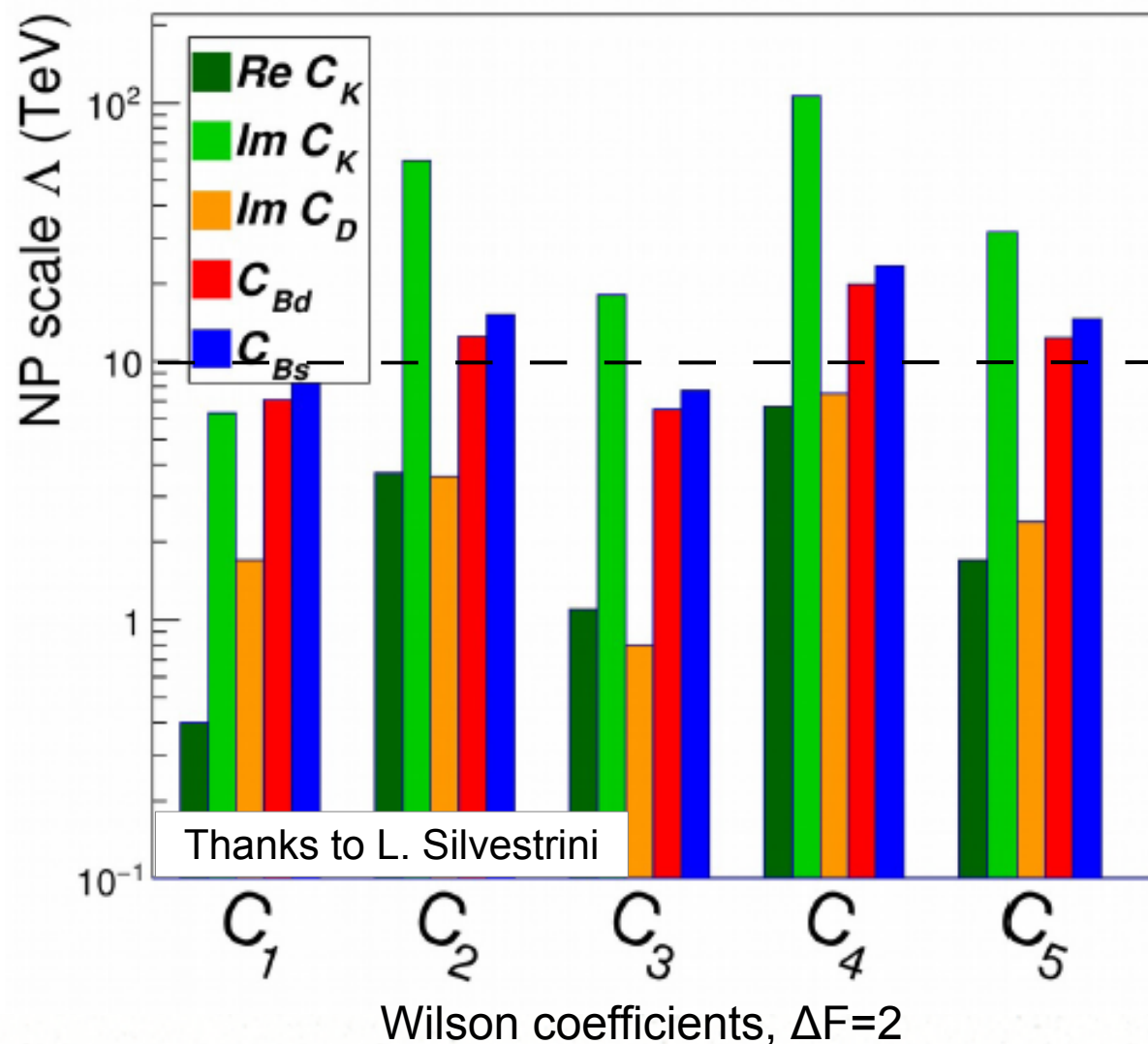
[Bobeth & Haisch, JHEP 1509 (2015) 018]

Just a couple of examples...

2)  $B \rightarrow \mu\mu$  now better than EWK precision tests on  $Zbb$  coupling  
[Guadagnoli & Isidori, PLB 724:63 (2013)]  
"BR( $B_s \rightarrow \mu\mu$ ) as an EWK precision test"]



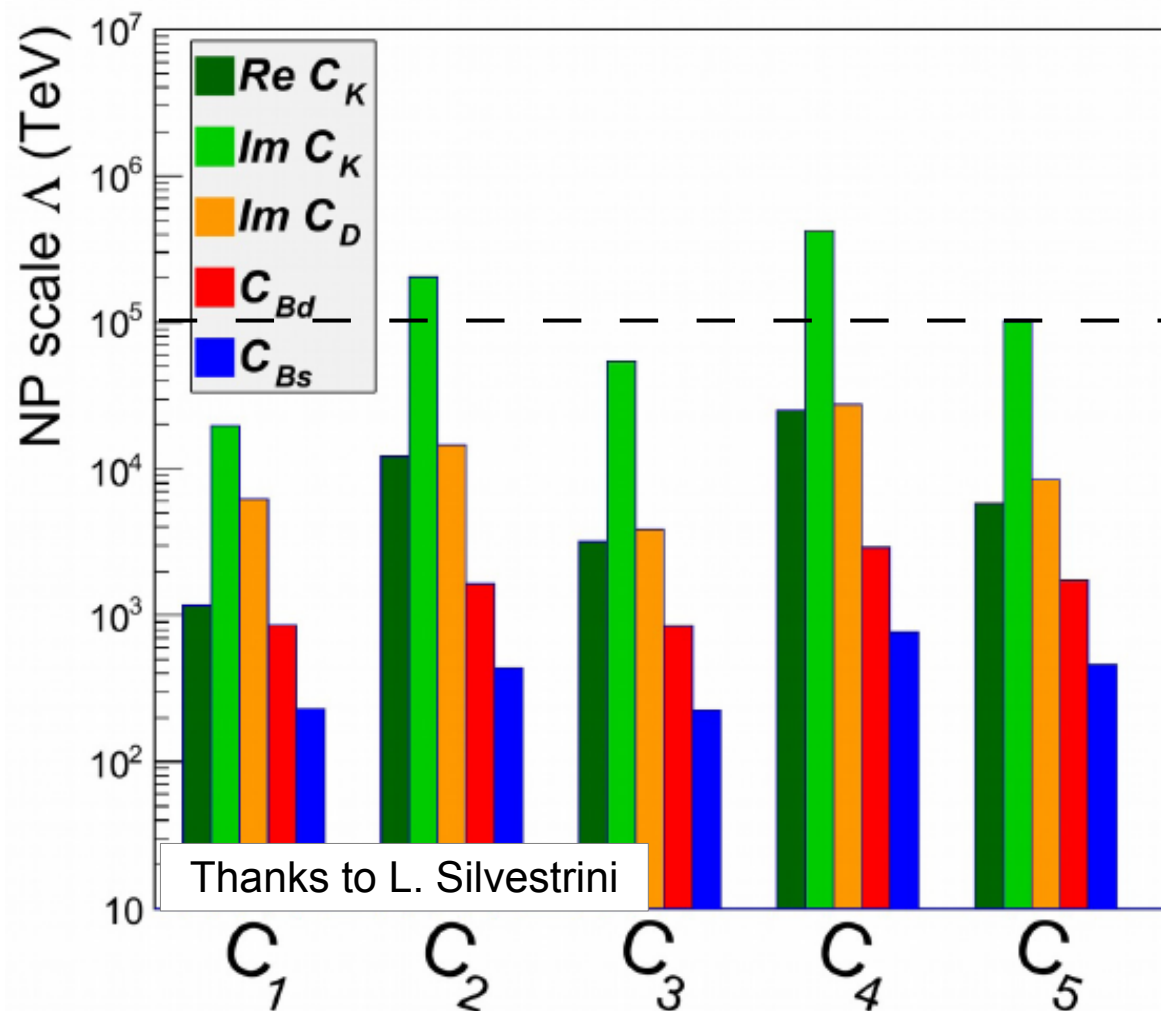
# Sensitivity of $f$ avor to NP scales (assuming CKM structure/MFV)



10 TeV

**Limits** to BSM physics from Flavor observables are now **comparable** (and complementary) to **direct searches**

# Sensitivity of $f$ avor to NP scales (under generic assumptions)



$10^5$  TeV

Cannot set *limits*  
at such high scales -  
**But** we might just be lucky  
and actually **see a signal**

This would be a great  
encouragement to  
direct searches at  
high energy

# Flavor @ HL-LHC

Huge HF cross sections at 13 TeV :

$5 \cdot 10^{11} \text{ bb} + 2.8 \cdot 10^{12} \text{ cc}$  in 1 fb<sup>-1</sup>  
 $2.5 \cdot 10^{13} \text{ bb} + 1.4 \cdot 10^{14} \text{ cc}$  in 50 fb<sup>-1</sup>  
 **$10^{15} \text{ bb} + 10^{16} \text{ cc}$  in 3000 fb<sup>-1</sup>**

Nominal sensitivities

Bd/Bs →  $\mu\mu$  down to th. u. (~5%)  
Rare:  $D^0 \rightarrow \mu\mu$ : [10<sup>-11</sup>÷10<sup>-12</sup>],  
 $K_s \rightarrow \mu\mu$  [10<sup>-10</sup>],  $\tau \rightarrow \mu\mu\mu$  [10<sup>-11</sup>]  
CKM:  $\sigma(\text{angles}) \sim 0.1 \text{ deg.}$   
Charm:  $x, y \sim 10^{-5}$ ,  $|q/p| \sim 10^{-5}$

[INFN WN White Paper]

- Actual performance depends on detector capabilities - Selectivity and DAQ
- LHCb oriented to higher rates → upgrades sooner than ATLAS and CMS  
*(LHCb recently started considering a further upgrade for Run-5)*

	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	100 fb	300 fb	→	3000 fb
LHCb	3 fb	8 fb	23 fb	46 fb	(300 fb)

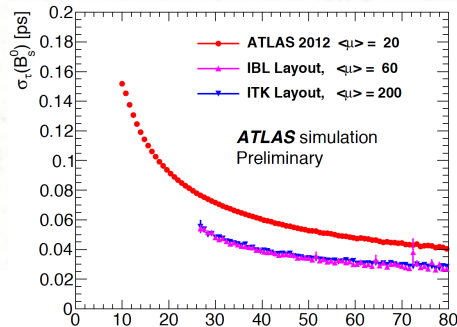
Today

LHCb upgrade

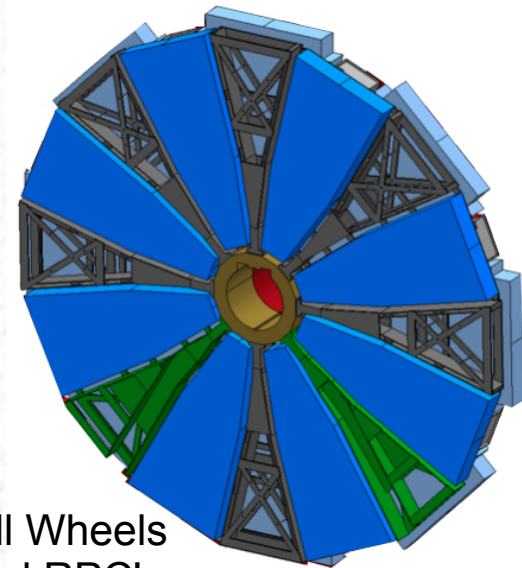
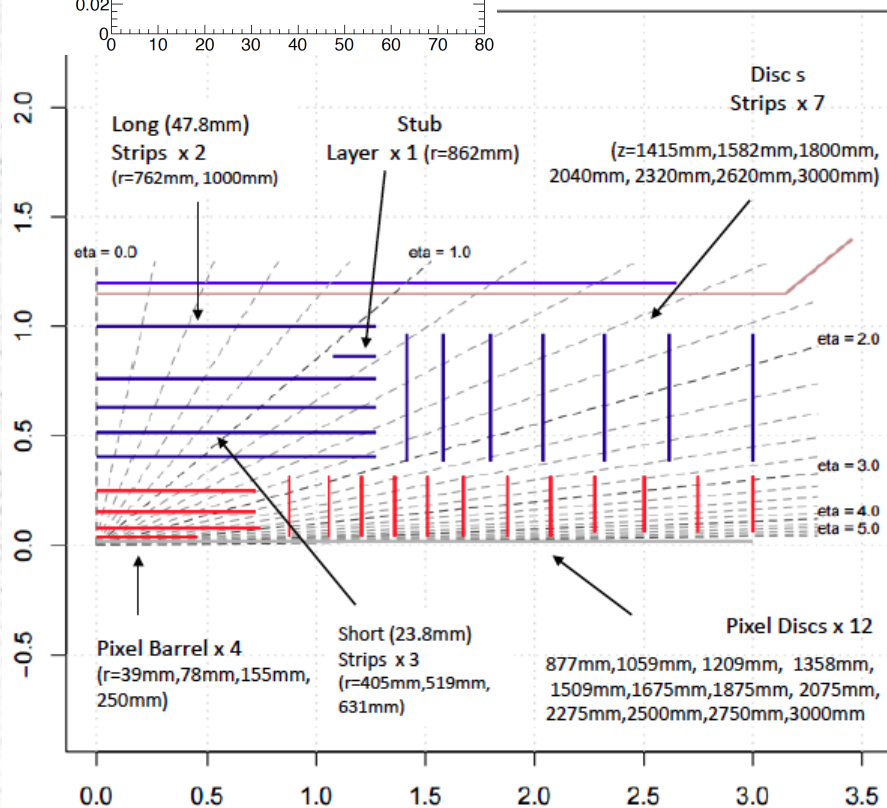
ATLAS, CMS upgrade

(LHCb 2<sup>nd</sup> phase)

# ATLAS B-related upgrades

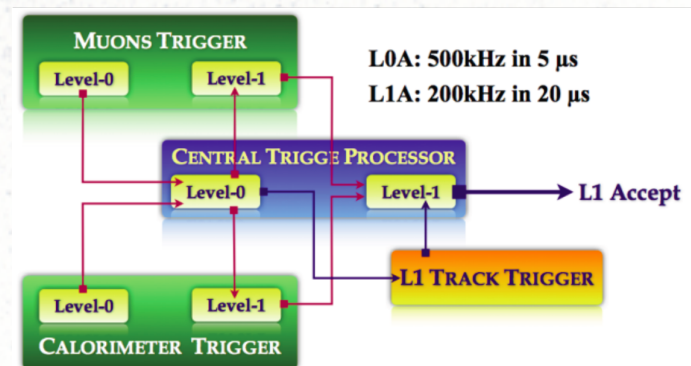


New all-silicon tracker (ITK)  
→ **better vertex resolution**



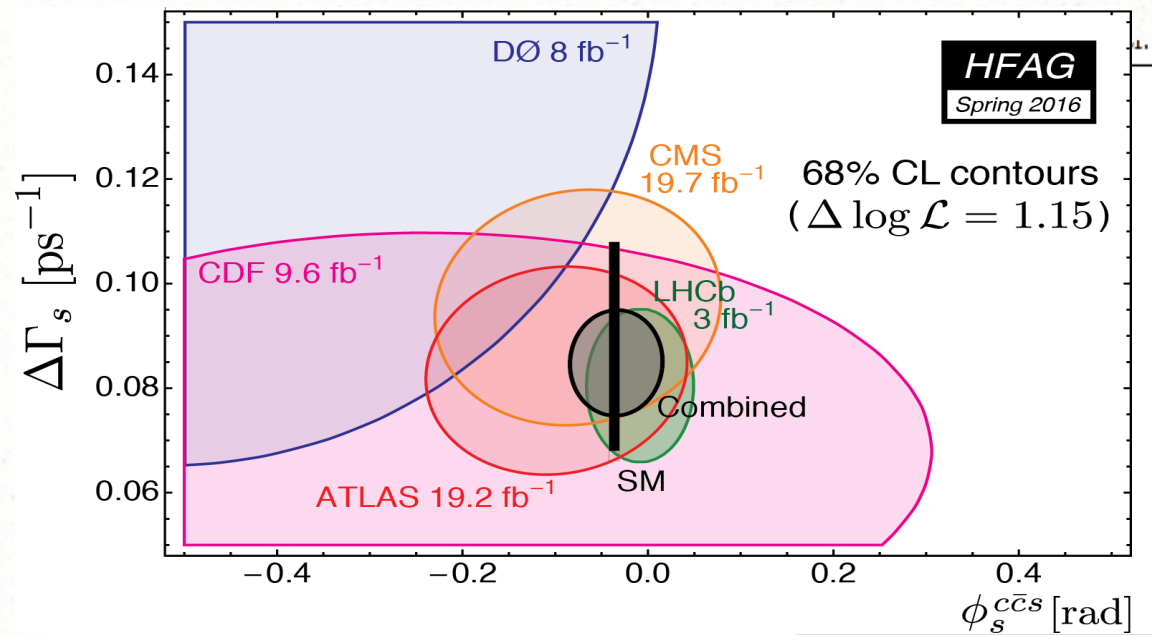
CERN-LHCC-2013-006; ATLAS-TDR-020

New Muon Small Wheels  
+ additional barrel RPC's  
→ **better acceptance, less background**



Move track trigger (FTK) to Level 1  
→ **better selectivity**

# ATLAS impact on $B_s$ mixing



Below SM expectation:  
 $\phi_s = -0.036 \pm 0.0013$

All combined  $-0.033 \pm 0.033$   $+0.084 \pm 0.007$

	2011	2012	2015-17		2019-21	2023-30+
Detector	current	current	IBL		IBL	ITK
Average interactions per BX $\langle \mu \rangle$	6-12	21	60		60	200
Luminosity, $\text{fb}^{-1}$	4.9	20	100		250	3 000
Di- $\mu$ trigger $p_T$ thresholds, GeV	4 - 4(6)	4 - 6	6 - 6	11 - 11	11 - 11	11 - 11
Signal events per $\text{fb}^{-1}$	4 400	4 320	3 280	460	460	330
Signal events	22 000	86 400	327 900	45 500	114 000	810 000
Total events in analysis	130 000	550 000	1 874 000	284 000	758 000	6 461 000
MC $\sigma(\phi_s)$ (stat.), rad	0.25	0.12	0.054	0.10	0.064	0.022

- Plans for further dimuon-based physics

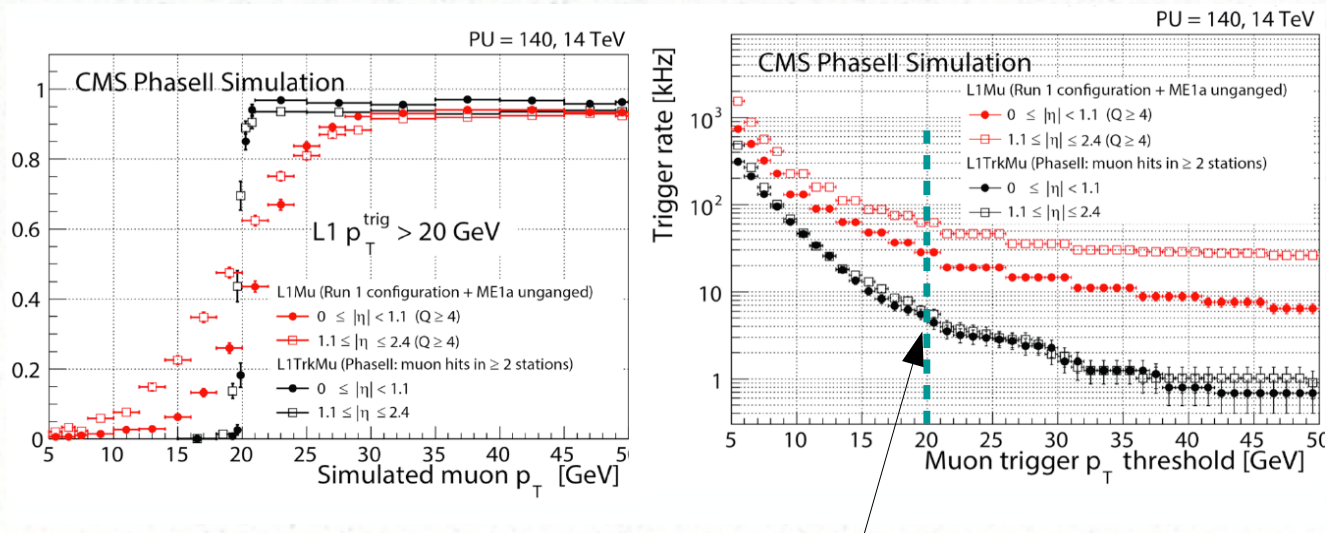
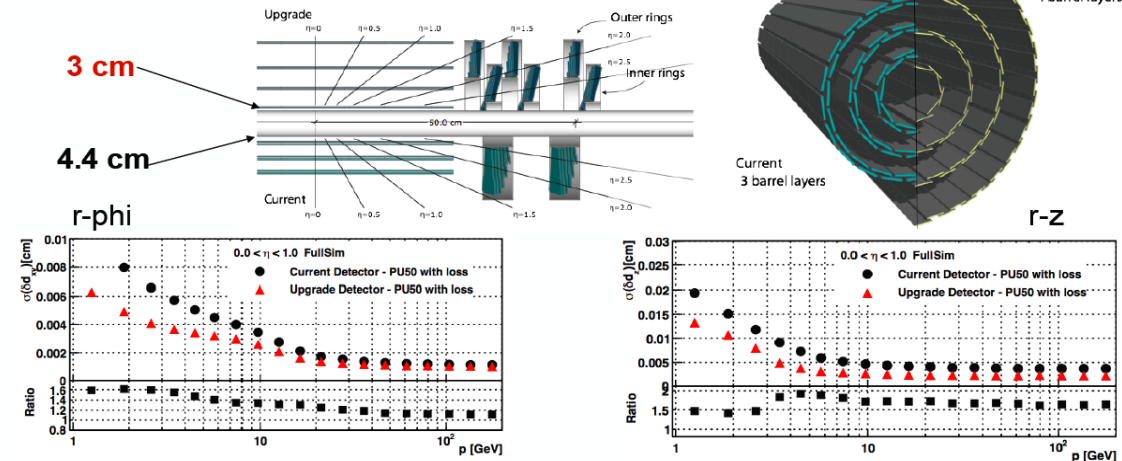
# CMS B-related upgrades

Overall better performance for B-Physics

CERN-LHCC-2012-016

<http://cds.cern.ch/record/1481838?ln=en>

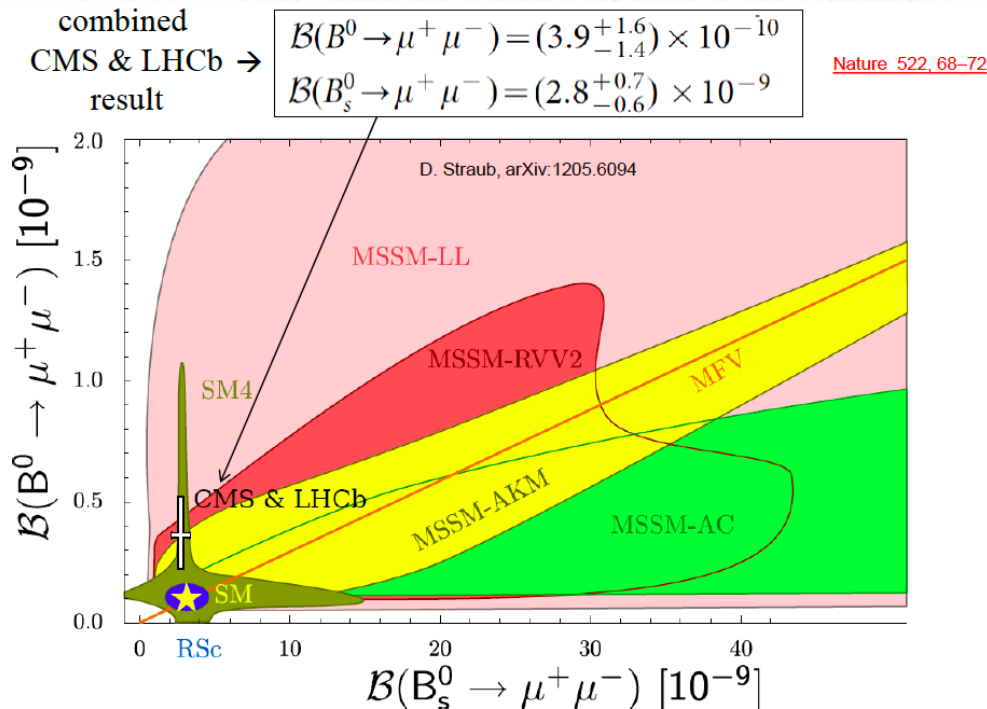
Upgrade Silicon pixel detector with a layer closer to beam  
→ **better vertex resolution**



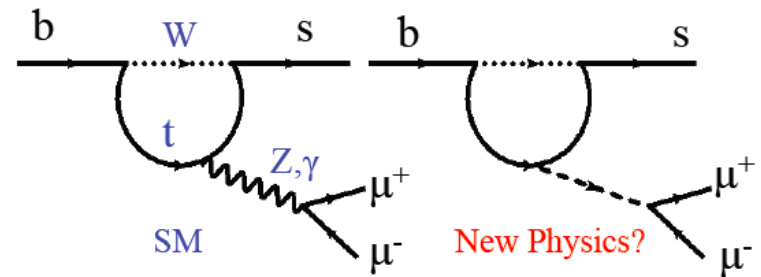
New L1 track trigger → **muon rate improved 10x at 20GeV**

# CMS Outlook for $B \rightarrow \mu\mu$

- $B_d \rightarrow \mu\mu / B_s \rightarrow \mu\mu$  already had high impact in limiting possible NP

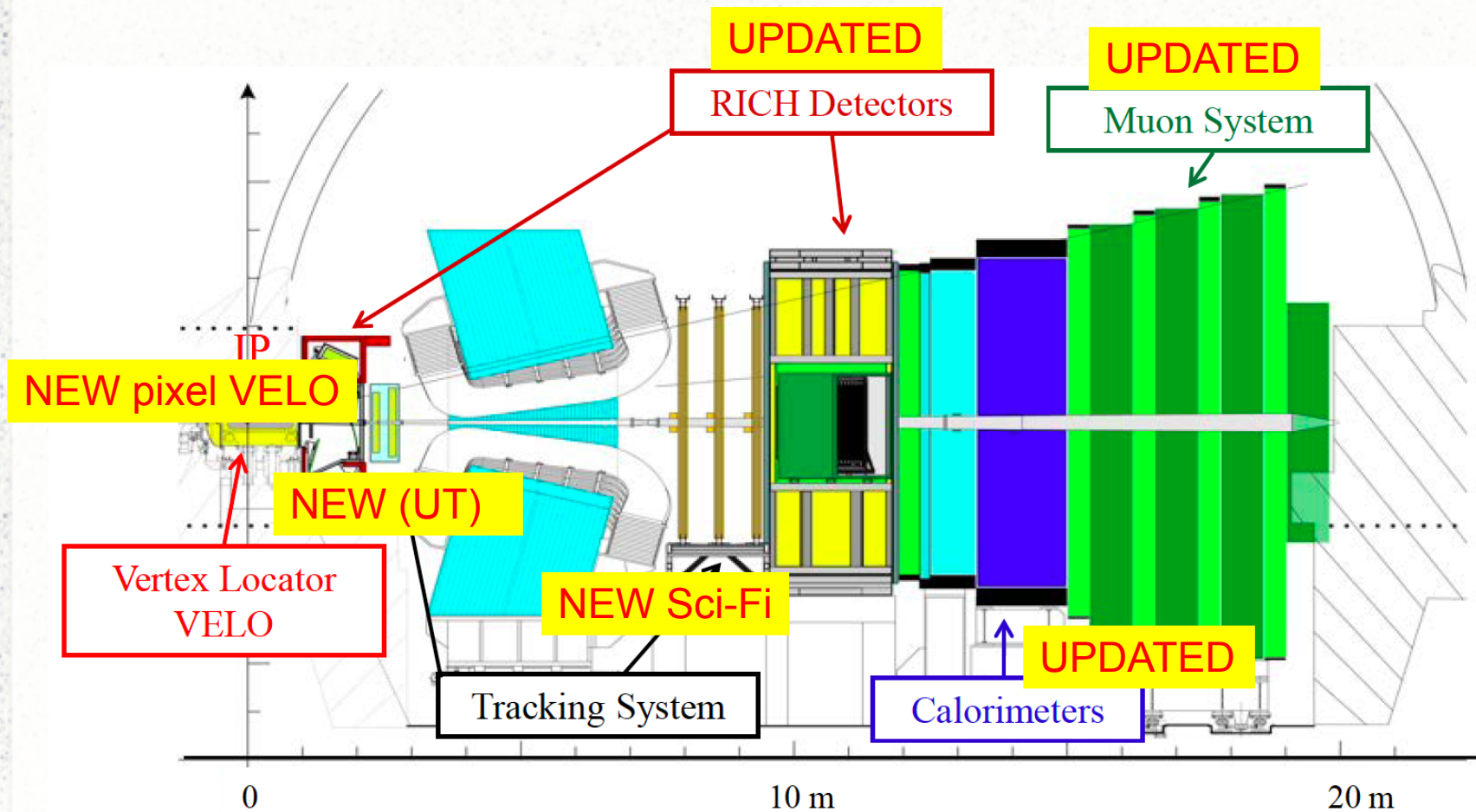


Currently probes NP scales  
0.5-1 TeV (as Higgs coupling)  
(Tree level probed at  $O(100\text{TeV})$ )



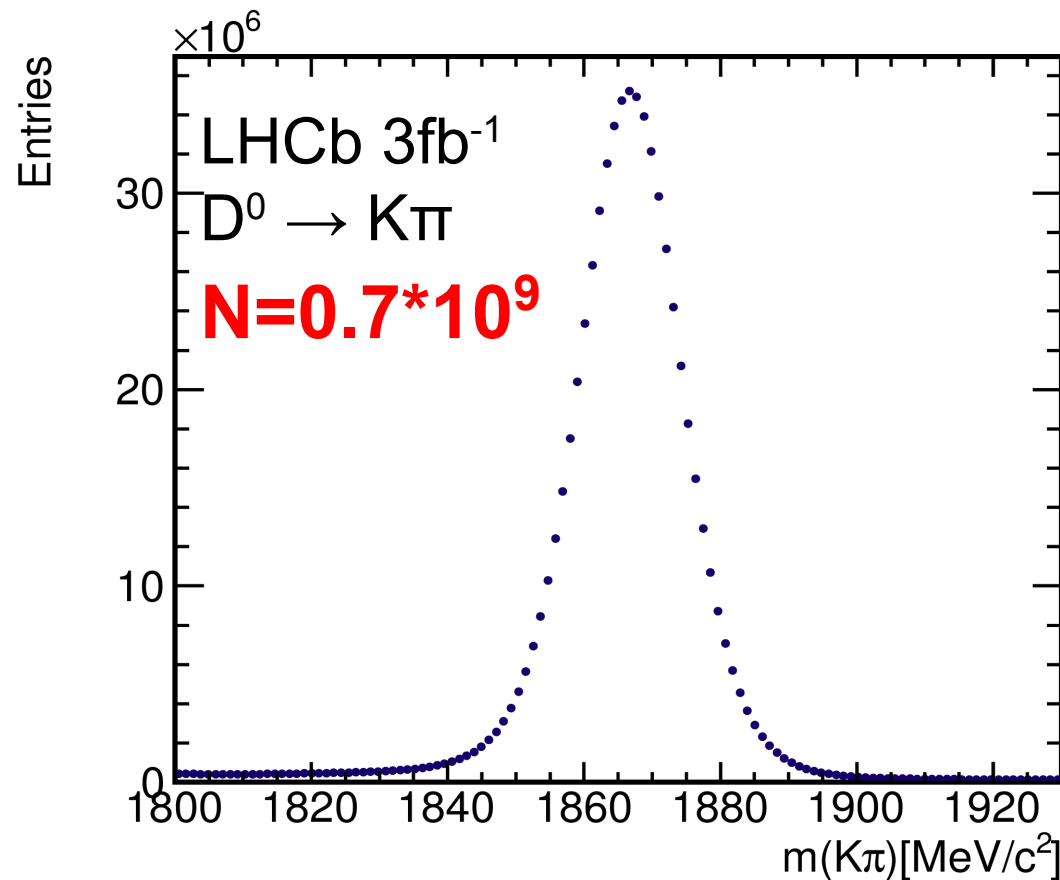
$\mathcal{L} \text{ (fb}^{-1}\text{)}$	$N(B_s^0)$	$N(B^0)$	$\delta\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	$\delta\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)$	$B^0$ sign.	$\delta \frac{\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)}{\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)}$
20	18.2	2.2	35%	$> 100\%$	$0.0 - 1.5 \sigma$	$> 100\%$
100	159	19	14%	63%	$0.6 - 2.5 \sigma$	66%
300	478	57	12%	41%	$1.5 - 3.5 \sigma$	43%
300 (barrel)	346	42	13%	48%	$1.2 - 3.3 \sigma$	50%
3000 (barrel)	2250	271	11%	18%	$5.6 - 8.0 \sigma$	21% <span style="color: red;">←</span>

# The LHCb upgrade: detector



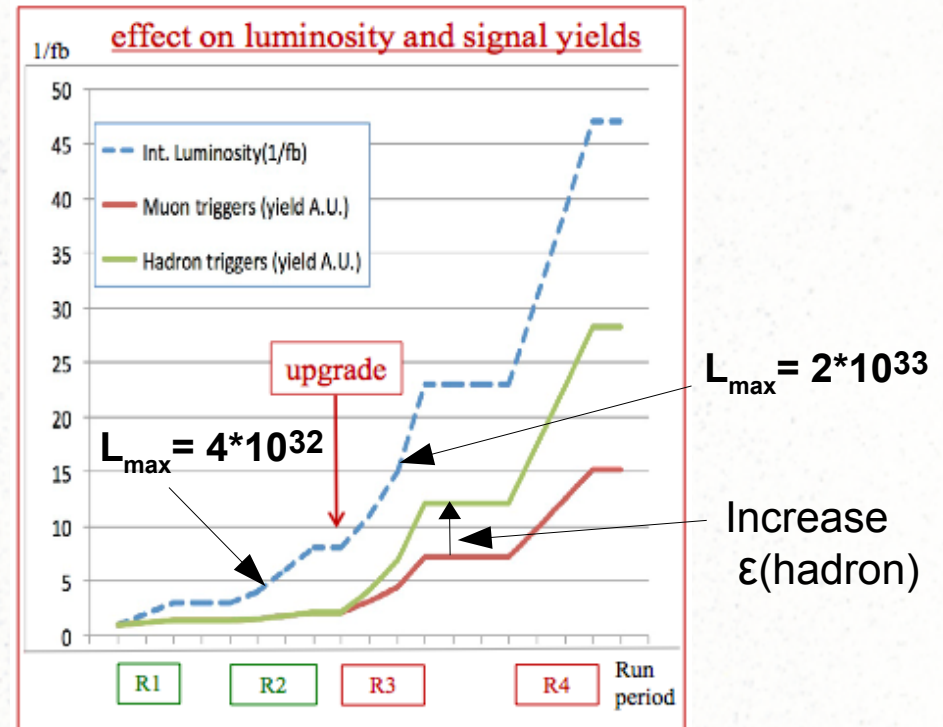
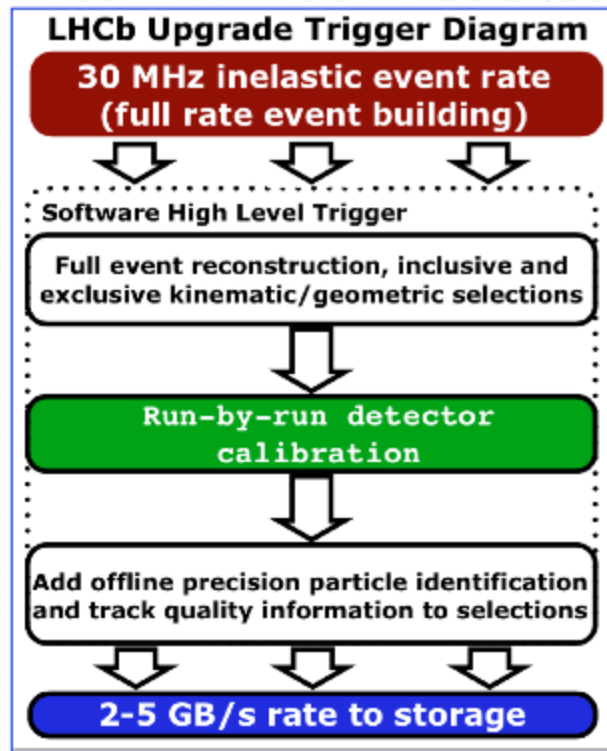
- Substantial upgrades to most detectors *[see A.Cardini talk]*
- Higher granularity + faster electronics to handle higher L

*LHCb is an experiment at the “Gev” scale  
... that is, Giga-events, not electronVolts.*



*this imposes unique requirements on the DAQ*

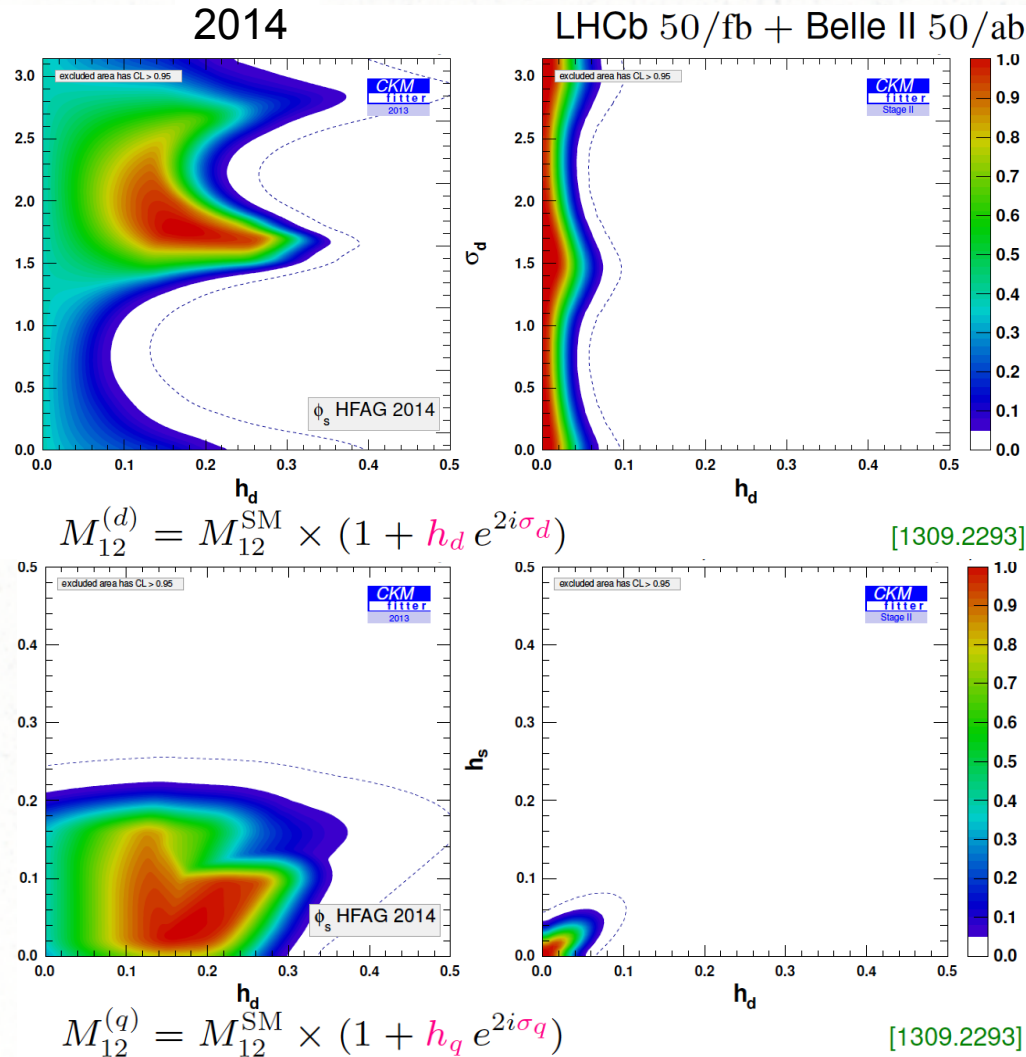
# The LHCb DAQ upgrade



- Detector readout and trigger at 40 MHz + higher rate to storage will be the drivers to handle 5x luminosity and collect larger samples
- Real-time data calibration and reconstruction [see L. Grillo talk]
- Based on new front-end electronics, large PC-based event-builder network, and large expansion of online CPU farm

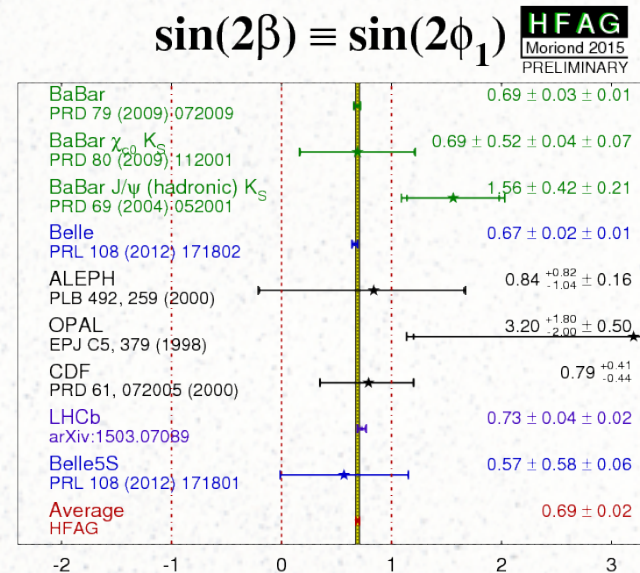
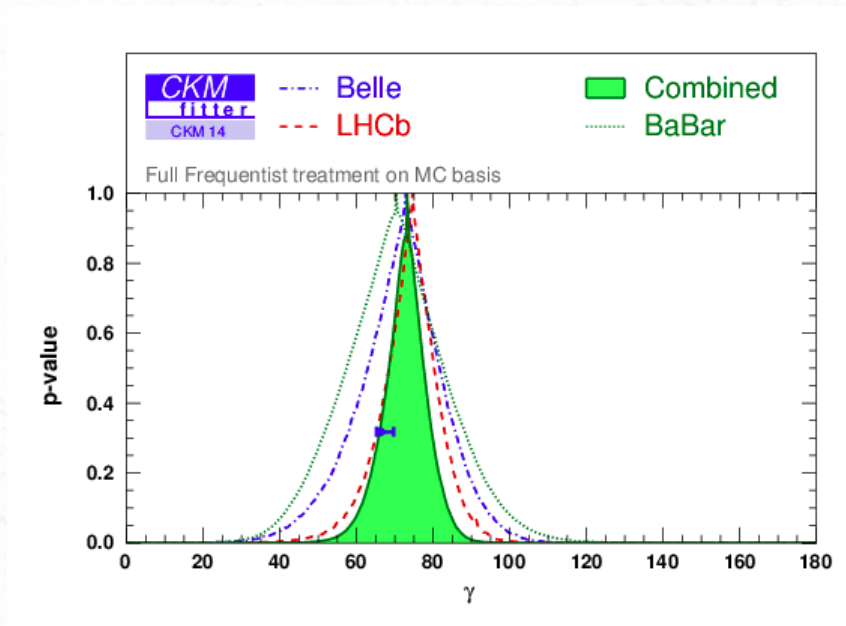
# LHCb NP impact via B-mixing

[J.Charles et al., Phys. Rev. D 89, 033016 (2014)]



- LHCb with 50 fb<sup>-1</sup> still dominates in HL era:  
 $\sigma(\phi_s) = 0.045 \rightarrow 0.009$   
 (observe SM at 3 $\sigma$  !)  
 $\sigma(\beta) = 0.2$  deg ( Belle II)
- Sensitivity to NP at 2 TeV (10<sup>3</sup> TeV) level, independent of phase  
 → gluino sensitivity in the same ballpark of direct searches

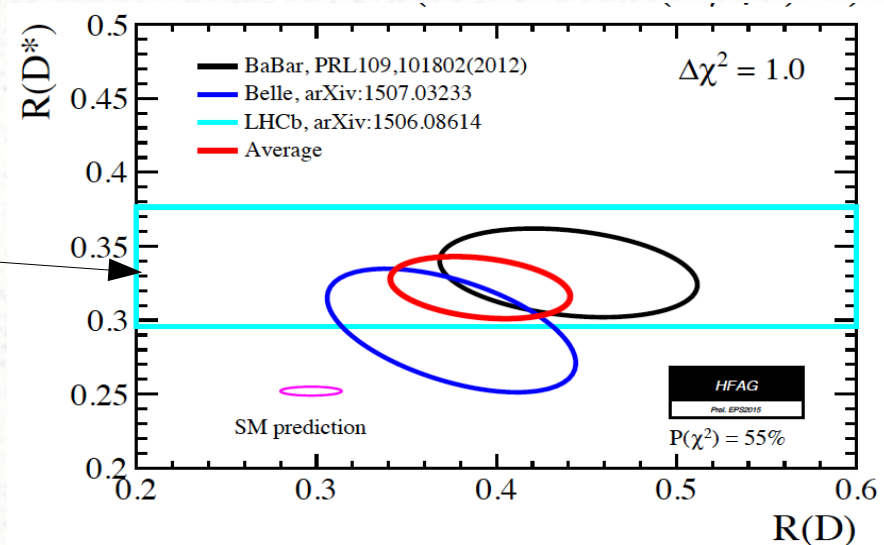
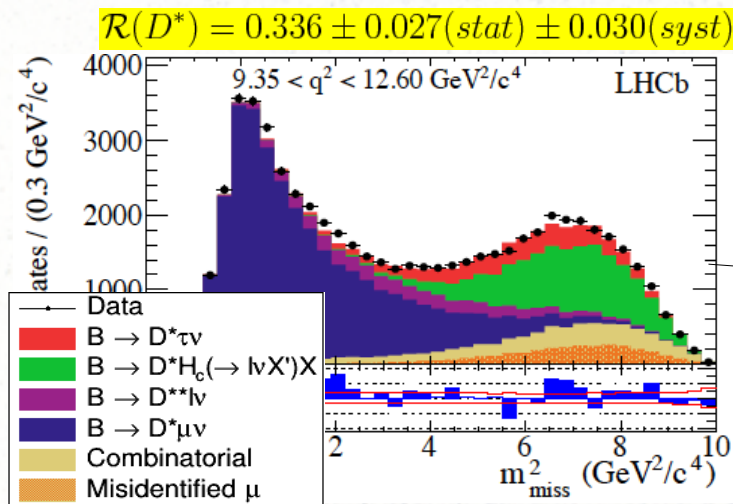
# Precision CKM @ LHC



- LHCb currently contributes the best determination of angle  $\gamma$ 
  - $\sigma(\gamma)$  from 4 deg in Run-2, down to 1 deg with 50 fb<sup>-1</sup>
- Important comparison to loop-level –  $O(20\%)$  NP still allowed
- No theory limitations - important item to keep improving with HL

# Given enough data, hadronic experiments can do tau modes as well...

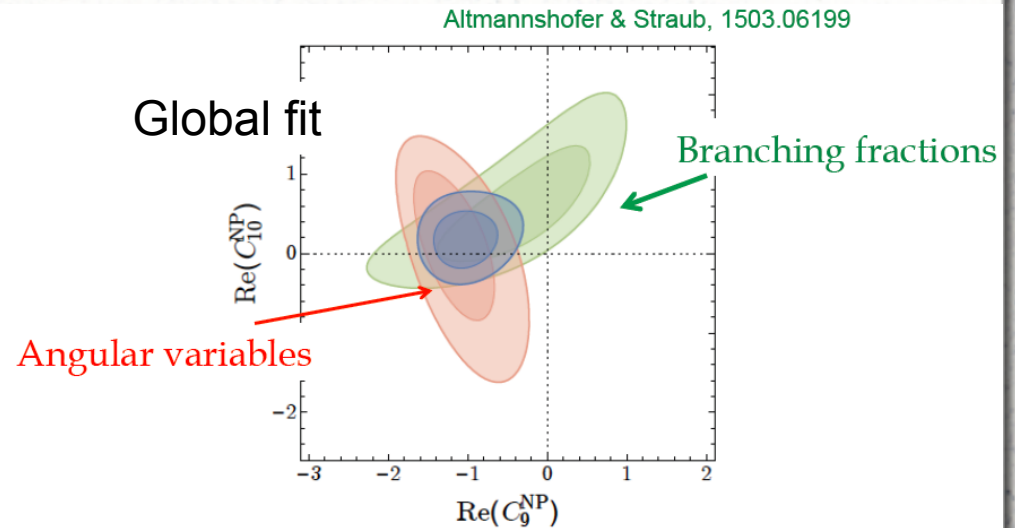
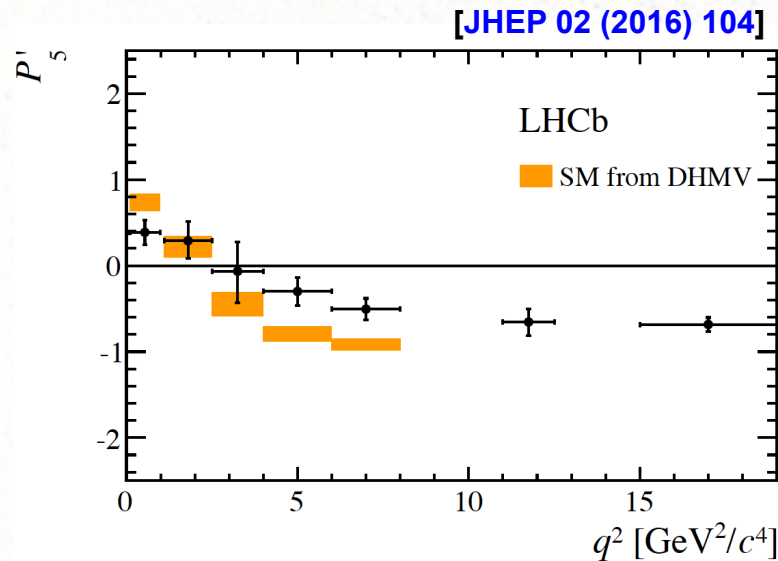
$$R(D^*) = \mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau) / \mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)$$



Separation via multi-D kinematic fits

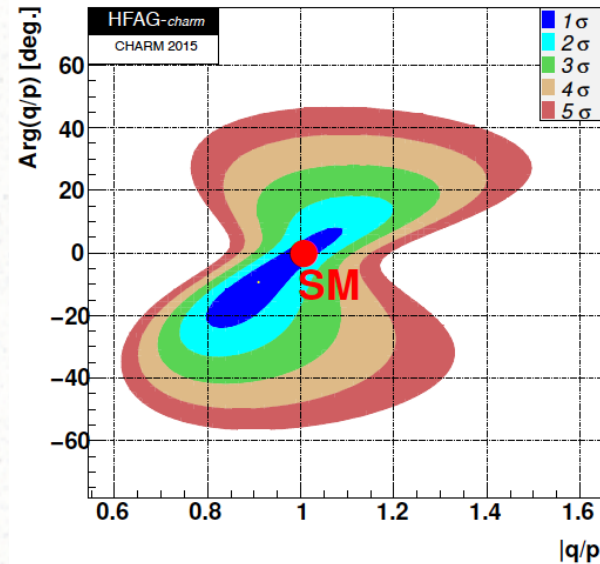
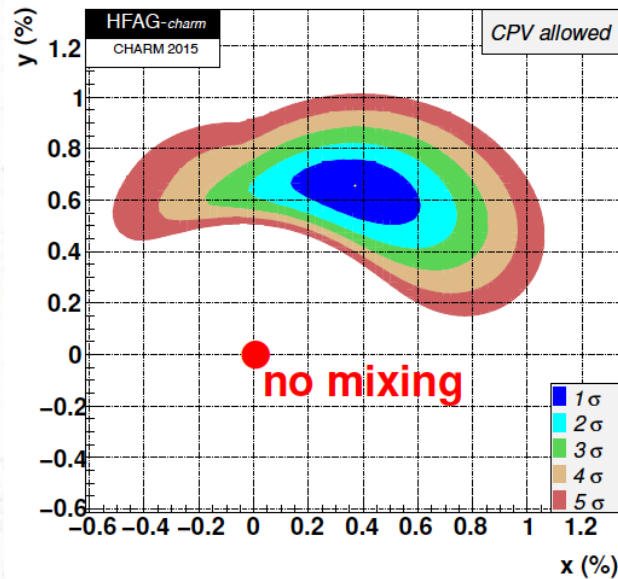
- LHCb now sees similar anomaly as Belle/Babar [PRL 115, 111803 (2015)]
- LHCb will produce a lot more useful info on this issue in future
- Will also study other tau modes (and in hadronic final states as well)

# Other existing deviations: $B \rightarrow K^* \mu \mu$



- Existing deviations will of course be investigated with more data
- More data means more than just increasing the significance of deviation: exploring further variables (e.g.  $A_{CP} \rightarrow$  access imaginary parts) and further channels will likely shed more light on the issue (e.g.  $b \rightarrow s$  modes [R. Barbieri et al., EPJC 76:67 (2016)] )
- NP or SM ? Either way, we are going to learn more *Physics*.

# Charm mixing/CPV



- LHCb the first single experiment to observe  $D^0$  mixing [PRL 110 (2013) 10180]
- CPV not yet observed. Interesting parameter related to top FCNC, not theory limited.
- Unique probe of up-quark sector
- **Huge promise from HL-LHC**

Analysis	Obs.	LHCb ( $3 \text{ fb}^{-1}$ )	LHCb ( $50 \text{ fb}^{-1}$ )
$K_S^0 \pi^+ \pi^-$	$x$	$2 \times 10^{-3}$	$4 \times 10^{-4}$
	$y$	$2 \times 10^{-3}$	$4 \times 10^{-4}$
	$ q/p $	0.2	0.04
	$\varphi$	$15^\circ$	$3^\circ$
$K^+ K^-$ , $\pi^+ \pi^-$	$y_{CP}$	$3 \times 10^{-4}$	$2 \times 10^{-5}$
	$A_\Gamma$	$3 \times 10^{-4}$	$2 \times 10^{-5}$
$K^+ \pi^-$	$x'^2$	$5 \times 10^{-5}$	$1 \times 10^{-5}$
	$y'$	$1 \times 10^{-3}$	$2 \times 10^{-4}$
	$ q/p $	0.25	0.05
	$A_D$	0.02	$4 \times 10^{-3}$
	$\varphi$	-	-

# A very rich program...

[LHCb-PUB-2014-40]

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

# ...and still room for improvement !

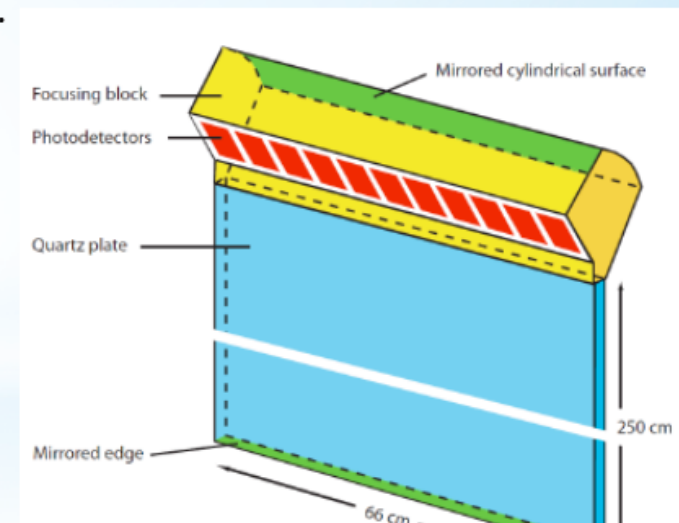
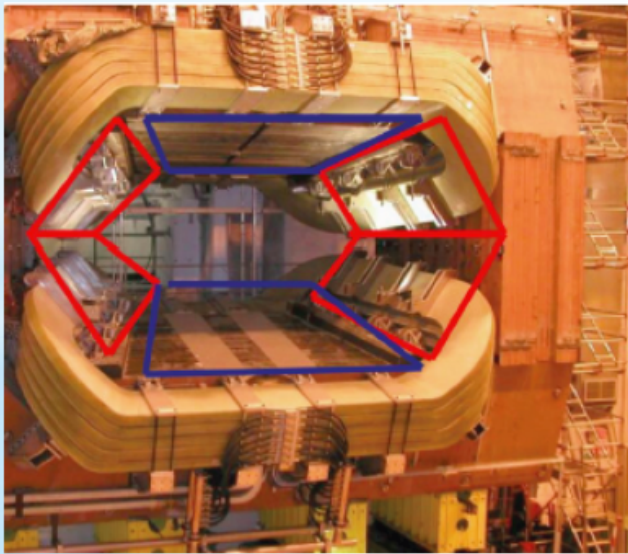
[LHCb-PUB-2014-40]

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	$q_0^2 A_{\text{FB}}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)$	10%	5%	<b>1.9%</b>	$\sim 7\%$
	$A_{\text{I}}(K \mu^+ \mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$	0.09	0.05	<b>0.017</b>	$\sim 0.02$
	$\mathcal{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-)/\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)$	14%	7%	<b>2.4%</b>	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$ ( $10^{-9}$ )	1.0	0.5	<b>0.19</b>	0.3
	$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	220%	110%	<b>40%</b>	$\sim 5\%$
Unitarity triangle angles	$\gamma(B \rightarrow D^{(*)} K^{(*)})$	$7^\circ$	$4^\circ$	<b><math>0.9^\circ</math></b>	negligible
	$\gamma(B_s^0 \rightarrow D_s^\mp K^\pm)$	$17^\circ$	$11^\circ$	<b><math>2.0^\circ</math></b>	negligible
	$\beta(B^0 \rightarrow J/\psi K_S^0)$	$1.7^\circ$	$0.8^\circ$	<b><math>0.31^\circ</math></b>	negligible
Charm	$A_\Gamma(D^0 \rightarrow K^+ K^-)$ ( $10^{-4}$ )	3.4	2.2	<b>0.4</b>	–
CP violation	$\Delta A_{CP}$ ( $10^{-3}$ )	0.8	0.5	<b>0.1</b>	–

# LHCb Upgrade Consolidation (Phase-1B)

**LHCb Phase-1b** upgrade during **LS3** aims for **moderate cost** improvements on the Phase-I detector. Possible improvements being investigated which have the potential to extend LHCb physics capabilities:

- Improve **tracking acceptance** for **low momentum** particles by installing **tracking stations** on the **dipole magnet internal side**.
- Improve **muon acceptance** by adding **muon chambers around the dipole magnet** using the **magnet yoke as shielding**.
- **Replace HCAL** with a **new shielding** for the muon chambers.
- **Innermost ECAL** region needs to be replaced during LS3. Rather than using existing spares, use **new technologies** (see later).
- **TORCH**: as standalone **PID detector**, or as a **timing device**, perhaps embedded in ECAL.
- **SciFi** may need some **module replacement** during LS3.
- ...



F. Teubert, BEAUTY 2016

# Possibility of LHCb Luminosity increase

Levelled luminosity LHCb [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	Opt fill length (IP1/5) [h]	Integrated luminosity ATLAS/CMS [ $\text{fb}^{-1}/\text{y}$ ]	Integrated luminosity LHCb [ $\text{fb}^{-1}/\text{y}$ ]	$\beta^*$ IP8 [m]	Levelling time IP8 [h]
0.2 (nom.)	9.3	261	10.4	3	9
1	9.1	258	28	3	0.5
1	9	257	37	2	3
1	8.8	256	47	1	6
2	9.1	258	28	3	0
2	8.9	257	41	2	0
2	8.5	253	70	1	2

G.Arduini, Preliminary

- Thanks to excellent efforts from the LHC team, the possibility of delivering up to  $2 \cdot 10^{34}$  to IP8 (LHCb) has been studied. This would require some extra absorbers to protect machine elements.
- Preliminary results allow for up to **300 fb<sup>-1</sup>** to be collected by LHCb – a **6x** enhancement – without perturbation to ATLAS/CMS.
- Calls for substantially upgraded detector, but unlocks great possibilities

# *LHCb upgrades being considered for future running at $2 \times 10^{34}$*

- VELO: double inner radius to survive radiation - or (better) replace with thinner sensor, smaller pixels
- Supplement downstream SciFi tracking with Silicon (granularity)
- Restructure PID (muon and RICH detectors)
- Upgraded calorimetry, possibly with TOF capabilities (TORCH)
- Timing of track hits to 200 ps to keep PV assignment mismatch at current levels

[→ see ["Beyond the LHCb Phase-1 Upgrade" workshop](#), 6/4/2016]

*To summarize ...*



*...also for Flavor !*