CP violation in beauty and charm

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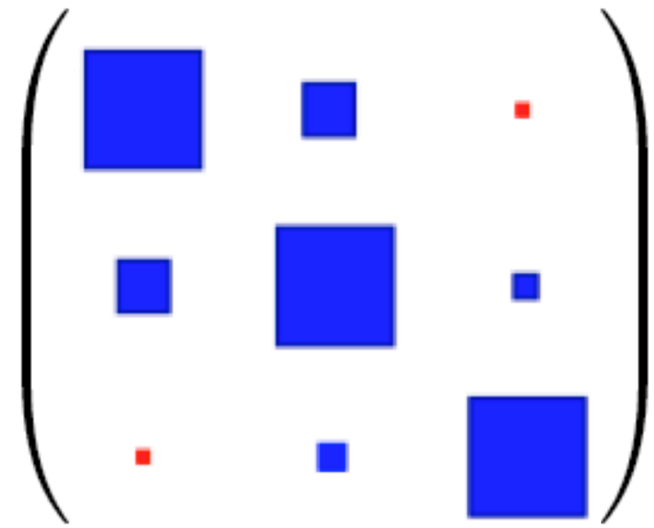
UK input to the European Particle Physics Strategy Update
IPPP Durham, 16—18 April 2018

Quark flavour mixing

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} =$$



Sensitive to BSM physics without such hierarchy.

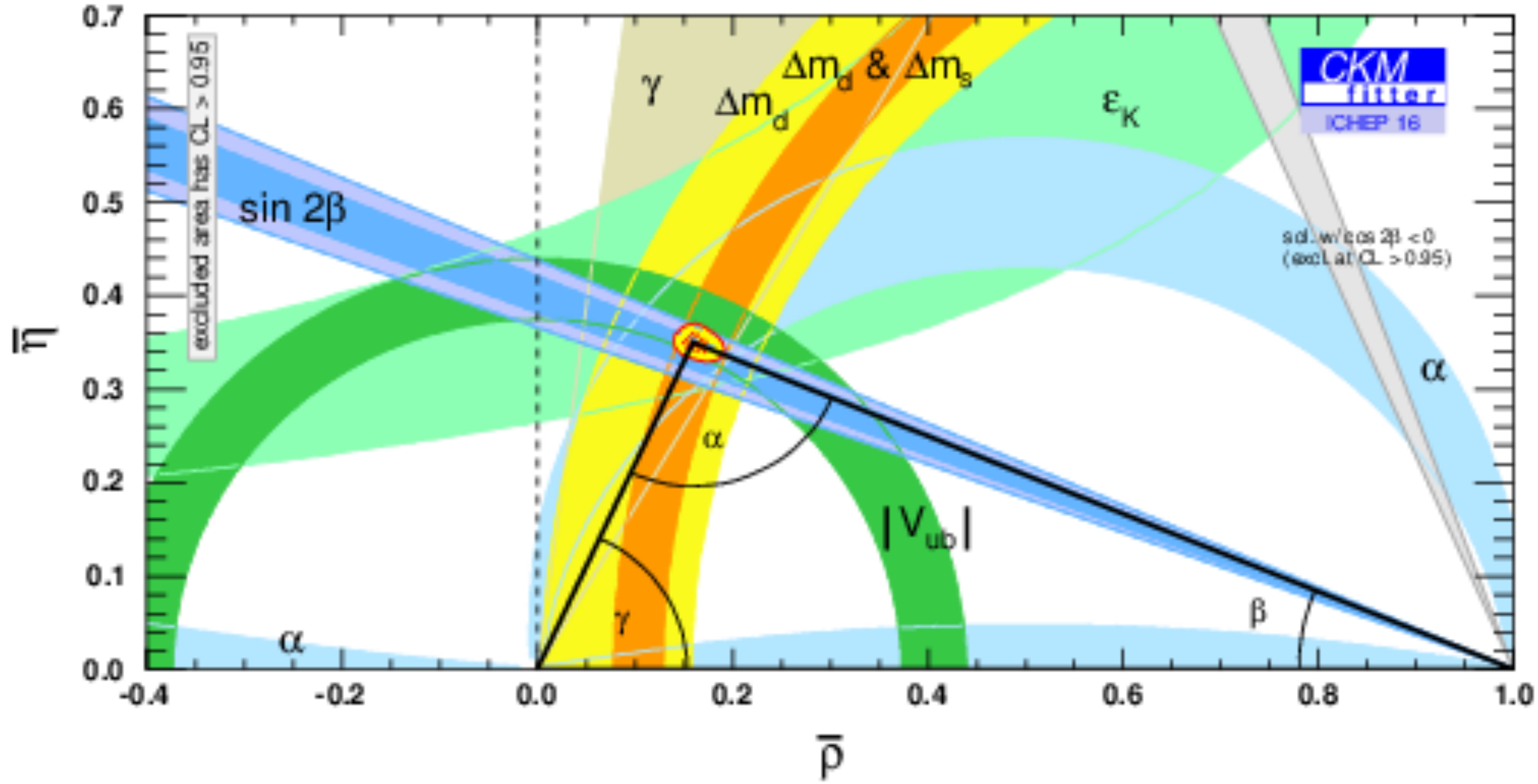
Irreducible phase is the sole source of CP violation in the SM*.

Highly predictive since V_{CKM} must be unitary, implying e.g.:

$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

*With $m_{\nu} = \theta_{QCD} = 0$ in the SM.

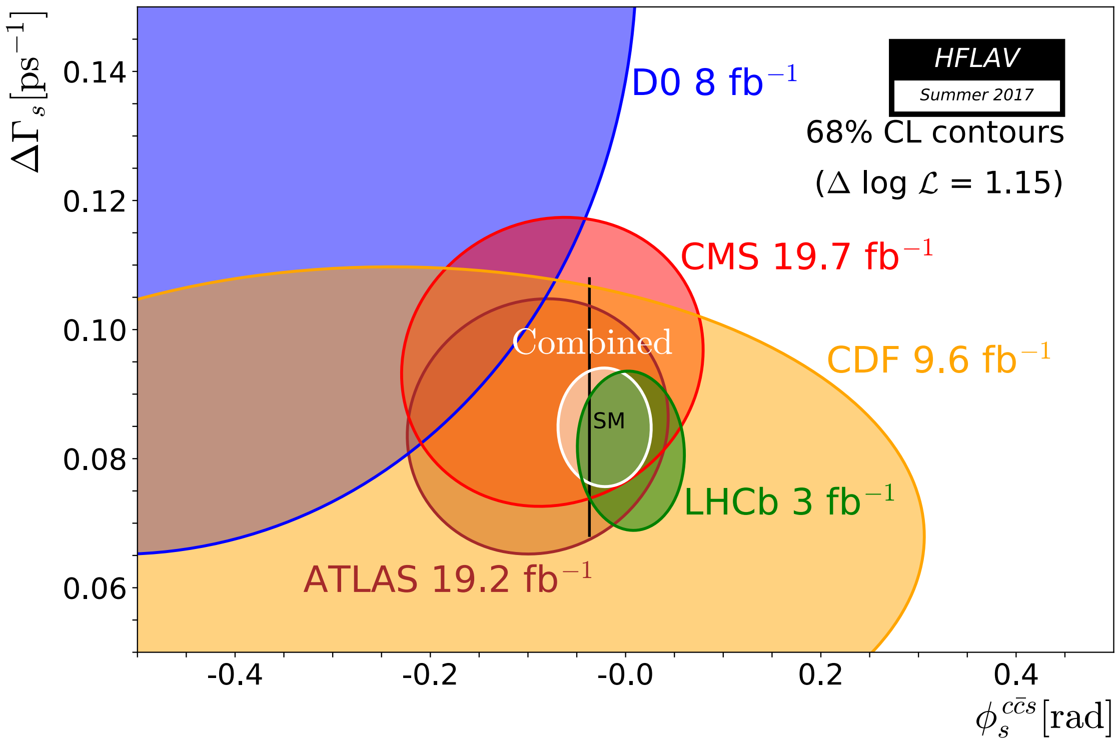
The Unitarity Triangle today

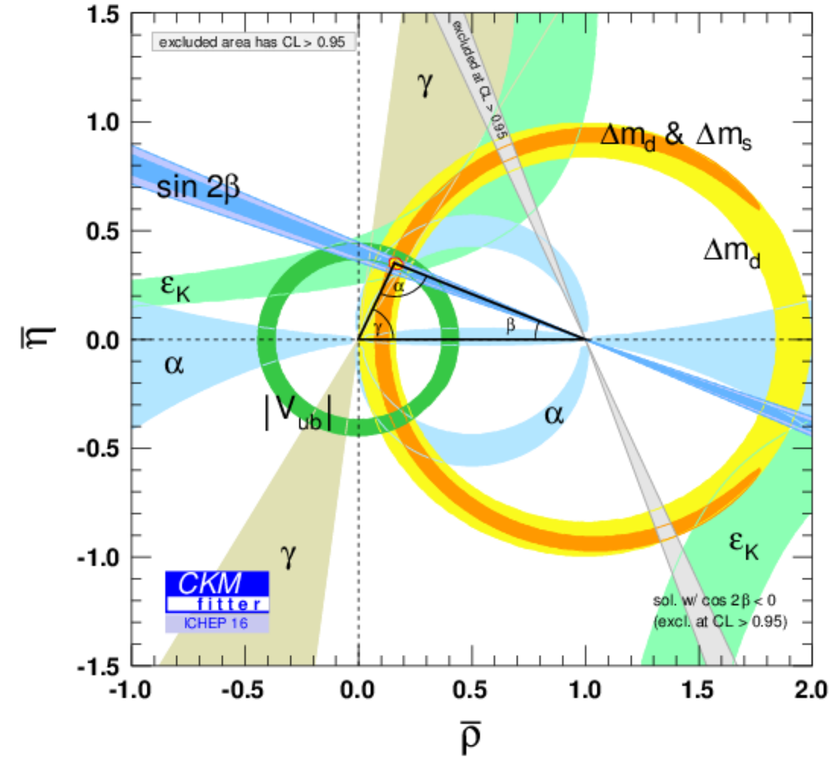


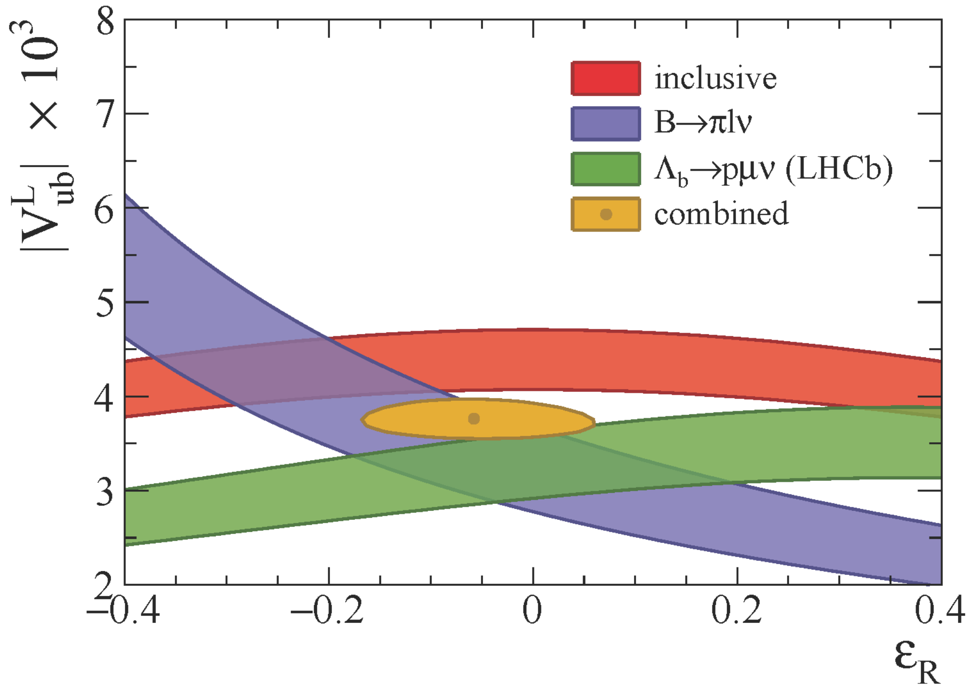
The CKM mechanism is the dominant source of CP violation in the SM.

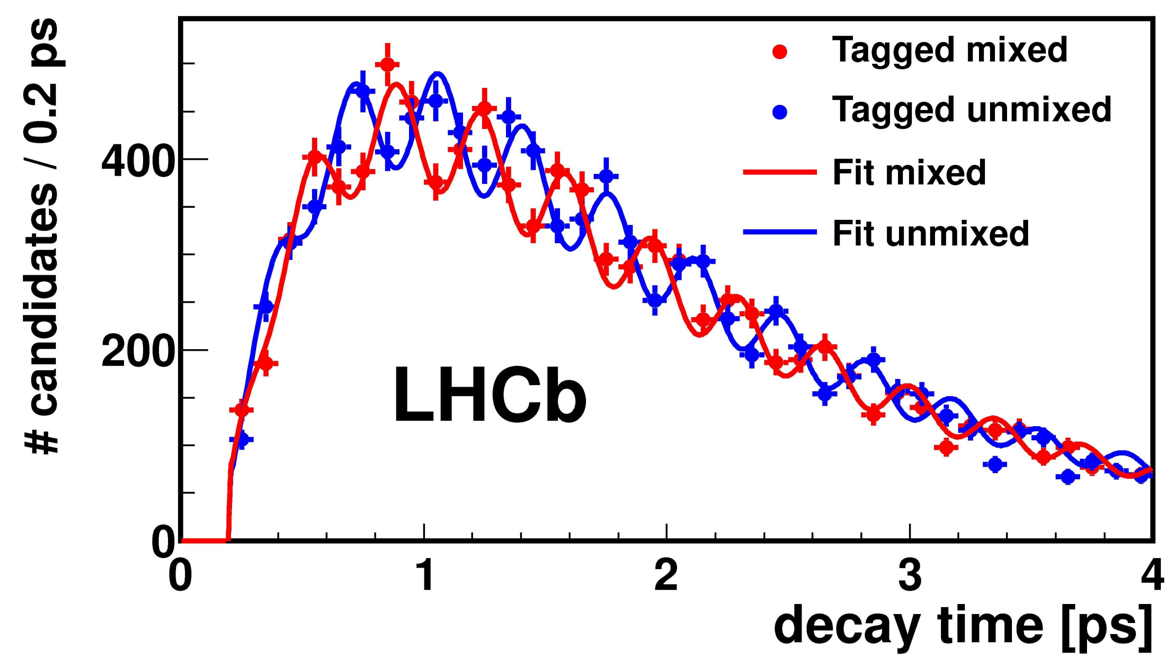
We are nowhere near exhausting the potential of quark-mixing in the search for BSM effects.

Some of the LHCb highlights in these areas…







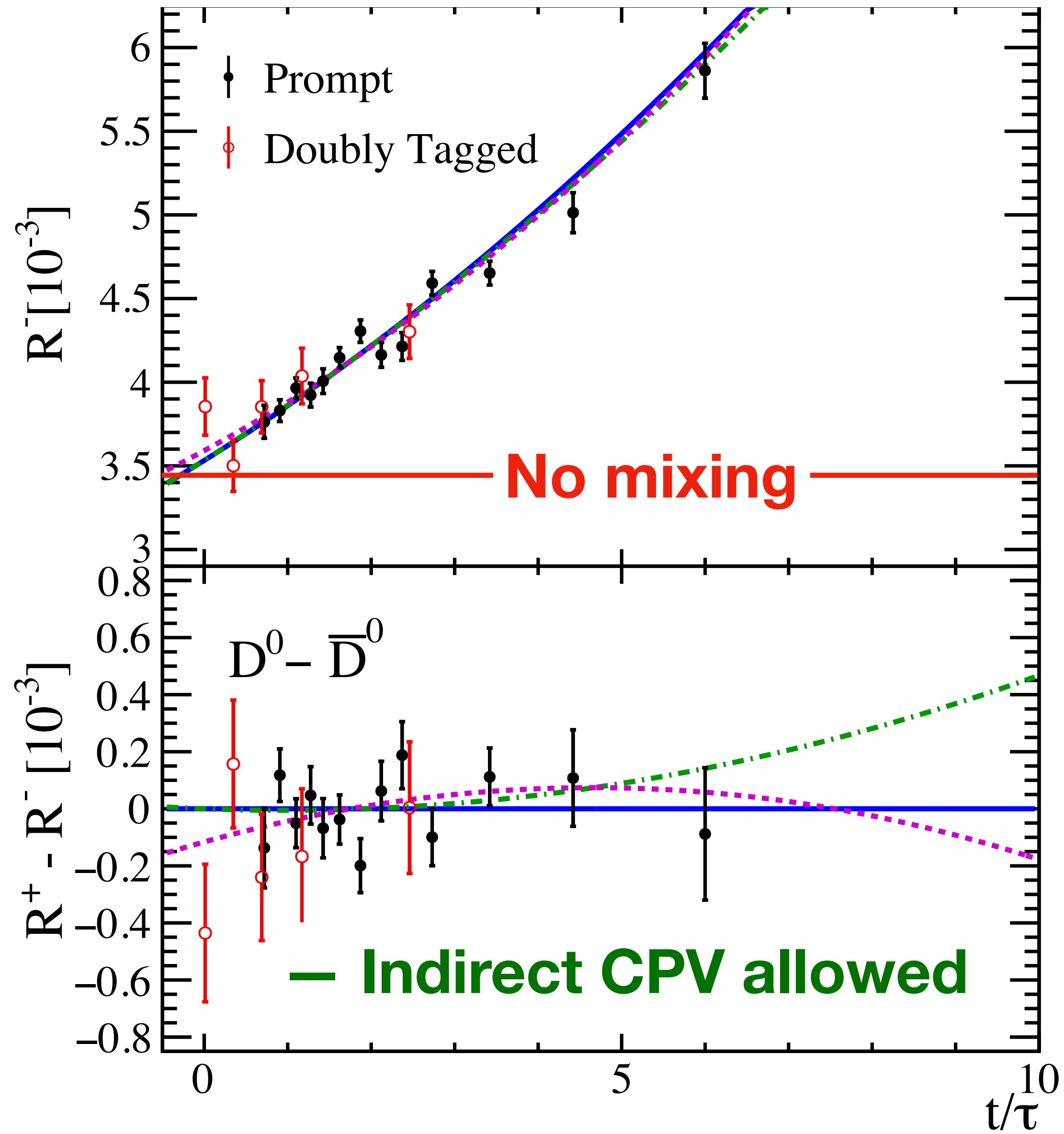


Amongst many notable results in rare B decays (Kostas' talk);
and charm, kaons, electroweak, QCD/spectroscopy, heavy ions, etc…

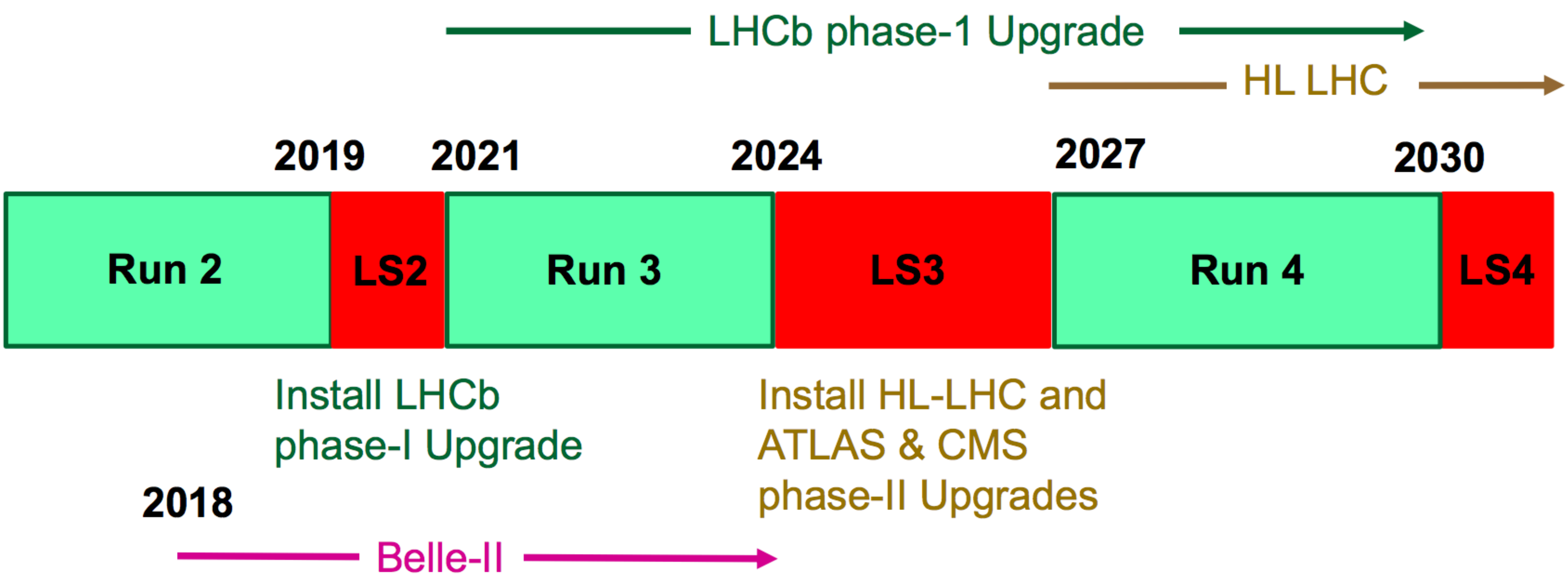
Charm

Compared to the beauty sector, CP-violation and (D-$\overline{D}$) mixing is GIM and CKM suppressed, but QCD plays a more troublesome role.

With mixing now firmly established by LHCb, the emphasis is on indirect CP violation, which is cleanly predicted to be tiny in the SM.



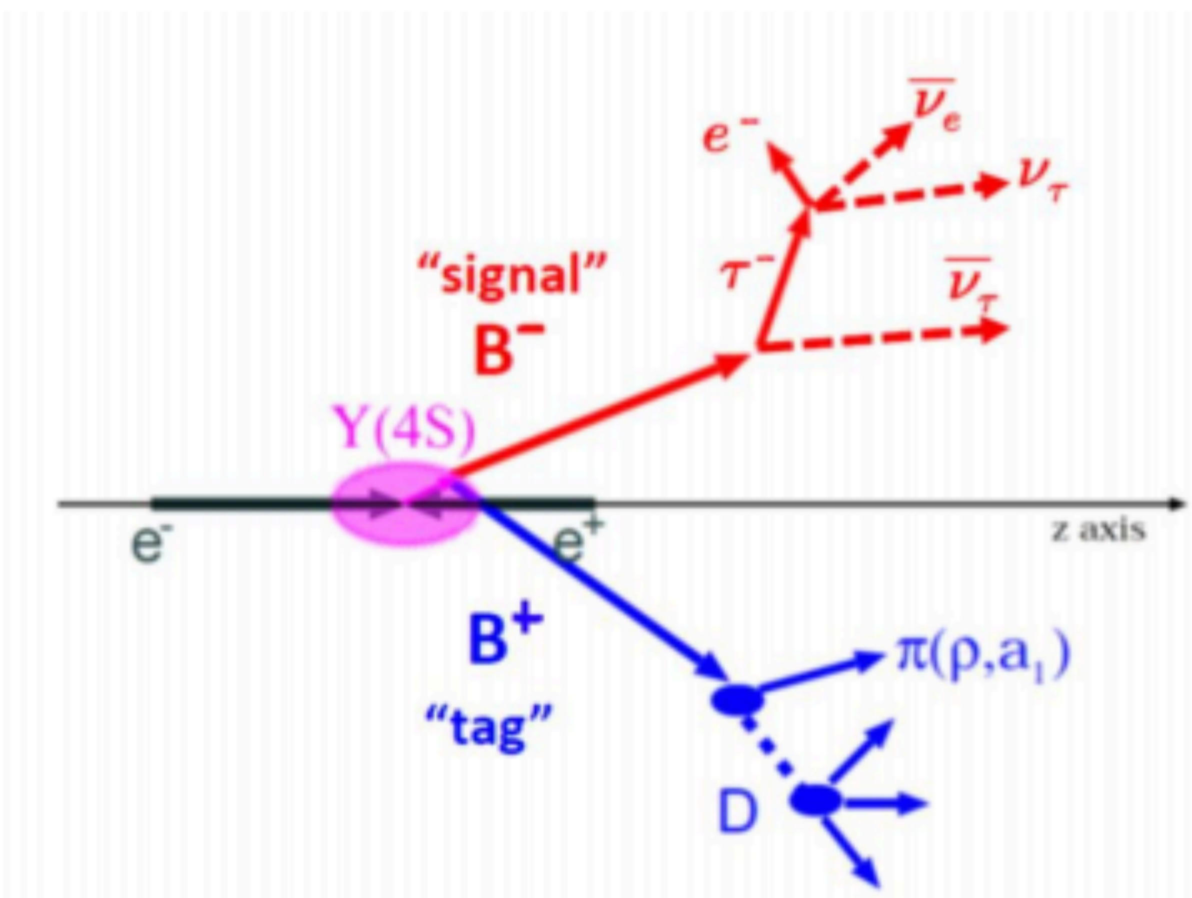
LHC schedule to 2030



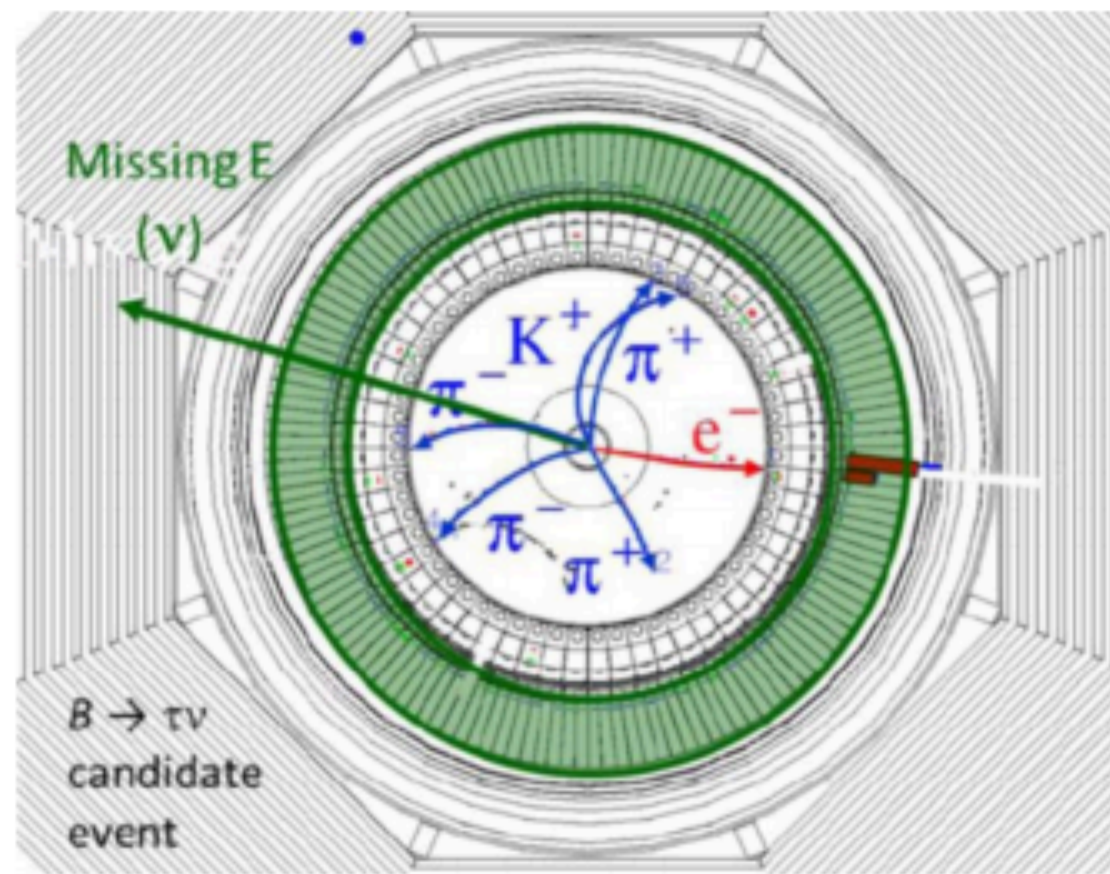
SuperKEKB and Belle II

BaBar and Belle were extremely successful experiments which confirmed the CKM mechanism as the leading source of CPV in the quark sector.

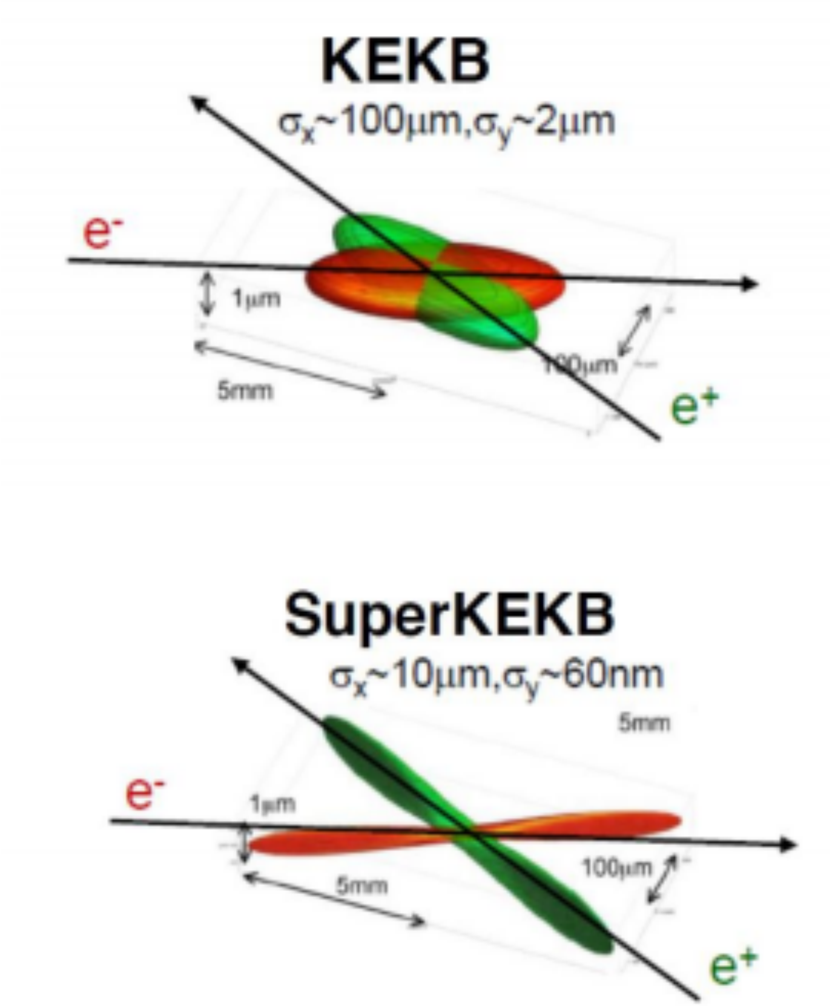
The e^+e^- mode boasts several key advantages over hadron colliders, primarily because of the full event reconstruction and access to inclusive and missing-energy modes.

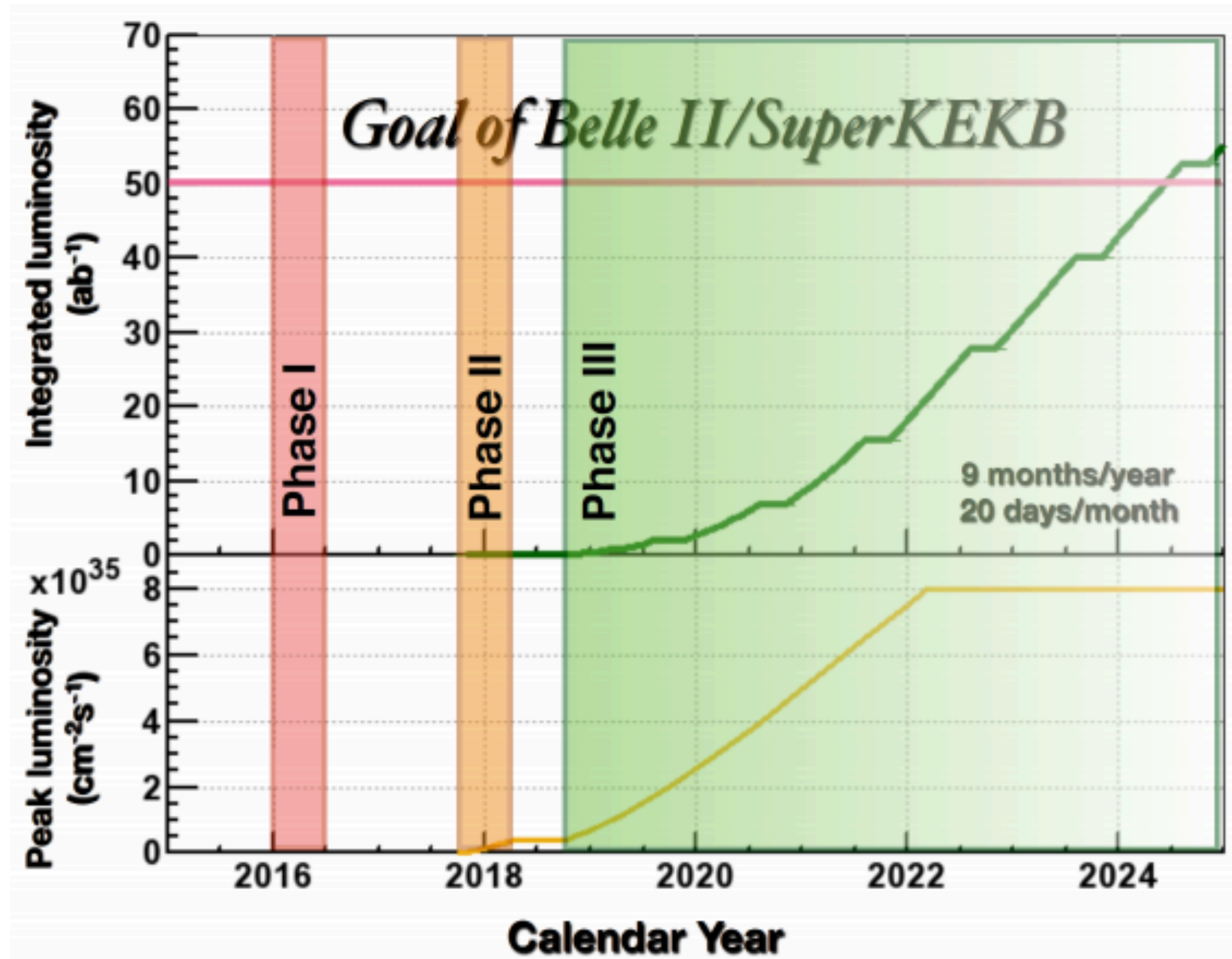


E.g. B→τν



SuperKEKB and Belle II





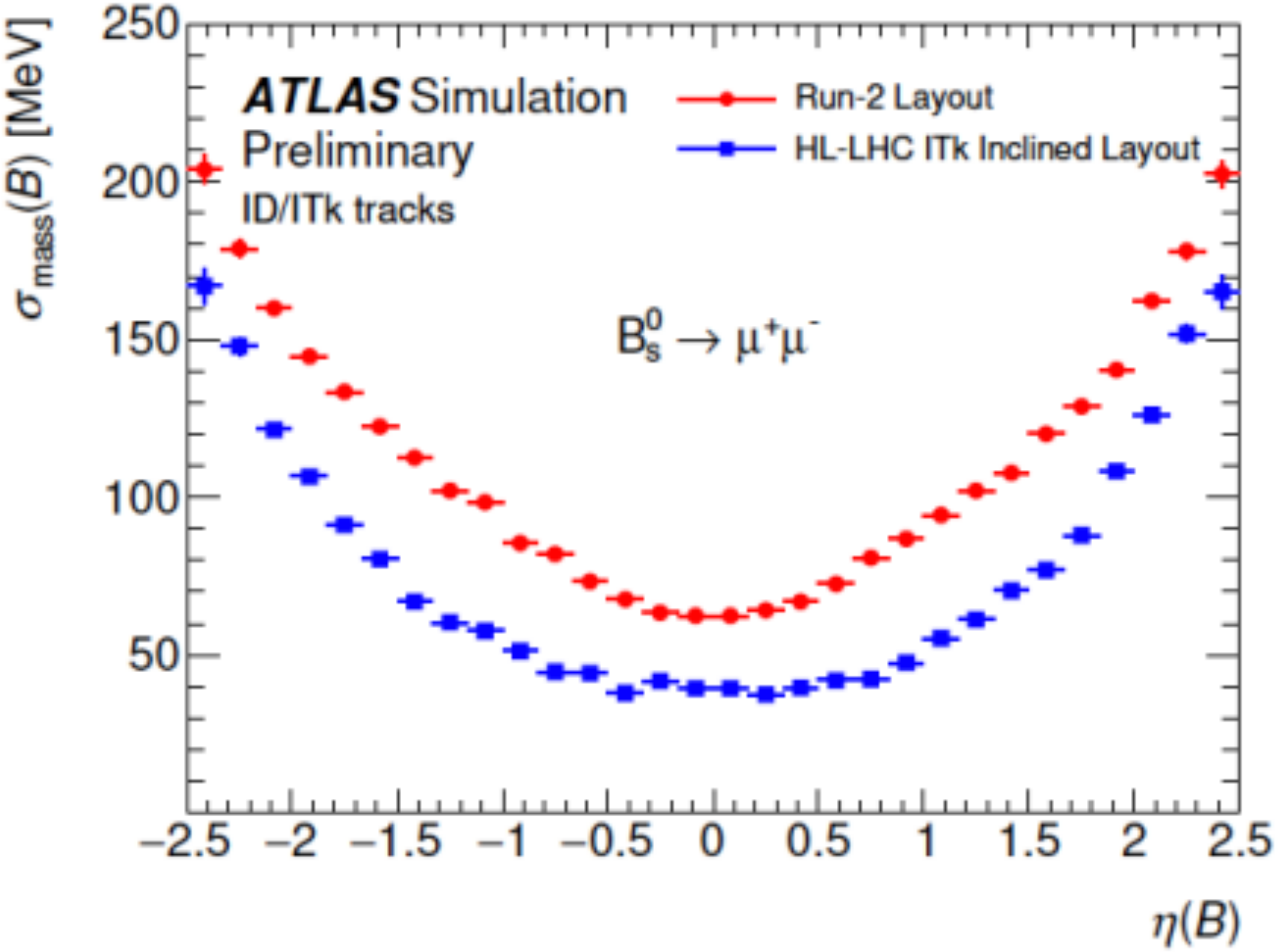
Target 50 ab^{-1} by 2025 (compared to ~1 ab^{-1} of Belle)

Exciting few years ahead.

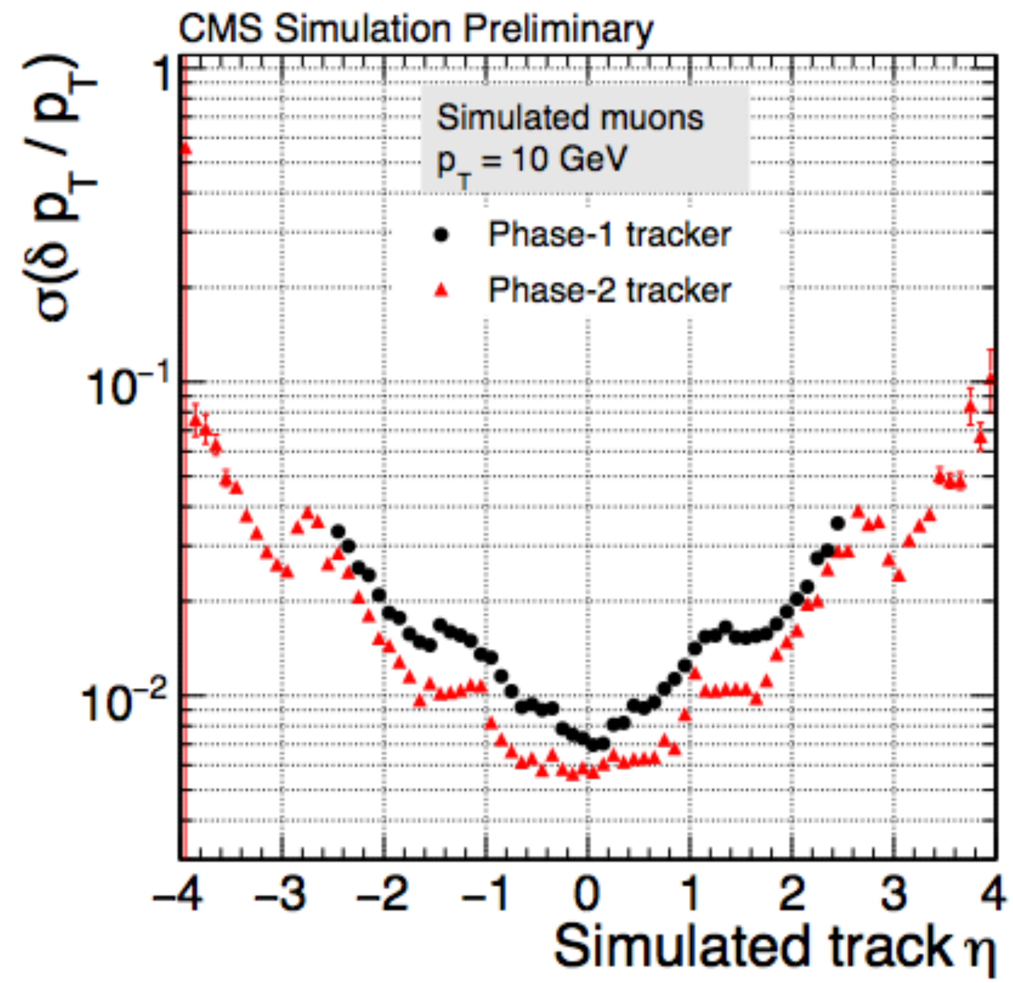
However, no current plans for future e^+e^- B factory experiments after Belle II.

ATLAS and CMS phase II upgrades

ATLAS-PHYS-PUB-2016-026



CMS-TDR-17-001



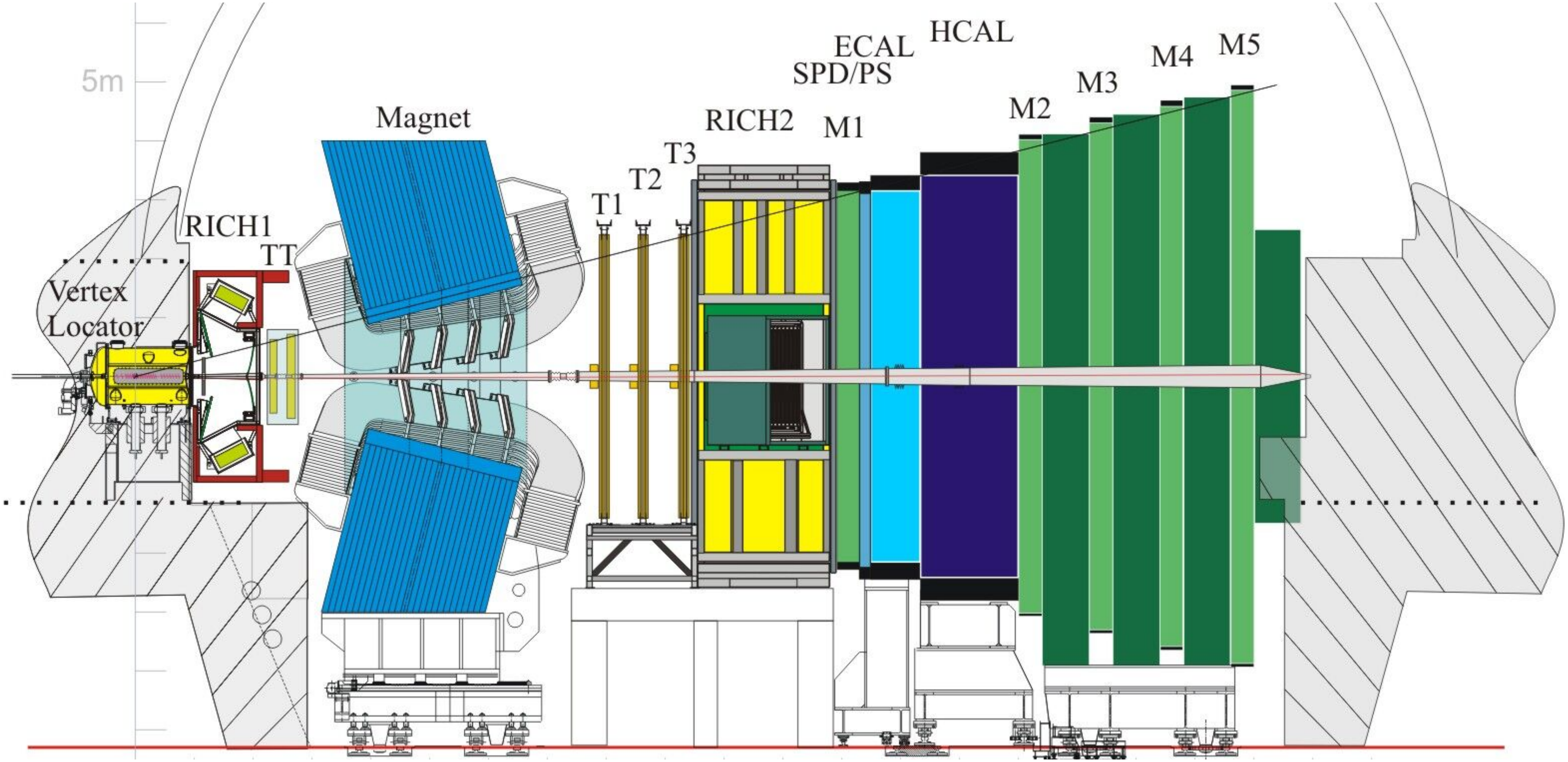
New tracking detectors will lead to greatly enhance the b physics capabilities of ATLAS and CMS. Their L1 track trigger could allow CMS to accumulate large samples even in hadronic modes.

LHCb upgrade I

Upgrade scheduled in LS2, ready for data taking to start in Run-3.

1. **Full software trigger** to allow effective operation at higher luminosities with higher efficiency for hadronic decays.

2. **Luminosity** to be raised (x5) to $2 \times 10^{33}\ \mathrm{cm^{-2}s^{-1}}$.



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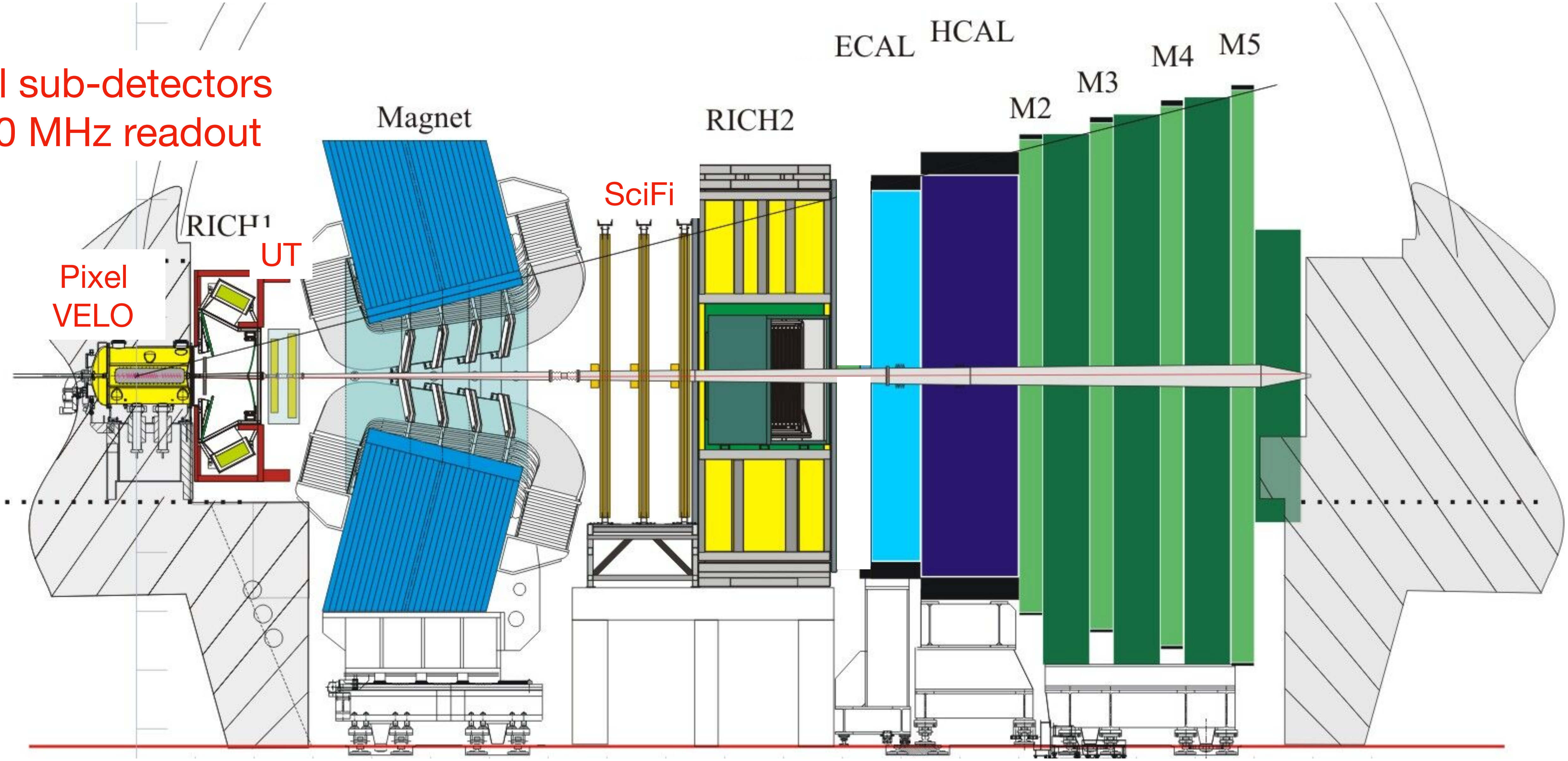
All sub-detectors 40 MHz readout



What will we know by 2030 then?

B2TiP report (in progress)

Observables	Expected th. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	Belle II/LHCb
$S(B_s \to J/\psi\phi)$	***	0.01	LHCb
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CPV			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\beta_s^{\mathrm{eff}}(B_s \to \phi\phi)$ [rad]	**	0.1	LHCb
$\beta_s^{\mathrm{eff}}(B_s \to K^{*0}\bar{K}^{*0})$ [rad]	**	0.1	LHCb
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb

1208.3355

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ $(B_s^0 \to J/\psi\ \phi)$	0.10 [138]	0.025	0.008	~ 0.003
	$2\beta_s$ $(B_s^0 \to J/\psi\ f_0(980))$	0.17 [214]	0.045	0.014	~ 0.01
	a_{sl}^s	6.4×10^{-3} [43]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [43]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [67]	0.025	0.008	0.02
	$s_0\, A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [67]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [76]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [85]	8 %	2.5 %	~ 10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ $(B \to D^{(*)}K^{(*)})$	$\sim$ 10–12° [244, 258]	4°	0.9°	negligible
	γ $(B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	β $(B^0 \to J/\psi\ K_S^0)$	0.8° [43]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

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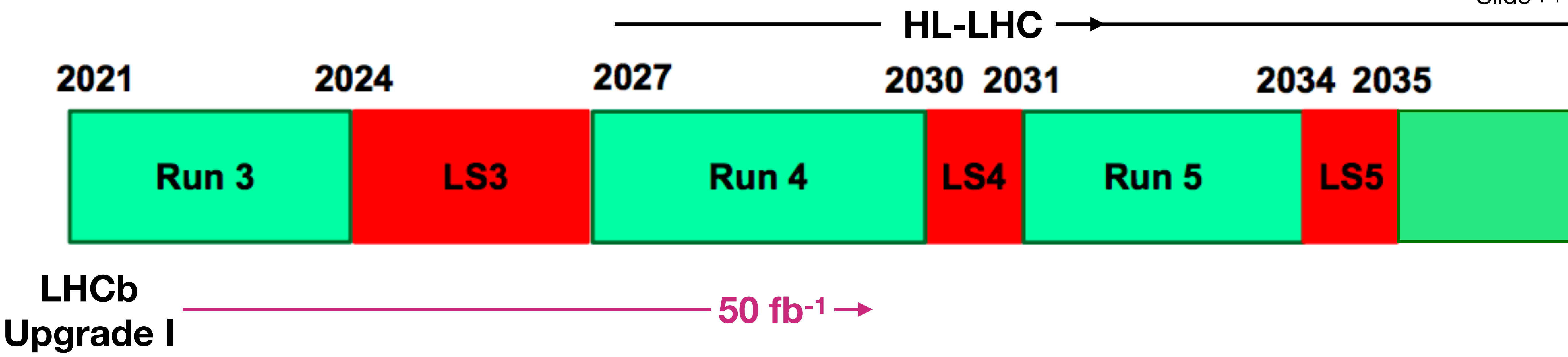
In a nutshell:

- Belle-II / BaBar+Belle ~ 50
- LHCb Upgrade I / LHCb run 1 ~ 30-60

I.e. roughly an order of magnitude in precision.

However, many key BSM-sensitive observables will still be far from the theory uncertainties.

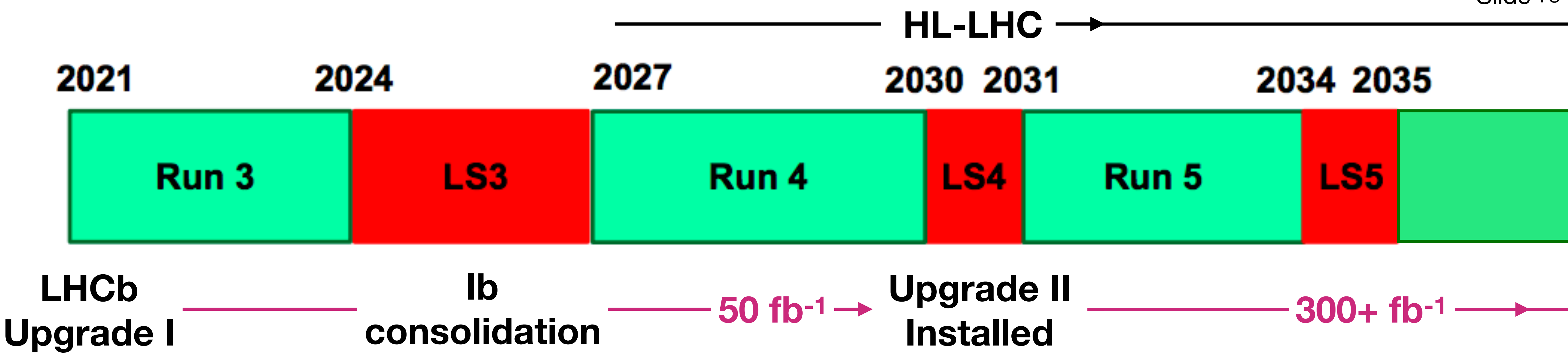


CERN-Council-S/106

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme. *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*



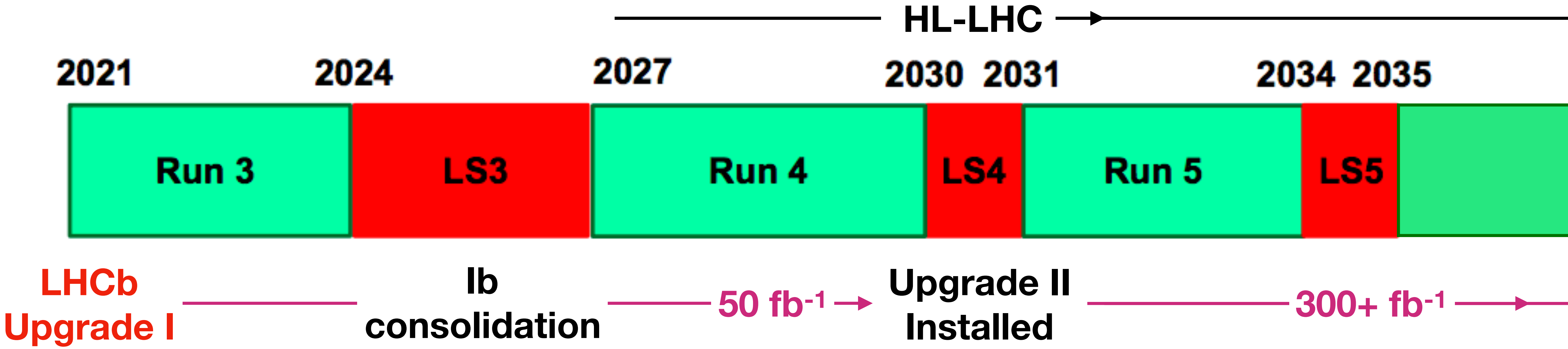
Expression of interest for LHCb upgrade II submitted to the LHCC in February 2017.

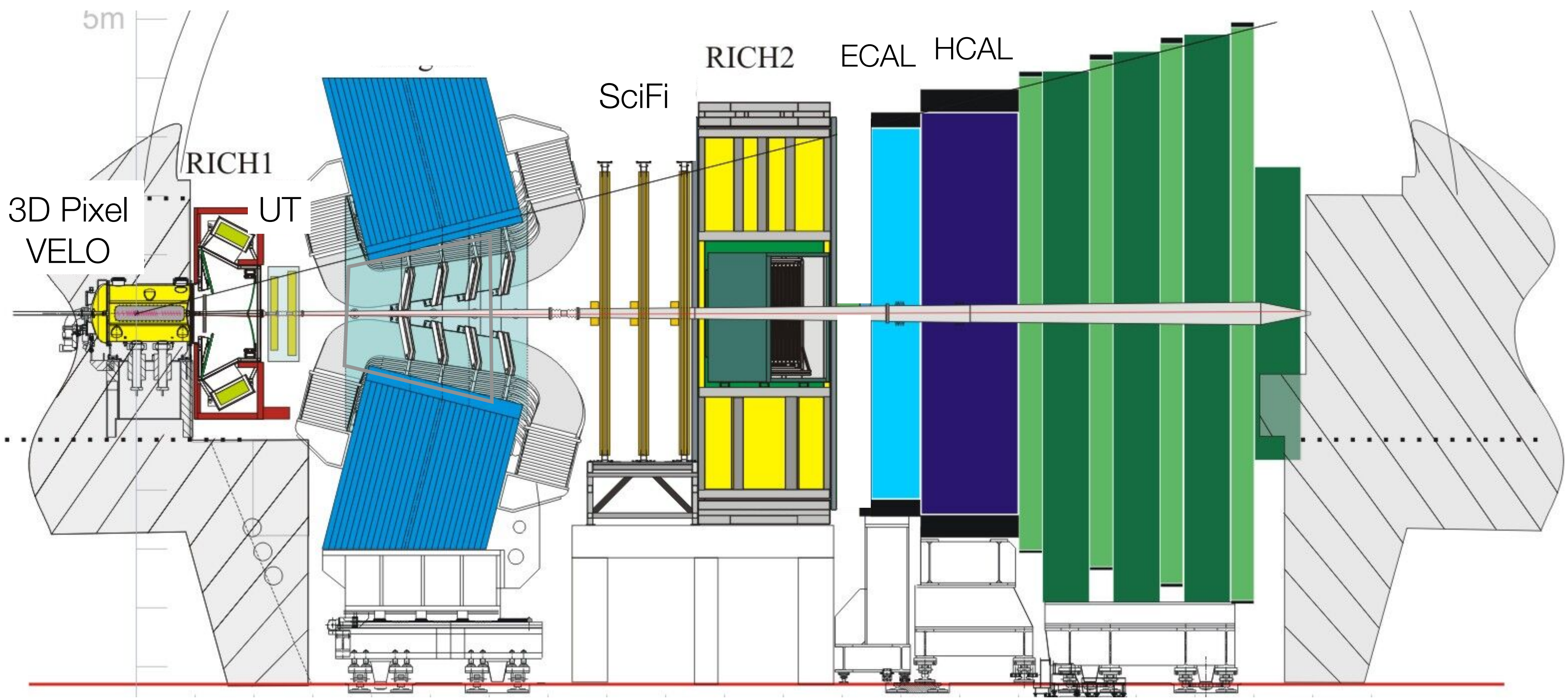
Target at least 300 fb^{-1} in Runs 5+6.

Luminosity increased to 1-2 x 10^{34} cm^{-2}, which can be achieved with negligible cost to ATLAS and CMS.

Detector upgraded to maintain its high performance at these luminosities, and even improve in some areas (e.g. neutral and partially reconstructed modes).

Certain elements can already be installed in LS3, boosting the physics output in Run-4.


HL-LHC
2021
2024
2027
2030 2031
2034 2035
Run 3
LS3
Run 4
LS4
Run 5
LS5
LHCb
Upgrade I
Ib
consolidation
50 fb-1
Upgrade II
Installed
300+ fb-1


5m
3D Pixel
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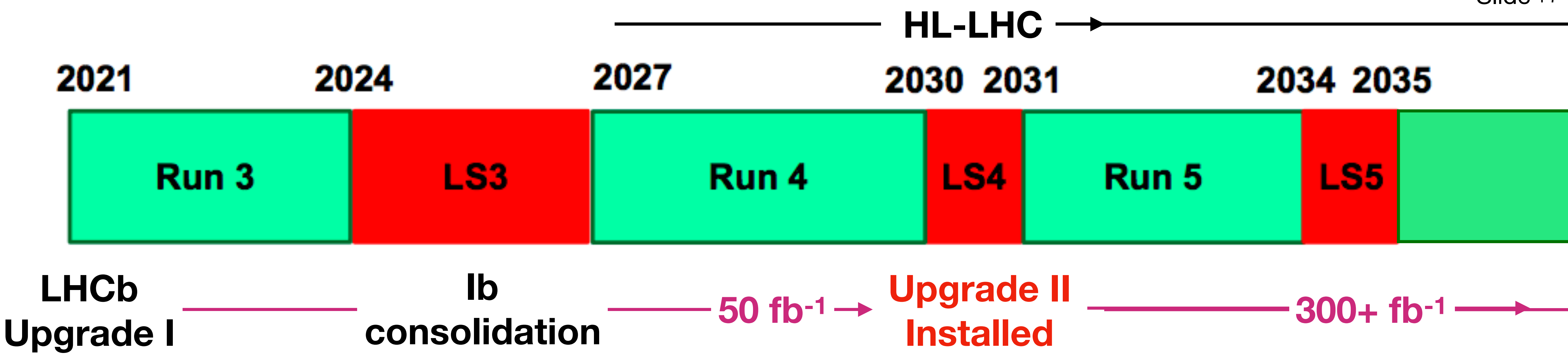
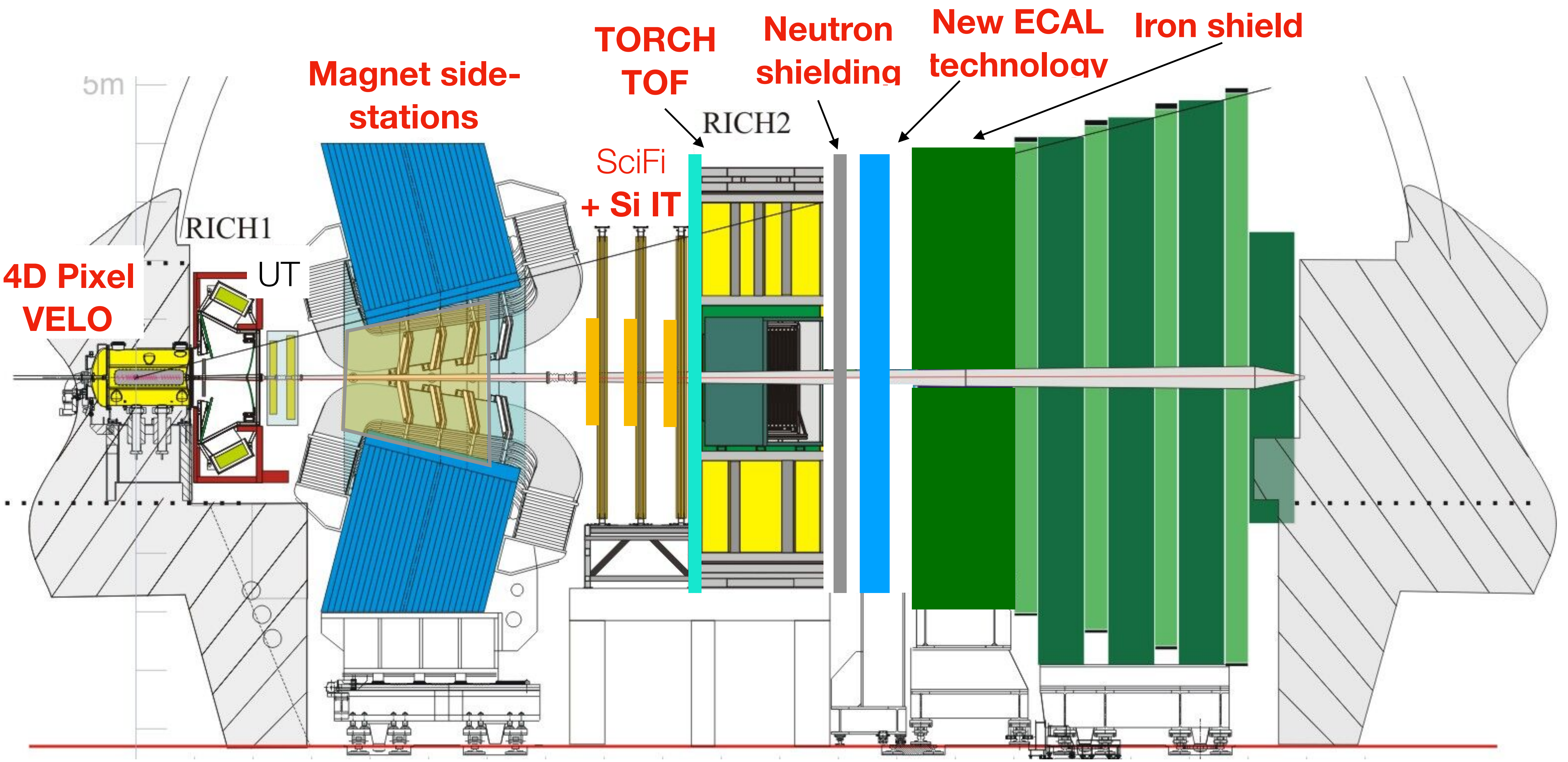
UT
SciFi
RICH2
ECAL
HCAL





Challenging environment, but common themes of fast-timing, granularity++, rad-hardness.
Clear synergies with ATLAS and CMS, and unique challenges.

The physics program

Physics case document, requested by the LHCC, in preparation

  - 5.4.2 Prospects with $R(J/\psi)$ and other ratios
- 5.5 Prospects with semileptonic D decays

6 *CP* violation and mixing in charm
- 6.1 Neutral D-meson mixing and indirect CP violation
  - 6.1.1 Measurements with $D^0 \to K^{\mp}\pi^{\pm}$
  - 6.1.2 Measurements with $D^0 \to K^{\mp}\pi^{\pm}\pi^+\pi^-$
  - 6.1.3 Amplitude analysis of $D^0 \to K^0_S h^+h^-$
  - 6.1.4 Measurement of A_Γ
- 6.2 Direct CP violation
  - 6.2.1 Measurement of A_{CP} in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$
  - 6.2.2 Measurements with $D^+ \to hhh$ and $D^+_s \to hhh$ decays
  - 6.2.3 Measurements with $D^0 \to h^+h^-h^+h^-$ decays
  - 6.2.4 Prospects with neutral final states
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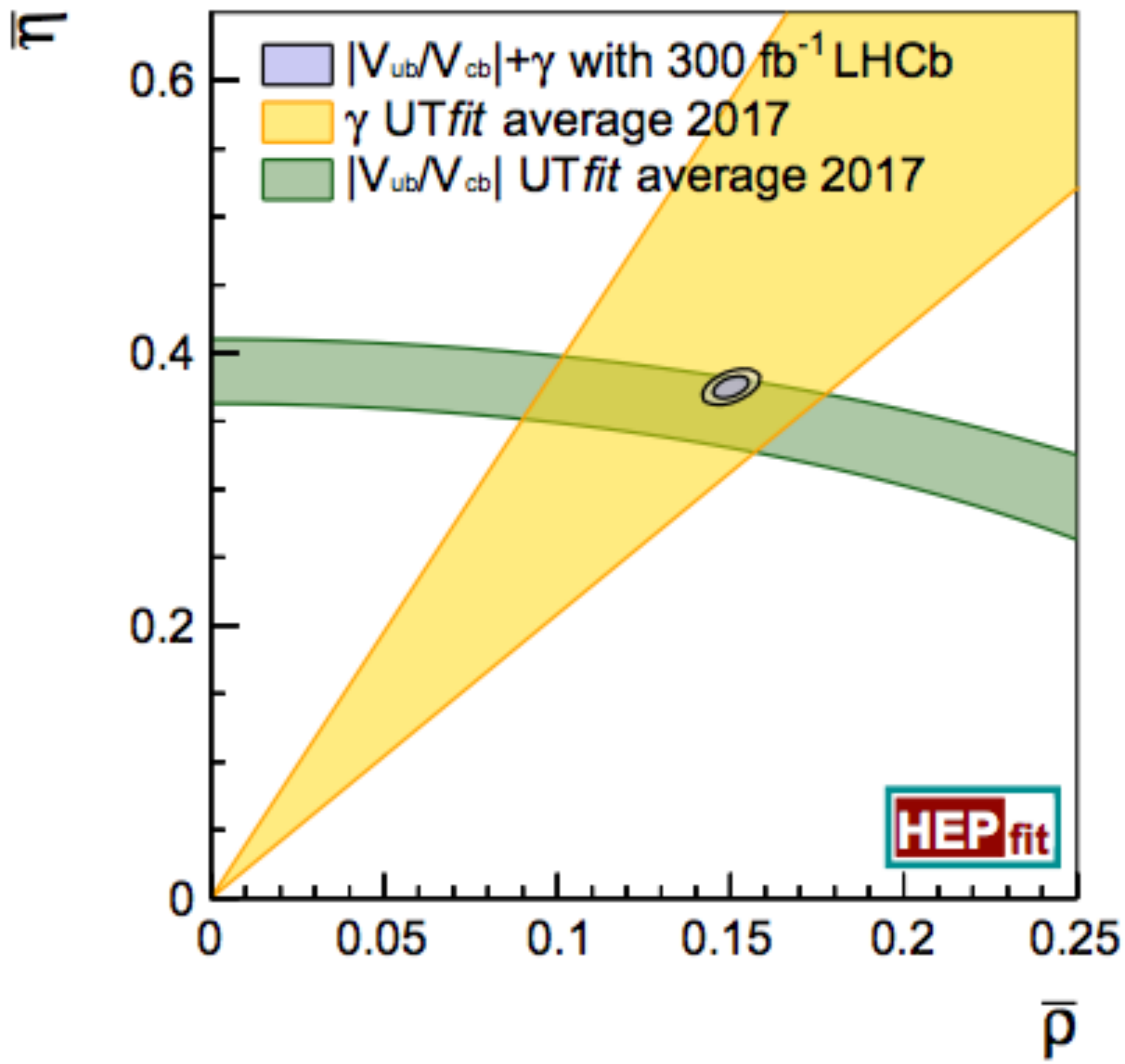
It was encouraging to see 100+ LHCb authors keenly contributing to this document.

Now for some prospects in the areas of beauty and charm CP violation…

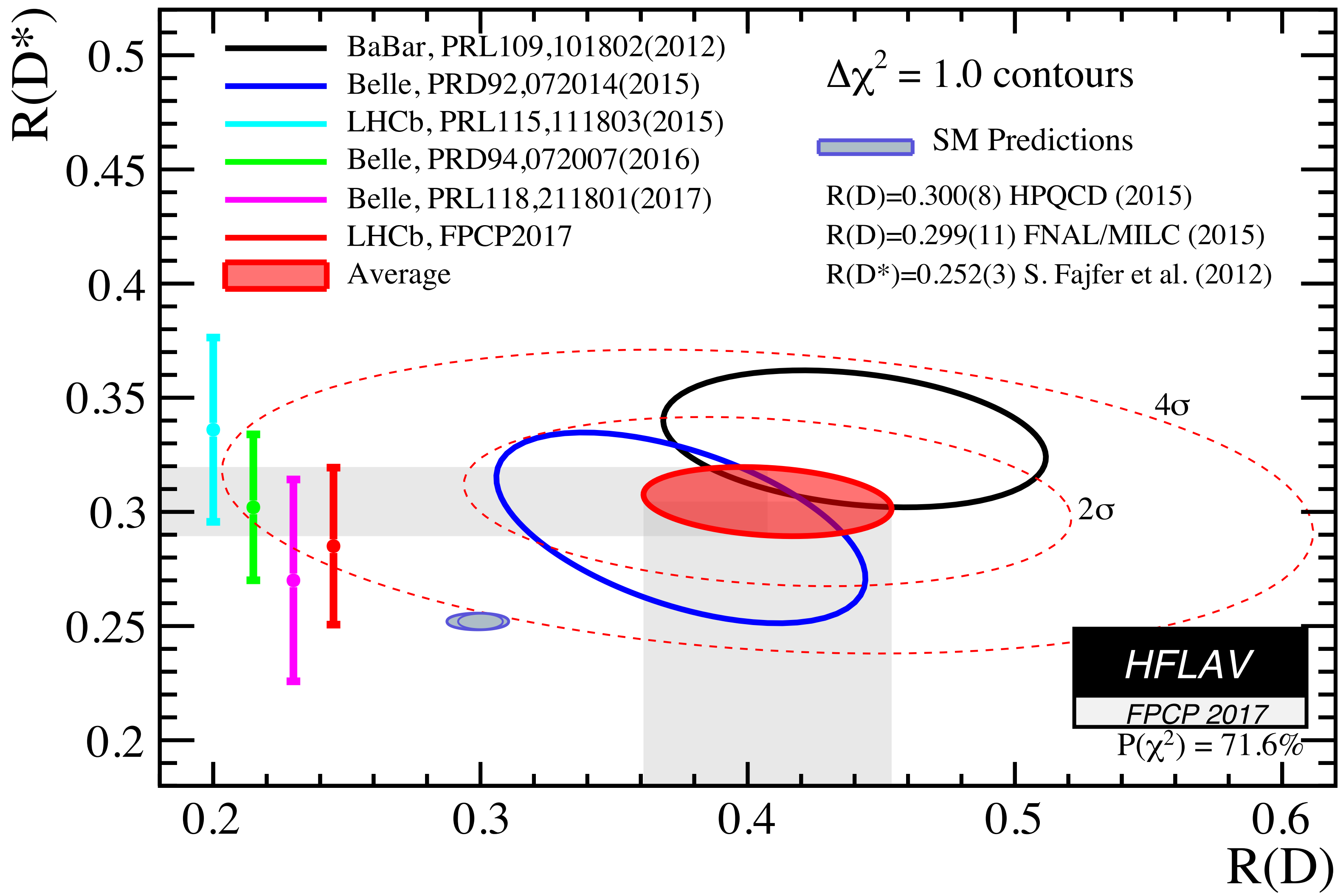
The tree-level UT apex



The phase γ is determined via the family of tree-level B→DK decays. Extremely clean theoretically and experimentally, but statistically challenging. LHCb Upgrade II can reach sub-degree precision in multiple modes.

The corresponding length depends on $|V_{ub}|/|V_{cb}|$. Belle-II + lattice improvements will greatly improve our knowledge, but LHCb will have access to decays with all b hadron species, including decays which are currently beyond statistical reach.

Tree-level LFU tests



LHCb Run-II and Belle-II could already confirm this anomaly so why would we need more luminosity?

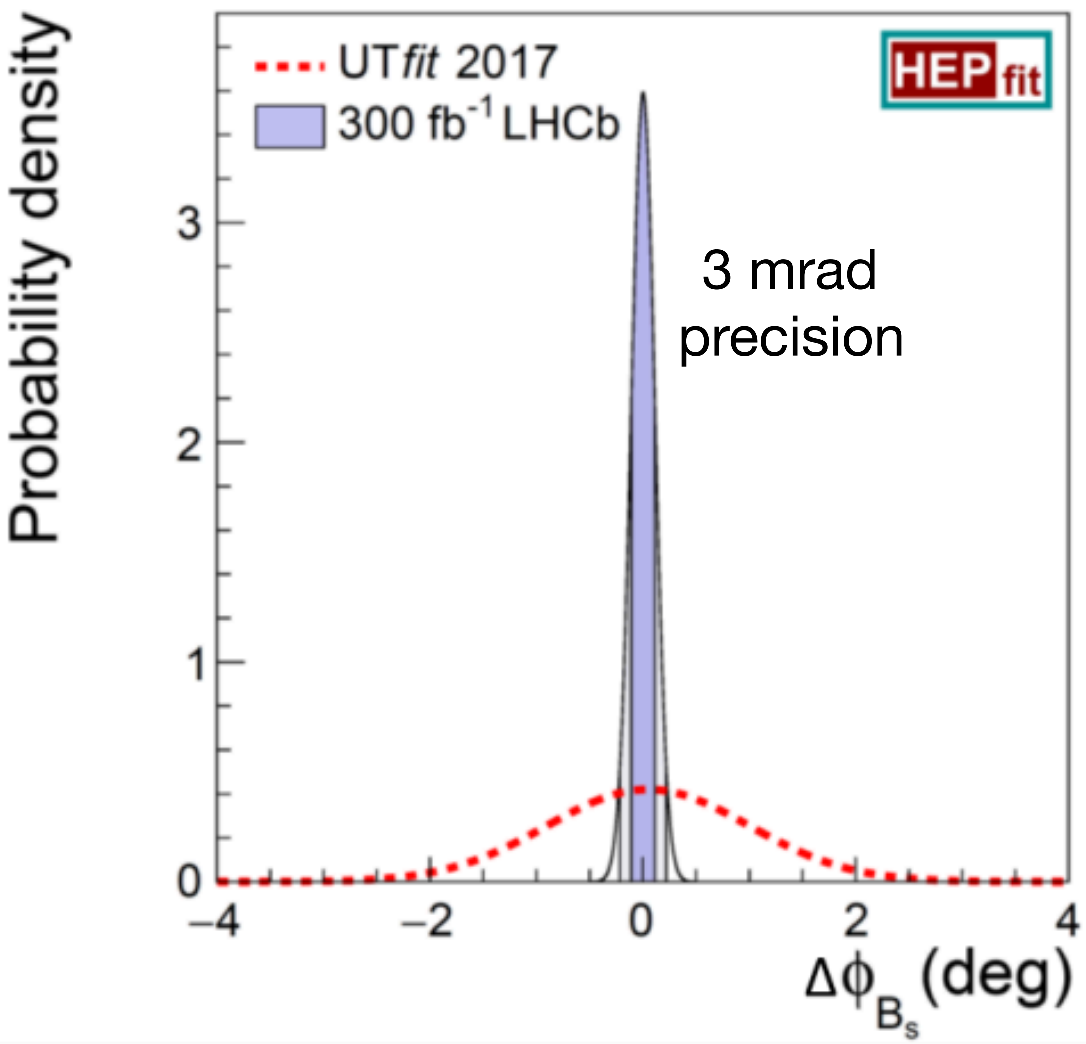
Distinguishing between BSM solutions would require far greater precision and more observables.

LHCb Upgrade II will allow differential measurements*, in addition to percent level ratios with a range of b meson and baryon species.

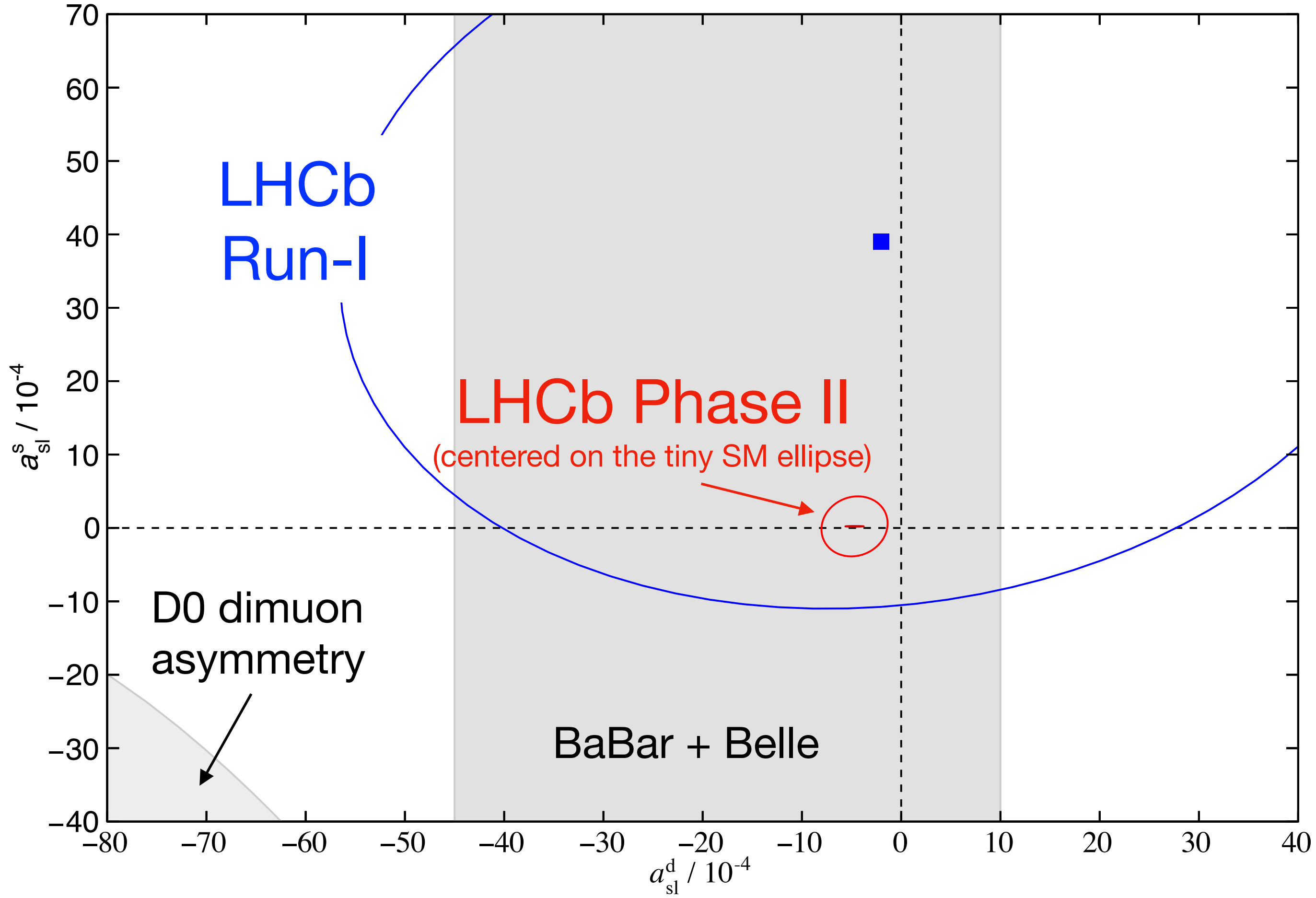
*In order to fully distinguish different operators we need measurements of the tau polarisation (1st measurement by Belle https://arxiv.org/abs/1612.00529) and other kinematic and angular properties of the decays. These are statistically far more challenging than the simple ratios in the plot above.

CPV in B-$\overline{\mathrm{B}}$ mixing and decays

The phase Φ_s with b→ccs decays



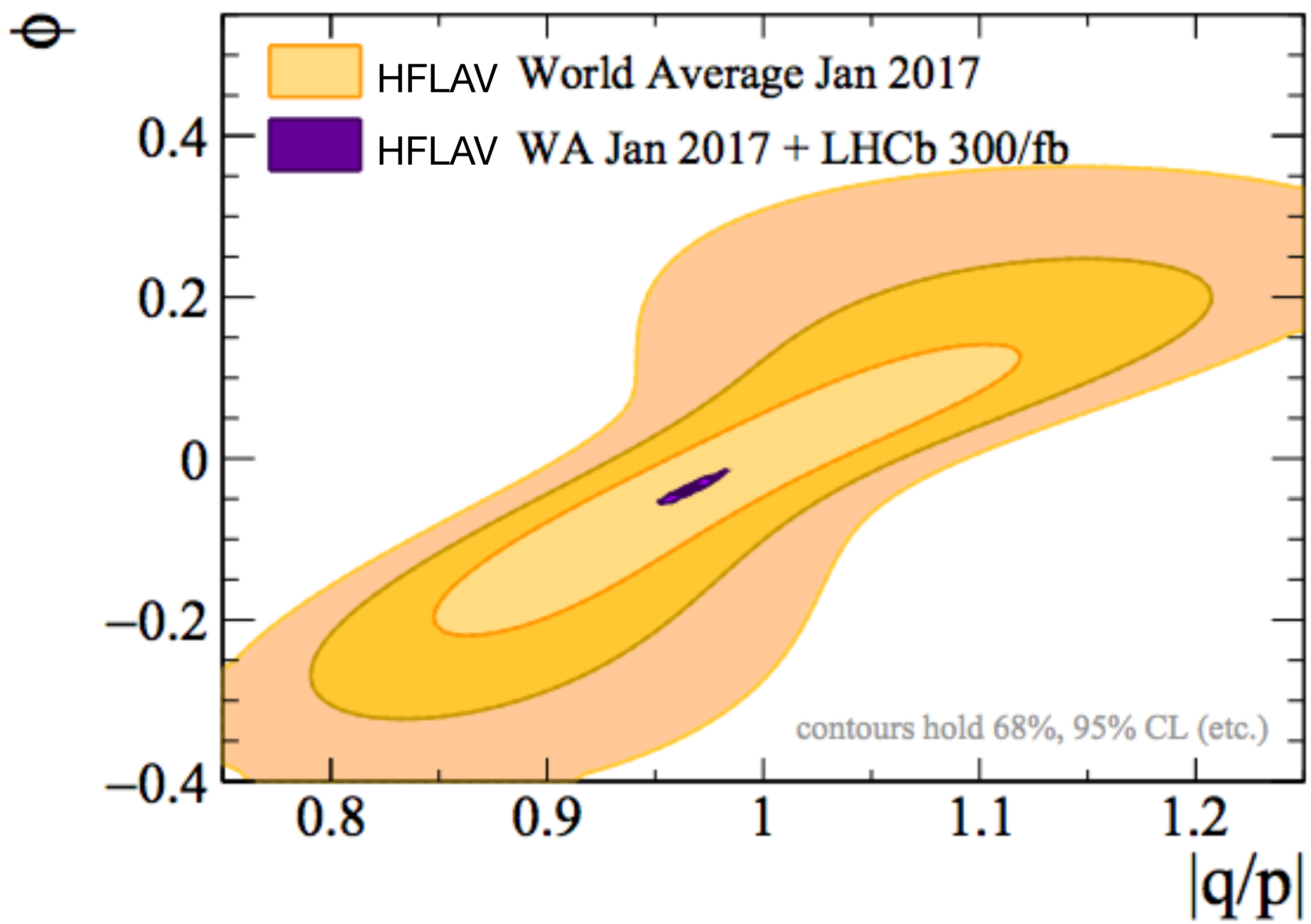
CP violation in B_d and B_s mixing



The measurement of Φ_s requires that we can maintain our performant flavour tagging in high pileup conditions*. This is a good example of why the detector upgrades must include fast timing, to unambiguously associate signals to primary vertices.

*Early studies on deep neural network inclusive flavour tagging look promising. See G. Cowan talk at the concurrent flavour workshop in Warwick https://indico.cern.ch/event/694666/contributions/2916469/.

CP violation in charm



Charm mixing is already well established but the theoretically clean, and BSM sensitive, indirect CP violation parameters Φ and |q/p| are poorly known. LHCb Upgrade II will reach incredible precision.

It will also be capable of characterising patterns of direct CP violation down to the 10^{-5} level across a range of D decay modes.

Conclusions

LHCb Upgrade-I and Belle II will greatly extend our knowledge of quark flavour physics by 2030.

Yet we will still be far from realising the full potential in BSM sensitivity.

LHCb Upgrade-II is the experiment to push the frontier of quark flavour physics through the 2030s.

Backup slides start here…

Machine considerations

β^* [m]	Maximum $\mathcal{L}$ [$\times 10^{34}$ cm^{-2}s^{-1}] −	Maximum $\mathcal{L}$ +	Target levelling $\mathcal{L}$ [$\times 10^{34}$ cm^{-2}s^{-1}]	Fill length [h] −	Fill length [h] +	Levelling time [h] −	Levelling time [h] +	$\int \mathcal{L}\, dt$ [fb^{-1}/yr] −	$\int \mathcal{L}\, dt$ +
3	1.04	0.78	0.20	8.1	8.1	8.1	8.1	10	10
2	1.53	1.04	1.00	7.7	7.8	2.8	0.4	39	31
2	1.53	1.04	/	7.6	7.8	/	/	43	31
1	2.90	1.66	1.00	7.5	7.6	6.0	3.5	48	42
1	2.90	1.66	2.00	7.3	7.5	2.3	0	73	48
1	2.90	1.66	/	7.2	7.5	/	/	80	48

PV association at high pileup with timing

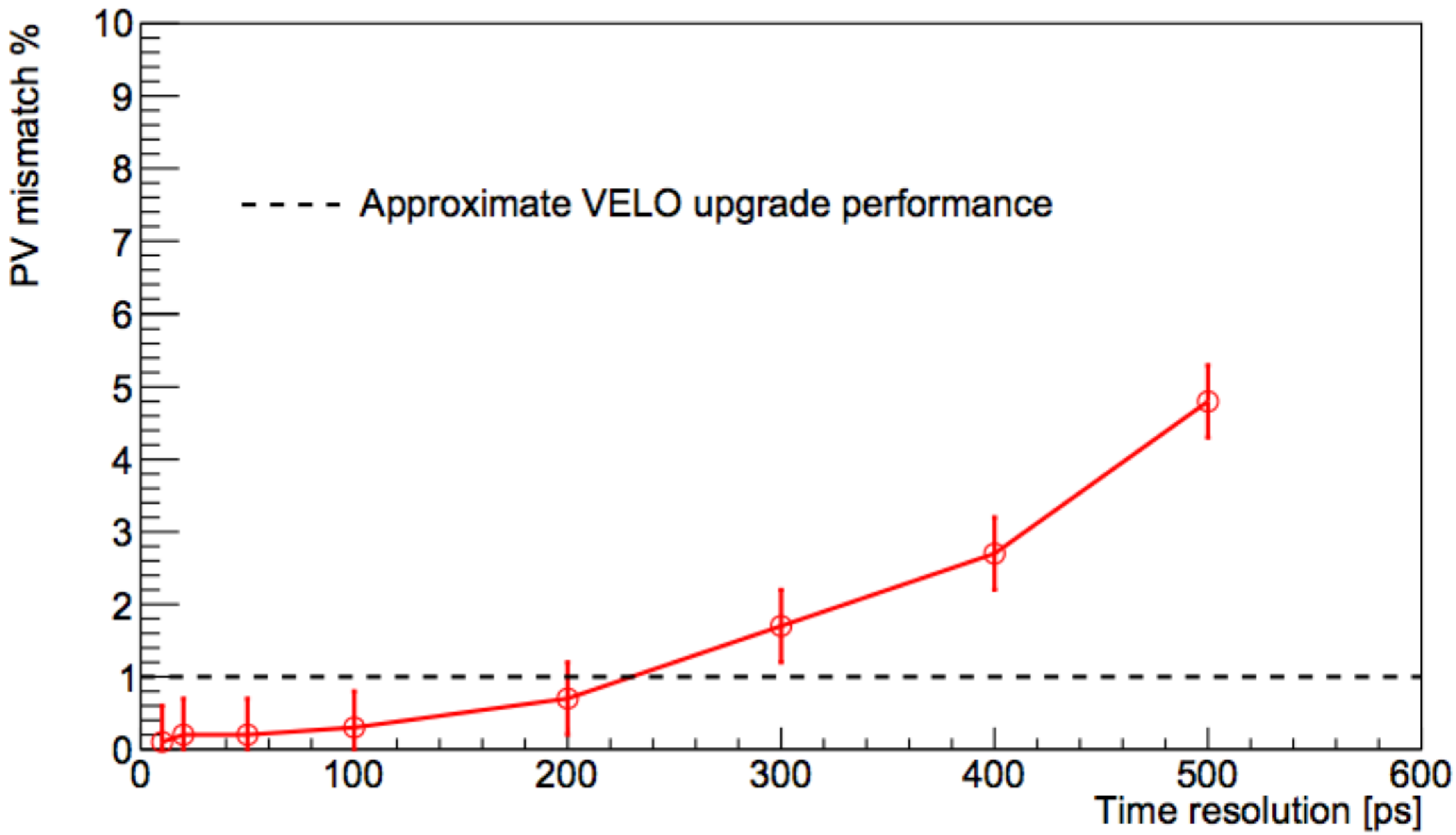
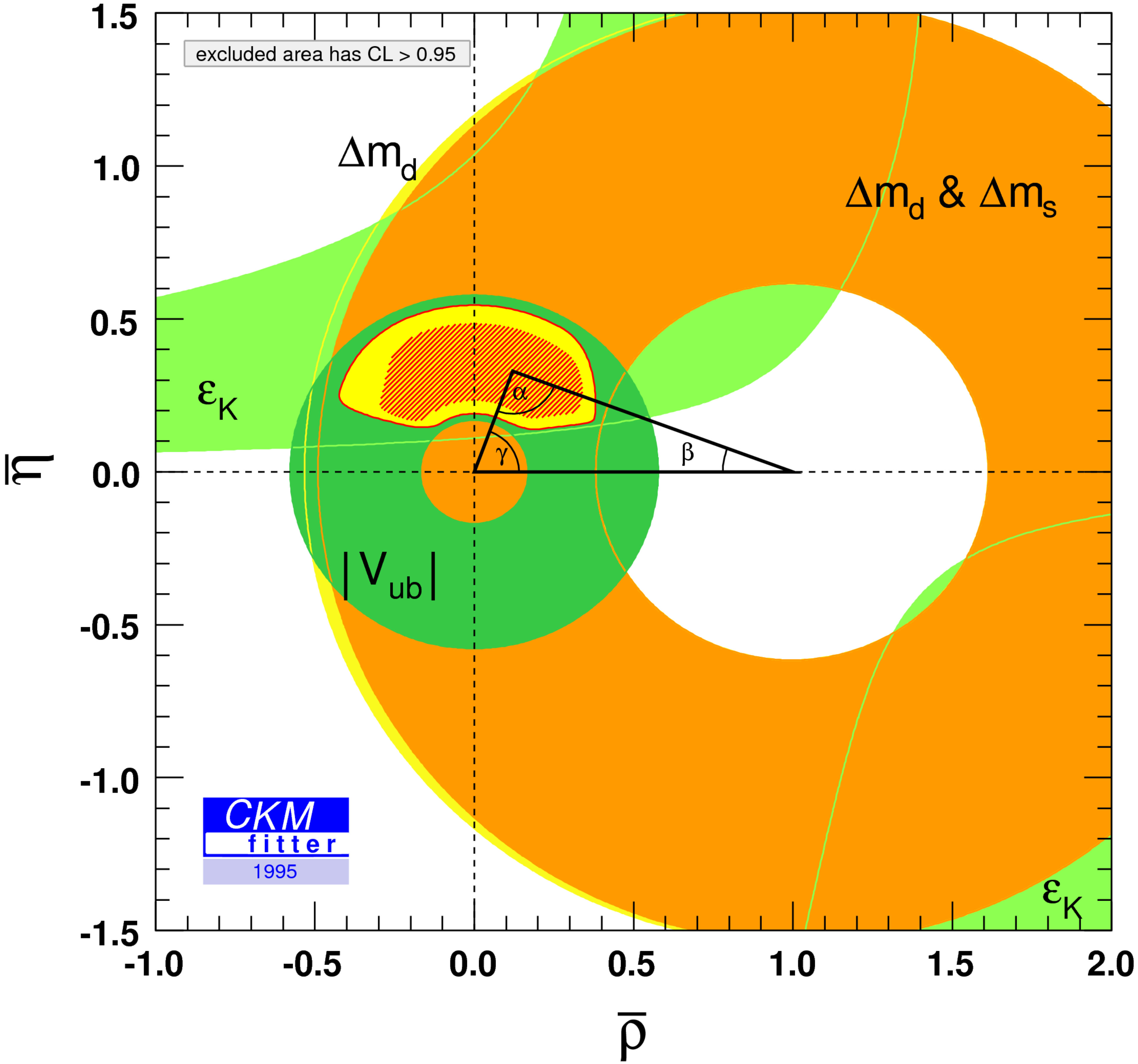
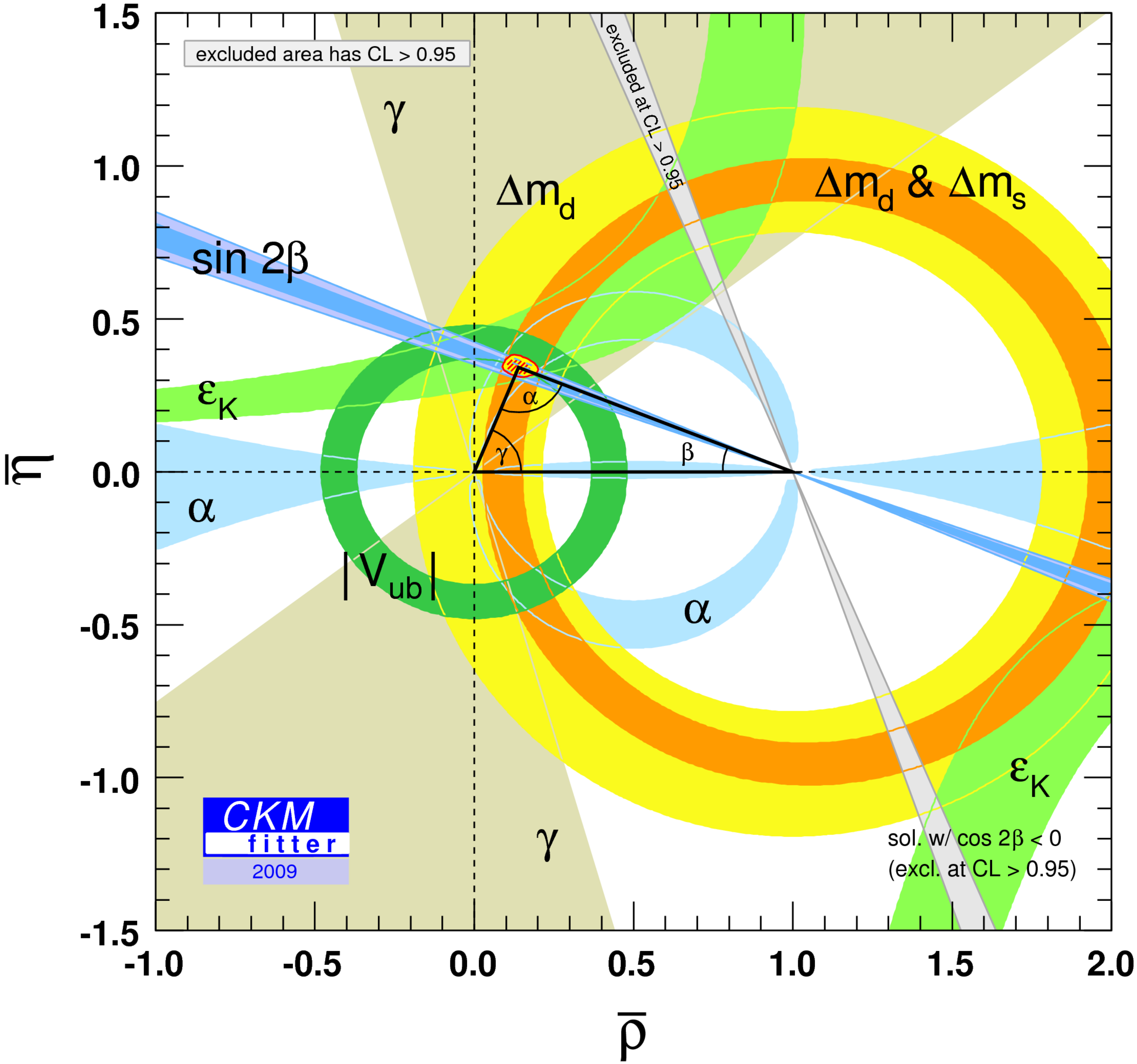


Figure 4.4: Fraction of b-hadron decays mismatched to the wrong PV as a function of the time resolution per hit at a luminosity of $2 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$. The horizontal dashed line shows the approximate performance of the Phase-I Upgrade VELO at $2 \times 10^{33}\,\mathrm{cm^{-2}s^{-1}}$. The hit information used as input to the study is obtained from a sample of simulated events assuming the layout of the Phase-I Upgrade VELO.

1995

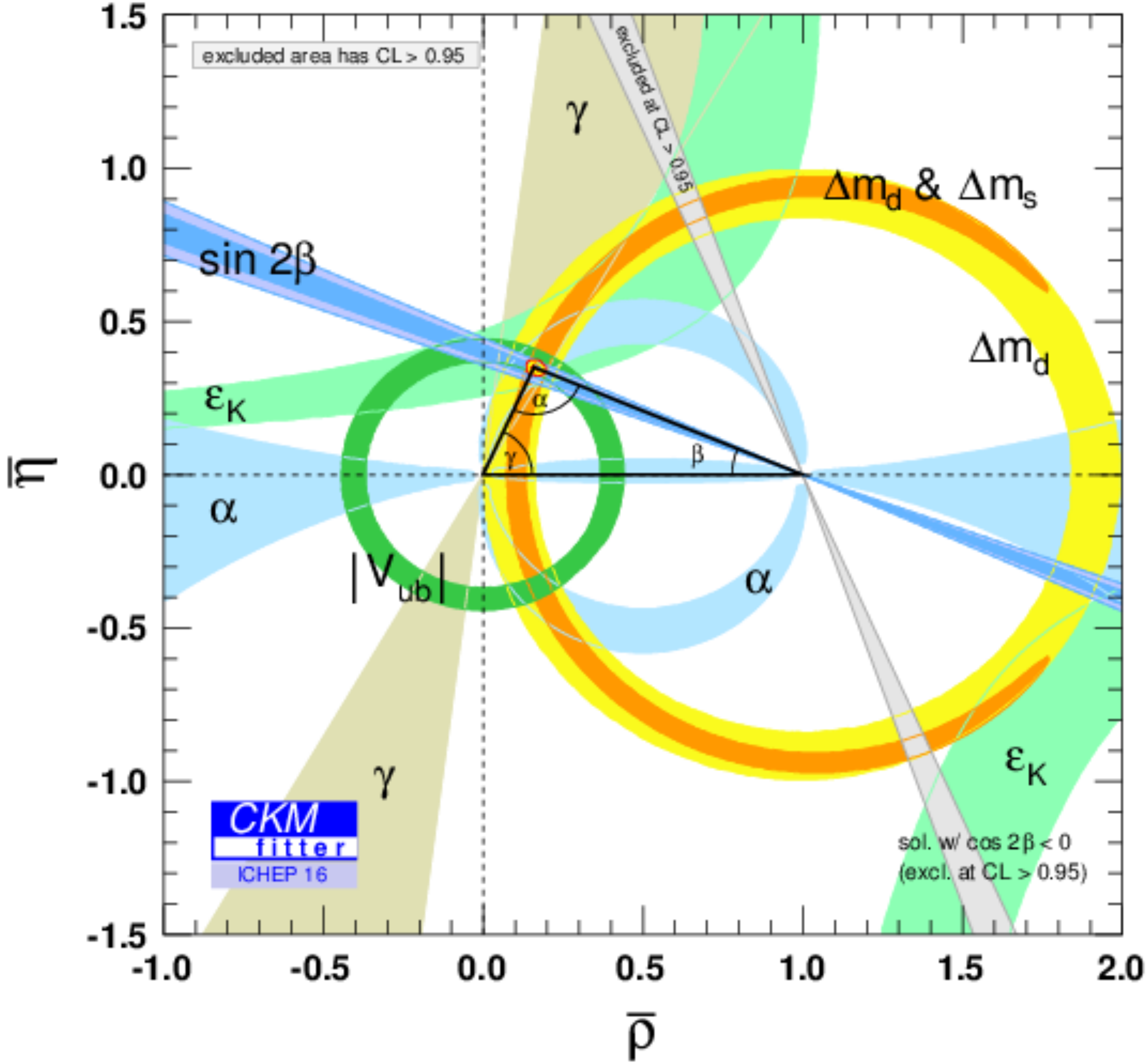

excluded area has CL > 0.95
Δm_d
Δm_d & Δm_s
ε_K
$|V_{ub}|$
α
β
γ
ε_K
CKM
fitter
1995
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
$\bar{\eta}$
$\bar{\rho}$

2009

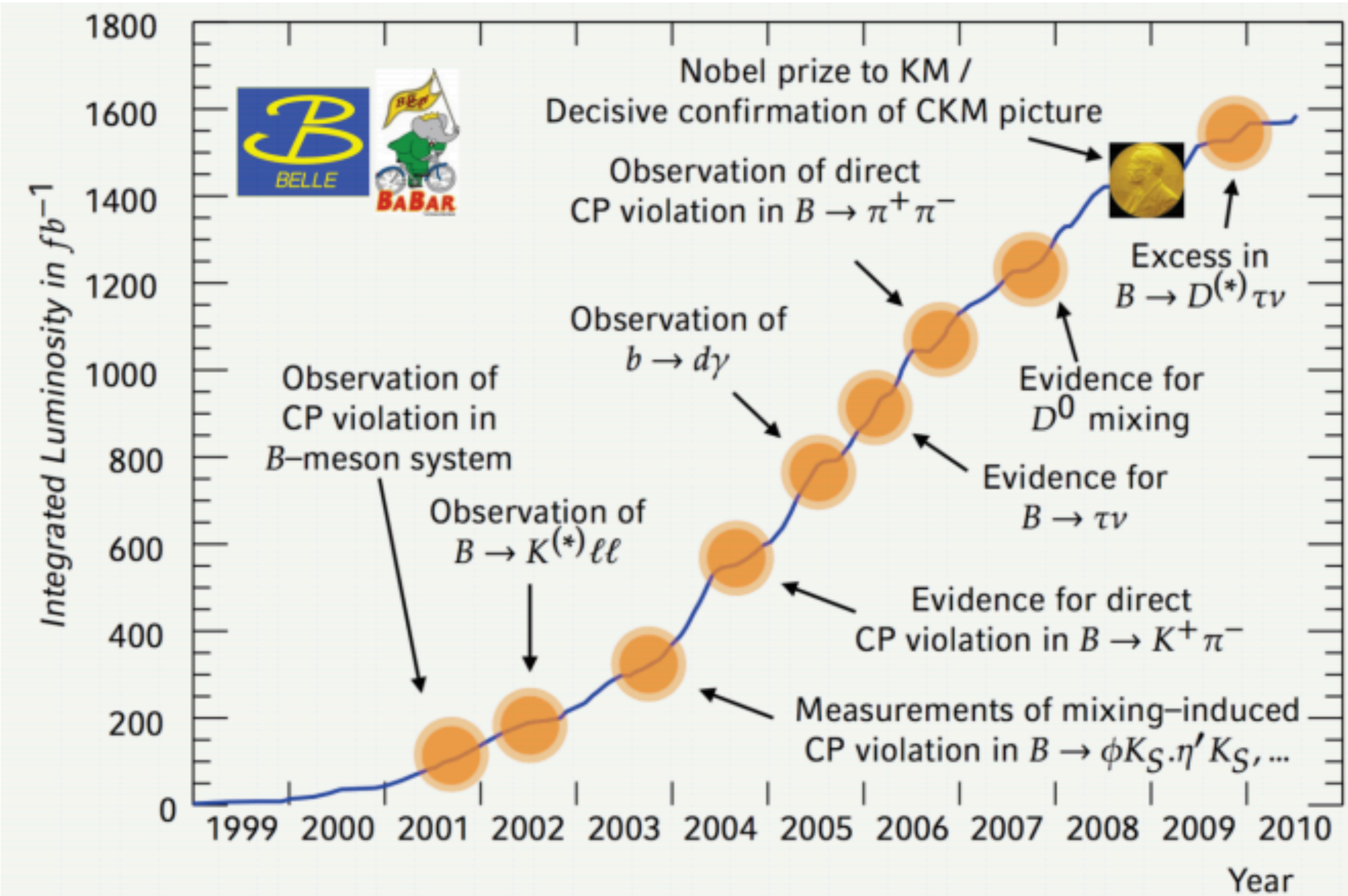


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d
Δm_d & Δm_s
sin 2β
ε_K
α
β
γ
α
|V_ub|
α
ε_K
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
CKM fitter
2009
γ
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
η̄
ρ̄

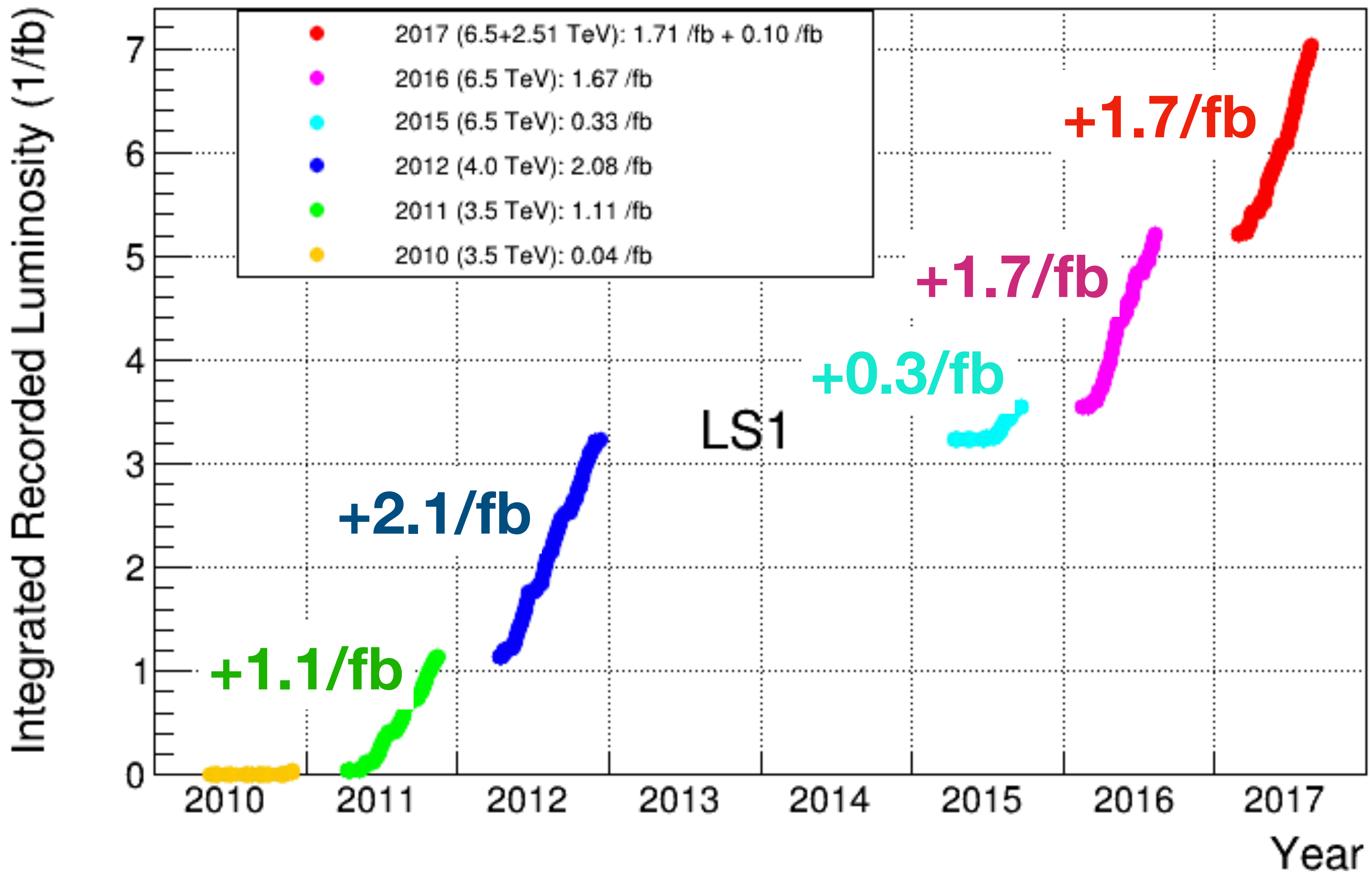
2016


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
α
|V_ub|
α
γ
ε_K
CKM fitter
ICHEP 16
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
η̄
ρ̄

The BaBar and Belle legacy



LHCb approaching Run-II culmination



A further 2 fb^{-1} is anticipated in 2018.

Given the higher b, c cross sections at $\sqrt{s}$ = 13 TeV, and trigger improvements, the Run-II dataset will correspond to a typical 4-5x increase over Run-I.