UK HEP Forum: What do the next 10 years have in store?

Heavy Flavour Physics Experiment

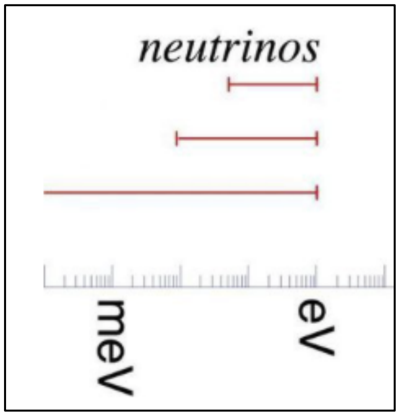
Val Gibson

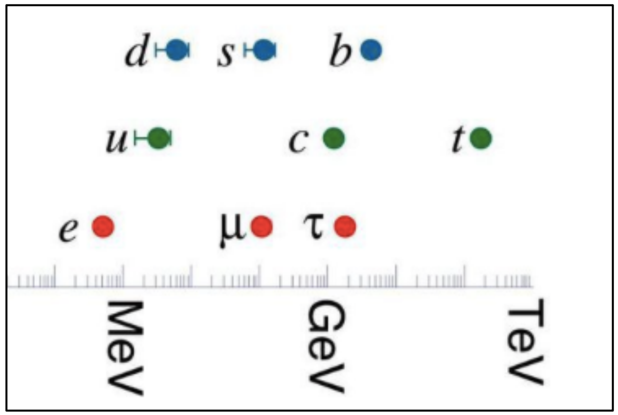
University of Cambridge

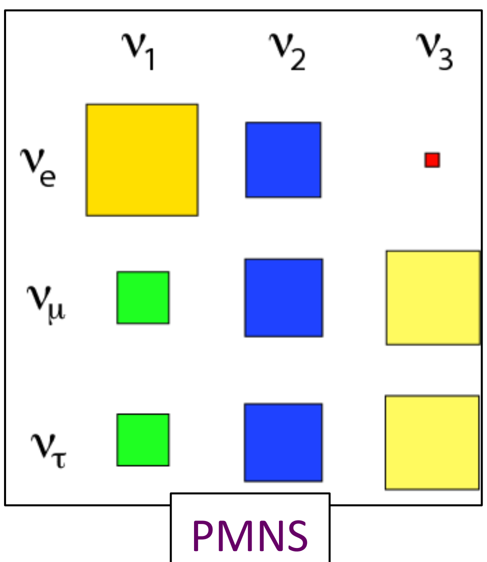
Athena SWAN Gold Award

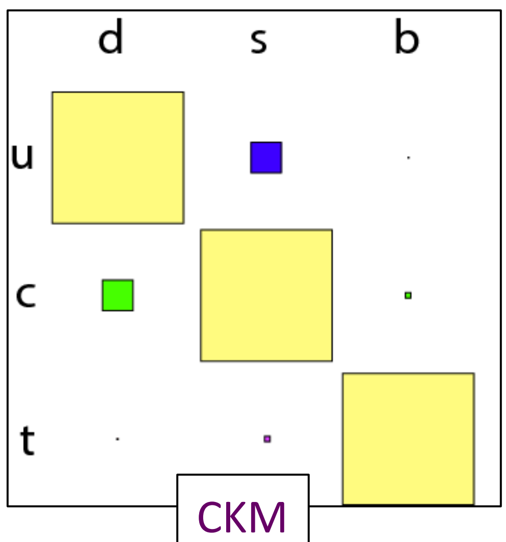
IOP Institute of Physics Juno Champion

The flavour puzzle









Why study flavour?

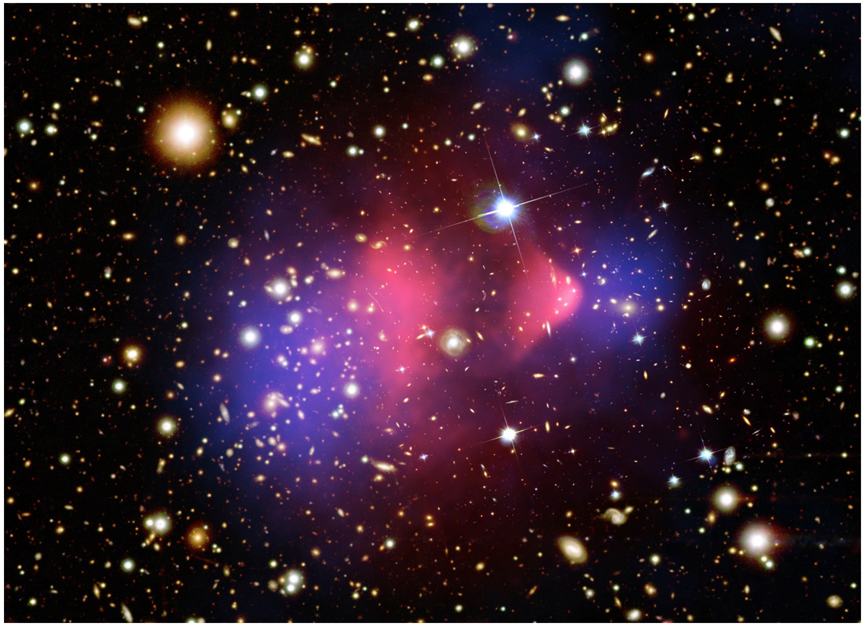
- 3 generations
- Large hierarchy of masses
- ν mass
- Origin of different mass matrices

Connection between flavour puzzle and electroweak hierarchy.

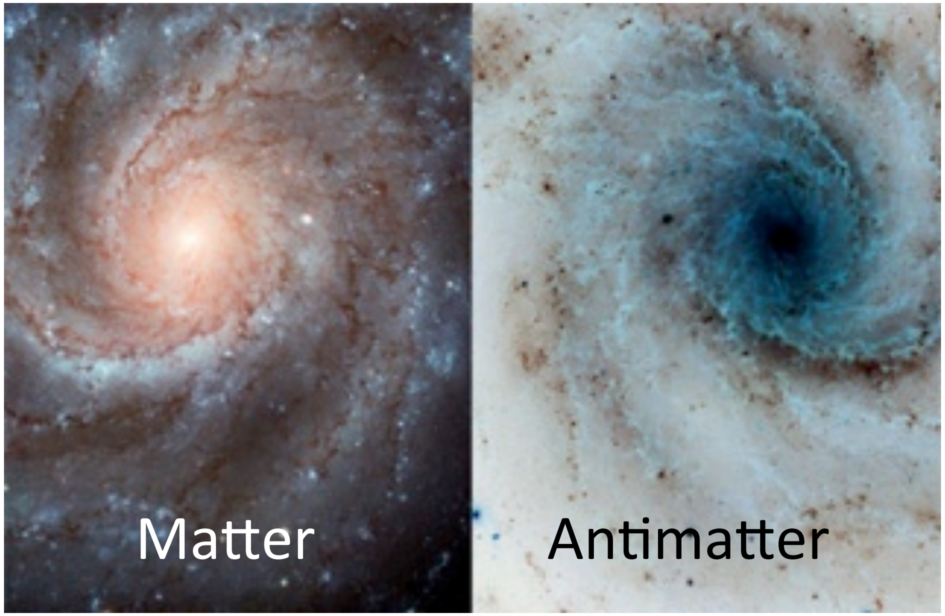
t, b, τ connected to Higgs sector.

Key open questions

Dark matter



Baryon asymmetry



New sources of CP violation?

New Physics must exist ➔ what is the energy scale?

Energy scale

Full discussion of theory, please see talk by Svjetlana Fajfer

Standard Model low-energy effective theory:

$$\mathcal{A}_0 \left(\frac{c_{\mathrm{SM}}}{v^2} + \frac{c_{\mathrm{NP}}}{\Lambda^2} \right)$$

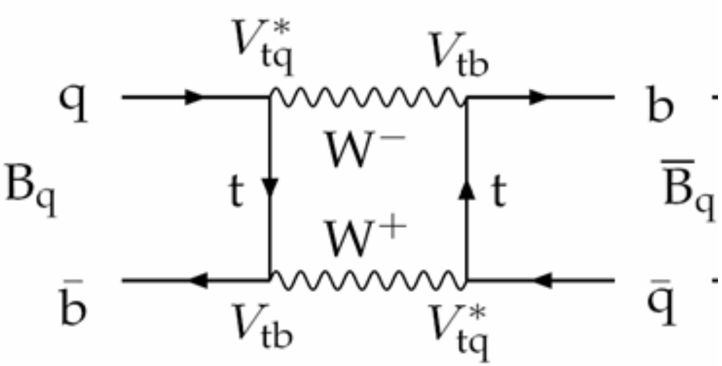
NP Couplings

NP scale

Electroweak scale

$$v = \left(\sqrt{2}G_F\right)^{-1/2} \approx 246\ \mathrm{GeV}$$

New Physics can have a big impact even if $\Lambda >> \nu$. Also more visible in FCNC due to extra loop factors:

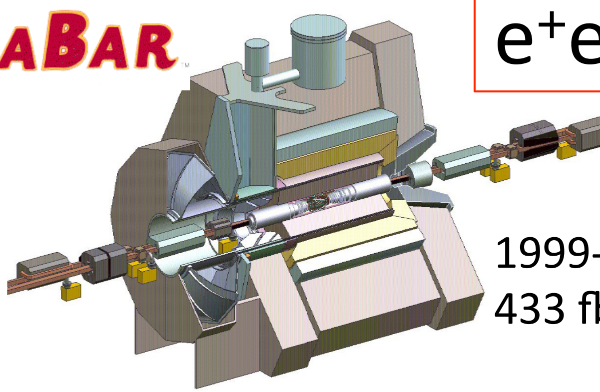


$$C_{SM} = \frac{V_{td}^2}{16\pi^2} \sim 10^{-6}$$

$$\boxed{\frac{\Lambda^2}{C_{NP}} \sim \left(10^3\ \mathrm{TeV}\right)^2}$$

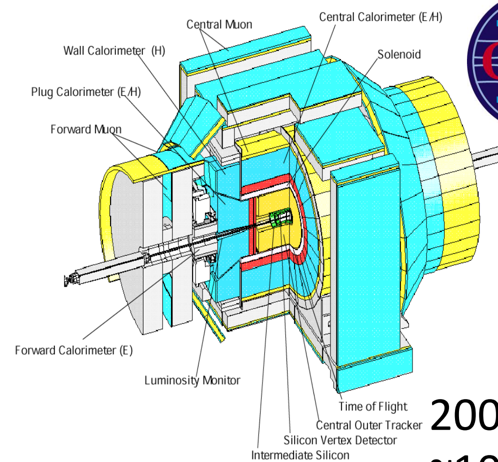
Key experiments (pre-LHC)

e^+e^-

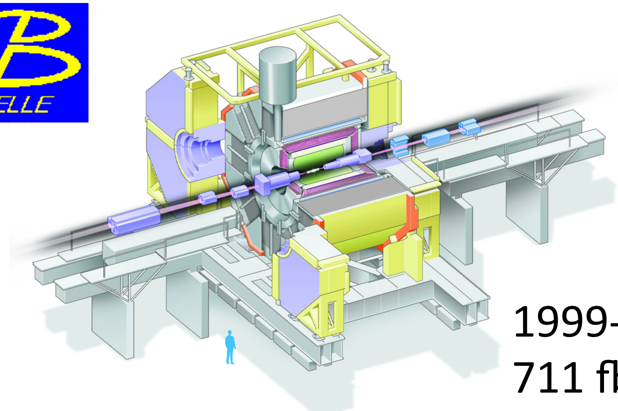


1999-2008
433 fb^{-1} @ Υ(4s)

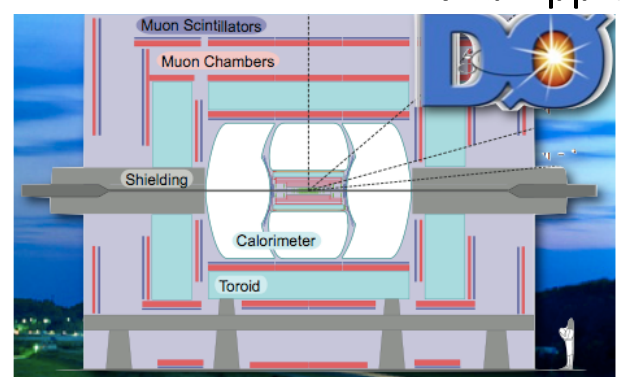
$p\bar{p}$



2001-2011 (Run II)
~10 fb^{-1} $p\bar{p}$ $\sqrt{s}$=1.96 TeV



1999-2010
711 fb^{-1} @ Υ(4s)



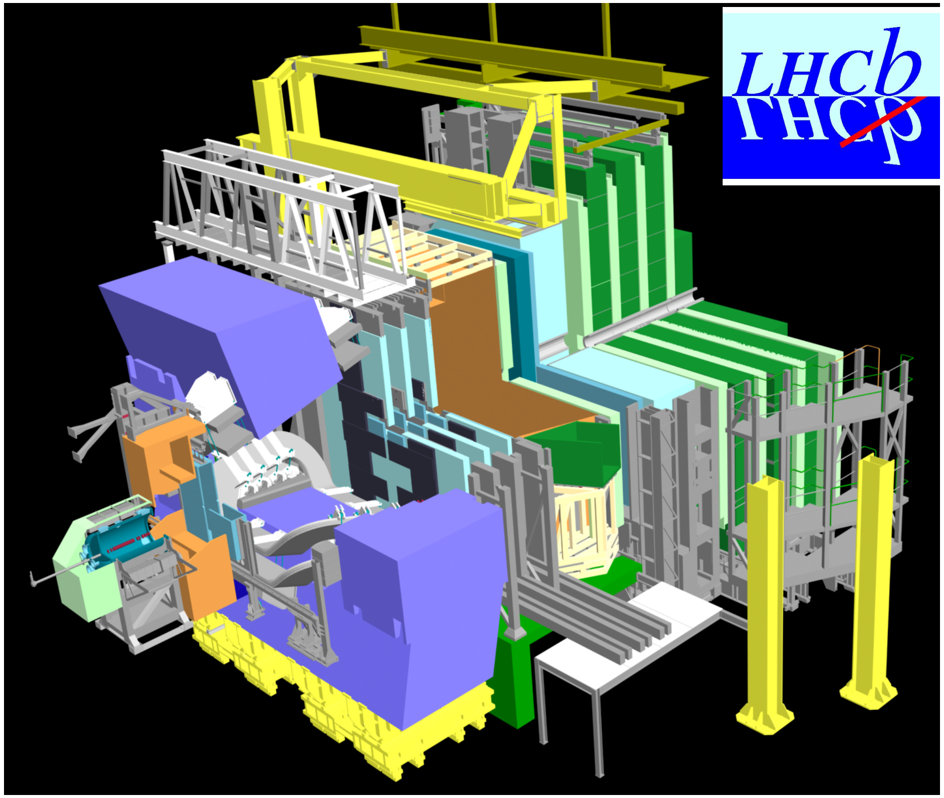
Discovery of CPV in B_d system

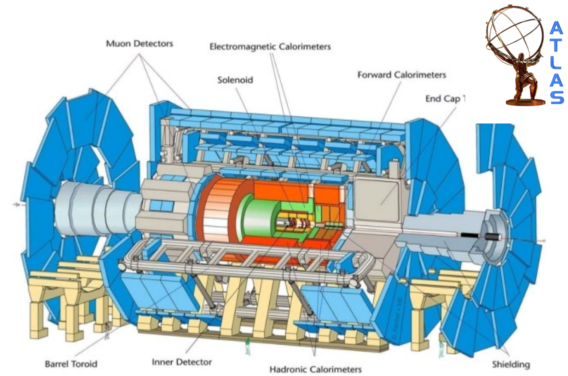
Established the CKM mechanism

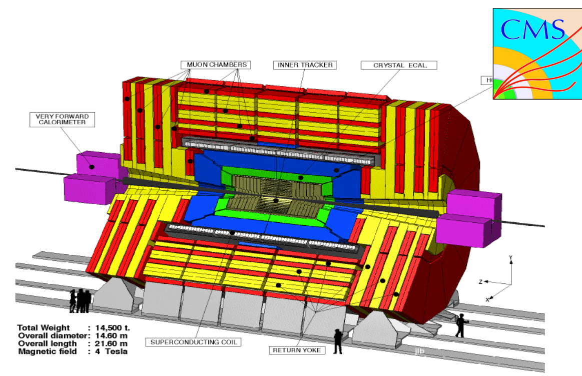
B_s mixing, discovery of top, B_c, ϕ_s

Demonstrated capabilities of hadron colliders

Key experiments (LHC)





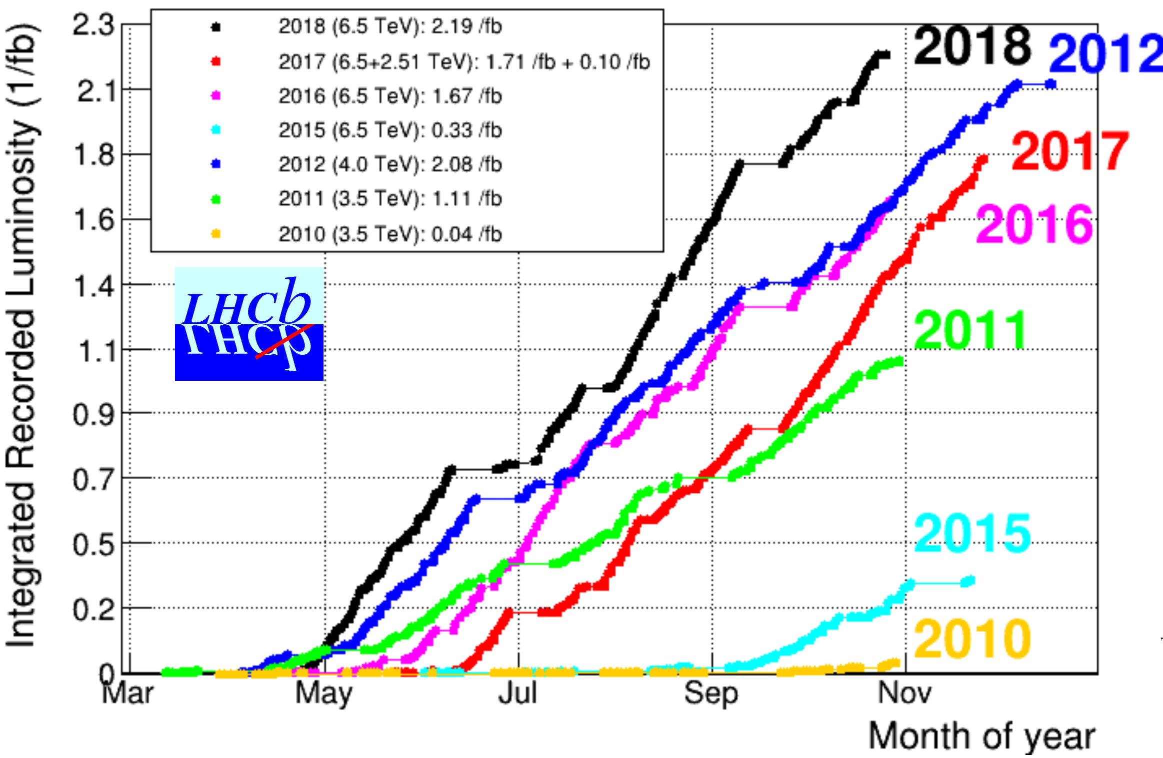


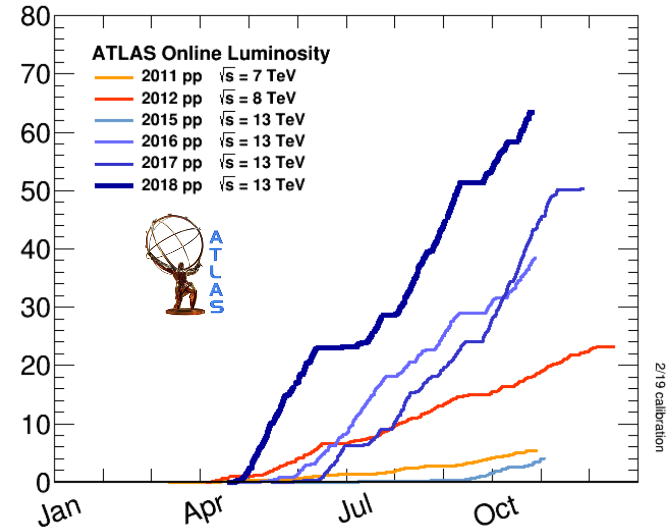
Precision measurements of CKM parameters;

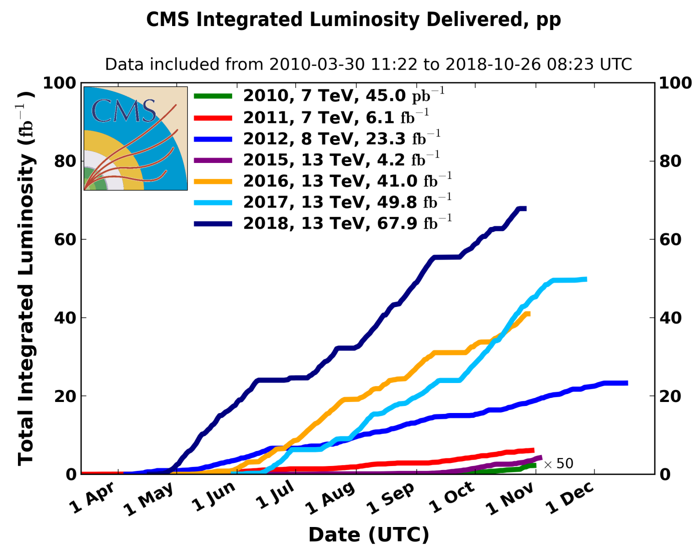
Search for New Physics in CP-violating phases and rare decays;

Broad physics programme (EW physics, heavy ions etc).

LHC Luminosity







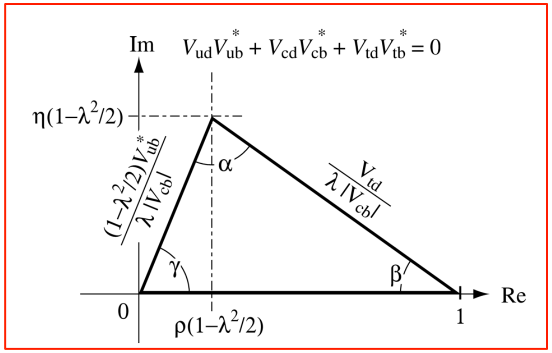
Total integrated luminosity (Run 1 & 2)

LHCb	9 fb^{-1}
ATLAS	139 fb^{-1}
CMS	178 fb^{-1}

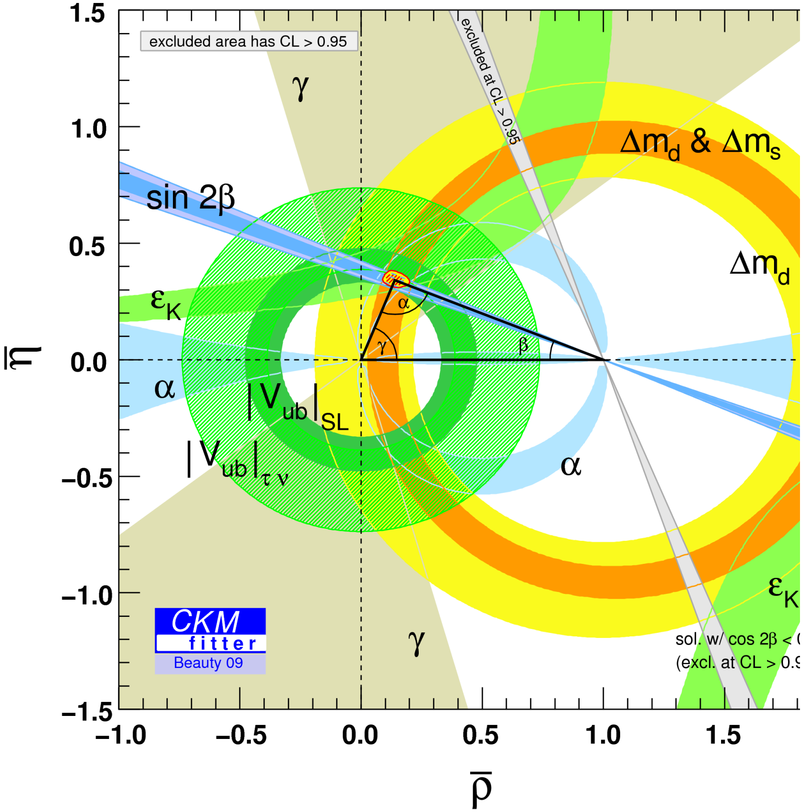
A decade of work from the flavour community

Encapsulated in the "The" Unitarity Triangle

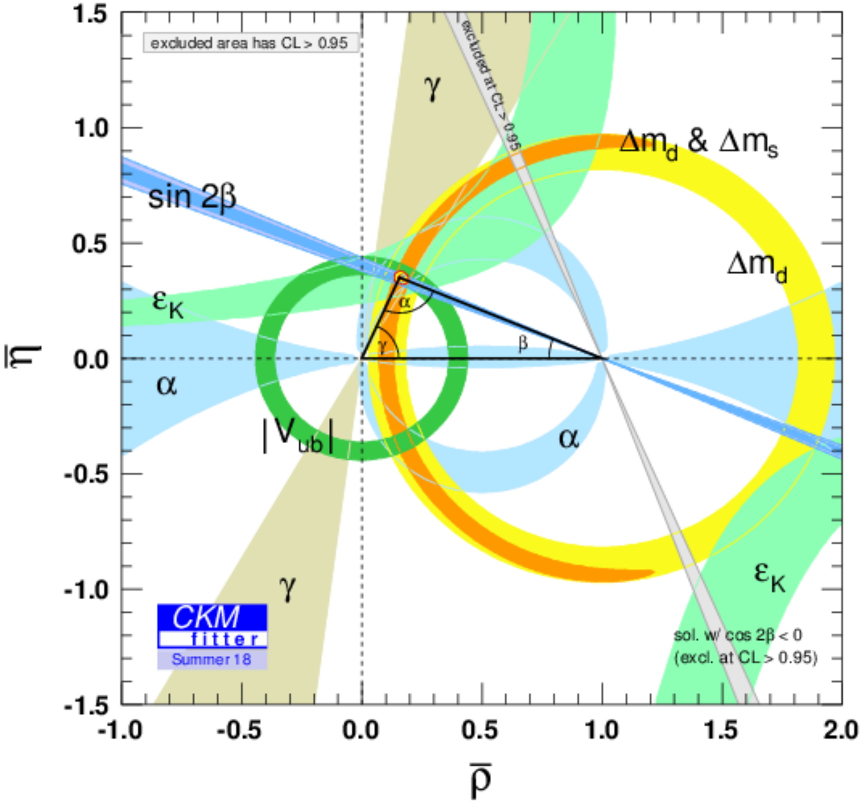
$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \qquad V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



2009



2019

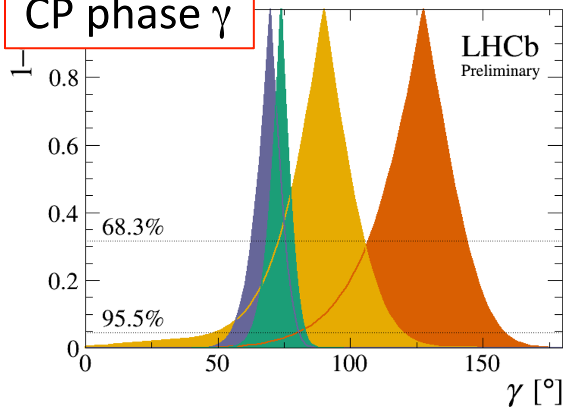


LHCb achievements

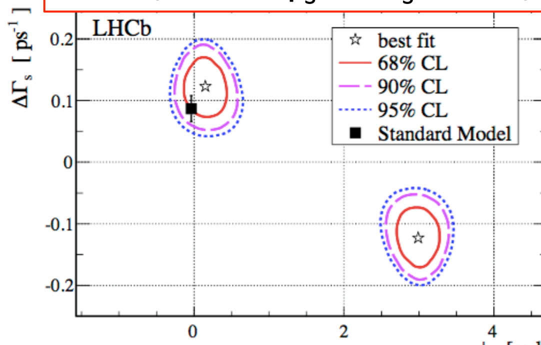
6 core measurements identified in **Roadmap for selected key measurements of LHCb**

LHCb-PUB-2009-029

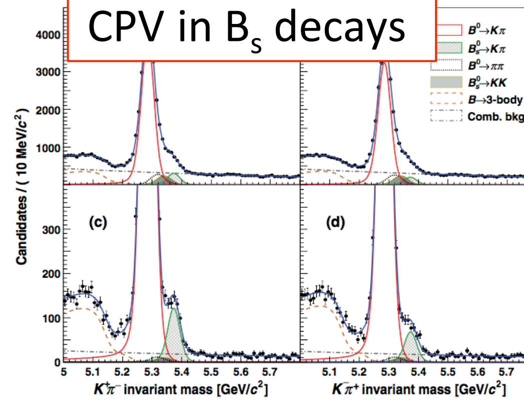
CP phase γ



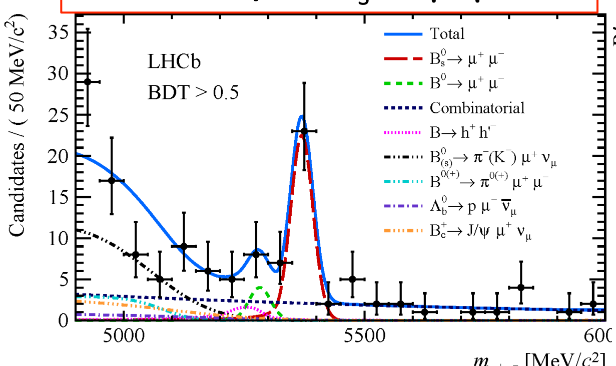
CPV phase ϕ_s in B_s decays



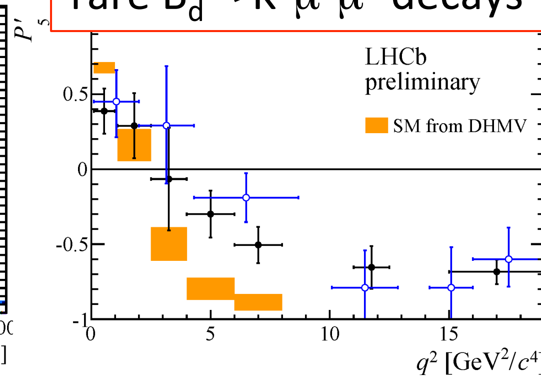
CPV in B_s decays



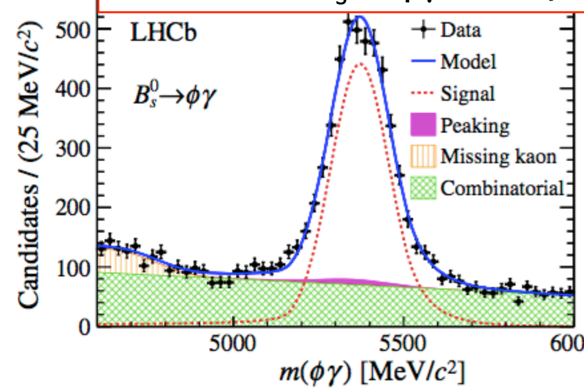
Discovery of $B_s \to \mu^+\mu^-$



Angular analysis of EW rare $B_d \to K^*\mu^+\mu^-$ decays



Radiative $B_s \to \phi\gamma$ decays

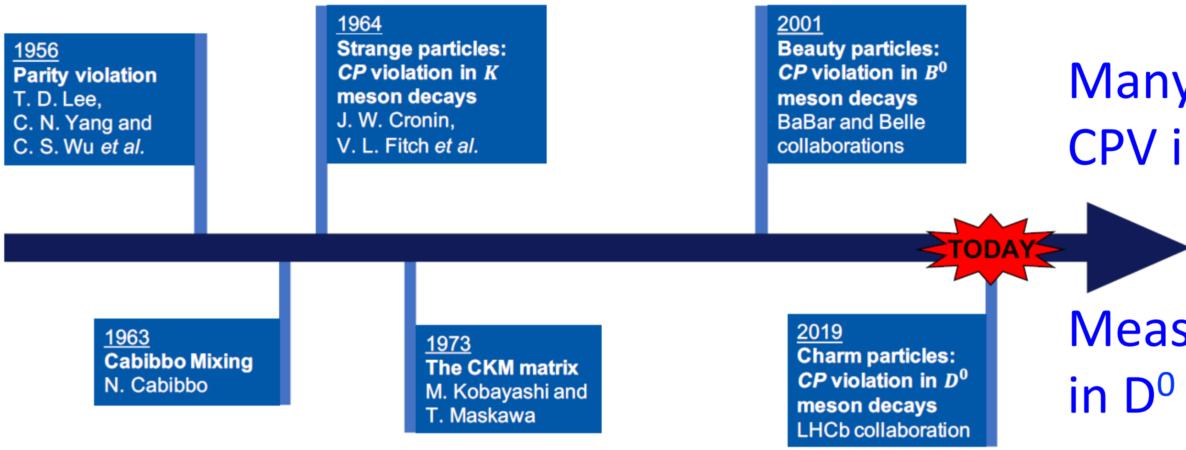


... as well as the unexpected ...

LHCb-CONF-2018-002, PRL 108 101803, PRL 110 221601, PRL 118 191801, JHEP 02 (2016) 104, PRL 118 021801

Discovery of CP violation in Charm

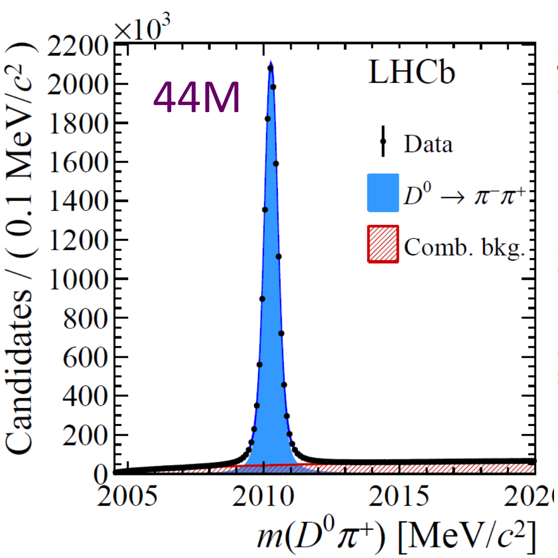
PRL 122 (2019) 211803

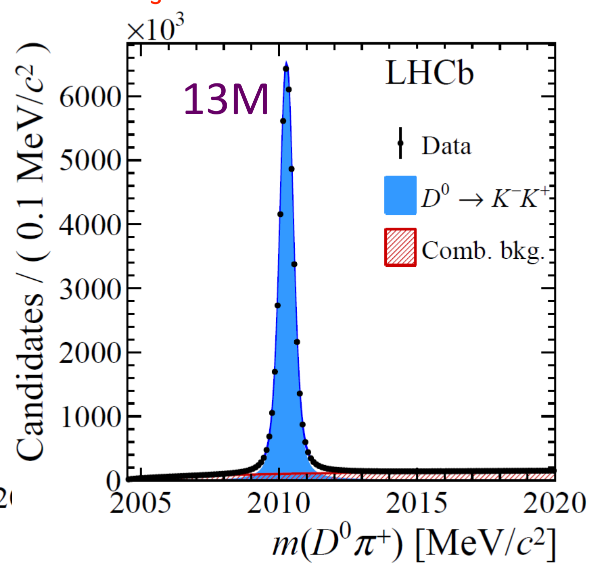


Many decades of searching for CPV in charm decays….

Measurement of the asymmetry in $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays

$D^{*+} \rightarrow D^0 \pi^+_s$





$$A = \frac{N(D \to f) - N(\overline{D} \to \overline{f})}{N(D \to f) + N(\overline{D} \to \overline{f})}$$

$$= A_{CP} + A_D + A_P$$

detection asymmetry (e.g. for slow pion tag)

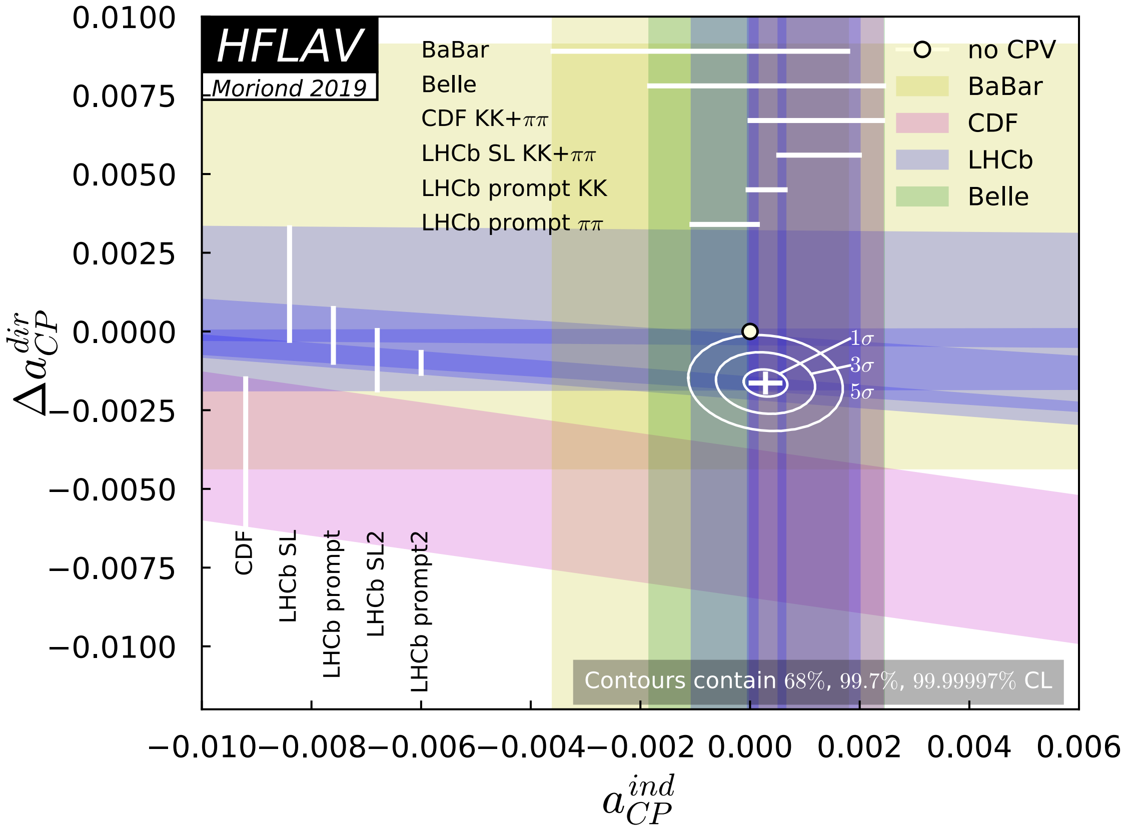
production asymmetry (e.g. for D^{*+} & D^{*-})

$$\boxed{\Delta A_{CP} = A(K^+K^-) - A(\pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4}}$$

5.3σ

CP Violation in Charm

Using charm mixing and CPV constraints from all experiments



HFLAV

$$\Delta a_{CP}^{dir} = (-16.4 \pm 2.8) \times 10^{-4}$$

$$a_{CP}^{ind} = (2.8 \pm 2.6) \times 10^{-4}$$

5.4σ observation of direct CPV in charm decays

Theory community (inevitably) divided on consistency with SM and potential for NP, e.g. compare

Chala, Lenz, Rusoz, Scholtz arXiv: 1903.10490

with

Grossman and Schacht arXiv: 1903.10952

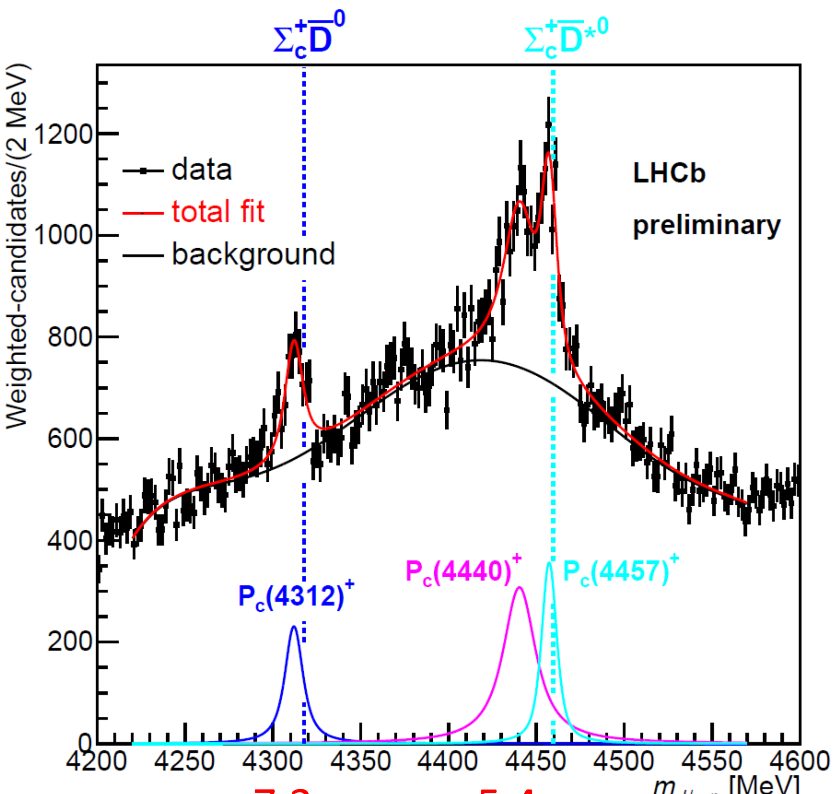
Opens a new era of CPV studies with up-type quarks.

Discovery of pentaquarks

Pentaquarks were discovered by LHCb in 2015 (Run 1) and updated with Run 2 data & improved selection.

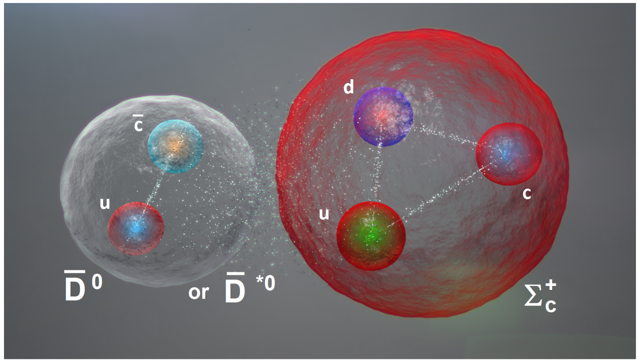
PRL 115 (2015) 072001
PRL 122 (2019) 222001

Full amplitude analysis of $\Lambda_b \rightarrow J/\psi\, pK^-$ decays



7.3σ 5.4σ

Resolve 2 peaks around 4450 MeV.
New peak at 4312 MeV.

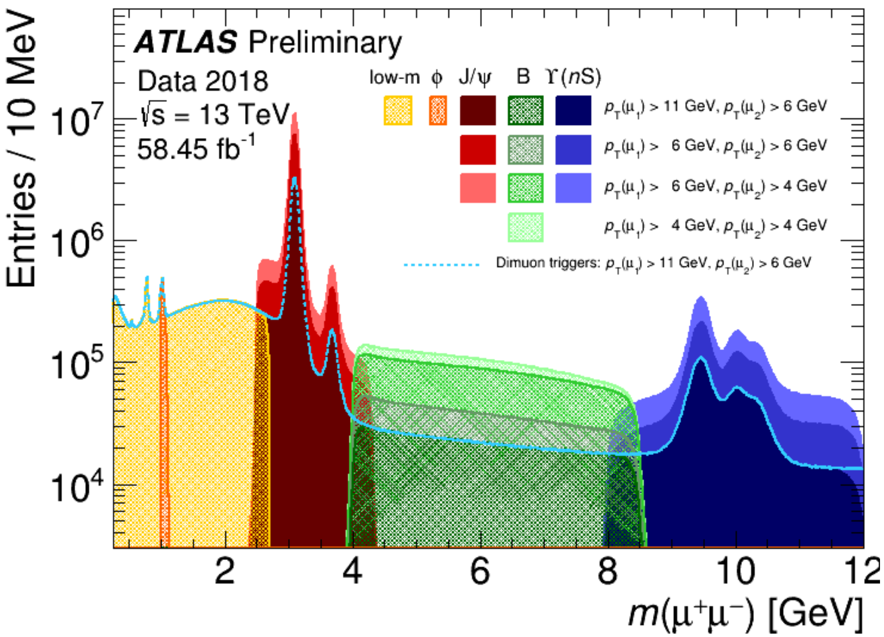


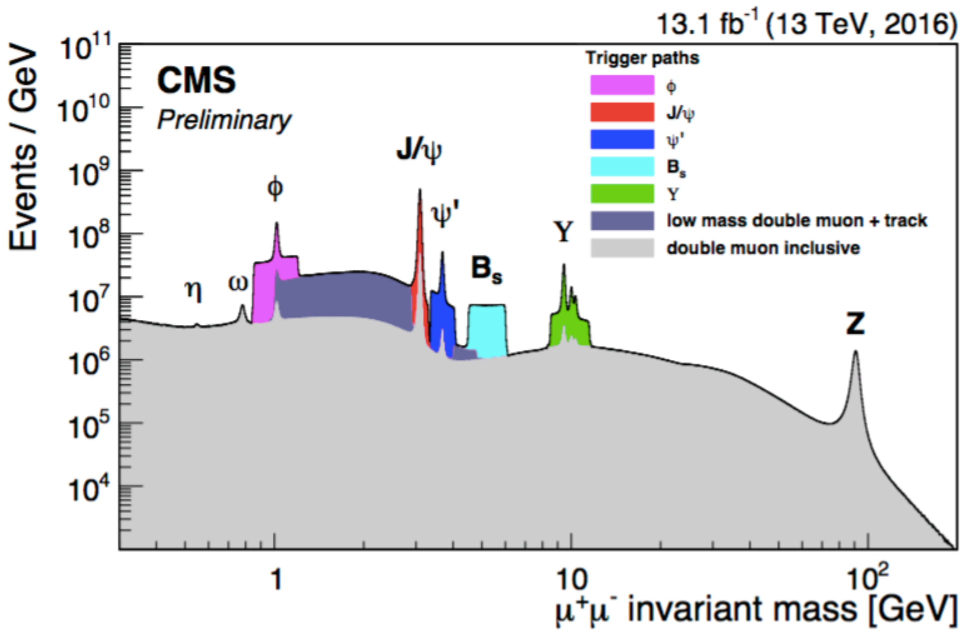
Molecular pentaquarks with meson-baryon substructure favoured

e.g. Wang et al; pRC 84 (2011) 015203,
Zhang et al; CPC 36 (2012) 6
Wu et al; PRC 85 (2012) 044002

ATLAS & CMS

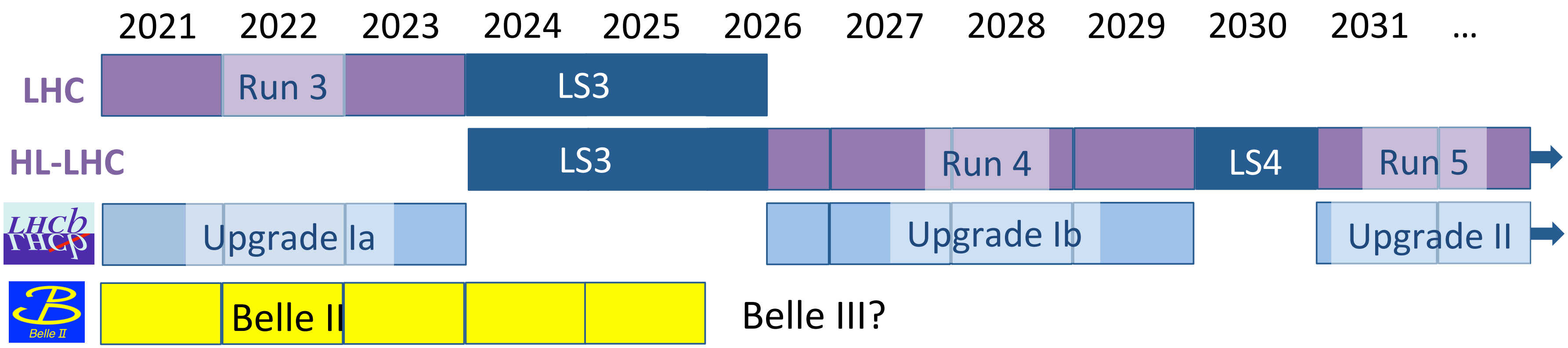
ATLAS & CMS have collected large datasets with μμ triggers allowing measurements of e.g. $B_d \to K^* \mu\mu$, $B_s \to \mu\mu$, ϕ_s



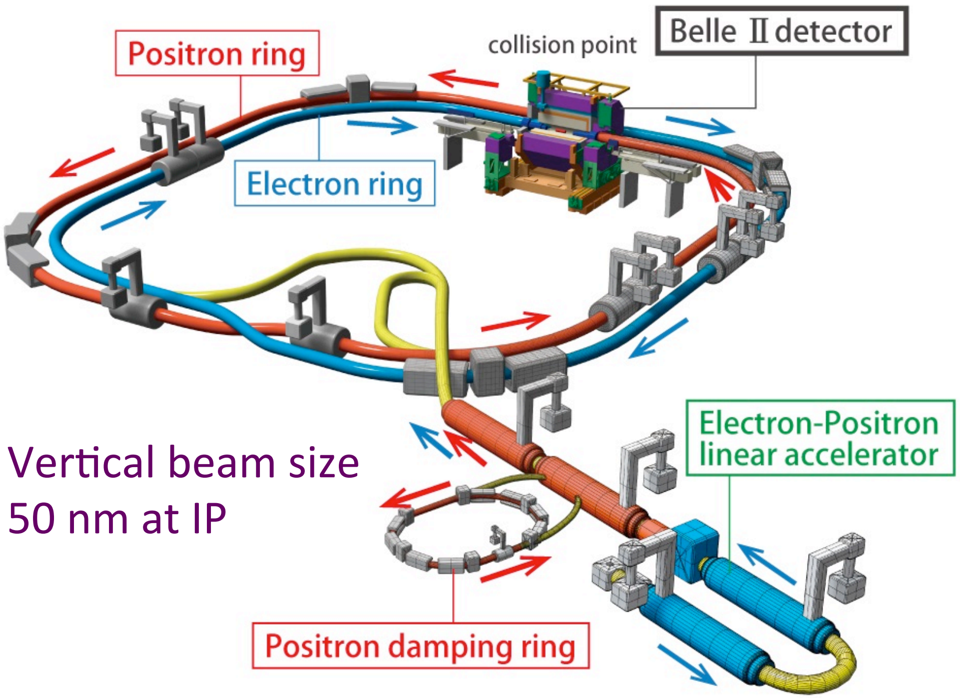


LHC ideal place to do flavour physics

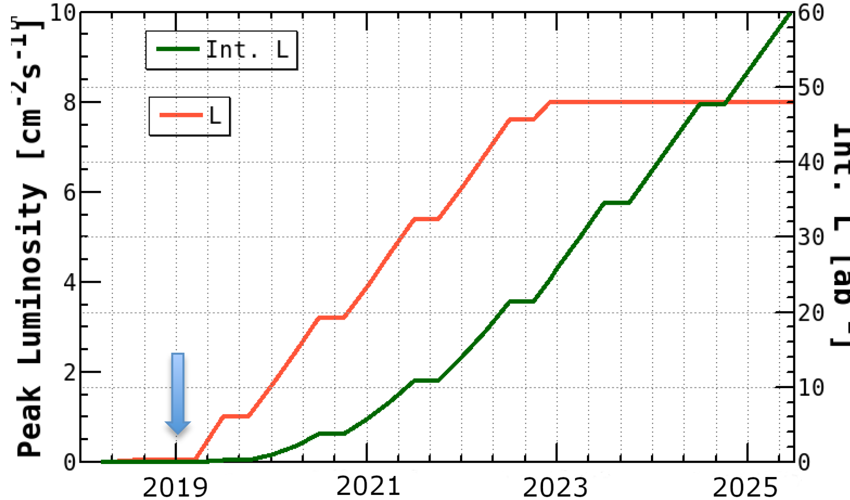
Future Schedule



SuperKEKB



Vertical beam size
50 nm at IP



First physics run with full Belle II detector

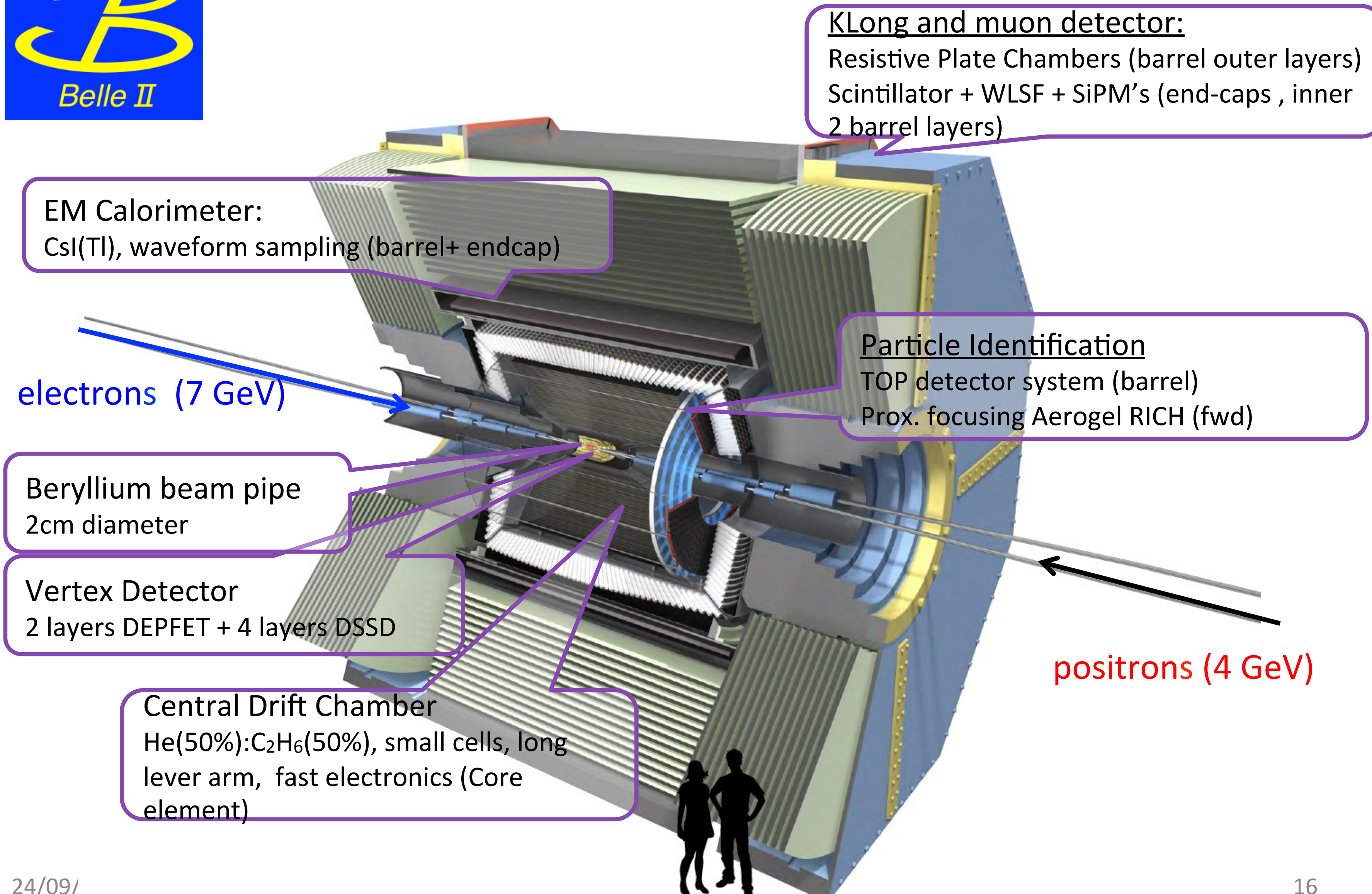
Mar-Jun 2019 Int. lumi = 6.5 fb^{-1}

Aim 2026 60 ab^{-1}

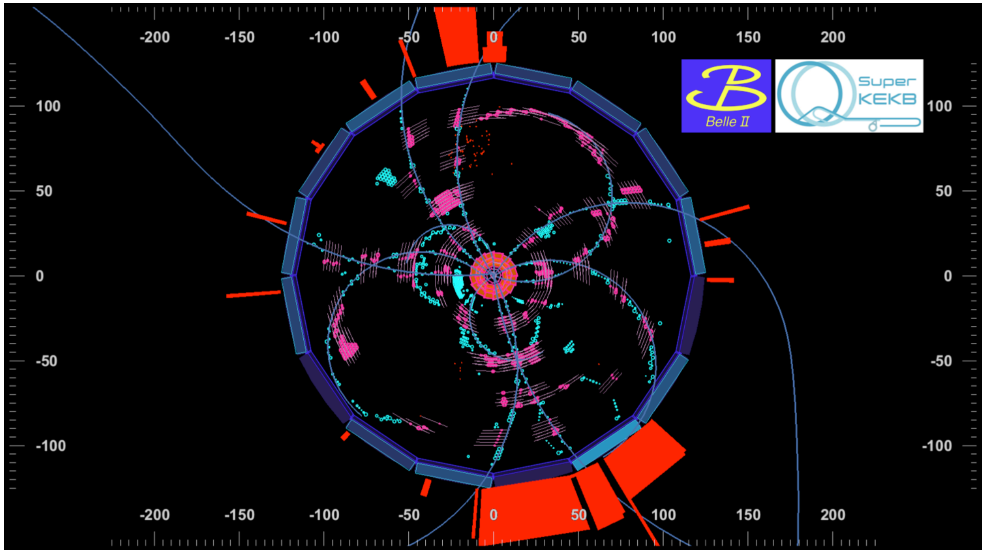
Belle recorded 1000 fb^{-1}

From T.E.Browder, Lepton-Photon 2019

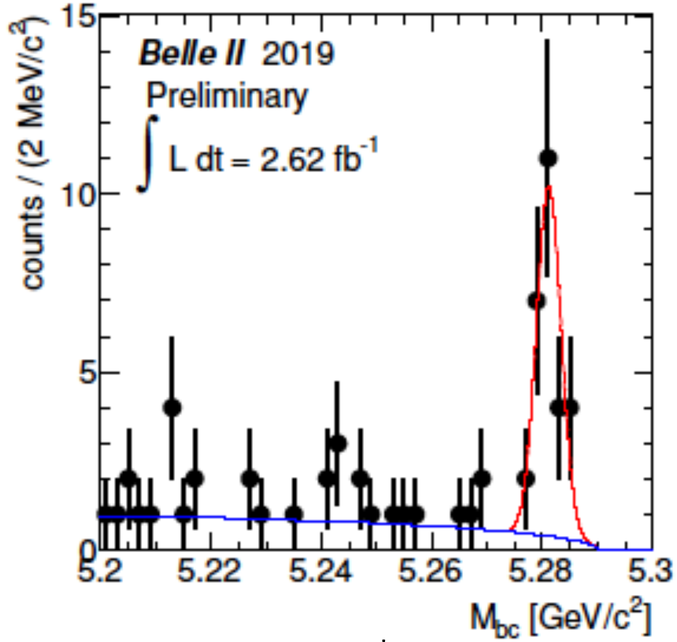
Belle II



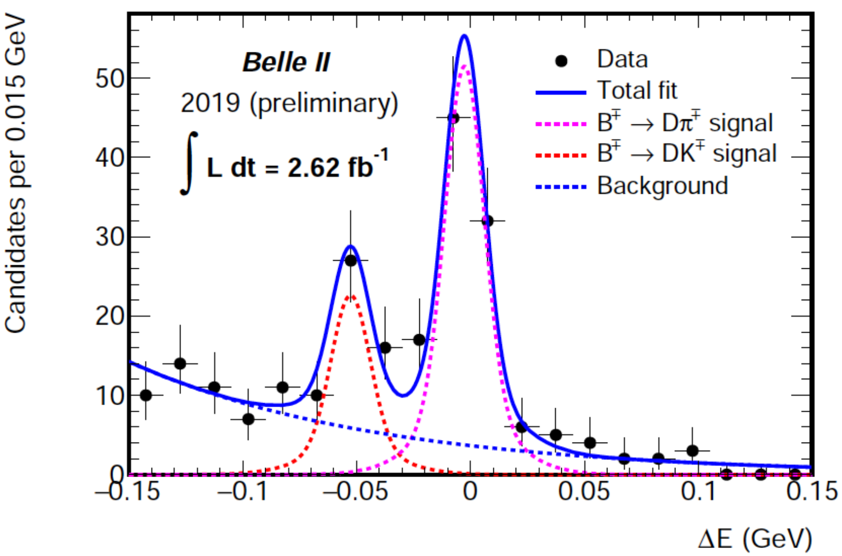
From T.E.Browder, Lepton-Photon 2019



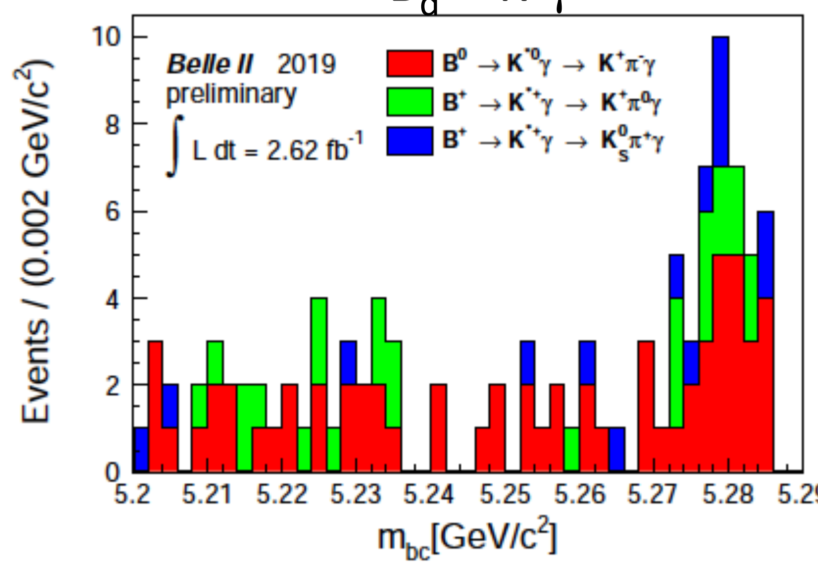
$B_d \to J/\psi K_S$



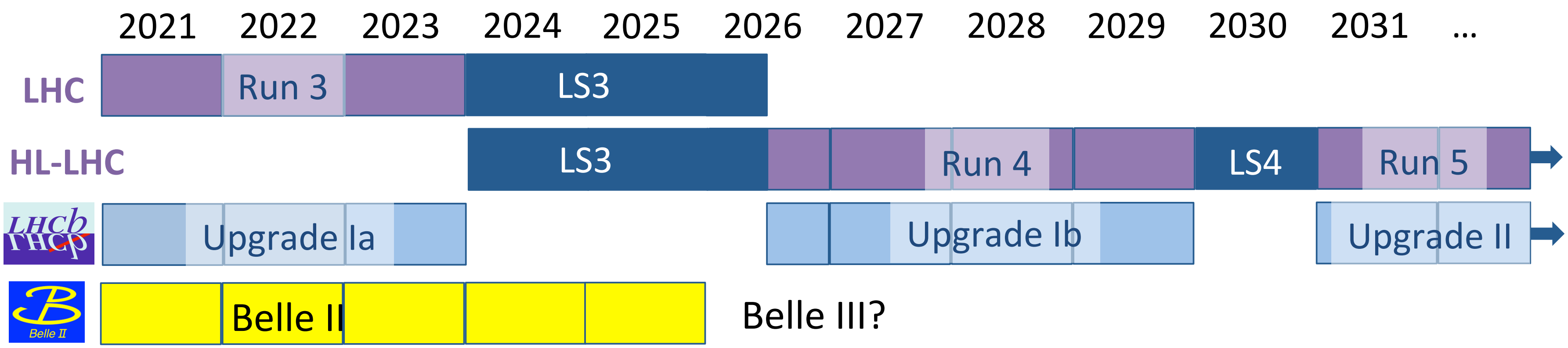
$B^- \to D^0 K^-$



$B_d \to K^* \gamma$



Future Schedule



Upgrade I

2021-2029

All sub-detectors read out at 40MHz

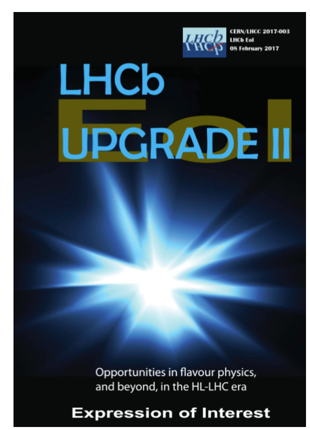
New detector (90%)

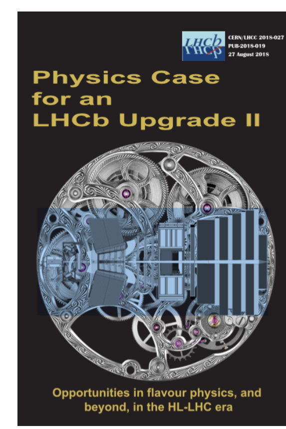
Full software trigger with real-time analysis

Upgrade II

2031-2038(?)

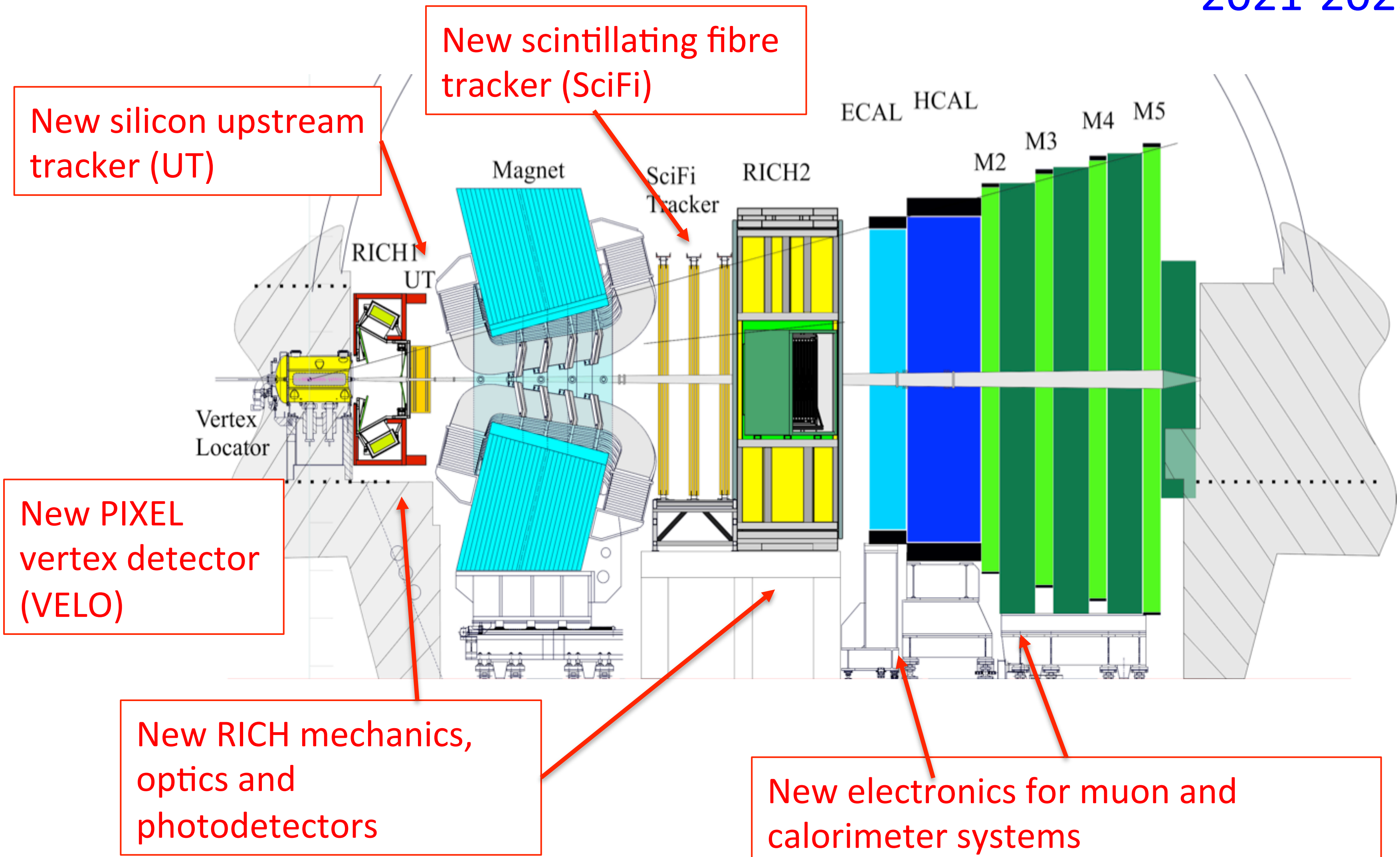
Opportunities for innovative detector development





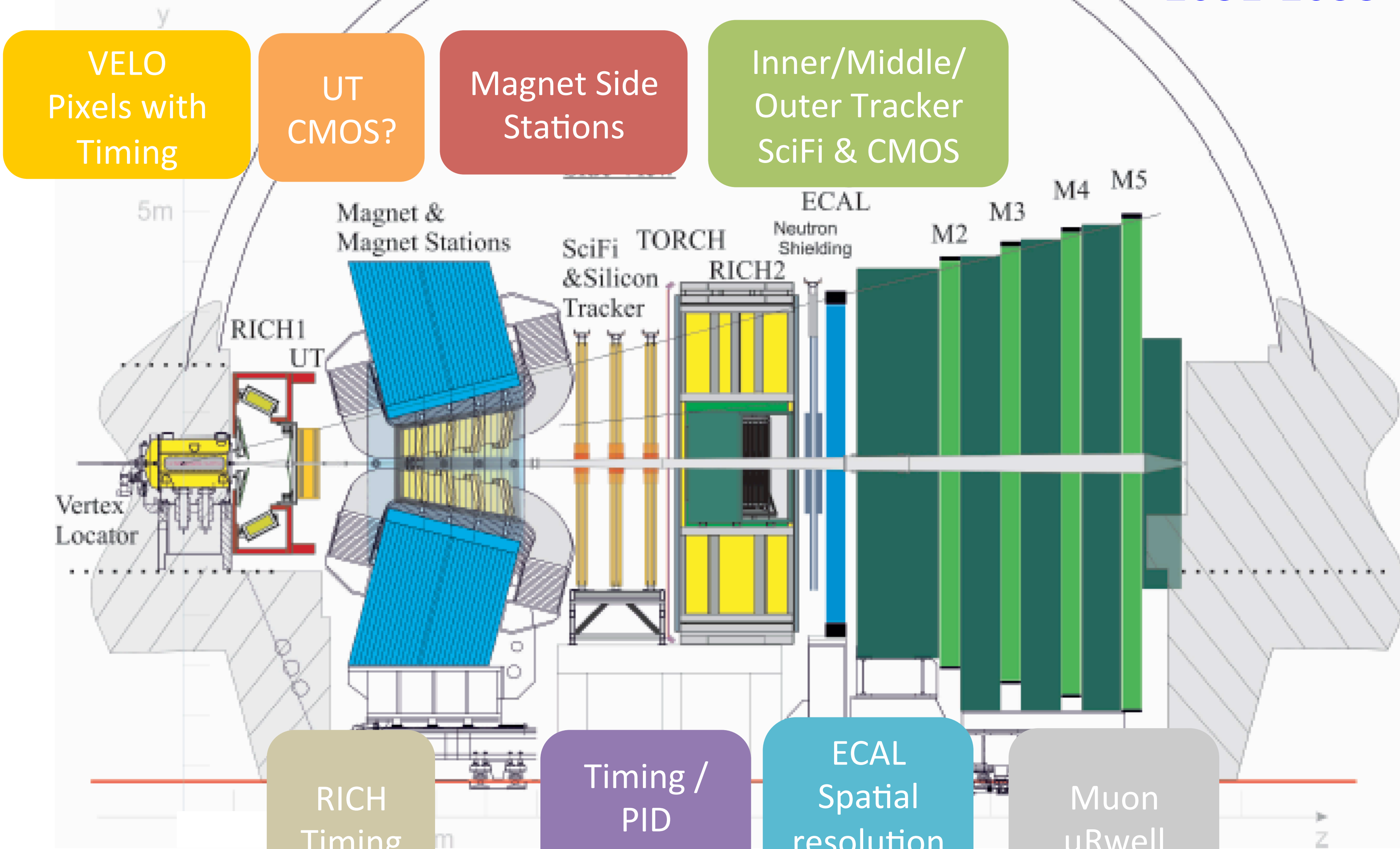
LHCb Upgrade I

2021-2029

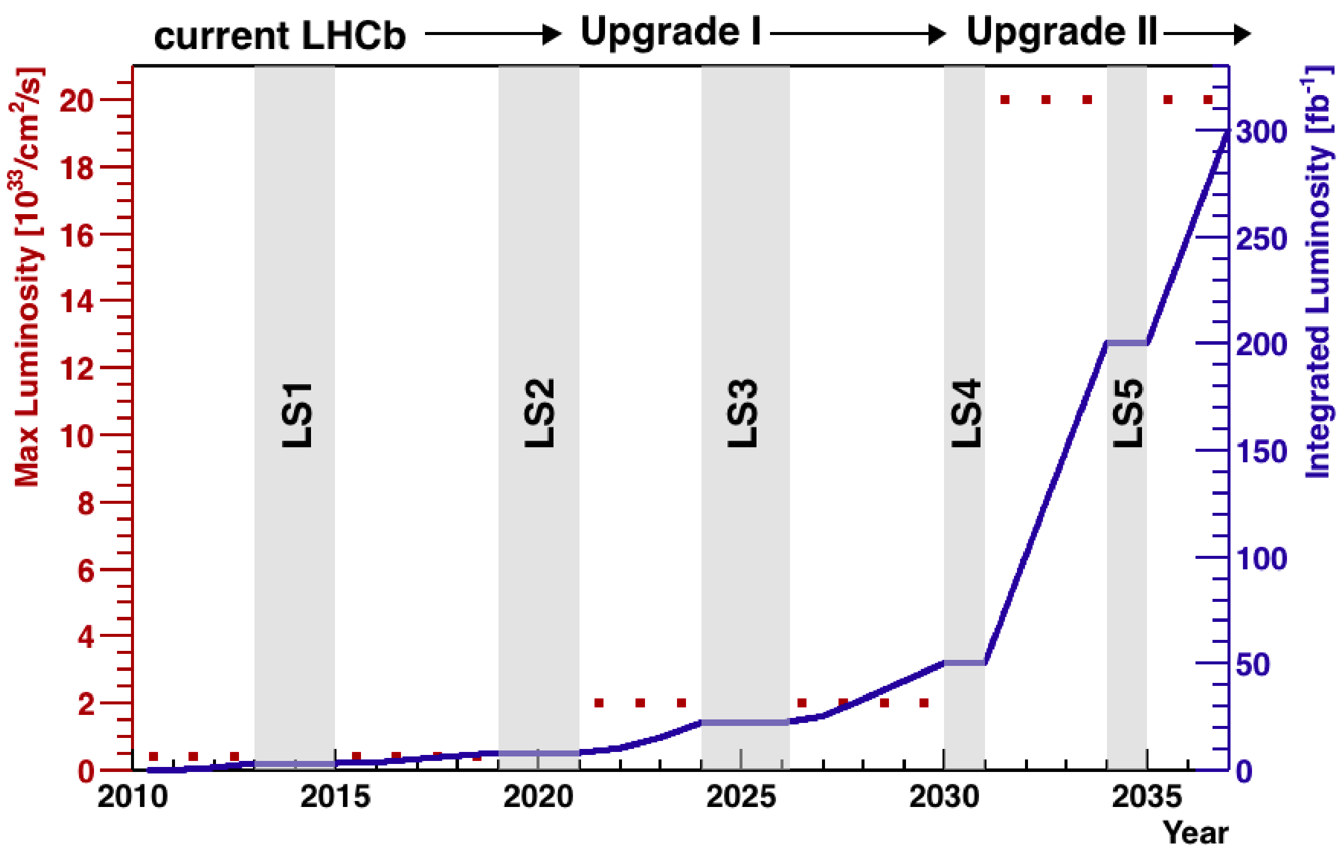


LHCb Upgrade II

2031-2038



LHCb luminosity

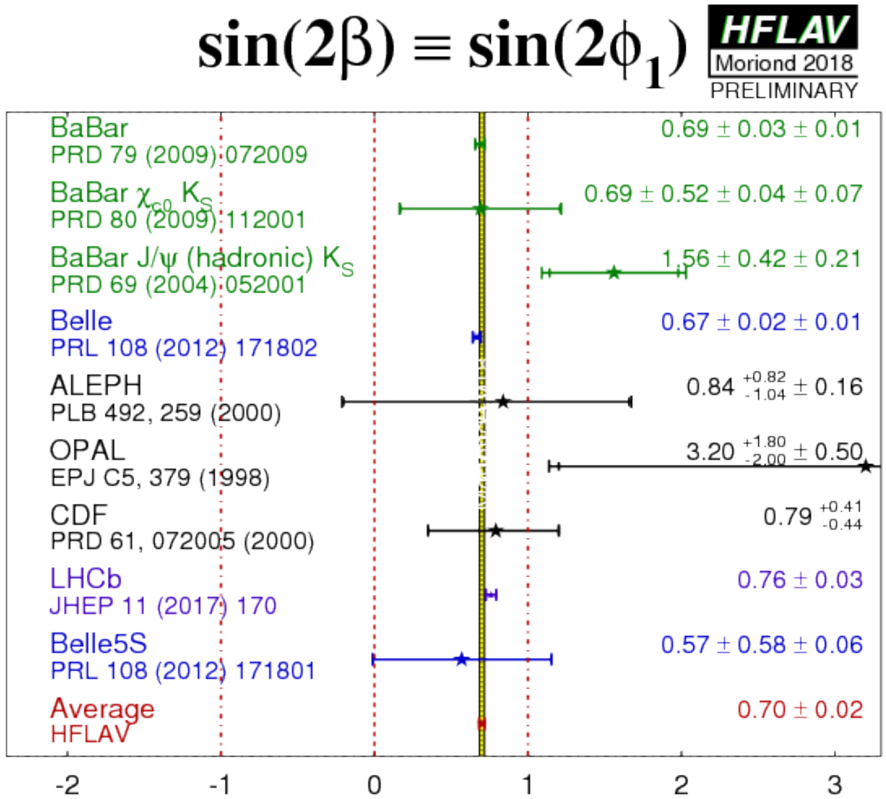


Current	Upgrade I		Upgrade II
2019	2025	2029	2035
10 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}

B_d CPV phase – sin2β

CPV due to the interference of the B_d mixing and tree diagrams.

Golden mode $B_d \to J/\psi K_s^0$ + other charmonium



Measure the time-dependent asymmetry

$$a_{CP}(t) \equiv \frac{\Gamma\left(\overline{B}^0(t) \to J/\psi K_s^0\right) - \Gamma\left(B^0(t) \to J/\psi K_s^0\right)}{\Gamma\left(\overline{B}^0(t) \to J/\psi K_s^0\right) + \Gamma\left(B^0(t) \to J/\psi K_s^0\right)}$$

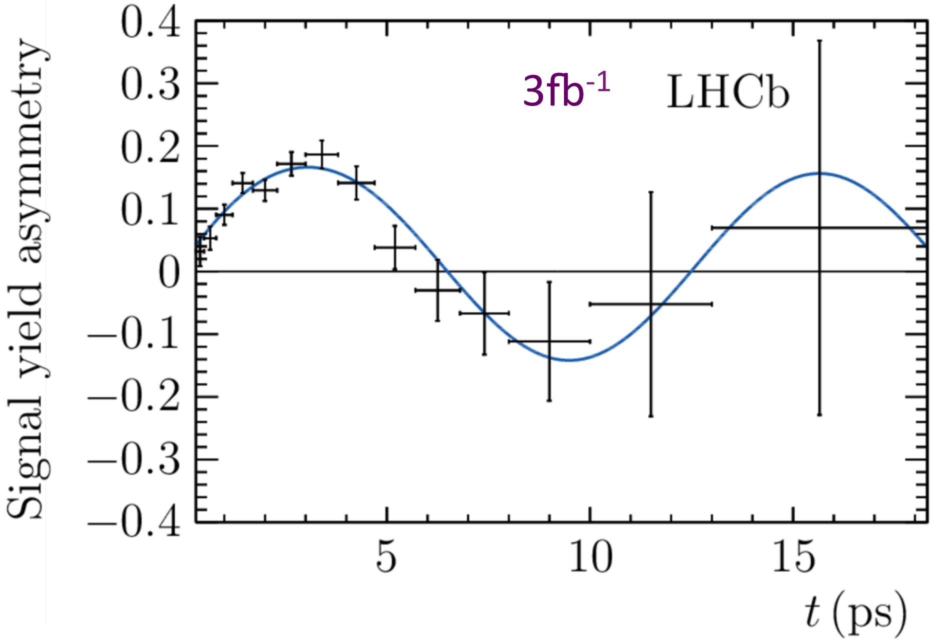
$$= \sin 2\beta \sin(\Delta m t)$$

sin2β in SM is expected to arise from CPV in B^0 mixing.

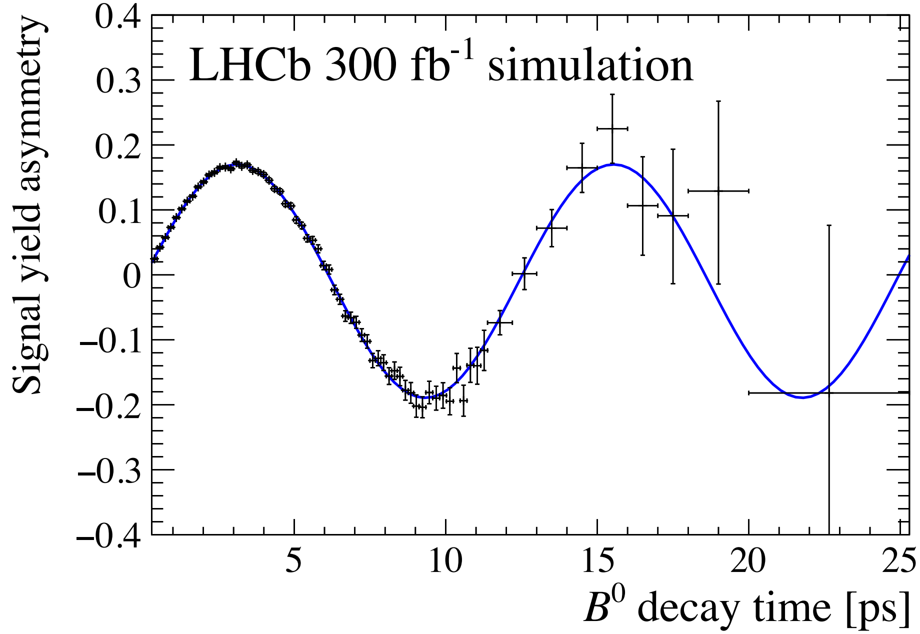
NP could mean that $\sin 2\beta_{meas} \neq \sin 2\beta_{SM}$

sin 2β now known to 3%, with significant improvements expected in next 10 years

B_d CPV phase – sin2β



B_d CPV phase – sin2β



	σ (sin2β)	
current	0.03	
23 fb^{-1}	0.011	
50 fb^{-1}	0.006	
50 ab^{-1}	0.005	Belle II
300 fb^{-1}	<0.003	

LHCb & Belle II measurements highly complementary with different experimental systematics. Future measurements of sin2β will also

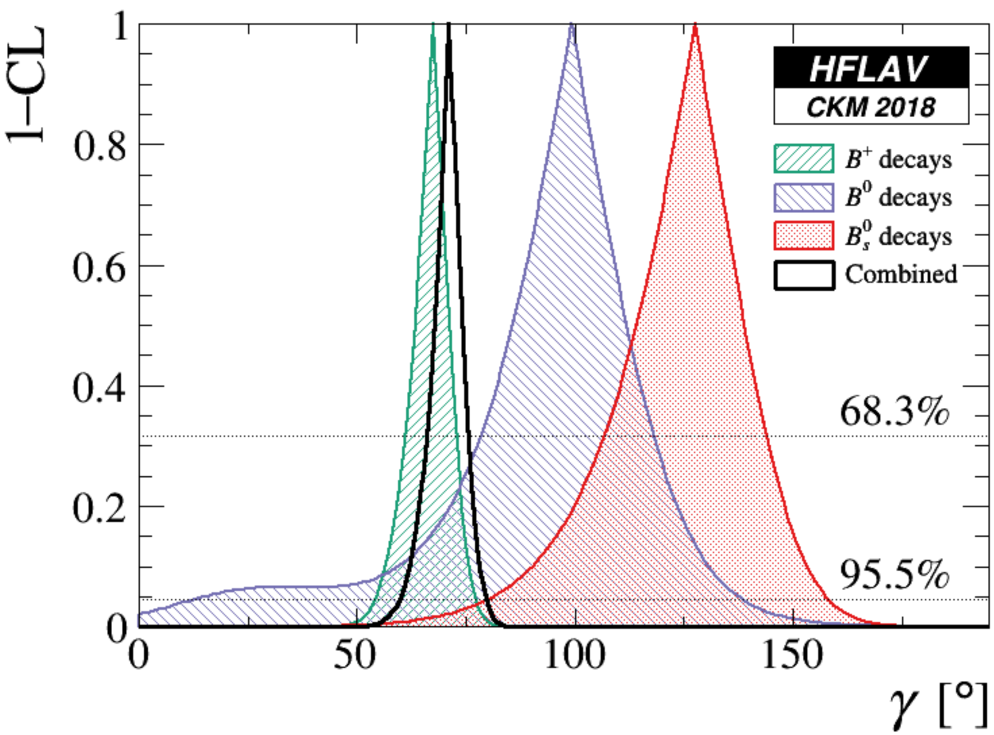
- Control penguin contributions using $B_s \to J/\psi K_s^0$ and $B_d \to J/\psi \pi^0$ decays
- Account for CPV in K^0 mixing and nuclear cross-section asymmetry
- Other decays modes e.g. $\overline{B}_d \to D^0\pi^+\pi^-$

CP phase γ

Measure from interference of $b \rightarrow c$ and $b \rightarrow u$ tree-level $B \rightarrow DK$ decays.

Small theoretical uncertainty $\Delta\gamma/\gamma \leq 10^{-7}$.

At LHC turn-on, experiment uncertainty on γ was $>20^{o}$.



Current status dominated by LHCb global average LHCb-CONF-2018-002

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

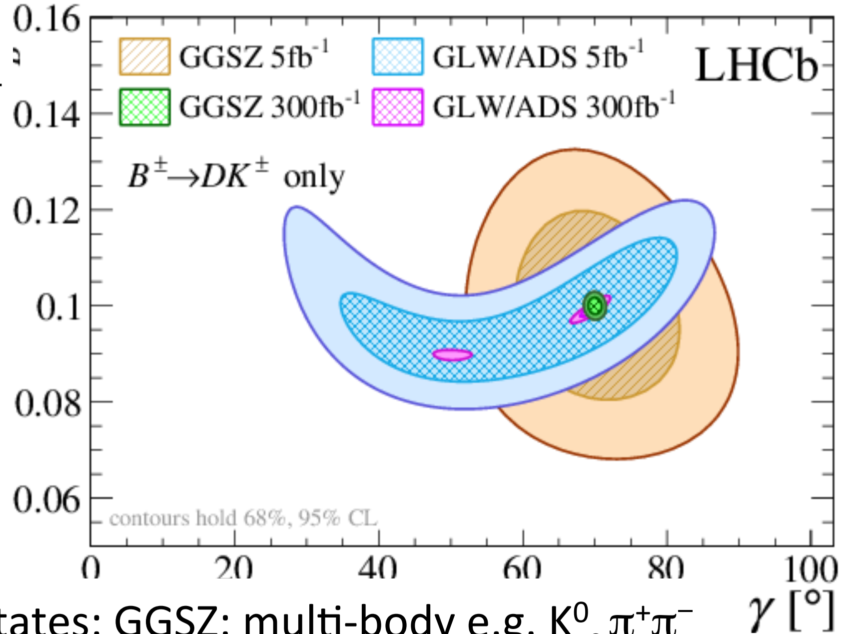
Result can be compared to indirect value extracted from global fit to other CKM parameters:

$$\boxed{\gamma = \left(65.6^{+1.0}_{-3.4}\right)^{\circ}}$$ CKM Fitter 2018

Compatible, albeit with ~2σ tension

CP phase γ

$$r_B = \frac{|A_{b\to u}|}{|A_{b\to c}|}$$



LHCb	σ (γ) deg.	
current	4	
23 fb^{-1}	1.5	
50 ab^{-1}	1.5	Belle II
50 fb^{-1}	< 1	
300 fb^{-1}	~ 0.4	

D^0 final states: GGSZ: multi-body e.g. $K^0{}_s\,\pi^+\pi^-$
GLW/ADS: CP eigenstate $K^+K^-/\pi^+\pi^-$ (GLW)
or flavour-specific $K^+\pi^-/K^-\pi^+$ (ADS)

Precision statistically dominated, incl. strong phase inputs from CLEOc & BESIII.

Improvements will include: knowledge of distribution of D decays over Dalitz plane; D^0 mixing; and new B & D decay modes, e.g. with π^0.

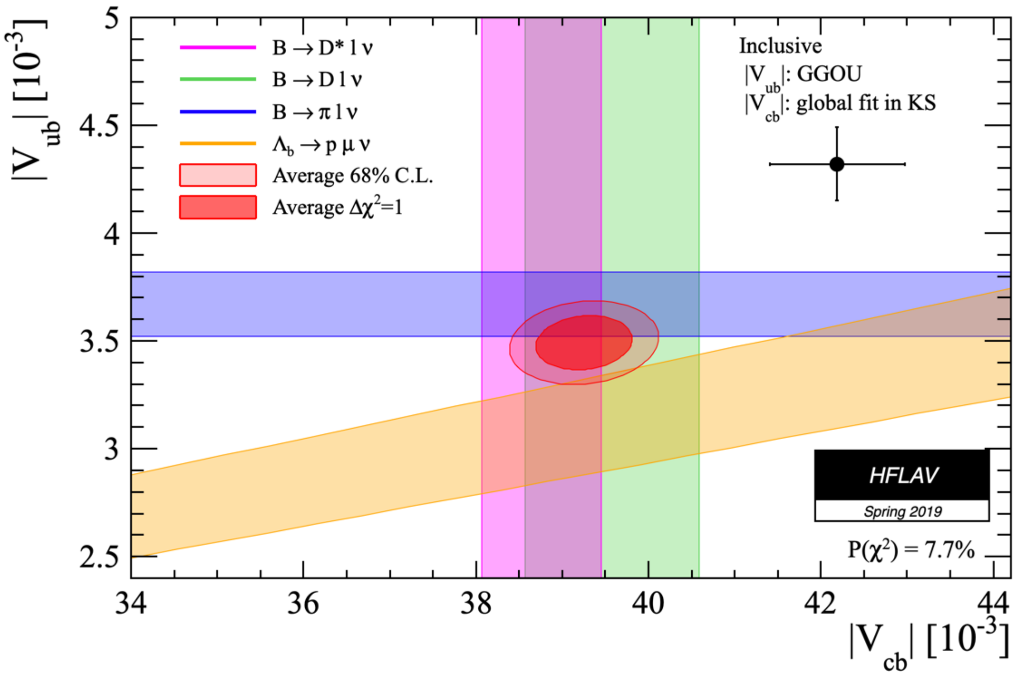
Comparison with penguin-dominated decays.

$|V_{ub}|$ and $|V_{cb}|$

$|V_{ub}|$ and $|V_{cb}|$ extracted from tree-level semi-leptonic inclusive and exclusive $b \rightarrow c\ell\nu$ and $b \rightarrow u\ell\nu$ decays.

LHCb $|V_{ub}/V_{cb}|$ from $\Lambda_b \rightarrow p\mu^- \overline{\nu}_\mu$ decays & precise Lattice QCD calculations.

Nature Physics 10 (2015) 1038
Detmold et al, PRD 92 (2015) 034503



HFLAV

$|V_{ub}|$ and $|V_{cb}|$ inclusive vs exclusive disagree by 3σ

$|V_{ub}|$ and $|V_{cb}|$

$|V_{ub}|$ and $|V_{cb}|$ extracted from tree-level semi-leptonic inclusive and exclusive $b \to c\ell\nu$ and $b \to u\ell\nu$ decays.

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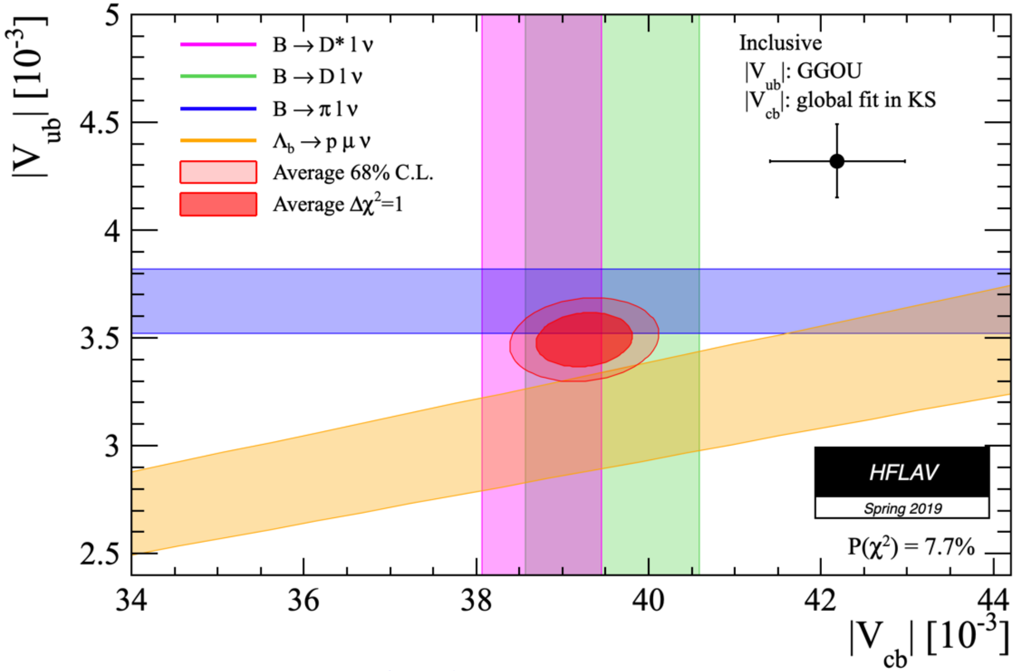
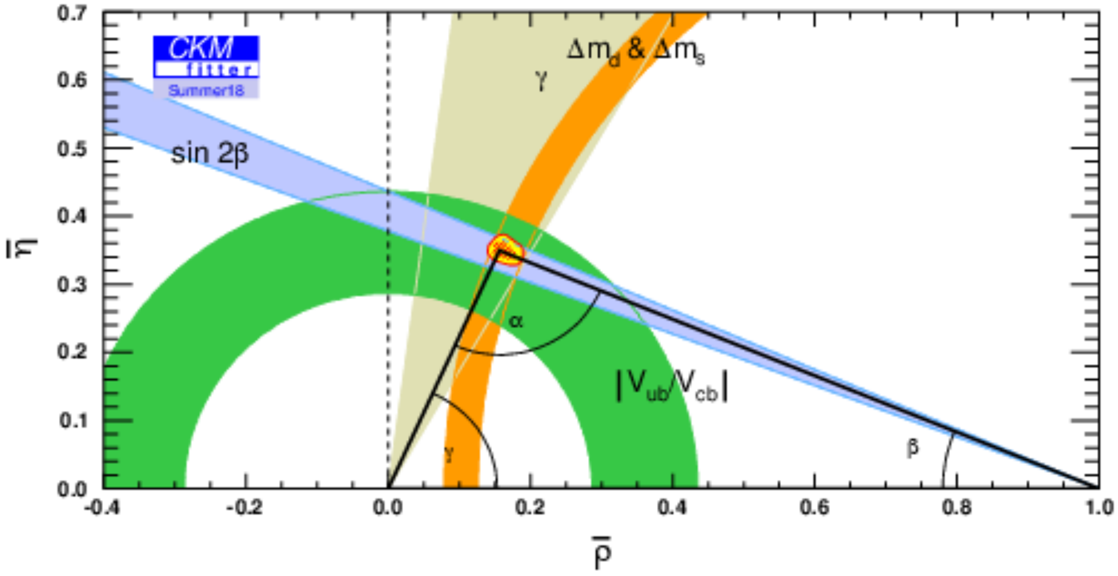


LHCb	$\sigma(\|V_{ub}\|/\|V_{cb}\|)$
current	6%
23 fb^{-1}	3%
50 fb^{-1}	
50 ab^{-1}	1% Belle II
300 fb^{-1}	<1%

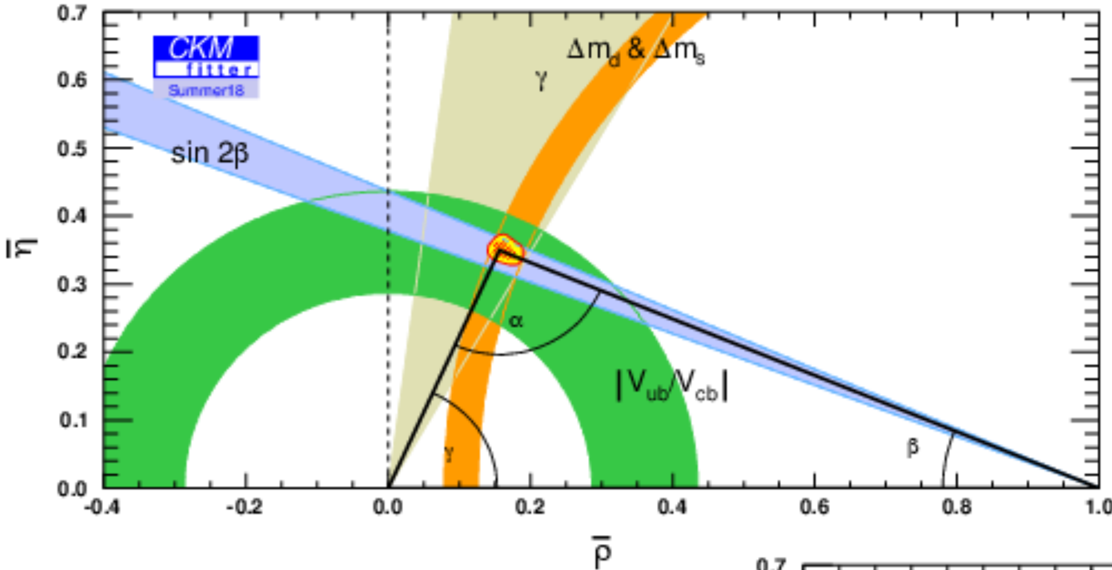
Future will benefit from increased statistics, B_s & B_c decay modes and Lattice QCD.

Unitarity triangle

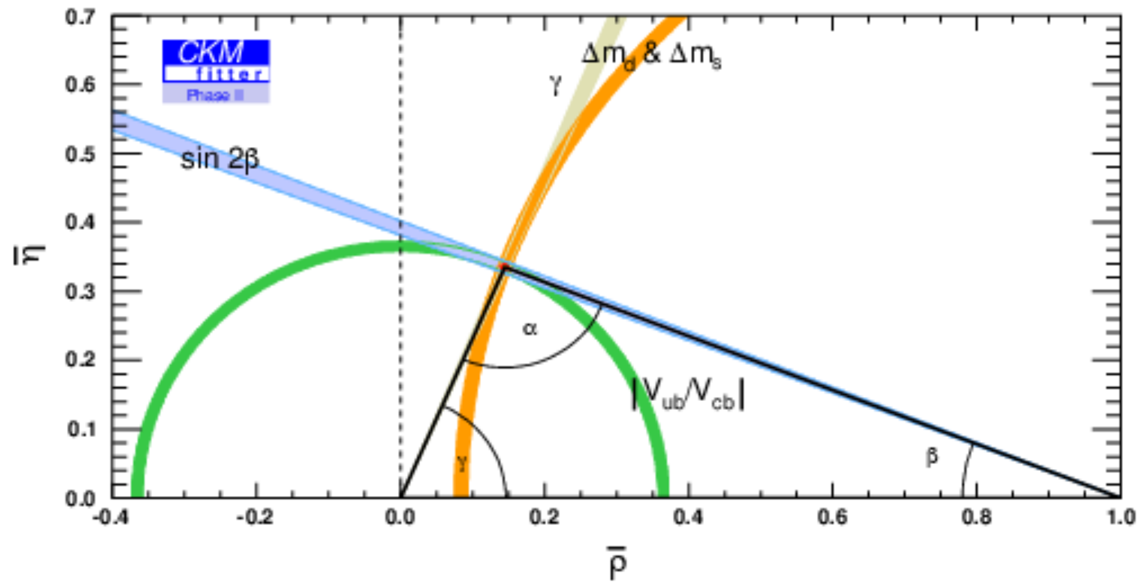


2019

Unitarity triangle



2019



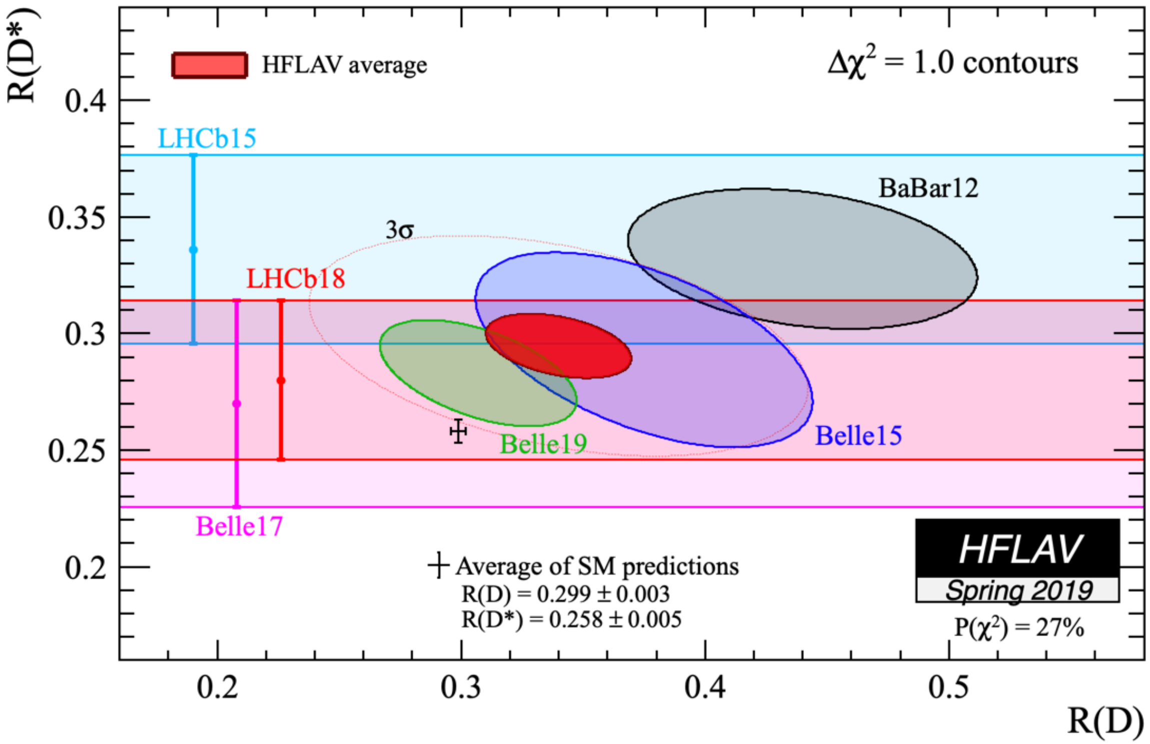
2035

300 fb^{-1}

LHCb only

R(D) and R(D*)

Tree-level semi-leptonic B decays also used to test lepton universality



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

HFLAV claim a discrepancy with SM of 3.1σ

$$R(J/\psi) = \frac{B\left(B_c^+ \to J/\psi\,\tau^+\nu_\tau\right)}{B\left(B_c^+ \to J/\psi\,\mu^+\nu_\mu\right)}$$

$$= 0.71 \pm 0.17 \pm 0.18$$

PRL 120 (2018) 121801

$$\mathcal{A}_0\left(\frac{c_{\rm SM}}{v^2} + \frac{c_{\rm NP}}{\Lambda^2}\right) \qquad C_{SM} \approx V_{cb} \qquad \boxed{\frac{\Lambda^2}{C_{NP}} \sim (3\ \mathrm{TeV})^2}$$

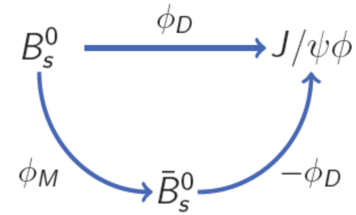
Future: more observables and full angular analysis.

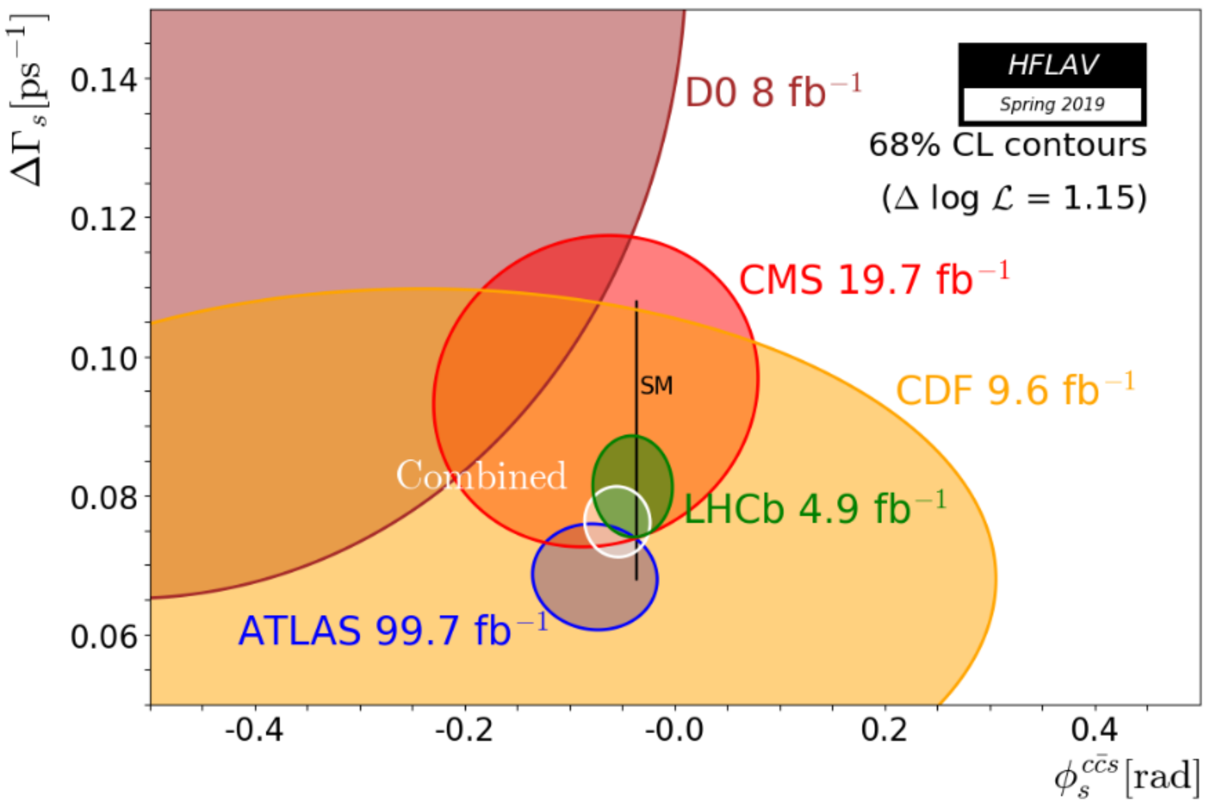
B_s CPV phase – ϕ_s

CPV due to the interference of the B^0 mixing and tree diagrams.

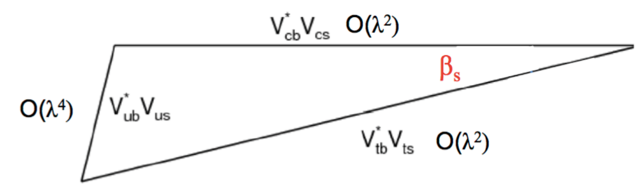
Golden mode $B_s^0 \to J/\psi\,\phi$

$$\phi_s = \phi_M + 2\phi_D$$
$$\phi_M^{SM} = -2\beta_s;\ \phi_D^{SM} \approx 0$$





The B_s Unitarity Triangle



$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

HFLAV

$$\boxed{\phi_s = (-55 \pm 21)\ \mathrm{mrad}}$$

Hint of a non-zero value – will be interesting with full Run 2 data set

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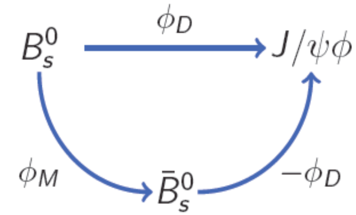
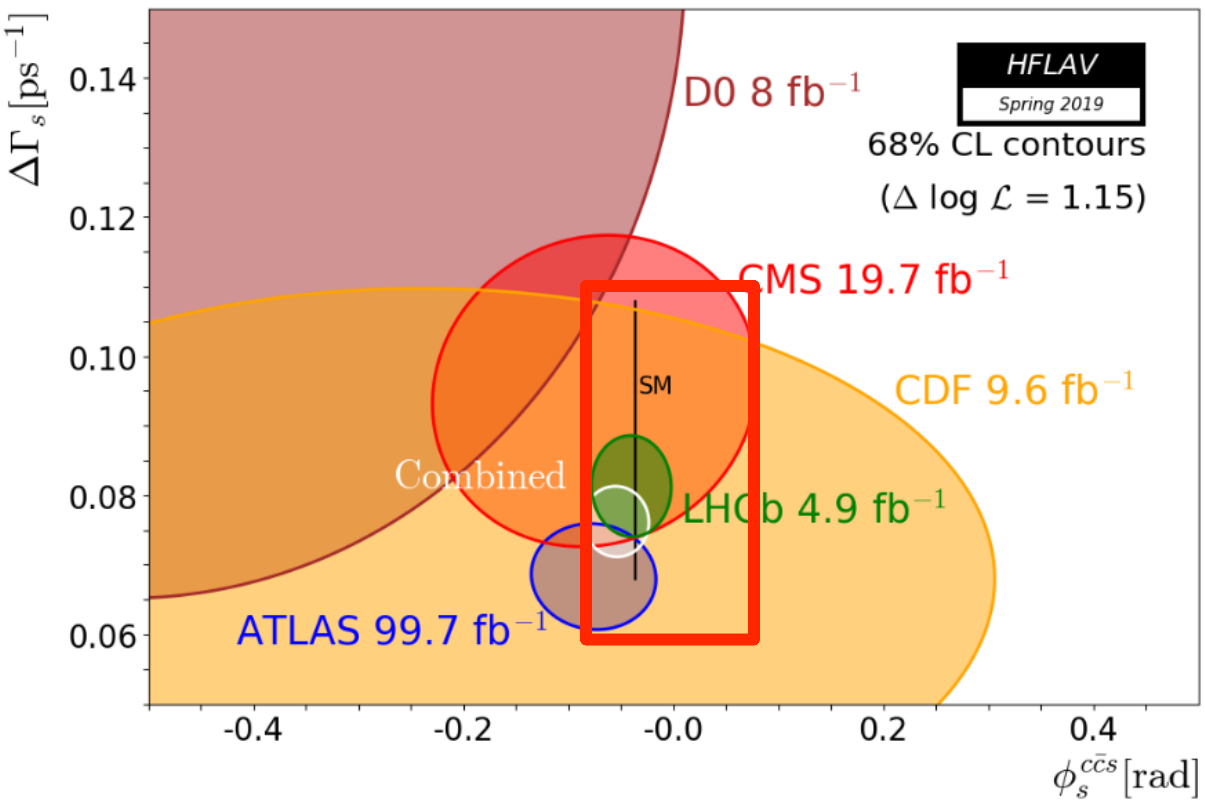
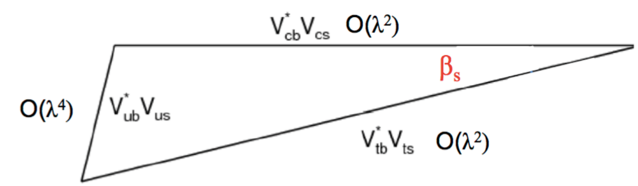




The B_s Unitarity Triangle



$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

HFLAV

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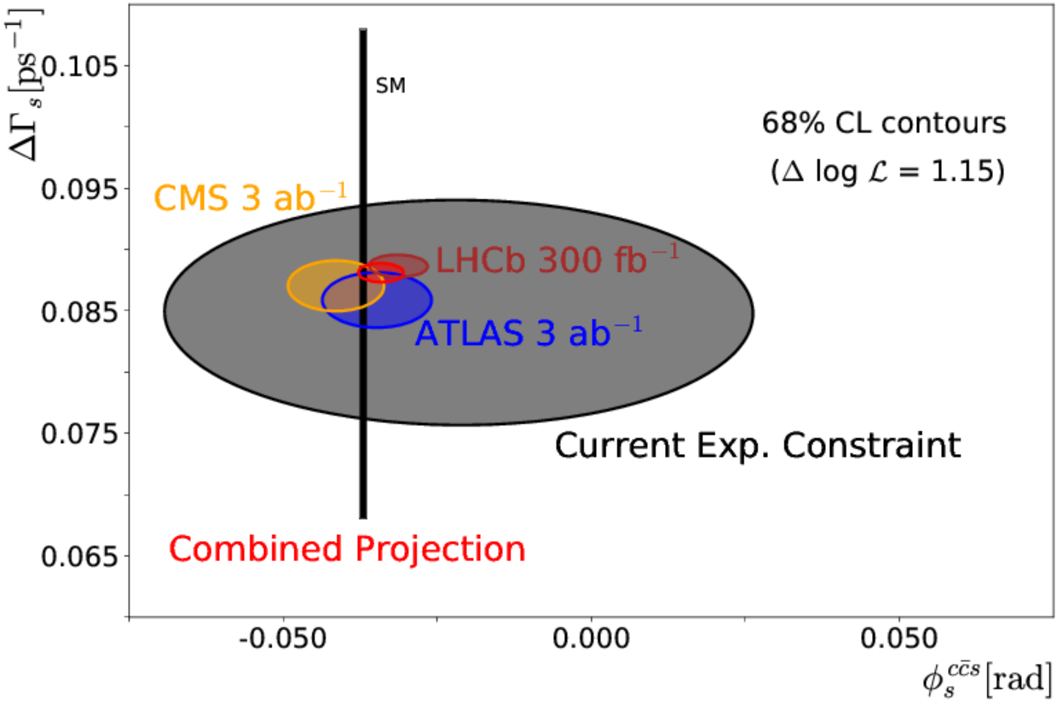
Hint of a non-zero value – will be interesting with full Run 2 data set

B_s CPV phase – ϕ_s



LHCb	$\sigma(\phi_s)$
current	49 mrad
23 fb^{-1}	14 mrad
50 fb^{-1}	
300 fb^{-1}	4 mrad

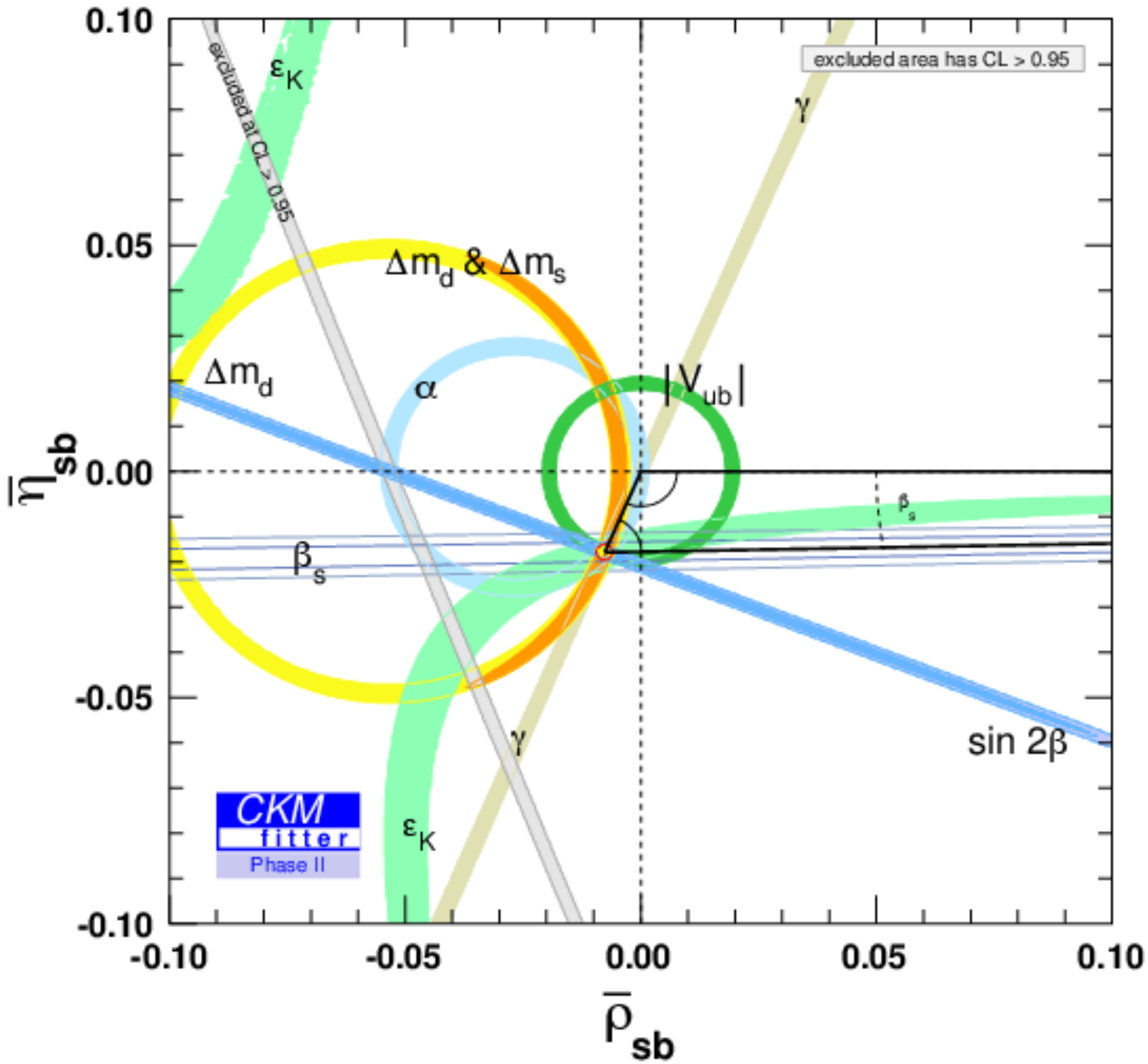
ATLAS 4-9 mrad, CMS 5.5 mrad for tagging power of 1.5%

Combined sensitvity ~2mrad

All experiments will benefit from improved decay time resolution offered by upgraded tracking detectors.

Also expand current measurements using $J/\psi K^+K^-$, $J/\psi\pi^+\pi^-$, $\psi(2s)\phi$, $D_s^+D_s^-$ and include new decay modes with improved calorimeter performance e.g. $B_s \to J/\psi\left(\to e^+e^-\right)\phi$ and $B_s \to J/\psi\eta', \eta' \to \rho^0, \eta + \text{neutrals}$

B_s CPV phase – ϕ_s



2035

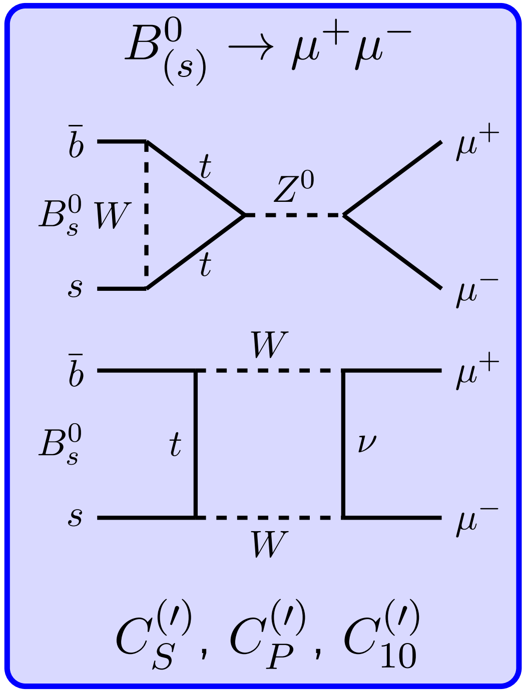
300 fb^{-1}

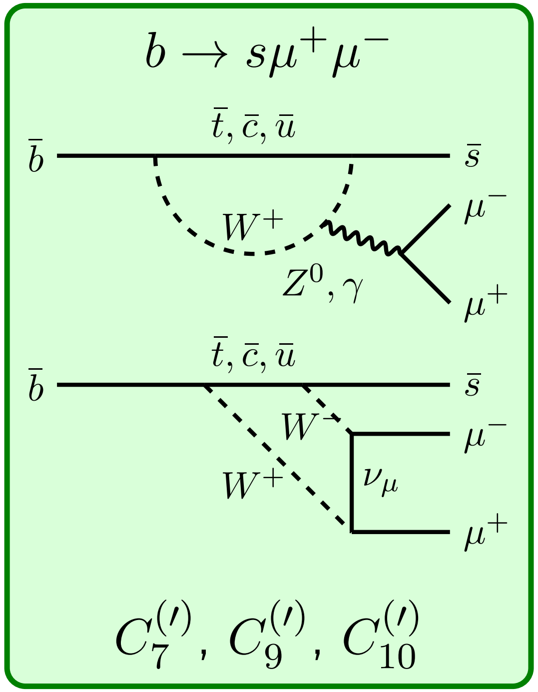
β_s

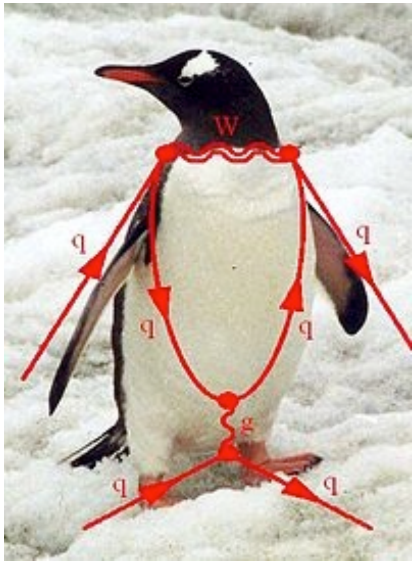
Rare B Decays

In the SM, decays involving b→s quark transitions are only allowed via loop diagrams (e.g. penguin diagrams).

See e.g. Buchalla et al, Rev. Mod. Phys 68 (1996) 1125







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

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

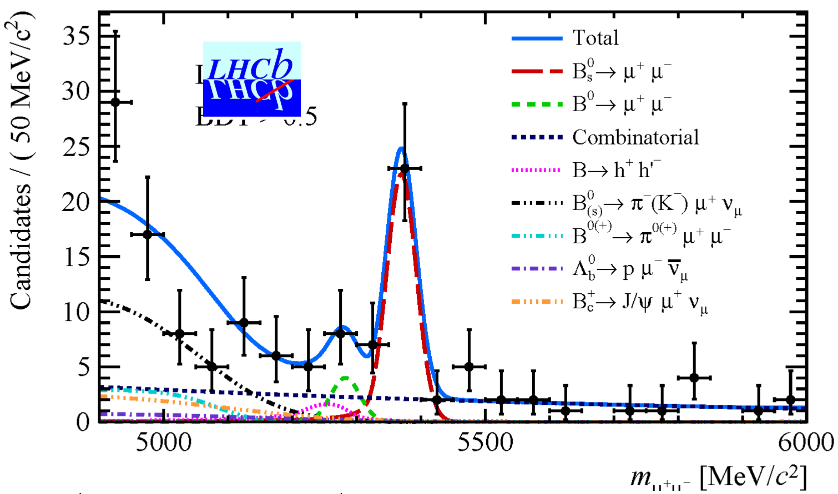
$B \to \mu^+\mu^-$

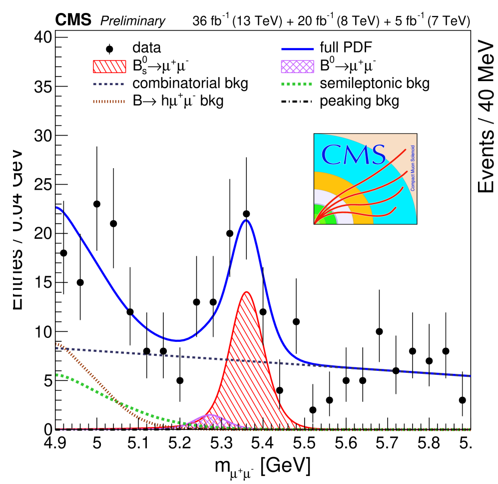
Golden very rare decay $B\left(B_s \to \mu^+\mu^-\right)_{SM} = \left(3.66 \pm 0.23\right)\times 10^{-9}$ Bobeth et al., PRL 112 (2014) 101801

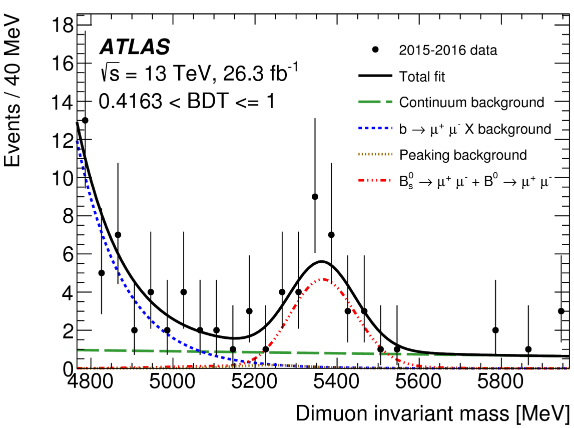
$$B\left(B_d \to \mu^+\mu^-\right)_{SM} = \left(1.06 \pm 0.09\right)\times 10^{-10}$$

Many models (e.g. SUSY) can modify the rate substantially.

Now observed by all LHC experiments





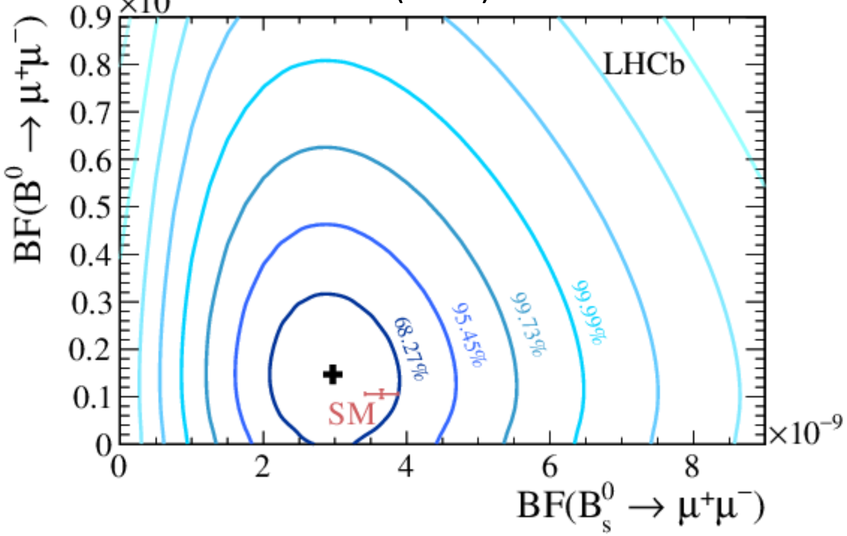


	LHCb	CMS	ATLAS
$B\left(B_s \to \mu^+\mu^-\right)$	$\left(3.0 \pm 0.6^{+0.3}_{-0.2}\right)\times 10^{-9}$	$\left(2.9^{+0.7}_{-0.6} \pm 0.2\right)\times 10^{-9}$	$\left(2.8^{+0.8}_{-0.7}\right)\times 10^{-9}$
$B\left(B_d \to \mu^+\mu^-\right)$	$< 3.4\times 10^{-10}$	$< 3.6\times 10^{-10}$	$< 2.1\times 10^{-10}$

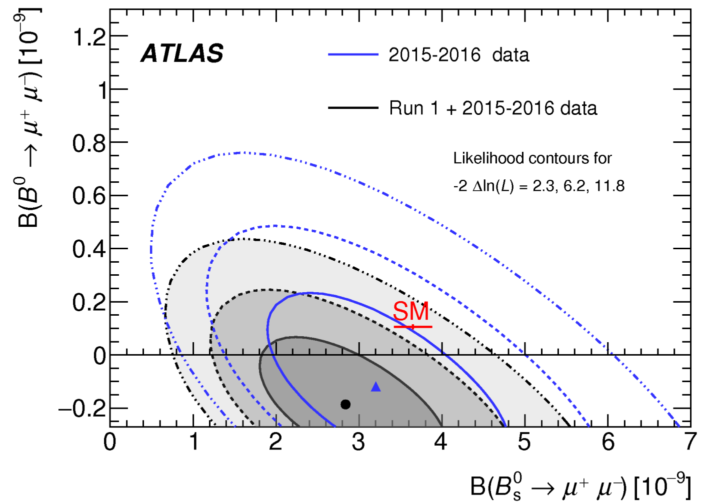
Upper limit 95% c.l.

$B \rightarrow \mu^+\mu^-$

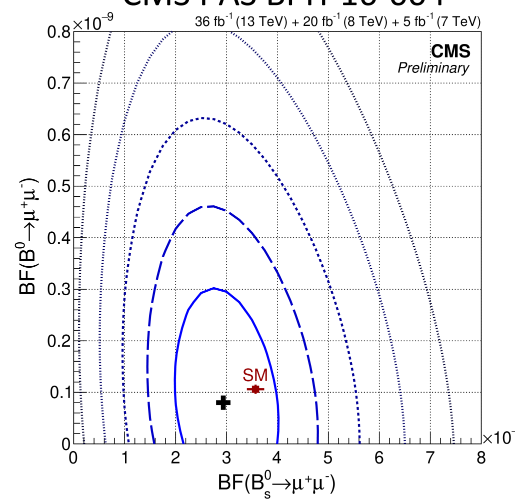
PRL 118 (2017) 191801



JHEP 04 (2019) 098



CMS PAS BPH-16-004



- Each result is compatible with the SM.
- $B_s \rightarrow \mu^+\mu^-$ BR measurements are tending to lie below SM (2σ)
- $B_d \rightarrow \mu^+\mu^-$ is proving elusive
- Full Run 2 results will be interesting

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

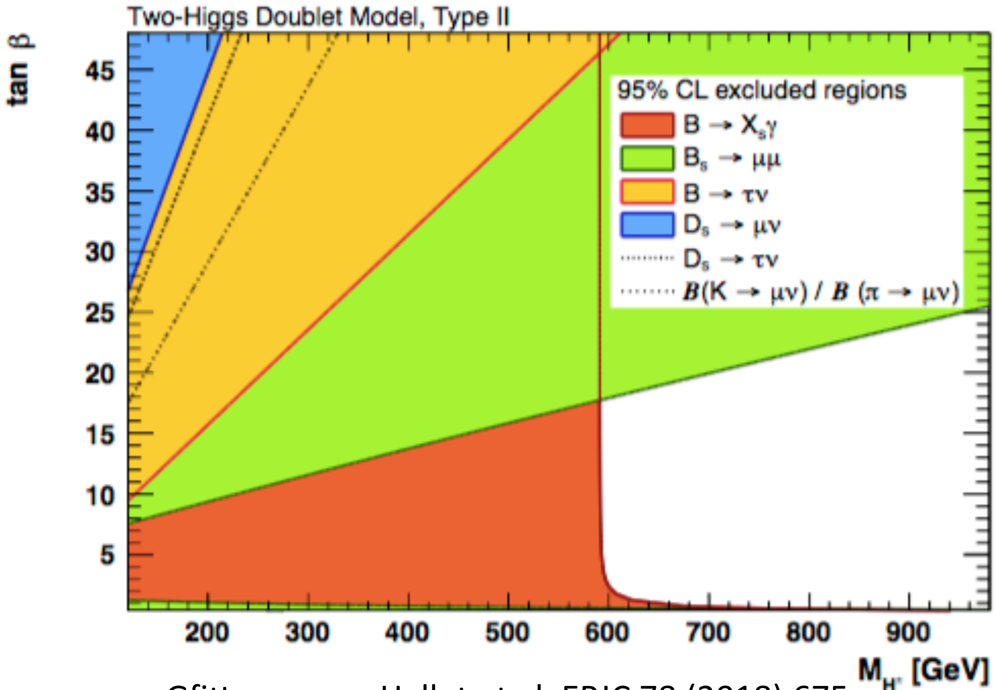
Prior to start of LHC, $B(B_s \to \mu^+\mu^-)$ was one of the great hopes for discovery of NP. Unfortunately, not realised.

Nonetheless, very powerful in excluding certain classes of NP models:

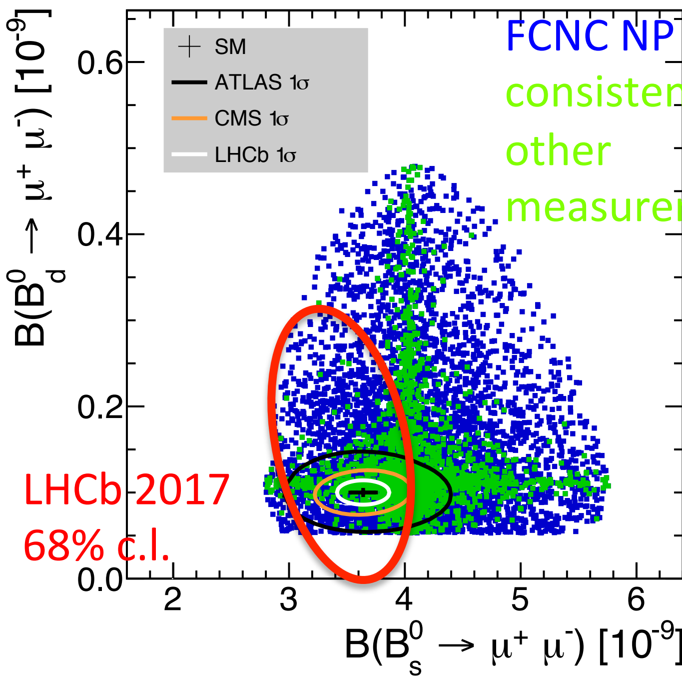
LHCb	$\sigma(R)$
current	90%
23 fb^{-1}	34%
50 fb^{-1}	
300 fb^{-1}	10%

$$R = \frac{B(B_d \to \mu^+\mu^-)}{B(B_s \to \mu^+\mu^-)}$$

ATLAS/CMS ~21%

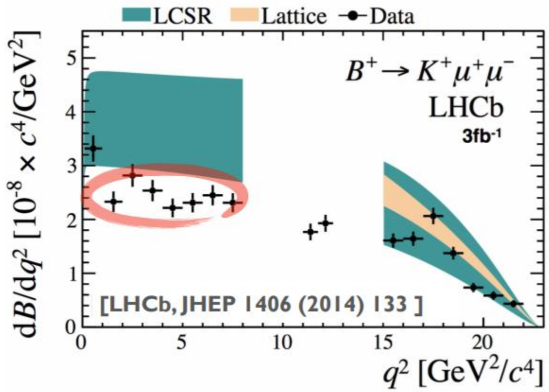


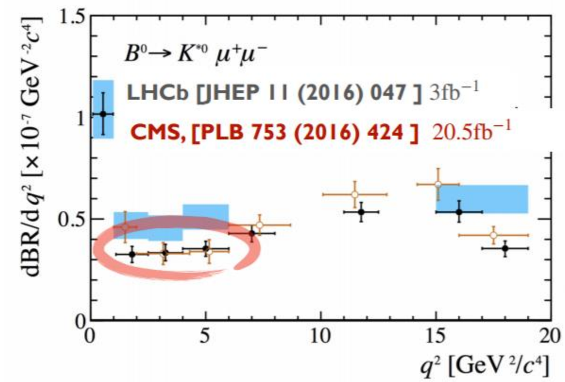
Gfitter group, Hallet et al, EPJC 78 (2018) 675

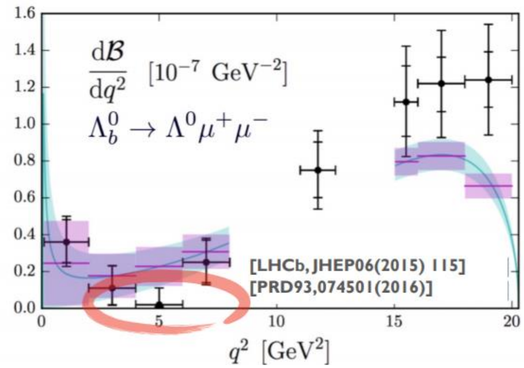


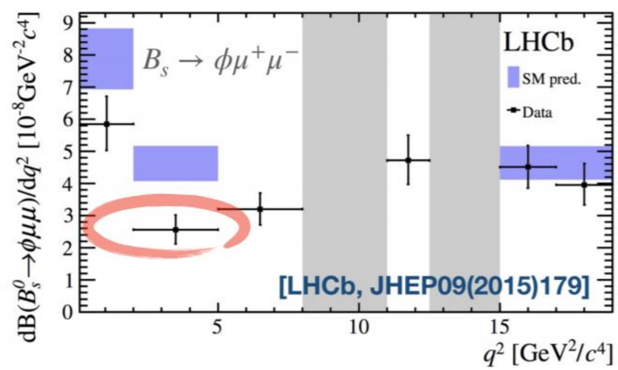
Electroweak penguins

Electroweak penguin b$\rightarrow$s,d$\ell^+\ell^-$ decays offer many observables to probe for NP effects e.g. differential cross-sections









Data (note all dimuon) lie below prediction at low q^2 in every case.

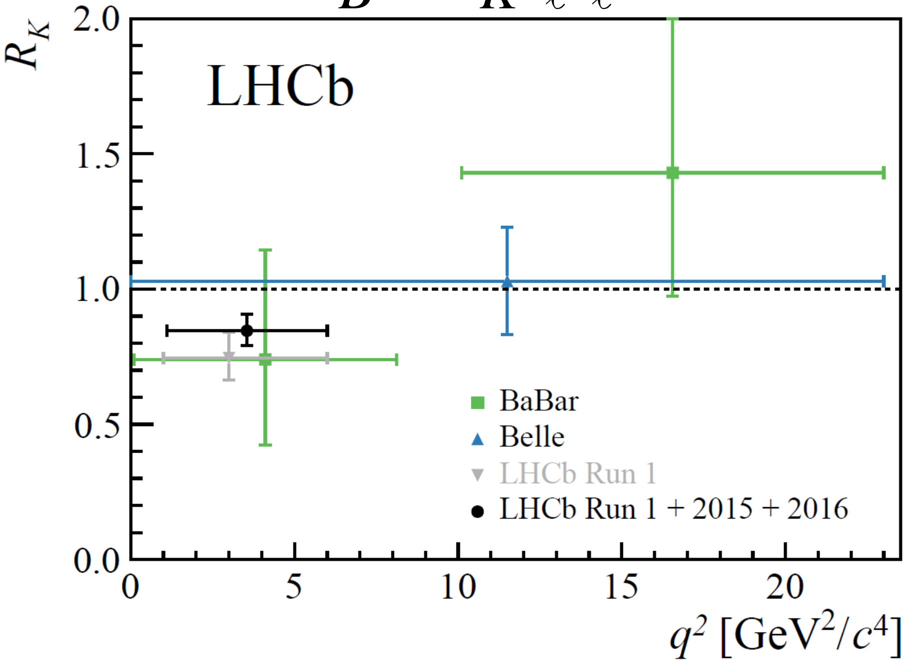
Theoretical uncertainties dominated by knowledge of B to light meson form factors.

Electroweak penguins

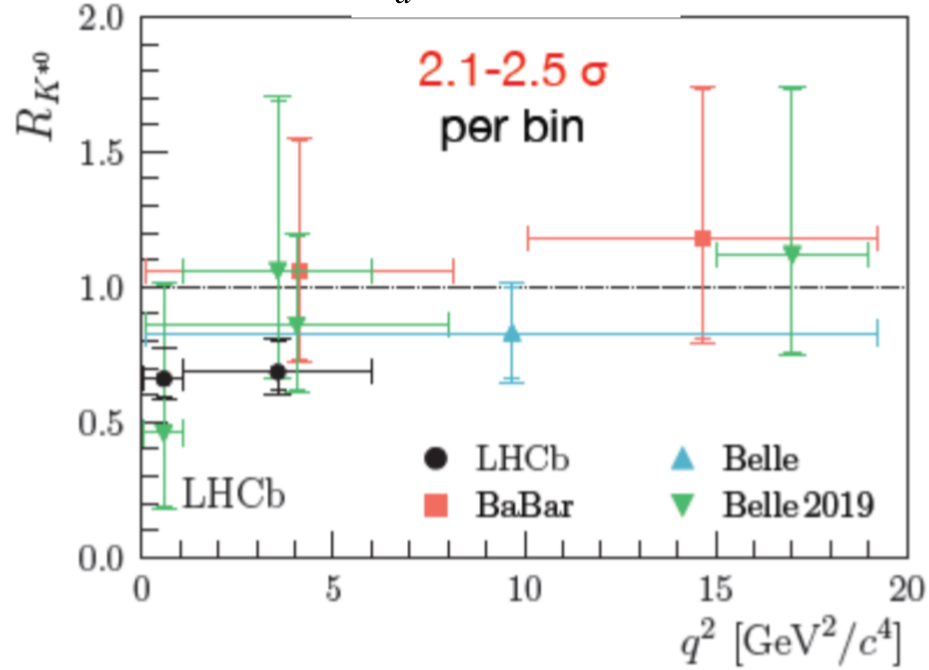
Lepton universality tests have negligible theory uncertainty.

$$R_X = \int \frac{\mathrm{d}\Gamma(B \to X\mu^+\mu^-)}{\mathrm{d}q^2}\,\mathrm{d}q^2 \Big/ \int \frac{\mathrm{d}\Gamma(B \to Xe^+e^-)}{\mathrm{d}q^2}\,\mathrm{d}q^2$$

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



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



Data lower than prediction at low q^2 by 2.5σ for each decay mode.

Precision only limited by statistics (electron samples).

Electroweak penguins

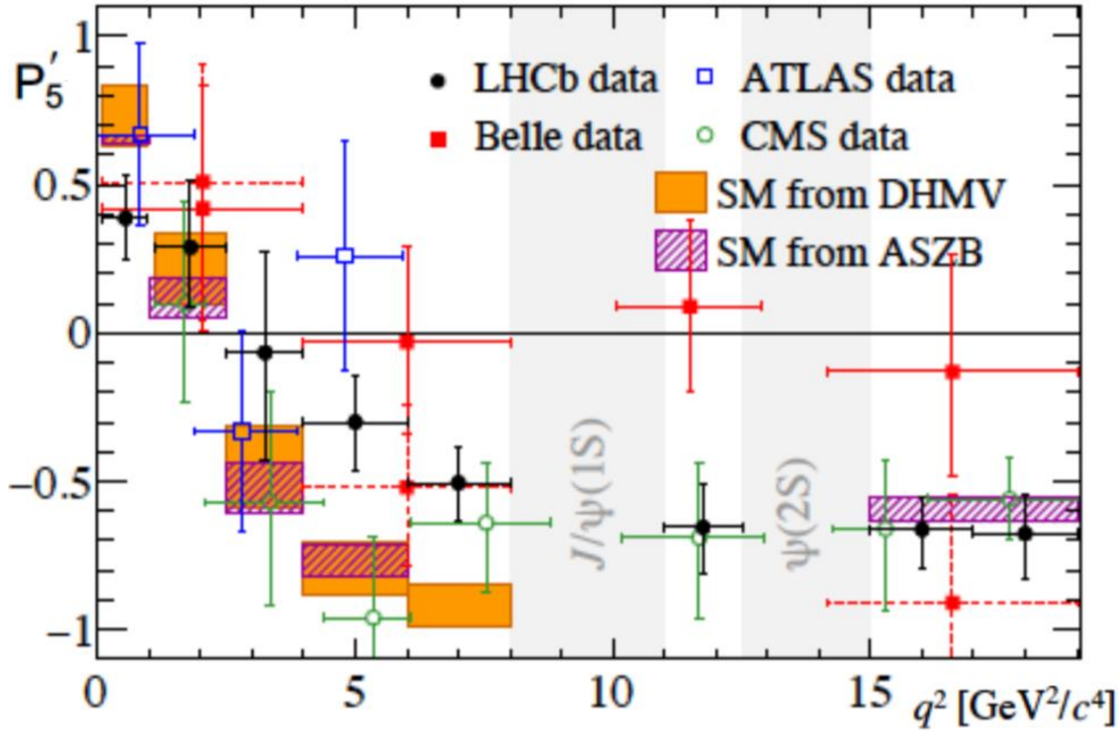
Angular distributions described in terms of 3 final state angles, q^2 and 8 coefficients.

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

Reformalism of coefficients to P_5' etc reduces form factor (ie QCD) uncertainties.

Descotes-Genon et al, JHEP 01 (2013) 048.

Predicted by SM & general NP rather well.



Data higher than prediction by nearly 4σ, CMS more SM-like. Belle result for $\mu\mu$ and ee, with $\mu\mu$ higher.

Current status of fits to FCNC data

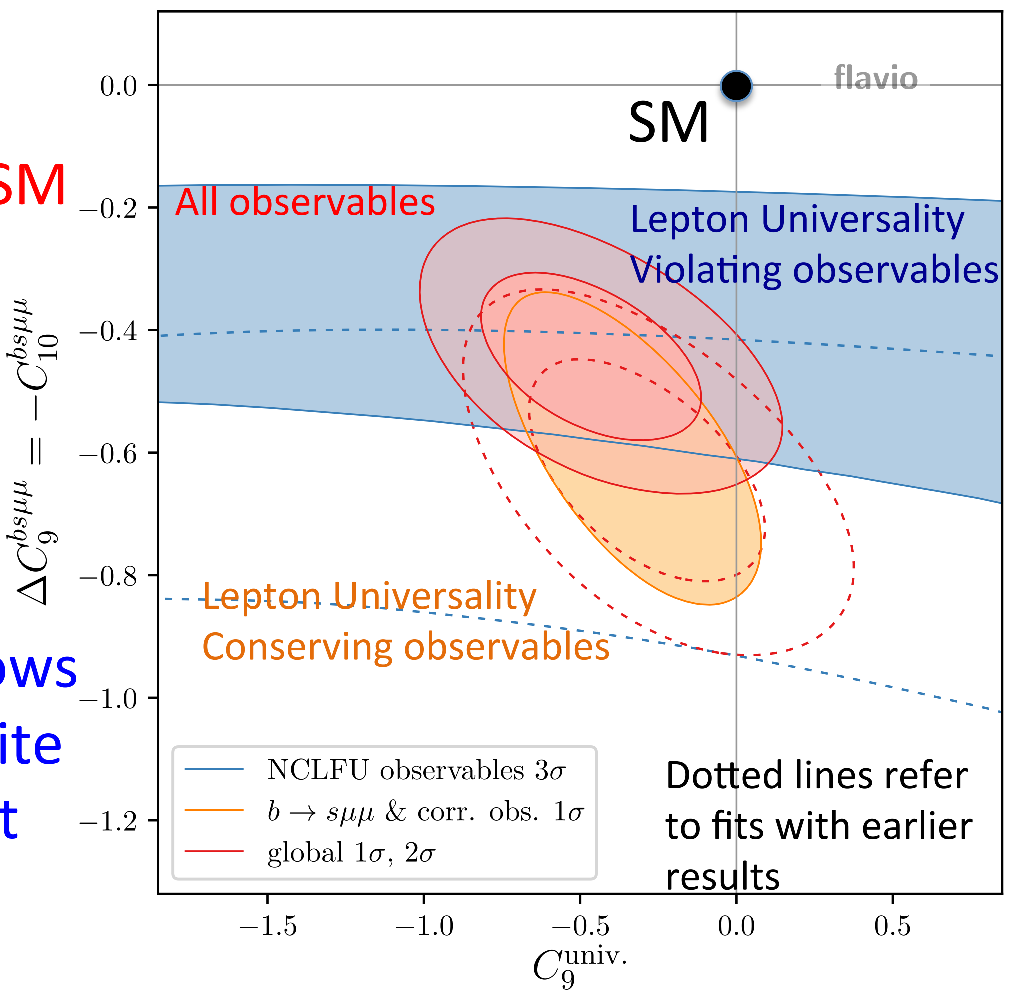
FCNC data give a consistent picture.

Best fit is inconsistent with SM by more than 5σ!...

…assuming no further uncertainties on SM predictions.

One example of good fit allows for NP in muons with opposite sign C_9 and C_{10} and a modest lepton universal shift in C_9.

Aebischer, Straub et al; arXiv:1903.10434

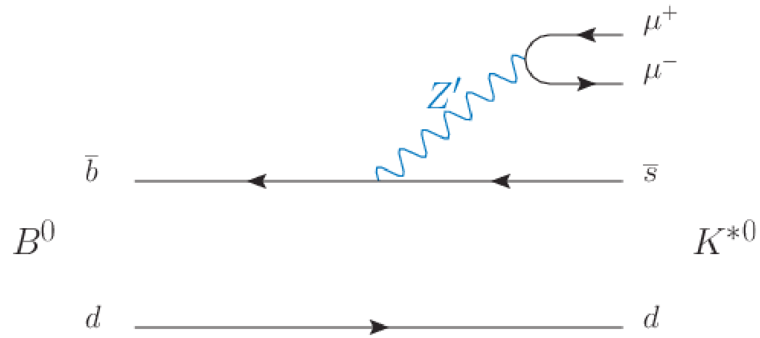


Popular NP explanations

$$\mathcal{A}_0\left(\frac{c_{\mathrm{SM}}}{v^2}+\frac{c_{\mathrm{NP}}}{\Lambda^2}\right) \qquad C_{SM}\approx V_{tb}V_{ts}^{*} \qquad \boxed{\frac{\Lambda^2}{C_{NP}}\sim(35\ \mathrm{TeV})^2}$$

- Flavour-changing Z’

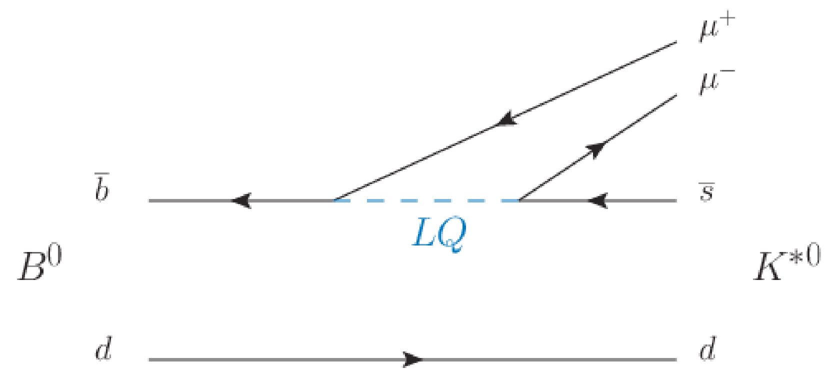
e.g. Altmannshofer & Straub EPJC 73 (2013) 2646
Gauld, Goertz & Haisch PRD 89 (2014) 015005
Altmannshofer & Straub EPJC 75 (2015) 382
Crivellin et al, PRD 92 (2015) 054013



Contribute only to O_9 operator

- Leptoquarks

e.g. Hiller & Schmaitz PRD 90 (2014) 054014
Alonson et al, arXivL1505.05164
Fajfer & Ksnik PLB 755 (2016) 270



Contributes equally to O_9 (vector) and O_{10} (pseudo-vector)

These may be within reach of direct detection at ATLAS & CMS

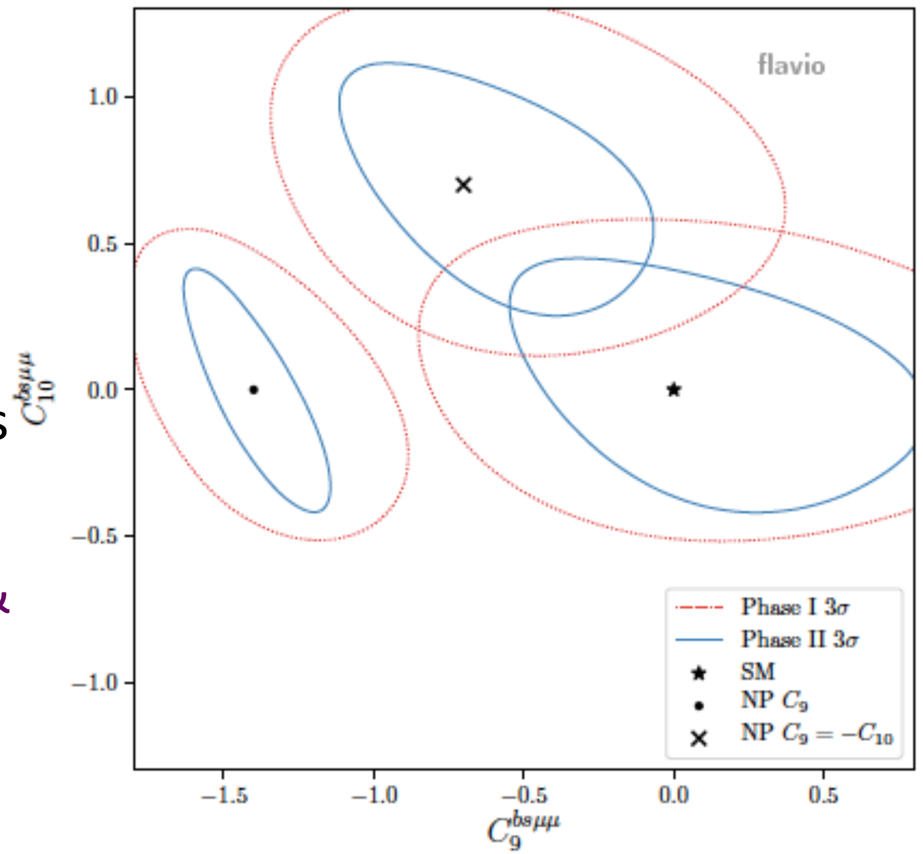
Future Rare B decays

Extrapolation of global fits to the LHC data after HL-LHC phase.

Includes $B(B_s \rightarrow \mu^+\mu^-)$ and angular distributions of $B_d \rightarrow K^{*0}\mu^+\mu^-$ at low q^2 (P_5' etc).

Other observables/measurements:

- $B(B_d \rightarrow \mu^+\mu^-)$
- BRs & angular distributions with di-electron channels
- LU tests with more decays modes e.g. $\Lambda_b \rightarrow pK\ell^+\ell^-$, $B_s \rightarrow \phi\ell^+\ell^-$
- Results from LHCb, ATLAS, CMS & Belle II



Direct searches for LFV decays

Summary

Future look taken from

CERN-LHCC-2018-027 ("Physics case for an LHCb Upgrade II")

CERN-LPCC-2018-06 ("Opportunities in Flavour Physics at the HL-LHC and HE-LHC")

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}	–

What do the next 10 years have in store?

Heavy flavour physics is moving rapidly to the next era with the advent of Belle II, the LHCb upgrade(s), ATLAS & CMS upgrades and the HL-LHC.

Specific considerations:

- important phenomena are still to be observed (*e.g.* mixing-induced CPV in B_s system, mixing related CPV in charm, $B_d \to \mu\mu$ *etc.*);
- many important new measurements will be made (*e.g.* electroweak penguins with $b \to d\ell^+\ell^-$ decays, or precise study of P_5' with $B_d \to K^*e^+e^-$);
- a very large number of observables are *theoretically clean* &/or *statistics limited*, so higher precision is strongly motivated (*e.g.* $\sin 2\beta$, γ, ϕ_s, R_K, R_{K^*}, $B(B_d \to \mu\mu)/B(B_s \to \mu\mu)$ *etc*);
- a rich field where surprises are guaranteed (*e.g.* no one was expecting charm mixing, direct charm CPV, the X(3872), pentaquarks...)....

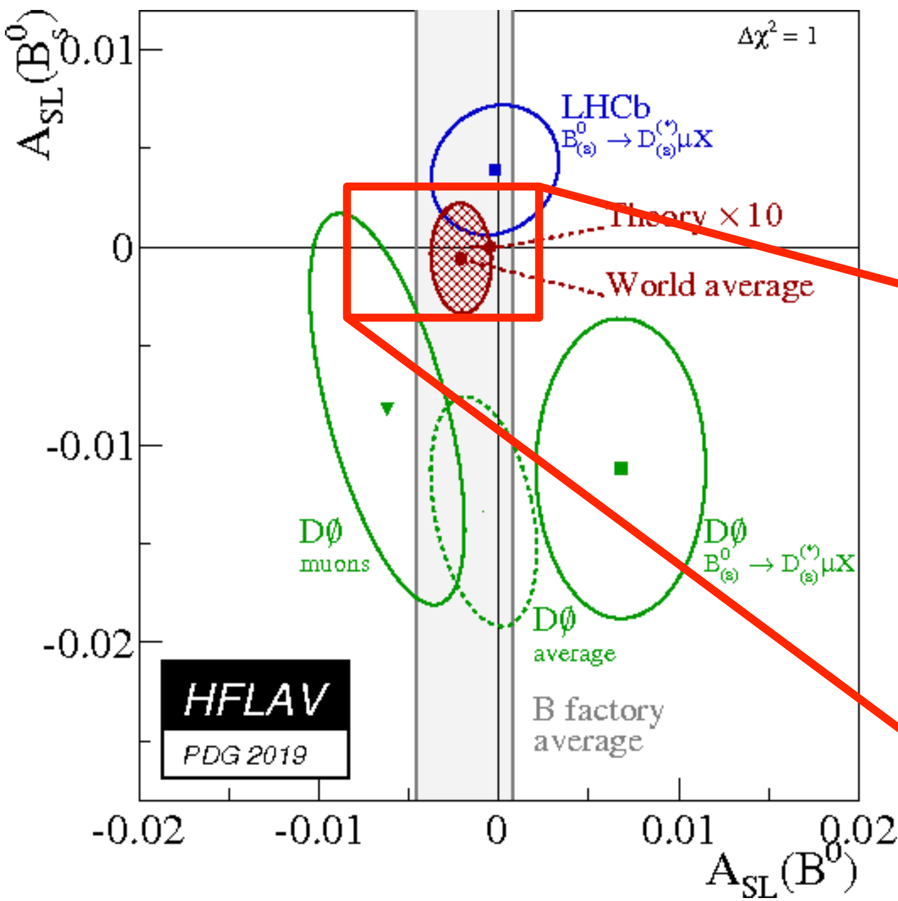
Flavour physics probes higher mass scales than direct searches, and may reveal the NP needed to explain the mysteries of the SM (& cosmos).

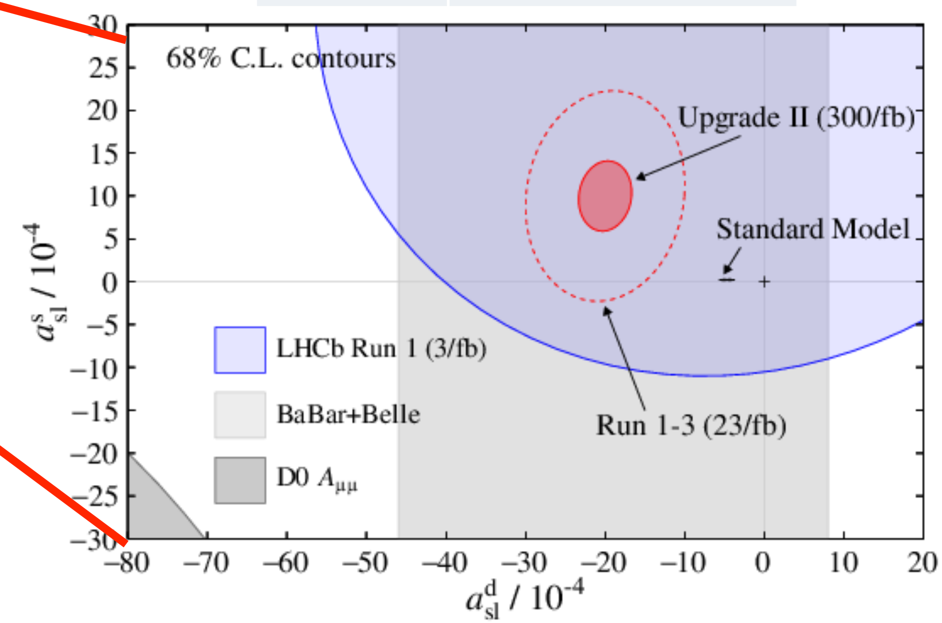

Thank you!

CP violation in mixing

$$a_{\rm sl}^q = \frac{\Gamma(\overline{B}{}_q^0 \to f) - \Gamma(B_q^0 \to \bar{f})}{\Gamma(\overline{B}{}_q^0 \to f) + \Gamma(B_q^0 \to \bar{f})} \approx \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_{12}^q,$$

	$\sigma(a^s_{sl})/\sigma(a^d_{sl})$ $(\times 10^4)$
current	33/36
23 fb^{-1}	10/8
50 fb^{-1}	
300 fb^{-1}	3/2





$B \rightarrow \mu^+\mu^-$

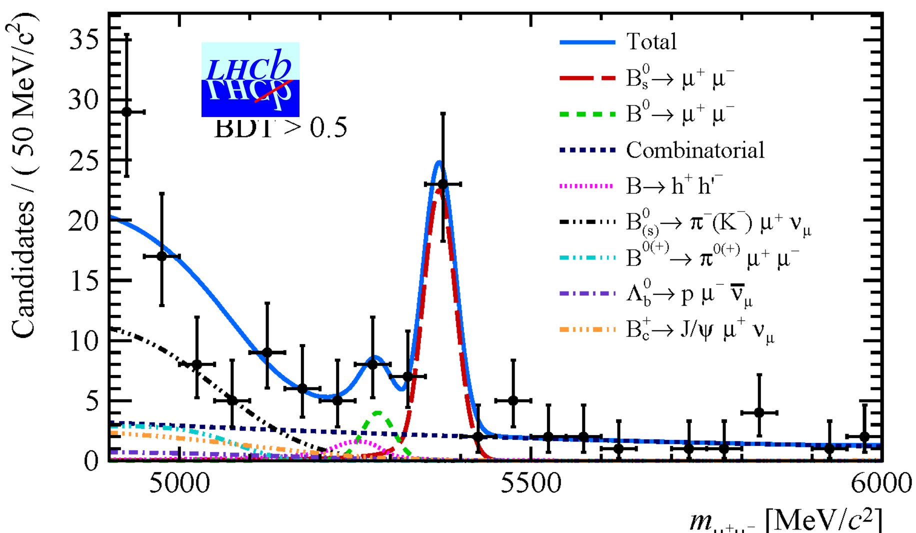
Golden very rare decay $B(B_s \rightarrow \mu^+\mu^-)_{SM} = (3.66 \pm 0.23) \times 10^{-9}$

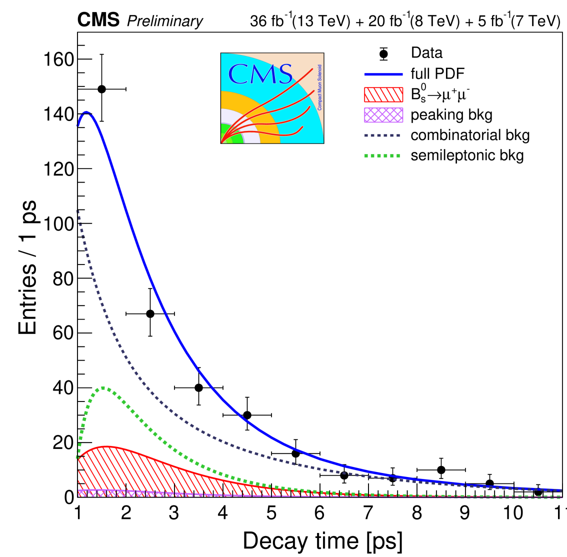
$B(B_d \rightarrow \mu^+\mu^-)_{SM} = (1.06 \pm 0.09) \times 10^{-10}$

Bobeth et al., PRL 112 (2014) 101801

Many models (e.g. SUSY) can modify the rate substantially.

Now observed by all LHC experiments





$$B(B_s \rightarrow \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$
$$B(B_d \rightarrow \mu^+\mu^-) < 3.4 \times 10^{-10}$$
$$\tau_{eff} = 2.04 \pm 0.44 \pm 0.5 \text{ ps}$$

$$B(B_s \rightarrow \mu^+\mu^-) = (2.9^{+0.7}_{-0.6} \pm 0.2) \times 10^{-9}$$
$$B(B_d \rightarrow \mu^+\mu^-) < 3.6 \times 10^{-10}$$
$$\tau_{eff}(B_s \rightarrow \mu^+\mu^-) = 1.70^{+0.61}_{-0.44} \text{ ps}$$