The age of flavour
(experimental flavour overview at WIN 2021)

- Introduction
- Selected highlights (including from the kaon sector)
- The future of flavour physics (with an emphasis on colliders)

Guy Wilkinson
University of Oxford
10 June 2021

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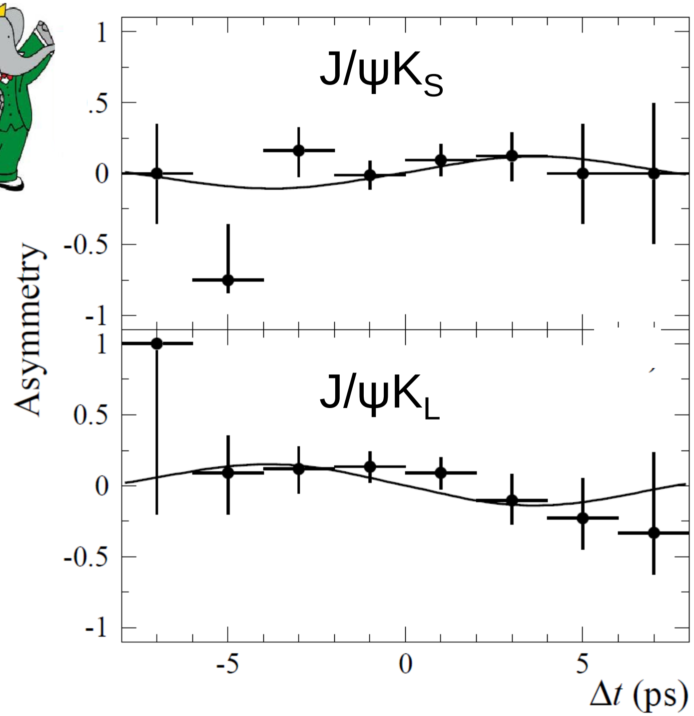
Confessions:
- discussion restricted to quarks, though there is *plenty* happening in the charged muon sector (*e.g*. g-2)
- unavoidably, most of the results shown will be from LHCb

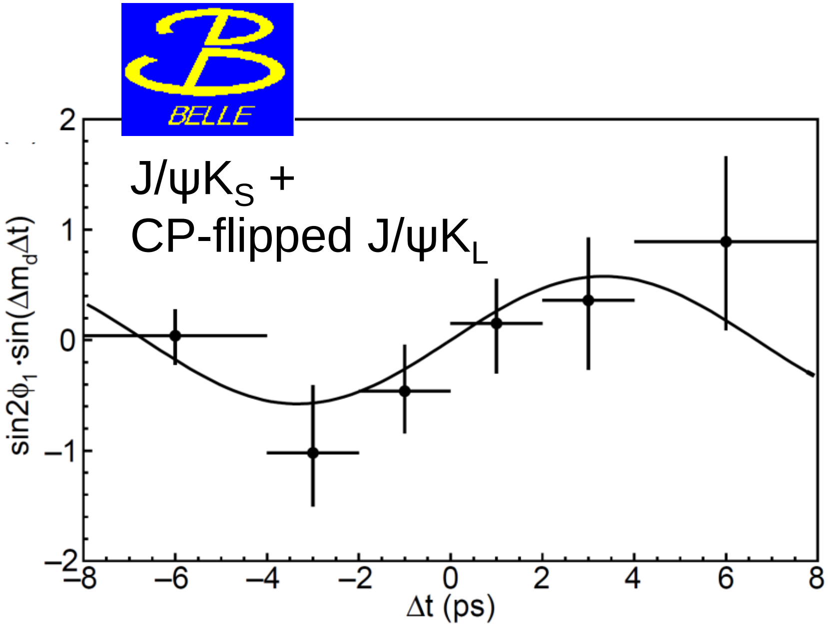
2001 - dawn of age of flavour

2008 Nobel Prize

We can date the dawn of the ‘age of flavour’ to the 2001 measurements of the CP-violating asymmetry in $B^0 \to J/\psi K^0$ decays that give unitarity triangle angle β (or φ_1).



[BaBar, PRL 86 (2001) 2515]



[Belle, PRL 86 (2001) 2509]

These studies, when improved with larger samples, confirmed the CKM paradigm as the dominant mechanism of CP violation in nature (→2008 Nobel Prize), and also opened up a rich and wide spectrum of complementary measurements.

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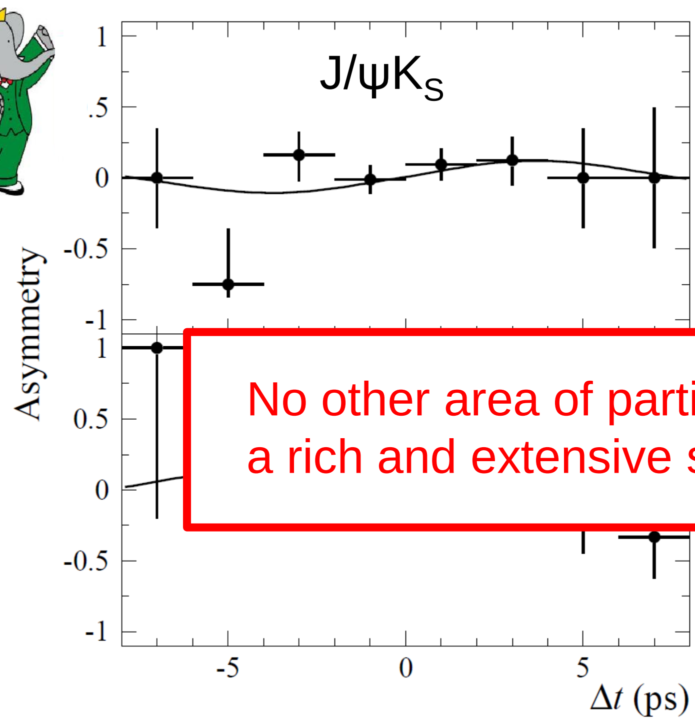

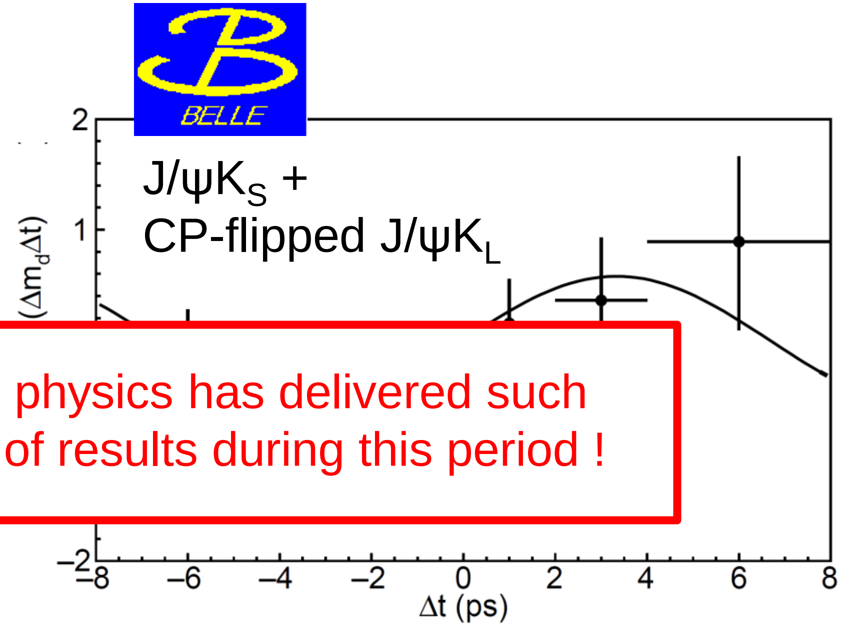

No other area of particle physics has delivered such a rich and extensive set of results during this period !

[BaBar, PRL 86 (2001) 2515]   [Belle, PRL 86 (2001) 2509]

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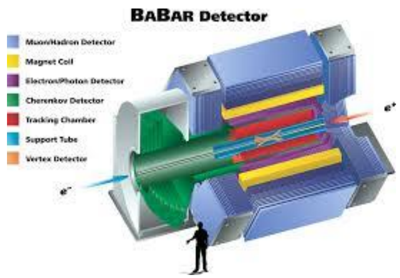
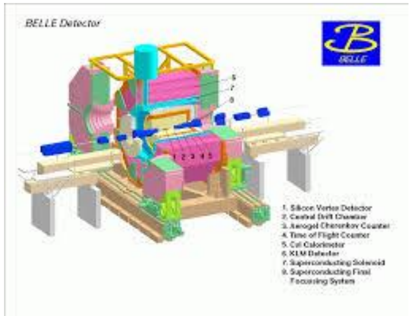
Heroes of the age of flavour

b-factories



BaBar (SLAC) & Belle (KEK)

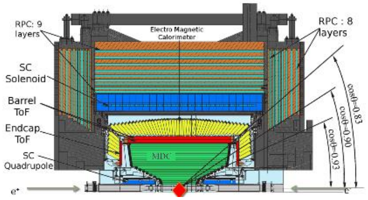
Operated in the 2000's
e^+e^- machines with asymmetric
beams for time-dep studies, mainly
at Y(4S), hence B^0 and B^+ samples.
Considered 'clean' environments.



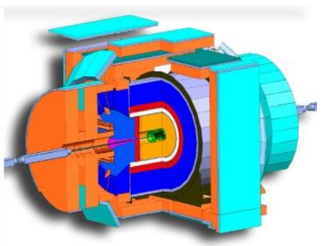
e^+e^- charm threshold

BESIII (Beijing)

Still data taking – provides clean &
often unique studies of charm properties.

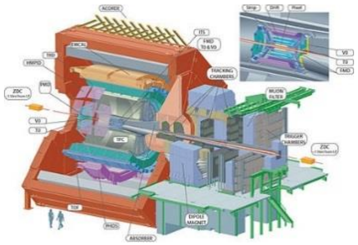


Tevatron experiments



CDF & D0

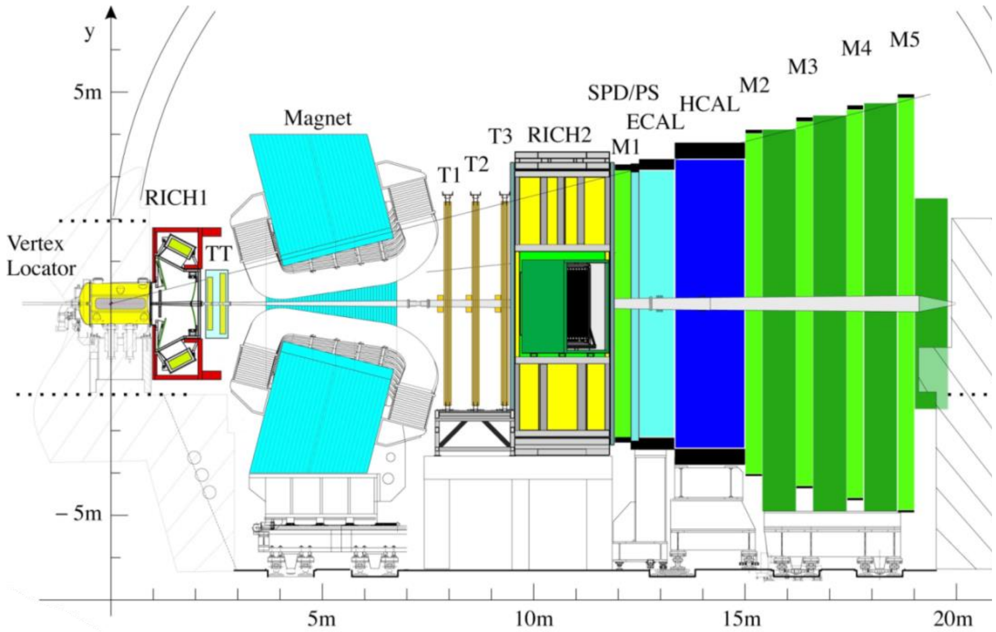
Tevatrons 'general purpose detectors'.
Pioneered *b*-physics in hadronic collisions.
Important early B_s and b-baryon studies.

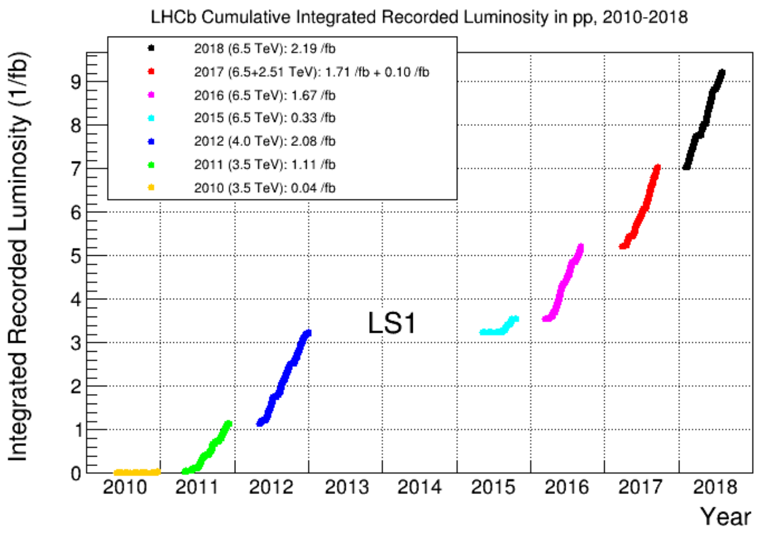


ATLAS & CMS

Their excellent instrumentation gives them
great capabilities in certain b-physics channels,
especially those with dilepton final states.

Heroes of the age of flavour - LHCb



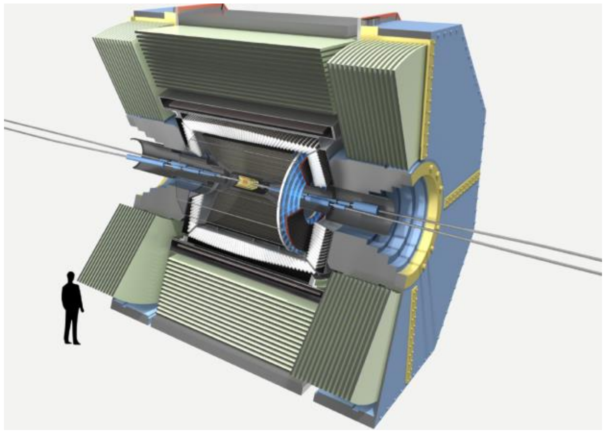


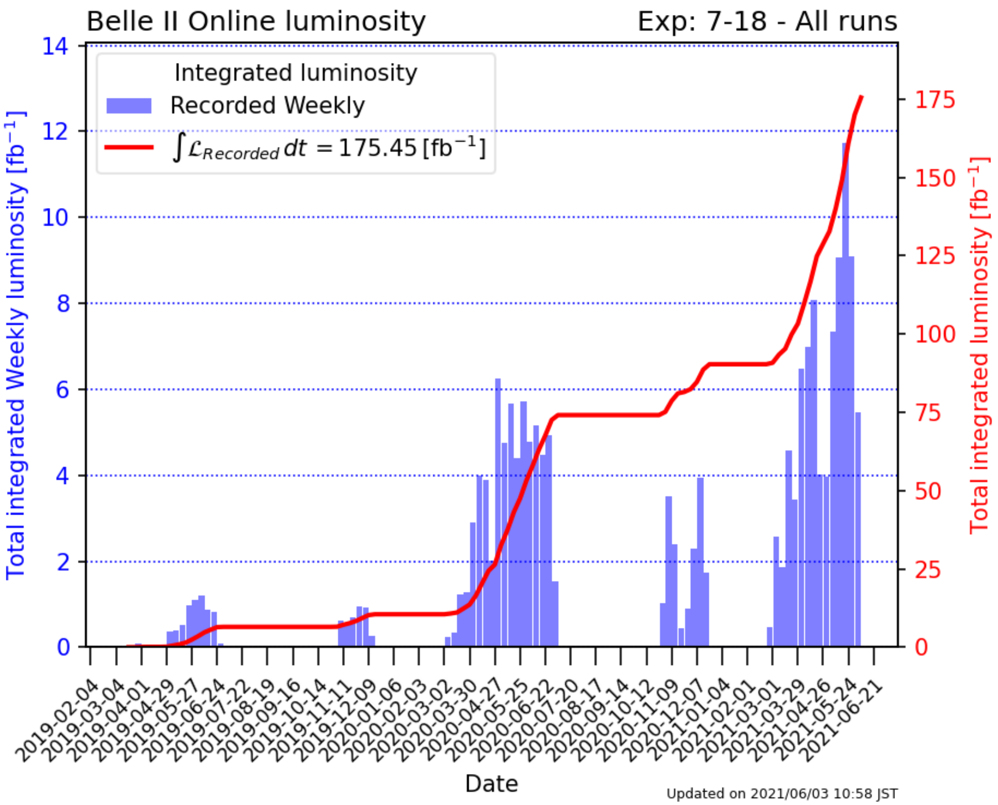
Experiment now being upgraded for Run 3 + 4 operation (see later).

Still many important results to emerge from the Run 1 + 2 9 fb^{-1} data set.

Belle II – rebooting the e^+e^- B-physics programme

Belle II is continuing where the B factories left off, aiming to accumulate ~50 ab^{-1}. Will perform measurements over a wide range of topics, with particular strengths in modes with neutrals and missing energy – highly complementary to LHCb.





So far has achieved:

- L up to 3×10^{34} $cm^{-2}s^{-1}$ (goal 8×10^{35} $cm^{-2}s^{-1}$)
- Integrated L of ~175 fb^{-1} (goal ~50 ab^{-1})

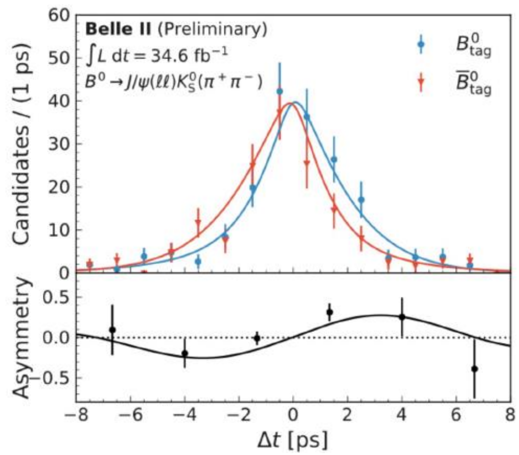
Belle II – rebooting the e^+e^- B-physics programme

Data starting to be explored in rediscovery of benchmark measurements, and in some cases already catching up with previous results through new techniques.

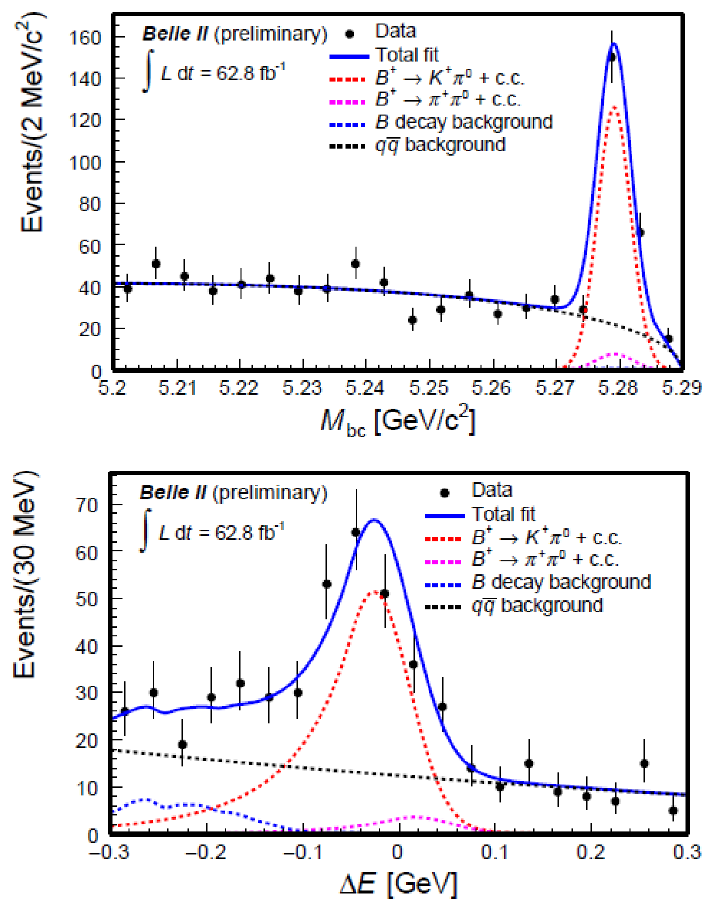
First sin2β measurement

(stat. precision of 0.21 with 35 fb^{-1})

[ICHEP2020]

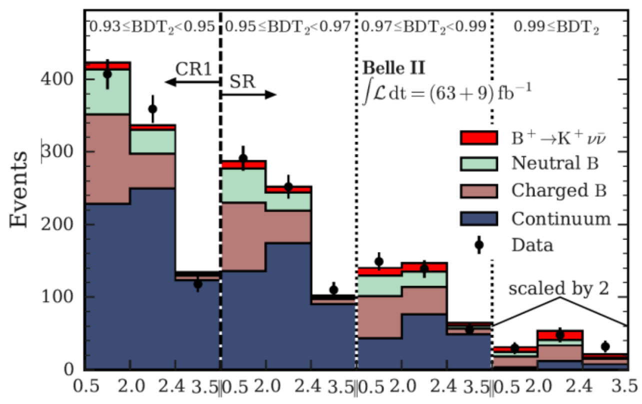


$B^+ \to \pi^+\pi^0$



[arXiv:2105.04111]

[arXiv:2104.12624]

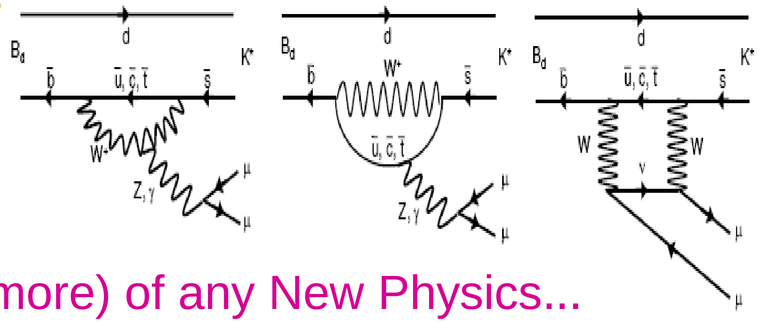


BR($B^+ \to K^+\nu\nu$ < 4.1 x 10^{-5} (90% C.L.)
(already better than Belle with 711 fb^{-1} !)

Selected measurements

- Electroweak penguins: $B^0 \rightarrow K^{(*)} l^+ l^-$ and friends
- CPV in the B system
- The charm renaissance
- Progress in the kaon sector

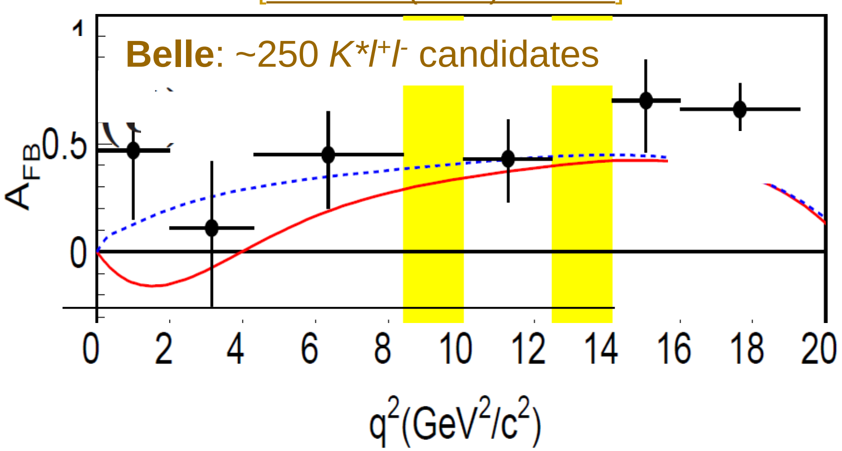
$B^0 \rightarrow K^* l^+ l^-$ and friends



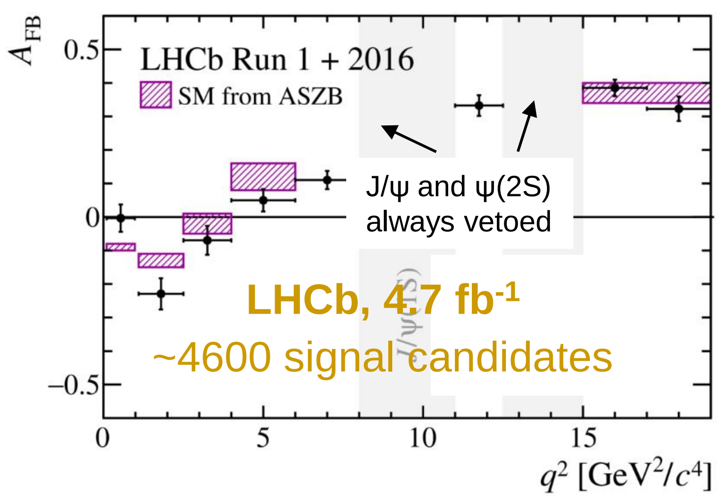
$b \rightarrow s l^+ l^-$ decays such as $B^0 \rightarrow K^* l^+ l^-$ offer many observables which probe helicity structure (& more) of any New Physics...

The B-factory experiments had inadequate statistics for meaningful tests. This has now all changed, *e.g.* forward-backward asymmetry vs q^2 (dilepton mass)^2.

[PRL 103 (2009) 171801]



[PRL 125 (2020) 011802]



General pattern as predicted; but mild tension at low q^2

But there are many other observables, which can be built from the measured amplitudes, & are constructed to be intrinsically robust against form-factor uncertainties, *e.g.* " $P_5{}'$ ".

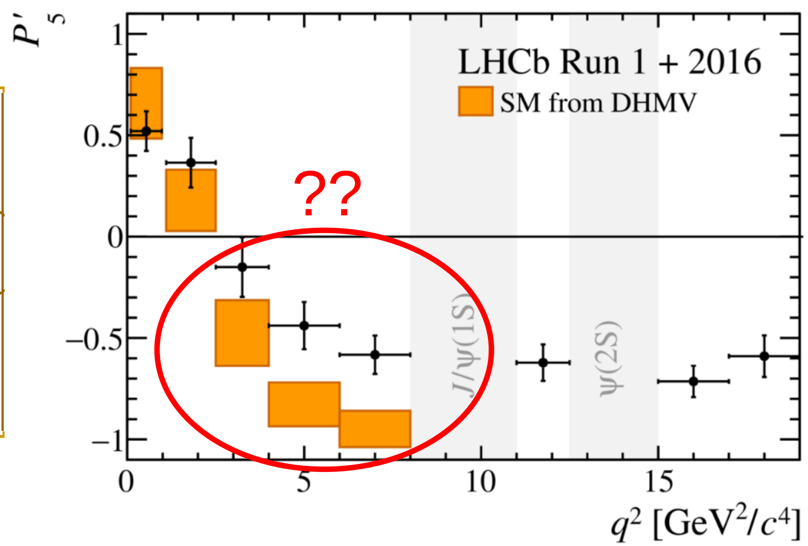
$B^0 \to K^* l^+ l^-$ and friends: the $P_5^{/}$ conundrum

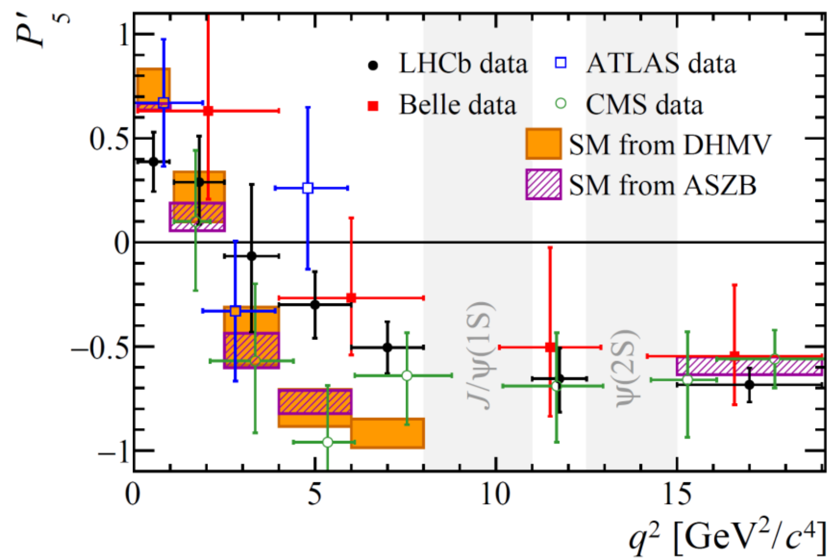
One such observable is $P_5^{/}$: What this describes physically is hard to visualise, but it is constructed from angular observables in a manner that is robust against form-factor uncertainties, and also easily relatable to the short-distance physics.

Interesting (and persistent) deviation at low q^2.

Same pattern seen by Belle and ATLAS, but CMS more SM-like.

[PRL 125 (2020) 011802]





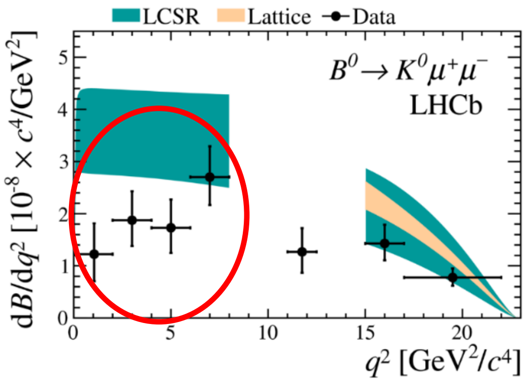
[ATLAS, JHEP 10 (2018) 047]
[CMS, PLB 781 (2018) 517]
[Belle, PRL 118 (2017) 111801]

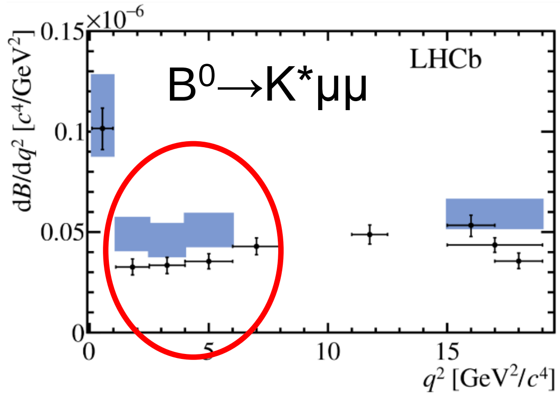
A word of caution. The SM uncertainties shown here are from one group. There are other values on the market, and some are more conservative.

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

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

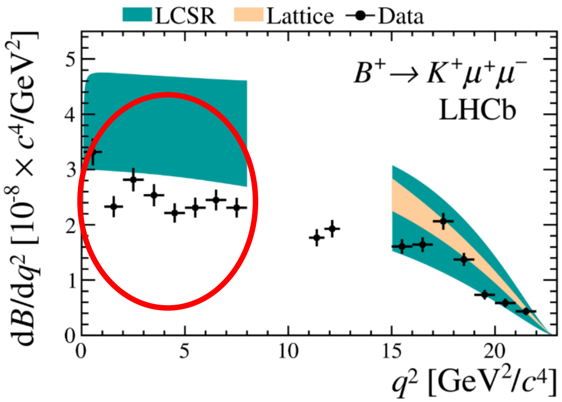
JHEP 06 (2014) 133





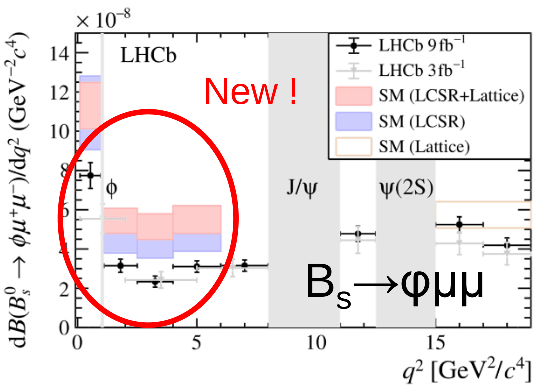
JHEP 04 (2017) 142

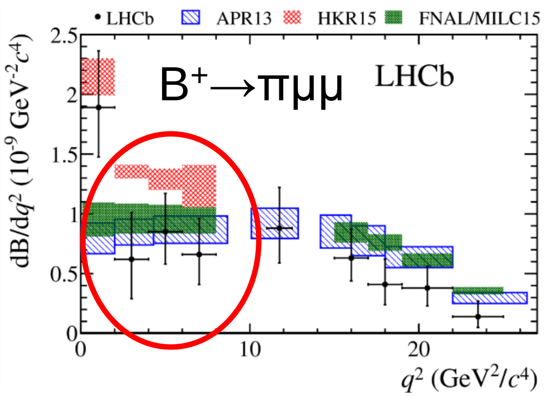
JHEP 11 (2016) 047,



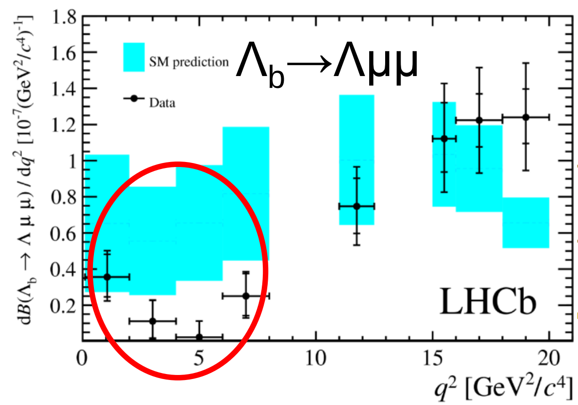
JHEP 06 (2014) 133

arXiv:2105.14007





JHEP 10 (2015) 034



JHEP 09 (2018) 145

JHEP 06 (2015) 009,

Consistent tendency for differential x-sections to undershoot prediction at low q^2. Intriguing – but maybe the uncertainties in theory are larger than claimed ?

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

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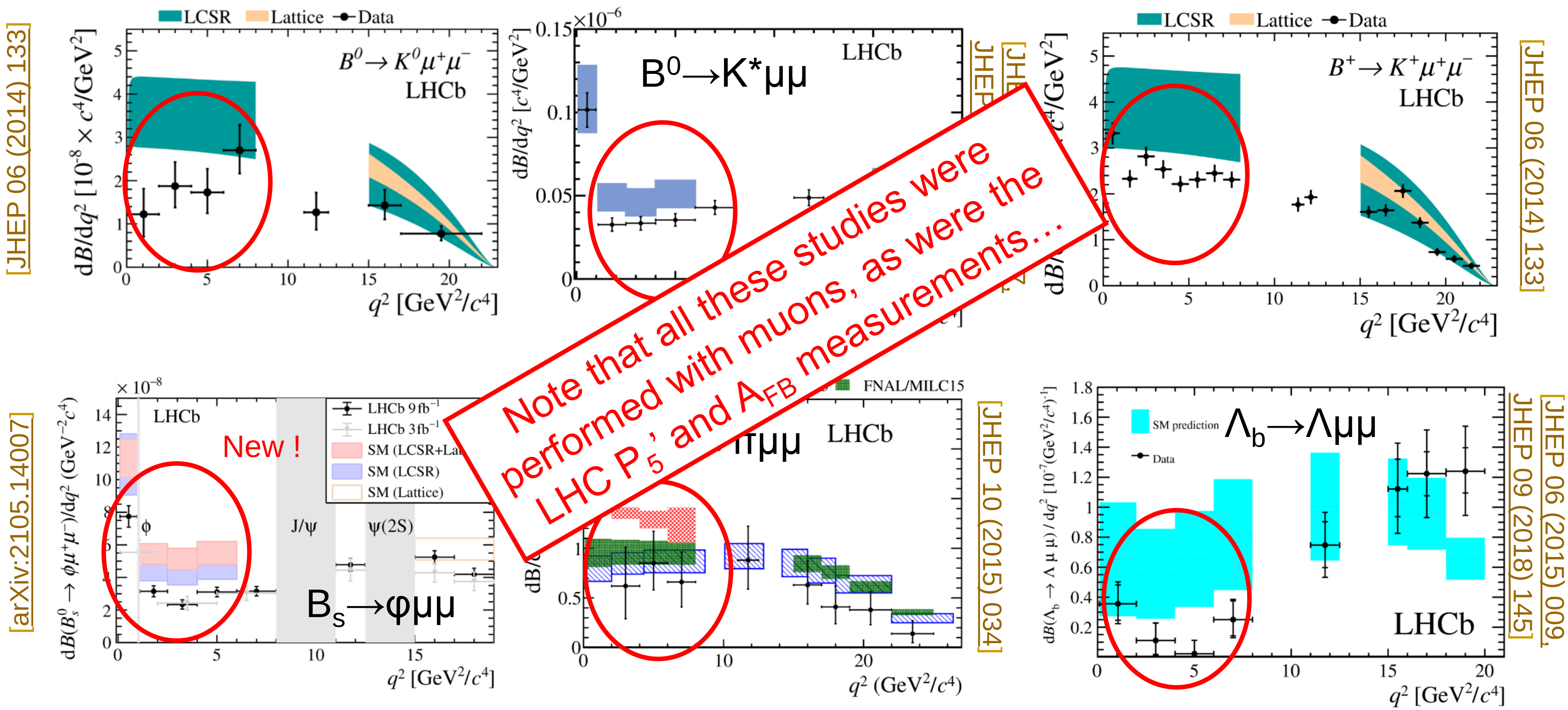

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$B^0 \to K^* l^+ l^-$ and friends: lepton-universality tests

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 $b \to s\mu^+\mu^- / b \to s e^+ e^-$ for $\sim 1 < q^2 < 6\ \mathrm{GeV}^2$ for both $B \to K l^+ l^-$ (R_K) and $B^0 \to K^* l^+ l^-$ (R_{K^*}). In SM we expect 1 for both.

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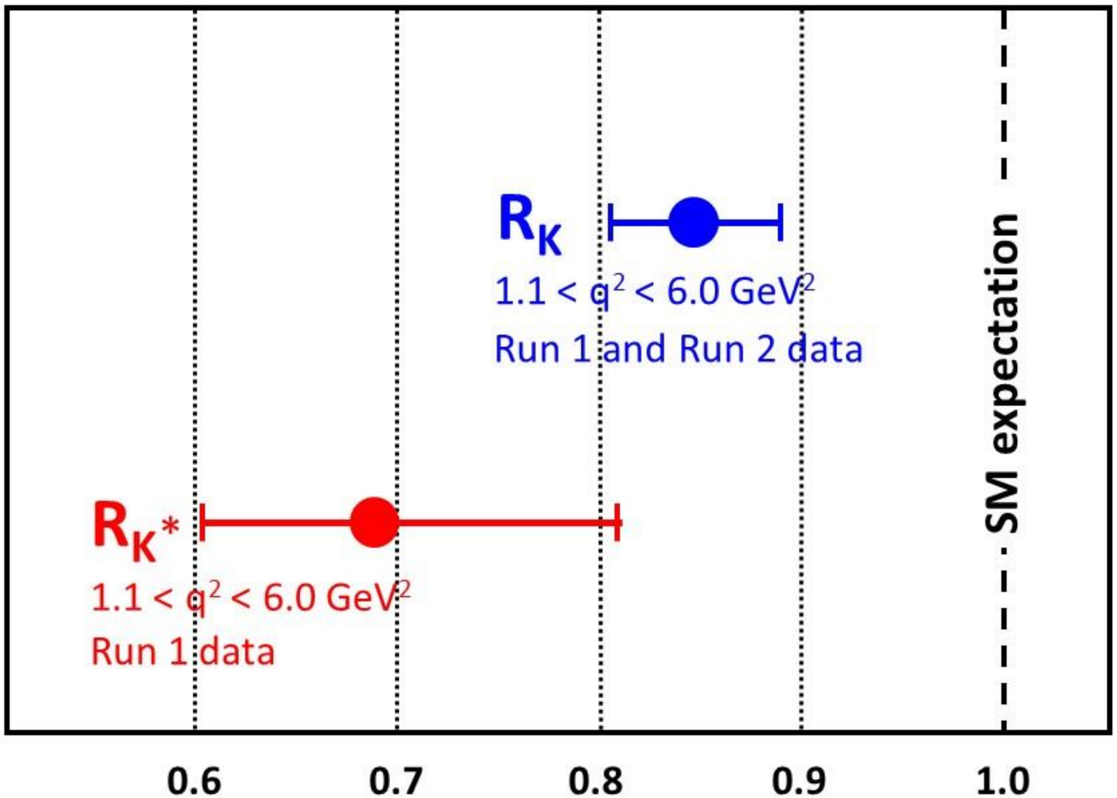
3.1 σ below SM

~2.5 σ below SM



[arXiv:2103.11769]

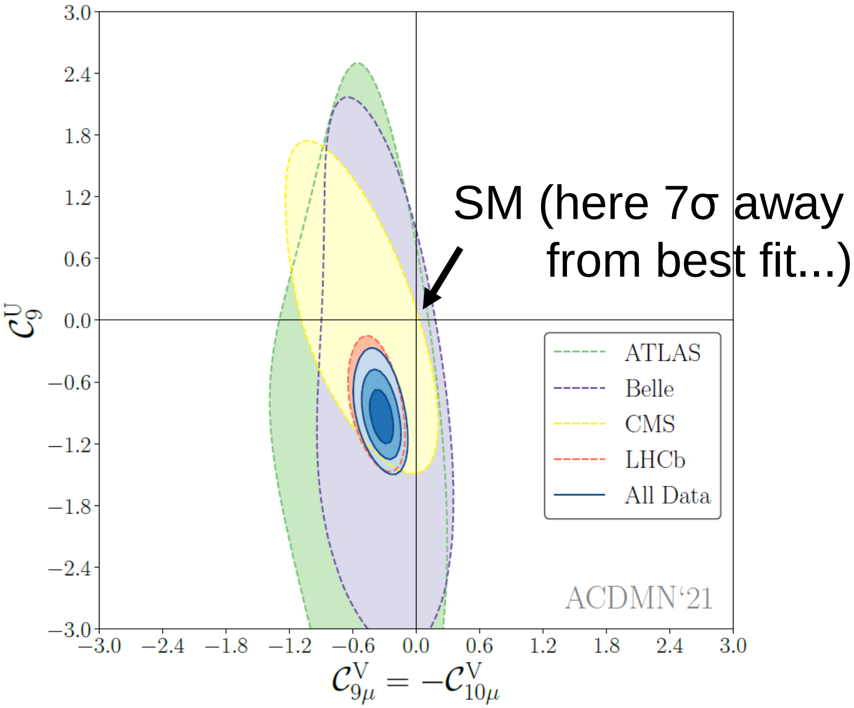
[JHEP 08 (2017) 055]:

$B^0 \to K^* l^+ l^-$ and friends: what does it all mean ?

I leave this to the next speaker (Gudrun Hiller), and tomorrow's speaker (Julian Garcia Pardinas) to tell you much more about the measurements, plus prospects. But the essentials are as follows:

- When analysed in context of an effective field theory these anomalies appear rather self-consistent, with most of the non-SM effect coming from the muons
- The degree of disagreement with the SM depends on whether you trust everything, or whether you privilege the theoretically clean LU observables.
- More LU observables are coming, from LHCb at least. In particular, watch out for:
  - R_{K^*} with full data set
  - P_5' *etc.* results with electrons

Example effective field theory fit to one scenario [arXiv:2104.08921]



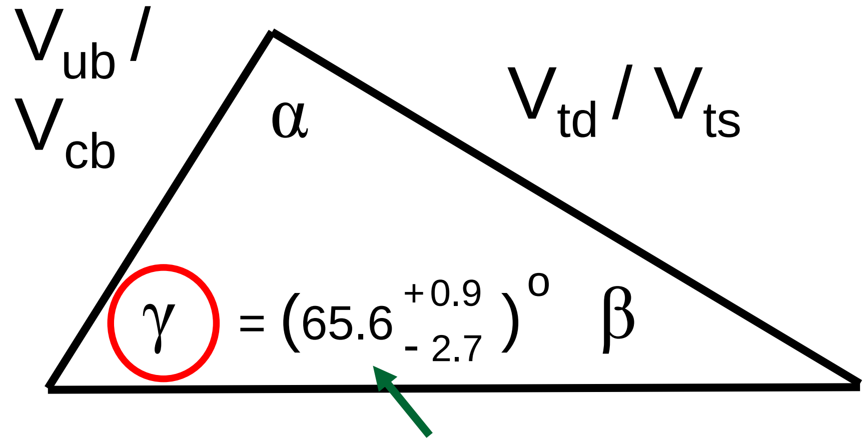
The Unitarity Triangle and CPV studies

LHCb has performed many measurements relevant to the Unitarity Triangle.

Most important task of LHCb in Unitarity Triangle studies has been to pursue programme to improve knowledge of γ.

At LHC turn-on this was very badly known [CKMfitter uncertainty >20^o].

Since then much progress, thanks to methods pioneered at B-factories, & LHCb statistical muscle.



Predicted value [CKMfitter 2019] from measurements of other triangle parameters & lattice QCD.

Best way to access γ is to study this decay chain, looking for interference effects when D^0 & $\bar{D}^0$ decay to common final state.

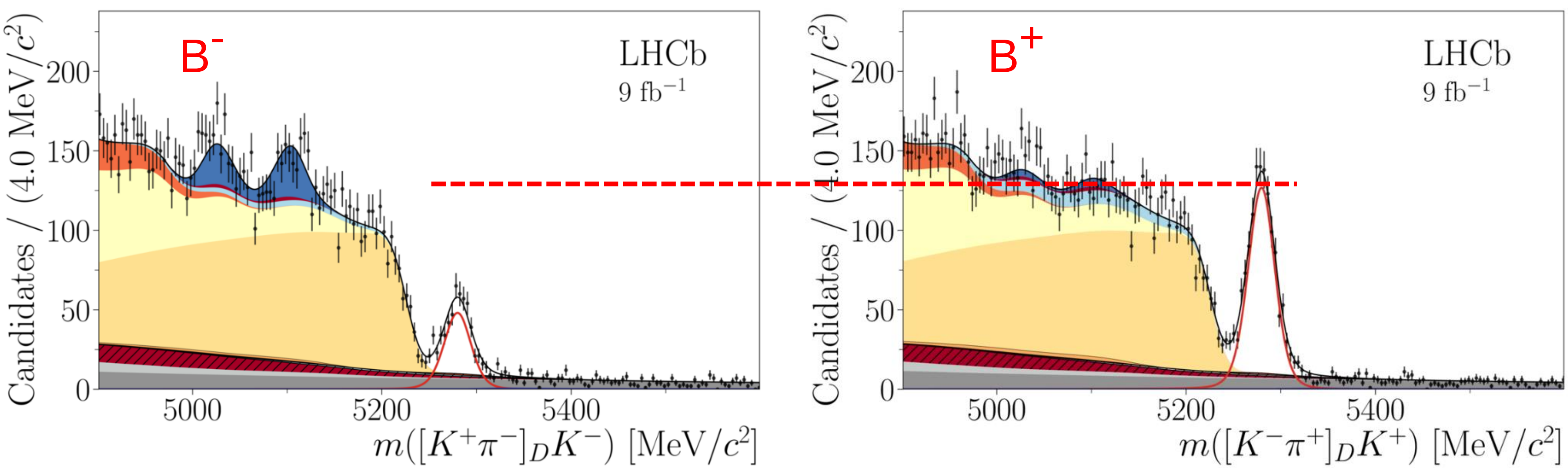
$B^- \rightarrow D^0 K^-$

$B^- \rightarrow \bar{D}^0 K^-$

phase γ between V_{ub} and V_{cb} amplitudes

The Unitarity Triangle: measuring γ

To access these interference effects means looking for rather suppressed decays, *e.g.* this $B^- \to DK^-$ decay, with $D \to K^+\pi^-$ (and B^+ conjugate case): visible BR ~10^{-8}, Hence out of reach to previous generation of flavour physics experiments.



JHEP 04 (2021) 081

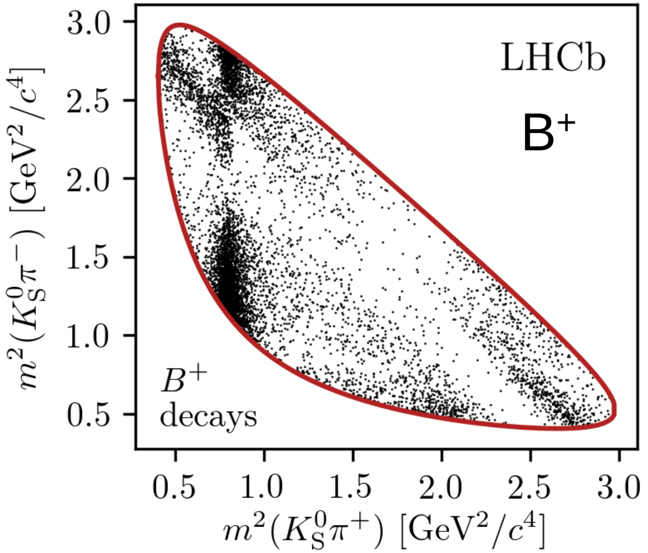
Very significant CP violation observed, that can be cleanly related to the phase γ.

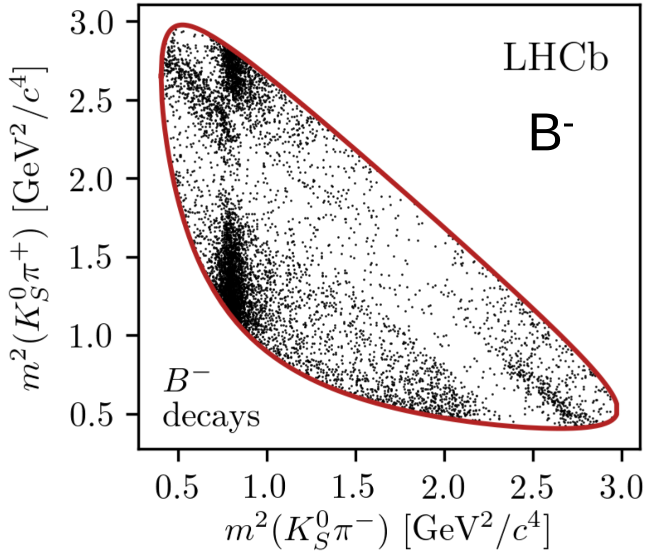
γ measurement at LHCb with $B \to DK$ decays: $D \to K_S\pi\pi$ (and K_SKK)

[JHEP 02 (2021) 169]

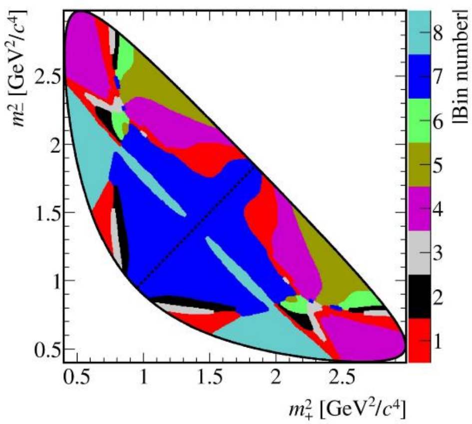
A powerful sub-set of B→DK analyses is when the D decays into a multibody final state, of which $K_S\pi\pi$ is the most prominent example. Variation of D strong phase over Dalitz space leads to corresponding variation in interference and CP violation.

Analysis of ~12,500 decays from Run 1 and Run 2 data





Study yields in bins of Dalitz space, chosen for optimal sensitivity.



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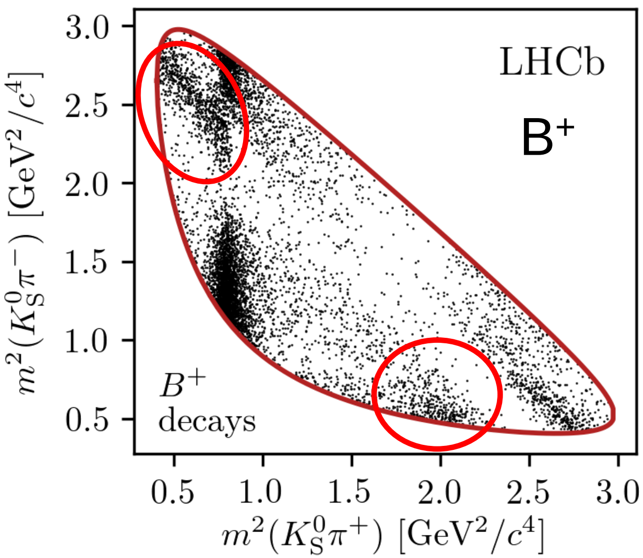

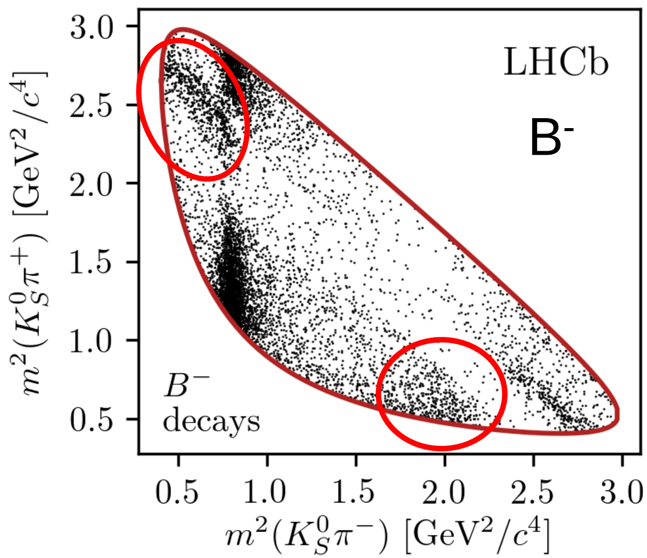

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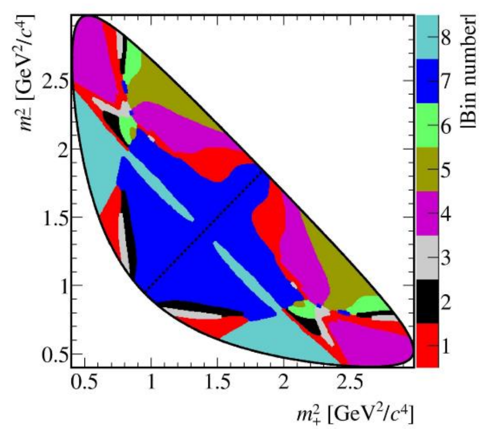
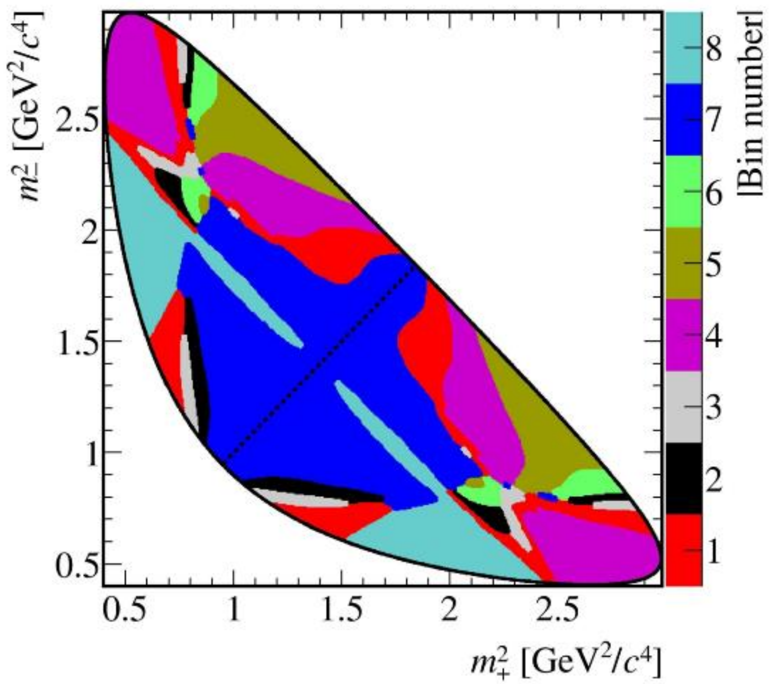


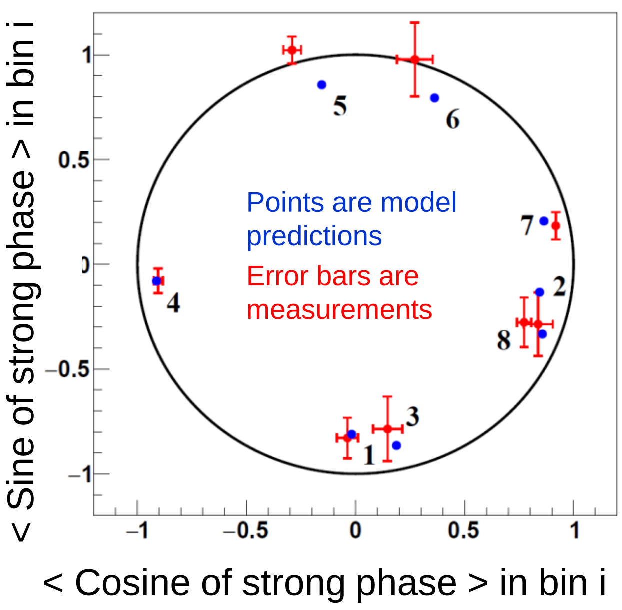
CP asymmetries visible by eye, but quantitative analysis requires external input...

Measuring γ – a synergy of experiments

In order to make sense of these *CP* asymmetries, we need to know how the CP-conserving strong phase between D & Dbar varies over the Dalitz plot.

This information can be measured in bins on the Dalitz plot from quantum-correlated ψ(3770)→DDbar events, available at BESIII [PRD 101 (2020) 112002].





BESIII data (here combined with older CLEO results) adequate for current LHCb sample sizes.

LHCb Upgrade data & Belle II will require improved measurements from BES III !

γ measurement at LHCb with B→DK decays: D→$K_S\pi\pi$ (and K_SKK)

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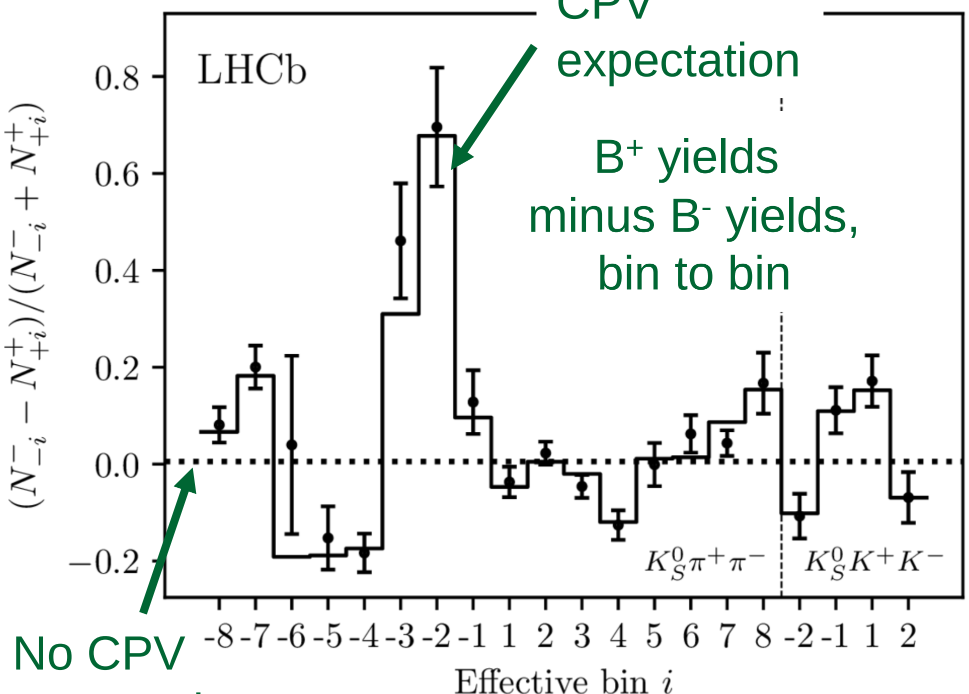


CPV expectation

B⁺ yields minus B⁻ yields, bin to bin

No CPV expectation

Gives a result of:

$$\gamma = (68.7^{+5.2}_{-5.1})^\circ$$

which is the single most precise determination of γ.

Not yet included in LHCb combination of results with other D-decay modes, But earlier average yielded:

$$(67 \pm 4)^\circ$$ [LHCb-CONF-2020-003]

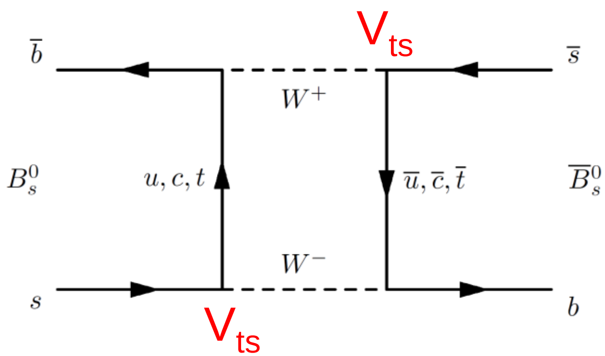
Final LHCb Run 1 + 2 result should have a precision of 2-3 degrees.

In agreement with indirect prediction but not yet as precise → need more data !

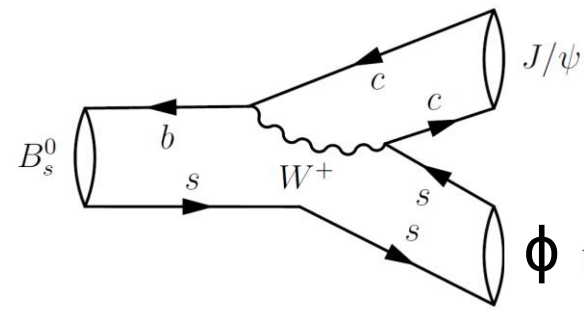
Mixing induced CPV in B_s system: φ_s

Measuring the CPV phase, φ_s, in B_s mixing-decay interference, *e.g.* with $B_s \rightarrow J/\Psi\Phi$, is the B_s analogue of the sin2β measurement. In the SM this phase is very small & precisely predicted. Box diagram offers tempting entry point for NP !

Once more interference between mixing…



…and decay



Now we probe CKM elements that are complex only at higher order

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\begin{pmatrix} -\frac{1}{8}\lambda^4 + \mathcal{O}(\lambda^6) & \mathcal{O}(\lambda^7) & 0 \\ \frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] + \mathcal{O}(\lambda^7) & -\frac{1}{8}\lambda^4(1+4A^2) + \mathcal{O}(\lambda^6) & \mathcal{O}(\lambda^8) \\ \frac{1}{2}A\lambda^5(\rho+i\eta) + \mathcal{O}(\lambda^7) & \boxed{\frac{1}{2}A\lambda^4(1-2(\rho+i\eta)) + \mathcal{O}(\lambda^6)} & -\frac{1}{2}A^2\lambda^4 + \mathcal{O}(\lambda^6) \end{pmatrix}$$

$$\phi_s^{\mathrm{SM}} \equiv -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -36.3^{+1.6}_{-1.5}\,\mathrm{mrad}$$

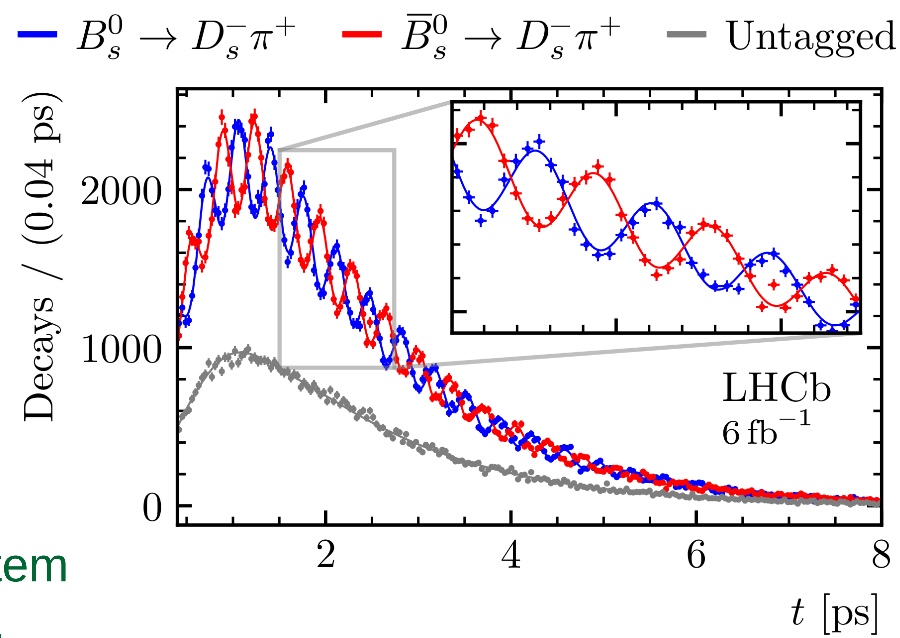
Very small, but very well predicted !

Mixing induced CPV in B_s system: φ_s

Measuring the CPV phase, φ_s, in B_s mixing-decay interference, *e.g.* with $B_s \rightarrow J/\Psi\Phi$, is the B_s analogue of the sin2β measurement. In the SM this phase is very small & precisely predicted. Box diagram offers tempting entry point for NP !

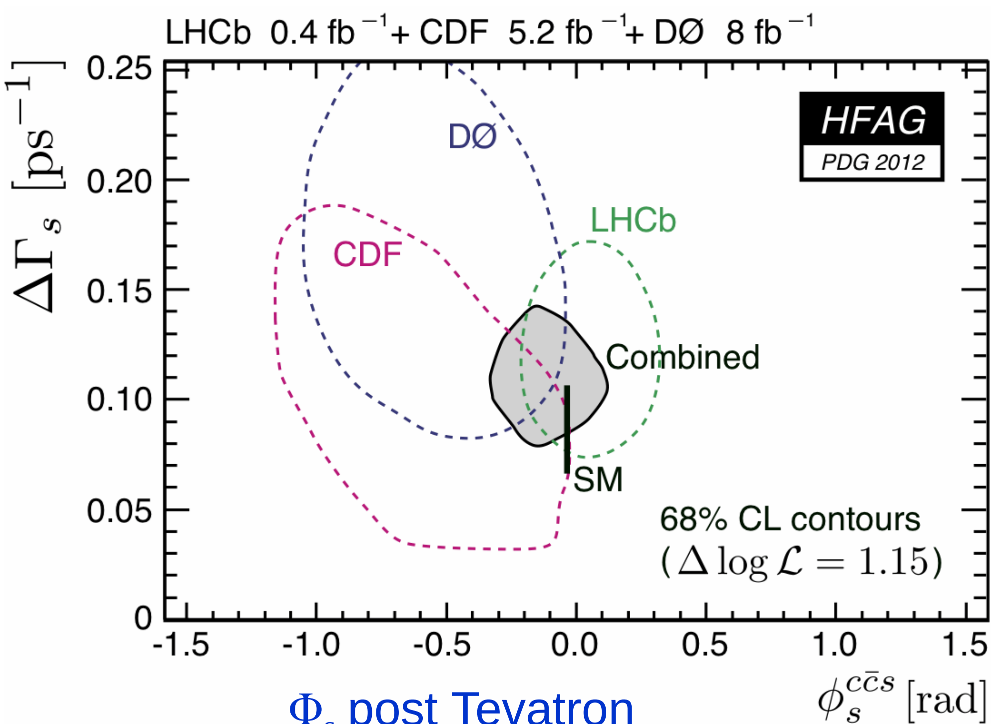
However the measurement is considerably trickier than is the case for sin2β:

- Very fast oscillations, requiring excellent proper-time resolution;
- J/Ψφ is a vector-vector final state, so requires angular analysis to separate out CP+ & CP- ;
- Possibility of KK S-wave under φ;
- Finite width splitting, $\Delta\Gamma_s$, of B_s system must also be measured in analysis.



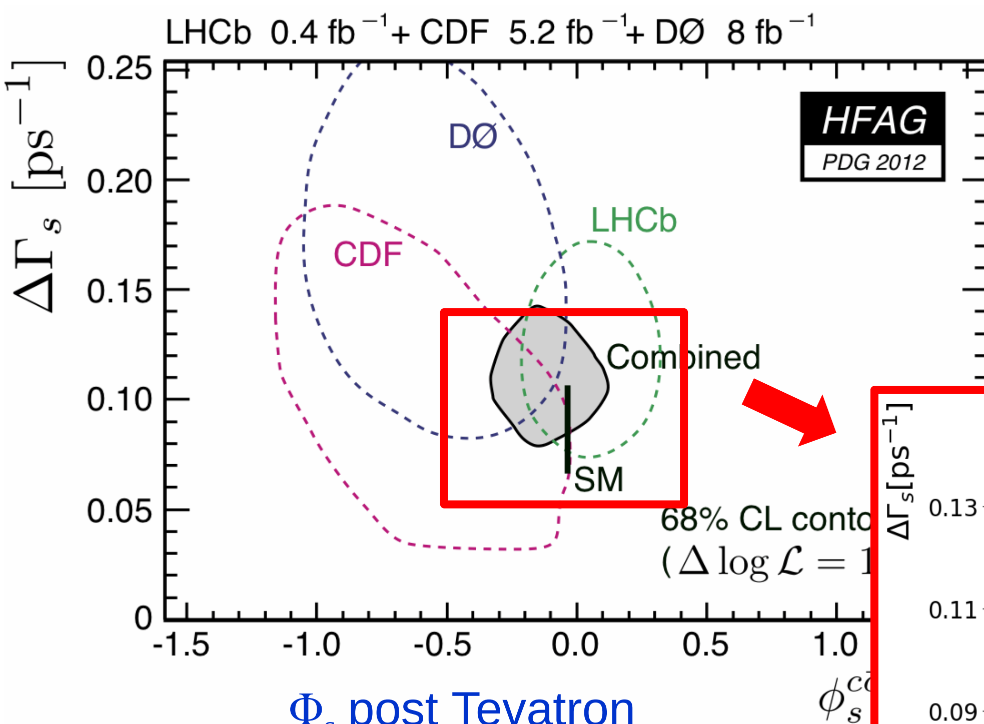
[arXiv:2104.04421]

φ_s : the impact of the LHC



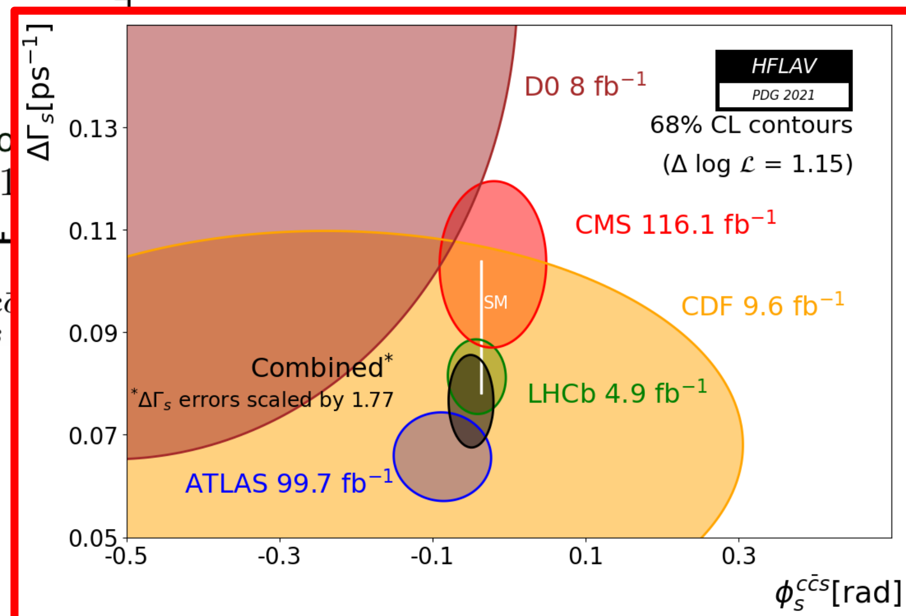
Φ_s post Tevatron
and early LHC data

ϕ_s : the impact of the LHC

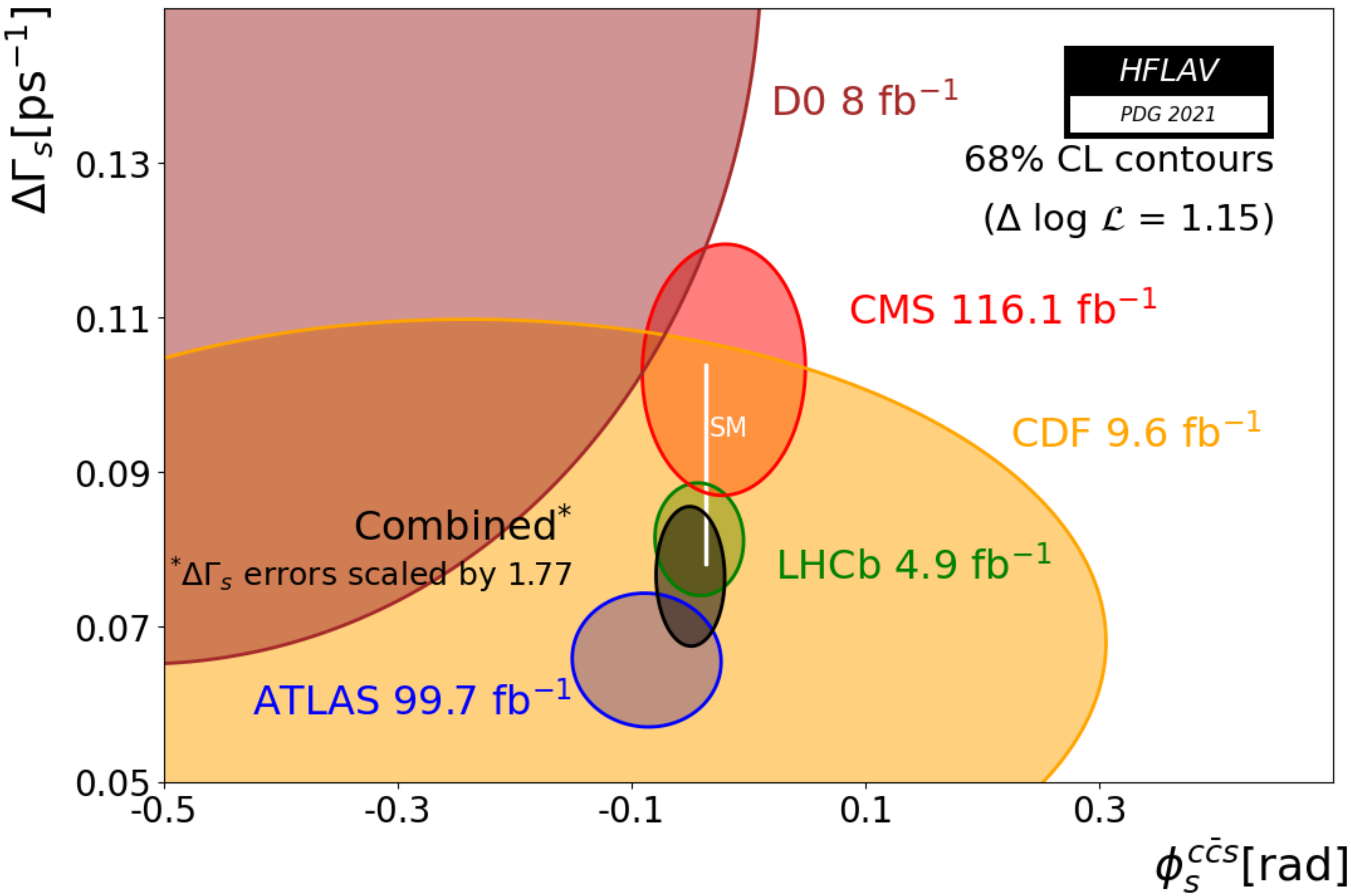


Φ_s post Tevatron
and early LHC data

Φ_s with Run 1 and (most of) Run 2 LHC data



φ_s : the current state of play



List of inputs: https://hflav-eos.web.cern.ch/hflav-eos/osc/PDG_2021/HFLAV_phis_inputs.pdf

Current average for φ_s = -0.050 ± 0.019. Compatible with SM, and approaching sensitivity where we can hope to resolve a non-zero value. Great scope for further progress, from ATLAS/CMS Phase II Upgrades, as well as LHCb.

The charm renaissance

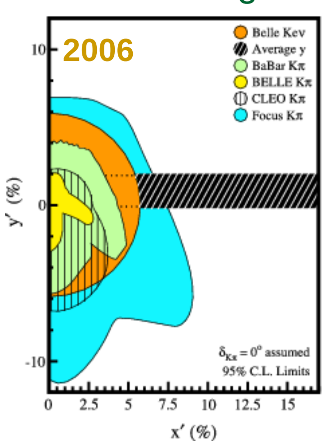
The 'age of flavour' has seen a renaissance in charm studies.

Charm oscillations are slow, and mediated by two parameters, which are hard to predict in SM.

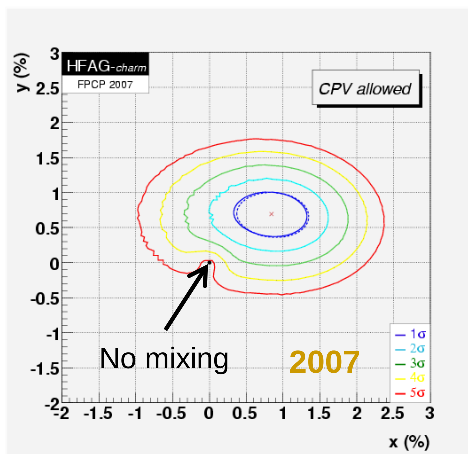
$$x \equiv \Delta m / \Gamma \qquad y \equiv \Delta\Gamma / 2\Gamma$$

For many years, nothing was seen, but then ensemble of B-factory data, followed by high statistics studies from CDF & LHCb, dramatically changed picture.

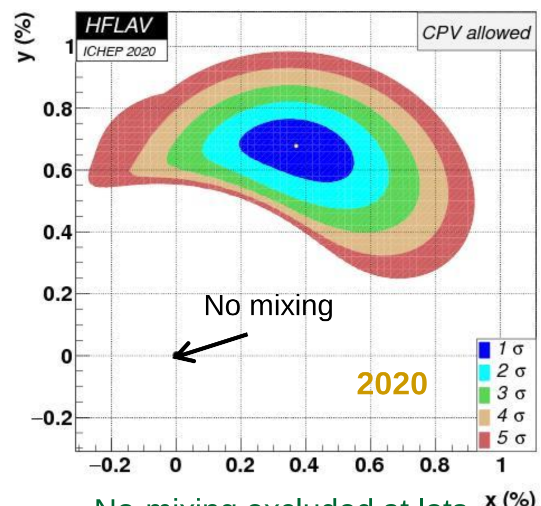
Excluded regions



"All results are null."
Ian Shipsey, Charm 2006.



Measurement contours;
no-mixing excluded at 5σ



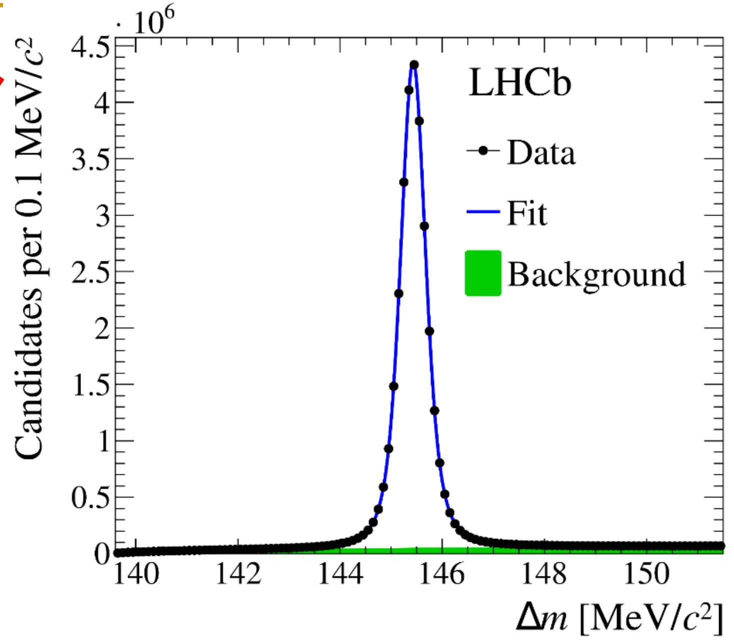
No-mixing excluded at lots and lots (but x=0 still possible…)

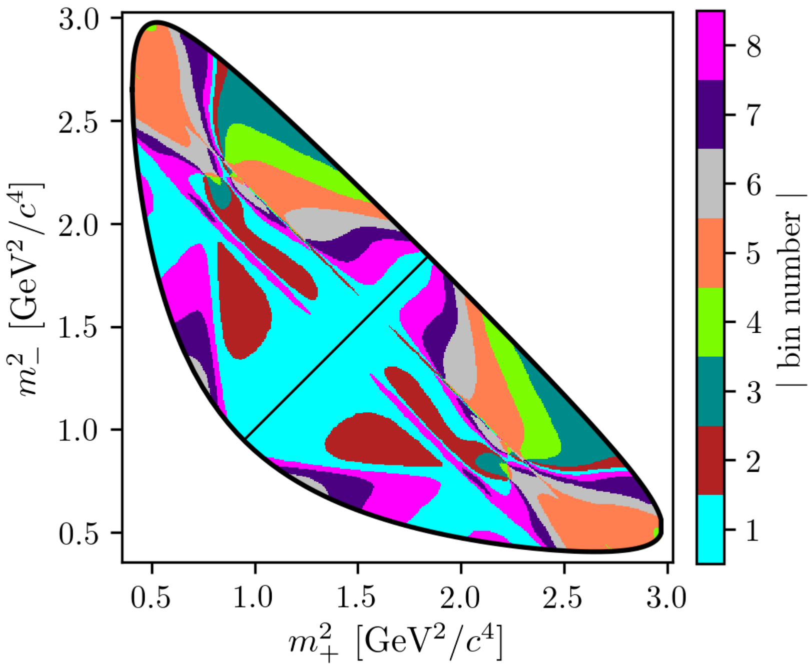
D^0-$\overline{D}^0$ oscillations with $D^0 \to K_S \pi^+ \pi^-$ at LHCb

New !

The rich resonance structure of $D^0 \to K_S \pi^+ \pi^-$ very advantageous for mixing & CPV studies.

New LHCb result [arXiv:2106.03744] exploits 5.4 fb^{-1} of data, corresponding to 31 million decays (x30 B-factory samples).





As in γ analysis, divide Dalitz plot into bins, whose strong-phase characteristics are known from BESIII measurements.

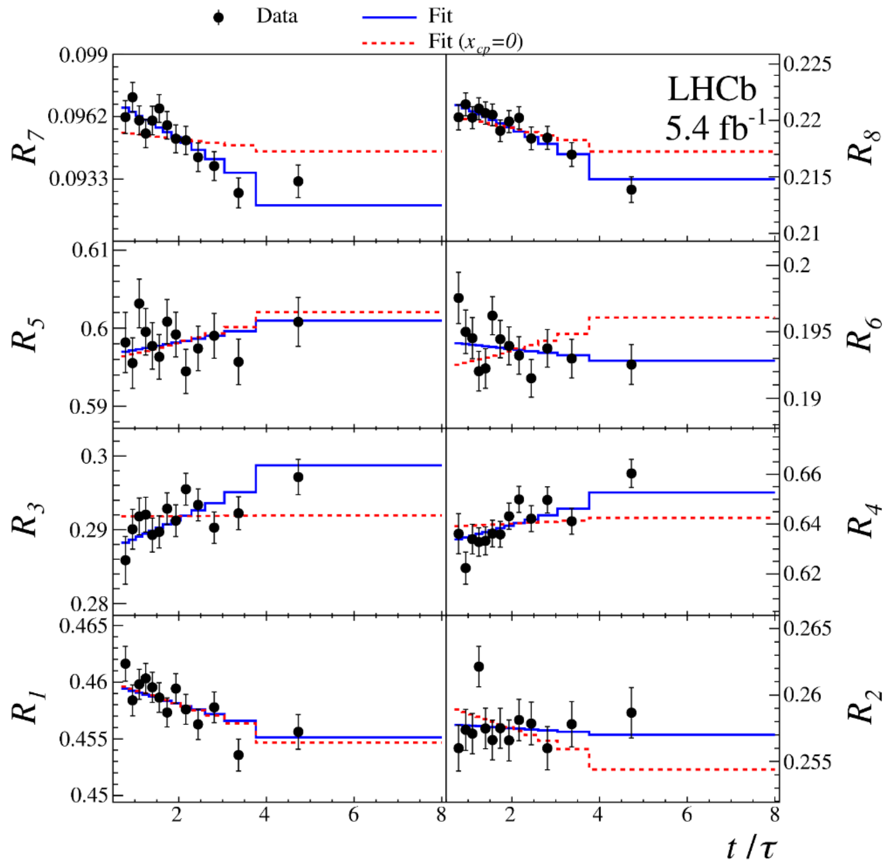
Study time-dependence of ratio of symmetric bins (the 'bin flip' method [PRD 99 (2019) 012007] . Particularly sensitive to x.

Use data-driven method to correct for trigger-induced correlations between decay time and phase space.

D^0-$\bar{D}^0$ oscillations with $D^0 \to K_S\pi^+\pi^-$ at LHCb

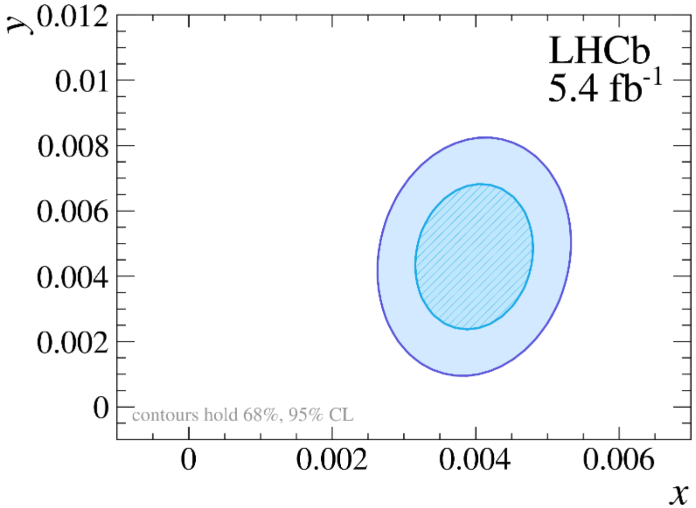
New !

Ratio of bin populations vs. proper time.
Slope indicates presence of mixing.



$$x = (3.98^{+0.56}_{-0.54}) \times 10^{-3},$$
$$y = (\ 4.6^{+1.5}_{-1.4}\ ) \times 10^{-3},$$
$$|q/p| = 0.996 \pm 0.052,$$
$$\phi = 0.056^{+0.047}_{-0.051}.$$

CPV parameters
No CPV when
|q/p|=1 & ϕ = 0

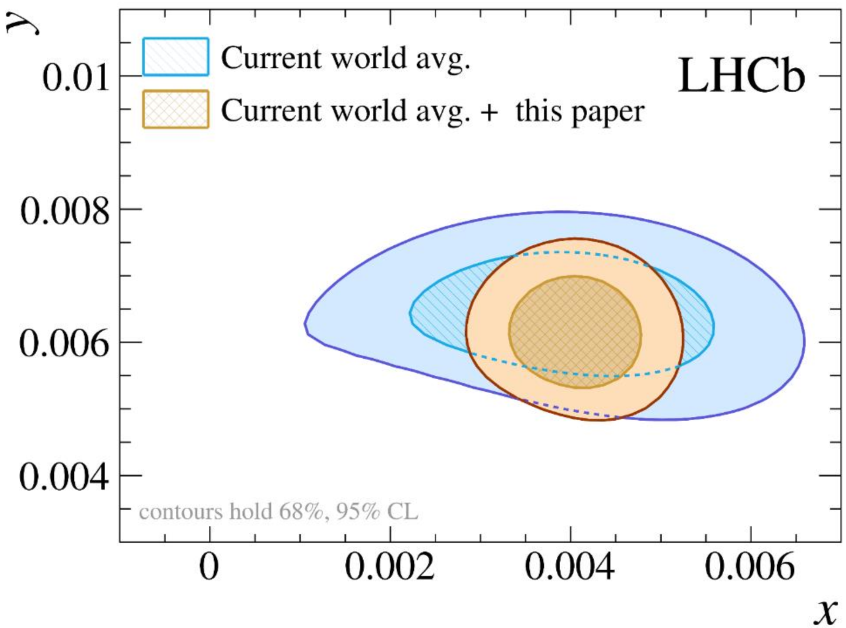


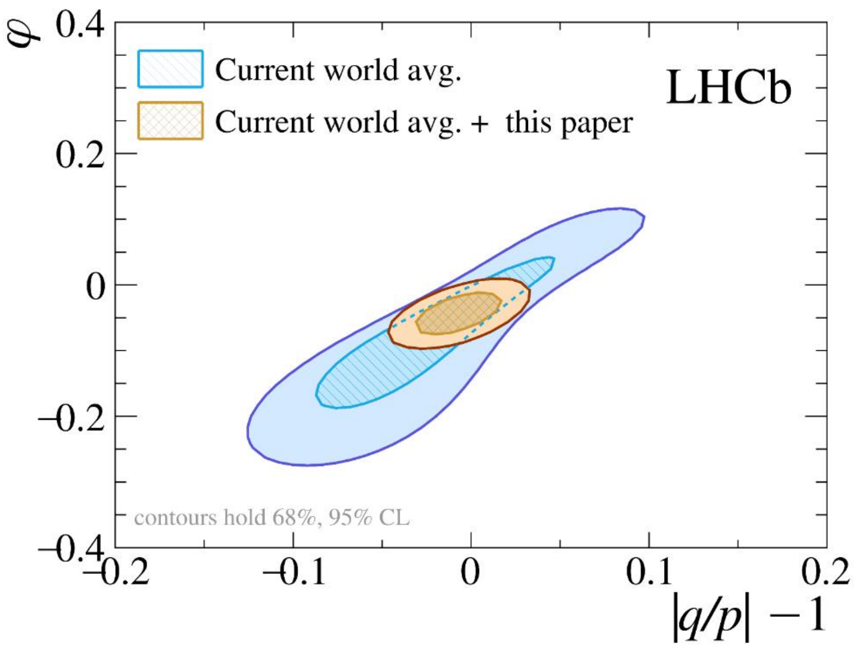
x non-zero with significance of >7σ !

D^0-$\overline{D}^0$ oscillations with $D^0 \to K_S\pi^+\pi^-$ at LHCb

New !

These result represents a huge step forward in precision for mixing & CPV searches.



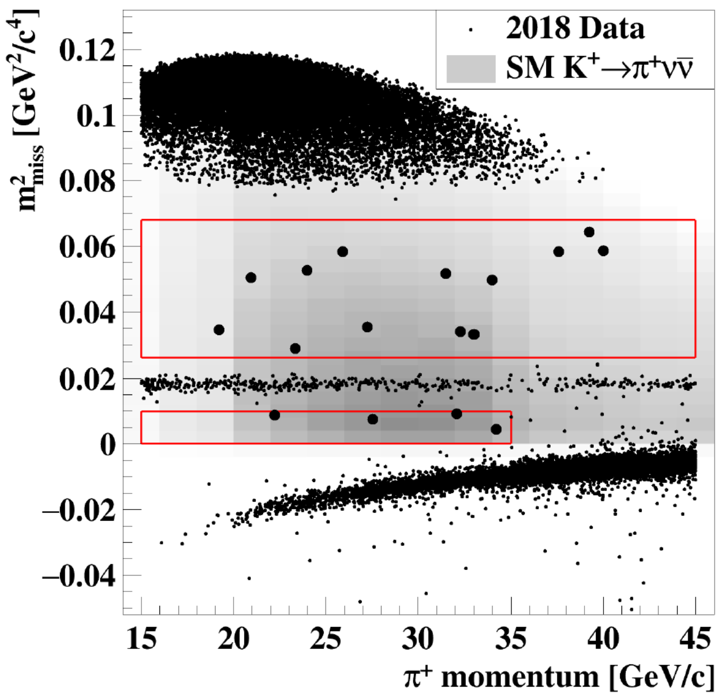


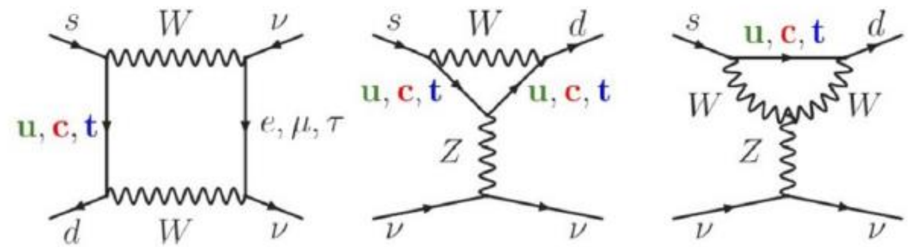
Knowing that both x and y are non-0, & significantly larger than once was guessed, bodes well for mixing-related CPV searches, as they pre-multiply any asymmetry. SM CPV may lie ~10x below current sensitivity, New Physics could be larger !

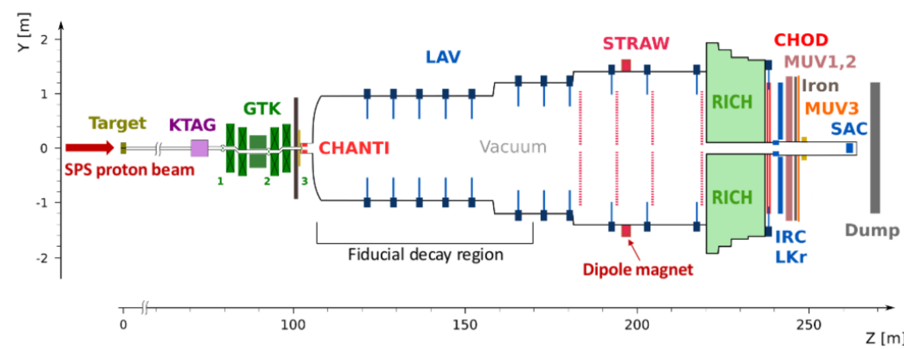
Flavour studies with kaons

Kaon sector very important in foundation of SM, & rare-decay studies continue to be an important New Physics probe, *e.g.* measurement of BR of highly suppressed, but theoretically clean, mode $K^+ \to \pi^+$vvbar. Great progress being made by NA62 !

[arXiv:2103.15389]







Recent unblinding of 2018 data: 20 events seen, with bckgd of 7, compatible with SM expectation.

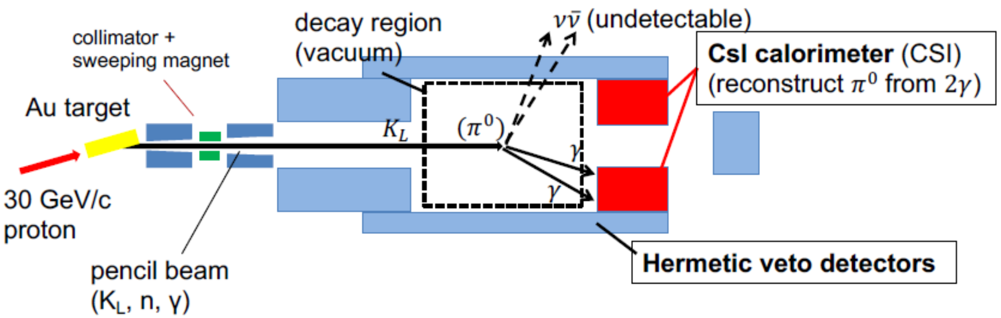
$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\text{stat}} \pm 0.09_{\text{syst}}) \times 10^{-11}$$

Aim for ~10% precision within next few years.

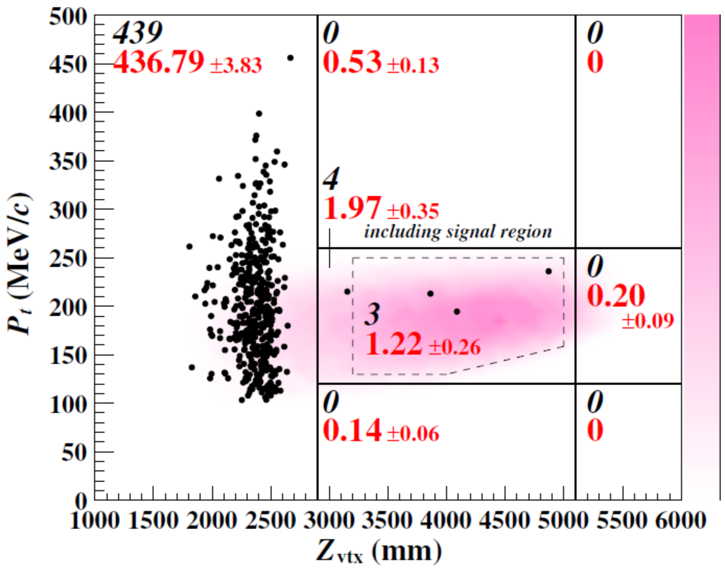
Flavour studies with kaons

Even more challenging is the search for the neutral mode $K^0_L \to \pi^0 \nu\bar{\nu}$, being pursued by the KOTO experiment. SM BR = (3.00 +/- 0.30) x 10^{-11} [JHEP 11 (2015) 033] .

$K_L \to \pi^0 \nu\bar{\nu}$: ($\pi^0 \to$) 2γ + nothing



2016-2018 data set with observed and expected background events



[PRL 126 (2021) 121801]

Studies following unblinding of 2016-18 sample revealed additional sources of background from $K_L \to 2\gamma$ in beam halo and K^+ decays.

3 events, 1.22 background

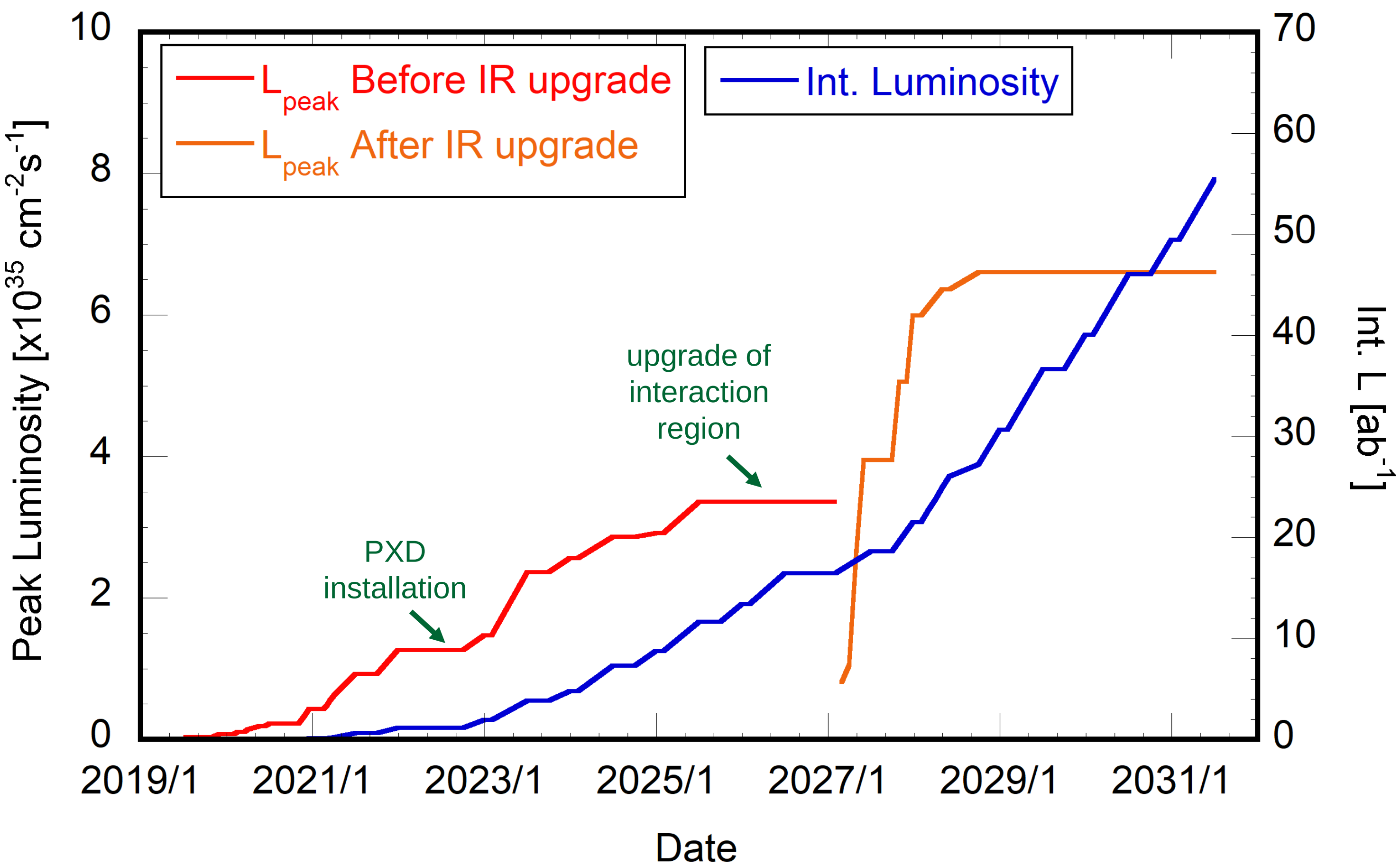
BR < 4.9 x 10^{-9} at 90% C.L.

These backgrounds will be suppressed in future runs / analysis by new veto counter *etc.* and software cuts.

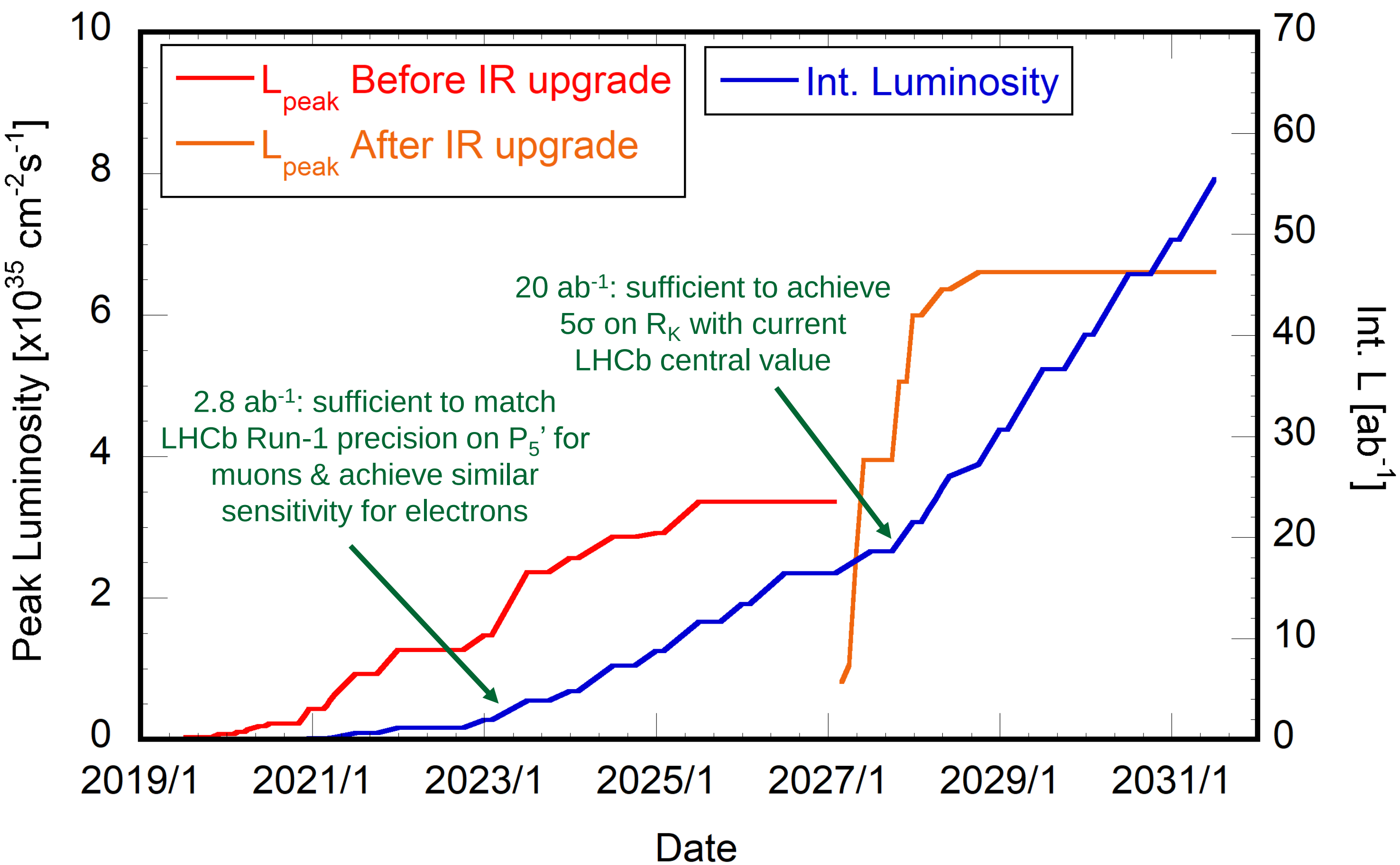
The future of flavour (with focus on colliders)

- Belle II prospects
- Tau-charm factories
- The LHCb Upgrades
- FCC-ee

Belle II tentative luminosity projections



Belle II tentative luminosity projections



e^+e^- below the $\Upsilon(4S)$

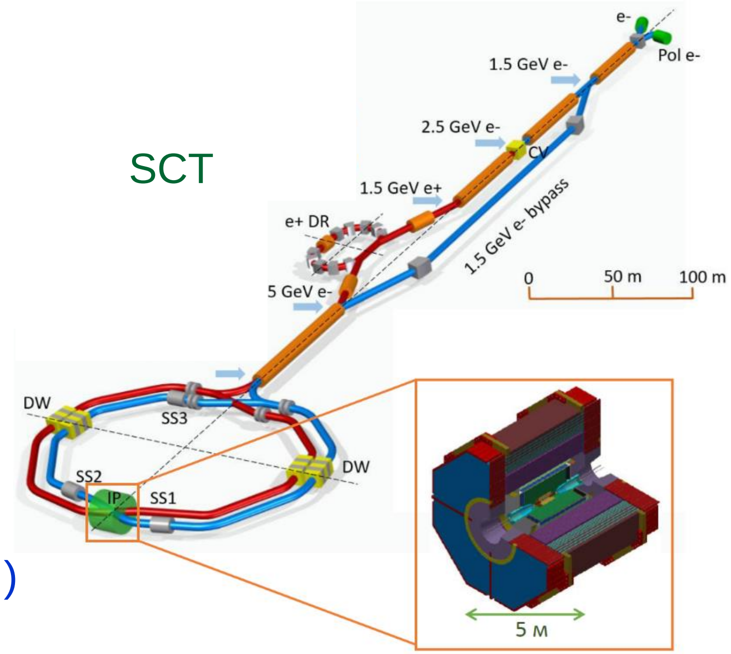
Two proposals seeking approval:

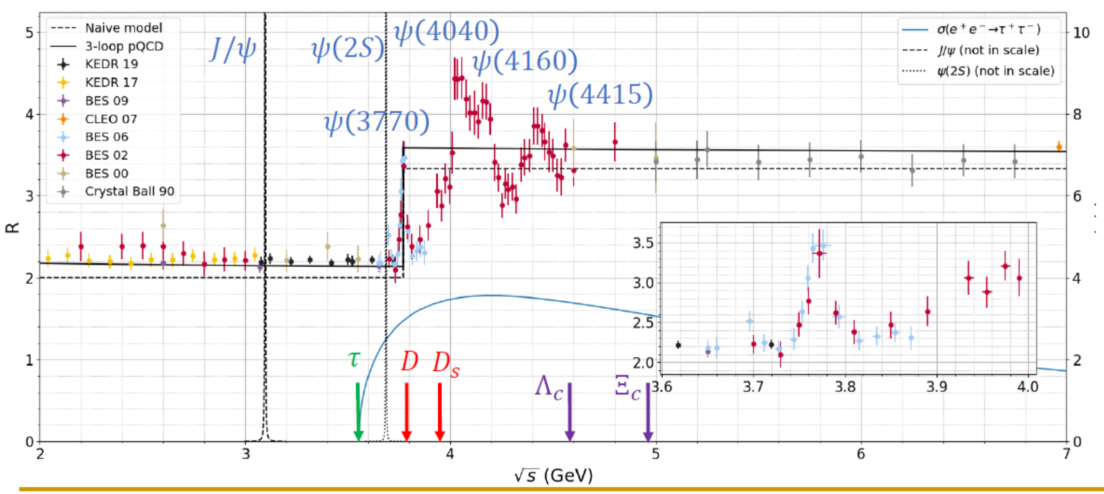
- China: Super Tau-Charm Factory (STCF)
- Russia: Super-Charm Tau Factory (SCT)

Similar capabilities for both:

- E_b between 1.5 and 3.5 GeV
- L ~ 10^{35} cm^{-2} s^{-1} at 2 GeV (x100 BEPCII / BESIII)
- Longitudinal polarisation for e^-
- Start of physics: 2028 Russia, 2030 China

SCT

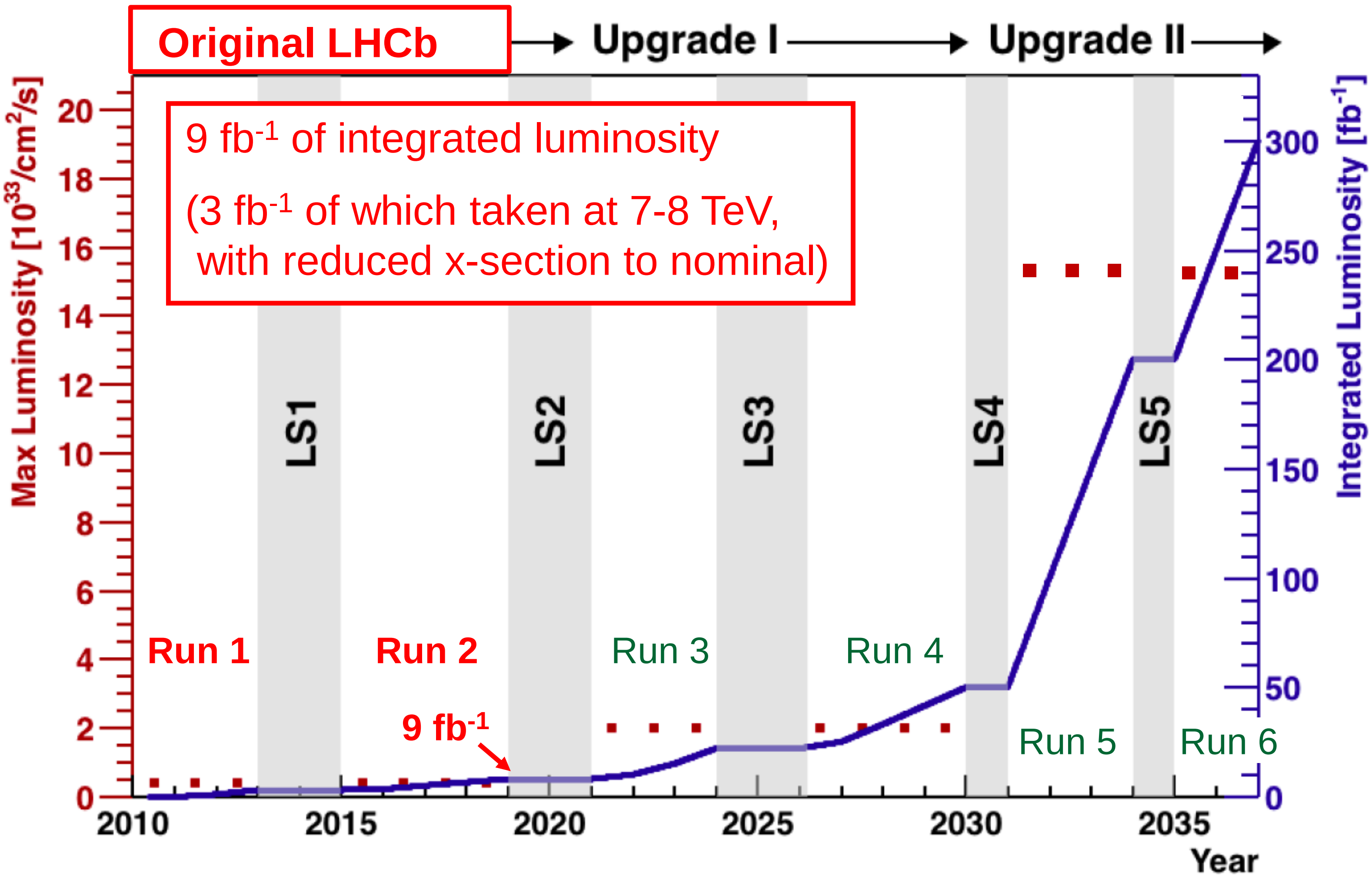




Annual yields (SCT)

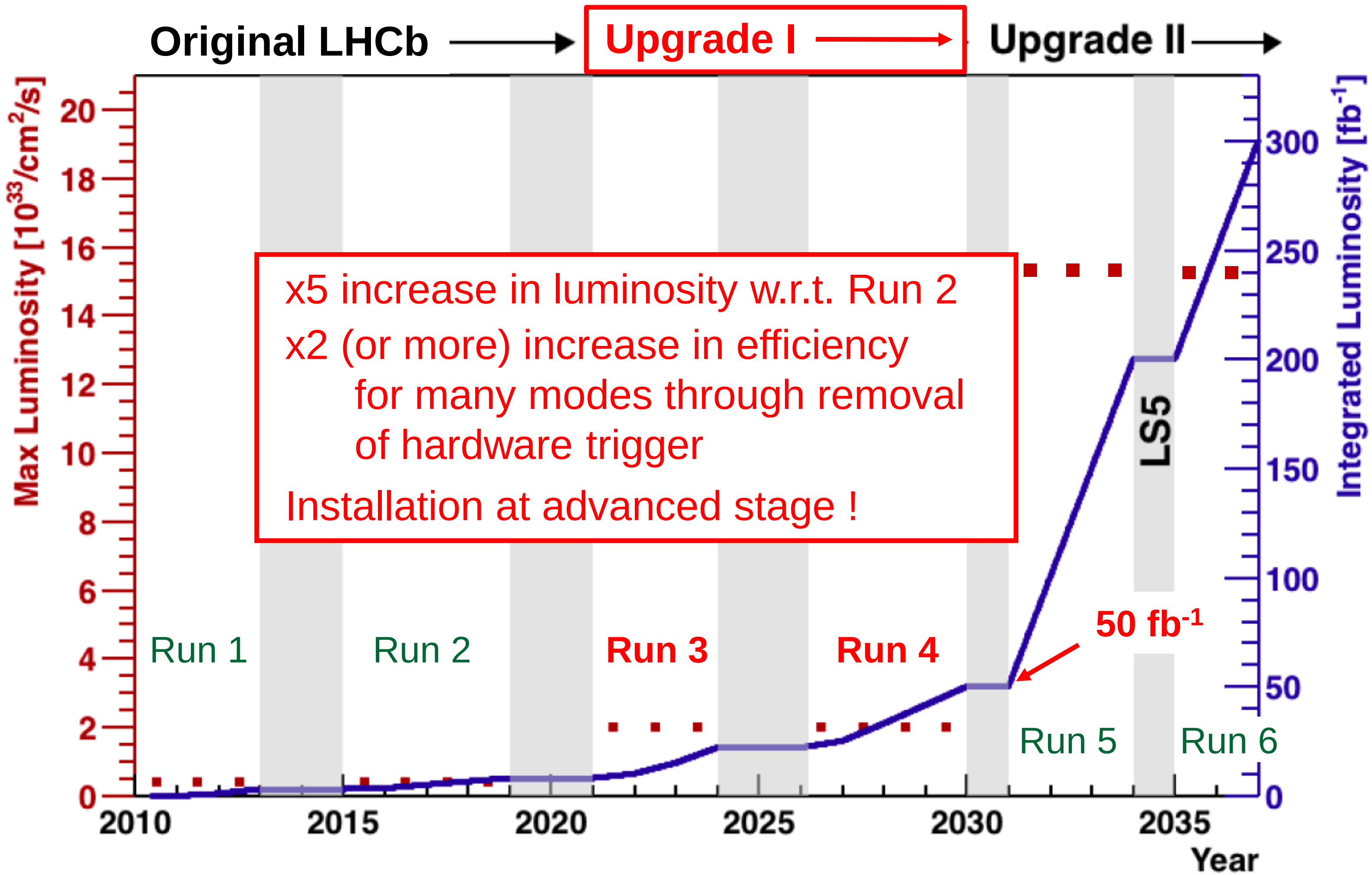
$2E$, GeV	Events recorded
3.1	$10^{12}\, J/\psi$
3.69	$10^{11}\, \psi(2S)$
3.77	$10^{9}\, D\bar{D}$
4.17	$10^{8}\, D_s\bar{D}_s$
3.55 ÷ 4.3	$10^{10}\, \tau\,\tau$
4.65	$10^{8}\, \Lambda_c^+\Lambda_c^-$

LHCb timeline: Upgrades I and II



(Note that LHC schedule has evolved since this plot was made;
Run 3 physics will only begin in 2022 and now will extend to end of 2024.)

LHCb timeline: Upgrades I and II



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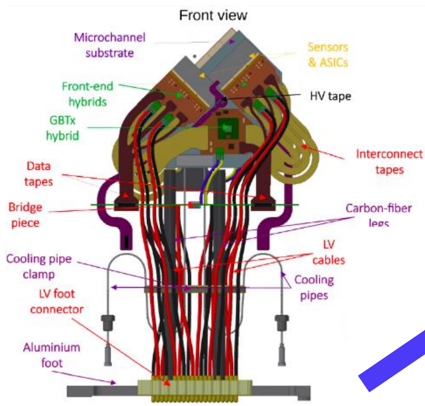
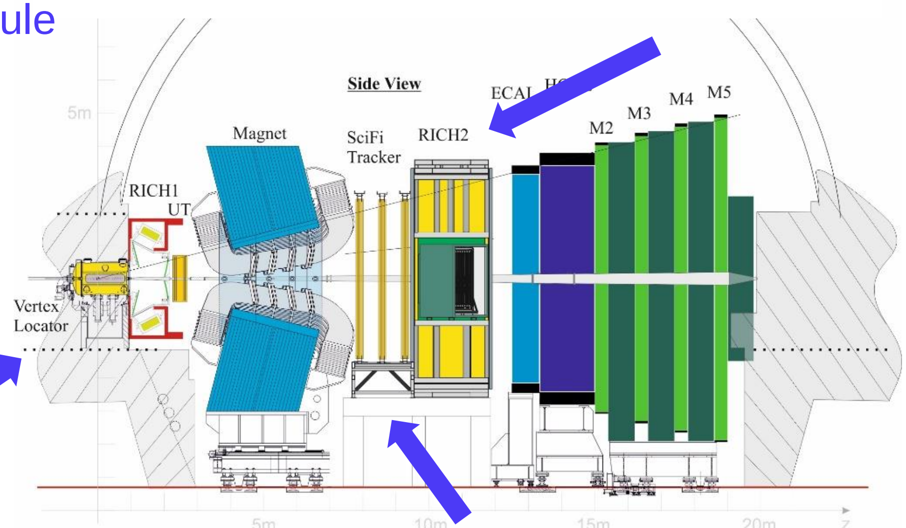
LHCb Upgrade I is now !

Essentially a new experiment – almost all subdetectors replaced, & all read out to a software trigger farm at 40 MHz !

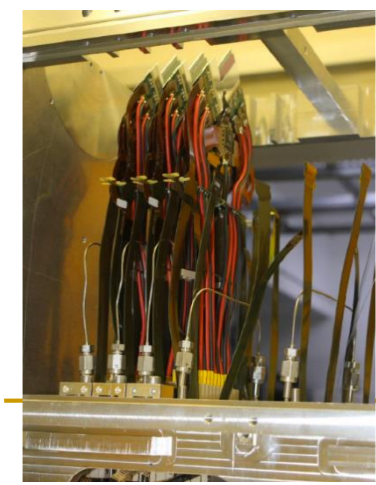
Half of RICH2 photodetector plane

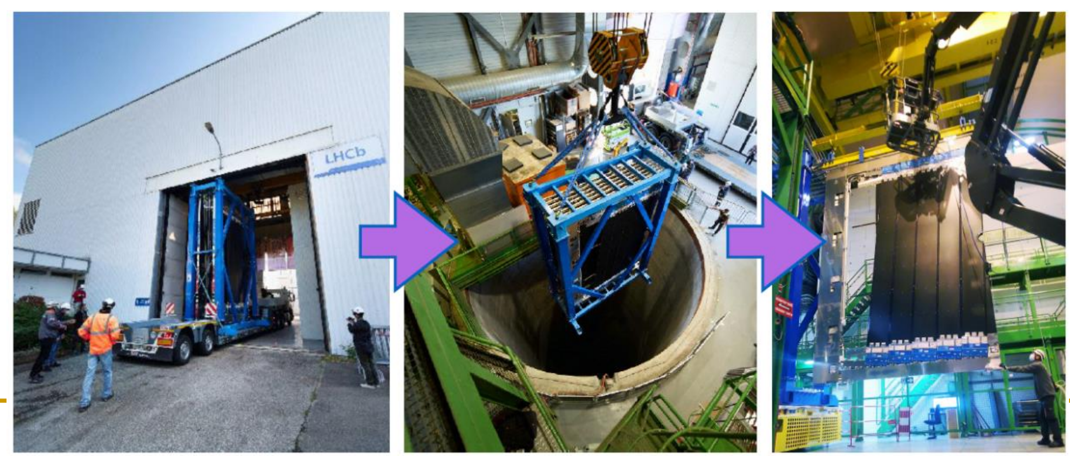
Schematic of VELO module





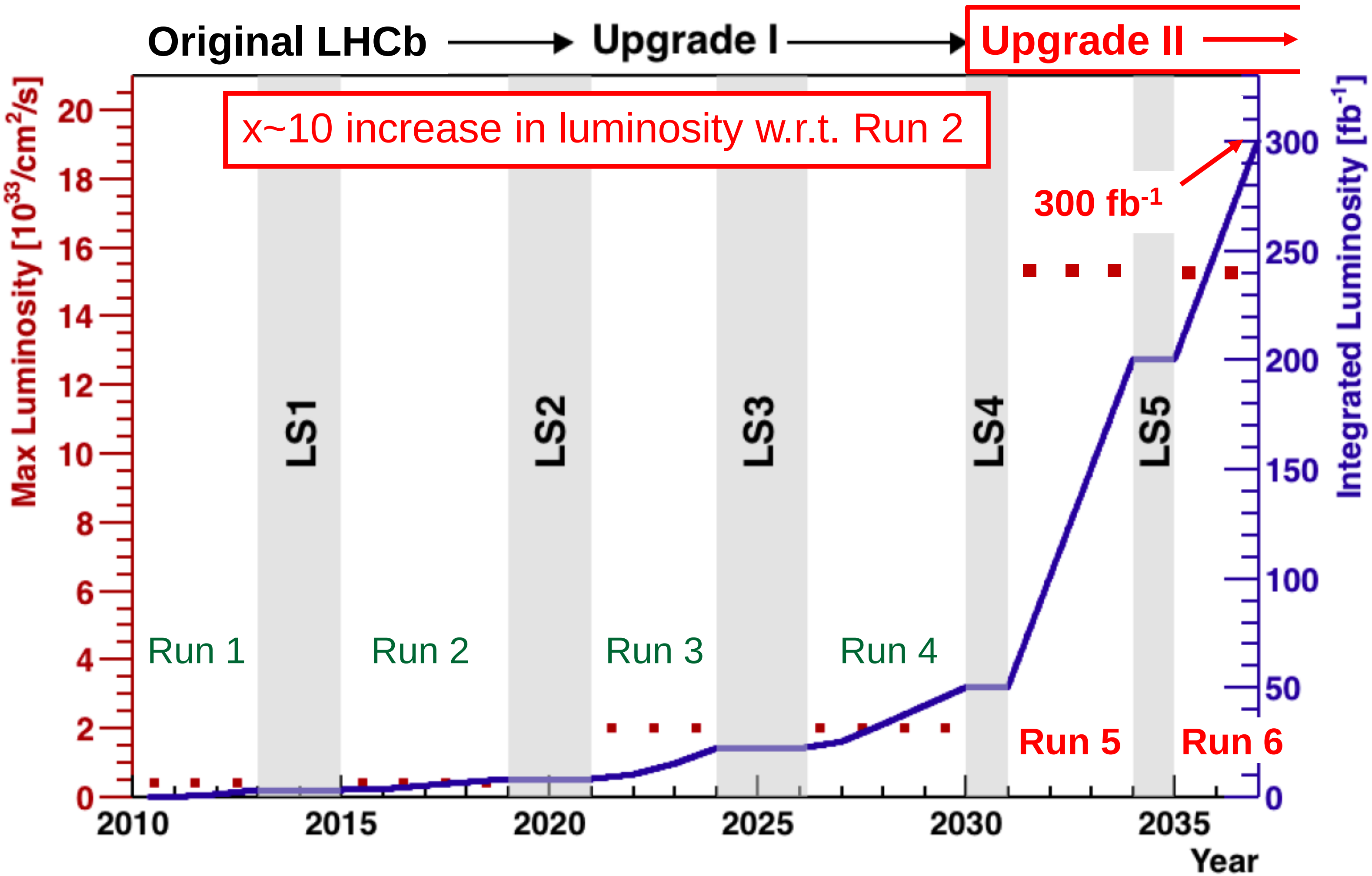
Installed VELO modules





Scintillator-fibre (SciFi) tracker being installed

LHCb timeline: Upgrades I and II



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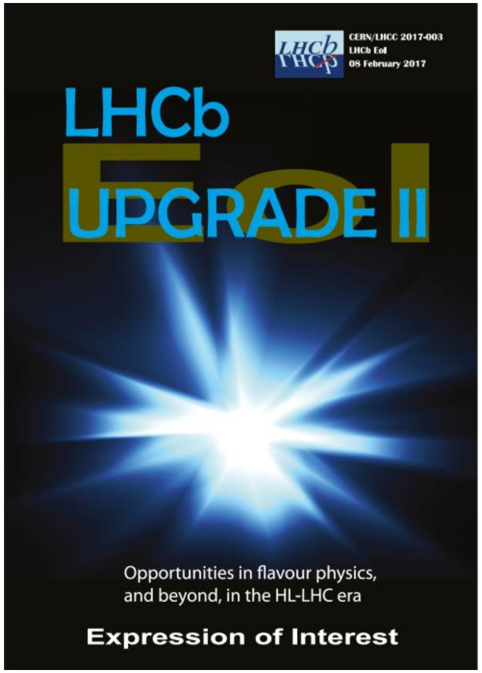
LHCb Upgrade II – the ultimate LHC flavour experiment

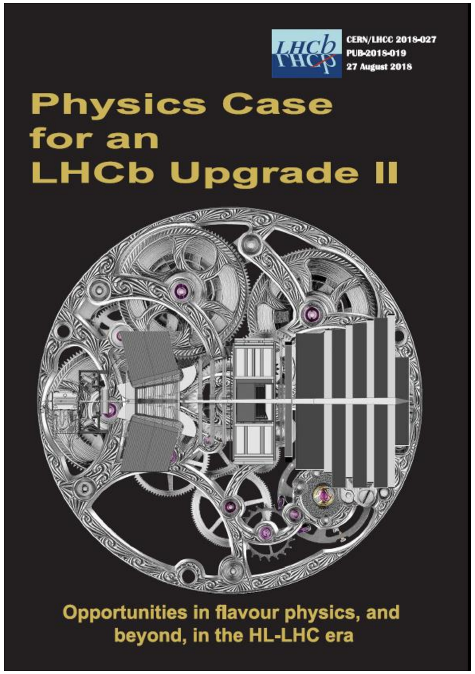
Begin after LS4 (~2030). Operate at up to 1.5 x 10^{34} $cm^{-2}s^{-1}$ & collect 300 fb^{-1} +.

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 x 10^{34} $cm^{-2}s^{-1}$ and permitting the collection of 300 fb^{-1} or more at IP8 during the envisaged lifetime of the LHC"

[CERN-ACC-NOTE-2018-038]

'Framework TDR' now being written, to be submitted this autumn.

Many fascinating detector challenges, *e.g.* high radiation, use of ~10 ps timing *etc*.

LHCb Upgrade II – the ultimate LHC flavour experiment

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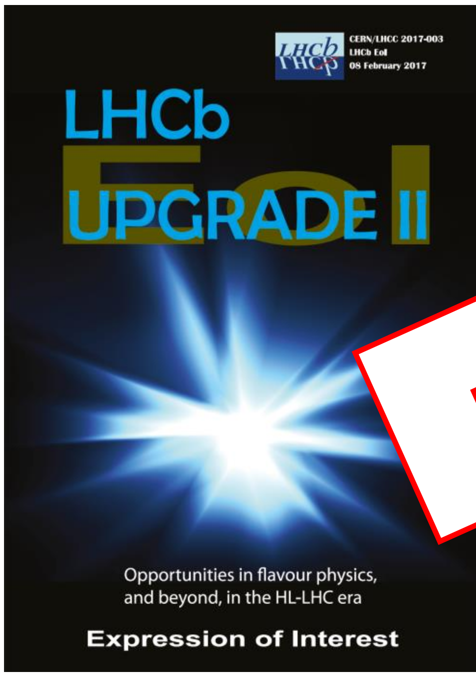

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Full physics case

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

New collaborators welcome !

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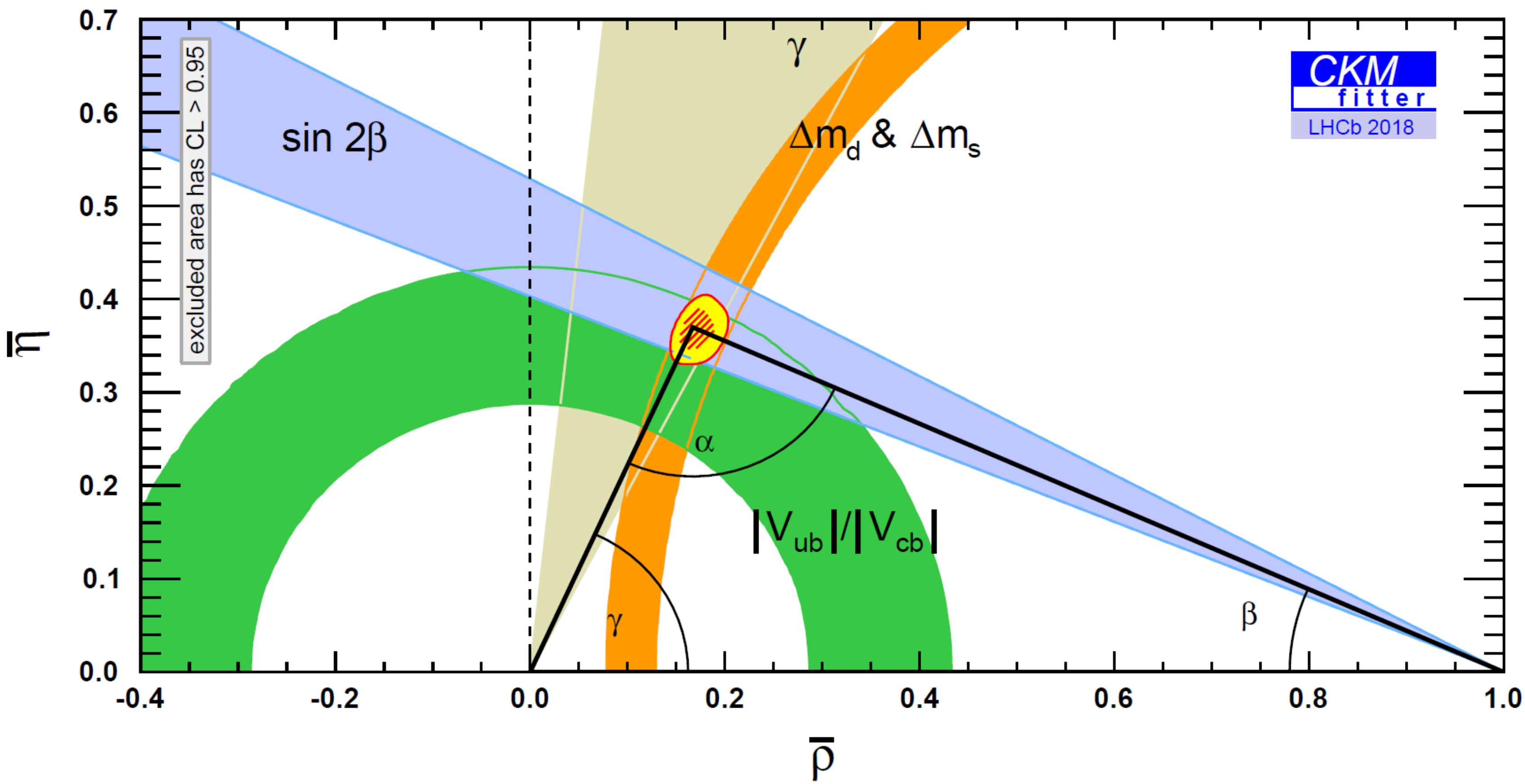
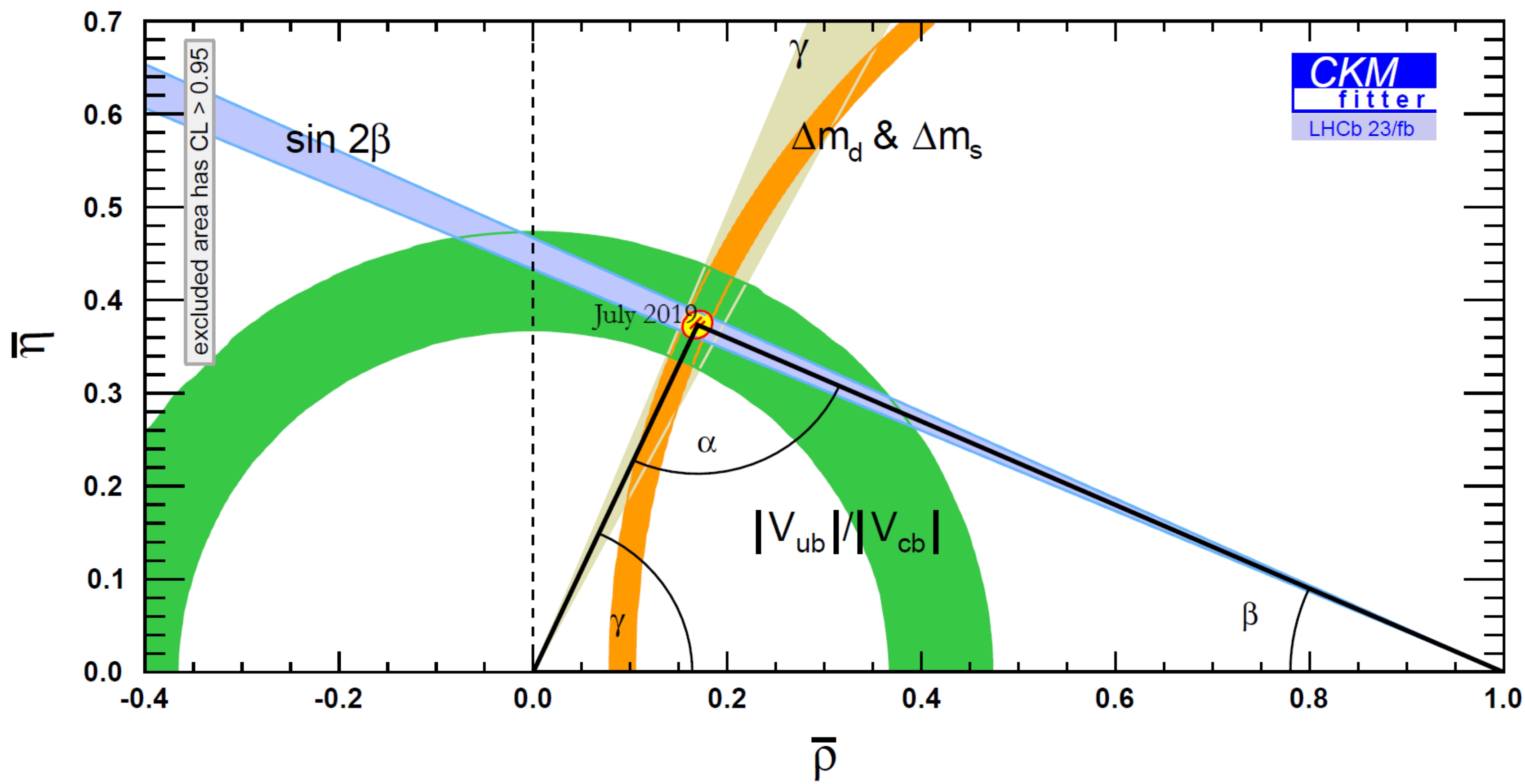
Evolution of constraints on Unitarity Triangle

UT plotted using constraints from LHCb alone (+ lattice QCD): 2018 status



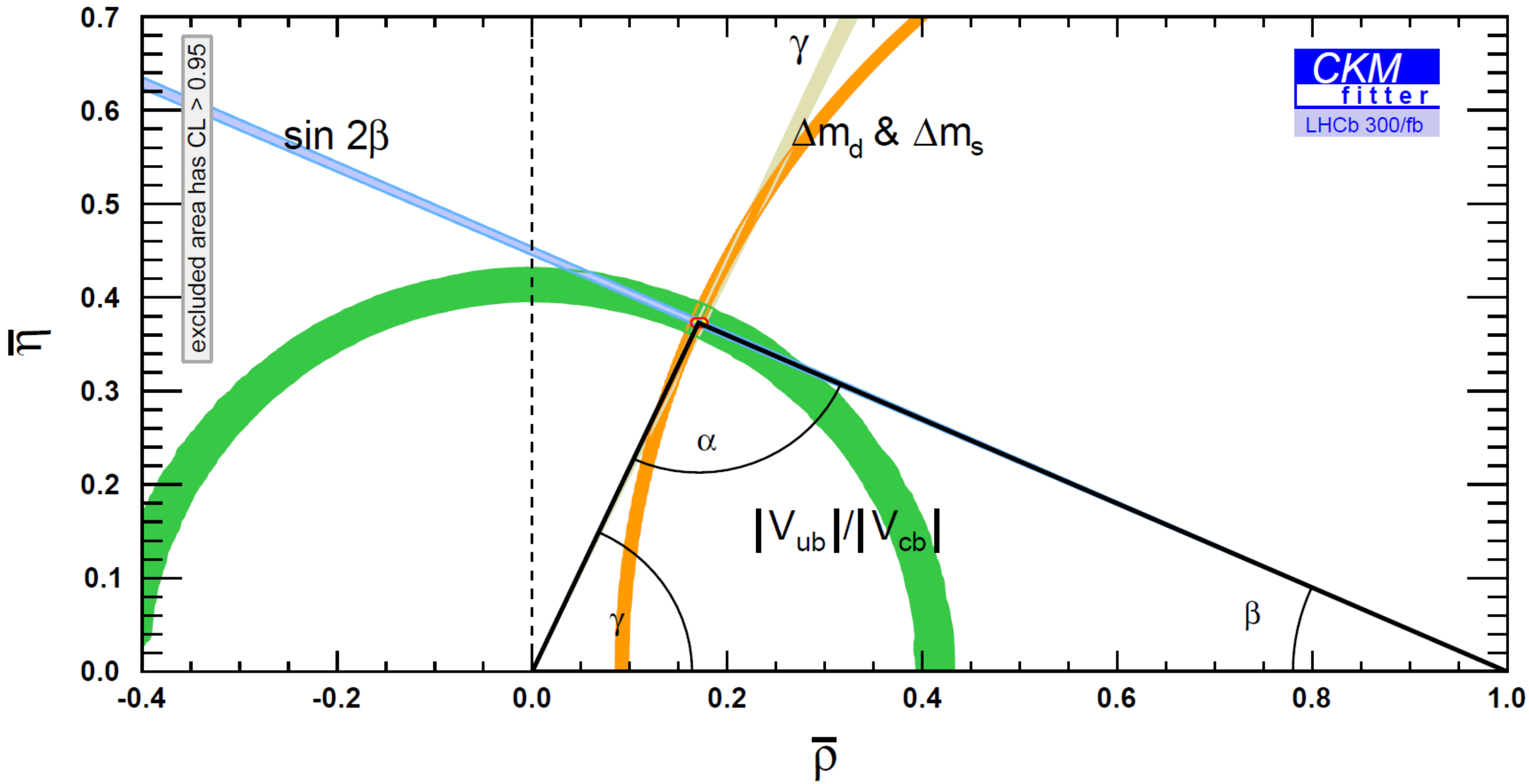
Evolution of constraints on Unitarity Triangle

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

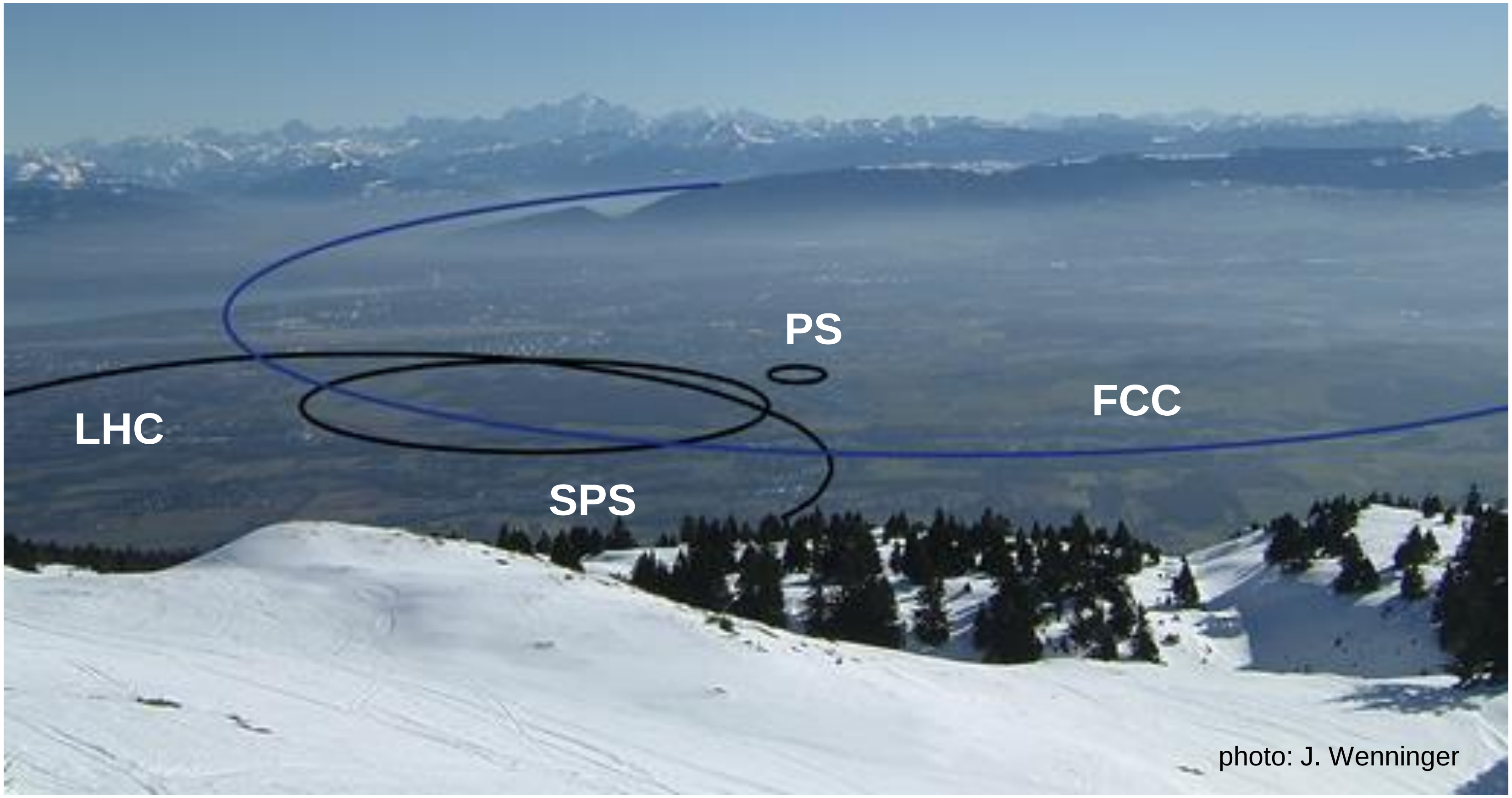


Evolution of constraints on Unitarity Triangle

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



Opportunities at the Z pole: FCC-ee



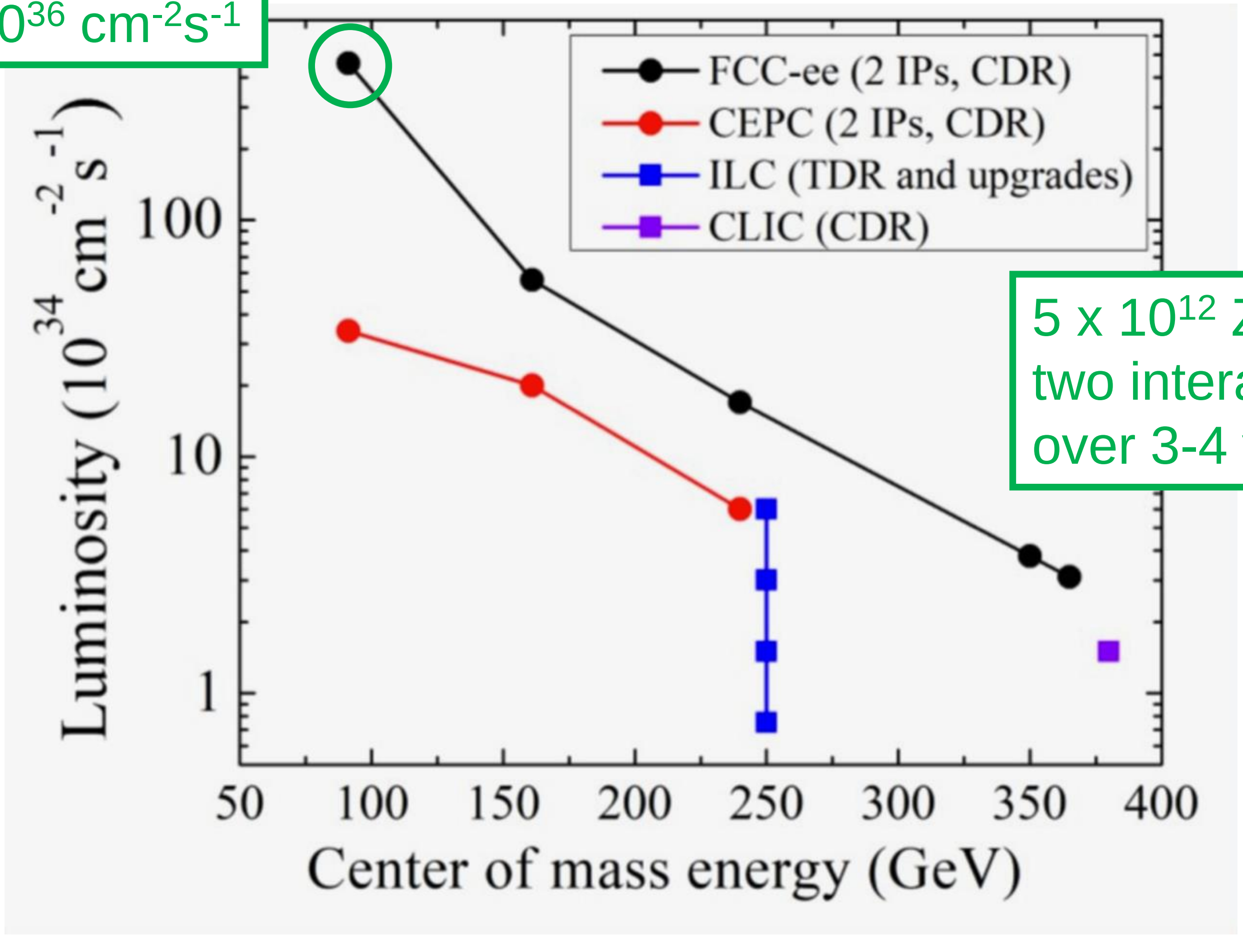
FCC-ee is a proposed e^+e^- collider for 2039→ that would run at the Z pole (91 GeV), WW threshold (161 GeV), HZ energies (240 GeV), ttbar energies (350 & 365 GeV).

(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 EW physics, and also b- and τ-physics.

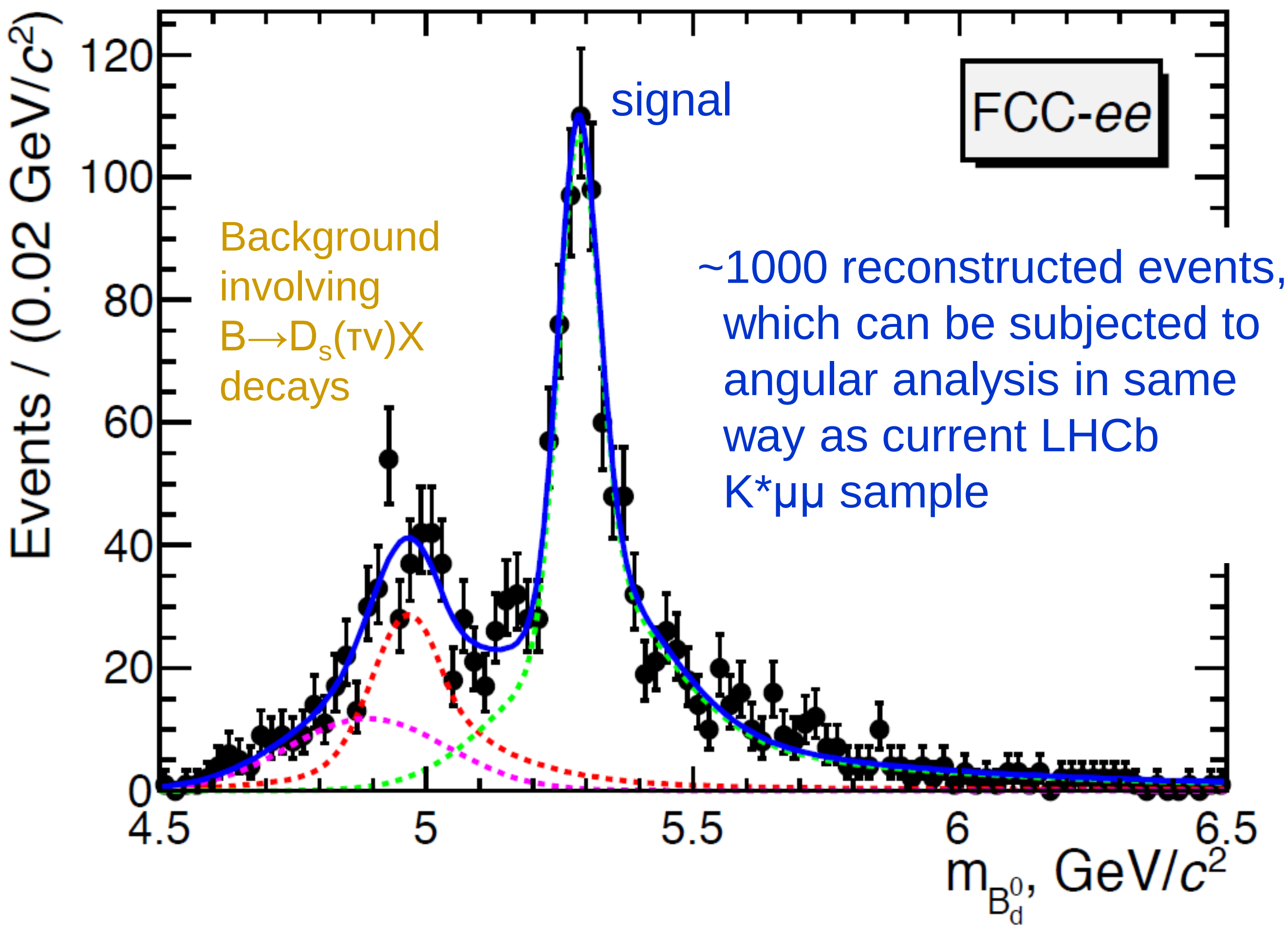
4.6 x 10^{36} $cm^{-2}s^{-1}$



5 x 10^{12} Z^0's with two interaction points over 3-4 years

Opportunities at the Z pole: FCC-ee

100 ab^{-1} at Z pole → >10^{12} bbar pairs. Exciting flavour-physics programme (essentially Belle-II x30, plus B_s, B_c and Λ_b), particularly promising for channels including neutrals & missing energy, *e.g.* $B_c \to \tau\nu$, $B^0 \to K^*\tau^+\tau^-$…



arXiv:2106.01259, arXiv:2105.13330

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 results now emerging from the LHC are remarkable in their precision and, in some cases, very intriguing. Run 2 still has much to tell us.

The programme is ongoing. Belle II and the LHCb Upgrades will bring great leap forwards in precision, and will make new observables accessible.

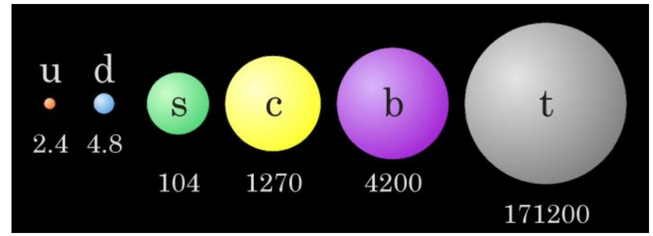
We are truly living through a golden age of flavour !

Backups

Why flavour ? A puzzle of the SM

Flavour encompasses many of the open questions of the Standard Model.

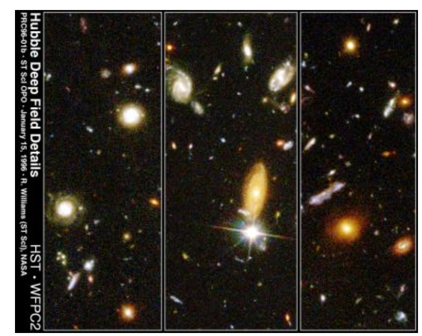
- Why 3 generations of quarks, and why the extreme hierarchy of masses ?



- What determines the hierarchical structure of the CKM matrix ?

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.9705 - 0.9770 & 0.21 - 0.24 & 0 - 0.014 \\ 0.21 - 0.24 & 0.971 - 0.973 & 0.036 - 0.070 \\ 0 - 0.014 & 0.036 - 0.070 & 0.997 - 0.999 \end{pmatrix}$$

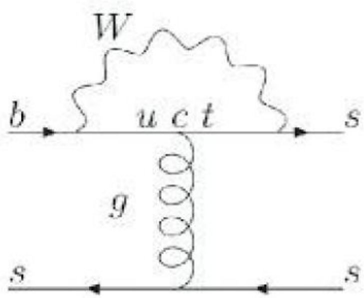
- The CKM paradigm accommodates CP violation, but it does not really explain it. Furthermore, can the study of quark flavour tell us anything about the matter-antimatter asymmetry of the universe ?

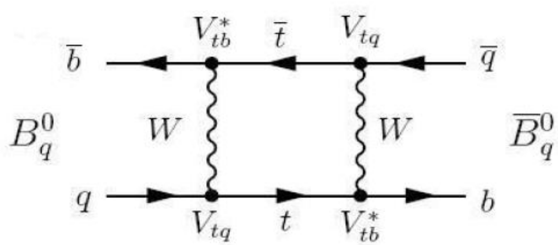


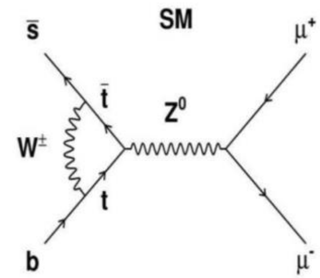
Most importantly, flavour physics is a tool of discovery !

Why flavour ? A tool of discovery

In flavour physics the guiding principle is to probe processes where loop diagrams are important, as here non-SM particles may contribute





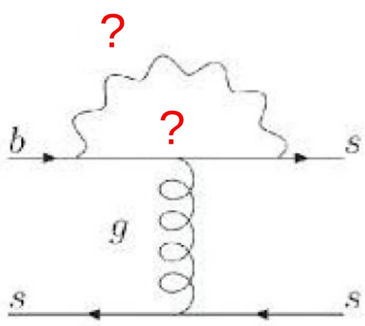


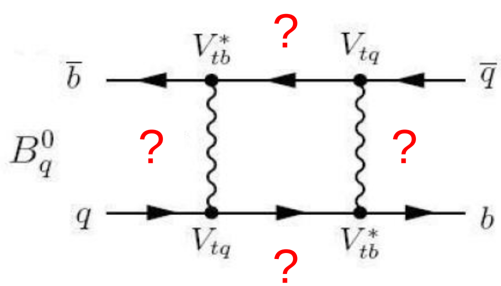
(but as we will see, tree-mediated decays also have their role to play).

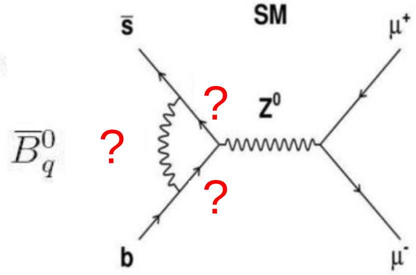
Indirect search principle ➡ Precise measurements of low energy phenomena tells us about unknown physics at (potentially *much*) higher energies

Why flavour ? A tool of discovery

In flavour physics the guiding principle is to probe processes where loop diagrams are important, as here non-SM particles may contribute







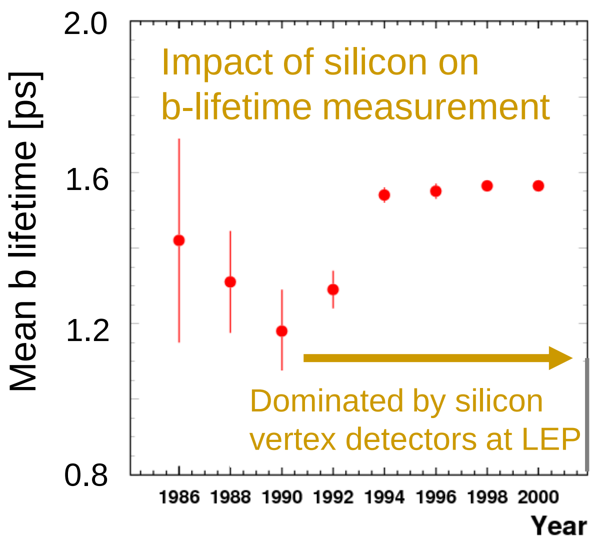
(but as we will see, tree-mediated decays also have their role to play).

Indirect search principle ➡ Precise measurements of low energy phenomena tells us about unknown physics at (potentially *much*) higher energies

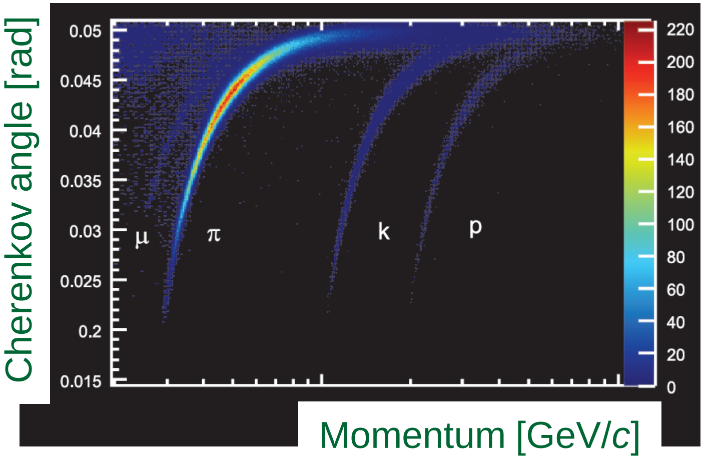
Why have we made progress?

Important flavour-physics measurements were performed prior to 2001 (*e.g.* at ARGUS, CLEO, the SPS and LEP), but since then there has been an avalanche of results. What has enabled this explosion of progress?

- High-luminosity accelerators with large bbbar production cross-sections;
  - Number of b-hadrons produced at LEP ~ 10^7
  - Number of b-hadrons produced (so far) at LHCb ~ 10^{12}
- Improved and dedicated instrumentation, *e.g.* vertex detectors and RICHes;



Cherenkov angle vs momentum in LHCb RICH



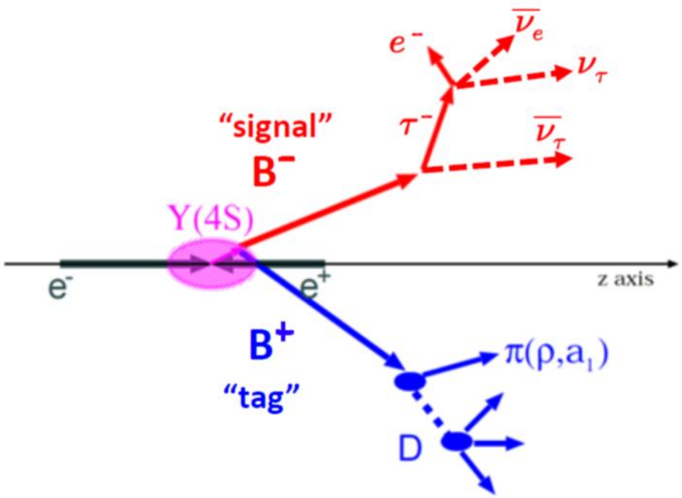
- Improved triggering, essential for hadron collider experiments;
- And not forgetting progress in theory, in particular lattice QCD.

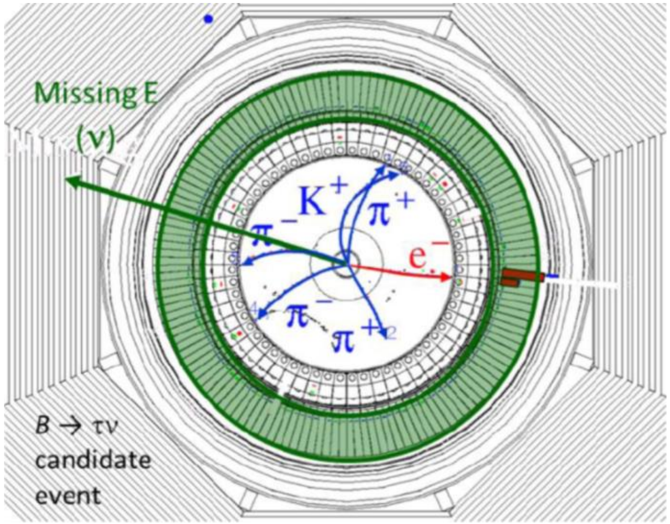
Why Belle II ?

B production at the Υ(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→τν





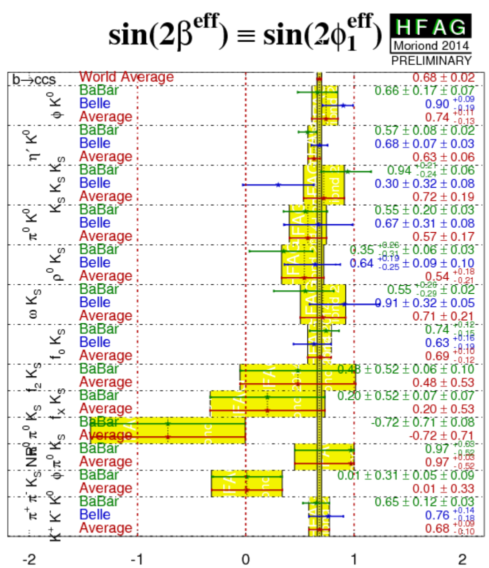
Why Belle II ?

B production at the $\Upsilon(4S)$ 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).

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

e.g. most modes suitable for sin2β measurements involving Penguin loops ($b\rightarrow c\bar{c}s$) 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 ?

B production at the Υ(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).

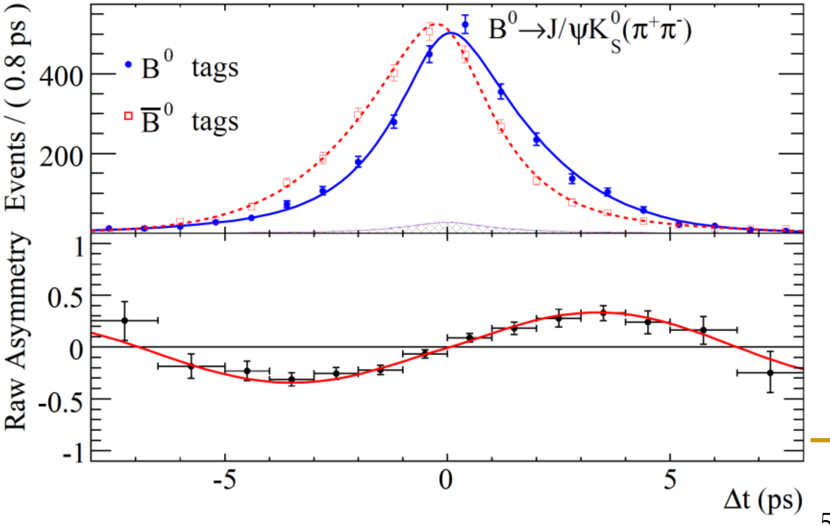
- Low multiplicity environment permits excellent performance for final states with π^0s, η's, photons. Also, good efficiency for long-lived particles K_S and K_L.

- Coherent B^0B^0bar production at Υ(4S) makes flavour tagging easier and compensates for lower sample sizes in time-dependent CP measurements

e.g. in sin2β measurement with $B^0 \to J/\psi K_S$

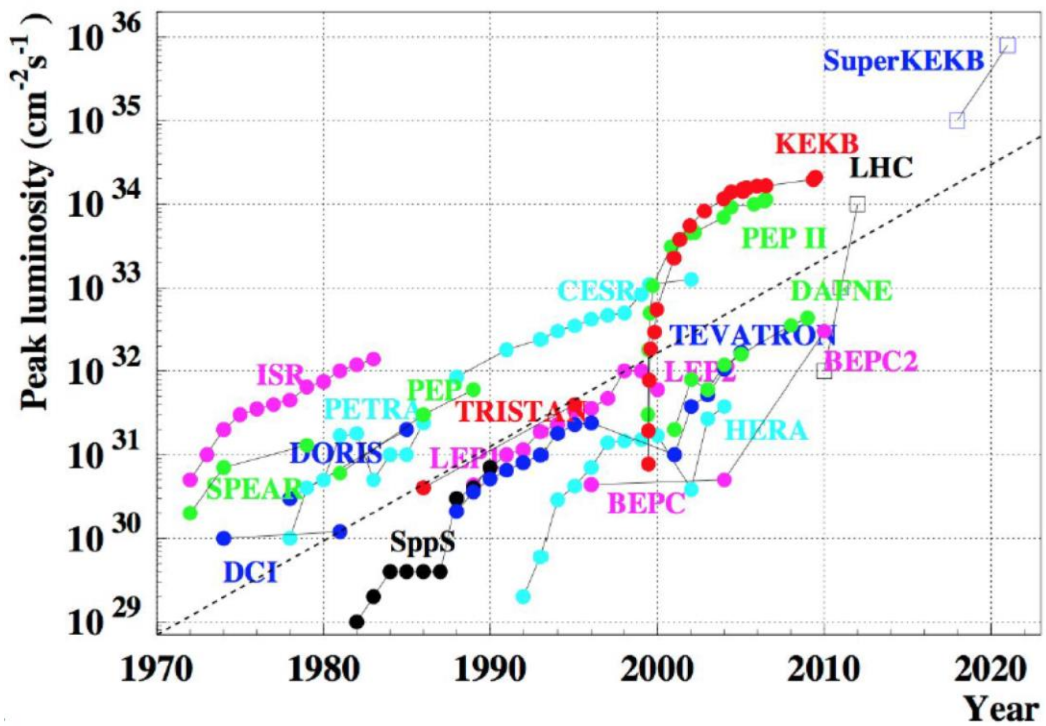
ε (tag effective) BaBar ~ 31 %
[PRD 79 (2009) 072009]

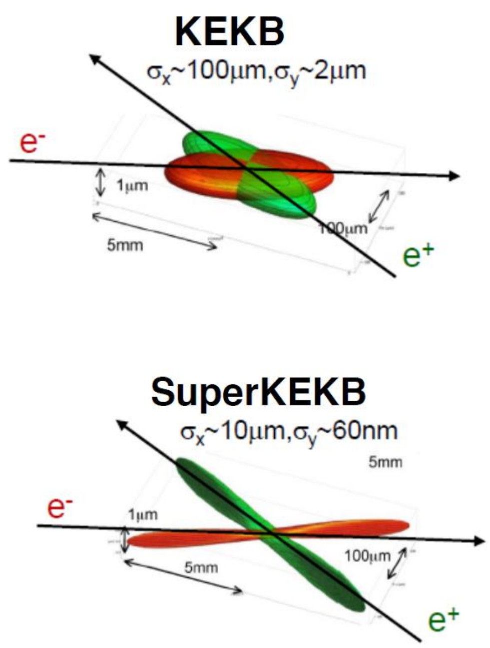
ε (tag effective) LHCb ~ 3 %
[PRL 115 (2015) 031601]



SuperKEKB

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





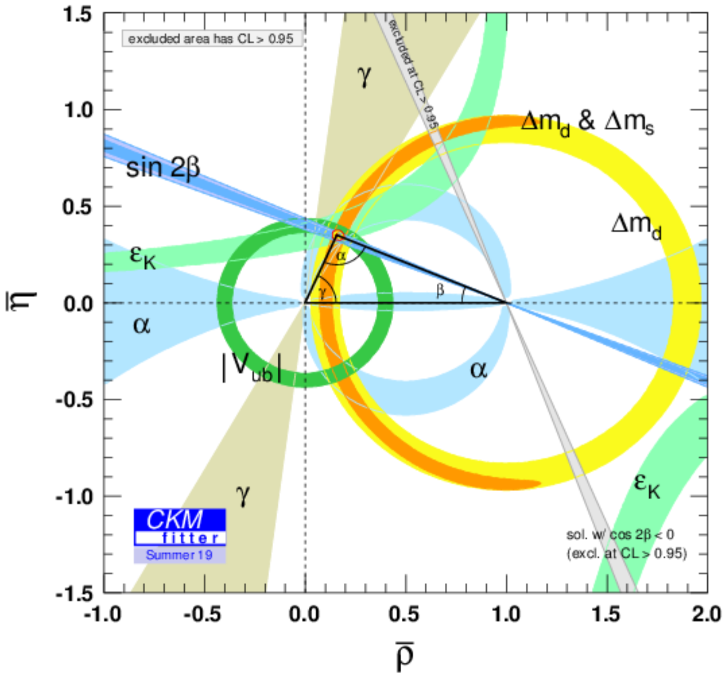
An ambitious 40-fold increase in luminosity on KEKB, to be achieved by squeezing the beams by ~1/20 and doubling the currents.

The Unitarity Triangle and CPV studies

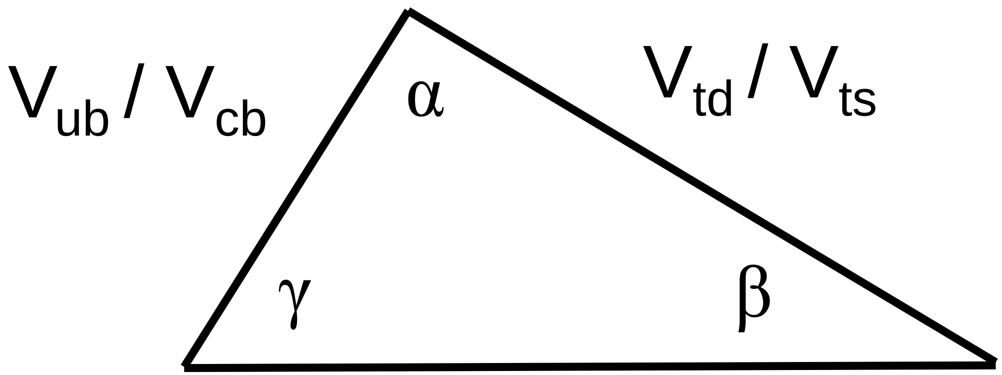
The Unitarity Triangle is a geometrical description of CP-violation within the context of the Standard Model, which in the flavour sector is the CKM mechanism.

We must check its consistency through precise measurements.

The B factories showed that the CKM paradigm dominates the picture (the first triumph of the 'age of flavour' !), but New Physics can still be lurking at ~20% level.



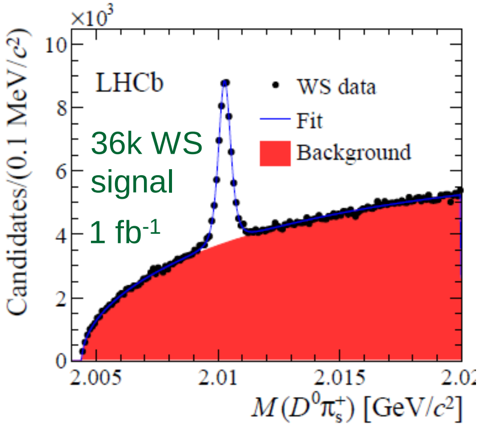
Let's see how the LHC is advancing this programme…

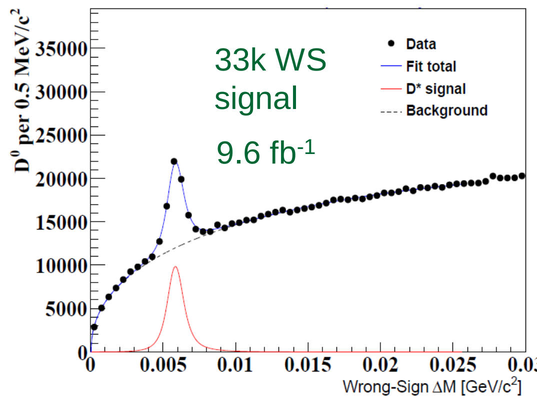


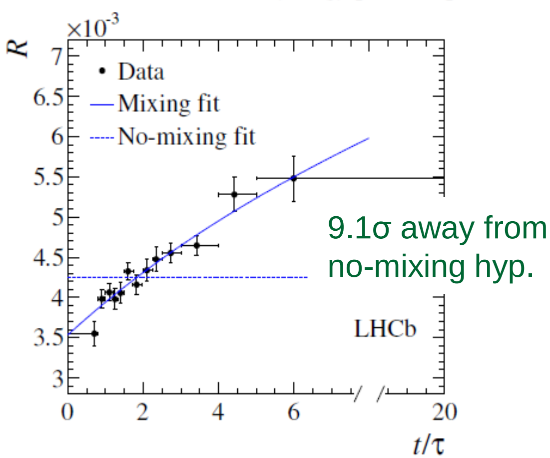
Rise of the hadron machines

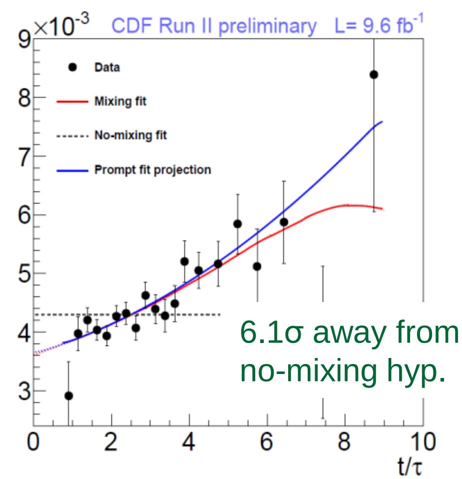
Power of hadron colliders is now clear. In 2013 LHCb and CDF published first individual (>)>5σ measurements, in `wrong sign' (WS) Kπ analyses.

LHCb, PRL 110 (2013) 101802









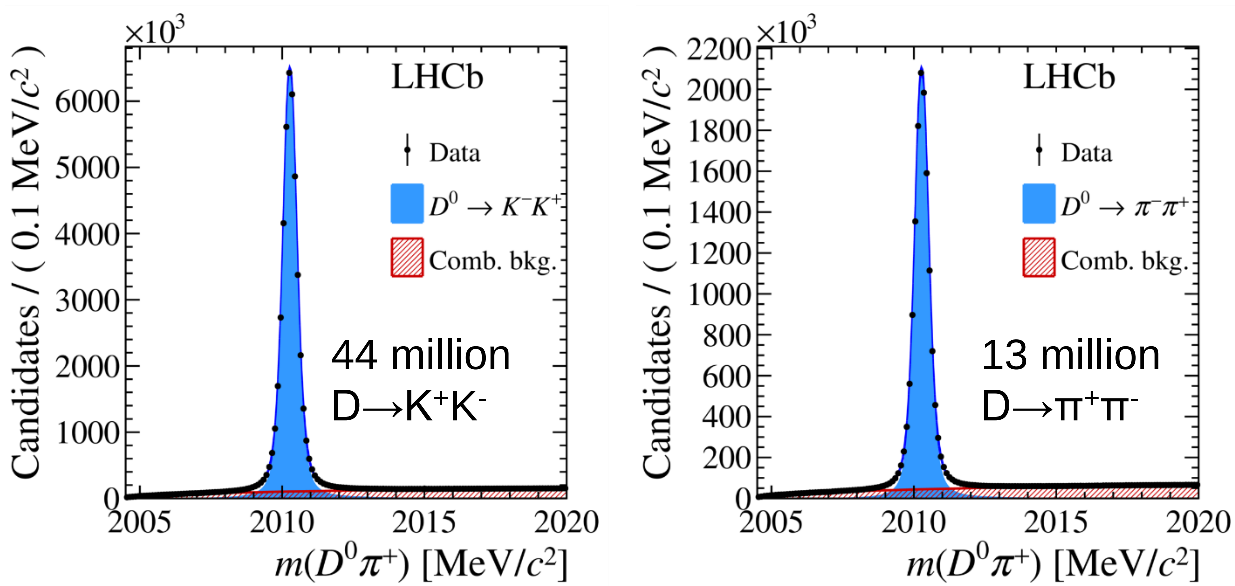
CDF, PRL 111 (2013) 231802

Although e^+e^- machines retain advantages for modes with neutrals, LHC has huge advantages for charged modes (*e.g.* # WS Kπ in above plot, which is a small fraction of Run 1, is 3x whole Belle sample) and also time resolution.

Observation of (direct) CPV in charm

Next step-change in knowledge came with discovery of CP violation in 2019.

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



[PRL 122 (2019) 211803]

Run 1 + Run 2 ➡

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

5.3σ from 0 !

Note this is direct CPV (or 'CPV in decay'). As with mixing, the effect is larger than had been expected, but can (probably) be accommodated in SM. Observation opens a new frontier of measurement !

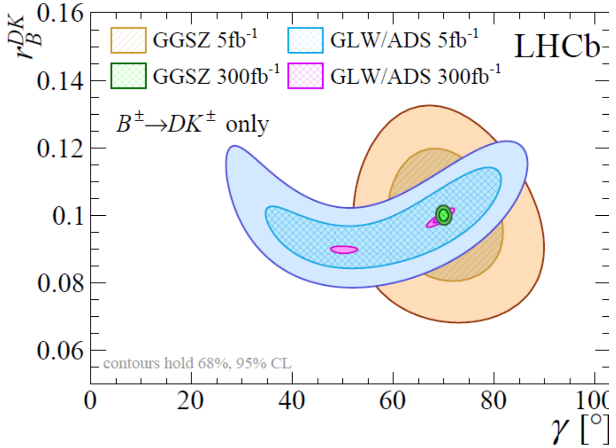
Physics reach – the obligatory table

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	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}	–

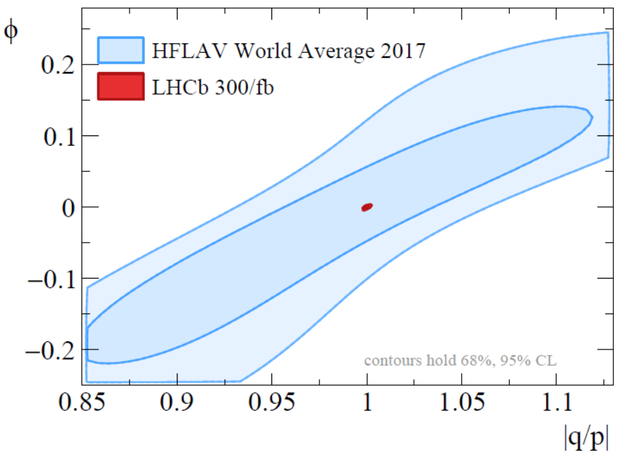
Upgrade-II physics highlights

Too much to cover – here are a few examples:

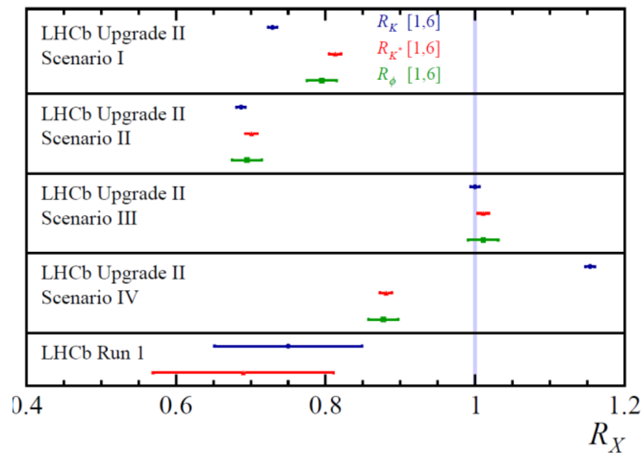
γ determination:
sub-degree precision



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, sin2β, R_K and friends, $B(B^0\to\mu\mu)/B(B_s\to\mu\mu)$…
- Also, will be able to access new observables *e.g.* angular studies of $b\to de^+e^-$.

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.

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^*} .