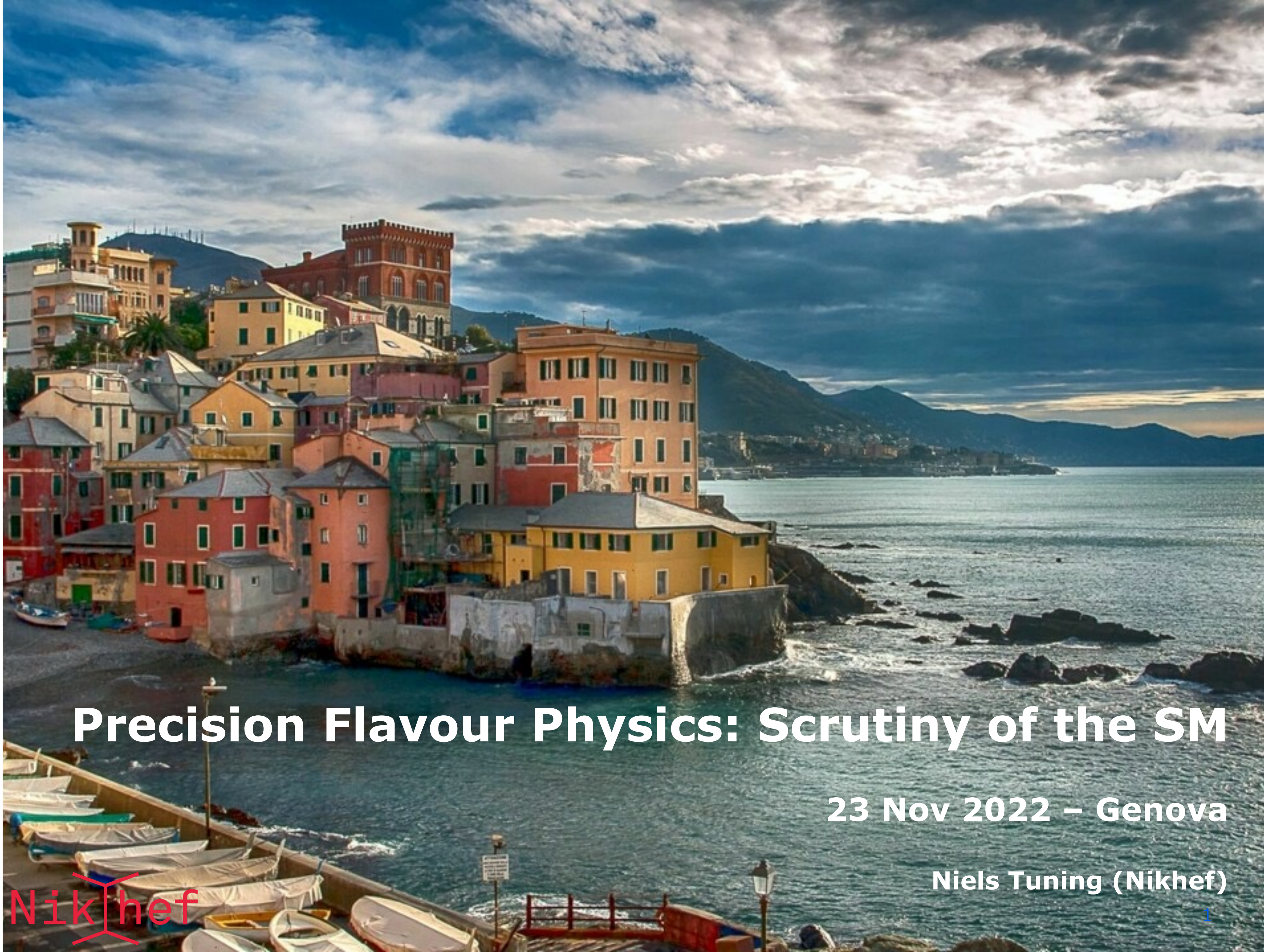


Precision Flavour Physics: Scrutiny of the SM

23 Nov 2022 – Genova

Niels Tuning (Nikhef)

Historical record of indirect discoveries

GIM mechanism in $K^0 \to \mu\mu$

Weak Interactions with Lepton-Hadron Symmetry*

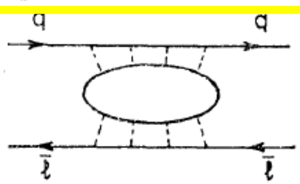
S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Mills theory is discussed.

splitting, beginning at order $G(G\Lambda^2)$, as well as contributions to such unobserved decay modes as $K_2 \to \mu^+ + \mu^-$, $K^+ \to \pi^+ + l + \bar{l}$, etc., involving neutral lepton

We wish to propose a simple model in which the divergences are properly ordered. Our model is founded in a quark model, but one involving four, not three, fundamental fermions; the weak interactions are medi-

new quantum number $\mathcal{C}$ for charm.



Glashow, Iliopoulos, Maiani,
Phys.Rev. D2 (1970) 1285

CP violation, $K_L^0 \to \pi\pi$

27 July 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

***CP*-Violation in the Renormalizable Theory of Weak Interaction**

Makoto Kobayashi and Toshihide Maskawa
Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

doublet with the same charge assignment. This is because all phases of elements of a 3×3 unitary matrix cannot be absorbed into the phase convention of six fields. This possibility of *CP*-violation will be discussed later on.

Christenson, Cronin, Fitch, Turlay,
Phys.Rev.Lett. 13 (1964) 138
Kobayashi, Maskawa,
Prog.Theor. Phys. 49 (1973) 652

$B^0 \leftrightarrow \overline{B}^0$ mixing

DESY 87-029
April 1987

OBSERVATION OF B^0-$\overline{B}^0$ MIXING

The ARGUS Collaboration

In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson-lepton events on the $\Upsilon(4S)$ leads to the conclusion that B^0-$\overline{B}^0$ mixing has been observed and is substantial.

Parameters	Comments
$r > 0.09$ 90% CL	This experiment
$x > 0.44$	This experiment
$B^{\frac{1}{2}} f_B \approx f_\pi < 160$ MeV	B meson ($\approx$ pion) decay constant
$m_b < 5\mathrm{GeV}/c^2$	b-quark mass
$\tau_b < 1.4 \cdot 10^{-12}$s	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi-Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [17]
$m_t > 50\mathrm{GeV}/c^2$	t quark mass

ARGUS Coll.
Phys.Lett.B192 (1987) 245

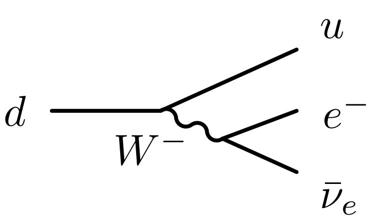
"Discovery" of charm

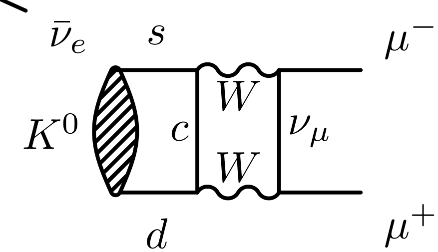
"Discovery" of beauty

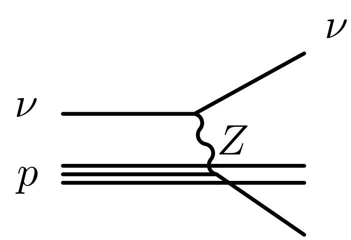
"Discovery" of top

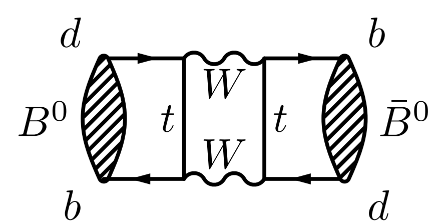
Historical record of indirect discoveries

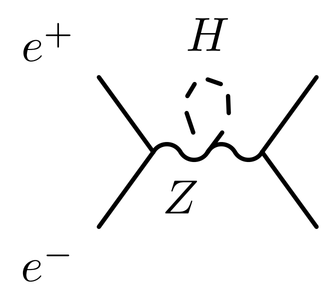
Particle	Indirect			Direct		
ν	β decay	Fermi	1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay	Fermi	1932	*W→eν*	UA1, UA2	1983
c	$K^0 \to \mu\mu$	GIM	1970	J/ψ	Richter, Ting	1974
b	CPV $K^0 \to \pi\pi$	CKM, 3rd gen	1964/72	Υ	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z \to e^+e^-$	UA1	1983
t	B mixing	ARGUS	1987	$t \to Wb$	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	$H \to 4\mu/\gamma\gamma$	CMS, ATLAS	2012
?	**What's next ?**		?			?









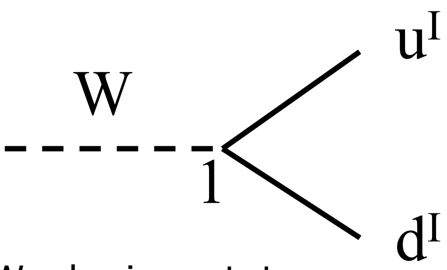


Outline

- CKM elements
  - sin2β
  - γ
  - Δm_s
  - V_{ub}
- Flavour Anomalies
  - $b \to c\, \tau\nu$
  - $b \to s\, \ell^+ \ell^-$
- Prospects
  - Upgrade
  - Upgrade II

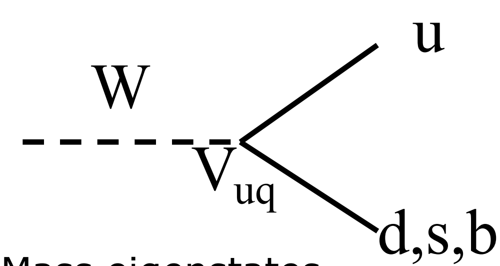
(CKM: a quick reminder…)

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



Weak eigenstates

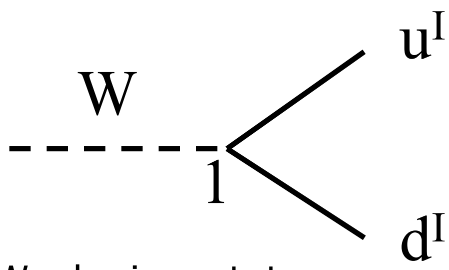
$$\begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix}.$$



Mass eigenstates

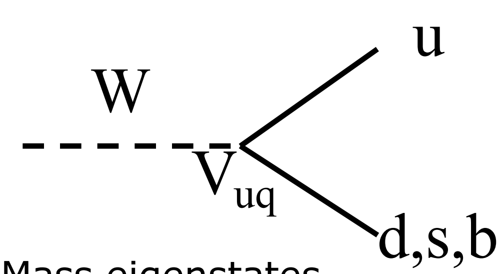
(CKM: a quick reminder…)

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



Weak eigenstates

$$\begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix}.$$



Mass eigenstates

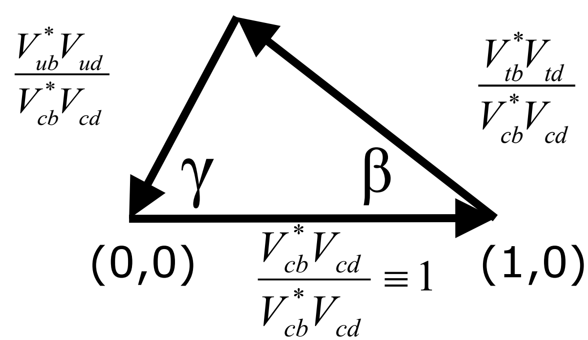
2) Matrix has complex phases:

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

3) Matrix is unitary:

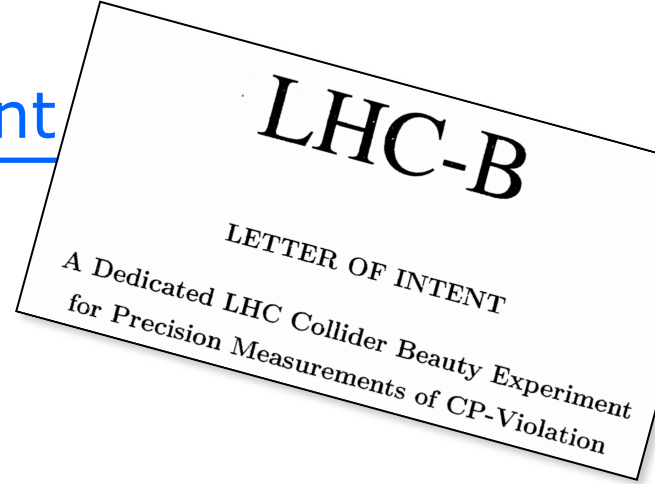
$$V^{+}V = \begin{pmatrix} V^{*}_{ud} & V^{*}_{cd} & V^{*}_{td} \\ V^{*}_{us} & V^{*}_{cs} & V^{*}_{ts} \\ V^{*}_{ub} & V^{*}_{cb} & V^{*}_{tb} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0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

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



CKM: (1995) LHCb Letter-of-Intent

- LHC-B Letter-of-Intent 1995



LHC-B

LETTER OF INTENT

A Dedicated LHC Collider Beauty Experiment for Precision Measurements of CP-Violation

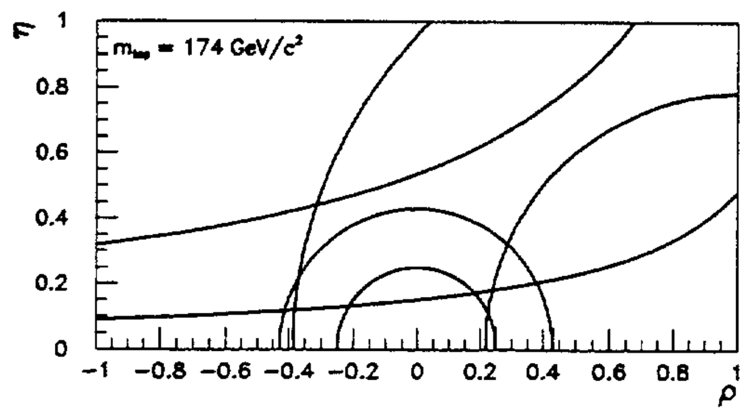


Figure 2.1: Limits on the CKM parameters (1σ) ρ and η for m_t = 174 GeV. The annular region cen-

CKM: (1995) LHCb Letter-of-Intent

- LHC-B Letter-of-Intent 1995

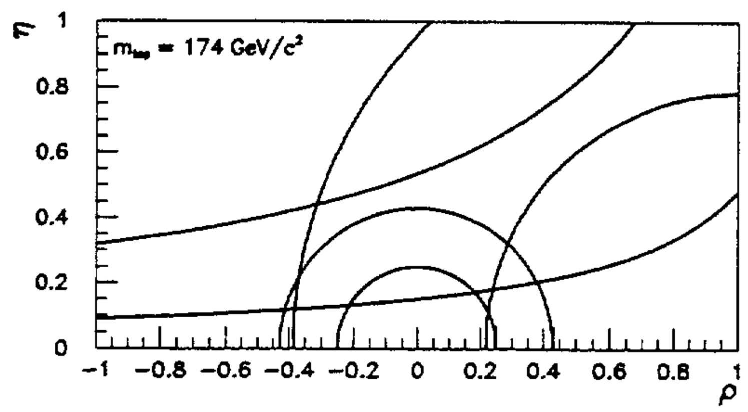


Figure 2.1: Limits on the CKM parameters (1σ) ρ and η for m_t = 174 GeV. The annular region cen-

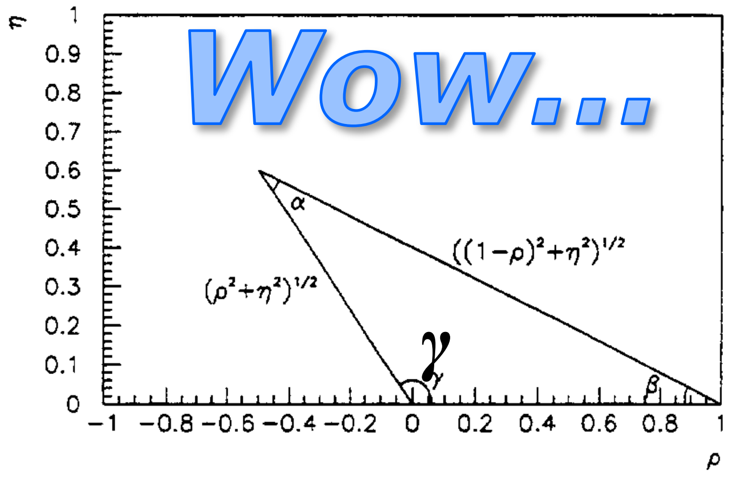
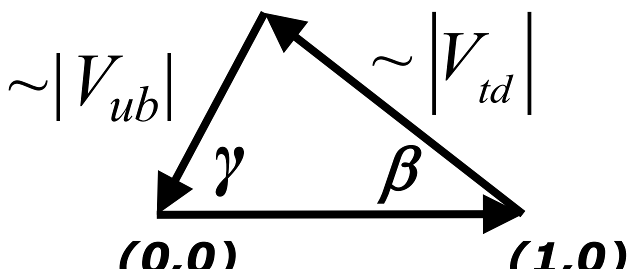
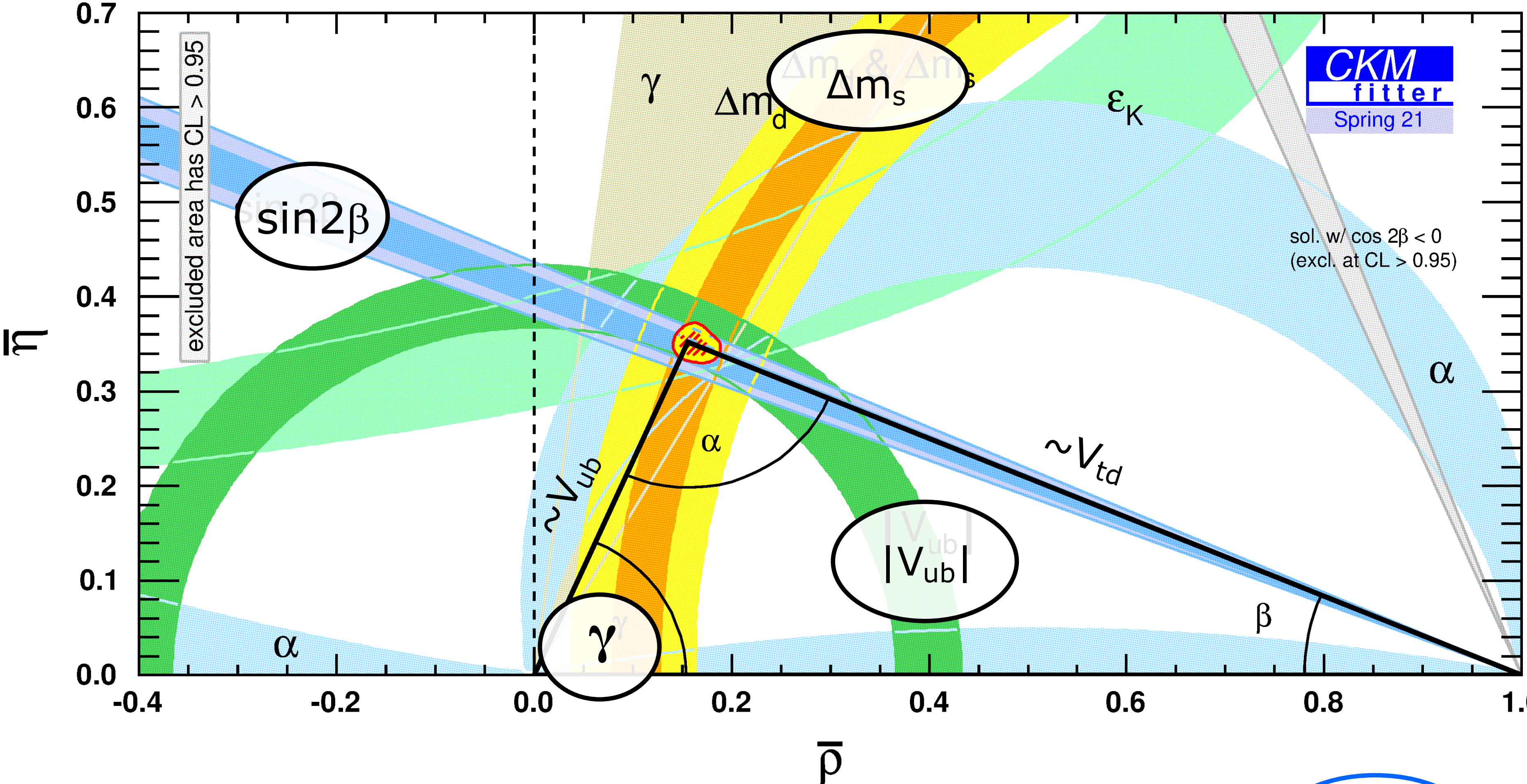


Figure 2.2: The Unitarity Triangle



CKM: recent results



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

Global fits:

CKMfitter: http://ckmfitter.in2p3.fr/

UTFit: http://www.utfit.org/Utfit/

Outline

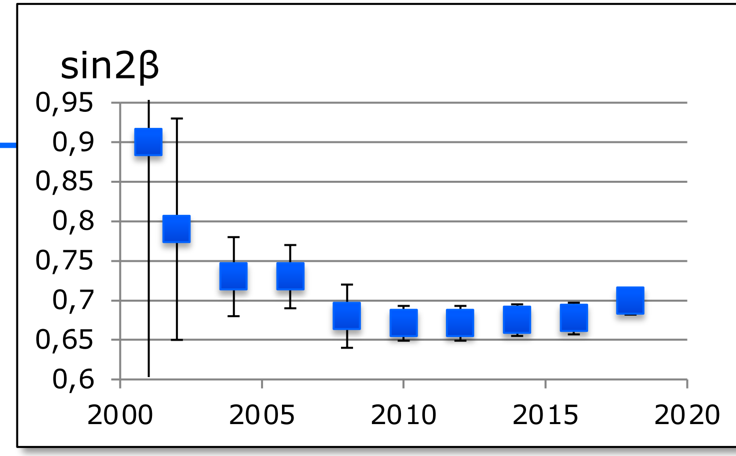
- CKM elements
  - $\sin 2\beta$
  - γ
  - Δm_s
  - V_{ub}
- Flavour Anomalies
  - $b \to c\, \tau\nu$
  - $b \to s\, \ell^+ \ell^-$
- Prospects
  - Upgrade
  - Upgrade II

Disclaimer:

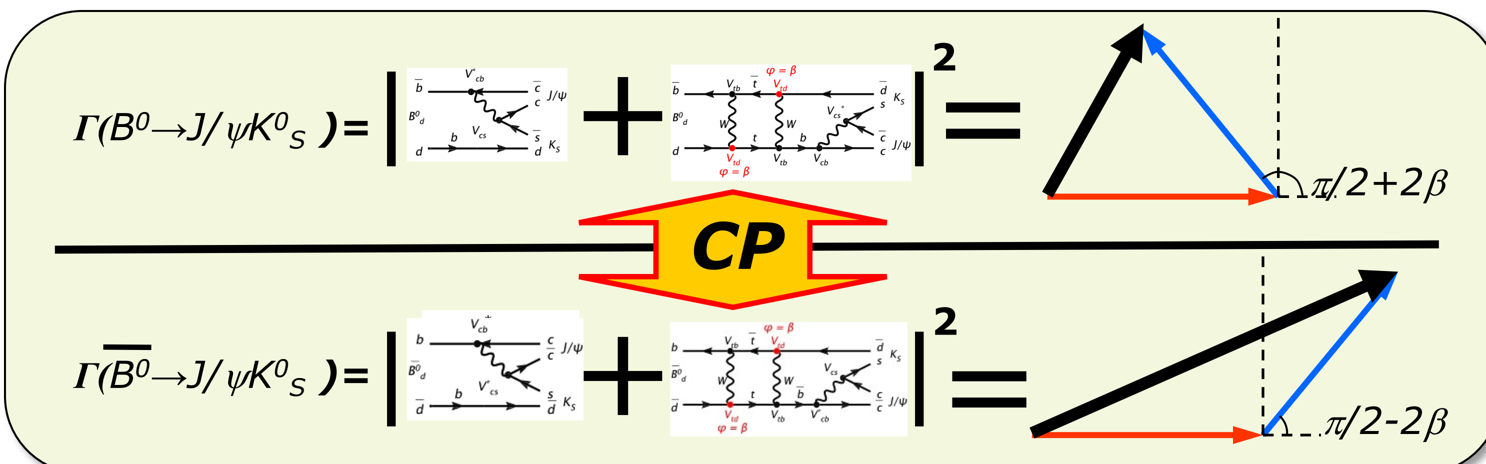
Physics programme of LHCb is much broader!

- Exotic Hadrons: tetra- and pentaquarks
- Heavy Ion and Fixed Target physics
- Electroweak: Z-production & W-mass

sin2β



- CP violation:
  - Two interfering amplitudes
  - Two relative phases
  - Different amplitude under CP conjugation
- $B^0 \to J/\psi K^0_S$: The golden mode!
  - Relative phase: $\arg(V_{td}^2)=2\beta$ (and $\pi/2$)

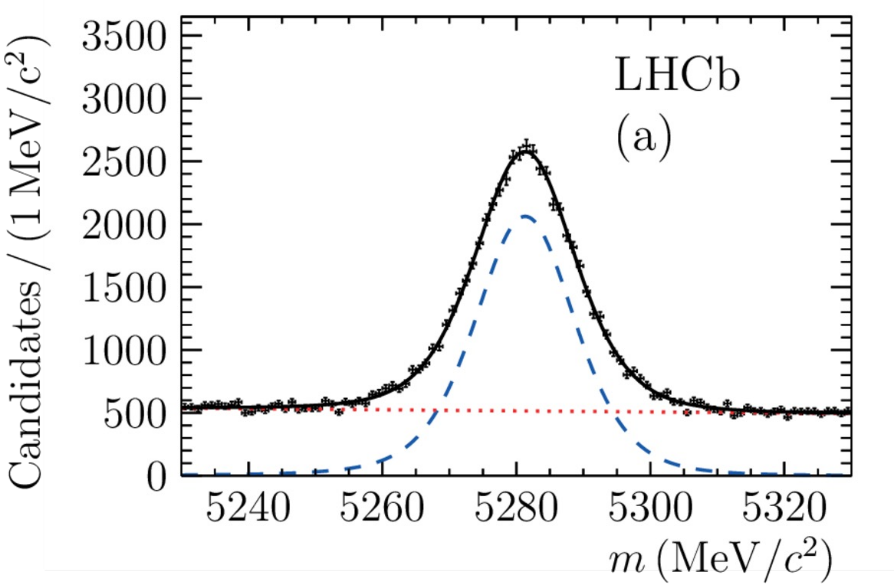


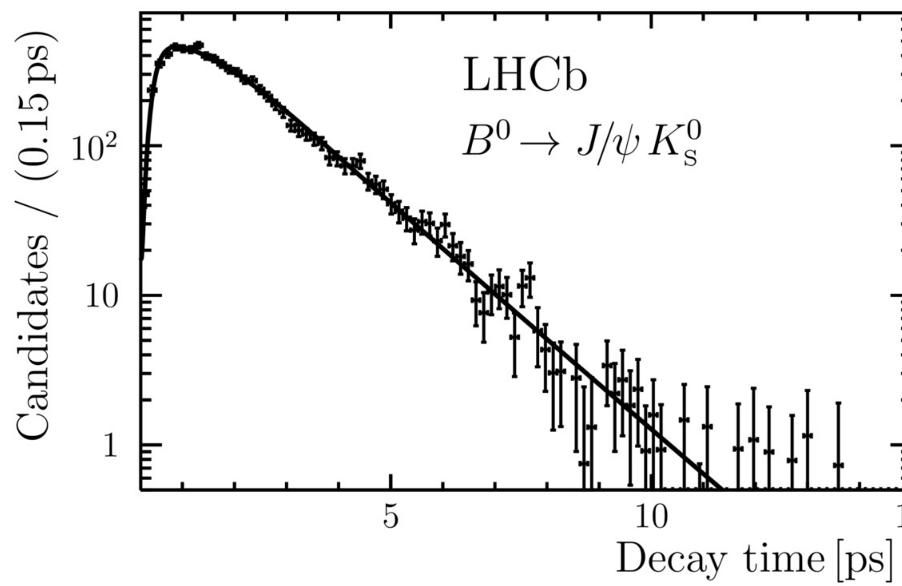
sin2β

$$\mathcal{A}_{[c\bar{c}]K^0_S}(t) \equiv \frac{\Gamma(\bar{B}^0(t)\to[c\bar{c}]K^0_S) - \Gamma(B^0(t)\to[c\bar{c}]K^0_S)}{\Gamma(\bar{B}^0(t)\to[c\bar{c}]K^0_S) + \Gamma(B^0(t)\to[c\bar{c}]K^0_S)}$$

$$= \frac{S\sin(\Delta m\, t) - C\cos(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2) + A_{\Delta\Gamma}\sinh(\Delta\Gamma\, t/2)} \approx S\sin(\Delta m\, t)$$

- Flavour tagging essential
  - Which B^0 was a $\overline{B^0}$?





LHCb, PRL 115 (2015) 031601

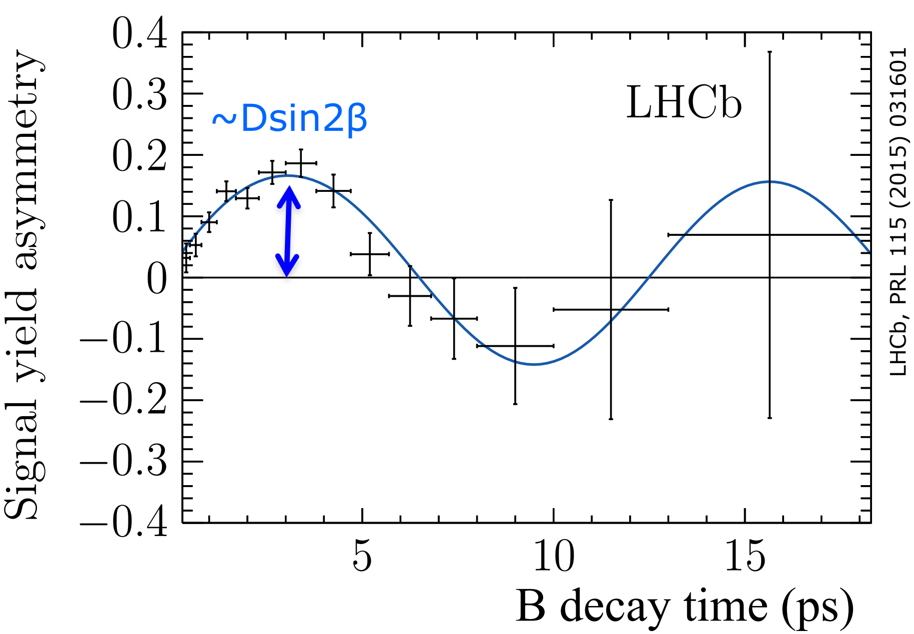
sin2β

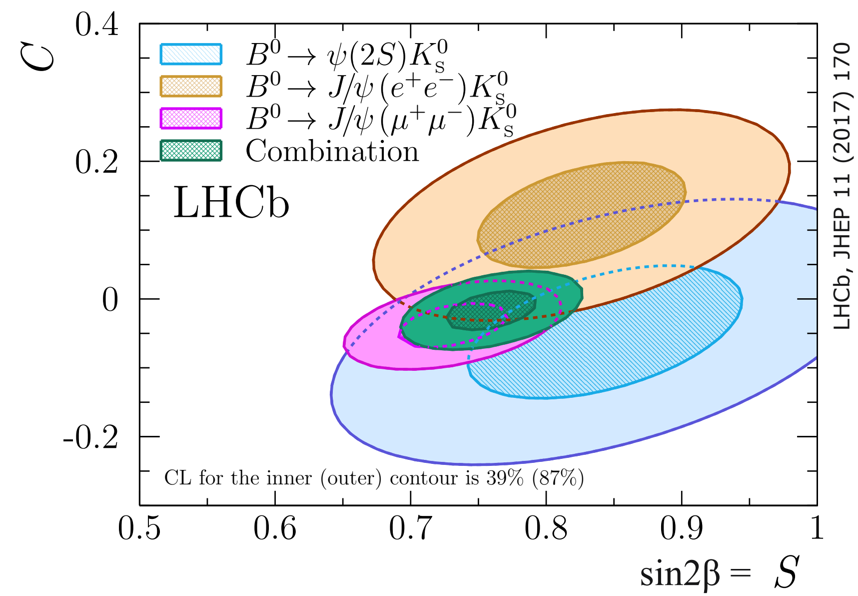
$$\mathcal{A}_{[c\bar{c}]K^0_S}(t) \equiv \frac{\Gamma(\bar{B}^0(t)\to[c\bar{c}]K^0_S) - \Gamma(B^0(t)\to[c\bar{c}]K^0_S)}{\Gamma(\bar{B}^0(t)\to[c\bar{c}]K^0_S) + \Gamma(B^0(t)\to[c\bar{c}]K^0_S)}$$

$$= \frac{S\sin(\Delta m\, t) - C\cos(\Delta m\, t)}{\cosh(\Delta\Gamma\, t/2) + A_{\Delta\Gamma}\sinh(\Delta\Gamma\, t/2)} \approx S\sin(\Delta m\, t)$$

- Flavour tagging essential
  - Wrong tag fraction w~35%
  - D=(1-2w)~0.3

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





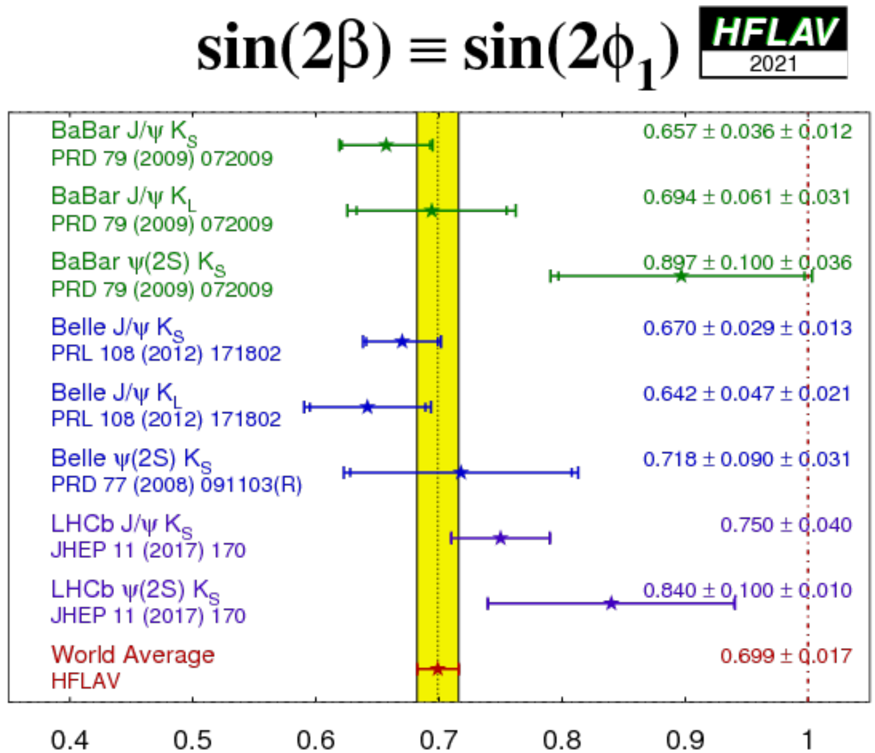
sin2β

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

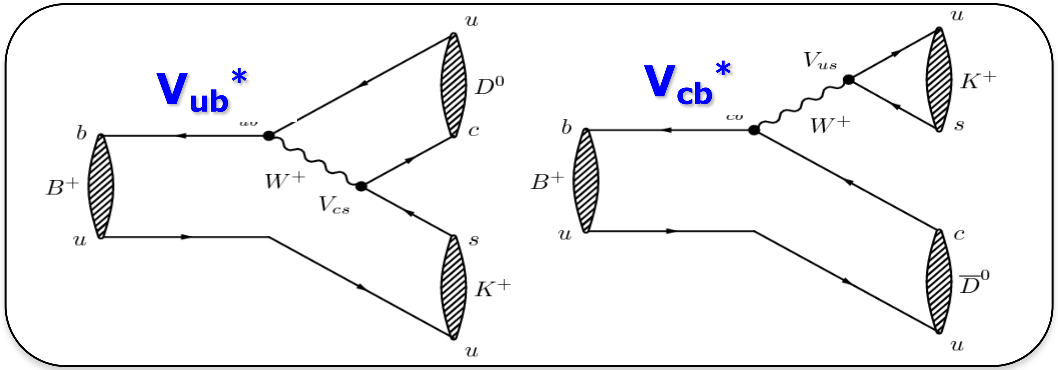


- Large *B* production competes with good tagging:

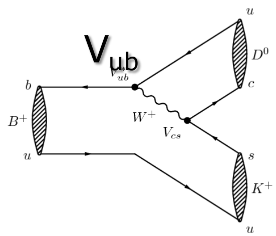
$\sigma_{stat}(\mathcal{S}(J/\psi K^0_S))$	now	50 ab^{-1}	
Belle/II	0.029	0.005	
	now	50 fb^{-1}	300 fb^{-1}
LHCb	0.035	0.006	0.003

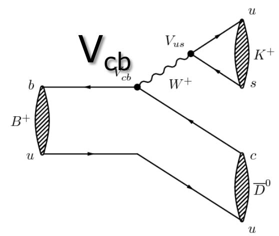
Constraints on angle γ

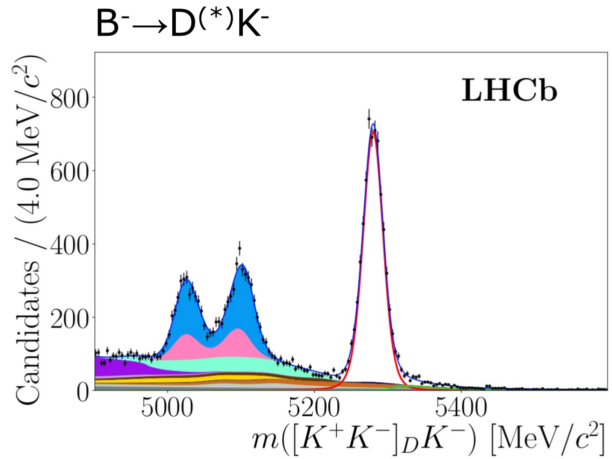
- Different yields for B^+ and B^- decays
  - two amplitudes contribute with different relative phase: $V_{ub} = |V_{ub}|e^{-i\gamma}$

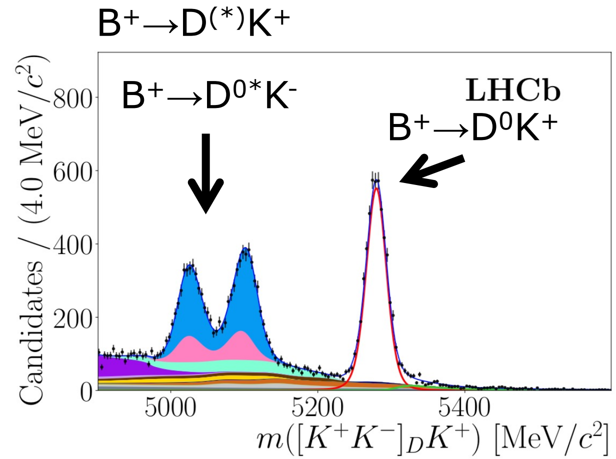


Constraints on angle γ - with $B^{\pm}\to D^{(*)}K^{\pm}$ and $D^0\to h^{\pm}h^{\pm}$









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

A_K^{CP}	=	0.136	$\pm$ 0.009	$\pm$ 0.001
A_π^{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,π^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,π^0}	=	1.051	$\pm$ 0.022	$\pm$ 0.028
$R_{K/\pi}^{K\pi,\gamma/\pi^0}$	=	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_π^{CP,π^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

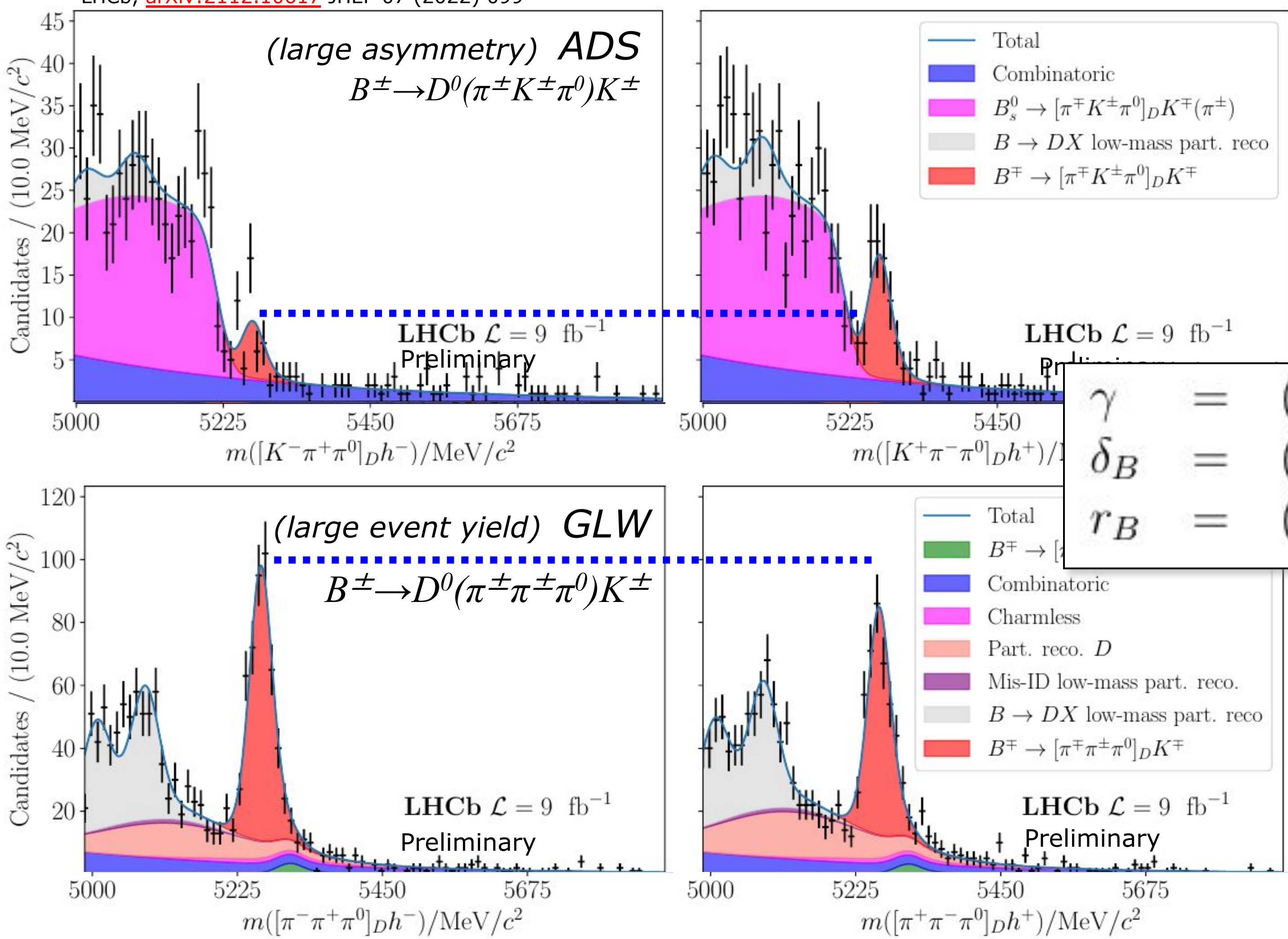
- Full run-2 ADS/GLW analysis, many final states
  - $B^{\pm}\to D^0K^{\pm}$, $B^{\pm}\to D^0\pi^{\pm}$, $B^{\pm}\to D^{0*}K^{\pm}$, $B^{\pm}\to D^{0*}\pi^{\pm}$
  - $D^0\to K^+K^-$, $D^0\to K^+\pi^-$, $D^0\to\pi^+\pi^-$
- Very precise input for gamma

LHCb, arXiv:2012.09903, JHEP 04(2021) 081

Constraints on angle γ - with $B^{\pm}\to D^0 h^{\pm}$ and $D^0\to h^{\pm}h^{\pm}\pi^0$

- Different yields for B^+ and B^- decays
  - two amplitudes contribute with different relative phase: $V_{ub} = |V_{ub}|e^{-i\gamma}$

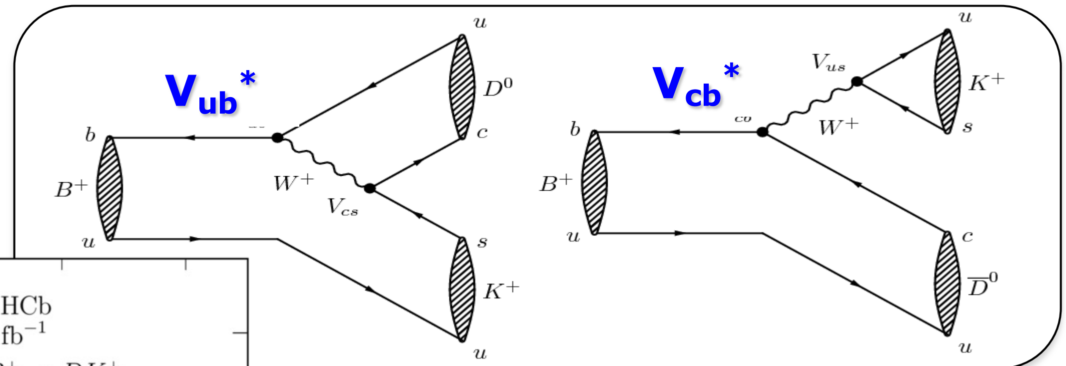
LHCb, arXiv:2112.10617 JHEP 07 (2022) 099



$$\gamma = (56^{+24}_{-19})^\circ$$
$$\delta_B = (122^{+19}_{-23})^\circ$$
$$r_B = (9.25^{+1.04}_{-0.85}) \times 10^{-2}$$

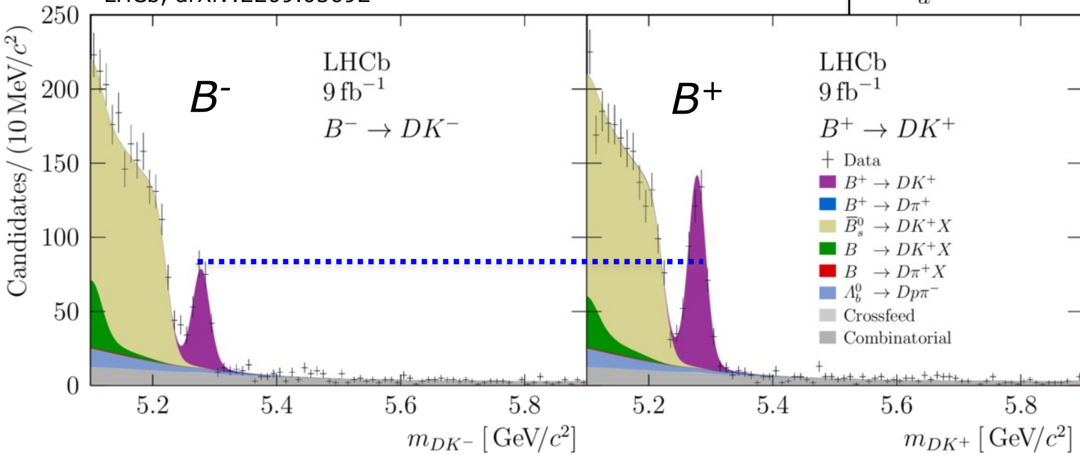
Constraints on angle γ - with $B^{\pm} \to D^0 K^{\pm}$ and $D^0 \to K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$

- Different yields for B^+ and B^- decays
  - two amplitudes contribute with different relative phase: $V_{ub} = |V_{ub}|e^{-i\gamma}$



New

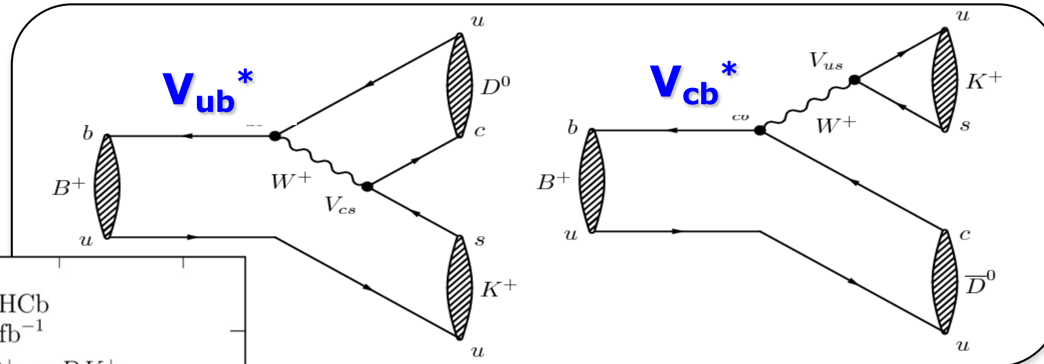
LHCb, arXiv:2209.03692



$$\Gamma_{B^{\pm}\to D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]K^{\pm}} \propto r_{K3\pi}^2 + (r_B^K)^2 + 2 r_{K3\pi} r_B^K R_{K3\pi} \cos(\delta_B^K + \delta_{K3\pi} \pm \gamma)$$

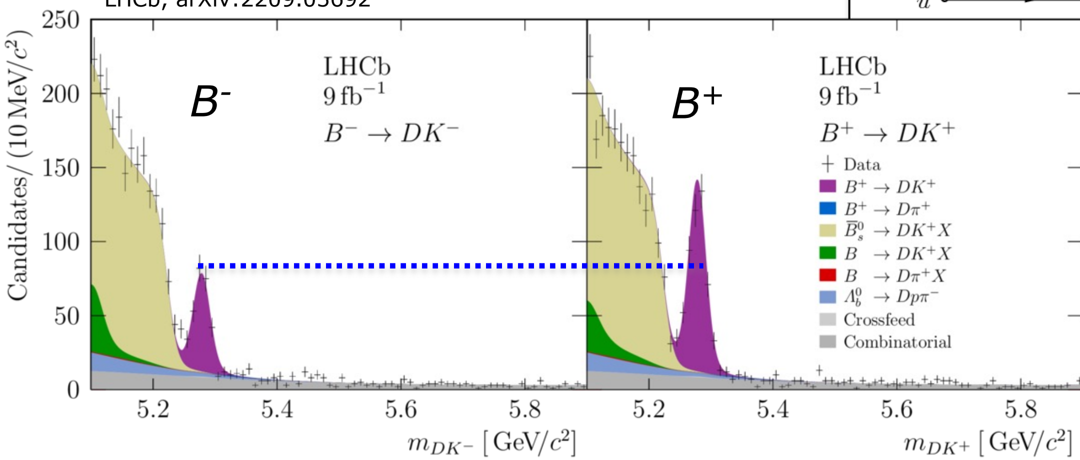
Constraints on angle γ - with $B^{\pm}\to D^0K^{\pm}$ and $D^0\to K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$

- Different yields for B^+ and B^- decays
  - two amplitudes contribute with different relative phase: $V_{ub} = |V_{ub}|e^{-i\gamma}$



New

LHCb, arXiv:2209.03692



$$\Gamma_{B^{\pm}\to D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]K^{\pm}} \propto r_{K3\pi}^2 + (r_B^K)^2 + 2r_{K3\pi}r_B^K R_{K3\pi}\cos(\delta_B^K + \delta_{K3\pi} \pm \gamma)$$

$$\gamma = (54.8\,^{+6.0}_{-5.8}\,^{+0.6}_{-0.6}\,^{+6.7}_{-4.3})^\circ$$

(Split in 4 regions of $K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$ Dalitz space:)

$$\mathcal{A}_K^1 = -0.469 \pm 0.088 \pm 0.009,$$
$$\mathcal{A}_K^2 = -0.852 \pm 0.077 \pm 0.012,$$
$$\mathcal{A}_K^3 = -0.284 \pm 0.080 \pm 0.009,$$
$$\mathcal{A}_K^4 = +0.107 \pm 0.083 \pm 0.009,$$

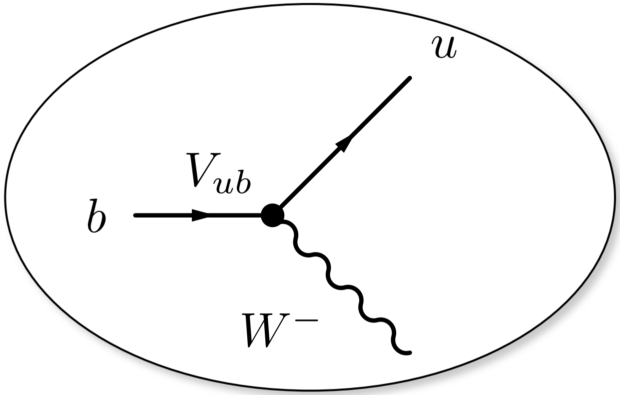
CKM angle γ: Combination

- 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:

New

B decay	D decay	Ref.	Dataset	Status since Ref. [14]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[30]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	[18]	Run 1&2	**New**
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[19]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[31]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[32]	Run 1&2	As before
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[33]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[34]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[36]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[37]	Run 1	As before
$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	[38]	Run 1	As before
$B^0_s \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[39]	Run 1&2	As before
D decay	**Observable(s)**	**Ref.**	**Dataset**	**Status since Ref. [14]**
$D^0 \to h^+h^-$	ΔA_{CP}	[24, 40, 41]	Run 1&2	As before
$D^0 \to K^+K^-$	$A_{CP}(K^+K^-)$	[16, 24, 25]	Run 2	**New**
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[42]	Run 1	As before
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[15]	Run 2	**New**
$D^0 \to h^+h^-$	ΔY	[43–46]	Run 1&2	As before
$D^0 \to K^+\pi^-$ (Single Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[47]	Run 1	As before
$D^0 \to K^+\pi^-$ (Double Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[48]	Run 1&2(*)	As before
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	[49]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x, y	[50]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[51]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[52]	Run 2	As before
$D^0 \to K^0_S\pi^+\pi^-$ (μ^- tag)	x_{CP}, y_{CP}, Δx, Δy	[17]	Run 2	**New**

LHCb-CONF-2022-002, Oct 2022



CKM angle γ

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

New

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$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	[38]	Run 1	As before
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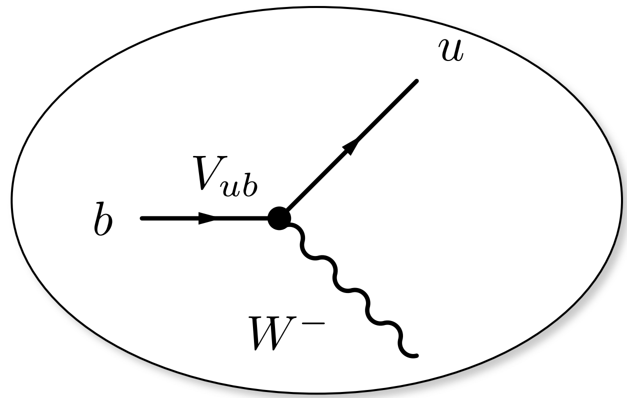
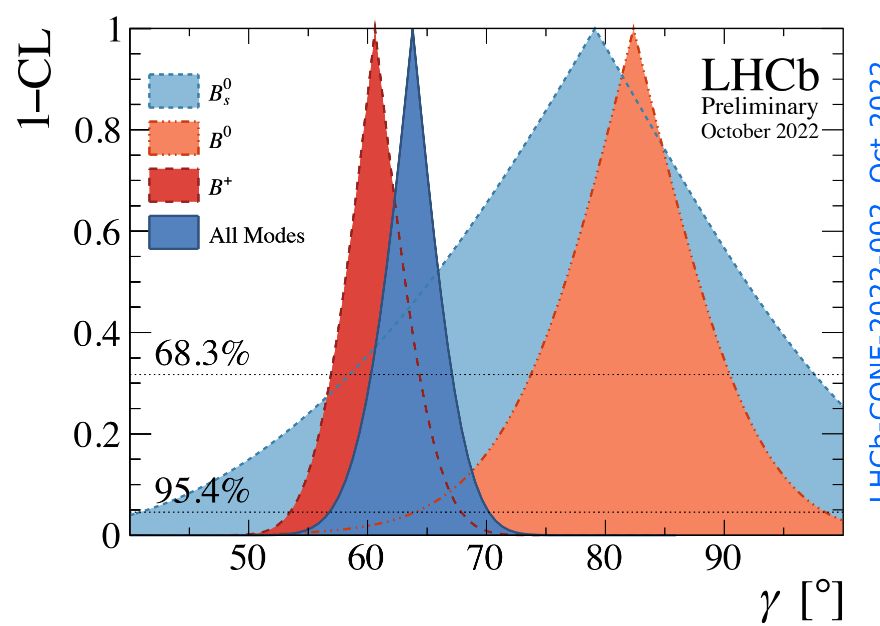


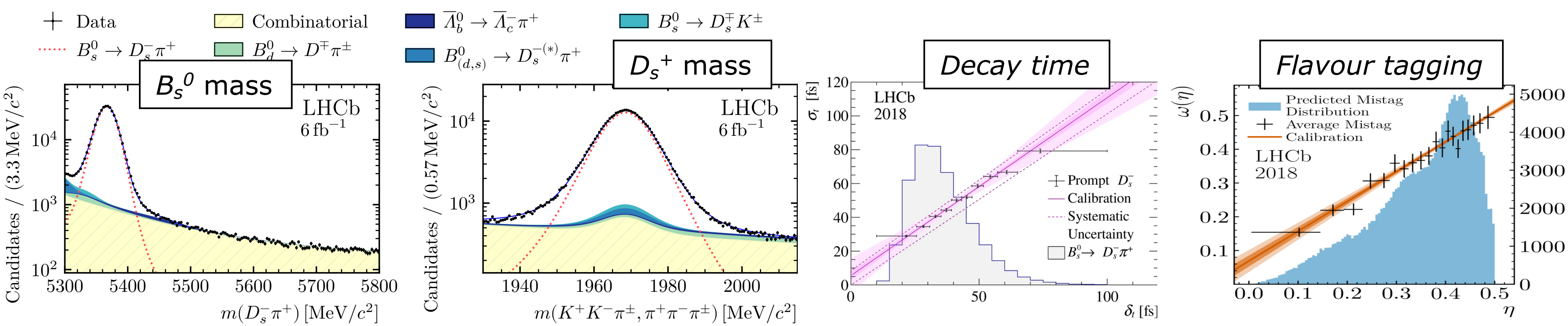
	γ (°)
LHCb	**$63.8^{+3.5}_{-3.7}$°**
CKMfitter	$65.6^{+1.1}_{-2.7}$°
UTFit	$65.8^{+2.2}_{-2.2}$°



Precision Δm_s with $B^0_s \to D_s^+\pi^-$

- Legacy "*textbook*" run-2 measurement
- Flavour specific : final state reveals flavour of the decaying *B*
- Precision: 3 x 10^{-4}
- "Standard candle" for run-3

- Analysis
  - 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



LHCb, arXiv:2104.04421 Nature Physics 18, (2022) 1-5

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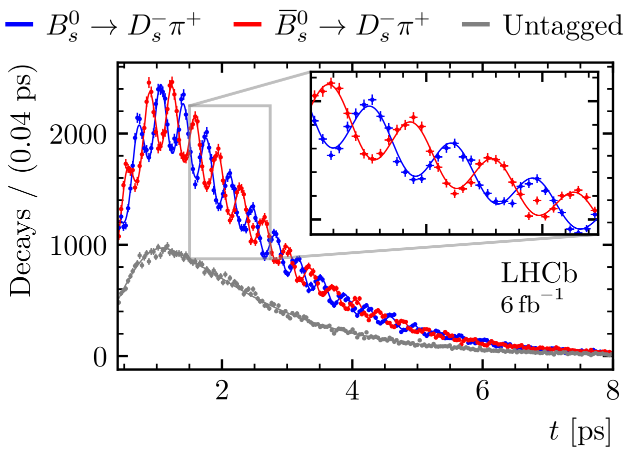
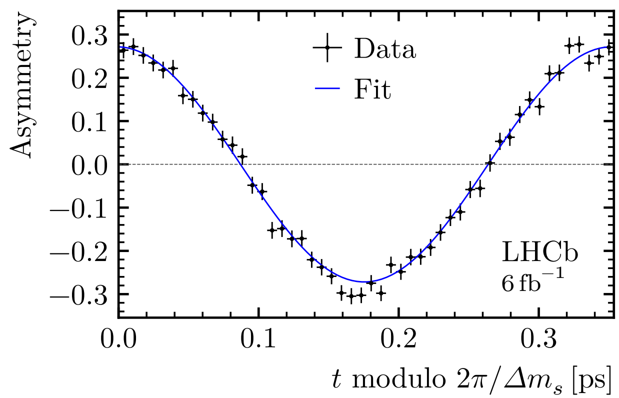
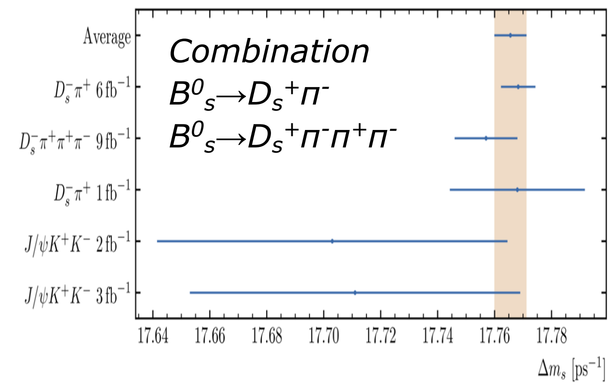




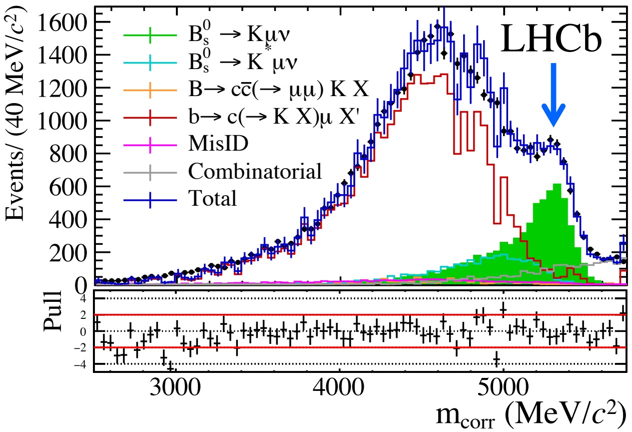


	Δm_s	Stat	Sys	Ref.
$B^0_s \rightarrow D_s^+\pi^-$	17.7683	0.0051	0.0032	arXiv:2104.04421 Nature Physics 18, (2022) 1-5
$B^0_s \rightarrow D_s^+\pi^-\pi^-\pi^-$	17.757	0.007	0.008	arXiv:2011.12041 JHEP 03(2021)137
Combination	**17.7656**	**0.0057**		arXiv:2104.04421 Nature Physics 18, (2022) 1-5

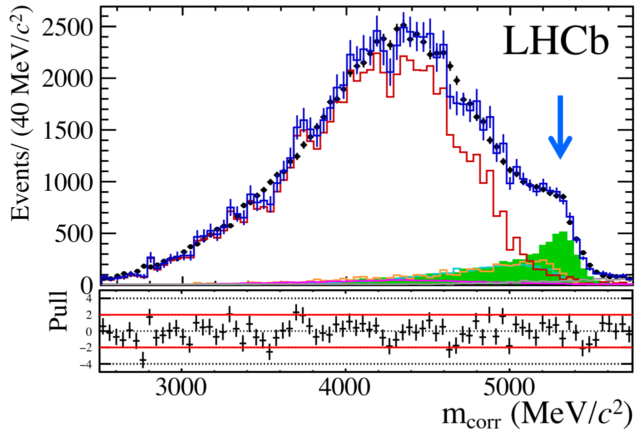
LHCb, arXiv:2104.04421 Nature Physics 18, (2022) 1-5

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

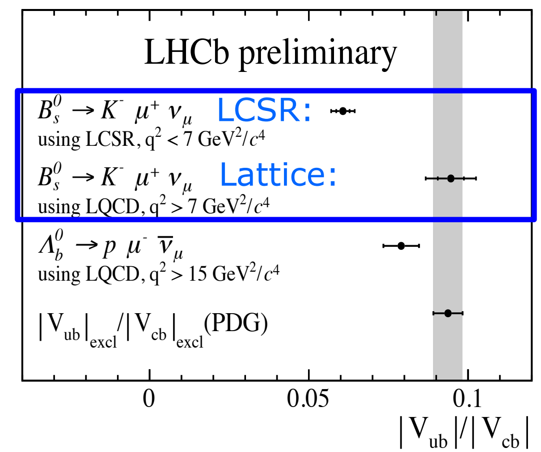
q² < 7 GeV²



q² > 7 GeV²



LHCb, arXiv:2012.05143 PRL126(2021)8, 081804



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

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

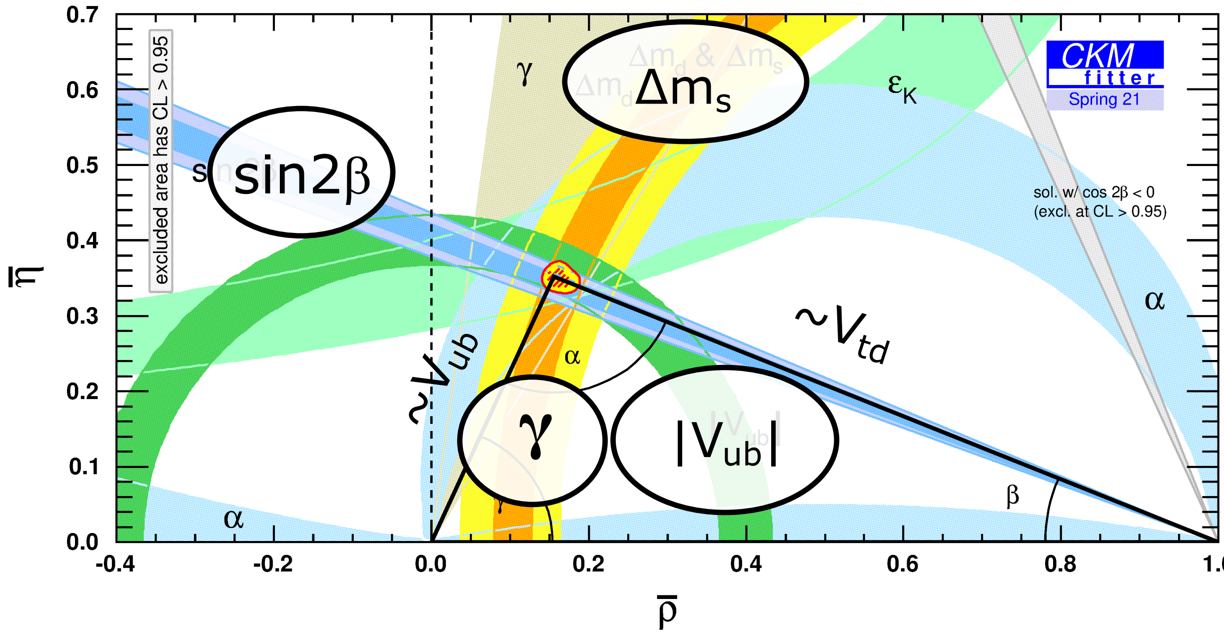
- First observation of $B_s^0 \to K^- \mu^+ \nu$

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

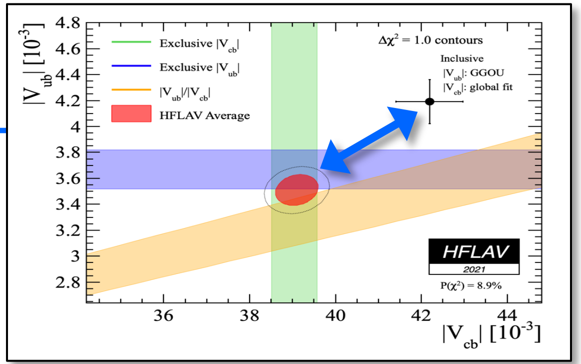
$$\begin{aligned} |V_{ub}|/|V_{cb}|(\text{low}) &= 0.0607 \pm 0.0015(\text{stat}) \pm 0.0013(\text{syst}) \pm 0.0008(D_s) \pm 0.0030(FF), \\ |V_{ub}|/|V_{cb}|(\text{high}) &= 0.0946 \pm 0.0030(\text{stat})^{+0.0024}_{-0.0025}(\text{syst}) \pm 0.0013(D_s) \pm 0.0068(FF). \quad (3) \end{aligned}$$

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

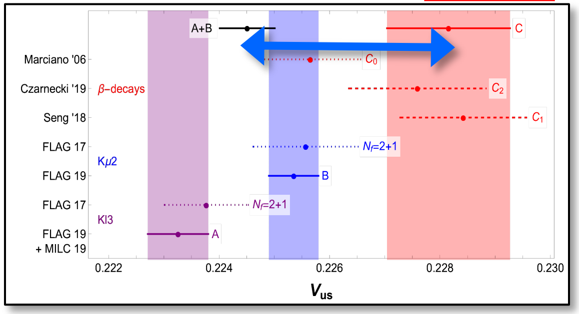
CKM: recent results



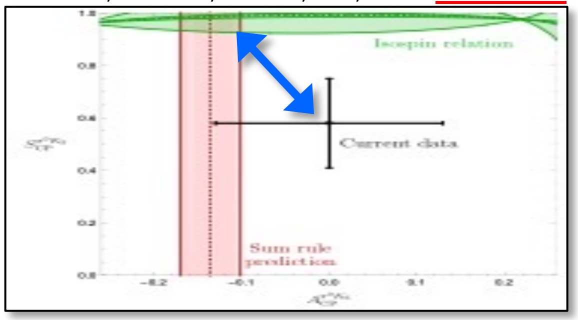
HFLAV, 2021



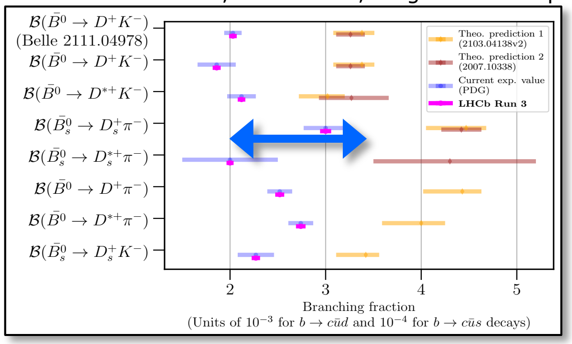
Belfatto, Berezhiani, arXiv:2103.05549



Fleischer, Jaarsma, Malami, Vos, arXiv:1806.08783



Skidmore, 2 Jun 2022, Siegen Workshop

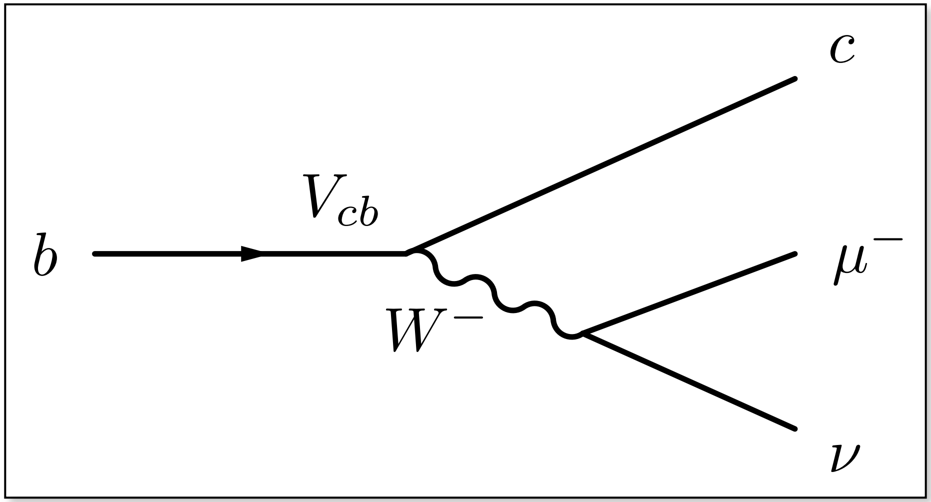


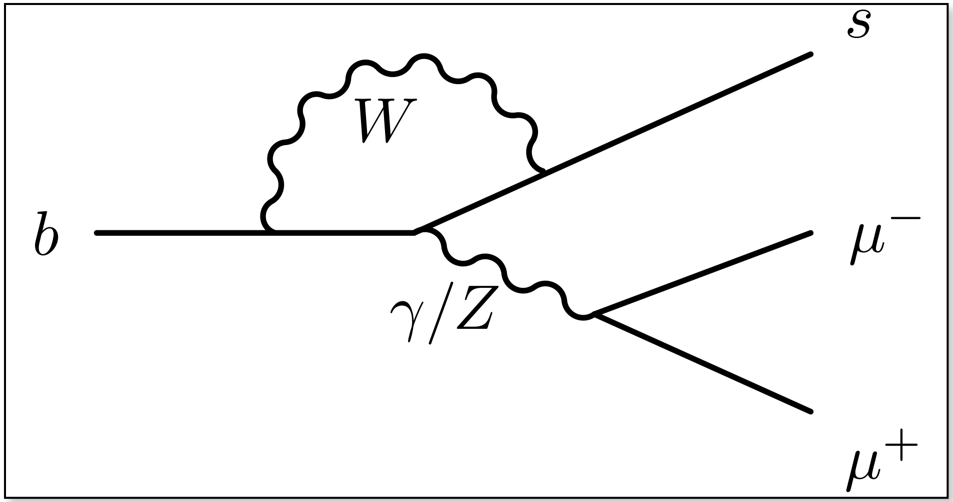
- So far so good, but stay vigilant…
  - V_{ub} and V_{cb} : incl. and excl. measurements differ…
  - V_{us}: too small for unitarity (Cabibbo angle anomaly)
  - $K\pi$ puzzle: CP asymmetries should be related through isospin symmetry…
  - BR($B \to Dh$): Factorisation?
  - …

Outline

- CKM elements
  - $\sin 2\beta$
  - γ
  - Δm_s
  - V_{ub}
- Flavour Anomalies
  - $b \rightarrow c\ \tau\nu$
  - $b \rightarrow s\ \ell^+ \ell^-$
- Prospects
  - Upgrade
  - Upgrade II

CC and FCNC



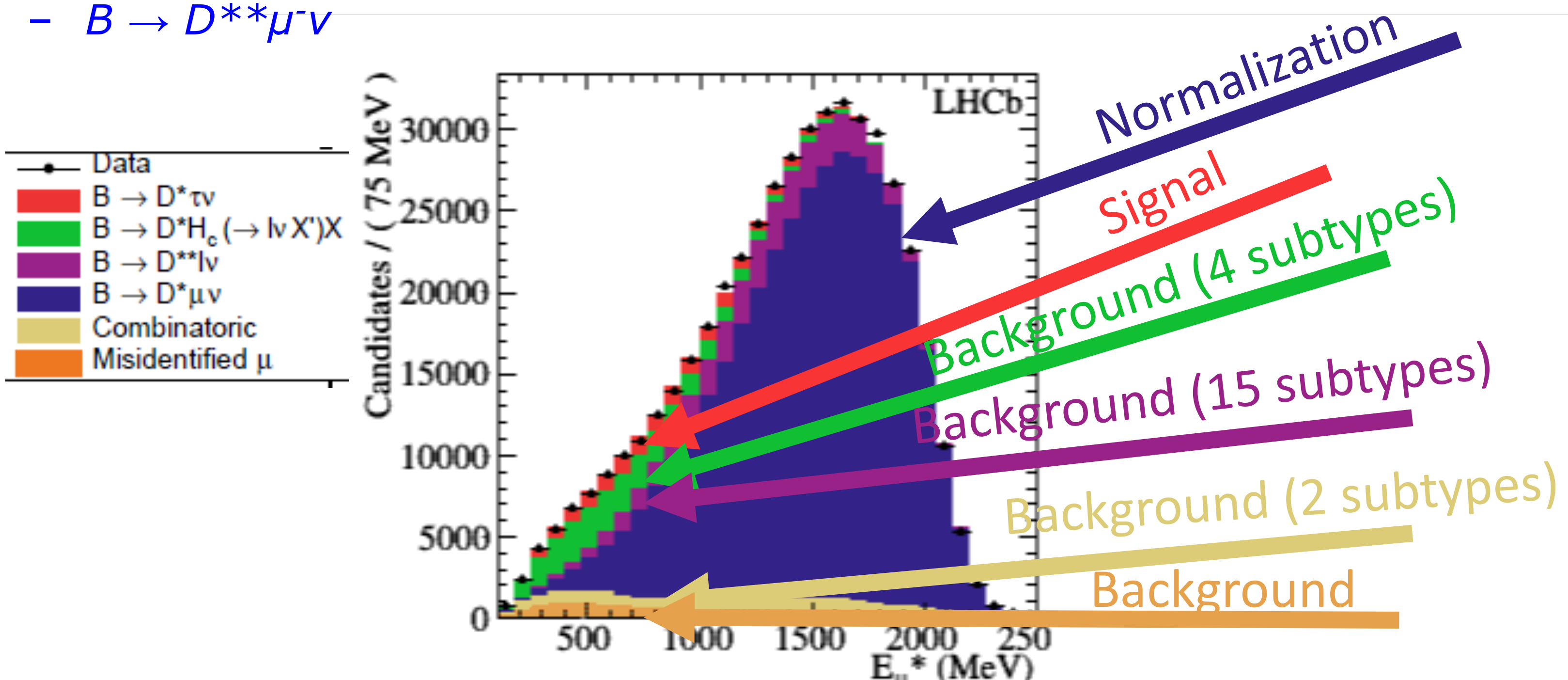


Semileptonic
CC
$b \to c l^- \nu$

"Semileptonic"
FCNC EWP Penguin
$b \to s l^+ l^-$

New measurement of R(D*) vs R(D) !

- Signal
  - $B \to D^* l^- \nu$ → $(D^{*+}\mu)$ sample
  - $B^+ \to D^0 l^- \nu$ → $(D^0\mu)$ sample
- Main backgrounds:
  - $B \to DDX$
  - $B \to D^{**}\mu^- \nu$

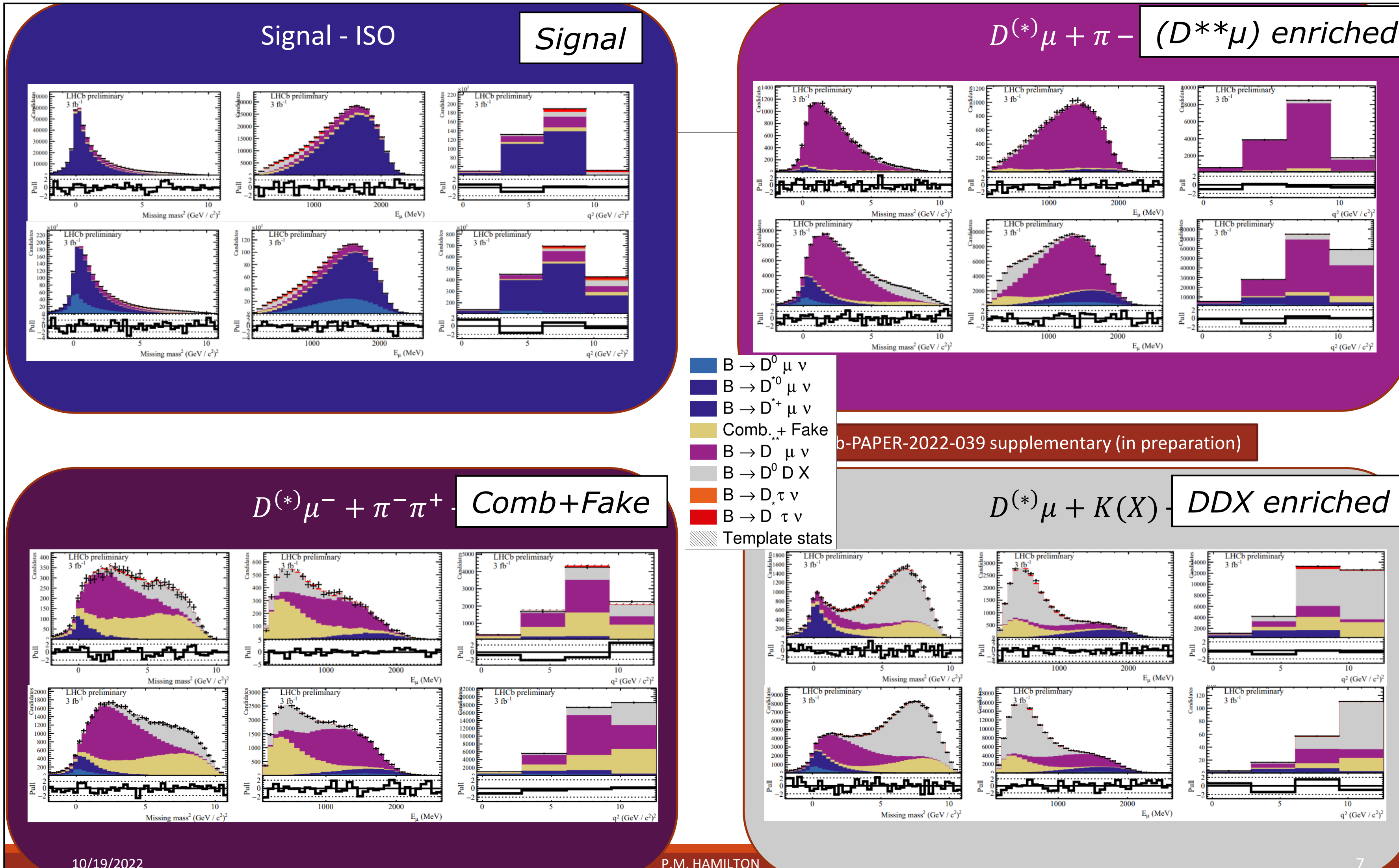


PRL 115 (2015) 111803

Courtesy:
P.Hamilton, Impl.Workshop, 19 Oct 2022

New measurement of R(D*) vs R(D) !

- Simultaneous 3D-fit (m_{miss}, E_μ, q^2) to 2x4 samples



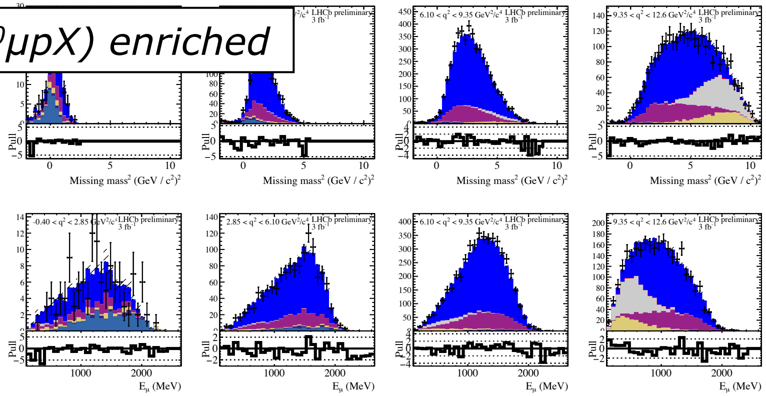
Courtesy: P.Hamilton, Impl.Workshop, 19 Oct 2022, LHCb-PAPER-2022-039, in preparation

Courtesy:
P.Hamilton, Impl.Workshop, 19 Oct 2022
LHCb-PAPER-2022-039, in preparation

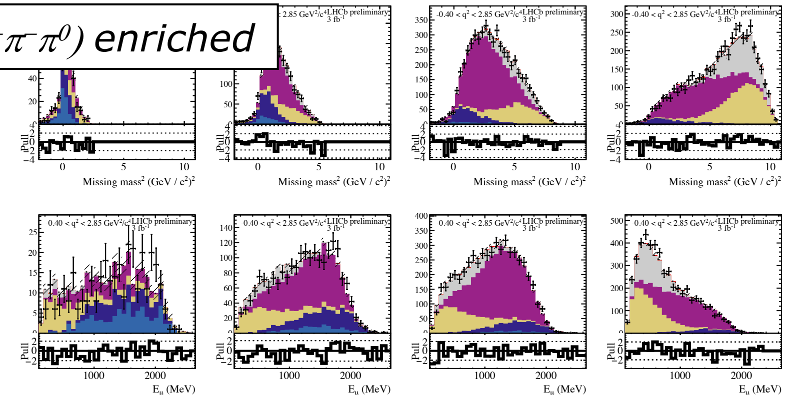
New measurement of R(D*) vs R(D) !

- Fit was checked on specific subsamples:

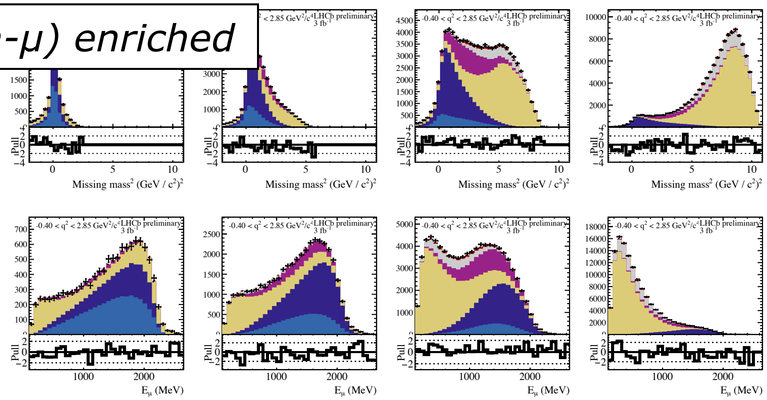
($\Lambda_b \to D^0 \mu p X$) enriched



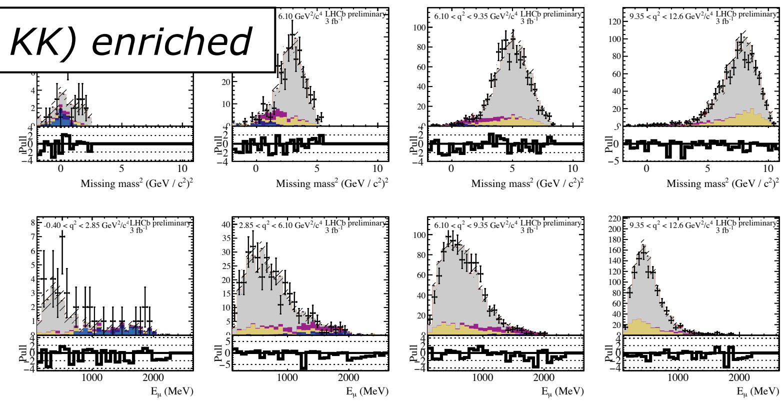
($\eta \to \pi^+ \pi^- \pi^0$) enriched



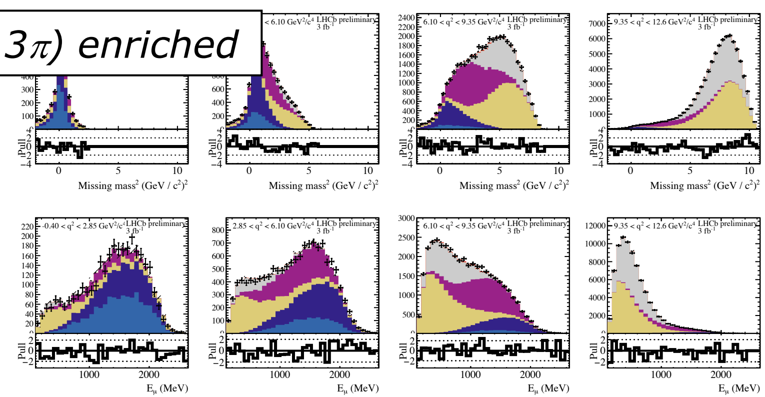
(D non-μ) enriched*



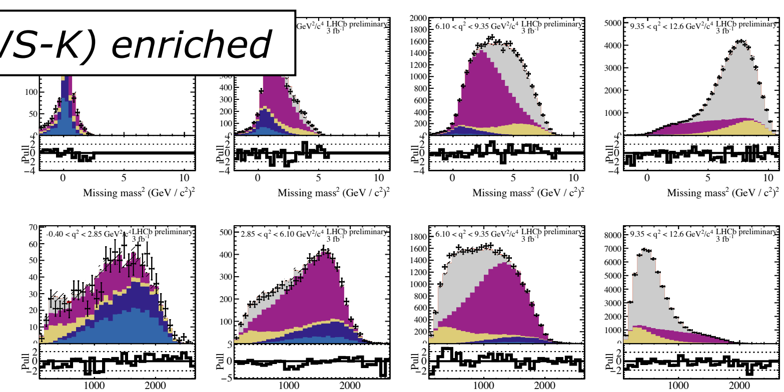
($\phi \to KK$) enriched



*(D*μ + 3π) enriched*

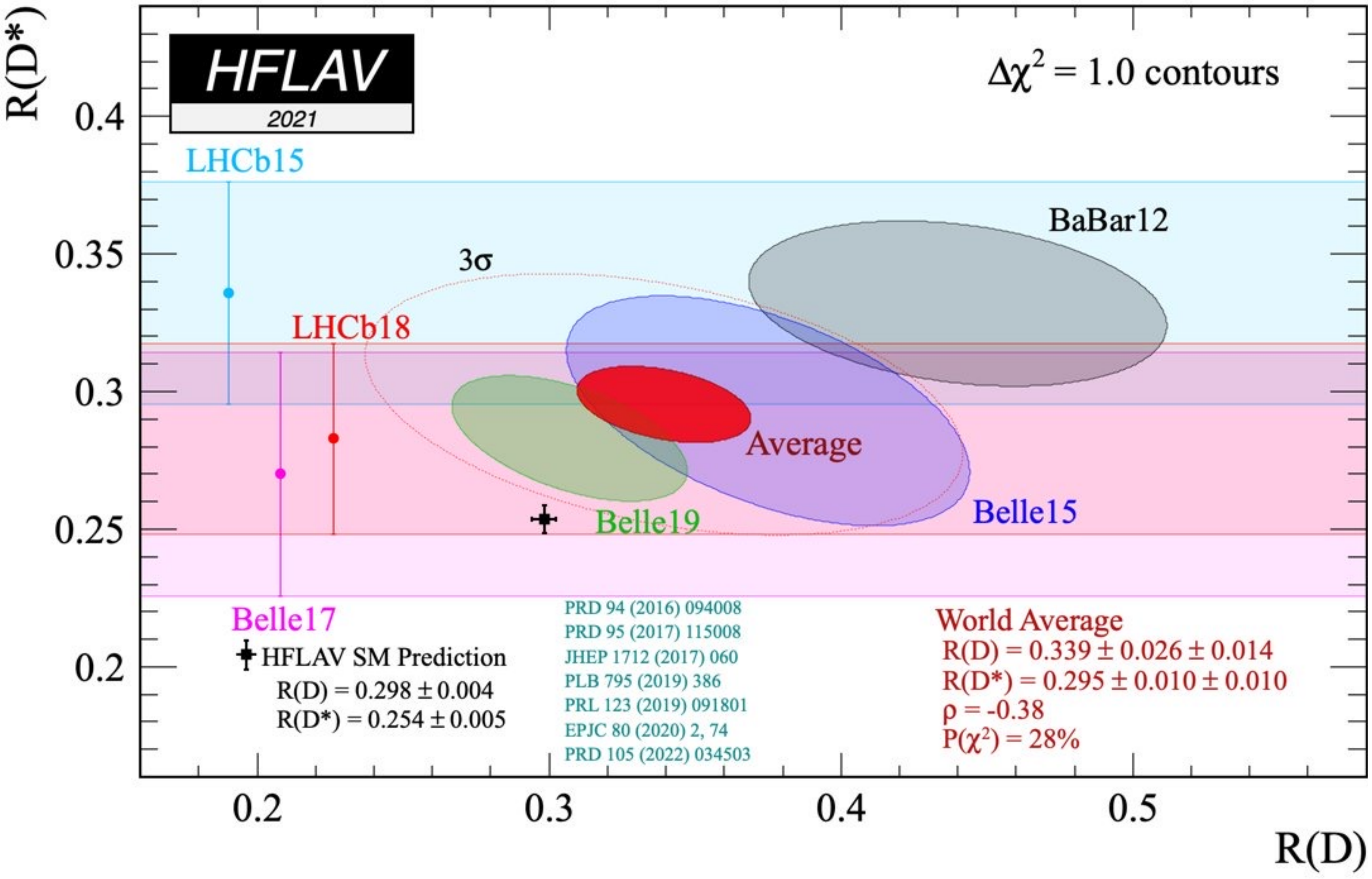


(DD WS-K) enriched



New measurement of R(D*) vs R(D) !

- World average 3.3σ to 3.2σ



NB: contours contain less than 68% CL…

New measurement of R(D*) vs R(D) !

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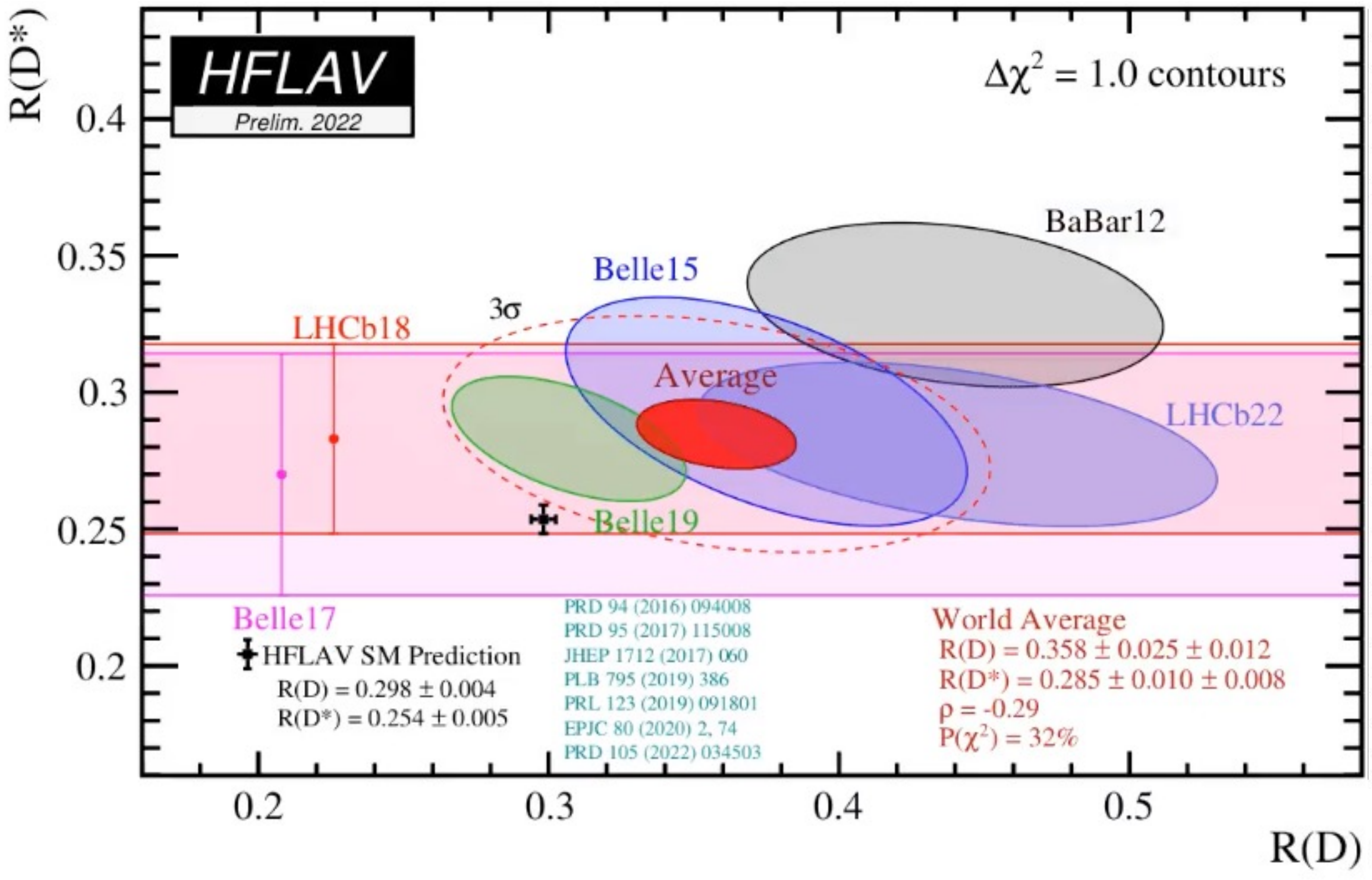
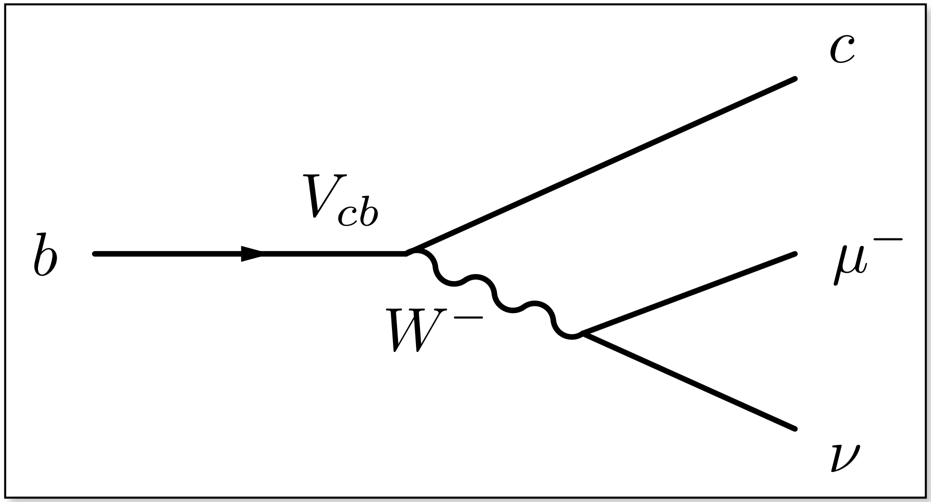
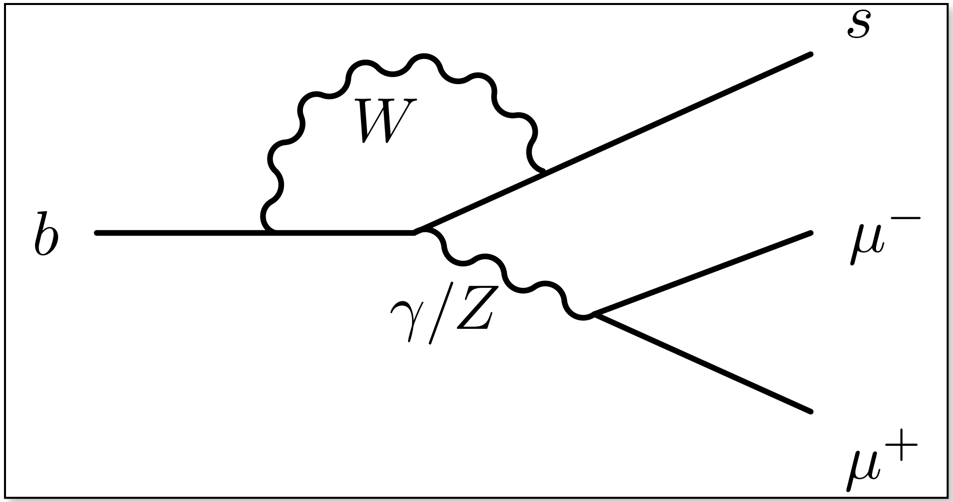


https://hflav-eos.web.cern.ch/hflav-eos/semi/fall22/html/RDsDsstar/RDRDs.html

CC and FCNC



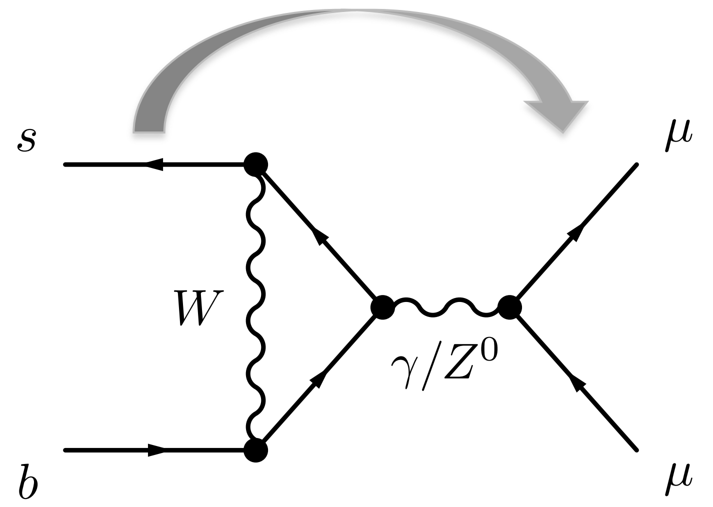


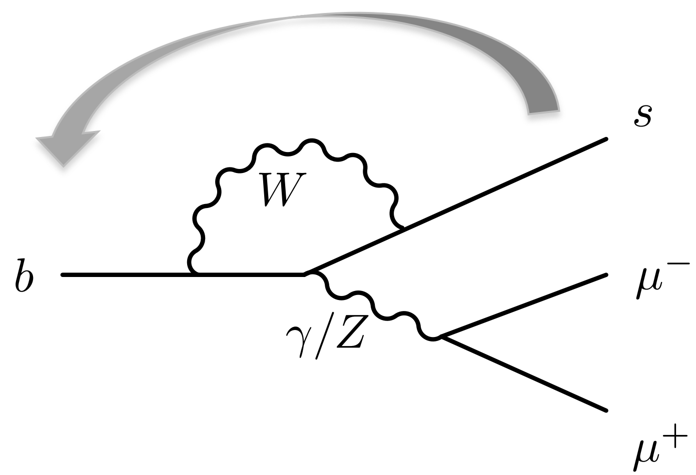
Semileptonic
CC
$b \to c l^- \nu$

"Semileptonic"
FCNC EWP Penguin
$b \to s l^+ l^-$

$B_s^0 \to \mu^+\mu^-$

- Purely leptonic $b \to s l^+ l^-$

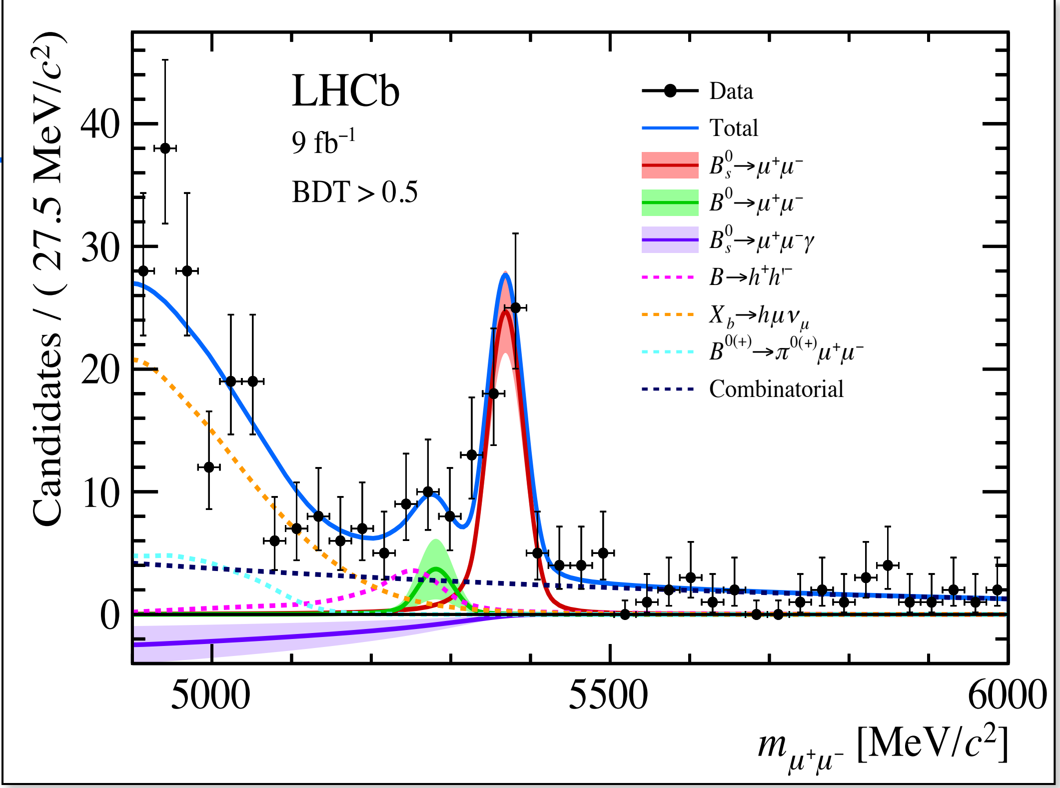




+ $B_s^0 \to e^+e^-$ (LHCb, arXiv:2003.03999)

+ $B_s^0 \to \tau^+\tau^-$ (LHCb, arXiv:1703.02508)

$B_s^0 \to \mu^+\mu^-$ (LHCb)



LHCb Coll. arXiv:2108.09284

Theory:

$$B(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

$$B(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

Beneke, Bobeth, Szafron, arXiv:1908.07011

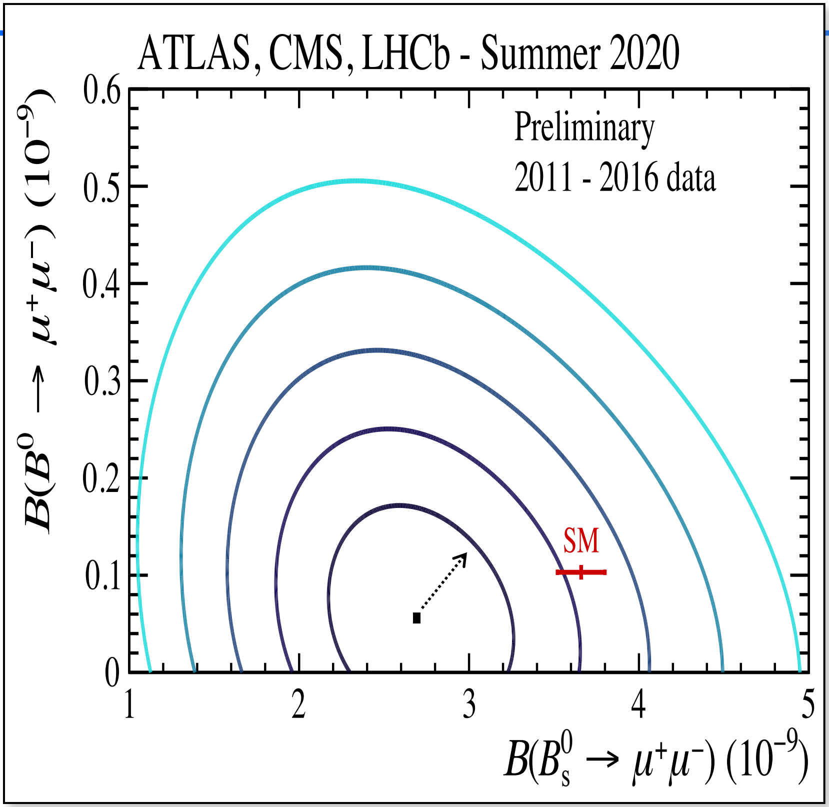
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}\right) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{m_{\mu\mu} > 4.9\,\mathrm{GeV}/c^2} < 2.0 \times 10^{-9}$$

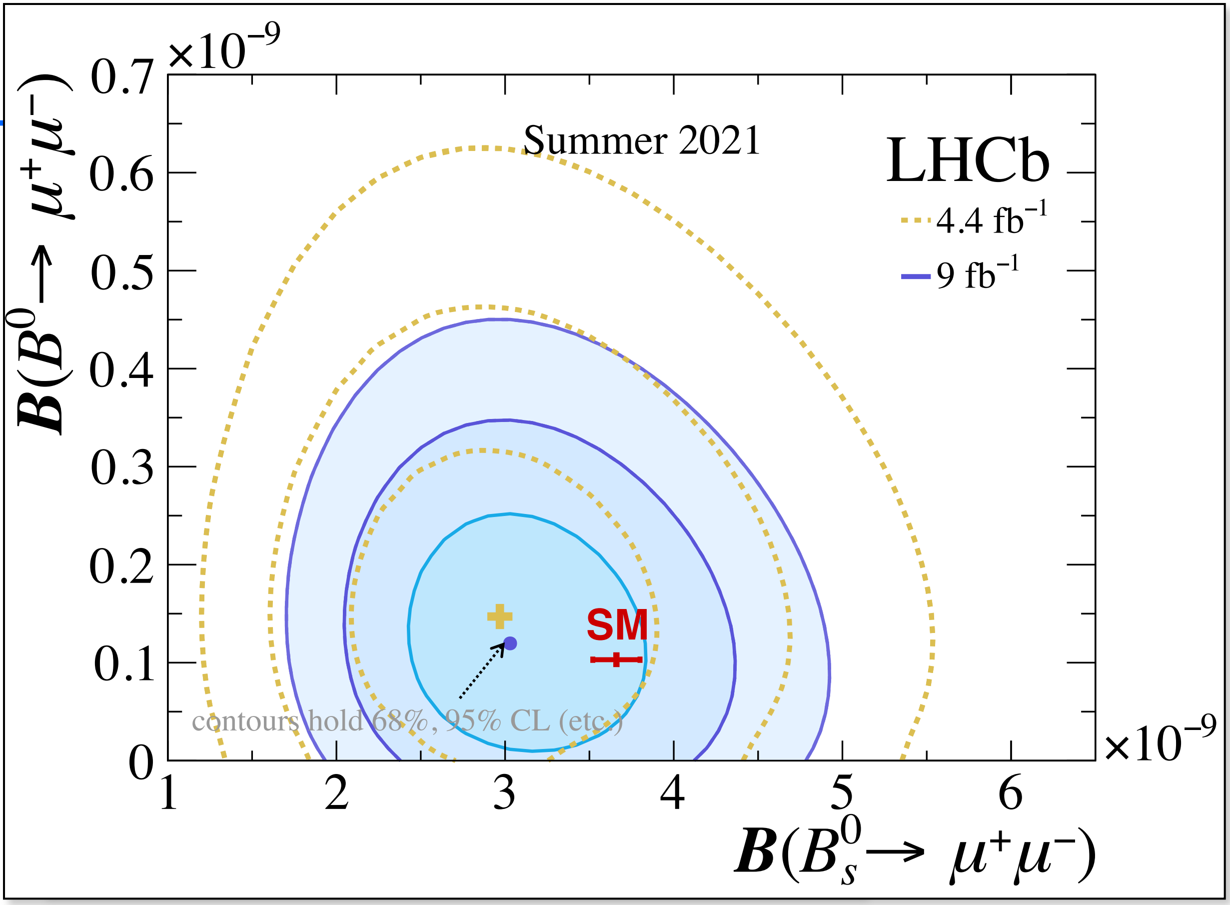
$B_{(s)}^0 \to \mu^+\mu^-$ (2020)

- Including B^0:



$B_{(s)}^0 \to \mu^+\mu^-$

- Including B^0:



LHCb Coll. arXiv:2108.09284

- NB: new result from CMS at ICHEP not included here

- Relative production of B_s^0 wrt B^0 mesons, f_s/f_d :

$$f_s/f_d\,(7\,\text{TeV}) = 0.2390 \pm 0.0076$$
$$f_s/f_d\,(8\,\text{TeV}) = 0.2385 \pm 0.0075$$
$$f_s/f_d\,(13\,\text{TeV}) = 0.2539 \pm 0.0079$$

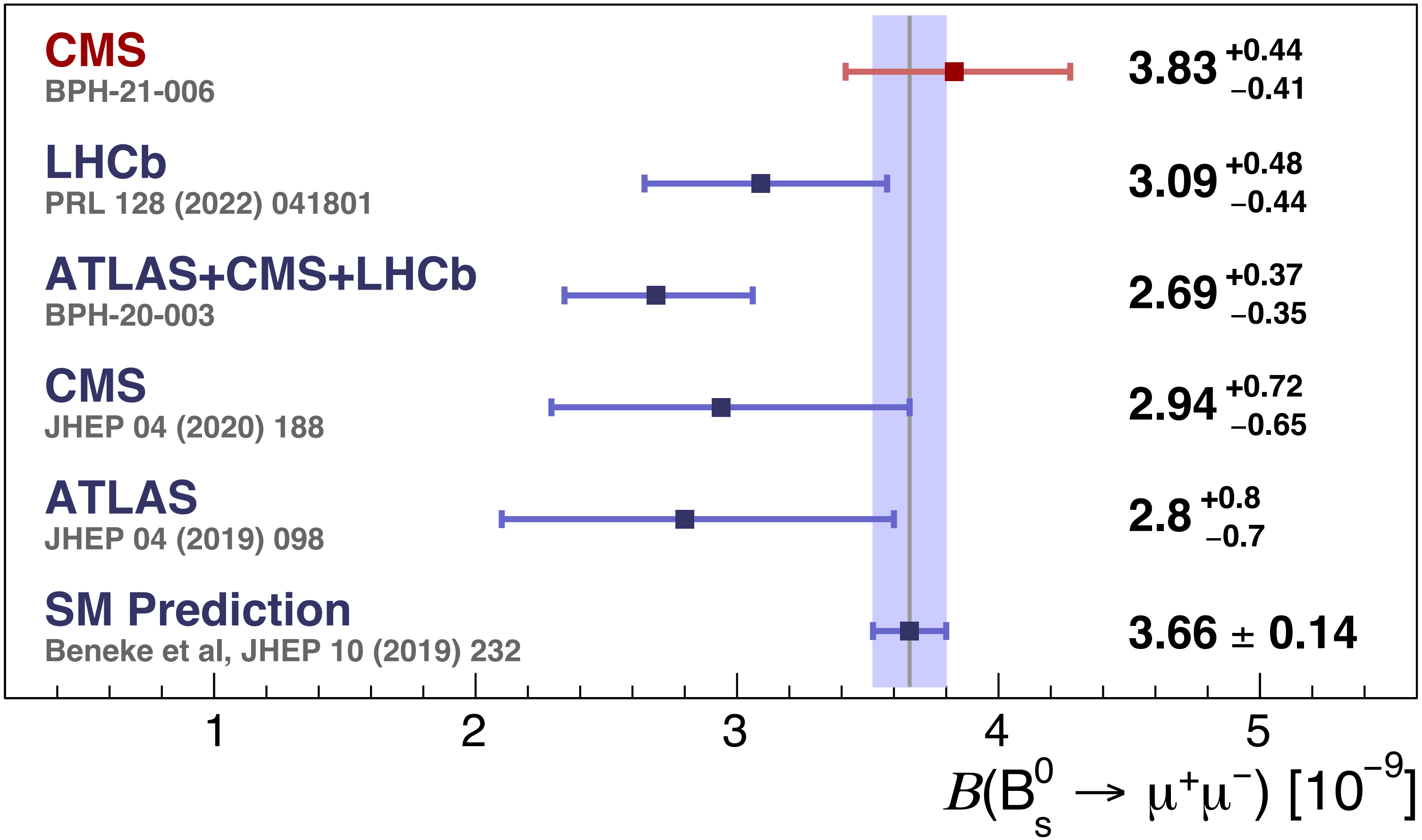
(Integrated, p_T [0.5,40] GeV/c, η [2.6,4])

$$f_s/f_d \quad (p_T, 7\,\text{TeV}) = (0.244 \pm 0.008) + ((-10.3 \pm 2.7) \times 10^{-4}) \cdot p_T$$
$$f_s/f_d \quad (p_T, 8\,\text{TeV}) = (0.240 \pm 0.008) + ((-\;3.4 \pm 2.3) \times 10^{-4}) \cdot p_T$$
$$f_s/f_d \quad (p_T, 13\,\text{TeV}) = (0.263 \pm 0.008) + ((-17.6 \pm 2.1) \times 10^{-4}) \cdot p_T$$

LHCb Coll, arXiv:2103.06810

$B_s^0 \rightarrow \mu^+\mu^-$

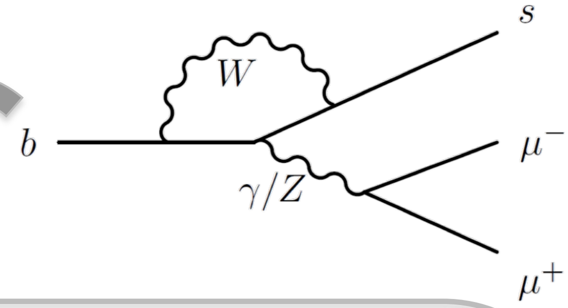
Summer 2022

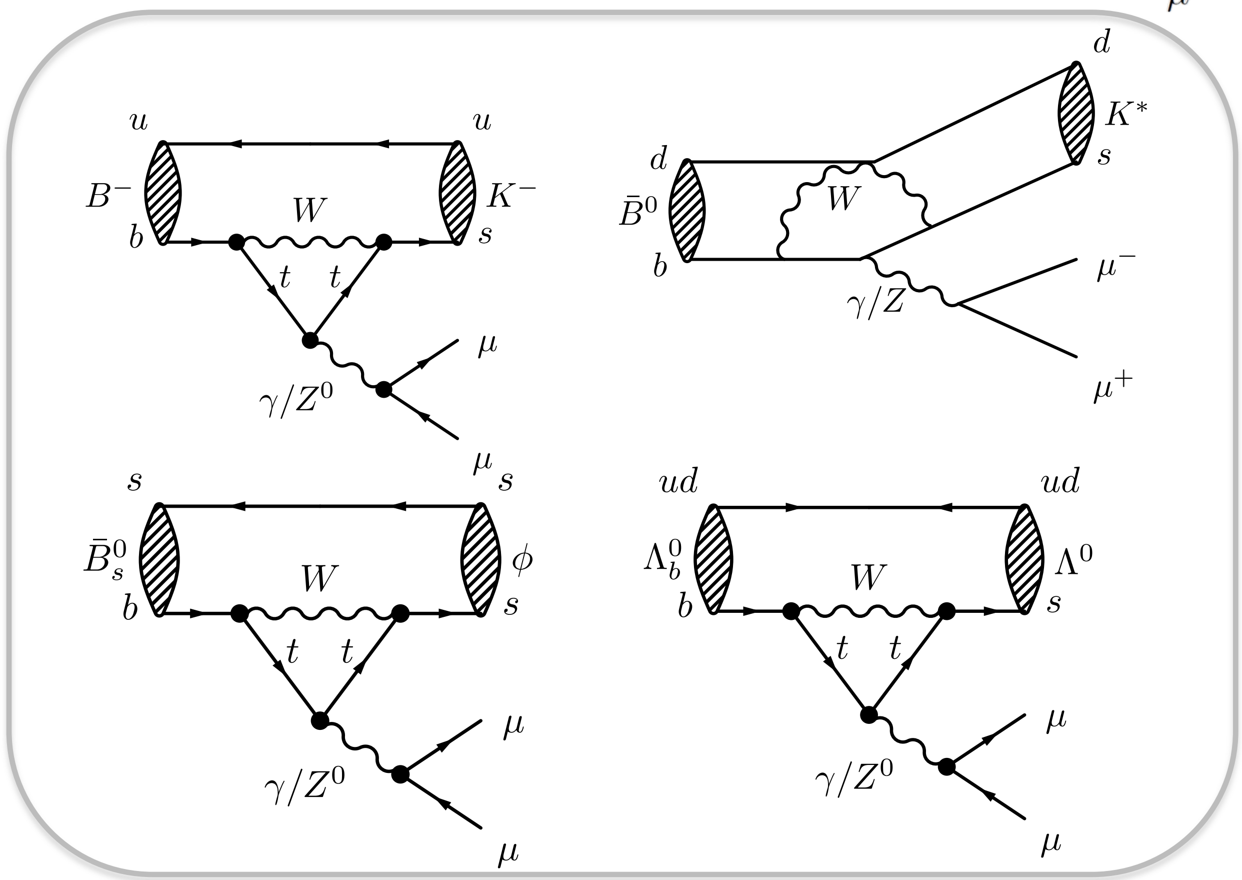


Courtesy: D.Kovalskyi (CMS), ICHEP, 9 July 2022, [CMS-PAS-BPH-21-006]

Decay rates

- Study same process with different hadrons:



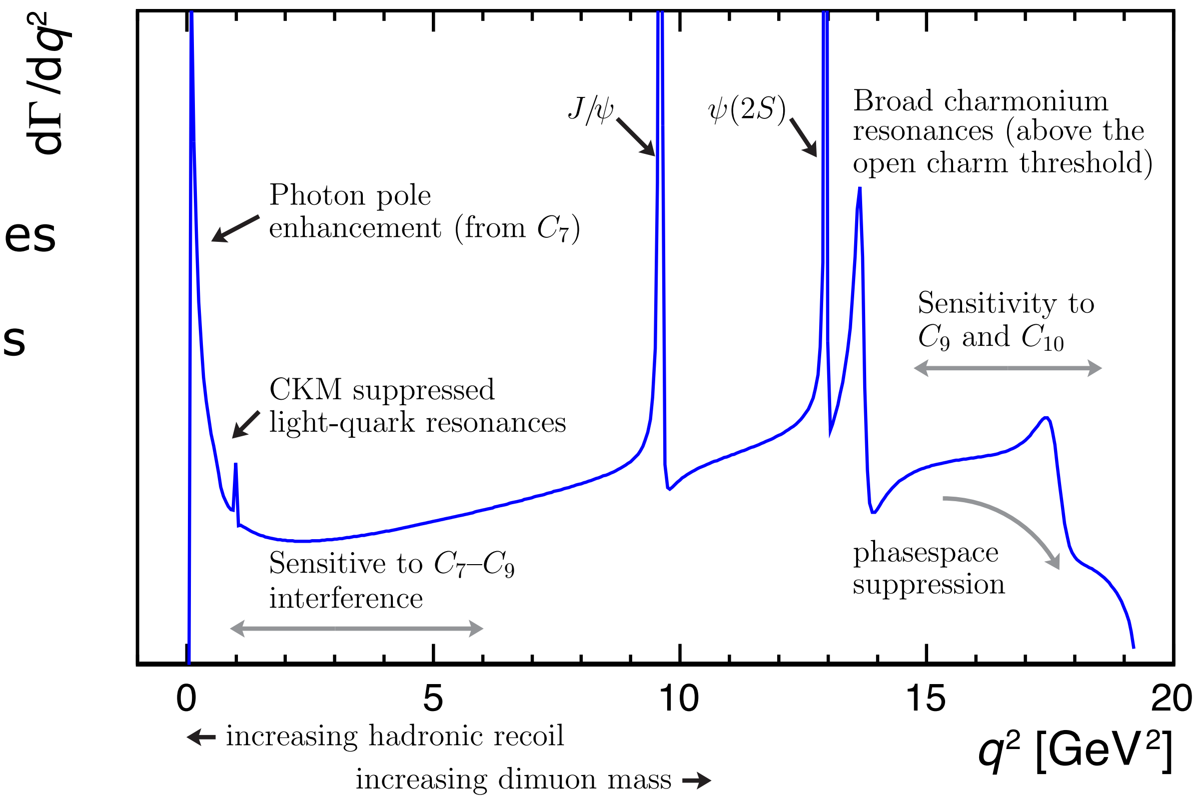


$b \rightarrow s l^+ l^-$

Rich laboratory:

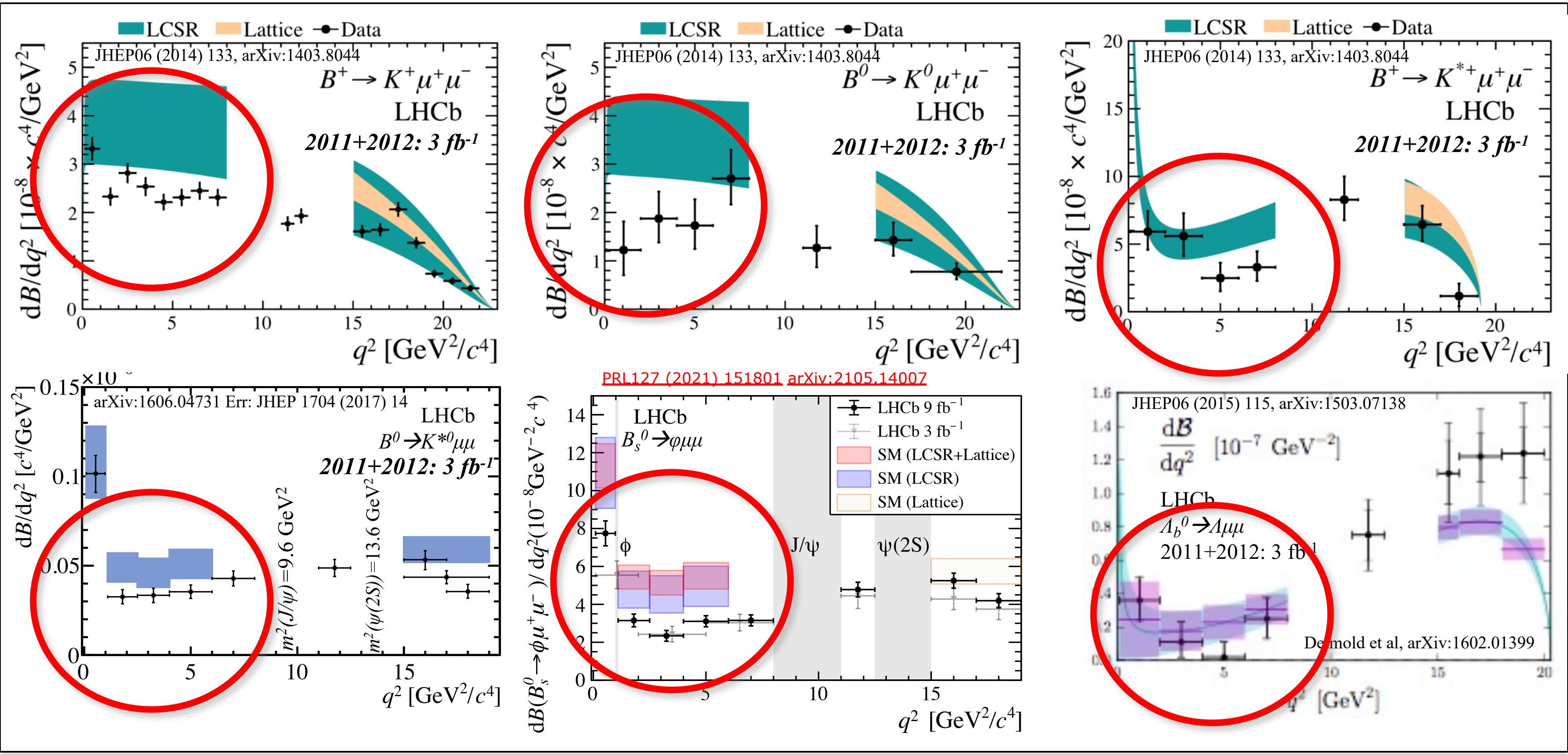
1) Purely leptonic
2) Decay rates
3) Angular asymmetries
4) Ratio of decay rates

T.Blake et al. arXiv:1606.00916



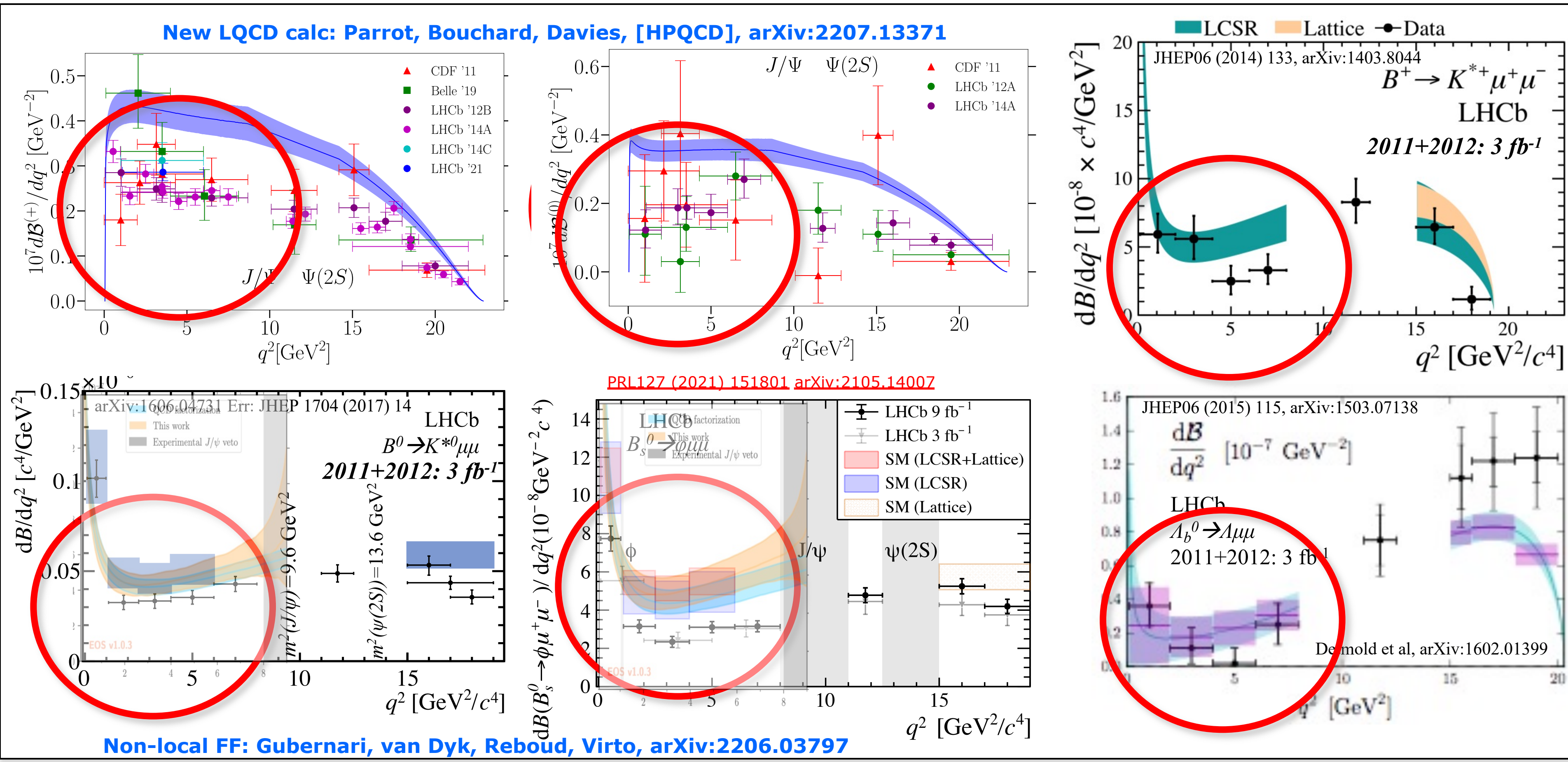
Decay rates

- Decay rate with muons in final state consistently low:

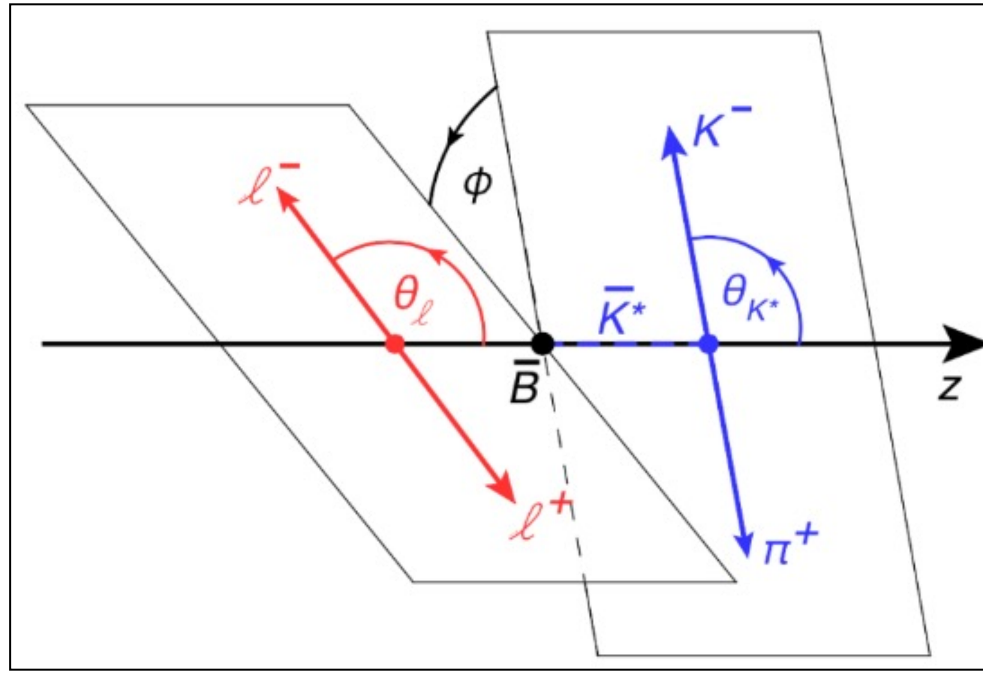


Decay rates

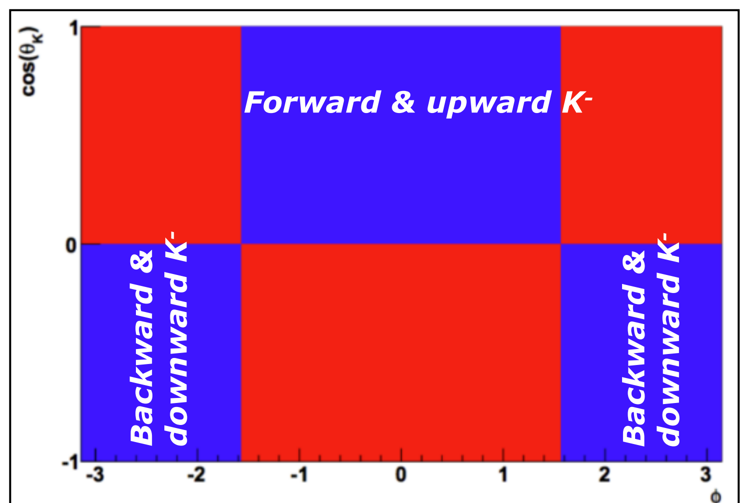
- Decay rate with muons in final state consistently low:



Angular asymmetries



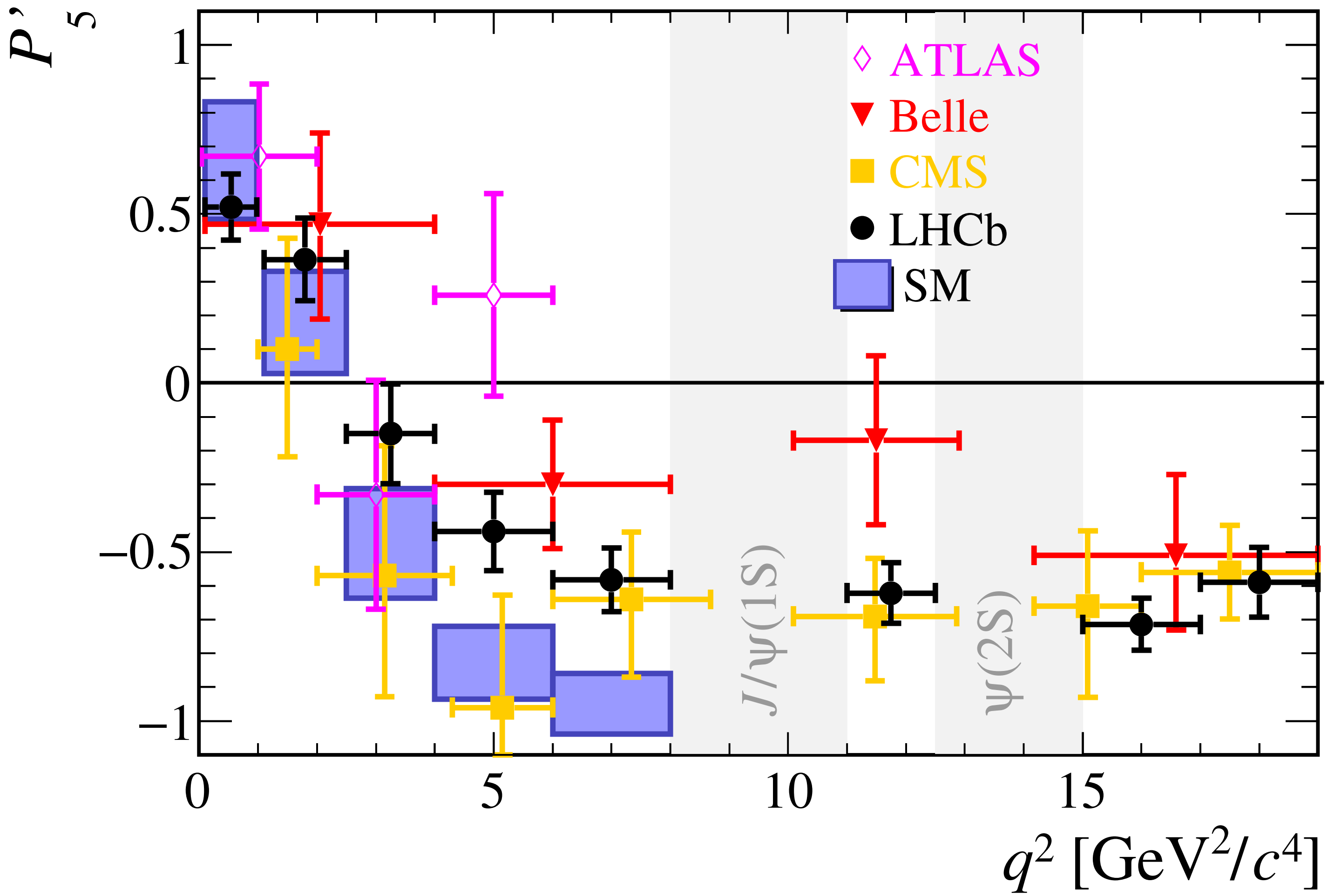
$P_5' \sim$ (N − N)/(N + N)



Counting S_5: blue minus red

Angular asymmetries: eg. P_5'

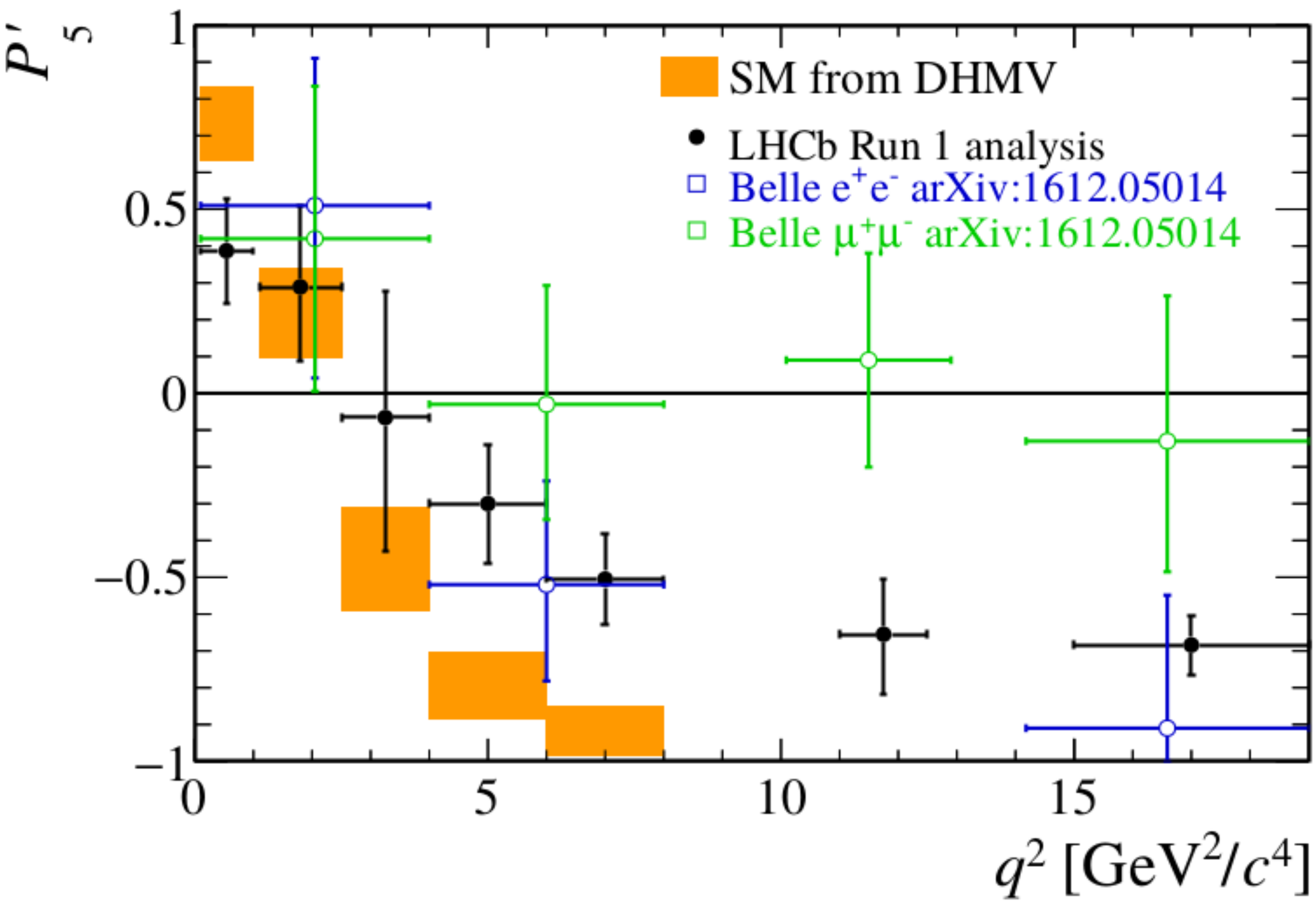
- Compilation:



Albrecht, van Dyk, Langenbruch, PIPNP120 (2021) 103885, arXiv:2107.04822

Angular asymmetries

- Interesting to compare angular asymmetries for μ and e

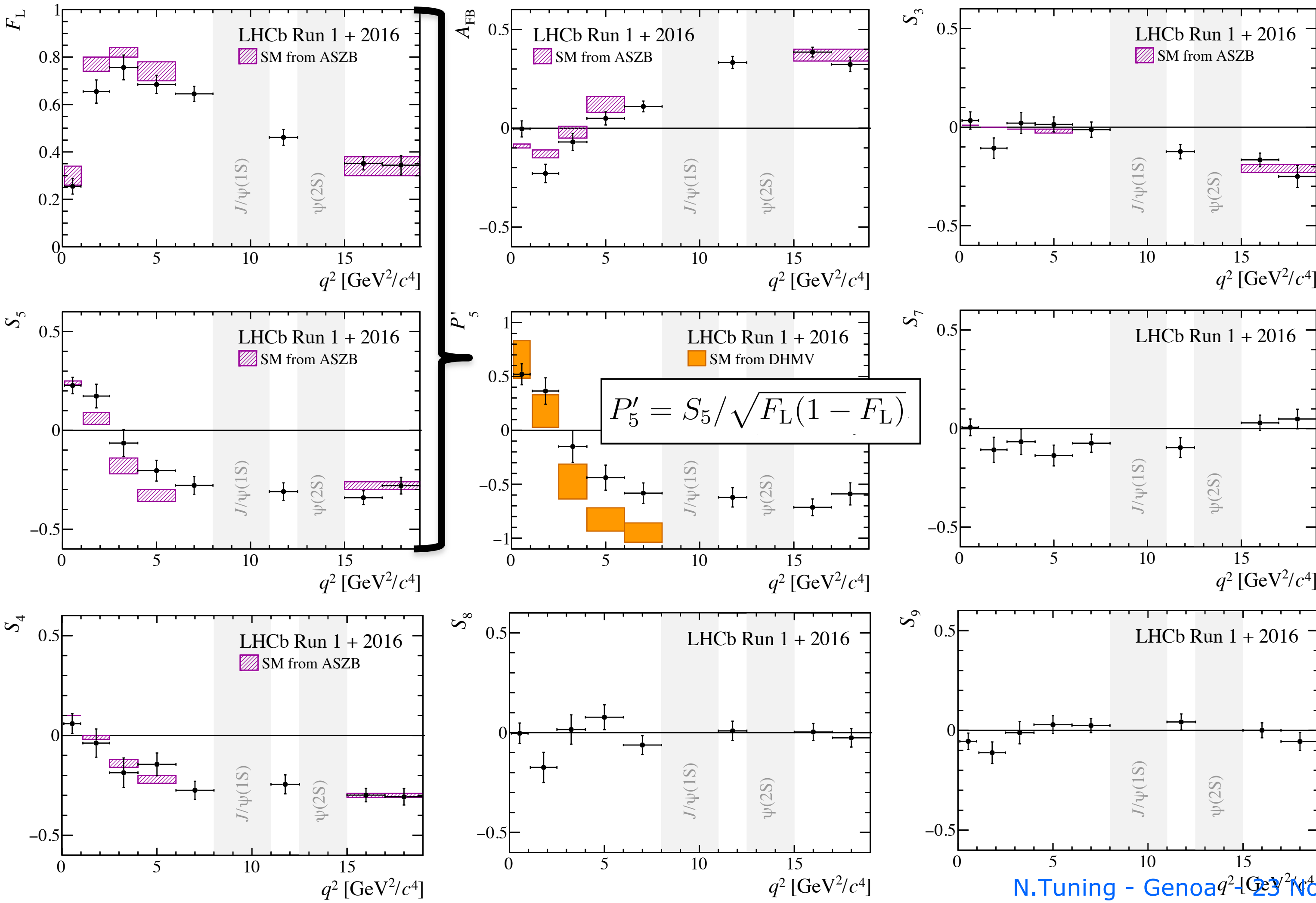


LHCb, arXiv:1512.04442

$B^0 \to K^{0*} \mu^+ \mu^-$: more than just P_5'

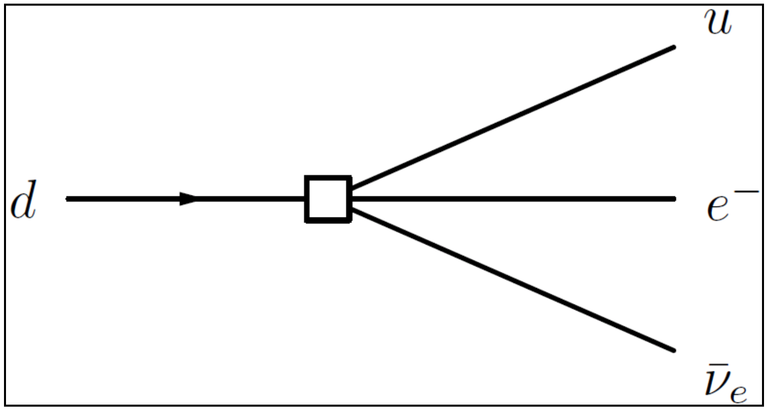
- Many measurements:

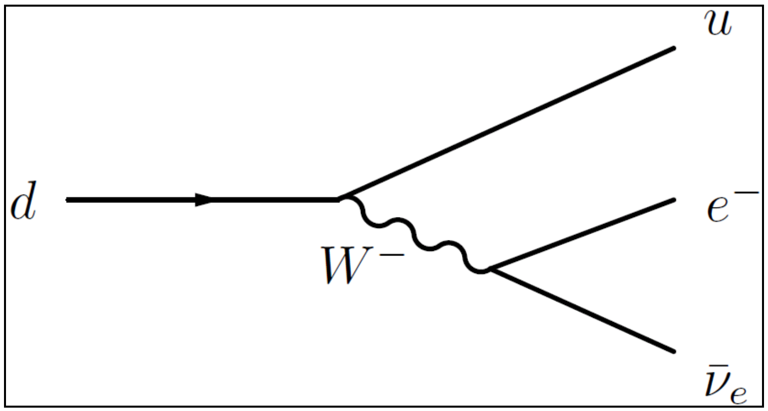
LHCb Coll, arXiv:2003.04831



Intermezzo: Effective couplings

- Historical example



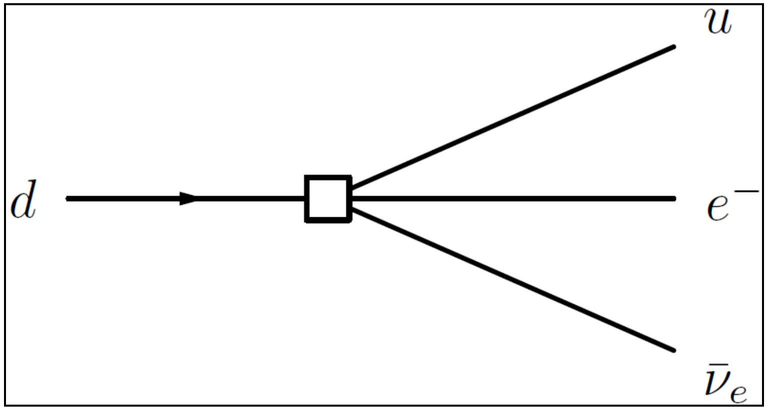


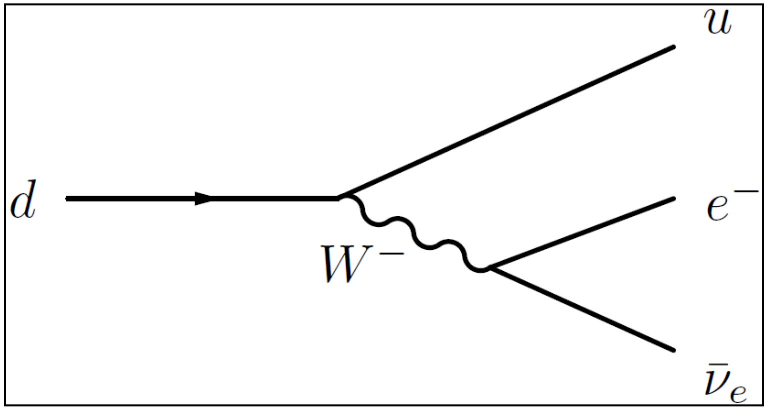
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

- Both are correct, depending on the energy scale you consider

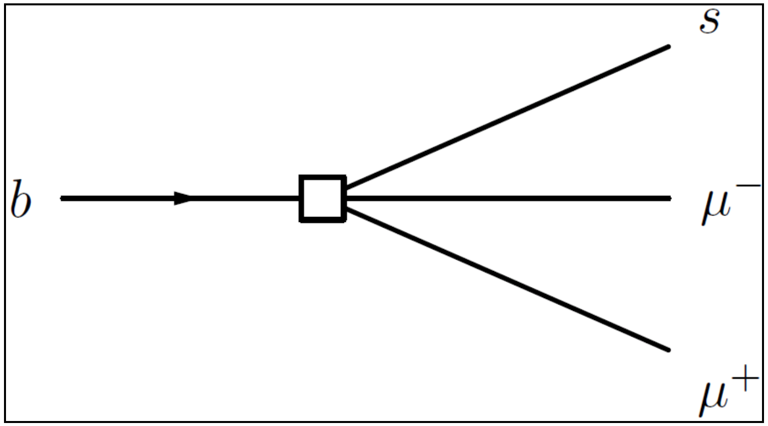
Intermezzo: Effective couplings

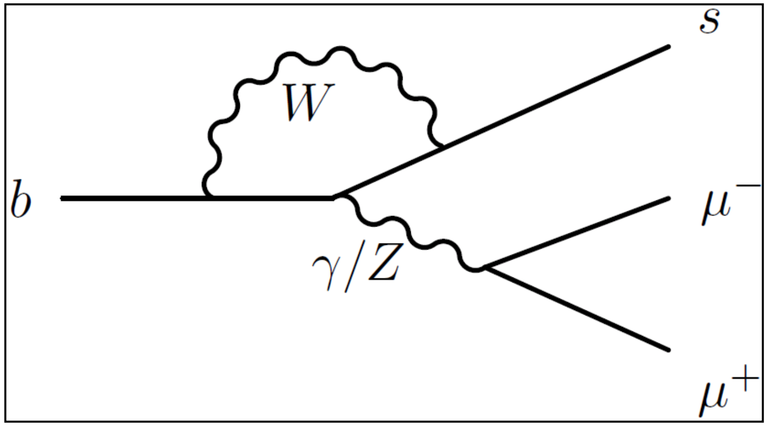
- Historical example





- Analog: *Flavour-changing neutral current*





Intermezzo: Effective couplings

- Effective coupling can be of various “kinds”
  - Vector coupling: C_9
  - Axial coupling: C_{10}
  - Left-handed coupling (V-A): C_9-C_{10}
  - Right-handed (to quarks): C_9', C_{10}', …
  - …

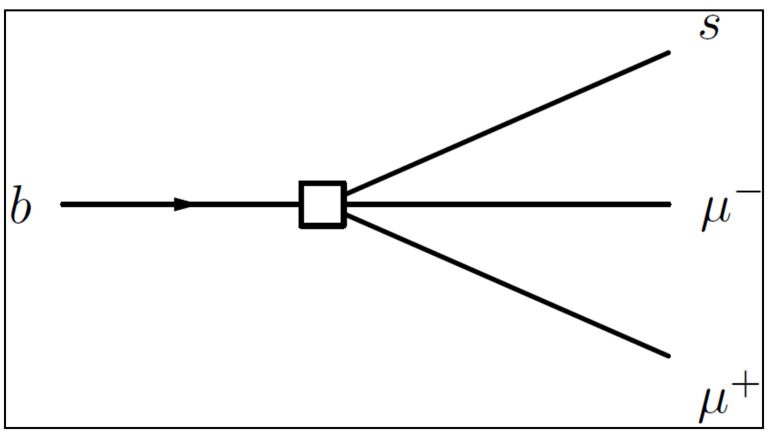
$$\mathcal{H}_{\rm eff} = \frac{G_{\rm F}}{\sqrt{2}} V_{\rm CKM} \sum_i C_i(\mu) Q_i$$

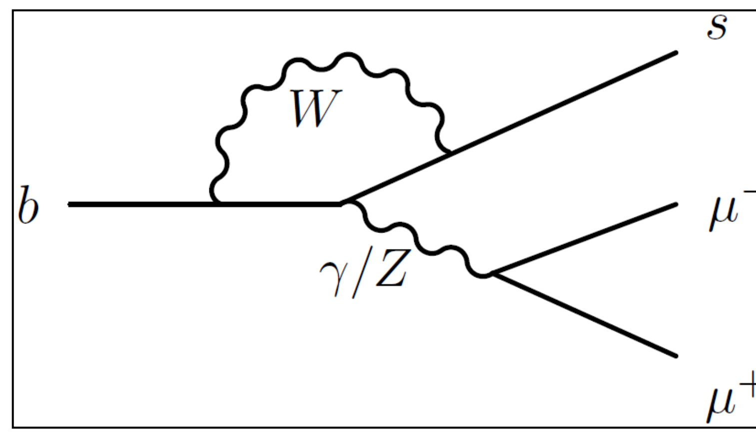
See e.g. Buras & Fleischer, hep-ph/9704376

Semi–Leptonic Operators (fig. 11f):

$$Q_{9V} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_V \qquad Q_{10A} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_A$$

- Analog: *Flavour-changing neutral current*





Intermezzo: Effective couplings

- C_7 (photon), C_9 (vector) and C_{10} (axial) couplings hide everywhere:

$$A_\perp^{L,R} \propto ((C_9^{eff} + C_9^{eff\prime}) \mp (C_{10}^{eff} + C_{10}^{eff\prime})\frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7^{eff} + C_7^{eff\prime})T_1(q^2)]$$

$$A_\parallel^{L,R} \propto ((C_9^{eff} - C_9^{eff\prime}) \mp (C_{10}^{eff} - C_{10}^{eff\prime})\frac{A_1(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(C_7^{eff} - C_7^{eff\prime})T_2(q^2)]$$

$$A_0^{L,R} \propto [(C_9^{eff} - C_9^{eff\prime}) \mp (C_{10}^{eff} - C_{10}^{eff\prime})] \times [(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*}A_1(q^2) - \lambda\frac{A_2(q^2)}{m_B + m_{K^*}})] + 2m_b(C_7^{eff} - C_7^{eff\prime})[(m_B^2 + 3m_{K^*}^2 - q^2)T_2(q^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2 T_3(q^2)}]$$

$$F_L = \frac{A_0^2}{A_\parallel^2 + A_\perp^2 + A_0^2}$$

$$S_3 = \frac{A_\perp^{L2} - A_\parallel^{L2}}{A_\perp^{L2} + A_\parallel^{L2} + A_0^{L2}} + L \to R$$

$$S_4 = \frac{\Re(A_0^{L*}A_\parallel^L)}{|A_0^L|^2|A_\parallel^L|^2 + |A_0^L|^2} + L \to R$$

$$S_5 = \frac{\Re(A_0^{L*}A_\perp^L)}{|A_0^L|^2 + |A_\perp^L|^2 + |A_0^L|^2} - L \to R$$

$$S_6 = \frac{\Re(A_\perp^{L*}A_\parallel^L)}{|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_0^L|^2} - L \to R = \frac{4}{3}A_{FB}$$

$$S_7 = \frac{\Im(A_0^{L*}A_\parallel^L)}{|A_0^L|^2 + |A_\parallel^L|^2 + |A_0^L|^2} + L \to R$$

$$S_8 = \frac{\Im(A_0^{L*}A_\perp^L)}{|A_0^L|^2 + |A_\parallel^L|^2 + |A_0^L|^2} + L \to R$$

$$S_9 = \frac{\Im(A_\perp^{L*}A_\parallel^L)}{|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_0^L|^2} - L \to R$$

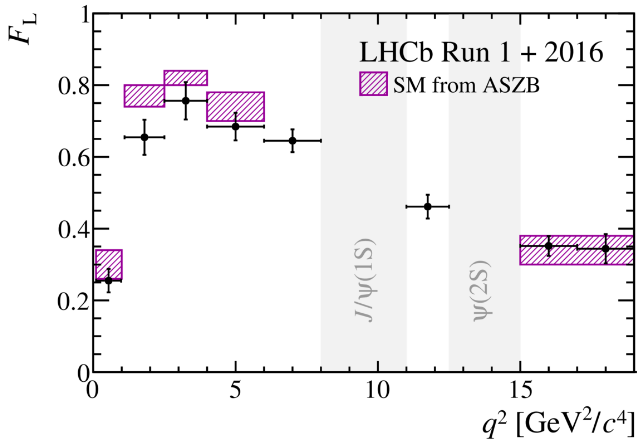
$$\frac{1}{\Gamma}\frac{d^3(\Gamma + \bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1 - F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1 - F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell +$$
$$S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi +$$
$$S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6^s\sin^2\theta_K\cos\theta_\ell +$$
$$S_7\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

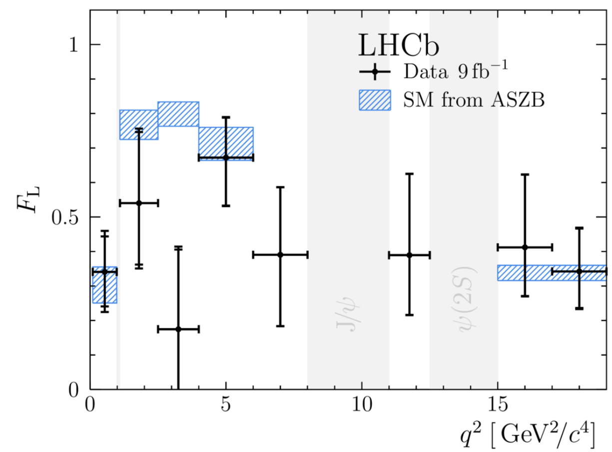
Coherent pattern

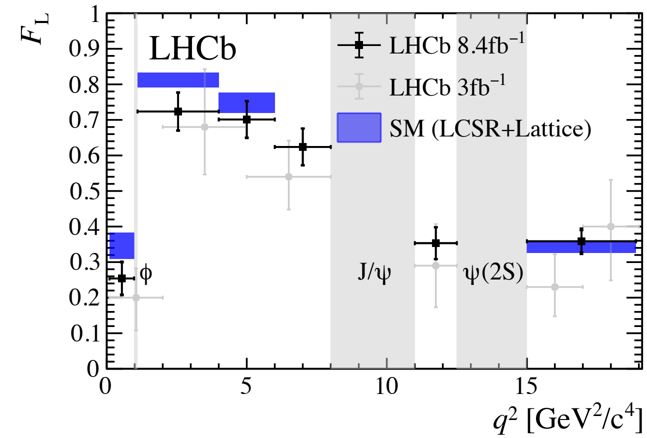
arXiv:2003.04831: $B^0 \to K^{*0}\mu^+\mu^-$

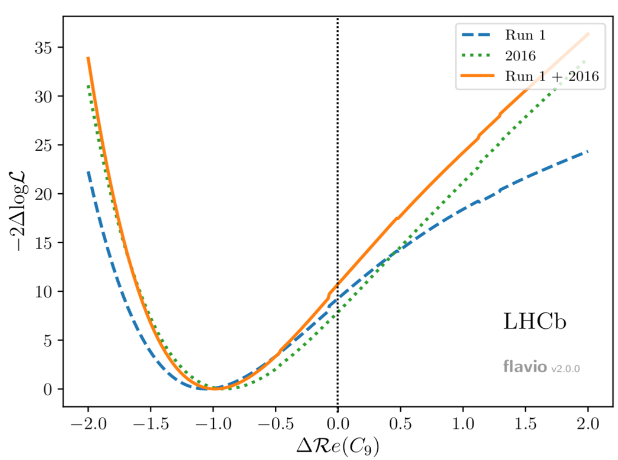
arXiv:2012.13241: $B^+ \to K^{*+}\mu^+\mu^-$

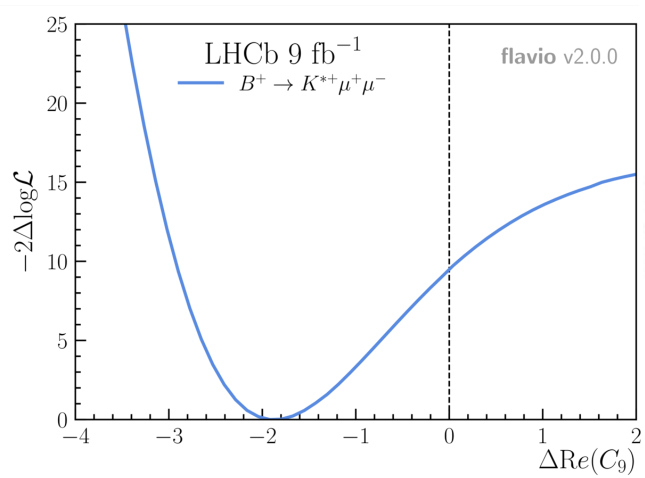
arXiv:2107.13428: $B^0_s \to \phi\mu^+\mu^-$

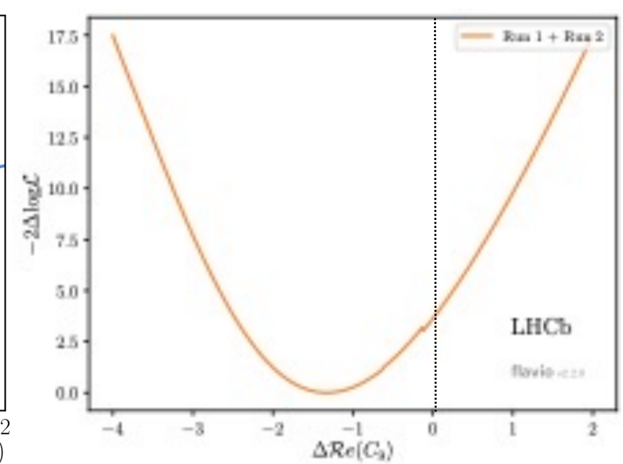


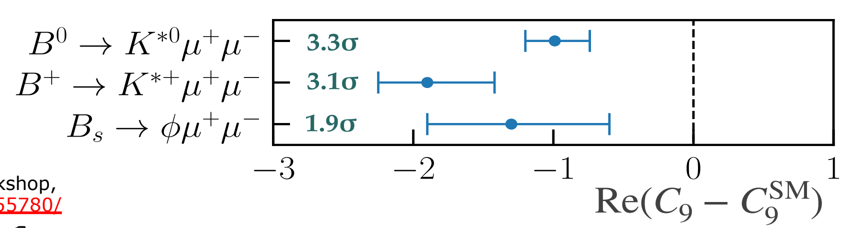










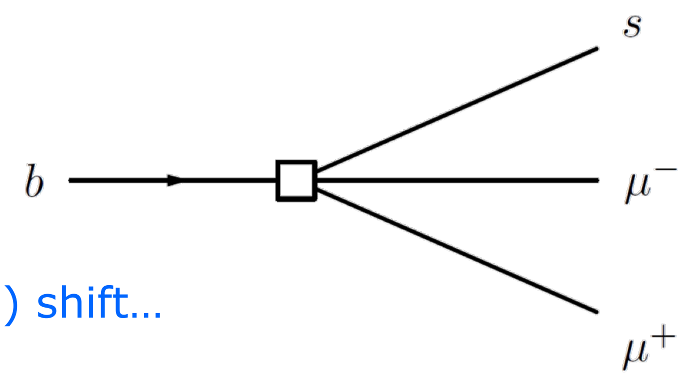


From: Martino Borsato, Flavour Anomaly Workshop, 20 Oct 2021, https://indico.cern.ch/event/1055780/

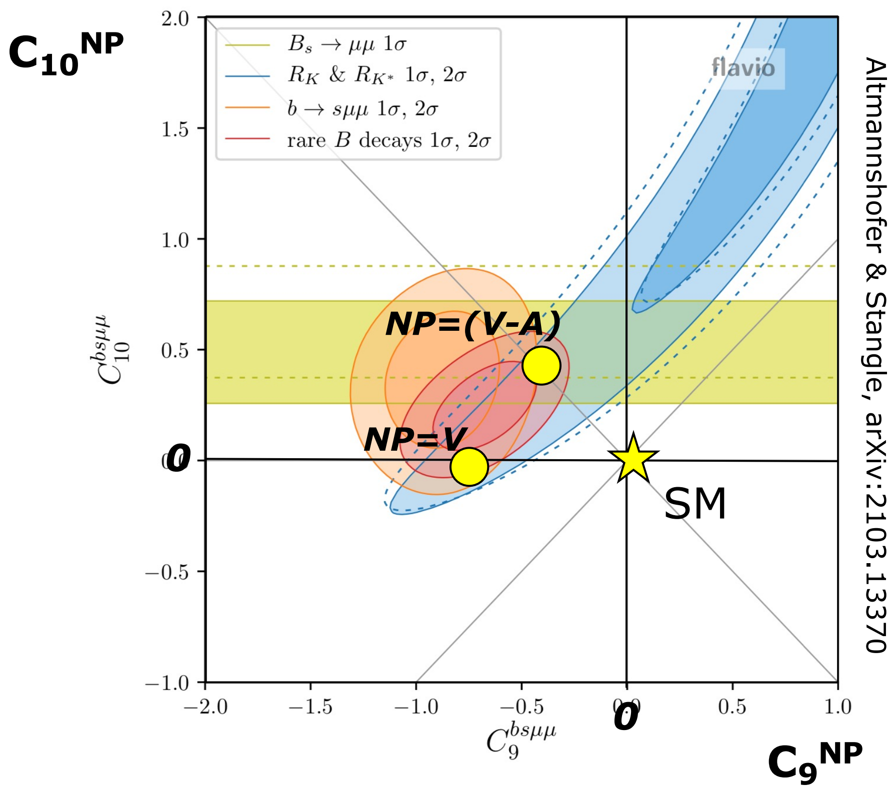
Coherent pattern

Model independent fits:

- C_9^{NP} deviates from 0 by >4σ
- Independent fits by many groups favour:
  - $C_9^{NP}=-1$ or
  - $C_9^{NP}=-C_{10}^{NP}$



➢*All* measurements (175) agree with a single (simple?) shift…



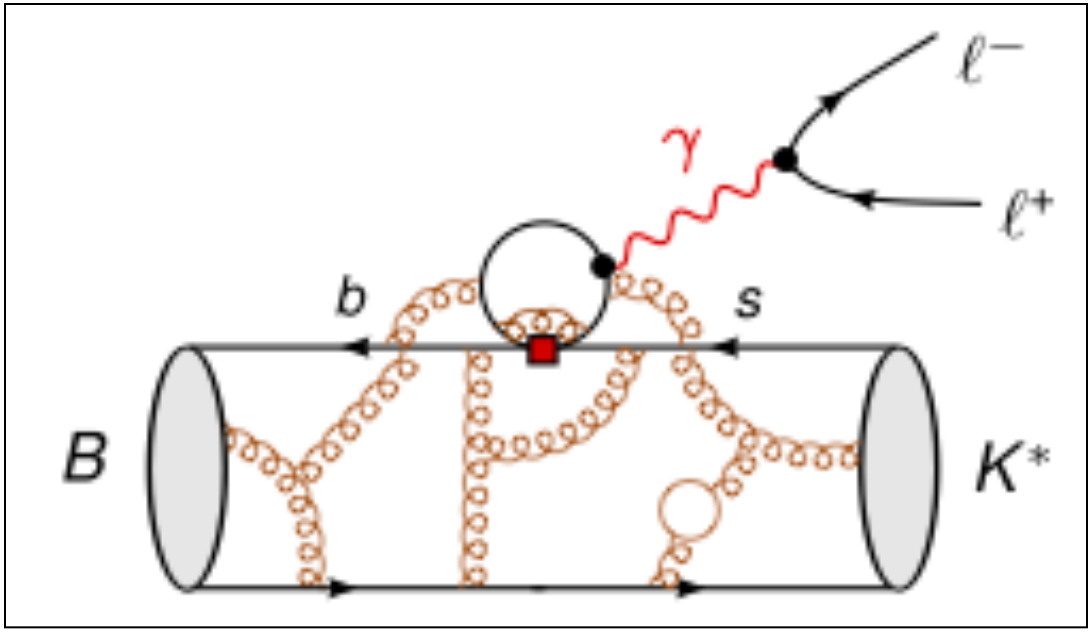
Wilson coefficient	all rare B decays best fit	pull
$C_9^{bs\mu\mu}$	$-0.82^{+0.14}_{-0.14}$	6.2σ
$C_{10}^{bs\mu\mu}$	$+0.56^{+0.12}_{-0.12}$	4.9σ
$C_9'^{bs\mu\mu}$	$-0.09^{+0.13}_{-0.13}$	0.7σ
$C_{10}'^{bs\mu\mu}$	$+0.01^{+0.10}_{-0.09}$	0.1σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$-0.06^{+0.11}_{-0.11}$	0.5σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.43^{+0.07}_{-0.07}$	6.2σ

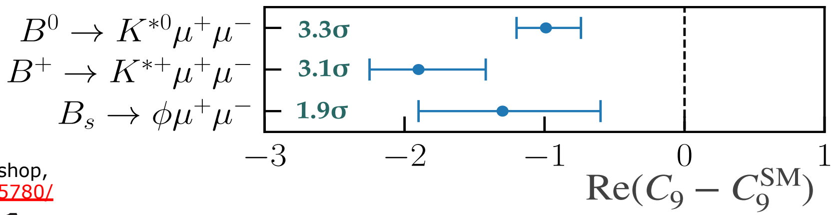
Similar improvement of fit for both scenario's

NB: p-value SM hypothesis ~0.5%

Coherent pattern

- Charm loop effects could also cause a shift in C_9



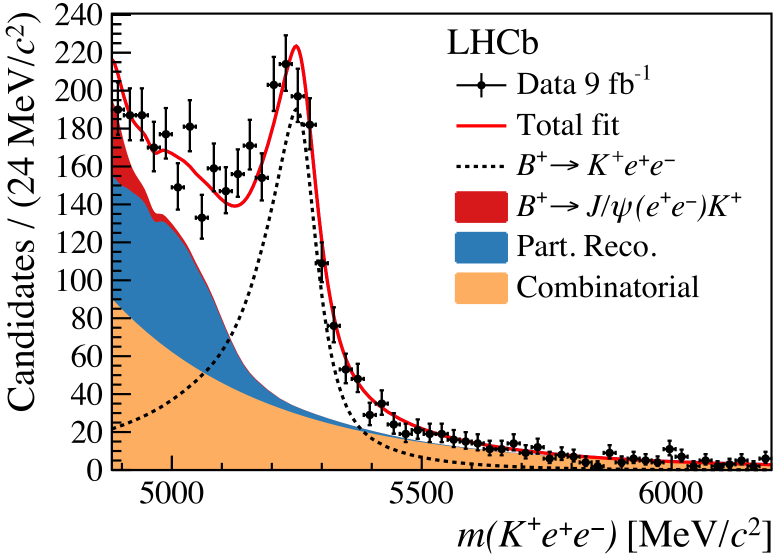


From: Martino Borsato, Flavour Anomaly Workshop, 20 Oct 2021, https://indico.cern.ch/event/1055780/

Ratio of decay rates

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+ \mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+ e^-))}$$

- Theoretically "clean"
- Experimentally
  - Signal yields
  - Backgrounds
  - Electron reconstruction
  - Efficiencies cancel in ratio
  - Belle II: good electron reconstruction
  - LHCb: large B sample



Ratio of decay rates

Kee | **Kμμ**

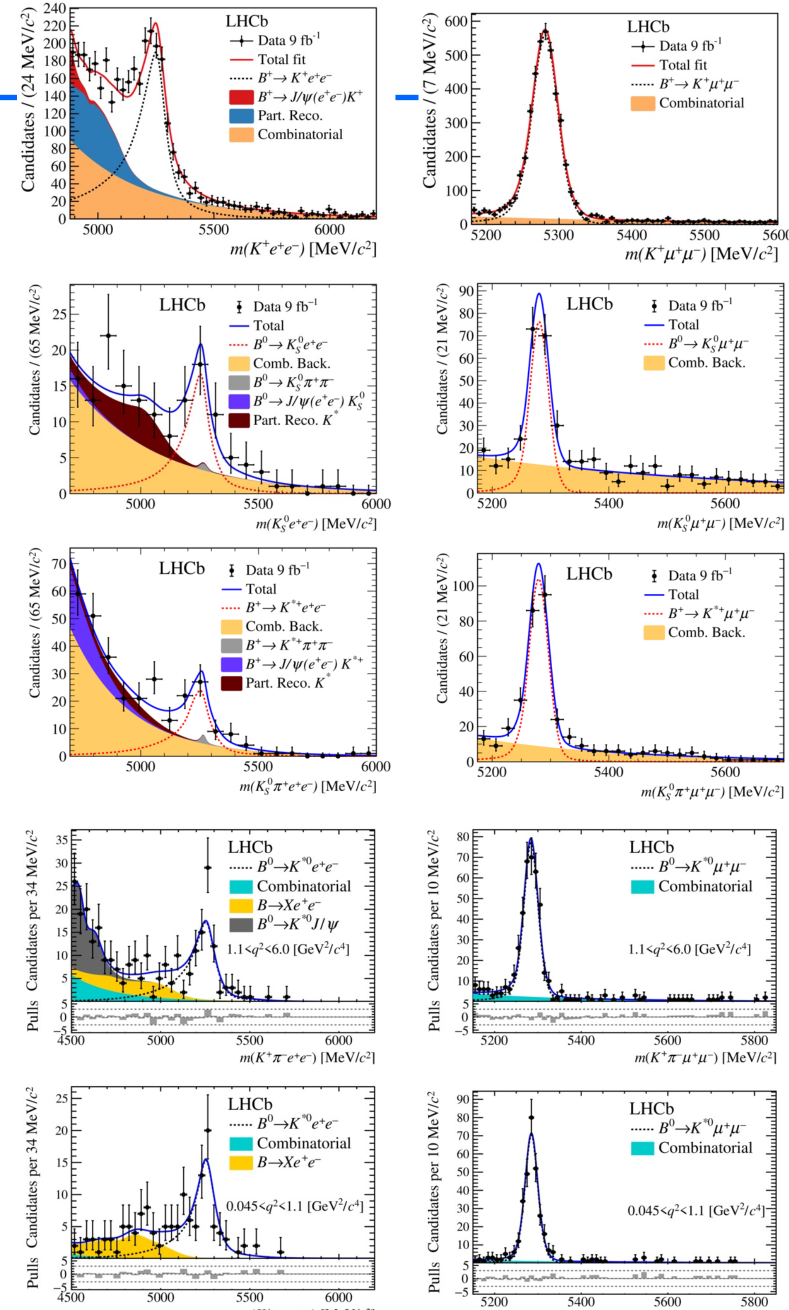
$B^+ \to K^+\mu^+\mu^-$

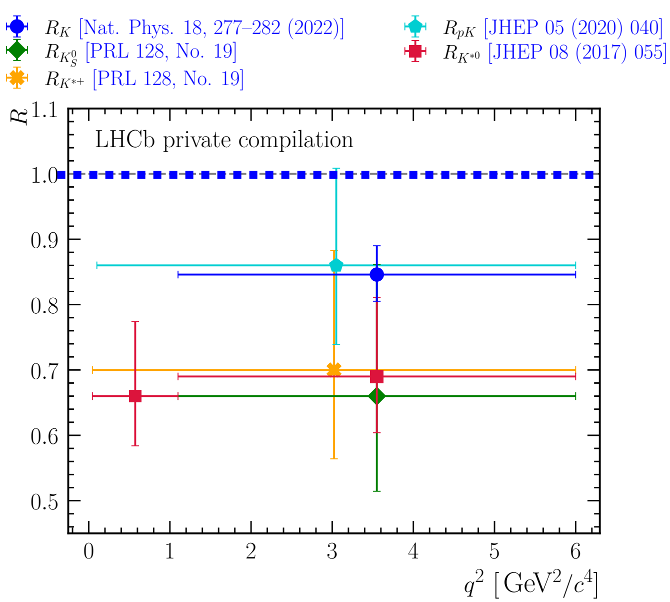
$B^0 \to K_S^0\mu^+\mu^-$

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

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

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





Analyses – where are we?

Analysis	Run 1	Run 2	
	2011-2012	2015-2016	2017-2018
$B_{(s)} \to \mu\mu$	✔	✔	✔
$B^0 \to K^{0*}\mu\mu$ (ang)	✔	✔	
$B^+_{/(s)} \to K^{*+}/\phi\mu\mu$ (ang)	✔	✔	✔
R_K	✔	✔	✔
R_{K*} (R_X)	✔		
R_{pK}	✔	✔	
$R_{KS,RK*+}$	✔	✔	✔
$R_{\phi,K\pi\pi,\pi,\Lambda}$			
R(D*)	✔		
R(D)	✔		
$R(\Lambda_c)$	✔	✔	✔
+ many others	…	…	…
…	…	…	…

- We are working on a unified analysis of $B^+ \to K^+ l^+ l^-$ and $B^0 \to K^{*0} l^+ l^-$ decay ratios with electron and muon final states
  - Final Run-1 and 2 results on these key b→sll LFNU observables
  - Important checks in the absence of competitive results from other experiments
- Will lead to a deeper understanding of our LFNU measurements and will be reflected in our final results

Outline

- CKM elements
  - $\sin 2\beta$
  - γ
  - Δm_s
  - V_{ub}
- Anomalies
  - $b \to c\, \tau\nu$
  - $b \to s\, \ell^+ \ell^-$
- Prospects
  - Upgrade
  - Upgrade II

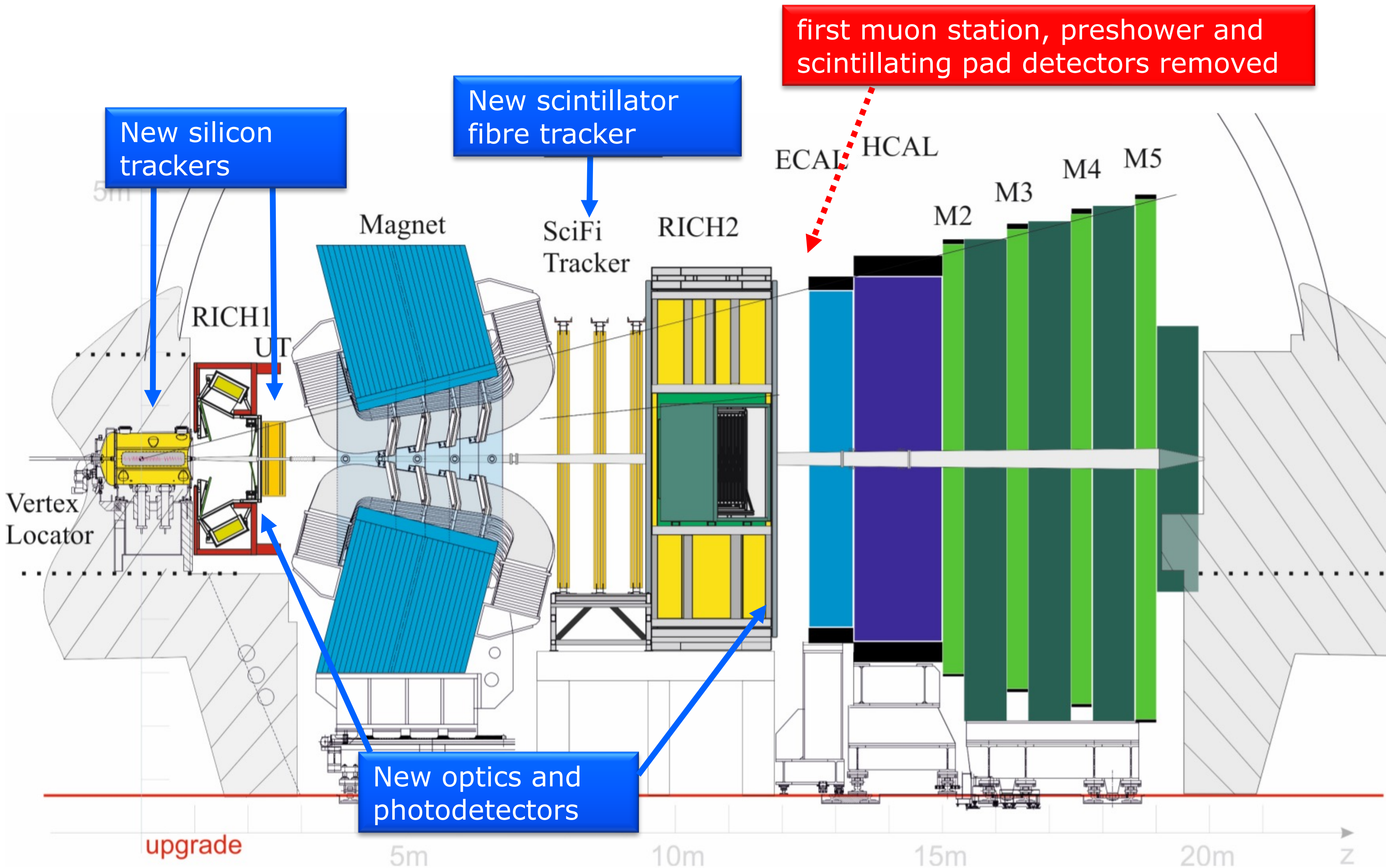
Future Plans

2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035+
			Run III					Run IV						Run V
LS2						**LS3**						**LS4**		
LHCb 40 MHz **UPGRADE I**			$L = 2 \times 10^{33}$		**LHCb** **Consolidate**				$L = 2 \times 10^{33}$ $50\ fb^{-1}$			**LHCb** **UPGRADE II**		$L=1\text{-}2 \times 10^{34}$ $300\ fb^{-1}$
ATLAS **Phase I Upgr**			$L = 2 \times 10^{34}$		**ATLAS** **Phase II UPGRADE**				**HL-LHC** $L = 5 \times 10^{34}$					**HL-LHC** $L = 5 \times 10^{34}$
CMS **Phase I Upgr**			$300\ fb^{-1}$		**CMS** **Phase II UPGRADE**									$3000\ fb^{-1}$
Belle II		$L = 3 \times 10^{35}$				$7\ ab^{-1}$					$L = 6 \times 10^{35}$		$50\ ab^{-1}$	

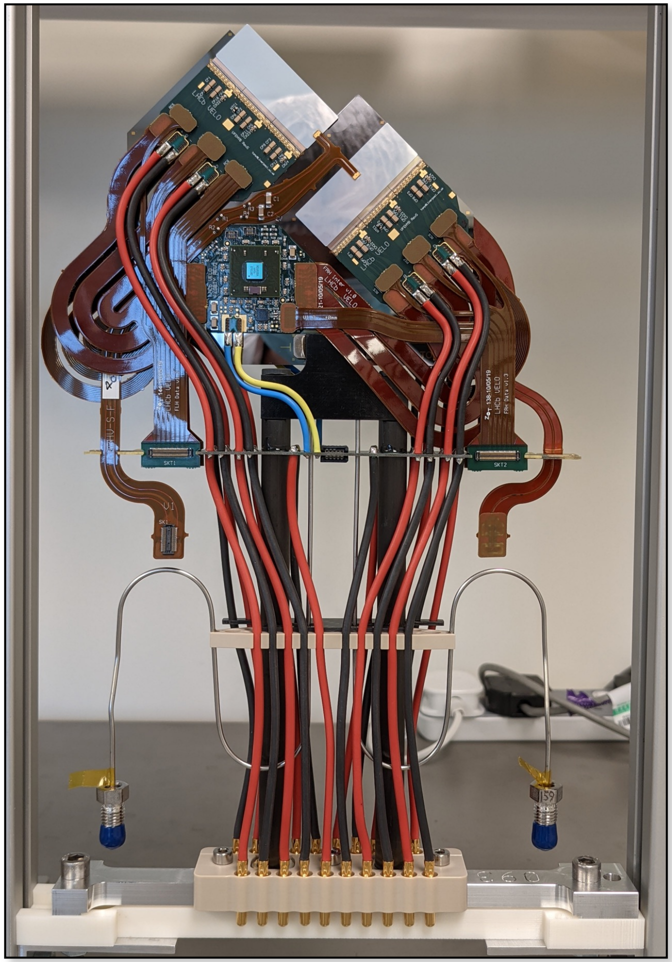
LHC schedule:
https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

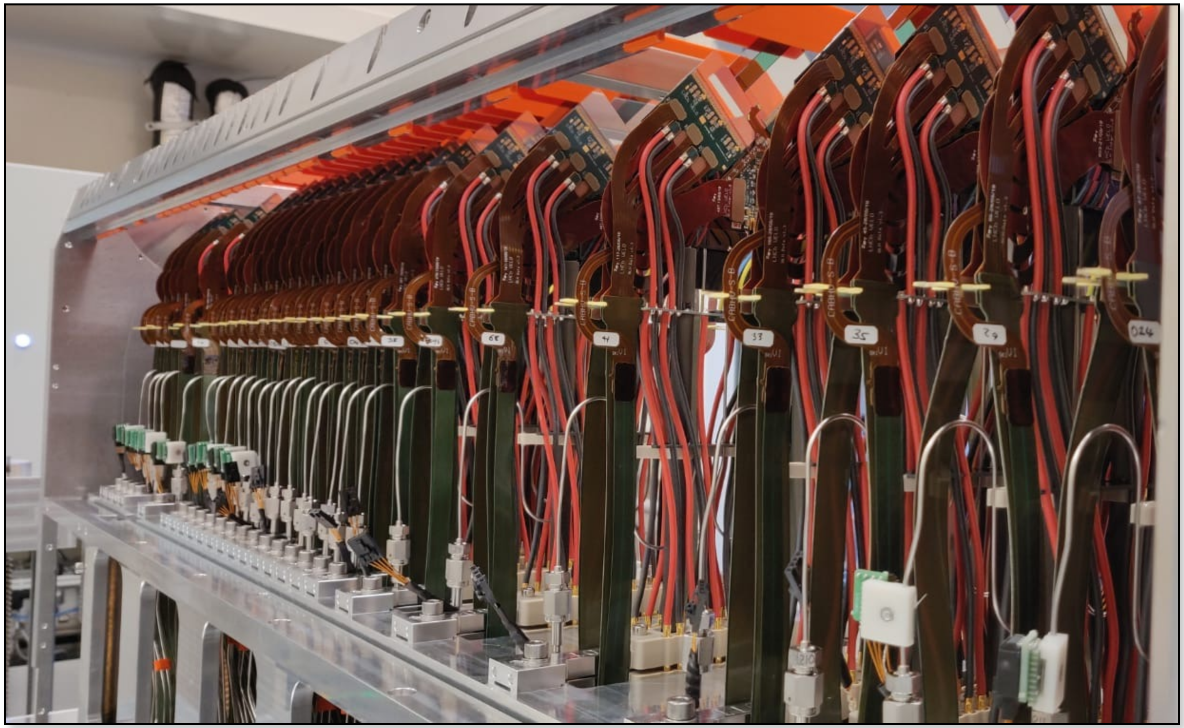
You are here!

Where do we go from here?

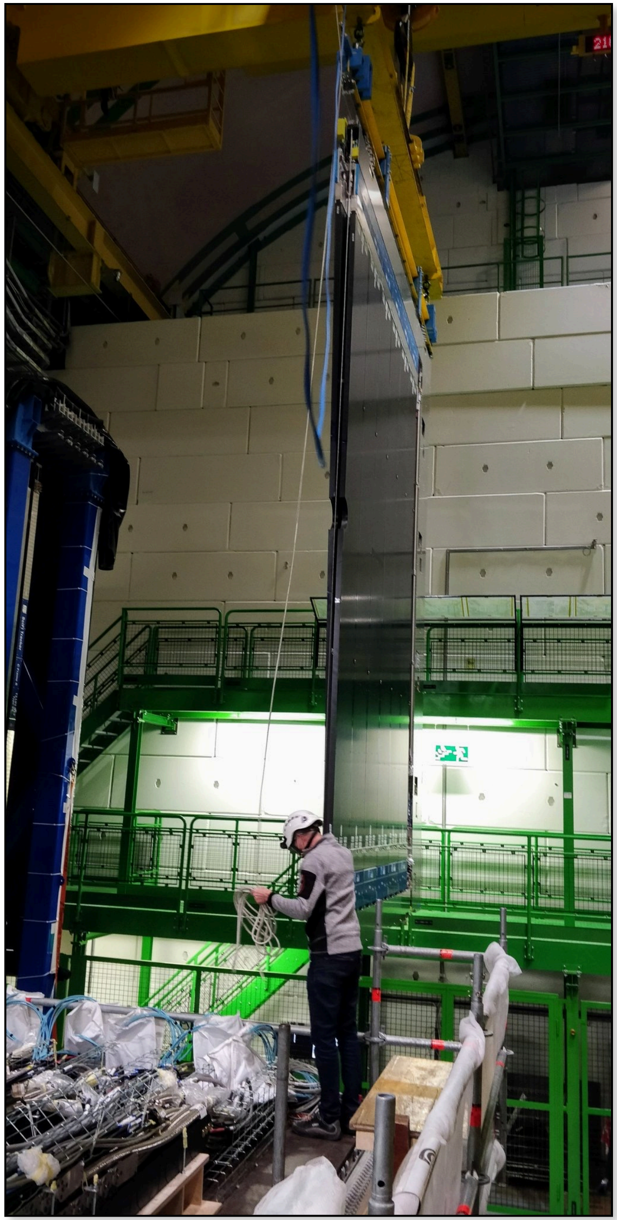


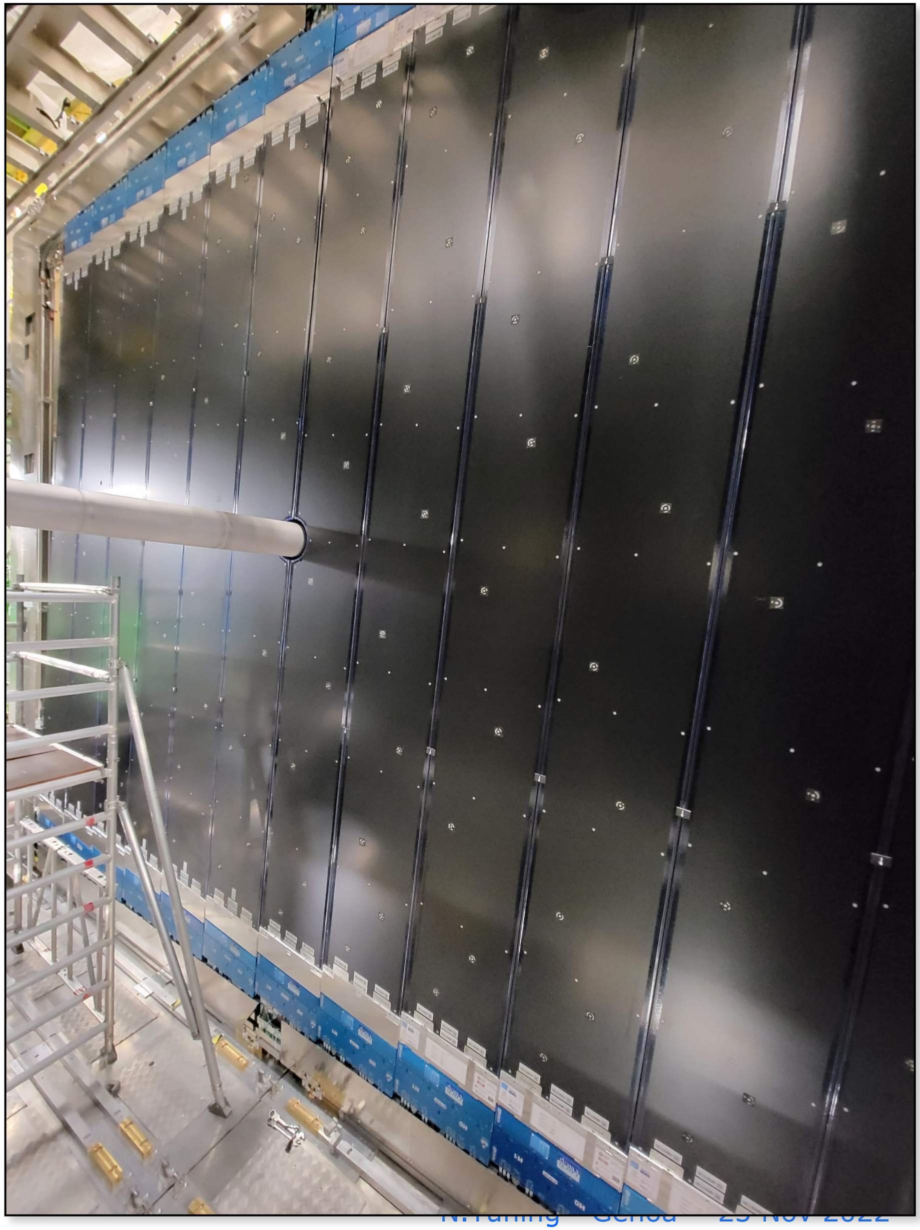
VELO



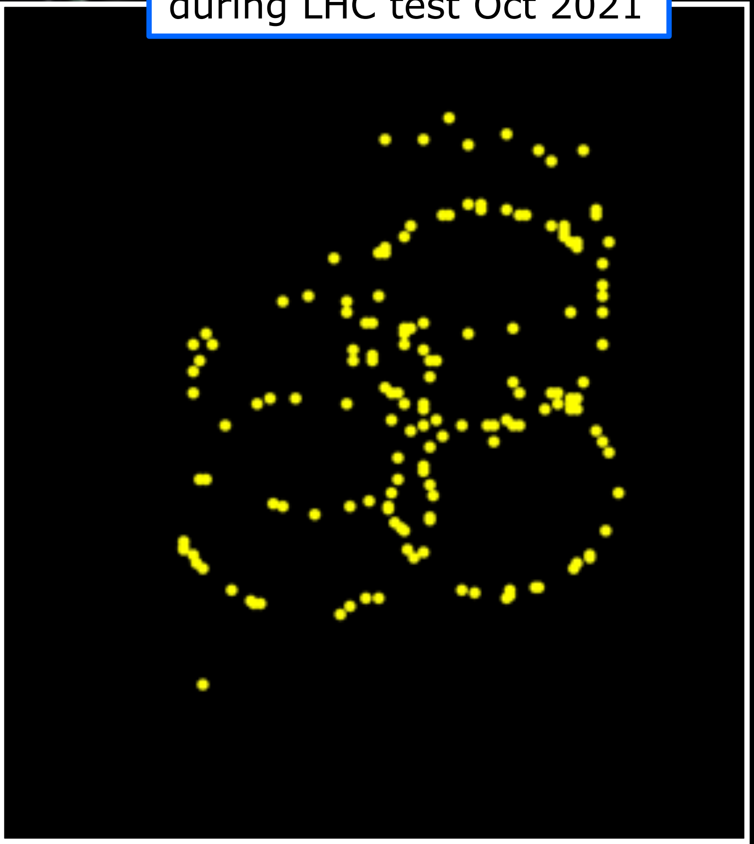


Tracker





Ring Imaging Cherenkov

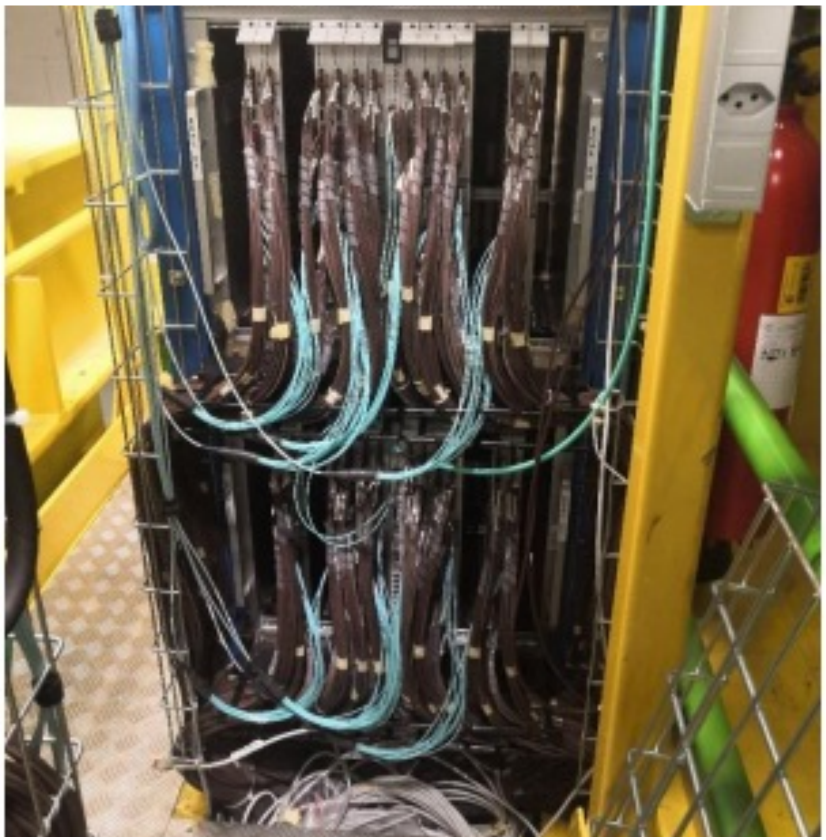


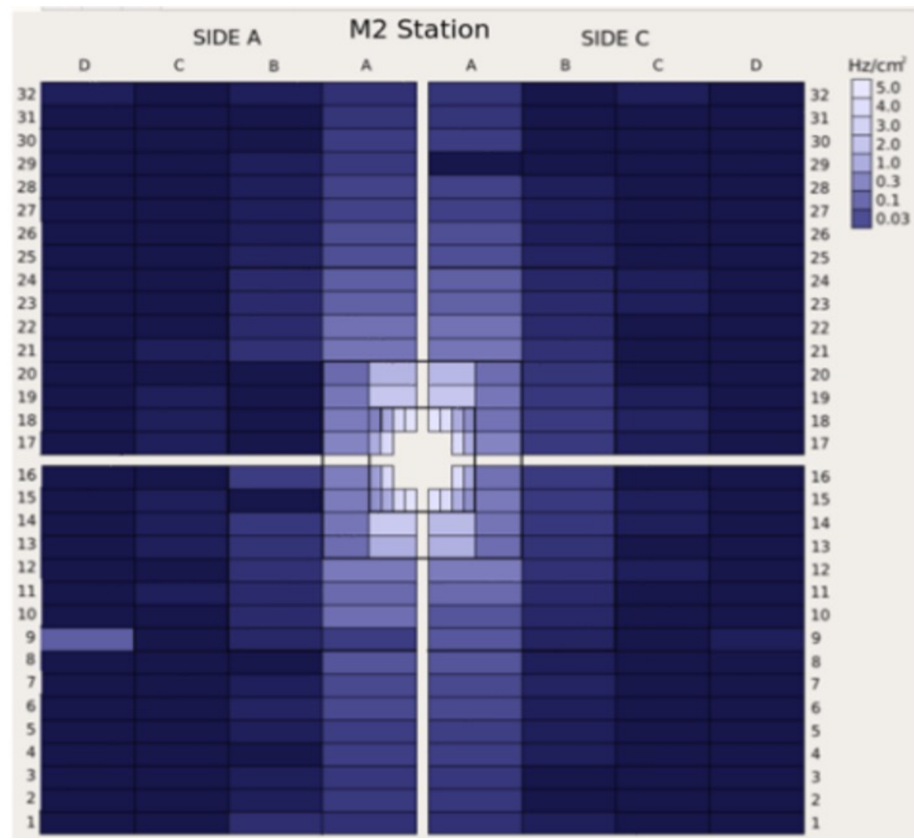
First rings in RICH2 during LHC test Oct 2021

Calorimeter & Muon detector

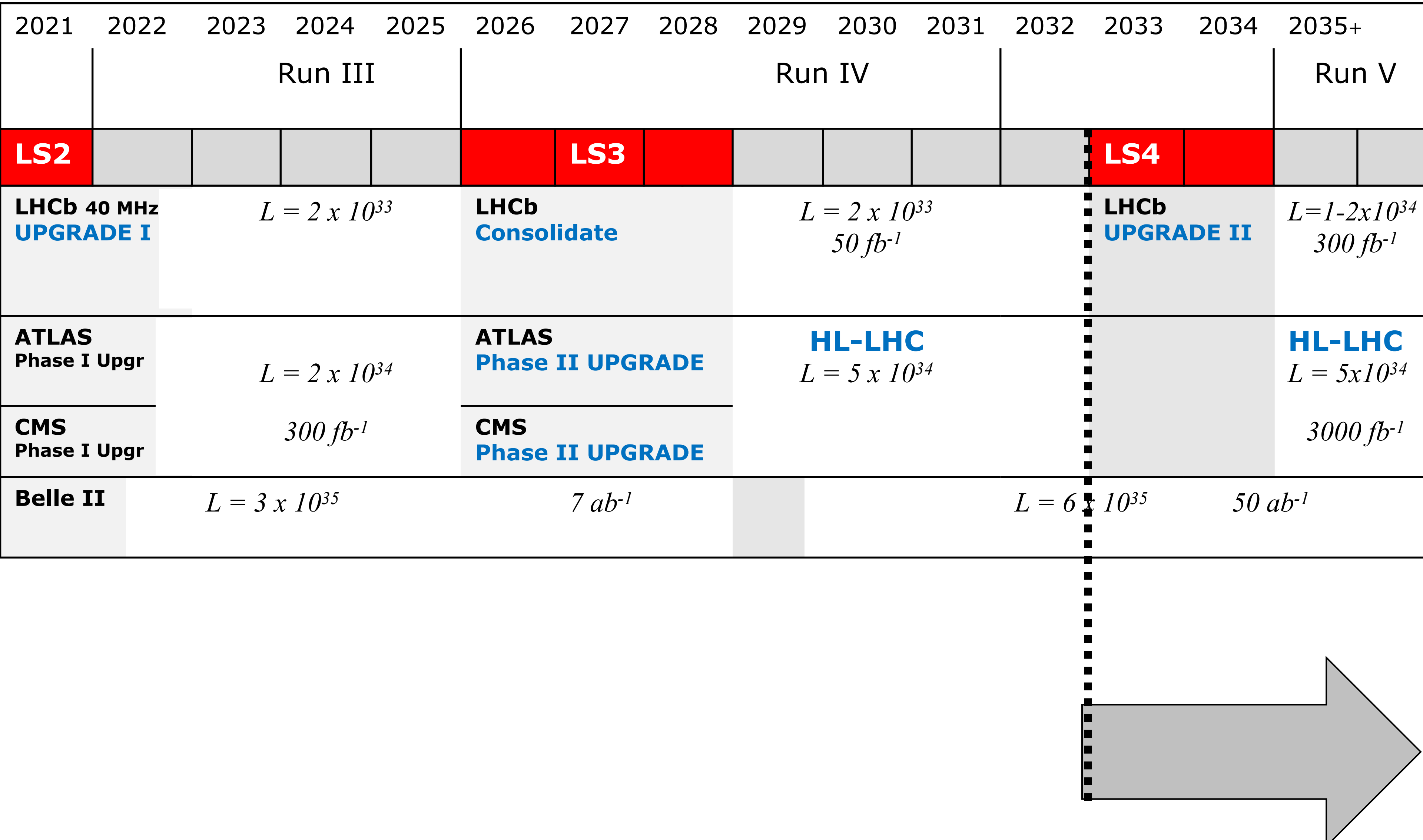
New CALO frontend and control boards

MUON Station 2 Hit map





… and beyond!


2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035+
Run III
Run IV
Run V
LS2
LS3
LS4
LHCb 40 MHz UPGRADE I
L = 2 x 10^33
LHCb Consolidate
L = 2 x 10^33 50 fb^-1
LHCb UPGRADE II
L=1-2x10^34 300 fb^-1
ATLAS Phase I Upgr
L = 2 x 10^34
ATLAS Phase II UPGRADE
HL-LHC L = 5 x 10^34
HL-LHC L = 5x10^34
CMS Phase I Upgr
300 fb^-1
CMS Phase II UPGRADE
3000 fb^-1
Belle II
L = 3 x 10^35
7 ab^-1
L = 6 x 10^35
50 ab^-1

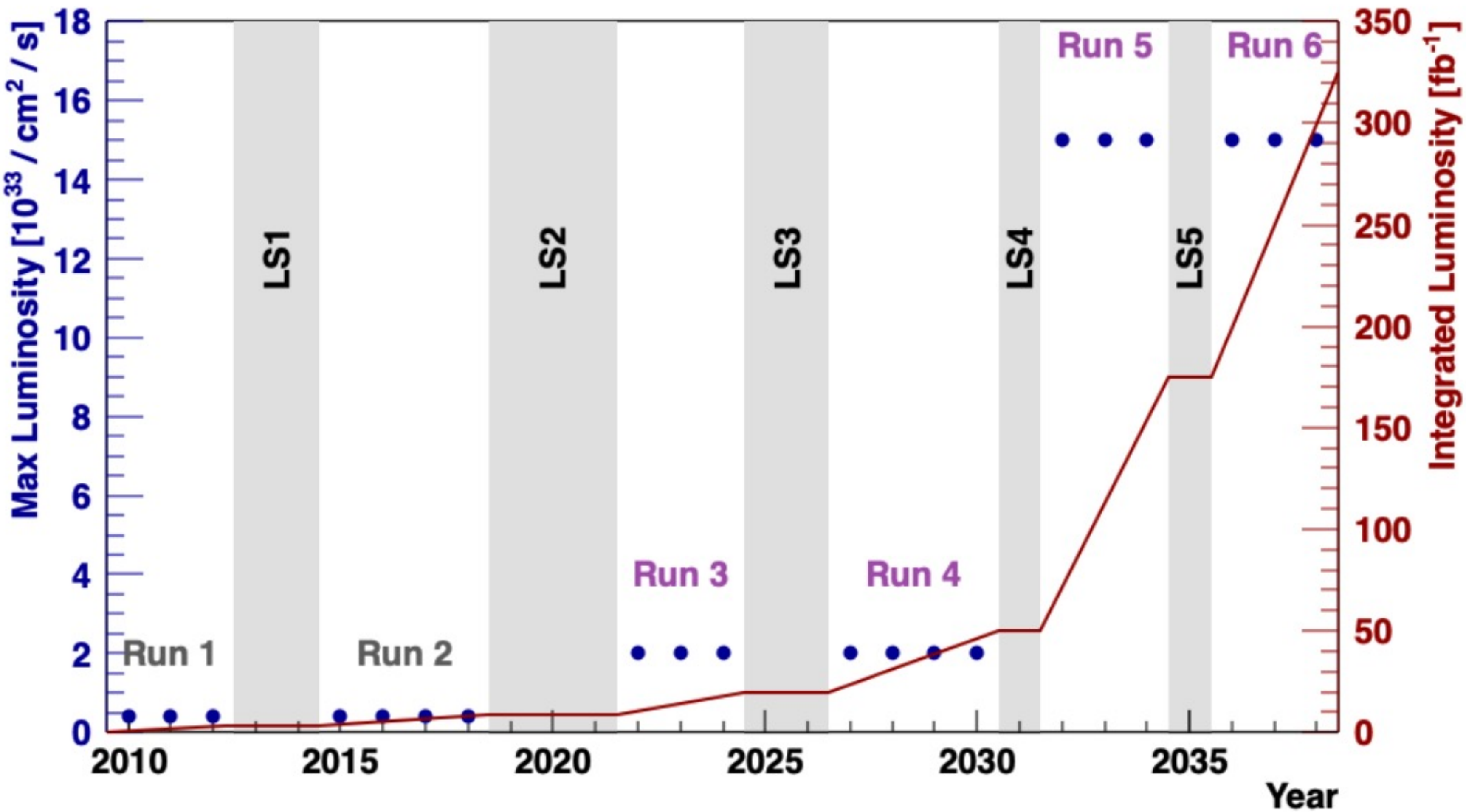
Planning for Upgrade II: many analyses stat. limited

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

LHCb, arXiv:1808.08865 ; CERN-LHCC-2018-027

Planning for Upgrade II

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



Planning for Upgrade II: Physics Reach

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

LHCb, arXiv:1808.08865 ; CERN-LHCC-2018-027

Planning for Upgrade II: Physics Reach

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9, 10]	1.5°	1°	0.35°
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$)	6%	[30]	3%	—	1%
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	71%	[40, 41]	34%	—	10%
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.10	[61]	0.031	0.021	0.008
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62, 64]	0.007	—	0.002

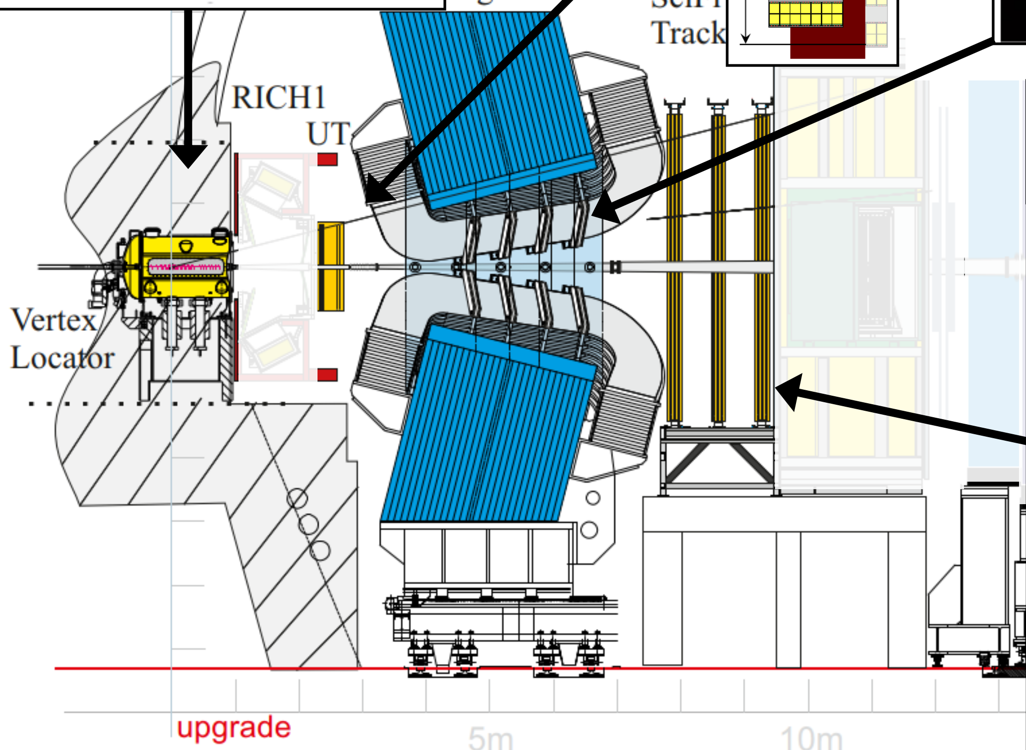
LHCb, arXiv:1808.08865 ; CERN-LHCC-2018-027

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

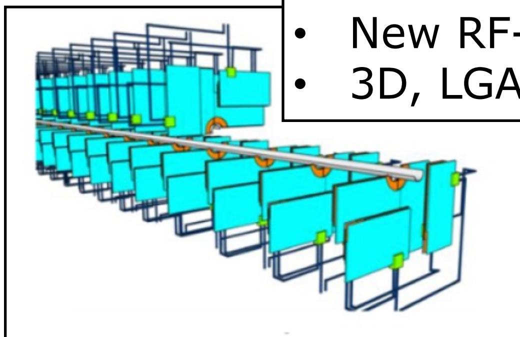
- LHCC and CERN Research Board (Sep 2019)
  - "The recommendation to prepare a framework TDR for the LHCb Upgrade-II was endorsed, noting that LHCb is expected to run throughout the HL-LHC era."
- European Strategy Update (Jun 2020)
  - "The flavour physics programme made possible with the proton collisions 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



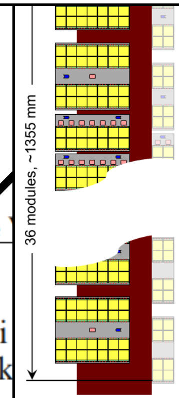
VELO pixel

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



UT pixel

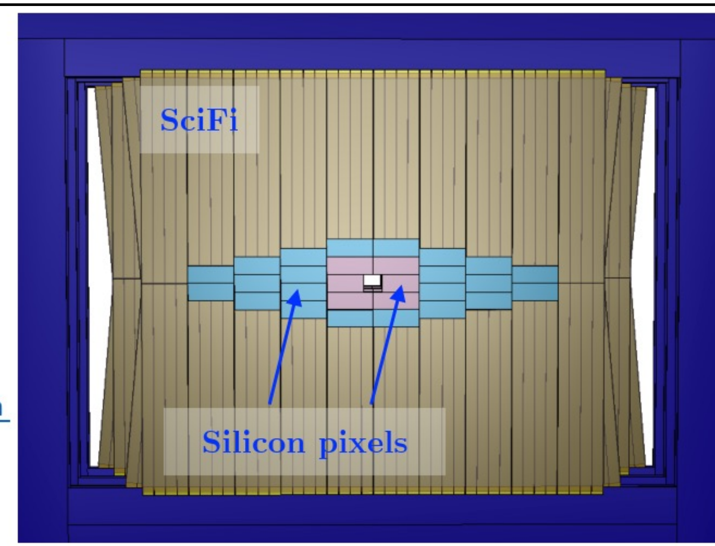
- MAPS, radiation tolerant



Magnet Station new

Mighty Tracker

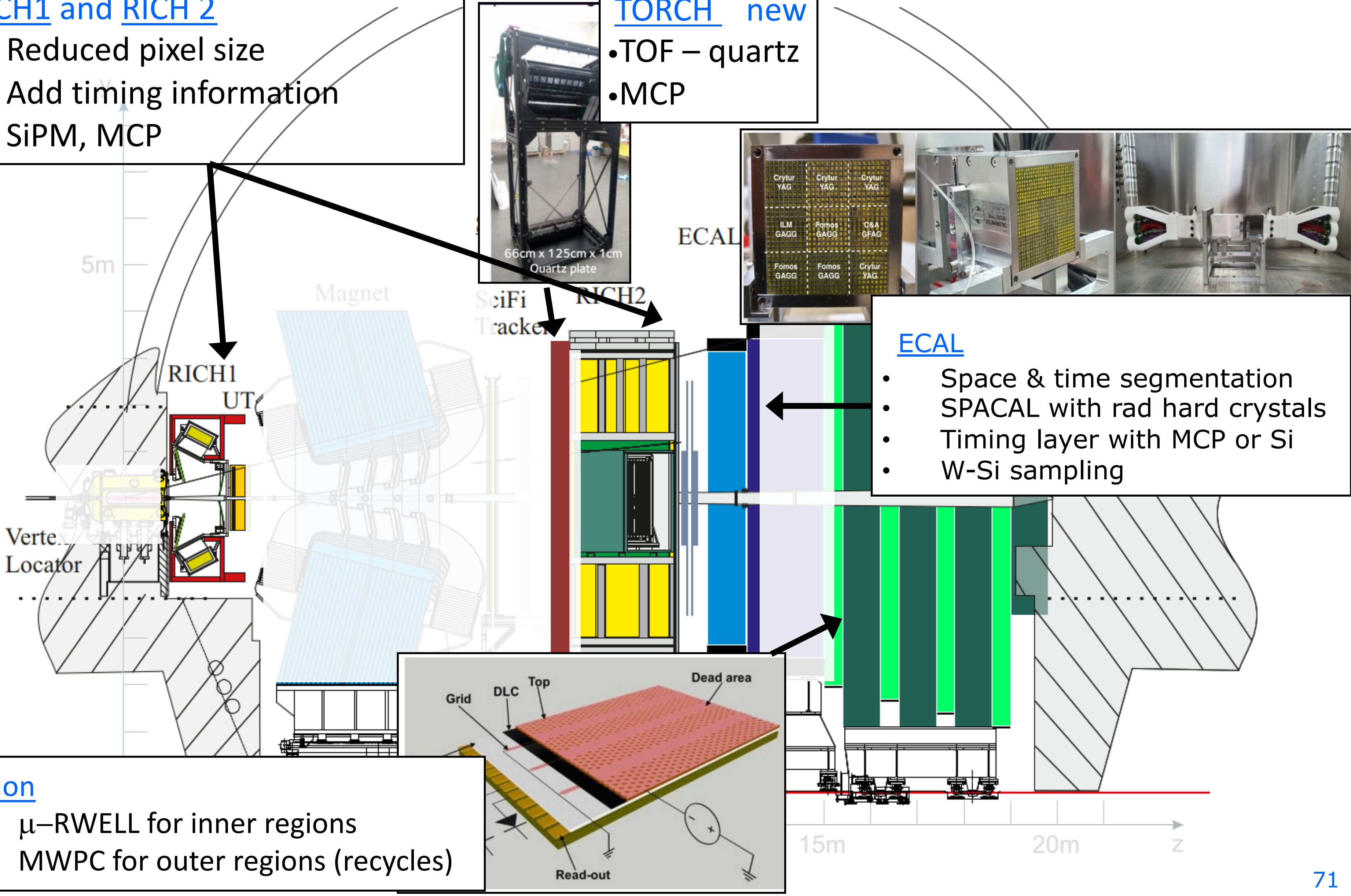
- MAPS pixel and Scintillating fibers



Planning for Upgrade II: PID detectors

RICH1 and RICH 2
- Reduced pixel size
- Add timing information
- SiPM, MCP

TORCH new
- TOF – quartz
- MCP

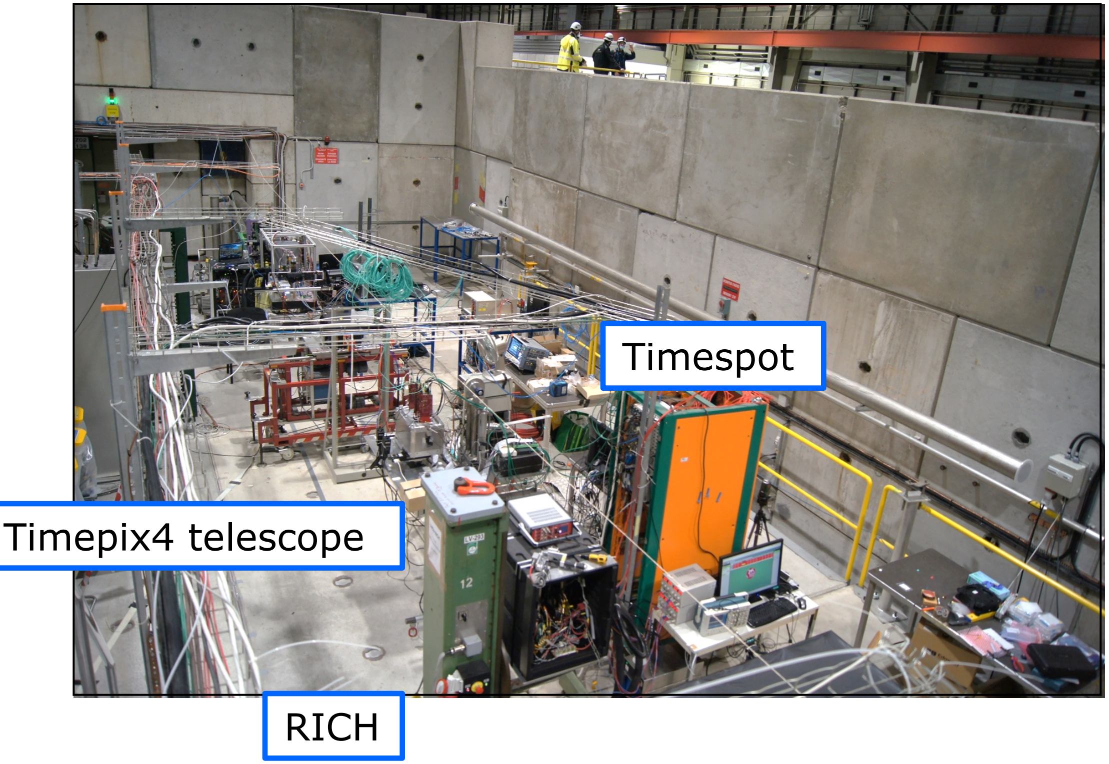


ECAL
- Space & time segmentation
- SPACAL with rad hard crystals
- Timing layer with MCP or Si
- W-Si sampling

Muon
- μ–RWELL for inner regions
- MWPC for outer regions (recycles)

Planning for Upgrade II: Testbeam

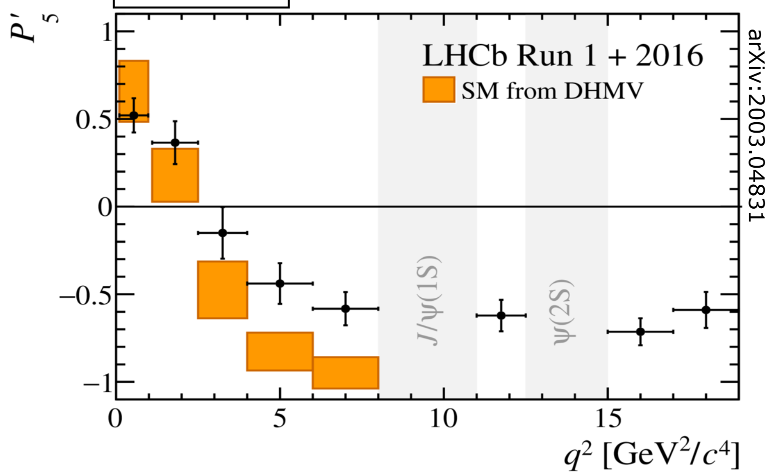
- Activities for RICH, VELO, ECAL, MUON
- Lots of opportunities for R&D in coming decade!



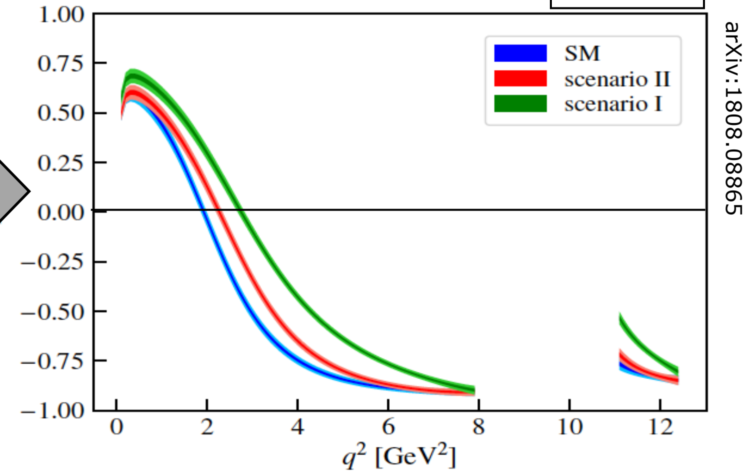
Conclusions

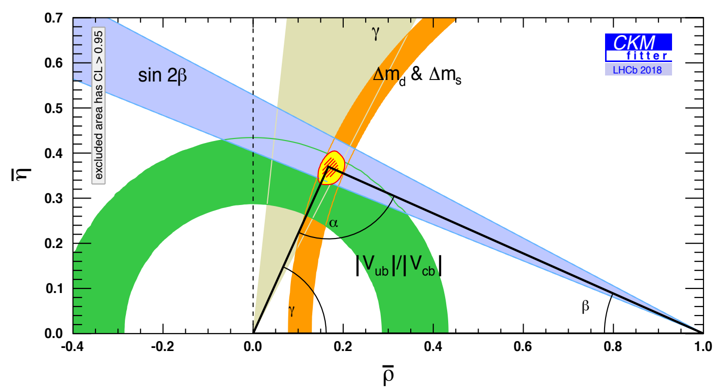
- Precision measurements to scrutinize the Standard Model
- Precision measurements reach very high mass scales
- Precision measurements are not yet precise enough
- Lots of opportunities to contribute to R&D

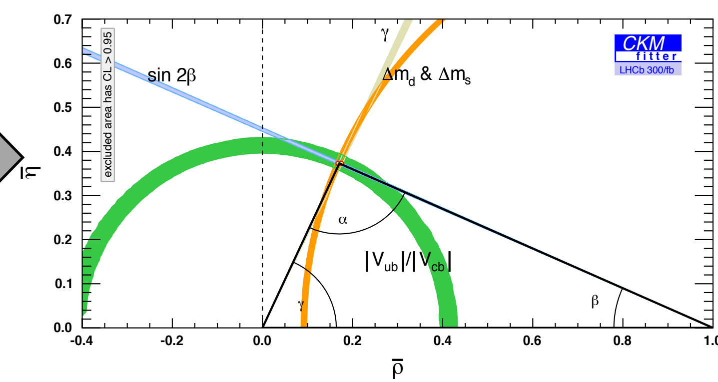
2018



2040

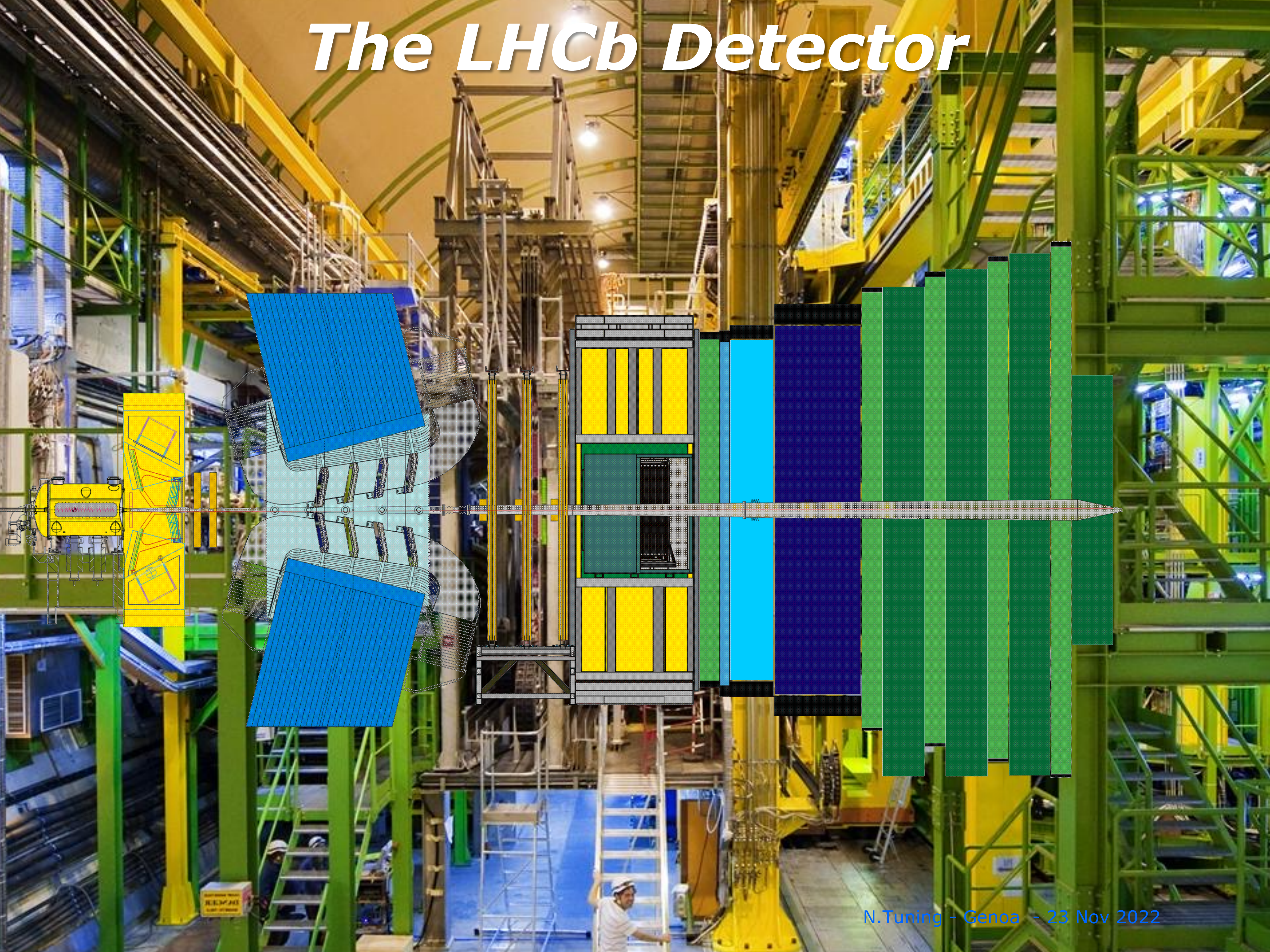




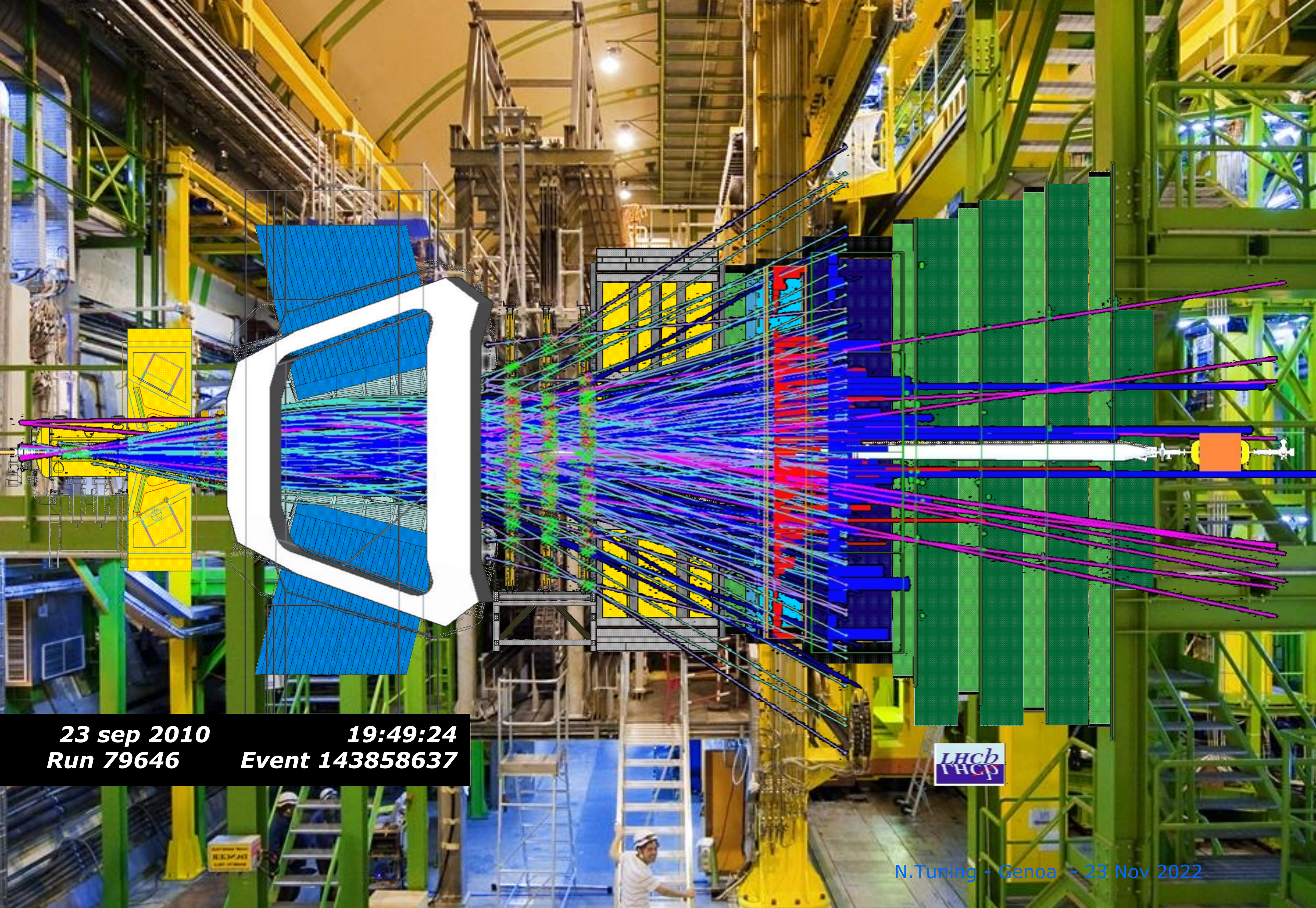


The LHCb Detector

The LHCb Detector

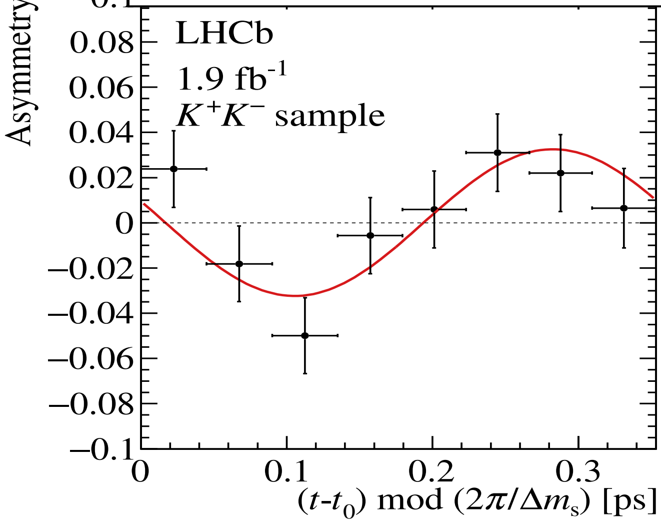


The LHCb Detector

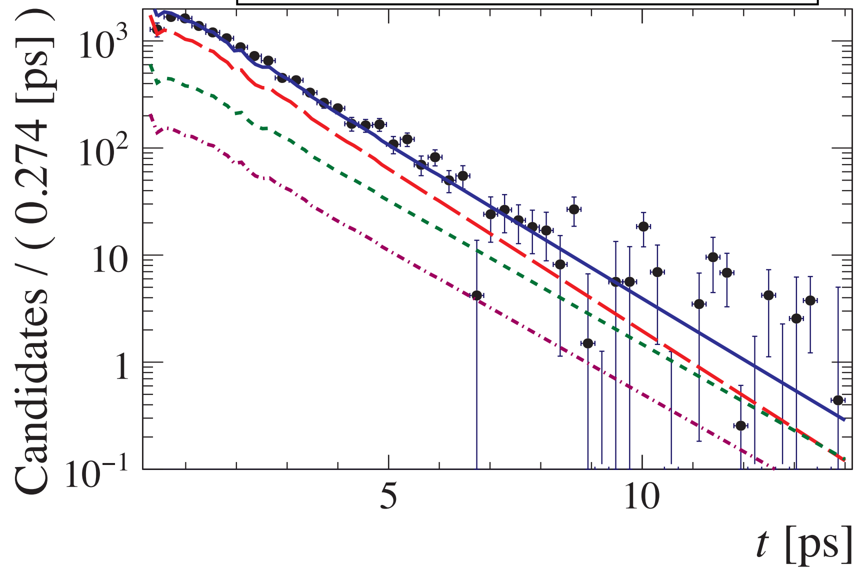


More results: CPV

arXiv:2012.05319: First TD CPV in B_s^0



arXiv:2105.14738 : φ_s with e^+e^-



arXiv:2012.12789: $A_{CP}(K^+\pi^0)$ & $K\pi$ puzzle