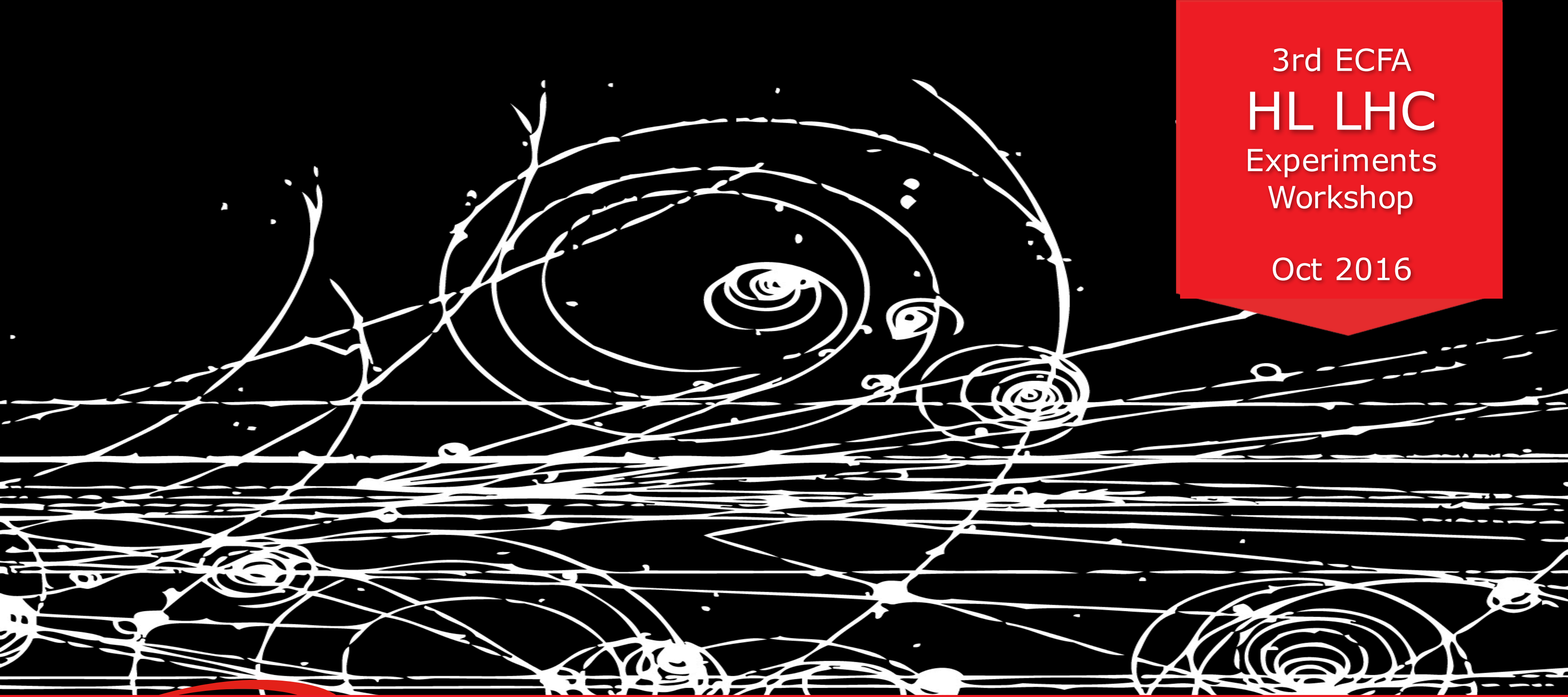


3rd ECFA
HL LHC
Experiments
Workshop

Oct 2016

Heavy Flavour Physics

at high luminosity

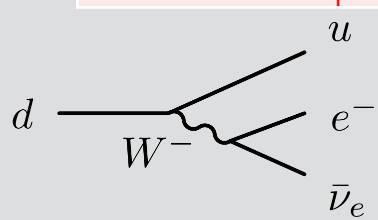
Niels Tuning
on behalf of LHCb, ATLAS, CMS

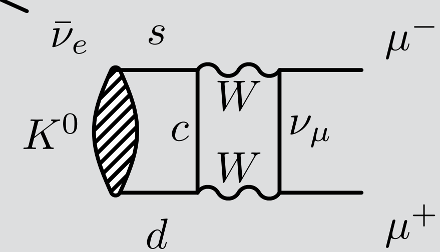
Nikhef

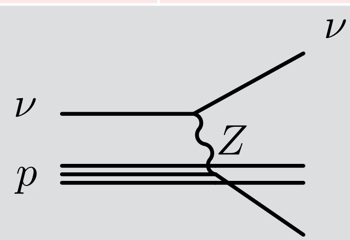
Heavy Flavour = Precision search for NP

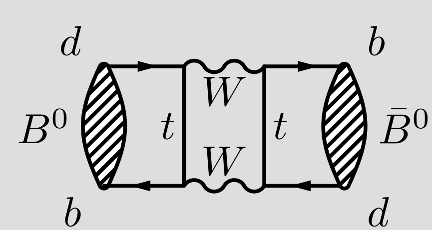
- Historical record of indirect discoveries:

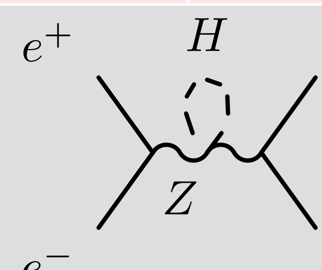
Particle	Indirect			Direct		
ν	β decay		1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay		1932	*W→eν*	UA1, UA2	1983
c	$K^0 \to \mu\mu$	GIM	1970	J/ψ	Richter, Ting	1974
b	CPV $K^0 \to \pi\pi$	CKM, 3rd gen	1964/72	*Y*	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z \to e^+e^-$	UA1	1983
t	B mixing	ARGUS	1987	$t \to Wb$	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	$H \to 4\mu/\gamma\gamma$	CMS, ATLAS	2012
?	**What's next ?**		?			?







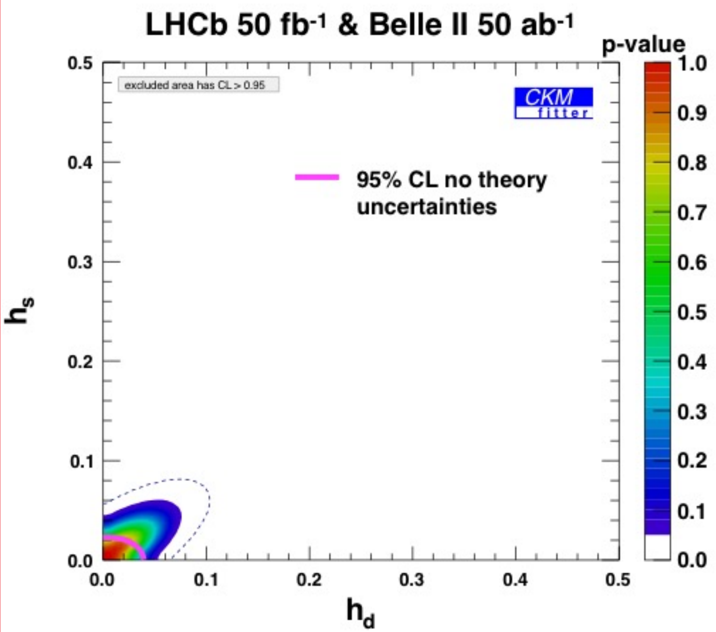




Heavy Flavour = Precision search for NP

- Depending on your model, sensitive to multi-TeV scales, eg:

[Charles et al., 1309.2293]



$$M_{12}^q = (M_{12}^q)_{\rm SM}\left(1 + h_q e^{2i\sigma_q}\right)$$

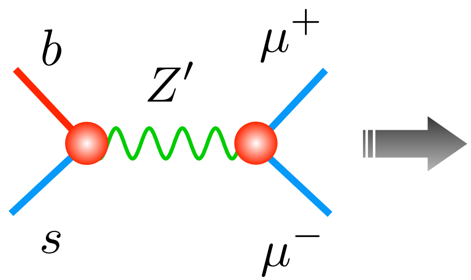
h_q parametrizes magnitude of NP in B_q mixing

$$h_d \lesssim 5\% \quad \Rightarrow \quad \Lambda \gtrsim \begin{cases} 2\cdot 10^3\,\text{TeV}, & \text{anarchic tree} \\ 1.4\,\text{TeV}, & \text{MFV loop} \end{cases}$$

From Uli Haisch, 31 Aug 2016

Heavy Flavour = Precision search for NP

- Depending on your model, sensitive to multi-TeV scales, eg:



$$\mu_{B_s\to\mu^+\mu^-} \simeq 1 \pm \frac{4\pi}{g^2\,|V_{tb}^* V_{ts}|^2}\,\frac{v^2}{\Lambda^2}$$

$\mu_{B\to\mu\mu}$ is ratio BR^{exp}/BR^{SM}

$$\Lambda \gtrsim \frac{v}{\sqrt{0.2}} \times \begin{cases} \dfrac{\sqrt{4\pi}}{g\,|V_{tb}^* V_{ts}|} \\ 1 \end{cases} \simeq \begin{cases} 50\,\mathrm{TeV}\,, & \text{anarchic tree} \\ 0.6\,\mathrm{TeV}\,, & \text{MFV loop} \end{cases}$$

From Uli Haisch, 31 Aug 2016

Outline

- Introduction
  - Timeline HL-LHC: Detector improvements

- Beauty: Rare Decays
  - Very rare: $B^0_{(s)} \rightarrow \mu\mu$ and f_s/f_d
  - FCNC: $B^0 \rightarrow K^*\mu\mu$
  - Searches: Dark photons, Majorana neutrino's

- Beauty: CP violation
  - CPV in B_s^0: φ_s, A_{fs} : $B^0_s \rightarrow J/\psi\varphi$, $B^0_s \rightarrow \varphi\varphi$, $B^0_{(s)} \rightarrow D_{(s)}X\mu\nu$
  - CKM angles: γ, β : $B \rightarrow DK$, $B^0 \rightarrow J/\psi K_S$

- Charm and Strange
  - Charm mixing: $D^{0*} \rightarrow D^0(hh)\pi$
  - Strange rare decays: $K_S{}^0 \rightarrow \mu\mu$, $K_S{}^0 \rightarrow \pi\pi ee$, $\Sigma^+ \rightarrow p\mu\mu$

- *("Top is not a heavy flavour")*

Preparatory workshop
(31 Aug 2016)

- https://indico.cern.ch/event/545639/timetable/

Heavy Flavour physics at HL-LHC

31 Aug 2016, 09:30 → 18:00 Europe/Zurich

222-R-001 - Filtration Plant (CERN)

- For details on detector upgrades, see presentations from yesterday morning:
  – Chris Parkes (LHCb)
  – Brian Petersen (ATLAS)
  – Meenakshi Narain (CMS)

09:30 → 10:00	What would permille constraints on flavour observables bring us? Speaker: Ulrich Andreas Haisch (University of Oxford (GB)) HF_HL-LHC_16_U_	30m
10:00 → 10:30	CMS : overview of HF activities and upgrade plans Speaker: Kai-Feng Chen (National Taiwan University (TW)) hf_at_hllhc-2016_	30m
10:30 → 11:00	Coffee	30m
11:00 → 11:30	ATLAS : overview of HF activities and upgrade plans Speaker: Pavel Reznicek (Charles University (CZ)) ATLAS_BphysHL_	30m
11:30 → 12:00	LHCb : overview of HF activities and upgrade plans Speaker: Johannes Albrecht (Technische Universitaet Dortmund (DE)) albrecht_v1.1.pdf	30m
12:00 → 13:30	Lunch	1h 30m
13:30 → 14:00	Complementarity between LHC experiments, Kaon physics, BES III, direct LFV searches, and Belle II Speakers: Jernej F. Kamenik (Jozef Stefan Institute) , Jernej Fesel Kamenik (Jozef Stefan Institute (SI)) kamenik.pdf	30m
14:00 → 14:20	CMS : what does the 40 MHz track trigger bring us? Speaker: Fabrizio Palla (Universita di Pisa & INFN (IT)) HL-LHC for ECFA_	20m
14:20 → 14:40	LHCb : potential for kaon physics with a full upfront reconstruction Speaker: Marc Olivier Bettler (CERN) Bettler_20160830_	20m
14:40 → 15:00	Potential for rare decay measurements in HL-LHC period Speaker: Patrick Haworth Owen (Universitaet Zuerich (CH)) RD_HLLHC.pdf	20m
15:00 → 15:20	Coffee	20m
15:20 → 15:40	Potential for CPV measurements in the HL-LHC period Speaker: Simon Akar (CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France) CPV_HLLHC2016_	20m
15:40 → 16:10	How well can we control detector effects for precision measurements in the HL-LHC period? Speaker: Andrea Contu (CERN) AContu_HFATHL_	30m
16:10 → 17:00	Open discussion : how do we make the most of our detectors?	50m

Schedule

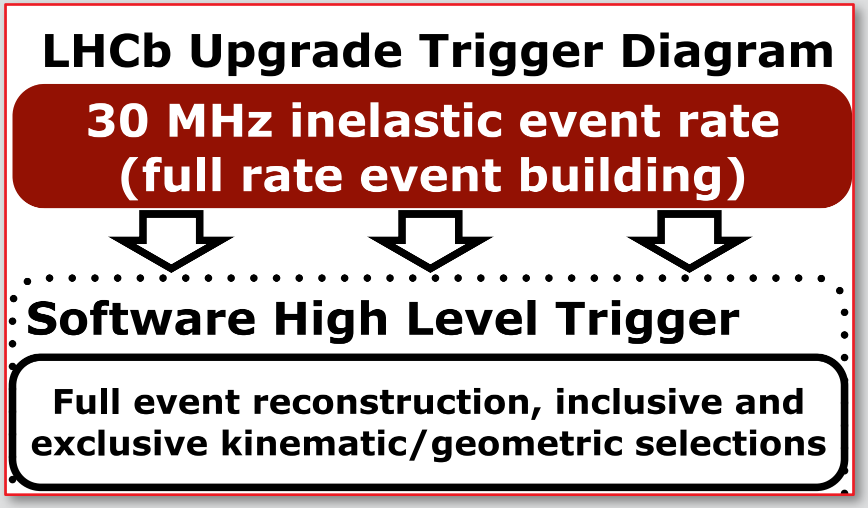
	2019 2020	2021 2022 2023	2024 2025 2026	2027 2028 2029	2030 2031	2032 203+
		Run III		Run IV		Run V
	LS2		LS3		LS4	
	LHCb 40 MHz UPGRADE	$L = 2 \times 10^{33}$	**LHCb Consolidation**	$L = 2 \times 10^{33}$ $50\ fb^{-1}$	**LHCb Ph II UPGRADE ***	$L = 2 \times 10^{34}$ $300\ fb^{-1}$
	ATLAS Phase I Upgr	$L = 2 \times 10^{34}$	**ATLAS Phase II UPGRADE**	**HL-LHC** $L = 5 \times 10^{34}$	**ATLAS**	**HL-LHC** $L = 5 \times 10^{34}$
	CMS Phase I Upgr	$300\ fb^{-1}$	**CMS Phase II UPGRADE**		**CMS**	$3000\ fb^{-1}$
	Belle II	$5\ ab^{-1}$ $L = 8 \times 10^{35}$	$50\ ab^{-1}$			

LHC schedule: Frederick Bordry, Jun 2015

Schedule: LS2 – 2019/2020

	2019 2020	2021 2022 2023	2024 2025 2026	2027 2028 2029	2030 2031	2032 203+
		Run III		Run IV		Run V
	LS2		LS3		LS4	
	LHCb 40 MHz UPGRADE	$L = 2 \times 10^{33}$	LHCb Consolidation	$L = 2 \times 10^{33}$ $50\ fb^{-1}$	LHCb Ph II UPGRADE *	$L = 2 \times 10^{34}$ $300\ fb^{-1}$
	ATLAS Phase I Upgr	$L = 2 \times 10^{34}$	ATLAS Phase II UPGRADE	HL-LHC $L = 5 \times 10^{34}$	ATLAS	HL-LHC $L = 5 \times 10^{34}$
	CMS Phase I Upgr	$300\ fb^{-1}$	CMS Phase II UPGRADE		CMS	$3000\ fb^{-1}$
Belle II	$5\ ab^{-1}$	$L = 8 \times 10^{35}$	$50\ ab^{-1}$			

- LHCb Upgrade
  - Upgrade to 40 MHz readout
  - New VELO: strips → pixel
  - New SciFi tracker
- ATLAS Phase 1
  - New small muon wheel
  - Fast tracking trigger at level 1.5
- CMS Phase 1
  - Pixel tracker



Schedule: LS2 – 2019/2020

2019 2020	2021 2022 2023	2024 2025 2026	2027 2028 2029	2030 2031	2032 203+
	Run III		Run IV		Run V
LS2		**LS3**		**LS4**	
LHCb 40 MHz UPGRADE	$L = 2 \times 10^{33}$	**LHCb Consolidation**	$L = 2 \times 10^{33}$ $50\ fb^{-1}$	**LHCb Ph II UPGRADE ***	$L = 2 \times 10^{34}$ $300\ fb^{-1}$
ATLAS Phase I Upgr	$L = 2 \times 10^{34}$	**ATLAS Phase II UPGRADE**	**HL-LHC** $L = 5 \times 10^{34}$	**ATLAS**	**HL-LHC** $L = 5 \times 10^{34}$
CMS Phase I Upgr	$300\ fb^{-1}$	**CMS Phase II UPGRADE**		**CMS**	$3000\ fb^{-1}$
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- LHCb Upgrade
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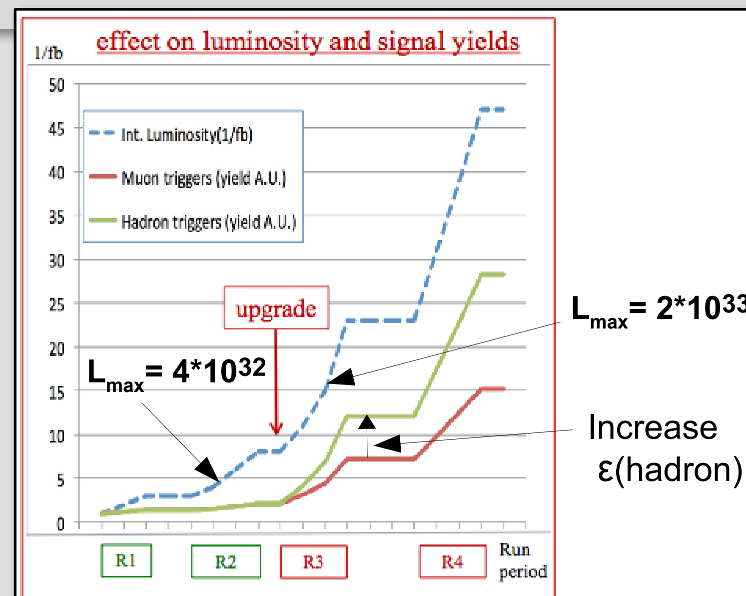
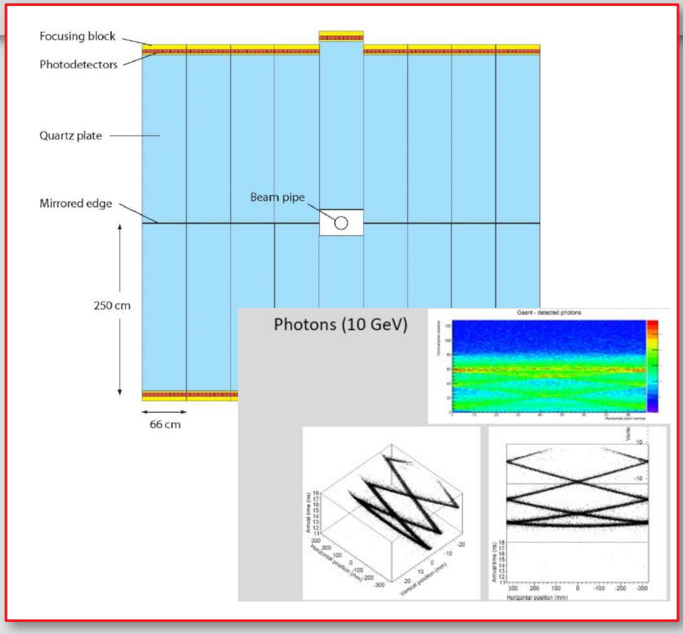
  - Pixel tracker



Schedule: LS3 – 2024/2026

2019 2020	2021 2022 2023	2024 2025 2026	2027 2028 2029	2030 2031	2032 203+
	Run III		Run IV		Run V
LS2		LS3		LS4	
LHCb **40 MHz** **UPGRADE**	$L = 2 \times 10^{33}$	**LHCb Consolidation**	$L = 2 \times 10^{33}$ $50\ fb^{-1}$	**LHCb Ph II UPGRADE ***	$L = 2 \times 10^{34}$ $300\ fb^{-1}$
ATLAS Phase I Upgr	$L = 2 \times 10^{34}$	**ATLAS Phase II UPGRADE**	**HL-LHC** $L = 5 \times 10^{34}$	**ATLAS**	**HL-LHC** $L = 5 \times 10^{34}$
CMS Phase I Upgr	$300\ fb^{-1}$	**CMS Phase II UPGRADE**		**CMS**	$3000\ fb^{-1}$
Belle II	$5\ ab^{-1}$ $L = 8 \times 10^{35}$	$50\ ab^{-1}$			

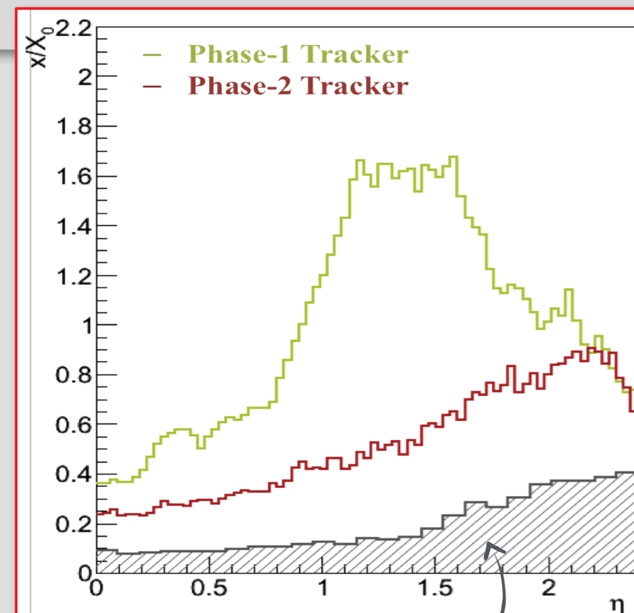
- LHCb consolidation possibilities include:
  - Improve PID: time-of-flight TORCH
  - Increase acceptance: Magnet tracking
  - Enhance ECAL
  - Supplement SciFi tracker with Si



Schedule: LS3 – 2024/2026

	2019–2020	2021–2023	2024–2026	2027–2029	2030–2031	2032–203+
		Run III		Run IV		Run V
	LS2		LS3		LS4	
LHCb	**LHCb** 40 MHz **UPGRADE**	$L = 2 \times 10^{33}$	**LHCb Consolidation**	$L = 2 \times 10^{33}$ $50\ fb^{-1}$	**LHCb Ph II UPGRADE ***	$L = 2 \times 10^{34}$ $300\ fb^{-1}$
ATLAS	**ATLAS Phase I Upgr**	$L = 2 \times 10^{34}$ $300\ fb^{-1}$	**ATLAS Phase II UPGRADE**	**HL-LHC** $L = 5 \times 10^{34}$	**ATLAS**	**HL-LHC** $L = 5 \times 10^{34}$ $3000\ fb^{-1}$
CMS	**CMS Phase I Upgr**		**CMS Phase II UPGRADE**		**CMS**	
Belle II		$5\ ab^{-1}$ $L = 8 \times 10^{35}$	$50\ ab^{-1}$			

- CMS Upgrade Phase 2
  - New Si tracker
  - Hardware track trigger at L1
    - Low pt dimuon $\sigma_M \sim 70$ MeV
  - Improved muon: RPC and GEM, $\eta<3$



Schedule: LS3 – 2024/2026

2019 – 2020	2021 – 2023	2024 – 2026	2027 – 2029	2030 – 2031	2032 – 203+
	Run III		Run IV		Run V
LS2		LS3		LS4	
LHCb 40 MHz UPGRADE	$L = 2 \times 10^{33}$	**LHCb Consolidation**	$L = 2 \times 10^{33}$ $50\ fb^{-1}$	**LHCb Ph II UPGRADE ***	$L = 2 \times 10^{34}$ $300\ fb^{-1}$
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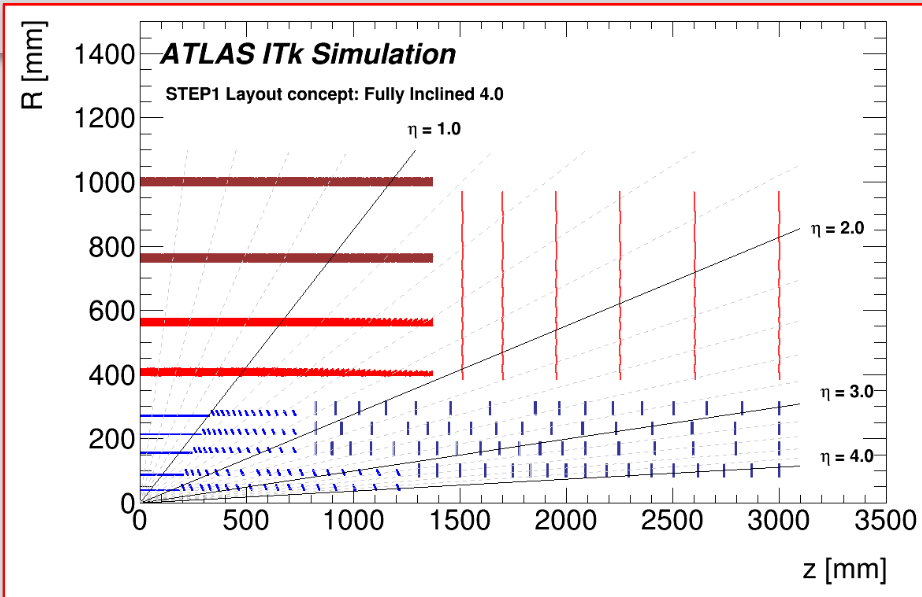
CMS Phase I Upgr		**CMS Phase II UPGRADE**		**CMS**	
Belle II	$5\ ab^{-1}$ $L = 8 \times 10^{35}$	$50\ ab^{-1}$			

- ATLAS Upgrade Phase 2
  - New Si tracker ITk
  - Full granularity calorimeter
  - Upgrade part of muon, fast trigger



Schedule: LS4 – 2030/2031

2019–2020	2021–2023	2024–2026	2027–2029	2030–2031	2032–203+
LS2	Run III	**LS3**	Run IV	**LS4**	Run V
LHCb **40 MHz UPGRADE**	$L = 2 \times 10^{33}$	**LHCb Consolidation**	$L = 2 \times 10^{33}$ $50\ fb^{-1}$	**LHCb Ph II UPGRADE ***	$L = 2 \times 10^{34}$ $300\ fb^{-1}$
ATLAS Phase I Upgr	$L = 2 \times 10^{34}$	**ATLAS Phase II UPGRADE**	**HL-LHC** $L = 5 \times 10^{34}$	**ATLAS**	**HL-LHC** $L = 5 \times 10^{34}$
CMS Phase I Upgr	$300\ fb^{-1}$	**CMS Phase II UPGRADE**		**CMS**	$3000\ fb^{-1}$
Belle II	$5\ ab^{-1}$ $L = 8 \times 10^{35}$	$50\ ab^{-1}$			

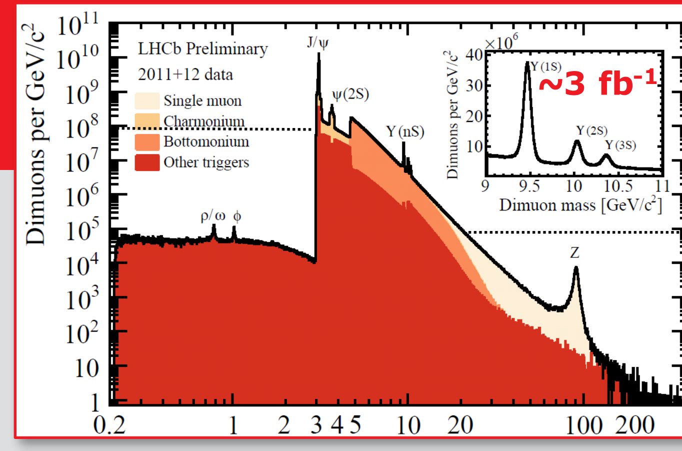
* Thinking underway for LHCb detector upgrades for $2 \times 10^{34}\ cm^{-2}s^{-1}$

- Considerations:
  - VELO: radiation hardness
  - Restructure MUON + RICH
  - Fast timing required to cope with high pile-up

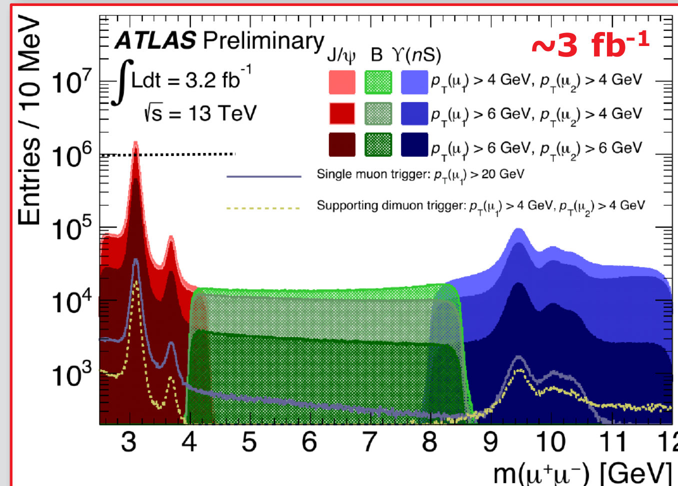
Di-muon trigger for *B*

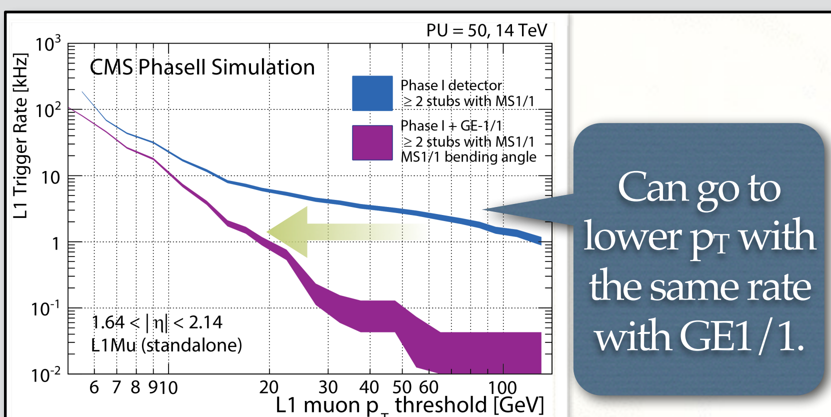
- Crucial to trigger at low p_T
- Resolution improves S/B

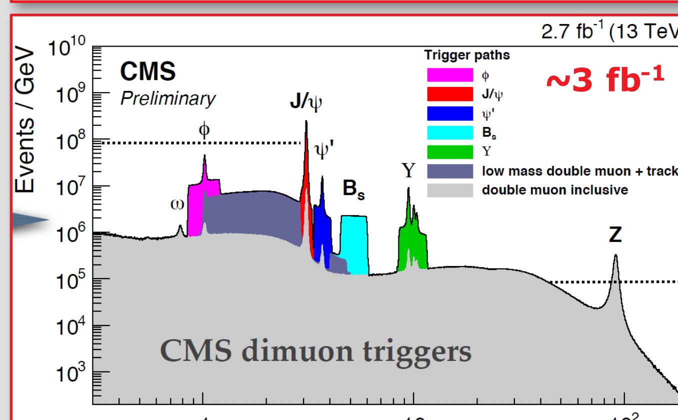
- Improvements by 2025
  - LHCb
    - 40 MHz software trigger
  - ATLAS
    - Fast tracking trigger
    - New Inner Tracker
  - CMS
    - Muon p>3 GeV, η<3
    - low p_T track trigger for phase II



LHCb-CONF-2016-005



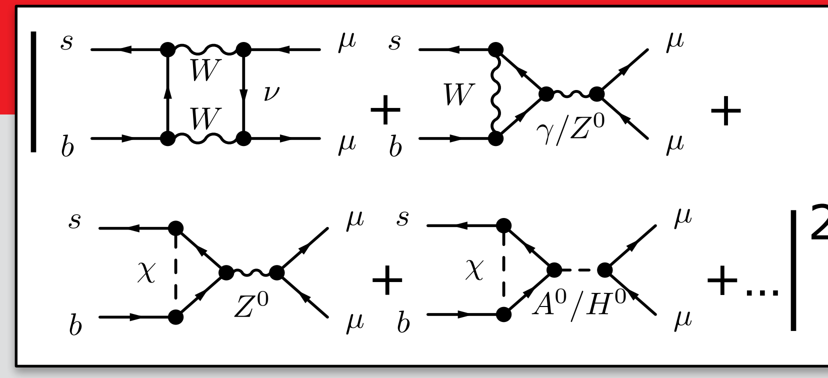




Outline

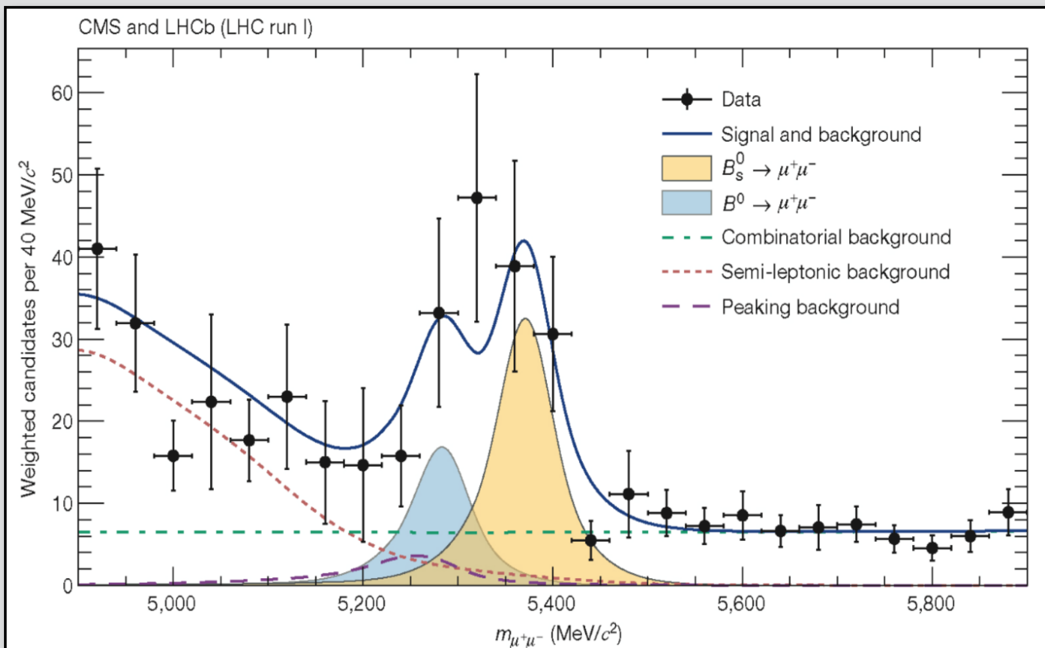
- Introduction
  - Timeline HL-LHC: Detector improvements
- Beauty: Rare Decays
  - Very rare: $B^0_{(s)} \rightarrow \mu\mu$ and f_s/f_d
  - FCNC: $B^0 \rightarrow K^*\mu\mu$
  - Searches: Dark photons, Majorana neutrino's
- Beauty: CP violation
  - CPV in B_s^0: φ_s, A_{fs} : $B^0_s \rightarrow J/\psi\varphi$, $B^0_s \rightarrow \varphi\varphi$, $B^0_{(s)} \rightarrow D_{(s)}X\mu\nu$
  - CKM angles: γ, β : $B \rightarrow DK$, $B^0 \rightarrow J/\psi K_S$
- Charm and Strange
  - Charm mixing: $D^{0*} \rightarrow D^0(hh)\pi$
  - Strange rare decays: $K_S{}^0 \rightarrow \mu\mu$, $K_S{}^0 \rightarrow \pi\pi ee$, $\Sigma^+ \rightarrow p\mu\mu$
- *("Top is not a heavy flavour")*

$B^0_{(s)} \rightarrow \mu\mu$



- *"Golden channel for SUSY"*

- Decay discovered in 2015



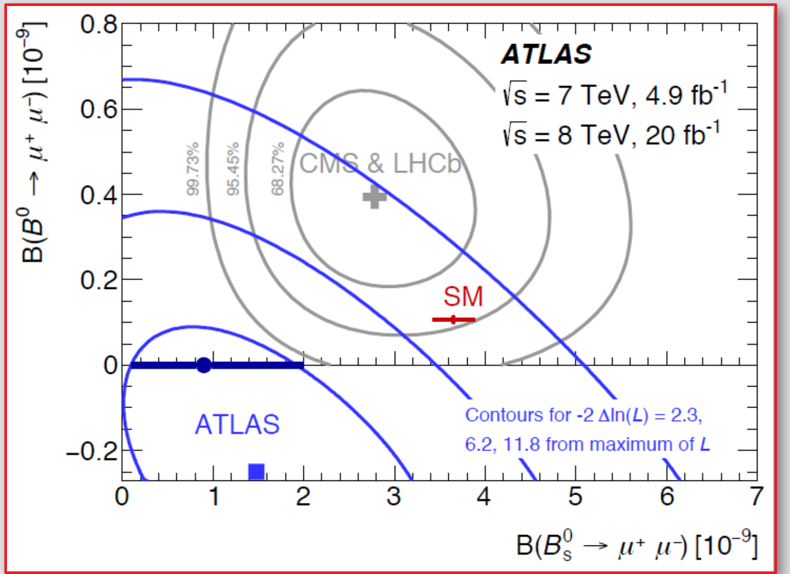
CMS & LHCb, Nature 522, 68–72 (2015)

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(2.8\,^{+0.7}_{-0.6}\right) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(3.9\,^{+1.6}_{-1.4}\right) \times 10^{-10}$$

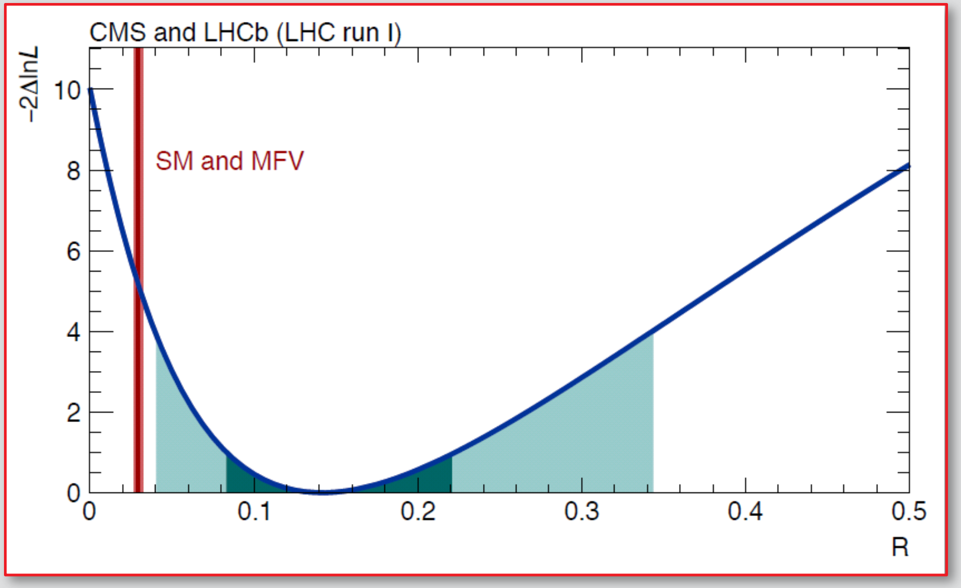
$B^0{}_{(s)} \rightarrow \mu\mu$

- BR($B^0 \rightarrow \mu\mu$): a little high?
  - First evidence at 3.0σ
  - 2.3σ above SM prediction:
    - $R_{SM} = 0.030 \pm 0.003$
    - $R_{exp} = 0.140^{+0.080}_{-0.060}$

$$R = \frac{\mathcal{B}(B^0 \to \mu\mu)}{\mathcal{B}(B^0_s \to \mu\mu)} = 0.14^{+0.08}_{-0.06}$$



ATLAS, EPJ C76 (2016) 513



LHCb & CMS, Nature 522, 68–72 (2015)

$B^0{}_{(s)} \to \mu\mu$: projections

- Statistics

(3 ab^{-1})

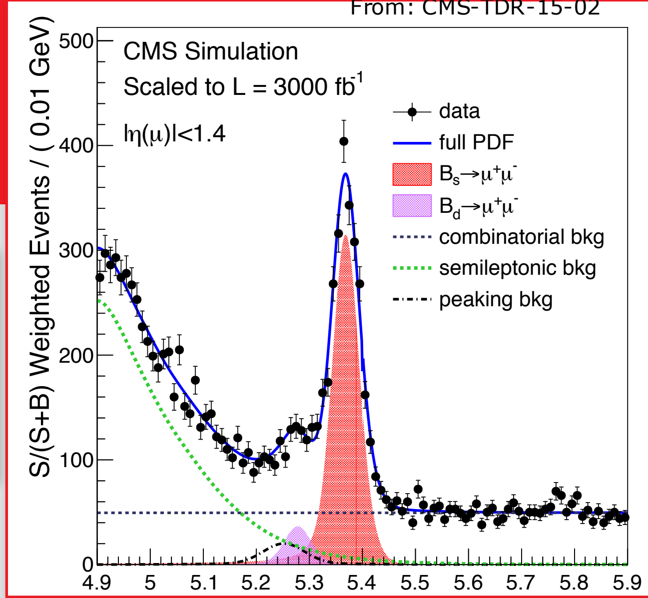
	CMS	LHCb (50fb-1)	LHCb (300fb-1)
N(Bd)	271	40	240
N(Bs)	2250	400	2400

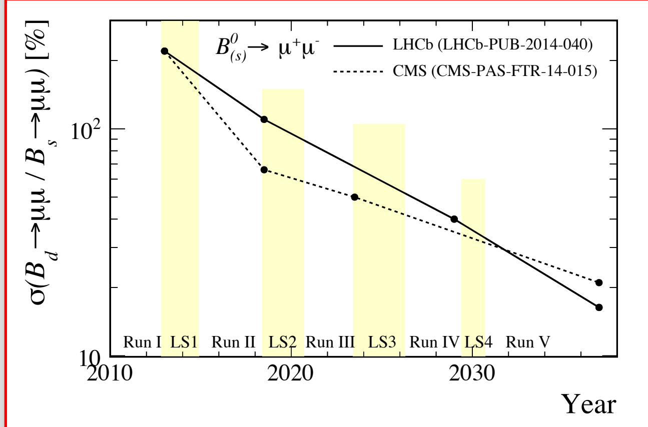
From: CMS-PAS-FTR-14-015

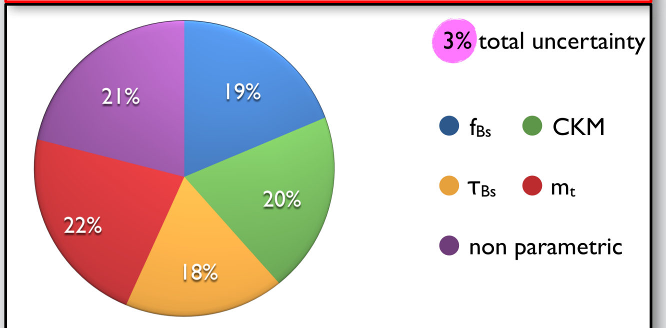
- Systematics
  - ATLAS+CMS: improved mass resolution
  - Limiting: f_s/f_d

- Theoretical prediction BR($B^0{}_{(s)} \to \mu\mu$)
  - CKM elements, B decay constants
    - Accuracy expected to increase with improved lattice
    - Future unc. might reach ~3% :
  - Exp. uncertainty will probably not decrease to theoretical uncertainty

From: CMS-TDR-15-02







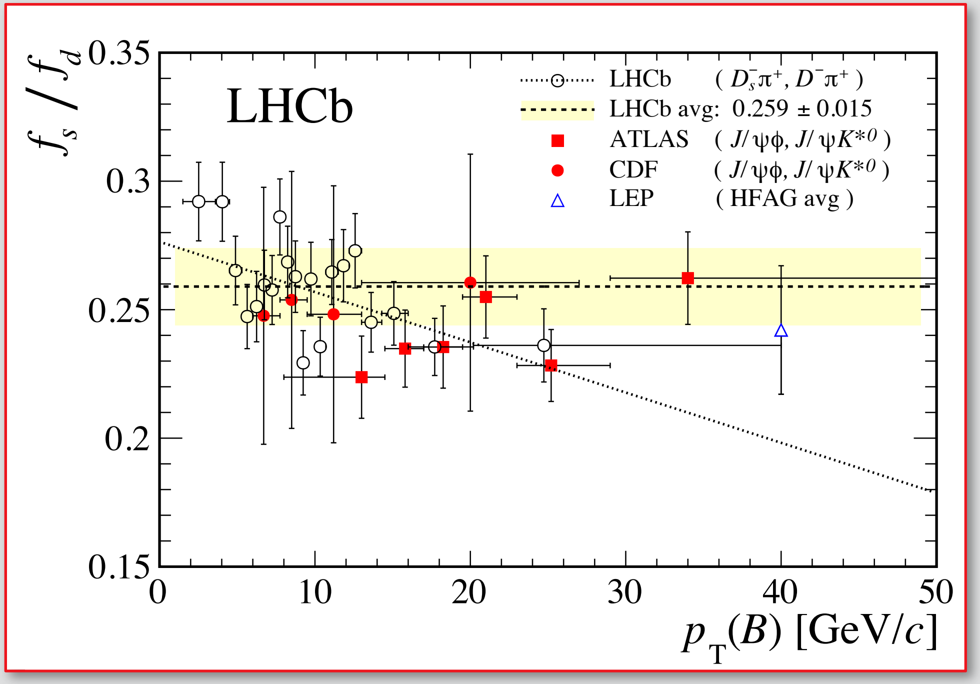
From: U.Haisch and USQCD Coll. http://www.usqcd.org/documents/13flavor.pdf

$B^0{}_{(s)} \rightarrow \mu\mu$: dominant systematic : f_s/f_d

- Dominant systematic uncertainty for BR($B_s^0 \rightarrow \mu\mu$)
- Relies on theoretical knowledge of ratio of BRs:
  - Semileptonic: $\Gamma(B_s^0 \rightarrow \mu X) = \Gamma(B \rightarrow \mu X)$
  - Hadronic: $$\frac{\mathrm{BR}(\bar{B}_s^0 \to D_s^+\pi^-)}{\mathrm{BR}(\bar{B}_d^0 \to D^+K^-)} = \frac{\Phi(D_s\pi)}{\Phi(DK)}\frac{\tau_{B_s}}{\tau_{B_d}}\left|\frac{V_{ud}}{V_{us}}\right|^2\left(\frac{f_\pi}{f_K}\right)^2\left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)}\right]^2\left|\frac{a_1(D_s\pi)}{a_1(D_dK)}\right|^2 = 14.2 \pm 1.3(\mathrm{FF})$$

    Fleischer, Serra, NT, PRD82 (2010) 034038
  - $B \rightarrow J/\psi X$: $$R^{\mathrm{th.}\prime}_{s/d} \equiv \frac{\mathrm{BR}(B_s \to J/\psi\phi)}{\mathrm{BR}(B_d \to J/\psi K^{*0})} \approx 0.83^{+0.03}_{-0.02}(\omega_B)^{+0.01}_{-0.00}(f_M)^{+0.01}_{-0.02}(a_i)^{+0.01}_{-0.02}(m_c)[0.83^{+0.03}_{-0.03}]$$

    Liu, Wang, Xie, PRD89 (2014) 094010



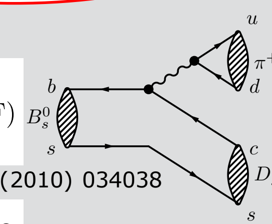
$B^0_{(s)} \to \mu\mu$: dominant systematic : f_s/f_d

- Dominant systematic uncertainty for BR($B_s^0 \to \mu\mu$)
- Relies on theoretical knowledge of ratio of BRs:
  - Semileptonic: $\Gamma(B_s^0 \to \mu X) = \Gamma(B \to \mu X)$
  - Hadronic:

$$\left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)}\right] = 1.046 \pm 0.044(\text{stat}) \pm 0.015(\text{sys})$$

Bailey et al, PRD.85(2012)114502

$$\frac{\text{BR}(\bar{B}_s^0 \to D_s^+\pi^-)}{\text{BR}(\bar{B}_d^0 \to D^+K^-)} = \frac{\Phi(D_s\pi)}{\Phi(DK)}\frac{\tau_{B_s}}{\tau_{B_d}}\left|\frac{V_{ud}}{V_{us}}\right|^2\left(\frac{f_\pi}{f_K}\right)^2\left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)}\right]^2\left|\frac{a_1(D_s\pi)}{a_1(D_dK)}\right|^2 = 14.2 \pm 1.3(\text{FF})$$

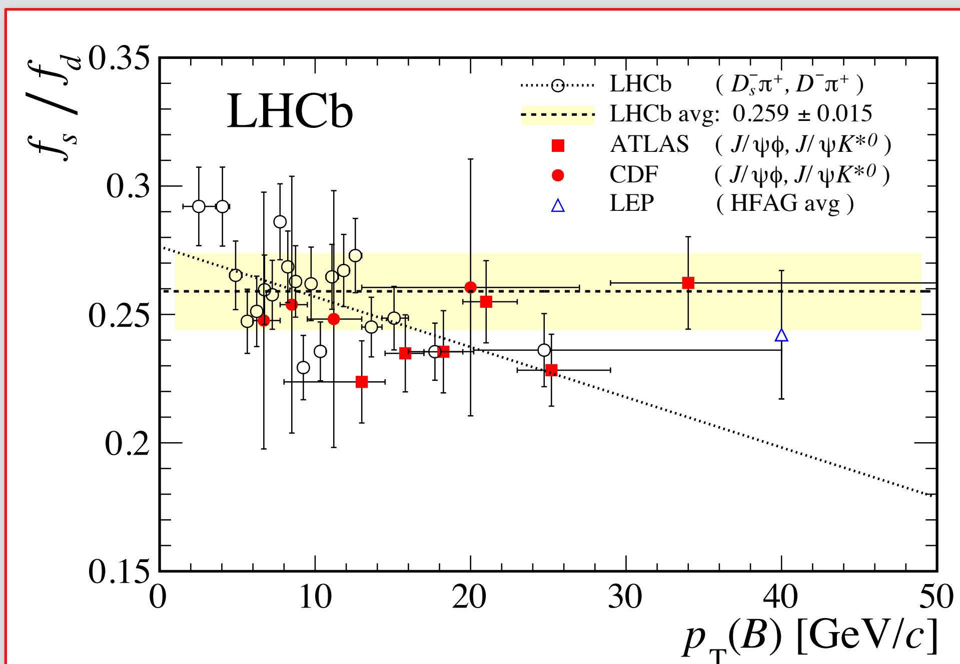


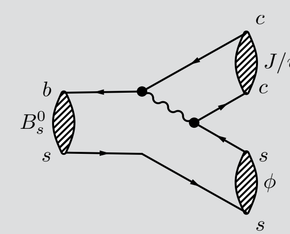
Fleischer, Serra, NT, PRD82 (2010) 034038

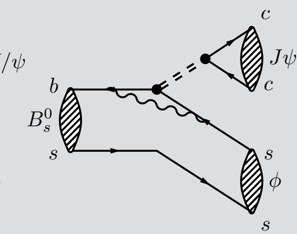
  - B→J/ψX:

$$R^{\text{th.}\prime}_{s/d} \equiv \frac{\text{BR}(B_s \to J/\psi\phi)}{\text{BR}(B_d \to J/\psi K^{*0})} \approx 0.83^{+0.03}_{-0.02}(\omega_B)^{+0.01}_{-0.00}(f_M)^{+0.01}_{-0.02}(a_i)^{+0.01}_{-0.02}(m_c)[0.83^{+0.03}_{-0.03}]$$

Liu, Wang, Xie, PRD89 (2014) 094010



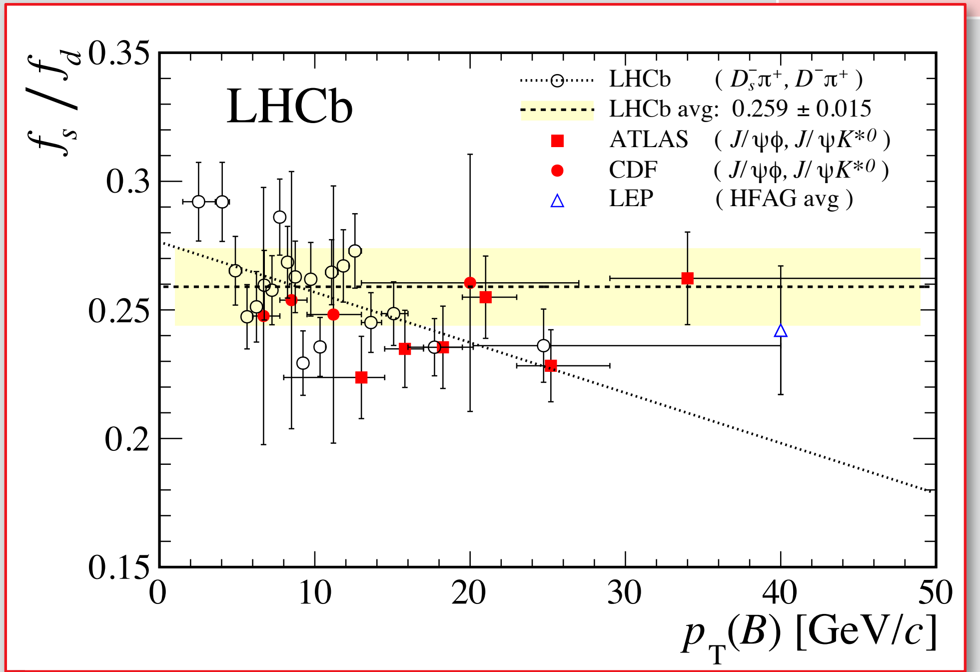




$B^0_{(s)} \rightarrow \mu\mu$: dominant systematic : f_s/f_d

- Dominant systematic uncertainty for BR($B_s^0 \rightarrow \mu\mu$)
- Measurements:

	Normalization	Dependence
LHCb	Semileptonic Phys. Rev. D 85 (2012) 032008 $B \rightarrow Dh$ Phys. Rev. Lett. 107 (2011) 211801 LHCb-CONF-2013-011	$B \rightarrow Dh$ JHEP 04 (2013) 001
CDF	Semileptonic Phys. Rev. D 77, 072003 (2008).	$B \rightarrow J/\psi X$ Public Note 10795
ATLAS	$B \rightarrow J/\psi X$	$B \rightarrow J/\psi X$ Phys.Rev.Lett. 115 (2015) 262001



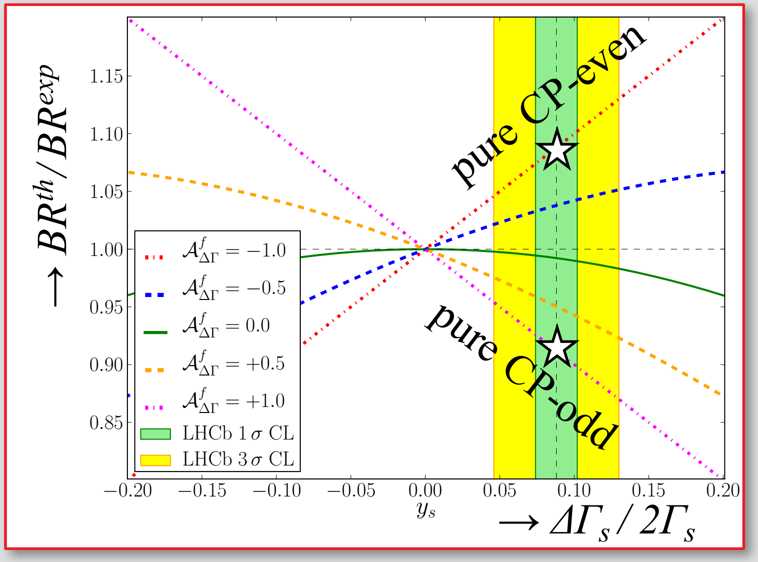
- Possible improvements:
  - $B_{(s)} \rightarrow D_{(s)}$ form factors: Lattice
  - $B_s \rightarrow D_s$ form factors: LHCb
  - BR($B \rightarrow DX\mu\nu$): BelleII
  - BR($D_{(s)}$): BESIII

$B^0_{(s)} \rightarrow \mu\mu$: effective lifetime

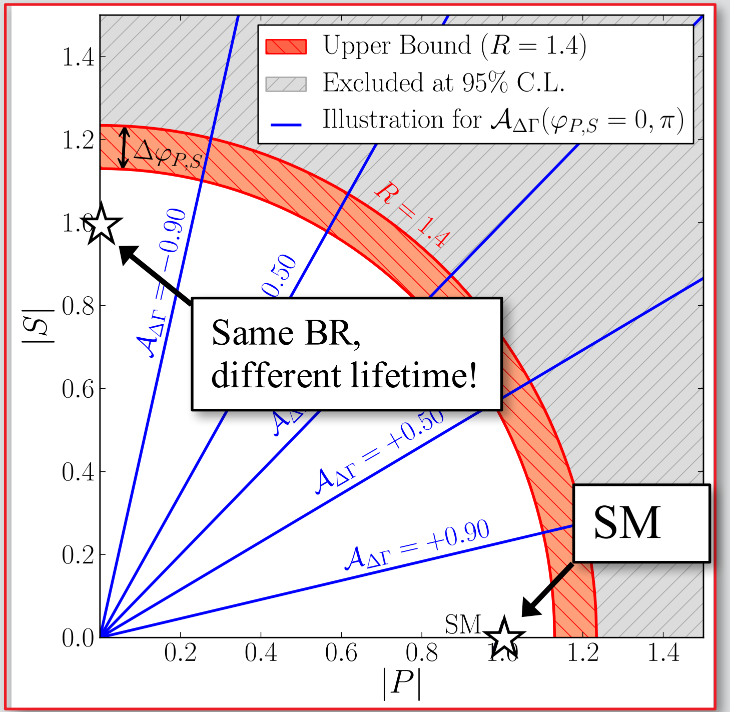
- Lifetime difference $B_s{}^0{}_H$ (CP-) and $B_s{}^0{}_L$ (CP+):

- SM: P-amplitude dominates, selecting CP-odd
- Different CP admixture affects effective lifetime
  - possibly not affecting the BR, when |S| and $A_{\Delta\Gamma}$ compensate…

➢ Could be due to scalar amplitude |S| from NP



De Bruyn, Fleischer, NT, et al. Phys.Rev. D86 (2012) 014027



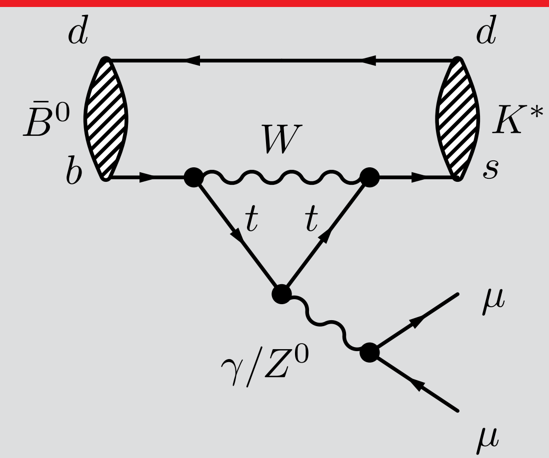
De Bruyn, Fleischer, NT, et al. Phys. Rev. Lett. 109, 041801 (2012)

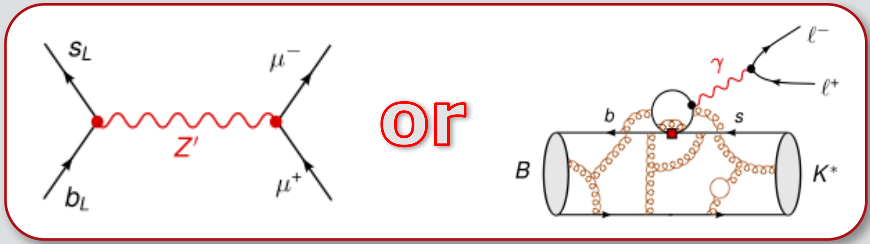
$$R \equiv \frac{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{exp}}}{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} = \left[\frac{1 + \mathcal{A}_{\Delta\Gamma} y_s}{1 - y_s^2}\right] \left(|P|^2 + |S|^2\right)$$

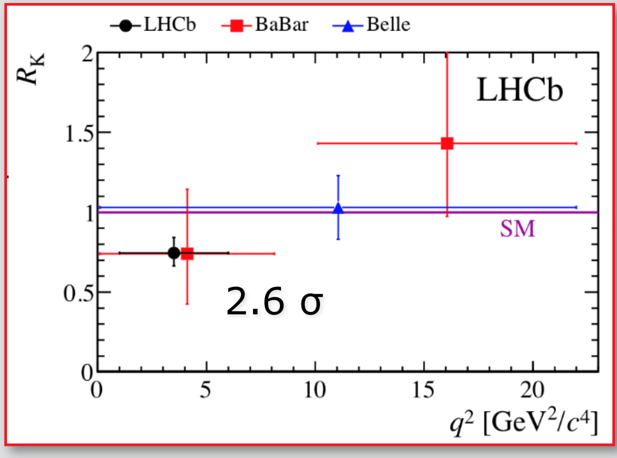
$b \rightarrow sll$ (i.e. $B^0 \rightarrow K^*\mu\mu$ and friends)

- FCNC: EW penguin

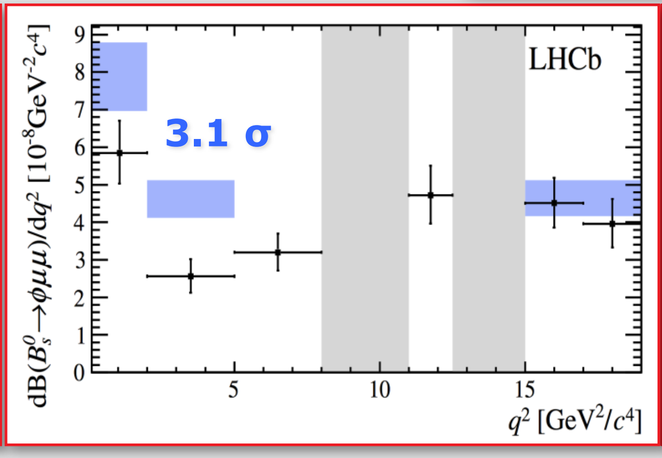
- Curious tensions:
  - Lepton flavour universality
  - Decay rates
  - Angular distributions, P_5'



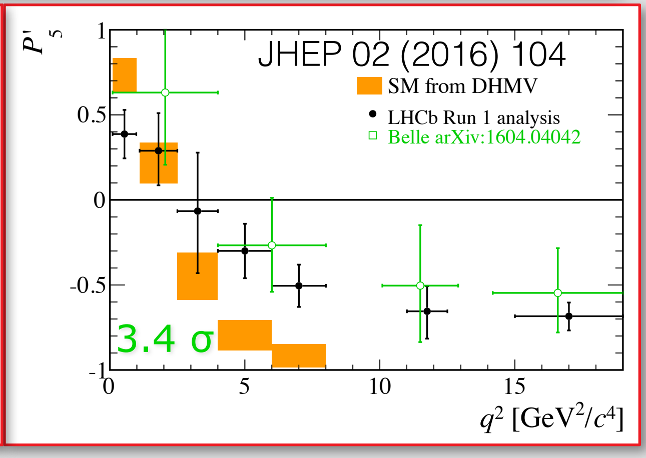




LHCb, PRL113 (2014) 151601



LHCb, JHEP 1509 (2015) 179



LHCb, JHEP 1602 (2016) 104

$B^0 \to K^*\mu\mu$: Projections

- Statistics for $B^0 \to K^*\mu\mu$:

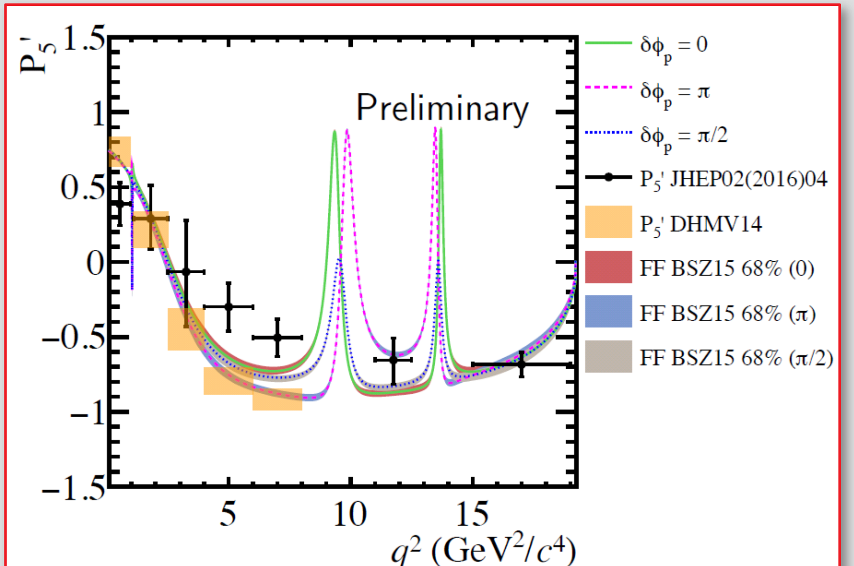
	Run 1	Run 1-3(4)	Run 1-5
LHCb JHEP 02 (2016) 104	600	20,000	120,000*
CMS Phys. Lett. B 753 (2016) 424	300	10,000	100,000
		(naïve scaling with lumi)	

From: P.Owen, 31 Aug 2016

- Understand theory:
  - Measure q^2 dependence
    - To disentangle charm loop effects!
  - Factorisable power corrections
  - Form factors

For P_5' in [4, 6] GeV^2 bin:

$$-0.82^{+0.01}_{-0.01}{}^{+0.02}_{-0.02}{}^{+0.03}_{-0.06}{}^{+0.06}_{-0.06}{}^{+0.07}_{-0.08}$$



Pomery, Egede, Owen, Petrides, Blake

$b \rightarrow sll$: Projections

- Statistics for $B^0 \rightarrow K^* \mu\mu$:

	Run 1	Run 1-3(4)	Run 1-5
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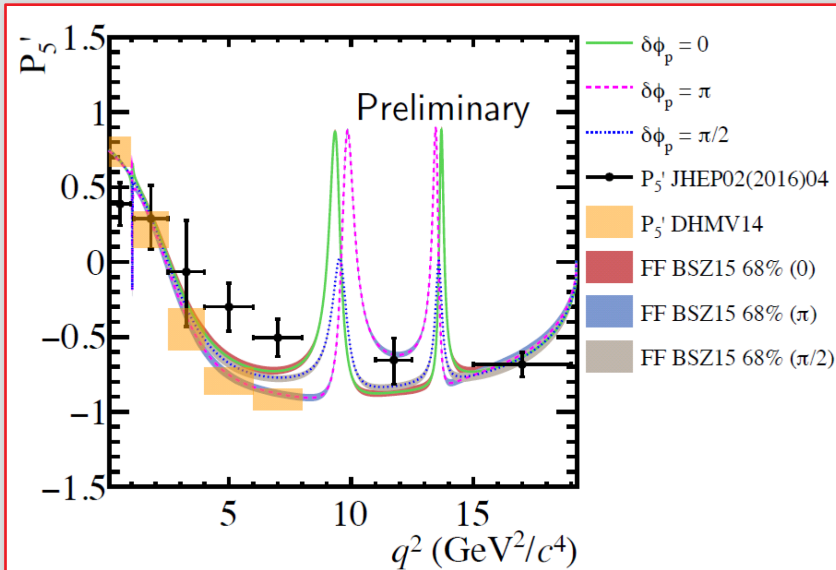


Pomery, Egede, Owen, Petrides, Blake

- Many more observables!
  - Lepton-flavour universality, R_{K*}
  - Lepton-flavour violation searches
  - BR's
  - A_{FB}(S6), A9, ...
  - $B^0 \rightarrow K^*ee$
  - ...

	Decay	Run 1	Run 2	50 fb^{-1}	300 fb^{-1}
R_K	$B^+ \rightarrow K^+\mu^+\mu^-$	11%	5%	2%	1%
R_{K^*}	$B^0 \rightarrow K^{*0}\mu^+\mu^-$	18%	8%	3%	1%
R_Φ	$B^0_s \rightarrow \phi\mu^+\mu^-$	36%	15%	8%	3%

From: P.Owen, 31 Aug 2016

Lepton flavour universality: R(D) & R(D*)

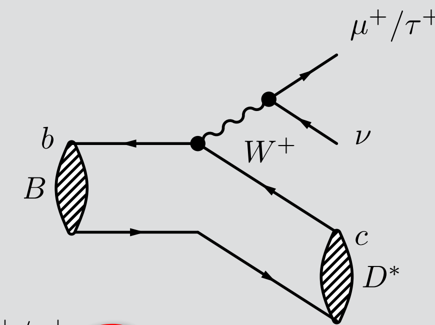
- Surprises possible in tree-level decays?
- There is more than “roadmap” channels with loops
- $B \to D^{*} l \nu$
  - Measure ratio τ/μ :

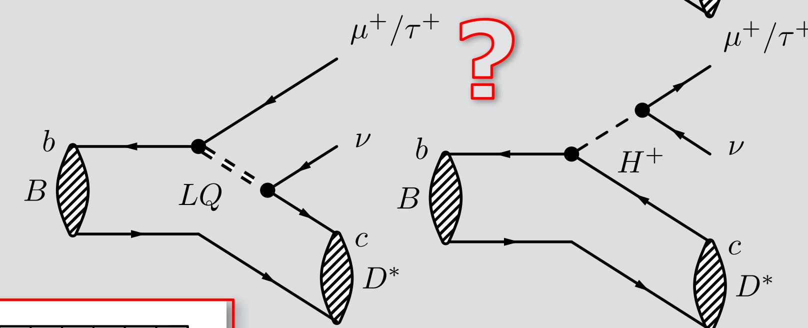
$$\mathcal{R}(D^{*}) \equiv \mathcal{B}(\overline{B}^{0} \to D^{*+}\tau^{-}\overline{\nu}_{\tau})/\mathcal{B}(\overline{B}^{0} \to D^{*+}\mu^{-}\overline{\nu}_{\mu})$$

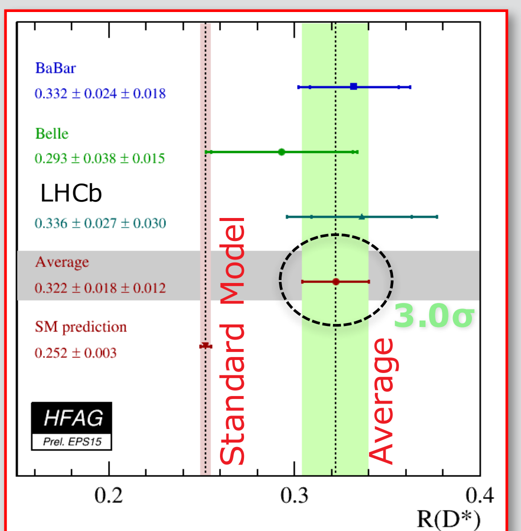
  - SM: R(D*)=0.252±0.003

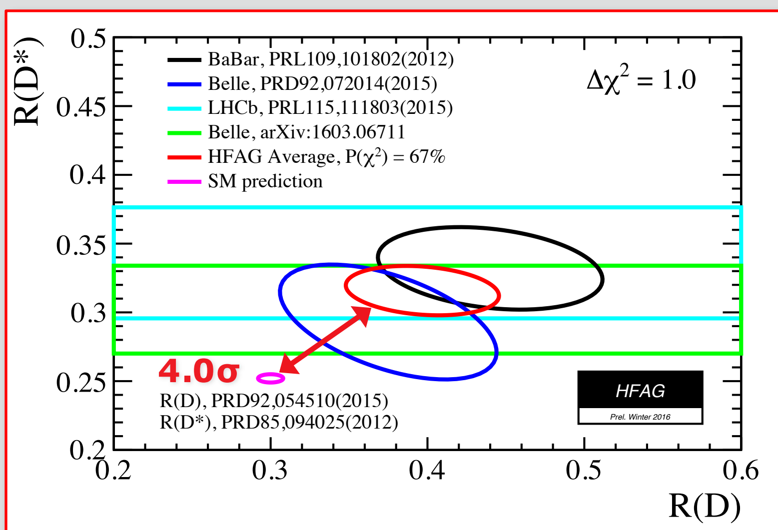
    Fajfer, Kamenik, Nisandzic PRD 85, 094025 (2012)

  - R(D) and R(D*) combined: 4.0σ





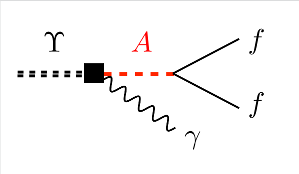


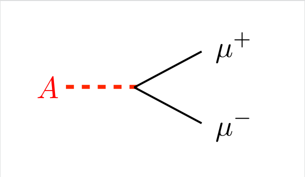


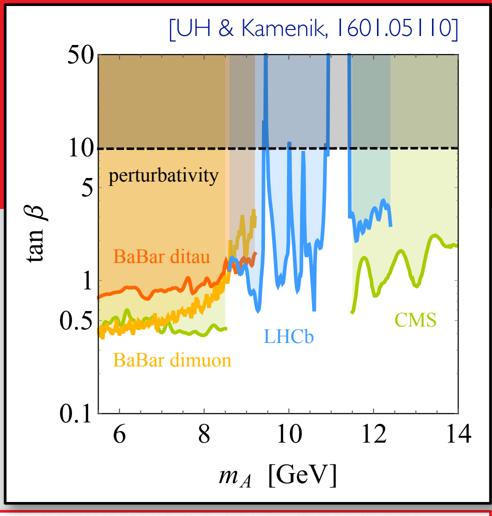
- Next:
  - R(J/ψ) from B_c
  - $R(\Lambda_c)$ from Λ_b
  - μ/e ratio
  - …

Searches
Dark photons, Majorana, light scalars

- Light scalars
  - A→μμ

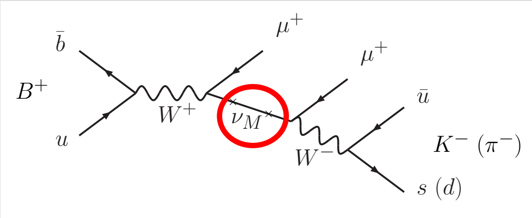


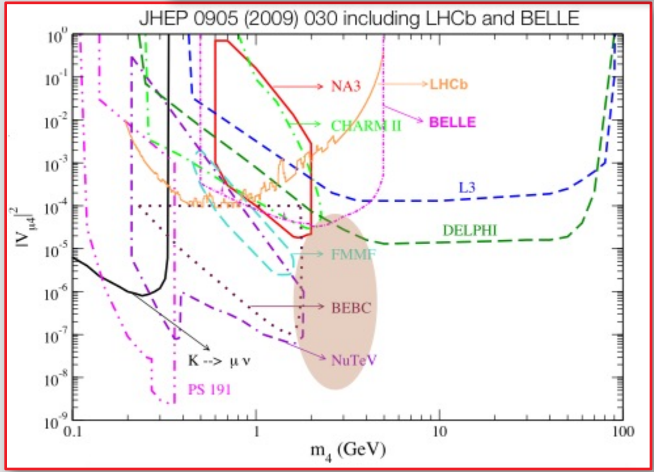




Haisch et al., PRD93 (2016) 055047

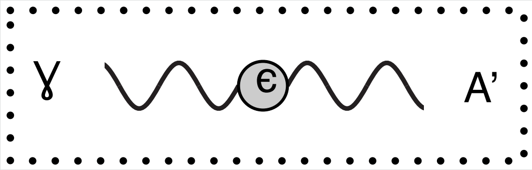
- Majorana neutrino’s
  - $B^{+} \to \pi^{-}\mu^{+}\mu^{+}$

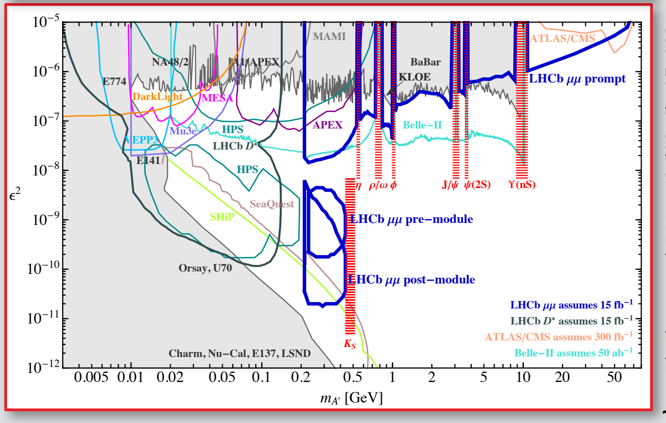




Atre et al., JHEP 0905 (2009) 030

- Dark photons
  - $D^{*0} \to D^{0}\gamma$, $A \to \mu\mu$





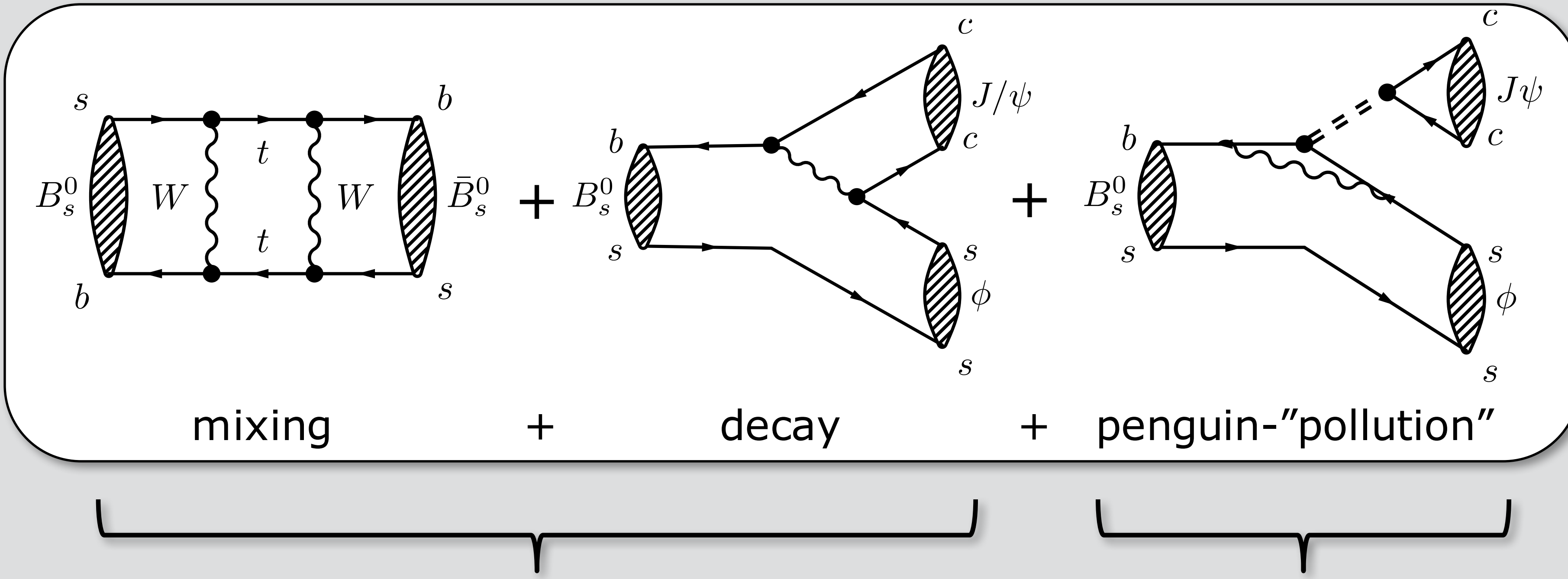
Ph.Ilten et al PRL 116 (2016) 251803

Outline

- Introduction
  - Timeline HL-LHC: Detector improvements
- Beauty: Rare Decays
  - Very rare: $B^0_{(s)} \rightarrow \mu\mu$ and f_s/f_d
  - FCNC: $B^0 \rightarrow K^*\mu\mu$
  - Searches: Dark photons, Majorana neutrino's
- Beauty: CP violation
  - CPV in B_s^0: φ_s, A_{fs} : $B^0_s \rightarrow J/\psi\varphi$, $B^0_s \rightarrow \varphi\varphi$, $B^0_{(s)} \rightarrow D_{(s)}X\mu\nu$
  - CKM angles: γ, β : $B \rightarrow DK$, $B^0 \rightarrow J/\psi K_S$
- Charm and Strange
  - Charm mixing: $D^{0*} \rightarrow D^0(hh)\pi$
  - Strange rare decays: $K_S^0 \rightarrow \mu\mu$, $K_S^0 \rightarrow \pi\pi ee$, $\Sigma^+ \rightarrow p\mu\mu$
- *("Top is not a heavy flavour")*

CP violation in B_s^0

- Heavy new particles can affect box and penguin:

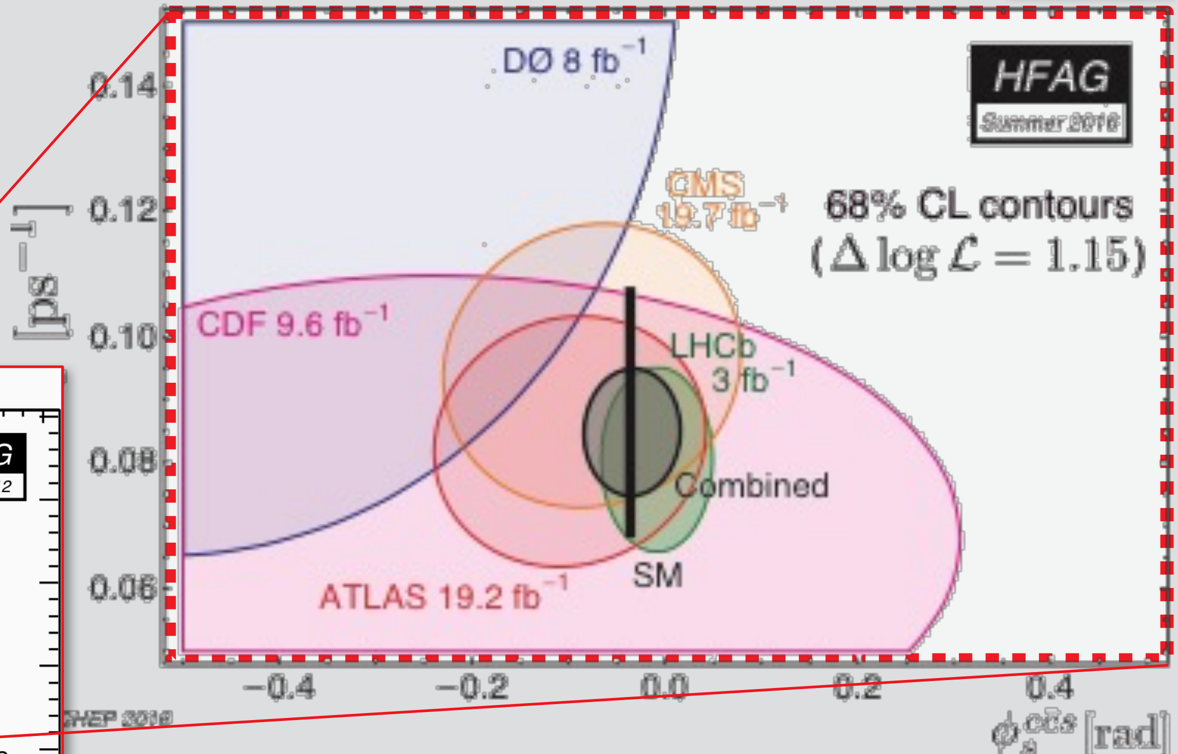


φ_s $\Delta\varphi_s$

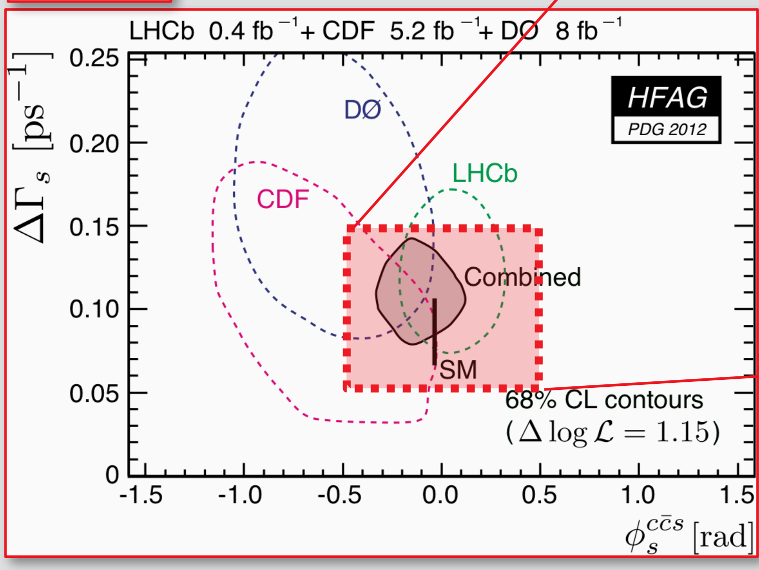
CP violation in B_s^0

- Heavy new particles can affect box and penguin
- Impressive precision:

2016



2012



$$\phi_s^{ccs} = -0.030 \pm 0.033 \text{ rad}$$
$$\phi_s^{SM} = -0.0376^{+0.0007}_{-0.0008} \text{ rad}$$

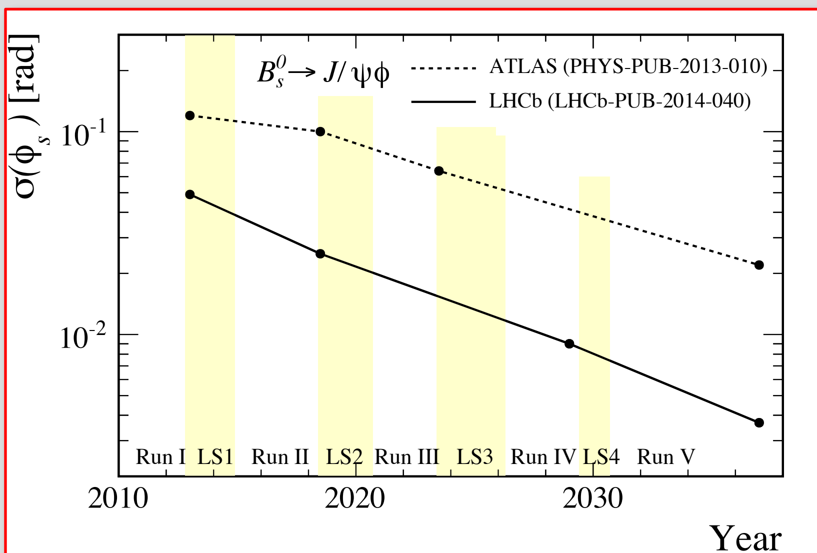
CP violation in B_s^0: Projections for φ_s

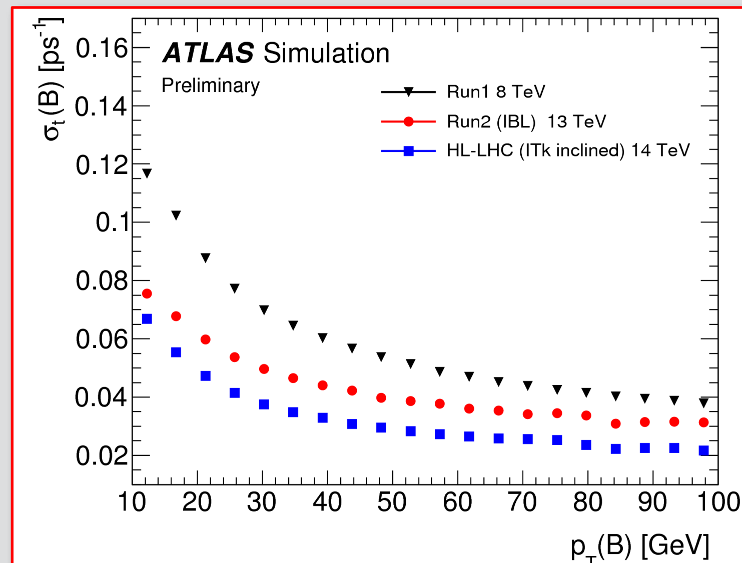
- Theoretical prediction for φ_s
  - very accurate → $\phi_s^{\mathrm{SM}} = -0.0376^{+0.0007}_{-0.0008}$ rad
  - penguin contributions under control (<0.5°) → $\Delta\phi_s^{\psi\phi} = \left[0.08^{+0.56}_{-0.72}\,(\mathrm{stat})^{+0.15}_{-0.13}\,(SU(3))\right]^\circ$
    - 10x larger uncertainty than arg(V_{ts})
    - but scales with increased statistics

De Bruyn & Fleischer, JHEP 03 (2015) 145

($0.5^\circ = 0.0087$ rad)

- Experimental improvements:
  - New vertex detectors at ATLAS and CMS → better decay time resolution
  - Statistical uncertainty at end Upgrade:
    - LHCb: 0.009 rad
    - ATLAS: 0.022 rad





Resolution dampens CPV sensitivity with dilution D:

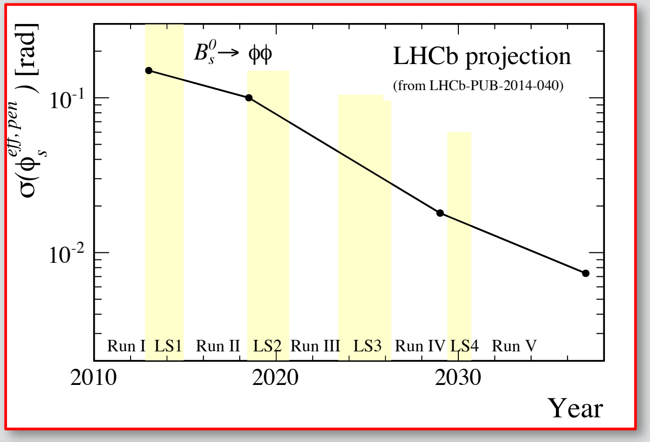
$$D = \exp\left(-\Delta m_s^2\,\delta(\sigma_t)^2\,/\,2\right)$$

CP violation and penguins: $B_s^0 \to \varphi\varphi$

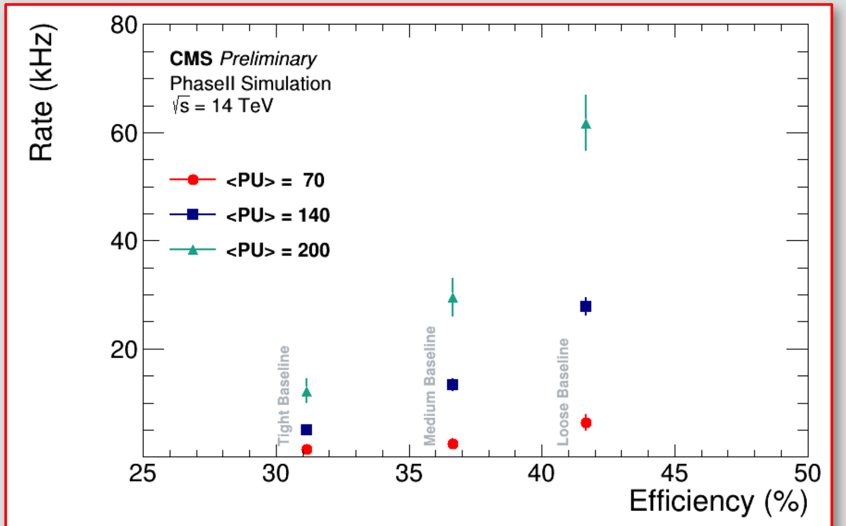
- FCNC gluonic penguin: sensitive to NP

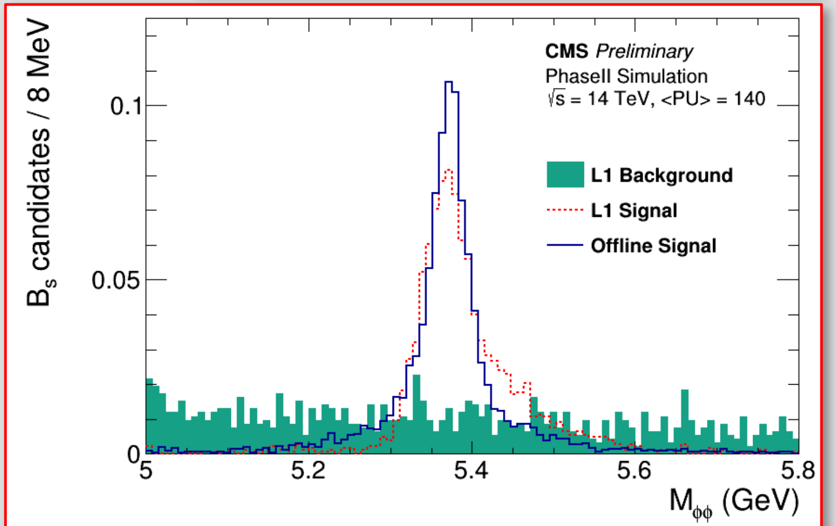
- Present situation:

$$\phi_s = -0.17 \pm 0.15\,(\text{stat}) \pm 0.03\,(\text{syst})\ \text{rad}$$



- Statistically limited in HL-LHC era
  - LHCb: Expected stat. unc. (300 fb^{-1}): 0.007 rad
  - CMS: expect L1 rate of 29kHz at 42% efficiency (<PU>=140)





Updates on Projections of Physics Reach with the Upgraded CMS Detector for High Luminosity LHC : CERN-CMS-DP-2016-064

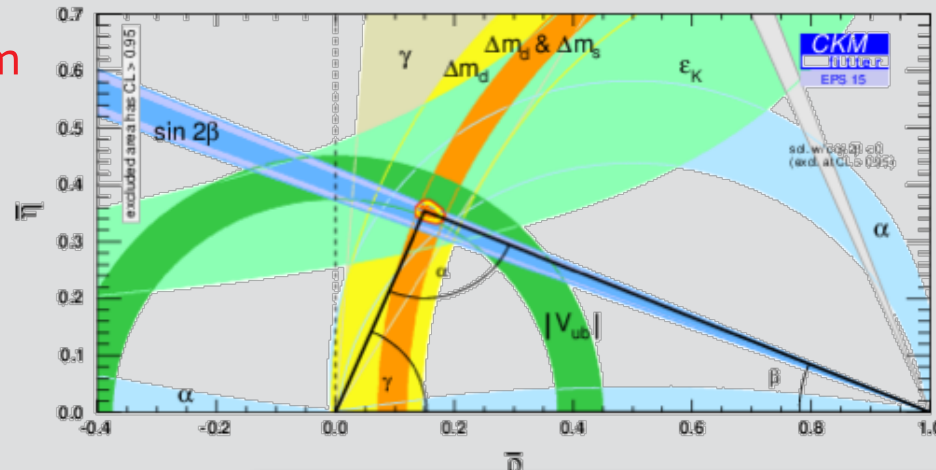
CP violation in B^0 decays: sin2β

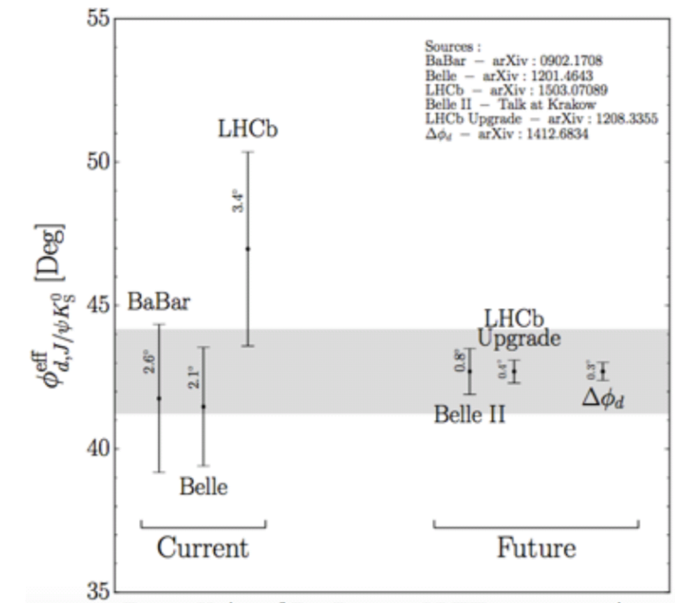
- Crucial parameter to test CKM paradigm

- Statistically limited
- Penguins uncertainty on sin2β ~0.005

$$\sin(2\beta)^{\text{SM}} = 0.748^{+0.030}_{-0.032}$$

$$\sin(2\beta)^{\text{exp}} = 0.691 \pm 0.017$$



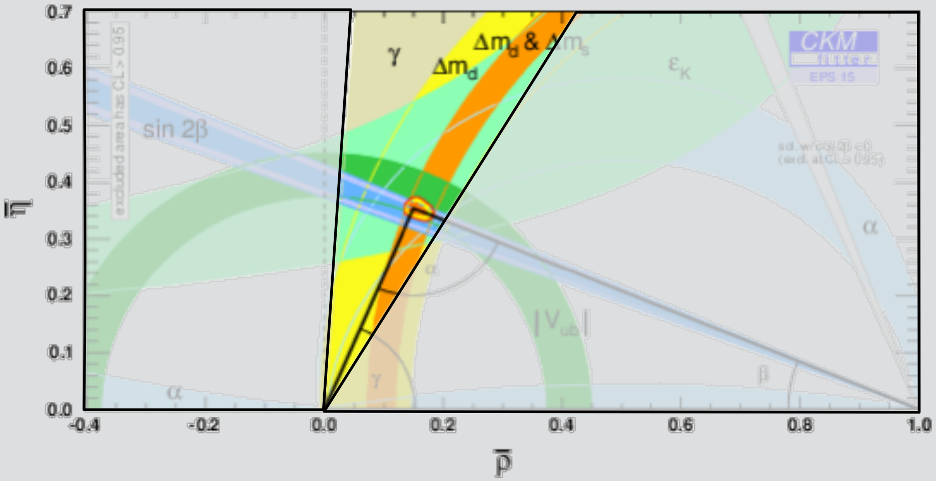


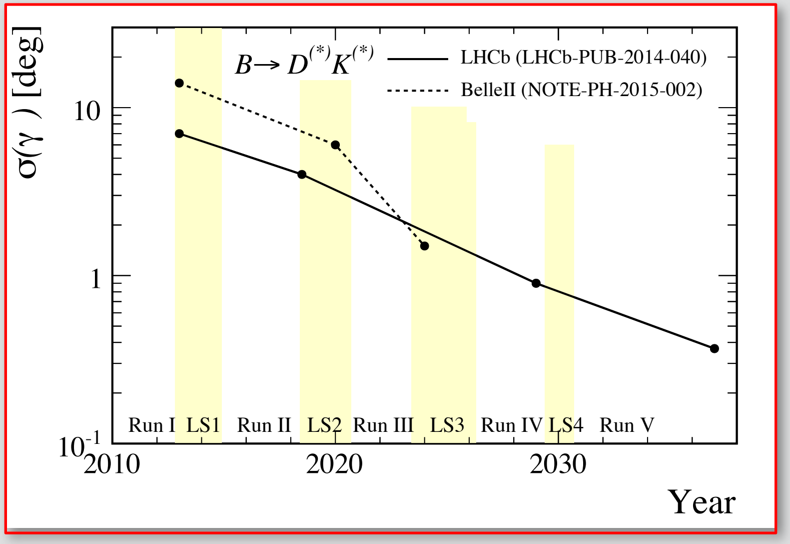
From Kristof De Bruyn CPTT presentation

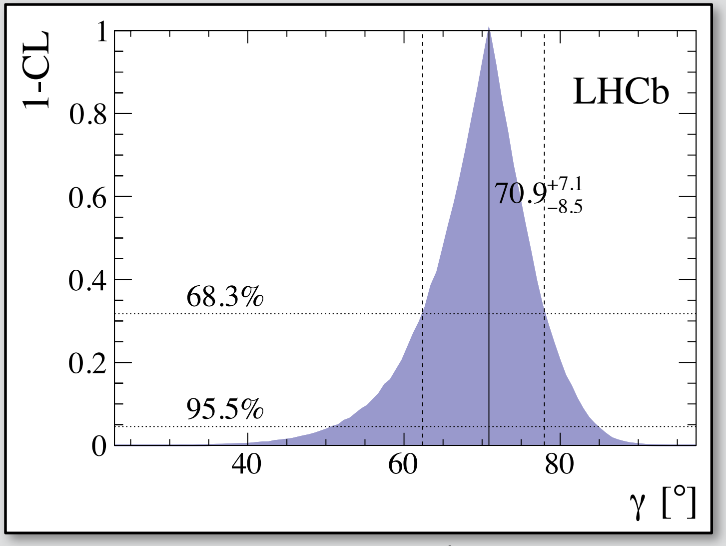
Observable	Mode	Run 1 (2010-12) $3\,\text{fb}^{-1}$	Run 2 (2015-18) $8\,\text{fb}^{-1}$	Upgrade (2021-2029) $50\,\text{fb}^{-1}$	CKMFitter (2015)
$\sin(2\beta)$	$B^0 \to J/\psi K^0_S$	0.040	0.021	0.007	~ 0.030

CP violation in *B* decays: γ

- Angle γ least known parameter
- LHCb dominates world average
  - σ(γ) ~ 7°
- No theoretical limitations
- No systematic limitations
  - Precision ≪ 1° in reach
- Result to be compared with:
  - UT fit
  - γ measurement from penguin decays







LHCb-PAPER-2016-032

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- *("Top is not a heavy flavour")*

Charm

Warning:
These are **1G** *D* decays, not a TF1("gauss") …

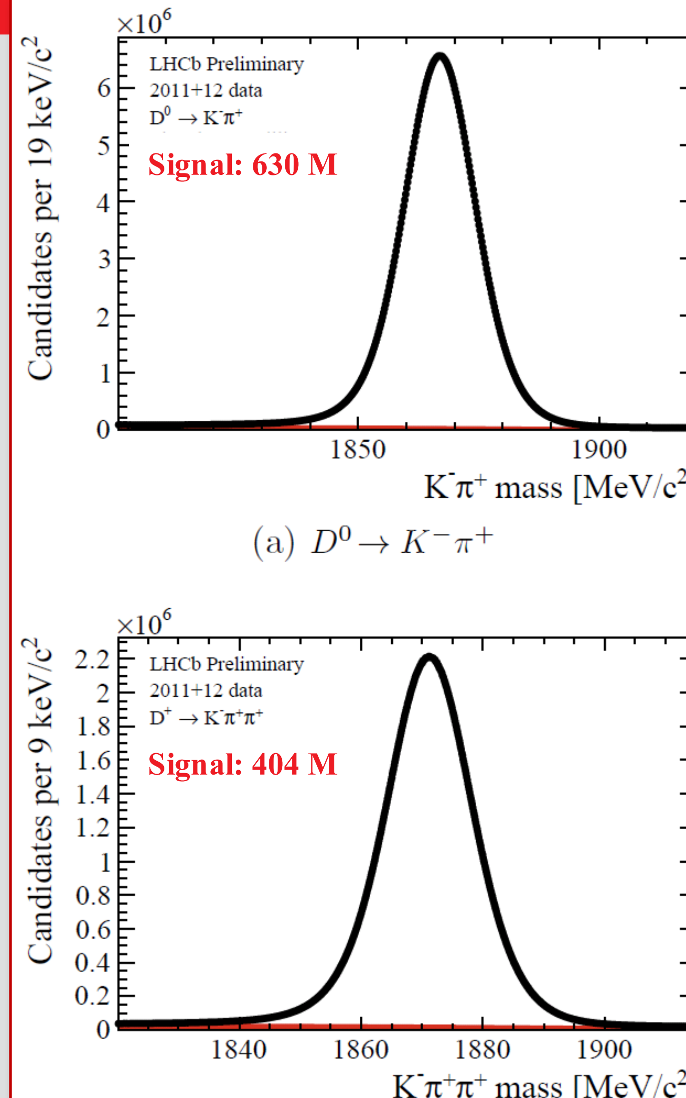
- Probing the up-quark sector

- Enormous data set
  - 10^9 *D*-decays in Run-I

- Prospects:
  - CPV in mixing (y_{CP},q/p) in $D^* \to D^0(K\pi)\pi$
  - A_{CP} in $D^0 \to KK/\pi\pi$, $D^0 \to K_S hh$
  - When is this theoretically limited?

	Run	σ(x) (10^{-3})	σ(y) (10^{-3})	σ(|q/p|) (10^{-3})	σ(Φ) (mrad)
	I	1.22	0.53	59	89
	II	0.92	0.37	44	70
LHCb Upgrade	III	0.42	0.15	20	33
HL-LHC / LHCb Upgrade	IV	0.25	0.09	12	20

mixing: $x = \frac{\Delta m}{\Gamma}$, $y = \frac{\Delta\Gamma}{2\Gamma}$ CPV: $|D_{\mp}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$



(a) $D^0 \to K^-\pi^+$

(c) $D^+ \to K^-\pi^+\pi^+$

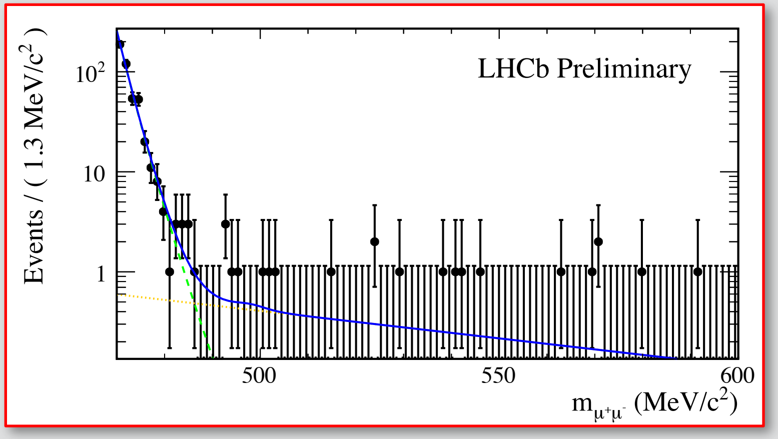
LHCb-CONF-2016-005

Strange

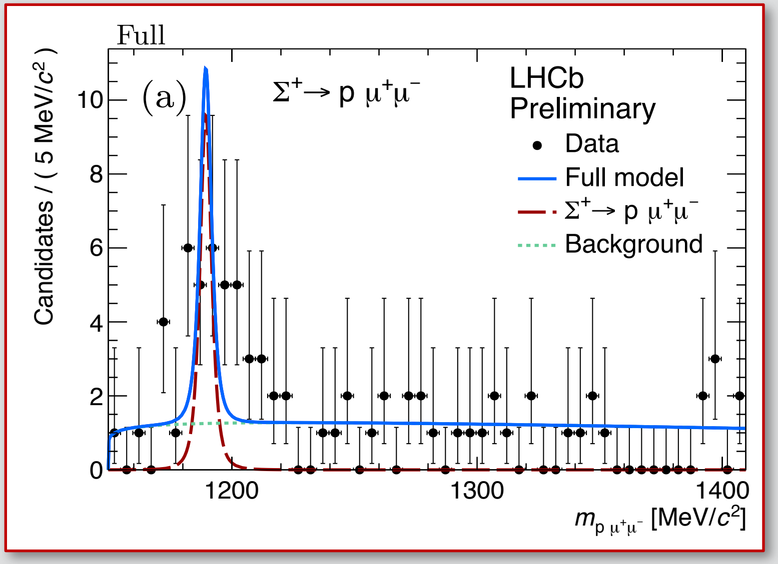
- New field within LHCb
- Dedicated triggers
- Rich program:
  - $K_S^0 \rightarrow \mu\mu$
    - *BR < 5.8 x 10^{-9} @ 90% CL*
    - *Software trigger, 23 fb^{-1}: 2 x 10^{-10}*
  - $K_S^0 \rightarrow \pi^0\mu\mu$
    - *Hardware trigger bottleneck → upgrade!*
  - $K_S^0 \rightarrow \mu\mu\mu\mu$
    - *No experimental constraint to date*
  - $K_S^0 \rightarrow \pi^+\pi^- ee$
    - *5σ observation possible in Run-II*
  - $K^+ \rightarrow \pi^+\pi^-\pi^+$
    - *10^6 events observed in Run-I*
    - *software trigger in upgrade: 2x 10^{10} /fb^{-1}*
  - $\Sigma^+ \rightarrow p\mu\mu$
    - *Check HyperCP (E871) events*

Strange

- New field within LHCb
- Dedicated triggers
- Rich program:
  - $K_S^0 \rightarrow \mu\mu$
    - *BR < 5.8 x 10^{-9} @ 90% CL*
    - *Software trigger, 23 fb^{-1}: 2 x 10^{-10}*
  - $K_S^0 \rightarrow \pi^0\mu\mu$
    - *Hardware trigger bottleneck → upgrade!*
  - $K_S^0 \rightarrow \mu\mu\mu\mu$
    - *No experimental constraint to date*
  - $K_S^0 \rightarrow \pi^+\pi^- ee$
    - *5σ observation possible in Run-II*
  - $K^+ \rightarrow \pi^+\pi^-\pi^+$
    - *10^6 events observed in Run-I*
    - *software trigger in upgrade: 2x 10^{10} /fb^{-1}*
  - $\Sigma^+ \rightarrow p\mu\mu$
    - *Check HyperCP (E871) events*



LHCb-CONF-2016-012

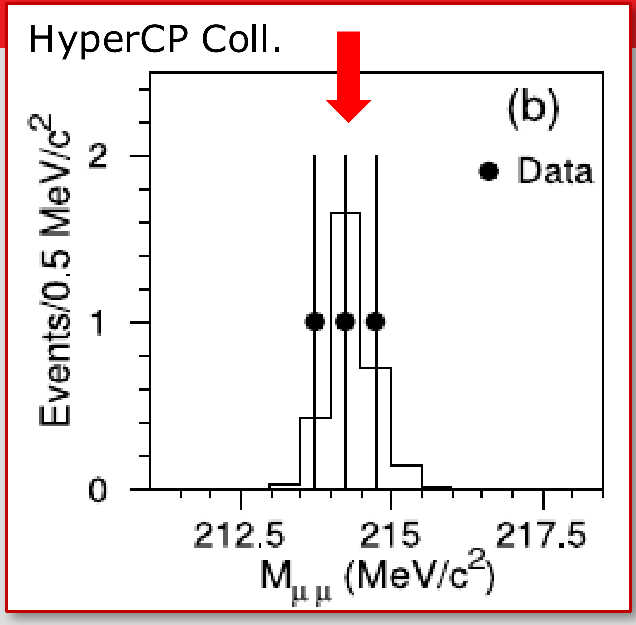


LHCb-CONF-2016-013

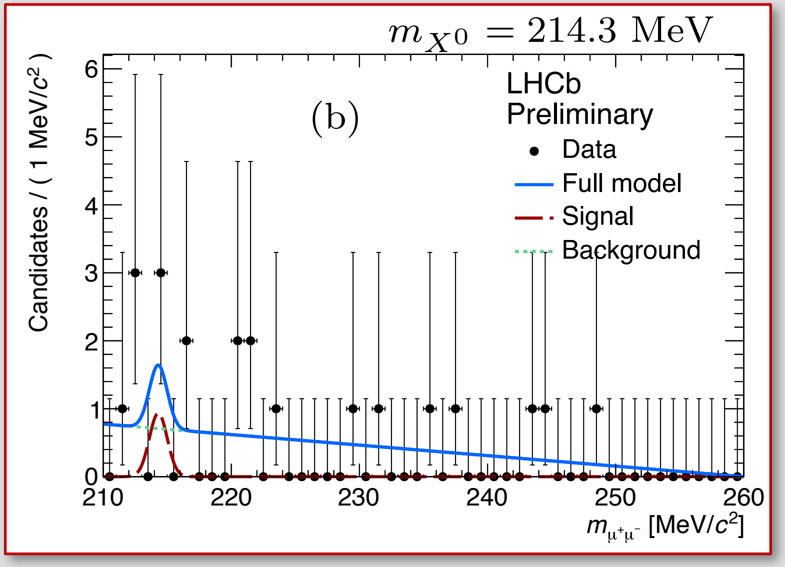
Strange

- New field within LHCb
- Dedicated triggers
- Rich program:
  - $K_S^0 \rightarrow \mu\mu$
    - BR < 5.8 x 10^{-9} @ 90% CL
    - Software trigger, 23 fb^{-1}: 2 x 10^{-10}
  - $K_S^0 \rightarrow \pi^0\mu\mu$
    - Hardware trigger bottleneck → upgrade!
  - $K_S^0 \rightarrow \mu\mu\mu\mu$
    - No experimental constraint to date
  - $K_S^0 \rightarrow \pi^+\pi^-ee$
    - 5σ observation possible in Run-II
  - $K^+ \rightarrow \pi^+\pi^-\pi^+$
    - 10^6 events observed in Run-I
    - software trigger in upgrade: 2x 10^{10} /fb^{-1}
  - $\Sigma^+ \rightarrow p\mu\mu$
    - Check HyperCP (E871) events
    - LHCb:
      - Fit at m=214.3 MeV: 1.6±1.9 evts

$$\Sigma^+ \rightarrow pX^0(\rightarrow \mu^+\mu^-)$$



HyperCP, PRL 94 (2005) 021801



LHCb-CONF-2016-013

Experiment vs Theory

- For very long, flavour observables will stay statistically limited!

	LHCb up to LS2		LHCb upgrade		Theory
	Run 1	Run 2	Run 3	Run 4	Theory uncertainty
Integrated lumi	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	
$\frac{Br(B_d \to \mu\mu)}{Br(B_s \to \mu\mu)}$	-	110 %	60%	40%	5%
$q_0^2 A_{FB}(B_d \to K^{*0}\mu\mu)$	10%	5%	2.8%	1.9%	7%
$\phi_s(B_s \to J/\psi\phi, B_s \to J/\psi\pi\pi)$	0.05	0.025	0.013	0.009	0.003
$\phi_s(B_s \to \phi\phi)$	0.18	0.12	0.04	0.026	0.02
γ	7°	4°	1.7°	1.1°	negl.
$A_\Gamma(D^0 \to KK)$	3.4 10^{-4}	2.2 10^{-4}	0.9 10^{-4}	0.5 10^{-4}	-

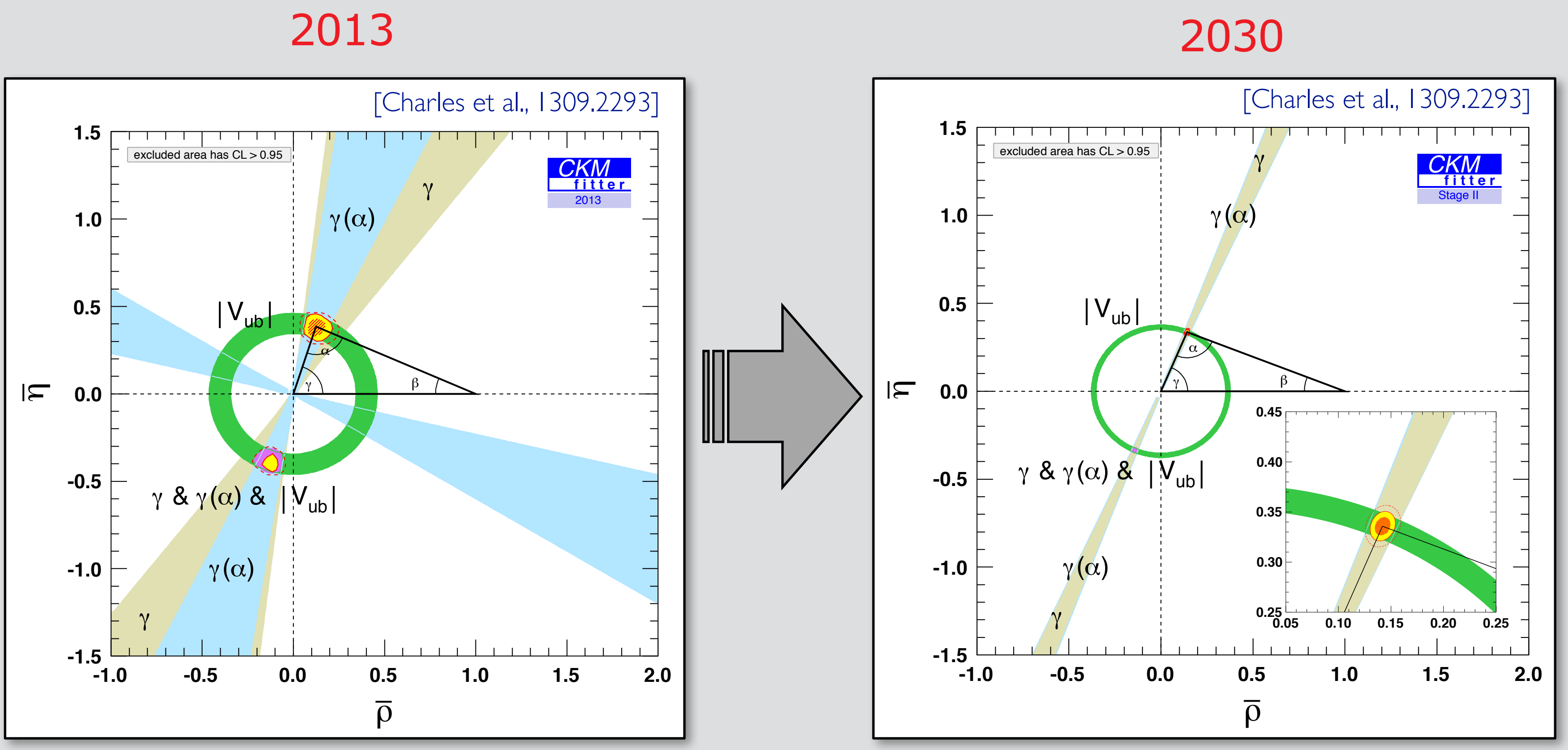
LHCb-PUB-2014-040

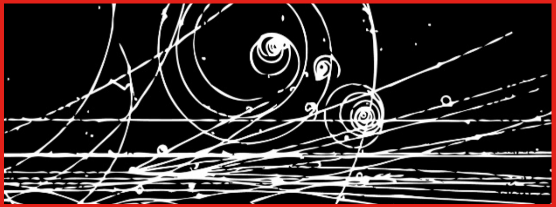
$\delta\gamma$	$\mathcal{O}(10^{-7})$	[Brod & Zupan, 1308.5663]
$\delta\beta$	$\mathcal{O}(1\%)$	[Ciuchini et al., hep-ph/0507290]
δR_{D^*}	$\mathcal{O}(1\%)$	[Fajfer et al., 1203.2654]
$\delta R_K, \delta R_{K^*}, \ldots$	$\mathcal{O}(1\%)$	[Bordone et al., 1605.07633]

From Uli Haisch, 31 Aug 2016

Conclusions

- Precision measurements to scrutinize the Standard Model
- Precision measurements only way to reach very high mass scales
- Precision measurements are not yet precise enough





Backup slides

The need for more precision

Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed"

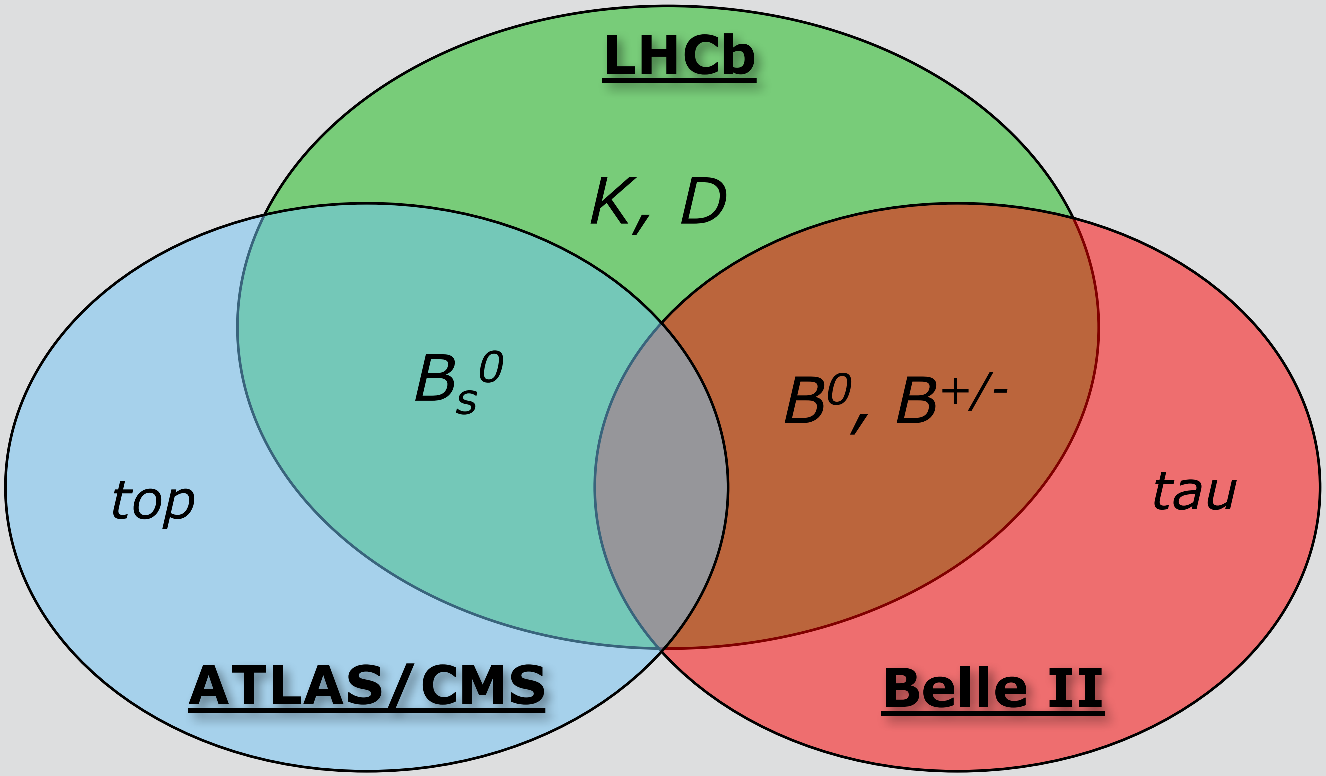
– A.Soni

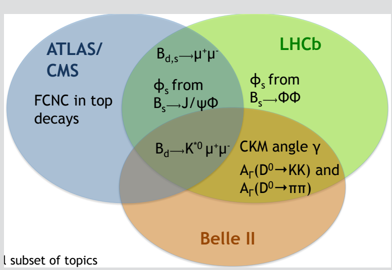
- "A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L^0 \to \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the lab. The group was unlucky."

– L.Okun

(remember: $B(K_L^0 \to \pi^+\pi^-) \sim 2\ 10^{-3}$)

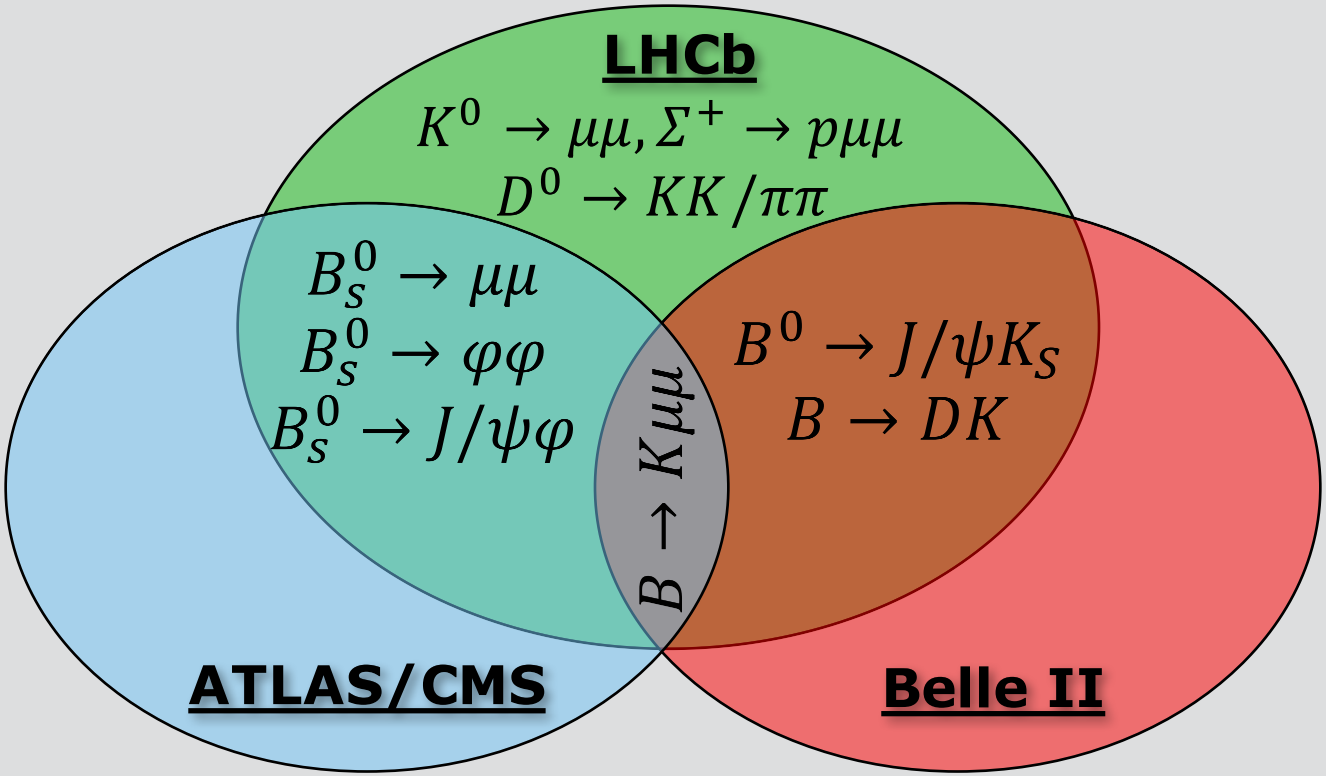
Playing field: heavy flavour

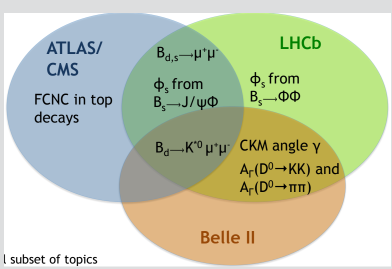




Sketch adopted from Marie-Hélène Schune ECFA2013, 1 Oct 2013

Playing field: today

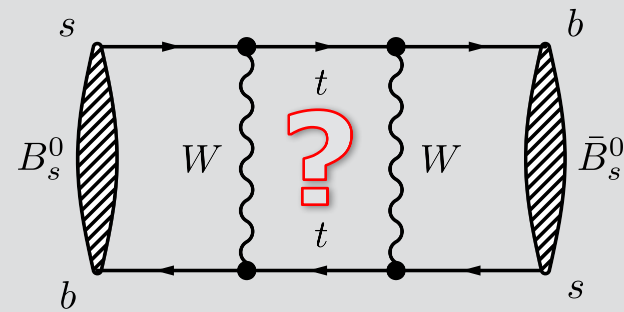




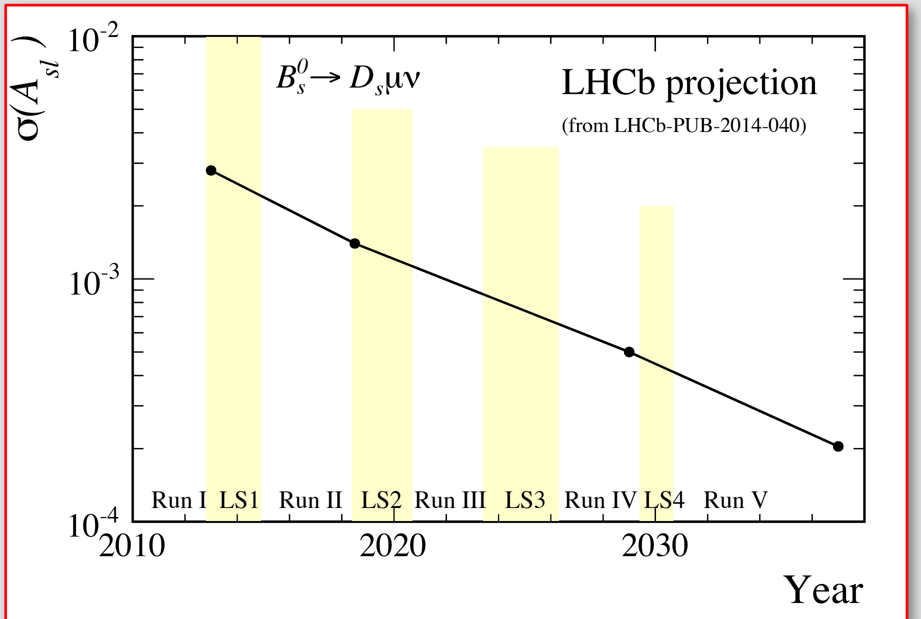
Sketch adopted from Marie-Hélène Schune ECFA2013, 1 Oct 2013

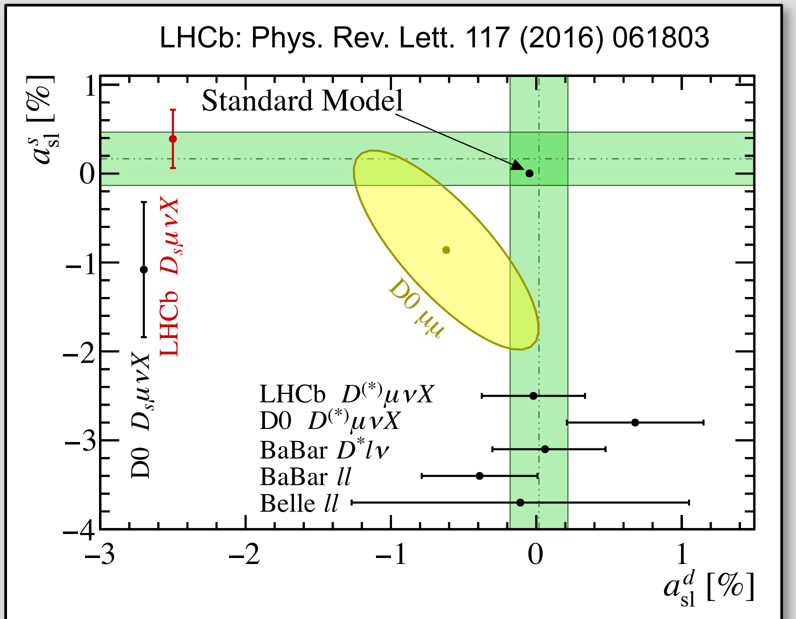
CP violation in *B* mixing

- New particles in the box diagram?



- Present results do not exclude D0 yet
- LHCb: with 300 fb^{-1} expect precision ~10^{-4}
  - Charged track asymmetry challenging

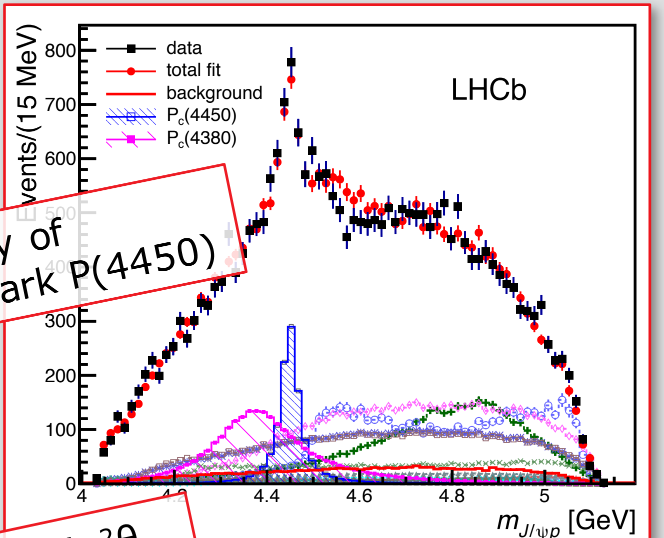




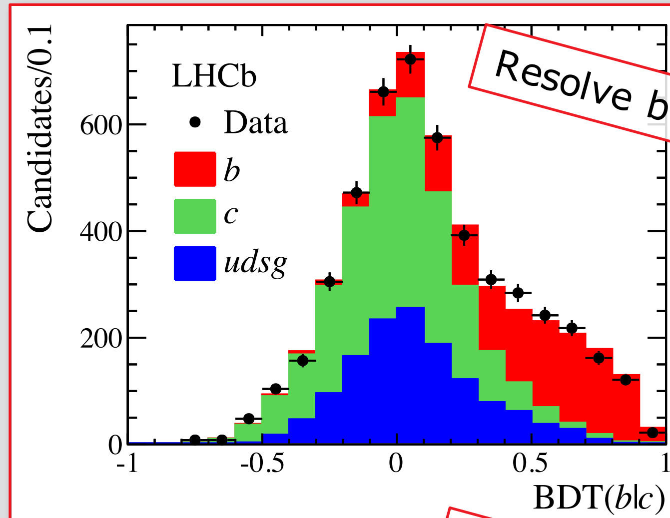
LHCb = more than flavour

pdfs, jets, heavy-ion, EW, exotic states…

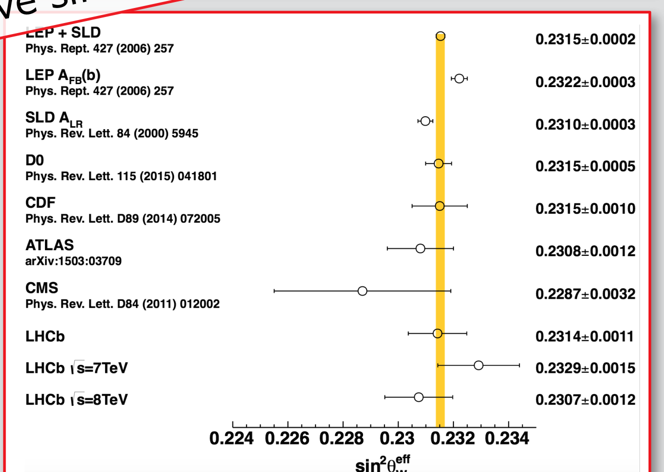
Discovery of pentaquark P(4450)



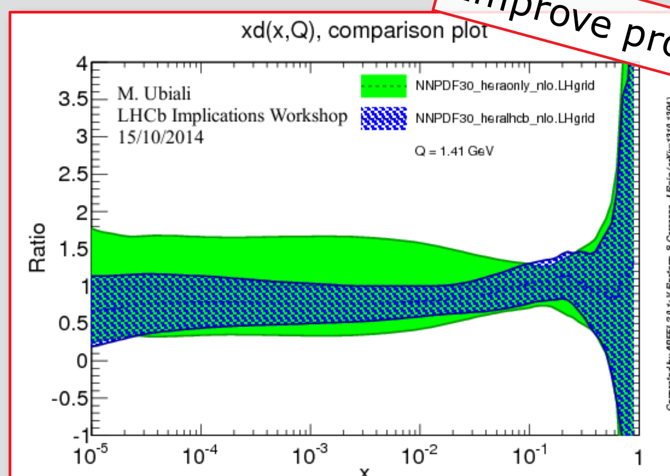
Resolve b and c jets



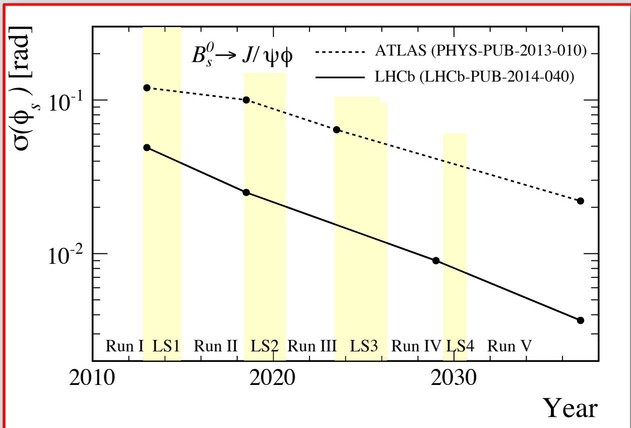
Impressive $\sin^2\theta_W$

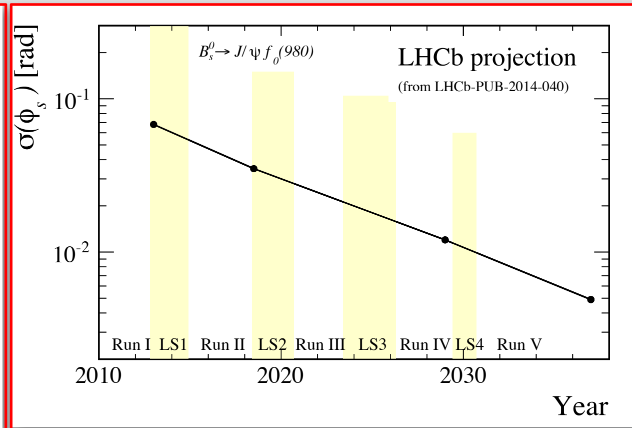


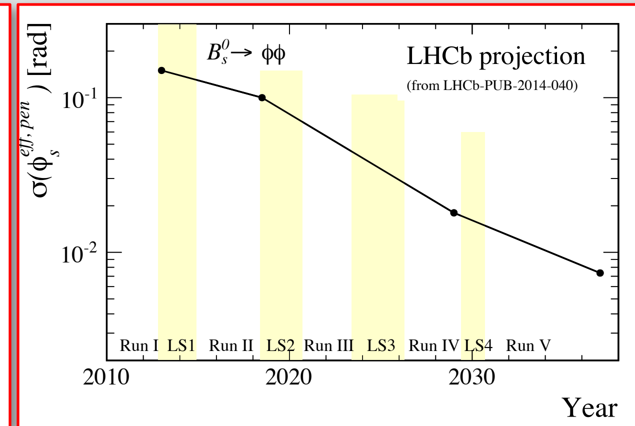
Improve proton pdf's

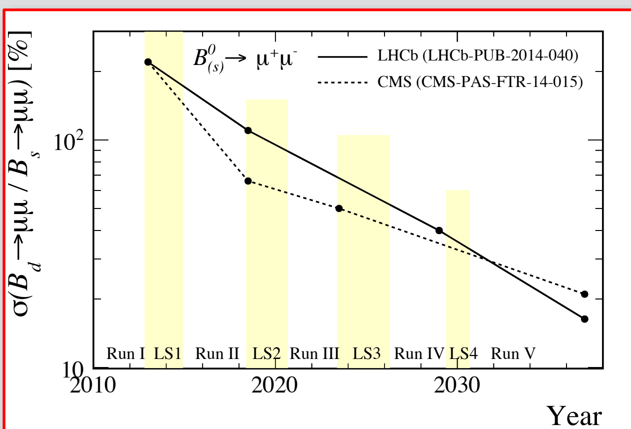


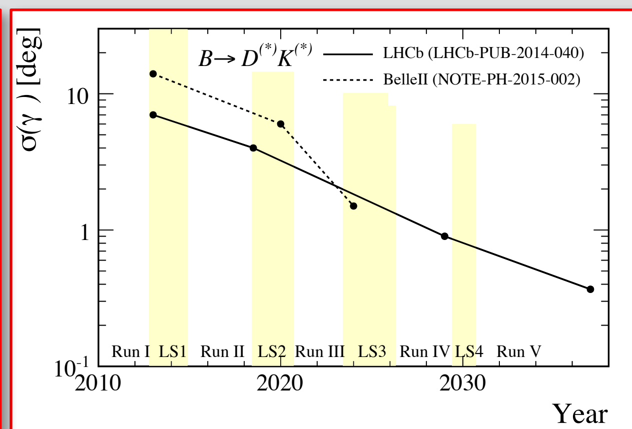
Projected sensitivities

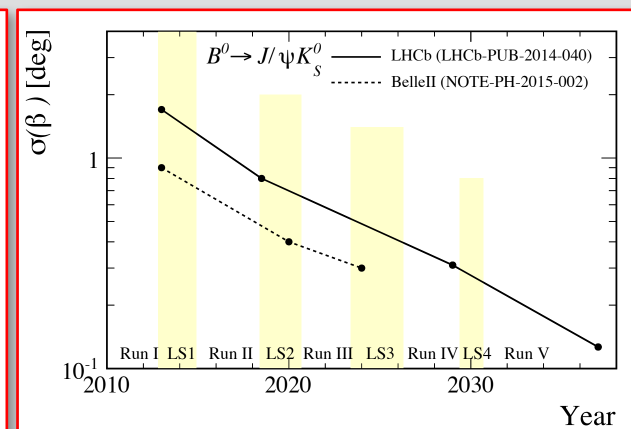












ATL-PHYS-PUB-2013-010
CMS-PAS-FTR-14-015

BELLE2-NOTE-PH-2015-002
LHCB-PUB-2014-040