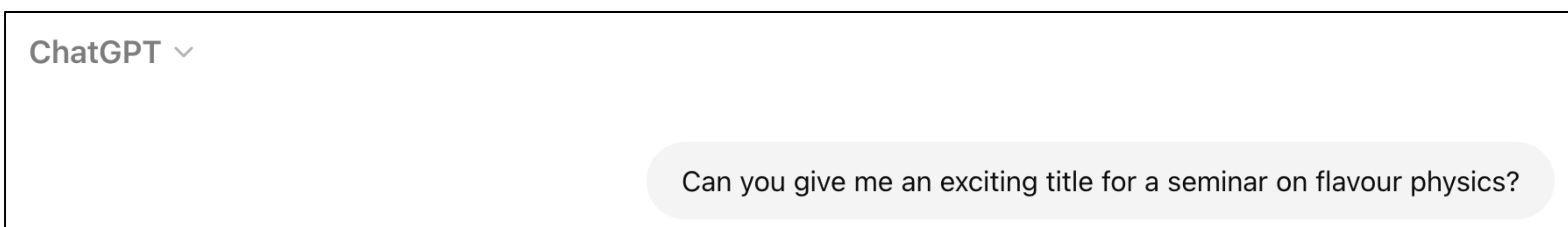
Exploring the Quantum Universe: Unveiling Mysteries with Flavour Physics*

2 Jul 2024 – Bari

Niels Tuning (Nikhef)

*courtesy chatGPT…



Historical record of indirect discoveries

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

Weak Interactions with Lepton-Hadron Symmetry*

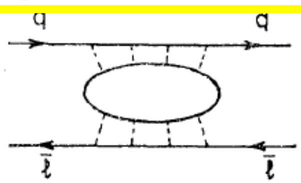
S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

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-Milis 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

"Discovery" of charm

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

"Discovery" of beauty

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

DESY 87-029
April 1987

OBSERVATION OF B^0-$\bar{B}^0$ 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-$\bar{B}^0$ mixing has been observed and is substantial.

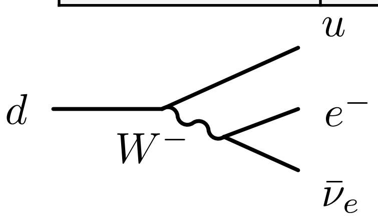
Parameters	Comments
$r > 0.09$ 90%CL	This experiment
$x > 0.44$	This experiment
$B^{\frac{1}{2}} f_B \approx f_\pi < 160$ MeV	B meson (≈ pion) decay constant
$m_b < 5$GeV$/c^2$	b-quark mass
$\tau_b < 1.4 \cdot 10^{-12}$s	B meson lifetime
$\lvert V_{td}\rvert < 0.018$	Kobayashi-Maskawa matrix element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

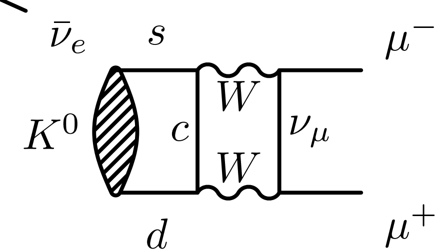
ARGUS Coll.
Phys.Lett.B192 (1987) 245

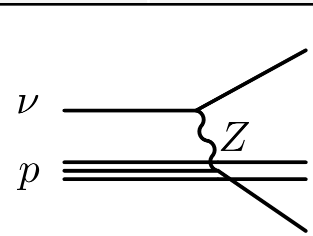
"Discovery" of top

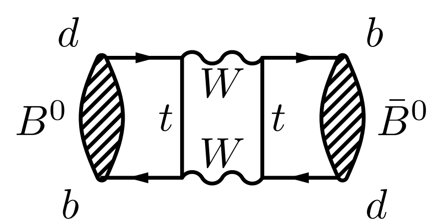
Historical record of indirect discoveries

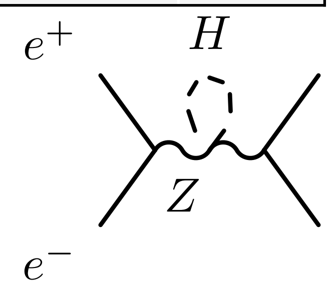
Particle	Indirect			Direct		
ν	β decay	Fermi	1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay	Fermi	1932	*W→eν*	UA1, UA2	1983
c	*K⁰→μμ*	GIM	1970	*J/ψ*	Richter, Ting	1974
b	CPV *K⁰→ππ*	CKM, 3rd gen	1964/72	*Υ*	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z \to e^+e^-$	UA1	1983
t	B mixing	ARGUS	1987	*t→Wb*	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	*H→4μ/γγ*	CMS, ATLAS	2012
?	**What's next ?**		?			?











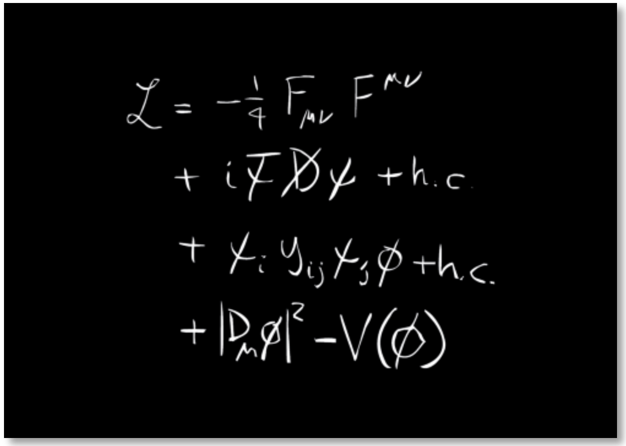
Outline

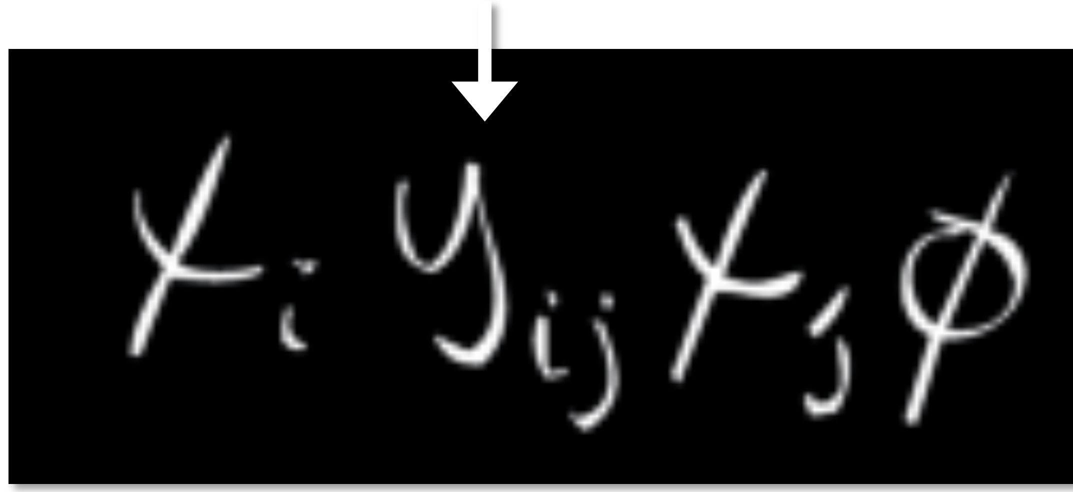
- CKM elements
  - $\sin 2\beta$
  - γ
  - Δm_s
  - V_{ub}
- Anomalies
  - $b \to c\ \tau\nu$
  - $b \to s\ \ell^+ \ell^-$
- Hadron physics
  - Heavy ion programme
  - Spectroscopy

To the backup slides...

- Prospects
  - Upgrade II

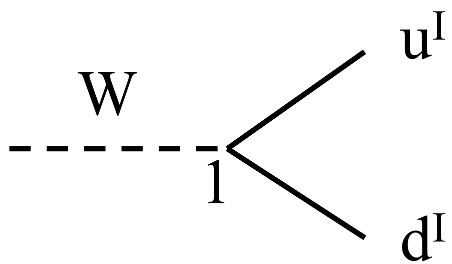
CKM at the heart of the SM





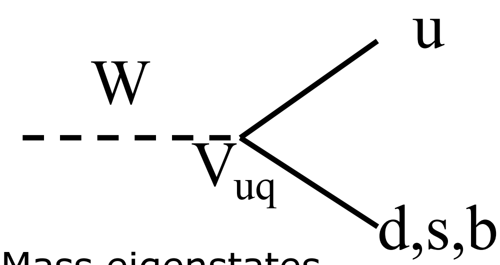
(CKM: a quick reminder…)

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



Weak eigenstates

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

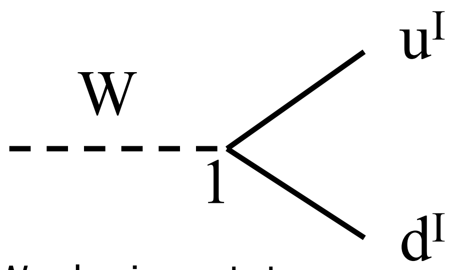


Mass eigenstates

i.e. diagonalize:

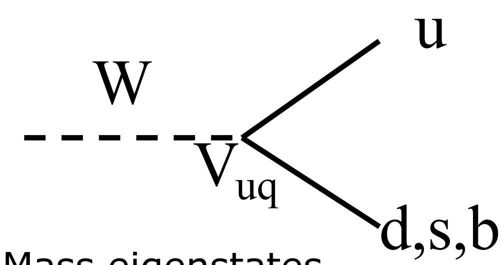
(CKM: a quick reminder…)

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

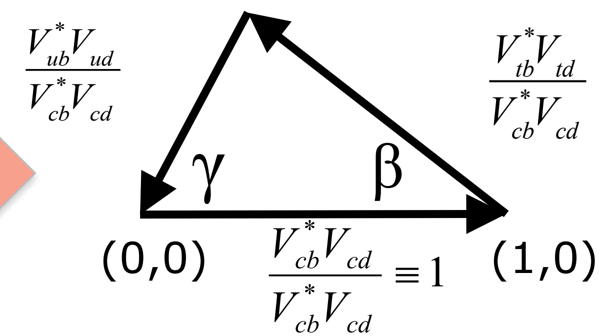
2) Matrix has complex phases:

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

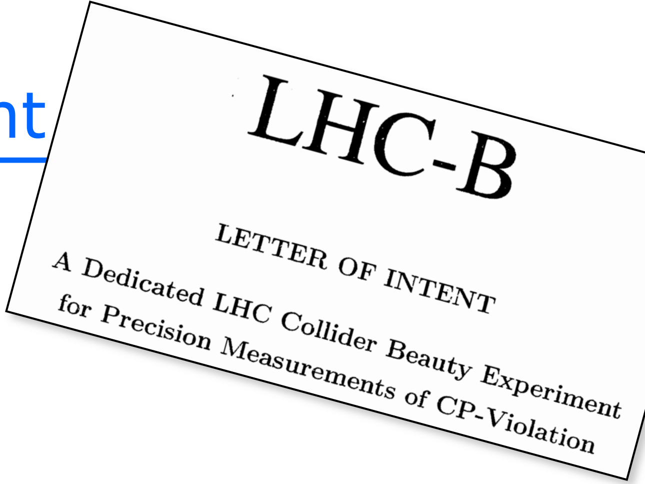
3) Matrix is unitary:

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

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



CKM: (1995) LHCb Letter-of-Intent



LHC-B

LETTER OF INTENT

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

- LHC-B Letter-of-Intent 1995

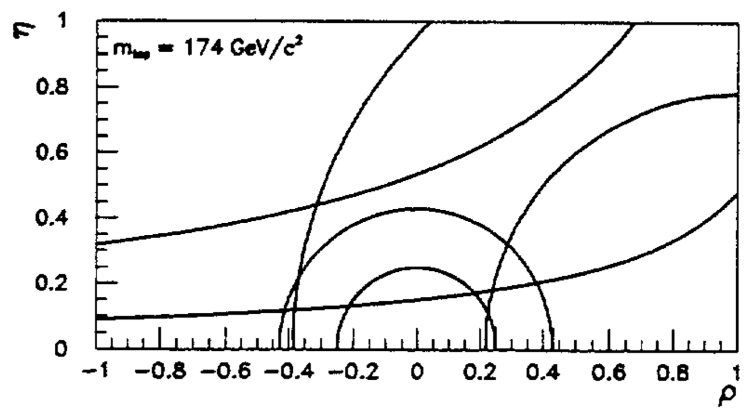


Figure 2.1: Limits on the CKM parameters (1σ) ρ and η for m_t = 174 GeV. The annular region cen-

CKM: (1995) LHCb Letter-of-Intent

- LHC-B Letter-of-Intent 1995

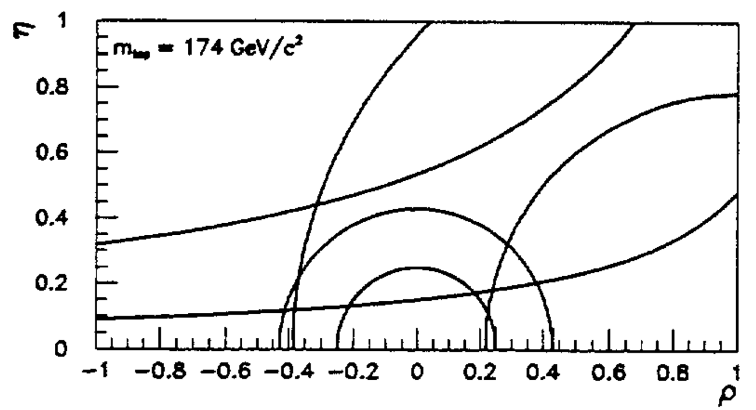


Figure 2.1: Limits on the CKM parameters (1σ) ρ and η for m_t = 174 GeV. The annular region cen-

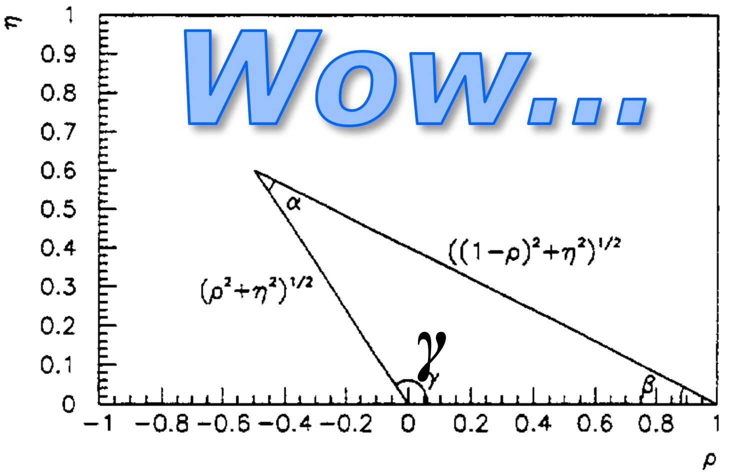
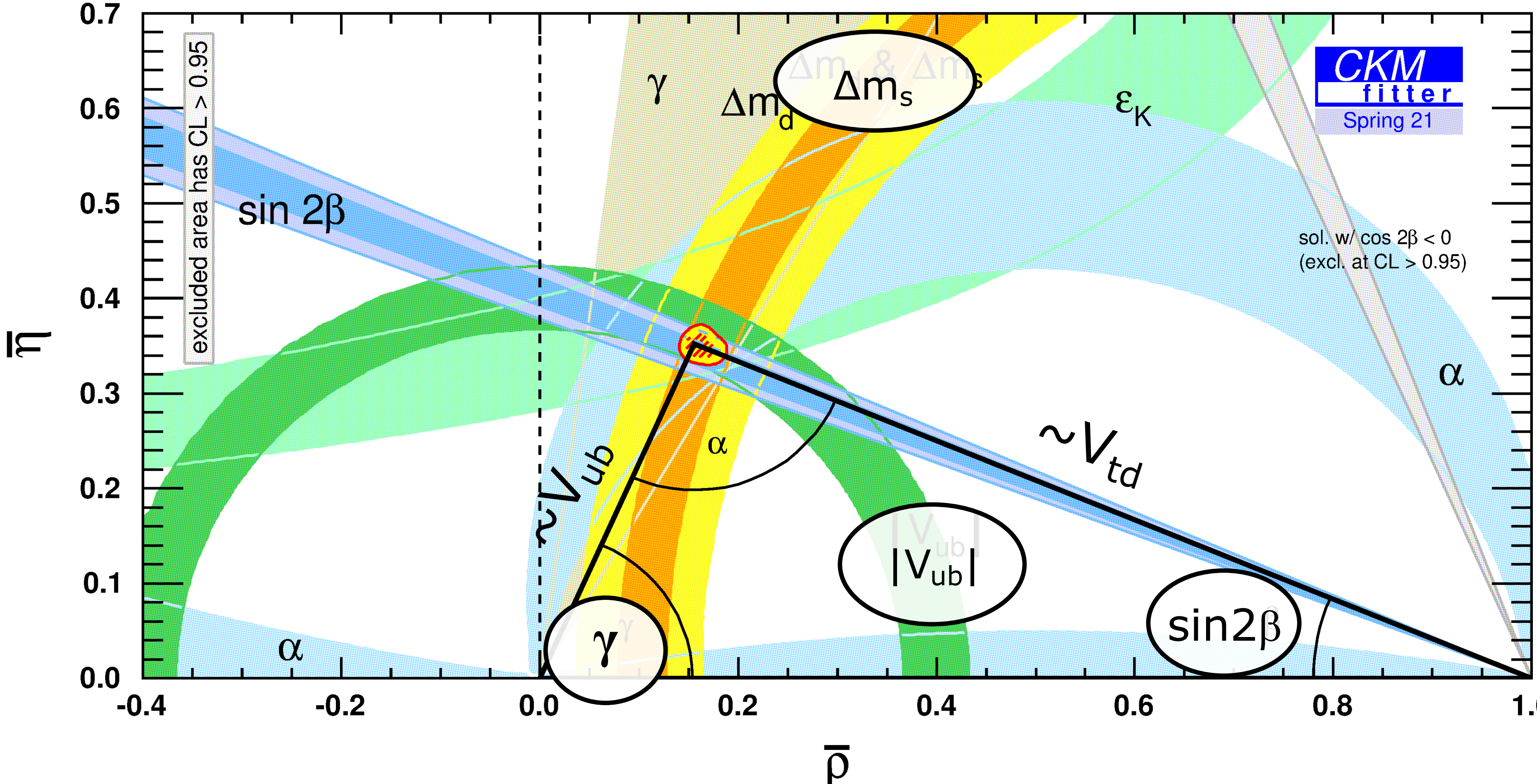


Figure 2.2: The Unitarity Triangle

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}
- Anomalies
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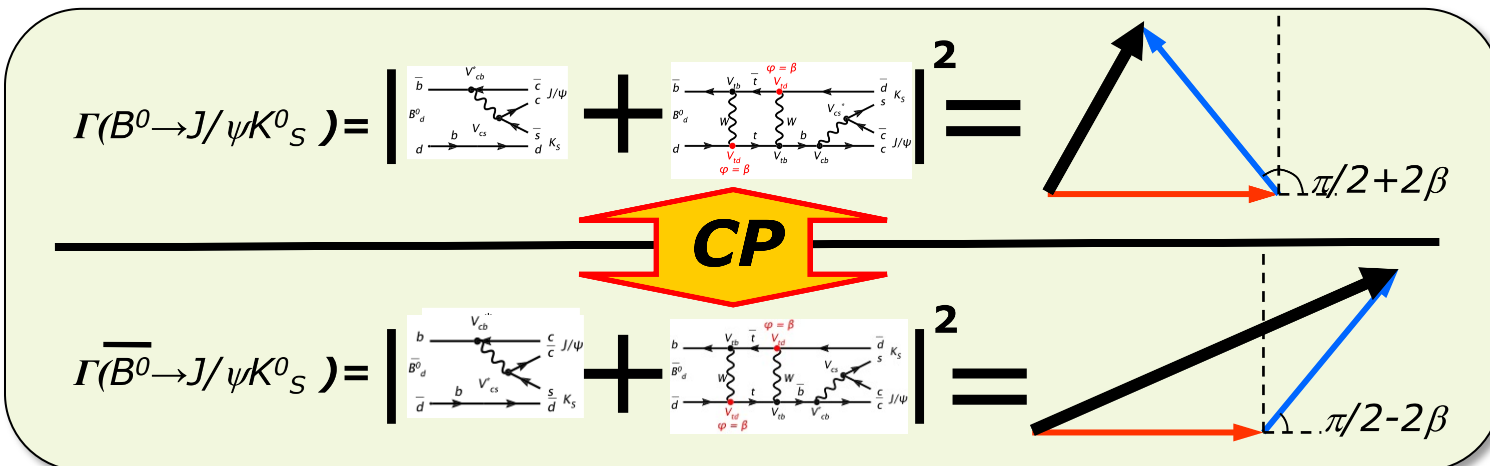
- Hadron physics
  - Heavy ion programme
  - Spectroscopy
- Prospects
  - Upgrade II

To the backup slides...

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 $\pi/2$)



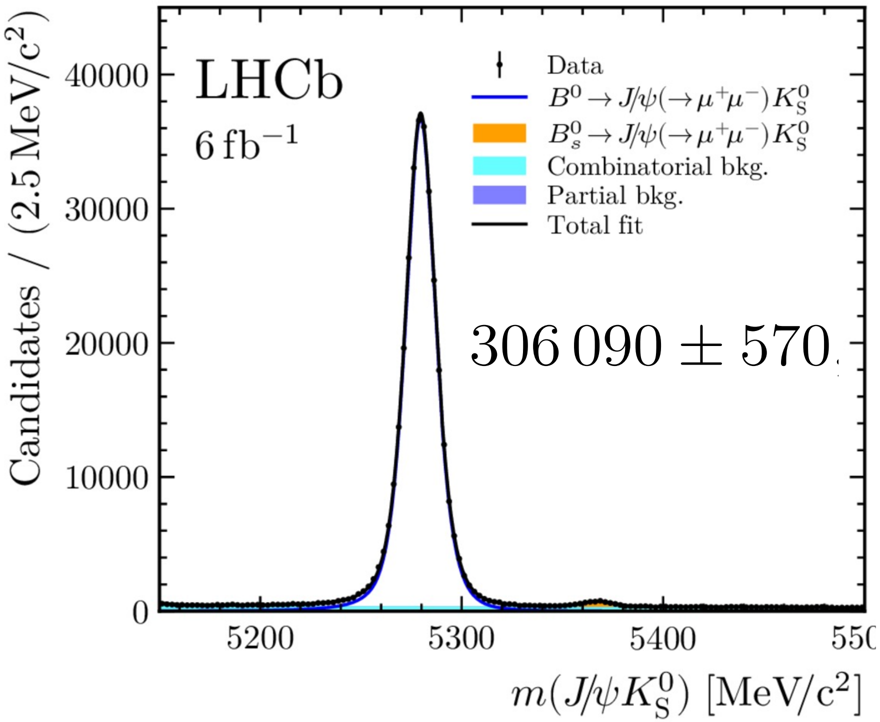
NEW

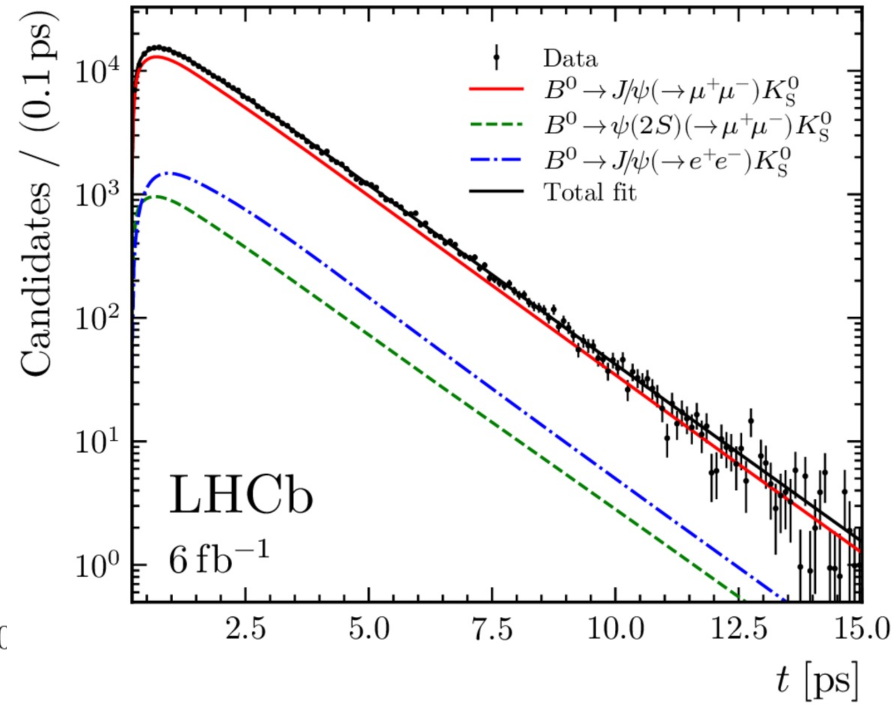
sin2β

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

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

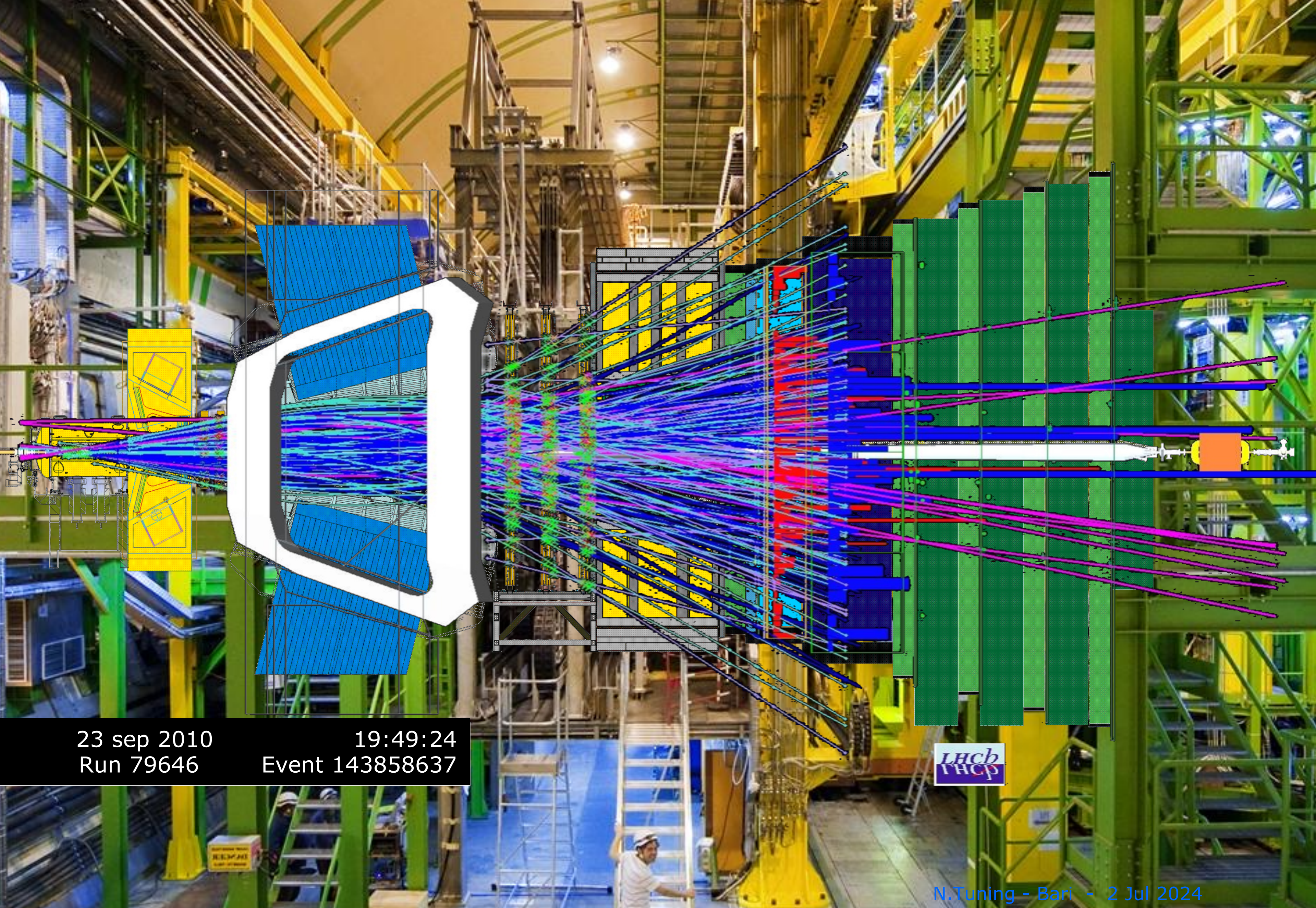
- "Flavour tagging" essential
  - Which B^0 was a $\overline{B^0}$?





LHCb arXiv:2309.09728
Phys. Rev. Lett. 132 (2024) 021801

The LHCb Detector



NEW

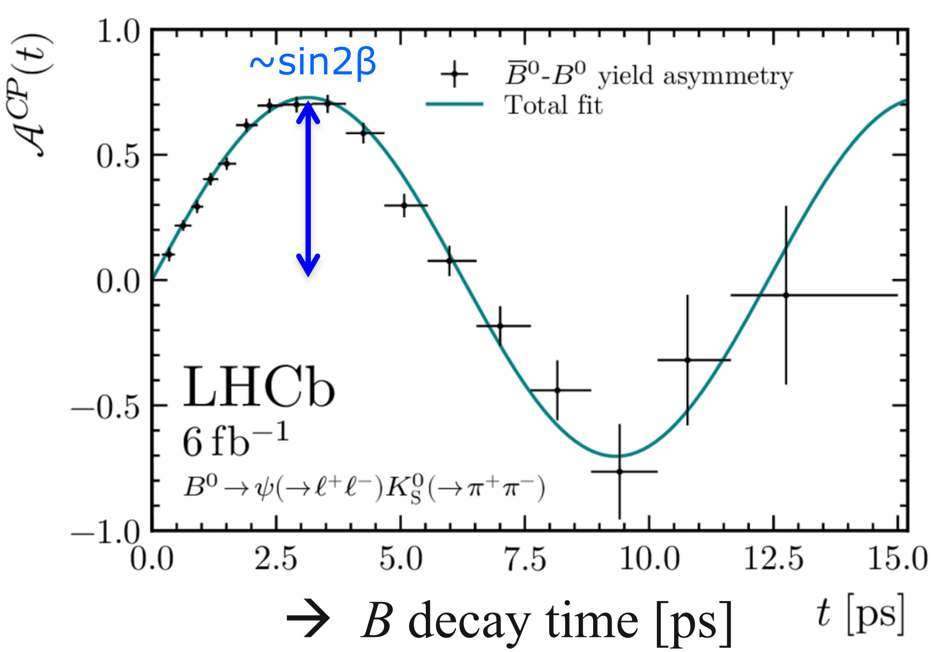
sin2β

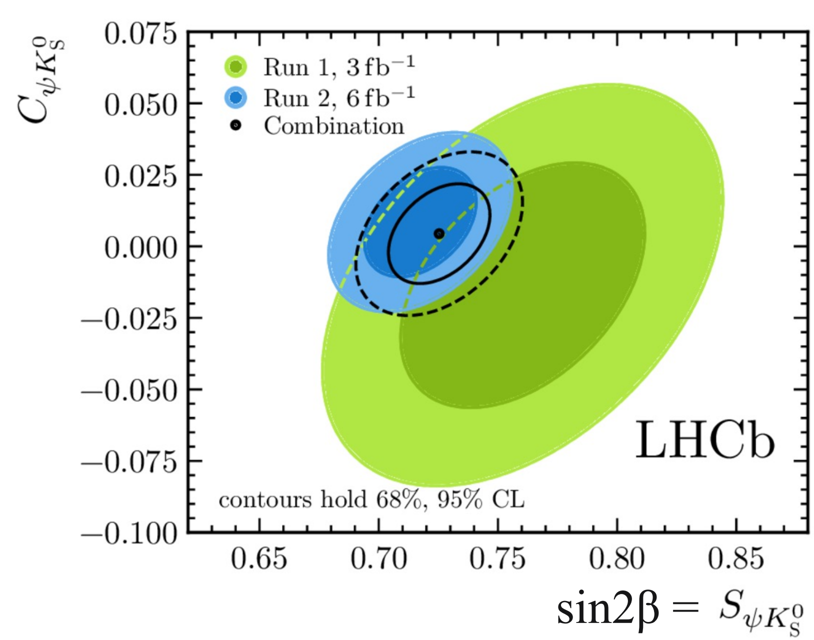
$$\mathcal{A}_{[c\bar{c}]K^0_S}(t) \equiv \frac{\Gamma(\overline{B}^0(t)\to[c\bar{c}]K^0_S) - \Gamma(B^0(t)\to[c\bar{c}]K^0_S)}{\Gamma(\overline{B}^0(t)\to[c\bar{c}]K^0_S) + \Gamma(B^0(t)\to[c\bar{c}]K^0_S)}$$

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

$(S = \sin 2\beta)$

- "Flavour tagging" essential
  - Wrong tag fraction w~39%
  - D=(1-2w)~0.22





LHCb arXiv:2309.09728
Phys. Rev. Lett. 132 (2024) 021801

sin2β

NEW:

$$S_{J/\psi(\to\mu^+\mu^-)K^0_S} = 0.716 \pm 0.015\,(\text{stat}) \pm 0.007\,(\text{syst})$$

(Run 2) LHCb arXiv:2309.09728 PRL132 (2024) 021801

OLD:

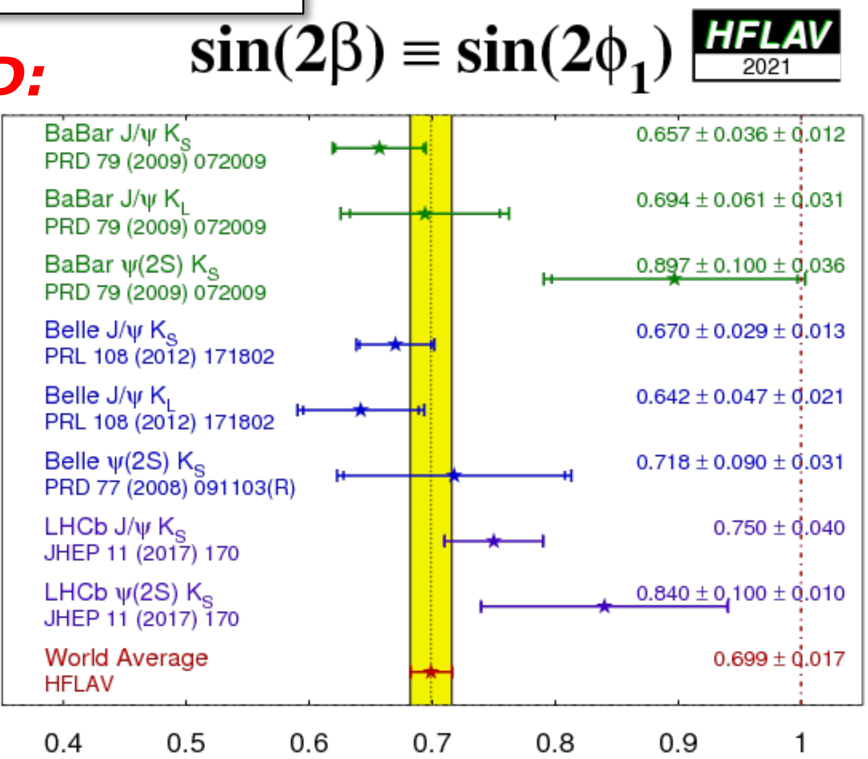
$$\text{BaBar: } \sin 2\beta = 0.691 \pm 0.031$$

$$\text{Belle: } \sin 2\beta = 0.667 \pm 0.026$$

$$\text{LHCb: } \sin 2\beta = 0.760 \pm 0.034$$

(Run 1)

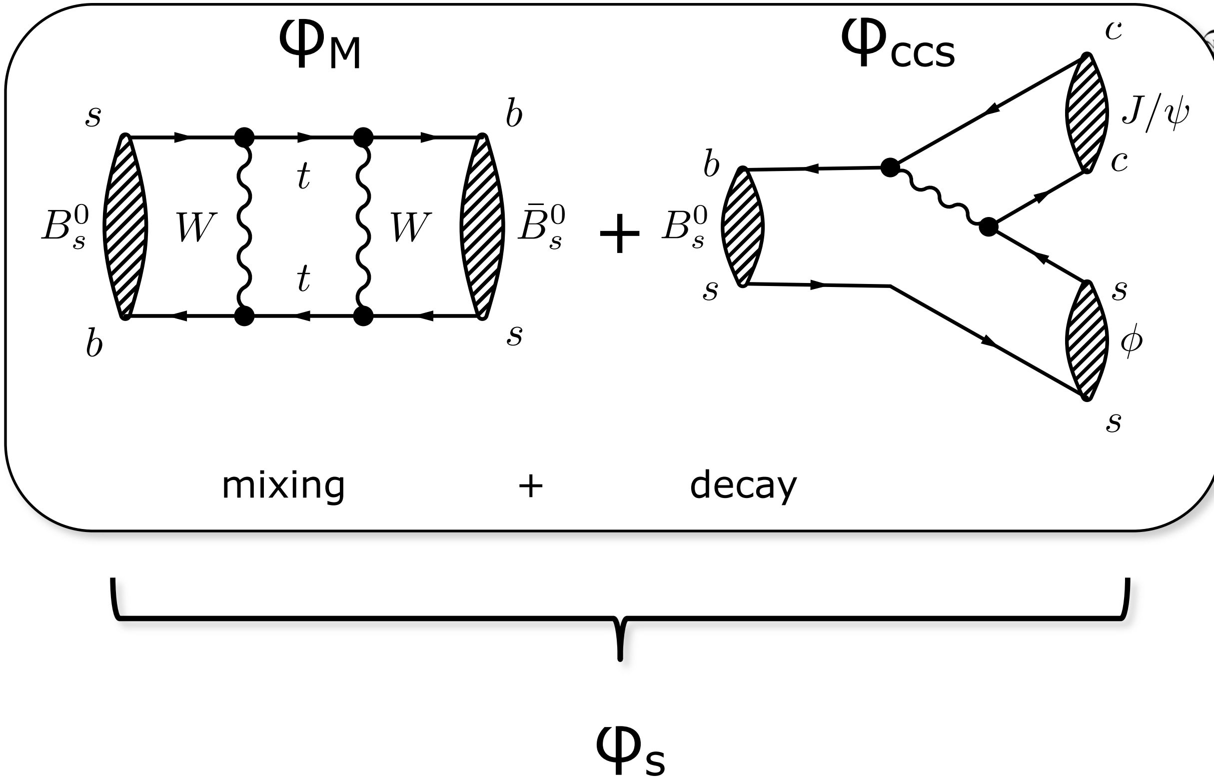
$$\text{Avg: } \sin 2\beta = 0.699 \pm 0.017$$

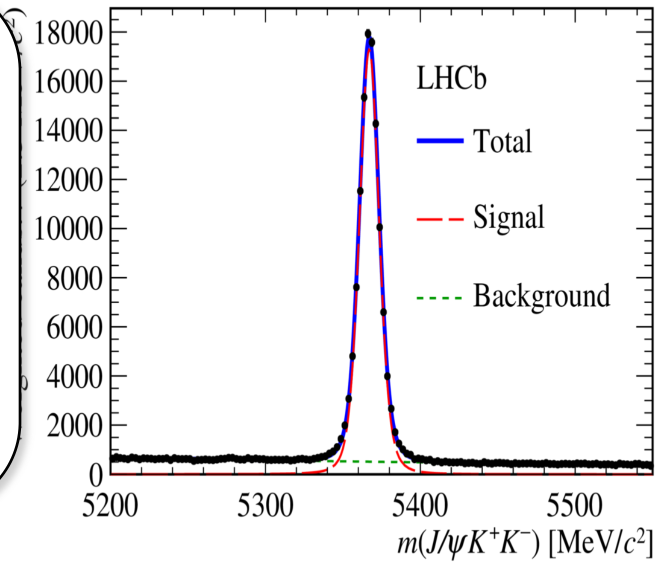


- Large *B* production competes with good tagging:

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

ϕ_s with $B_s^0 \to J/\psi\phi$ ("the sin2β of the B_s^0 system")





LHCb, arXiv:1906.08356
EPJC 79 (2019) 8, 706,
EPJC 80 (2020) 7, 601 (erratum)

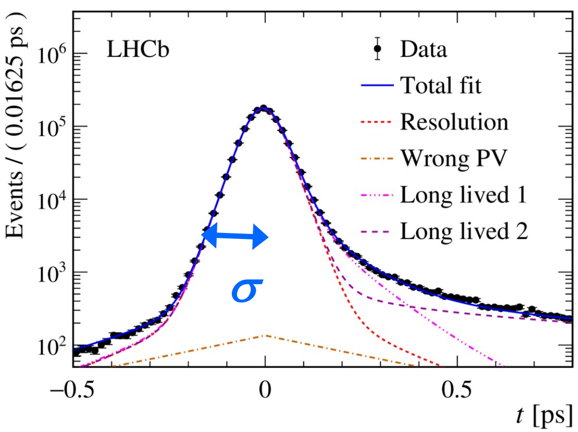
ϕ_s with $B_s^0 \to J/\psi\phi$

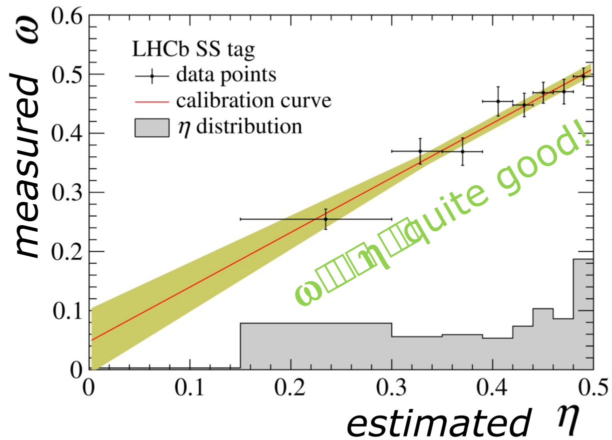
- Some challenges:
  1) Rapid B_s^0 oscillations: decay time resolution
  2) "Same side" kaon-tagging: calibration with hadronic final state
  3) Mix of CP eigenstates: angular analysis

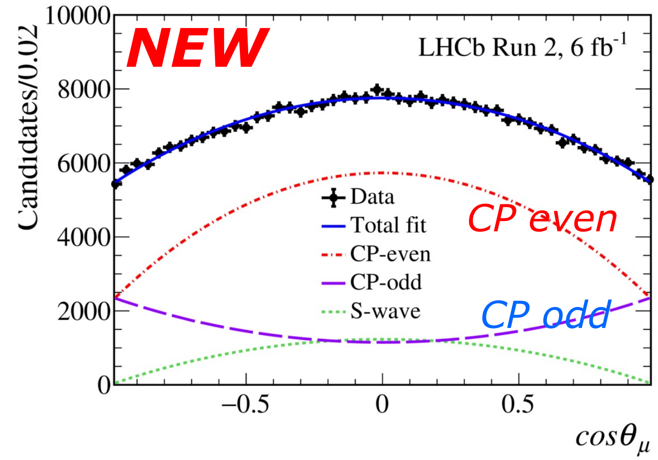
1) Decay time resolution from prompt J/ψ

2) Tagging calibration from $B_s^0 \to D_s\pi$

3) Angular analysis to disentable CP + and CP -





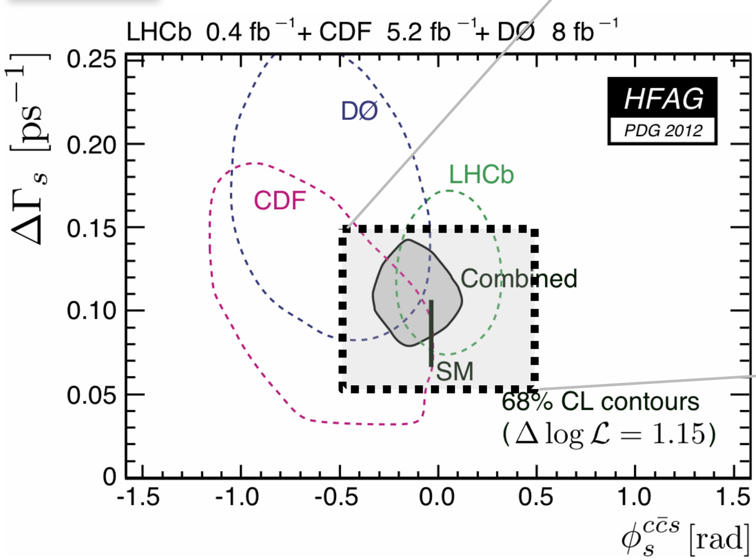


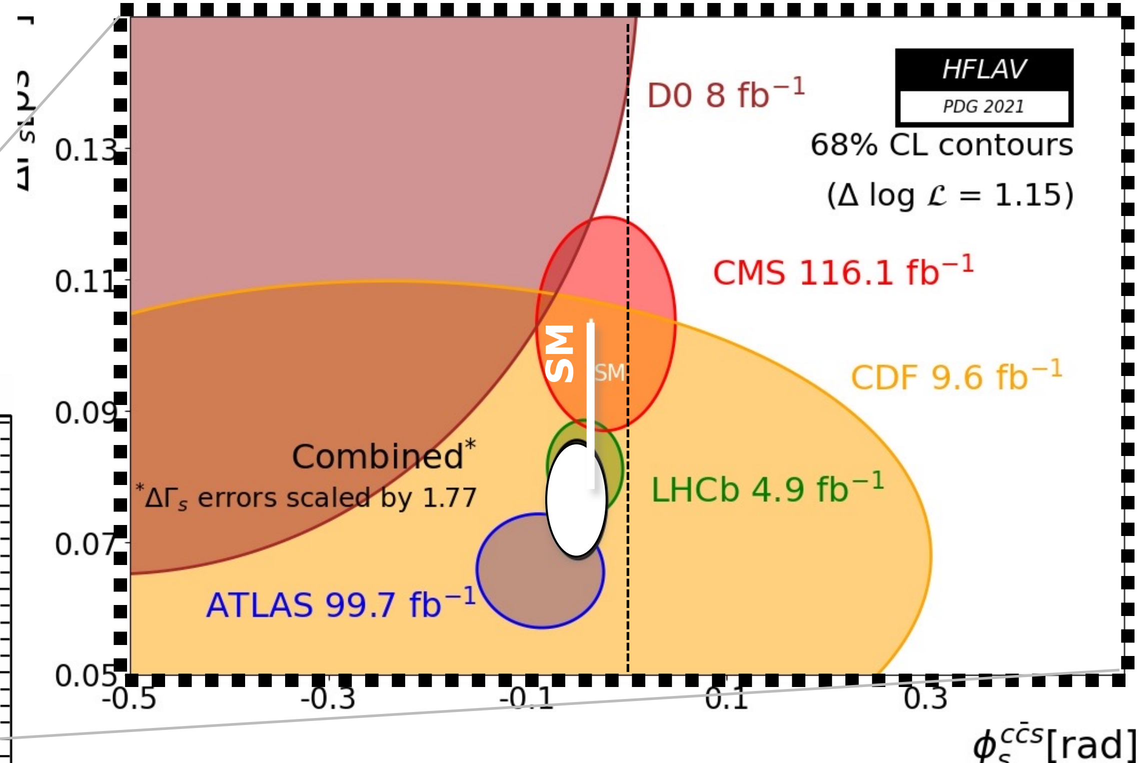
LHCb, arXiv:1906.08356
EPJC 79 (2019) 8, 706,
EPJC 80 (2020) 7, 601 (erratum)

LHCb, arXiv:2308.01468
Phys.Rev.Lett. 132 (2024) 5, 051802

φ_s

- LHCb 2011-2016





$$\phi_s = -50 \pm 19 \text{ mrad (HFLAV, 2021)}$$

$$\phi_s = -44 \pm 20 \text{ mrad (LHCb, 2023)}$$ (9 fb^{-1})

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

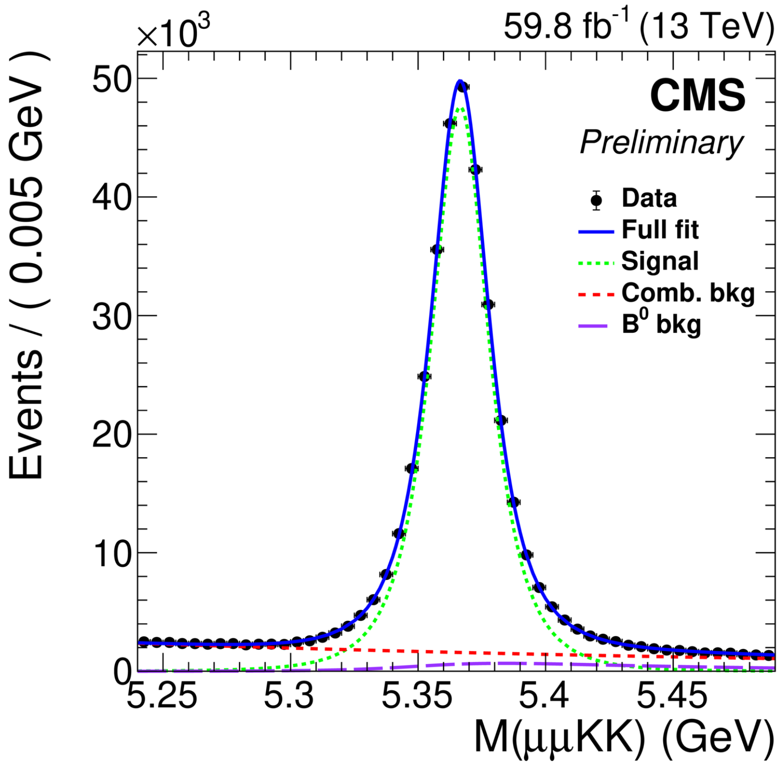
CKMfitter,
Phys. Rev. D84, 033005 (2011),
updated with Summer 2019 results

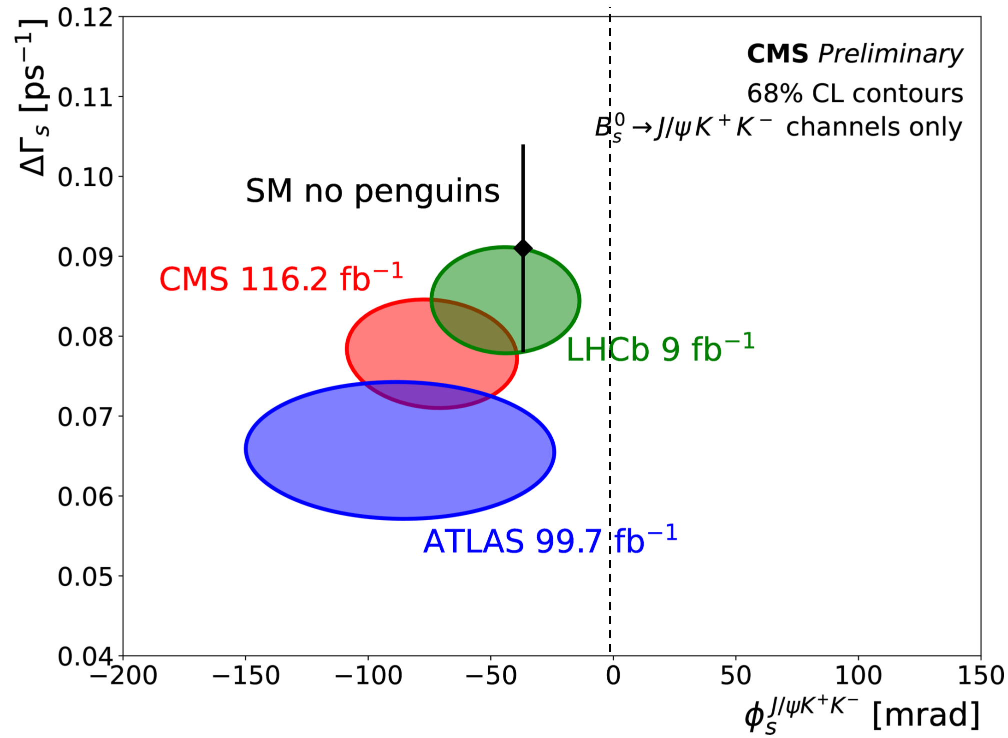
LHCb, arXiv:2308.01468
Phys.Rev.Lett. 132 (2024) 5, 051802

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

φ_s at CMS

- Clean sample of $B_s^0 \to J/\psi\varphi$ decays (2017-2018, 96 fb^{-1})
  - new pioneering flavor tagging algorithm





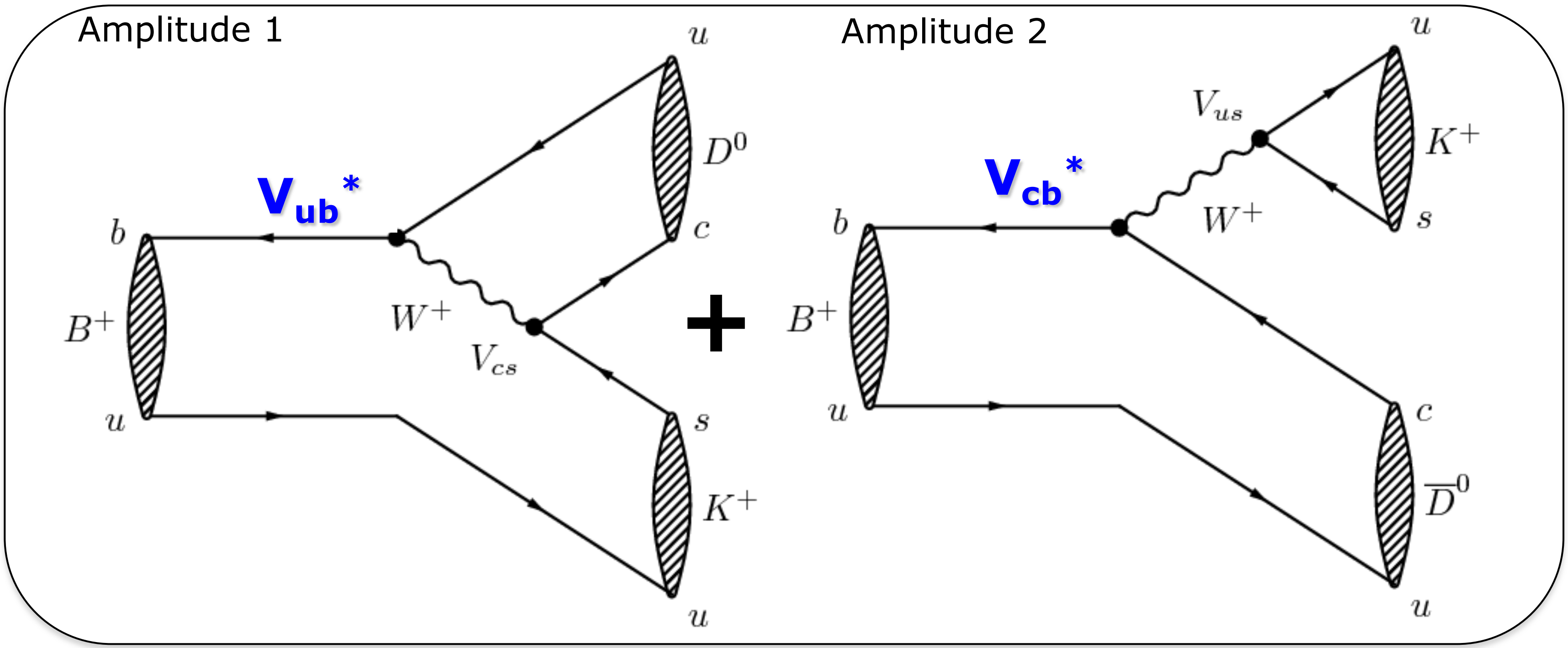
- CPV at 3.2σ from 0

ϕ_s =-74 ±23 mrad (CMS)
ϕ_s =-44 ±20 mrad (LHCb)

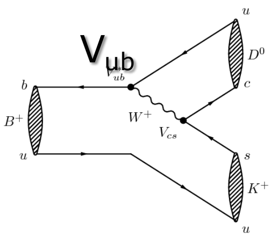
CMS-PAS-BPH-23-004
https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/BPH-23-004/index.html
Supersedes publication on same data set: Phys.Lett.B 816 (2021) 136188 arXiv:2007.02434

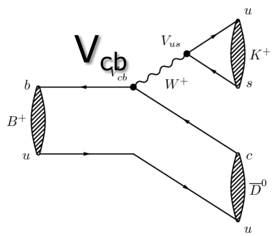
Constraints on angle γ

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

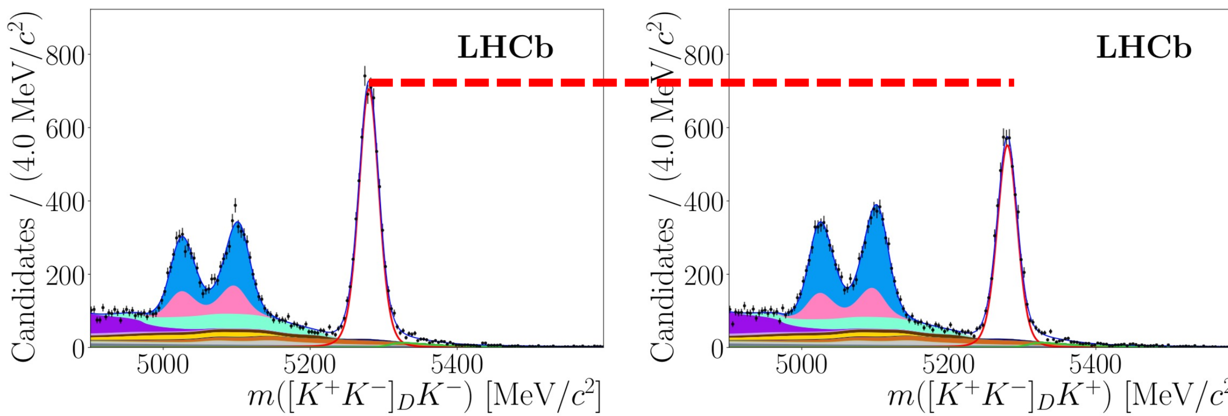


Constraints on angle γ - with $B^\pm \to D^{(*)}K^\pm$ and $D^0 \to h^\pm h^\pm$





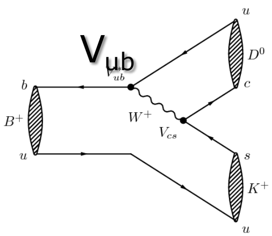
$B^- \to D^{(*)}K^-$ $B^+ \to D^{(*)}K^+$

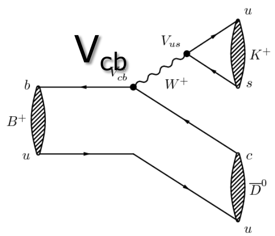


LHCb, arXiv:2012.09903, JHEP 04(2021) 081

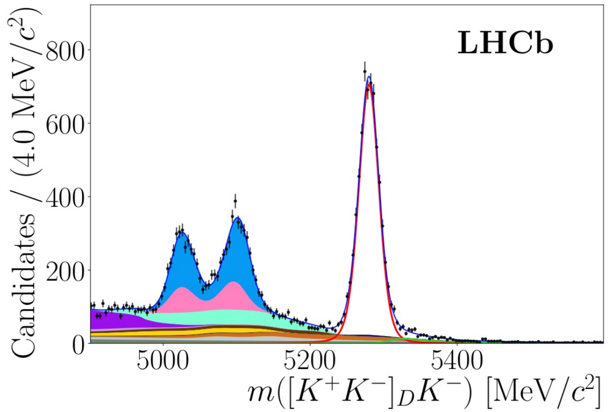
$$\Gamma(B^\pm \to [CP]_D h^\pm) \propto 1 + (r_B^{Dh})^2 + 2 r_B^{Dh} \cos(\delta_B^{Dh} \pm \gamma)$$

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

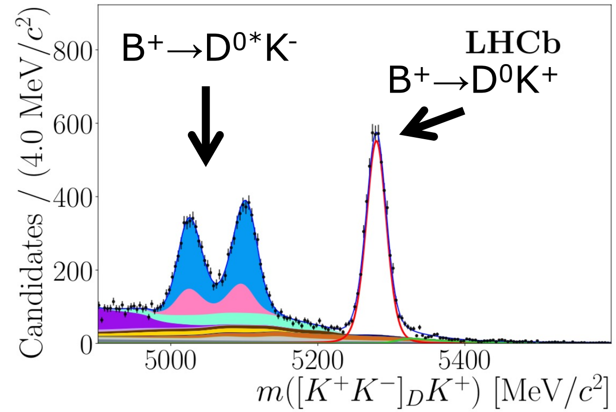




$B^-\rightarrow D^{(*)}K^-$



$B^+\rightarrow D^{(*)}K^+$



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

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

- Many final states for D^{*0} or D^0 !
  - $B^{\pm}\rightarrow D^0K^{\pm}$, $B^{\pm}\rightarrow D^0\pi^{\pm}$, $B^{\pm}\rightarrow D^{0*}K^{\pm}$, $B^{\pm}\rightarrow D^{0*}\pi^{\pm}$
  - $D^0\rightarrow K^+K^-$, $D^0\rightarrow K^+\pi^-$, $D^0\rightarrow \pi^+\pi^-$, $D^0\rightarrow K_S{}^0K^-K^+$, $D^0\rightarrow K_S{}^0\pi^-\pi^+$,

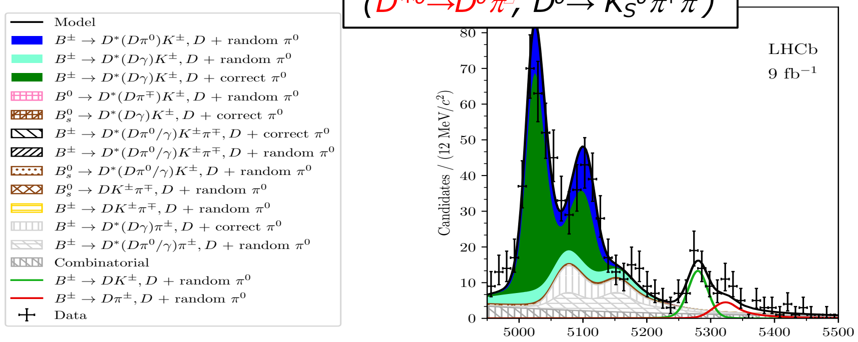
➢ Very precise input for gamma

NEW

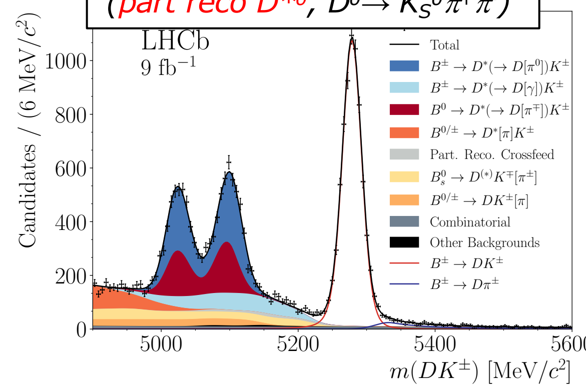
Constraints on angle γ - with $B^{\pm}\rightarrow D^{*0}h^{\pm}$ and $D^0\rightarrow K_S{}^0h^+h^-$

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

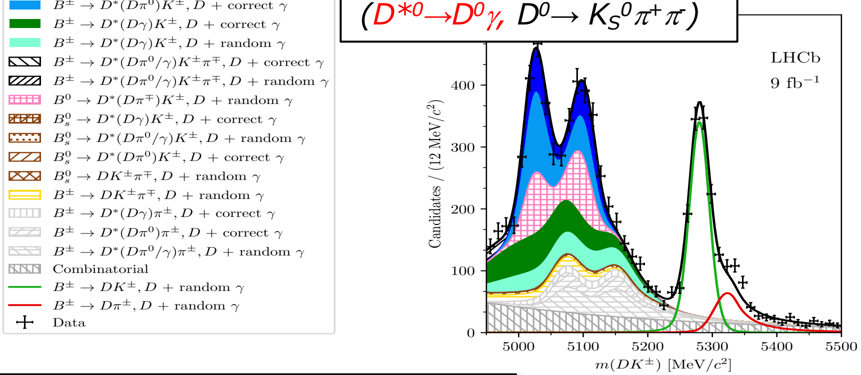
$B^{\pm}\rightarrow D^0K^{\pm}$
($D^{*0}\rightarrow D^0\pi^0$, $D^0\rightarrow K_S{}^0\pi^+\pi^-$)



$B^{\pm}\rightarrow D^0K^{\pm}$
(part reco D^{*0}, $D^0\rightarrow K_S{}^0\pi^+\pi^-$)



$B^{\pm}\rightarrow D^0K^{\pm}$
($D^{*0}\rightarrow D^0\gamma$, $D^0\rightarrow K_S{}^0\pi^+\pi^-$)



$B^+ \to D^*K^+, D^* \to D\pi^0$	112 ± 7
$B^+ \to D^*K^+, D^* \to D\gamma$	358 ± 33
$B^- \to D^*K^-, D^* \to D\pi^0$	109 ± 6
$B^- \to D^*K^-, D^* \to D\gamma$	419 ± 35

$\Rightarrow$ $\gamma = (69^{+13}_{-14})^\circ$

LHCb, JHEP12(2023)013, arXiv:2310.04277

Component	Reconstructed $B^{\pm} \to DK^{\pm}$
$B^{\pm} \to D^*[D\pi^0]K^{\pm}$	6244 ± 12
$B^{\pm} \to D^*[D\pi^0]\pi^{\pm}$	340 ± 1
$B^{\pm} \to D^*[D\gamma]K^{\pm}$	3144 ± 6
$B^{\pm} \to D^*[D\gamma]\pi^{\pm}$	166 ± 1

$\Rightarrow$ $\gamma = (92^{+21}_{-17})^\circ$

LHCb, JHEP 02 (2024) 118, arXiv:2311.10434

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:

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
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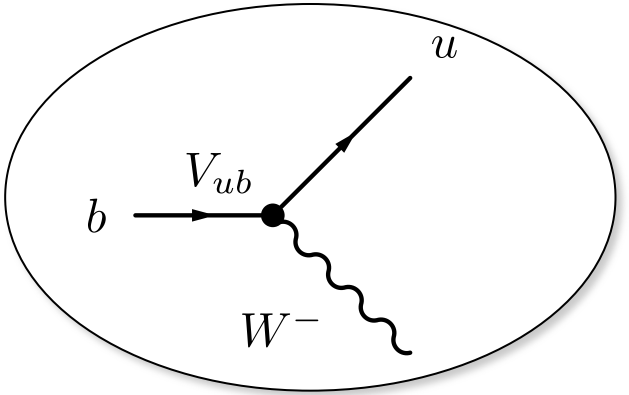
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[36]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[37]	Run 1	As before
$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	[38]	Run 1	As before
$B^0_s \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[39]	Run 1&2	As before

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: $V_{ub} = |V_{ub}|e^{-i\gamma}$
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$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
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$B^0 \to DK^{*0}$	$D \to h^+h^-$	[35]	Run 1&2(*)	As before
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$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[37]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	[38]	Run 1	As before
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D decay	Observable(s)	Ref.	Dataset	Status since Ref. [14]
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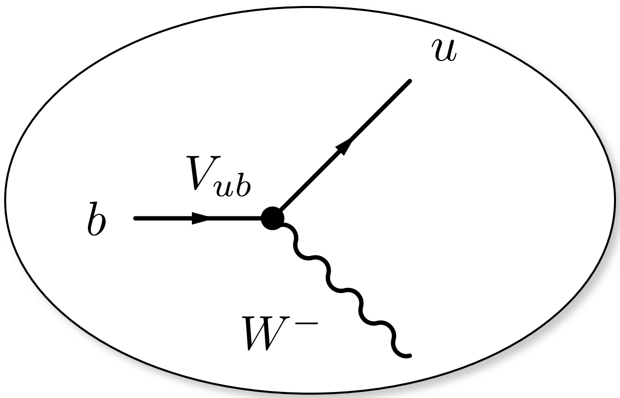
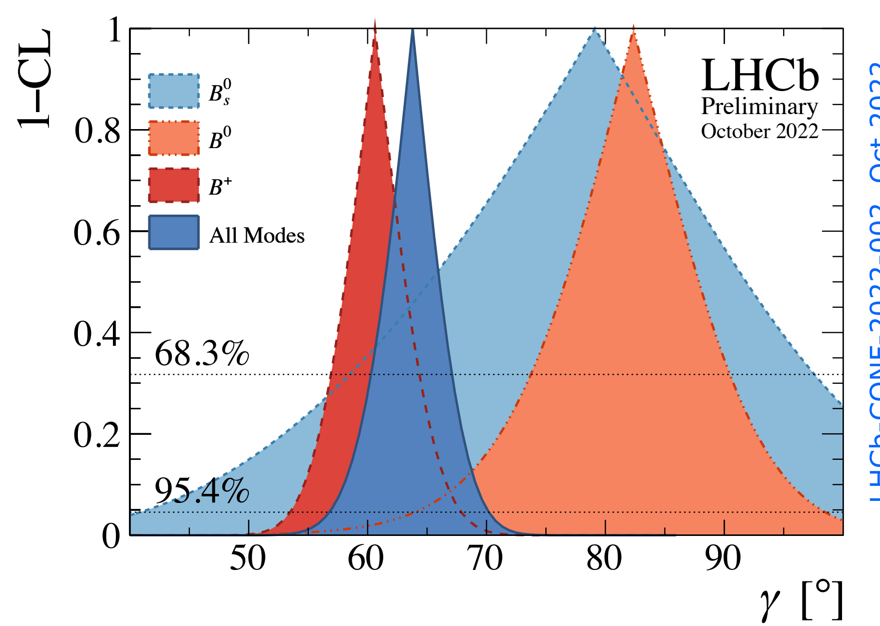
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[52]	Run 2	As before
$D^0 \to K^0_S\pi^+\pi^-$ (μ^- tag)	x_{CP}, y_{CP}, Δx, Δy	[17]	Run 2	**New**

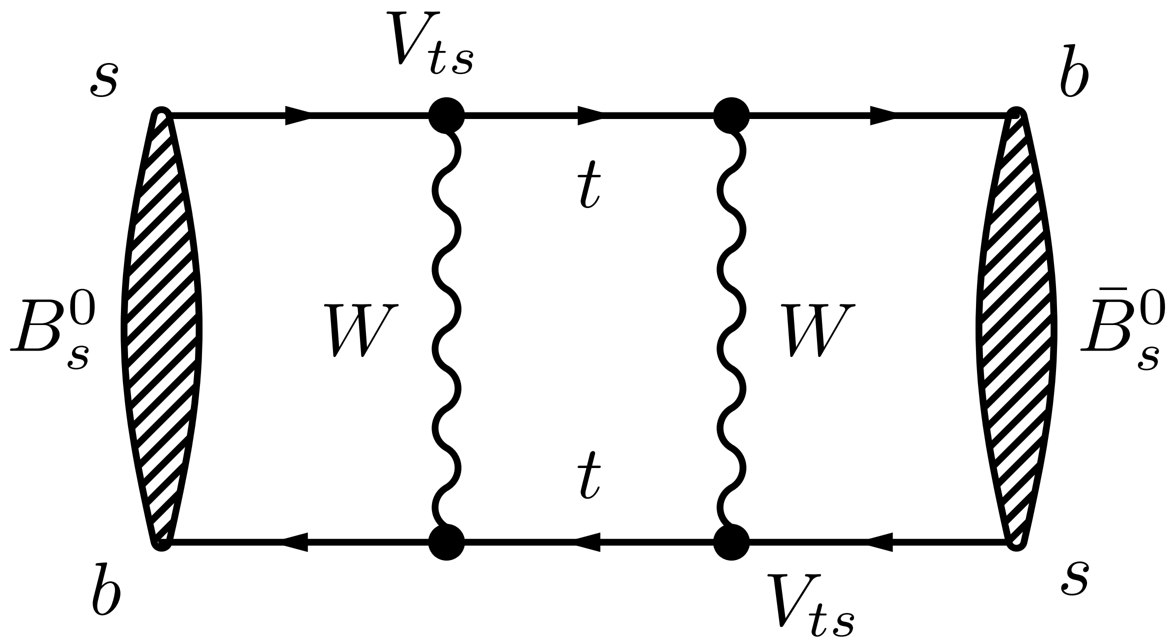


	γ (°)
LHCb	**$63.8^{+3.5}_{-3.7}$ °**
CKMfitter	$65.6^{+1.1}_{-2.7}$ °
UTFit	$65.8^{+2.2}_{-2.2}$ °



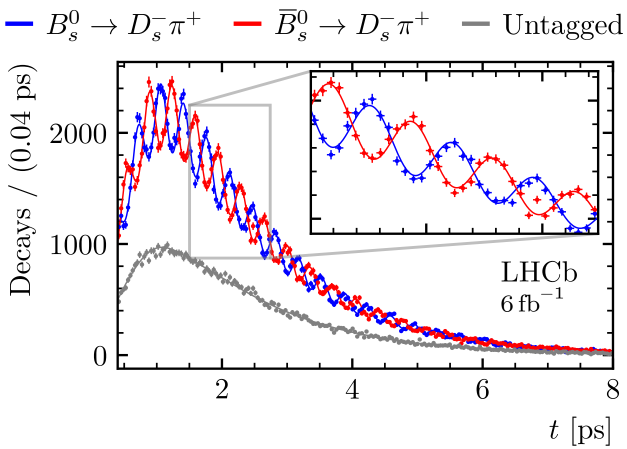
Precision Δm_s with $B^0_s \rightarrow D_s^+ \pi^-$

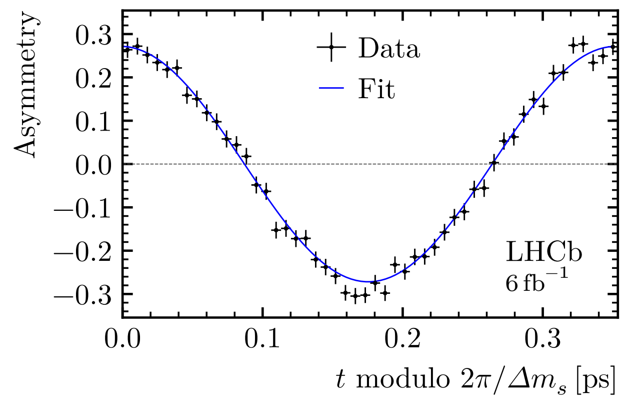
- Frequency ~ transition rate!
- "Flavour specific" : final state reveals flavour of the decaying *B*

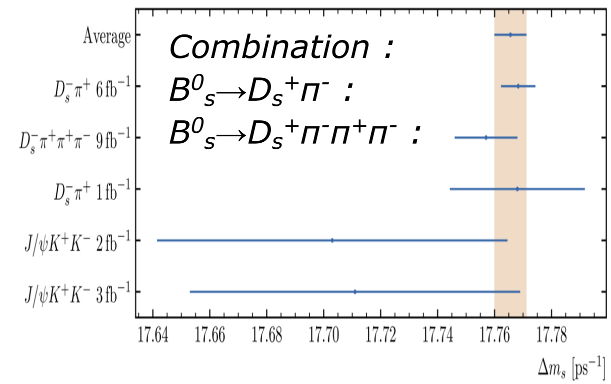


Precision Δm_s with $B^0_s \to D_s^+\pi^-$

- Legacy "*textbook*" measurement
- "Flavour specific" : final state reveals flavour of the decaying *B*
- 3 trillion oscillations per second, with 3 x 10^{-4} precision



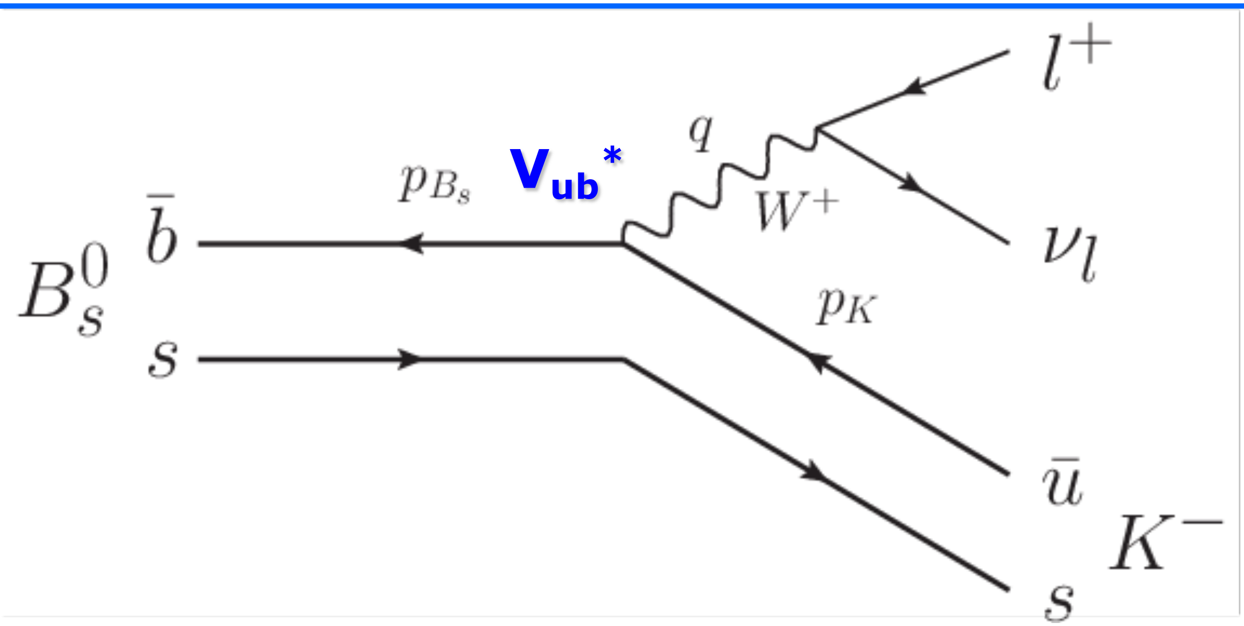




	Δm_s (ps^{-1})	Stat	Sys	Ref.
$B^0_s \to D_s^+\pi^-$	17.7683	0.0051	0.0032	arXiv:2104.04421 acc. Nat.Phys
$B^0_s \to D_s^+\pi^-\pi^-\pi^-$	17.757	0.007	0.008	arXiv:2011.12041 JHEP 03(2021)137
Combination	**17.7656**	**0.0057**		arXiv:2104.04421 acc. Nat.Phys

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

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

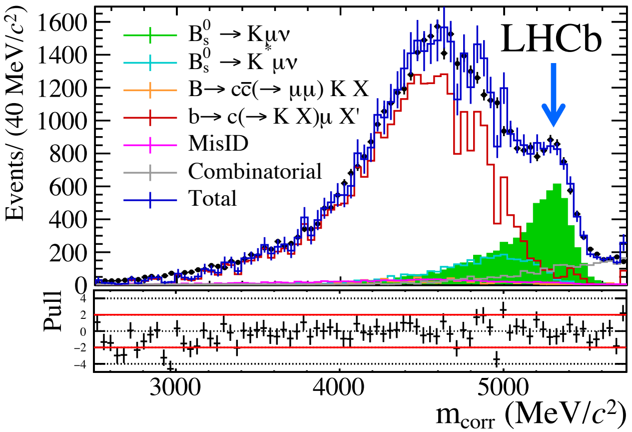


$$\mathcal{B}(B_s \to K\mu\nu)/\mathcal{B}(B_s \to D_s\mu\nu) = |V_{ub}|^2/|V_{cb}|^2 \times \mathrm{FF}_K/\mathrm{FF}_{D_s}$$

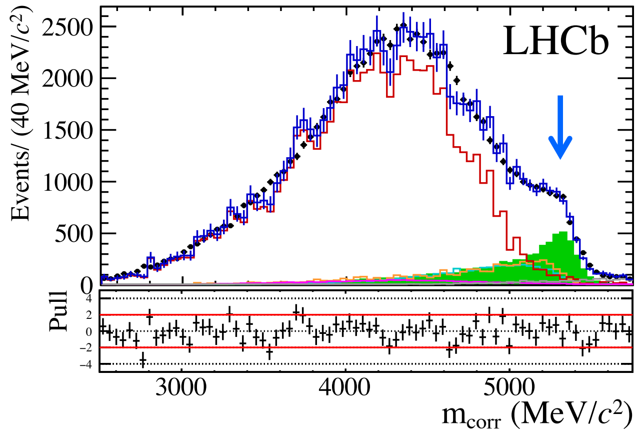
- Interesting input to $|V_{ub}|$! (and form factor calculations)

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

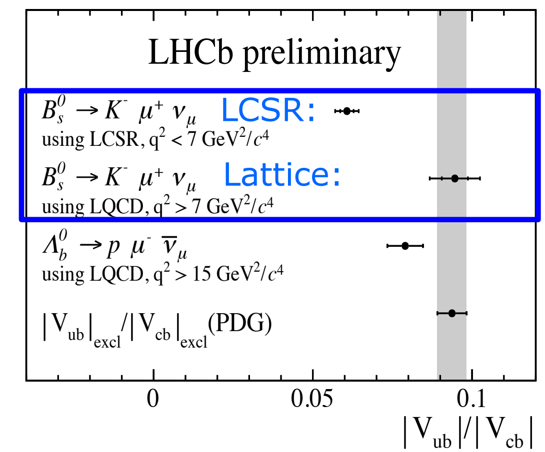
$q^2 < 7$ GeV^2



$q^2 > 7$ GeV^2



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



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

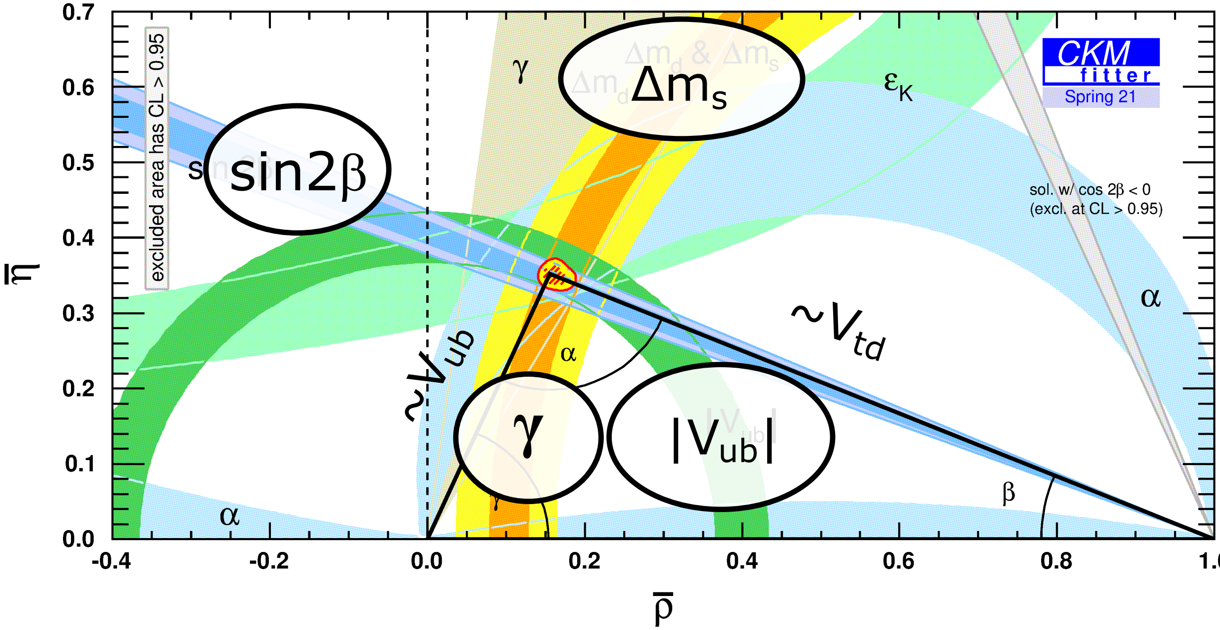
$$\mathcal{B}(B_s \to K\mu\nu) = (1.06 \pm 0.05(\text{stat})) \pm 0.04(\text{syst}) \pm 0.06(\text{ext}) \pm 0.04(\text{FF})) \times 10^{-4}$$

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

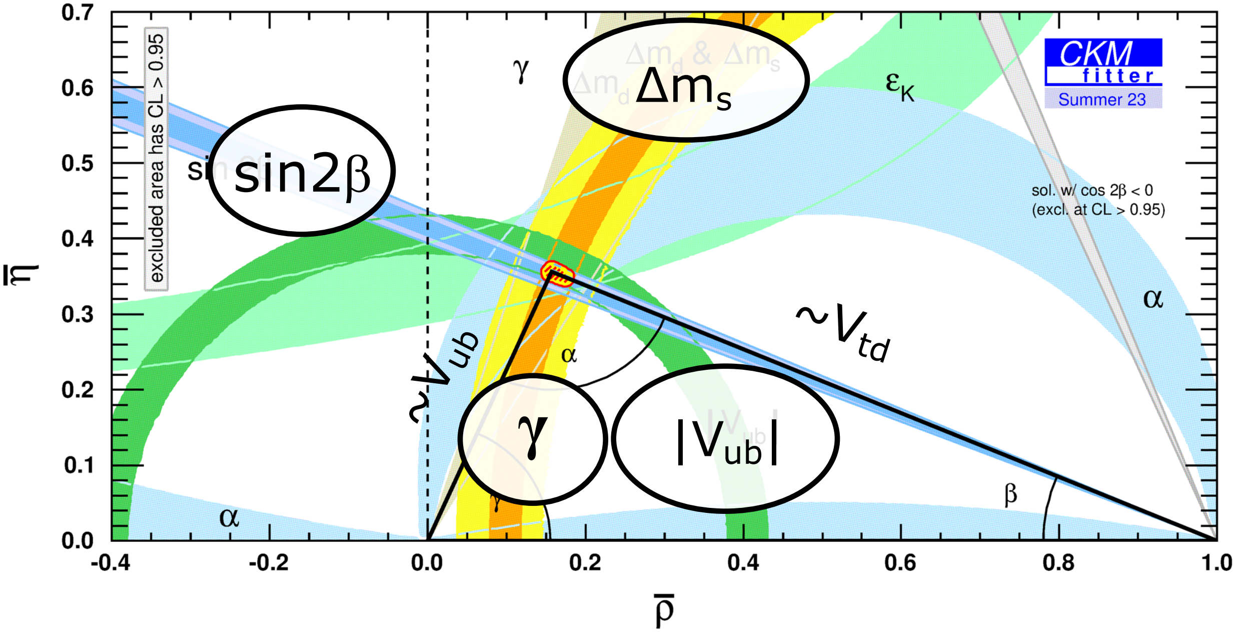
$$R_{BF} = |V_{ub}|^2/|V_{cb}|^2 \times \text{FF}_K/\text{FF}_{D_s}$$

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

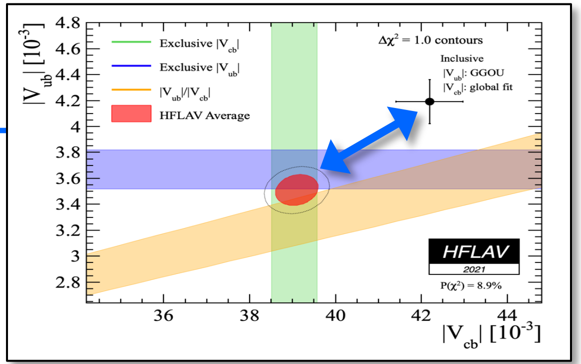
CKM: recent results



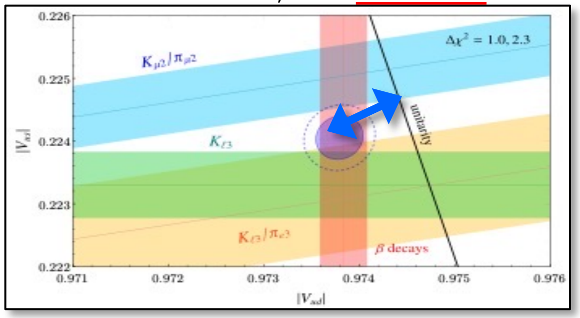
CKM: recent results



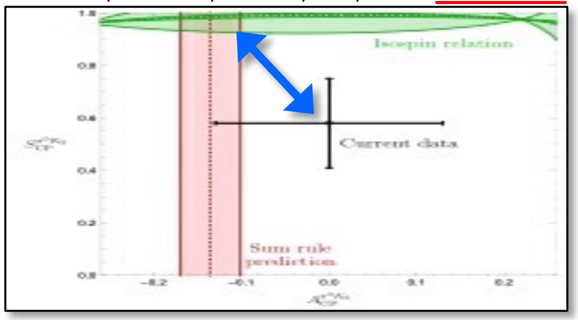
HFLAV, 2021



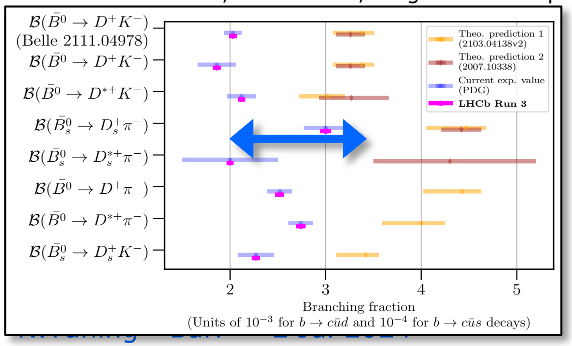
Crivellin et al, arXiv:2212.06862



Fleischer, Jaarsma, Malami, Vos, arXiv:1806.08783



Skidmore, 2 Jun 2022, Siegen Workshop

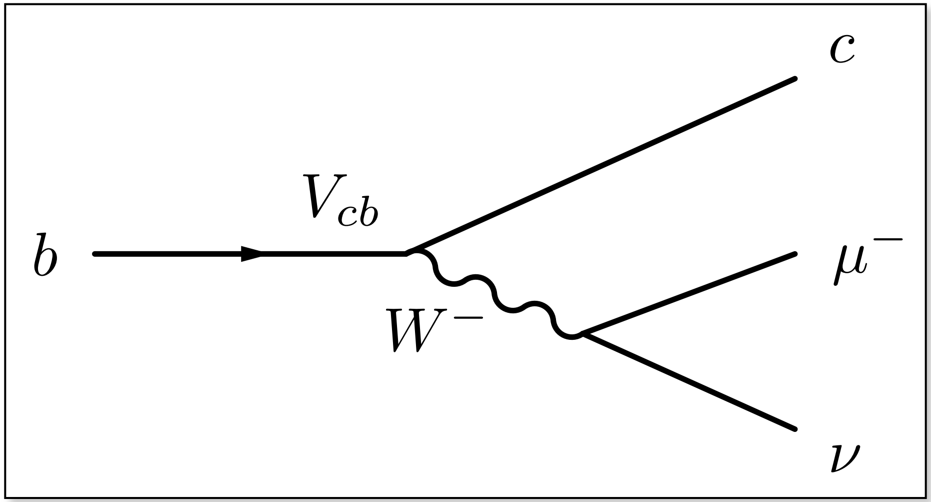


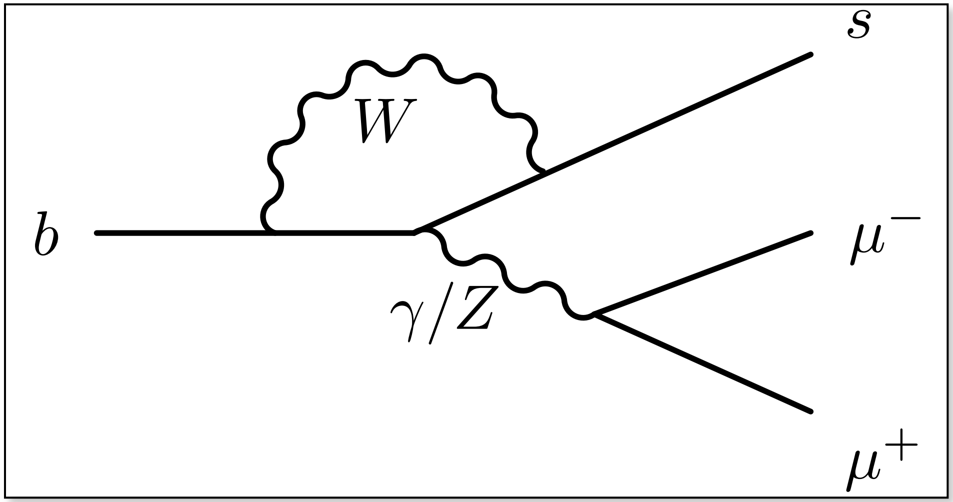
- So far so good, but stay vigilant…
  - V_{ub} and V_{cb} : incl. and excl. measurements differ…
  - V_{us}: too small for unitarity (Cabibbo angle anomaly)
  - $K\pi$ puzzle: CP asymmetries should be related through isospin symmetry…
  - BR($B \to Dh$): Factorisation?
  - …

Outline

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

Anomalies



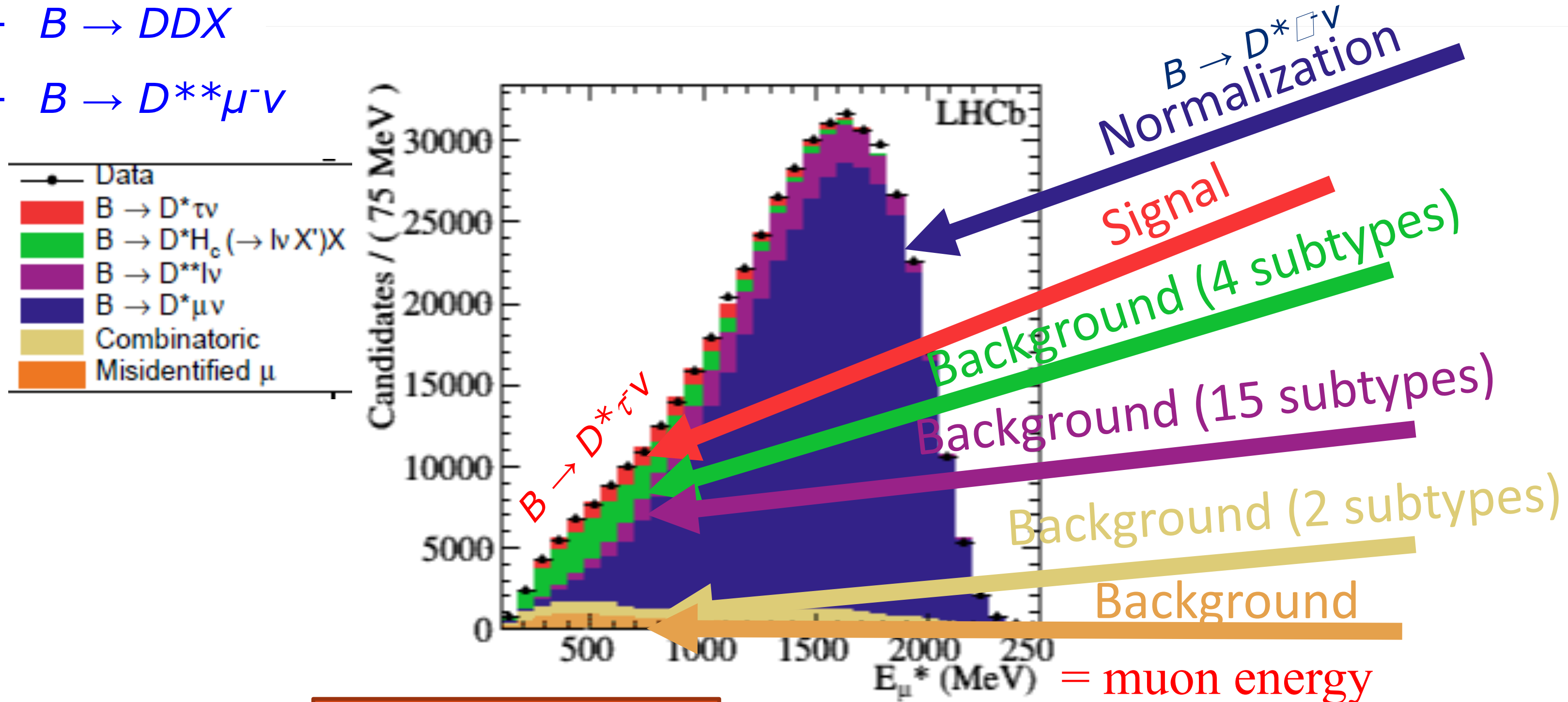


Semileptonic
CC
$b \rightarrow c l^- \nu$

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

R(D*) vs R(D)

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



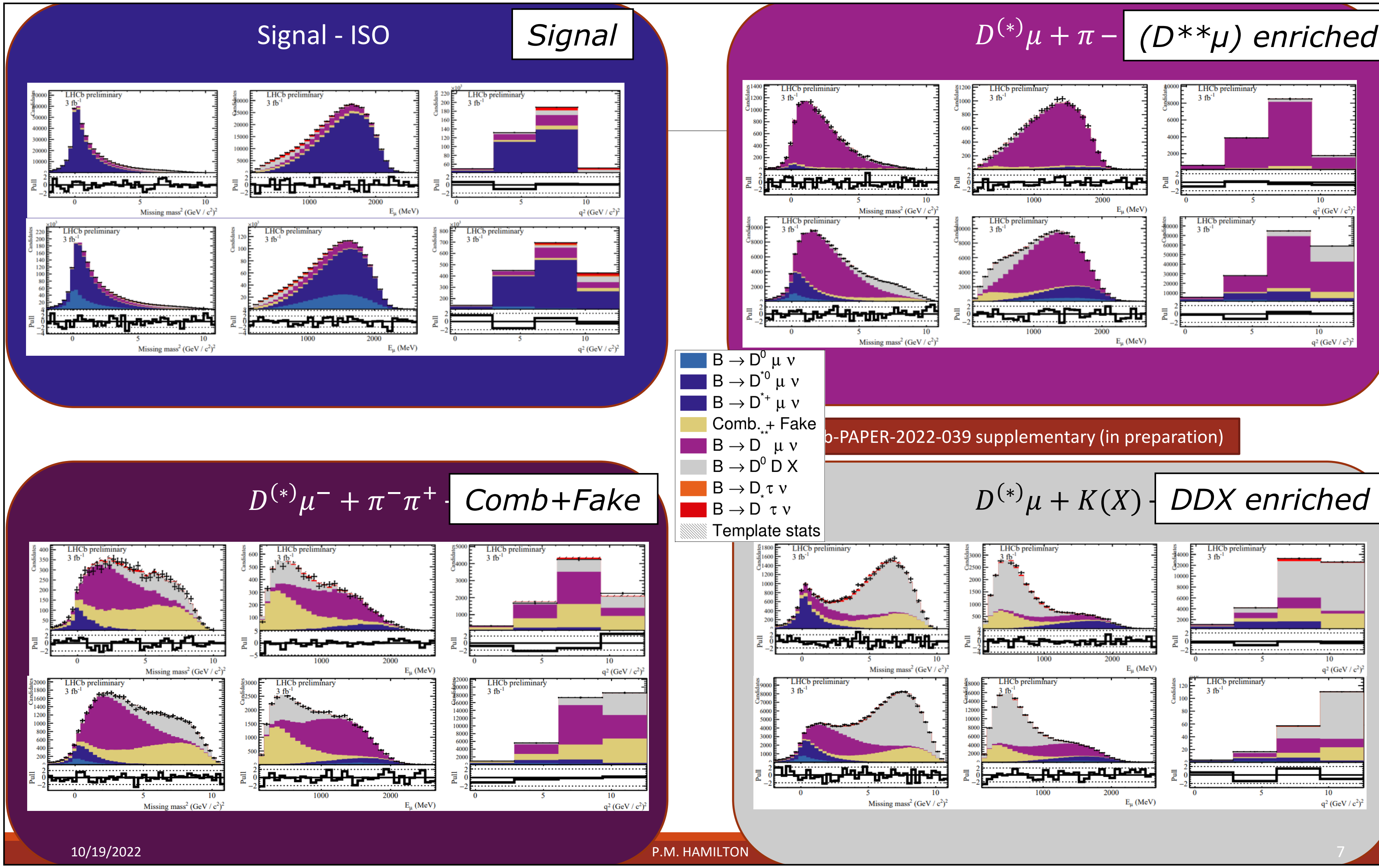
PRL 115 (2015) 111803

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

LHCb, arXiv:2302.02886 Phys. Rev. Lett. 131 (2023) 111802

R(D*) vs R(D)

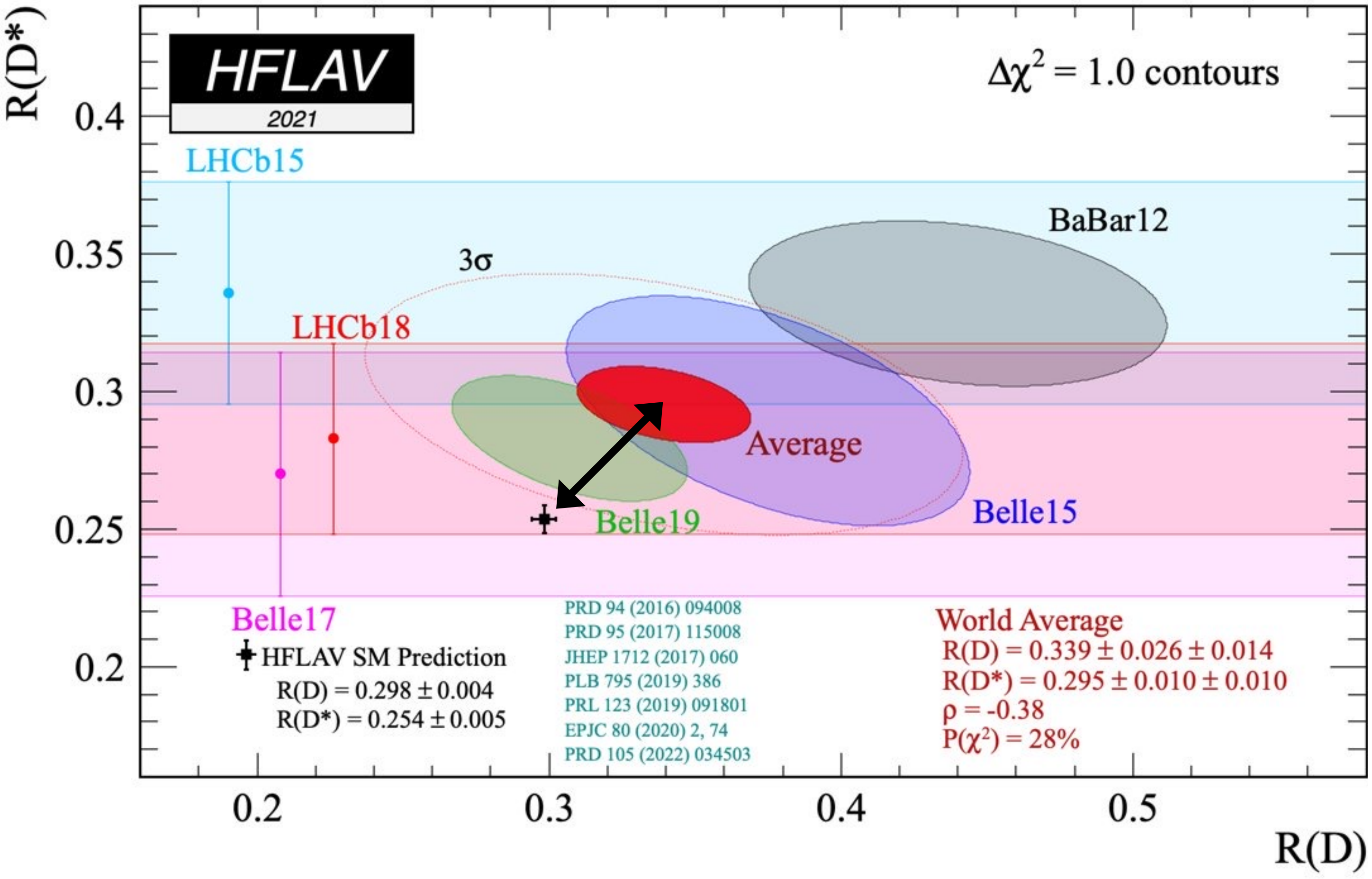
- Simultaneous 3D-fit to 8 samples (and in 4 q^2 bins…)



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

R(D*) vs R(D)

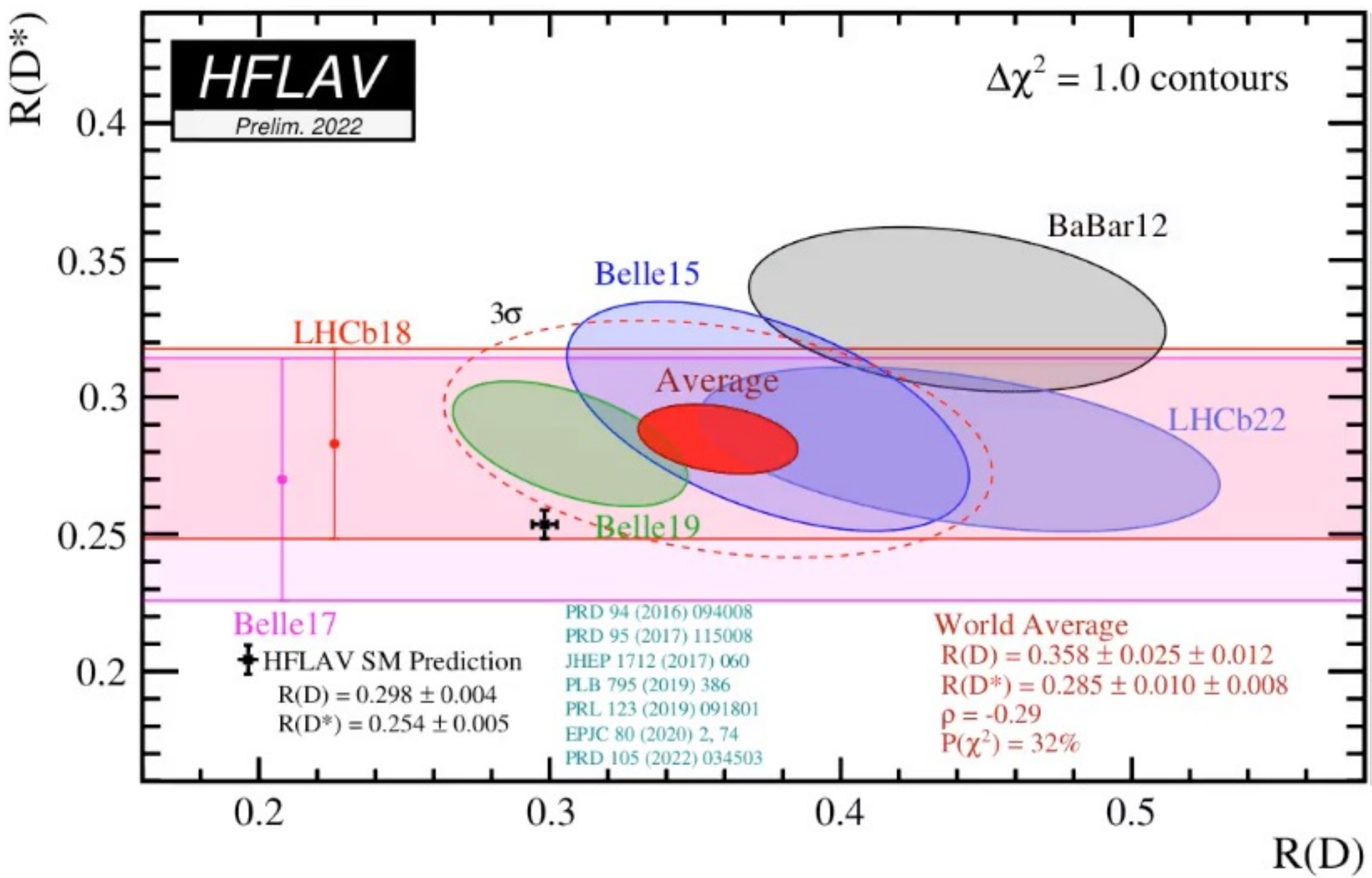
- World average 3.3σ to 3.2σ



NB: contours contain less than 68% CL…

R(D*) vs R(D)

- World average 3.3σ to 3.2σ



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

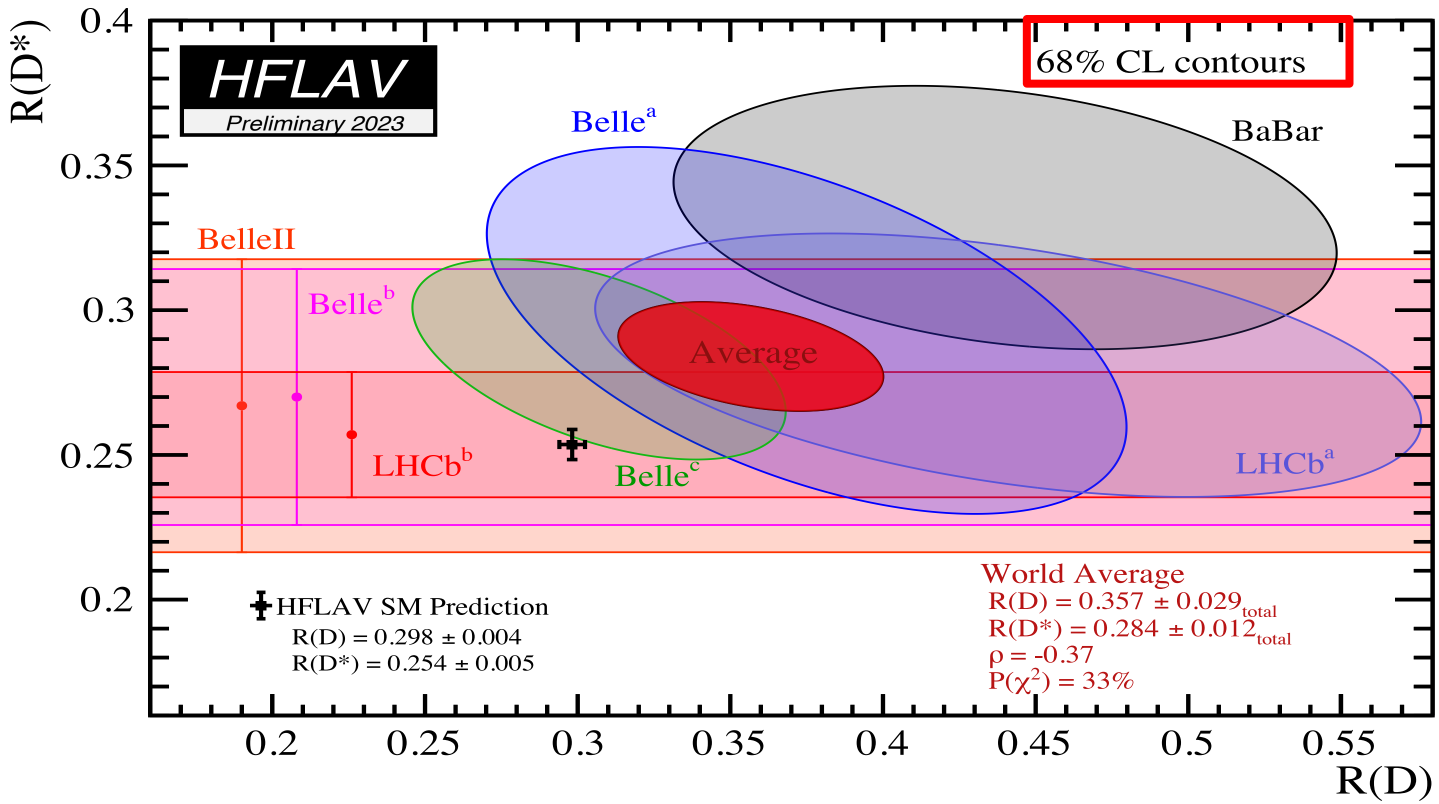
NEW

New measurement of R(D*) (hadronic tau decay)

- World average 3.3σ to 3.2σ to 3.34σ

LHCb[b]	0.267 ± 0.012 ± 0.019

LHCb, arXiv:2305.01463 Phys. Rev. D108 (2023) 012018



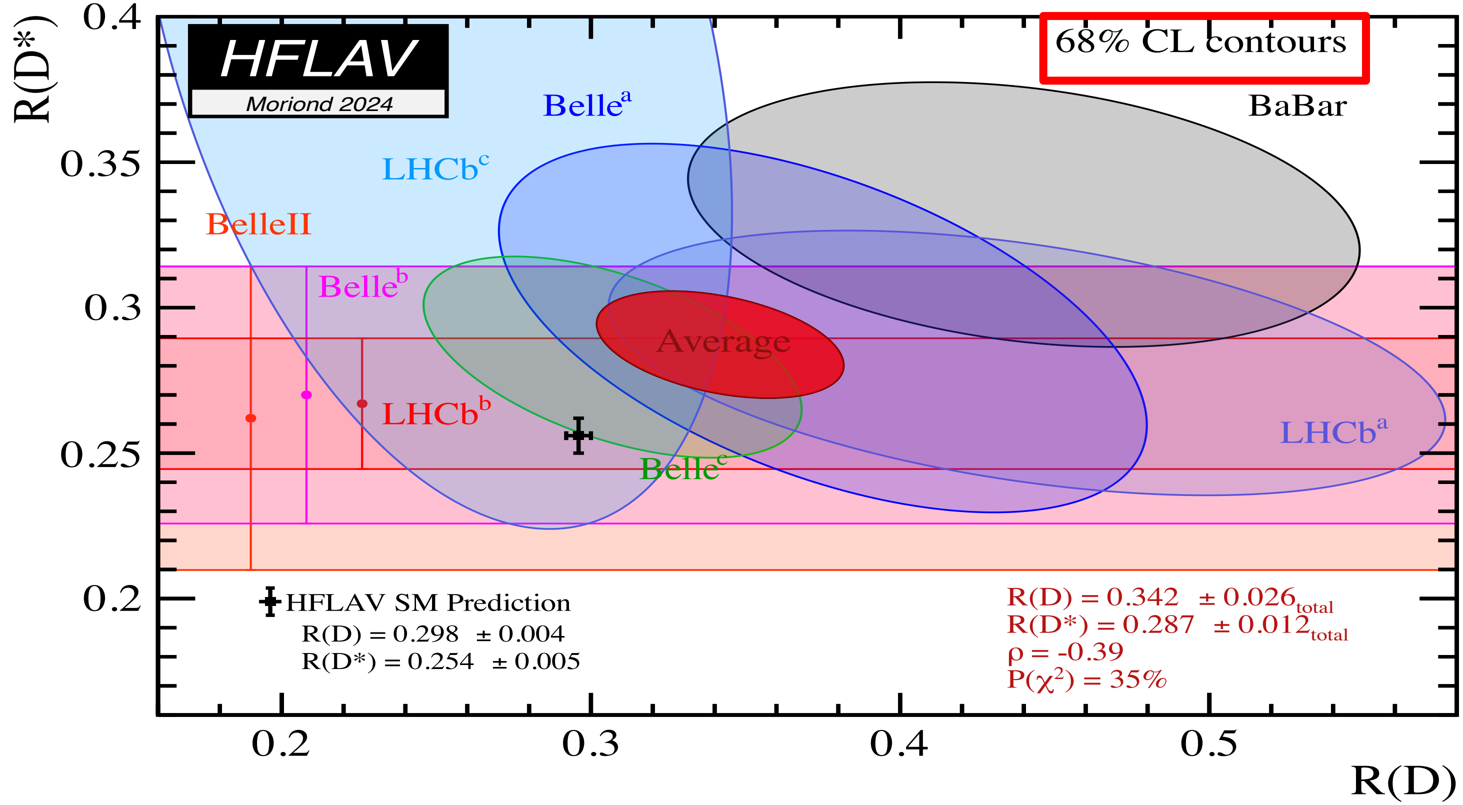
https://hflav-eos.web.cern.ch/hflav-eos/semi/fall22/html/RDsDsstar/RDRDs.html

New measurement of R(D⁺), R(D*⁺)(muonic tau decay)

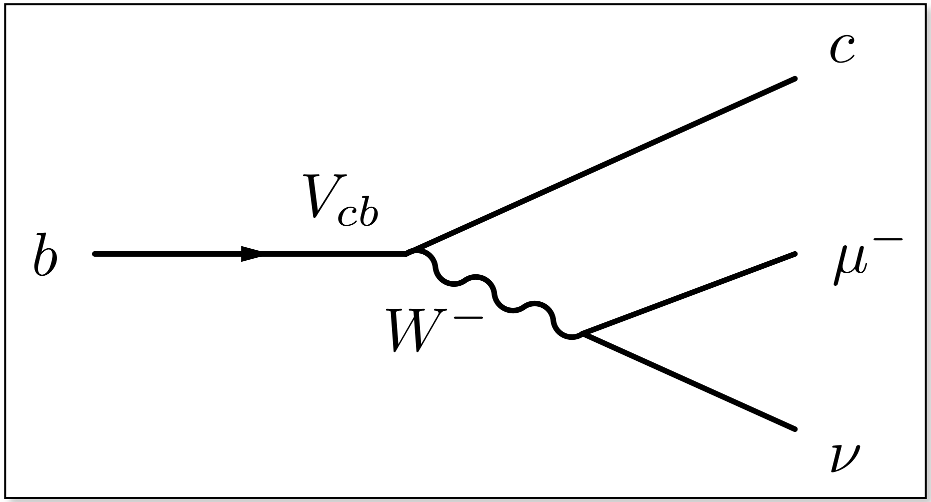
- World average 3.3σ to 3.2σ to 3.34σ to 3.33σ

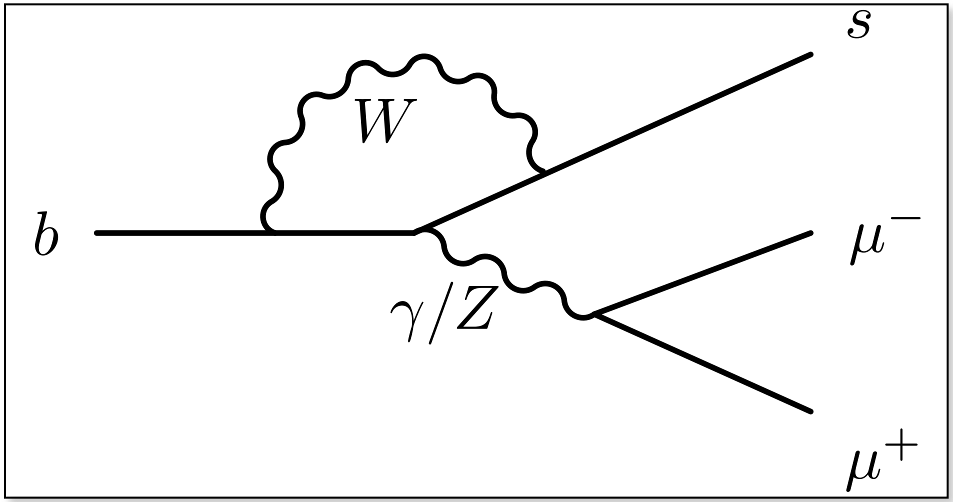
LHCb[c]	0.402 ± 0.081 ± 0.085	0.249 ± 0.043 ± 0.047

LHCb, arXiv:2406.03387



CC and FCNC



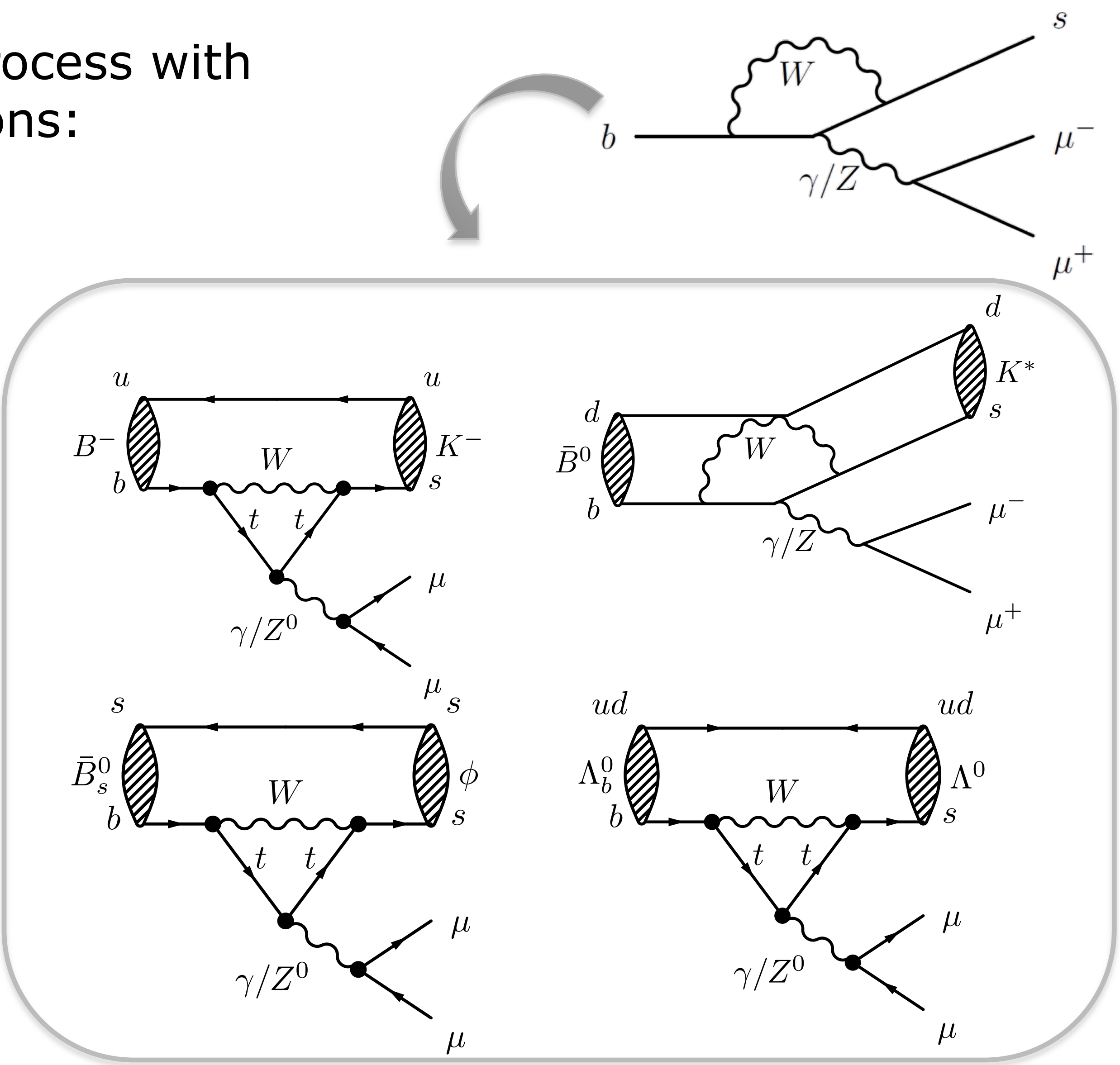


Semileptonic
CC
$b \rightarrow c l^- \nu$

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

Decay rates

- Study same process with different hadrons:

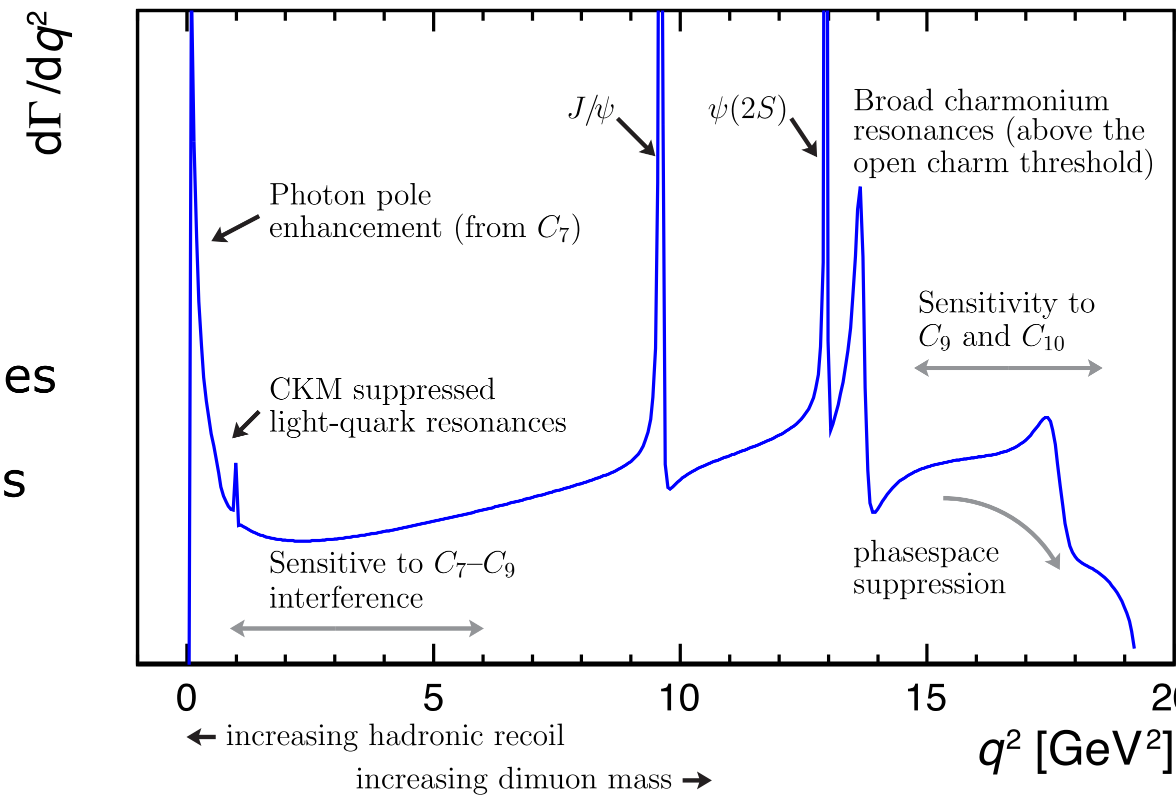


b→sl⁺l⁻

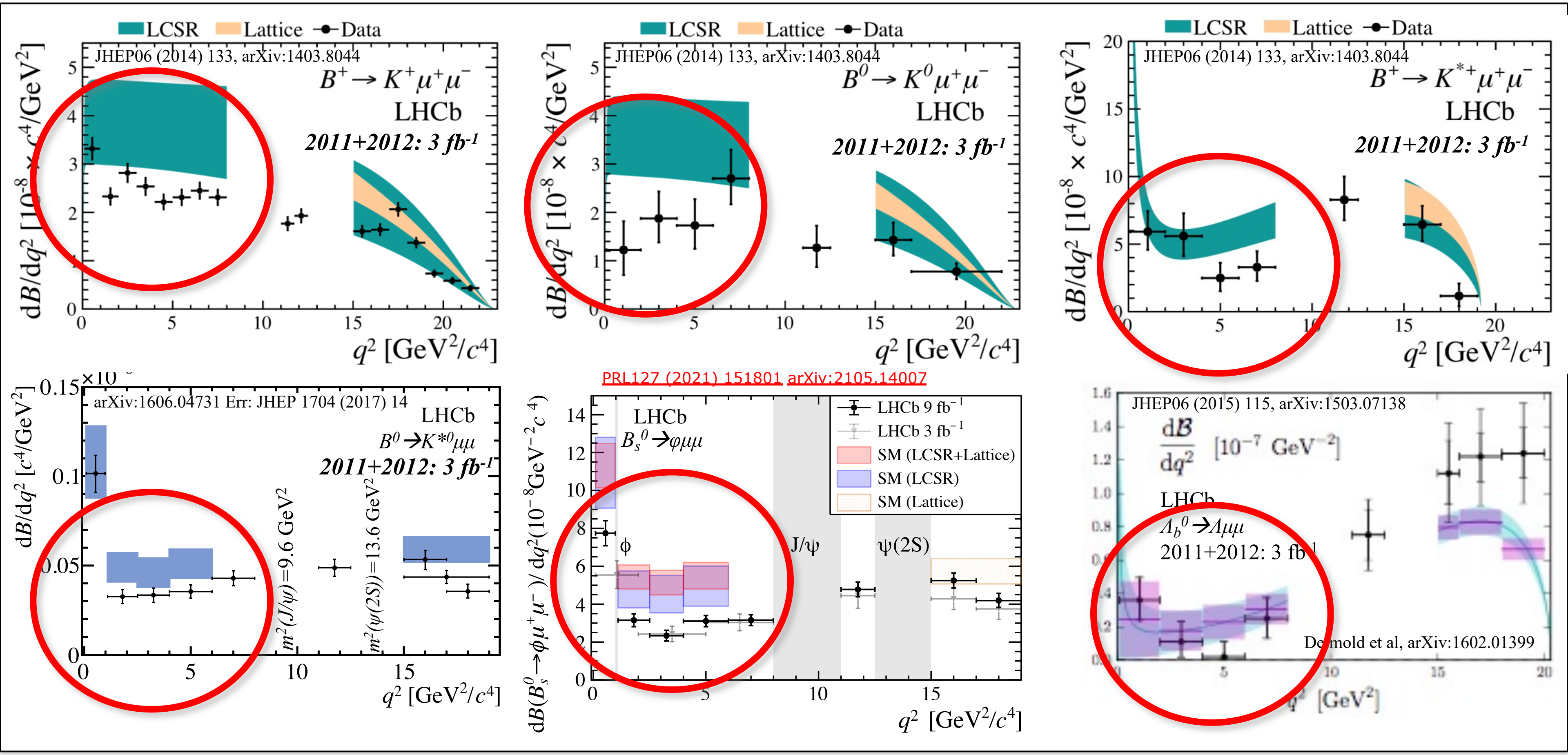
Rich laboratory:

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

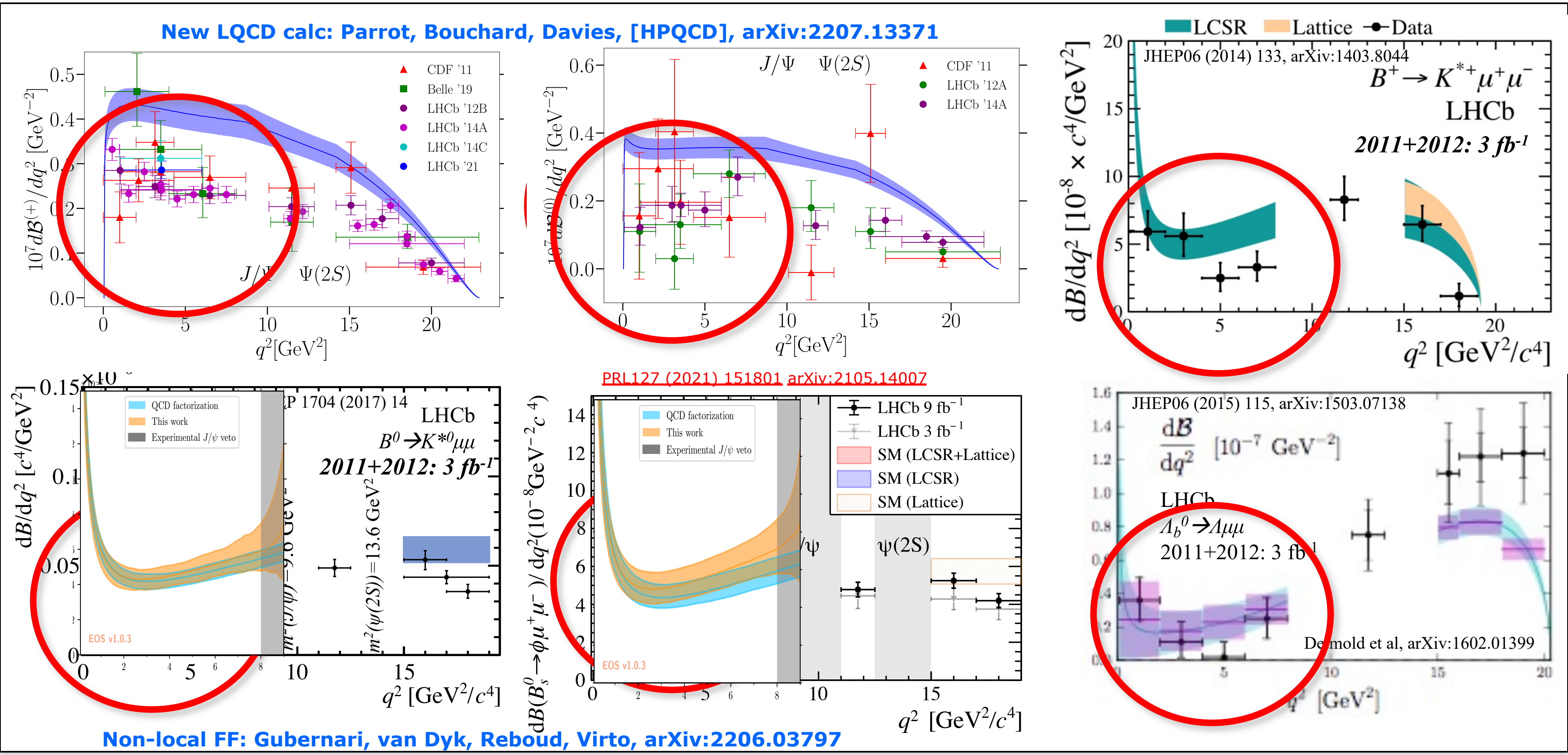
T.Blake et al. arXiv:1606.00916



Decay rates: consistently low

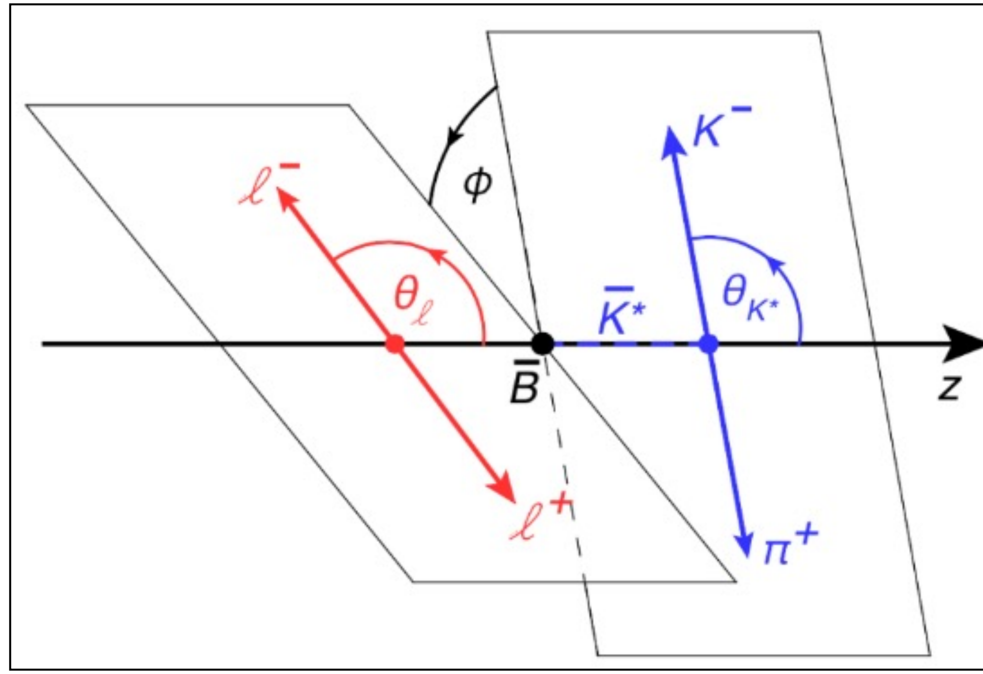


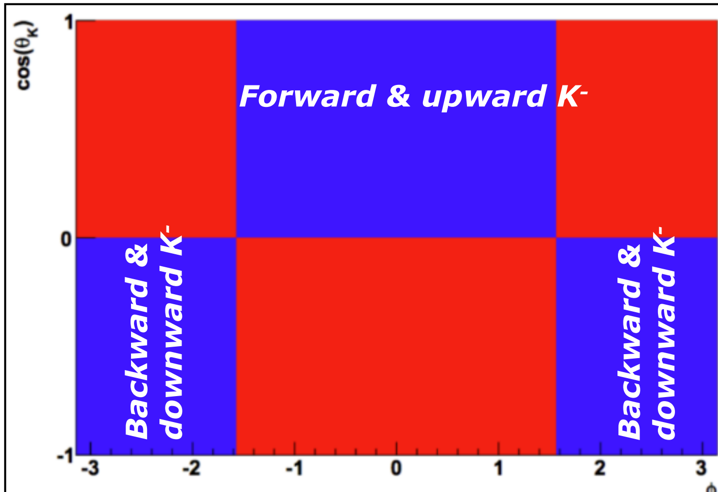
Decay rates: consistently low



Angular asymmetries

P_5':

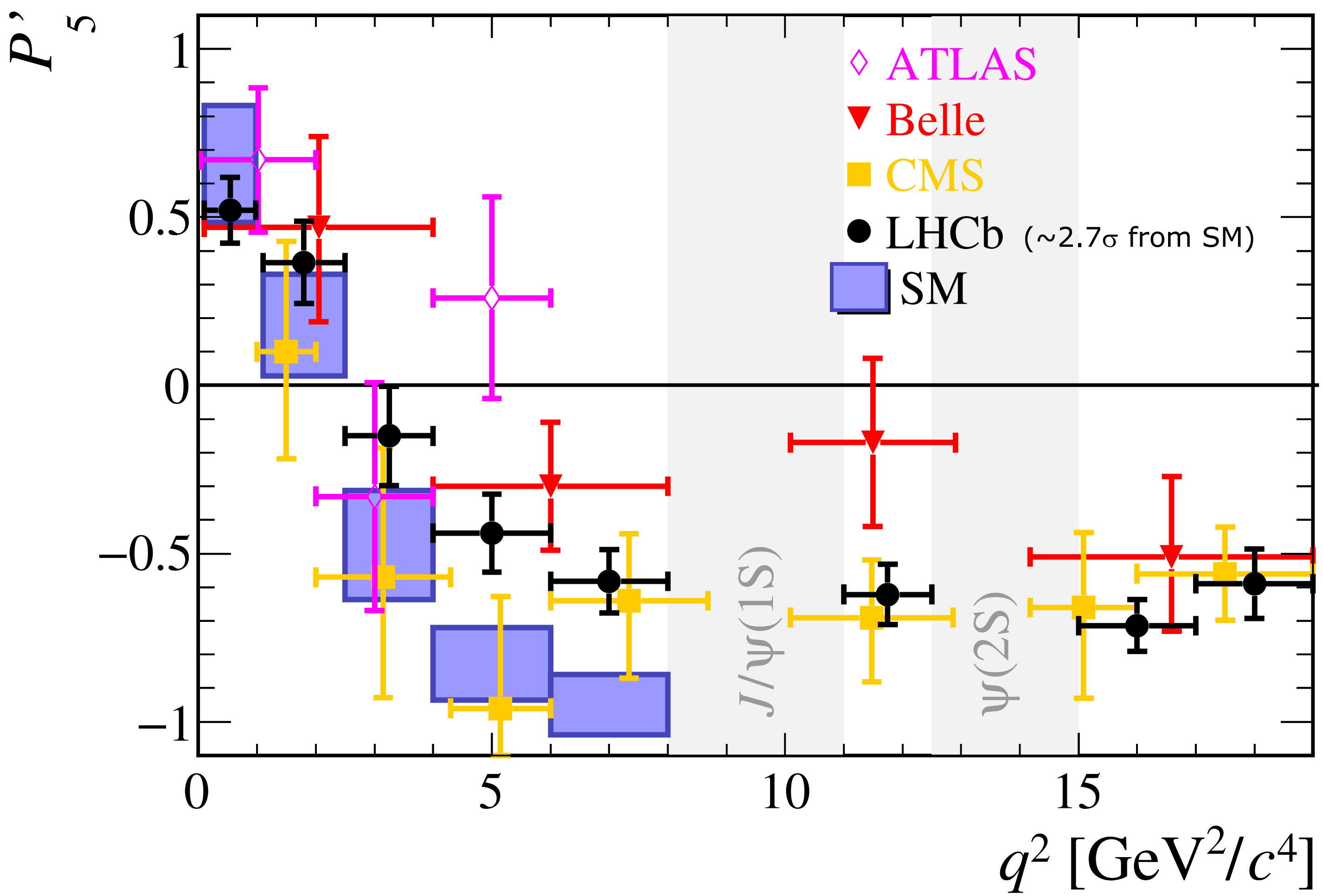




Counting S_5: blue minus red

Angular asymmetries: eg. P_5'

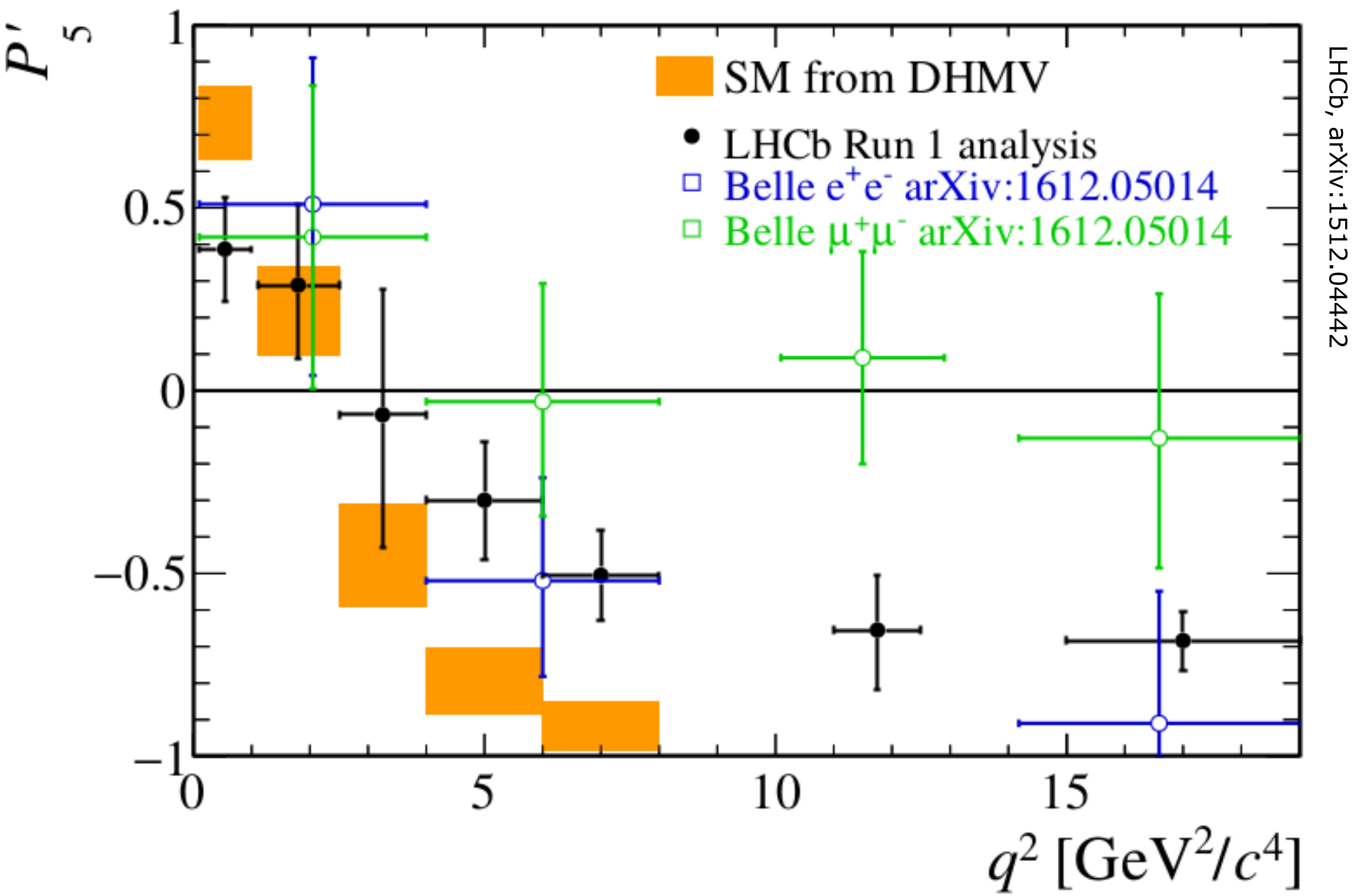
- Compilation:



LHCb, arXiv:2003.04831 Phys. Rev. Lett. 125 (2020) 011802
Plot from:
Albrecht, van Dyk, Langenbruch, PIPNP120 (2021) 103885, arXiv:2107.04822

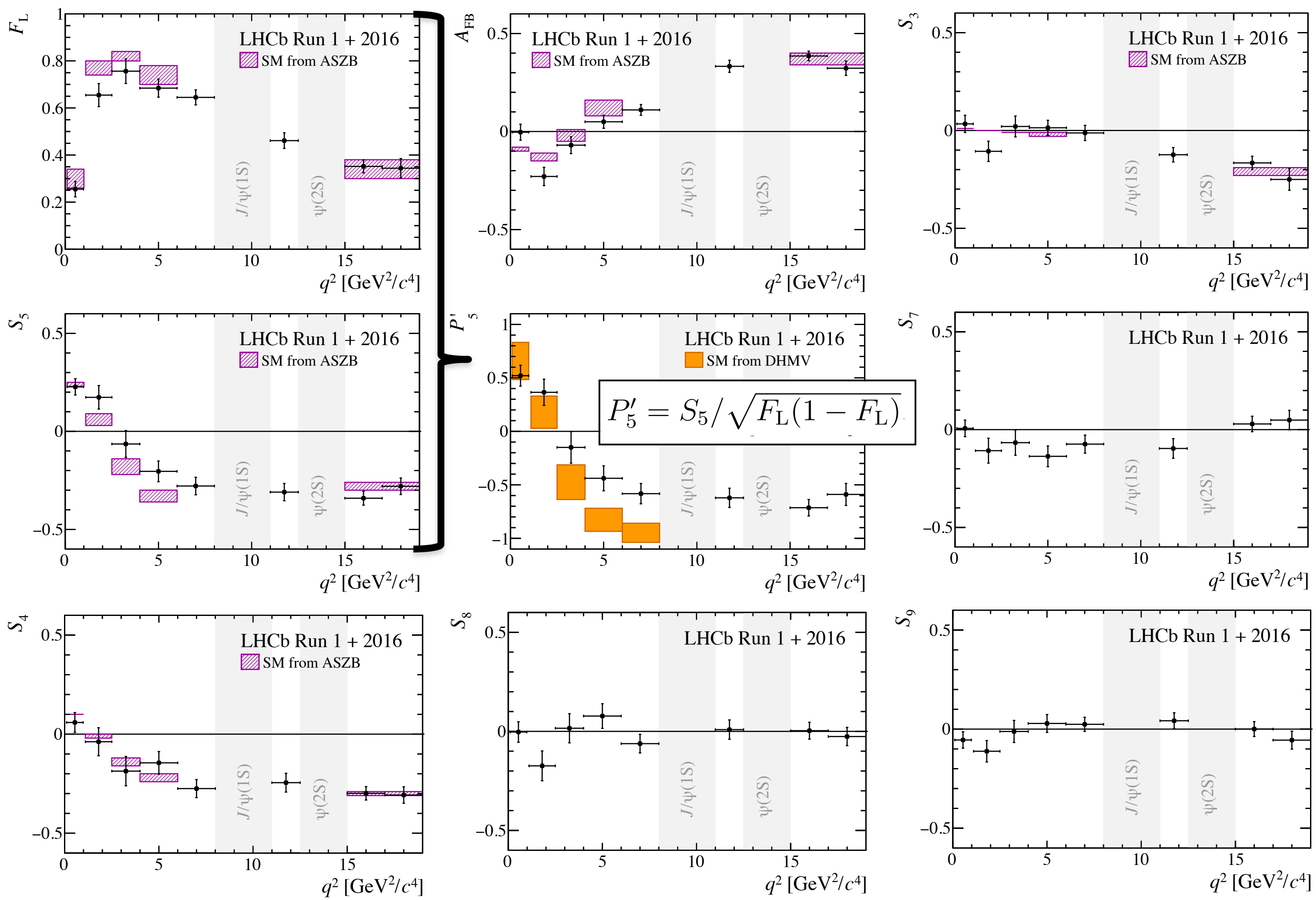
Angular asymmetries

- Interesting to compare angular asymmetries for μ and e



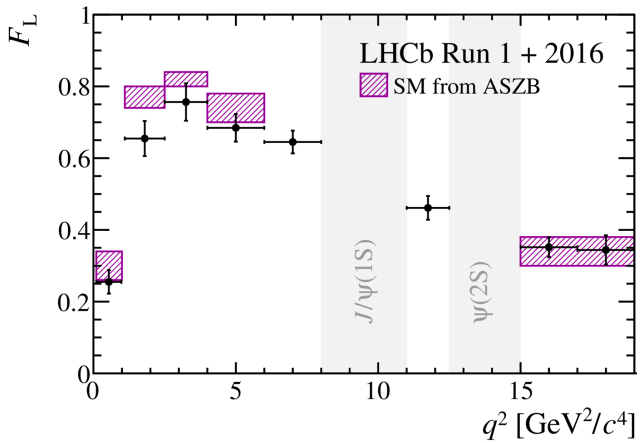
$B^0 \to K^{0*}\mu^+\mu^-$: more than just P_5'

LHCb Coll, arXiv:2003.04831

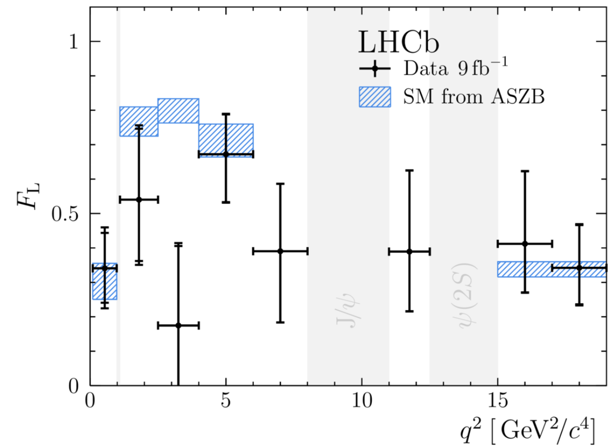


Coherent pattern

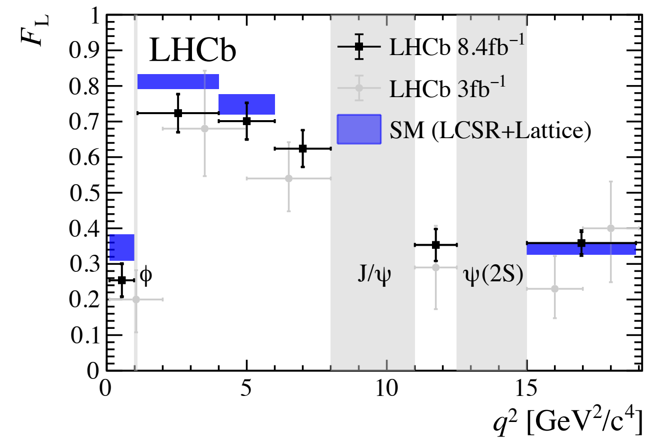
arXiv:2003.04831: $B^0 \to K^{*0}\mu^+\mu^-$

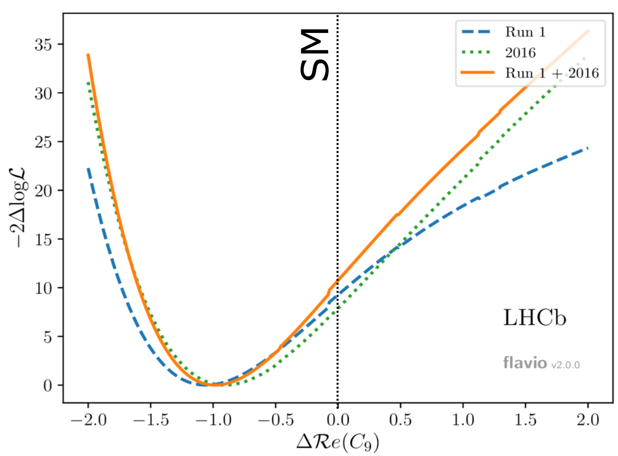


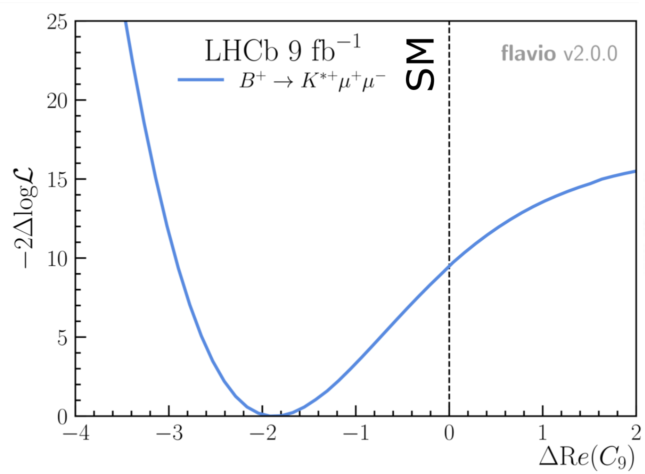
arXiv:2012.13241: $B^+ \to K^{*+}\mu^+\mu^-$

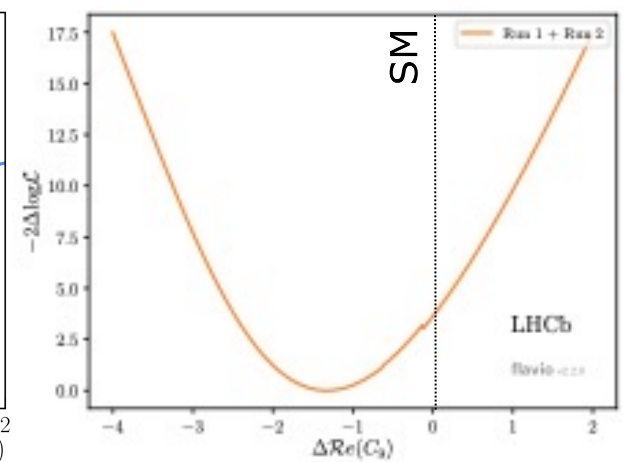


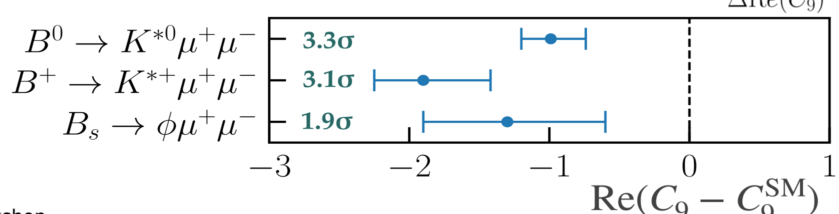
arXiv:2107.13428: $B^0_s \to \phi\mu^+\mu^-$









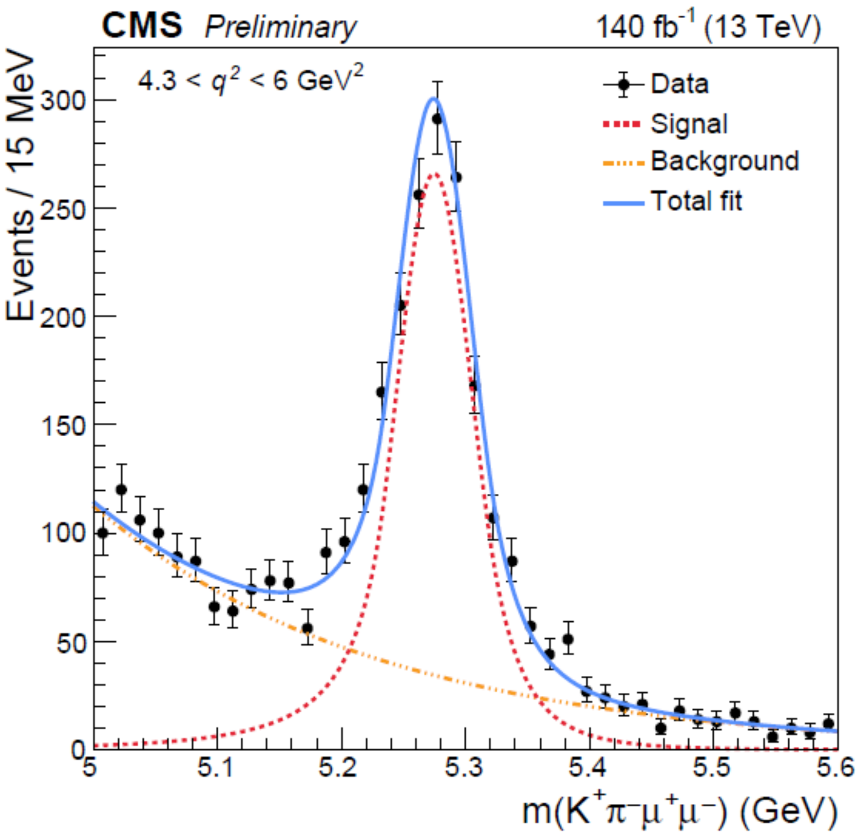


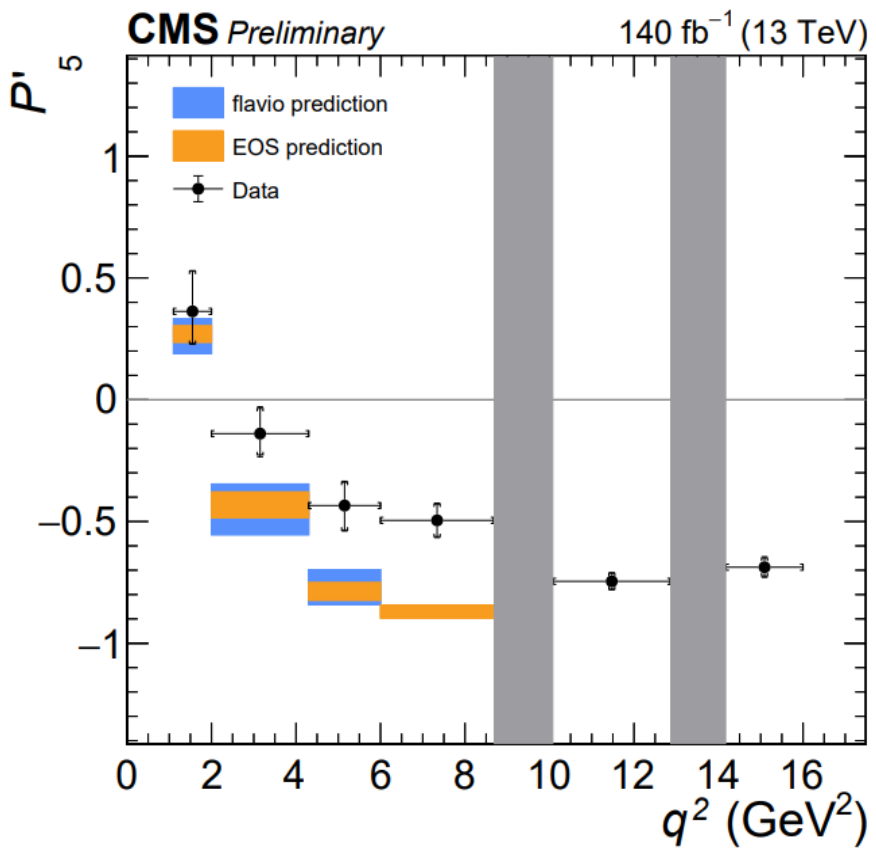
→ New vector coupling?

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

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

- New results with full Run1+Run2 statistics

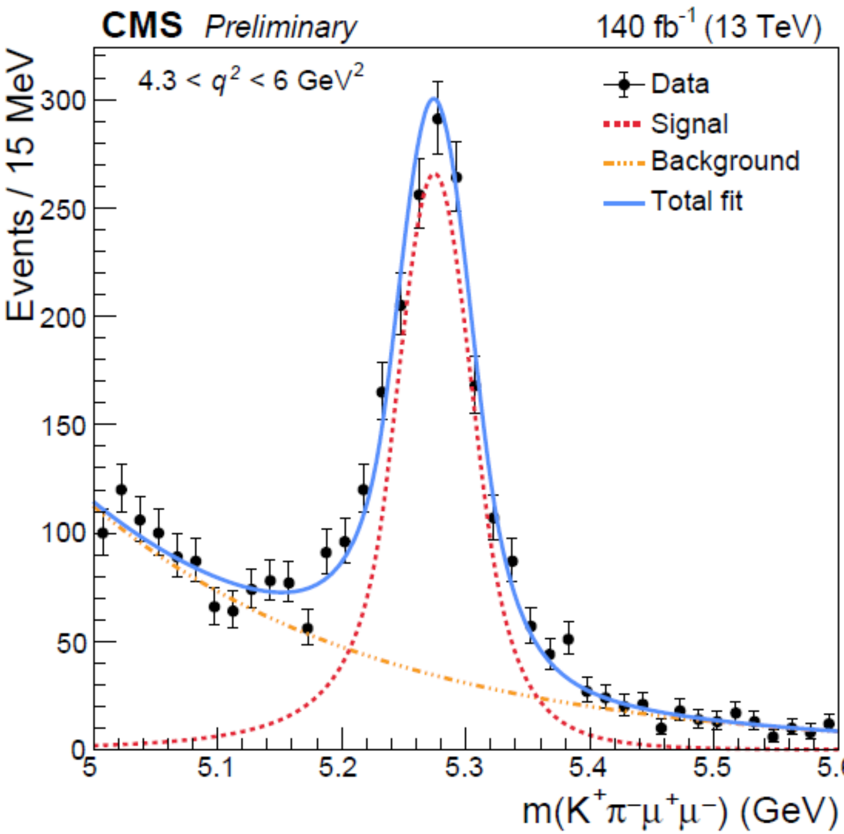


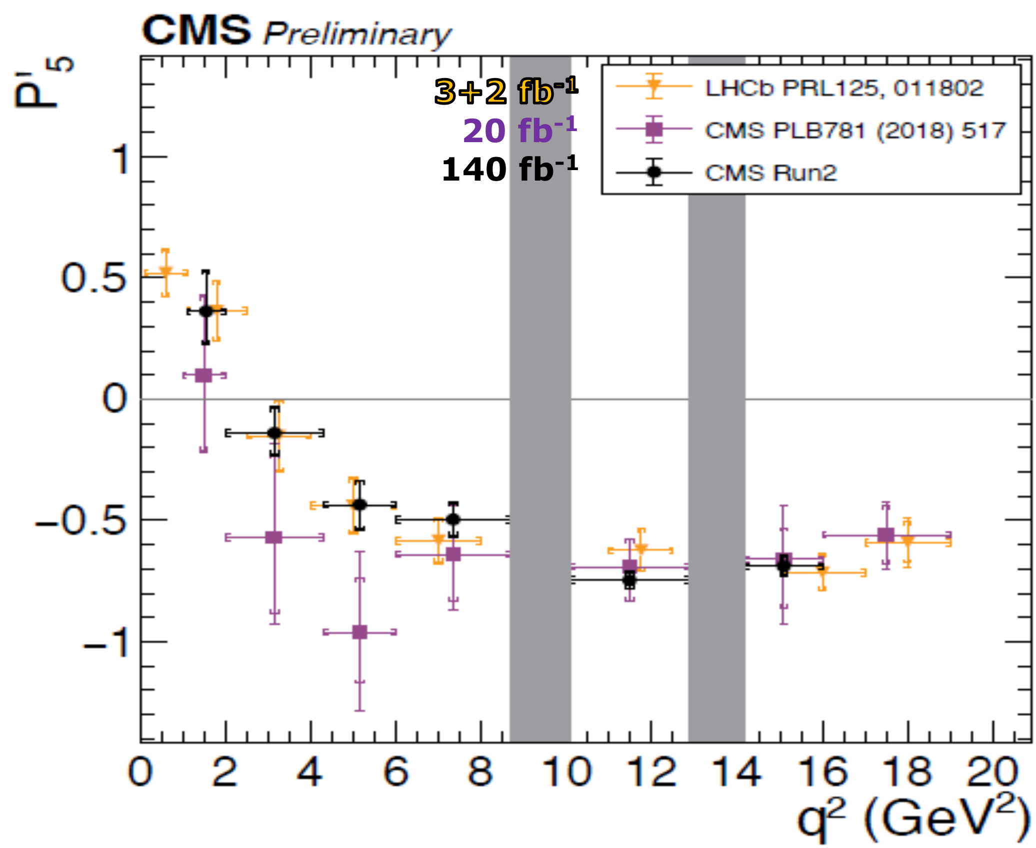


CMS-PAS-BPH-21-002
https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/BPH-21-002/index.html

CMS

- New results with full Run1+Run2 statistics
  - In agreement with LHCb

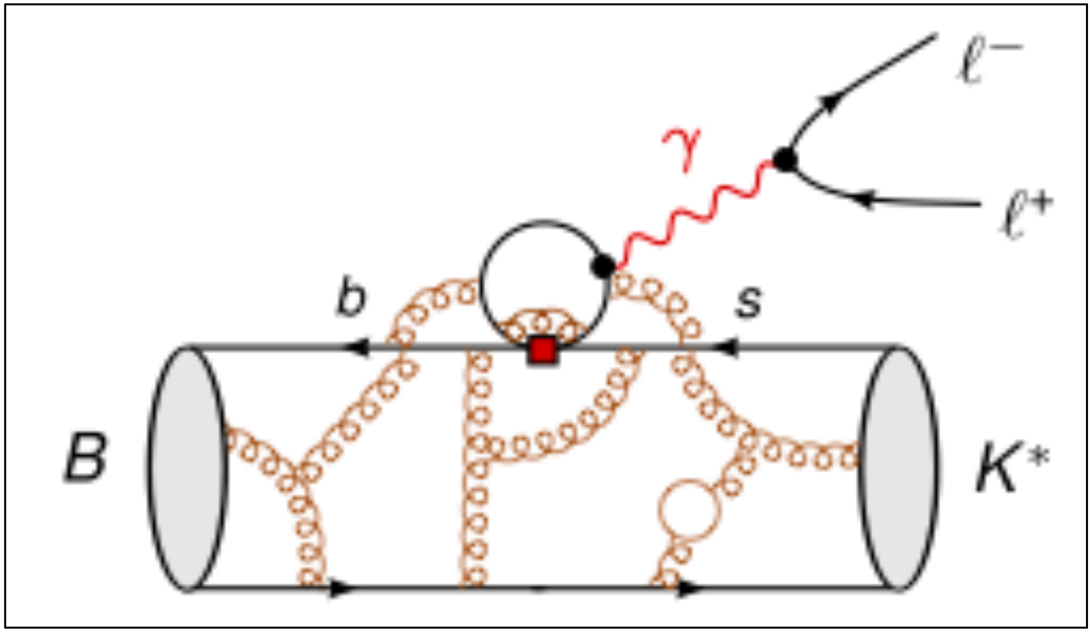


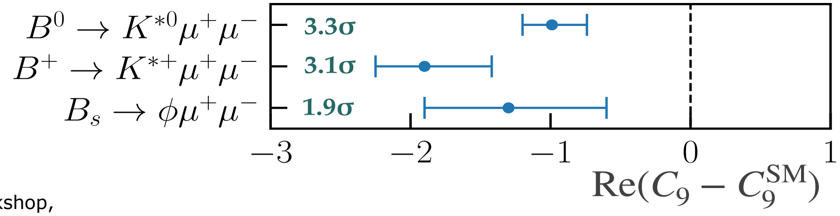


CMS-PAS-BPH-21-002
https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/BPH-21-002/index.html

Coherent pattern

- Charm loop effects could also cause a shift in C_9

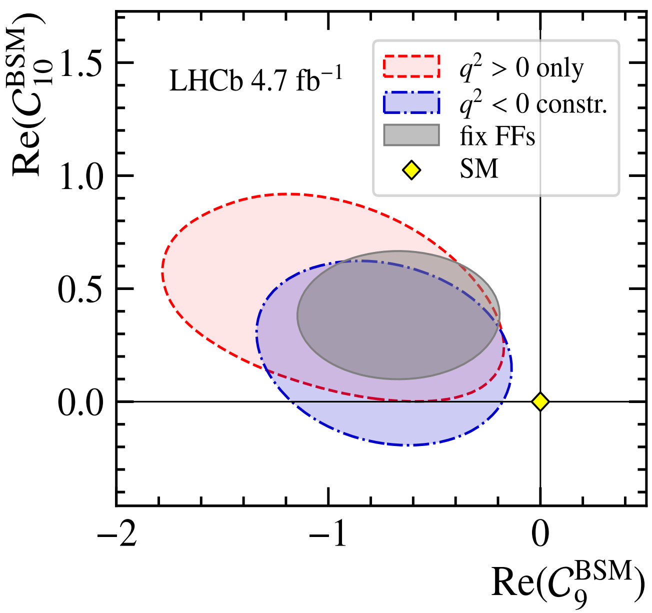


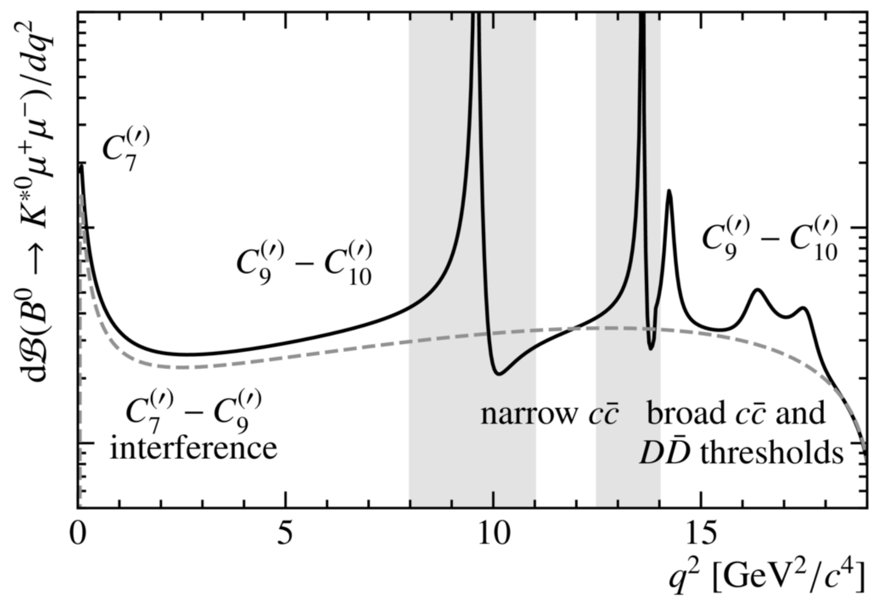


From: Martino Borsato, Flavour Anomaly Workshop, 20 Oct 2021, https://indico.cern.ch/event/1055780/

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

- New analysis without q^2 binning
  - Run-1 + 2016
  - Use *all* the information (resonant decays with J/ψ or $\psi(2S)$ are removed)
  - Control long-distance (non-factorisable) QCD effects ($B^0 \to K^{0*} J/\psi$)
  - ➢ Reduced discrepancy: consistent with SM at 1.8σ (1.4σ global signficance)



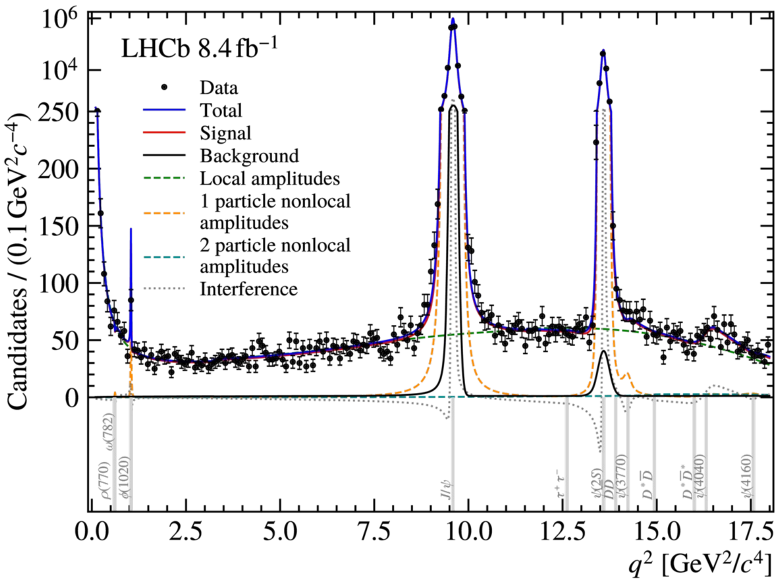


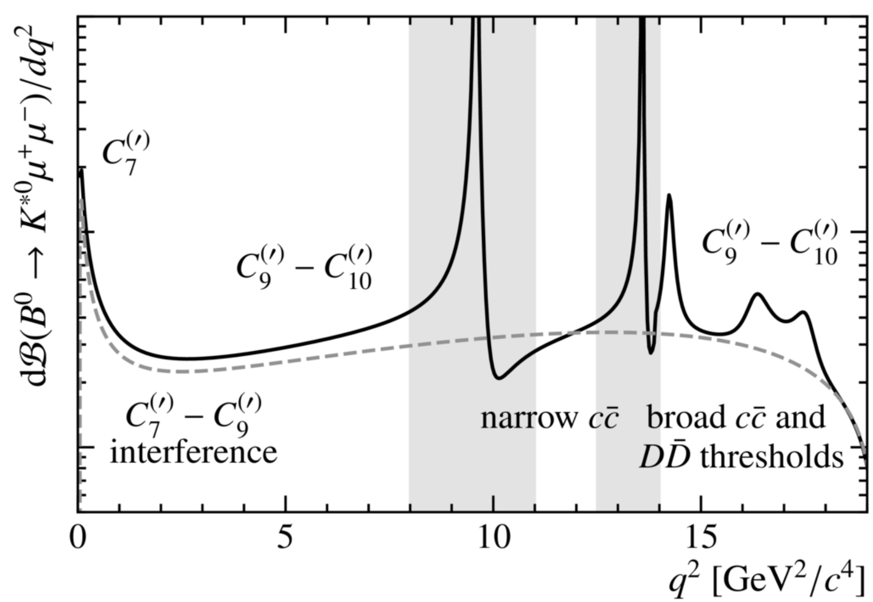
LHCb-PAPER-2023-032/033, arXiv:2312.09102, arXiv:2312.09115

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

NEW

- New analysis without q^2 binning
  - Run-1 + 2016-2018
  - Use *all* the information, in full range $0.1<q^2<18$ GeV^2
  - Control long-distance (non-factorisable) QCD effects ($B^0 \to K^{0*} J/\psi$)
  - ➢ Reduced discrepancy: consistent with SM at 2.1σ (1.5σ global signficance)





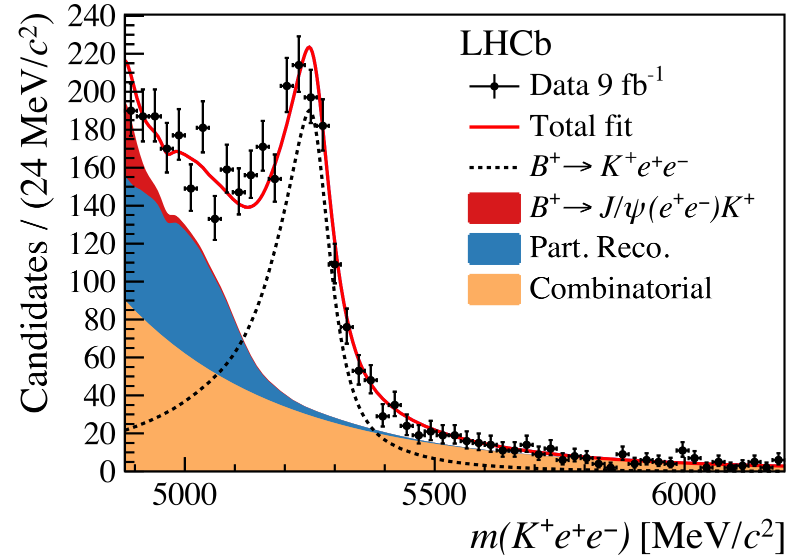
May 2024: LHCb Coll., arXiv:2405.17347

Ratio of decay rates

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

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

Pre 2022



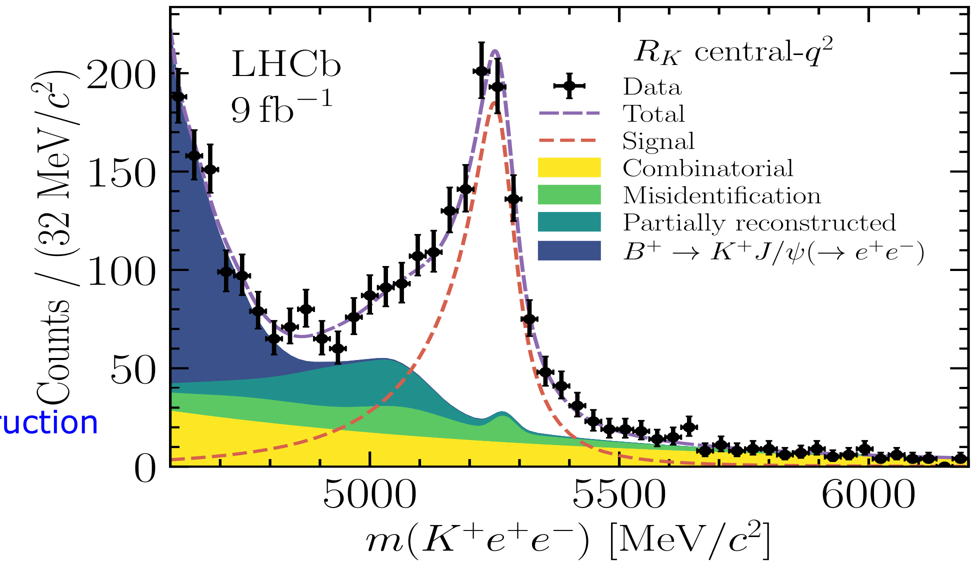
LHCb, arXiv:2103.11769
Nature Physics 18, (2022) 277-282

Ratio of decay rates

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

December 2022

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



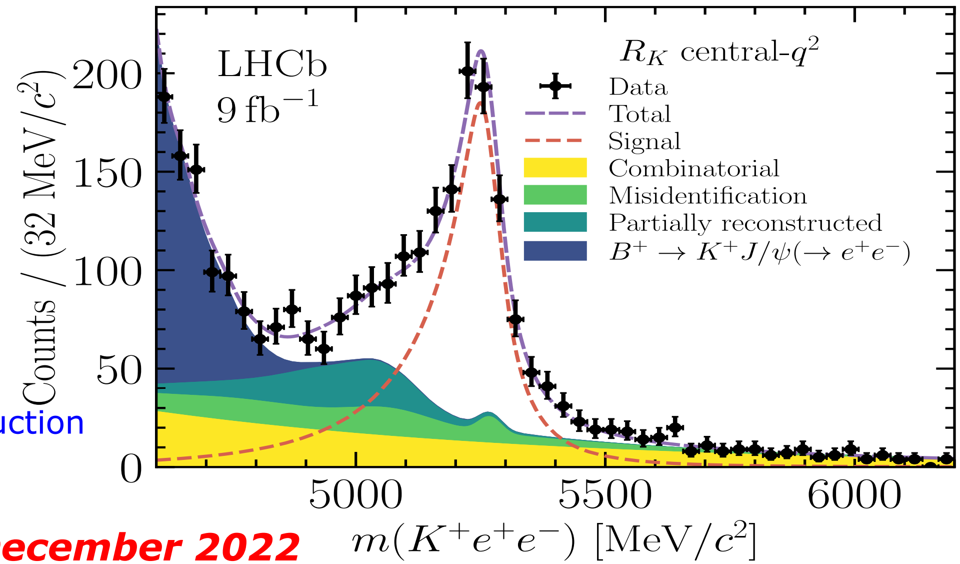
LHCb, arXiv:2212.09152
Phys. Rev. Lett. 131 (2023) 051803

Ratio of decay rates

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

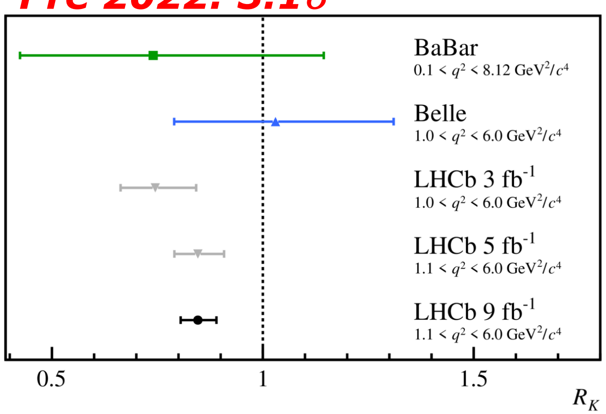
- Theoretically "clean"
- Experimentally
  - Signal yields
  - Backgrounds
  - Electron reconstruction
  - Efficiencies cancel in ratio
  - Belle II: good electron reconstruction
  - LHCb: large B sample

December 2022

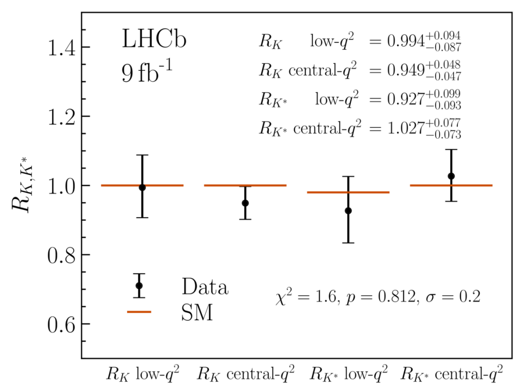


LHCb, arXiv:2212.09152
Phys. Rev. Lett. 131 (2023) 051803

Pre 2022: 3.1σ



December 2022



- Tightening electron PID
  - Led to uncovering previously underestimated peaking backgrounds
  - Estimated from data by inverting mis-id cuts and forming control regions

Outline

- CKM elements
  - sin2β
  - γ
  - Δm_s
  - V_{ub}
- Anomalies
  - $b \rightarrow c\ \tau\nu$
  - $b \rightarrow s\ \ell^+ \ell^-$
- Hadron physics
  - Heavy ion programme
  - Spectroscopy
- Prospects
  - Upgrade II

Future Plans

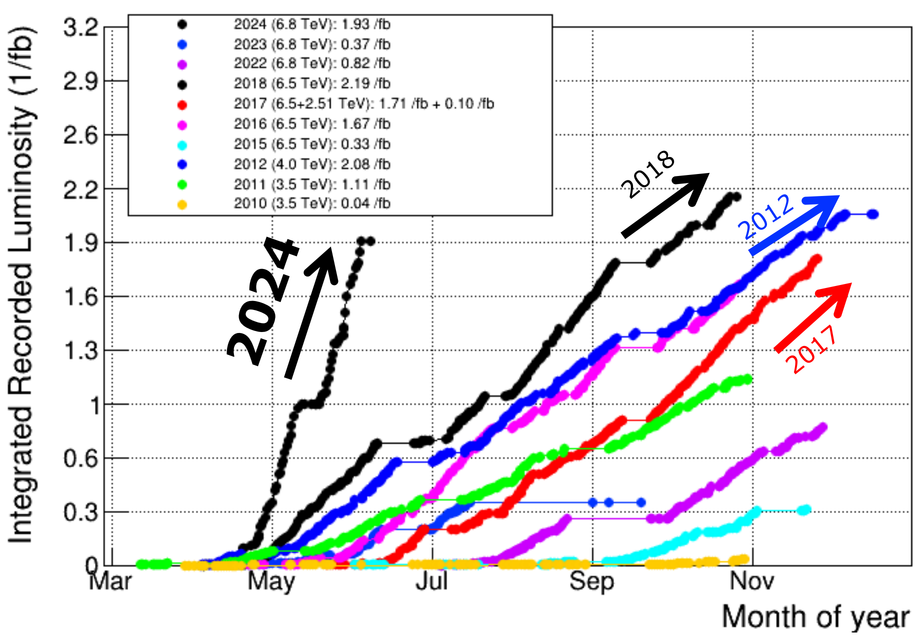
2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035+
			Run III						Run IV					Run V
LS2						**LS3**						**LS4**		
LHCb 40 MHz **UPGRADE I**			$L = 2 \times 10^{33}$		**LHCb** **Consolidate**				$L = 2 \times 10^{33}$ $50\ fb^{-1}$			**LHCb** **UPGRADE II**		$L = 1\text{-}2 \times 10^{34}$ $300\ fb^{-1}$
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

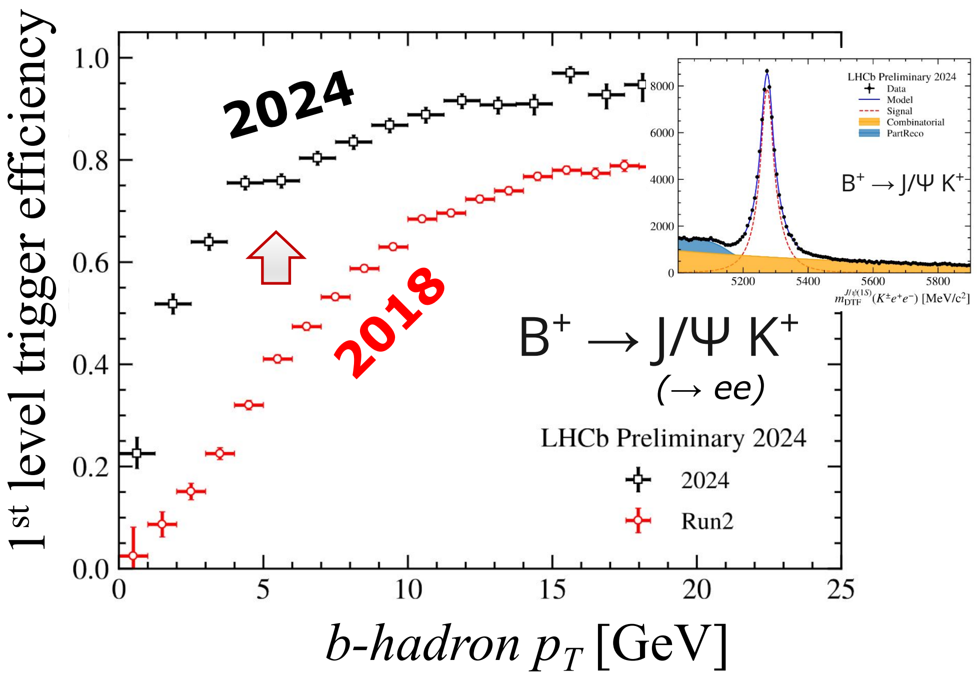
You are here!

LHCb is back 🤩

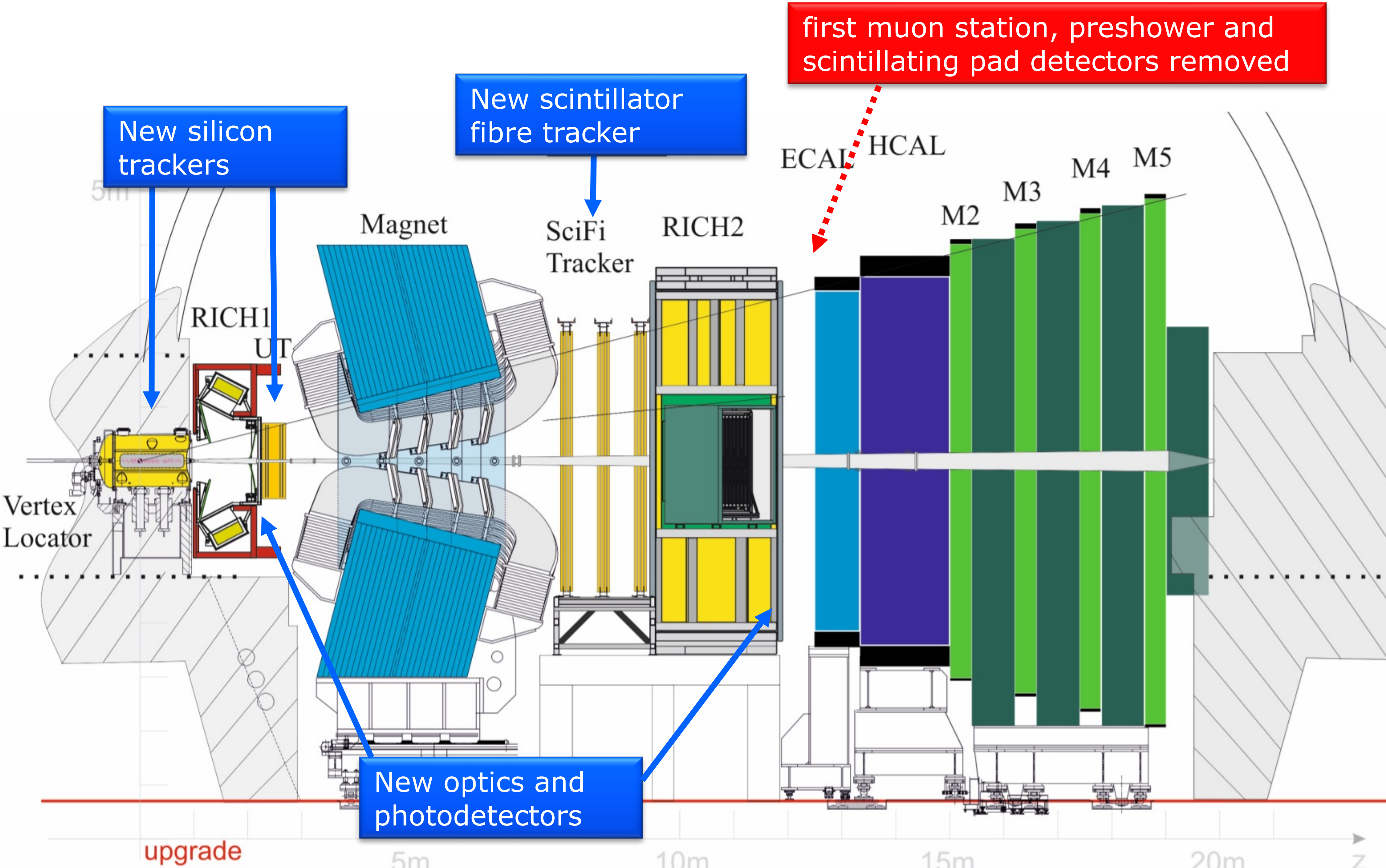
1) More luminosity



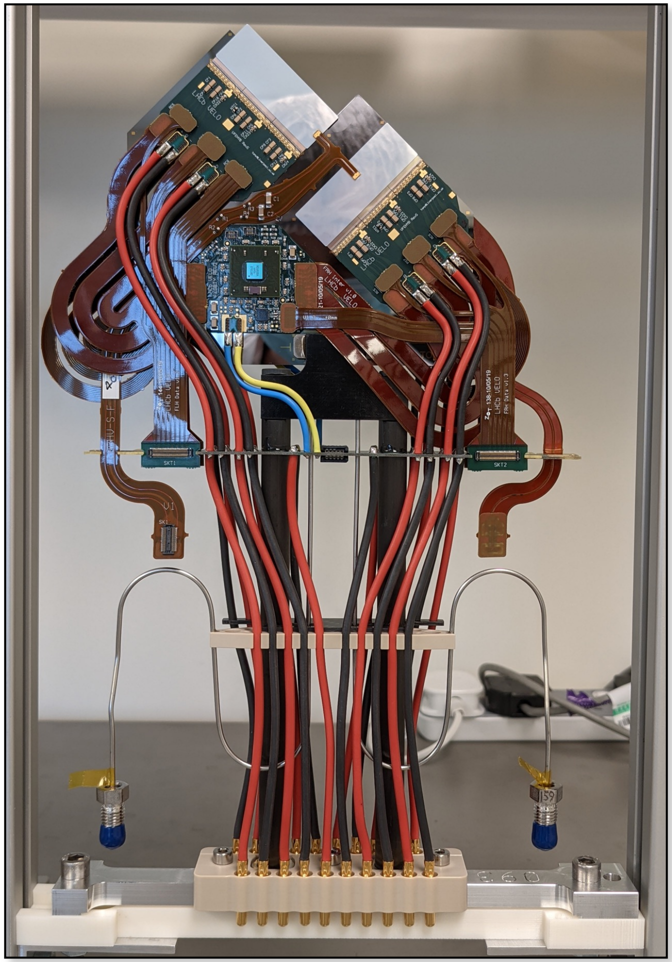
2) Better trigger

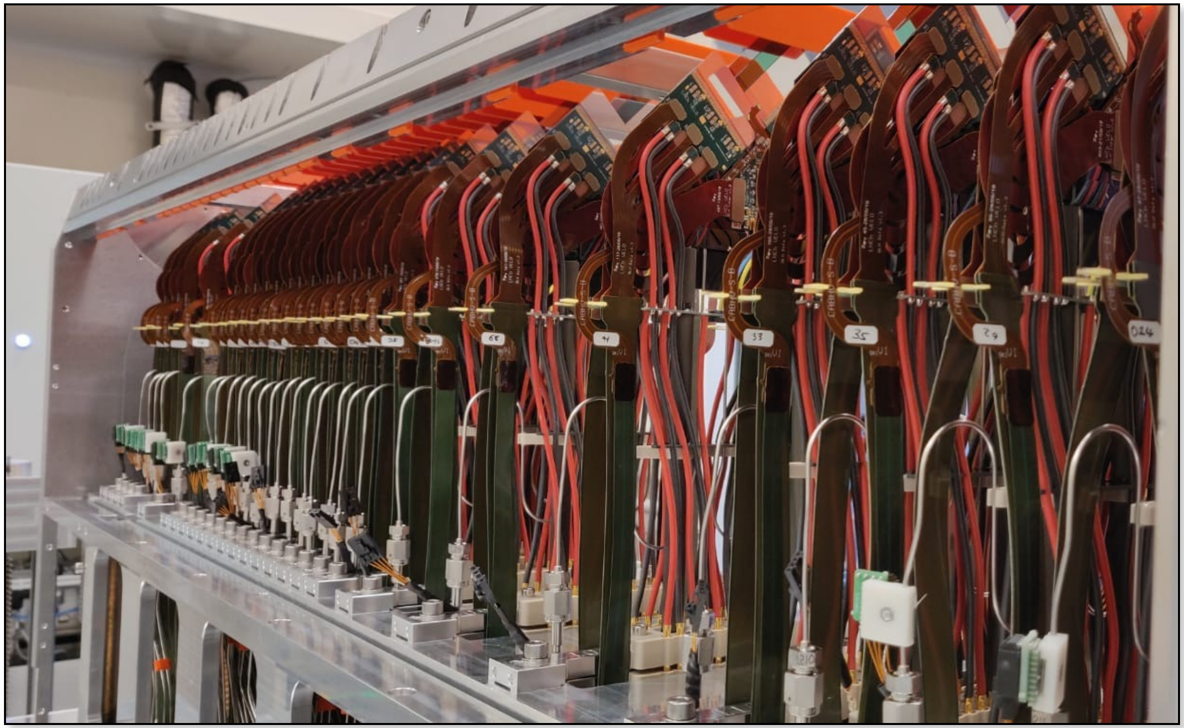


New detector since 2022 !

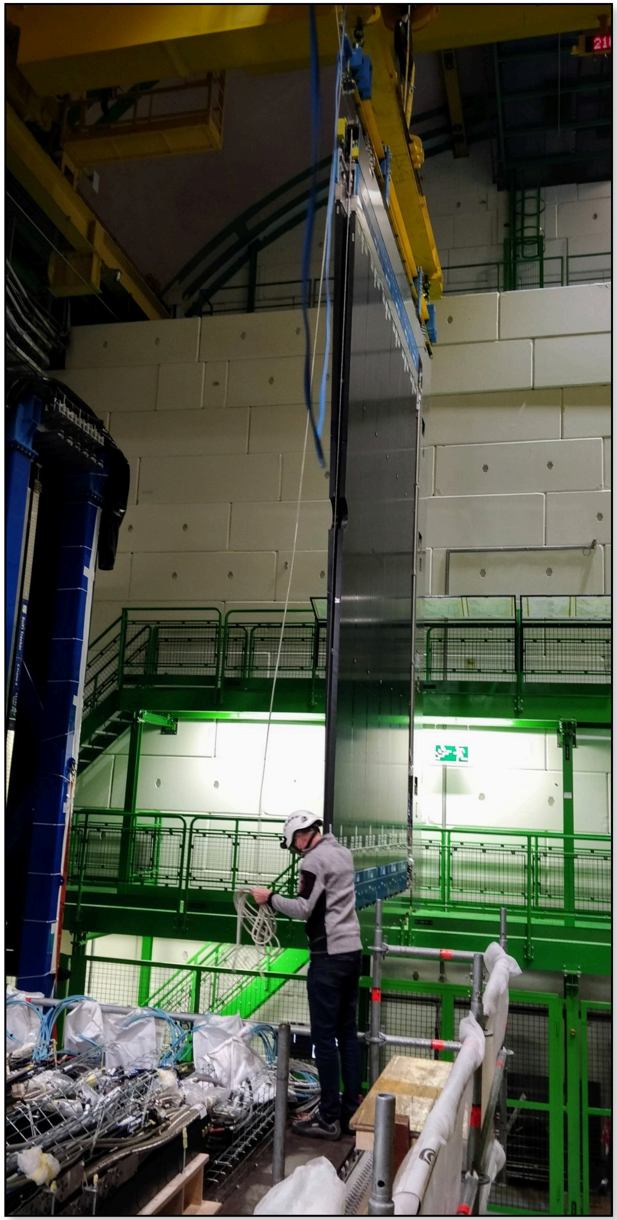


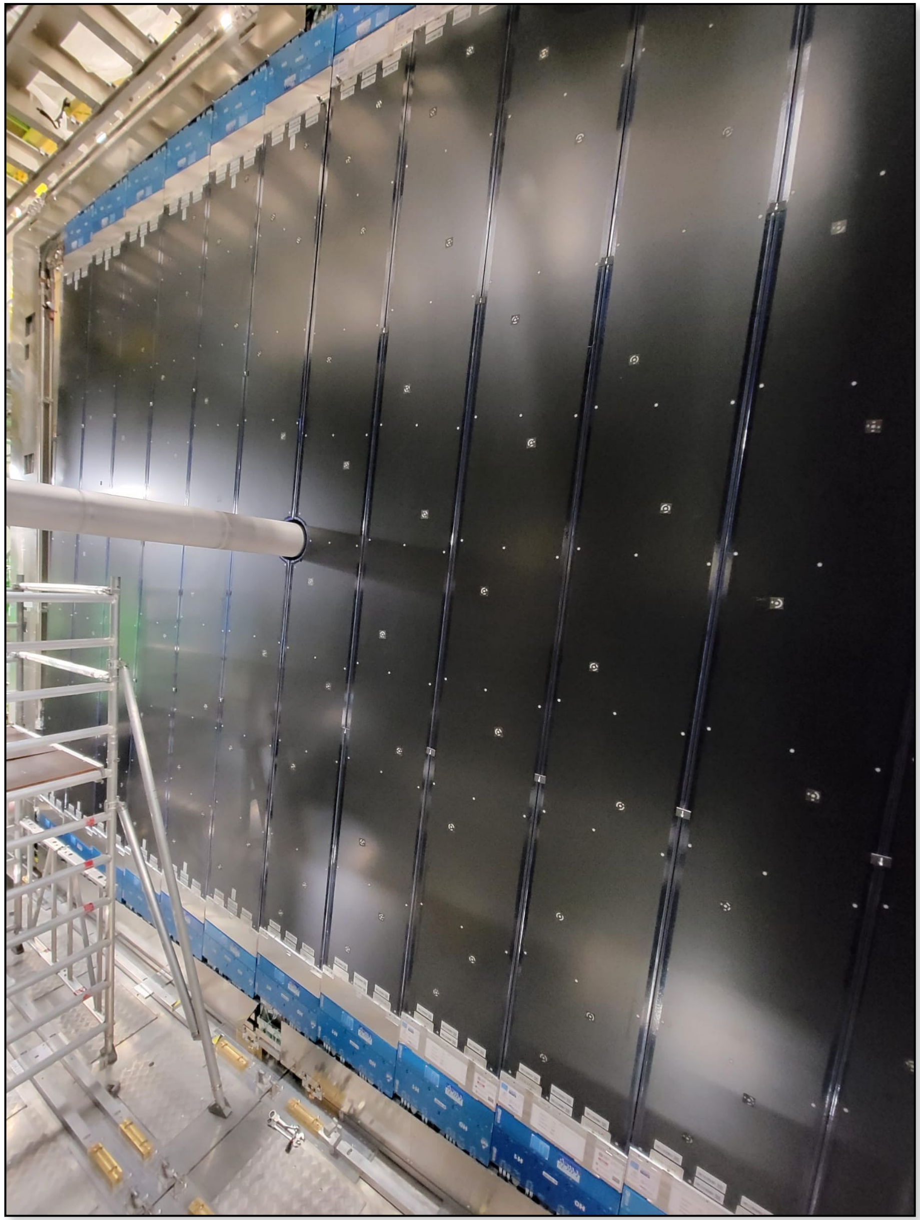
VELO (pixel)



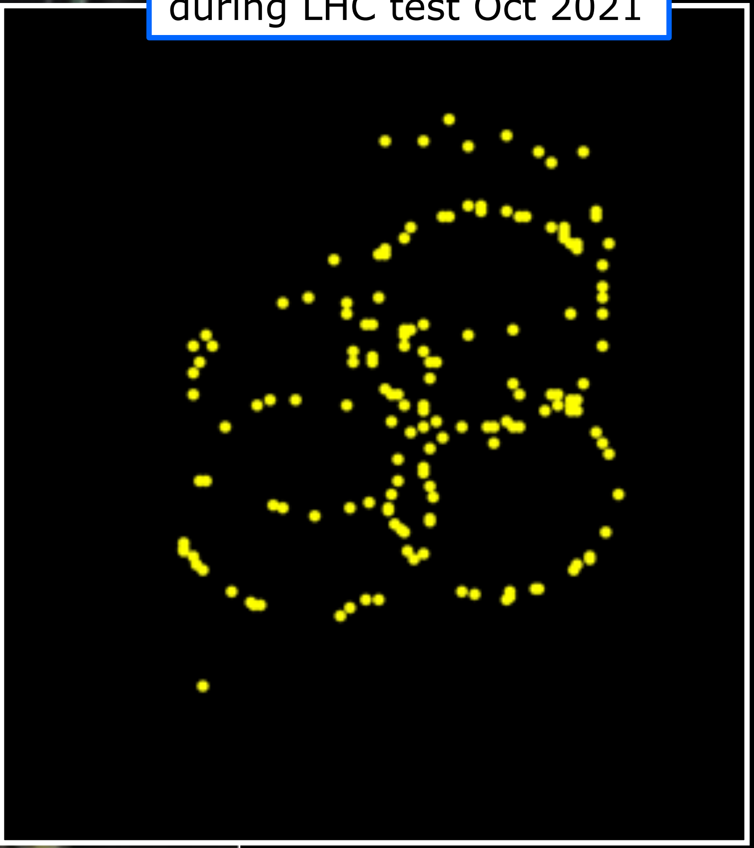


Tracker (scintillating fibers with SiPM)





Ring Imaging Cherenkov

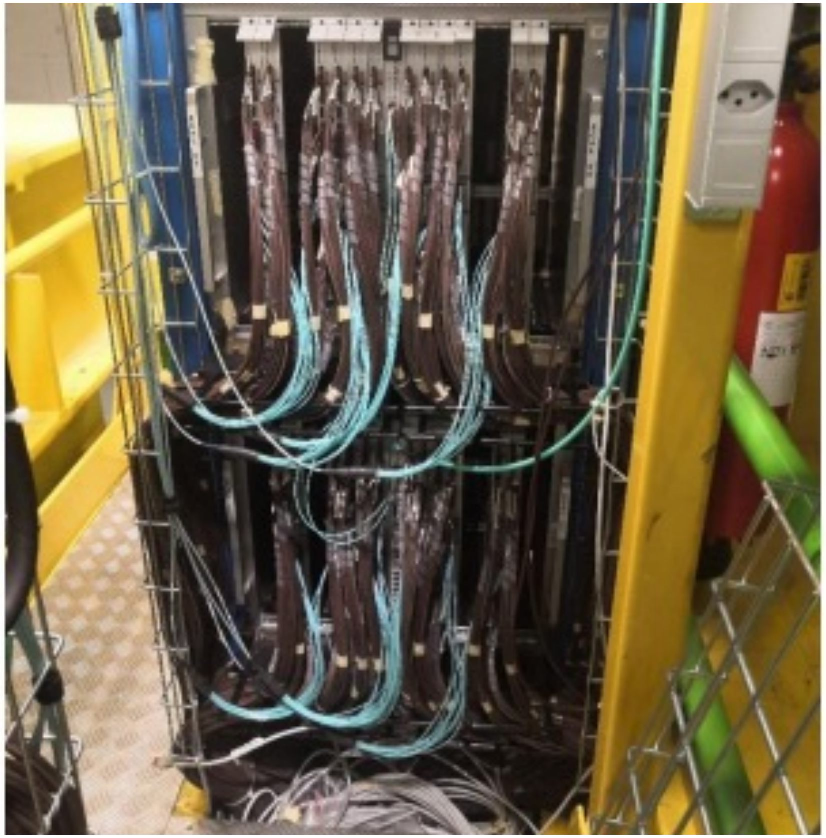


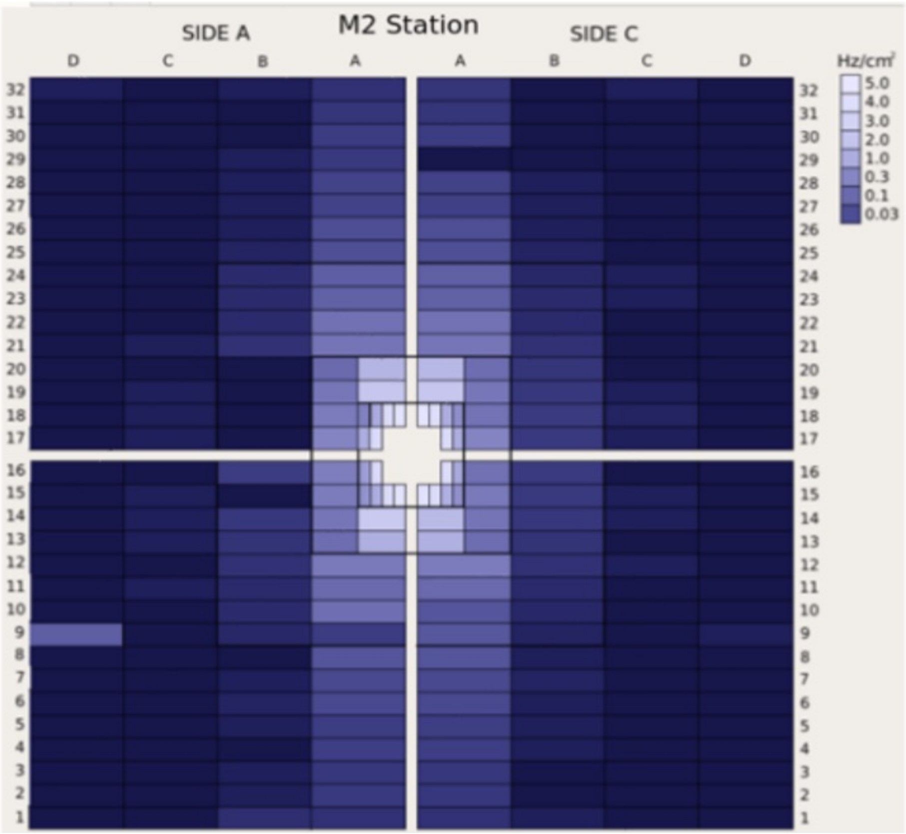
First rings in RICH2
during LHC test Oct 2021

Calorimeter & Muon detector (new electronics)

New CALO frontend and control boards

MUON Station 2 Hit map





… and beyond!

2021	2022–2025	2026–2028	2029–2032	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	$L = 3 \times 10^{35}$	$7\ ab^{-1}$	$L = 6 \times 10^{35}$	$50\ ab^{-1}$	

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

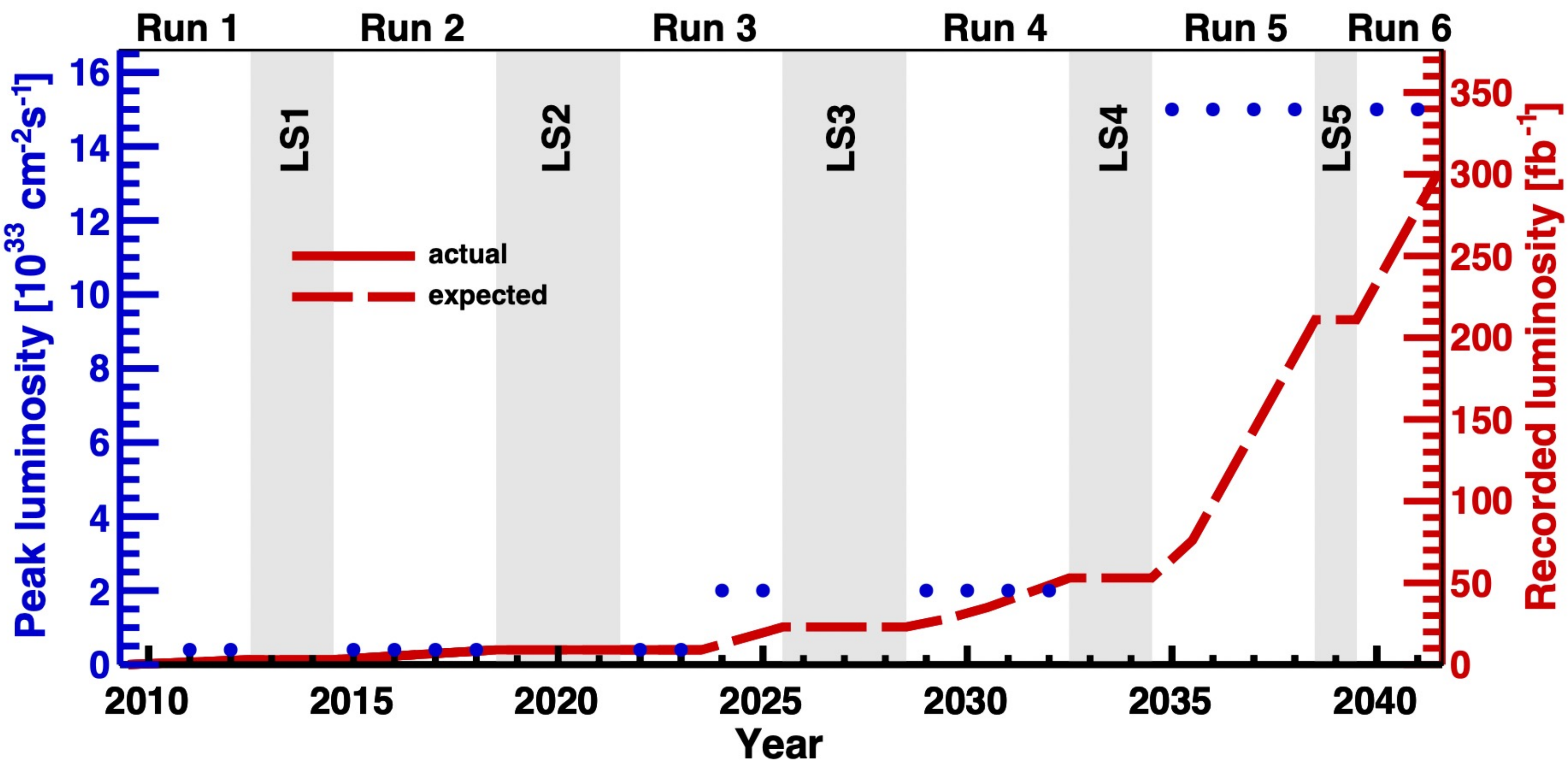
Planning for Upgrade II: many analyses stat. limited

Observable	Current LHCb (up to $9\,\text{fb}^{-1}$)		Upgrade I ($23\,\text{fb}^{-1}$)	Upgrade I ($50\,\text{fb}^{-1}$)
CKM tests				
γ ($B \to DK$, *etc.*)	$4°$	[9, 10]	$1.5°$	$1°$
ϕ_s ($B^0_s \to J/\psi\phi$)	49 mrad	[8]	14 mrad	10 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda^0_b \to p\mu^-\overline{\nu}_\mu$)	6%	[30]	3%	—
a^d_{sl} ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}
a^s_{sl} ($B^0_s \to D^-_s\mu^+\nu_\mu$)	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 ($D^0 \to K^0_{\text{S}}\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}
Rare Decays				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	71%	[40, 41]	34%	—
$S_{\mu\mu}$ ($B^0_s \to \mu^+\mu^-$)	—		—	—
$A^{(2)}_{\text{T}}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043
A^{Im}_{T} ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043
$\mathcal{A}^{\Delta\Gamma}_{\phi\gamma}(B^0_s \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083
$S_{\phi\gamma}(B^0_s \to \phi\gamma)$	0.32	[51]	0.093	0.062
$\alpha_\gamma(\Lambda^0_b \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[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%
$a_{\rm sl}^d$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a_{\rm sl}^s$ ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	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
$A_{\rm T}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\rm T}^{\rm Im}$ ($B^0 \to K^{*0}e^+e^-$)	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

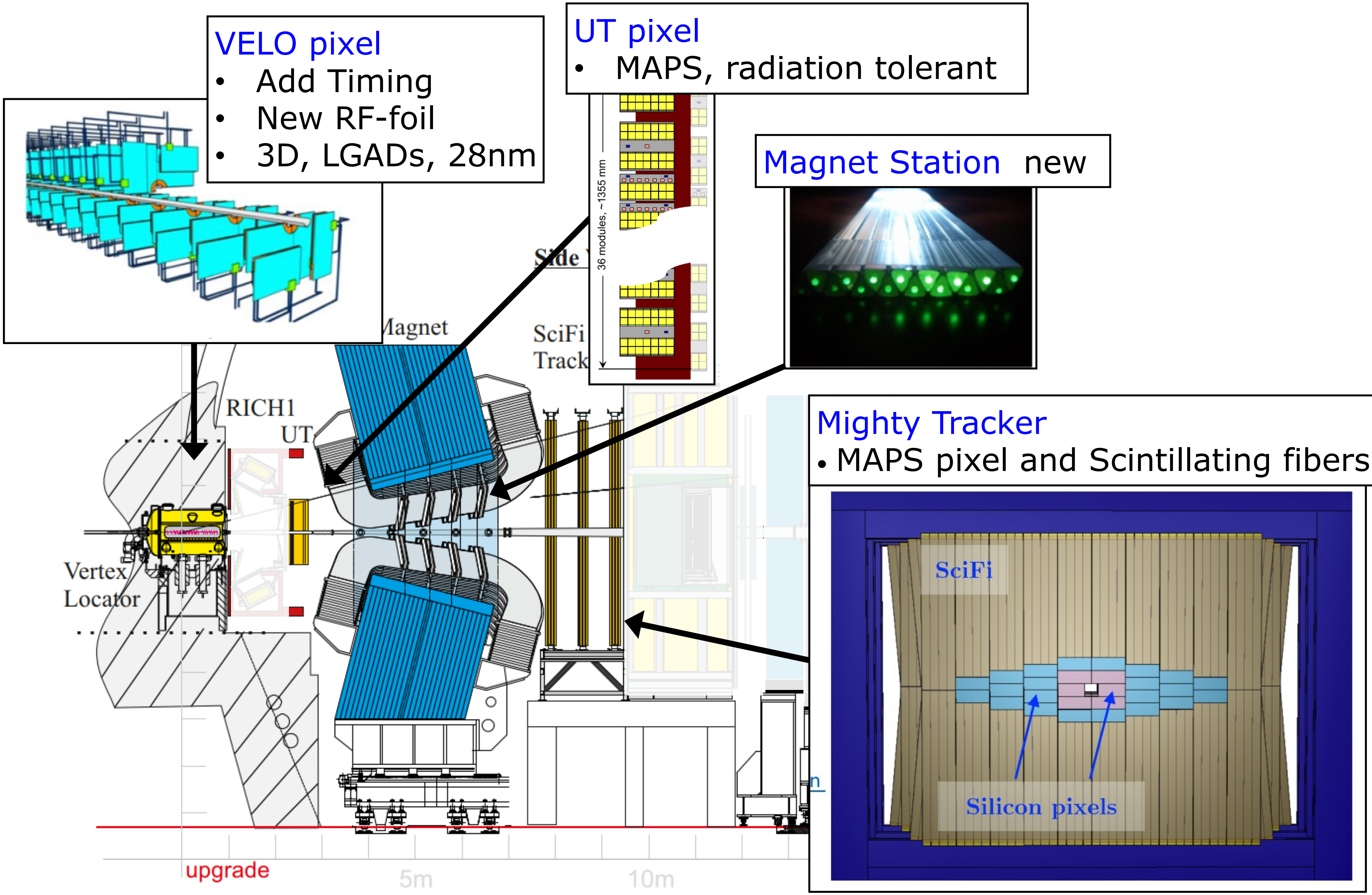
LHCb, arXiv:1808.08865 ; CERN-LHCC-2018-027

Planning for Upgrade II: 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"

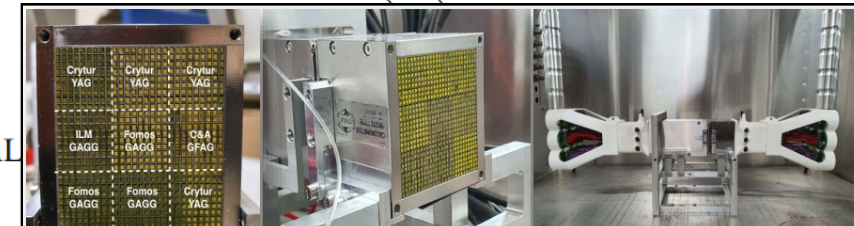
Planning for Upgrade II: Tracking



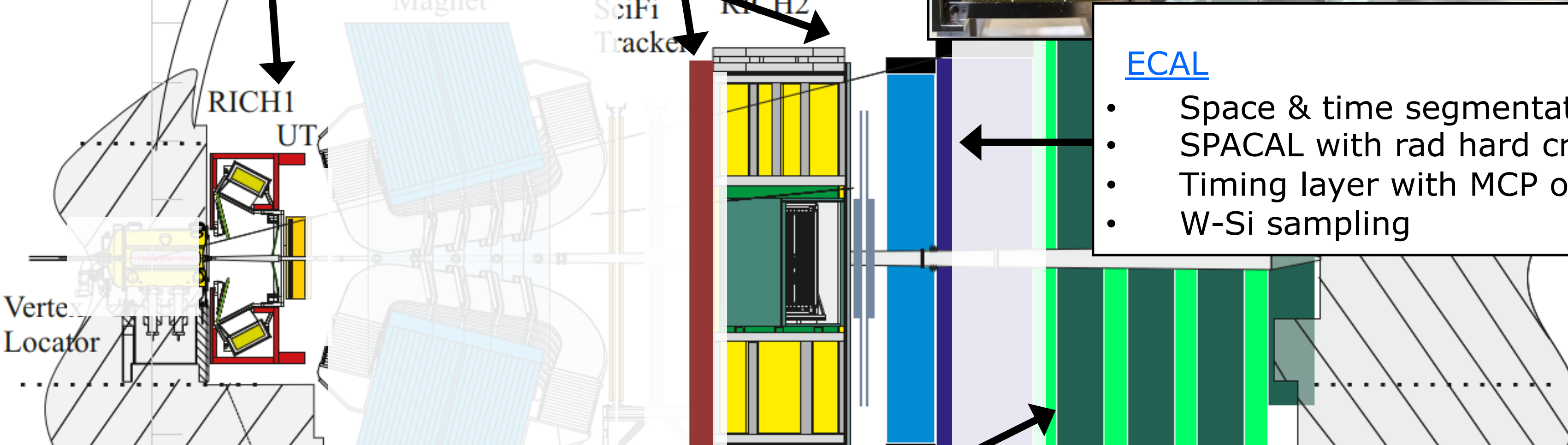
Planning for Upgrade II: PID detectors

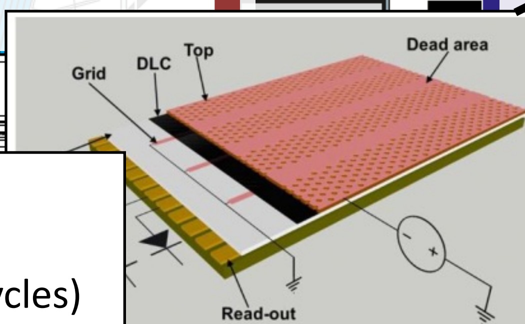
RICH1 and RICH 2
- Reduced pixel size
- Add timing information
- SiPM, MCP

TORCH new
- TOF – quartz
- MCP



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

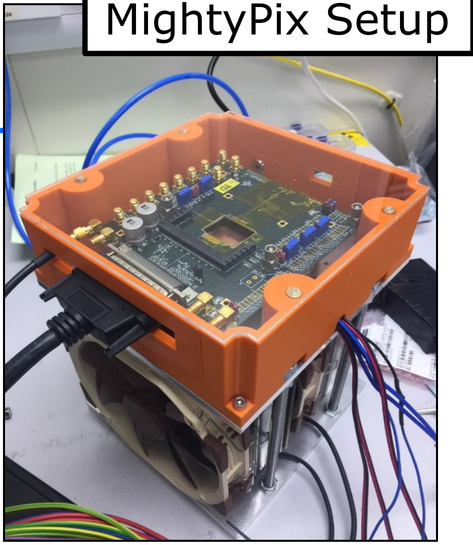


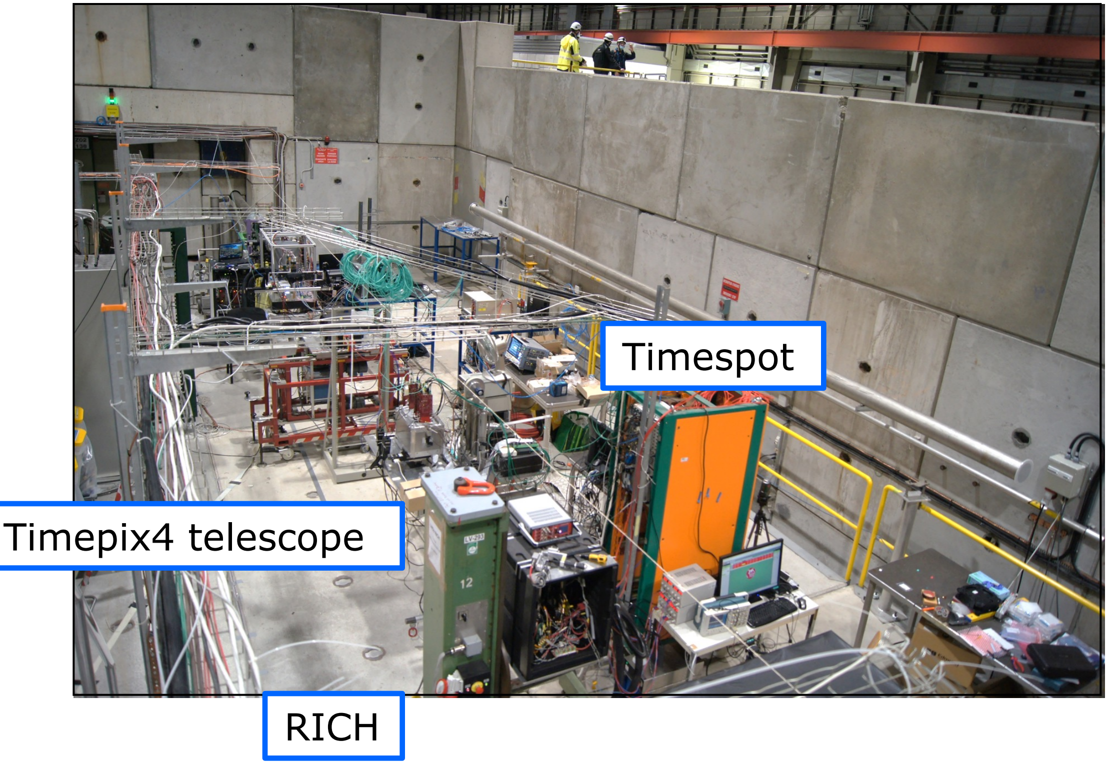


Muon
- □–RWELL for inner regions
- MWPC for outer regions (recycles)

Planning for Upgrade II: Testbeam

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

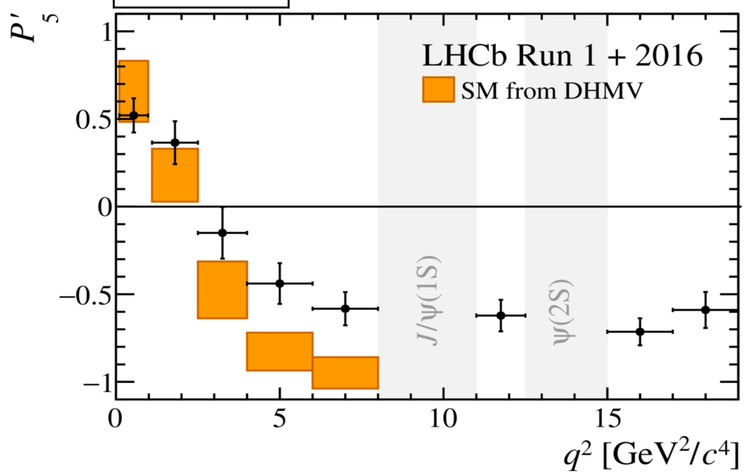




Conclusions

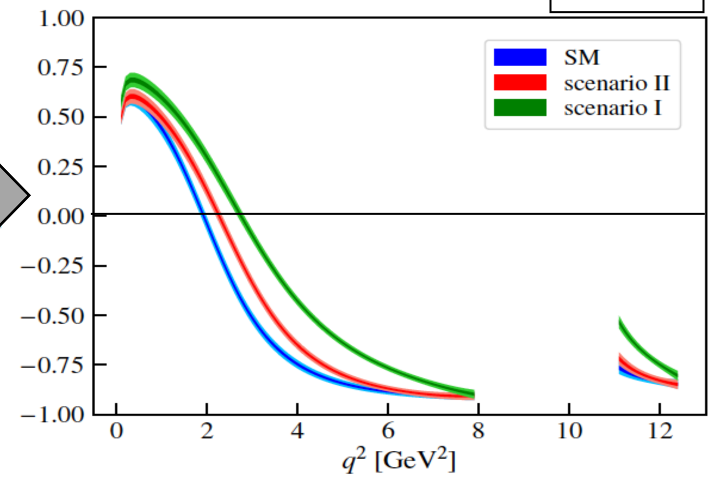
- Precision measurements to scrutinize the Standard Model
- Precision measurements reach very high mass scales
- Precision measurements are not yet precise enough
- Lots of opportunities to contribute to R&D

2024

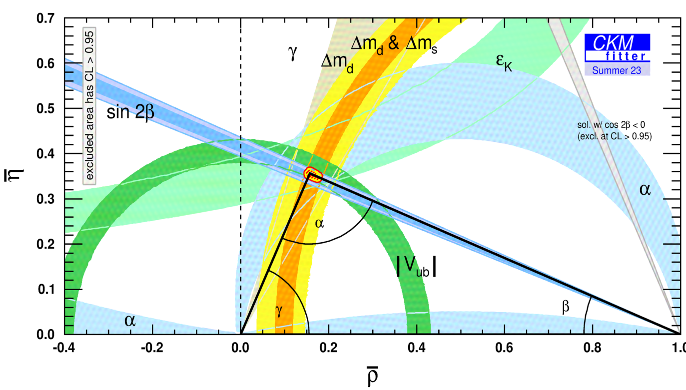


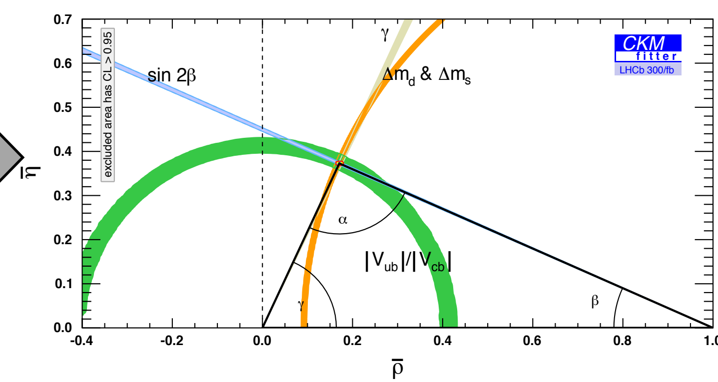
arXiv:2003.04831

2040



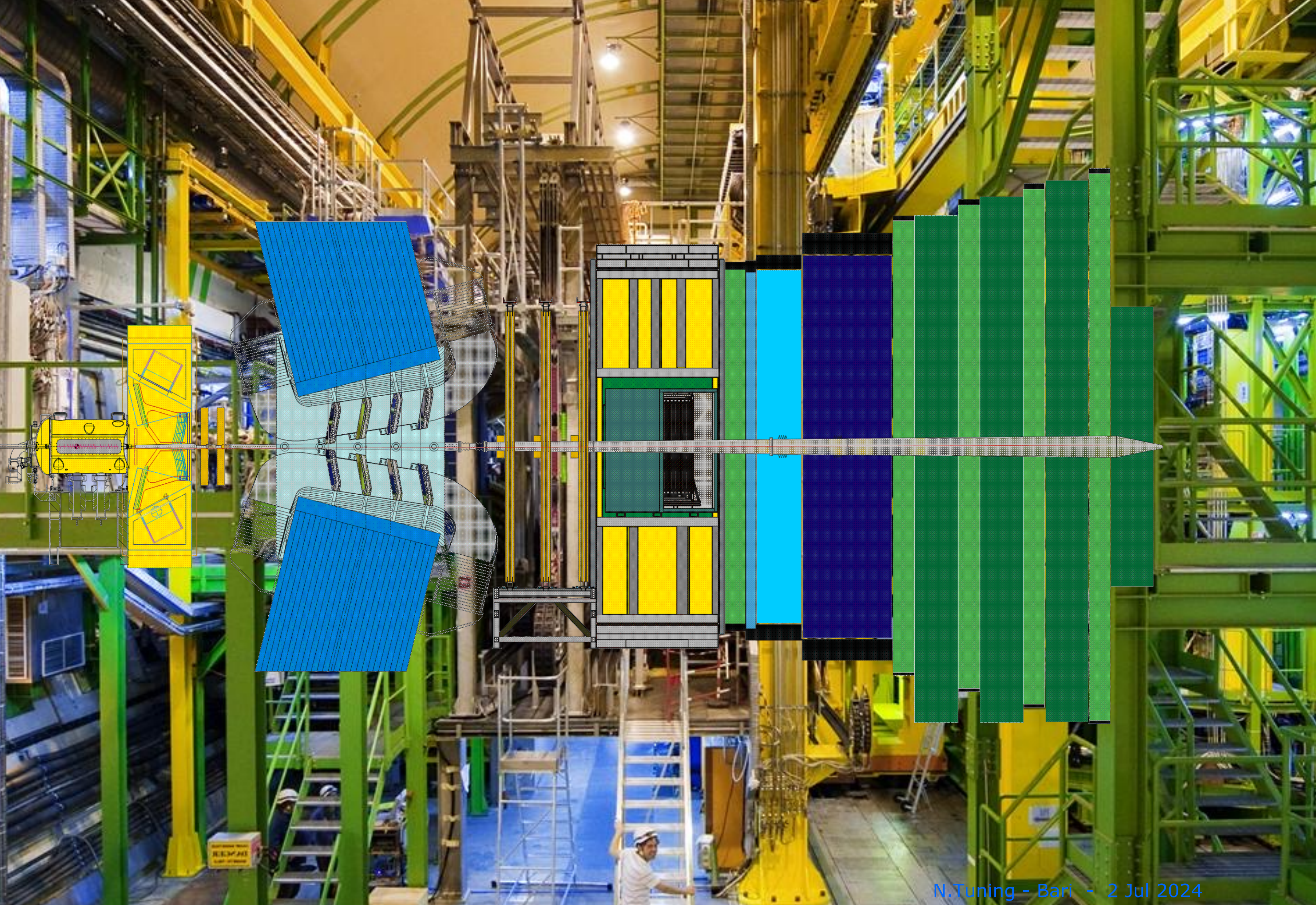
arXiv:1808.08865



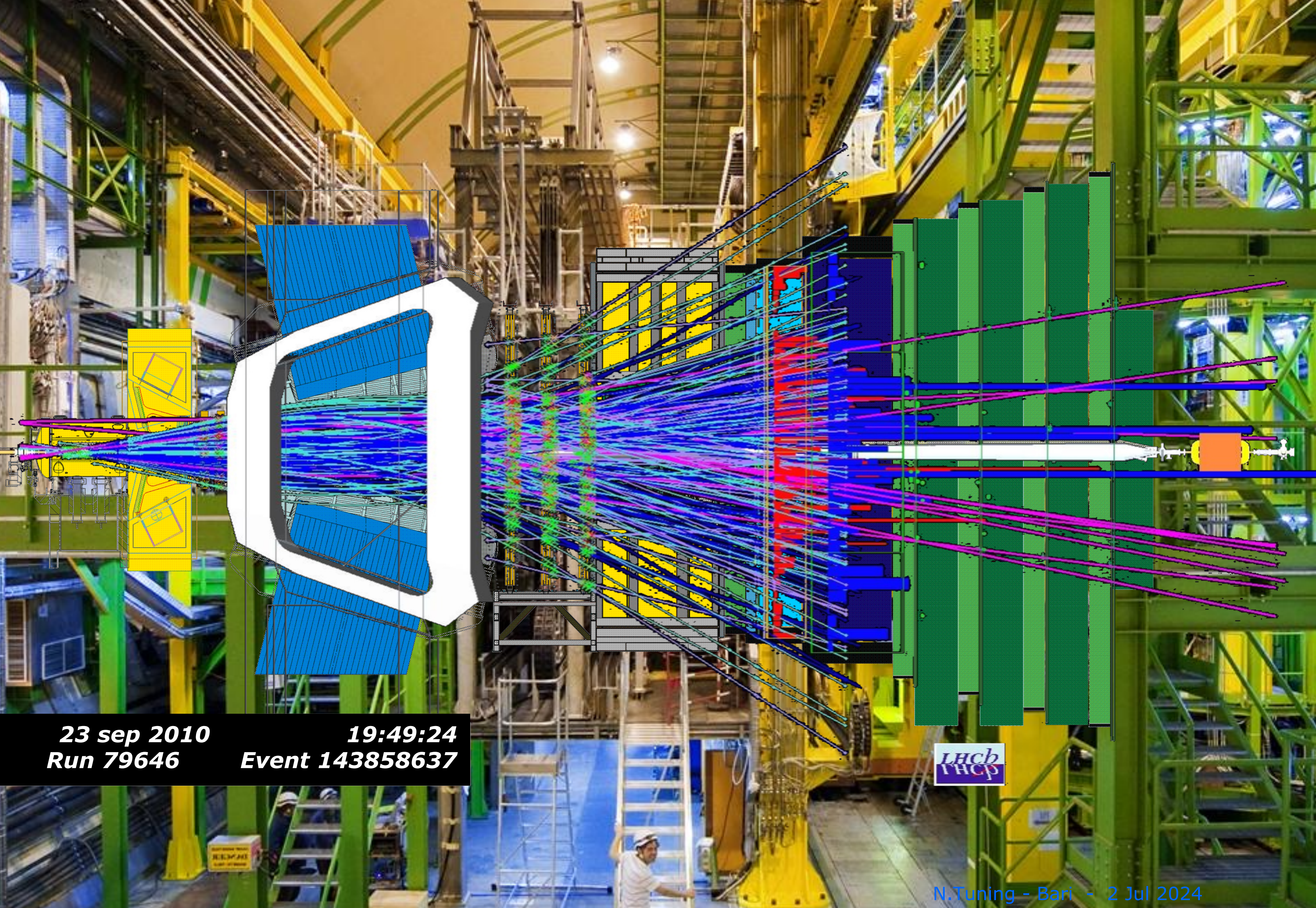


The LHCb Detector

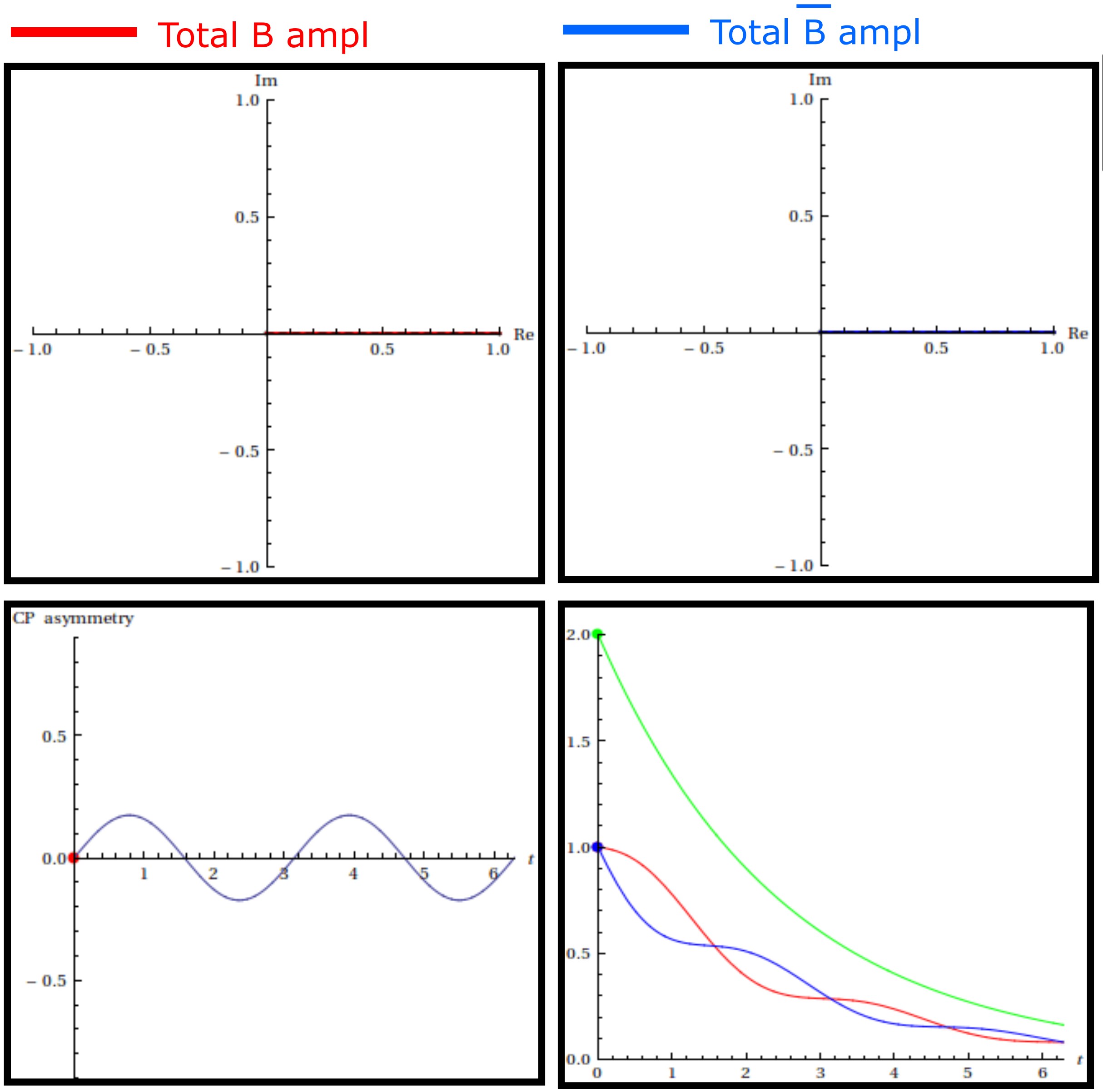
The LHCb Detector



The LHCb Detector



Amplitude interferometry

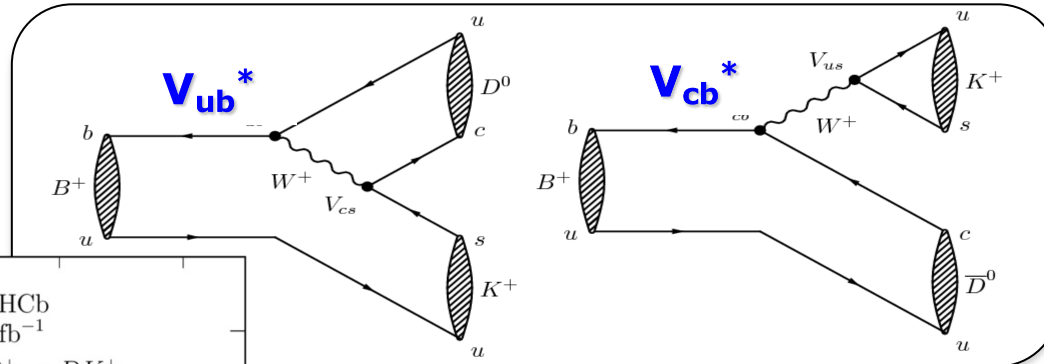


$\phi = 10^o$
$\Gamma/\Delta m = 1.3$

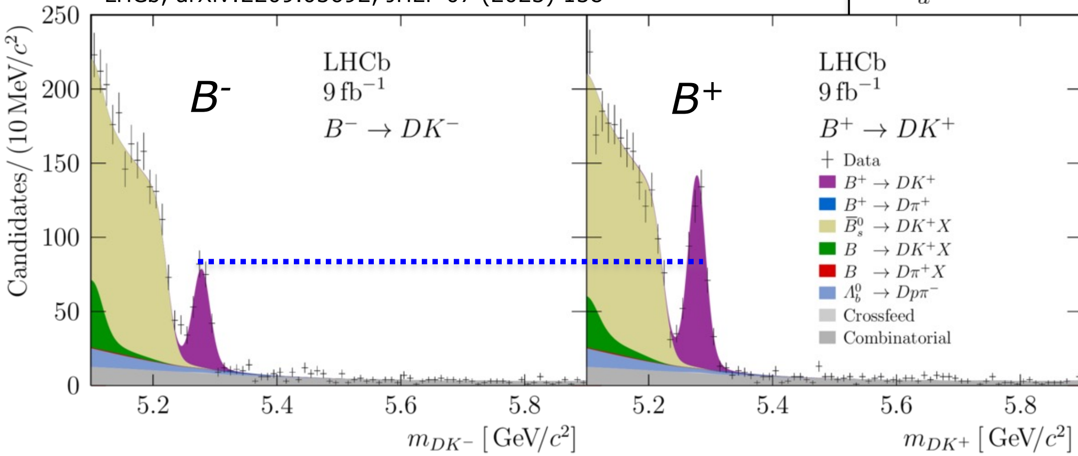
Animation from Daan van Eijk

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

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



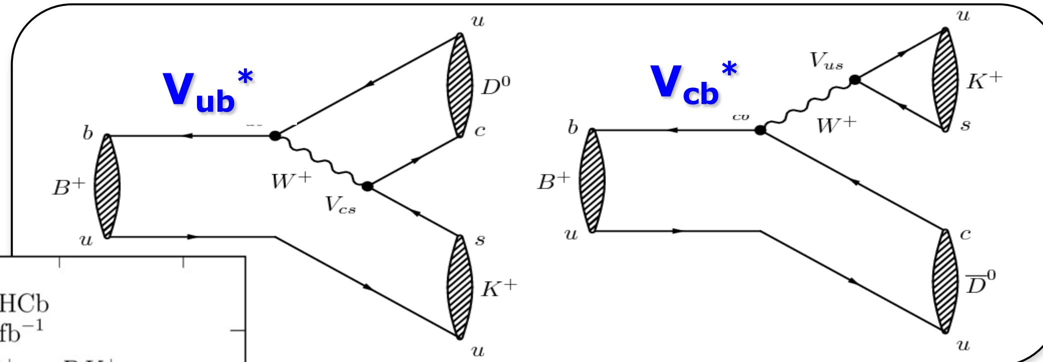
LHCb, arXiv:2209.03692, JHEP 07 (2023) 138



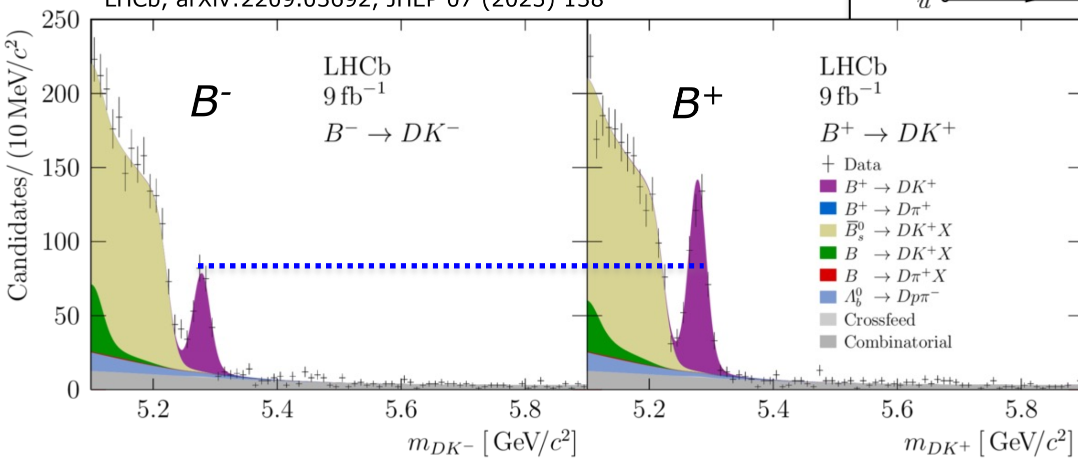
$$\Gamma_{B^{\pm}\rightarrow D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]K^{\pm}} \propto r^2_{K3\pi} + (r^K_B)^2 + 2r_{K3\pi}r^K_B R_{K3\pi}\cos(\delta^K_B + \delta_{K3\pi} \pm \gamma)$$

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

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



LHCb, arXiv:2209.03692, JHEP 07 (2023) 138



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

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

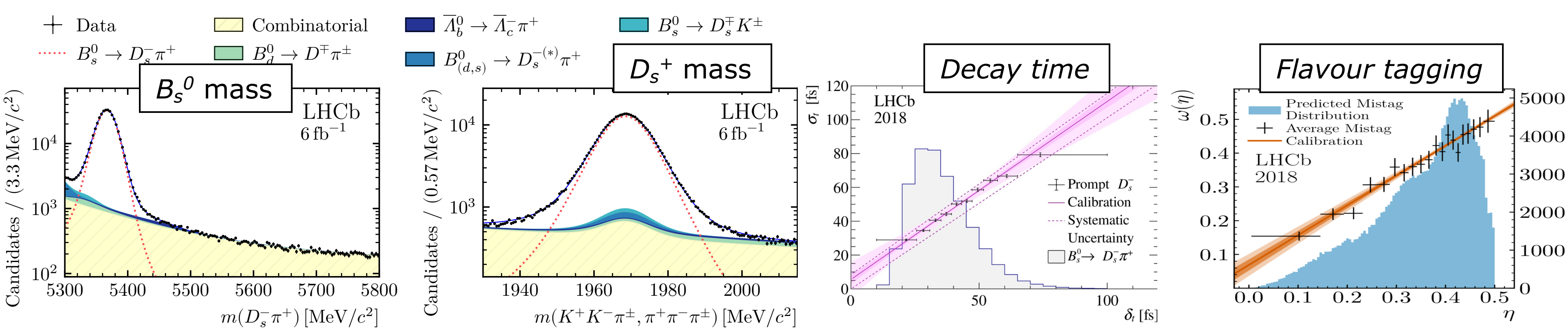
(Split in 4 regions of $K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$ Dalitz space:)

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

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

- 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

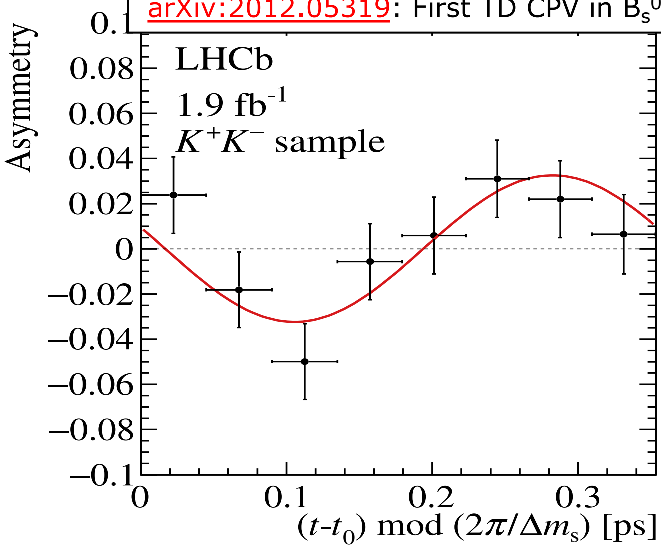
- 2D mass fit on B_s^0 and D_s^+ mass, followed by decay time fit
- Detailed study of tagging, decay time resolution and bias



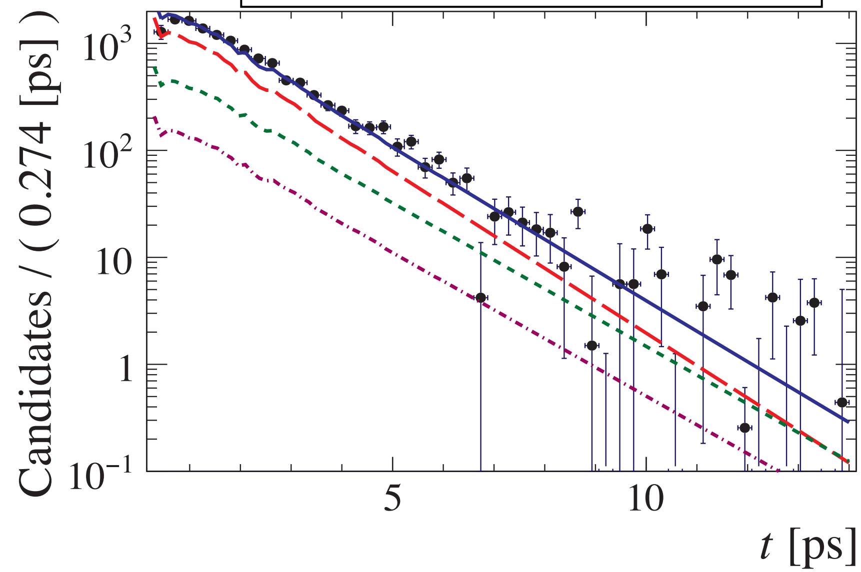
LHCb, arXiv:2104.04421 Nature Physics 18, (2022) 1-5

More results: CPV

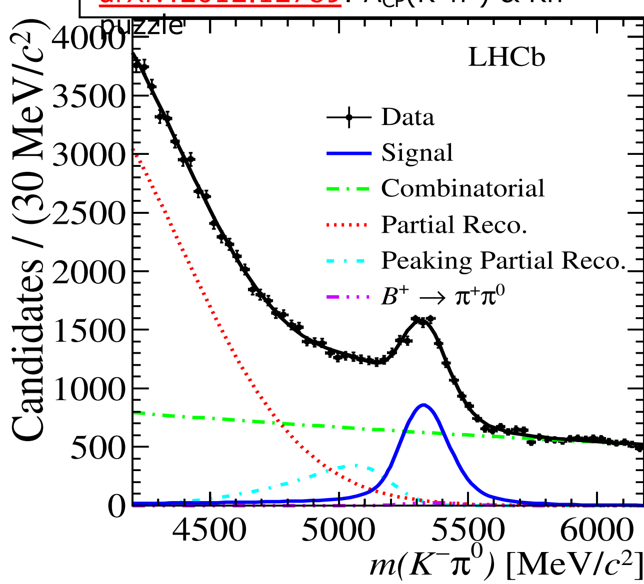
arXiv:2012.05319: First TD CPV in B_s^0

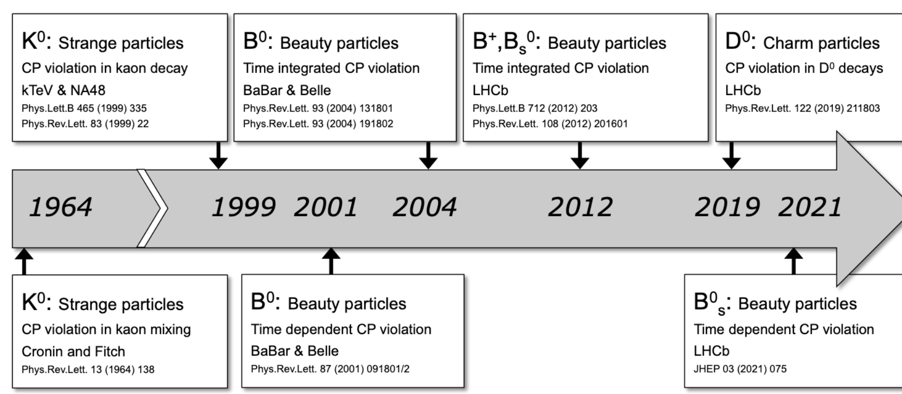


arXiv:2105.14738 : φ_s with e^+e^-

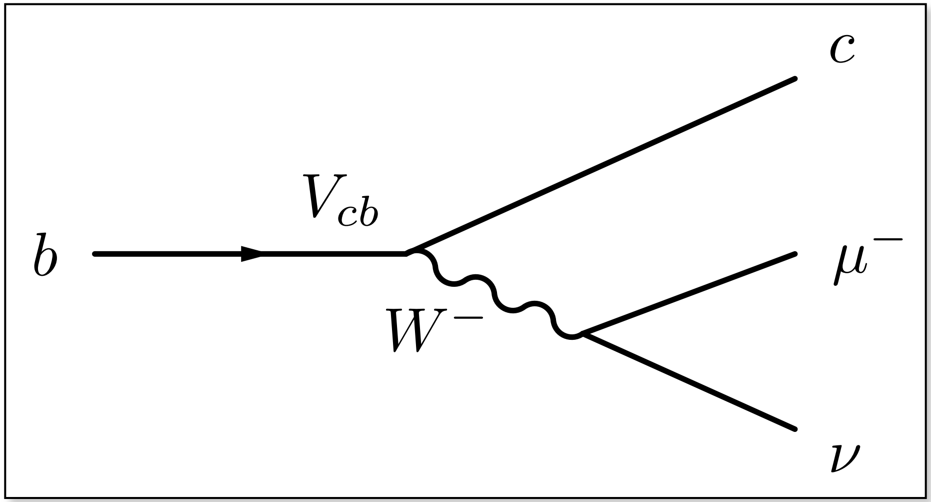


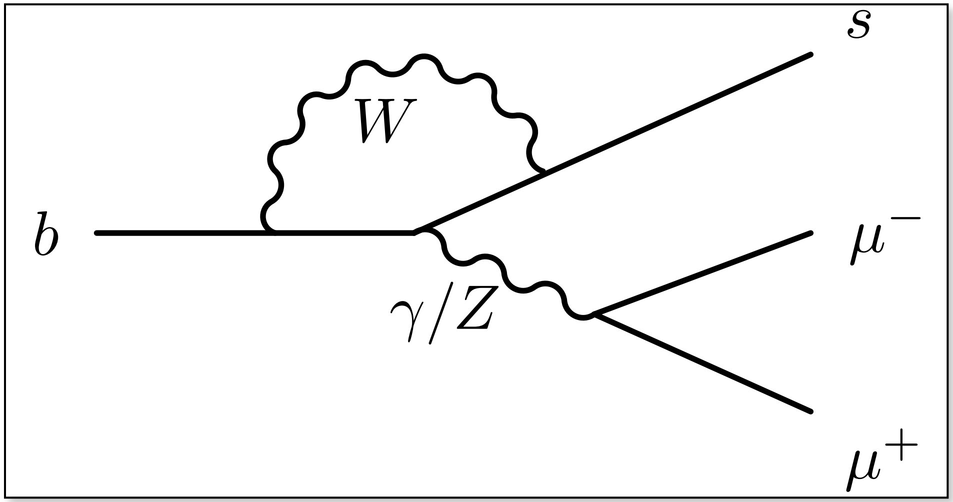
arXiv:2012.12789: $A_{CP}(K^+\pi^0)$ & $K\pi$ puzzle





CC and FCNC





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

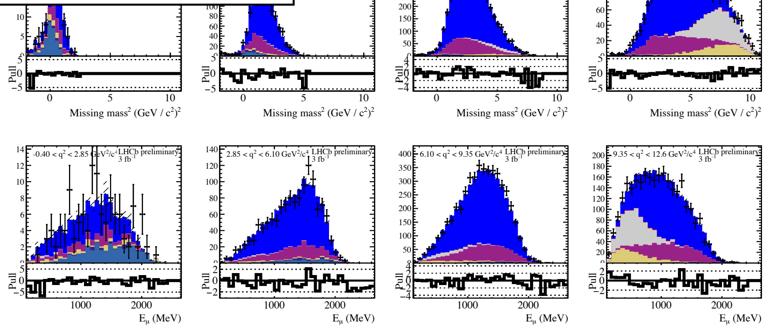
“Semileptonic”
FCNC EWP Penguin
$b \rightarrow s l^+ l^-$

LHCb, arXiv:2302.02886 Phys. Rev. Lett. 131 (2023) 111802
Courtesy: P.Hamilton, Impl.Workshop, 19 Oct 2022

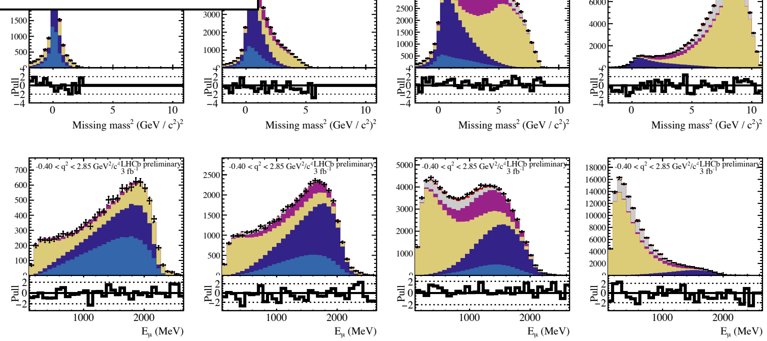
R(D*) vs R(D)

- Fit was checked on specific subsamples:

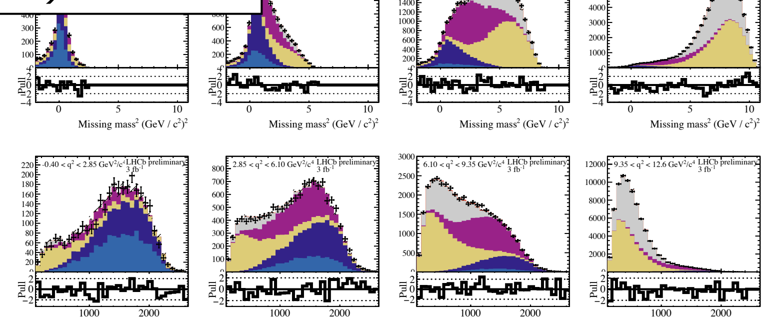
$(\Lambda_b \to D^0 \mu p X)$ enriched



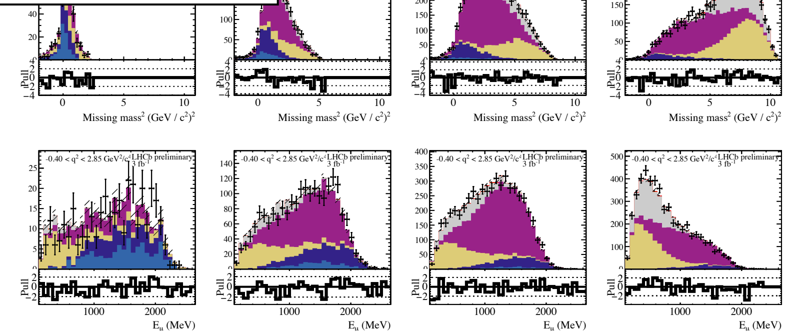
$(D^*$ non-$\mu)$ enriched



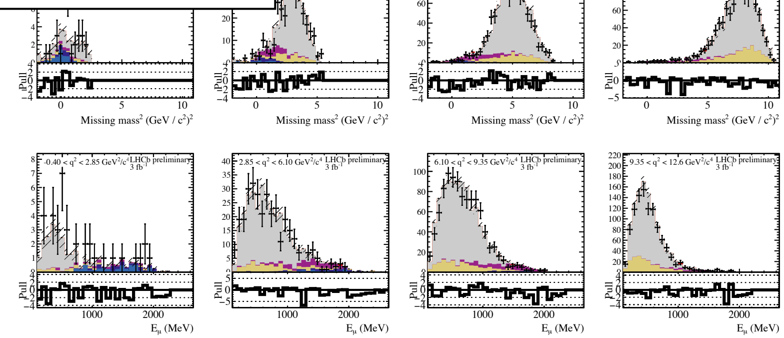
$(D^*\mu + 3\pi)$ enriched



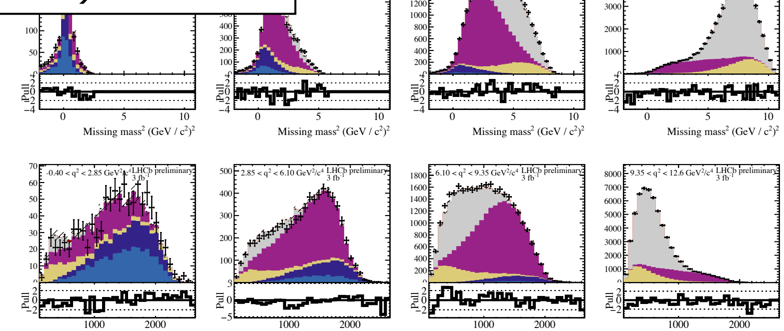
$(\eta\to\pi^{+}\pi^{-}\pi^{0})$ enriched



$(\phi \to KK)$ enriched

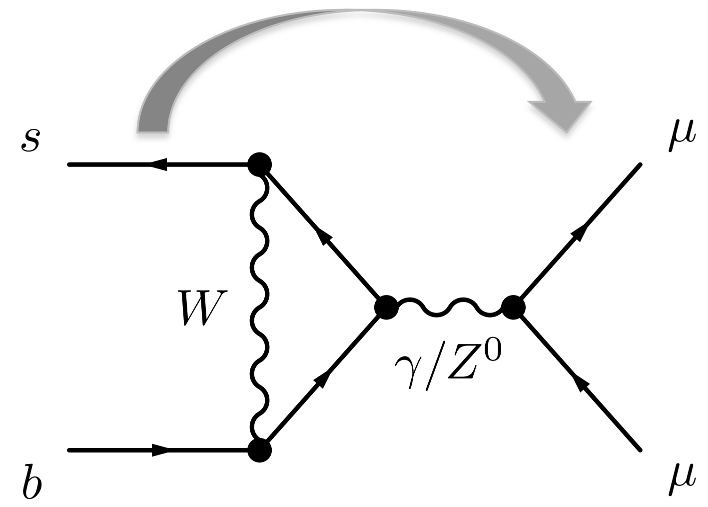


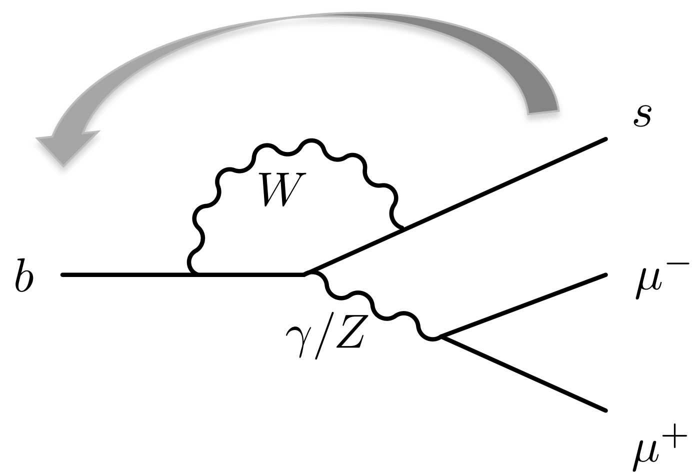
(DD WS-K) enriched



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

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

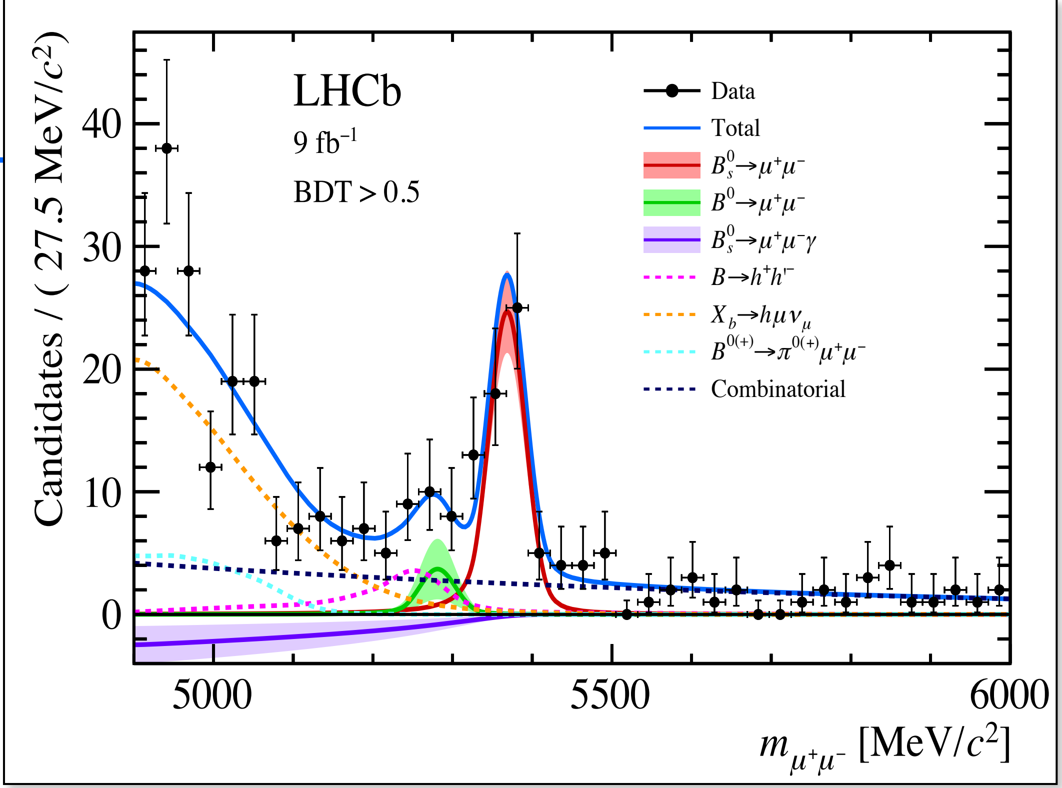




+ $B_s^0 \to e^+e^-$ (LHCb, arXiv:2003.03999)

+ $B_s^0 \to \tau^+\tau^-$ (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

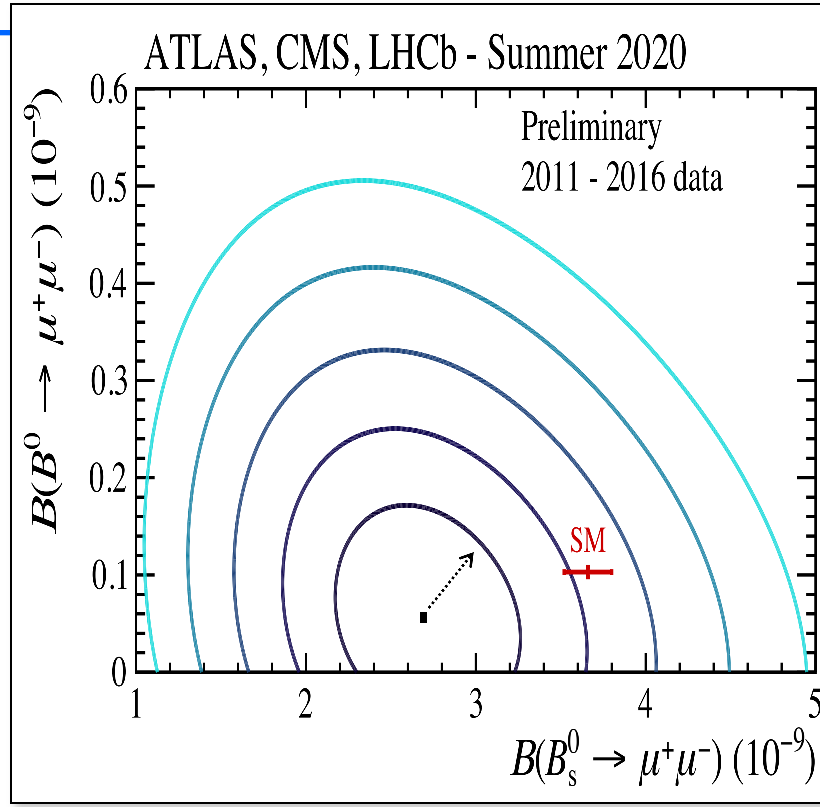
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}\right) \times 10^{-9}$$

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

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

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

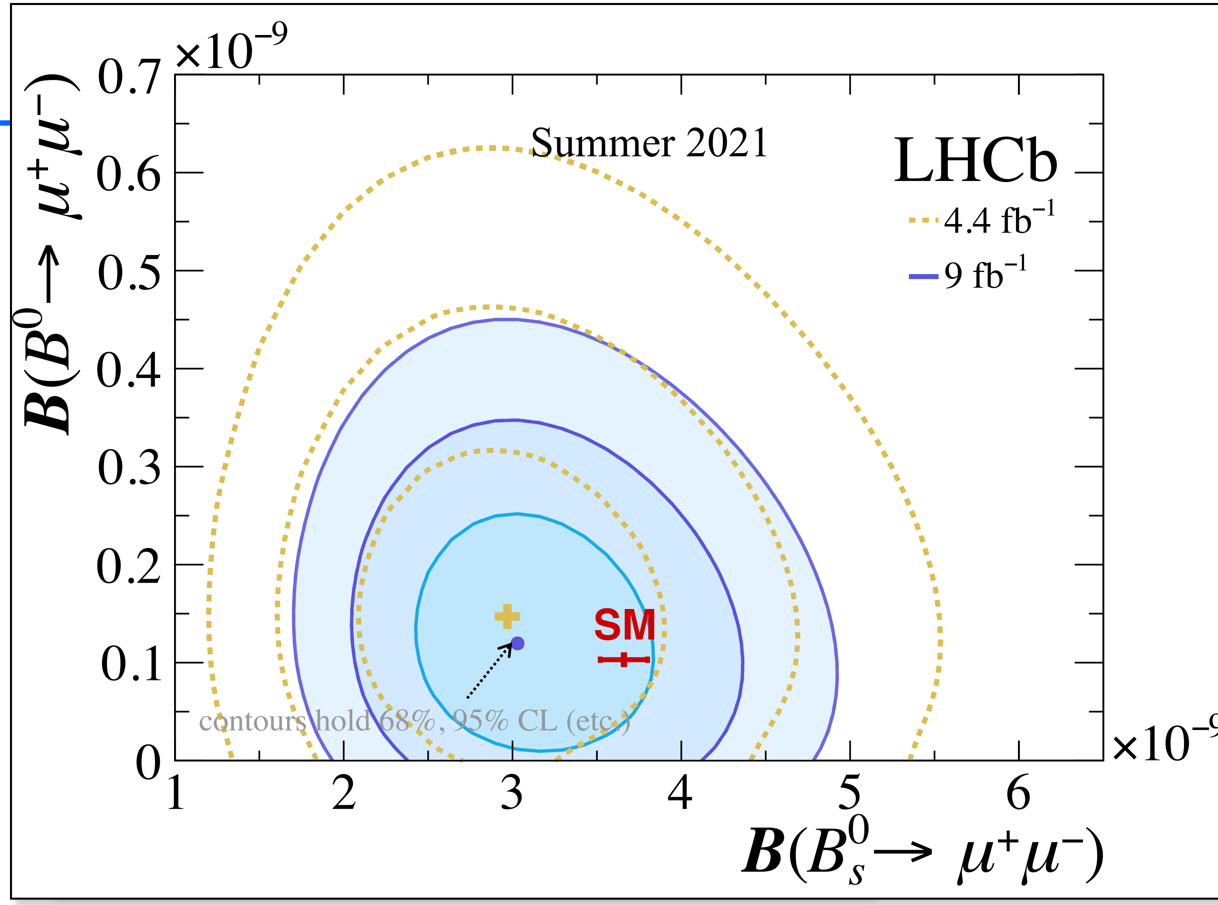
- Including B^0:



ATLAS, CMS, LHCb Coll, Aug. 2020 https://inspirehep.net/literature/1810424

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

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

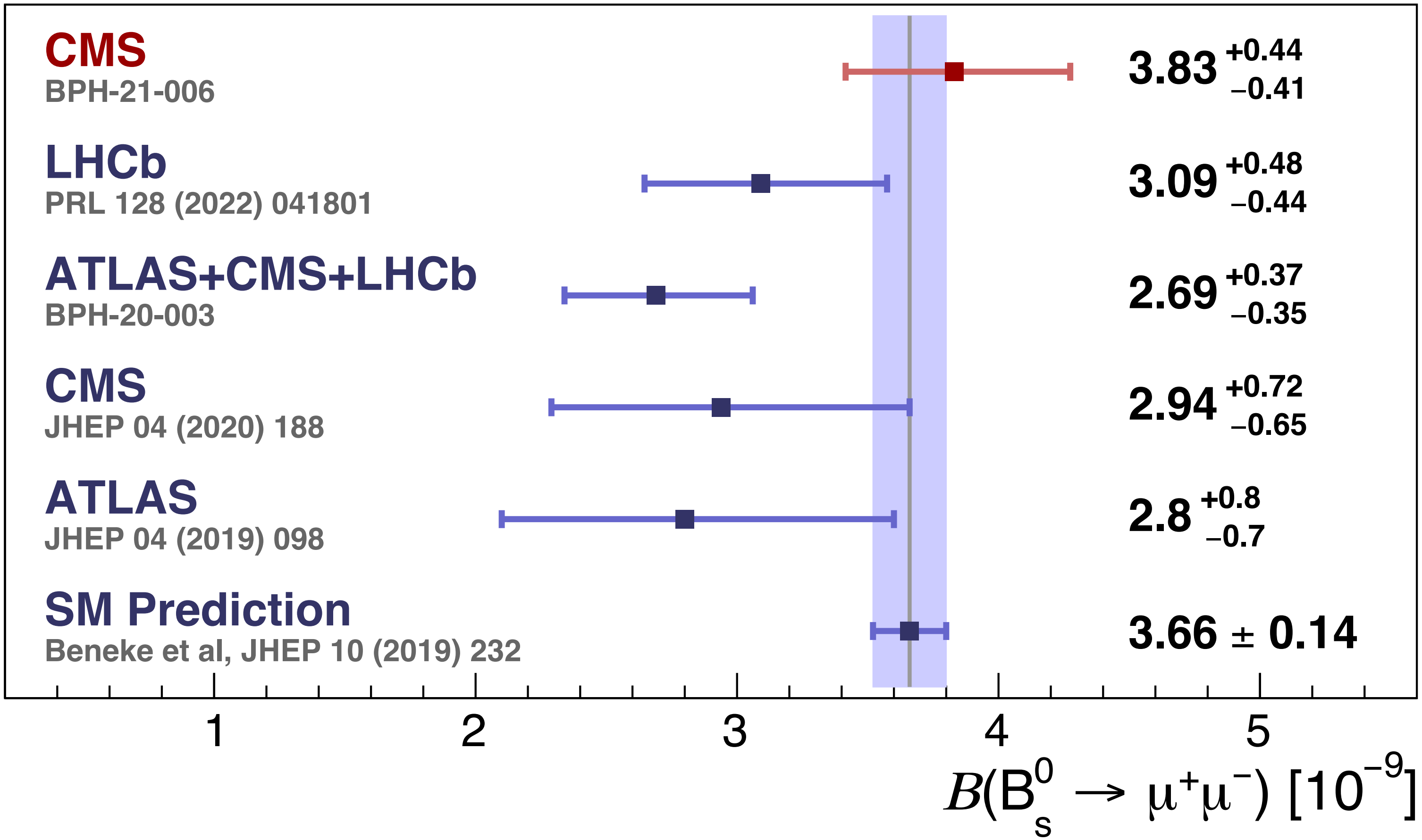
(Integrated, p_T [0.5,40] GeV/c, η [2.6,4])

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

LHCb Coll, arXiv:2103.06810

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

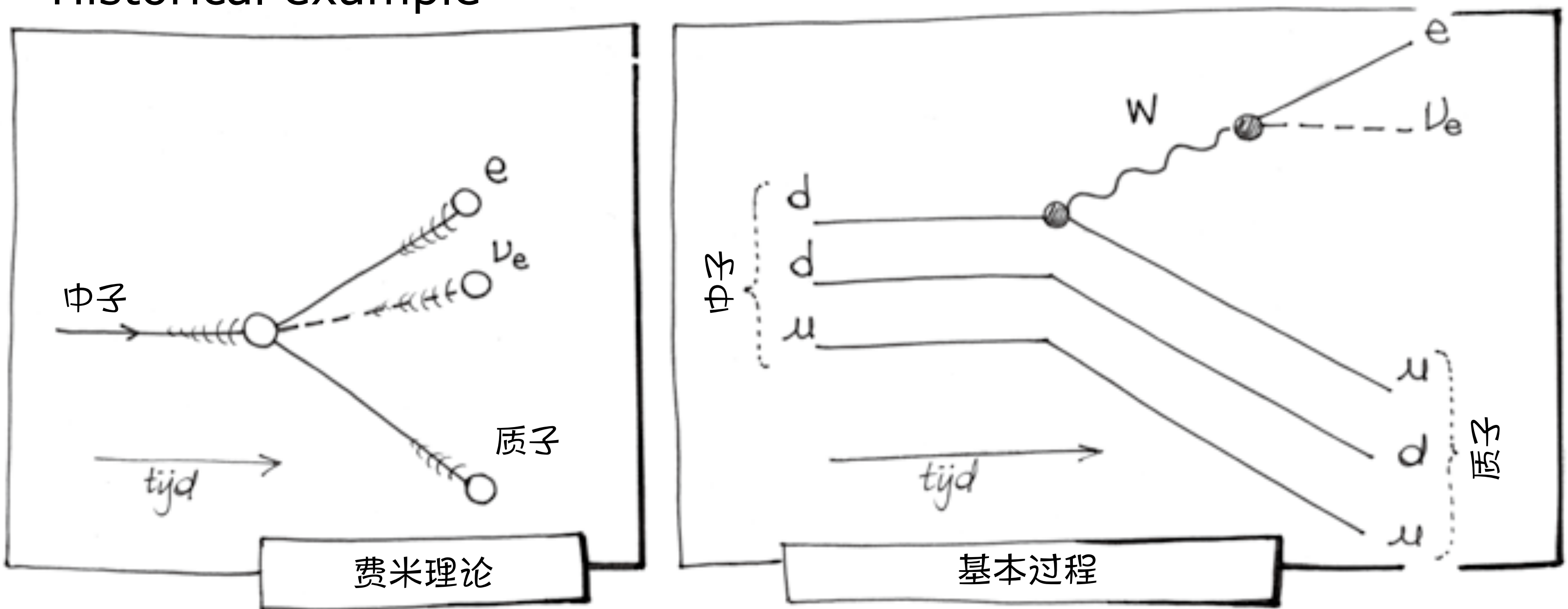
Summer 2022



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

Intermezzo: Effective couplings

- Historical example

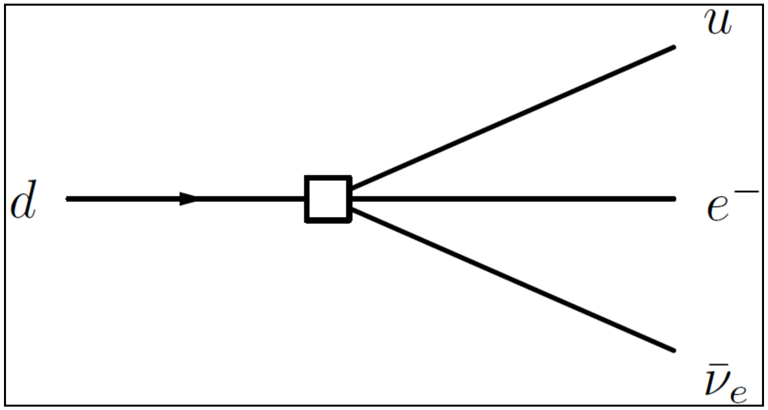


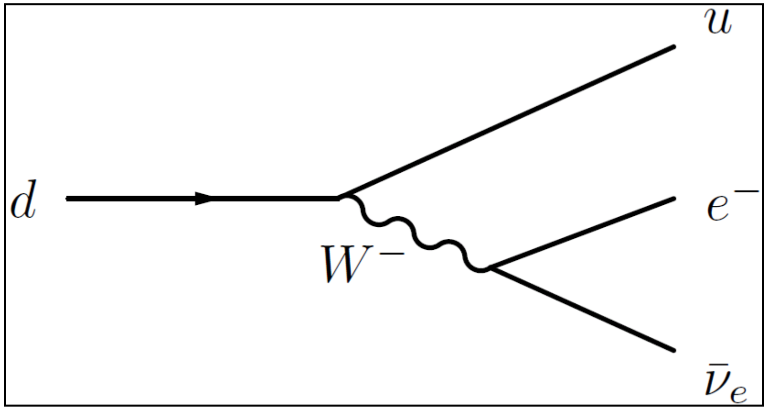
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

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

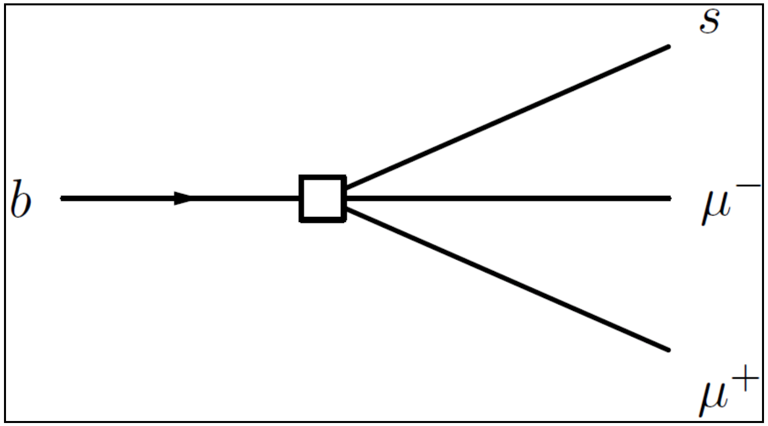
Intermezzo: Effective couplings

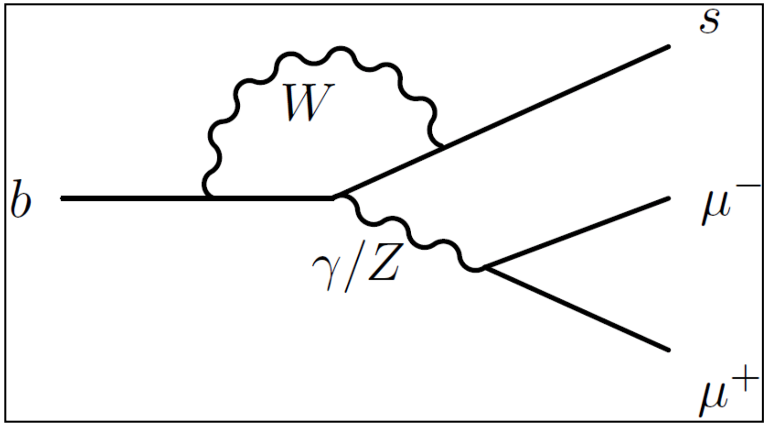
- Historical example





- 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}', …
  - …

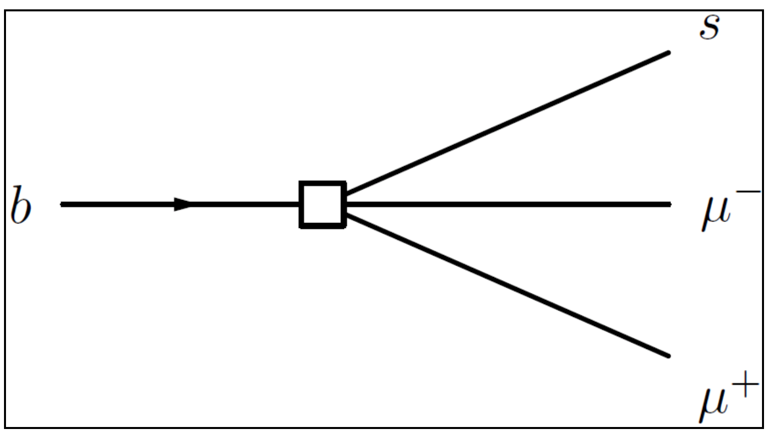
$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{\text{CKM}} \sum_i C_i(\mu) Q_i$$

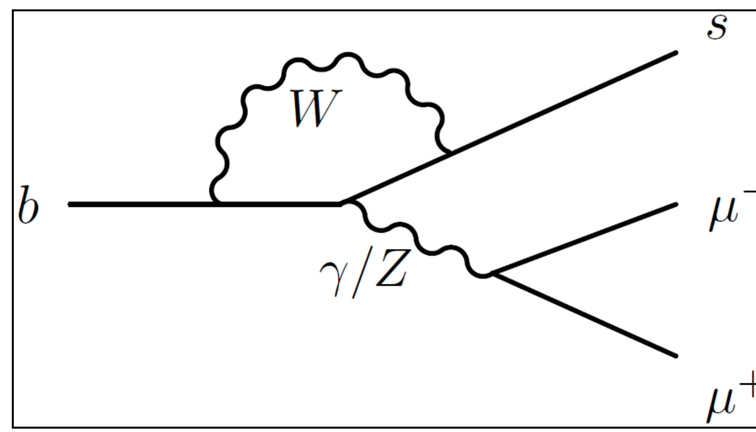
See e.g. Buras & Fleischer, hep-ph/9704376

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:

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

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

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

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

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

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

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

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

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

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

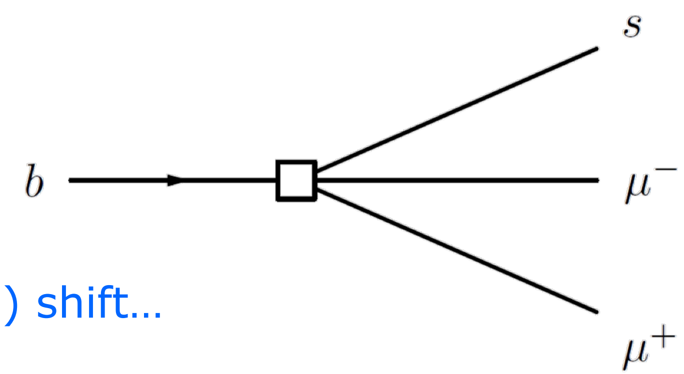
$$S_9 = \frac{\Im(A_\perp^{L*}A_\parallel^L)}{|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_0^L|^2} - L \to R$$

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

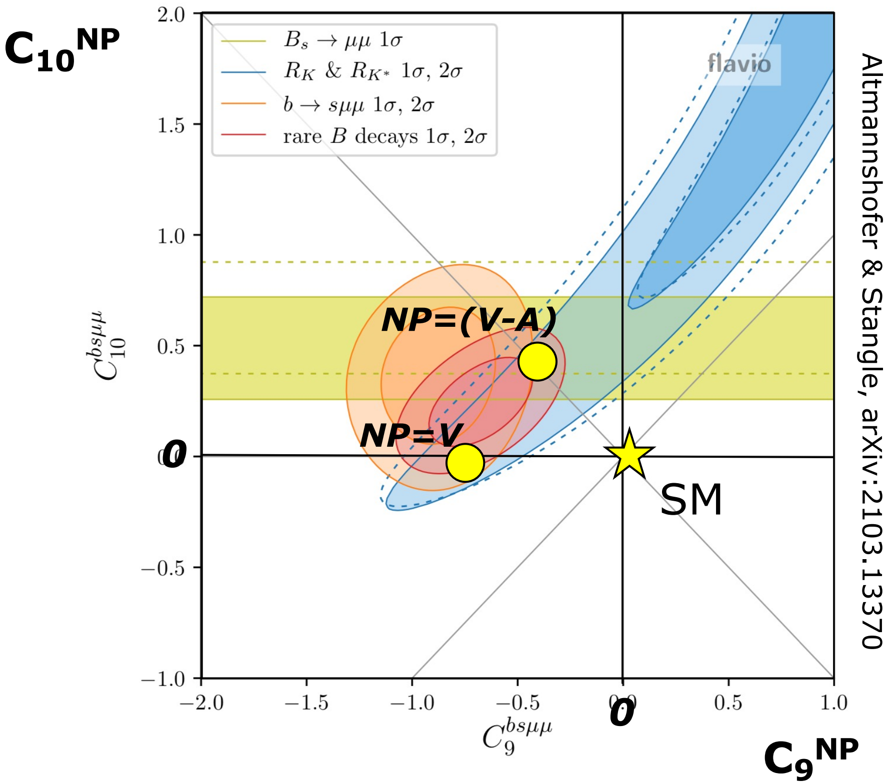
Coherent pattern

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
$C_9^{\prime bs\mu\mu}$	$-0.09^{+0.13}_{-0.13}$	0.7σ
$C_{10}^{\prime bs\mu\mu}$	$+0.01^{+0.10}_{-0.09}$	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%