B physics experiments II

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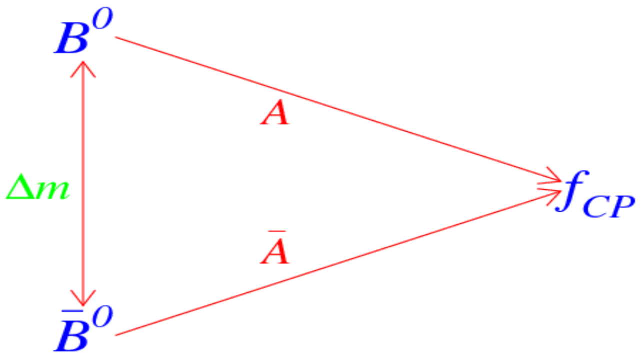
16th August 2019

Categories of CP violation

- Consider decay of neutral particle to a CP eigenstate

$$\lambda_{CP} = \frac{q}{p}\frac{\bar{A}}{A}$$



$$|\frac{q}{p}| \neq 1$$ CP violation in mixing

$$|\frac{\bar{A}}{A}| \neq 1$$ CP violation in decay

$$\Im\left(\frac{q}{p}\frac{\bar{A}}{A}\right) \neq 0$$ CP violation in interference between mixing and decay

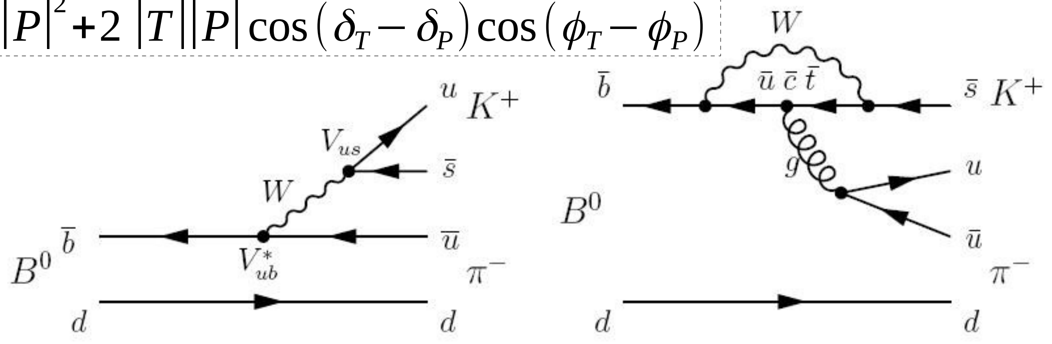
CP violation in decay

- Condition for CPV in decay: $|\bar{A}/A| \neq 1$
- Need $\bar{A}$ and A to consist of (at least) two parts
  - with different weak (φ) and strong (δ) phases
- Often realised by “tree” and “penguin” diagrams

$$A = |T| e^{i(\delta_T - \phi_T)} + |P| e^{i(\delta_P - \phi_P)} \qquad \bar{A} = |T| e^{i(\delta_T + \phi_T)} + |P| e^{i(\delta_P + \phi_P)}$$

$$A_{CP} = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} = \frac{2\,|T||P| \sin(\delta_T - \delta_P) \sin(\phi_T - \phi_P)}{|T|^2 + |P|^2 + 2\,|T||P| \cos(\delta_T - \delta_P) \cos(\phi_T - \phi_P)}$$

Example: B→Kπ
(weak phase difference is γ)



Feynman tree (a) and penguin (b) diagrams for the $B^0_d \to K^+\pi^-$ decay

The famous penguin story

Penguin diagram

From Wikipedia, the free encyclopedia

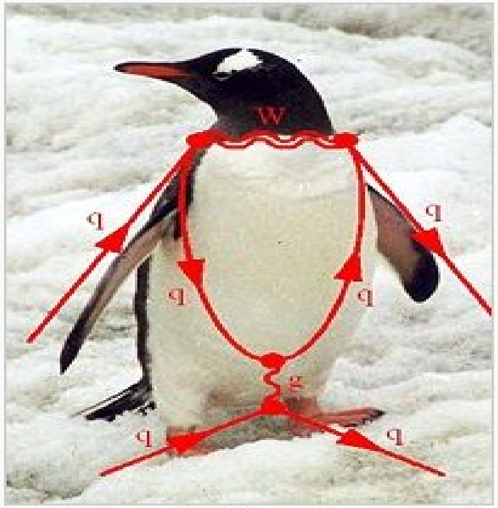
In quantum field theory, **penguin diagrams** are a class of Feynman diagrams which are important for understanding CP violating processes in the standard model. They were first isolated and studied by Mikhail Shifman, Arkady Vainshtein, and Valentin Zakharov.[1] The processes which they describe were first directly observed in 1991 and 1994 by the CLEO collaboration.

Origin of the name

[edit]

John Ellis was the first to refer to a certain class of Feynman diagrams as **penguin diagrams**, due in part to their shape, and in part to a legendary bar-room bet with Melissa Franklin. According to John Ellis:[2]

> Mary K. [Gaillard], Dimitri [Nanopoulos] and I first got interested in what are now called penguin diagrams while we were studying CP violation in the Standard Model in 1976... The penguin name came in 1977, as follows.
>
> In the spring of 1977, Mike Chanowitz, Mary K and I wrote a paper on GUTs predicting the b quark mass before it was found. When it was found a few weeks later, Mary K, Dimitri, Serge Rudaz and I immediately started working on its phenomenology. That summer, there was a student at CERN, Melissa Franklin who is now an experimentalist at Harvard. One evening, she, I, and Serge went to a pub, and she and I started a game of darts. We made a bet that if I lost I had to put the word penguin into my next paper. She actually left the darts game before the end, and was replaced by Serge, who beat me. Nevertheless, I felt obligated to carry out the conditions of the bet.
>
> For some time, it was not clear to me how to get the word into this b quark paper that we were writing at the time. Then, one evening, after working at CERN, I stopped on my way back to my apartment to visit some friends living in Meyrin where I smoked some illegal substance. Later, when I got back to my apartment and continued working on our paper, I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history.



Example of a penguin diagram

The famous penguin story

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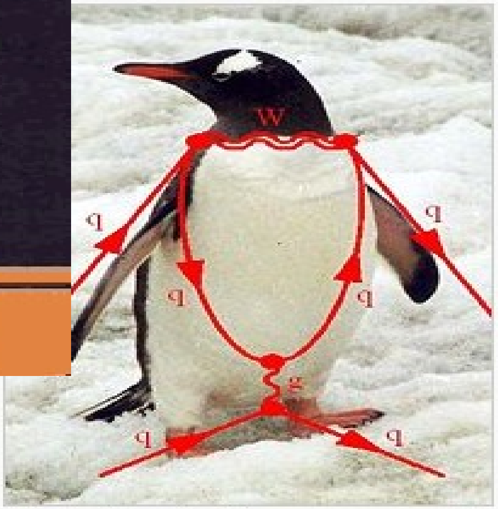


Example of a penguin diagram

Direct CP violation in B→Kπ

Direct CP violation in B→Kπ sensitive to γ

too many hadronic parameters ⇒ need theory input

NB. interesting deviation from naïve expectation

"Kπ puzzle"

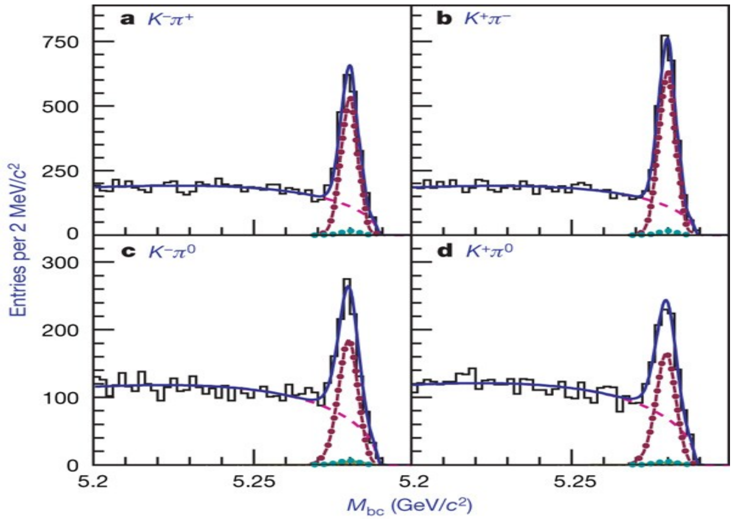
$A_{CP}(K^-\pi^+) = -0.087 \pm 0.008$

$A_{CP}(K^-\pi^0) = +0.037 \pm 0.021$

Could be a sign of new physics …

… first need to rule out possibility of larger than expected QCD corrections

Belle Nature 452 (2008) 332



Importance of γ from B → DK

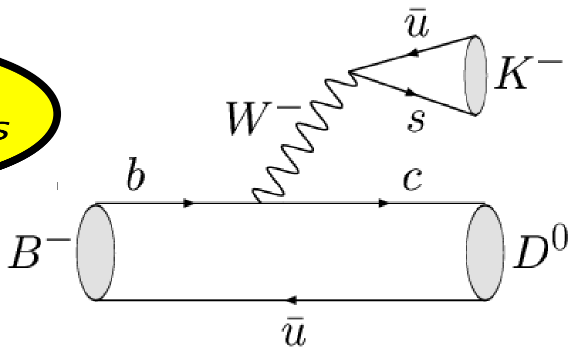
- γ plays a unique role in flavour physics

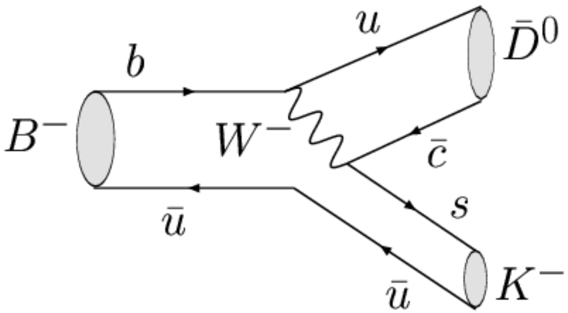
  the only CP violating parameter that can be measured through tree decays (*)

  (*) more-or-less

- A benchmark Standard Model reference point
  - doubly important after New Physics is observed

$\propto V_{cb} V^*_{us}$





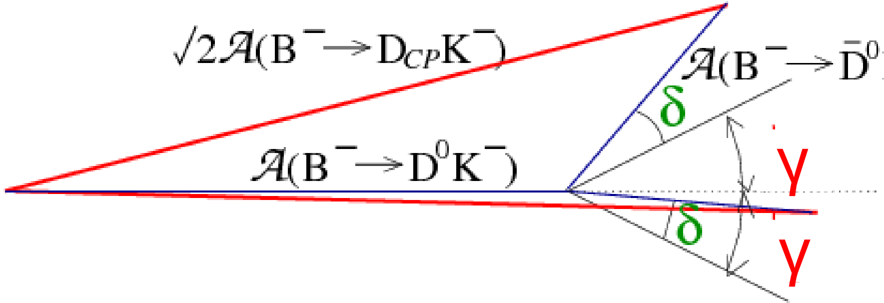
$\propto V_{ub} V^*_{cs}$

Variants use different B or D decays

require a final state common to both D^0 and $\overline{D}^0$

Why is B → DK so nice?

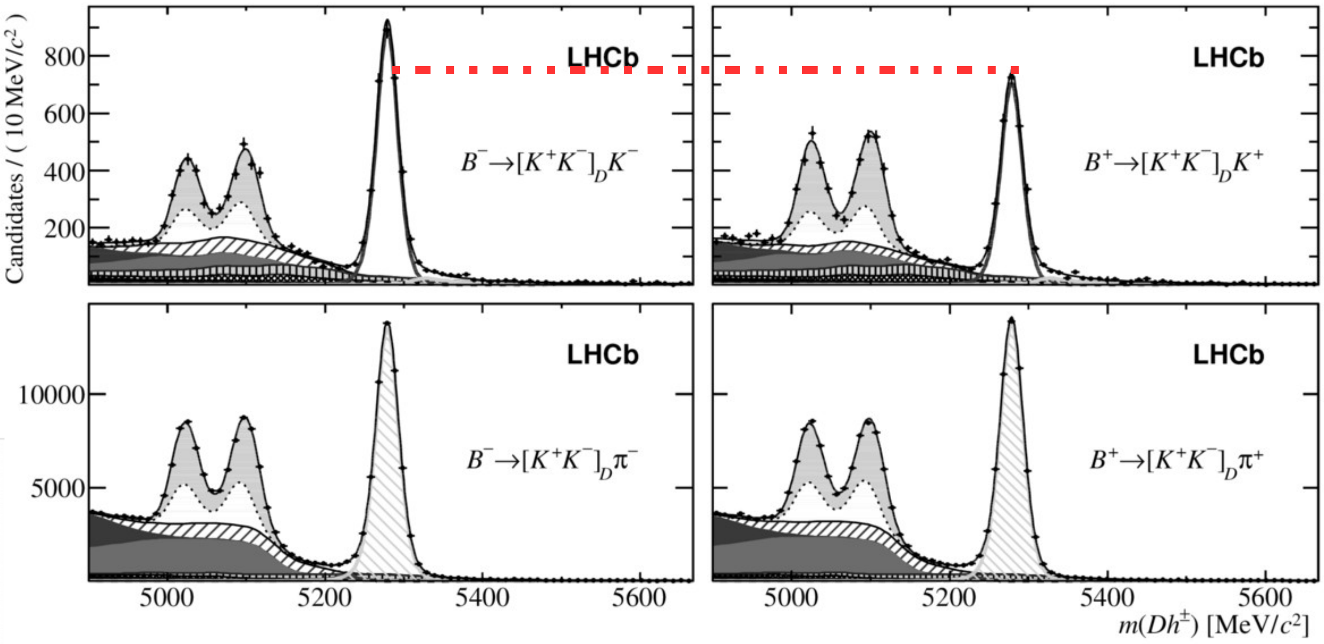
- For theorists:
  - theoretically clean: no penguins; factorisation works
  - all parameters can be determined from data
- For experimentalists:
  - many different observables (different final states)
  - all parameters can be determined from data
  - γ & δ_B (weak & strong phase differences), r_B (ratio of amplitudes)

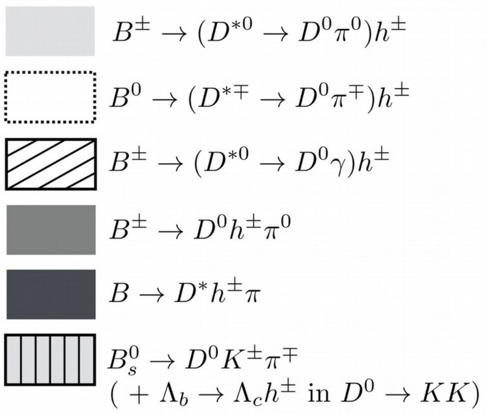


Latest results on B → DK : GLW

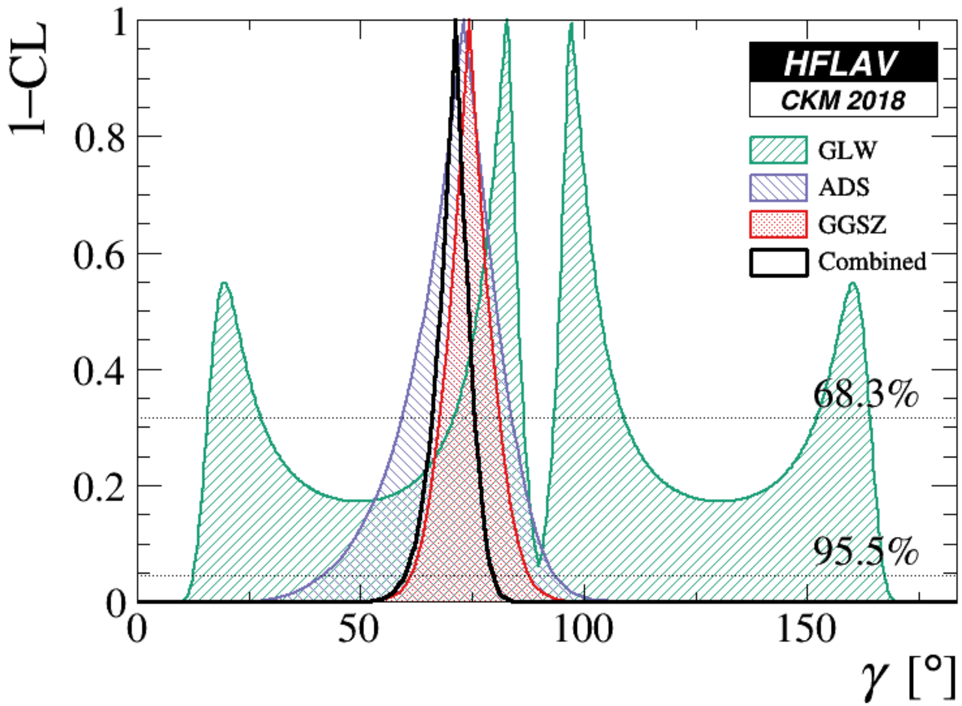
PLB 777 (2018) 16

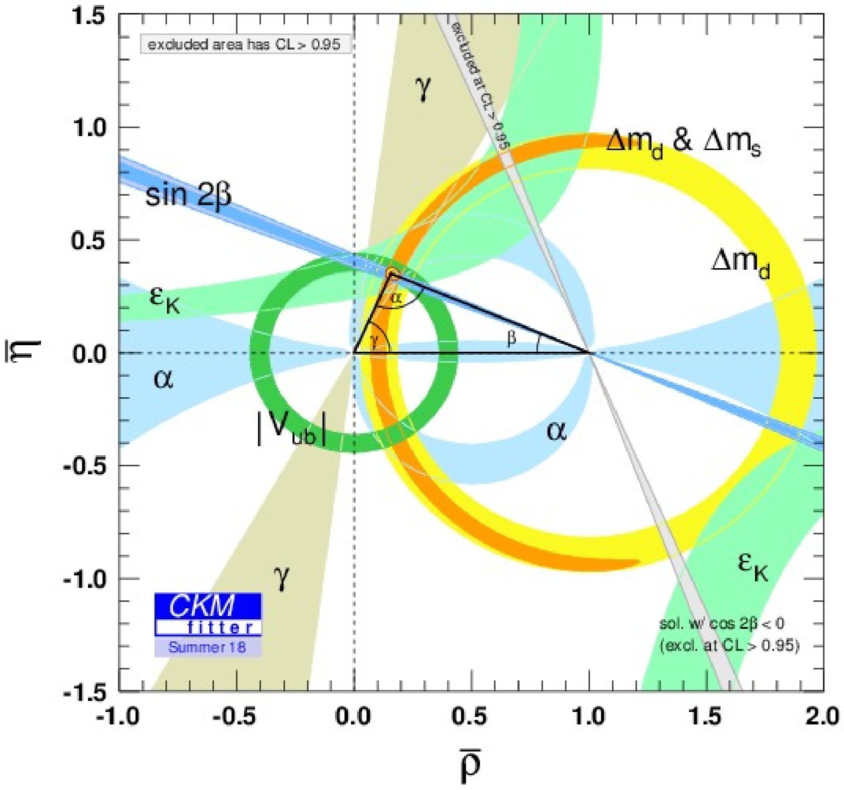
CP violation (γ≠0)





World average for γ



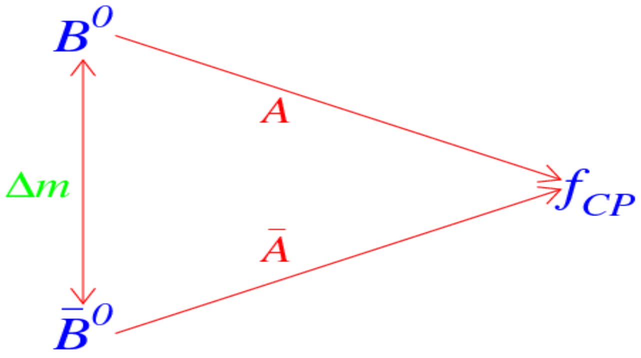


$\gamma = (71.1\ ^{+4.6}_{-5.3})^\circ$

Categories of CP violation

- Consider decay of neutral particle to a CP eigenstate

$$\lambda_{CP} = \frac{q}{p}\frac{\bar{A}}{A}$$



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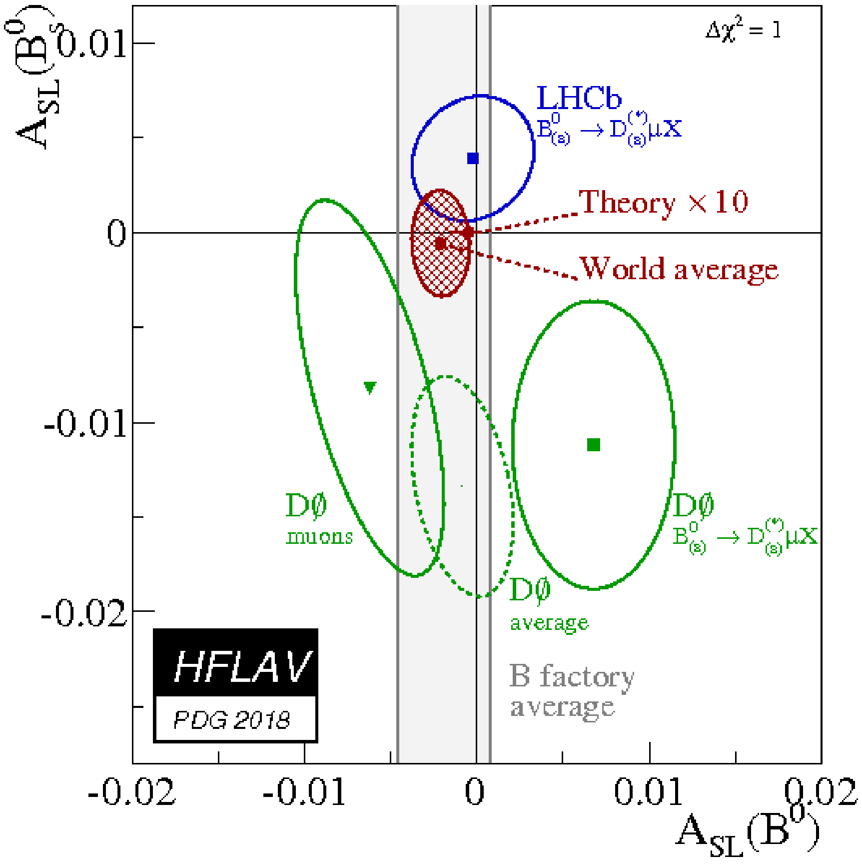
CP violation in mixing

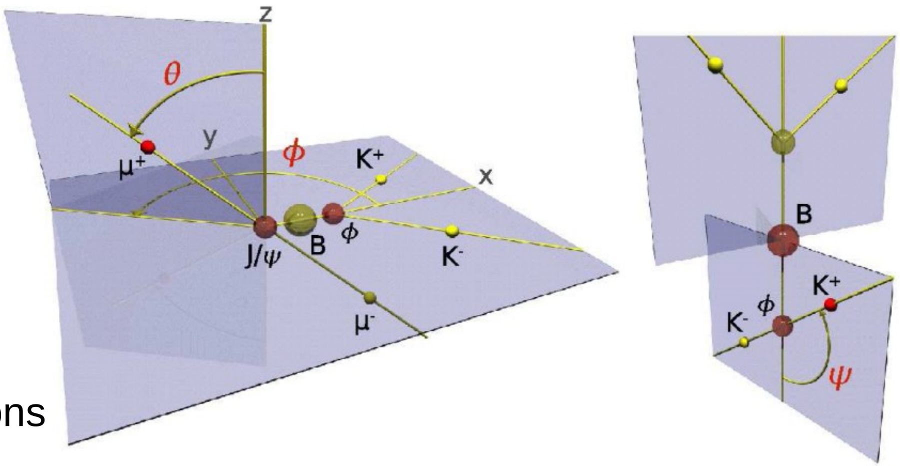
- Equivalent of ε_K from kaon system
- Measured using decays to flavour-specific final states, without CPV in decay
  - mainly semileptonic decays, hence A_{SL} notation:

$$A_{SL} \approx 4\,\mathrm{Re}(\varepsilon_B)/(1+|\varepsilon_B|^2)$$

- Tiny in the SM, hence good null test
- Challenging to measure to ‰ precision



$\varphi_s = -2\beta_s$ ($B_s \to J/\psi\varphi$)

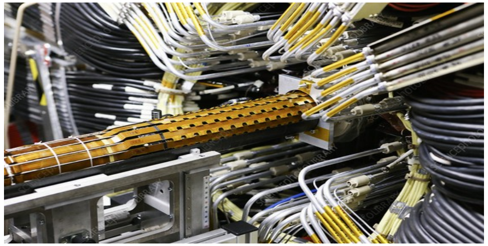


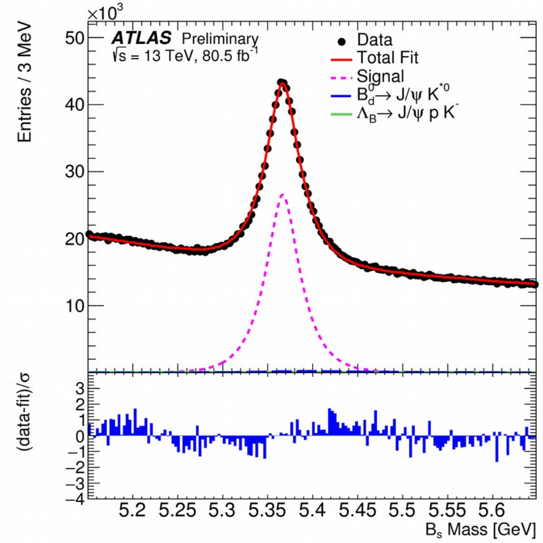
- Equivalent of $B^0 \to J/\psi K_S$
  - CP violation in mixing/decay interference
- VV final state
  - three helicity amplitudes
    - → mixture of CP-even and CP-odd
  - disentangled using angular & time-dependent distributions
    - → additional sensitivity
  - many correlated variables
    - → complicated analysis
- LHCb also uses $B_s \to J/\psi f_0$ ($f_0 \to \pi^+\pi^-$)
  - CP eigenstate; simpler analysis
  - fewer events; requires input from $J/\psi\varphi$ analysis (Γ_s, $\Delta\Gamma_s$)

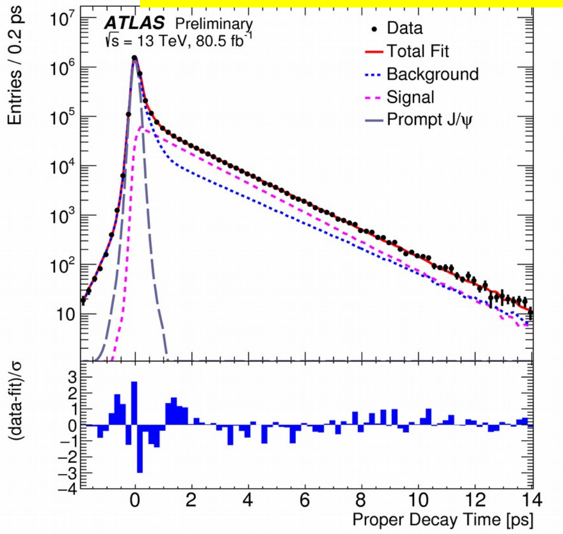
φ_s from $B_s^0 \rightarrow J/\psi\varphi$ (ATLAS)

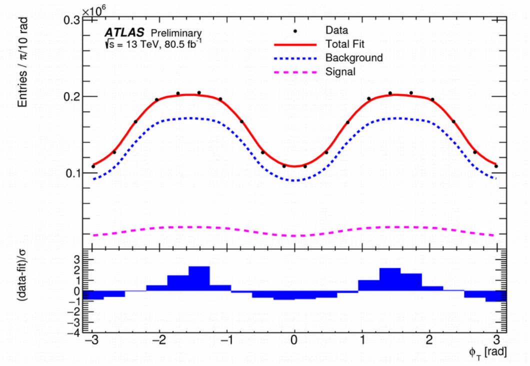
ATLAS-CONF-2019-009

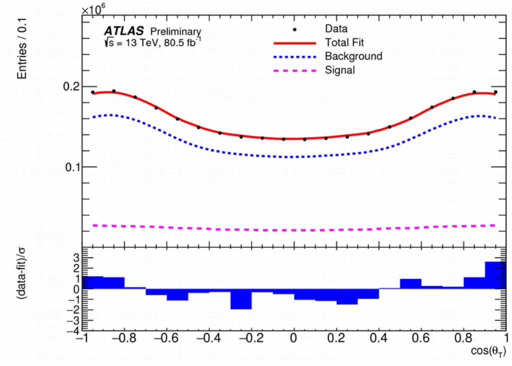
- Data from 2015-17
- Signal yield ~ 450k
- New Insertable B Layer (IBL) detector improves σ_t: 100 → 70 fs
- Tagging power ~ 1.6%

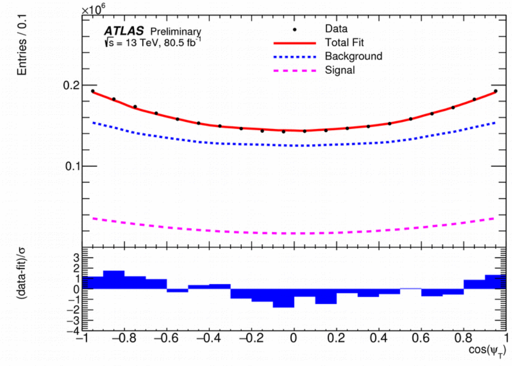






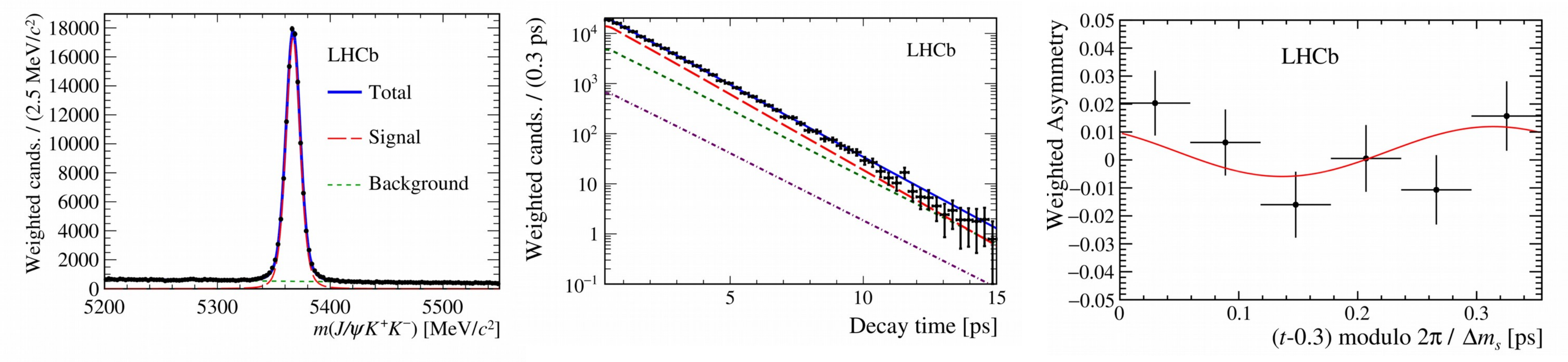




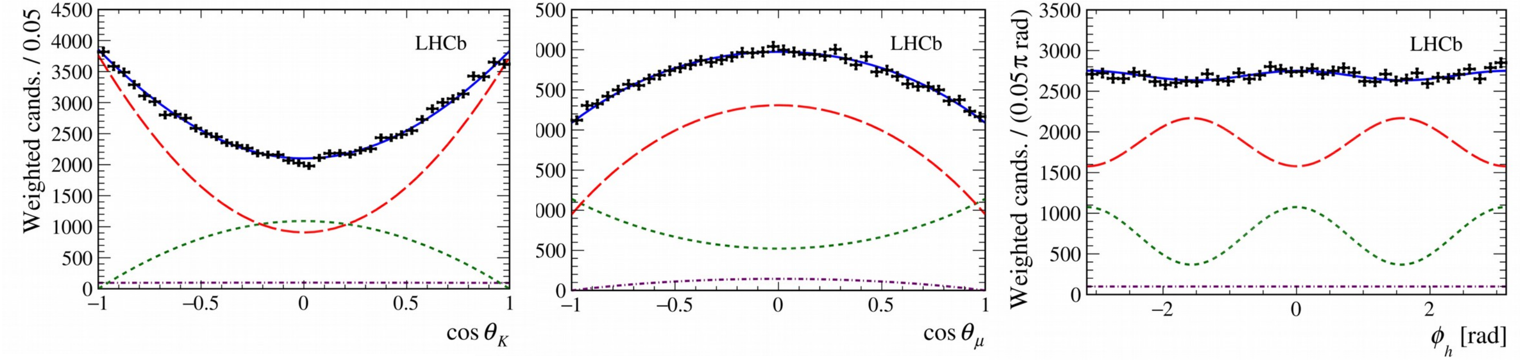


φ_s from $B_s^0 \rightarrow J/\psi\varphi$ (LHCb)

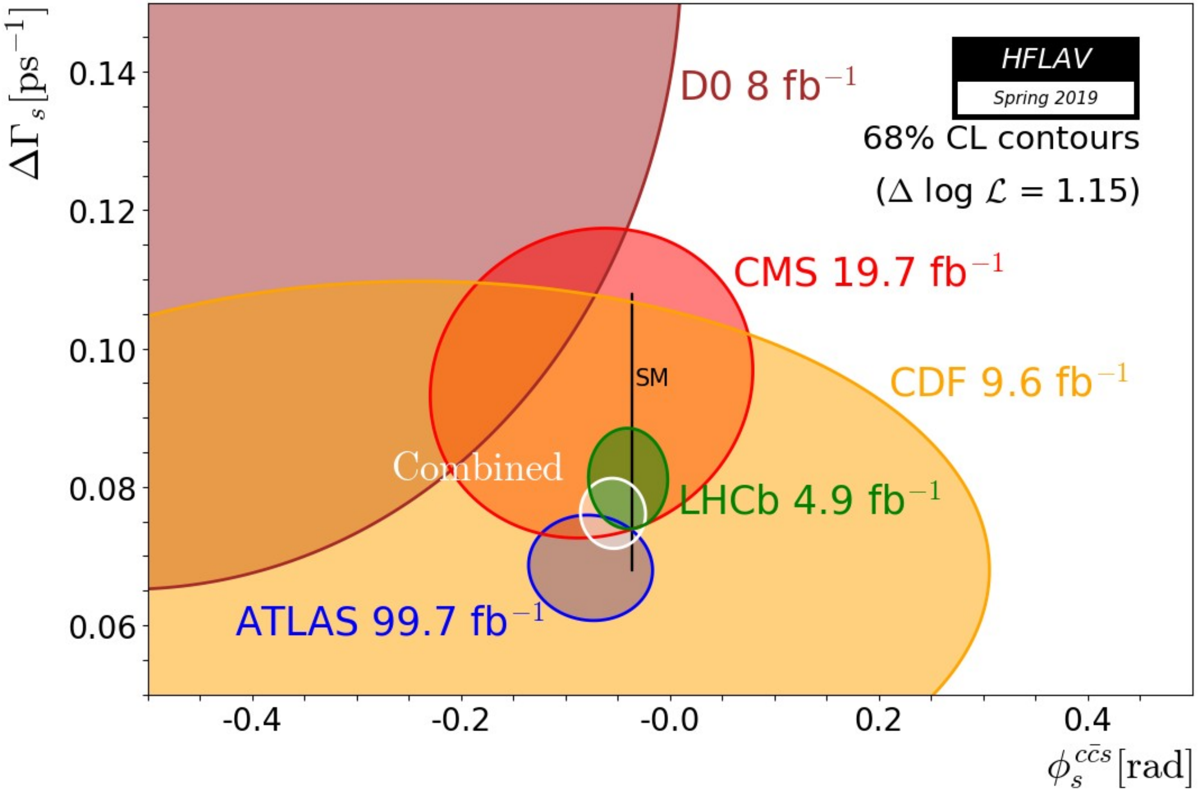
arXiv:1906.08356



- Data from 2015-16
- Signal yield ~ 120k
- Time resolution σ_t ~ 45 fs
- Tagging power ~ 4.7%



φ_s combination



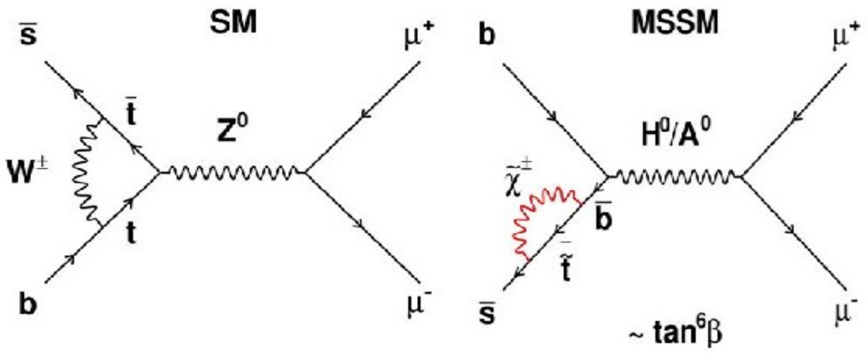
HFLAV world average: $\varphi_s = -0.054 \pm 0.020$ rad

Rare Decays

$B_{(s)}^0 \to \mu^+\mu^-$

Killer app. for new physics discovery

- Very small in the SM
  - no tree-level FCNC
  - CKM suppression
  - helicity suppression

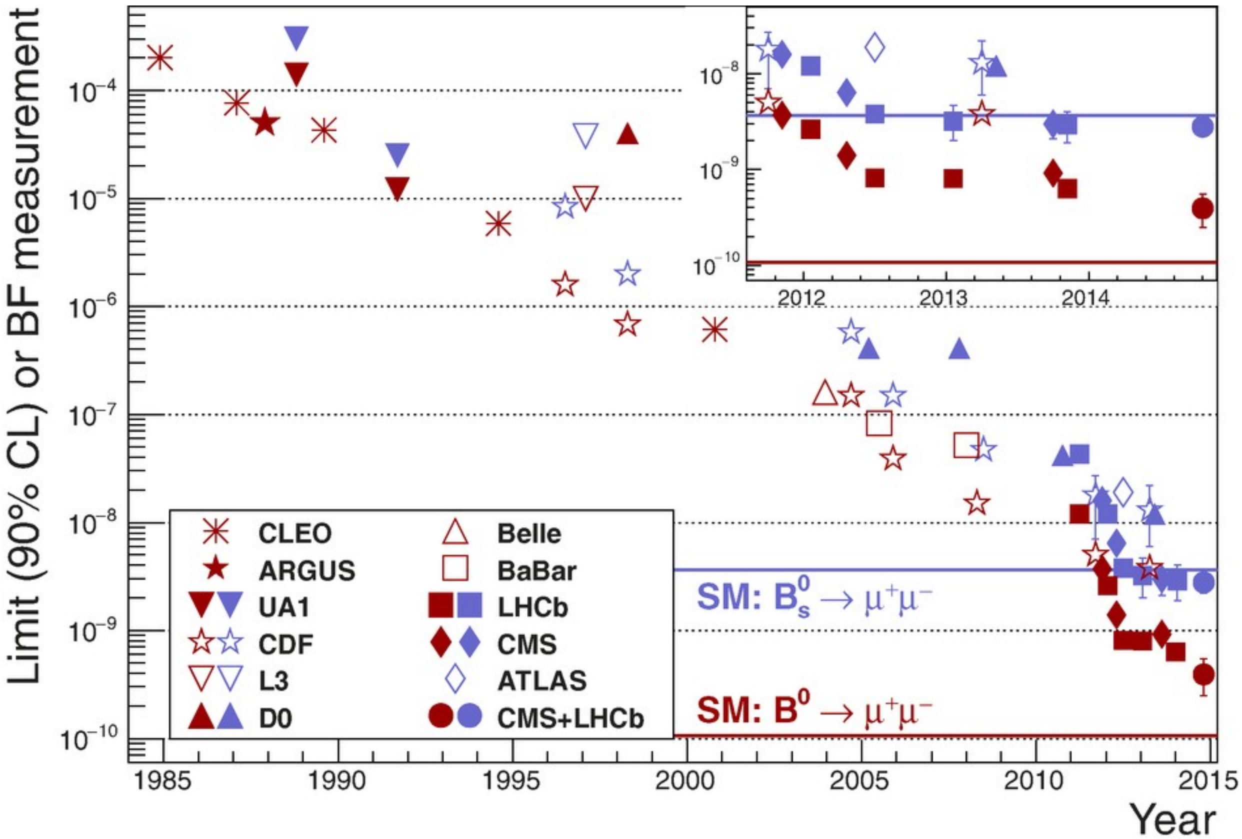


- Huge NP enhancement possible (tan β = ratio of Higgs vevs)

$$BR(B_s \to \mu^+\mu^-)^{SM} = (3.3 \pm 0.3) \times 10^{-9} \qquad BR(B_s \to \mu^+\mu^-)^{MSSM} \propto \tan^6\beta / M_{A0}^4$$

- Clean experimental signature

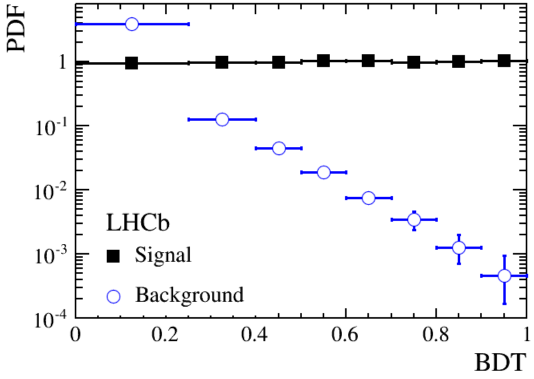
$B_{(s)}^0 \rightarrow \mu^+\mu^-$



Searches over 30 years

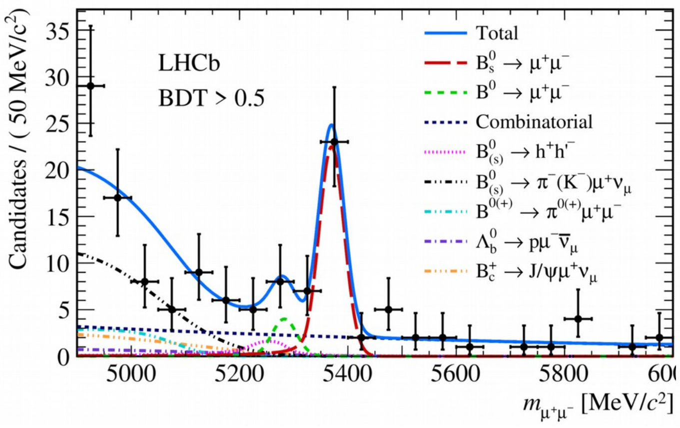
$B_{(s)}^0 \to \mu^+\mu^-$ – analysis ingredients

- Produce a very large sample of B mesons
- Trigger efficiently on dimuon signatures
- Reject background
  - excellent vertex resolution (identify displaced vertex)
  - excellent mass resolution (identify B peak & resolve B^0 from B_s^0 decays)
  - powerful muon identification (reject misidentified pion background)
  - typical to combine discriminating variables into a multivariate classifier

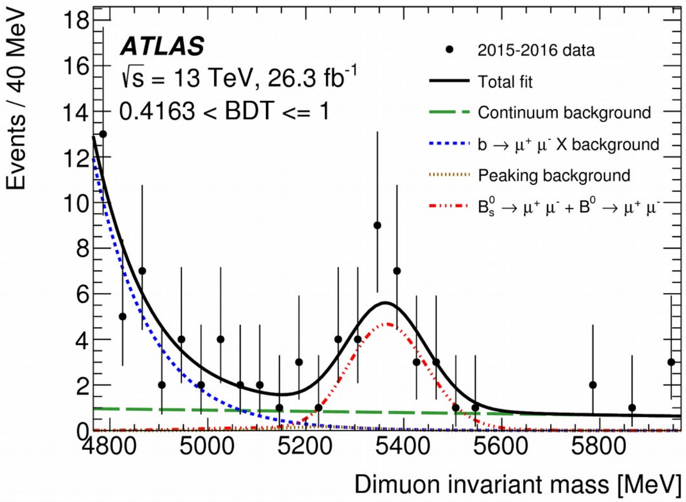


$B_{(s)}^0 \to \mu^+\mu^-$ latest results

LHCb PRL 118 (2017) 191801



ATLAS JHEP 04 (2019) 098



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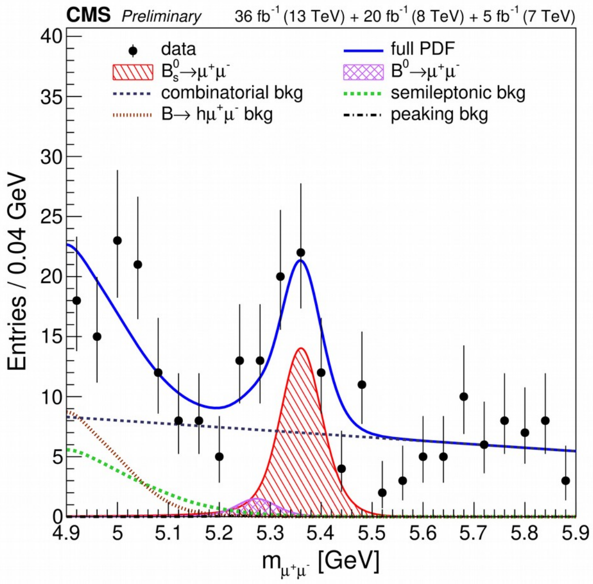

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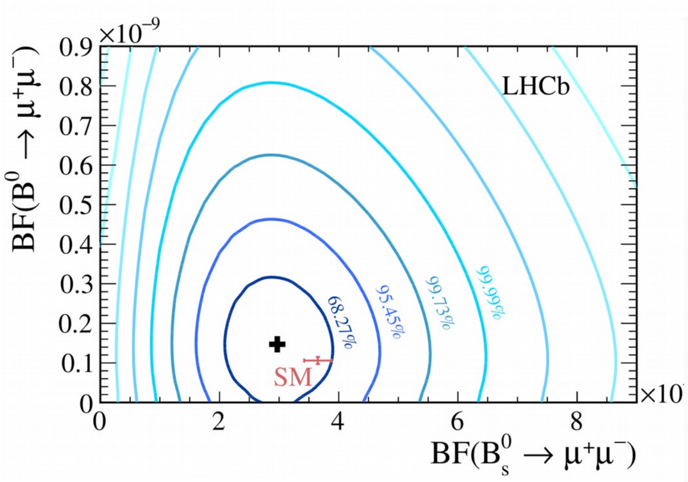

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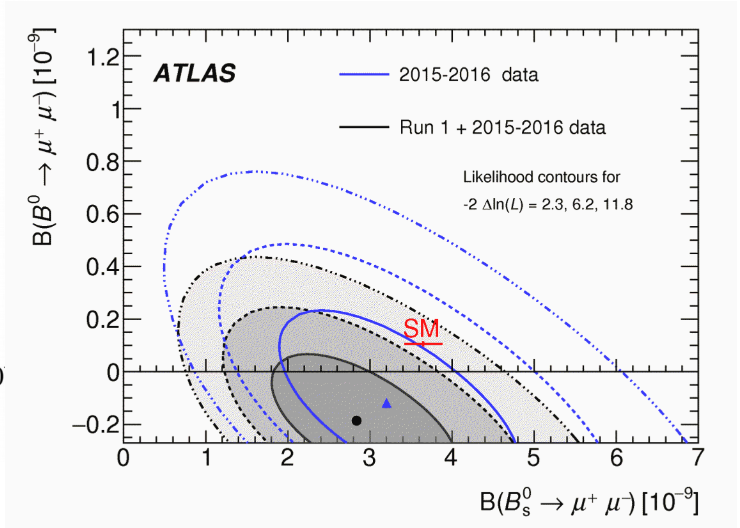

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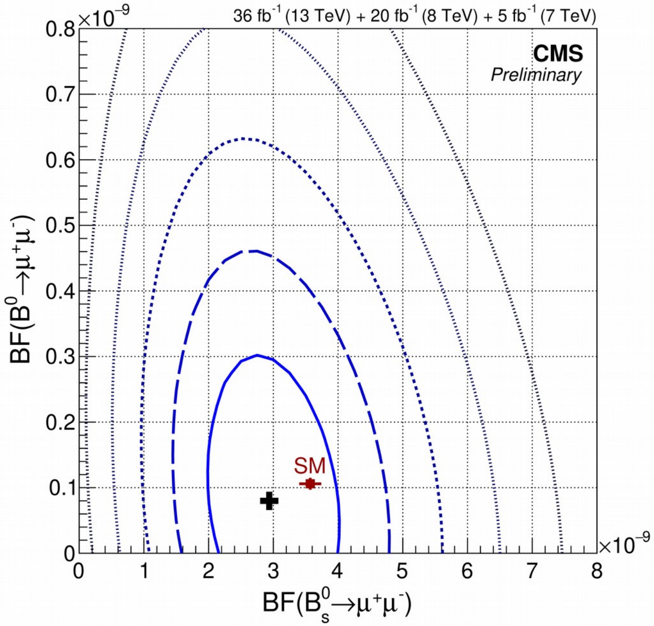
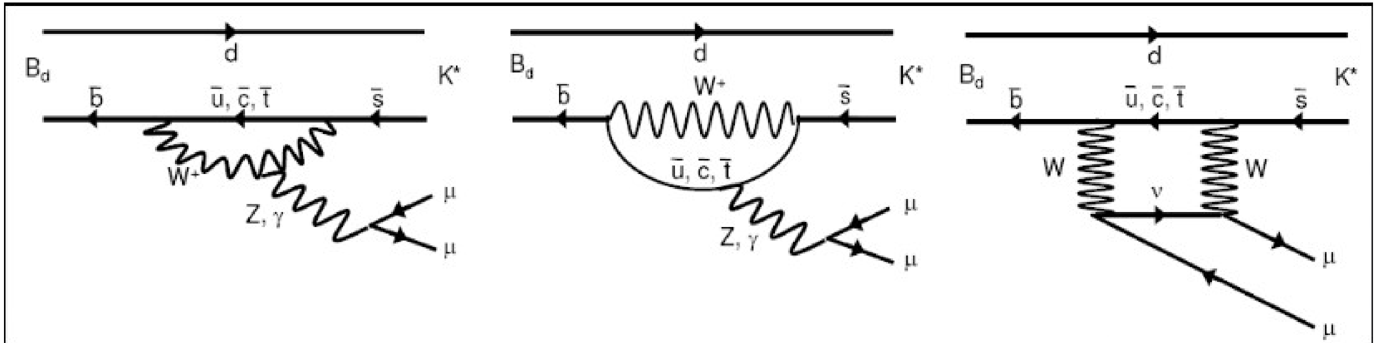


LHC average coming soon …

All experiments yet to analyse full Run 2 data samples

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

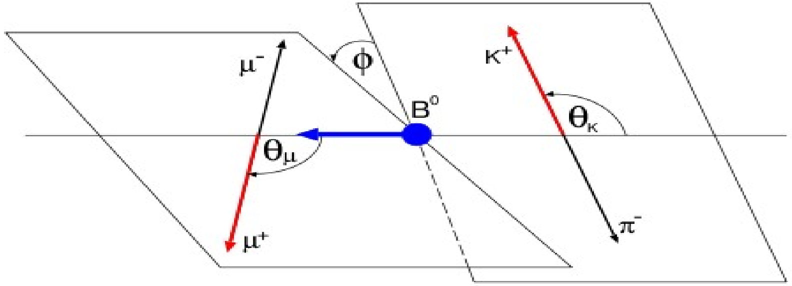
- $b \to s l^+ l^-$ processes also governed by FCNCs
  - rates and asymmetries of many exclusive processes sensitive to NP
- Queen among them is $B_d \to K^{*0} \mu^+ \mu^-$
  - superb laboratory for NP tests
  - experimentally clean signature
  - many kinematic variables …
  - … with clean(ish) theoretical predictions



Angular analysis of $B \to K^{*}\mu^{+}\mu^{-}$

- Differential decay distribution

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big].$$

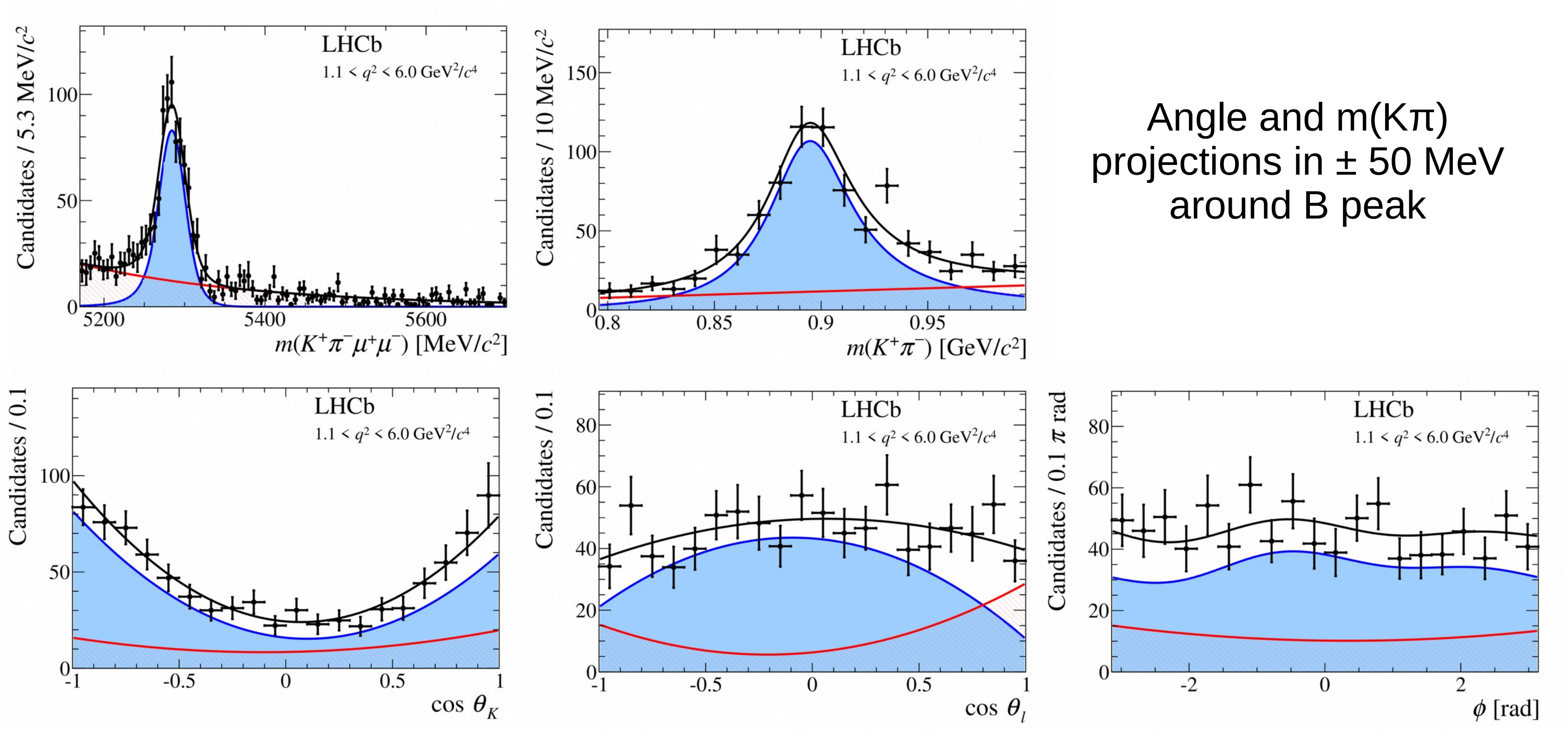


S_i terms related to Wilson coefficients and form factors

Full angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

JHEP 02 (2016) 104

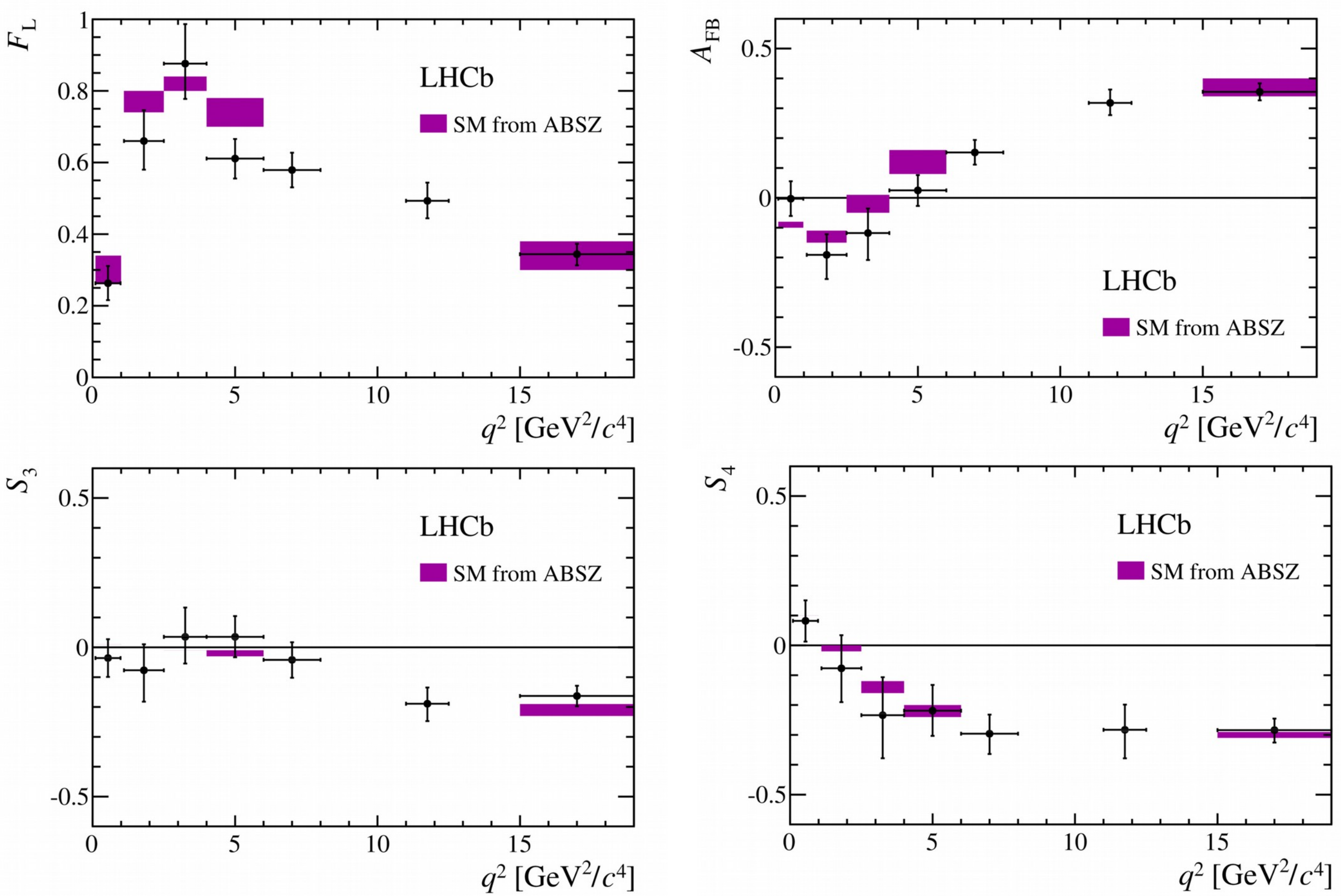
- Example of fits, in $1.1 < q^2 < 6.0$ GeV^2 bin



Angle and m(Kπ) projections in ± 50 MeV around B peak

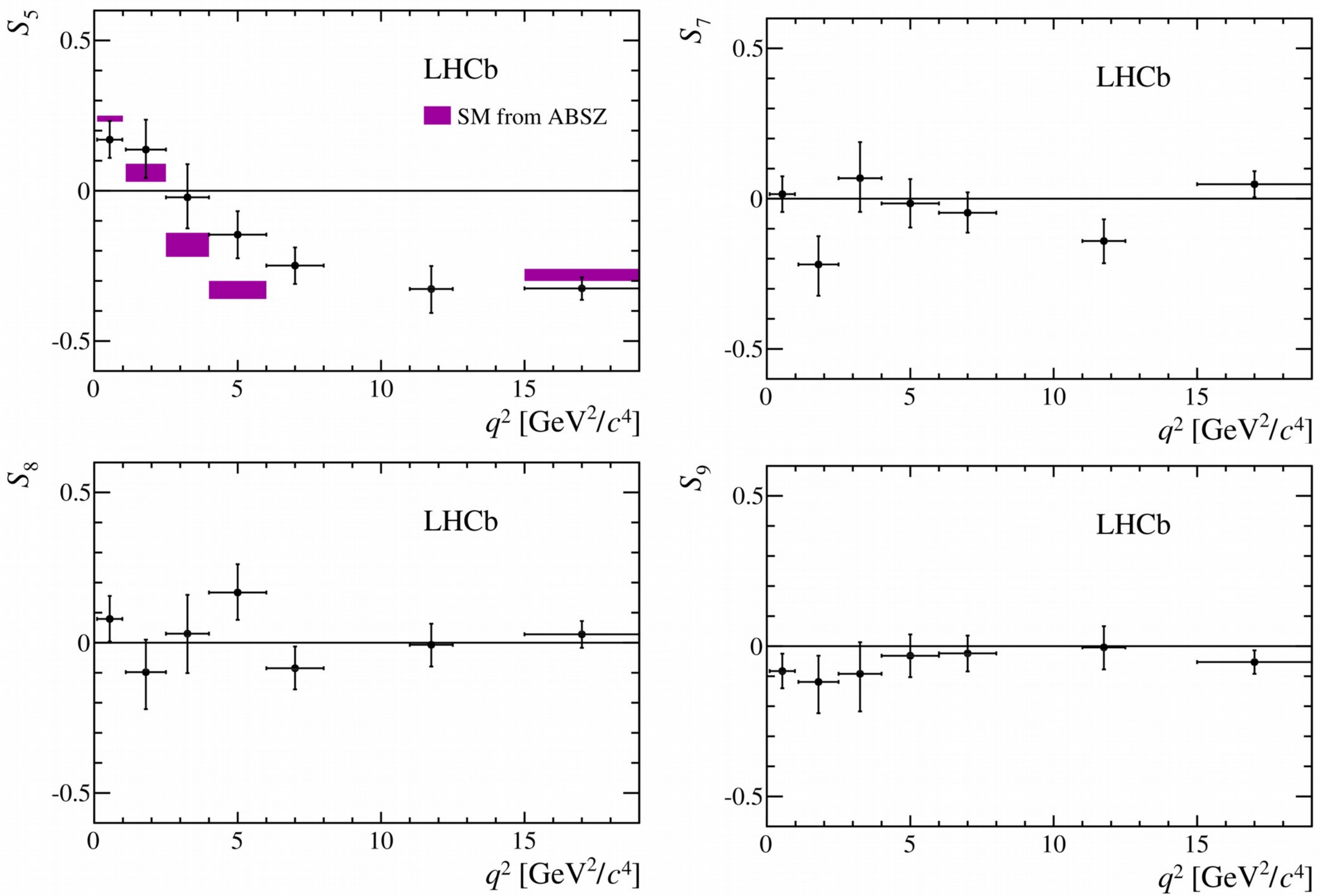
Full angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

JHEP 02 (2016) 104



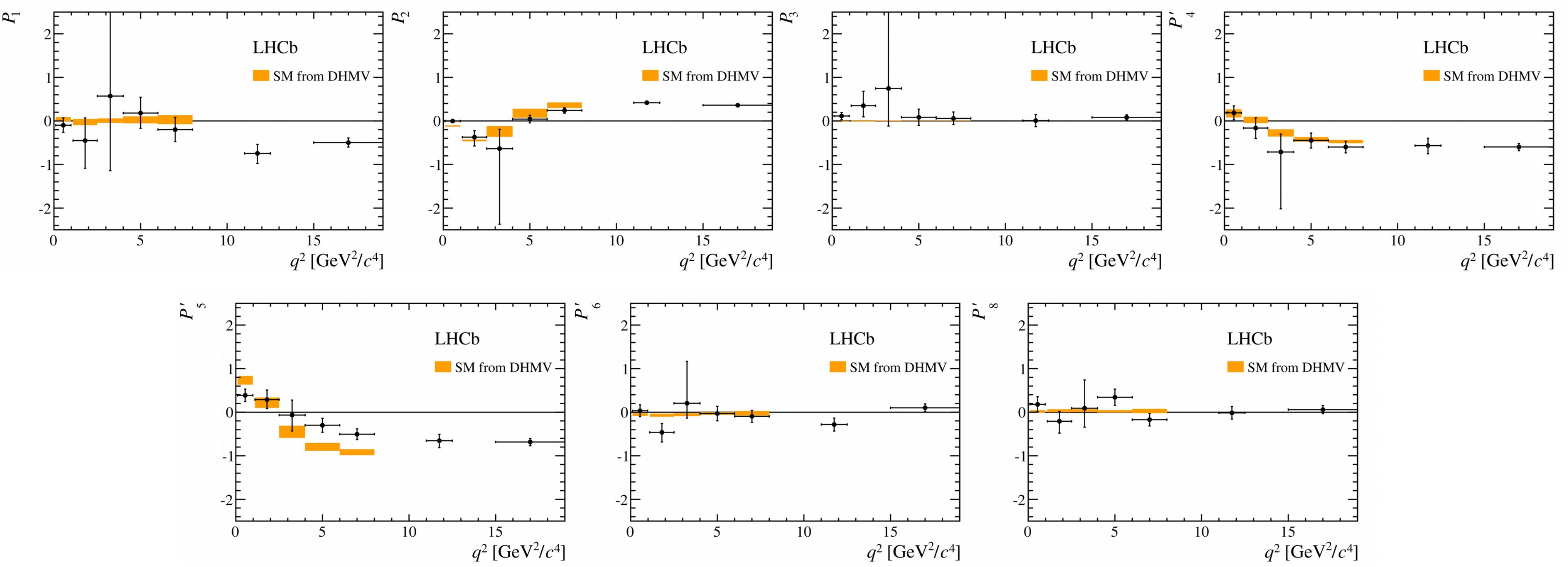
Full angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

JHEP 02 (2016) 104

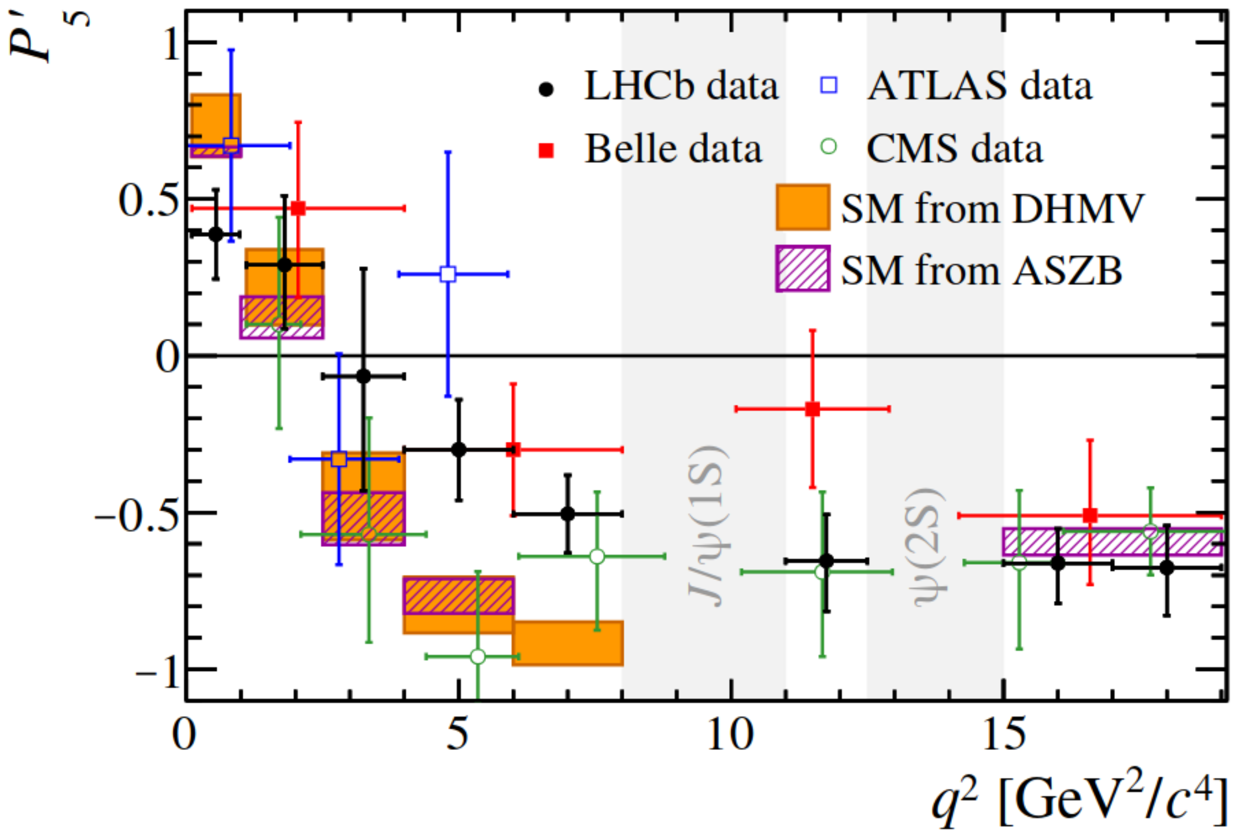


$B^0 \to K^{*0}\mu^+\mu^-$ "Optimised Observables"

JHEP 02 (2016) 104



The P_5' anomaly



Future prospects

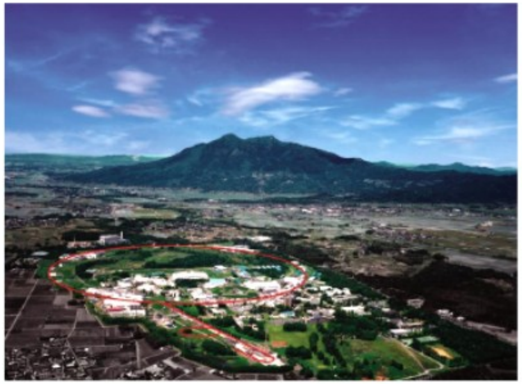
SuperKEKB/Belle II

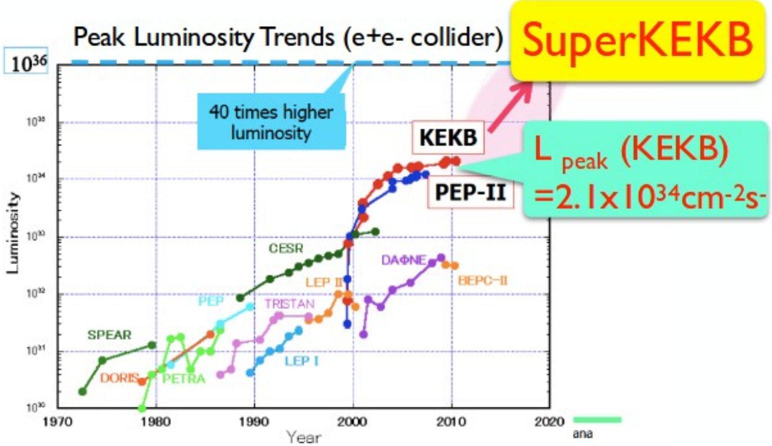
New intensity frontier facility at KEK

- Target luminosity ; $L_{peak} = 8 \times 10^{35} cm^{-2}s^{-1}$

  $\Rightarrow \sim 10^{10}\ B\bar{B}, \tau^{+}\tau^{-}$ and charms per year !

  $L_{int} > 50\ ab^{-1}$
- Rich physics program
  - Search for New Physics through processes sensitive to virtual heavy particles.
  - New QCD phenomena (XYZ, new states including heavy flavors) + more





The first particle collider after the LHC !

SuperKEKB Accelerator

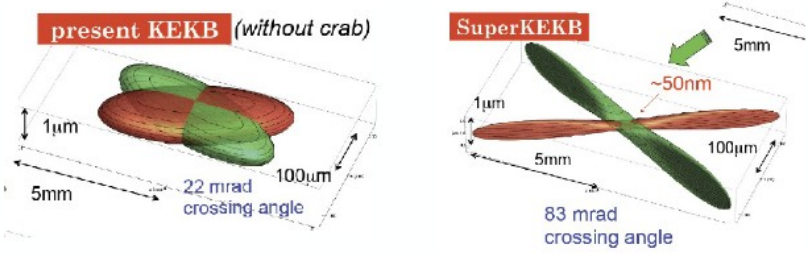
- Low emittance ("nano-beam") scheme employed (originally proposed by P. Raimondi)

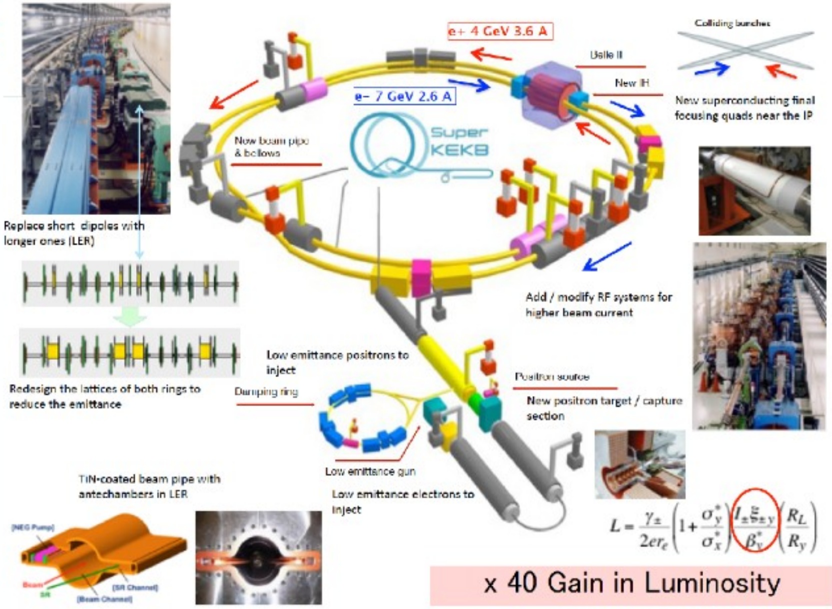
Machine parameters

	SuperKEKB LER/HER	KEKB LER/HER
E(GeV)	4.0/7.0	3.5/8.0
ε_x (nm)	3.2/4.6	18/24
β_y at IP(mm)	0.27/0.30	5.9/5.9
β_x at IP(mm)	32/25	120/120
Half crossing angle(mrad)	41.5	11
I(A)	3.6/2.6	1.6/1.2
Lifetime	~10min	130min/200min
L($cm^{-2}s^{-1}$)	80×10^{34}	2.1×10^{34}

x20

x2



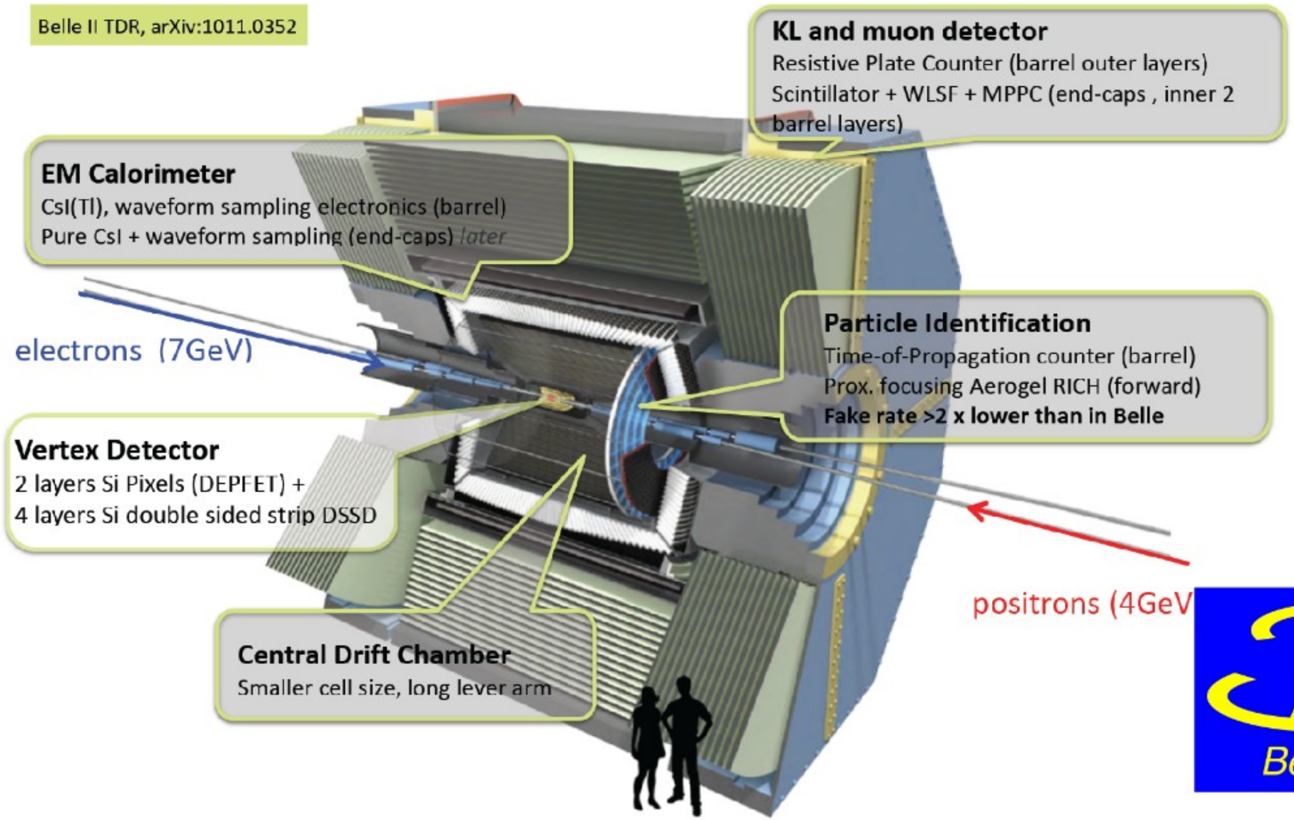


$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

x 40 Gain in Luminosity

Belle II Detector

- Deal with higher background (10-20×), radiation damage, higher occupancy, higher event rates (L1 trigg. 0.5→30 kHz)
- Improved performance and hermeticity



Belle2 physics

arXiv:1808.10567

Physics programme includes a broad range of CP violation measurements and rare decay studies

Both competition and complementarity with LHCb

Examples of unique potential:

- B → lν
- B → $K^{(*)}\nu\bar{\nu}$
- Inclusive B→$X_s\gamma$, $X_s l^+l^-$

Also much non-B physics

- including charm & tau

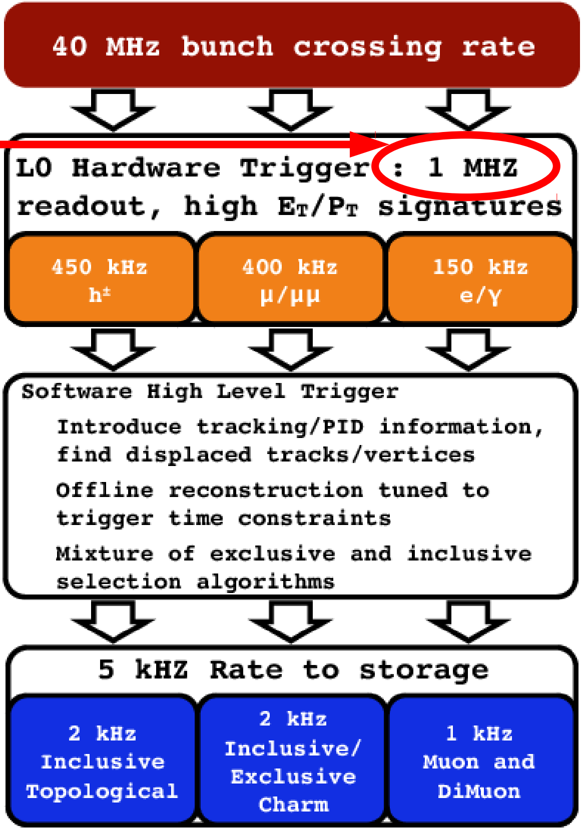
Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CP Violation			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***	0.03	Belle II
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\bar{\nu})$ $[10^{-6}]$	***	15%	Belle II
$\mathcal{B}(B \to K\nu\bar{\nu})$ $[10^{-6}]$	***	20%	Belle II
$R(B \to K^*\ell\ell)$	***	0.03	Belle II/LHCb

The LHCb Upgrade

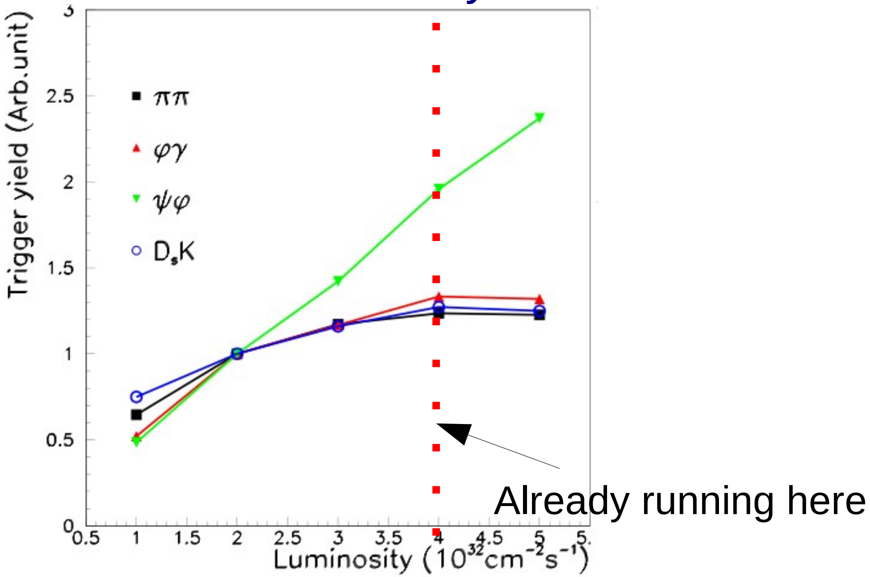
- Beyond LHC Run II, the data-doubling time for LHCb becomes too long
  - Due to 1 MHz readout limitation and associated hardware (L0) trigger
- However, there is an excellent physics case to push for improved precision and an ever-broader range of observables
- Upgrade the LHCb detector during LHC LS2 (2019-20)
  - Change subdetector electronics to 40 MHz readout
  - Make all trigger decisions in software
  - Restart data taking in 2021 at instantaneous luminosity increasing up to 2 x $10^{33}/cm^2/s$, and with improved efficiency
  - Upgrade detector qualified to accumulate 50/fb

LHC upgrade and the all important trigger

Limitation is here

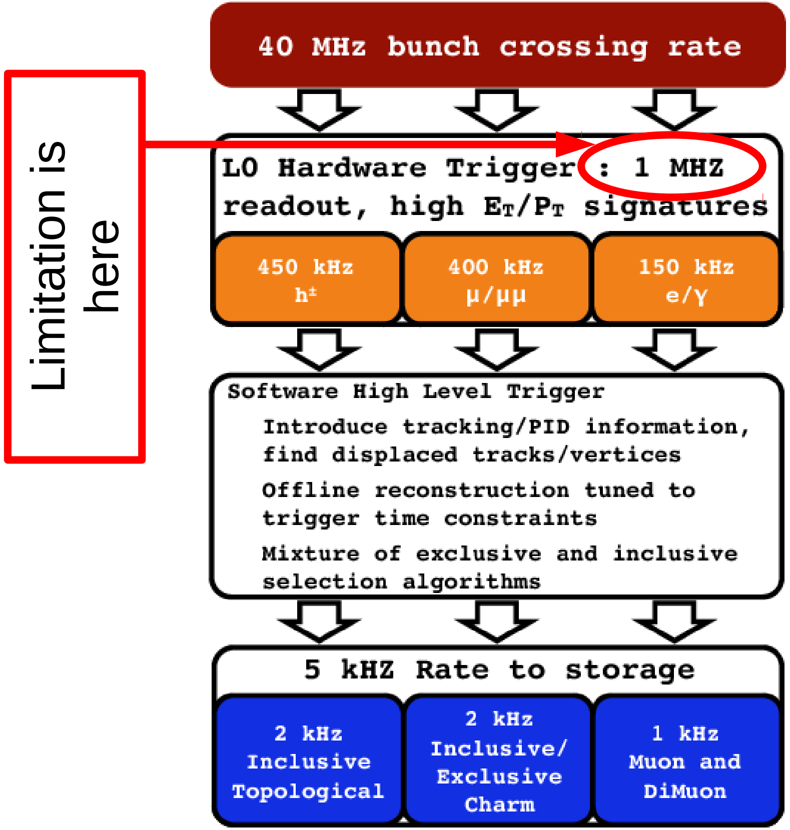


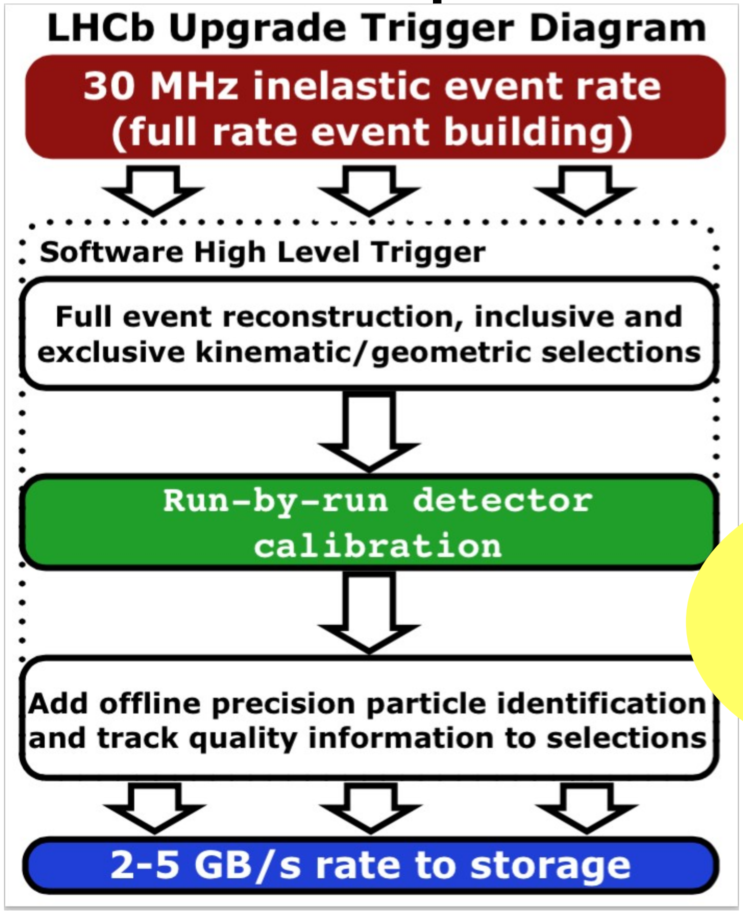
higher luminosity
→ need to cut harder at L0 to keep rate at 1 MHz
→ lower efficiency



- readout detector at 40 MHz
- trigger fully in software → efficiency gains
- run at L_{inst} up to 2 $10^{33}/cm^2/s$

LHC upgrade and the all important trigger



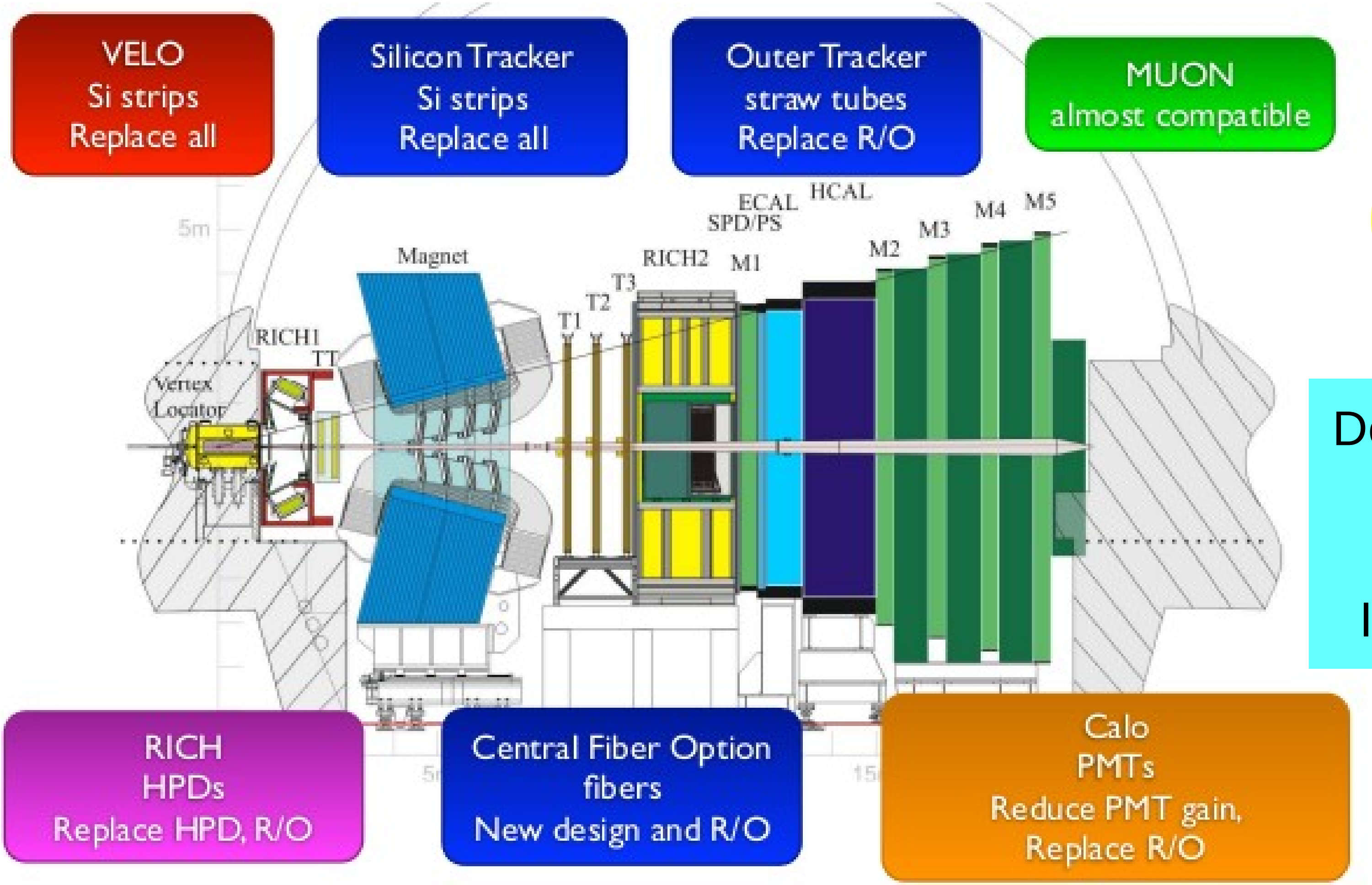


Real-time analysis

Real-time analysis

- Hadron collider experiments need triggers
  - Not enough storage to record all events
- Typically record entire event
  - Can reconstruct data and perform analysis offline
- Computing resources increasing (relatively) scarce
  - Perform offline quality calibration & alignment online
    - No need to re-reconstruct, no need to record raw data
    - No need to record entire event (PV tracks, effects of pile-up)
- A new paradigm for HEP data processing
  - Partially validated in Run II (similar concepts also exploited by ATLAS & CMS)

LHCb detector upgrade



Almost an entirely new detector

Deinstallation complete

On track
for commissioning
In 2021 (LHC Run 3)

LHCb upgrade sensitivities

Table 28: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming $5\,\text{fb}^{-1}$ recorded during Run 2) and for the LHCb Upgrade ($50\,\text{fb}^{-1}$). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.050	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	**0.023**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	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%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	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°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible

Will not reach limiting theory uncertainty!

Personal view – not an official schedule!

LHC long term future

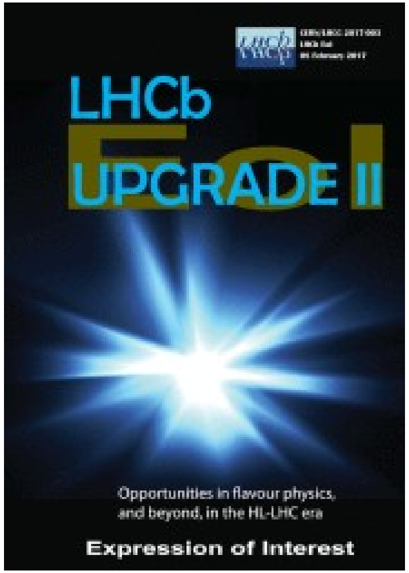
Bearing in mind that "Europe's top priority should be the exploitation of the full potential of the LHC" it seems natural to aim for a further major LHCb upgrade during LS4

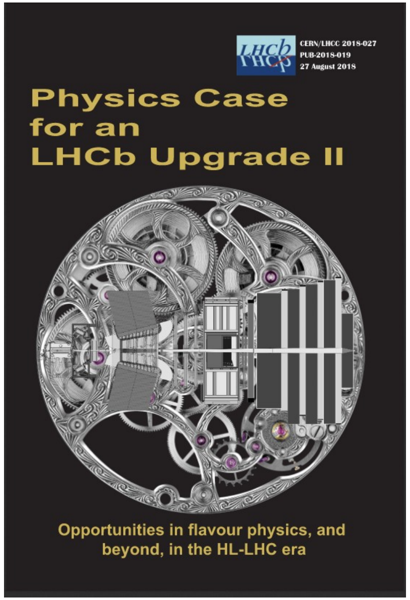
		2013/14		2019/20		2024-26		2030/31	
	Run 1	**LS1**	Run 2	**LS2**	Run 3	**LS3**	Run 4	**LS4**	Run 5
LHC machine		**Energy upgrade**				**Luminosity upgrade**			
ATLAS & CMS		**Detector completion**		Consolidation		**Major upgrades to handle high lumi**		Consolidation	
LHCb		Consolidation		**40 MHz upgrade**		Consolidation		**Major upgrade to handle high lumi**	

Upgrade during LS4 will allow to increase data sample
50/fb $\rightarrow$ $\geq$ 300/fb

CERN-LHCC-2017-003,
CERN-LHCC-2018-027

"Phase II" upgrade





- Increase total integrated luminosity 50/fb → ≥ 300/fb
- Improve detector capabilities

  (options currently under discussion)
  - improve EM calorimetry
  - increase tracking acceptance
  - reduce material
  - add timing information to control pile-up
  - new low-momentum particle ID capability
- Enhance HL-LHC discovery potential!

LHCb upgrade II sensitivities

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert / \lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Summary

- In the 40+ years since the b quark discovery, data samples have increased (on average) by an order of magnitude every ~5 years
- Improvements in accelerator and detector technologies have led to remarkable discoveries
  - Both e^+e^- & hadron collider experiments important
  - Good overall consistency with the SM, but ...
  - … exciting anomalies in the current data (not for the first time, however)
- Can expect dramatic further progress in coming years
  - Start of the Belle2 & LHCb upgrade era

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

When are the updates coming?

“Do not look sad. We shall meet soon again."

— C.S. Lewis, The Voyage of the Dawn Treader