
Flavour Physics

lecture 3

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Useful resources & acknowledgments

- Heavy Flavour Averaging Group (HFLAV) <https://hflav.web.cern.ch>
- CKMfitter ckmfitter.in2p3.fr Ufit www.utfit.org/UTfit/
- Particle Data Group reviews pdg.lbl.gov
- Books:
 - CP violation, I.I. Bigi and A.I. Sanda (CUP, 2000)
 - CP violation, G.C. Branco, L. Lavoura & J.P.Silva (OUP, 1999)
- Reviews & lectures:
 - M. Blanke, [arXiv:1704.03753](https://arxiv.org/abs/1704.03753)
 - O. Gedalia & G. Perez, [arXiv:1005.3106](https://arxiv.org/abs/1005.3106)
 - Y. Grossman & P. Tanedo, [arXiv:1711.03624](https://arxiv.org/abs/1711.03624)
 - J.F. Kamenik, [arXiv:1708.00771](https://arxiv.org/abs/1708.00771)
 - Z. Ligeti, [arXiv:1502.01372](https://arxiv.org/abs/1502.01372)
 - Y. Nir, [arXiv:0708.1872](https://arxiv.org/abs/0708.1872), [arXiv:1605.00433](https://arxiv.org/abs/1605.00433)

Thanks to flavour lecturers at this school in previous years, who provided inspiration for some of the material shown (esp. T. Gerson, J. Zupan & M-H. Schune).

Lecture outline

- Introduction ✓
- Birth of flavour physics & the kaon sector ✓
- The beautiful millennium ✓
- Flavour structure of the SM ✓
- The Unitarity Triangle and CPV measurements ✓
- Spectroscopy (a brief digression) ✓
- FCNCs or 'rare decays' - topic begun
- Charm physics
- Future of flavour

Note the approach will (necessarily) be from an experimentalist's perspective.

Flavour-changing Neutral Currents (FCNCs) or 'rare decays' as a probe of New Physics

From last time

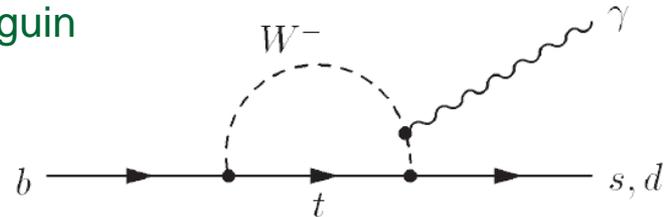
FCNC decays proceed through higher order diagrams → suppressed in SM and susceptible to New Physics contributions.

e.g. Penguin diagram (nomenclature introduced by John Ellis in 1977 after lost bet [[Ellis et al., NPB 131 \(1977\) 285](#)].)

Most interesting measurements involve EM & weak penguins, with photon or dileptons – precise predictions.



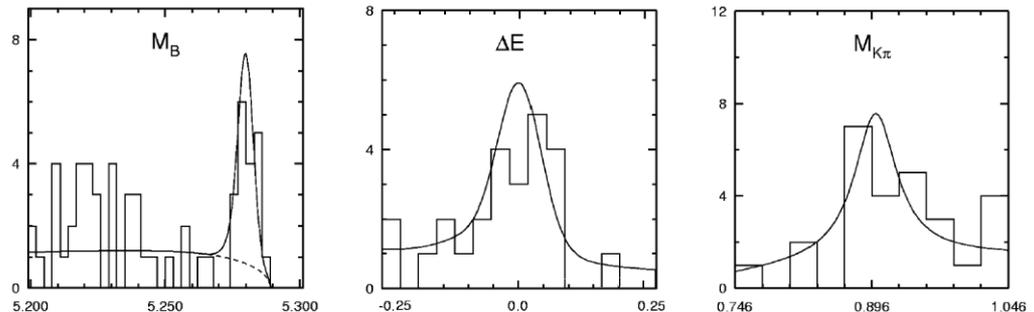
(EM) Radiative penguin



EM penguin first discovered by CLEO in $B \rightarrow K^*(892)\gamma$ ($BR \sim 10^{-5}$) [[CLEO, PRL 71 \(1993\) 674](#)].



Studies of radiative penguins still very important, but we will not discuss them further.



The golden modes: $B_s \rightarrow \mu^+ \mu^-$, $B^0 \rightarrow \mu^+ \mu^-$

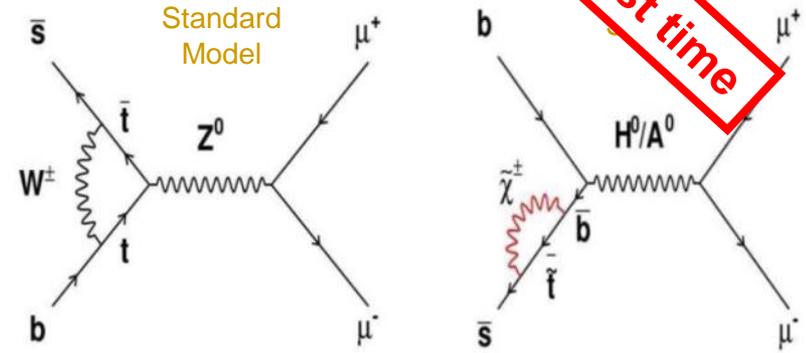
From last time

These decay modes can only proceed through suppressed loop diagrams.

In SM they happen extremely rarely ($B_s \rightarrow \mu\mu \sim 4 \times 10^{-9}$, $B^0 \rightarrow \mu\mu$ 30x lower), but the rate is very well predicted (e.g. <5% for $B_s \rightarrow \mu\mu$).

Many models of New Physics (e.g. SUSY) can modify rate significantly !

A 'needle-in-the haystack' search, which has been pursued for over 25 years.



ARGUS, 1987

UA1, 1991

CLEO, 2000

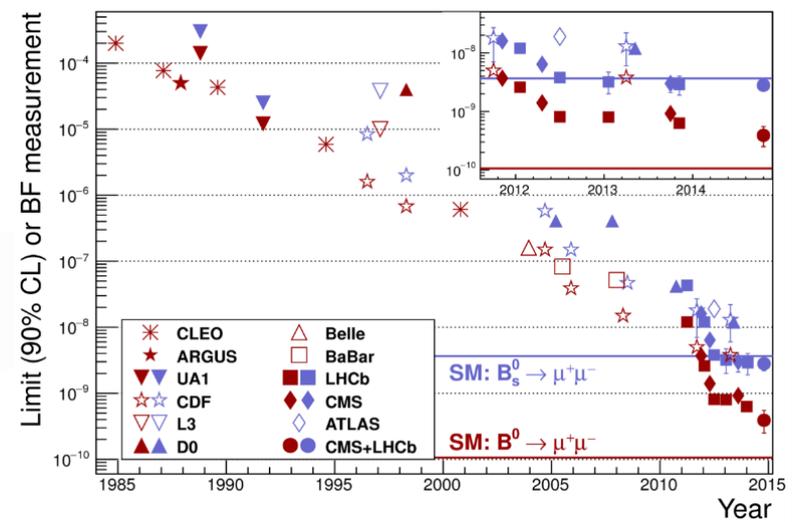
EXPERIMENTAL CONSTRAINTS

Search for rare B meson decays at the CERN SppS Collider

(CLEO Collaboration) published 2 October 2000

Upper limits for exclusive B^0 decays

Decay channel	Upper limit
$B^0 \rightarrow e^+ e^-$	8.5
$B^0 \rightarrow \mu^+ \mu^-$	5.0
$B^0 \rightarrow e^+ \mu^-$	5.0



Before the LHC, Fermilab experiments were pushing the limits down towards 10^{-8} .

The state of play

From last time

LHCb

[PRL 118 (2017) 191801]

$$\text{BR}(B_s \rightarrow \mu\mu) = 3.0^{+0.7}_{-0.6} \times 10^{-9}$$

$$\text{BR}(B^0 \rightarrow \mu\mu) \text{ [upper limit @ 95\% C.L.]} < 3.4 \times 10^{-10}$$

CMS (prelim)

[CMS PAS BPH-16-004]

$$2.9^{+0.7}_{-0.6} \times 10^{-9}$$

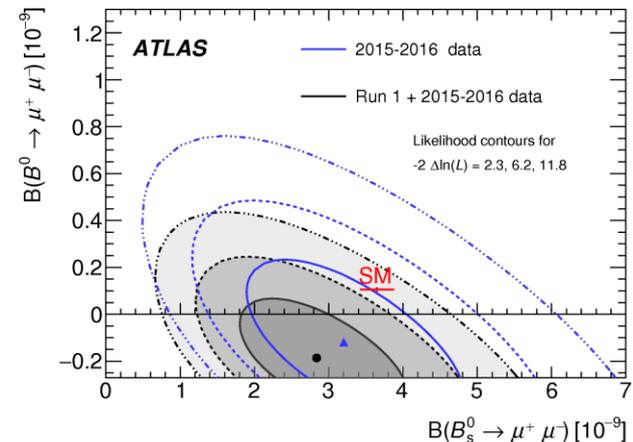
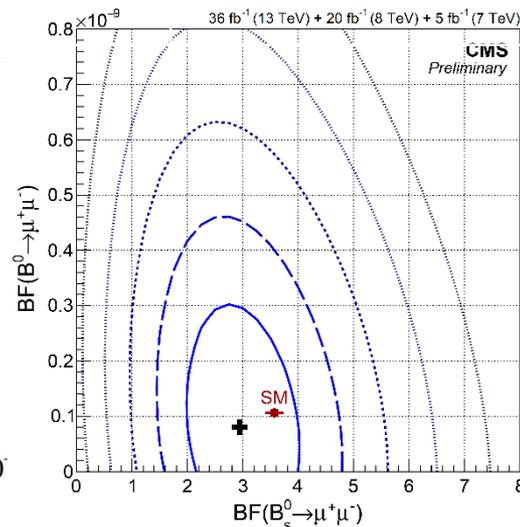
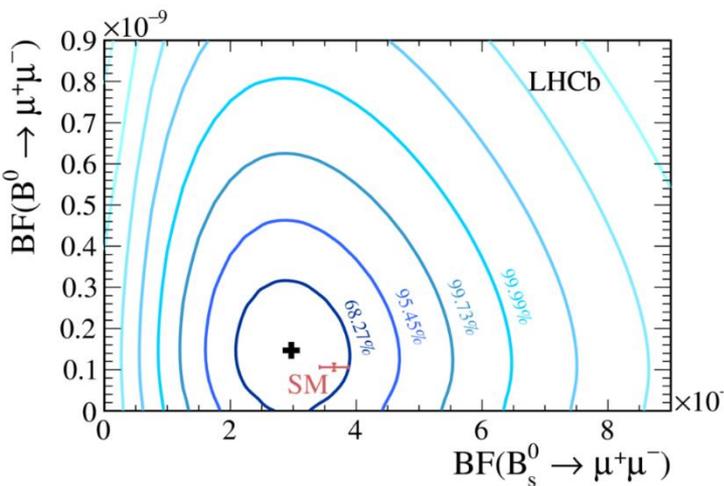
$$< 3.6 \times 10^{-10}$$

ATLAS

[JHEP 04 (2019) 098]

$$2.8^{+0.8}_{-0.7} \times 10^{-9}$$

$$< 2.1 \times 10^{-10}$$



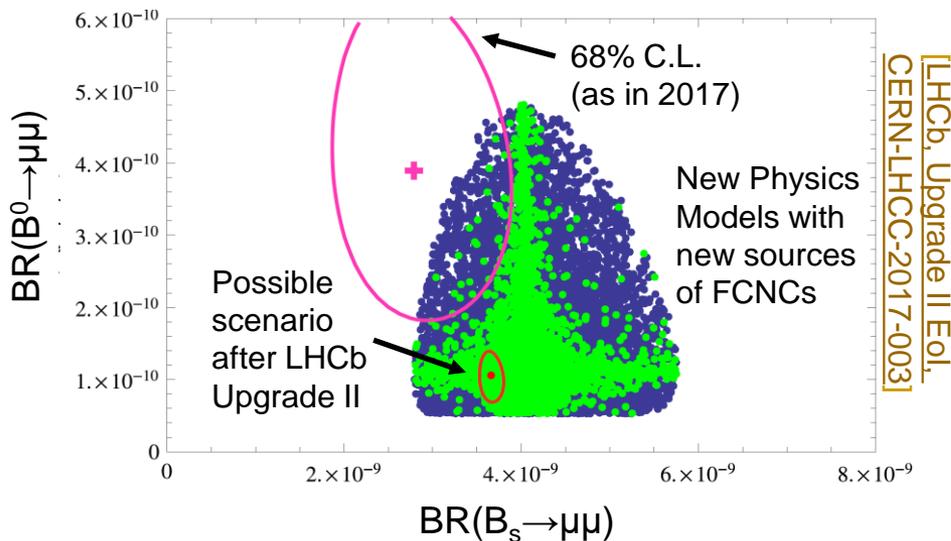
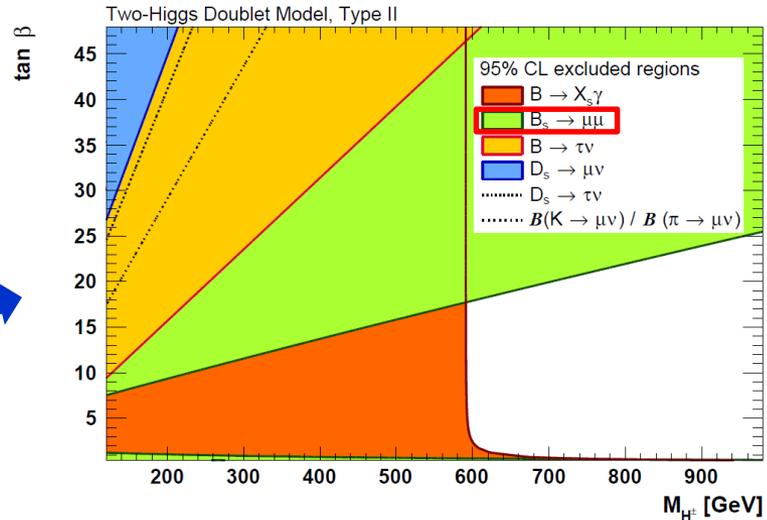
- Each result is compatible with the SM;
- $B_s \rightarrow \mu\mu$ measurements are clustering at a slightly lower value than SM (at level of $\sim 2\sigma$);
- $B^0 \rightarrow \mu\mu$ is proving elusive;
- Full Run 2 results will be interesting;

Lessons from, & future of, $B^0_{(s)} \rightarrow \mu\mu$ measurements

From last time

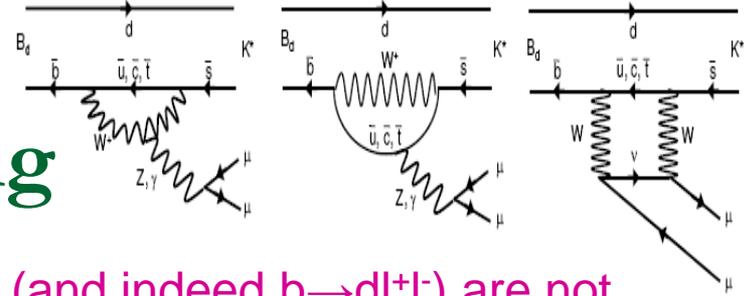
- Prior to LHC turn on, an enhanced $BR(B_s \rightarrow \mu\mu)$ was one of the great hopes for a rapid discovery of New Physics. This hope has not been realised.
- Nonetheless, the absence of an enhancement is a very powerful input in excluding certain classes of New Physics model.

e.g. 95% CL excluded region in M_{H^\pm} vs. $\tan\beta$ space for two-Higgs doublet model [Gfitter group, Hallet *et al.*, EPJC 78 (2018) 675].



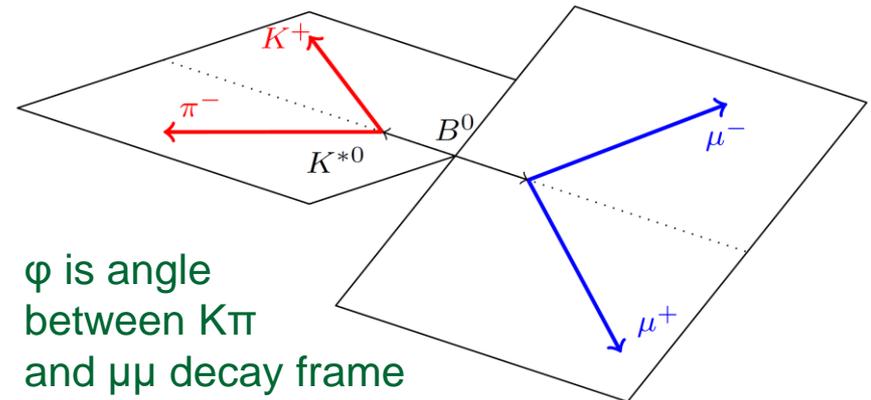
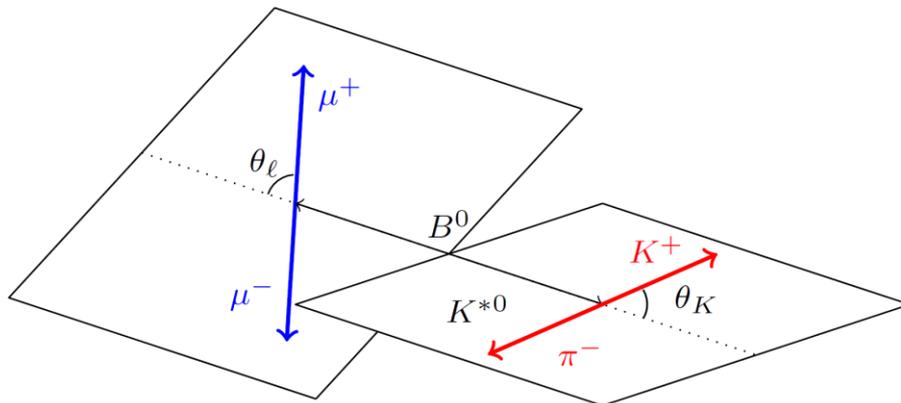
- Better measurements are *essential*, as we are still far from theory limit (which will improve). Even truer for ratio $BR(B_s \rightarrow \mu\mu)/BR(B^0 \rightarrow \mu\mu)$. These decays still have much to tell us!
- Next step in the journey will be observation of $B^0 \rightarrow \mu\mu$.

$B^0 \rightarrow K^{*0} l^+ l^-$ and friends – the gift that keeps on giving



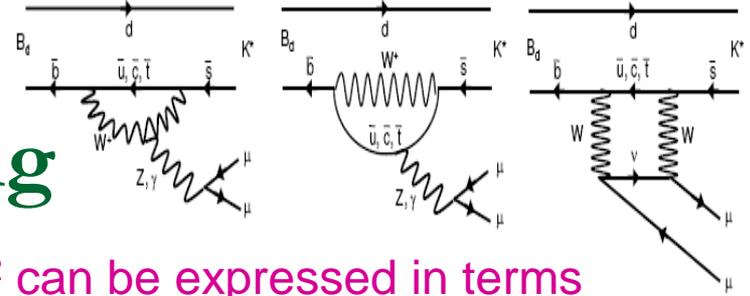
FCNC processes involving the transition $b \rightarrow s l^+ l^-$ (and indeed $b \rightarrow d l^+ l^-$) are not ultra rare, but provide an exceedingly rich set of observables to probe for NP effects, that are sensitive to non-SM helicity structures (and more).

Many realisations, but the poster-child decay is $B^0 \rightarrow K^{*0} l^+ l^-$, with $K^{*0} \rightarrow K^+ \pi^-$.



Four-body final state can be characterised in terms of three angles, Θ_l , Θ_K and ϕ , & q^2 , & the invariant-mass of the dilepton pair (see e.g. [\[LHCb, PRL 111 \(2013\) 191801\]](#)).

$B^0 \rightarrow K^* l^+ l^-$ and friends – the gift that keeps on giving



Differential cross-section w.r.t. solid angle and q^2 can be expressed in terms of eight coefficients: F_L , A_{FB} and S_i (other choices are available):

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\vec{\Omega}} = \frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right.$$

$$+ \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_l$$

$$- F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi$$

$$+ S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi$$

$$+ \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi$$

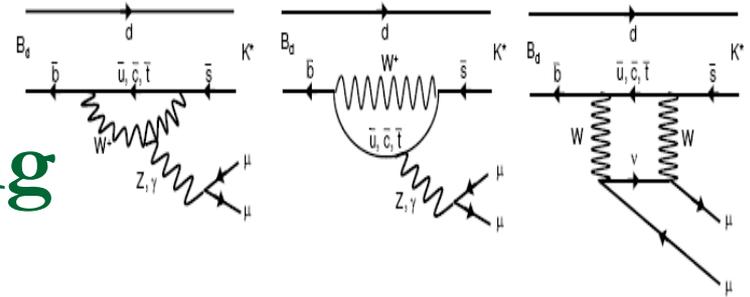
$$\left. + S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right]$$

Note, this is the
CP-averaged expression
(i.e. assuming no CPV).

F_L – fraction of longitudinal
polarisation of K^*

A_{FB} – forward-backward
asymmetry of dilepton
pair in B-meson frame

$B^0 \rightarrow K^* l^+ l^-$ and friends – the gift that keeps on giving



Three practical considerations:

1. Analysis must allow for an S-wave contribution in $K\pi$ system, in addition to P wave that comes from $K^*(892)$ – important, but we won't discuss it here.
2. In pp environment, it is easier to reconstruct muons than electrons, so unless stated, measurements are made with di-muon final state.
3. Form-factor (*i.e.* QCD) uncertainties in predictions of coefficients can be reduced by changing to a set of optimised uncertainties [Descotes-Genon *et al.*, [JHEP 01 \(2013\) 048](#)], in which first order uncertainties cancel, *i.e.* more robust:

$$P_1 = \frac{2 S_3}{(1 - F_L)} = A_T^{(2)}, \quad P_3 = \frac{-S_9}{(1 - F_L)}, \quad P'_6 = \frac{S_7}{\sqrt{F_L(1 - F_L)}}.$$

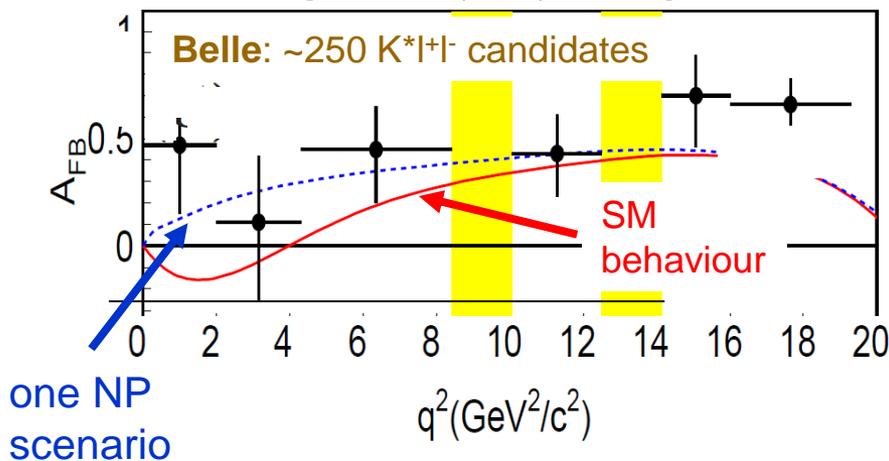
$$P_2 = \frac{2}{3} \frac{A_{\text{FB}}}{(1 - F_L)}, \quad P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1 - F_L)}}, \quad (\text{LHCb definitions, see } \text{[JHEP 02 (2016) 104]})$$

Hard to visualise what these mean, but they can be predicted in SM, & in terms of general NP predictions, rather well. Also very robust against detector bias !

$B^0 \rightarrow K^* l^+ l^-$ - impact of the LHC

The B factories studied $B^0 \rightarrow K^* l^+ l^-$ with enthusiasm. Initial results, e.g. for forward-backward asymmetry, were intriguing. But sample sizes inadequate for firm conclusions. Situation changed with the turn-on of the LHC.

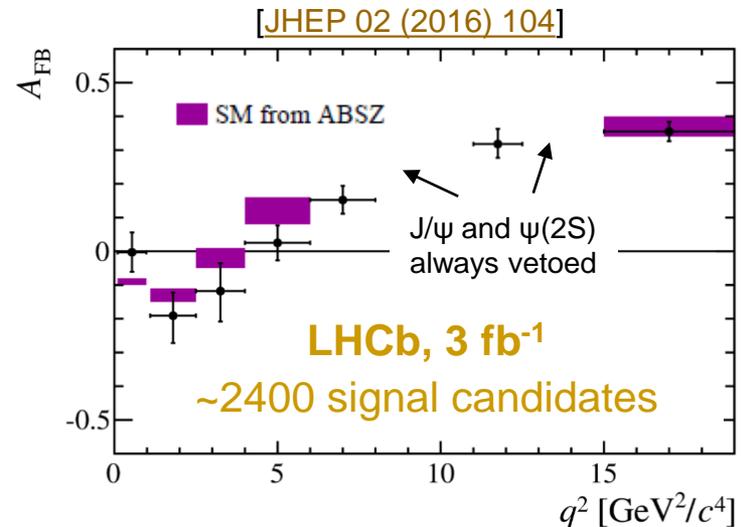
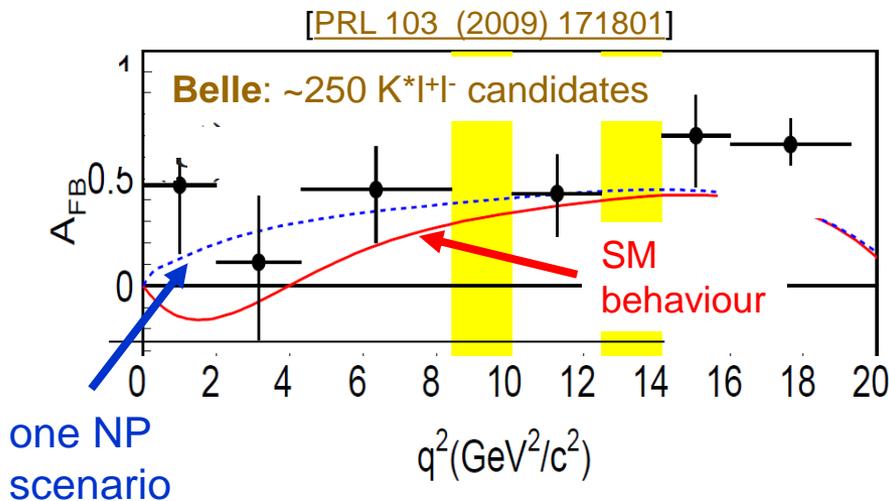
[PRL 103 (2009) 171801]



(NB: the J/ψ and ψ' regions are excluded, as these $c\bar{c}$ resonances occur through tree-level processes and do not probe physics we are interested in.)

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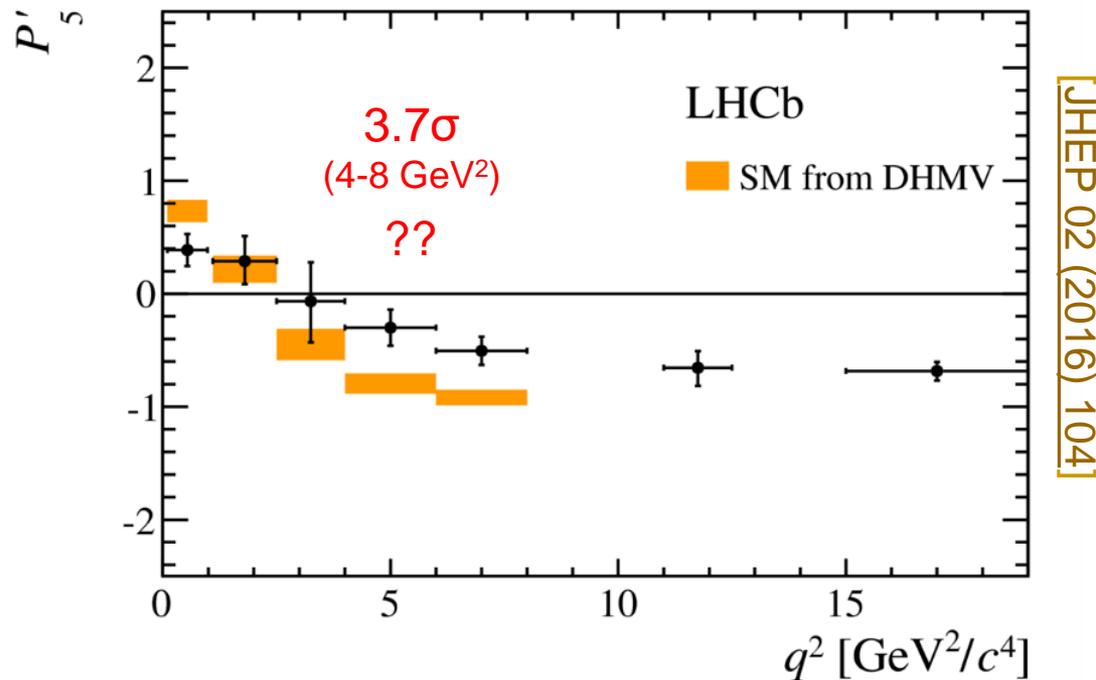


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Hints of non-SM behaviour in early analyses not confirmed by high-statistics measurement (although mild tension at low q^2). What about 'optimal observables' ?

$B^0 \rightarrow K^{*1}l^+l^-$ and friends: the P_5' puzzle

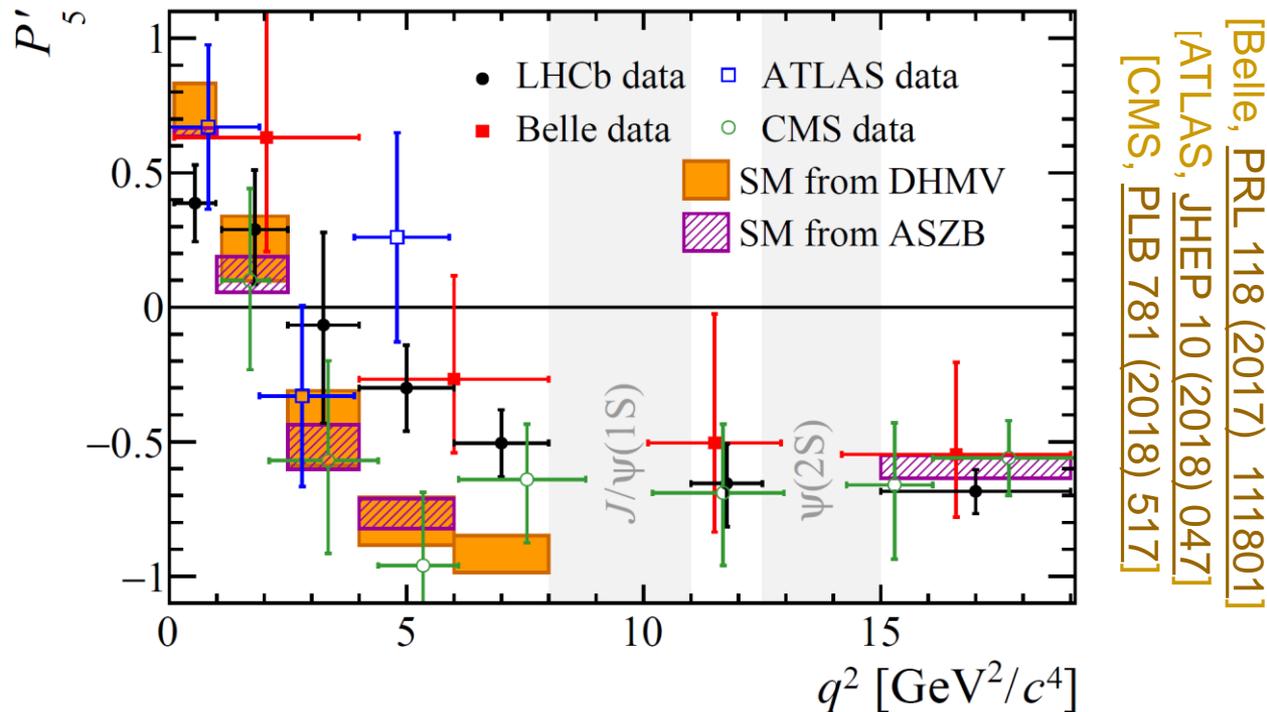
The 'optimum observable' that has attracted most attention is P_5' . A deviation at low q^2 , first seen in an early LHCb analysis [[PRL 108 \(2012\) 181806](#)], persisted with the full Run 1 data set [[JHEP 02 \(2016\) 104](#)], & is not contradicted by other experiments.



A word of caution. The SM uncertainties shown here are from one group. There are other values on the market, and some are more conservative. Meanwhile, work is ongoing to constrain QCD uncertainties from data, e.g. [LHCb, [EPJ C77 \(2017\) 161](#)].

$B^0 \rightarrow K^{*1}l^+l^-$ and friends: the P_5' puzzle

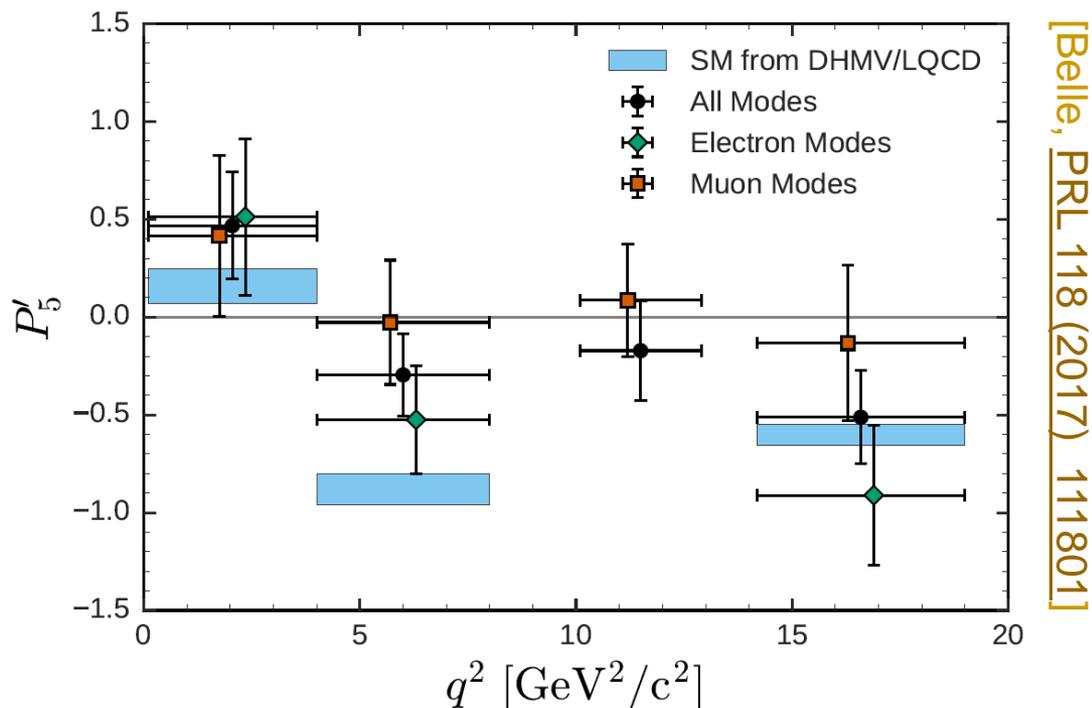
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Same pattern seen by Belle and ATLAS, whereas CMS sees more SM-like behaviour. None of these measurements are individually precise, but the overall picture is very similar to LHCb. Does not smell like a statistical fluctuation...

$B^0 \rightarrow K^* l^+ l^-$ and friends: the P_5' puzzle

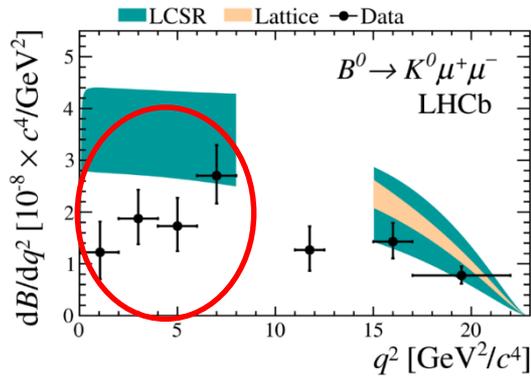
There is another interesting observation. All the LHC measurements are made with dimuons, whereas the Belle result comes from dimuons and dielectrons. Individual results are also available for each lepton final state.



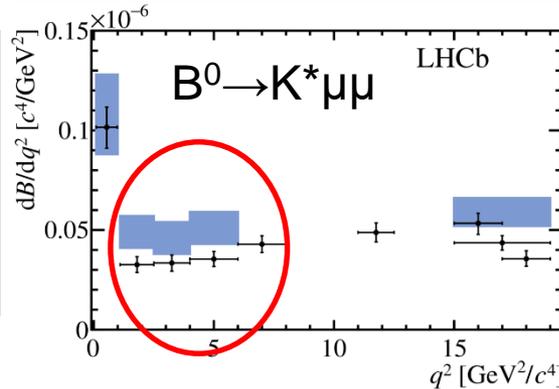
In the bin of interest it is the dimuon result that is most discrepant, although with the small sample size there is consistency between both final states.

$B^0 \rightarrow K^* l^+ l^-$ and friends: differential x-secs

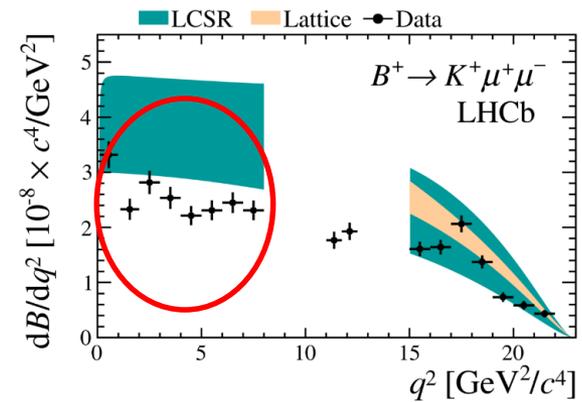
P_5' is not the only funny thing going on in $b \rightarrow (s,d) l^+ l^-$ decays.



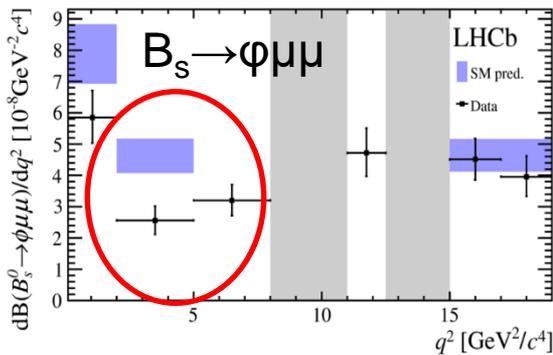
[JHEP 06 (2014) 133]



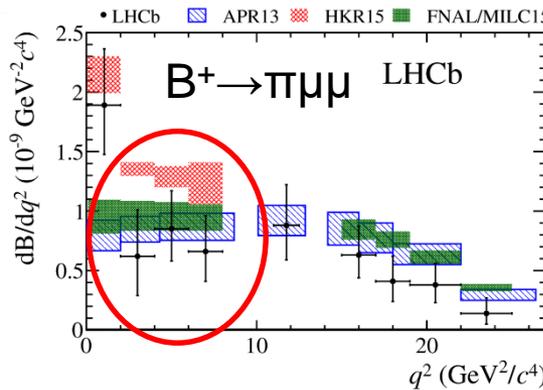
[JHEP 11 (2016) 047]



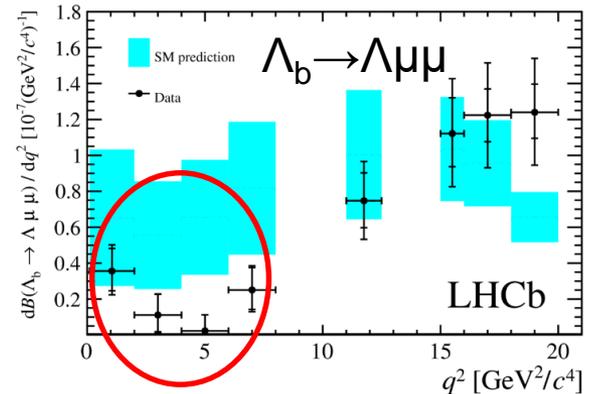
[JHEP 06 (2014) 133]



[JHEP 09 (2015) 179]



[JHEP 10 (2015) 034]



[JHEP 06 (2015) 009]

All measurements undershoot prediction at low q^2 . (BTW, all made with *dimuons*...) Intriguing – but maybe the uncertainties in theory are larger than claimed ?

Can we identify an observable where the theory uncertainties are negligible ?

$B^0 \rightarrow K^* l^+ l^-$ and friends: lepton universality tests

The cleanest way to probe these decays are with lepton universality (LU) tests, *i.e.* comparing decays with di-electrons and di-muons. *Negligible* theory uncertainty.

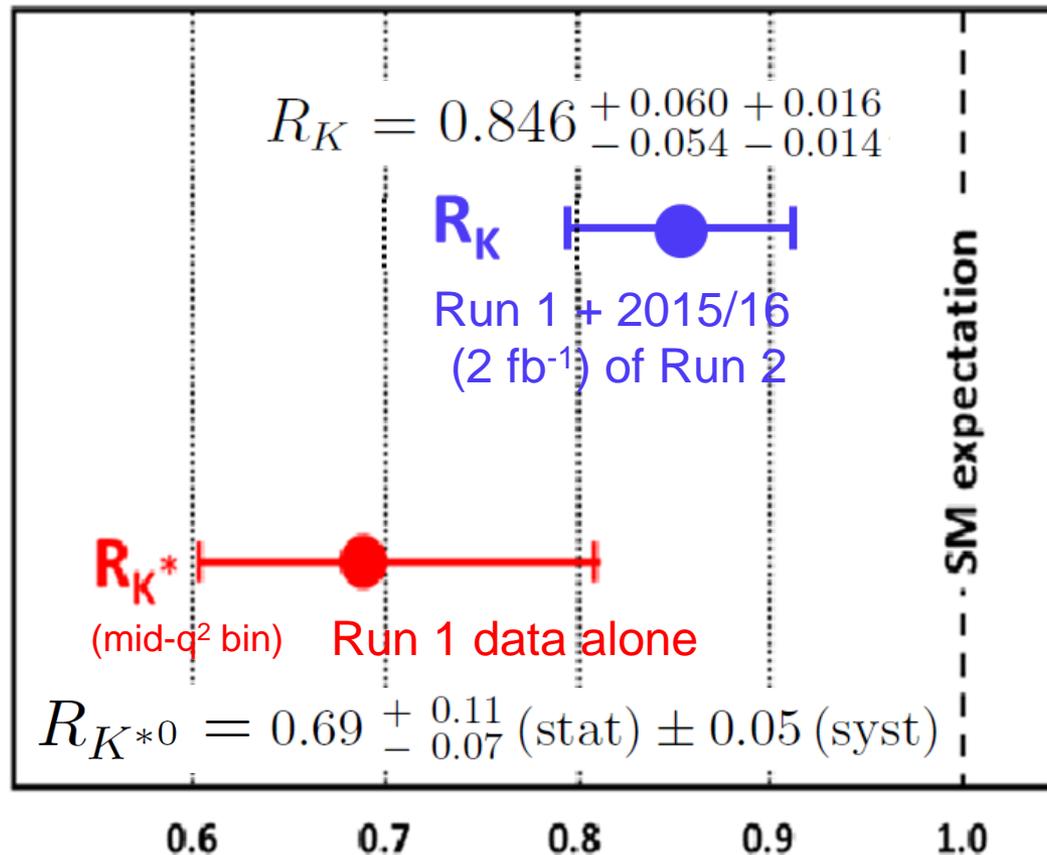
Ratios of decay rates have been measured for $b \rightarrow s \mu^+ \mu^- / b \rightarrow s e^+ e^-$ for $\sim 1 < q^2 < 6 \text{ GeV}^2$ for both $B \rightarrow K l^+ l^-$ (R_K) and $B^0 \rightarrow K^* l^+ l^-$ (R_{K^*}). In SM we expect ≈ 1 for both.

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In both cases measurements are $\sim 2.5 \sigma$ below SM!

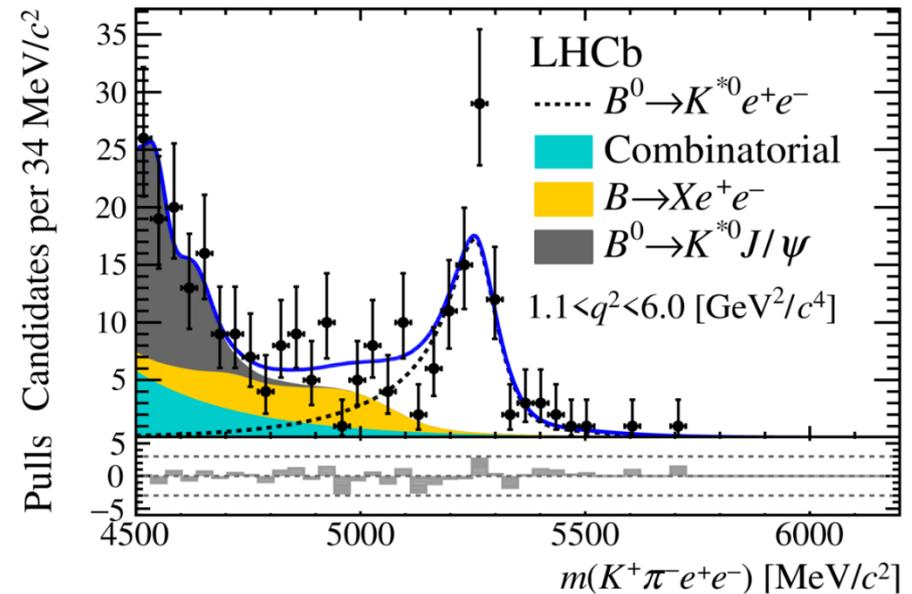
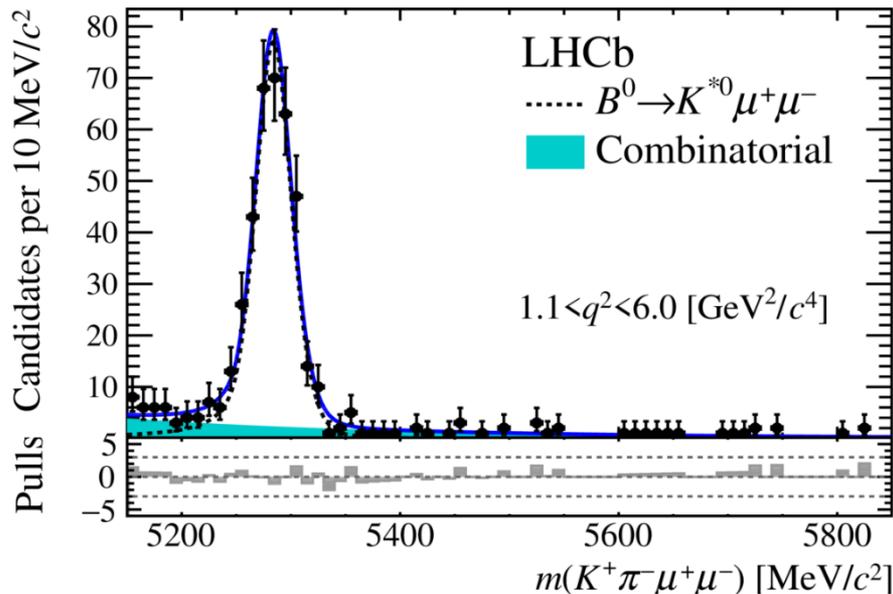


[PRL 122 (2019) 191801]

[JHEP 08 (2017) 055]

$b \rightarrow sl^+l^-$ lepton universality tests – more about the measurements (with focus on R_{K^*}) [JHEP 08 (2017) 055]

Precision is limited by size of electron sample, which is ~ 100 decays in bin of measurement (muon sample is around 3-4 x larger).



$b \rightarrow s l^+ l^-$ lepton universality tests – more about the measurements (with focus on R_{K^*}) [[JHEP 08 \(2017\) 055](#)]

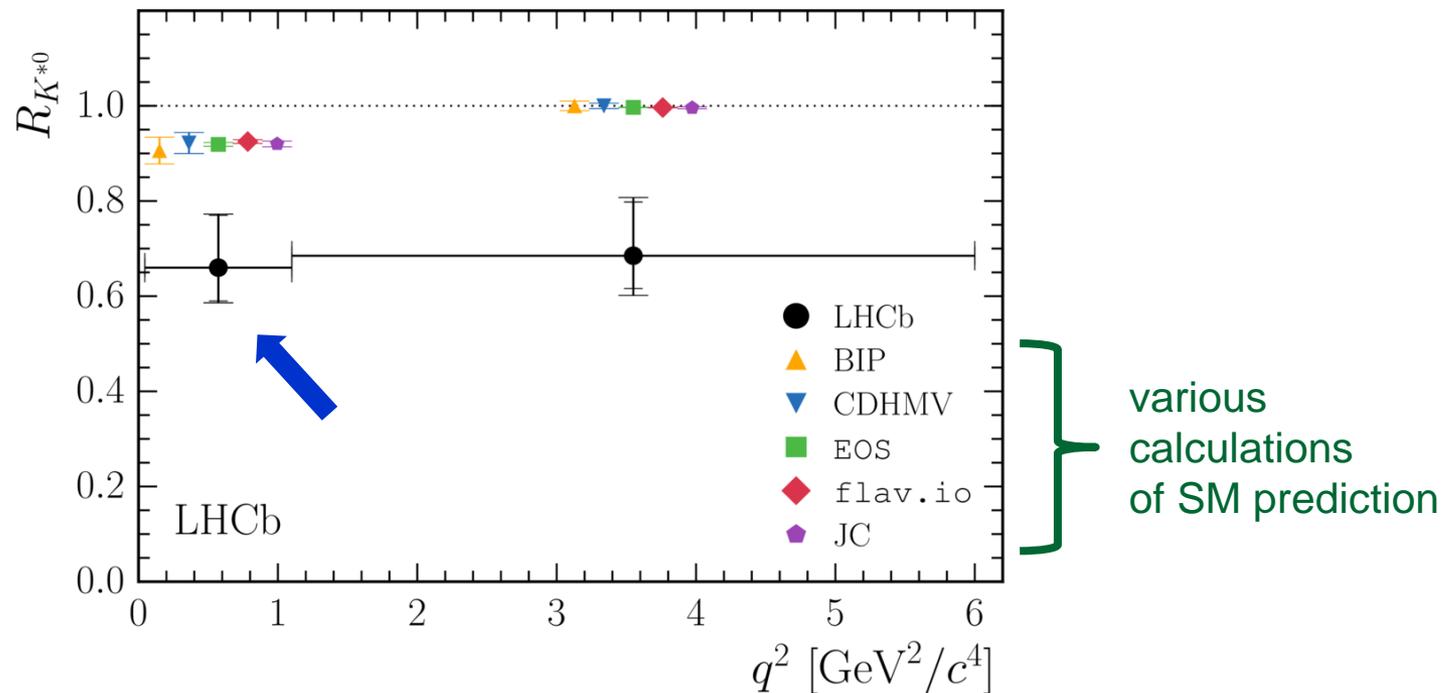
Isn't measurement vulnerable to knowledge of lepton id efficiency? No, because R_{K^*} is normalised to $B^0 \rightarrow K^* J/\psi$ (and its known $J/\psi \rightarrow l^+ l^-$ obeys lepton universality) which makes all such dependencies second order.

$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu^+ \mu^-))} \bigg/ \frac{\mathcal{B}(B^0 \rightarrow K^{*0} e^+ e^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow e^+ e^-))}$$

Nonetheless, checks are made by measuring whether the relevant ratios for $B^0 \rightarrow K^* J/\psi$ and indeed $B^0 \rightarrow K^* \psi(2S)$ are compatible with unity – they are.

$b \rightarrow s l^+ l^-$ lepton universality tests – more about the measurements (with focus on R_{K^*}) [[JHEP 08 \(2017\) 055](#)]

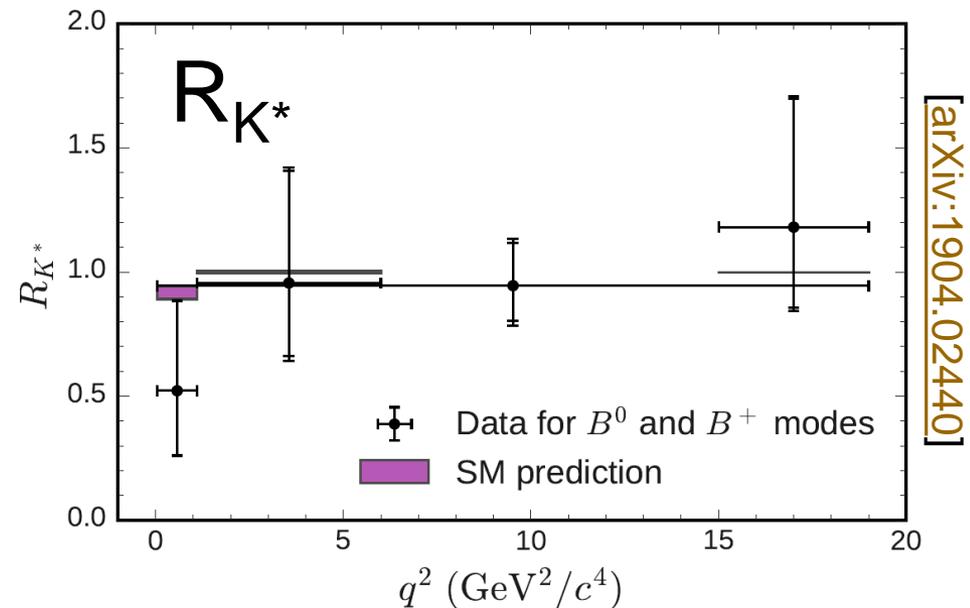
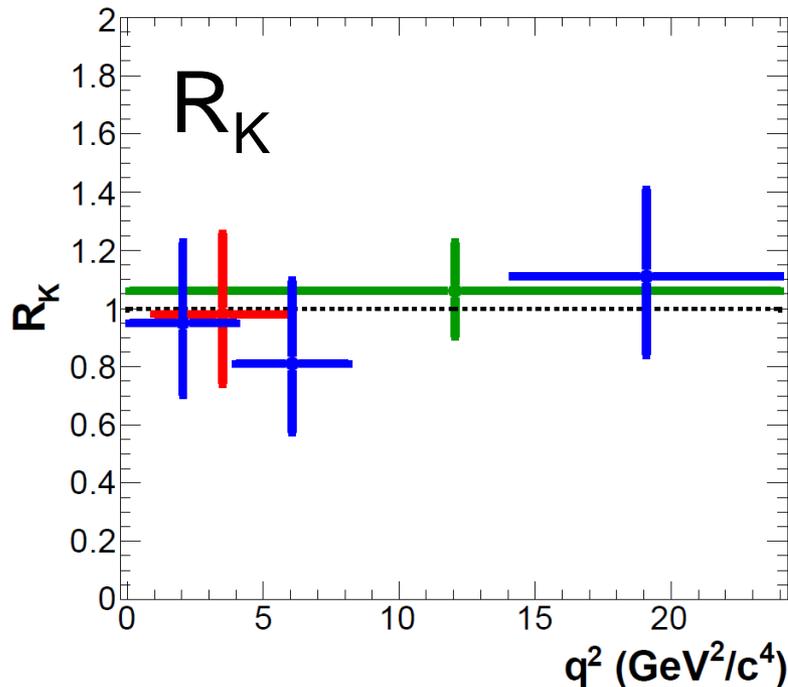
Measurements are made below J/ψ – it is the low q^2 region where odd behaviour has been seen in other studies. High q^2 measurements will come in future.



However a second R_{K^*} measurement exists at very low q^2 . This also is $>2\sigma$ low w.r.t. SM. Interesting! However, any deviation in this region is harder to explain by New Physics (see later), as ‘photon pole’ dominates decay process.

$b \rightarrow sl^+l^-$ lepton universality tests – Belle results

Belle has recently released R_K and R_{K^*} measurements (both exploiting B^0 and B^+ modes, assuming isospin conservation) in a variety of binning schemes.

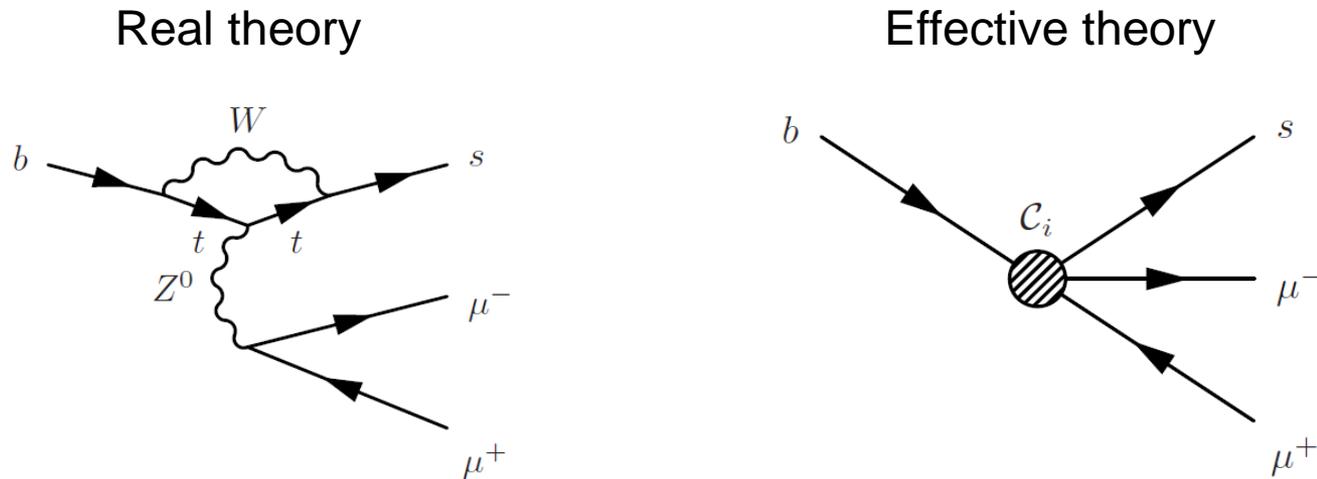


All results compatible with LHCb & SM (but significantly less precise than LHCb).

Analysing FCNC data in context of effective field theory

The $b \rightarrow s l^+ l^-$ results can be qualitatively 'explained' by hypothesising that $b \rightarrow s e^+ e^-$ largely obeys the SM, but New Physics intervenes for $b \rightarrow s \mu^+ \mu^-$ at low q^2 .

A more quantitative analysis can be made in context of effective field theory.



$$\mathcal{A}(i \rightarrow f) = \langle f | \mathcal{H}_{eff} | i \rangle$$

See, e.g. [Buchalla *et al.*, [Rev. Mod. Phys. 68 \(1996\) 1125](#)].

Analysing FCNC data in context of effective field theory

Operator product expansion:

$$H_{eff} \propto V_{tb} V_{ts}^* \sum_i (C_i \mathcal{O}_i + C'_i \mathcal{O}'_i)$$

Model independent ! Expansion performed in a complete basis of four-body operators that contribute differently to each FCNC process.

$$O_7^{(')} \propto (\bar{s} \sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$

$$O_9^{(')} \propto (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{l} \gamma_\mu l)$$

$$O_{10}^{(')} \propto (\bar{s} \gamma_\mu P_{L(R)} b) (\bar{l} \gamma_\mu \gamma_5 l)$$

$$O_S^{(')} \propto (\bar{s} P_{L(R)} b) (\bar{l} l)$$

$$O_P^{(')} \propto (\bar{s} P_{L(R)} b) (\bar{l} \gamma_5 l)$$

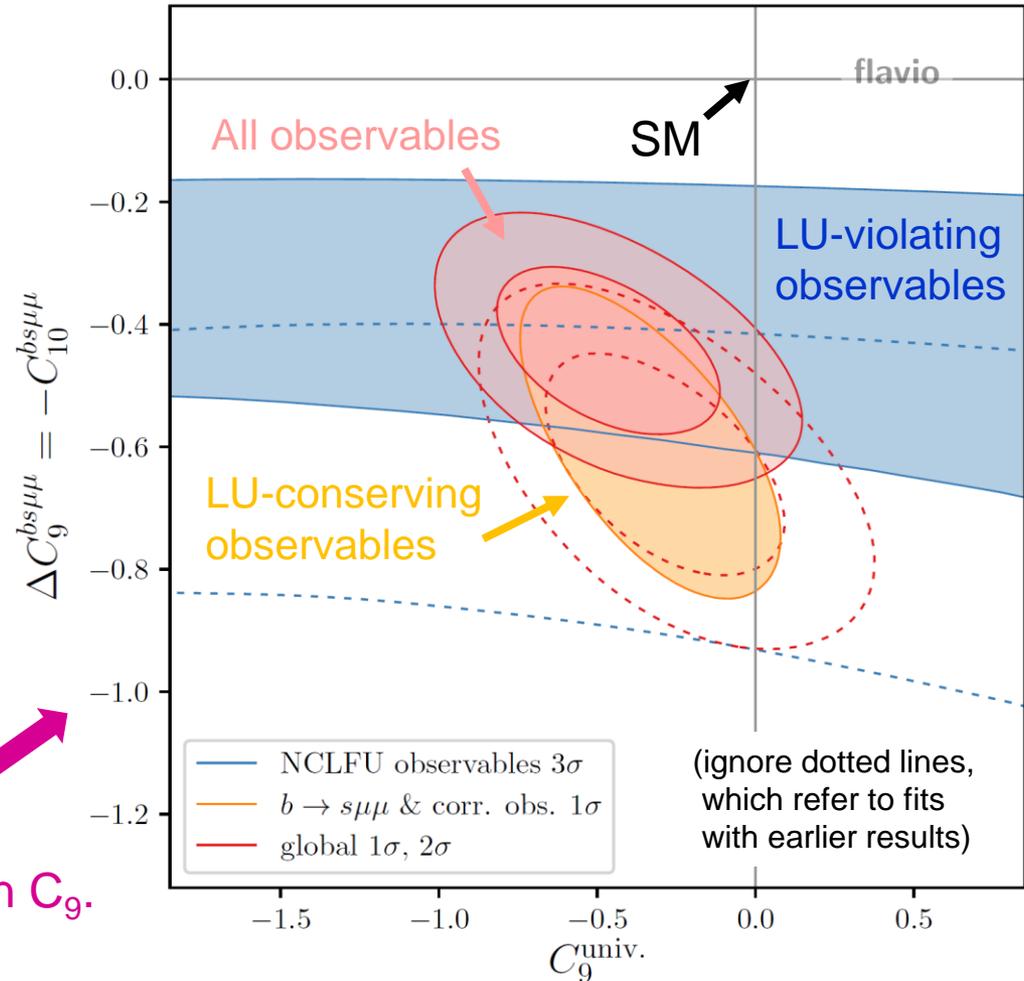
Transition	$C_7^{(')}$	$C_9^{(')}$	$C_{10}^{(')}$	$C_{S,P}^{(')}$
$b \rightarrow s \gamma$	X			
$b \rightarrow l^+ l^-$			X	X
$b \rightarrow s l^+ l^-$	X	X	X	

C_i are the *Wilson coefficients*. Calculable in SM, but can be affected by New Physics.

Current status of fits to FCNC data

[Aebischer, Straub *et al.*, arXiv:1903.10434]

- Ensemble of *all* FCNC data gives a consistent picture
- Best fit is inconsistent with SM by more than 5σ !
- *BUT*, this assumes taking uncertainties on SM predictions for, e.g., P_5' at face value.
- One excellent fit allows for NP shift for muons alone of opposite sign in C_9 & C_{10} , & a modest lepton-universal shift in C_9 .



Current status of fits to FCNC data

[Aebischer, Straub *et al.*, arXiv:1903.10434]

- Ens give
- Bes SM
- BU unc pred at fa
- One NP opp mod

Popular explanations of these effects include:

- Flavour-changing Z'

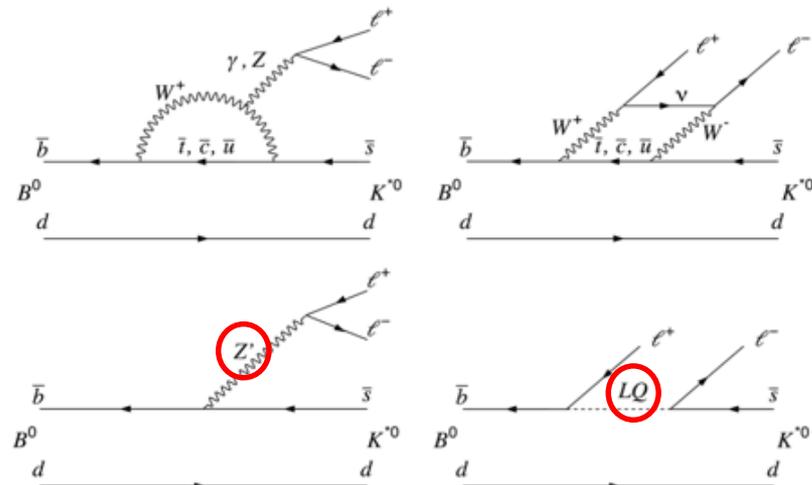
e.g. [Altmannshofer & Straub, EPJC 73 (2013) 2646],
 [Gauld, Goertz & Haisch, PRD 89 (2014) 015005],
 [Altmannshofer & Straub, EPJC 75 (2015) 382],
 [Crivellin *et al.*, PRD 92 (2015) 054013].

- Leptoquarks

e.g. [Hiller & Schmaltz, PRD 90 (2014) 054014],
 [Alonson *et al.*, arXiv:1505.05164],
 [Fajfer & Ksniik, PLB 755 (2016) 270].

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

Standard Model



New Physics

$C_9^{\text{univ.}}$

$b \rightarrow (s,d)l^+l^-$: near-term experimental prospects

New experimental input is mandatory to conclude on the $b \rightarrow sl^+l^-$ anomalies.

- LHCb Run 2 dimuon results on P_5' and other optimal observables, and equivalent studies with dielectrons
- LHCb full Run 2 results on R_K (so far only 2015-16 analysed) and on R_{K^*} (so far only Run 1 analysed), and analogous modes, e.g. $\Lambda_b \rightarrow pKl^+l^-$, $B_s \rightarrow \phi l^+l^-$.
- R_K and R_{K^*} results from other LHC experiments.
- Results from Belle II.

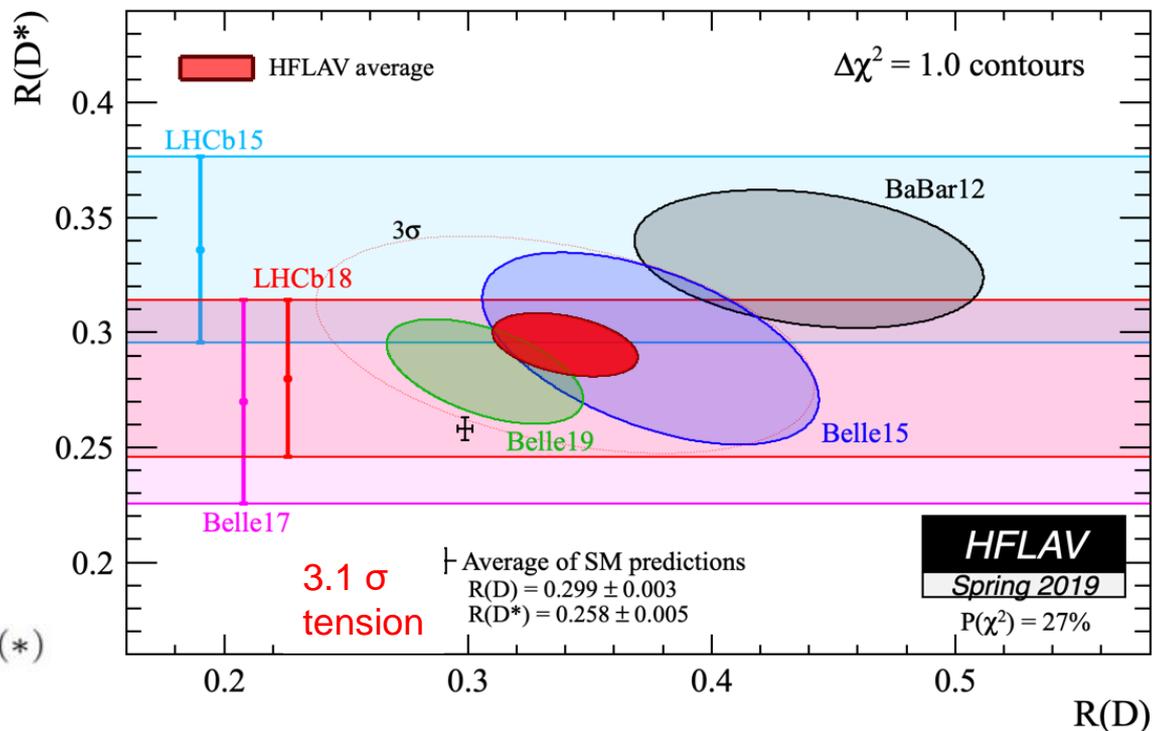
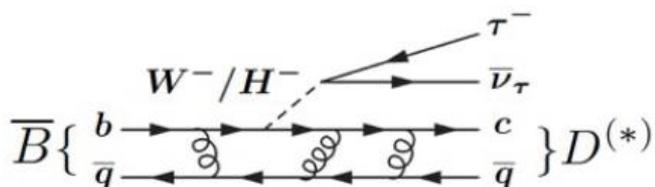
Most valuable will be *theoretically clean* observables that test lepton universality.

Personal opinion: even if current anomaly dissipates, the story has been very useful for focusing attention on one of the less well understood features of the SM (lepton universality), & also illustrating the power of a complementary ensemble of measurements. Whatever, $b \rightarrow (s,d)l^+l^-$ studies are sure to remain of great interest !

Other hints of lepton universality violation

There is another class of decays, $b \rightarrow cl\nu$, (tree level – not a FCNC!) where there is a stubborn longstanding tension between data and the SM expectation.

$$R(D^{(*)}) \equiv \frac{\text{BR}(B \rightarrow D^{(*)} \tau \nu)}{\text{BR}(B \rightarrow D^{(*)} \mu \nu)}$$



Studies originally motivated by sensitivity to charged Higgs, but results do not favour this explanation and fit better with leptoquark explanation, but requires some ingenuity to simultaneously explain this and $b \rightarrow sl^+ l^-$ anomaly.

Missing energy means that measurements are ideal for B-factories, but competitive studies have come from LHCb. More experimental input essential!

Charm physics

Mixing and CPV in charm

~15 years ago, a flavour-physics lecturer would have been strongly tempted to skip over charm. A subject with a glorious past (e.g. GIM, J/ψ), but little future.

Why so? Firstly, mixing known to be small (GIM cancellations almost exact, due to absence of super-heavy quarks in loops), maybe very small.

Charm mixing parameters

off-shell
intermediate
(short-range)
states sensitive
to New Physics

$$x_D = \frac{\Delta m}{\Gamma}$$

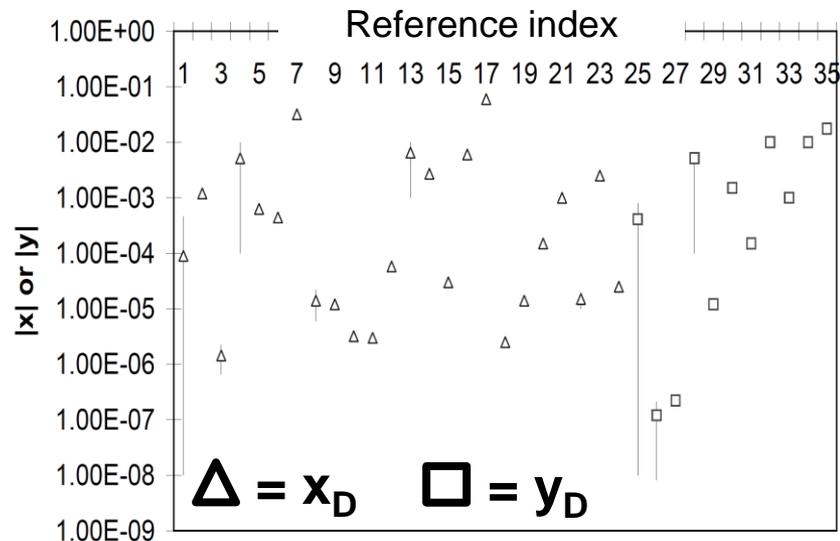
on-shell
intermediate
(long-range)
states

$$y_D = \frac{\Delta\Gamma}{2\Gamma}$$

(Δ 's refer to splittings between neutral-D mass eigenstates)



How small is small? ~ 0.01? $\ll 0.01$? This is the other problem. Charm is neither 'heavy' or 'light' & so hadronic calculations are tough.



[A. Petrov,
arXiv:hep-ph.0311371]

Infamous plot, first made by Nelson, & here updated by Petrov, showing (very) wide range in predicted values of x_D & y_D .

Mixing and CPV in charm

~15 years ago, a flavour-physics lecturer would have been strongly tempted to skip over charm. A subject with a glorious past (e.g. GIM, J/ψ), but little future.

Similarly, CPV, both indirect (*i.e.* in mixing-related phenomena) and direct, is also expected to be very small, once more because of absence of third-generation participating in virtual loops (a 2x2 CKM matrix is almost real...).

Reminder:

- CPV in mixing \rightarrow

$$\left| \frac{q}{p} \right| \neq 1$$

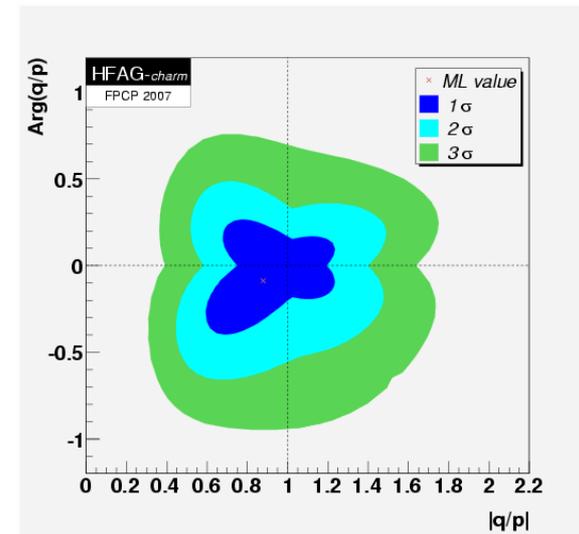
- CPV in decay-mixing interference \rightarrow

$$\phi = \arg\left(\frac{qAbar}{pA}\right) \neq 0$$

10+ years ago, the constraints on indirect CPV in charm were very weak (unsurprising, as one first needs sensitivity to mixing).

But charm *is* a priori a good place to look for New Physics (NP) effects !

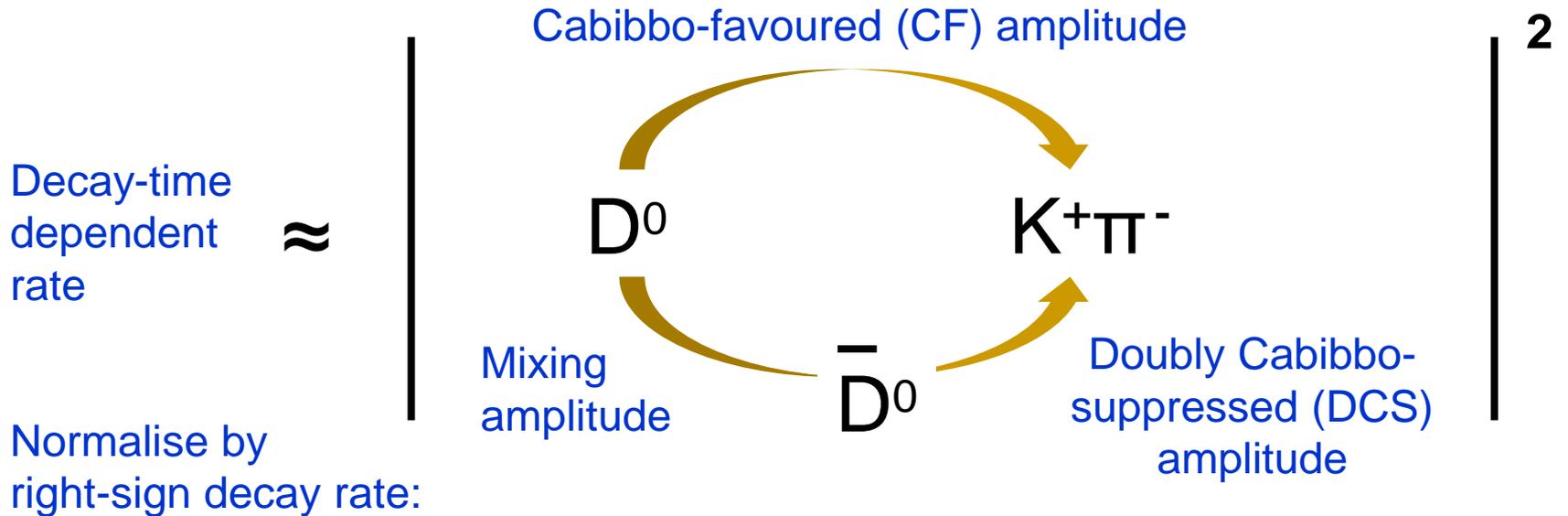
- (i) Only system in which virtual loops involving up-type quarks can be probed;
- (ii) NP effects will be easier to see when the SM 'background' is so small.



Mixing studies with 'wrong-sign' $D^0 \rightarrow K^+ \pi^-$

cf. 'right-sign' $K^- \pi^+$

Several ways to access mixing. One sensitive way is to search for interference effects involving Doubly Cabibbo-Suppressed decays, e.g. $D^0 \rightarrow K^+ \pi^-$.



$$R(t) \approx R_D + \sqrt{R_D} y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau} \right)^2$$

$$x' = x_D \cos \delta + y_D \sin \delta$$

$$y' = y_D \cos \delta - x_D \sin \delta$$

$$\left| \frac{\text{DCS amp}}{\text{CF amp}} \right|^2 \sim |0.06|^2$$

Mixing-decay interference

Mixing

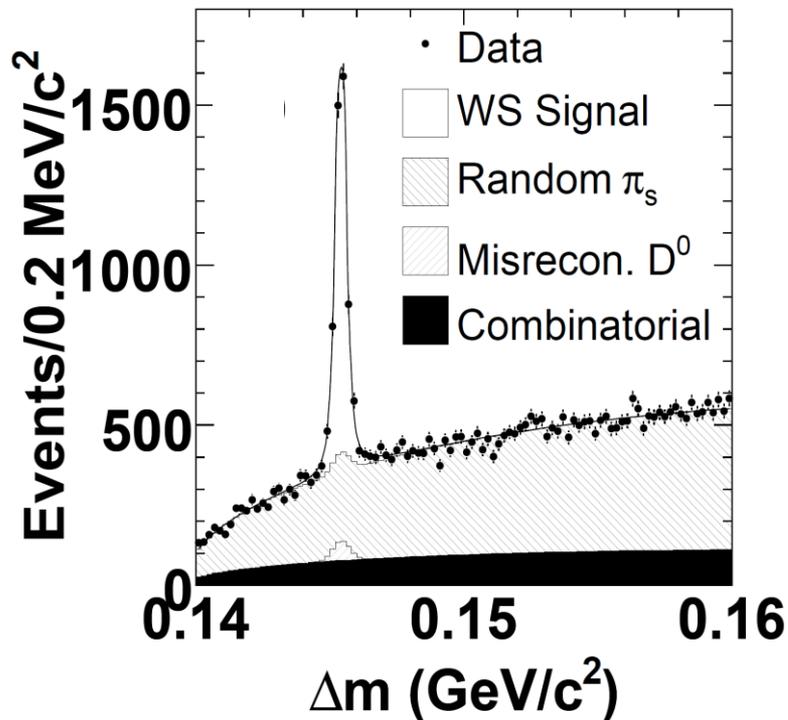
Where $\delta \sim 10^\circ$ is strong-phase difference between CF & DCS amplitudes

(expansion in x' & y' , which are small)

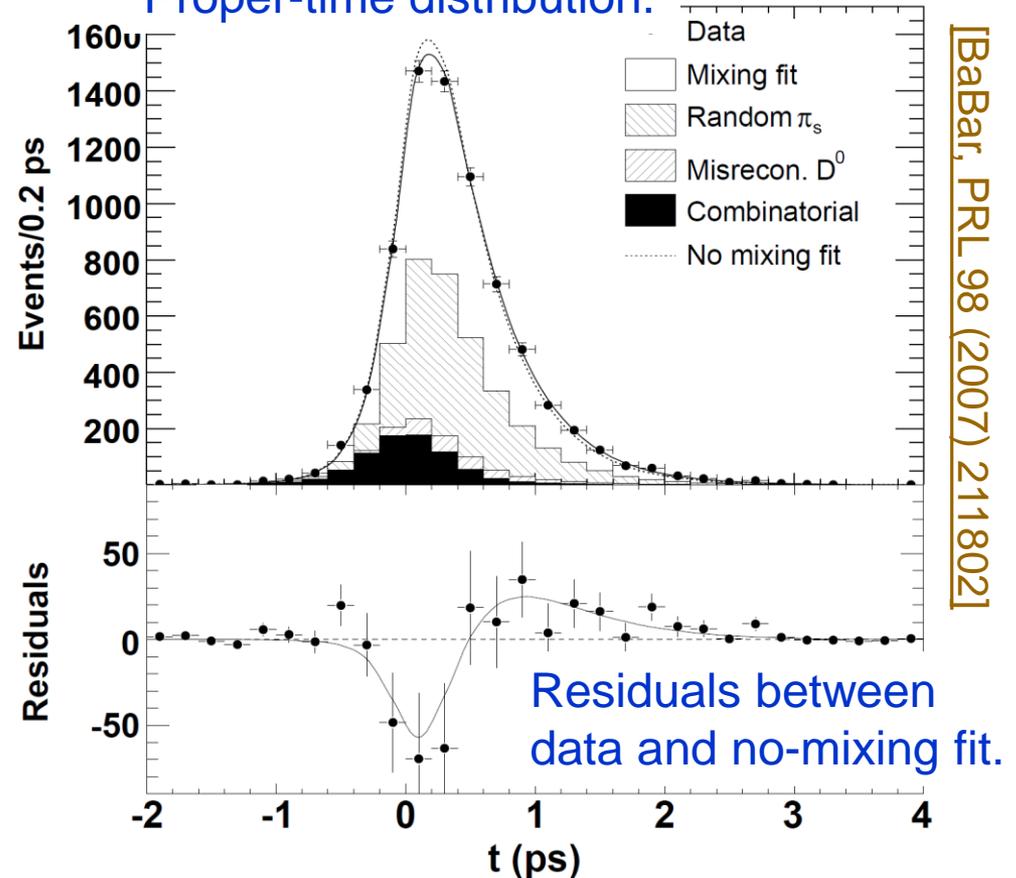
First evidence from the B-factories !

As data accumulated at the B-factories, a non-zero mixing signal began to emerge.

BaBar: 4k WS $K\pi$ signal decays with 384 fb^{-1} .



Proper-time distribution.



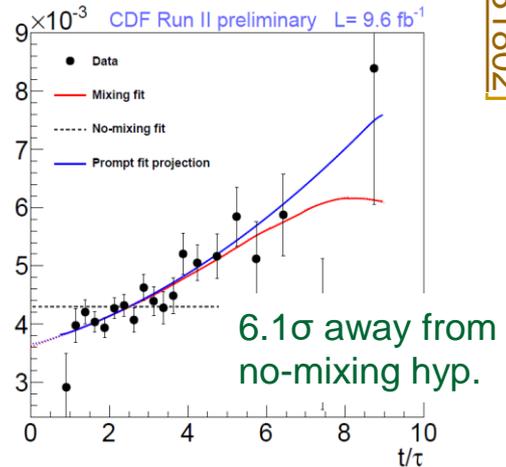
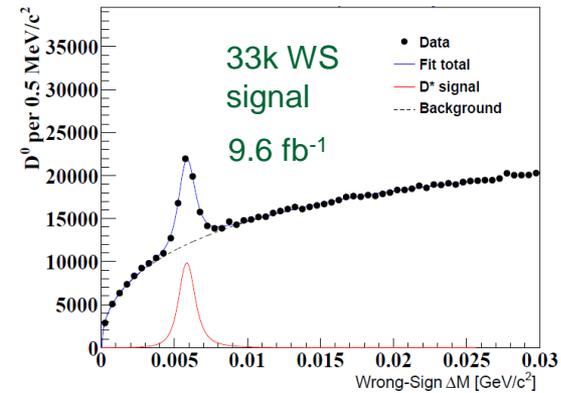
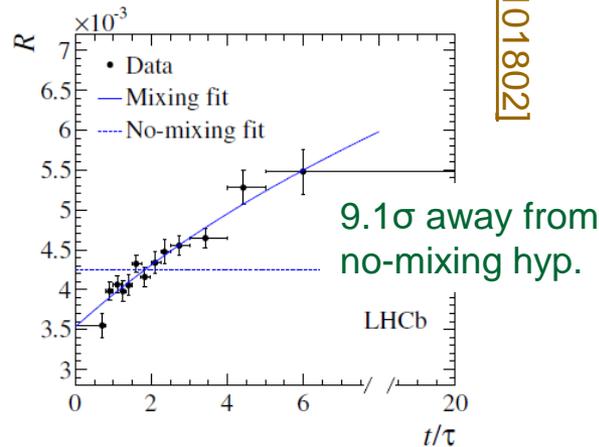
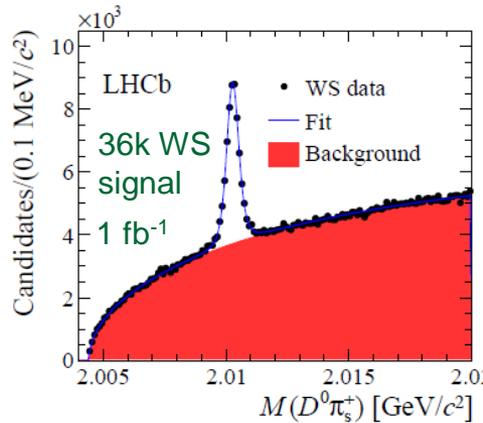
[BaBar, PRL 98 (2007) 211802]

Rise of the hadron machines

First observation of signal in single measurement required statistical muscle of hadron machines.. In 2013 LHCb & CDF published first ($>$) $>5\sigma$ measurements.

This is the WS/RS ratio vs. proper time.

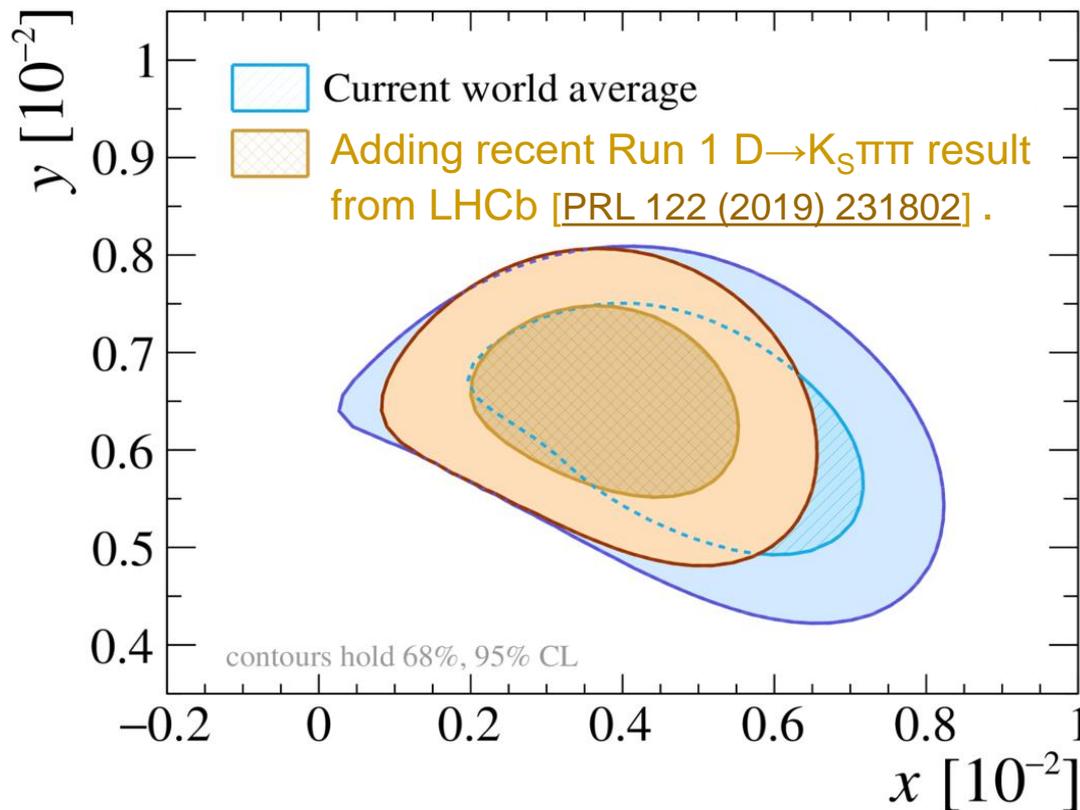
Linear slope comes from mixing-decay interference.



LHCb sample is a just small fraction of Run 1, but is order of magnitude larger than that of BaBar. These measurements also benefit from better time resolution.

Where are we now with charm mixing ?

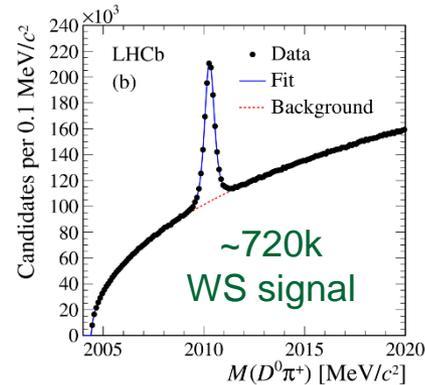
y_D is now reasonably well known, but x_D less so. In fact there is still only $\sim 3\sigma$ evidence that x_D is non zero. Important to improve our knowledge of x_D , as size of mixing parameters modulated size of any indirect CPV observable.



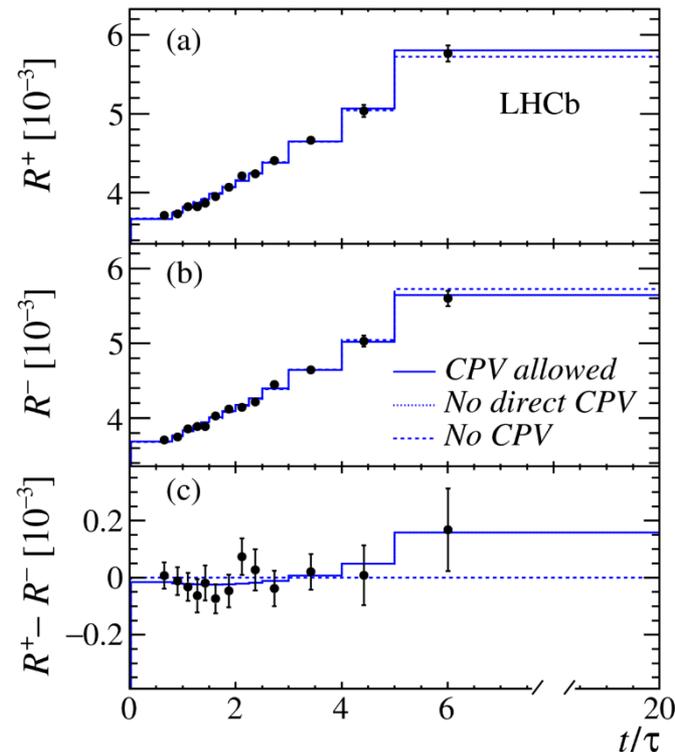
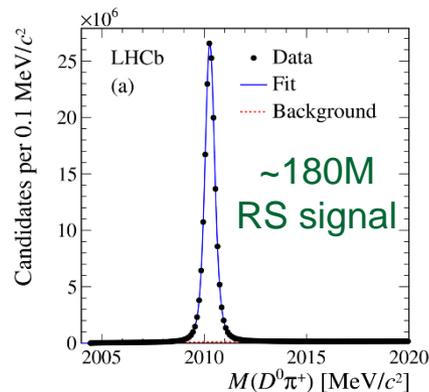
Search for indirect CPV in charm with Run 2 data

LHCb samples have grown rapidly, and now allow for high sensitivity searches for mixing-induced CPV, e.g. take WS $K\pi$ analysis used for mixing discovery, now updated with full Run 1 data & 2 fb^{-1} from Run 2, and study D^0 & D^0 bar separately.

Study ratio of WS
(i.e. $D^0 \rightarrow K^+ \pi^-$)...



...to RS
(i.e. $D^0 \rightarrow K^- \pi^+$),
vs. proper decay time



For D^0 ...

...and D^0 bar...

...and difference of both.

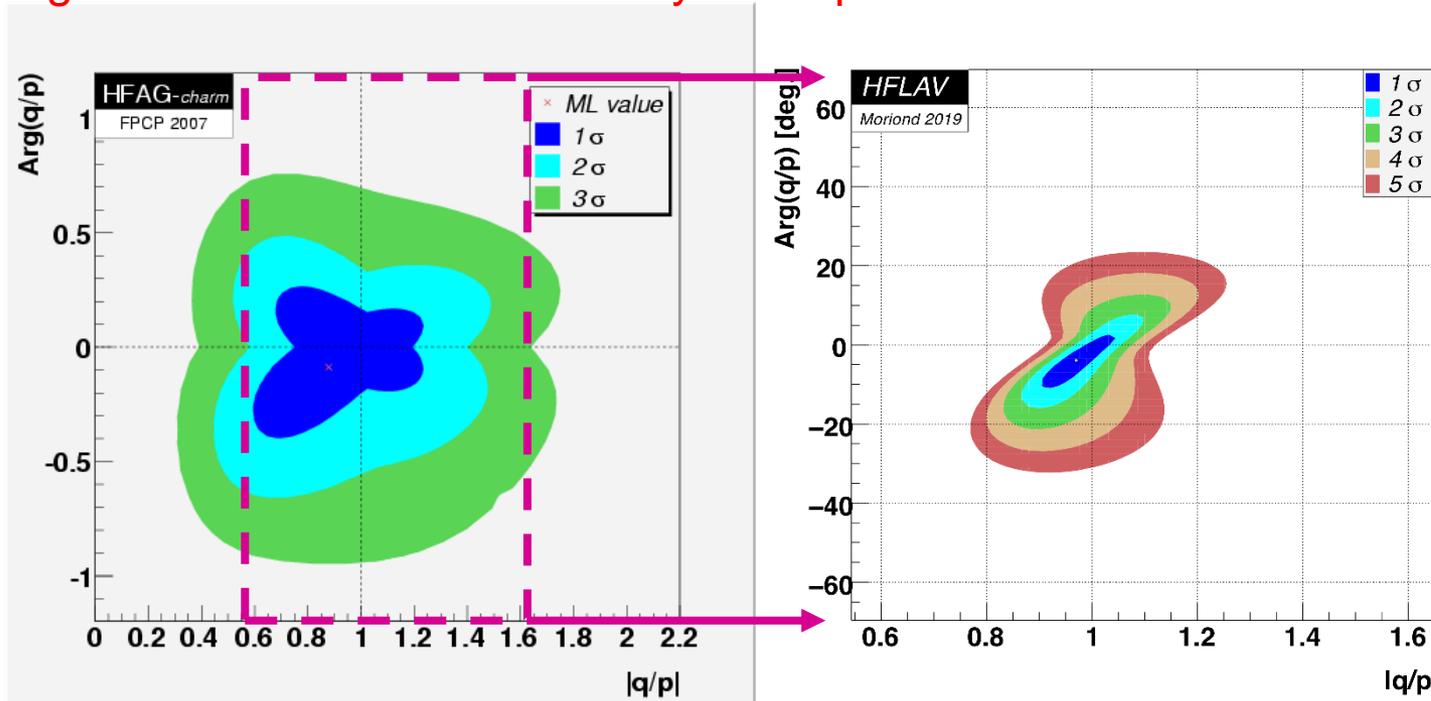
Difference flat \rightarrow no sign of indirect CPV (yet).

[PRD 97 (2018) 031101]

Search for indirect CPV in charm with Run 2 data

LHCb samples have grown rapidly, and now allow for high sensitivity searches for indirect CPV in charm. This is particularly true for the $D^0 \rightarrow \pi^+ \pi^-$ decay, where the difference between the two pions is flat, leading to no sign of indirect CPV (yet).

Significant increase in sensitivity since pre-LHC era...



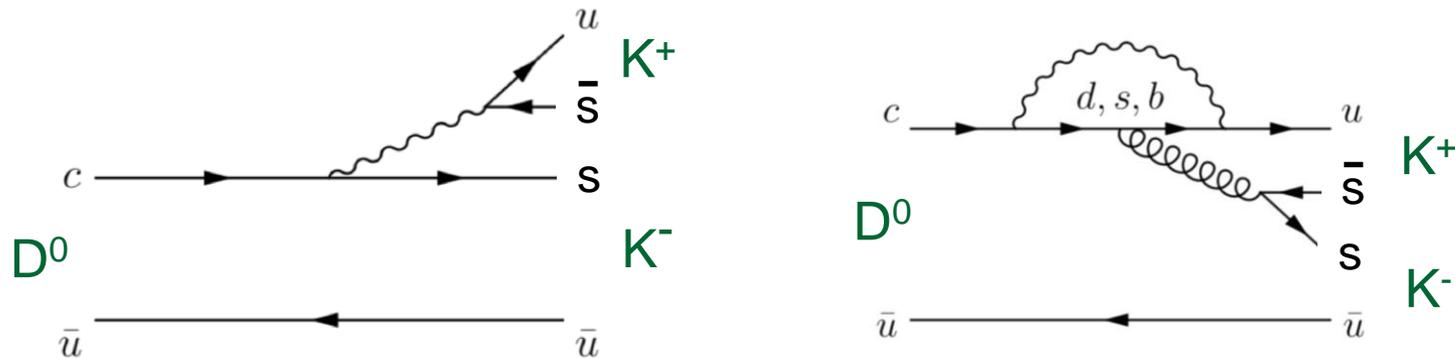
...now starting to approach the region where indirect CPV could lurk !

[PRD 97 (2018) 031101]

Difference flat → no sign of indirect CPV (yet).

Searches for direct CPV in charm

And what of direct CPV ? Recall we need (at least) two interfering diagrams, so we should pick a decays where leading tree diagram is not overwhelmingly dominant \rightarrow singly Cabibbo-suppressed (SCS) decays, e.g. $D^0 \rightarrow K^+ K^-$, $D^0 \rightarrow \pi^+ \pi^-$.



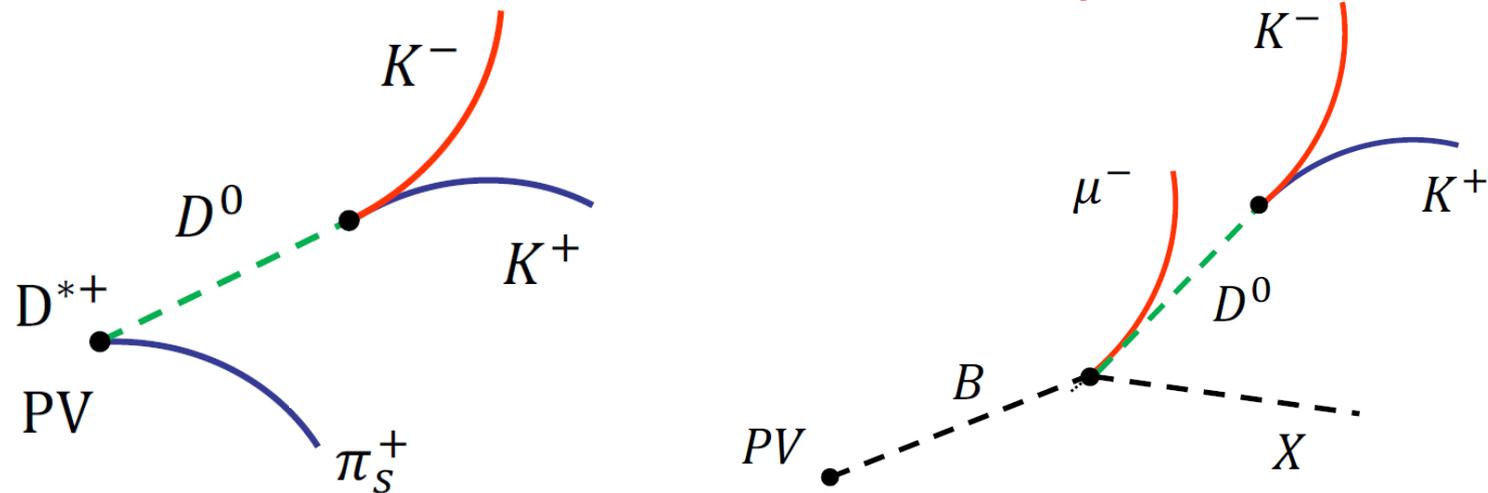
We measure an asymmetry

$$\mathcal{A}_{CP} = \frac{D^0 \rightarrow K^+ K^- - \bar{D}^0 \rightarrow K^+ K^-}{D^0 \rightarrow K^+ K^- + \bar{D}^0 \rightarrow K^+ K^-}$$

The meson is neutral, but we are interested in direct CPV, so measure the time-integrated asymmetry (still, possible residual indirect CPV effects must be accounted for in interpretation - a charged decay, e.g. $D^+ \rightarrow \pi^+ \pi^- \pi^+$, does not have this issue).

Direct CPV measurements – practical considerations

At the LHC can exploit two production modes, prompt (*i.e.* from primary interaction / vertex (PV)), or secondary (from B decay). Prompt is more abundant.



Furthermore, in prompt case, choose to reconstruct $D^{*+} \rightarrow D^0 \pi_S^+$ decays, as the charge of the ‘slow pion’ tags flavour (D^0 or D^0 bar) - needed to construct A_{CP} . In secondary case the tag comes from charge of muon in a semileptonic B decay.

Direct CPV measurements – practical considerations

When probing a sub-% A_{CP} , one must worry about sources of fake asymmetry that will contribute to raw value. So for D^* tagged events* & final state f :

$$\mathcal{A}_{\text{raw}}(f) = \mathcal{A}_{CP}(f) + \mathcal{A}_D(f) + \mathcal{A}_D(\pi_S) + \mathcal{A}_P(D^{*+})$$

what we
are after

detection
asymmetry
for final state

must be zero for
decays of D^0 into
two pseudoscalars !

detection
asymmetry
for slow pion

production asymmetry:
there can be different
numbers of D^{*+} and D^{*-}
produced in acceptance

Direct CPV measurements – practical considerations

When probing a sub-% A_{CP} , one must worry about sources of fake asymmetry that will contribute to raw value. So for D^* tagged events* & final state f :

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what we
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Consider A_{raw} for two final states: K^+K^- and $\pi^+\pi^-$:

- A_{CP} is not expected to be the same, as direct CP violation is final-state specific (indeed the naïve expectation if hadronic physics works just the same for both is that $A_{CP}(KK) = -A_{CP}(\pi\pi)$);
- But $A_D(\pi_S)$ & $A_P(D^{*+})$ is independent of final state, in given phase space region.

So measure ΔA_{CP} , the *difference* between the two raw asymmetries:

$$\Delta \mathcal{A}_{CP} \equiv \mathcal{A}_{\text{raw}}(KK) - \mathcal{A}_{\text{raw}}(\pi\pi) = \mathcal{A}_{CP}(KK) - \mathcal{A}_{CP}(\pi\pi)$$

taking care to weight samples so both have same distribution in phase space.

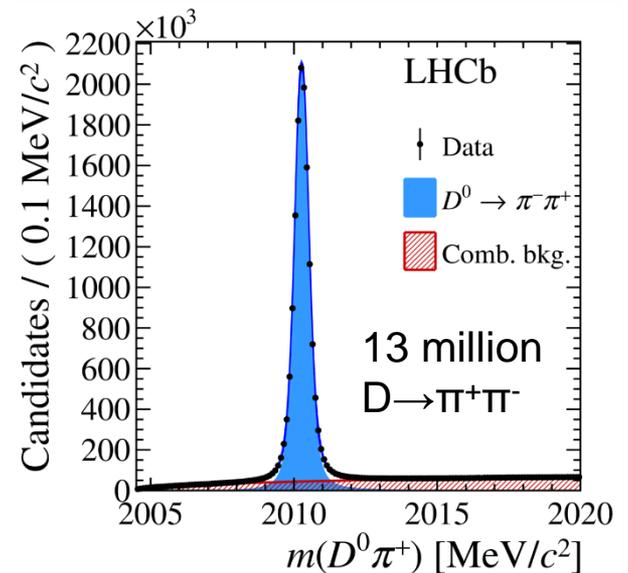
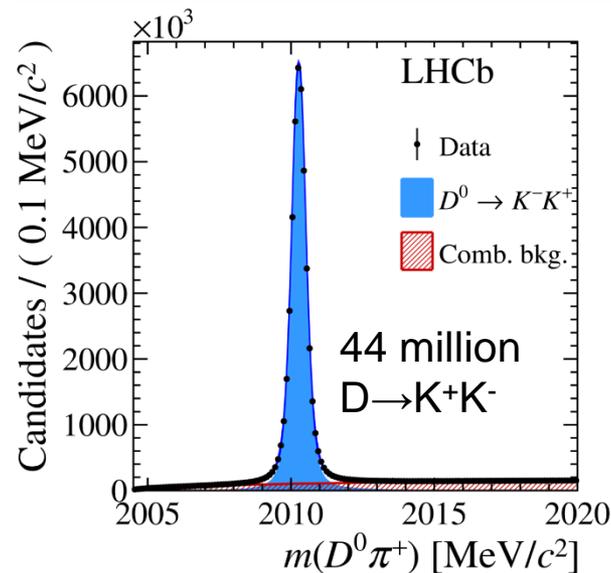
Dawn of a new era: observation of (direct) CPV in charm

[PRL 122 (2019) 211803]

ΔA_{CP} measurement, published earlier this year by LHCb, harnesses full statistical might of experiment, being first to use full Run 2 data set.

Method is intrinsically robust: e.g. syst. uncertainty on prompt analysis is $< 10^{-4}$.

Dull plots, because effect is tiny, and almost impossible to visualise



Run 1 +
Run 2



$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

5.3 σ
from 0 !

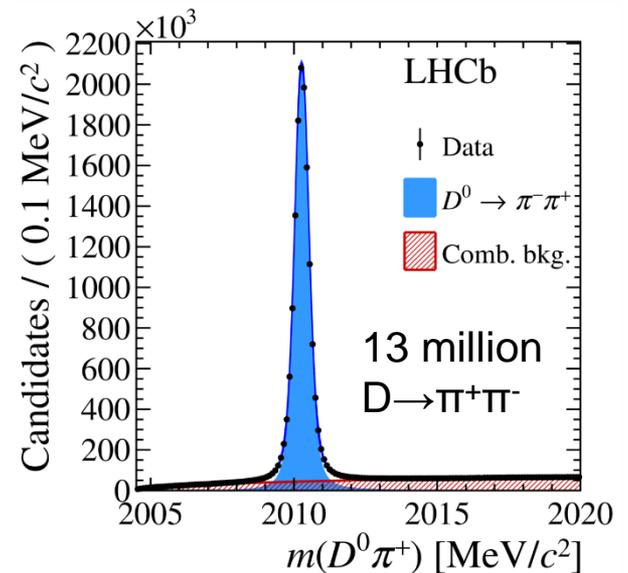
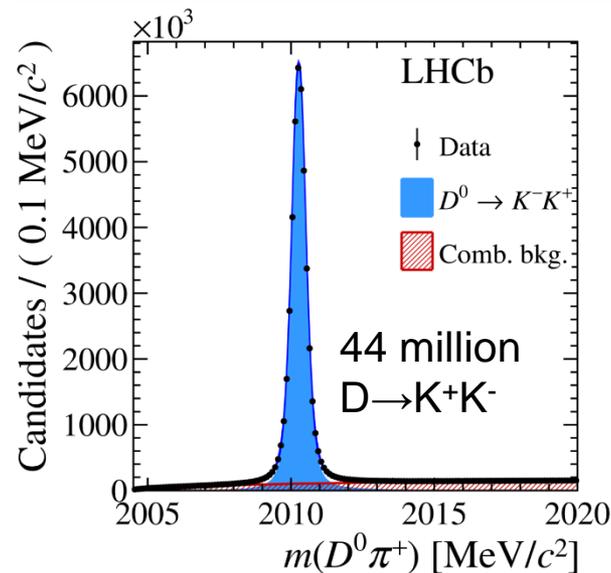
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Using indirect CPV constraints in these channels can deduce

$$\Delta a_{CP}^{\text{dir}} = (-15.7 \pm 2.9) \times 10^{-4}$$

i.e. direct CPV saturates result

Dawn of a new era: observation of (direct) CPV in charm

[PRL 122 (2019) 211803]

ΔA_{FB}^{ℓ} measurement published earlier this year by LHCb [https://arxiv.org/abs/1903.10490](#)

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- Is the size of the effect compatible with SM expectations, or is it too high, indicating possible NP contributions ?
The theoretical community is (inevitably) divided.
(e.g. compare [\[Chala, Lenz, Rusov & Scholz arXiv:1903.10490\]](#) with [\[Grossman and Schacht arXiv:1903.10952\]](#))
- Next tasks for experiment: measure individual asymmetries & intensify searches in other modes.
A very exciting programme lies ahead !
- Charm is certainly no longer the 'poor relation' of flavour physics !

Using indirect CPV constraints in these channels can deduce

$$\Delta a_{CP}^{\text{dir}} = (-15.7 \pm 2.9) \times 10^{-4}$$

i.e. direct CPV saturates result

Future of flavour

Why persevere with flavour studies ?

Devil's advocate: given that CKM mechanism does a good job, and given that we have observed $B^0_s \rightarrow \mu\mu$ at (roughly) the right BR, why continue?

The big picture answer:

- The SM is incomplete;
- Many of the mysteries in the SM (& the cosmos) are related to flavour;
- Flavour observables can probe much higher mass scales than direct searches

And some specific considerations:

- We *know* there are important phenomena still to be observed (e.g. mixing-induced CPV in B^0_s system, mixing related CPV in charm, $B^0 \rightarrow \mu\mu$ etc.);
- Similarly, there are many important measurements that can be made, which are unfeasible with current sample sizes (e.g. electroweak Penguin studies with $b \rightarrow dl^+l^-$ decays, or precise study of P_5' with $B^0 \rightarrow K^* e^+ e^-$);
- A very large number of current 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^*} , $BR(B^0_s \rightarrow \mu\mu)/BR(B^0 \rightarrow \mu\mu)$ etc);
- A rich field where surprises are guaranteed (e.g. no one was expecting charm mixing, direct charm CPV, the X(3872), pentaquarks...).

Unwise to assume $\sim 10\%$ (or even 0.1%) is 'good enough'

Courtesy Browder
and Soni

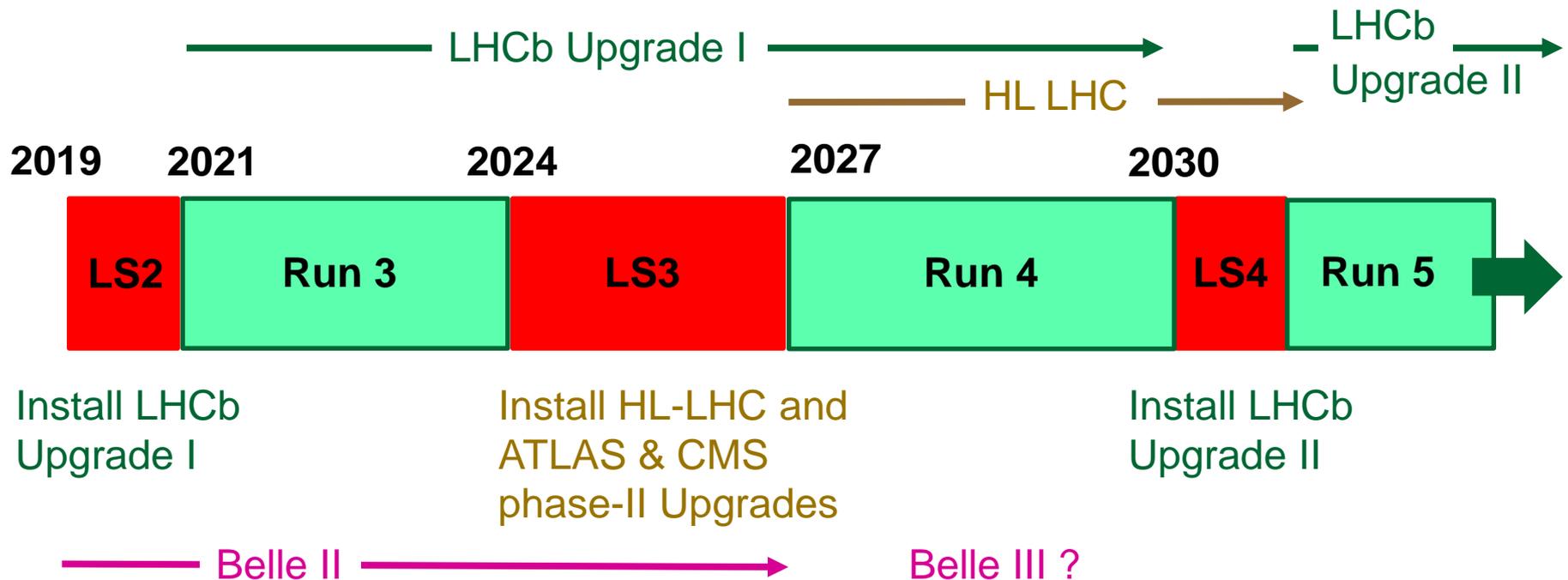
"A special search at Dubna was carried out by E. Okonov and his group. They did not find a single $K_L \rightarrow \pi^+ \pi^-$ event among 600 decays into charged particles [12] (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the Lab. The group was unlucky."

-Lev Okun, "The Vacuum as Seen from Moscow"

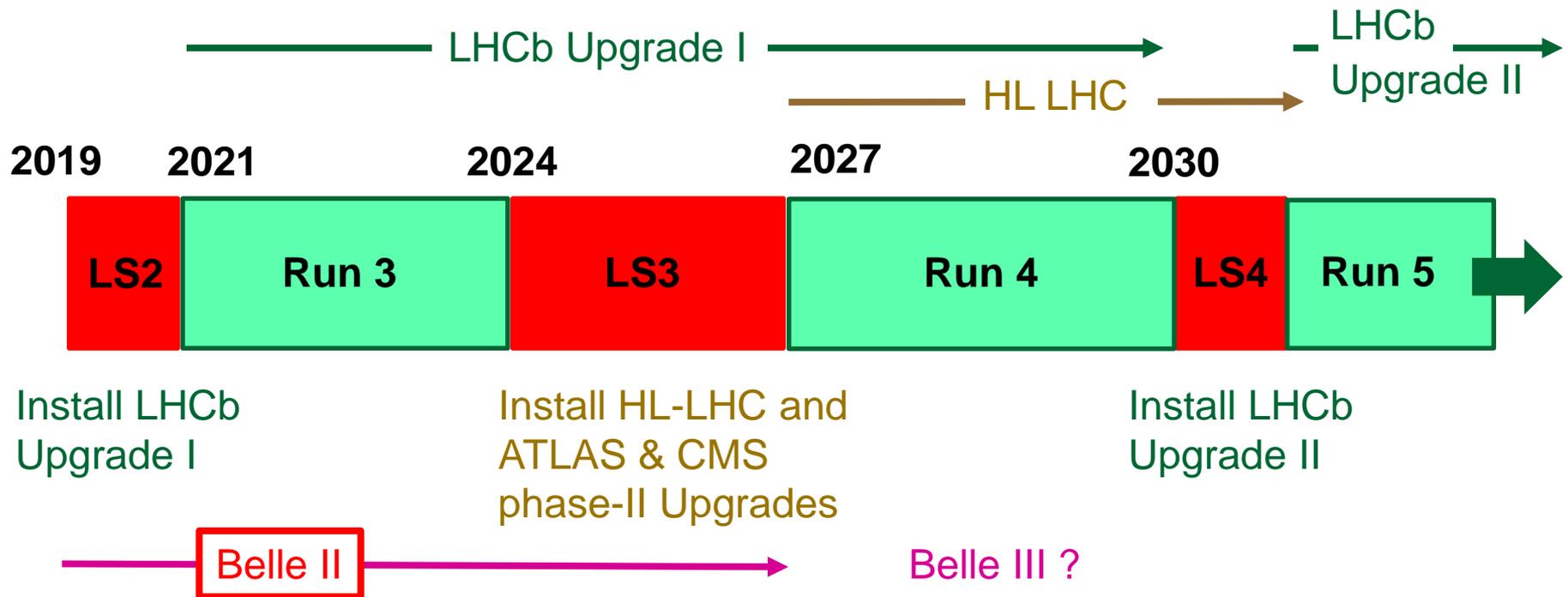
$$\text{BR}(K_L^0 \rightarrow \pi\pi) \sim 2 \times 10^{-3}$$

Cronin, Fitch *et al.*, 1964

The LHC schedule – current planning



The LHC schedule – current planning

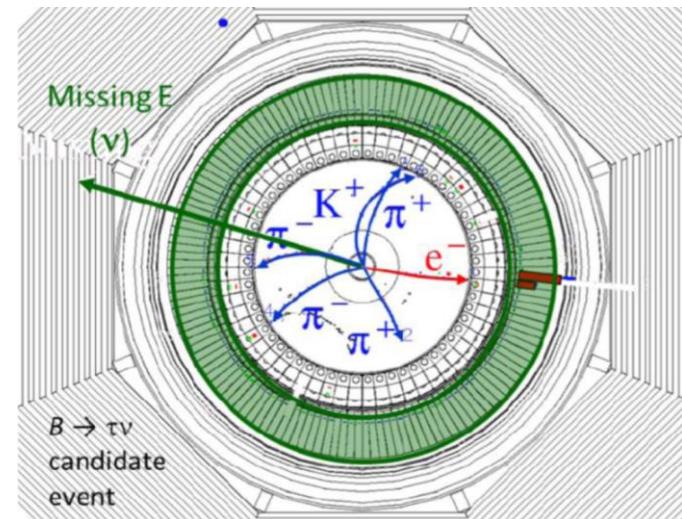
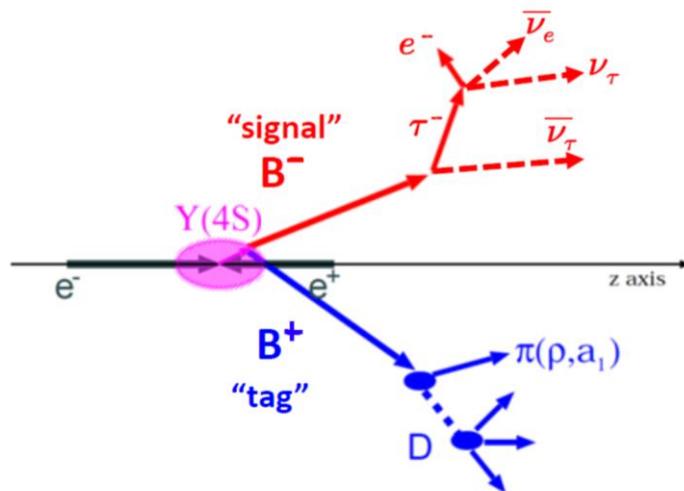


Why Belle II ?

B production at the $Y(4S)$ presents several advantages over hadron environment

- Can reconstruct full event, which is beneficial for missing energy modes and also inclusive measurements (typically lower theory uncertainties).

e.g. $B \rightarrow \tau \nu$

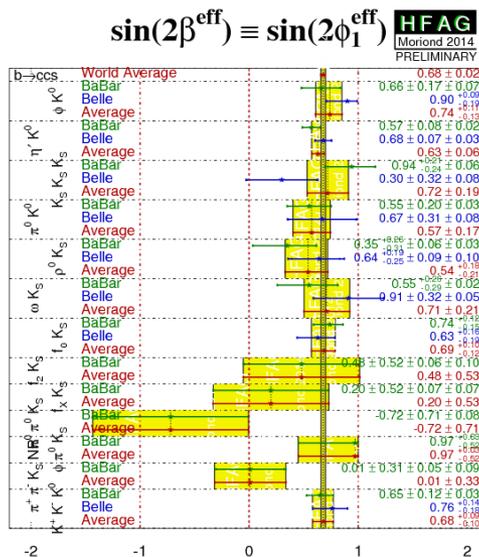


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- Low multiplicity environment permits excellent performance for final states with π^0 s, η 's, photons. Also, good efficiency for long-lived particles K_S and K_L .

e.g. most modes suitable for $\sin 2\beta$ measurements involving Penguin loops ($b \rightarrow c\bar{c}b s$) are rather tough at LHCb...



...and other important decays e.g. $D^0 \rightarrow \gamma\gamma$, $B^0 \rightarrow \pi^0\pi^0$... are essentially inaccessible.

Why Belle II ?

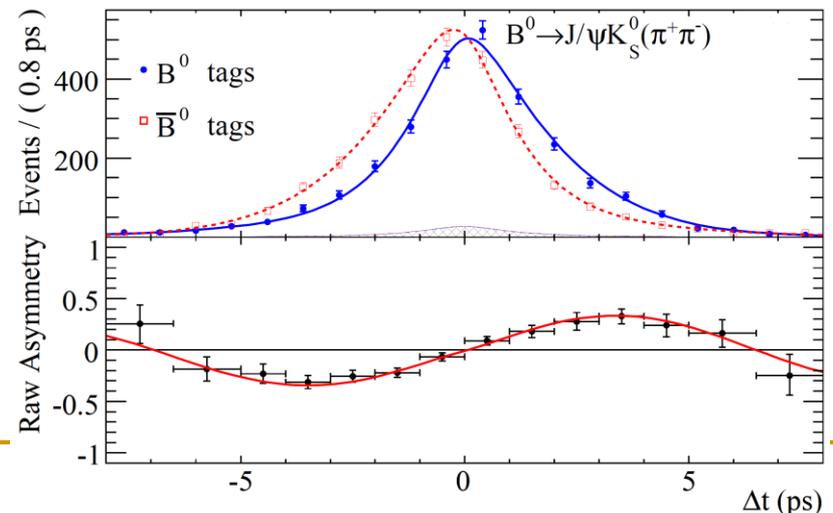
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- Can reconstruct full event, which is beneficial for missing energy modes and also inclusive measurements (typically lower theory uncertainties).
- Low multiplicity environment permits excellent performance for final states with π^0 s, η 's, photons. Also, good efficiency for long-lived particles K_S and K_L .
- Coherent $B^0\bar{B}^0$ production at Y(4S) makes flavour tagging easier and compensates for lower sample sizes in time-dependent CP measurements

e.g. in $\sin 2\beta$ measurement
with $B^0 \rightarrow J/\psi K_S$

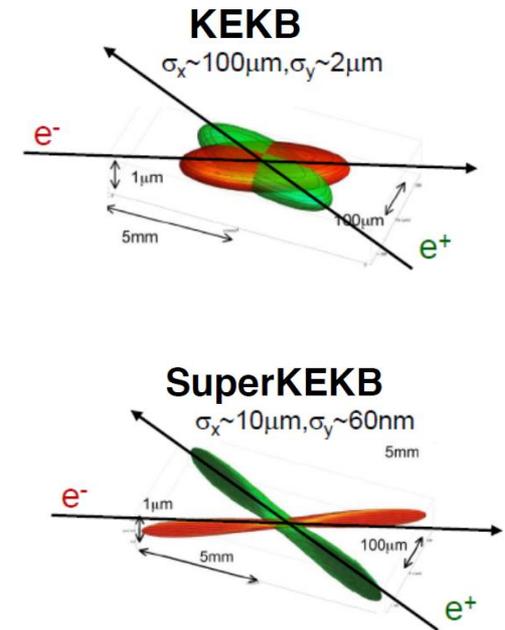
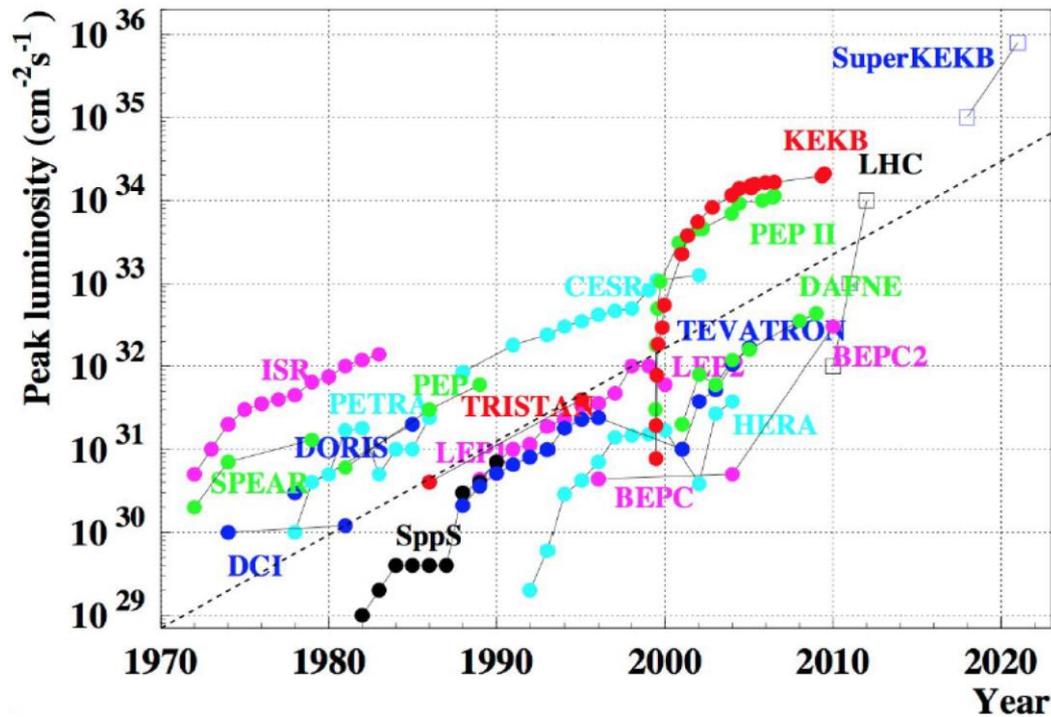
ε (tag effective) BaBar $\sim 31\%$
[PRD 79 (2009) 072009]

ε (tag effective) LHCb $\sim 3\%$
[PRL 115 (2015) 031601]



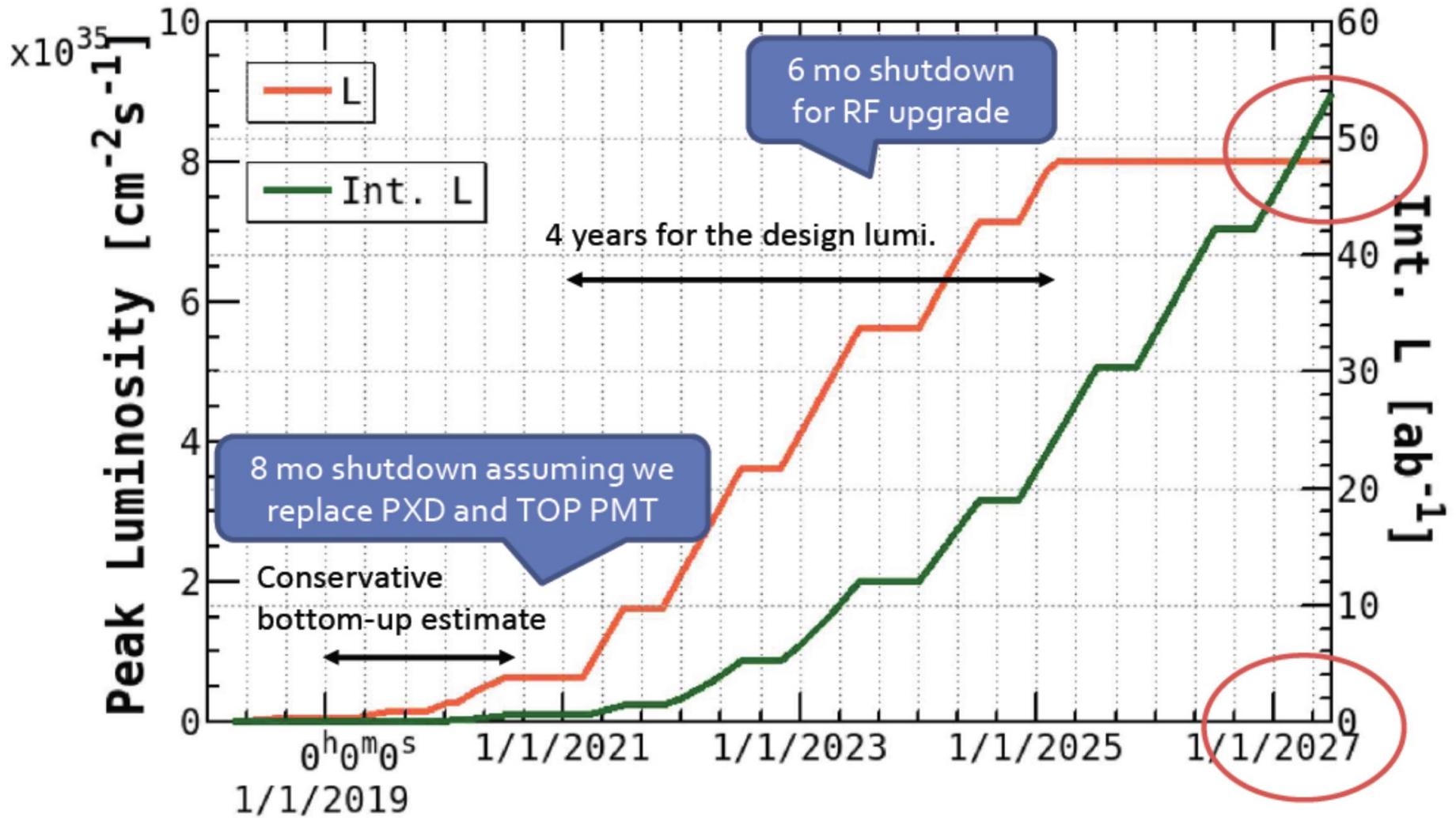
SuperKEKB

SuperKEKB goals: luminosity of $8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ and 50 ab^{-1} by 2027



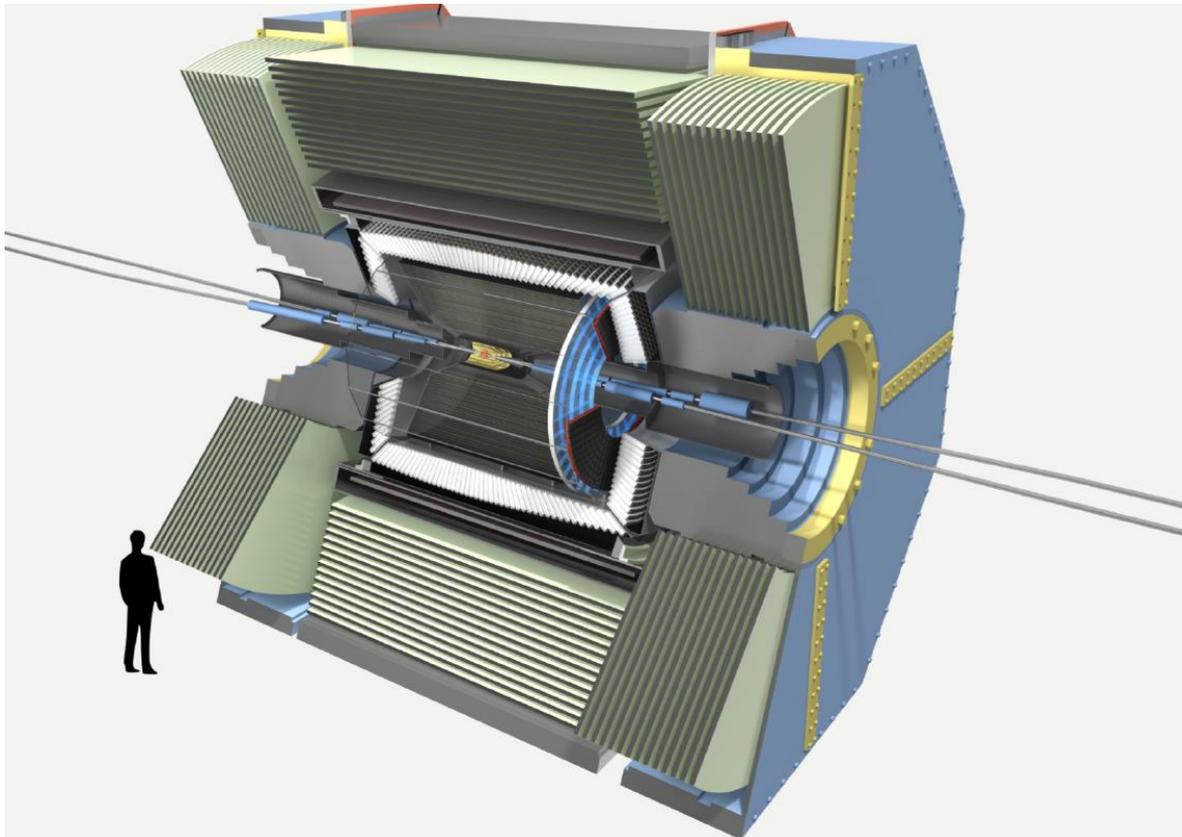
An ambitious 40-fold increase in luminosity on KEKB, to be achieved by squeezing the beams by $\sim 1/20$ and doubling the currents.

SuperKEKB and Belle II roadmap

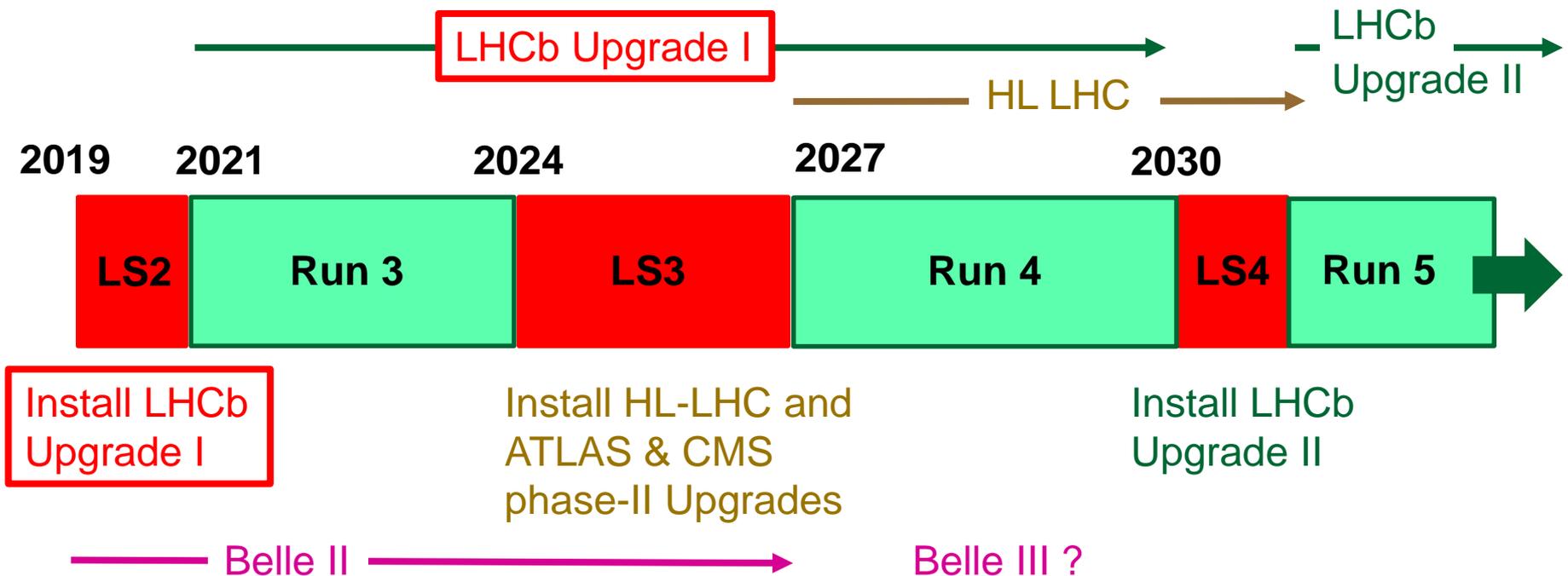


Belle II detector

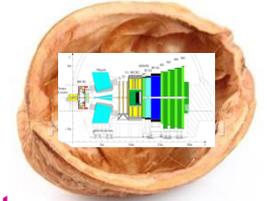
All sub-detectors upgraded from Belle, except for ECL crystals and part of the barrel KLM



The LHC schedule – current planning



LHCb Upgrade 1 (LS2) in a nutshell



Indirect search strategies for New Physics, e.g. precise measurements & the study of suppressed processes in the flavour sector become ever-more attractive following the experience of Runs 1 & 2 that direct signals are elusive

Our knowledge of flavour physics has advanced spectacularly thanks to LHCb. Maintaining this rate of progress beyond Run 2 requires significant changes.

The LHCb Upgrade

- 1) Full software trigger
 - Allows effective operation at higher luminosity
 - Improved efficiency in hadronic modes
- 2) Raise operational luminosity to $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

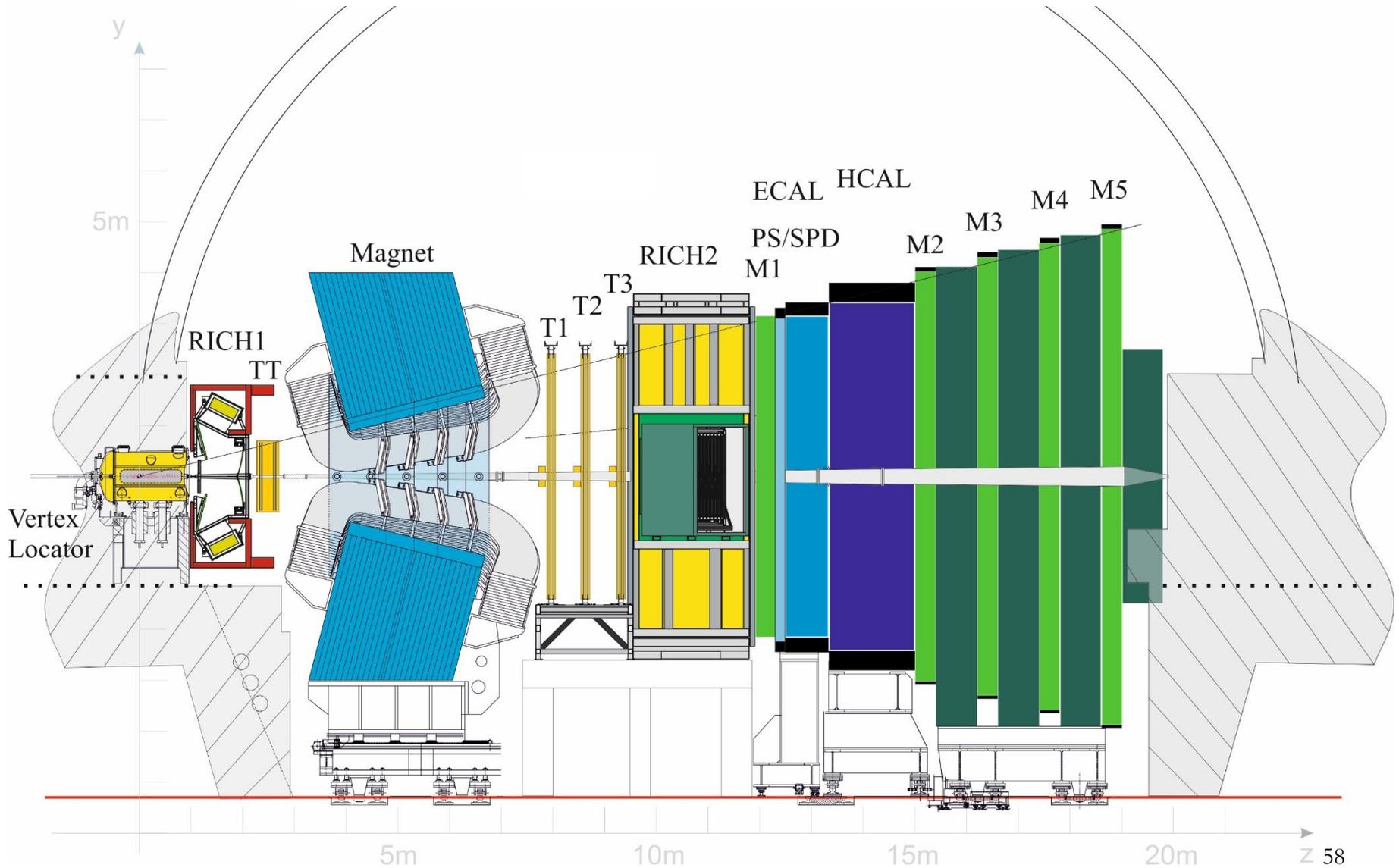
Necessitates redesign of several sub-detectors & overhaul of readout

Huge increase in precision: Upgrade + Run 2 yield in hadronic modes ~ 60x that of Run 1; also perform studies beyond the reach of the current detector.



Flexible trigger and unique acceptance also opens up opportunities in other topics apart from flavour ('a general purpose detector in the forward region').

Run 1 & 2 detector



Required modifications

Full s/w trigger →

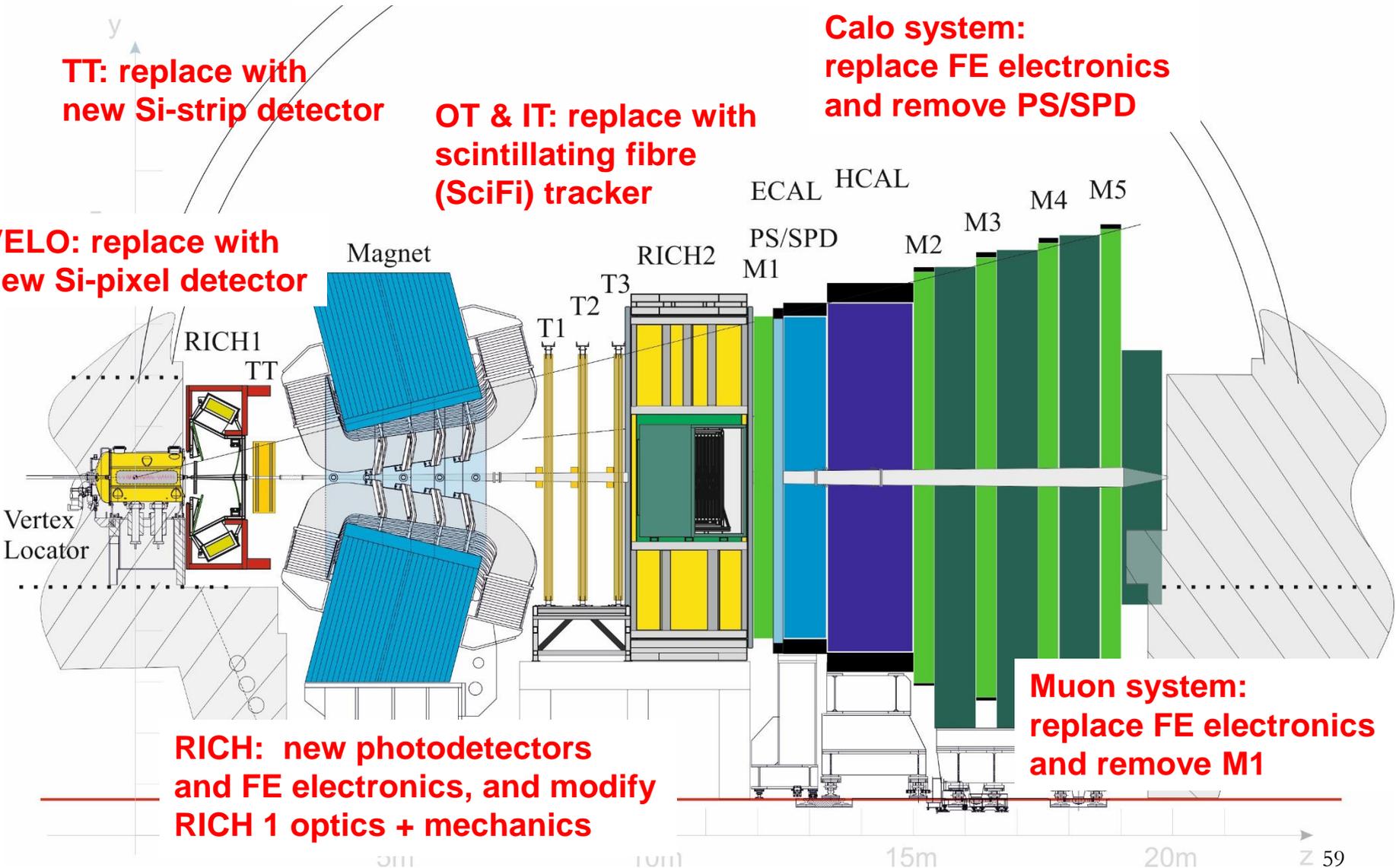
Replace read-out boards and DAQ

TT: replace with new Si-strip detector

OT & IT: replace with scintillating fibre (SciFi) tracker

Calo system: replace FE electronics and remove PS/SPD

VELO: replace with new Si-pixel detector

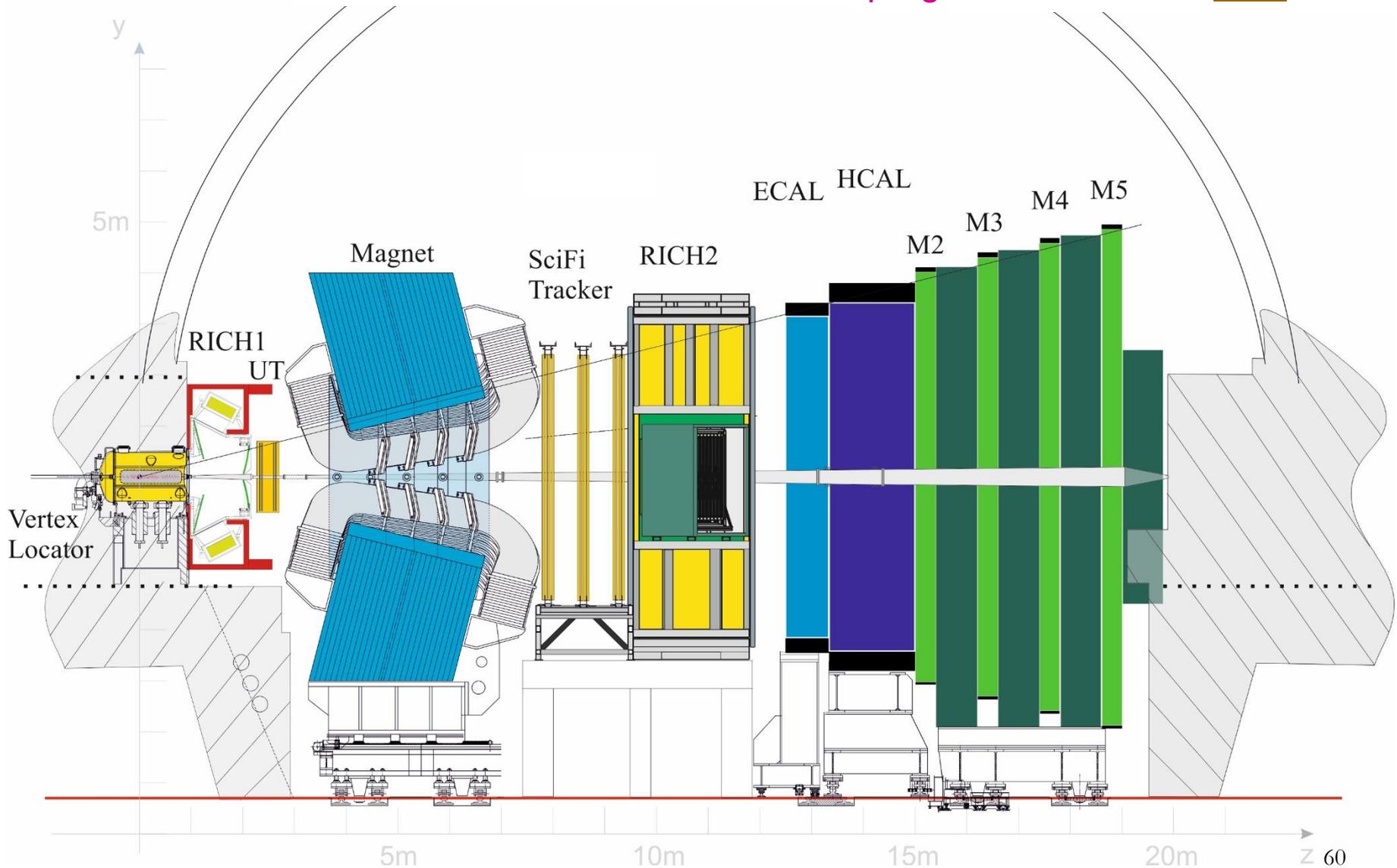


RICH: new photodetectors and FE electronics, and modify RICH 1 optics + mechanics

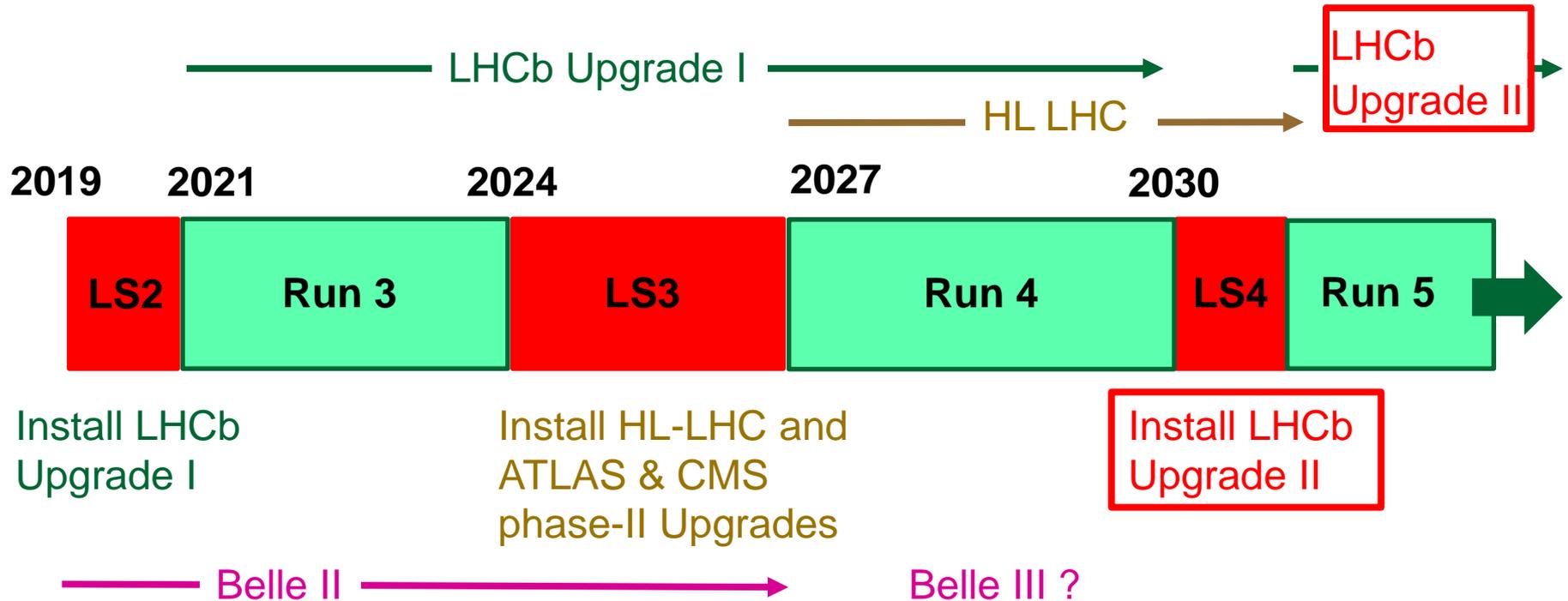
Muon system: replace FE electronics and remove M1

Upgrade I detector

Installation is occurring in LS2, *i.e.* right now! For monthly progress videos look [here](#).



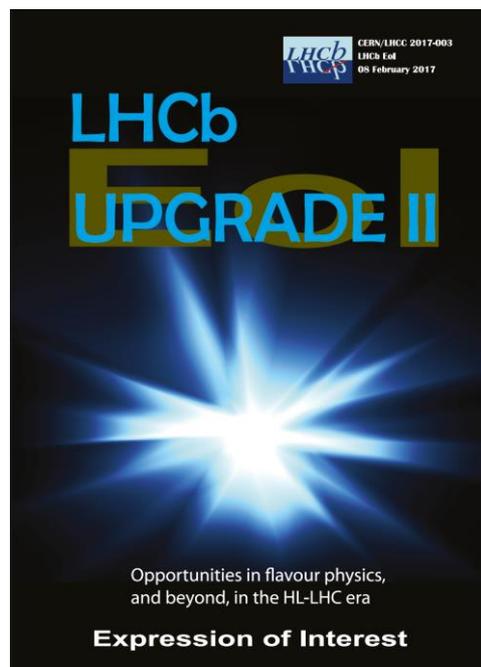
The LHC schedule – current planning



LHCb Upgrade II – the ultimate LHC flavour experiment

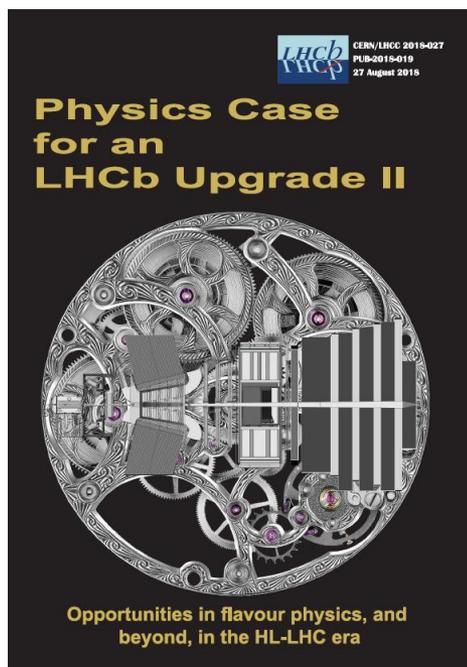
Begin after LS4 (2030). Operate at up to $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ & collect (at least) 300 fb^{-1} .

Expression of interest



[[CERN-LHCC-2017-003](#)]

Full physics case



[[CERN-LHCC-2018-027](#),
also [arXiv:1808.08865](#)]

In parallel, many studies from the machine side, summarised in a report which identifies

“a range of potential solutions for operating LHCb Upgrade II at a luminosity of up to $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and permitting the collection of 300 fb^{-1} or more at IP8 during the envisaged lifetime of the LHC”

[[CERN-ACC-NOTE-2018-038](#)]

LHCb Upgrade II – the ultimate LHC flavour experiment

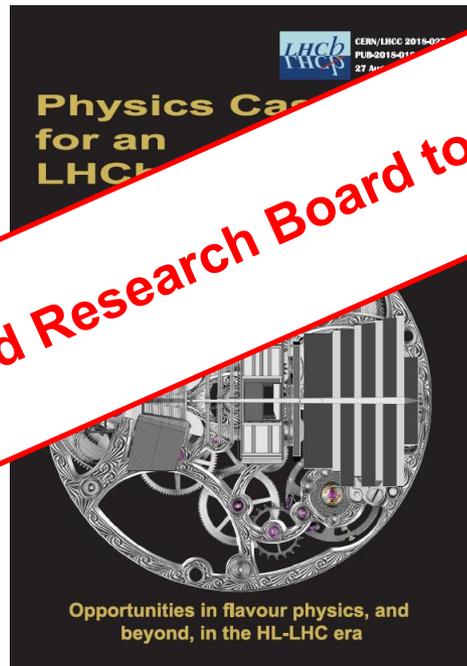
Begin after LS4 (2030). Operate at up to $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ & collect (at least) 300 fb^{-1} .

Expression of interest



[[CERN-LHCC-2017-003](#)]

Full physics case

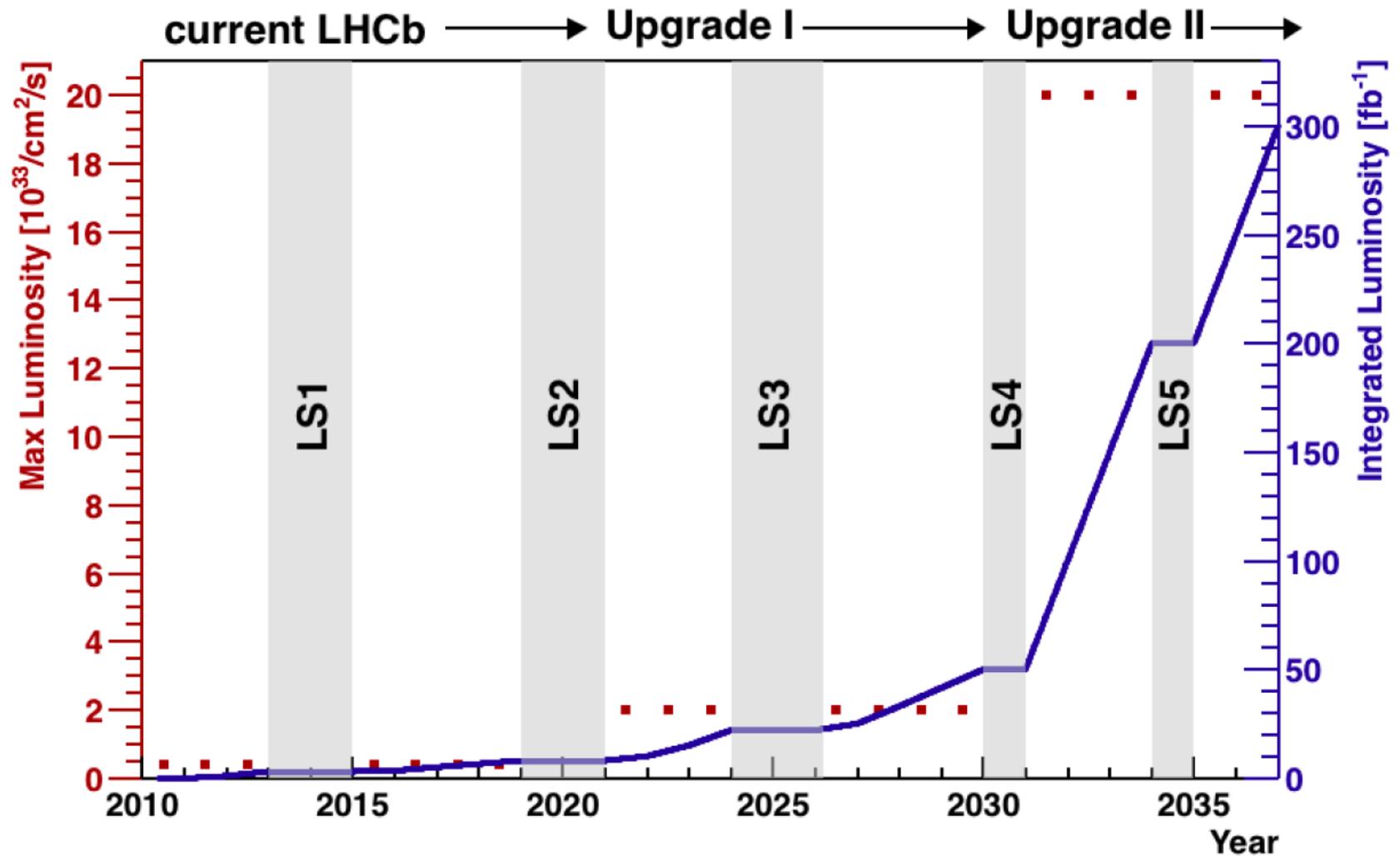


[[CERN-LHCC-2018-027](#), also [arXiv:1808.08865](#)]

In parallel studies from the LHCb Upgrade II physics case, the LHCb Upgrade II identifies a range of potential solutions for operating LHCb Upgrade II at a luminosity of up to $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and permitting the collection of 300 fb^{-1} or more at IP8 during the envisaged lifetime of the LHC”

[[CERN-ACC-NOTE-2018-038](#)]

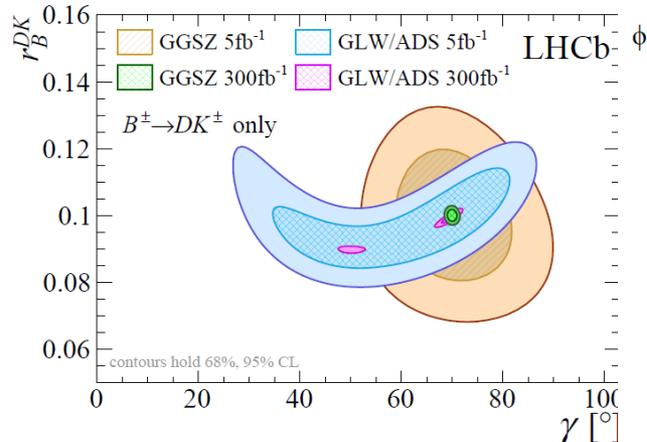
LHCb Upgrade II – the ultimate LHC flavour experiment



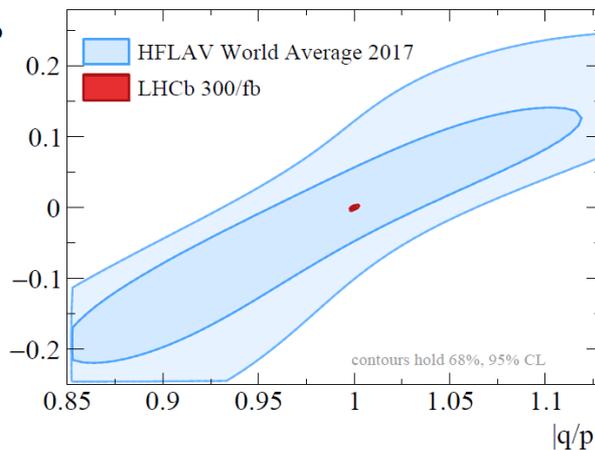
Upgrade-II physics highlights

Too much to cover – here are a few examples:

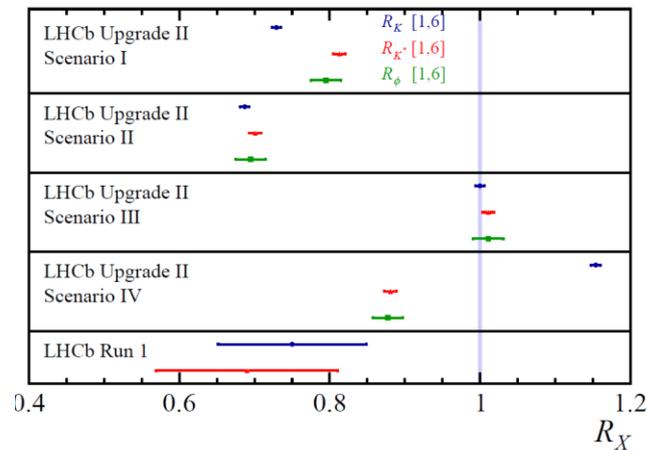
γ determination:
sub-degree precision



CPV in charm
down to 10^{-5}



Resolving New Physics
models with R_K and friends



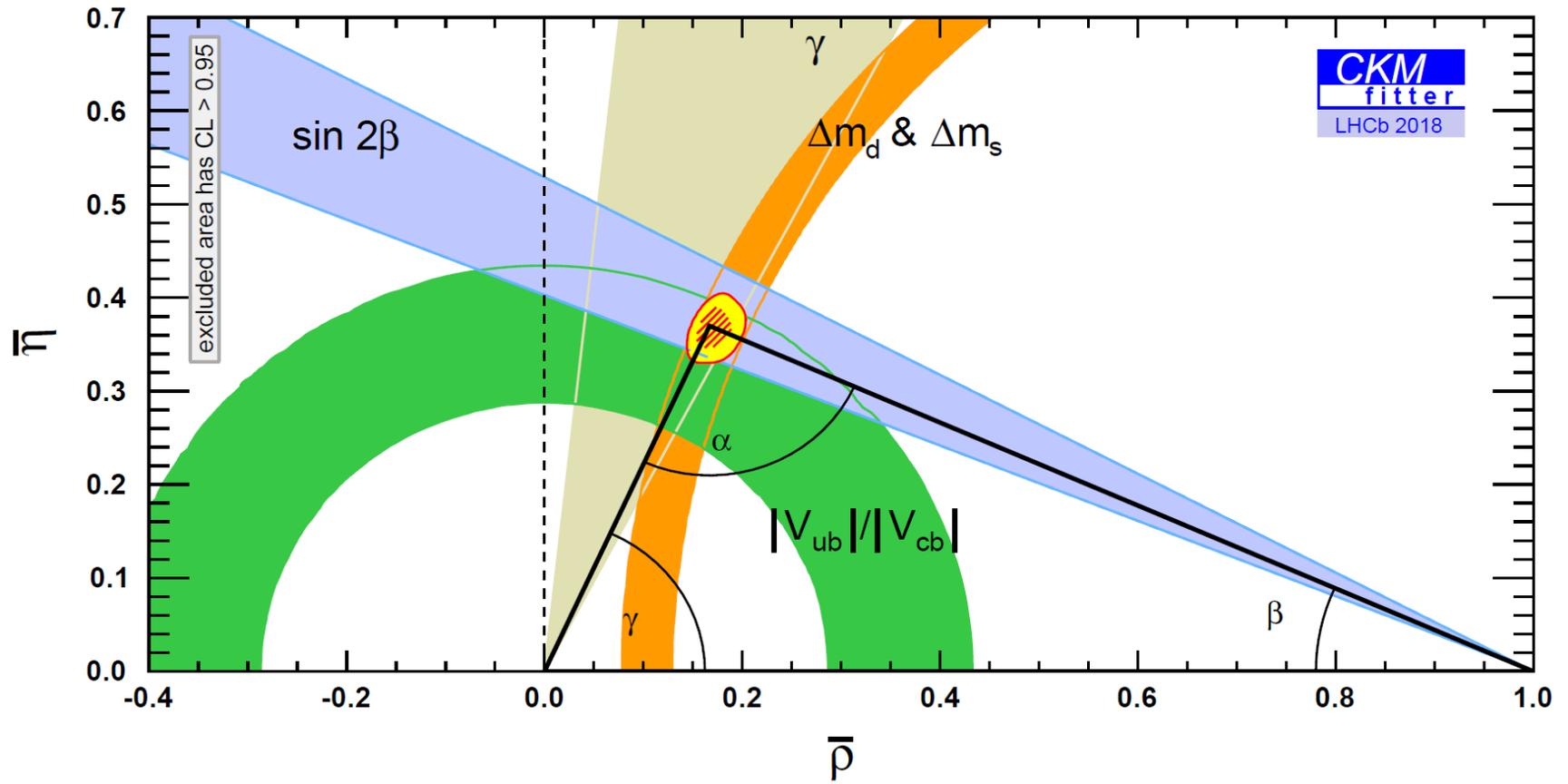
Two key points:

- Many key theoretically clean observables will remain statistics limited even after Upgrade I (e.g. γ , φ_s , $\sin 2\beta$, R_K and friends, $B(B^0 \rightarrow \mu\mu)/B(B_s \rightarrow \mu\mu)$...)
- Also, will be able to access new observables e.g. angular studies of $b \rightarrow de^+e^-$.

This will enable great advances in CPV tests, and will give an almost doubling of the New Physics mass scale (w.r.t. start of HL-LHC era) to which we are sensitive.

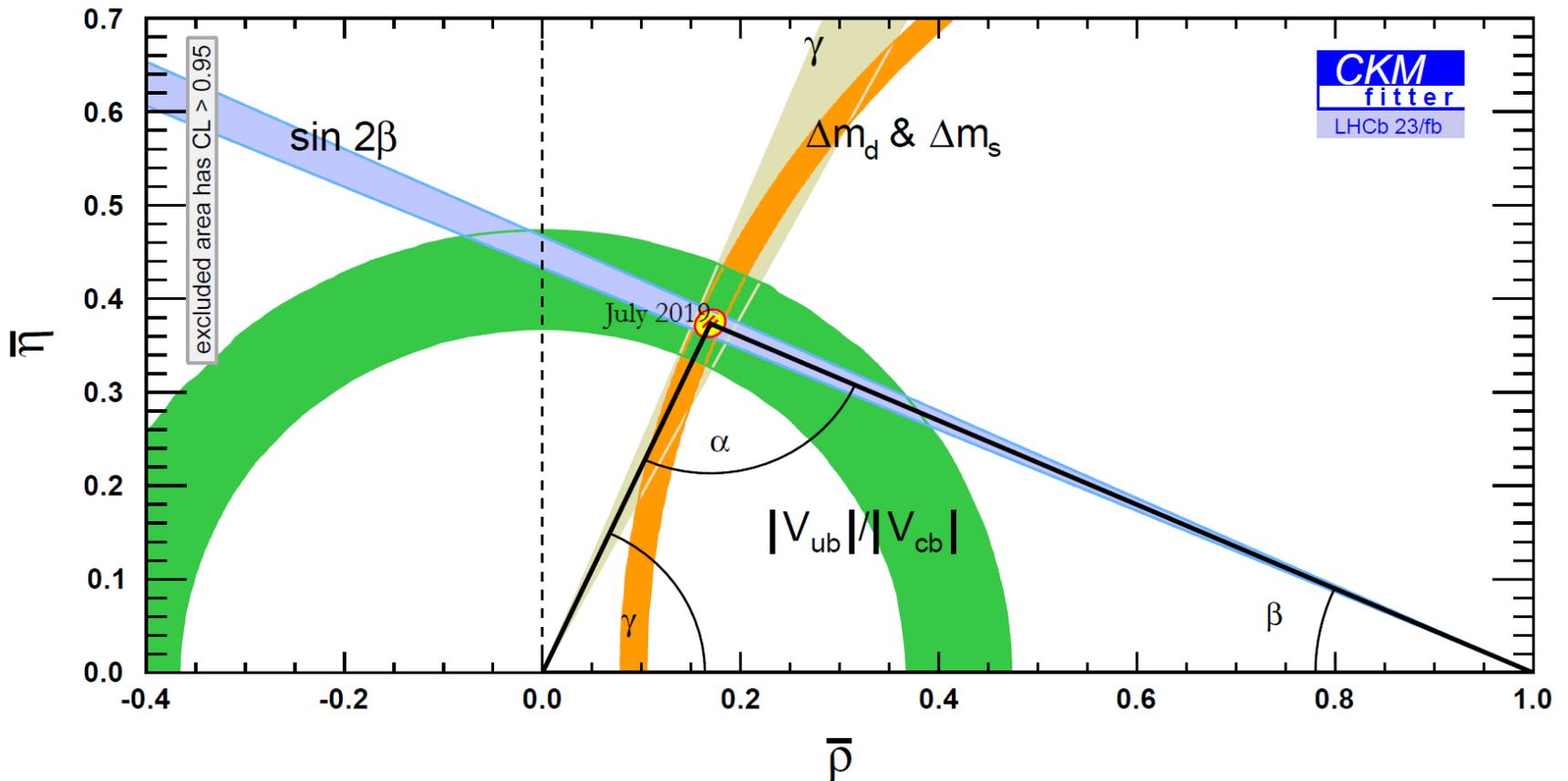
Evolution of constraints on Unitarity Triangle

UT plotted using constraints from LHCb alone (+ lattice QCD): current status



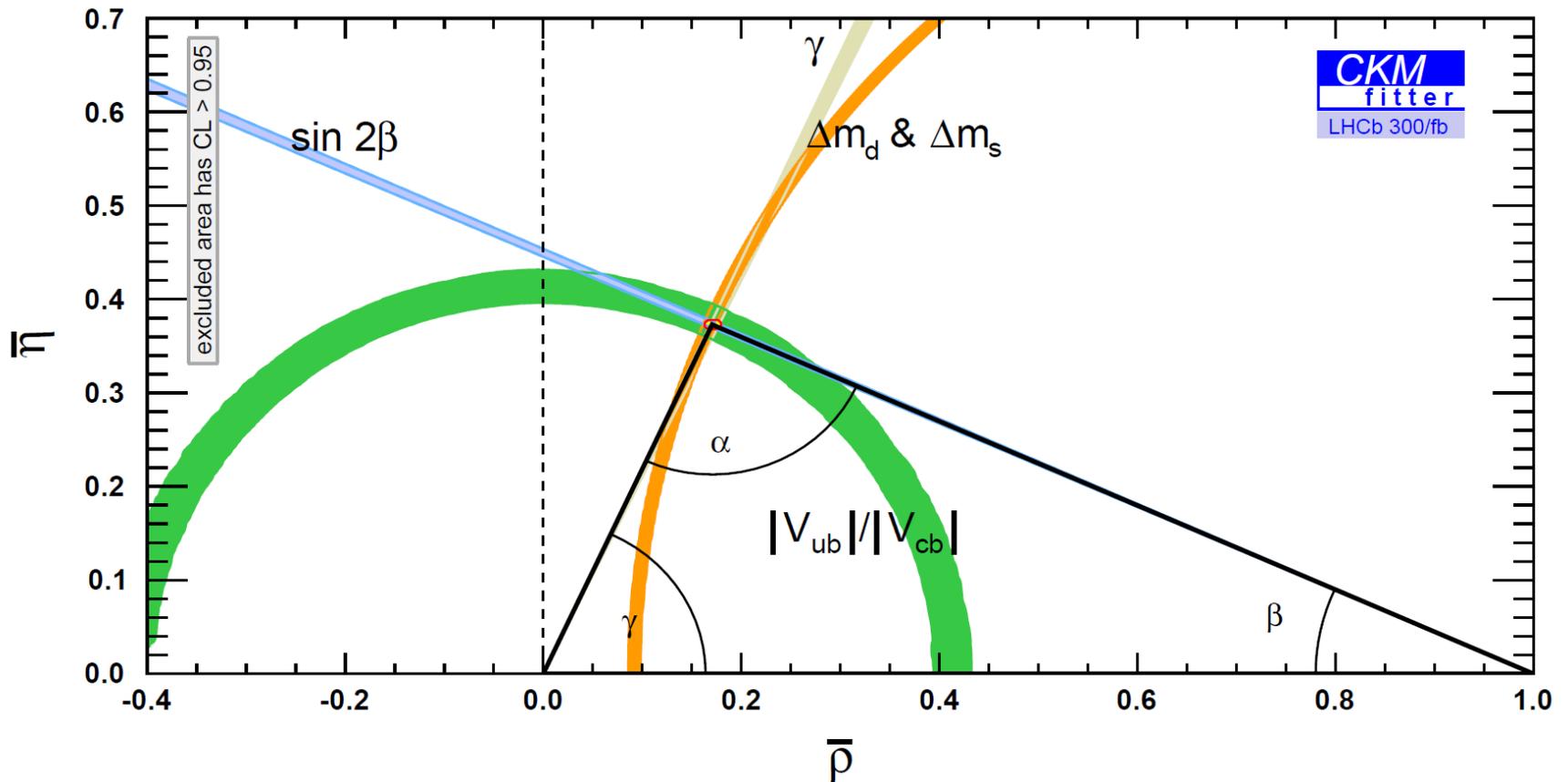
Evolution of constraints on Unitarity Triangle

UT plotted using constraints from LHCb alone (+ lattice QCD): start of HL-LHC

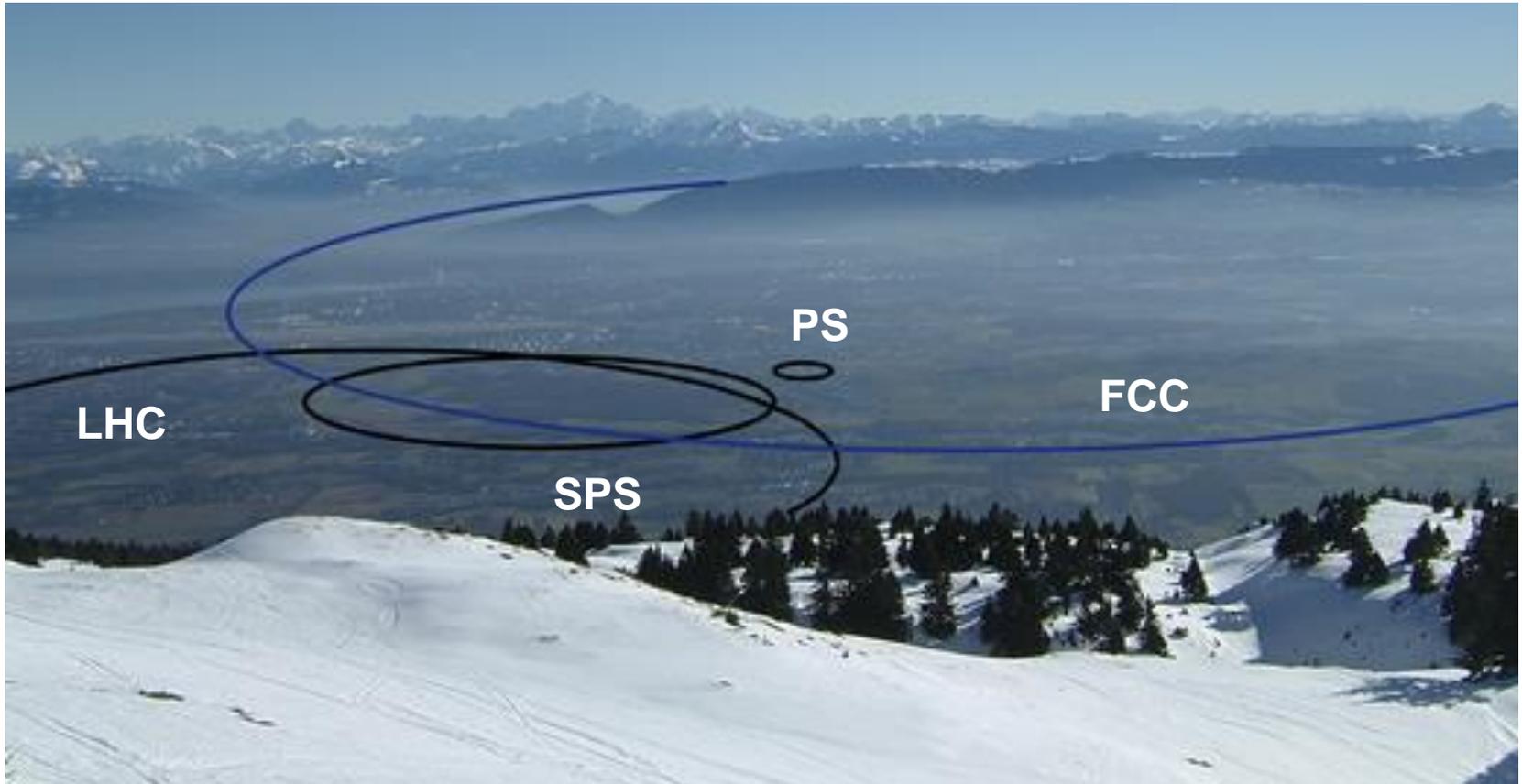


Evolution of constraints on Unitarity Triangle

UT plotted using constraints from LHCb alone (+ lattice QCD): after Upgrade II



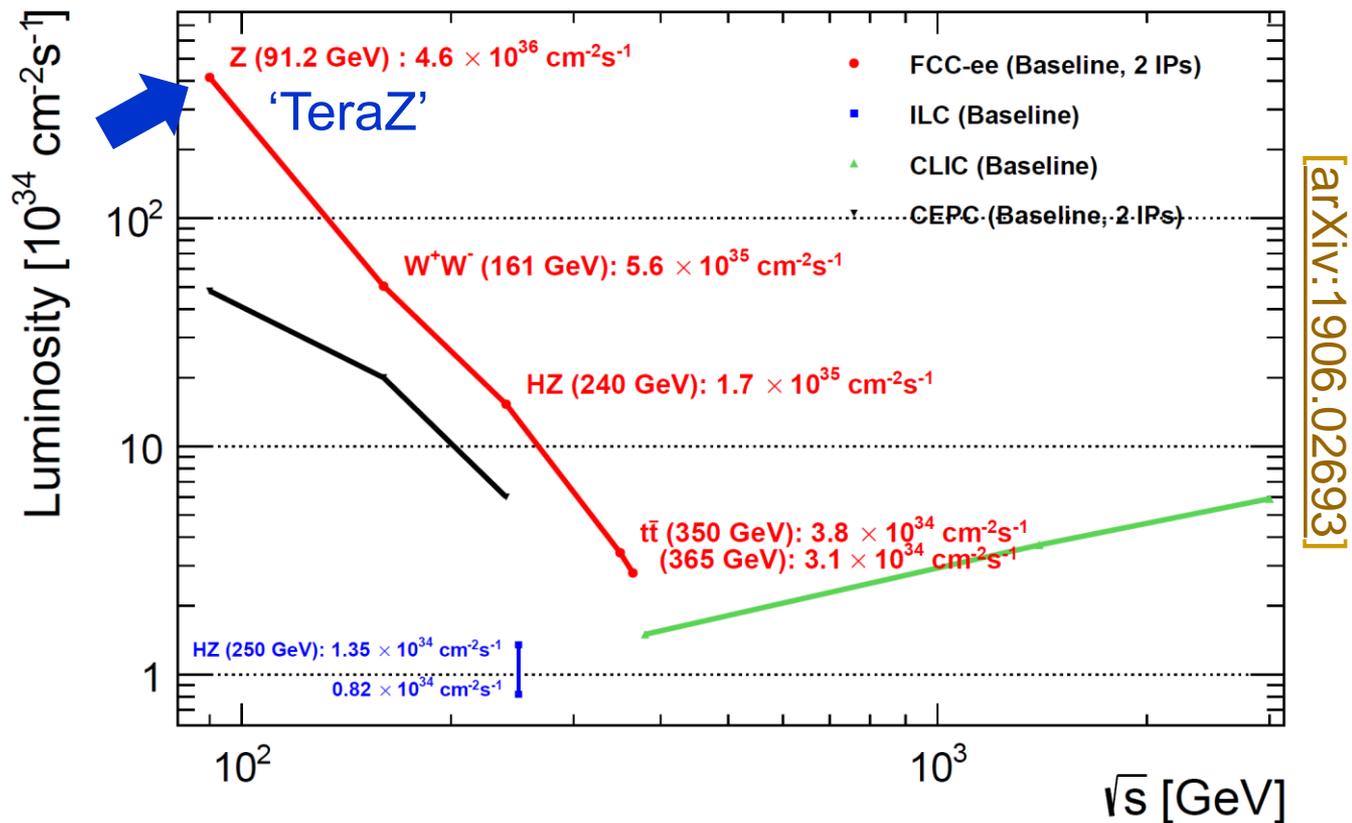
Opportunities at the Z pole: FCC-ee



FCC-ee is a proposed e^+e^- collider for 2039→ that would run at the Z pole (91 GeV), WW threshold (161 GeV), HZ energies (240 GeV), ttbar energies (350 & 365 GeV). (CEPC is a parallel Chinese project, with shorter timescale & ~lower design lumi.).

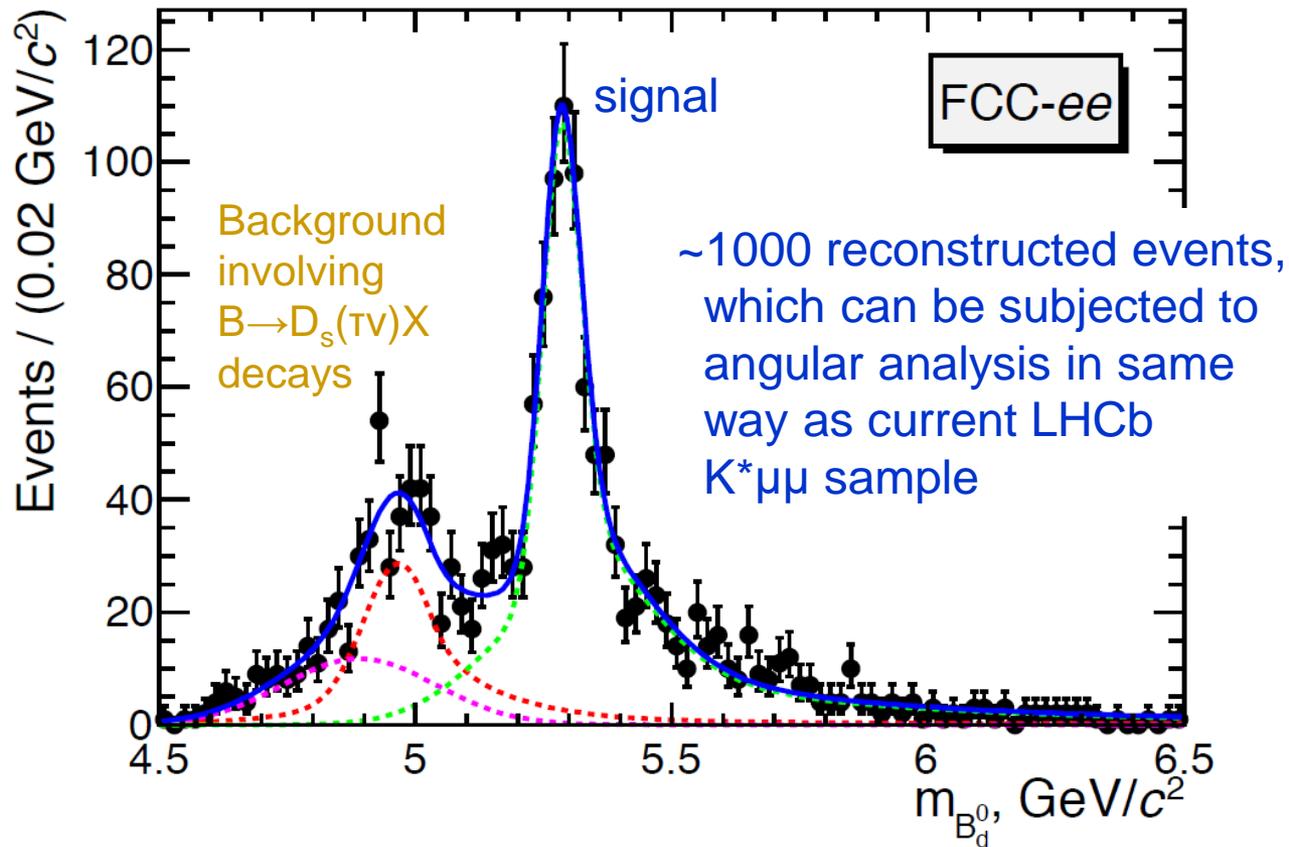
Opportunities at the Z pole: FCC-ee

FCC-ee was initially conceived as a facility for precision-Higgs physics, but it could also operate at Z^0 with ultra-high luminosity (10^5 [!] above LEP). Extremely interesting possibilities for electroweak physics, and also b-physics.



Opportunities at the Z pole: FCC-ee

100 ab^{-1} at Z pole $\rightarrow >10^{12}$ bbar pairs. Exciting b-physics programme, particularly promising for channels including neutrals & missing energy, e.g. $B_s \rightarrow \tau^+\tau^-$, $B^0 \rightarrow K^*\tau^+\tau^-$.



Conclusions

The last ~20 years has delivered a rich and extensive set of results in the field of quark-flavour physics.

The measurements are important because they both address many of the open questions of the Standard Model, and they are intrinsically sensitive to very high mass scales.

The programme is ongoing. Belle II and the LHCb Upgrades will bring great leap forwards in precision, and will make new observables accessible. New experiments in very different facilities will bring complementary information.

We are truly living through a golden age of flavour !

Backups

New Physics sensitivity through FCNCs

Improving sensitivity to the Wilson coefficient C_9 and the corresponding limits on New Physics mass scales, under different assumptions, from R_K and R_{K^*} .

