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# Present and future CKM studies from B physics at the LHC

22 Nov 2021

Niels Tuning

## See also:

Brossa Gonzalo, Arnau: [Gamma measurements with BPGGSZ channel and search for  \$B\_c\$  decays into two charmed mesons](#)  
Khanji, Basem: [CKM elements measurements with SL B decays at LHCb](#)  
Lupato, Anna: [Time-dependent measurements of  \$\gamma\$  and  \$\Delta m\_s\$  at LHCb](#)  
Ruiz Fernandez, Ramon: [Measurements of  \$\alpha\$ ,  \$\beta\$ ,  \$\phi\_s\$  and B meson lifetime properties at LHCb](#)  
Suljik, Fidan: [Gamma measurements in ADS and GLW\(-like\) channels at LHCb](#)

# Outline

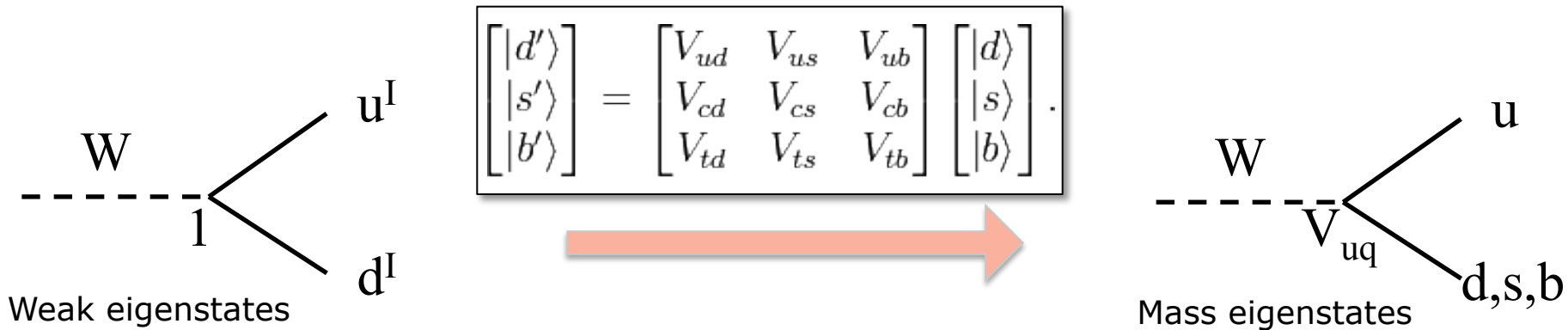
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- CKM elements
  - $V_{ub}$
  - $V_{cb}$
  - $\Delta m_s$
- CKM phases
  - $\sin 2\beta$
  - $\Phi_s$
  - $\gamma$
- Prospects
  - Upgrade
  - Upgrade II



# (CKM: a quick reminder...)

## 1) Matrix to transform weak- and mass-eigenstates:



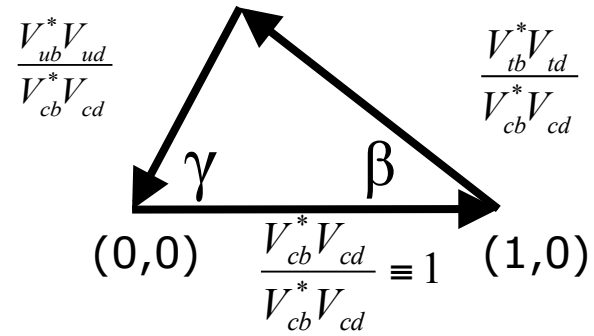
## 2) Matrix has complex numbers:

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

## 3) Matrix is unitary:

$$V^+V = \begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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



# CKM: (1995) LHCb Letter-of-Intent

- LHC-B Letter-of-Intent 1995

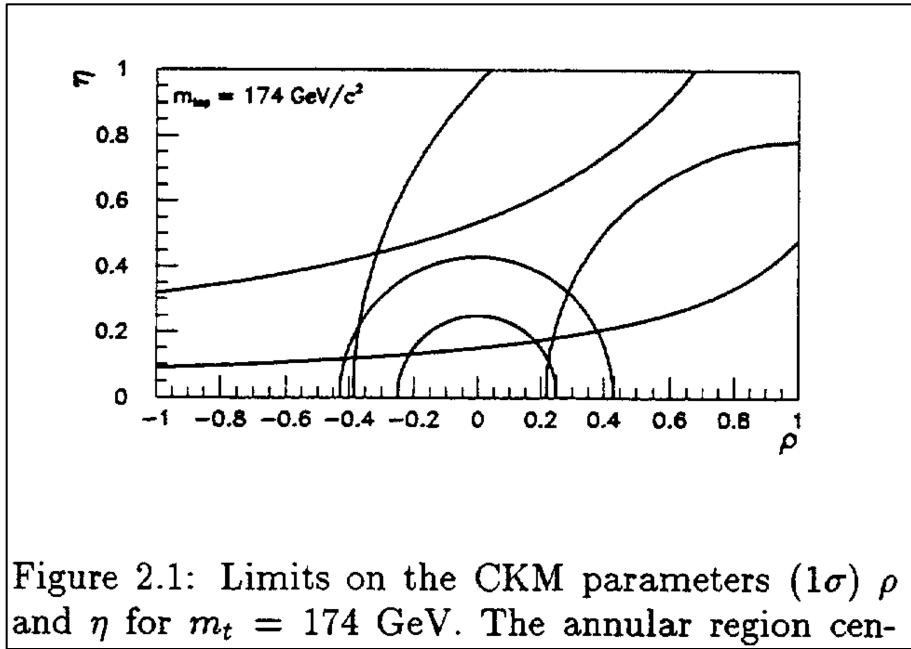
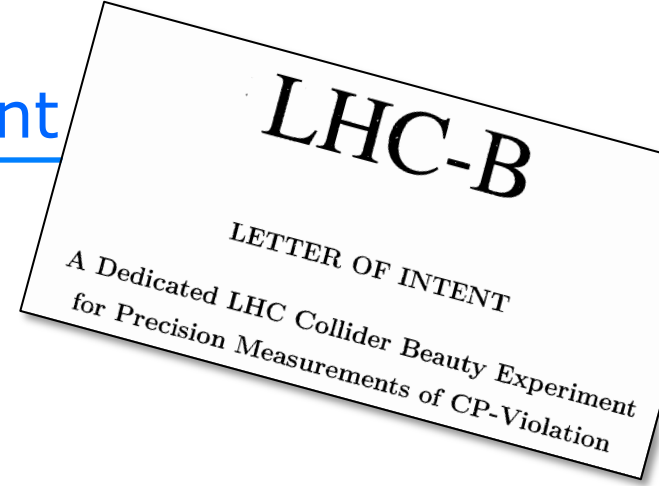
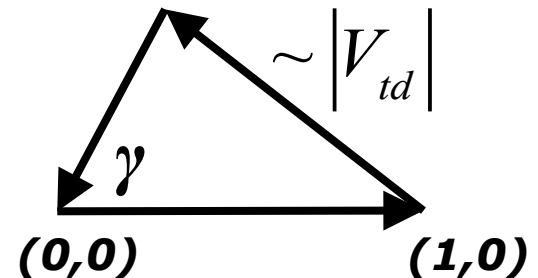
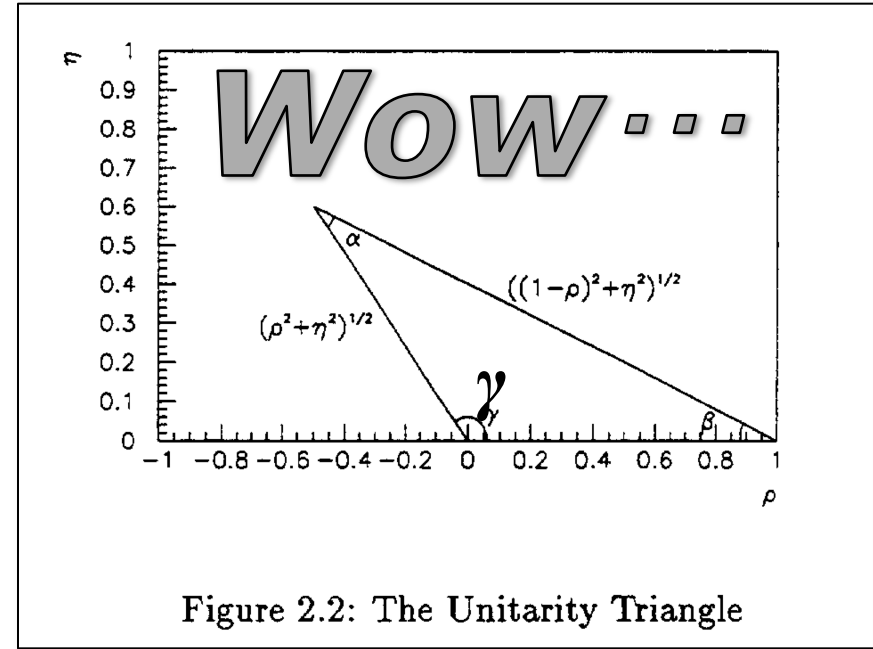
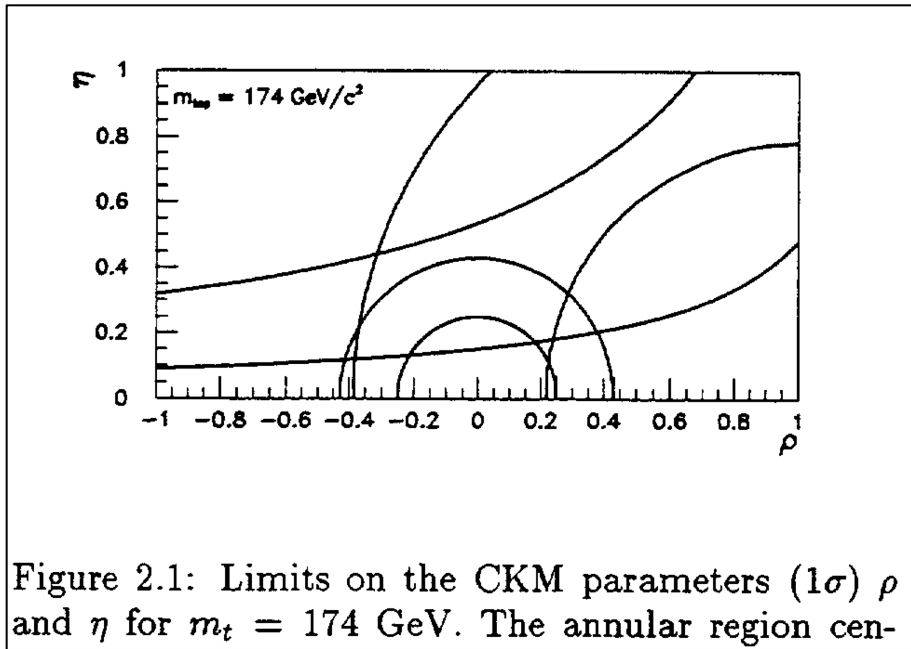


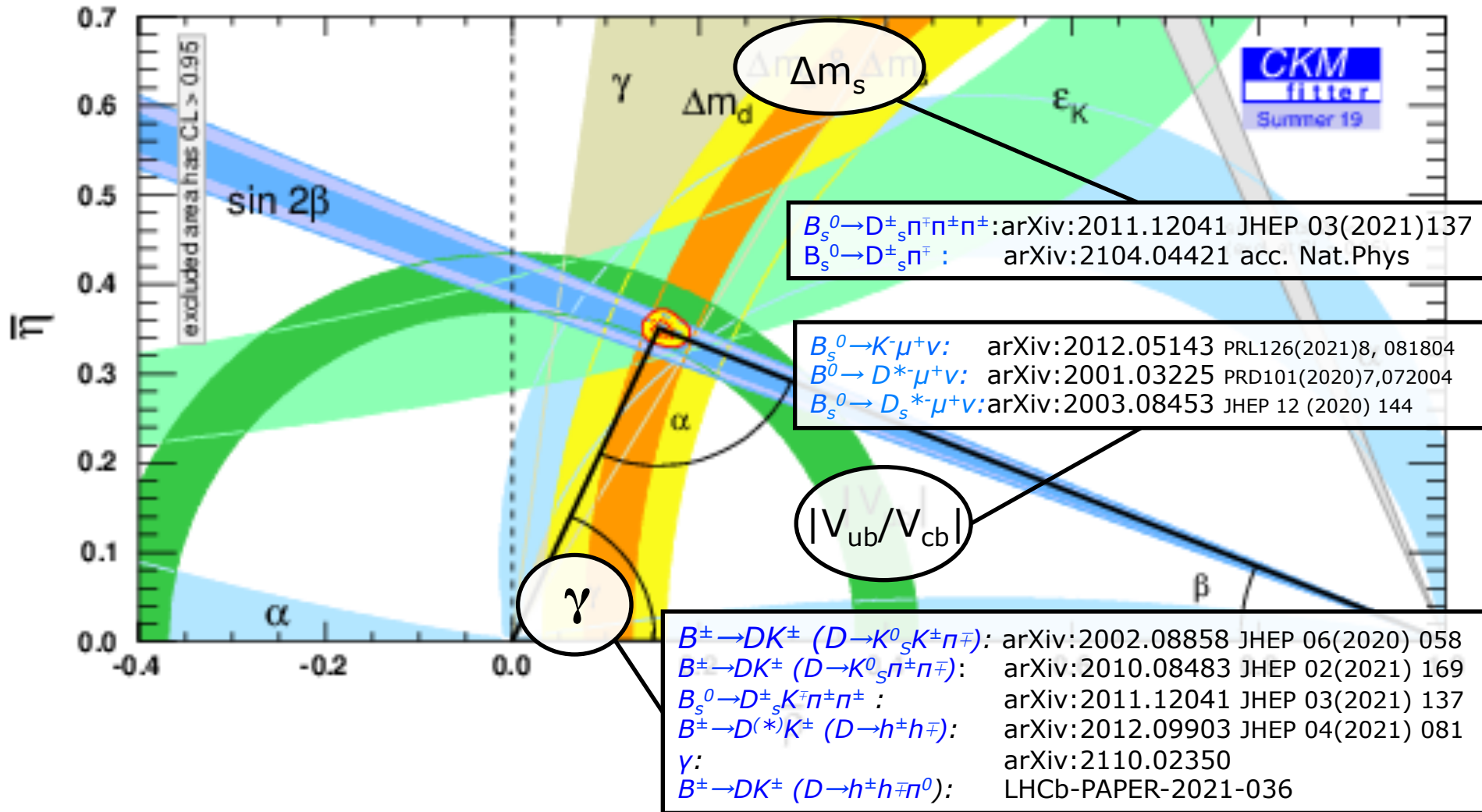
Figure 2.1: Limits on the CKM parameters ( $1\sigma$ )  $\rho$  and  $\eta$  for  $m_t = 174 \text{ GeV}$ . The annular region cen-

# CKM: (1995) LHCb Letter-of-Intent

- LHC-B Letter-of-Intent 1995



# CKM: recent results (2020 and later)



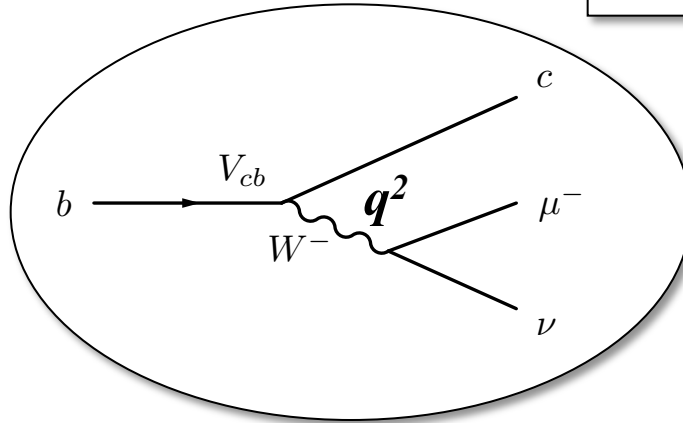
Global fits:

CKMfitter: <http://ckmfitter.in2p3.fr/>  
 UFit: <http://www.utfit.org/Utfit/>

# Measurement on $|V_{cb}|$

- Measure decay rate of  $B_s^0 \rightarrow D_s^{*-} \mu^+ \nu$ 
  - Depends on momentum transfer  $q^2$  :

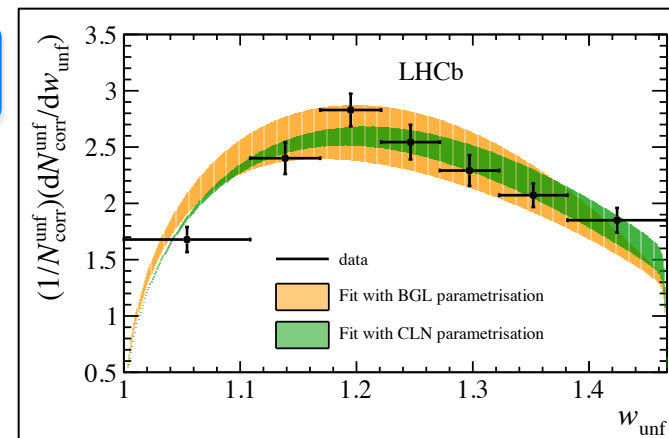
$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| e^{-i\beta} & -|V_{ts}| e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$



$$\frac{d\Gamma(B_s^0 \rightarrow D_s^{*-} \mu^+ \nu_\mu)}{dq^2} = \frac{G_F^2 |V_{cb}|^2 |\eta_{EW}|^2 |\vec{p}| q^2 \left(1 - \frac{m_\mu^2}{q^2}\right)^2}{96 \pi^3 m_{B_s^0}^2} \times \left[ (|H_+|^2 + |H_-|^2 + |H_0|^2) \left(1 + \frac{m_\mu^2}{2q^2}\right) + \frac{3}{2} \frac{m_\mu^2}{q^2} |H_t|^2 \right]$$

➤ Determine  $|V_{cb}|$  and form factors

LHCb, arXiv:2003.08453, JHEP 12(2020) 144



# Measurement on $|V_{cb}|$

- Measure rate relative to known  $B^0$  decay rate from B-factories:

$$R^* \equiv \frac{BR(B_s^0 \rightarrow D_s^{*-} \mu^+ \nu)}{BR(B^0 \rightarrow D^{*-} \mu^+ \nu)} \sim \frac{|V_{cb}|^2}{BR_{\text{measured B-factories}}}$$

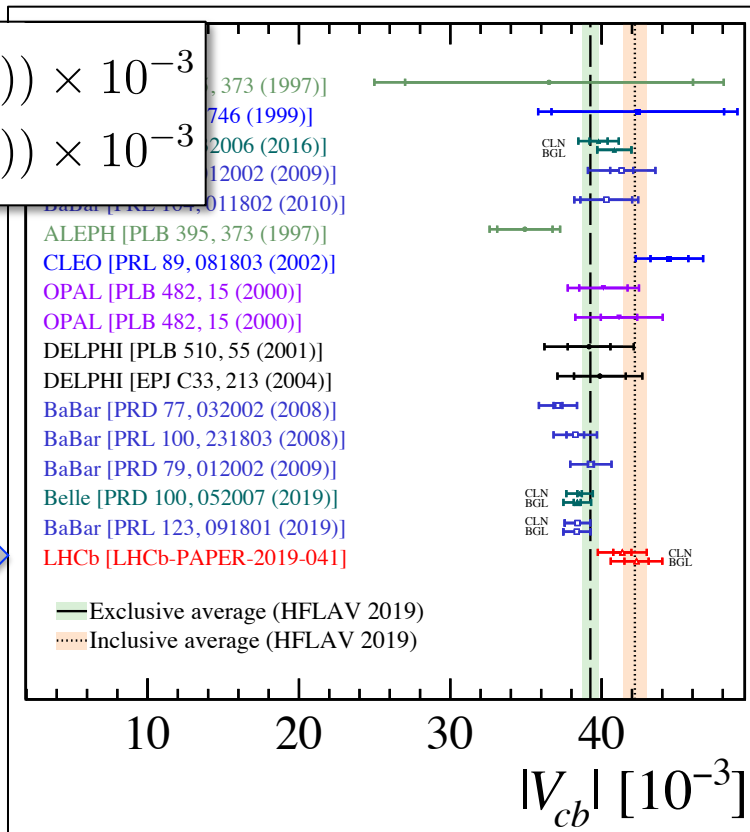
- Result depends on the assumed form factor parametrization:

$$|V_{cb}|_{\text{CLN}} = (41.4 \pm 0.6 \text{ (stat)} \pm 0.9 \text{ (syst)} \pm 1.2 \text{ (ext)}) \times 10^{-3}$$

$$|V_{cb}|_{\text{BGL}} = (42.3 \pm 0.8 \text{ (stat)} \pm 0.9 \text{ (syst)} \pm 1.2 \text{ (ext)}) \times 10^{-3}$$

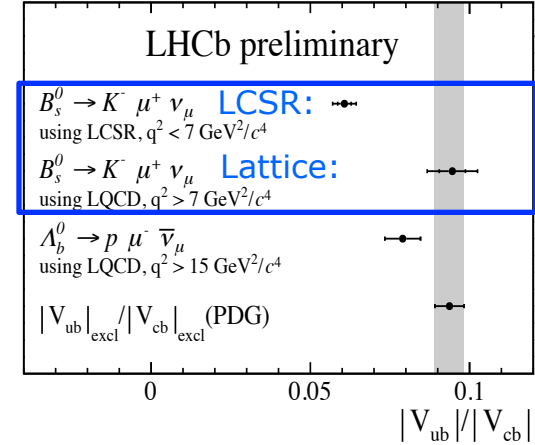
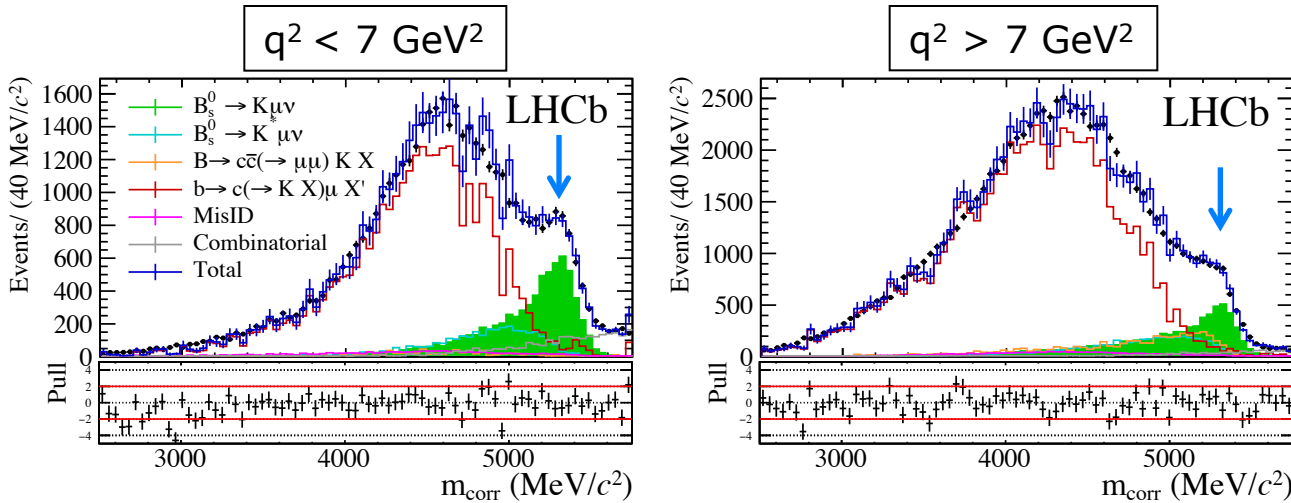
- Conclusions:

- First measurement of  $V_{cb}$  with pp
- First measurement using  $B_s^0$
- Parametrisation is not responsible for **inclusive vs exclusive disagreements**
- Result in agreement with the exclusive **and** inclusive averages



# Measurement $|V_{ub}|/|V_{cb}|$ from $B(B_s^0 \rightarrow K^- \mu^+ \nu)$

LHCb, [arXiv:2012.05143](https://arxiv.org/abs/2012.05143) PRL126(2021)8, 081804



$$R_{BF} = \mathcal{B}(B_s \rightarrow K \mu \nu) / \mathcal{B}(B_s \rightarrow D_s \mu \nu) = \frac{N_K}{N_{D_s}} \frac{\epsilon_{D_s}}{\epsilon_K} \times \mathcal{B}(D_s \rightarrow K K \pi)$$

$$\mathcal{B}(B_s \rightarrow K \mu \nu) = (1.06 \pm 0.05(\text{stat})) \pm 0.04(\text{syst}) \pm 0.06(\text{ext}) \pm 0.04(\text{FF}) \times 10^{-4}$$

- First observation of  $B_s^0 \rightarrow K^- \mu^+ \nu$

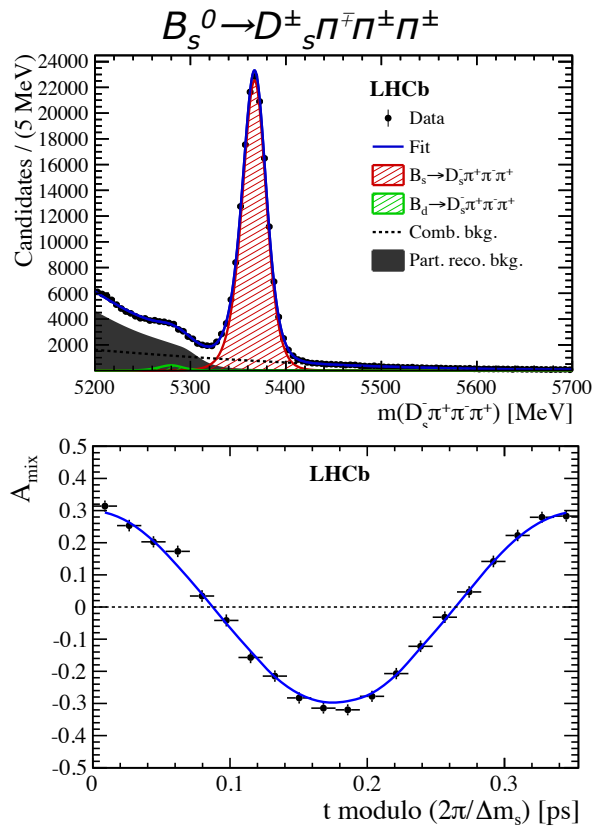
$$R_{BF} = |V_{ub}|^2 / |V_{cb}|^2 \times \text{FF}_K / \text{FF}_{D_s}$$

$$|V_{ub}|/|V_{cb}|(\text{low}) = 0.0607 \pm 0.0015(\text{stat}) \pm 0.0013(\text{syst}) \pm 0.0008(D_s) \pm 0.0030(\text{FF}),$$

$$|V_{ub}|/|V_{cb}|(\text{high}) = 0.0946 \pm 0.0030(\text{stat})_{-0.0025}^{+0.0024}(\text{syst}) \pm 0.0013(D_s) \pm 0.0068(\text{FF}). \quad (?)$$

- Interesting input to  $|V_{ub}|$  ! (and form factor calculations)

# Measurement of $\Delta m_s$ using $B_s^0 \rightarrow D^\pm_s \pi^\mp \pi^\pm \pi^\pm$ decays

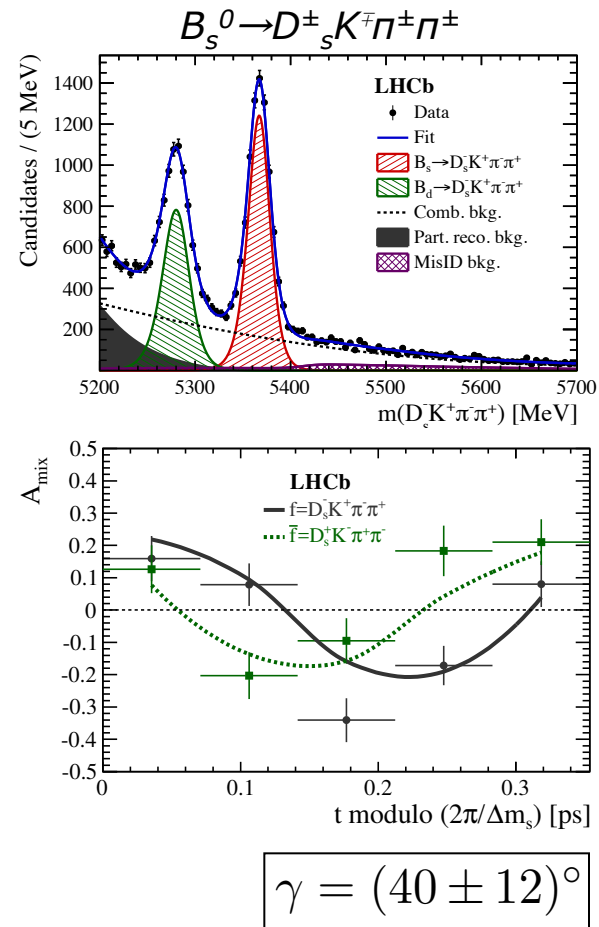


$$\Delta m_s = (17.7567 \pm 0.0070 \pm 0.0085) \text{ ps}^{-1}$$

- Precise measurement of  $\Delta m_s$



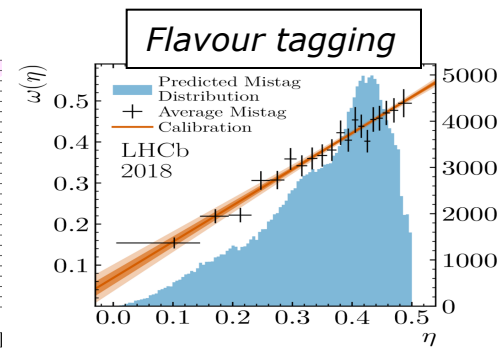
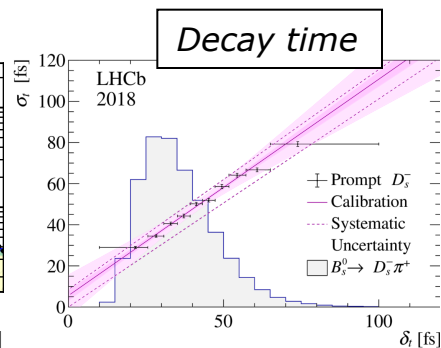
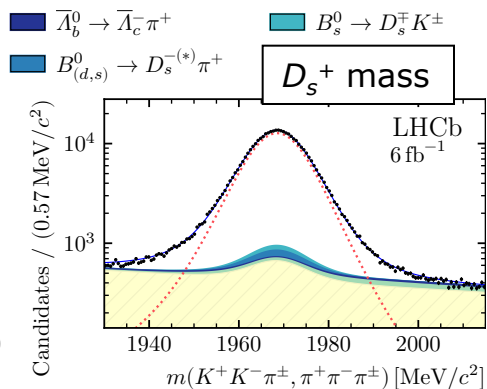
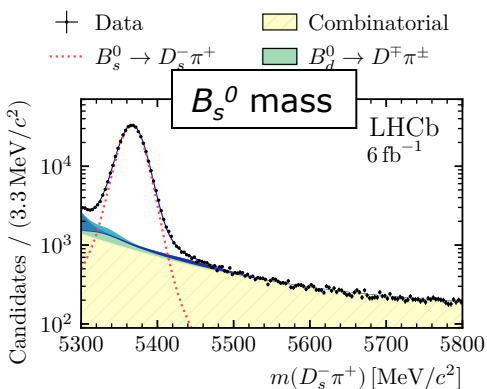
# Measurement of the CKM angle $\gamma$ using $B_s^0 \rightarrow D_s^\pm K^\mp \pi^\pm \pi^\pm$ decays



- New value for  $\gamma$  from TD  $B_s^0$

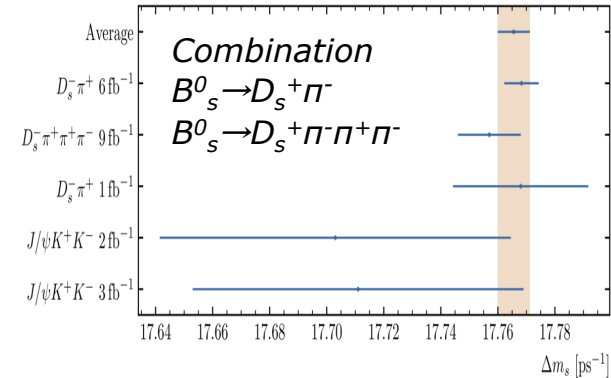
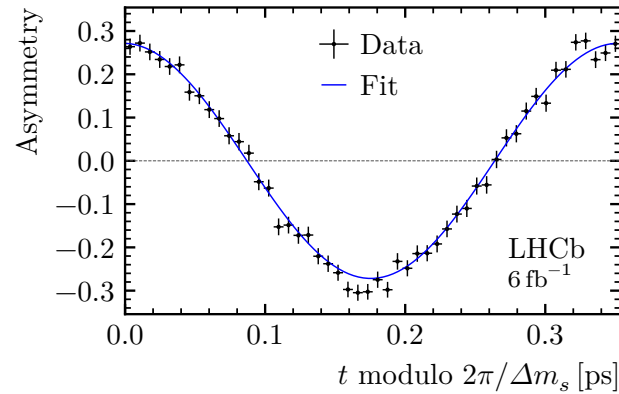
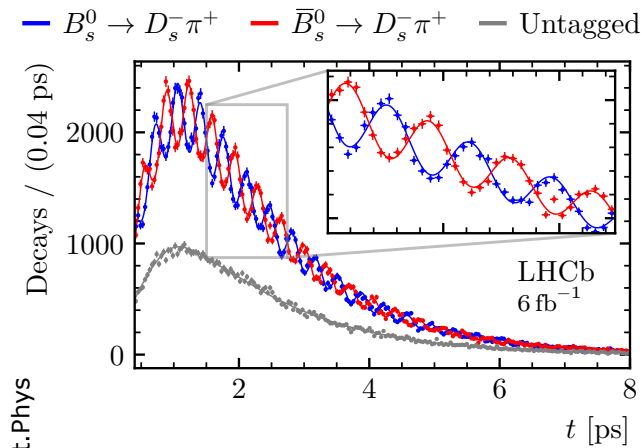
# Precision $\Delta m_s$ with $B_s^0 \rightarrow D_s^+ \pi^-$

- Legacy “textbook” run-2 measurement
- Precision:  $3 \times 10^{-4}$
- “Standard candle” for run-3
- 2D mass fit on  $B_s^0$  and  $D_s^+$  mass, followed by decay time fit
- Detailed study of tagging, decay time resolution and bias



# Precision $\Delta m_s$ with $B_s^0 \rightarrow D_s^+ \pi^-$

- Legacy “textbook” run-2 measurement
- Precision:  $3 \times 10^{-4}$
- “Standard candle” for run-3

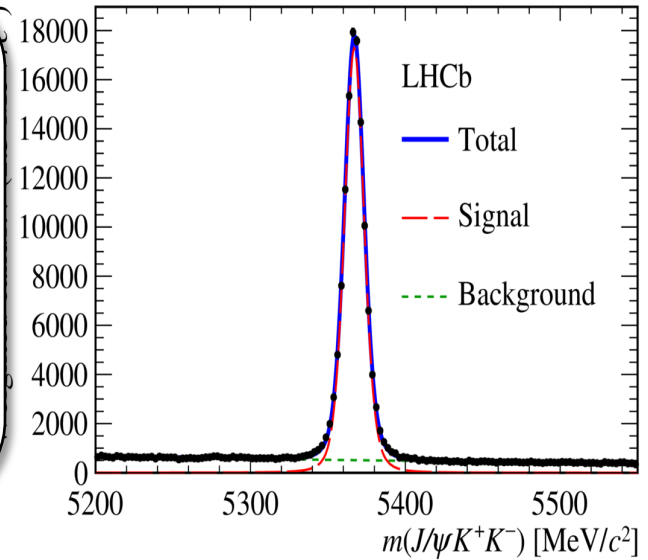
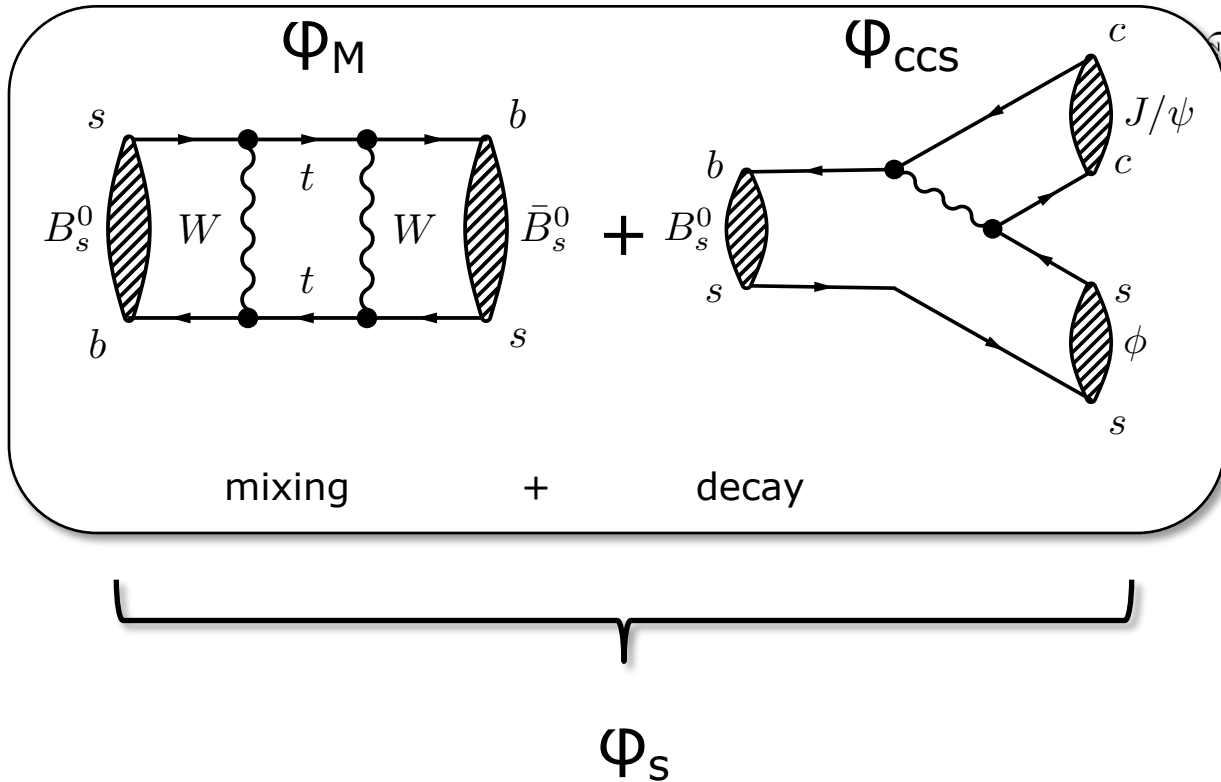


	$\Delta m_s$	Stat	Sys	Ref.
$B_s^0 \rightarrow D_s^+ \pi^-$	17.7683	0.0051	0.0032	arXiv:2104.04421 acc. Nat.Phys
$B_s^0 \rightarrow D_s^+ \pi^- \pi^- \pi^-$	17.757	0.007	0.008	arXiv:2011.12041 JHEP 03(2021)137
Combination	<b>17.7656</b>	<b>0.0057</b>		arXiv:2104.04421 acc. Nat.Phys

# Outline

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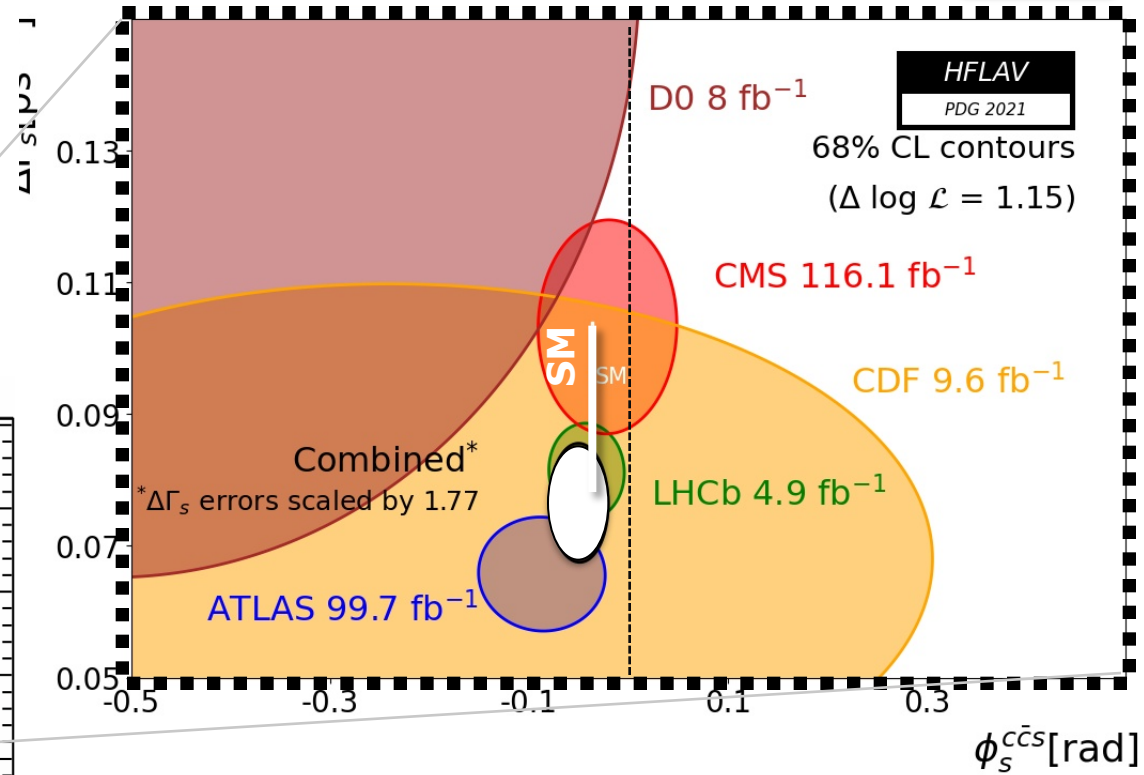
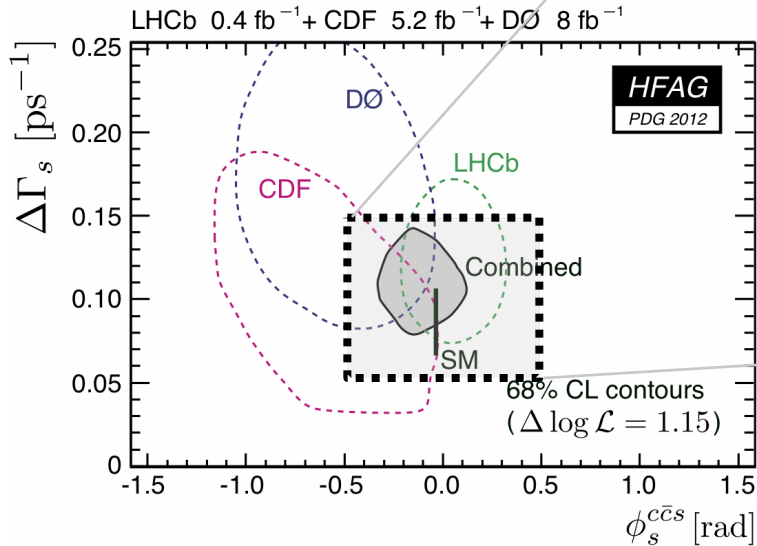
- CKM elements
  - $V_{ub}$
  - $V_{cb}$
  - $\Delta m_s$
- CKM phases
  - $\sin 2\beta$
  - $\Phi_s$
  - $\gamma$
- Prospects
  - Upgrade
  - Upgrade II



LHCb, [arXiv:1906.08356](https://arxiv.org/abs/1906.08356)  
 EPJC 79 (2019) 8, 706,  
 EPJC 80 (2020) 7, 601 (erratum)

- LHCb 2011-2016

2012



$$\phi_s = -50 \pm 19 \text{ mrad (HFLAV)}$$

$$\phi_s = -42 \pm 25 \text{ mrad (LHCb)}$$

$$\phi_s = -37 \pm 1 \text{ mrad (SM)}$$

CKMfitter,  
 Phys. Rev. D84, 033005 (2011),  
 updated with Summer 2019 results

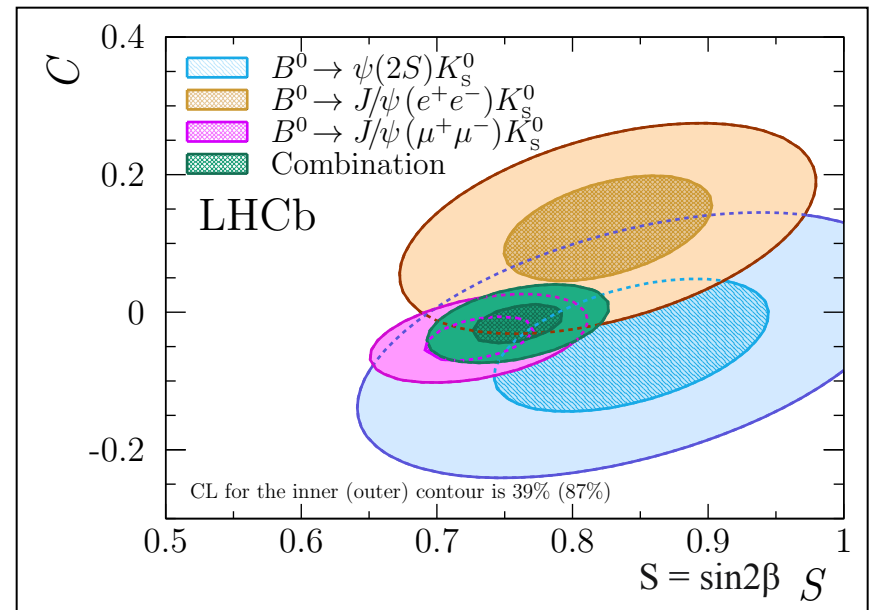
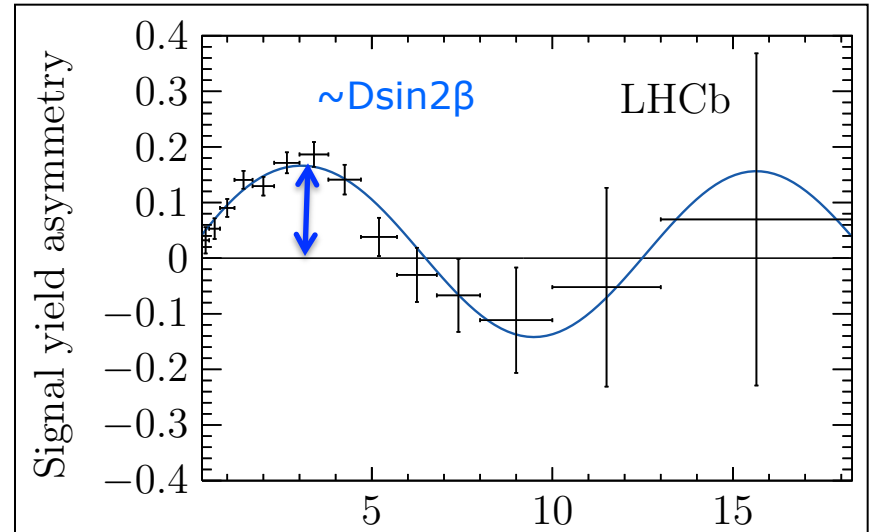
# sin2β

- Flavour tagging essential!

- Wrong tag fraction  $w \sim 35\%$
- $D = (1 - 2w) \sim 0.3$

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0 \rightarrow f)(t) - \Gamma(B^0 \rightarrow f)(t)}{\Gamma(\bar{B}^0 \rightarrow f)(t) + \Gamma(B^0 \rightarrow f)(t)}$$

$$A_{CP}(t) = D \sin 2\beta \sin \Delta mt$$



LHCb, JHEP 11 (2017) 170

# sin2β

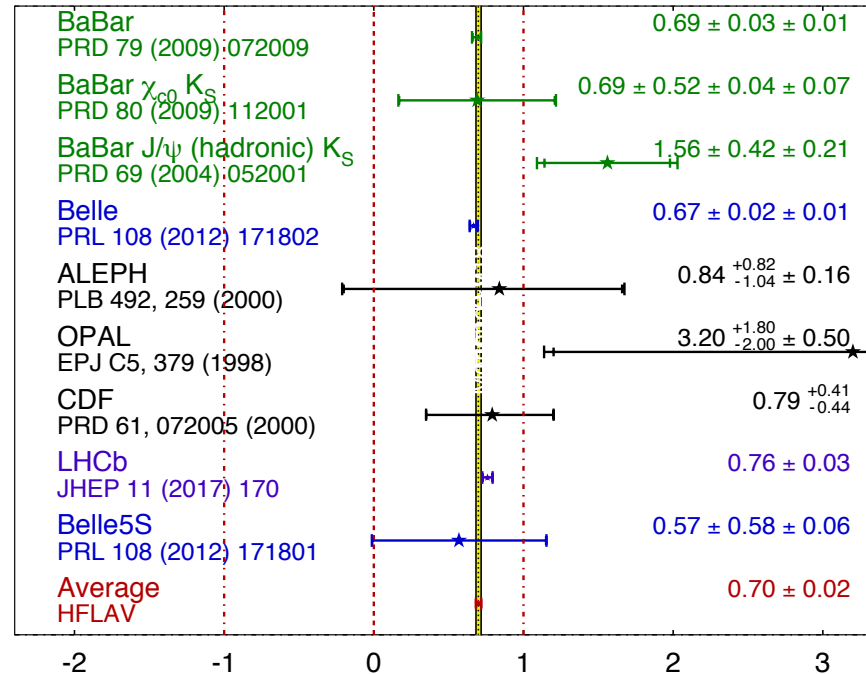
BaBar:  $\sin 2\beta = 0.691 \pm 0.031$

Belle:  $\sin 2\beta = 0.667 \pm 0.026$

LHCb:  $\sin 2\beta = 0.760 \pm 0.034$

Avg:  $\sin 2\beta = 0.699 \pm 0.017$

$\sin(2\beta) \equiv \sin(2\phi_1)$  **HFLAV**  
Moriond 2018  
PRELIMINARY



- Large  $B$  production competes with good tagging:

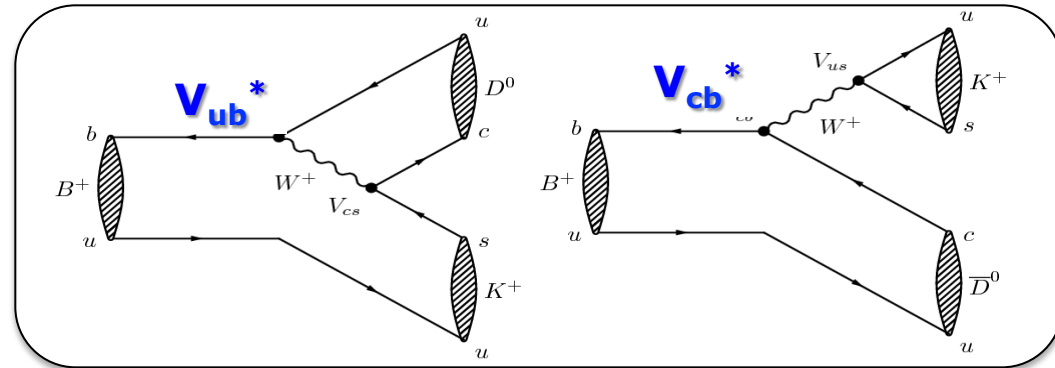
$\sigma_{\text{stat}}(\mathcal{S}(J/\psi K_S^0))$	now	$50 \text{ ab}^{-1}$	
Belle/II	0.029	0.005	
	now	$50 \text{ fb}^{-1}$	$300 \text{ fb}^{-1}$
LHCb	0.035	0.006	0.003



# Constraints on angle $\gamma$

- Different yields for  $B^+$  and  $B^-$  decays

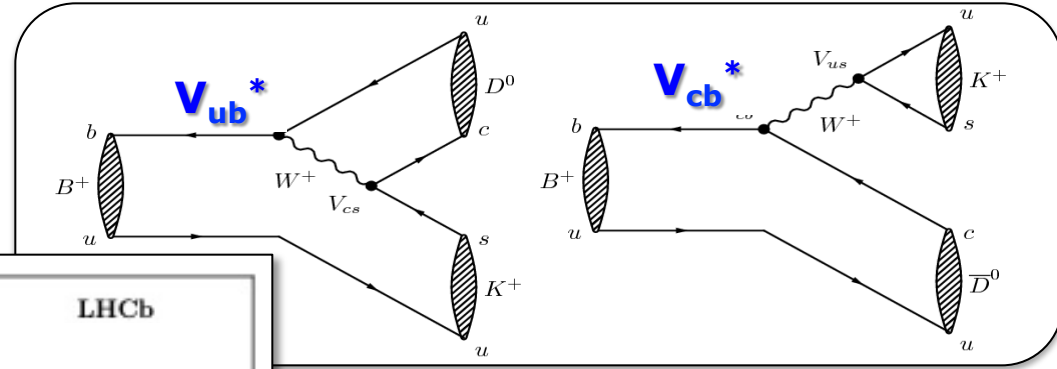
– two amplitudes contribute with different relative phase:  $V_{ub} = |V_{ub}|e^{-i\gamma}$



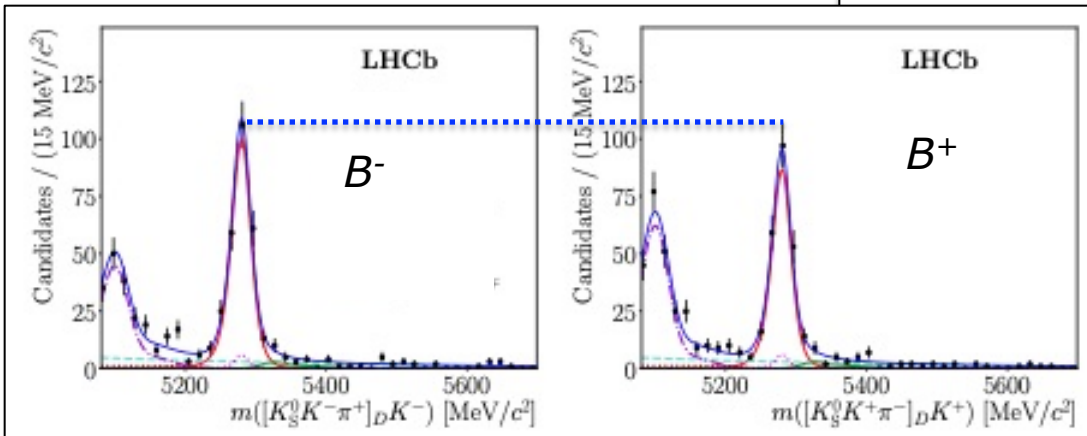
# Constraints on angle $\gamma$ - with $B^\pm \rightarrow D^{(*)}K^\pm$ and $D^0 \rightarrow K^0_S K^\pm \pi^\mp$

- Different yields for  $B^+$  and  $B^-$  decays

- two amplitudes contribute with different relative phase:  $V_{ub} = |V_{ub}|e^{-i\gamma}$



LHCb, arXiv:2002.08858, JHEP 06(2020) 058



$$\begin{aligned}
 N_{SS}^{DK^\pm} &\propto 1 + r_B^2 r_D^2 + 2r_B r_D \kappa_D \cos(\delta_B \pm \gamma - \delta_D) \\
 N_{OS}^{DK^\pm} &\propto r_B^2 + r_D^2 + 2r_B r_D \kappa_D \cos(\delta_B \pm \gamma + \delta_D) \\
 N_{SS}^{D\pi^\pm} &\propto 1 + (r_B^\pi)^2 r_D^2 + 2r_B^\pi r_D \kappa_D \cos(\delta_B^\pi \pm \gamma - \delta_D) \\
 N_{OS}^{D\pi^\pm} &\propto (r_B^\pi)^2 + r_D^2 + 2r_B^\pi r_D \kappa_D \cos(\delta_B^\pi \pm \gamma + \delta_D)
 \end{aligned}$$

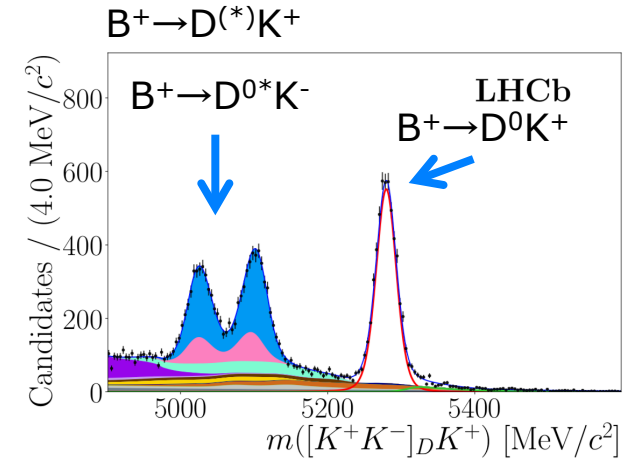
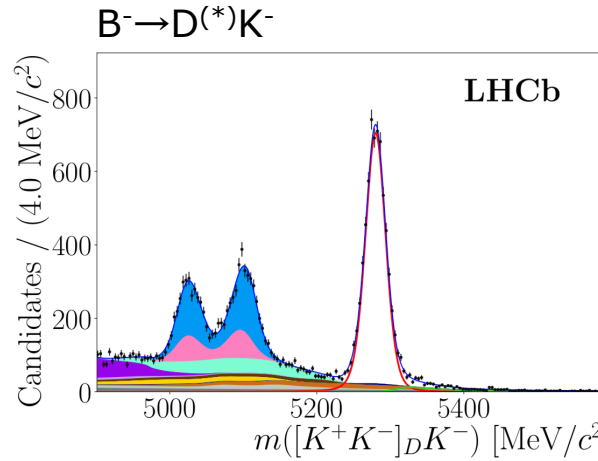
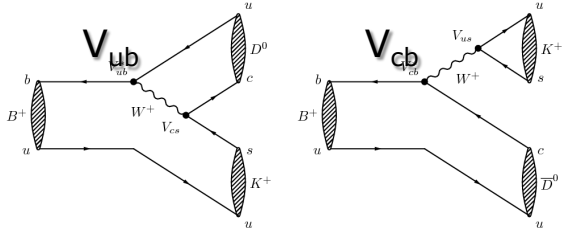


	non- $K^{*+}$ region	$K^{*+}$ region
$N_{SS}^{DK^\pm}$	$266 \pm 27$	$715 \pm 37$
$N_{OS}^{DK^\pm}$	$336 \pm 27$	$217 \pm 22$
$N_{SS}^{D\pi^\pm}$	$3304 \pm 73$	$8977 \pm 106$
$N_{OS}^{D\pi^\pm}$	$4686 \pm 76$	$3471 \pm 66$



$$\begin{aligned}
 A_{SS}^{D\pi} &= -0.020 \pm 0.011 \pm 0.003 \\
 A_{OS}^{D\pi} &= 0.007 \pm 0.017 \pm 0.003 \\
 A_{SS}^{DK} &= 0.084 \pm 0.049 \pm 0.008 \\
 A_{OS}^{DK} &= 0.021 \pm 0.094 \pm 0.017
 \end{aligned}$$

# Constraints on angle $\gamma$ - with $B^\pm \rightarrow D^{(*)}K^\pm$ and $D^0 \rightarrow h^\pm h^\pm$



$$\Gamma(B^\pm \rightarrow [CP]_D h^\pm) \propto 1 + (r_B^{Dh})^2 + 2r_B^{Dh} \cos(\delta_B^{Dh} \pm \gamma)$$

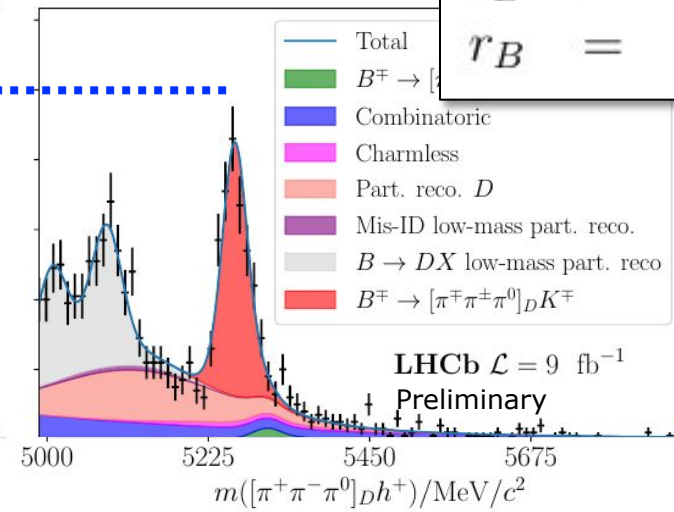
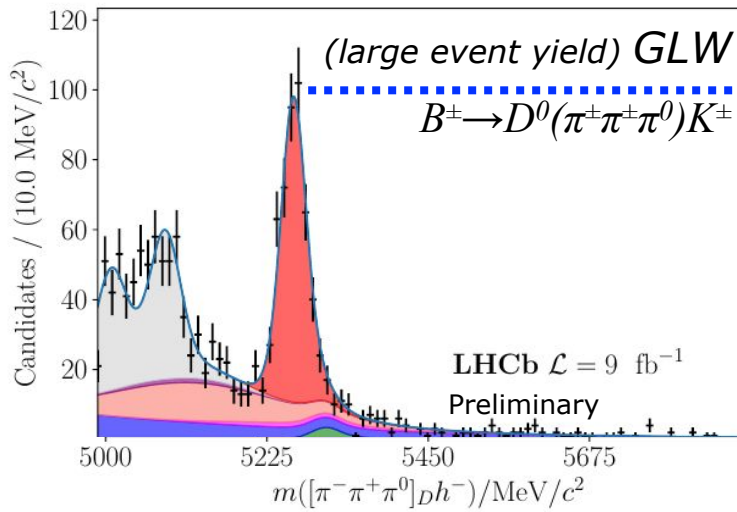
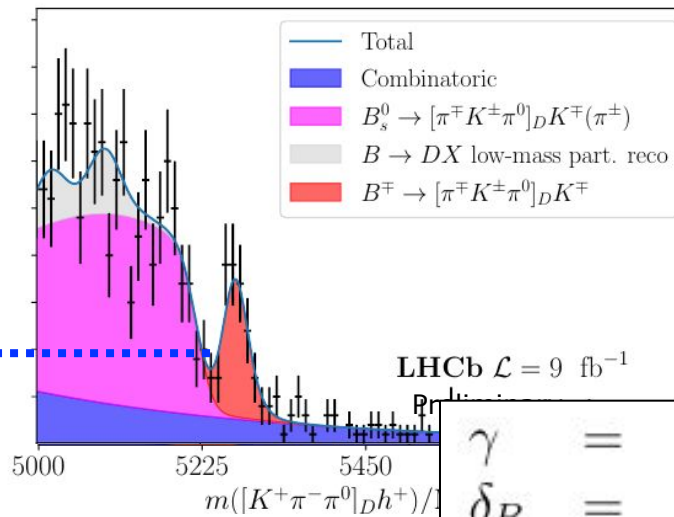
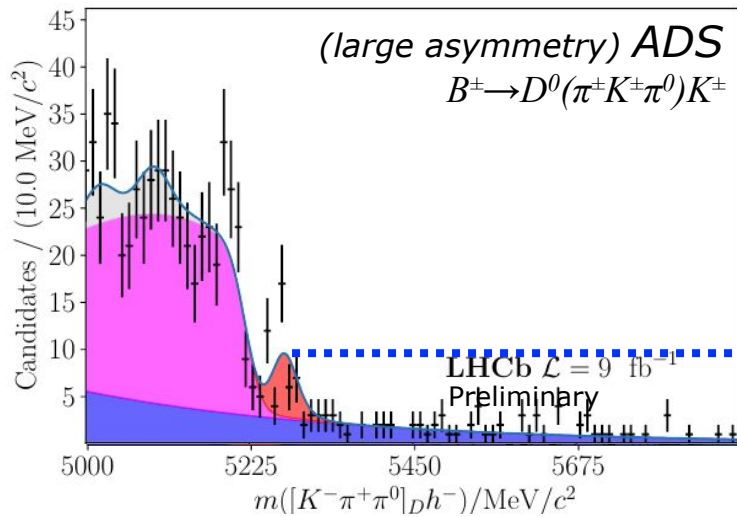
$A_K^{CP} = 0.136 \pm 0.009 \pm 0.001$
$A_\pi^{CP} = -0.008 \pm 0.002 \pm 0.002$
$A_K^{K\pi} = -0.011 \pm 0.003 \pm 0.002$
$R^{CP} = 0.950 \pm 0.009 \pm 0.010$
$R_{K/\pi}^{K\pi} = 0.0796 \pm 0.0003 \pm 0.0013$
$R_{K^-}^{\pi K} = 0.0095 \pm 0.0005 \pm 0.0003$
$R_{\pi^-}^{\pi K} = 0.00415 \pm 0.00008 \pm 0.00004$
$R_{K^+}^{\pi K} = 0.0252 \pm 0.0008 \pm 0.0004$
$R_{\pi^+}^{\pi K} = 0.00320 \pm 0.00007 \pm 0.00004$
$A_K^{CP,\gamma} = 0.123 \pm 0.054 \pm 0.031$
$A_K^{CP,\pi^0} = -0.115 \pm 0.019 \pm 0.009$
$A_K^{K\pi,\gamma} = -0.004 \pm 0.014 \pm 0.003$
$A_K^{K\pi,\pi^0} = 0.020 \pm 0.007 \pm 0.003$
$R^{CP,\gamma} = 0.952 \pm 0.062 \pm 0.065$
$R^{CP,\pi^0} = 1.051 \pm 0.022 \pm 0.028$
$R_{K/\pi}^{K\pi,\pi^0} = 0.0851 \pm 0.0012 \pm 0.0048$
$R_{K^-}^{\pi K,\gamma} = 0.0117 \pm 0.0215 \pm 0.0313$
$R_{K^-}^{\pi K,\pi^0} = 0.0202 \pm 0.0035 \pm 0.0023$
$R_{K^+}^{\pi K,\gamma} = 0.0292 \pm 0.0214 \pm 0.0312$
$R_{K^+}^{\pi K,\pi^0} = 0.0033 \pm 0.0035 \pm 0.0022$
$A_\pi^{CP,\gamma} = 0.000 \pm 0.014 \pm 0.006$
$A_\pi^{CP,\pi^0} = 0.013 \pm 0.007 \pm 0.003$
$A_\pi^{K\pi,\gamma} = -0.004 \pm 0.004 \pm 0.001$
$A_\pi^{K\pi,\pi^0} = 0.001 \pm 0.002 \pm 0.001$
$R_\pi^{\pi K,\gamma} = 0.00472 \pm 0.00092 \pm 0.00118$
$R_\pi^{\pi K,\pi^0} = 0.00405 \pm 0.00056 \pm 0.00059$
$R_\pi^{\pi K,\gamma} = 0.00403 \pm 0.00091 \pm 0.00114$
$R_{\pi^+}^{\pi K,\pi^0} = 0.00536 \pm 0.00056 \pm 0.00058$

- Full run-2 ADS/GLW analysis, many final states
  - $B^\pm \rightarrow D^0 K^\pm, B^\pm \rightarrow D^0 \pi^\pm, B^\pm \rightarrow D^{0*} K^\pm, B^\pm \rightarrow D^{0*} \pi^\pm$
  - $D^0 \rightarrow K^+ K^-, D^0 \rightarrow K^+ \pi^-, D^0 \rightarrow \pi^+ \pi^-$
- Very precise input for gamma

# Constraints on angle $\gamma$ - with $B^\pm \rightarrow D^0 h^\pm$ and $D^0 \rightarrow h^\pm h^\pm \pi^0$

- Different yields for  $B^+$  and  $B^-$  decays

- two amplitudes contribute with different relative phase:  $V_{ub} = |V_{ub}|e^{-i\gamma}$



$$\gamma = (56_{-19}^{+24})^\circ$$

$$\delta_B = (122_{-23}^{+19})^\circ$$

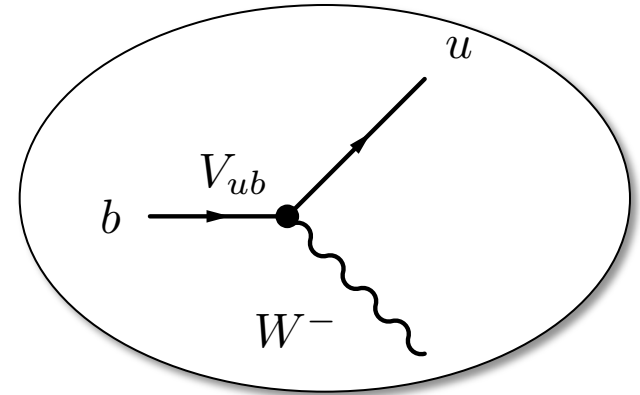
$$r_B = (9.25_{-0.85}^{+1.04}) \times 10^{-2}$$

# CKM angle $\gamma$

- Different yields for  $B$  and anti- $B$  decays

- two amplitudes contribute with different relative phase:  $V_{ub} = |V_{ub}|e^{-i\gamma}$
- many  $D^{(*)}_{(s)}$  final states:

$B$ decay	$D$ decay	Method	Ref.	Dataset	Lumi ( $\text{fb}^{-1}$ )	Status since Ref. [4]
$B^+ \rightarrow Dh^+$	$D \rightarrow h^+h^-$	GLW/ADS	[19]	Run 1&2	9	<b>Updated</b>
$B^+ \rightarrow Dh^+$	$D \rightarrow h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1	3	As before
$B^+ \rightarrow Dh^+$	$D \rightarrow h^+h^-\pi^0$	GLW/ADS	[21]	Run 1	3	As before
$B^+ \rightarrow Dh^+$	$D \rightarrow K_S^0 h^+h^-$	BPGGSZ	[22]	Run 2	9	<b>Updated</b>
$B^+ \rightarrow Dh^+$	$D \rightarrow K_S^0 K^\pm \pi^\mp$	GLS	[23]	Run 1&2	9	<b>Updated</b>
$B^+ \rightarrow D^+h^+$	$D \rightarrow h^+h^-$	GLW/ADS	[19]	Run 1&2	5	<b>Updated</b>
$B^+ \rightarrow DK^{*+}$	$D \rightarrow h^+h^-$	GLW/ADS	[24]	Run 1&2	5	As before
$B^+ \rightarrow DK^{*+}$	$D \rightarrow h^+\pi^-\pi^+\pi^-$	GLW/ADS	[24]	Run 1&2	5	As before
$B^+ \rightarrow DK^{*+}\pi^-$	$D \rightarrow h^+h^-$	GLW/ADS	[25]	Run 1	3	As before
$B^0 \rightarrow DK^{*0}$	$D \rightarrow K^+\pi^-$	GLW/ADS	[26]	Run 1&2	5	<b>Updated</b>
$B^0 \rightarrow DK^{*0}$	$D \rightarrow h^+\pi^-\pi^+\pi^-$	GLW/ADS	[26]	Run 1&2	5	<b>New</b>
$B^0 \rightarrow DK^{*+}\pi^-$	$D \rightarrow h^+h^-$	GLW-Dalitz	[27]	Run 1	3	<b>Superseded</b>
$B^0 \rightarrow DK^{*0}$	$D \rightarrow K_S^0 \pi^+\pi^-$	BPGGSZ	[28]	Run 1	3	As before
$B^0 \rightarrow D^{\mp}\pi^\pm$	$D^+ \rightarrow K^-\pi^+\pi^+$	TD	[29]	Run 1	3	As before
$B_s^0 \rightarrow D_s^{\mp}K^\pm$	$D_s^+ \rightarrow h^+h^-\pi^+$	TD	[30]	Run 1	3	As before
$B_s^0 \rightarrow D_s^{\mp}K^\pm\pi^\pm\pi^\mp$	$D_s^+ \rightarrow h^+h^-\pi^+$	TD	[31]	Run 1&2	9	<b>New</b>
$D$ decay	Inputs		Ref.	Dataset	Lumi ( $\text{fb}^{-1}$ )	Status since Ref. [4]
$D \rightarrow h^+h^-$	$\Delta\alpha_{CP}^{\text{dir}}$		[32-34]	Run 1&2	9	<b>New</b>
$D \rightarrow h^+h^-$	$y_{CP}$		[35]	Run 1	3	<b>New</b>
$D \rightarrow h^+h^-$	$\Delta Y(A_r)$		[36]	Run 1&2	9	<b>New</b>
$D \rightarrow K^+\pi^-$	$x_D^2, y_D, R_D^{K\pi}$		[37]	Run 1&2	5	<b>New</b>
$D \rightarrow K^\pm\pi^+\pi^+\pi^-$	$y_D^{K3\pi}, R_D^{K3\pi}, R_M/2, r_D^{K3\pi}$		[38]	Run 1	3	<b>New</b>
$D \rightarrow K_S^0\pi^+\pi^-$	$x_{CP}, \Delta x, y_{CP}, \Delta y$		[?, 39]	Run 1&2	9	<b>New</b>
$D \rightarrow K_S^0\pi^+\pi^-$	$x_D, y_D$		[40]	Run 1	1	<b>New</b>



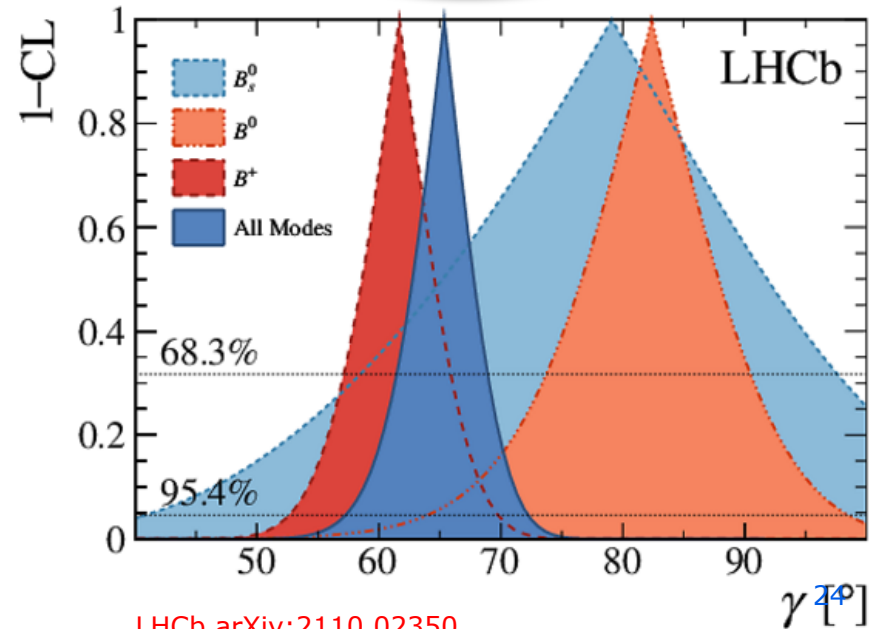
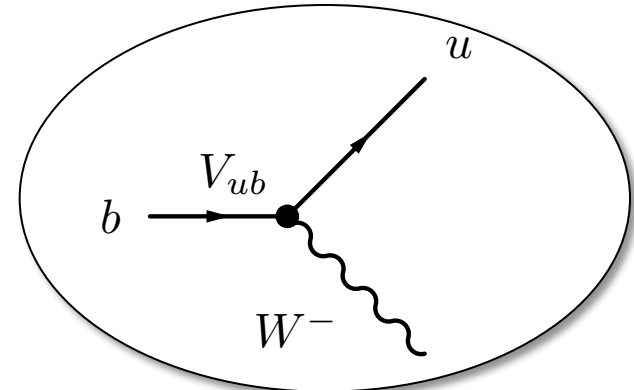
[LHCb arXiv:2110.02350](https://arxiv.org/abs/2110.02350)

# CKM angle $\gamma$

- Different yields for  $B$  and anti- $B$  decays

- two amplitudes contribute with different relative phase:  $V_{ub} = |V_{ub}|e^{-i\gamma}$
- many  $D^{(*)}_{(s)}$  final states:

$B$ decay	$D$ decay	Method	Ref.	Dataset	Lumi (fb <sup>-1</sup> )	Status since Ref. [4]
$B^+ \rightarrow Dh^+$	$D \rightarrow h^+h^-$	GLW/ADS	[19]	Run 1&2	9	Updated
$B^+ \rightarrow Dh^+$	$D \rightarrow h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1	3	As before
$B^+ \rightarrow Dh^+$	$D \rightarrow h^+h^-\pi^0$	GLW/ADS	[21]	Run 1	3	As before
$B^+ \rightarrow Dh^+$	$D \rightarrow K_S^0 h^+ h^-$	BPGGSZ	[22]	Run 2	9	Updated
$B^+ \rightarrow Dh^+$	$D \rightarrow K_S^0 K^\pm \pi^\mp$	GLS	[23]	Run 1&2	9	Updated
$B^+ \rightarrow D^* h^+$	$D \rightarrow h^+ h^-$	GLW/ADS	[19]	Run 1&2	5	Updated
$B^+ \rightarrow DK^{*+}$	$D \rightarrow h^+ h^-$	GLW/ADS	[24]	Run 1&2	5	As before
$B^+ \rightarrow DK^{*+}$	$D \rightarrow h^+ \pi^-\pi^+\pi^-$	GLW/ADS	[24]	Run 1&2	5	As before
$B^+ \rightarrow DK^{*+}\pi^-$	$D \rightarrow h^+ h^-$	GLW/ADS	[25]	Run 1	3	As before
$B^0 \rightarrow DK^{*0}$	$D \rightarrow K^+ \pi^-$	GLW/ADS	[26]	Run 1&2	5	Updated
$B^0 \rightarrow DK^{*0}$	$D \rightarrow h^+ \pi^-\pi^+\pi^-$	GLW/ADS	[26]	Run 1&2	5	New
$B^0 \rightarrow DK^{*+}\pi^-$	$D \rightarrow h^+ h^-$	GLW-Dalitz	[27]	Run 1	3	Superseded
$B^0 \rightarrow DK^{*0}$	$D \rightarrow K_S^0 \pi^+ \pi^-$	BPGGSZ	[28]	Run 1	3	As before
$B^0 \rightarrow D^* \pi^\pm$	$D^+ \rightarrow K^- \pi^+ \pi^+$	TD	[29]	Run 1	3	As before
$B_s^0 \rightarrow D_s^* K^\pm$	$D_s^+ \rightarrow h^+ h^- \pi^+$	TD	[30]	Run 1	3	As before
$B_s^0 \rightarrow D_s^* K^\pm \pi^\pm \pi^\mp$	$D_s^+ \rightarrow h^+ h^- \pi^+$	TD	[31]	Run 1&2	9	New
$D$ decay	Inputs		Ref.	Dataset	Lumi (fb <sup>-1</sup> )	Status since Ref. [4]
$D \rightarrow h^+ h^-$	$\Delta\alpha_{CP}^{dir}$		[32-34]	Run 1&2	9	New
$D \rightarrow h^+ h^-$	$y_{CP}$		[35]	Run 1	3	New
$D \rightarrow h^+ h^-$	$\Delta Y(A_r)$		[36]	Run 1&2	9	New
$D \rightarrow K^+ \pi^-$	$x_D^2, y_D, R_D^{K\pi}$		[37]	Run 1&2	5	New
$D \rightarrow K^\pm \pi^+ \pi^+ \pi^-$	$y_D^{K3\pi}, R_D^{K3\pi}, R_M/2, r_D^{K3\pi}$		[38]	Run 1	3	New
$D \rightarrow K_S^0 \pi^+ \pi^-$	$x_{CP}, \Delta x, y_{CP}, \Delta y$		[?, 39]	Run 1&2	9	New
$D \rightarrow K_S^0 \pi^+ \pi^-$	$x_D, y_D$		[40]	Run 1	1	New

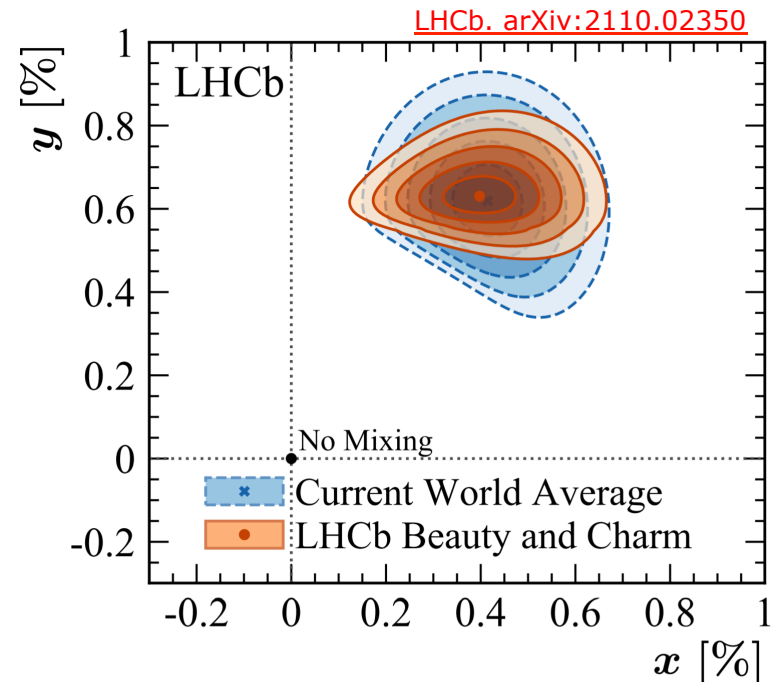
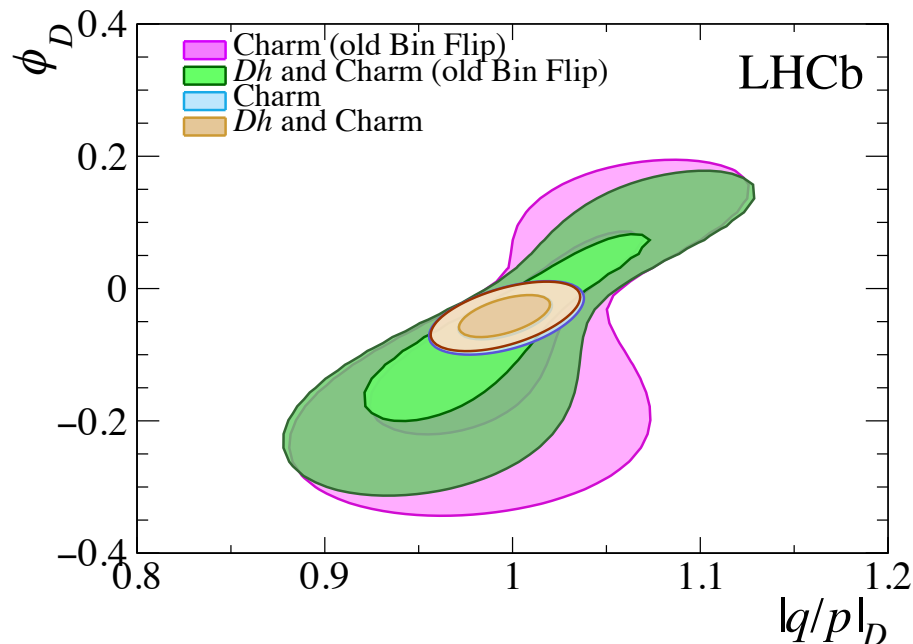


	$\gamma$ (°)
LHCb	$65.3^{+3.6}_{-3.9}$
CKMfitter	$65.6^{+0.9}_{-2.7}$
UTFit	$65.8^{+2.2}_{-2.2}$

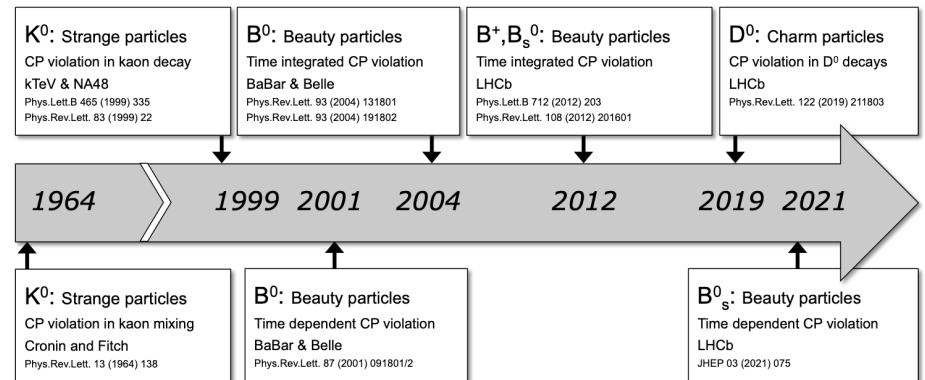
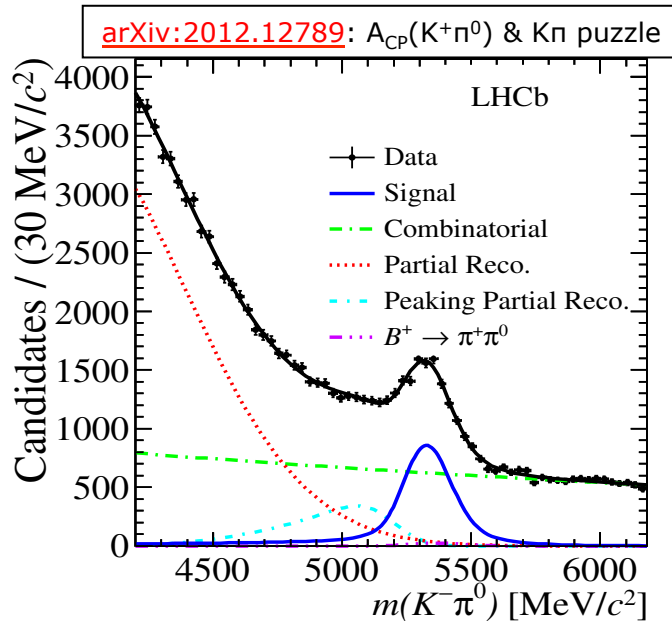
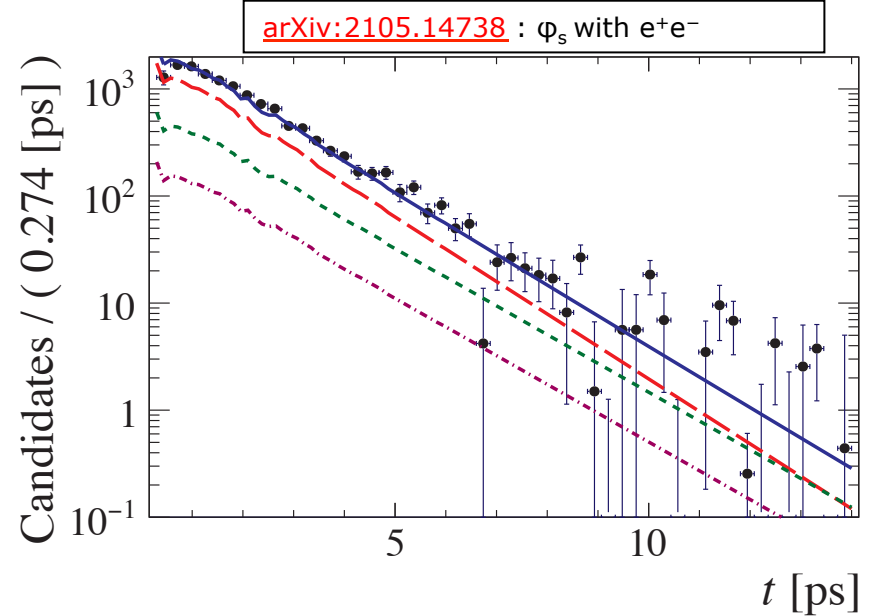
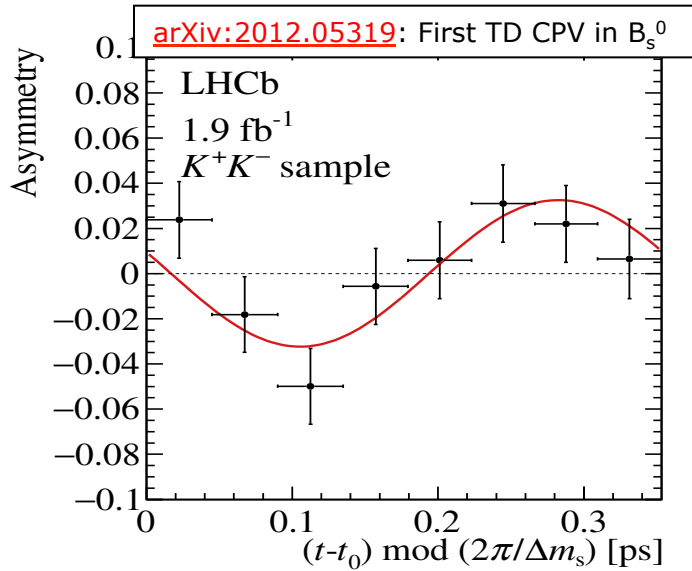
# CKM angle $\gamma$ – and $D^0$ mixing

- New strategy wrt to previous LHCb combinations
- Exploit sensitivity to charm observables
  - and avoid iterating

➤ Charm:  $\gamma$  twice more precise



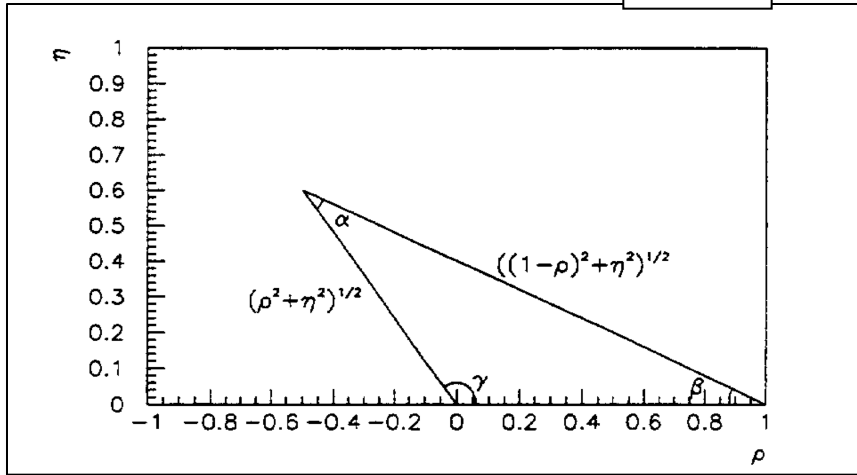
# More results: CPV



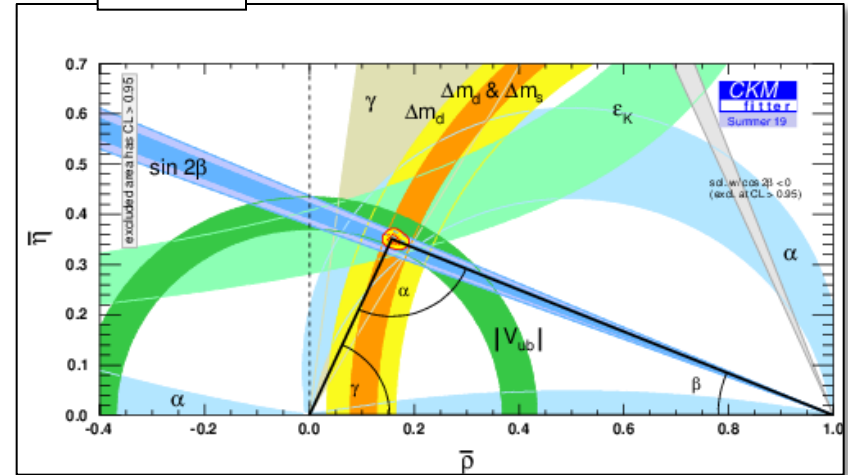


# CKM

1995



2019



- Continuous improvement over the years
- Consistent picture

# Outline

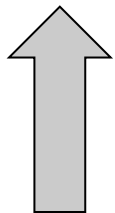
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- CKM elements
  - $V_{ub}$
  - $V_{cb}$
  - $\Delta m_s$
- CKM phases
  - $\sin 2\beta$
  - $\Phi_s$
  - $\gamma$
- **Prospects**
  - Upgrade
  - Upgrade II

# Where do we go from here?

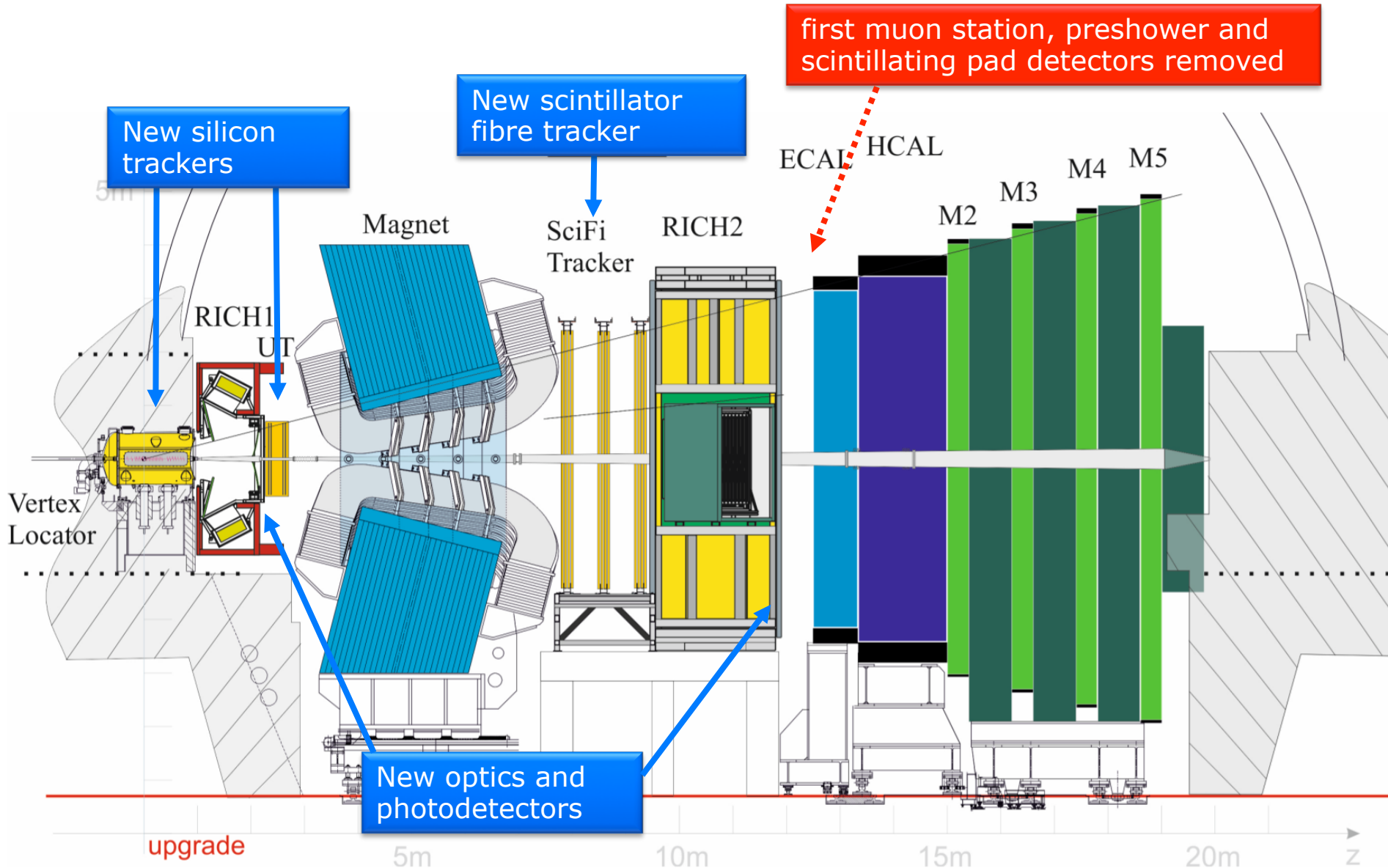
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2020	2021	2022	2023	2024	2025	2026
		Run III				
<b>LS2</b>						<b>LS3</b>
<b>LHCb 40 MHz UPGRADE I</b>		$L = 2 \times 10^{33}$			<b>LHCb Consolidate: UPGRADE Ib</b>	
<b>ATLAS Phase I Upgr</b>		$L = 2 \times 10^{34}$			<b>ATLAS Phase II UPG</b>	
<b>CMS Phase I Upgr</b>		$300 \text{ fb}^{-1}$			<b>CMS Phase II UPG</b>	



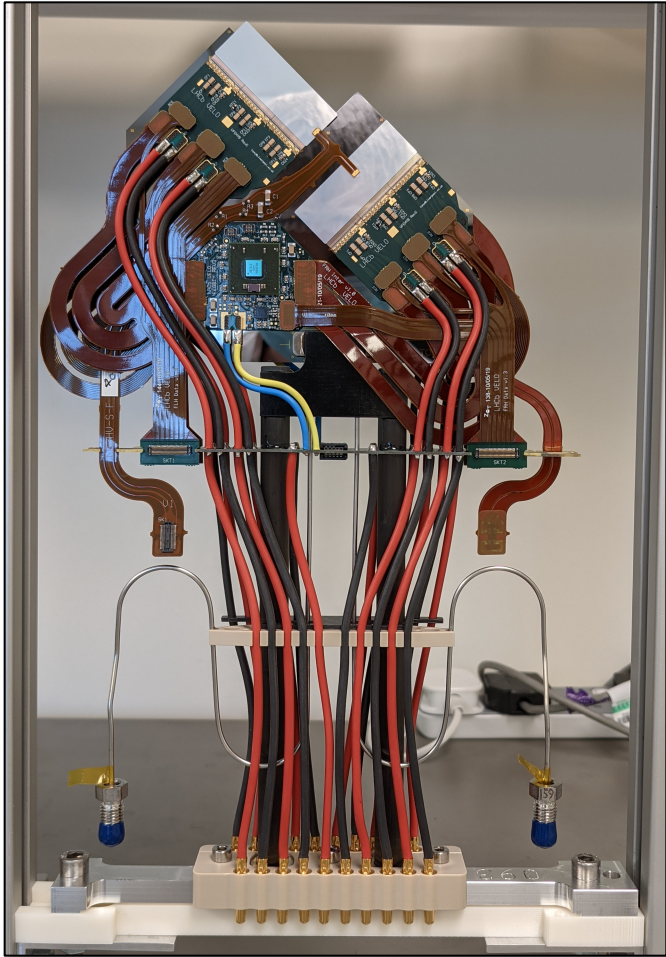
You are here!

# Where do we go from here?



# VELO

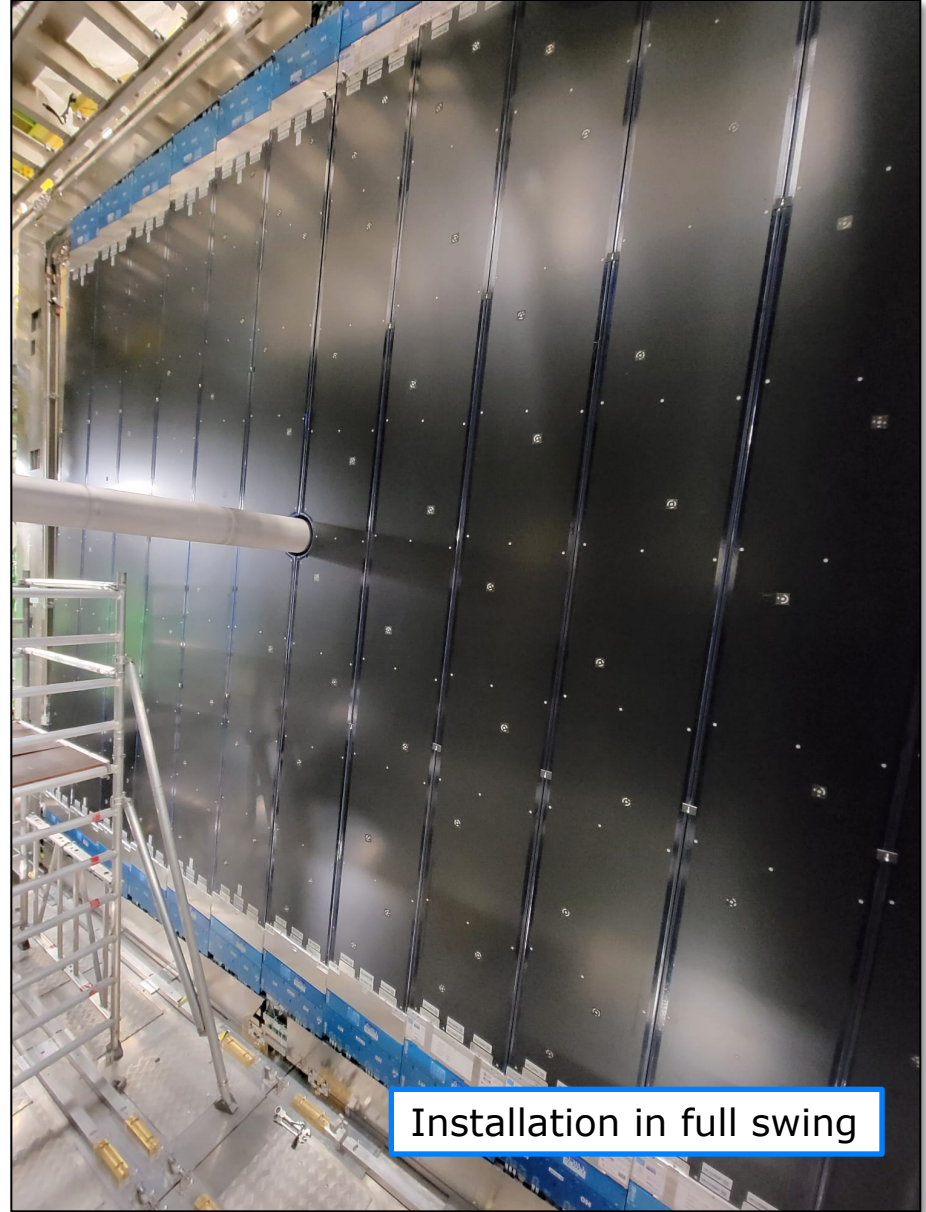
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Modules ready  
One half assembled

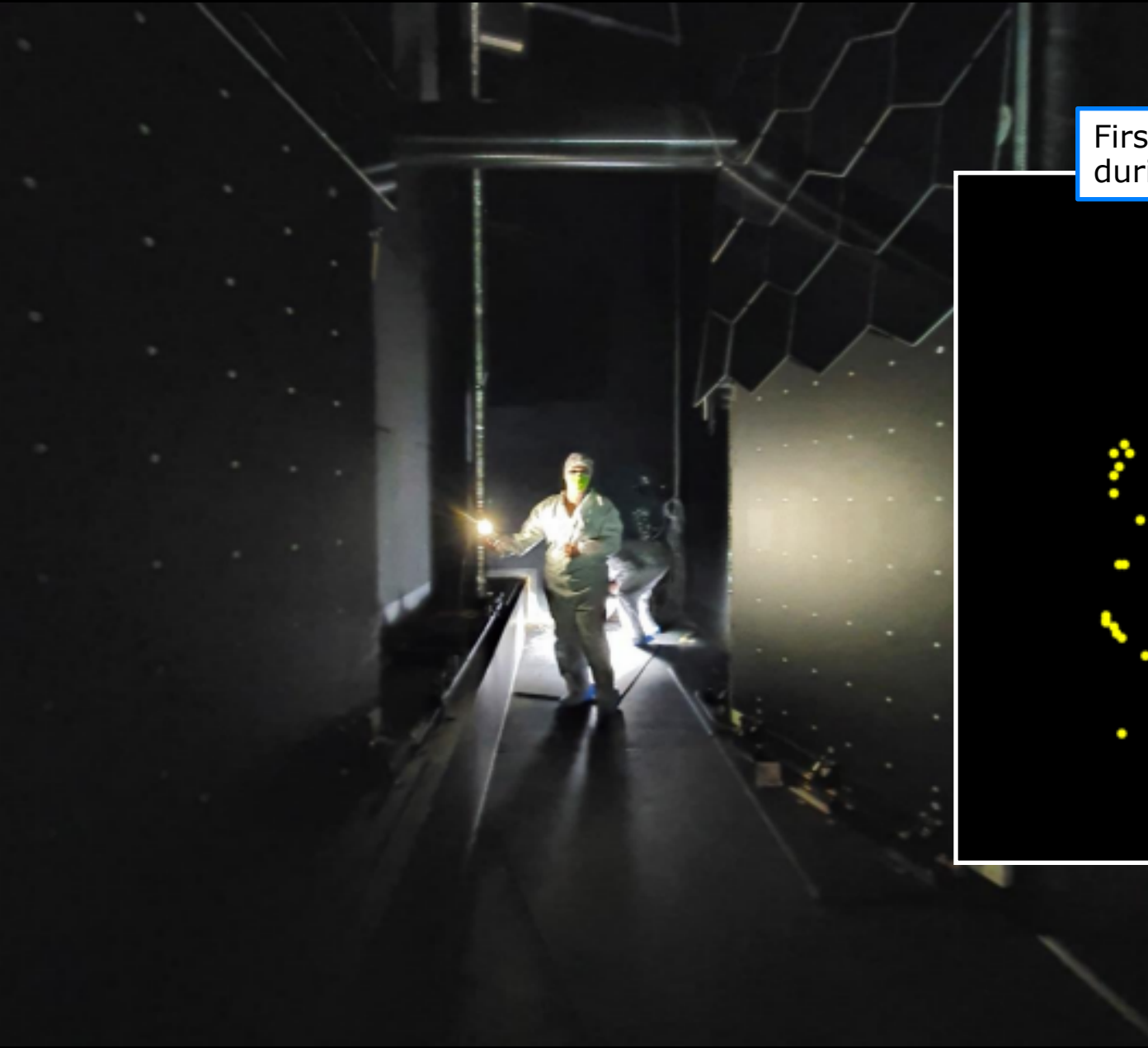


# Tracker

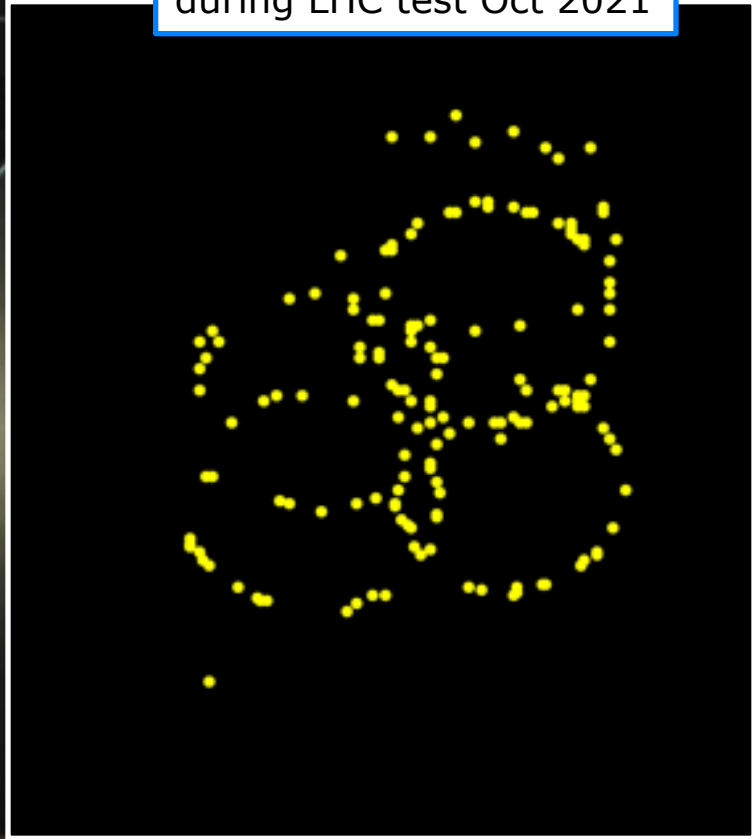


Installation in full swing

# Ring Imaging Cherenkov

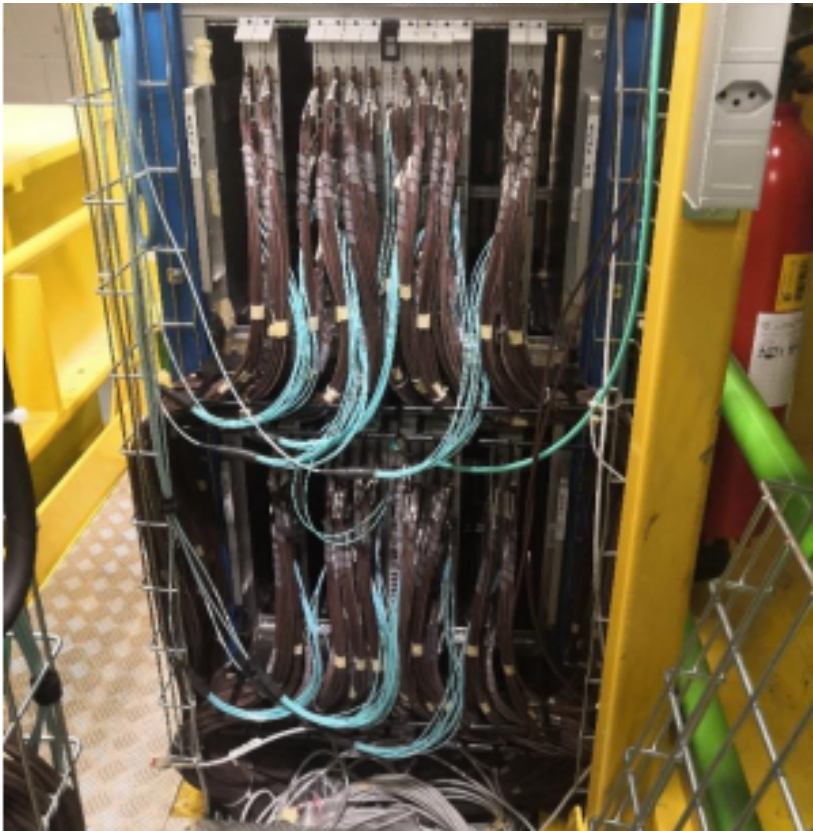


First rings in RICH2  
during LHC test Oct 2021

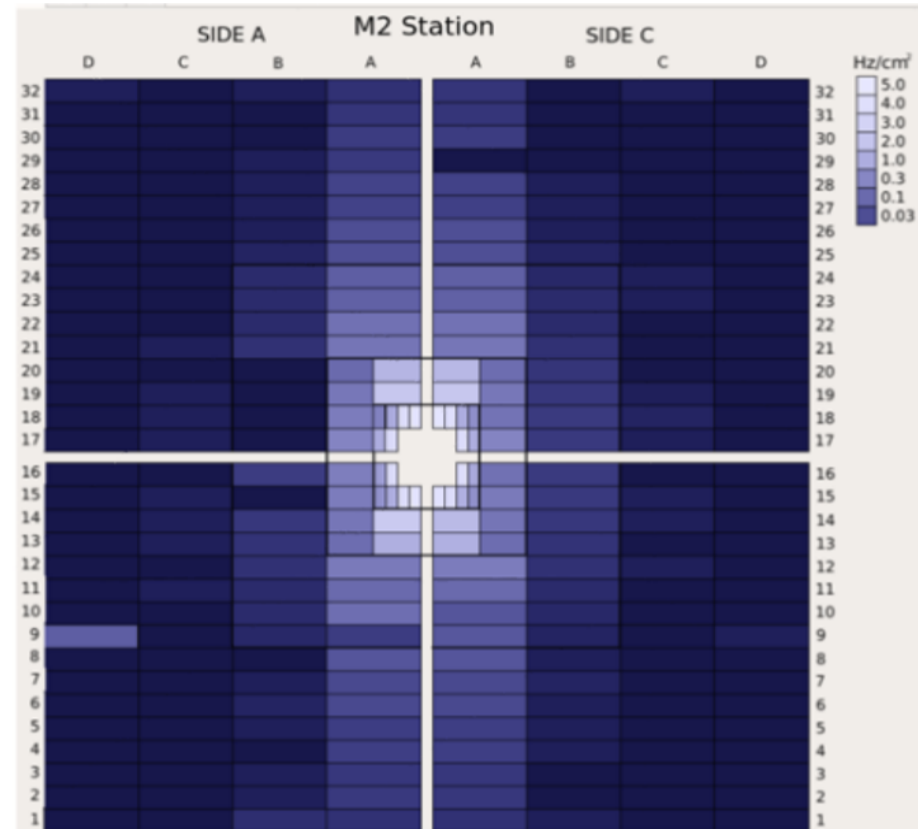


# Calorimeter & Muon detector

New CALO  
frontend and  
control boards  
installed

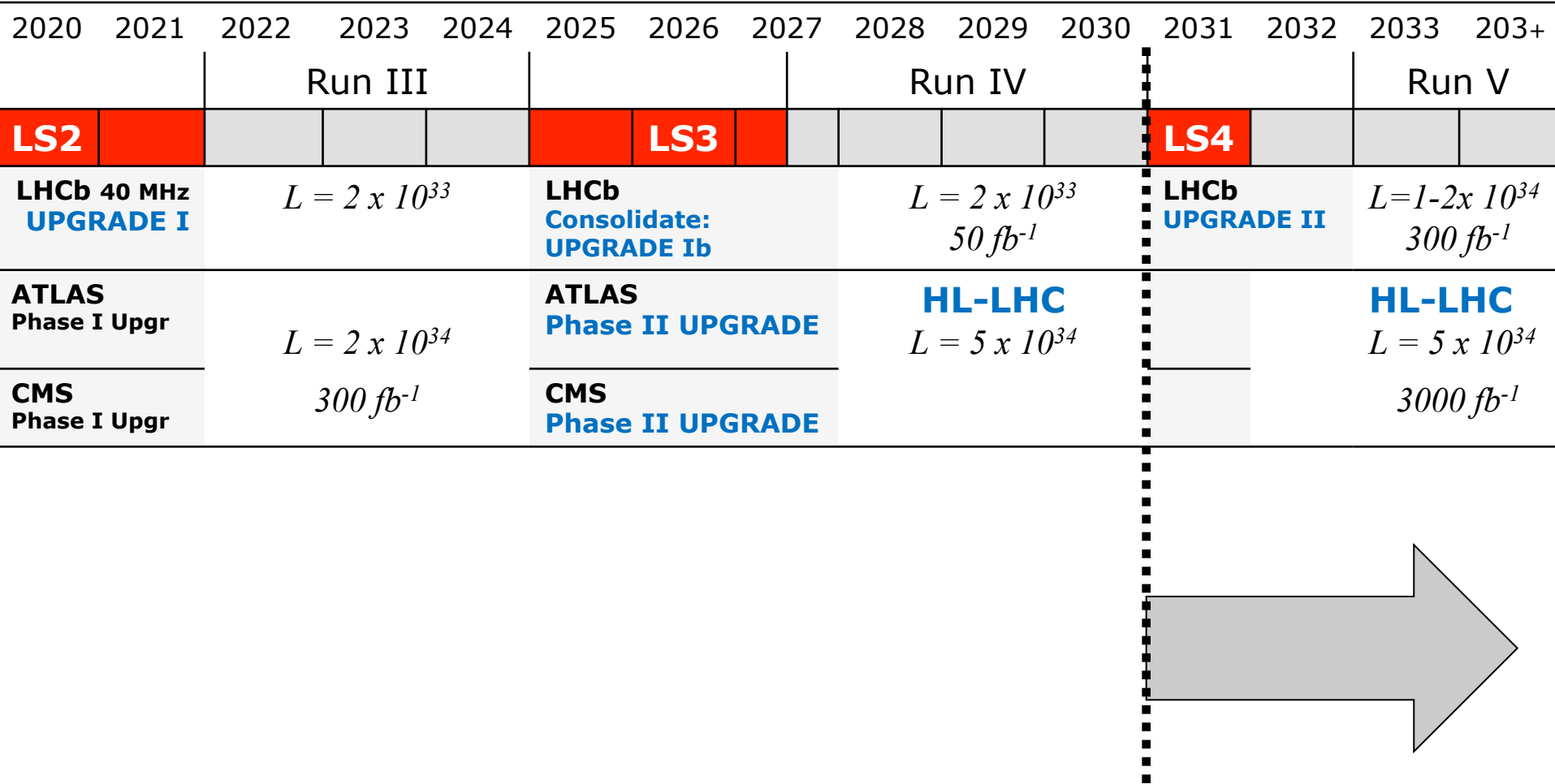


MUON Station 2  
Hit map during  
machine test Oct  
2021





# ...and beyond!

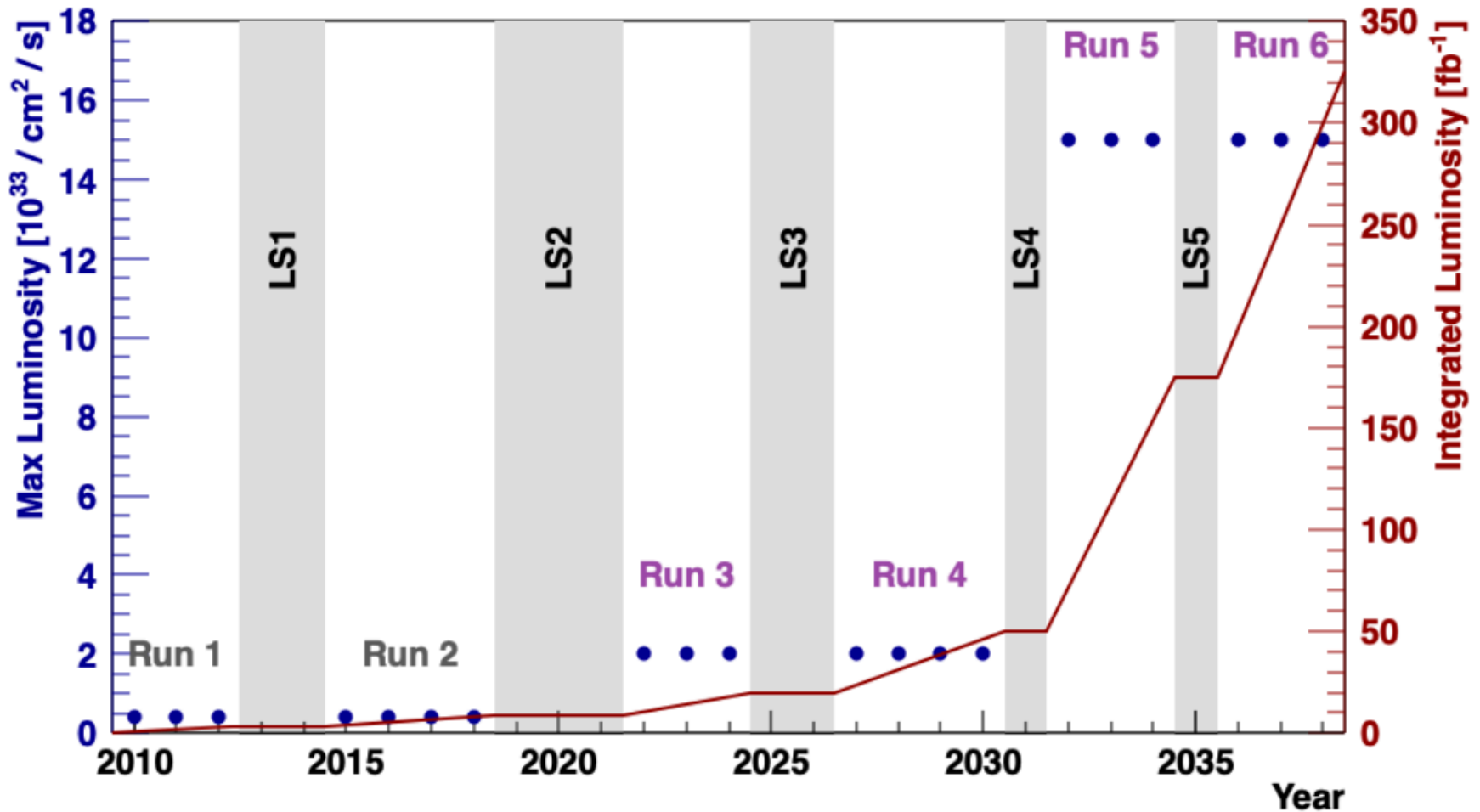


# Planning for Upgrade II: many analyses stat. limited

Observable	Current LHCb (up to $9 \text{ fb}^{-1}$ )	Upgrade I	
		( $23 \text{ fb}^{-1}$ )	( $50 \text{ fb}^{-1}$ )
<b>CKM tests</b>			
$\gamma$ ( $B \rightarrow DK$ , etc.)	$4^\circ$ [9, 10]	$1.5^\circ$	$1^\circ$
$\phi_s$ ( $B_s^0 \rightarrow J/\psi\phi$ )	49 mrad [8]	14 mrad	10 mrad
$ V_{ub} / V_{cb} $ ( $\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}_\mu$ )	6% [30]	3%	—
$a_{\text{sl}}^d$ ( $B^0 \rightarrow D^-\mu^+\nu_\mu$ )	$36 \times 10^{-4}$ [34]	$8 \times 10^{-4}$	$5 \times 10^{-4}$
$a_{\text{sl}}^s$ ( $B_s^0 \rightarrow D_s^-\mu^+\nu_\mu$ )	$33 \times 10^{-4}$ [35]	$10 \times 10^{-4}$	$7 \times 10^{-4}$
<b>Charm</b>			
$\Delta A_{CP}$ ( $D^0 \rightarrow K^+K^-, \pi^+\pi^-$ )	$29 \times 10^{-5}$ [5]	$17 \times 10^{-5}$	—
$A_\Gamma$ ( $D^0 \rightarrow K^+K^-, \pi^+\pi^-$ )	$13 \times 10^{-5}$ [38]	$4.3 \times 10^{-5}$	—
$\Delta x$ ( $D^0 \rightarrow K_s^0\pi^+\pi^-$ )	$18 \times 10^{-5}$ [37]	$6.3 \times 10^{-5}$	$4.1 \times 10^{-5}$
<b>Rare Decays</b>			
$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$	71% [40, 41]	34%	—
$S_{\mu\mu}$ ( $B_s^0 \rightarrow \mu^+\mu^-$ )	—	—	—
$A_T^{(2)}$ ( $B^0 \rightarrow K^{*0}e^+e^-$ )	0.10 [52]	0.060	0.043
$A_T^{\text{Im}}$ ( $B^0 \rightarrow K^{*0}e^+e^-$ )	0.10 [52]	0.060	0.043
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}$ ( $B_s^0 \rightarrow \phi\gamma$ )	$^{+0.41}_{-0.44}$ [51]	0.124	0.083
$S_{\phi\gamma}$ ( $B_s^0 \rightarrow \phi\gamma$ )	0.32 [51]	0.093	0.062
$\alpha_\gamma$ ( $\Lambda_b^0 \rightarrow \Lambda\gamma$ )	$^{+0.17}_{-0.29}$ [53]	0.148	0.097
<b>Lepton Universality Tests</b>			
$R_K$ ( $B^+ \rightarrow K^+\ell^+\ell^-$ )	0.044 [12]	0.025	0.017
$R_{K^*}$ ( $B^0 \rightarrow K^{*0}\ell^+\ell^-$ )	0.10 [61]	0.031	0.021
$R(D^*)$ ( $B^0 \rightarrow D^{*-}\ell^+\nu_\ell$ )	0.026 [62, 64]	0.007	—

# Planning for Upgrade II

- Increase instantaneous luminosity to  $1.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Increase integrated luminosity to  $300 \text{ fb}^{-1}$



# Planning for Upgrade II: Physics Reach

Observable	Current LHCb (up to $9 \text{ fb}^{-1}$ )		Upgrade I ( $23 \text{ fb}^{-1}$ )    ( $50 \text{ fb}^{-1}$ )		Upgrade II ( $300 \text{ fb}^{-1}$ )
	<b>CKM tests</b>				
$\gamma (B \rightarrow DK, \text{ etc.})$	$4^\circ$	[9, 10]	$1.5^\circ$	$1^\circ$	$0.35^\circ$
$\phi_s (B_s^0 \rightarrow J/\psi\phi)$	49 mrad	[8]	14 mrad	10 mrad	4 mrad
$ V_{ub} / V_{cb}  (\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}_\mu)$	6%	[30]	3%	—	1%
$a_{\text{sl}}^d (B^0 \rightarrow D^-\mu^+\nu_\mu)$	$36 \times 10^{-4}$	[34]	$8 \times 10^{-4}$	$5 \times 10^{-4}$	$2 \times 10^{-4}$
$a_{\text{sl}}^s (B_s^0 \rightarrow D_s^-\mu^+\nu_\mu)$	$33 \times 10^{-4}$	[35]	$10 \times 10^{-4}$	$7 \times 10^{-4}$	$3 \times 10^{-4}$
<b>Charm</b>					
$\Delta A_{CP} (D^0 \rightarrow K^+K^-, \pi^+\pi^-)$	$29 \times 10^{-5}$	[5]	$17 \times 10^{-5}$	—	$3.0 \times 10^{-5}$
$A_\Gamma (D^0 \rightarrow K^+K^-, \pi^+\pi^-)$	$13 \times 10^{-5}$	[38]	$4.3 \times 10^{-5}$	—	$1.0 \times 10^{-5}$
$\Delta x (D^0 \rightarrow K_s^0\pi^+\pi^-)$	$18 \times 10^{-5}$	[37]	$6.3 \times 10^{-5}$	$4.1 \times 10^{-5}$	$1.6 \times 10^{-5}$
<b>Rare Decays</b>					
$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$	71%	[40, 41]	34%	—	10%
$S_{\mu\mu} (B_s^0 \rightarrow \mu^+\mu^-)$	—	—	—	—	0.2
$A_T^{(2)} (B^0 \rightarrow K^{*0}e^+e^-)$	0.10	[52]	0.060	0.043	0.016
$A_T^{\text{Im}} (B^0 \rightarrow K^{*0}e^+e^-)$	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma} (B_s^0 \rightarrow \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma} (B_s^0 \rightarrow \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma (\Lambda_b^0 \rightarrow \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
<b>Lepton Universality Tests</b>					
$R_K (B^+ \rightarrow K^+\ell^+\ell^-)$	0.044	[12]	0.025	0.017	0.007
$R_{K^*} (B^0 \rightarrow K^{*0}\ell^+\ell^-)$	0.10	[61]	0.031	0.021	0.008
$R(D^*) (B^0 \rightarrow D^{*-}\ell^+\nu_\ell)$	0.026	[62, 64]	0.007	—	0.002

# Planning for Upgrade II: started in 2017

Expression of Interest

Physics Case

Accelerator Study

Luminosity Scenarios

[LHCC-2017-003](#)

[LHCC-2018-027](#)

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

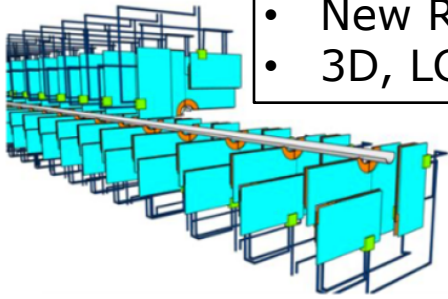
[LHCb-PUB-2019-001](#)

- **LHCC and CERN Research Board (Sep 2019)**
  - "The recommendation to prepare a framework TDR for the LHCb Upgrade-II was endorsed, noting that LHCb is expected to run throughout the HL-LHC era."
- **European Strategy Update (Jun 2020)**
  - "The flavour physics programme made possible with the proton collisions delivered by the LHC is very rich, and will be enhanced with the ongoing and proposed future upgrade of the LHCb detector."
  - "The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited"

# Planning for Upgrade II: Tracking

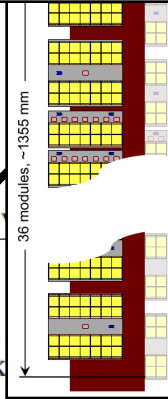
## VELO pixel

- Add Timing
- New RF-foil
- 3D, LGADs, 28nm



## UT pixel

- MAPS, radiation tolerant

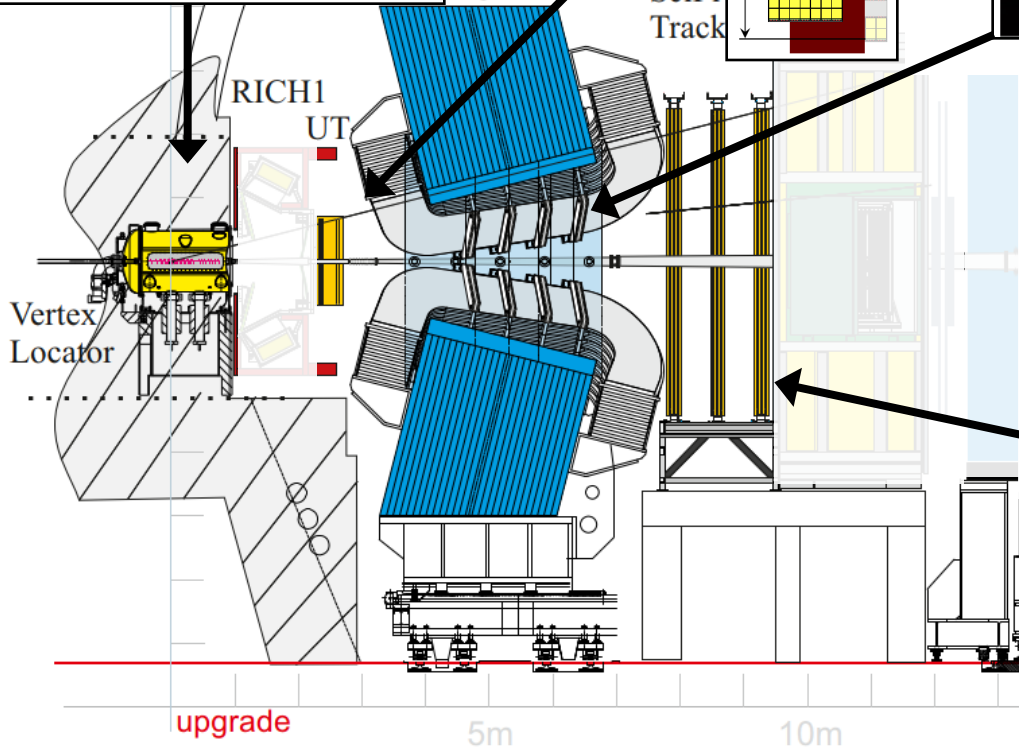
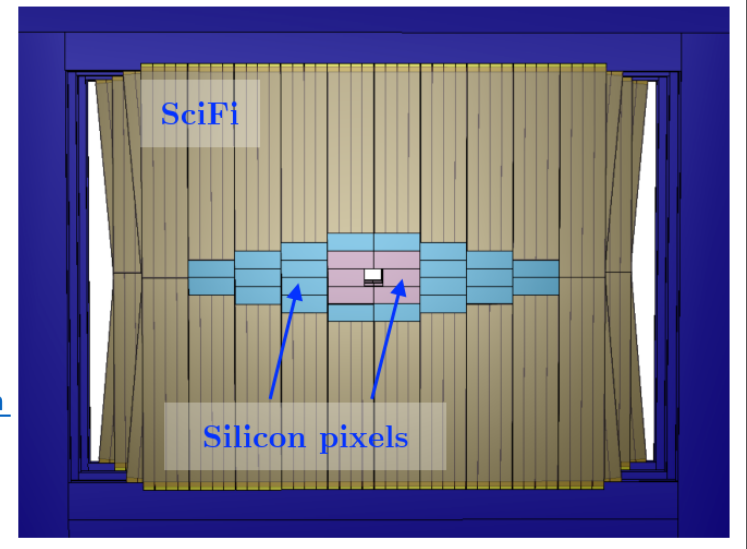


## Magnet Station new



## Mighty Tracker

- MAPS pixel and Scintillating fibers



# Planning for Upgrade II: PID detectors

## RICH1 and RICH 2

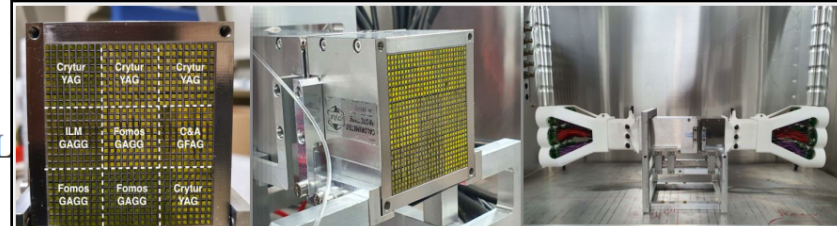
- Reduced pixel size
- Add timing information
- SiPM, MCP

## TORCH new

- TOF – quartz
- MCP

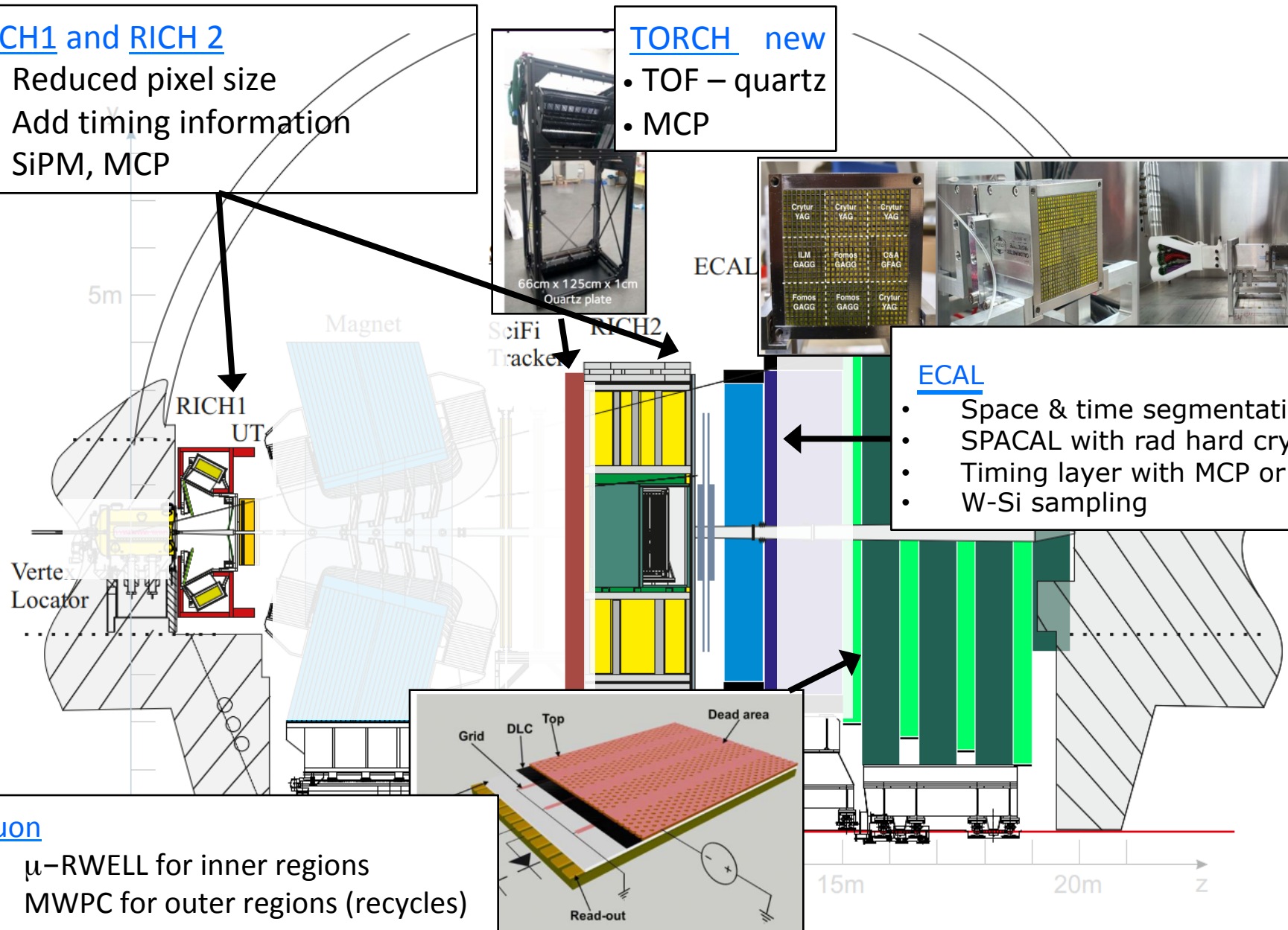


ECAL



## ECAL

- Space & time segmentation
- SPACAL with rad hard crystals
- Timing layer with MCP or Si
- W-Si sampling



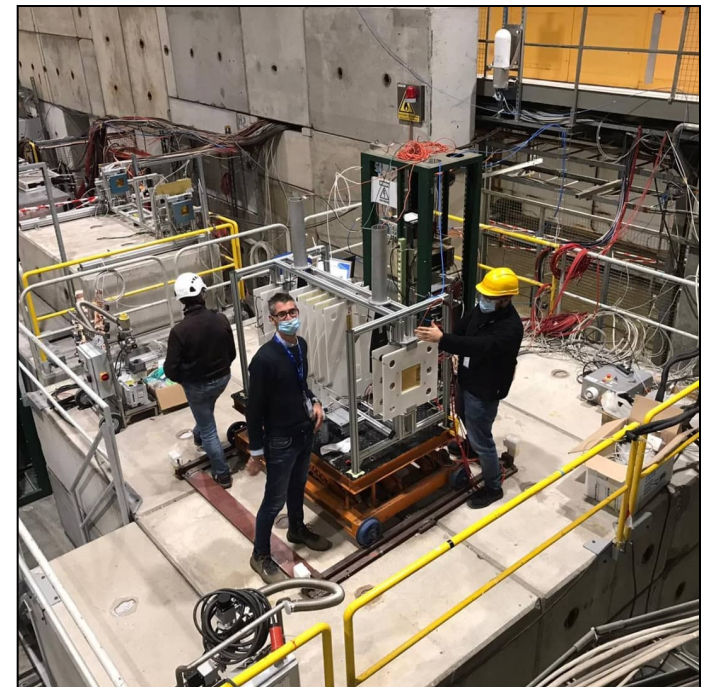
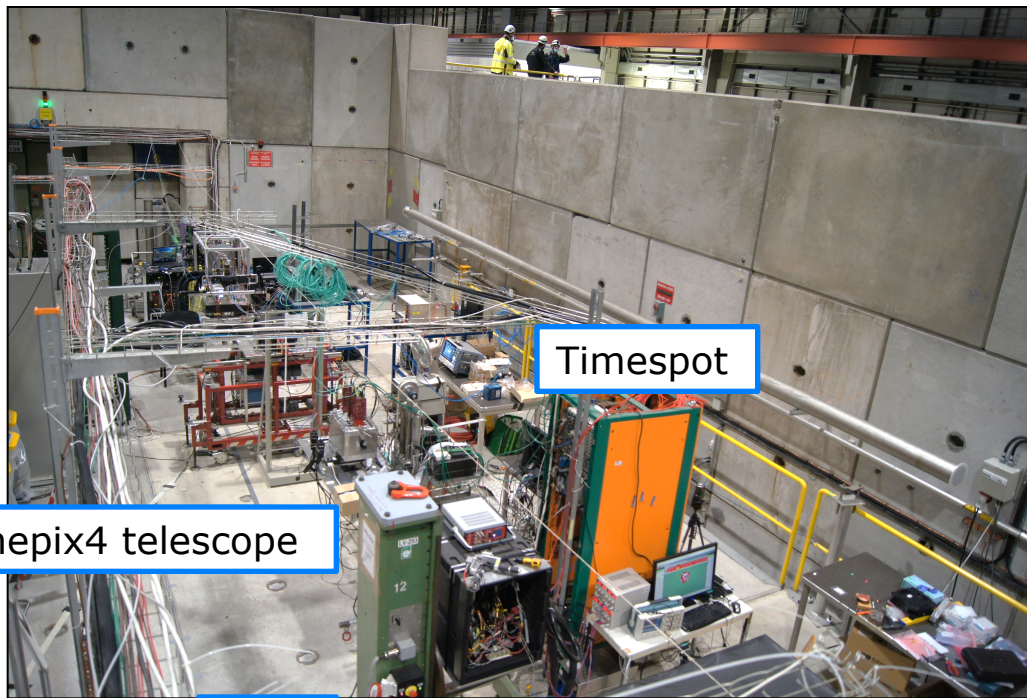
## Muon

- $\mu$ -RWELL for inner regions
- MWPC for outer regions (recycles)



# Planning for Upgrade II: Testbeam

- Activities for RICH, VELO, ECAL, MUON
- Lots of opportunities for R&D in coming decade!

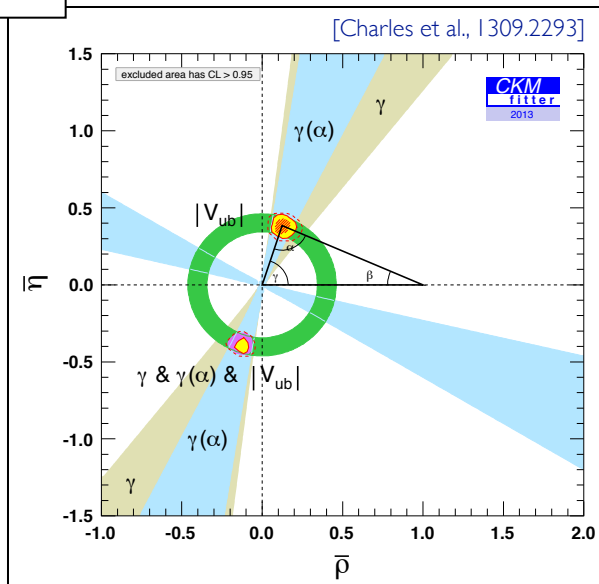




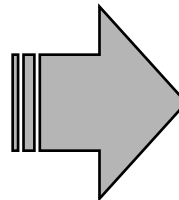
# Conclusions

- Precision measurements to scrutinize the Standard Model
- Precision measurements reach very high mass scales
- Precision measurements are not yet precise enough
- Lots of opportunities to contribute to R&D

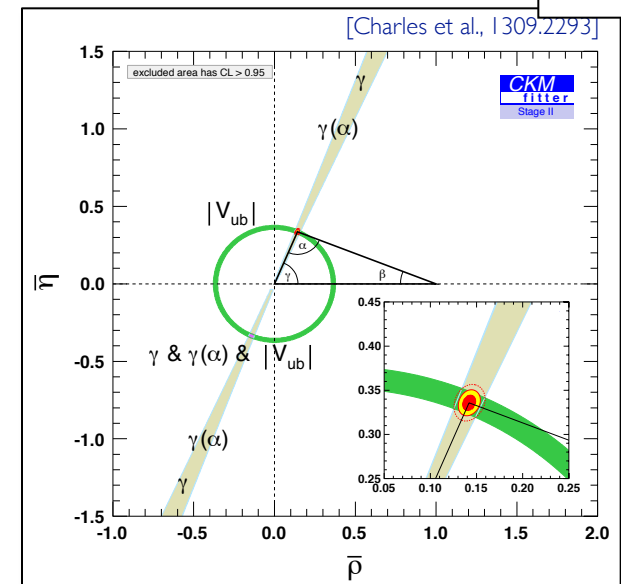
2019



$\gamma, V_{ub}$



2030



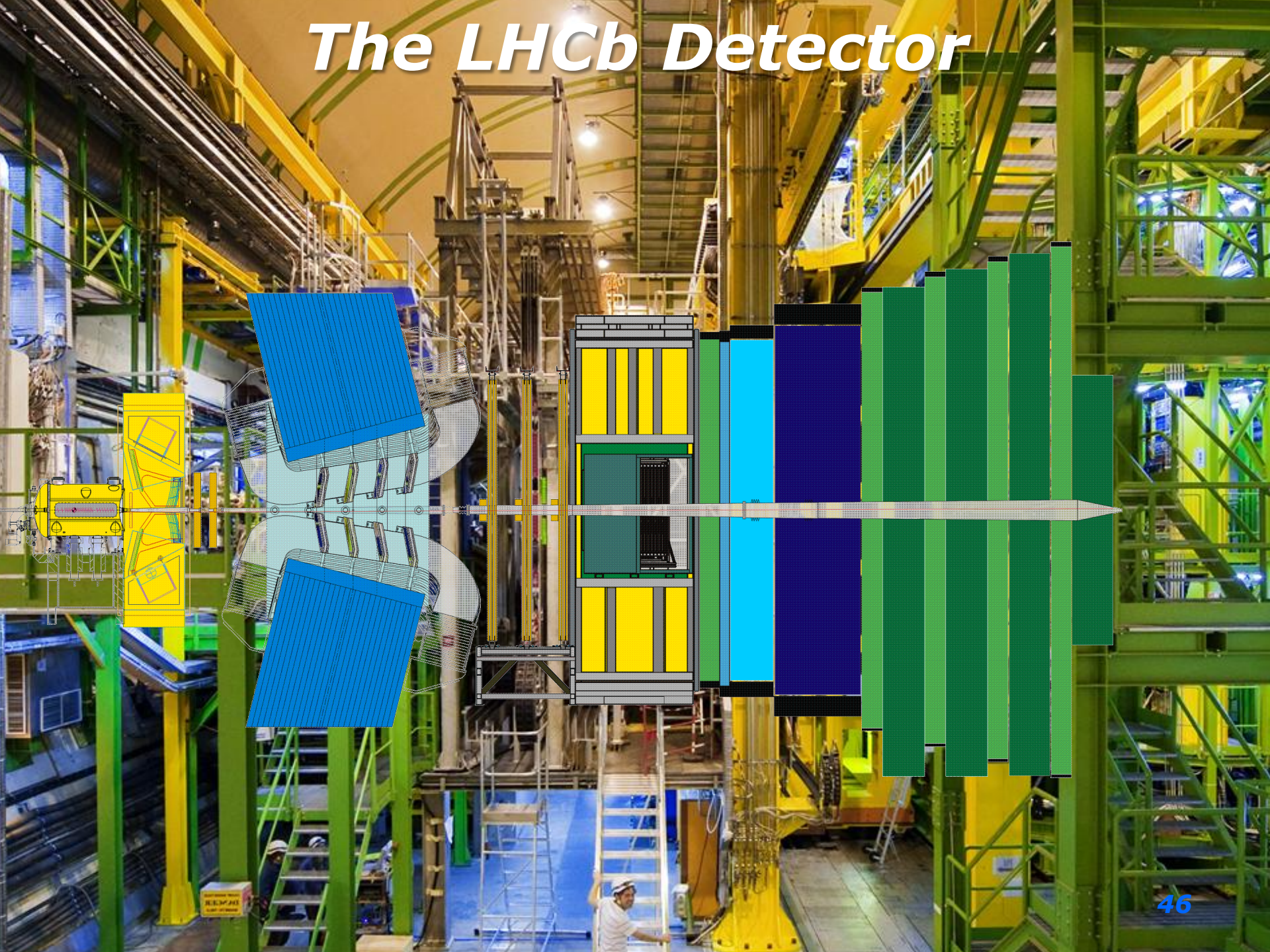


# *The LHCb Detector*



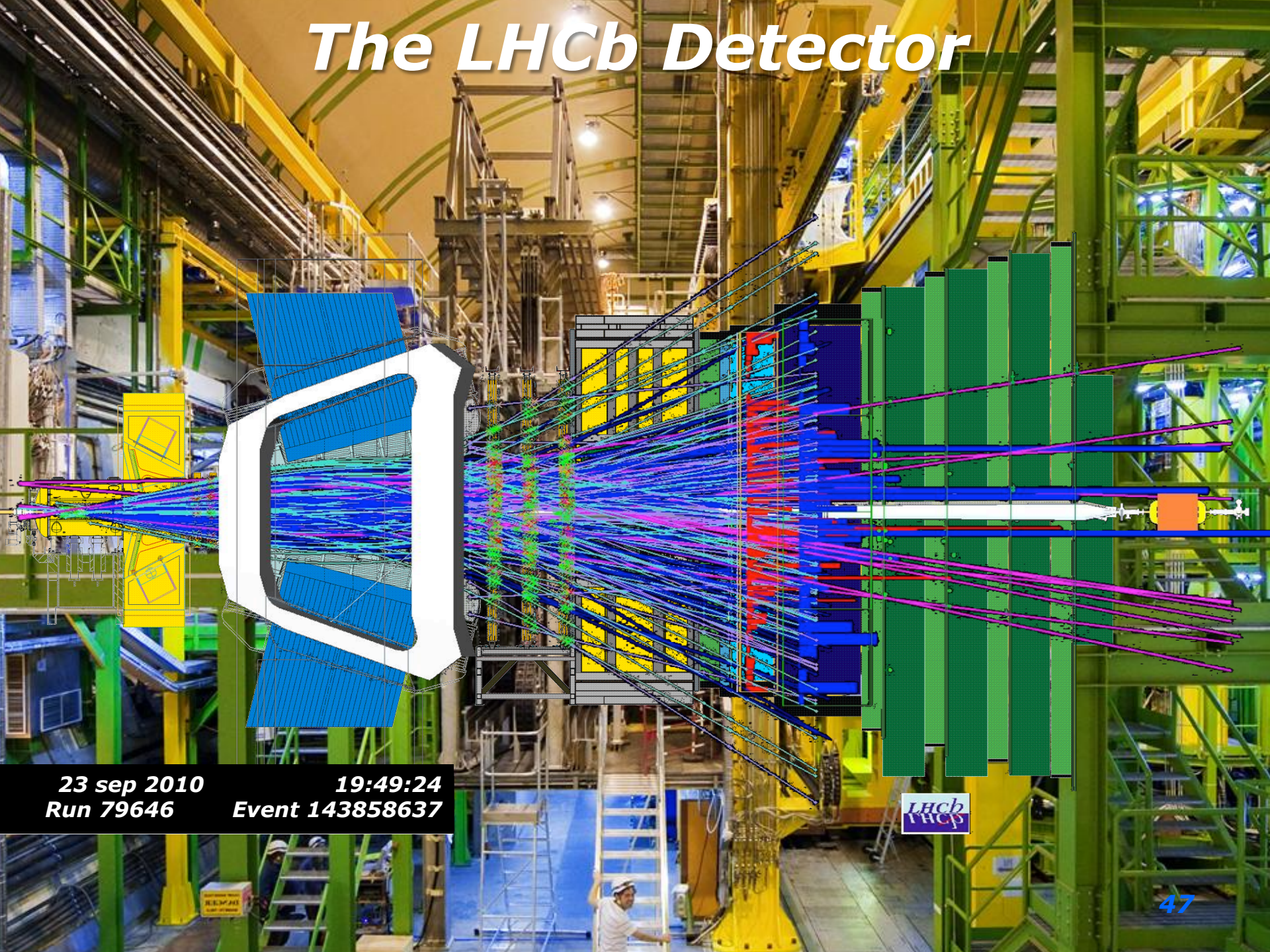


# The LHCb Detector





# The LHCb Detector



23 sep 2010  
Run 79646

19:49:24  
Event 143858637

