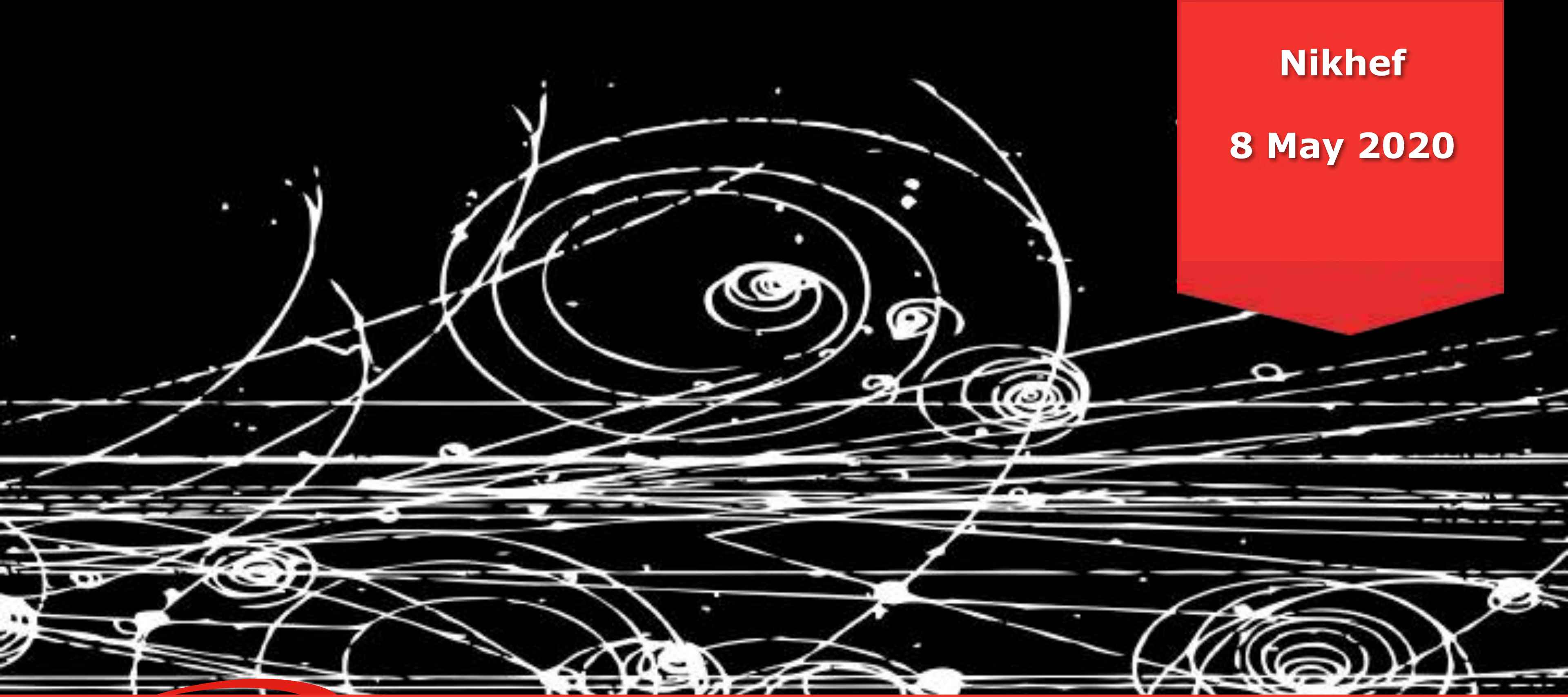


Nikhef

8 May 2020

LHCb Highlights

Niels Tuning

On the menu

- Introduction
  - Precision measurements
  - The LHCb physics menu
- Selection of dishes:
  - Recent highlights on CP violation
  - Recent highlights on Rare decays (*aka Flavour Anomalies*)

History of Flavour physics

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

Weak Interactions with Lepton-Hadron Symmetry*

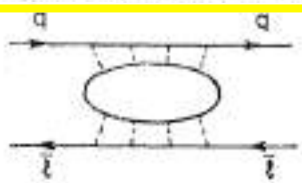
S. L. Glashow, J. Iliopoulos, and L. Maiani
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

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 $G(GA^2)$, as well as contributions to such unobserved decay modes as $K_2 \rightarrow \mu^+ + \mu^-$, $K^+ \rightarrow \pi^+ + l + \bar{l}$, 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, $K_L^0 \rightarrow \pi\pi$

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

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

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

Flavour physics has a track record

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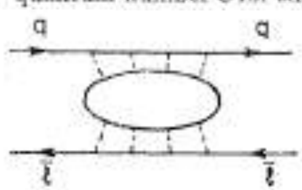

"…a quark model, but involving **four**, not three fundamental fermions…"

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"… phases of elements of 3x3 unitary matrix cannot be absorbed into […] **six** fields …"

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" $m_t > 50$ GeV/c^2 *t* quark mass "

Rare decay implied
2nd up quark
"discovery" of charm?

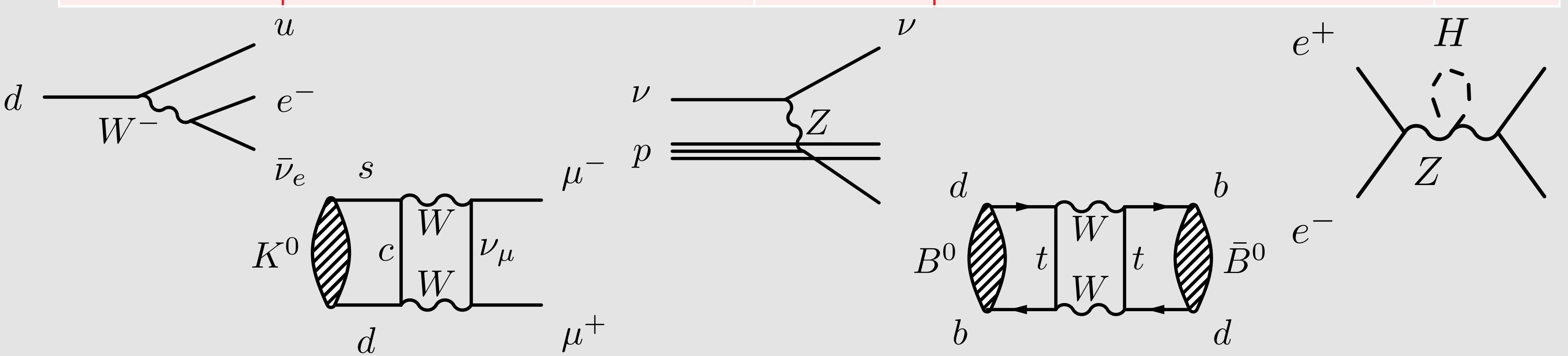
CP violation implied
3rd family:
"discovery" of bottom?

Mixing implied
heavy quark:
"discovery" of top?

Precise flavour measurements

- 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→μμ*	GIM	1970	*J/ψ*	Richter, Ting	1974
b	CPV *K^0→ππ*	CKM, 3rd gen	1964/72	*Υ*	Ledermann	1977
Z	ν-NC	Gargamelle	1973	*Z→ 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 ?**		?			?



Precise flavour measurements

- Direct discoveries rightfully higher valued:

Particle	Indirect			Direct		
ν	β decay	Fermi	1932	Reactor ν-CC	Cowan, Reines	1956
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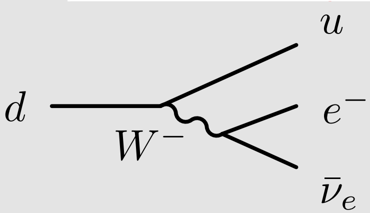
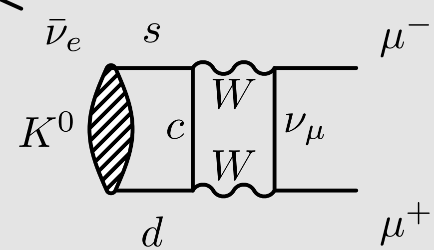
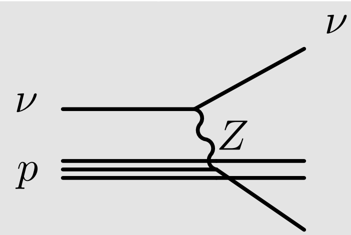
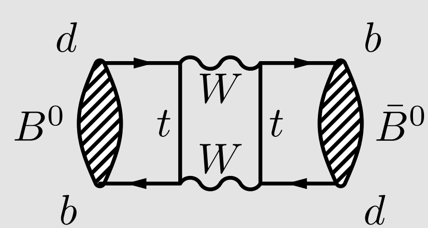
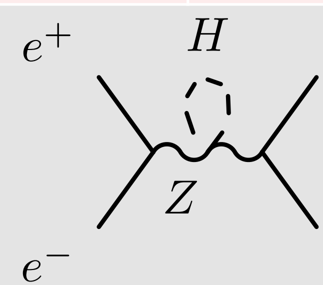




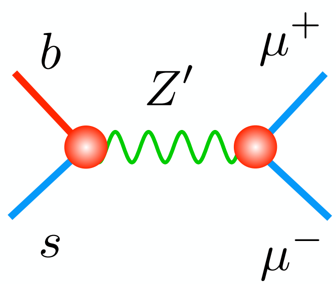






Precise flavour measurements

- Depending on your model, sensitive to multi-TeV scales, eg:



$$\mu_{B_s \to \mu^+\mu^-} \simeq 1 \pm \frac{4\pi}{g^2 |V_{tb}^* V_{ts}|^2} \frac{v^2}{\Lambda^2}$$

$\mu_{B\to\mu\mu}$ is ratio BR^{exp}/BR^{SM}

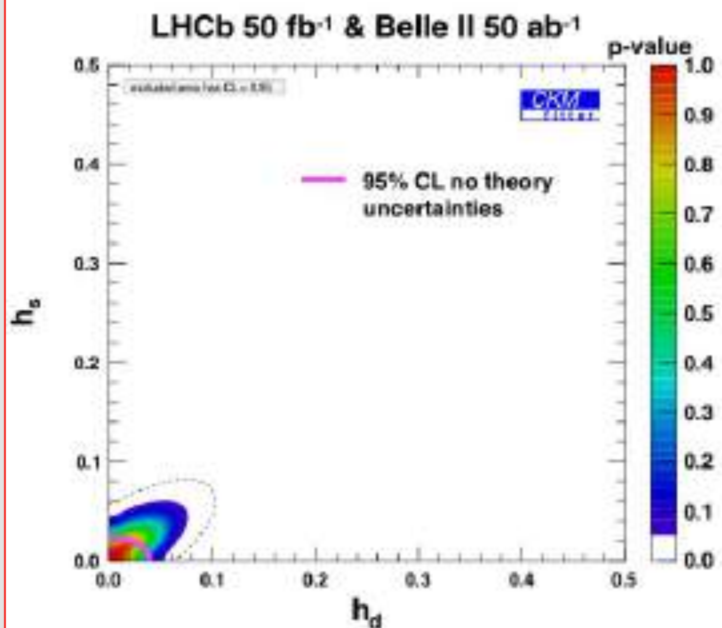
$$\Lambda \gtrsim \frac{v}{\sqrt{0.2}} \times \begin{cases} \dfrac{\sqrt{4\pi}}{g\,|V_{tb}^* V_{ts}|} \\ 1 \end{cases} \simeq \begin{cases} 50\,\text{TeV}\,, & \text{anarchic tree} \\ 0.6\,\text{TeV}\,, & \text{MFV loop} \end{cases}$$

From Uli Haisch, 31 Aug 2016
arXiv:1510.03341

Precise flavour measurements

- Depending on your model, sensitive to multi-TeV scales, eg:

[Charles et al., 1309.2293]



$$M_{12}^q = (M_{12}^q)_{\rm SM}\left(1 + h_q e^{2i\sigma_q}\right)$$

h_q parametrizes magnitude of NP in B_q mixing

$$h_d \lesssim 5\% \quad \Rightarrow \quad \Lambda \gtrsim \begin{cases} 2\cdot 10^3\,\text{TeV}, & \text{anarchic tree} \\ 1.4\,\text{TeV}, & \text{MFV loop} \end{cases}$$

From Uli Haisch, 31 Aug 2016

On the menu

- Introduction
  - Precision measurements
  - The LHCb physics menu
- Selection of dishes:
  - Recent highlights on CP violation
  - Recent highlights on Rare decays (*aka Flavour Anomalies*)

LHCb Physics Landscape

QCD

W/Z

Heavy Ion
&
Fixed Target

b→sll

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

$|V_{cb}|$, $|V_{ub}|$

R(D)

Charm

CP violation
& rare decays

Tetra-
&
Pentaquarks

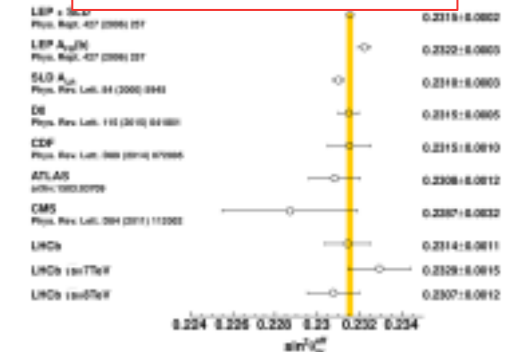
CP violation:
γ

CP violation:
α

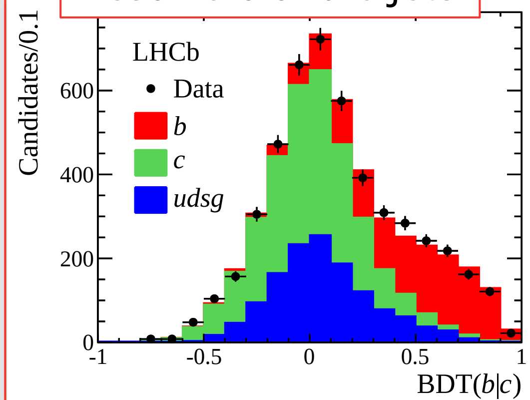
CP violation:
β
φ_s

LHCb Physics Landscape: more than b

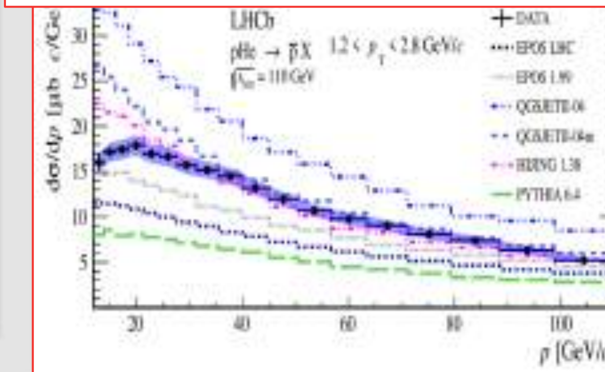
Impressive $\sin^2\theta_w$



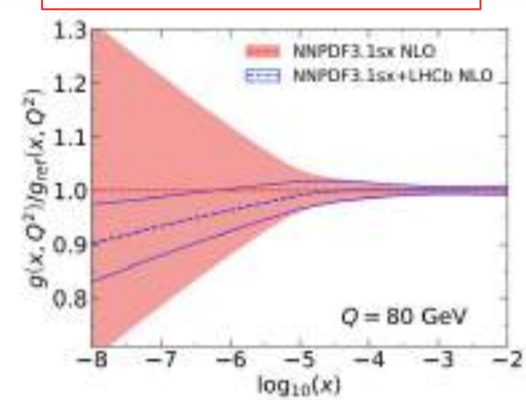
Resolve b and c jets



Anti-proton flux for cosmic rays

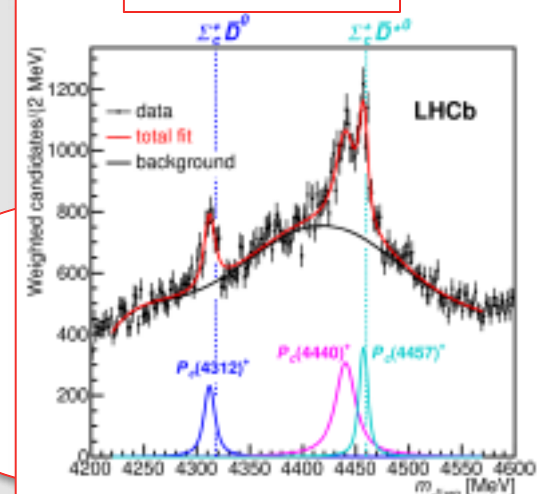


Improve proton pdf's



A.Garcia, R.Gauld, A.Heijboer, J.Rojo
arXiv:2004.04756

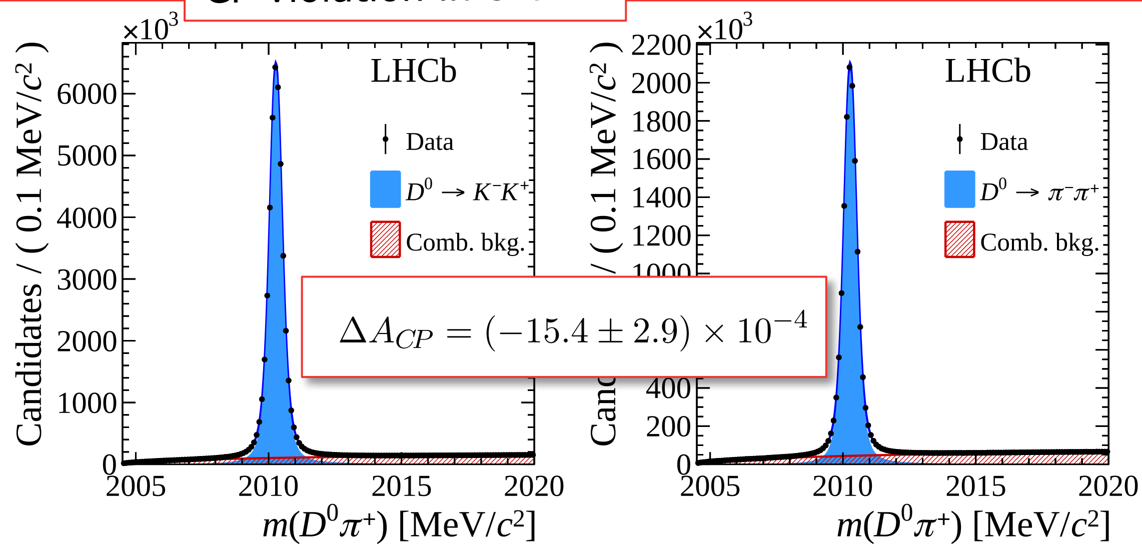
Discovery of pentaquarks



LHCb Physics Landscape: charm

arXiv:1903.08726

CP violation in charm



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

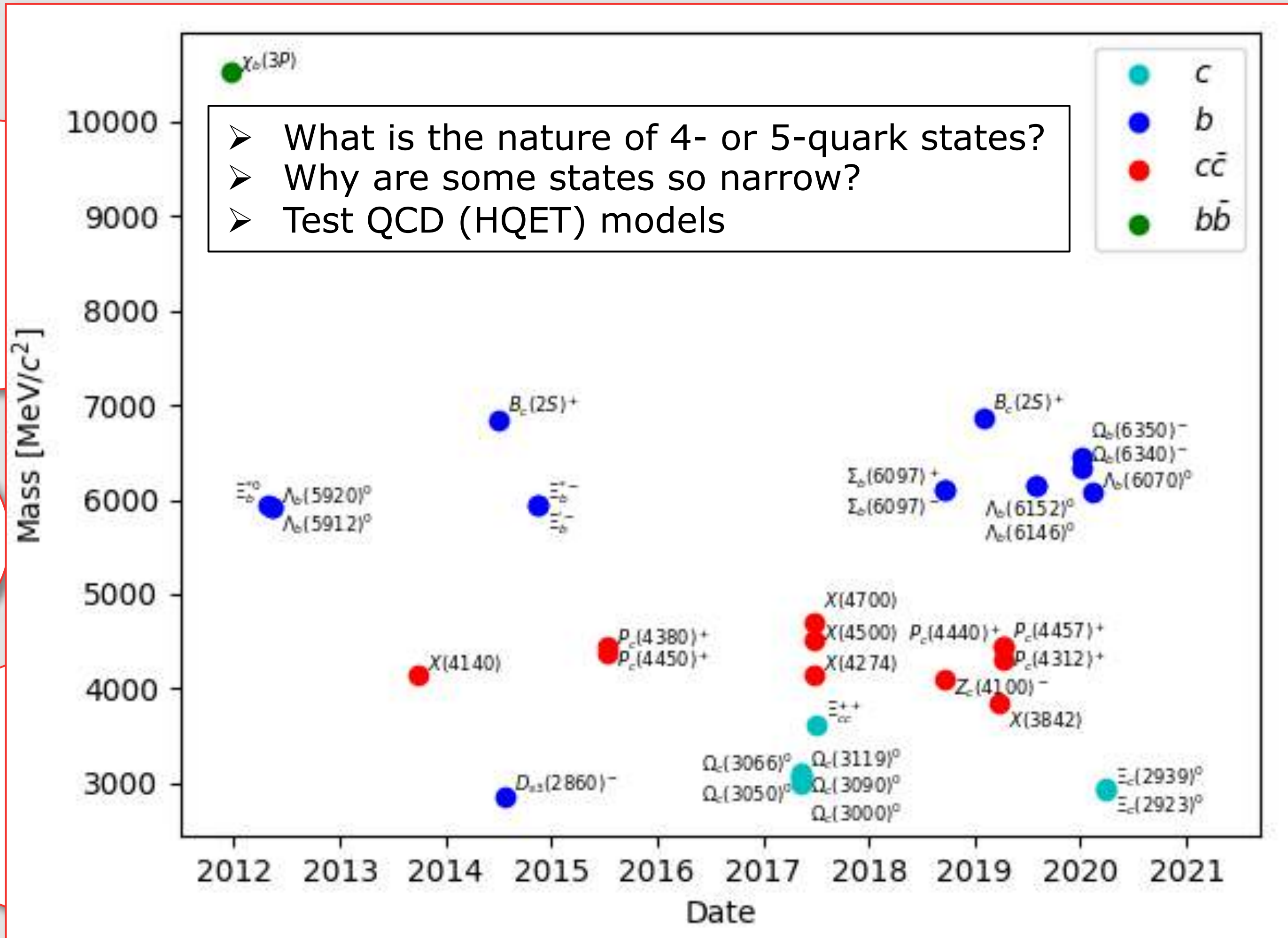
$$A_{CP}(f;\, t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)}$$

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

LHCb Physics Landscape: spectroscopy

Spectroscopy 35(29) hadrons discovered at LHC(b):

- What is the nature of 4- or 5-quark states?
- Why are some states so narrow?
- Test QCD (HQET) models



Collected by Patrick Koppenburg: https://www.nikhef.nl/~pkoppenb/particles.html

LHCb Physics Landscape

$b \to sll$

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

R_K

Today

$|V_{cb}|$, $|V_{ub}|$

R(D)

CP violation:

γ

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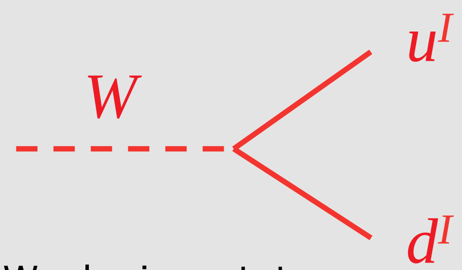
- New results
  1) $|V_{cb}|$ with decay $B_s^0 \rightarrow D_s^{*-}\mu^+\nu$
  2) γ with decay $B^- \rightarrow D^0(\rightarrow K_S^0 K^+ \pi^-)K^-$
  3) γ with decay $B^0 \rightarrow D^0 K^{*0}$
- A remark on consistency

(CKM: a quick reminder…)

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



Weak eigenstates
(like ν_e, ν_μ, ν_τ)

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

Mass eigenstates
(like ν_1, ν_2, ν_3)

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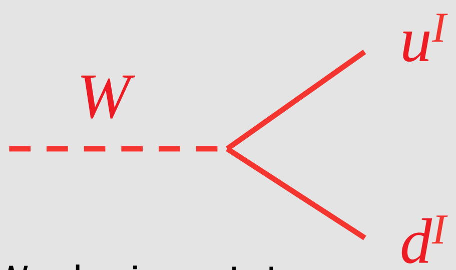

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Mass eigenstates

- 2) Matrix has imaginary numbers:

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

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Weak eigenstates

Mass eigenstates

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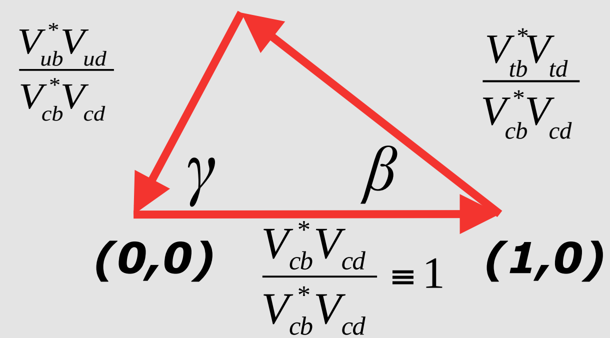
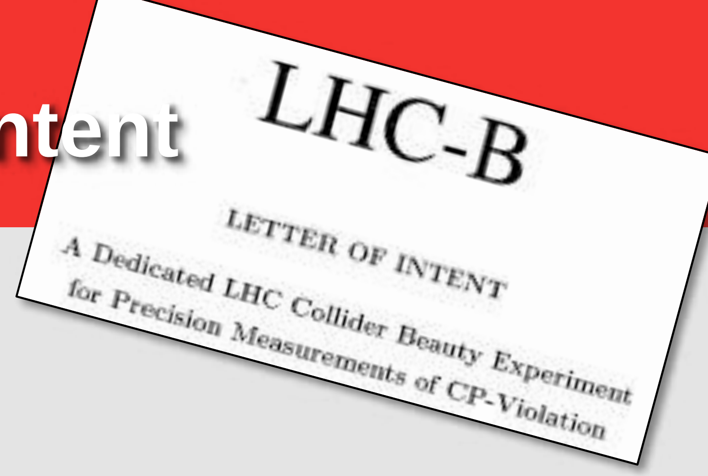
- 3) Matrix is unitary:

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

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



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

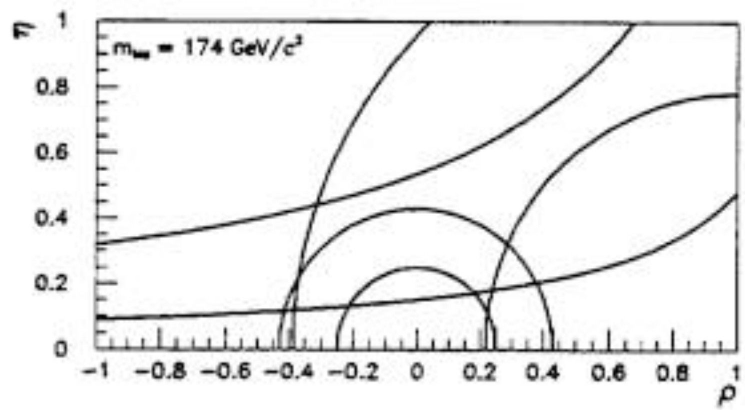
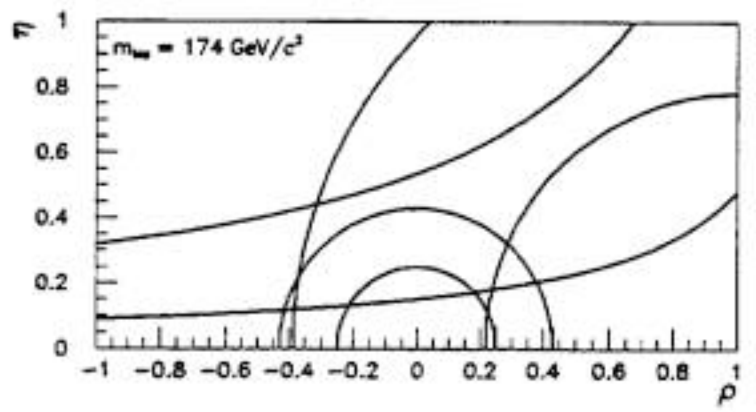


Figure 2.1: Limits on the CKM parameters (1σ) ρ and η for m_t = 174 GeV. The annular region cen-

CKM: (1995) LHCb Letter-of-Intent …

- Letter-of-Intent 1995



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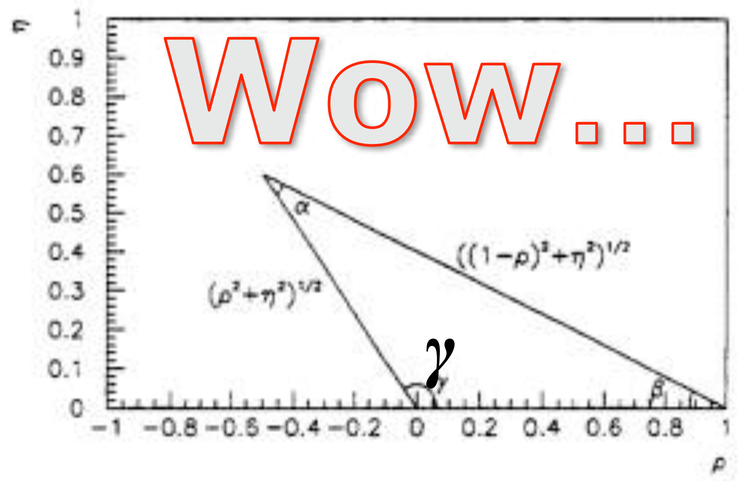
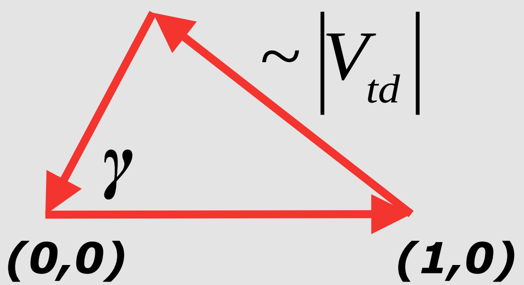


Figure 2.2: The Unitarity Triangle

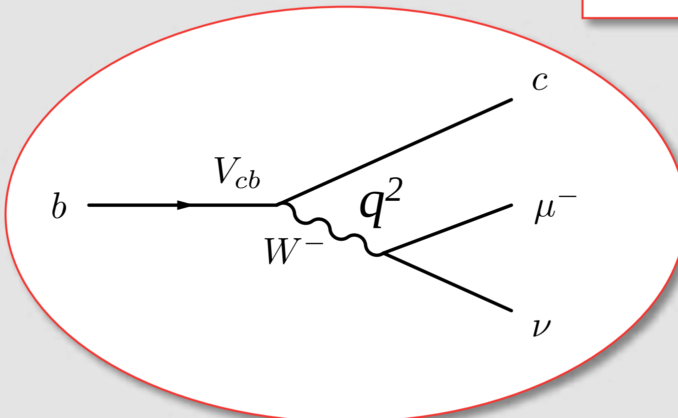


New measurement on $|V_{cb}|$

arXiv:2003.08453

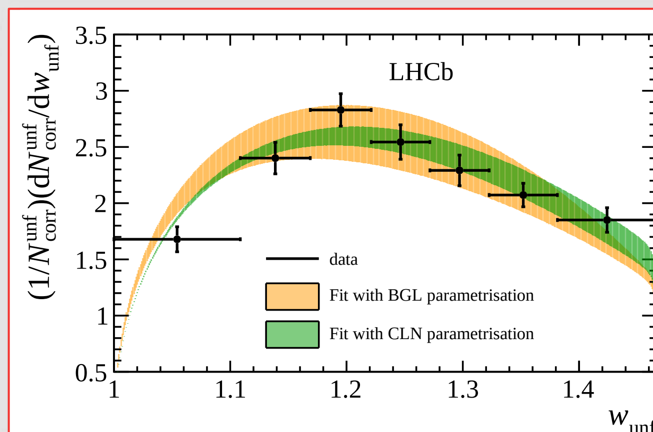
$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

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



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

➢ Determine $|V_{cb}|$ *and* form factors



(Suzanne Klaver et al.)
LHCb, "*Measurement of the shape of the $B^0_s \to D^{*-}_s \mu^+ \nu_\mu$ differential decay rate*" , arXiv:2003.08453

New measurement on $|V_{cb}|$

arXiv:2001.03225

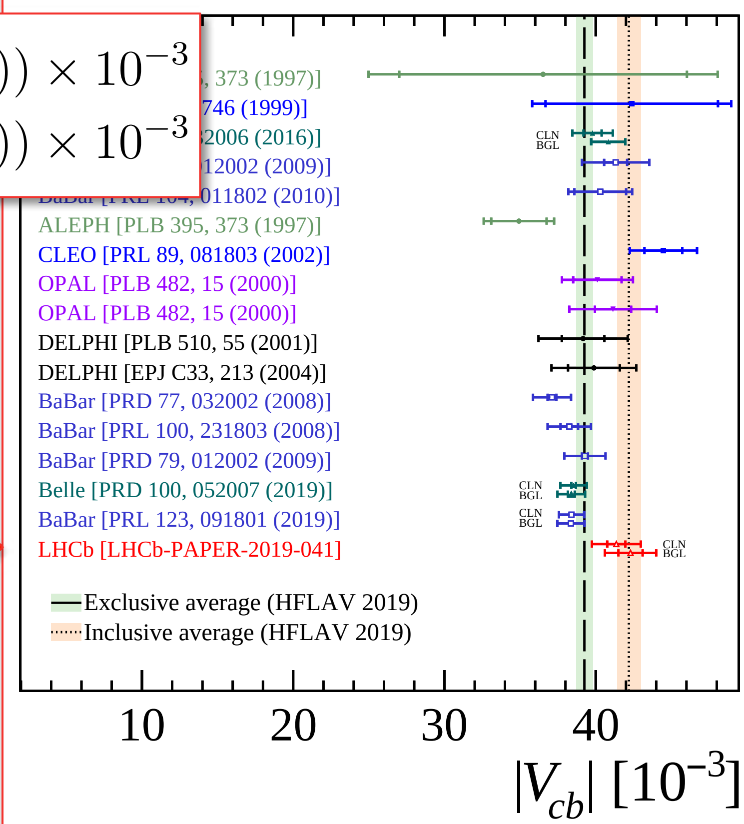
- Measure rate relative to known B^0 decay rate from B-factories:

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

- Result depends on the assumed form factor parametrization:

$$|V_{cb}|_{\text{CLN}} = (41.4 \pm 0.6\,(\text{stat}) \pm 0.9\,(\text{syst}) \pm 1.2\,(\text{ext})) \times 10^{-3}$$
$$|V_{cb}|_{\text{BGL}} = (42.3 \pm 0.8\,(\text{stat}) \pm 0.9\,(\text{syst}) \pm 1.2\,(\text{ext})) \times 10^{-3}$$

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

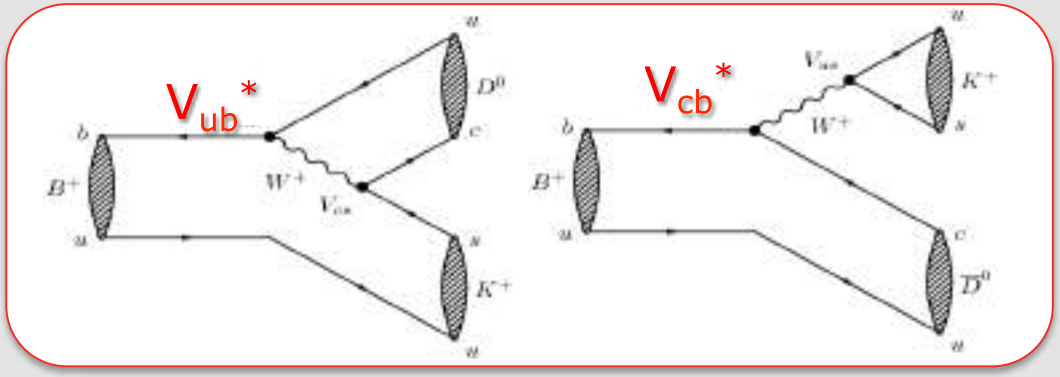


(Suzanne Klaver et al.)
LHCb, "*Measurement of $|V_{cb}|$ with $B^0_s \to D^{(*)-}_s \mu^+\nu_\mu$ decays*", arXiv:2001.03225

New constraints on angle γ

arXiv:2002.08858

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



LHCb, "*Measurement of CP observables in $B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$ with $D \to K^0_S K^\pm \pi^\mp$ decays*", arXiv:2002.08858

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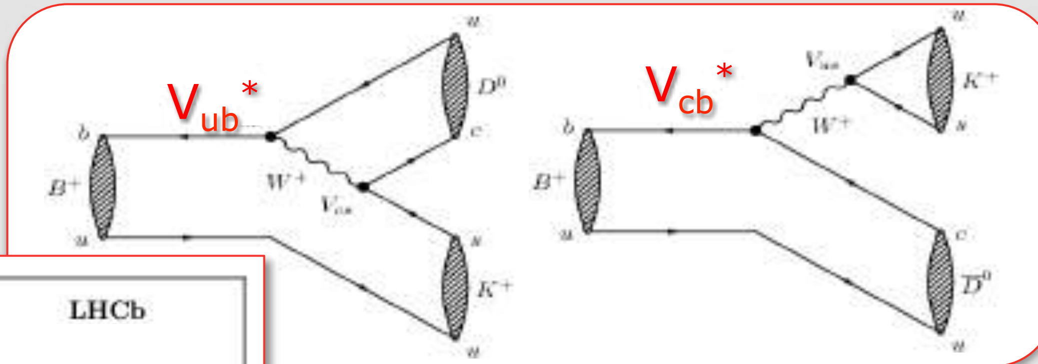
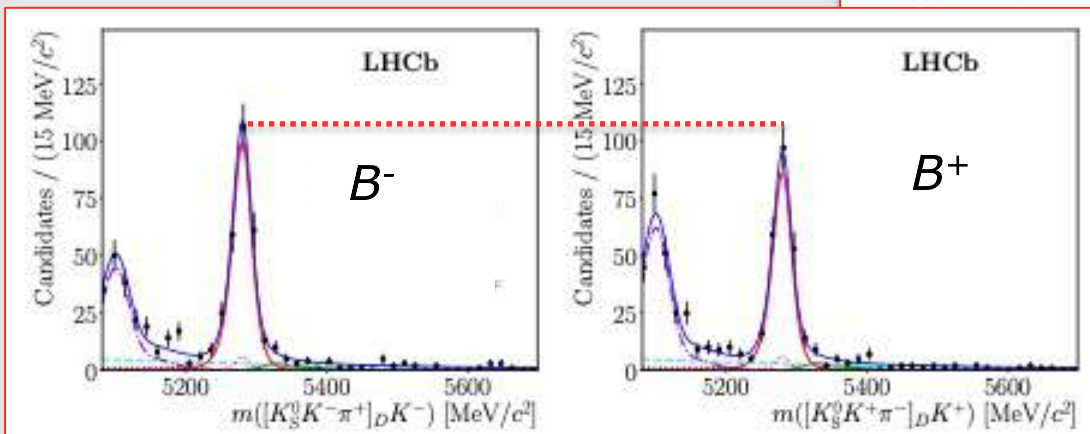


  - $B^{\pm} \to DK^{\pm}$ with $D \to K^0_S K^{\pm} \pi^{\mp}$:



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

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

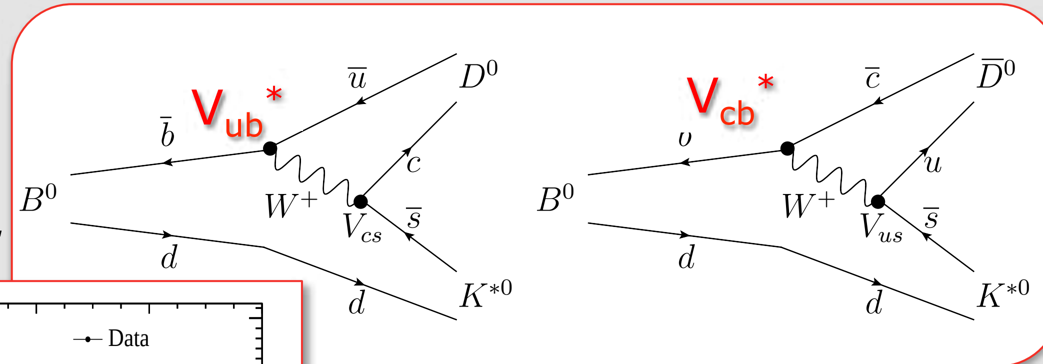
$$A_{SS}^{D\pi} = -0.020 \pm 0.011 \pm 0.003$$
$$A_{OS}^{D\pi} = 0.007 \pm 0.017 \pm 0.003$$
$$A_{SS}^{DK} = 0.084 \pm 0.049 \pm 0.008$$
$$A_{OS}^{DK} = 0.021 \pm 0.094 \pm 0.017$$

LHCb, "*Measurement of CP observables in $B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D\pi^{\pm}$ with $D \to K^0_S K^{\pm} \pi^{\mp}$ decays*", arXiv:2002.08858

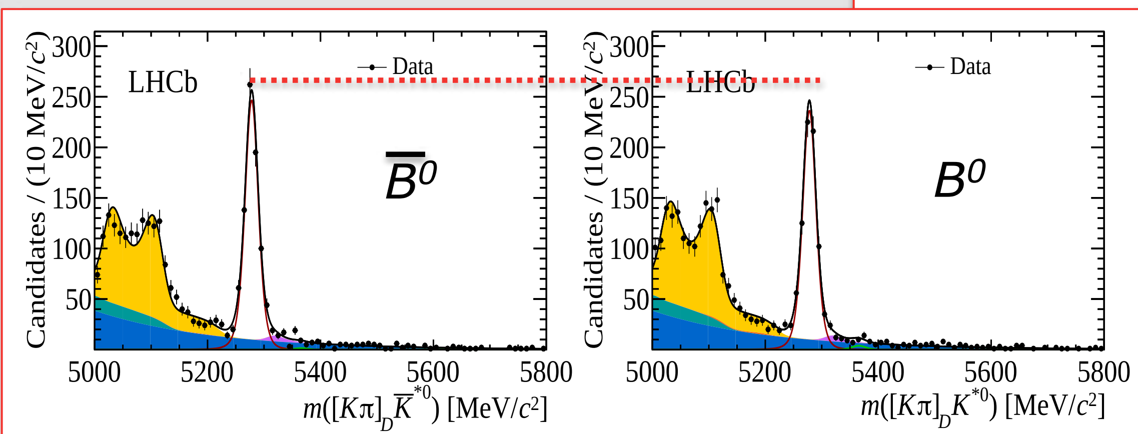
New constraints on angle γ

arXiv:1906.08297

- Different yields for B^0 and $\overline{B}^0$ decays
  - two amplitudes contribute with different relative phase: $V_{ub} = |V_{ub}|e^{-i\gamma}$



  - $B^0 \to DK^{*0}$ with $D \to h^\pm h^\mp (h^\pm h^\mp)$:



$$\mathcal{A}_{CP} = \frac{2\kappa r_B^{DK^{*0}} \sin\delta_B^{DK^{*0}} \sin\gamma}{\mathcal{R}_{CP}}$$

Decay channel	$\overline{B}^0$ yield	B^0 yield
$B^0 \to D(K^+K^-)K^{*0}$	67 ± 10	77 ± 11
$B^0 \to D(\pi^+\pi^-)K^{*0}$	27 ± 6	40 ± 7
$B^0 \to D(\pi^+\pi^-\pi^+\pi^-)K^{*0}$	32 ± 7	35 ± 8
$B^0 \to D(K^+\pi^-)K^{*0}$	786 ± 29	754 ± 29
$B^0 \to D(\pi^+K^-)K^{*0}$	76 ± 16	47 ± 15
$B^0 \to D(K^+\pi^-\pi^+\pi^-)K^{*0}$	557 ± 25	548 ± 25
$B^0 \to D(\pi^+K^-\pi^+\pi^-)K^{*0}$	41 ± 14	40 ± 14

$$\begin{aligned}
\mathcal{A}_{CP}^{KK} &= -0.05 \pm 0.10 \pm 0.01, \\
\mathcal{A}_{CP}^{\pi\pi} &= -0.18 \pm 0.14 \pm 0.01, \\
\mathcal{A}_{CP}^{4\pi} &= -0.03 \pm 0.15 \pm 0.01, \\
\mathcal{A}_{\rm ADS}^{K\pi} &= 0.047 \pm 0.027 \pm 0.010, \\
\mathcal{A}_{\rm ADS}^{K\pi\pi\pi} &= 0.037 \pm 0.032 \pm 0.010,
\end{aligned}$$

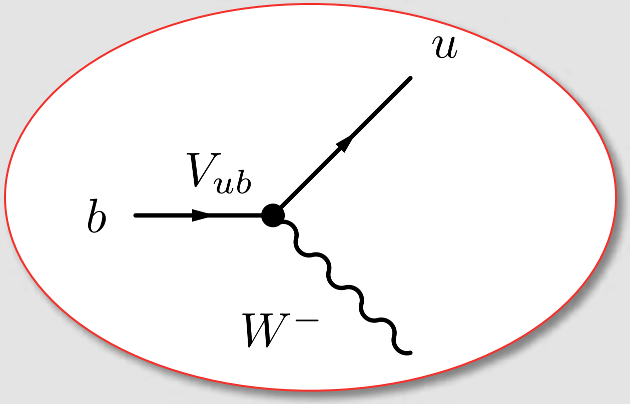
LHCb, "*Measurement of CP observables in the process $B^0 \to DK^{*0}$ with two- and four-body D decays*", arXiv:1906.08297

CKM angle γ

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

B decay	D decay	Method	Ref.	Dataset†	Status since last combination [3]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[17]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[18]	Run 2	New
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[19]	Run 1	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2	Updated results
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2	New
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[24]	Run 1	As before
$B^0_s \to D^{\mp}_s K^{\pm}$	$D^+_s \to h^+h^-\pi^+$	TD	[25]	Run 1	Updated results
$B^0 \to D^{\mp}\pi^{\pm}$	$D^+ \to K^-\pi^+\pi^+$	TD	[26]	Run 1	New

† Run 1 corresponds to an integrated luminosity of 3 fb^{-1} taken at centre-of-mass energies of 7 and 8 TeV. Run 2 corresponds to an integrated luminosity of 2 fb^{-1} taken at a centre-of-mass energy of 13 TeV.



CKM angle γ

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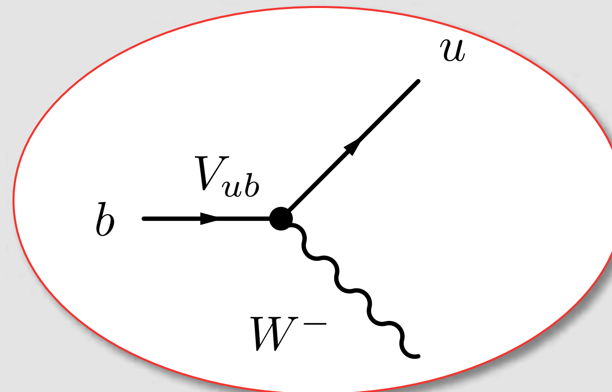

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$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2	New
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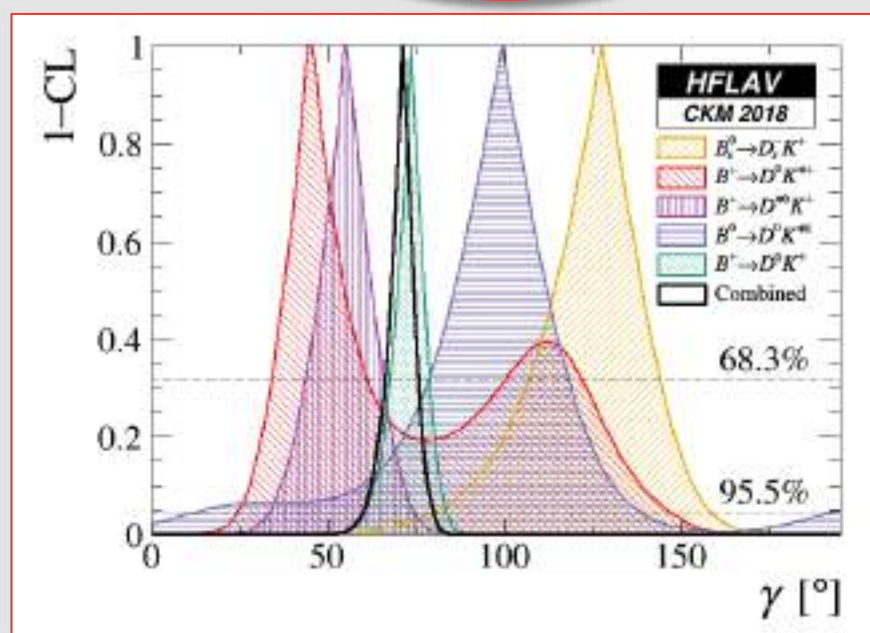
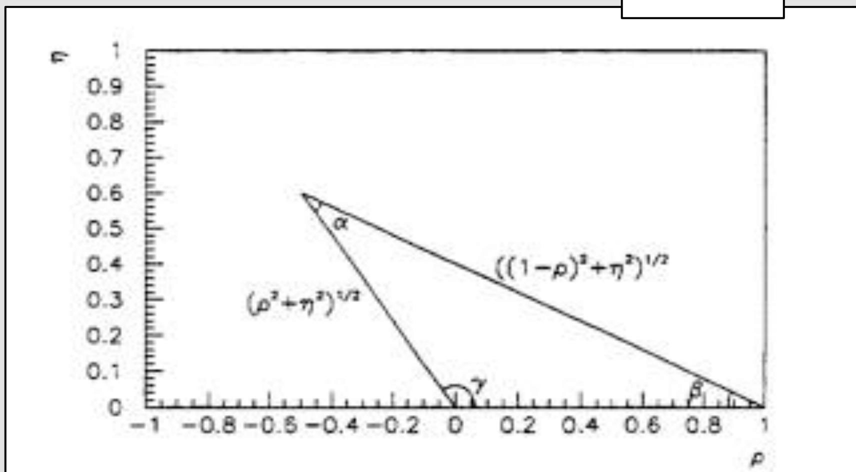
	γ (°)
LHCb	$74.0^{+5.0}_{-5.8}$
BaBar	69^{+17}_{-16}
World Avg (HFLAV)	$71.1^{+4.6}_{-5.3}$



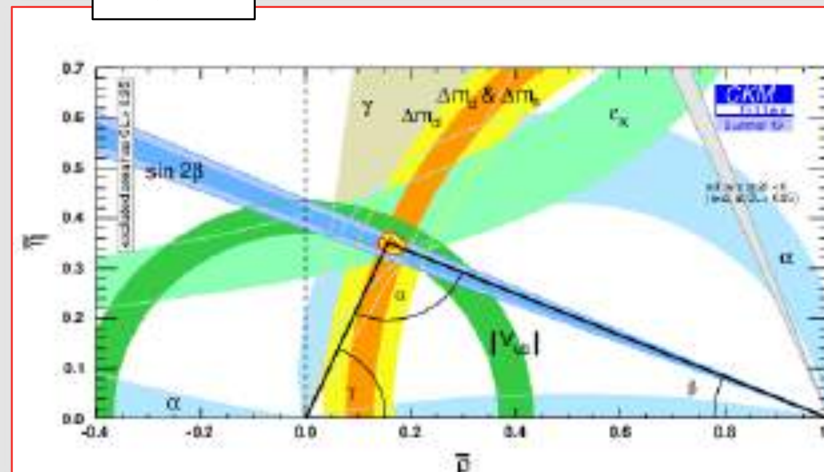
LHCb-2018-002, *Update of the LHCb combination ofthe CKM angle γ*

CKM

1995



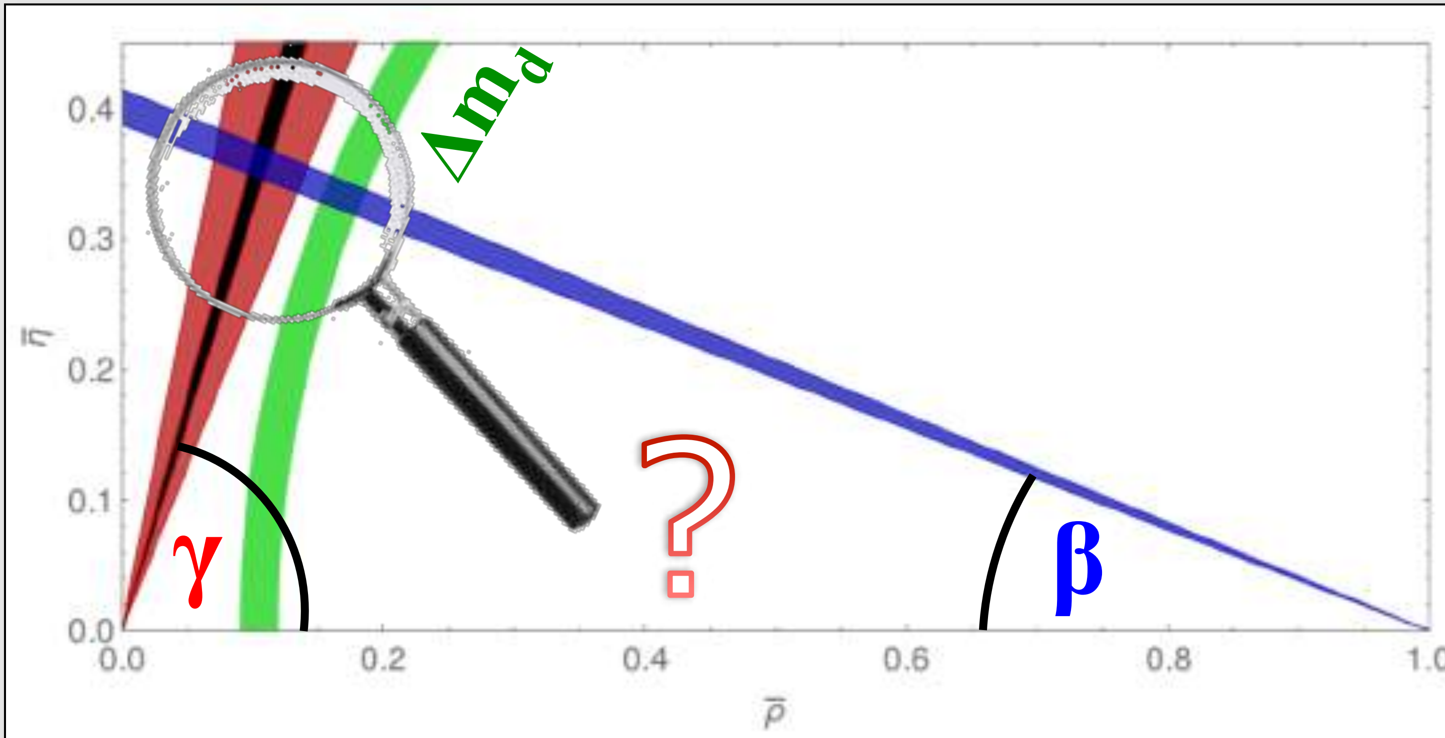
2019



- Continuous improvement over the years

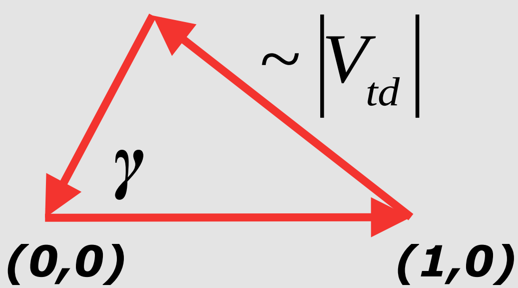
- All consistent?

CKM



M.Blanke & A.Buras, EPJ C79 (2019) 159, arXiv:1812.06963
Emerging ΔM_d-Anomaly from Tree-Level Determinations of $|V_{cb}|$ and the Angle γ

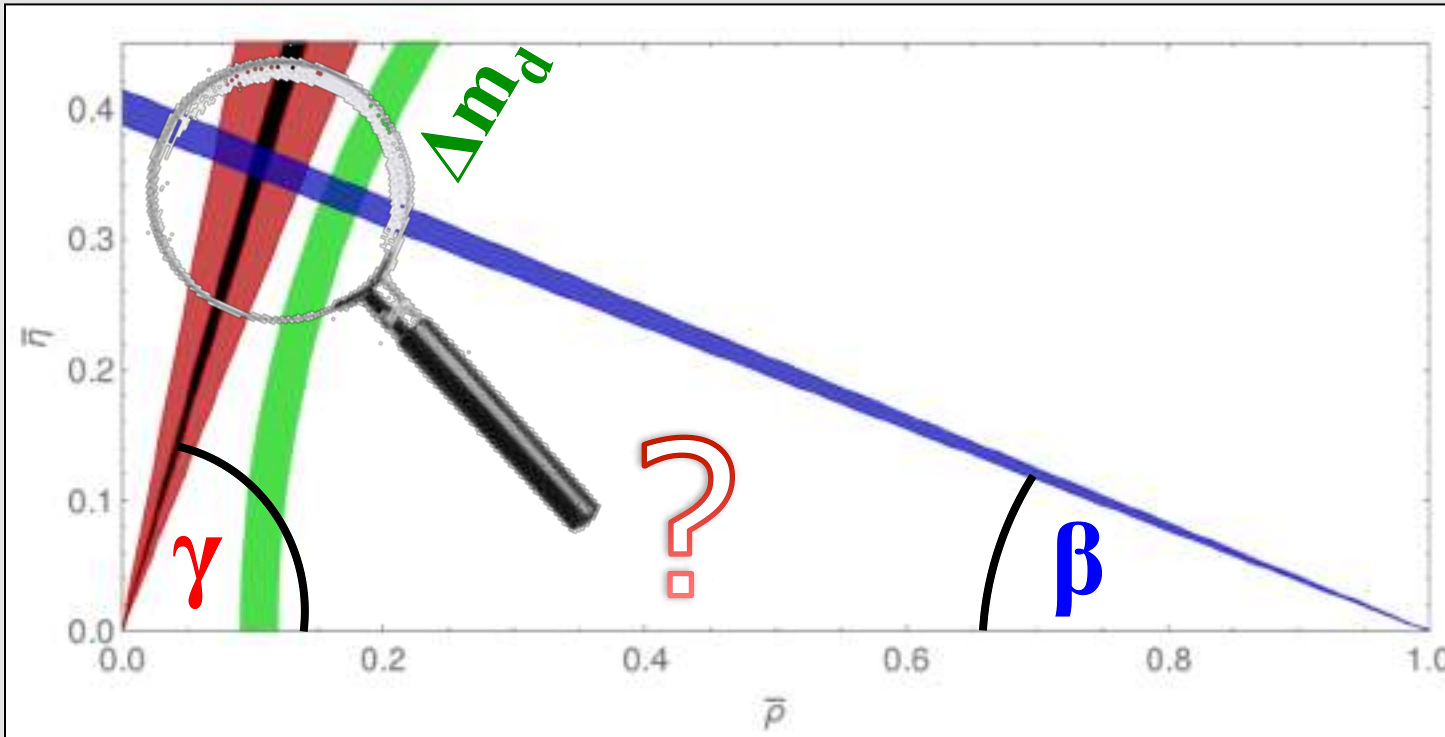
- All consistent…?



QCD

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{Bs}}{m_{Bd}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

CKM



M.Blanke & A.Buras, EPJ C79 (2019) 159, arXiv:1812.06963
Emerging ΔM_d-Anomaly from Tree-Level Determinations of $|V_{cb}|$ and the Angle γ

- Interesting ~2σ tension:

	γ (º)
LHCb	$74.0^{+5.0}_{-5.8}$
World Avg (HFLAV)	$71.1^{+4.6}_{-5.3}$
QCD (**Δm**^{exp}, ξ(Sum Rules))	63.4 ± 0.9

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{Bs}}{m_{Bd}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

QCD → ξ

D. King, A. Lenz, Th. Rauh, arXiv:1911.07856, *$|V_{cb}|$ and γ from mixing (addendum)*

On the menu

- Introduction
  - Precision measurements
  - The LHCb physics menu
- Selection of dishes:
  - Recent highlights on CP violation
  - Recent highlights on Rare decays (*aka Flavour Anomalies*)

On the menu

- Introduction
  - Precision measurements
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- Selection of dishes:
  - Recent highlights on CP violation
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- New results
  1) Lepton flavour non-universality $\Lambda_b^0 \to pK\mu^+\mu^-$
  2) Angular analysis of decay $B^0 \to K^{*0}\mu^+\mu^-$
  3) Search for LFV $B^0 \to K^{*0}\tau^+\mu$
  4) New limit on $B_s^0 \to e^+e^-$
  5) New limit on $K^0_S \to \mu^+\mu^-$
  6) New limit on (x25 !) $D^+_{(s)} \to hll'$

  (1–3: Flavour anomalies)

- A remark on consistency

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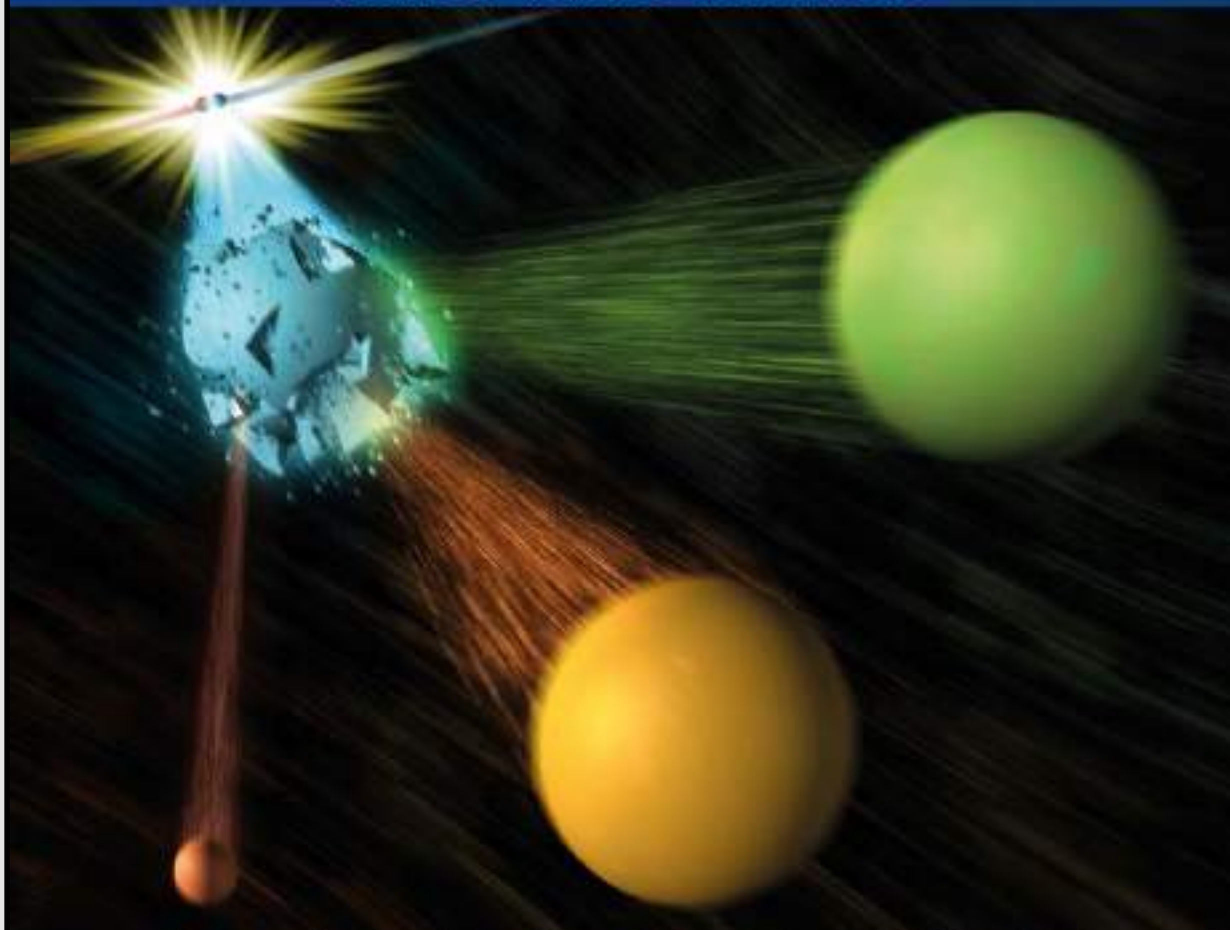
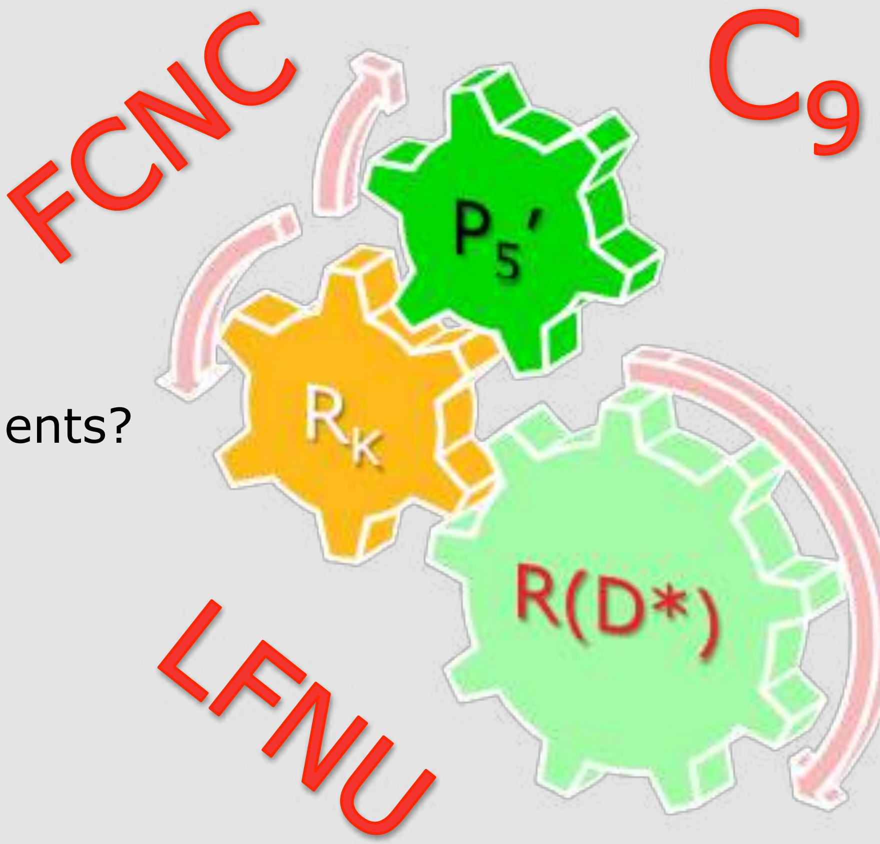


Tensions in the Standard Model

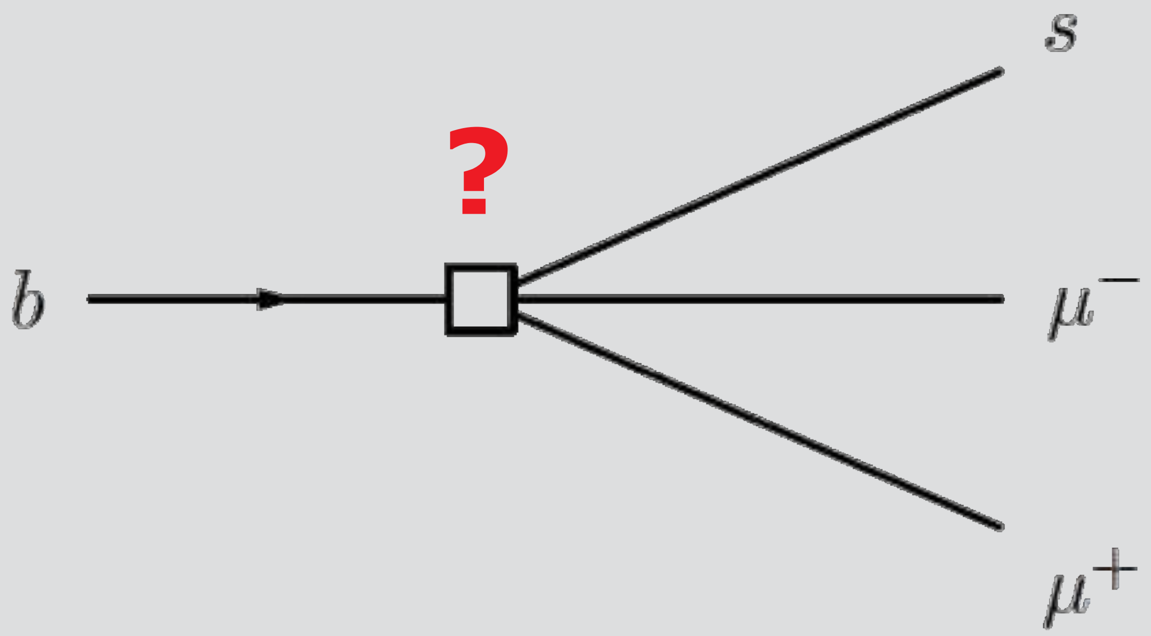
Flavour anomalies? A reminder



- What are the (anomalous) measurements?
  - FCNC: b→sll
  - LFNU: b→sll and b→clν

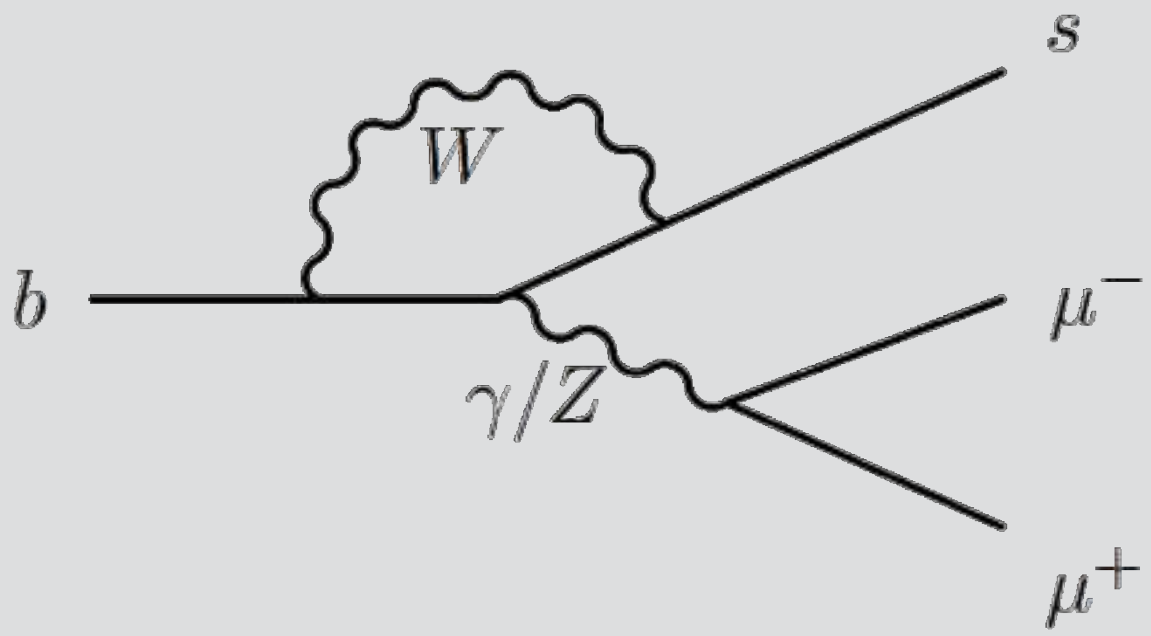
FCNC: *b→ sll*

- b→s transition forbidden at tree level in SM



FCNC: *b→ sll*

- b→s transition occurs at loop level
  - Suppressed in SM
  - NP can compete with SM

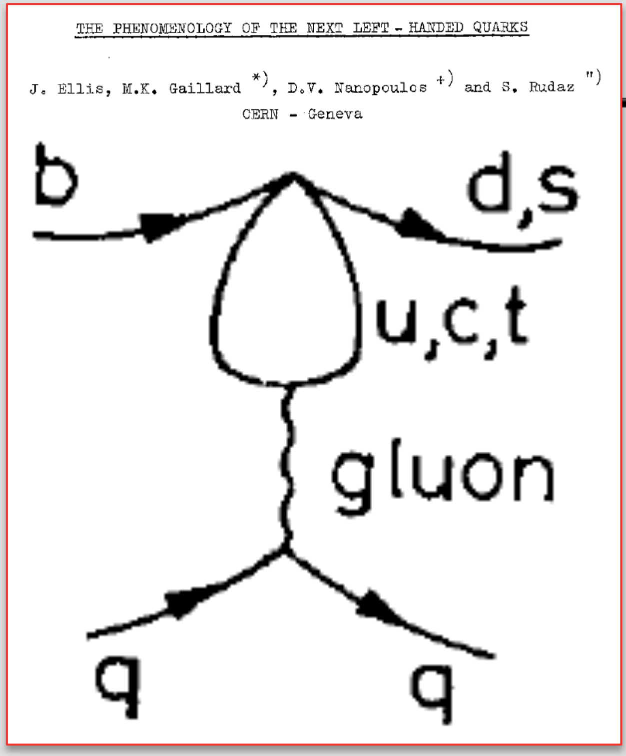


Flavour-Changing-Neutral-Current-Electro-Weak-Penguin diagram

FCNC: *b*→ *sll*

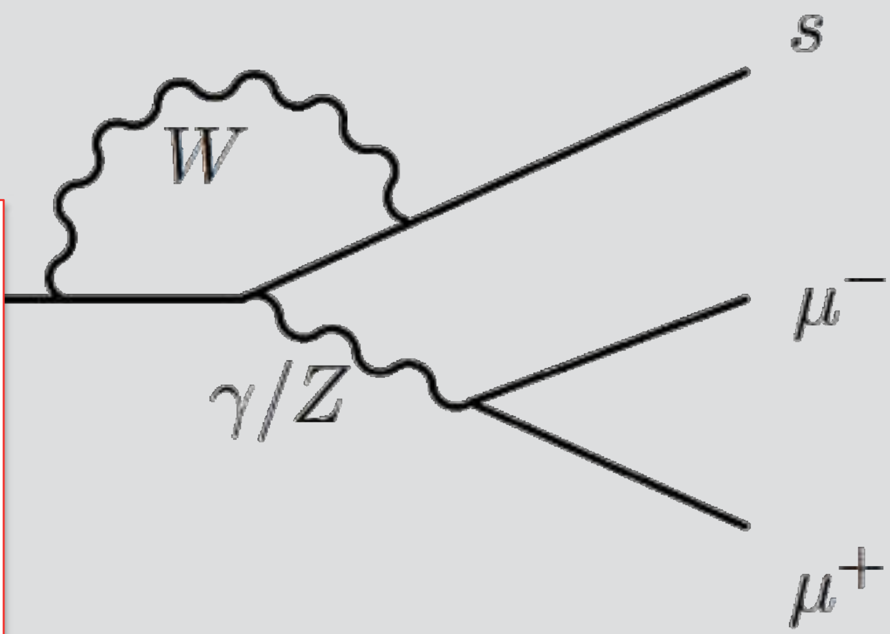
- b→s transition occurs at loop level
  - Suppressed in SM
  - NP can compete with SM

The first penguin:


THE PHENOMENOLOGY OF THE NEXT LEFT - HANDED QUARKS

J. Ellis, M.K. Gaillard *), D.V. Nanopoulos +) and S. Rudaz ")

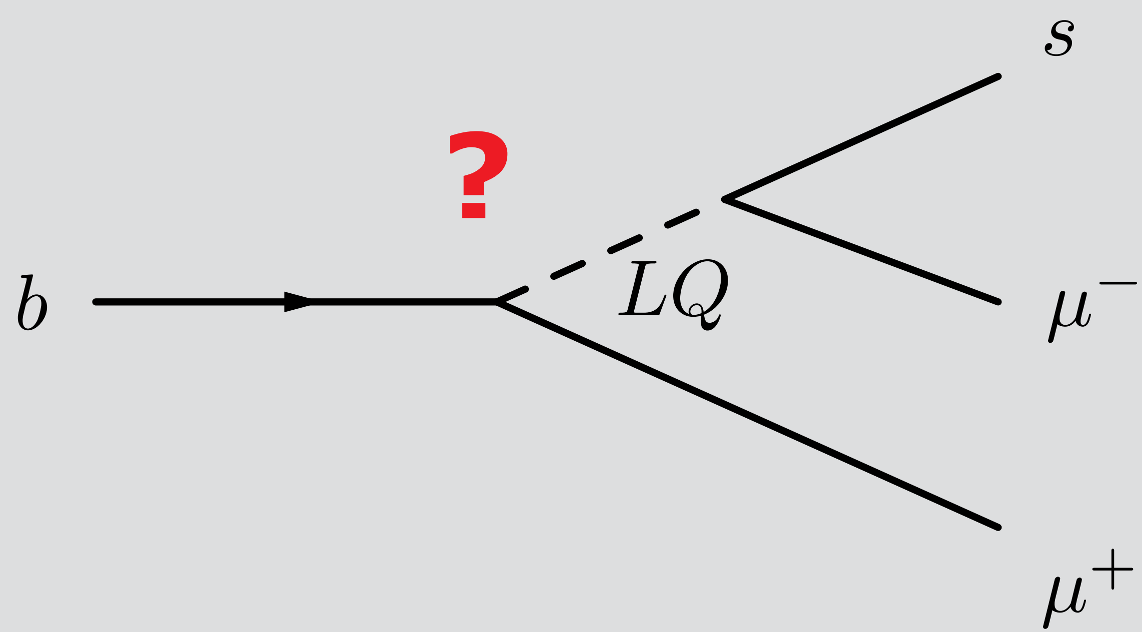
CERN - Geneva



Nucl. Phys. B131 (1977) 285

FCNC: *b→ sll*

- b→s transition occurs at loop level
  - LQ quite fashionable these days



de Volkskrant

Moeder aller deeltjes: de zoektocht naar de leptoquark

Is het fundamenteelste deeltje in het universum altijd over het hoofd gezien? Komende week kan de wereld opgeschud worden, als natuurkundigen in Seoul hun resultaten bekendmaken. Leptoquark, onthoud dat woord.

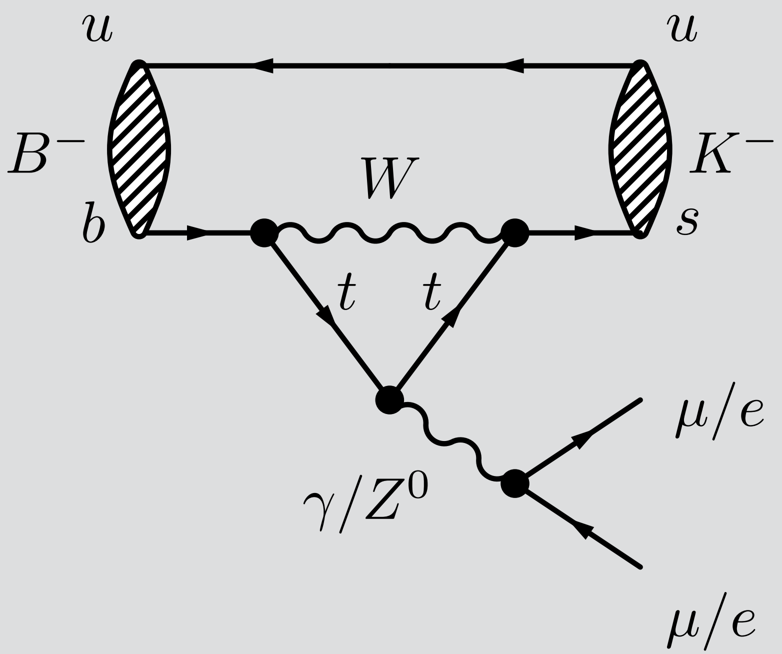
Martijn van Calmthout

R_K: $B^+ \rightarrow K^+\mu^+\mu^-$ and $B^+ \rightarrow K^+e^+e^-$

- Similar loop diagram!

- Measure ratio μ/e
- SM expectation: R_K=1

$$R_K = \frac{\Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^+ \to K^+e^+e^-)}$$

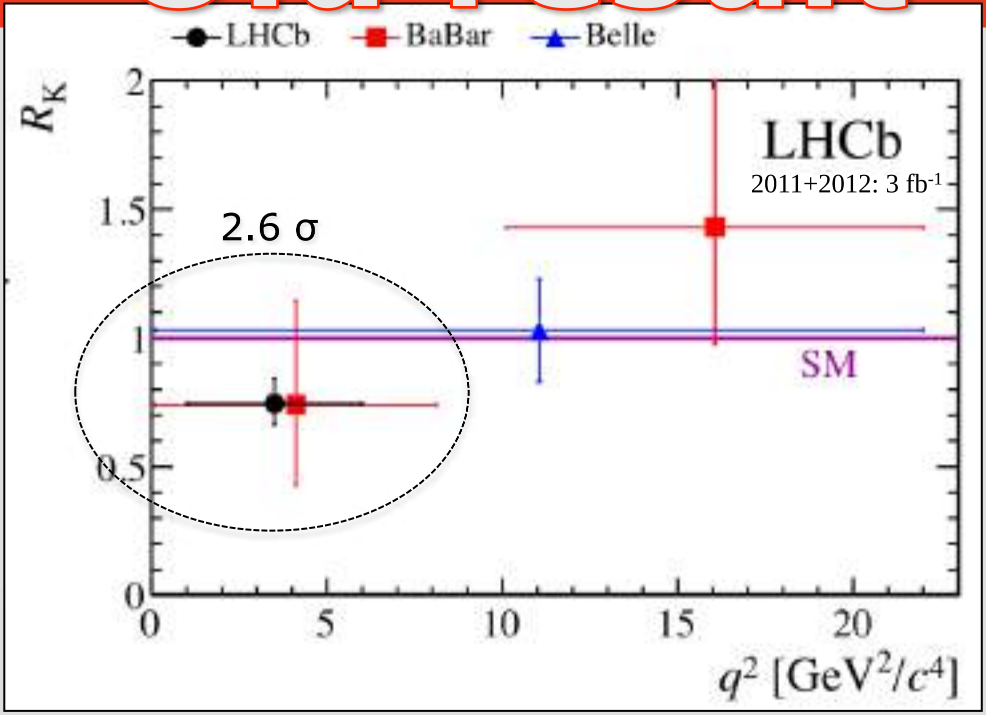


R_K: $B^+ \to K^+\mu^+\mu^- / B^+ \to K^+e^+e^-$ Old result

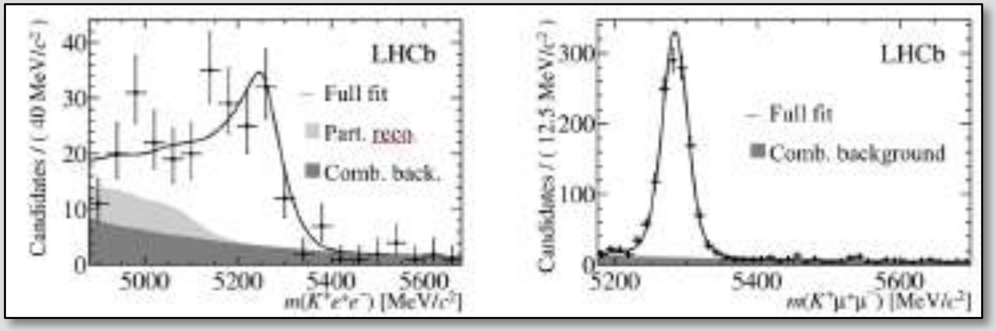
- Similar loop diagram!
- Measure ratio μ/e
- SM expectation: $R_K=1$

$$R_K = \frac{\Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^+ \to K^+e^+e^-)}$$

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$



LHCb,PRL 113 (2014) 151601



- **Lepton flavour "non-universal" ?**

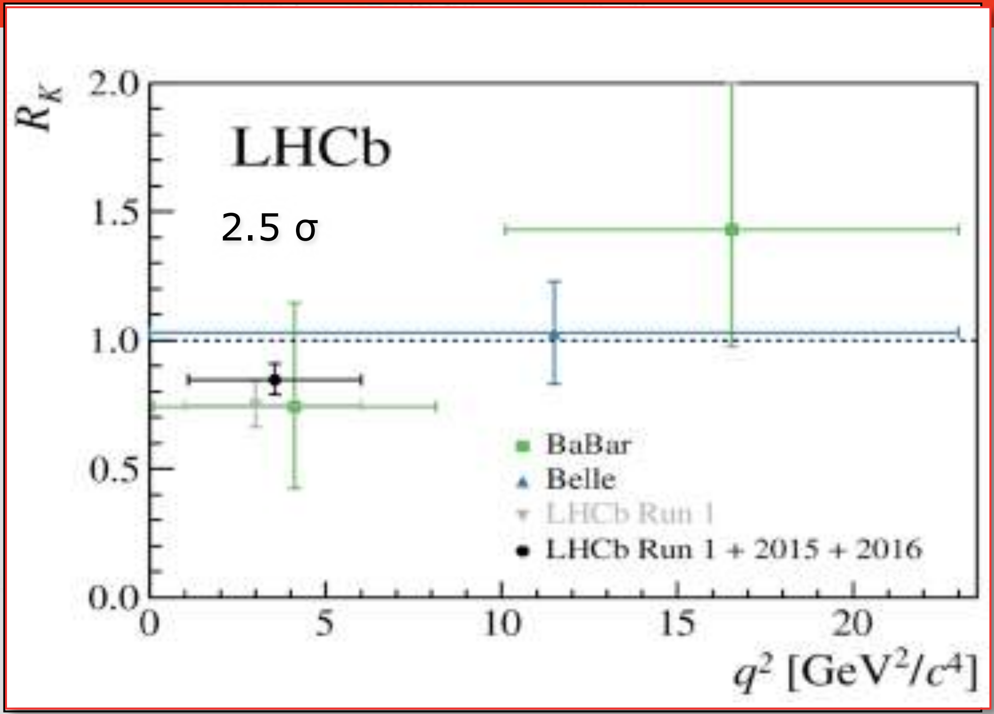
R_K: $B^+ \to K^+\mu^+\mu^- / B^+ \to K^+e^+e^-$ arXiv:1903.09252

- Similar loop diagram!

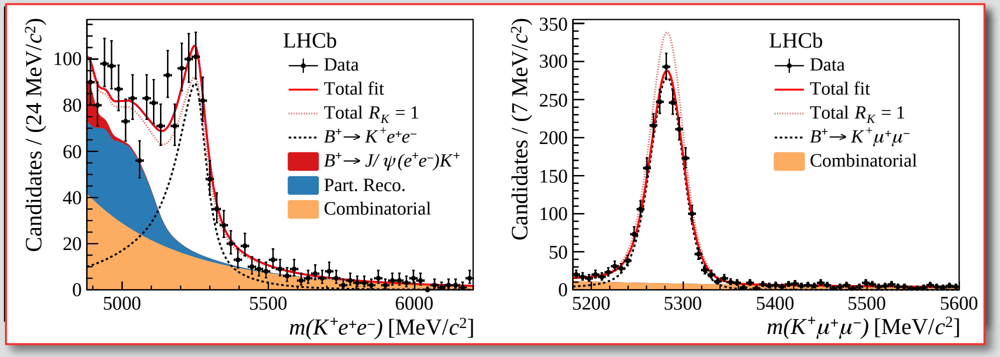
- Measure ratio μ/e
- SM expectation: $R_K=1$

$$R_K = \frac{\Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^+ \to K^+e^+e^-)}$$

$$R_K = 0.846\,^{+0.060}_{-0.054}\,^{+0.016}_{-0.014}$$



LHCb,PRL 122 (2019) 191801



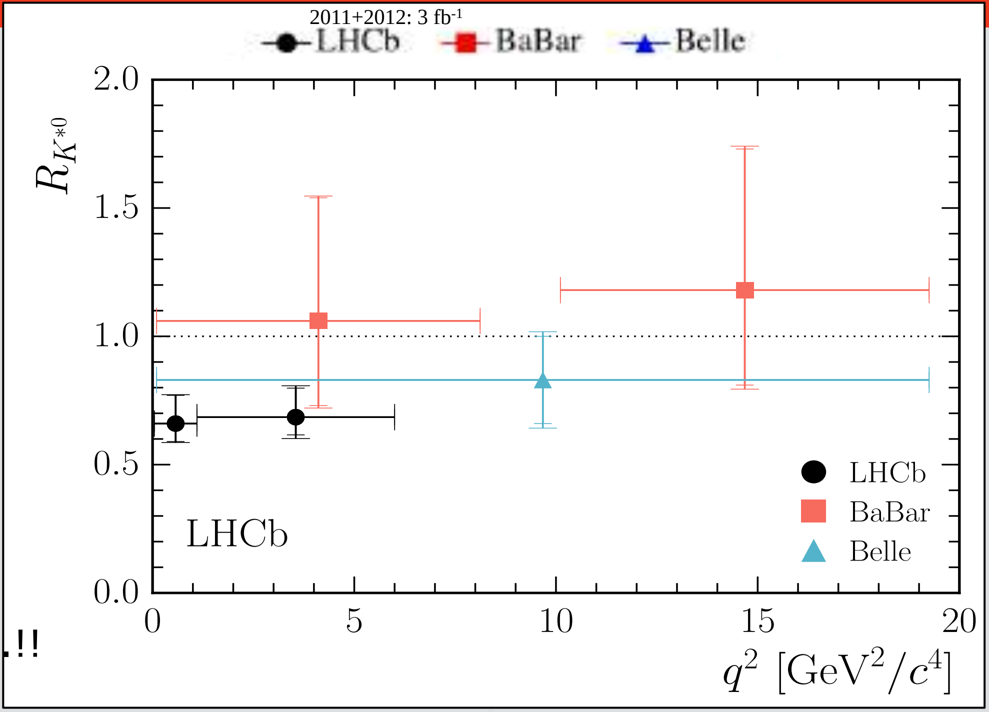
- **Lepton flavour "non-universal" ?**

R_{K*}: $B^0 \to K^{0*}\mu^+\mu^-$ and $B^0 \to K^{0*}e^+e^-$

- Similar loop diagram!

- Measure ratio μ/e
- SM expectation: $R_{K*}=1$

➢ Extra bin at low q^2…
  - $q^2 \sim 0$ not helicity suppressed
  - But dominated by photon pole
  - EM coupling to photon undebated…!!



LHCb Coll., JHEP 1708 (2017) 055

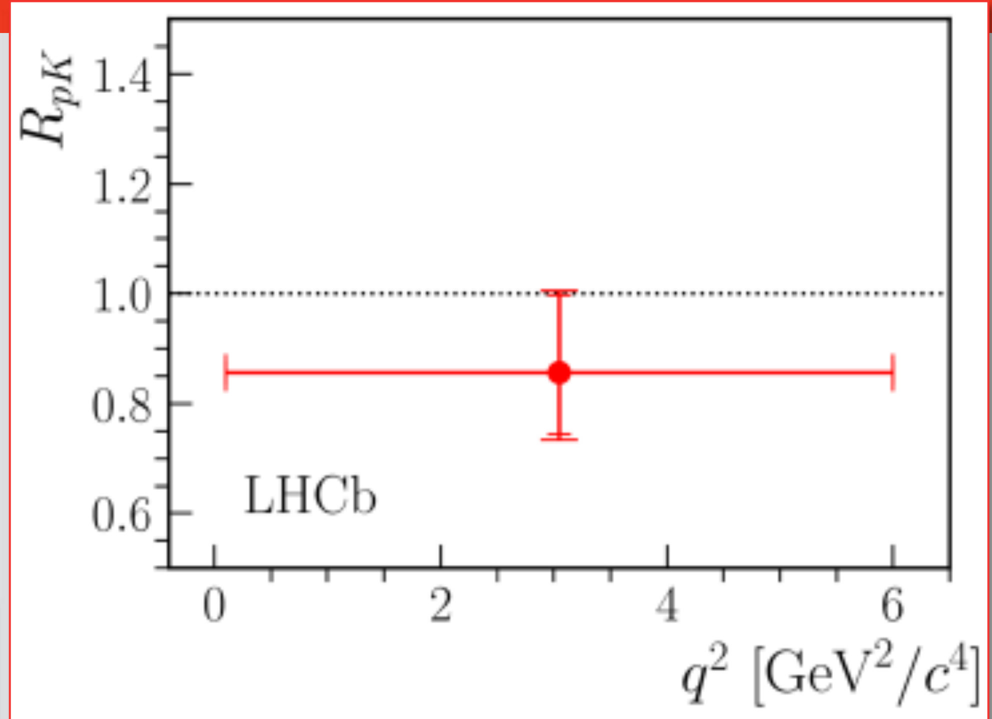
$$R_{K^{*0}} = \begin{cases} 0.66 \,{}^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1 \;\; \text{GeV}^2/c^4 \\ 0.69 \,{}^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 \;\;\; < q^2 < 6.0 \;\; \text{GeV}^2/c^4 \end{cases}$$

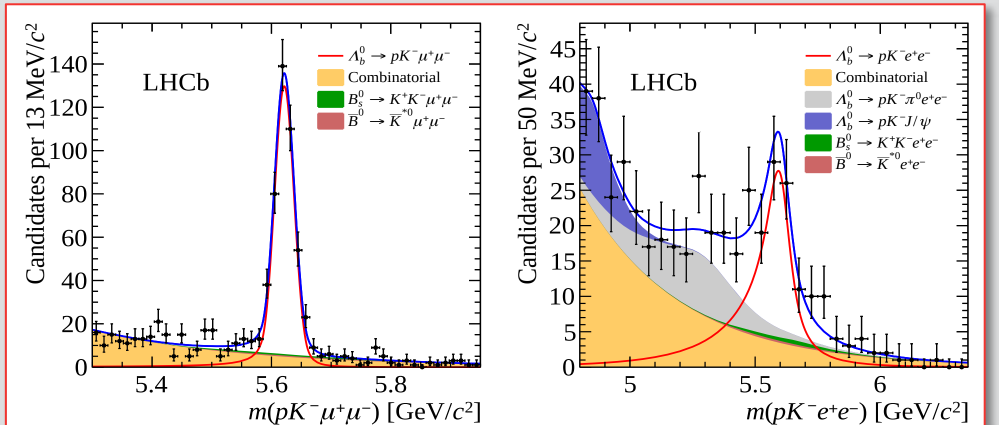
➢ **Lepton flavour “non-universal” ?**

R_{pK}: $\Lambda_b^0 \to pK\mu^+\mu^- / \Lambda_b^0 \to K^{0*}e^+e^-$ arXiv:1912.08139

- Similar loop diagram!
- Measure ratio μ/e
- SM expectation: $R_{pK}=1$

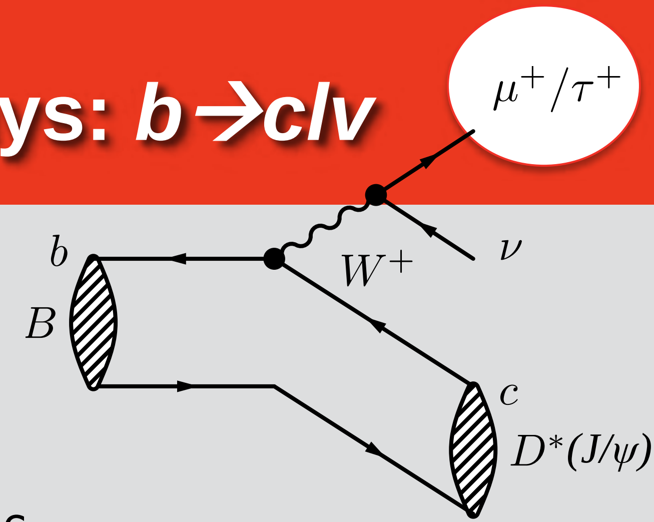
$$R_{pK}|_{0.1<q^2<6\,\mathrm{GeV}^2/c^4} = 0.86\,^{+0.14}_{-0.11} \pm 0.05$$



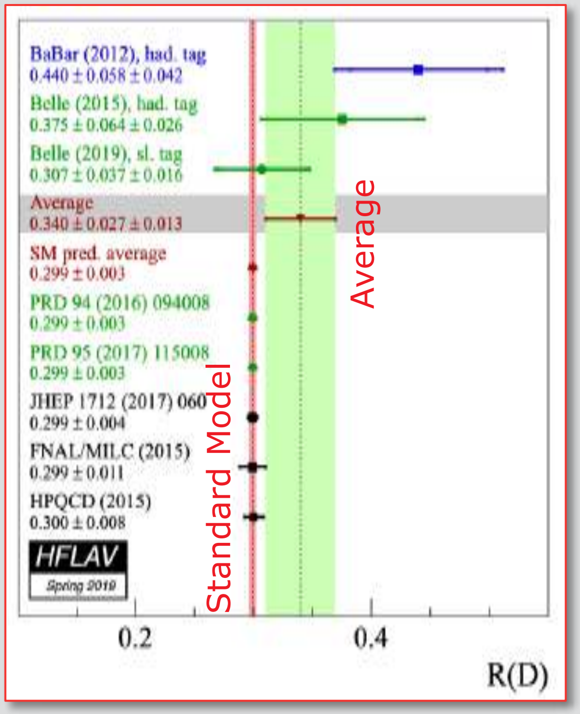


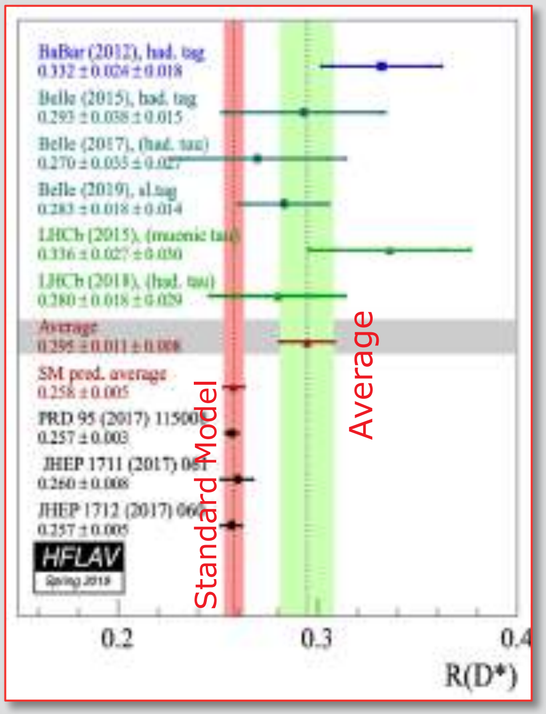
- **Lepton flavour "non-universal" ?**

More LFNU? Semileptonic decays: *b→clν*



- $B^0 \to D^{(*)} l \nu$ Measured ratio τ/μ
  - Multiple experiments: Belle, BaBar, LHCb
  - Multiple c-modes: *D, D*, J/ψ*
  - Multiple tau final states: μ, 1-prong, 3-prong
  - Multiple tags: semileptonic, hadronic

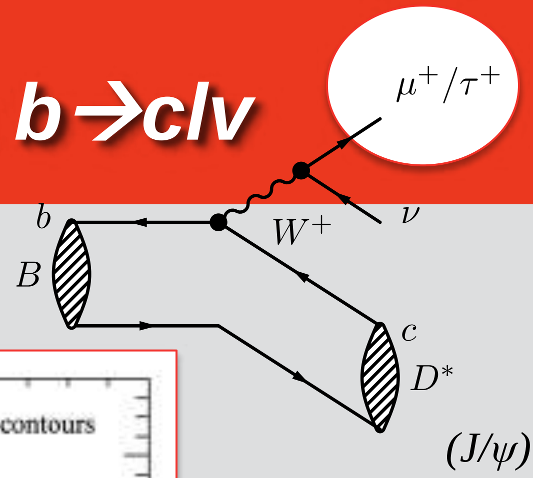




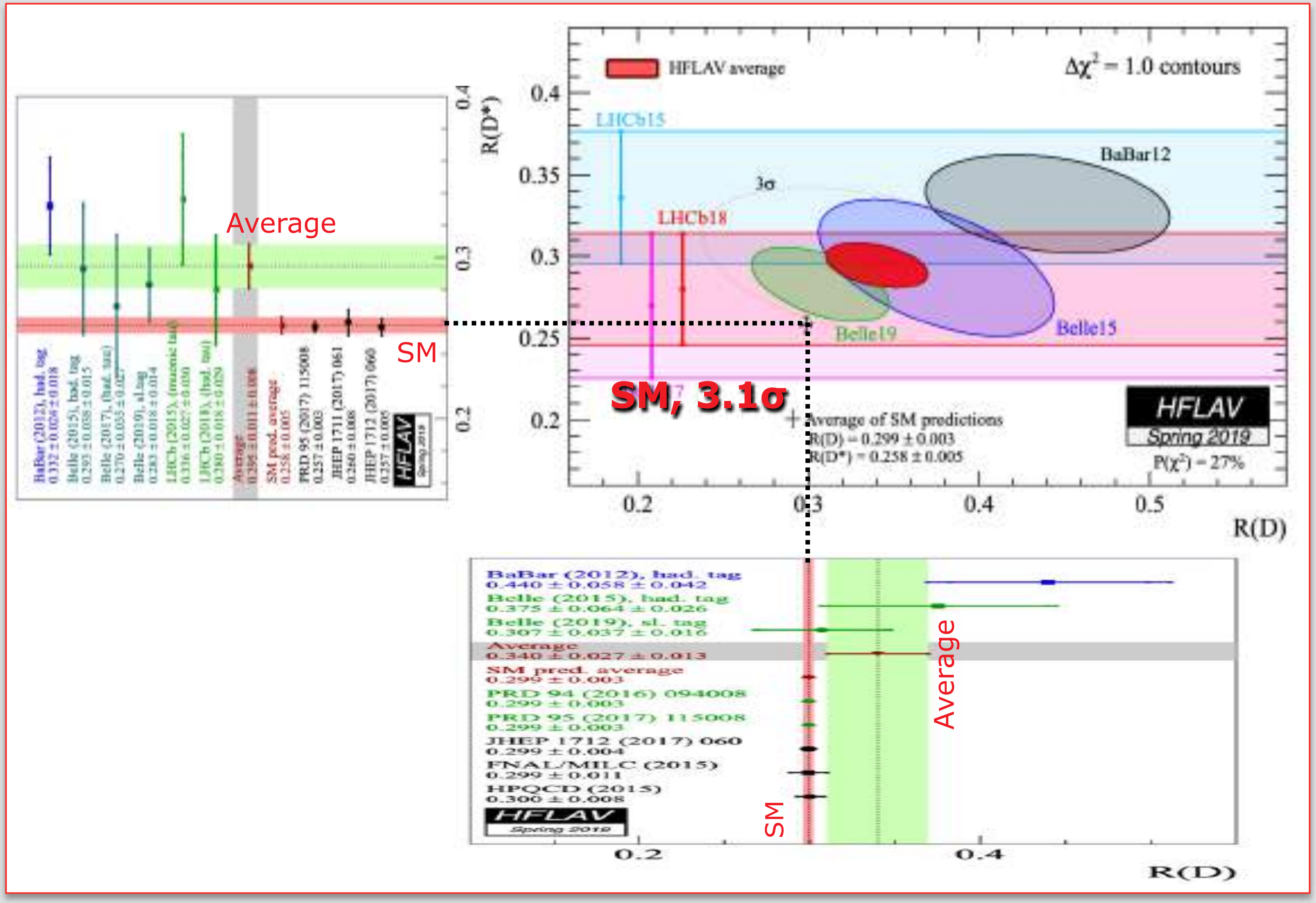
and with B_c^+: $\mathcal{R}(J/\psi) = 0.71 \pm 0.17\,(\text{stat}) \pm 0.18\,(\text{syst})$

LHCb Coll. arXiv:1711.05623

More LFNU? Semileptonic decays: $b \to c l \nu$

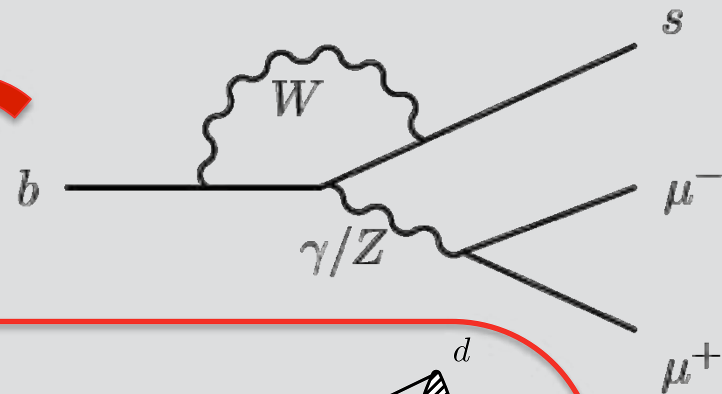


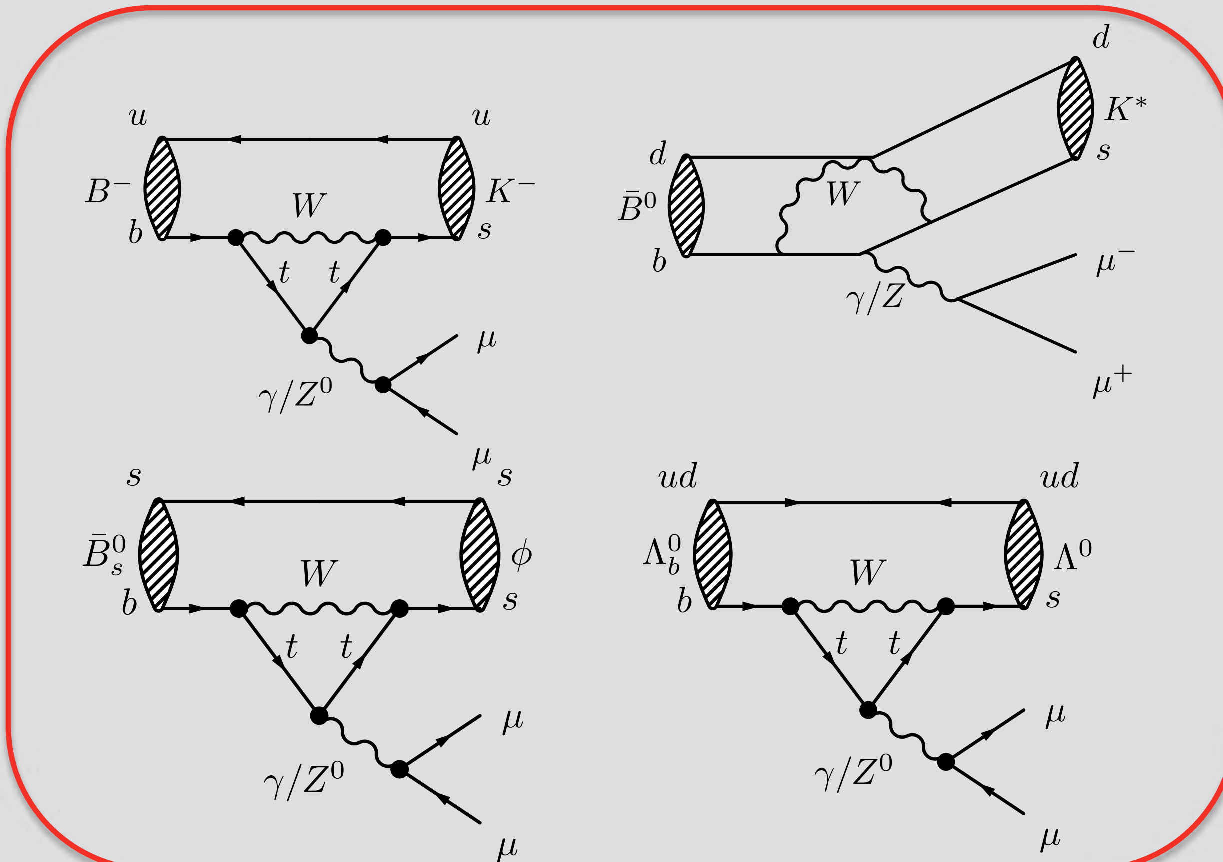
- Discrepancy in 2D about 3σ



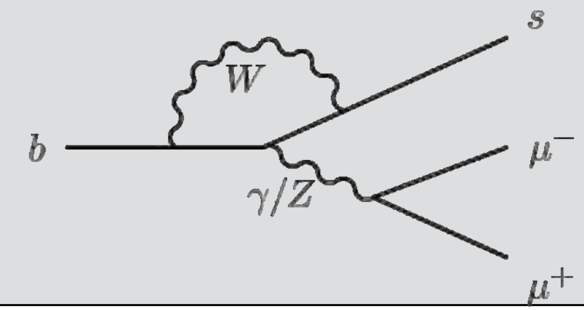
Decay rates: *b→ sll*

- Study same process with different hadrons:

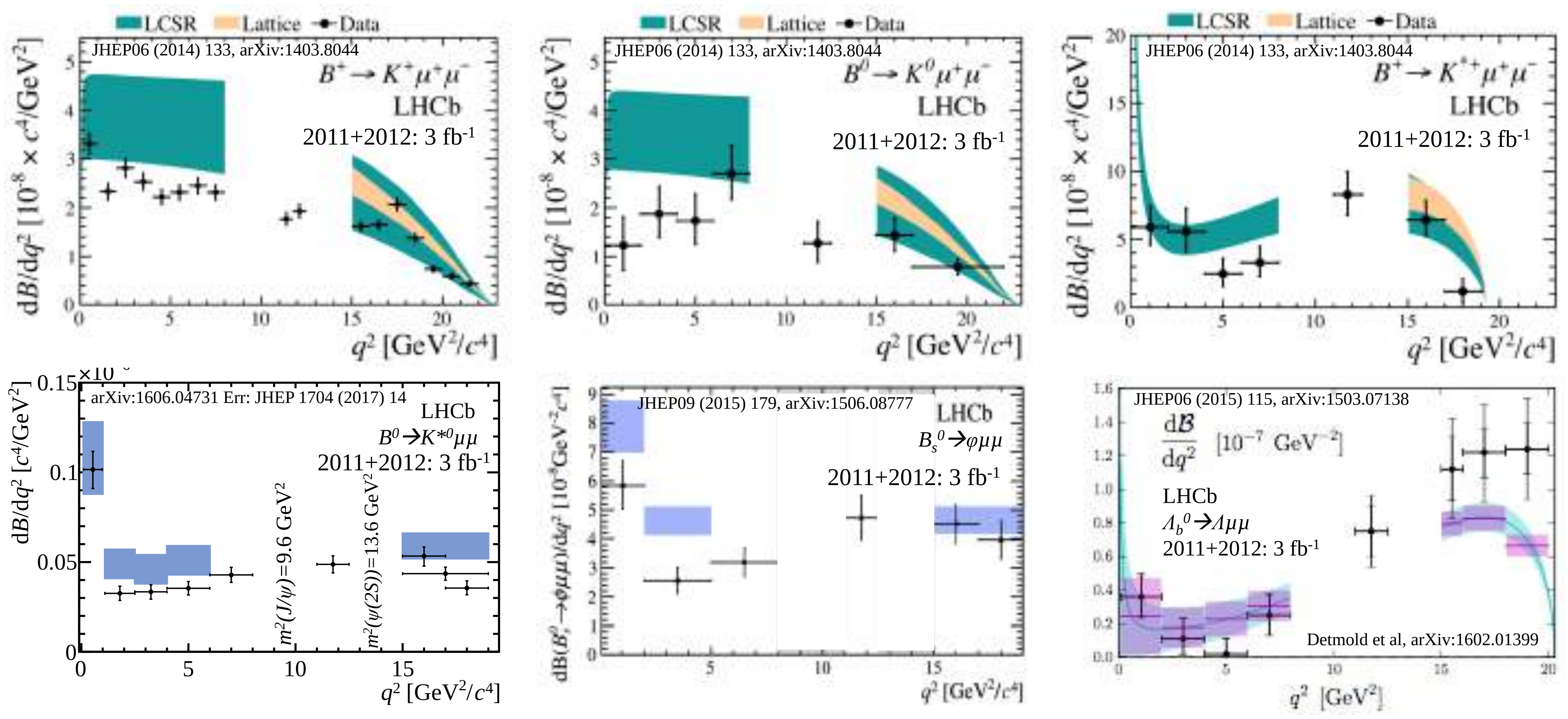




Decay rates: *b→ sll*



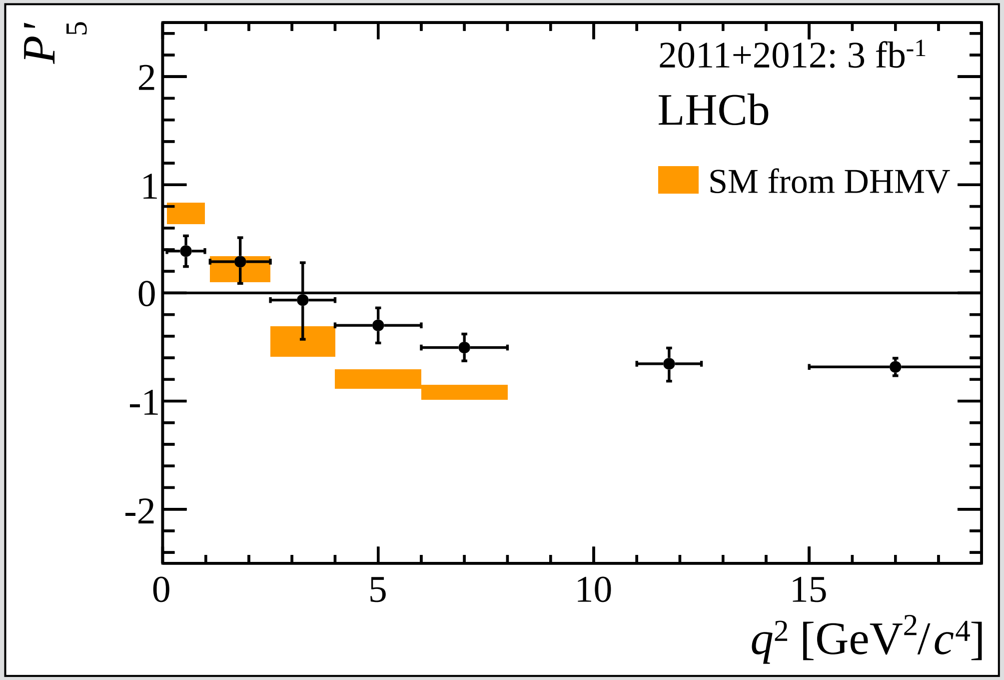
- Decay rate is consistently low:



$B^0 \rightarrow K^{0*}\mu^+\mu^-$: P_5'

Old result

- Similar loop diagram!
- More observables
  - Invariant mass of μμ-pair
  - Angles of *K* and *μ*



LHCb, JHEP02 (2016) 104, arXiv:1512.04442

$B^0 \rightarrow K^{0*}\mu^+\mu^-$: P_5' Old result

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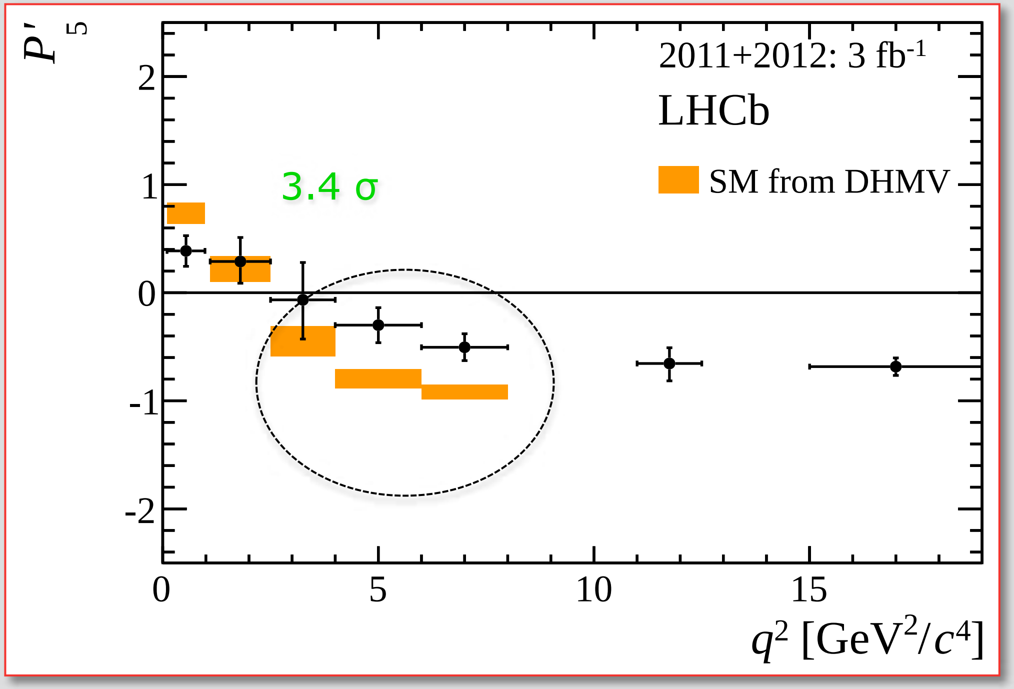


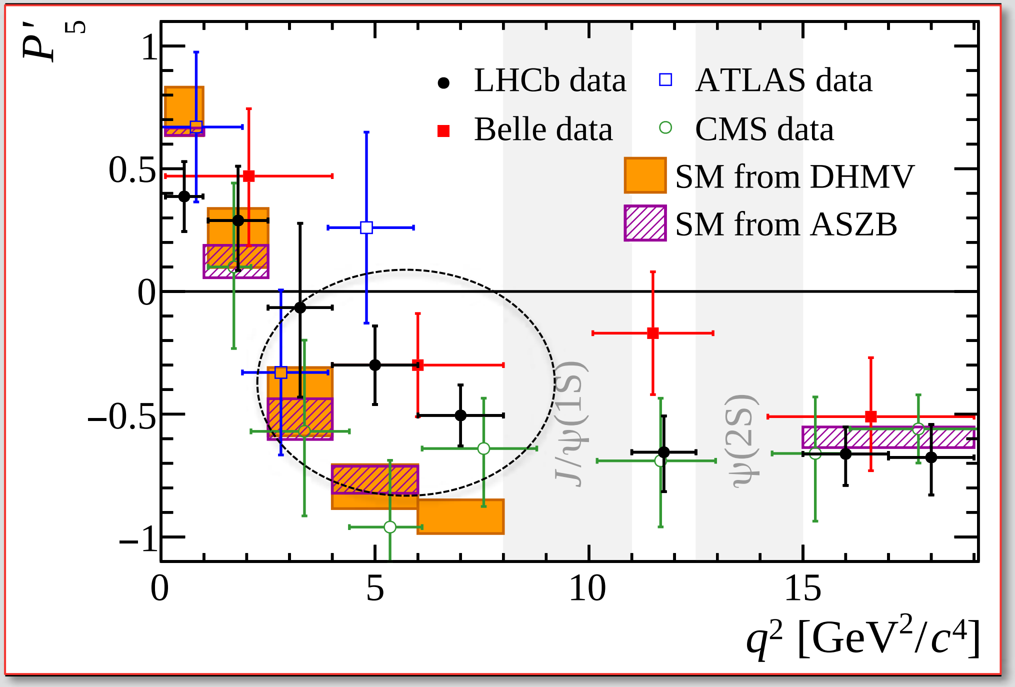
LHCb, JHEP02 (2016) 104, arXiv:1512.04442

$B^0 \rightarrow K^{0*}\mu^+\mu^-$: P_5'

Old result

- Similar loop diagram!
- More observables
  - Invariant mass of μμ-pair
  - Angles of *K* and *μ*
- *Many experiments contribute!*

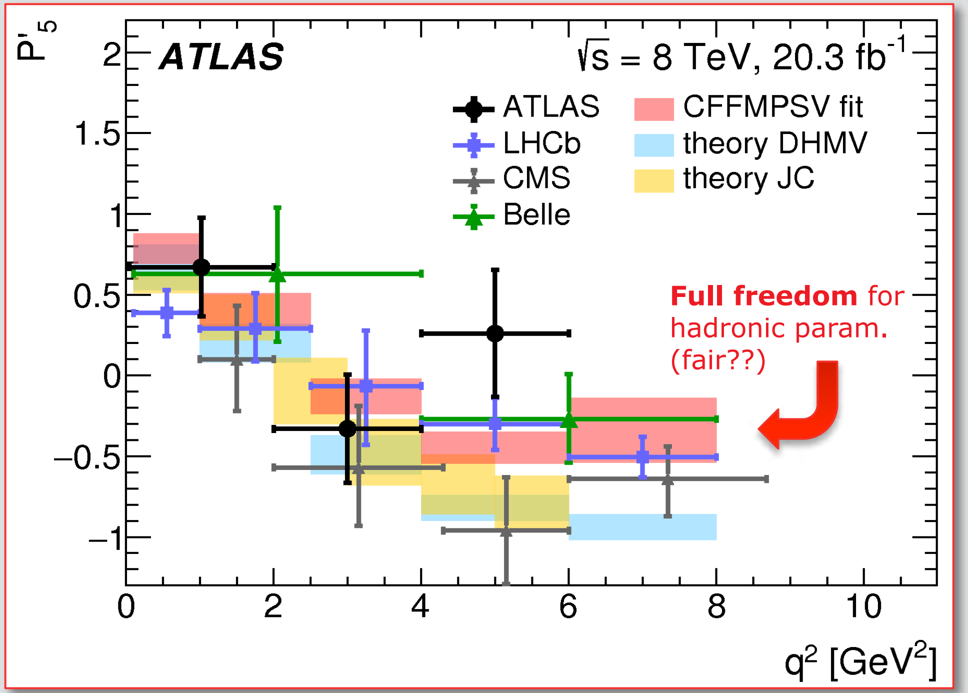
Private compilation, courtesy T. Blake



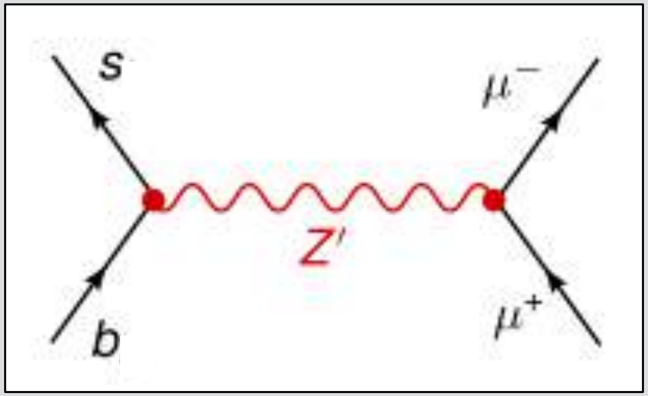
- LHCb, JHEP02 (2016) 104
- Belle, PRL 118 (2017) 111801
- ATLAS-CONF-2017-023
- CMS, PLB 81 (2018) 517

$B^0 \rightarrow K^{0*}\mu^+\mu^-$: P_5' Old result

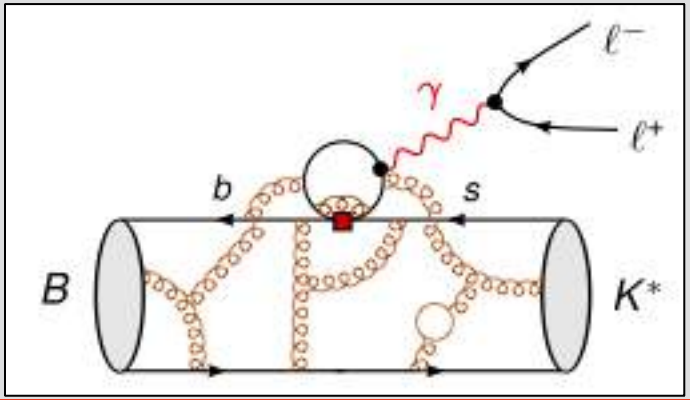
- Similar loop diagram!
- More observables
  - Invariant mass of μμ-pair
  - Angles of *K* and *μ*
- Debate on SM calculation
  - Non-perturbative "charm loop" effects?



- ATLAS, arXiv:1805.04000
- LHCb, JHEP02 (2016) 104
- Belle, PRL 118 (2017) 111801



or

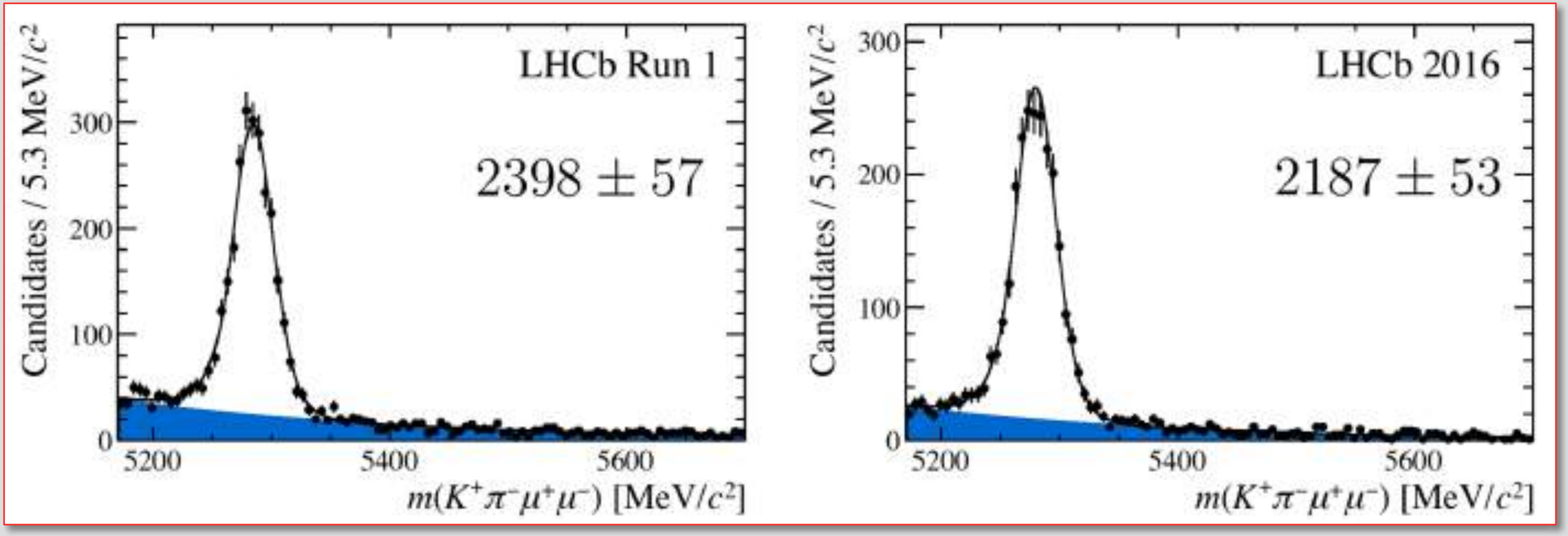


?

$B^0 \rightarrow K^{0*}\mu^+\mu^-$: P_5'

arXiv:2003.04831

- Updated with (part of) run-2 data

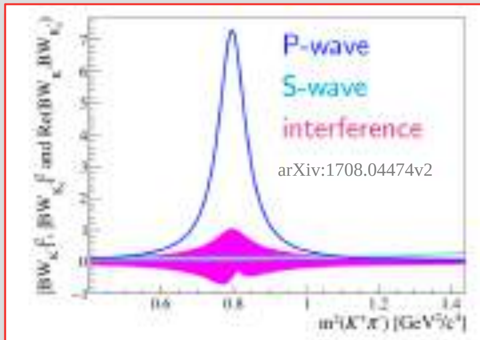


$B^0 \rightarrow K^{0*}\mu^+\mu^-$: P_5'

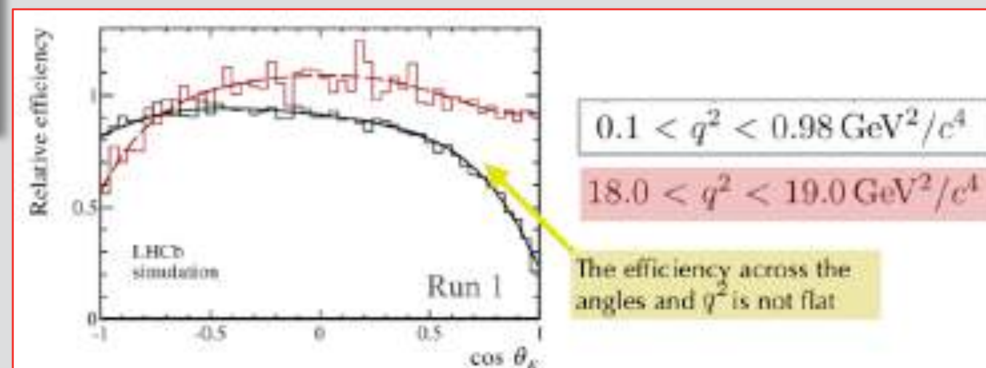
arXiv:2003.04831

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\Big|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

- Fit validation
- S-wave



- Angular acceptance



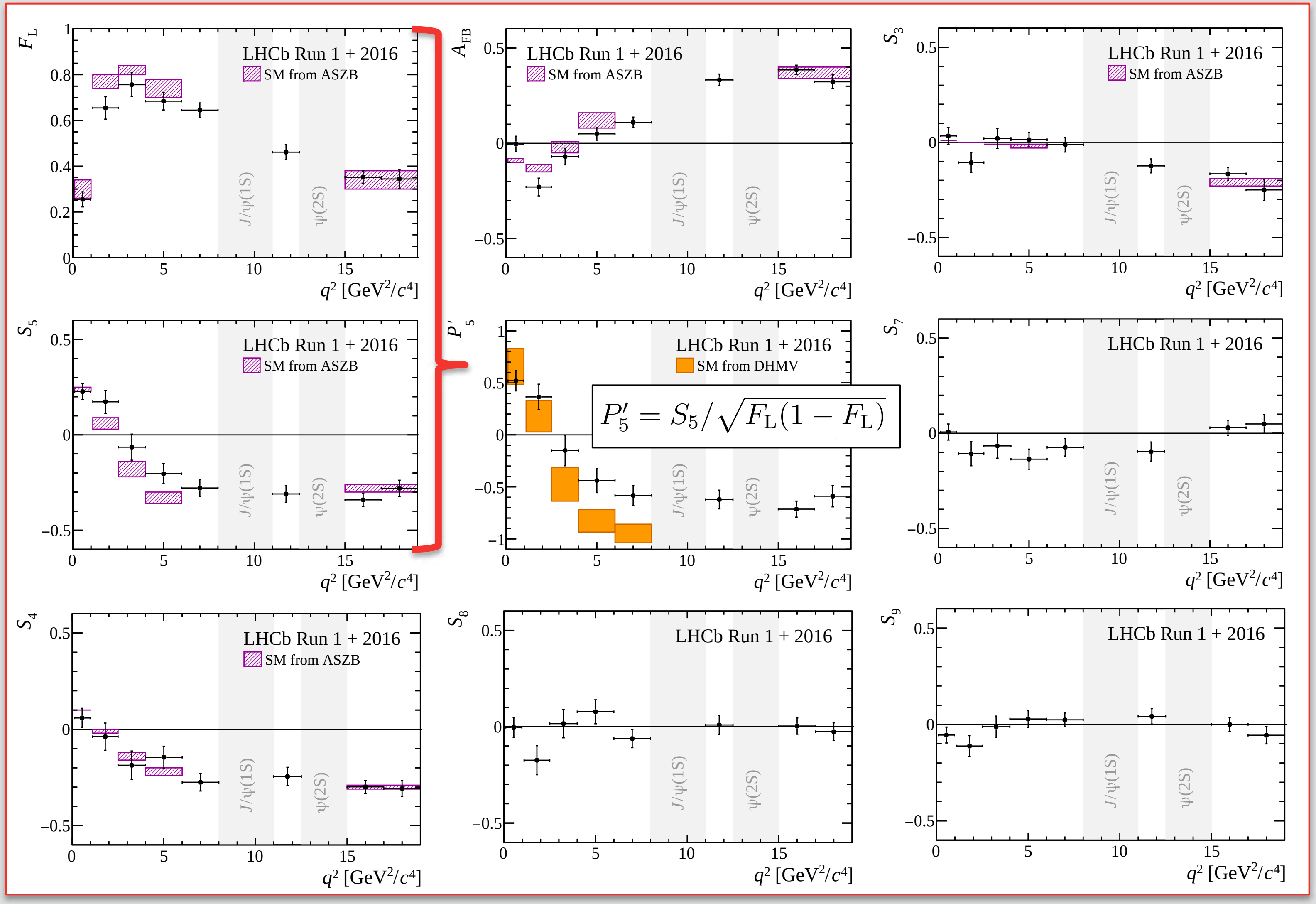
- Systematics

Source	F_{L}	S_3–S_9	P_1–P_8'
Acceptance stat. uncertainty	<0.01	<0.01	<0.01
Acceptance polynomial order	<0.01	<0.01	<0.02
Data-simulation differences	<0.01	<0.01	<0.01
Acceptance variation with q^2	<0.03	<0.01	<0.09
$m(K^+\pi^-)$ model	<0.01	<0.01	<0.01
Background model	<0.01	<0.01	<0.02
Peaking backgrounds	<0.01	<0.02	<0.03
$m(K^+\pi^-\mu^+\mu^-)$ model	<0.01	<0.01	<0.01
$K^+\mu^+\mu^-$ veto	<0.01	<0.01	<0.01
Trigger	<0.01	<0.01	<0.01
Bias correction	<0.02	<0.01	<0.03

- Compatibility
  - Run1/2, Magnet polarity, Yields, angular, control channel, …

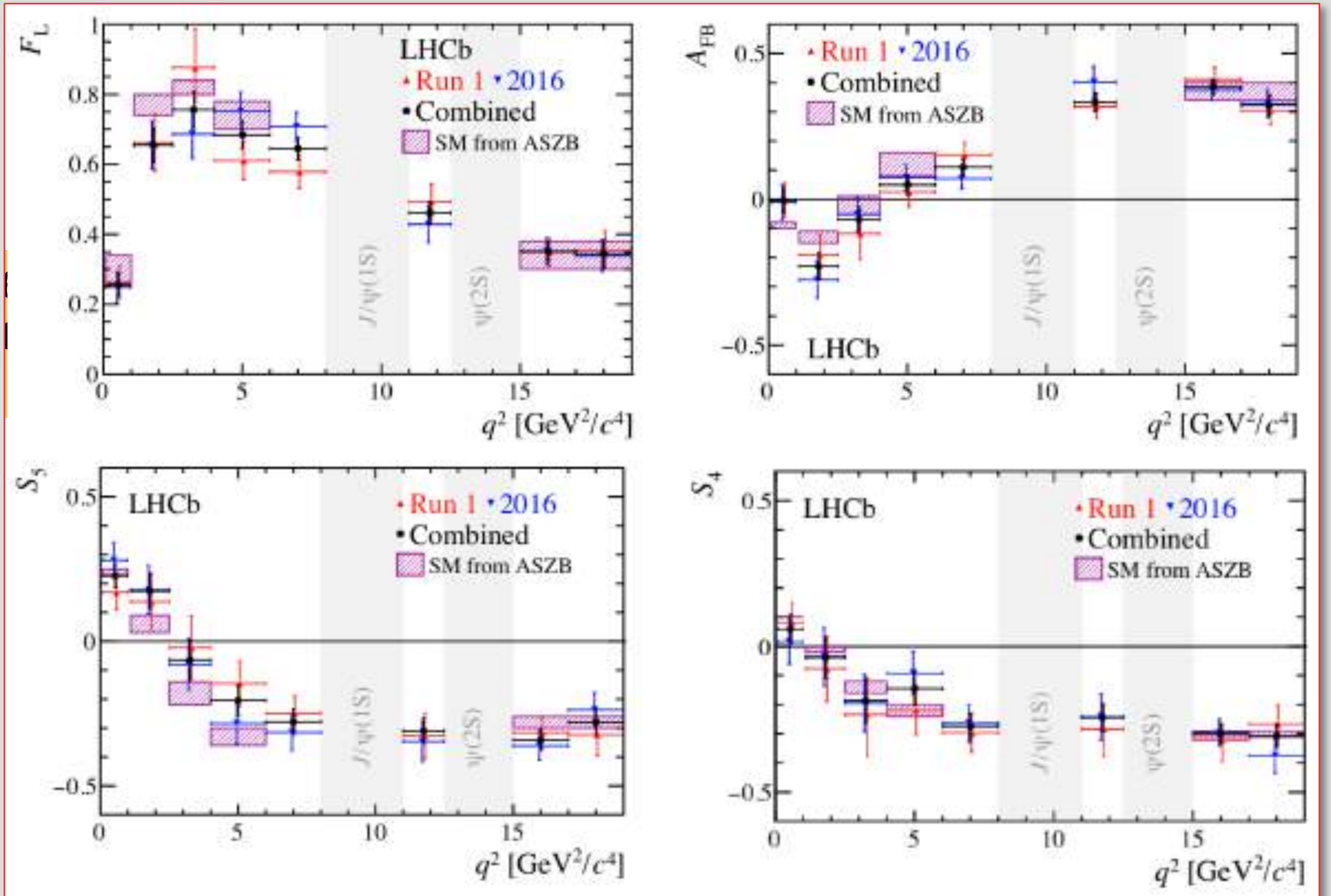
$B^0 \rightarrow K^{0*}\mu^+\mu^-$: more than just P_5' arXiv:2003.04831

- Many measurements:



$B^0 \rightarrow K^{0*}\mu^+\mu^-$: more than just P_5' arXiv:2003.04831

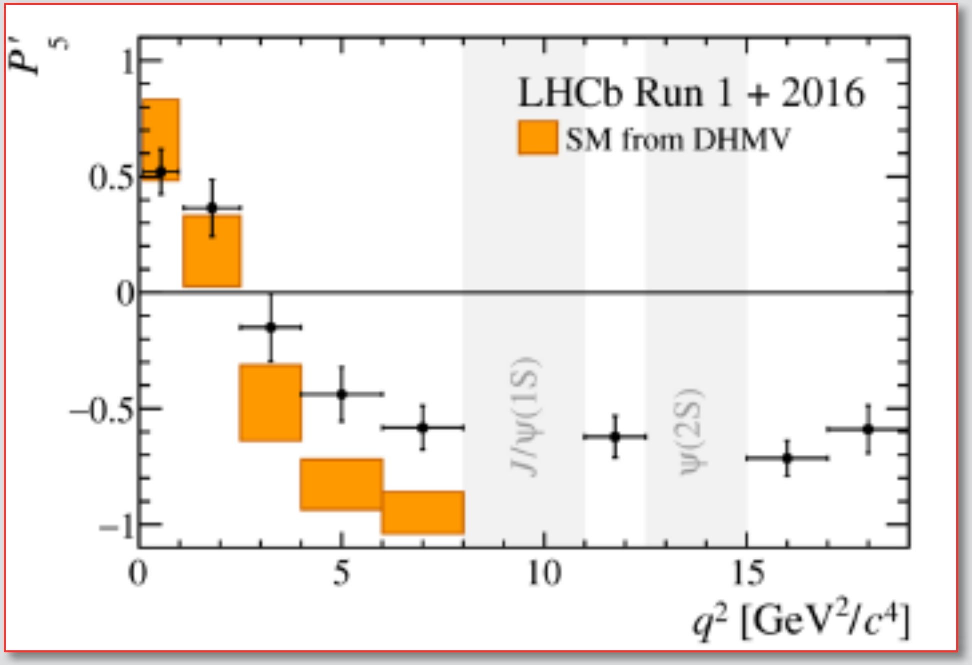
- Excellent agreement run-1 and 2016:



$B^0 \rightarrow K^{0*}\mu^+\mu^-$: P_5'

arXiv:2003.04831

- What about the tension?



	$4<q^2<6$	$6<q^2<8$	Comb
Run-1	2.8σ	3.0σ	3.4σ*
Run-1+2016	2.5σ	2.9σ	3.3σ

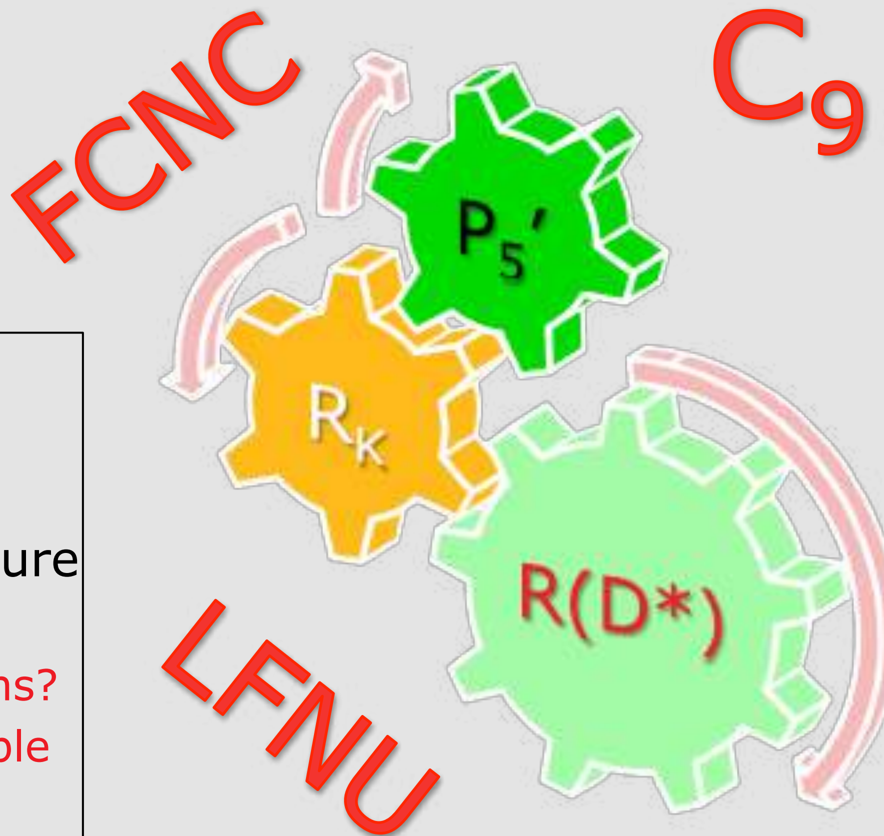
- Similar tension in P_5'
- What about overall significance?

*if same theory knowledge is used, significance reduces to 2.8σ

Flavour anomalies? Why excitement?

- ***Individually,*** measurements are consistent with SM

- ***Combined*** they give an intriguing picture
  - Difference between (lepton) generations?
  - Consistent New Physics scenario possible
  - Simple New Physics scenario possible



On the menu

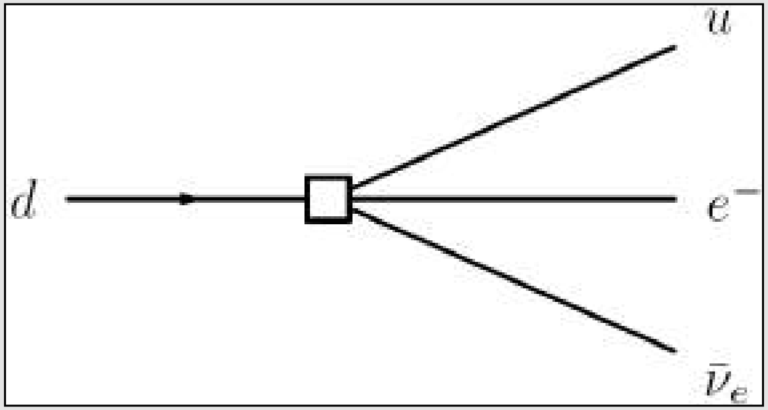
- Introduction
  - Precision measurements
  - The LHCb physics menu
- Selection of dishes:
  - Recent highlights on CP violation
  - Recent highlights on Rare decays (*aka Flavour Anomalies*)

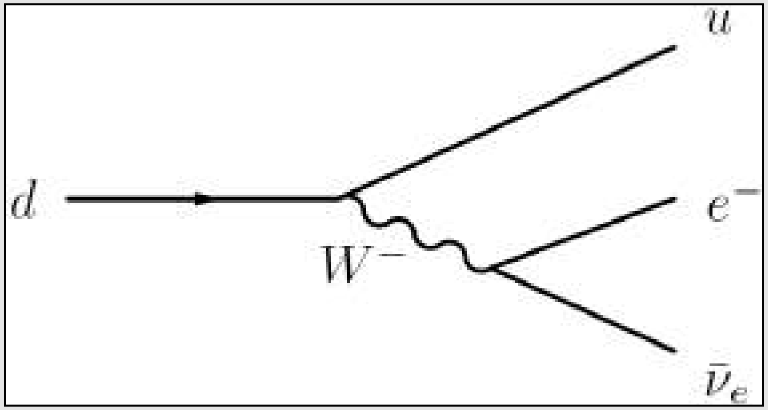
- New results
  1) Lepton flavour non-universality $\Lambda_b^0 \rightarrow pK\mu^+\mu^-$
  2) Angular analysis of decay $B^0 \rightarrow K^{*0}\mu^+\mu^-$
  3) Search for LFV $B^0 \rightarrow K^{*0}\tau^+\mu$
  4) New limit on $B_s^0 \rightarrow e^+e^-$
  5) New limit on $K^0_S \rightarrow \mu^+\mu^-$
  6) New limit on (x25 !) $D^+_{(s)} \rightarrow hll'$

- A remark on consistency

Intermezzo: Effective couplings

- Historical example



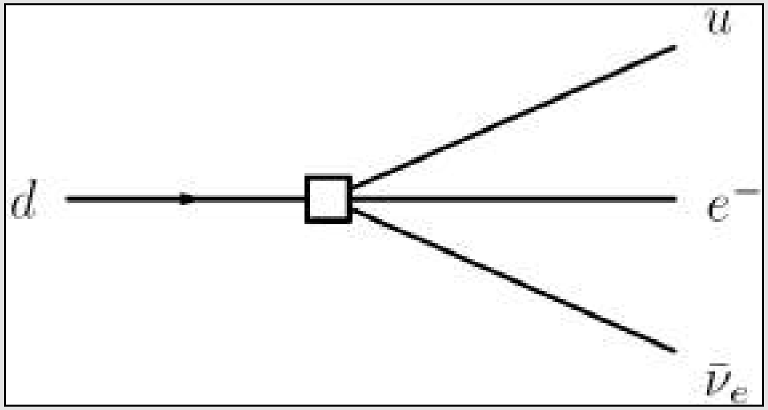


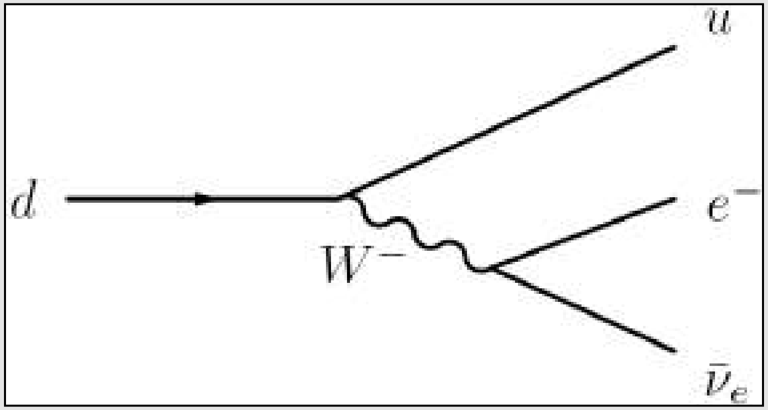
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

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

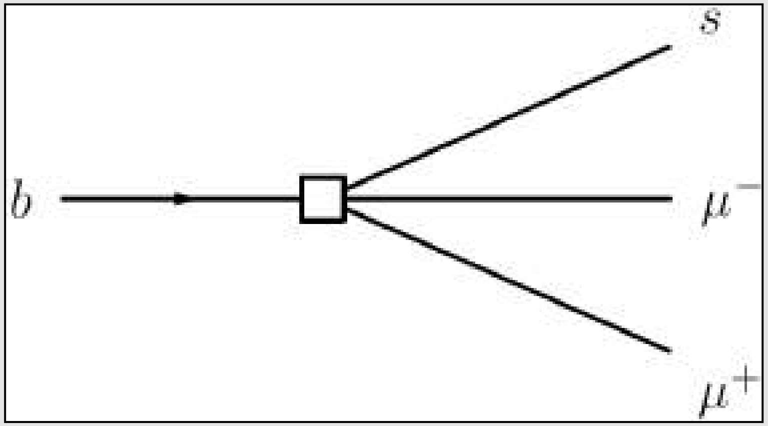
Intermezzo: Effective couplings

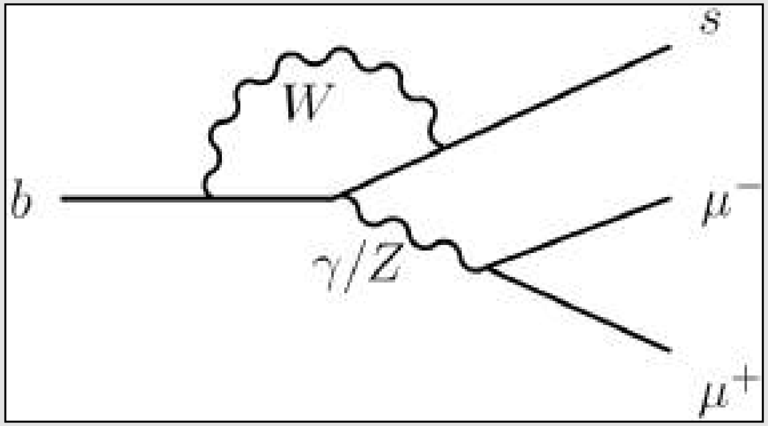
- Historical example





- Analog: Flavour-changing neutral current



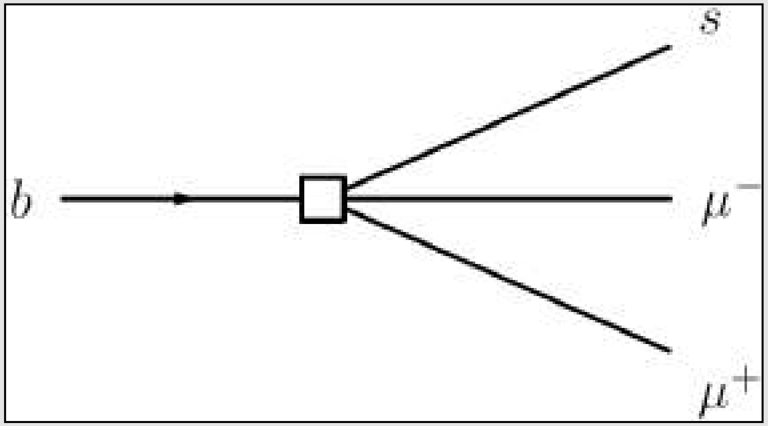


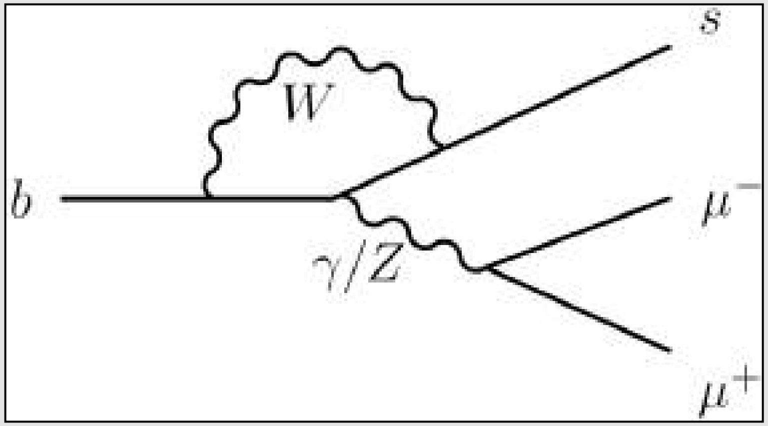
Intermezzo: Effective couplings

- Effective coupling can be of various "kinds"
  - Vector coupling
  - Axial coupling
  - Left-handed coupling (V-A)
  - Right-handed (to quarks)
  - …

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

- 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}', …
  - Many more! C_7, $C_{1,2}$, …

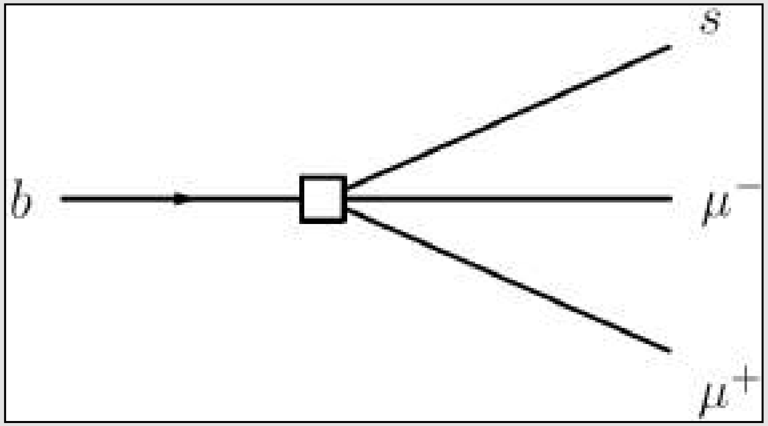
$$\mathcal{H}_{\rm eff} = \frac{G_{\rm F}}{\sqrt{2}} V_{\rm CKM} \sum_i C_i(\mu) Q_i$$

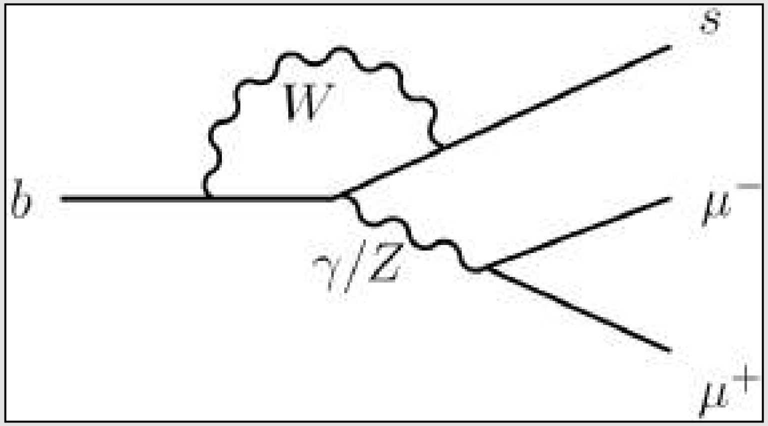
See e.g. Buras & Fleischer, hep-ph/9704376

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





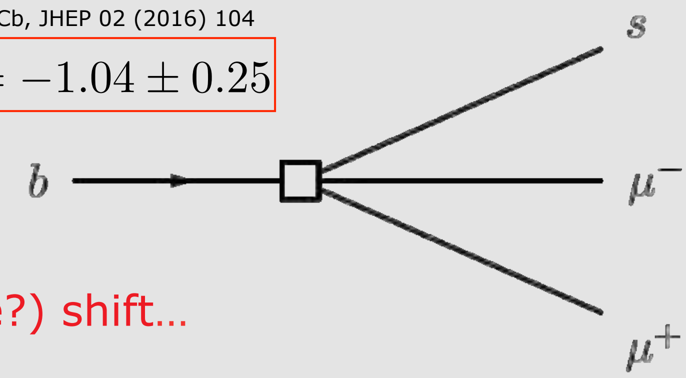
Intermezzo: Effective couplings

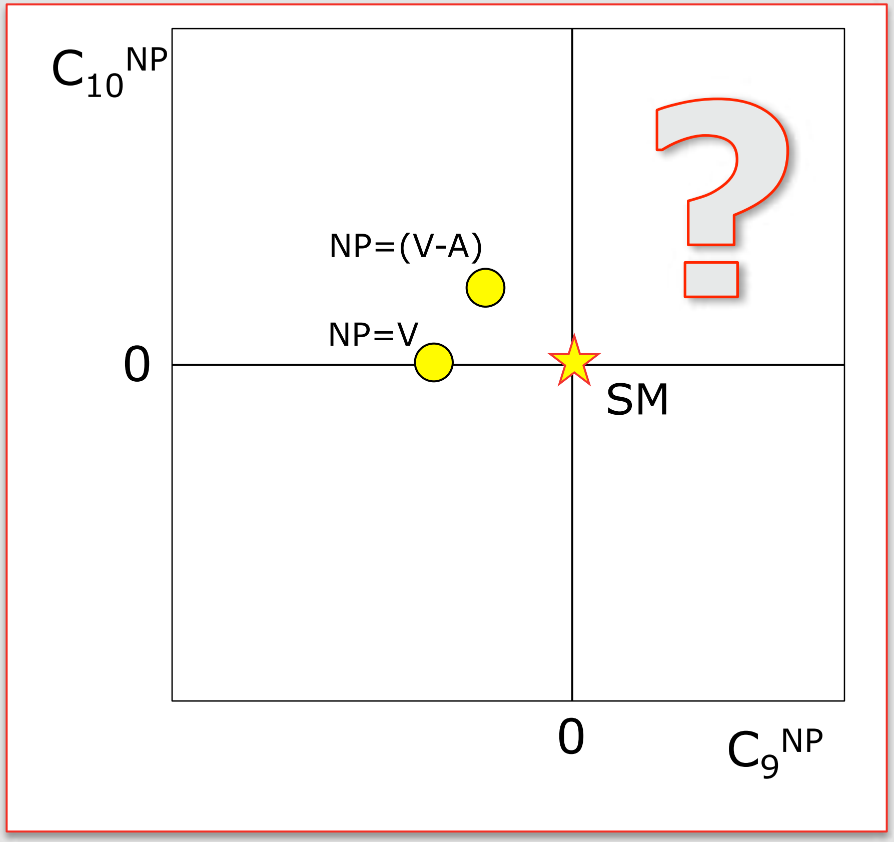
Model independent fits:

- 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…

LHCb, JHEP 02 (2016) 104

$$\Delta \mathrm{Re}(\mathcal{C}_9) = -1.04 \pm 0.25$$





Intermezzo: Effective couplings

LHCb, JHEP 02 (2016) 104

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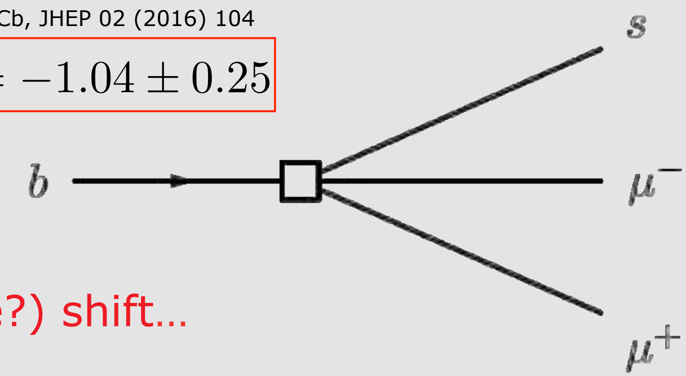

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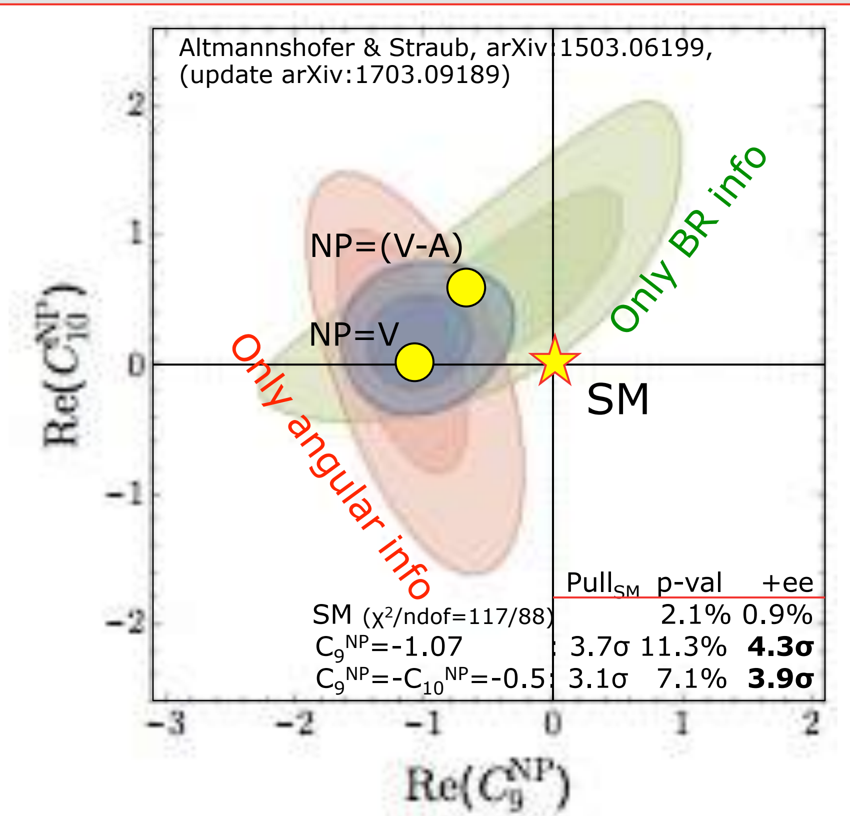

	Pull$_{SM}$	p-val	+ee
SM (χ^2/ndof=117/88)		2.1%	0.9%
C_9^{NP}=-1.07	3.7σ	11.3%	**4.3σ**
$C_9^{NP}=-C_{10}^{NP}$=-0.5	3.1σ	7.1%	**3.9σ**

Intermezzo: Effective couplings

Model independent fits:

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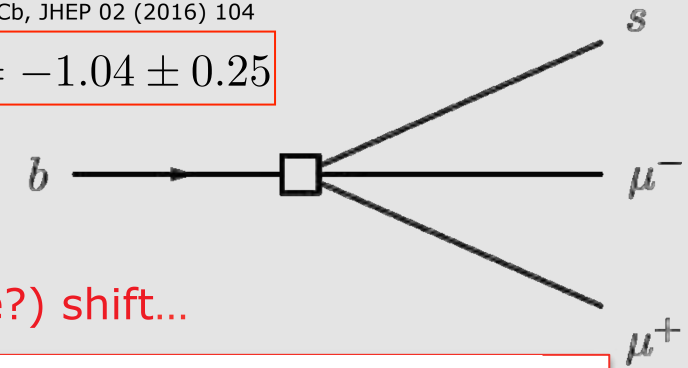

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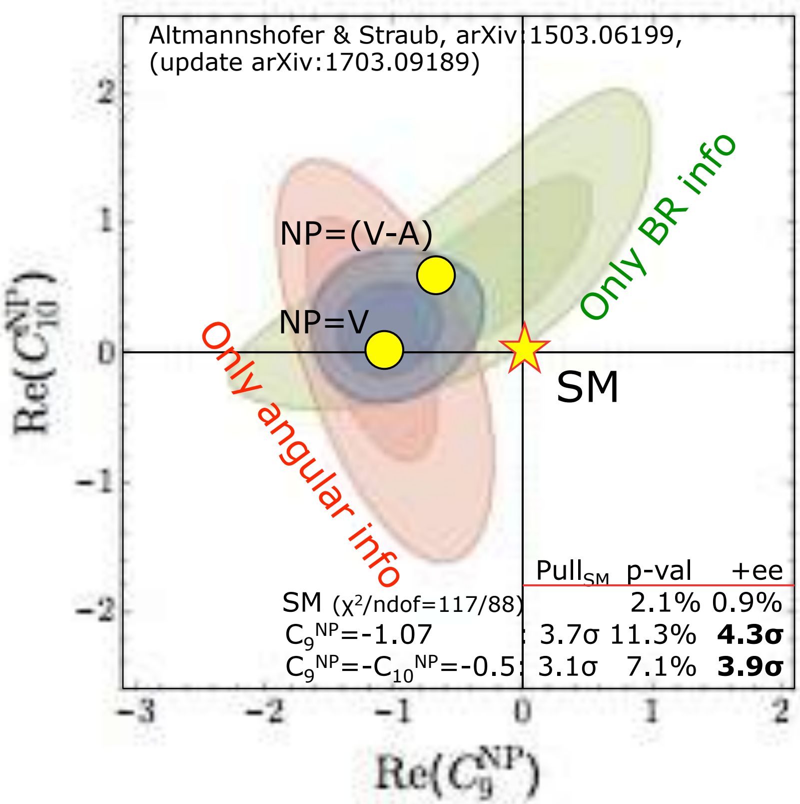
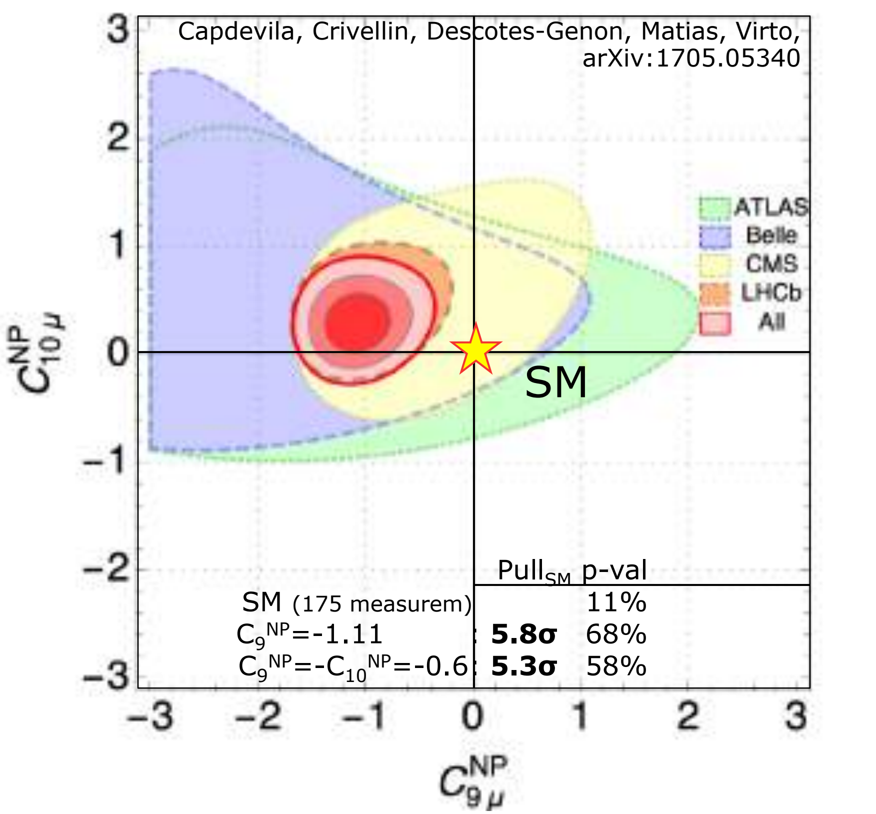
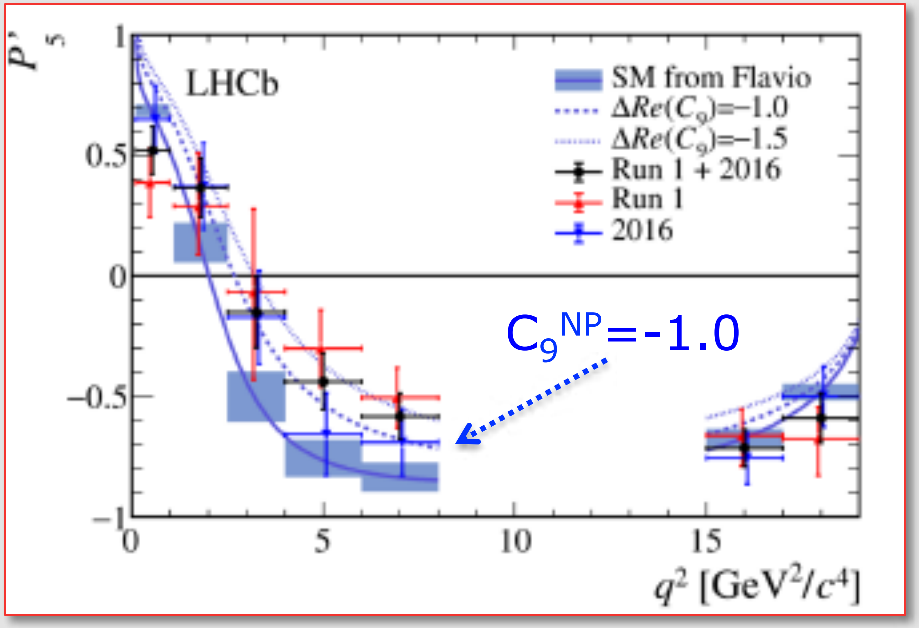




$B^0 \to K^{0*}\mu^+\mu^-$: P_5'

- All (175) measurements favor C_9^{NP}=-1.0
- New P_5' closer to SM, but also in *better* agreement with C_9^{NP}=-1.0
- It is not only about P_5'



Many variables; all sensitive to effective couplings:

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

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

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

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

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

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

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

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

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

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

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

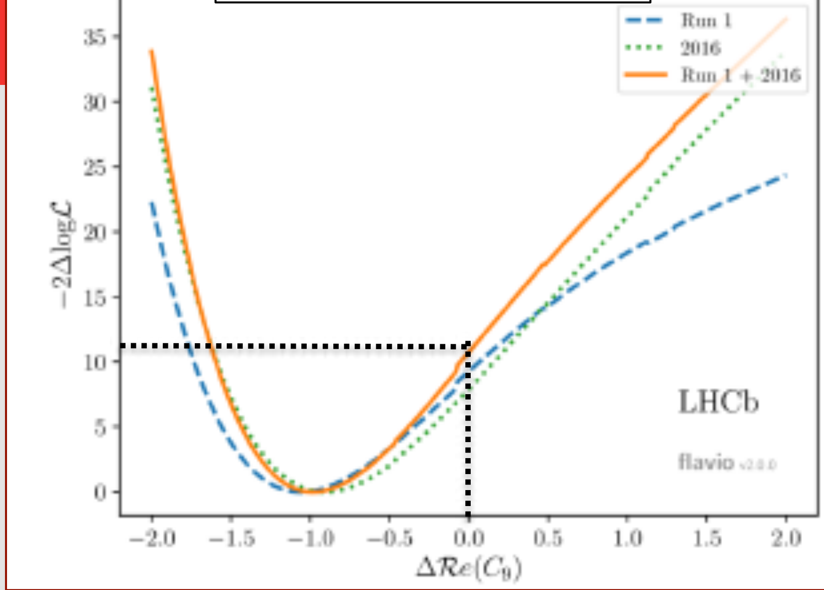
$$S_9 = \frac{\Im(A_\perp^{L*} A_\parallel^L)}{|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_0^L|^2} - L \to R$$

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

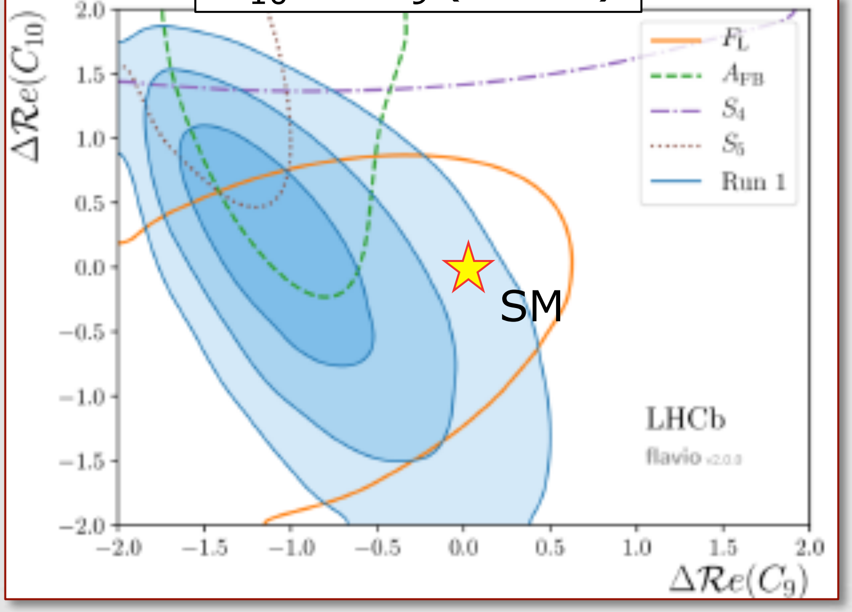
Best fit

- Improved fit for C_9^{NP}=-1.0

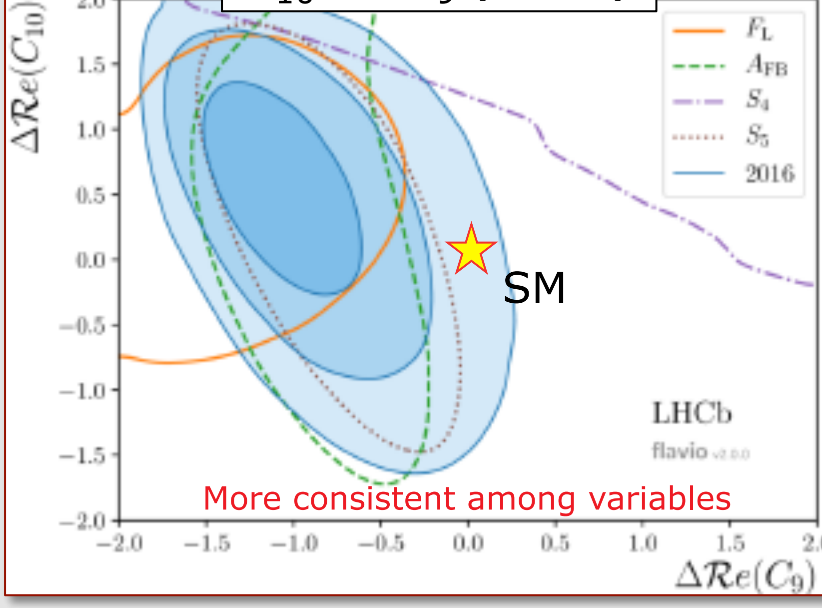
Likelihood vs C_9



C_{10} vs C_9 (run-1)



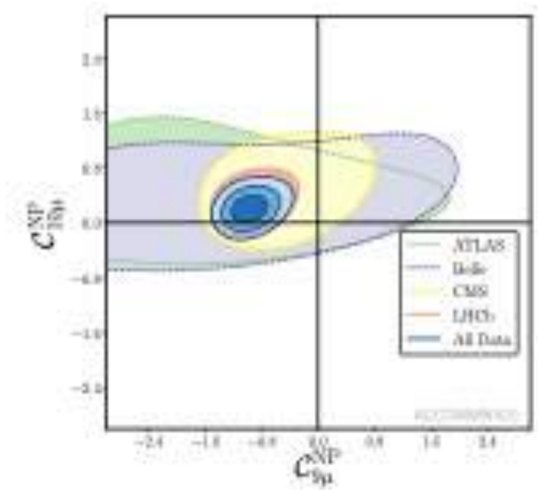
C_{10} vs C_9 (2016)



Global fit

Emerging patterns of New Physics with and without Lepton Flavour Universal contributions

Marcel Algueró[a,b], Bernat Capdevila[a,b,c], Andreas Crivellin[d,e], Sébastien Descotes-Genon[f], Pere Masjuan[a,b], Joaquim Matias[a,b], Martín Novoa Brunet[f] and Javier Virto[g].



	All			
1D Hyp.	Best fit	1 σ/2 σ	Pull$_{\rm SM}$	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	-1.03	$[-1.19, -0.88]$ $[-1.33, -0.72]$	6.3	37.5 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	-0.50	$[-0.59, -0.41]$ $[-0.69, -0.32]$	5.8	25.3 %

- There is a reduction of the internal tensions between some of the most relevant observables of the fit, in particular, between the new averages of R_K and P_5'. This leads to an increase in consistency between the different anomalies. This is illustrated
- The reduced uncertainties of the $B \to K^*\mu\mu$ data and its improved internal consistency sharpen statistical statements on the hypotheses considered. There is a significant increase of the statistical exclusion of the SM hypothesis as its p-value is reduced down to 1.4% (i.e. 2.5σ). The Pull$_{\rm SM}$ of the 6D fit is now higher (5.8σ).

arXiv:1903.09578, **addendum 6 Apr 2020**

- Similar picture as before
- Reduction of internal tensions
- Increase of statistical exclusion of SM hypothesis
  - p-value 1.4%, Pull 5.8σ

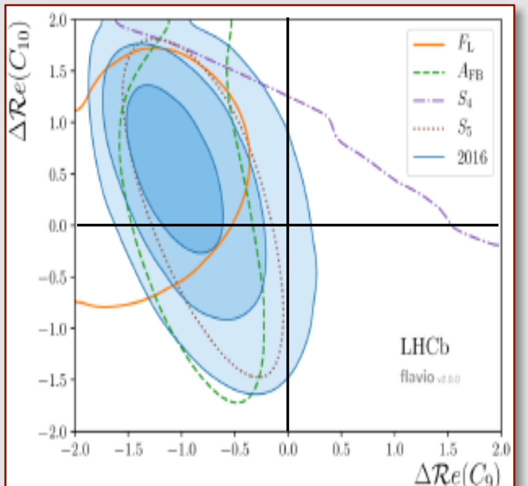
Outlook

Years	2020 2021	2022 2023 2024	2025 2026 2027	2028 2029 2030	2031 2032	2033 203
Run		Run III		Run IV		Run V
Shutdown	**LS2** ?		**LS3**		**LS4**	
LHCb	**LHCb 40 MHz** **UPGRADE I**	$L = 2 \times 10^{33}$	**LHCb** **Consolidate: Upgr Ib**	$L = 2 \times 10^{33}$ $50\ fb^{-1}$	**LHCb** **UPGRADE II**	$L = 1\text{-}2 \times 10^{3}$ $300\ fb^{-1}$
ATLAS	**ATLAS** **Phase I Upgr**	$L = 2 \times 10^{34}$	**ATLAS** **Phase II UPGRADE**	**HL-LHC** $L = 5 \times 10^{34}$	**ATLAS**	**HL-LHC** $L = 5 \times 10^{3}$
CMS	**CMS** **Phase I Upgr**	$300\ fb^{-1}$	**CMS** **Phase II UPGRADE**		**CMS**	$3000\ fb^{-1}$
Belle II	**Belle II**	$5\ ab^{-1}$ $L = 8 \times 10^{35}$	$50\ ab^{-1}$			

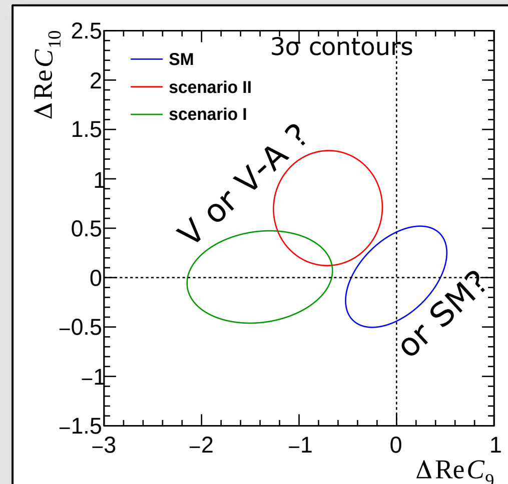
LHC schedule: Frederick Bordry, 2019
https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

Conclusions

- Precision measurements to scrutinize the Standard Model
- Precision measurements reach very high mass scales
- Precision measurements are not yet precise enough

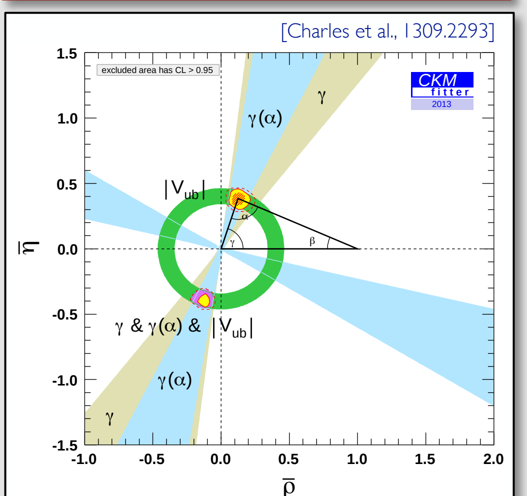


C_{10}^{NP} vs C_9^{NP}

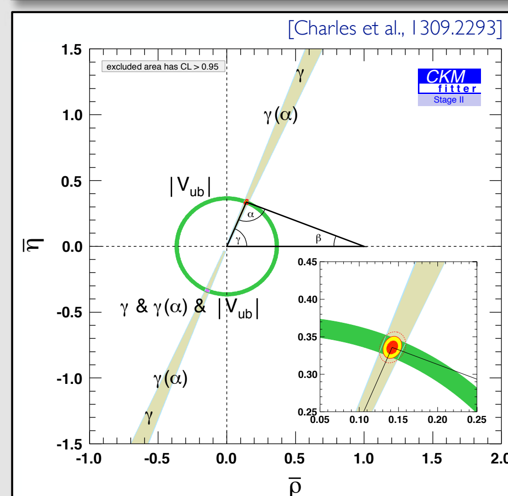


2019

2030



CKM: γ , V_{ub}, Δm_s



What NP could it be?

- If interpreted as NP signals, both set of anomalies are not in contradiction among themselves & with existing low- & high-energy data. Taken together, they point out to NP coupled mainly to 3rd generation, with a flavor structure connected to that appearing in the SM Yukawa couplings

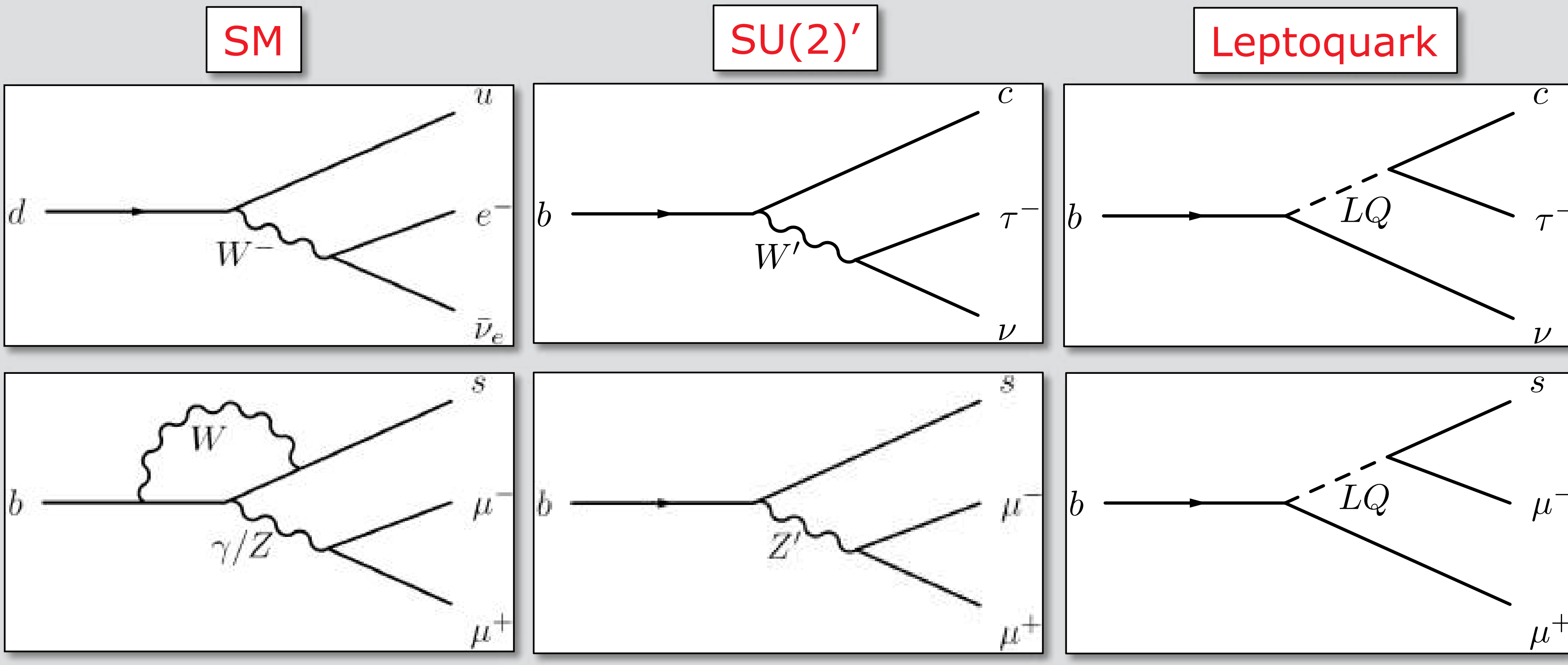
G. Isidori, *Implications workshop*, CERN, 10 Nov 2017
https://indico.cern.ch/event/646856/timetable/

- Anomalous measurements:
  - FCNC: b→sll
  - LFNU: b→sll and b→clν

- What are the interpretations?

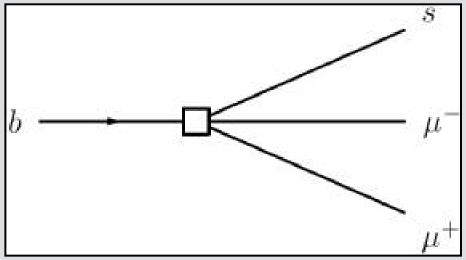
Model building

- Most popular models: Z′ or Leptoquark



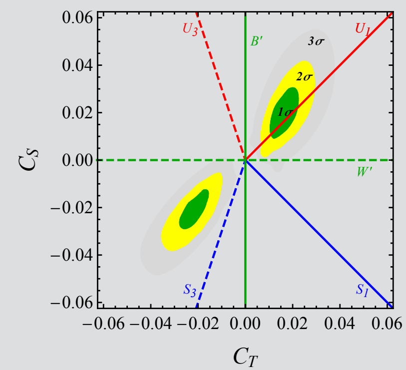
Model building

- Step 1: Effective theory

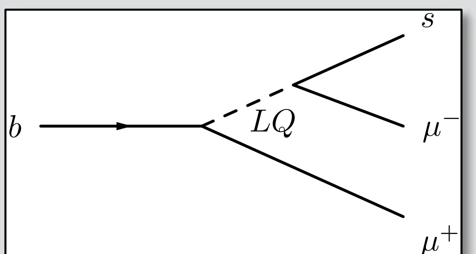


$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\ (\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\ (\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

Observable	Experimental bound	Linearised expression
$R^{\tau\ell}_{D^{(*)}}$	1.237 ± 0.053	$1 + 2C_T(1 - \lambda^q_{sb}V^*_{tb}/V^*_{ts})(1 - \lambda^\ell_{\mu\mu}/2)$
$\Delta C^\mu_9 = -\Delta C^\mu_{10}$	-0.61 ± 0.12 [36]	$-\frac{\pi}{\alpha_{\text{em}}V_{tb}V^*_{ts}}\lambda^\ell_{\mu\mu}\lambda^q_{sb}(C_T + C_S)$
$R^{\mu e}_{b\to c} - 1$	0.00 ± 0.02	$2C_T(1 - \lambda^q_{sb}V^*_{tb}/V^*_{ts})\lambda^\ell_{\mu\mu}$
$B_{K^{(*)}\nu\bar{\nu}}$	0.0 ± 2.6	$1 + \frac{2}{3}\frac{\pi}{\alpha_{\text{em}}V_{tb}V^*_{ts}C^{\text{SM}}_\nu}(C_T - C_S)\lambda^q_{sb}(1 + \lambda^\ell_{\mu\mu})$
$\delta g^Z_{\tau_L}$	-0.0002 ± 0.0006	$0.033C_T - 0.043C_S$
$\delta g^Z_{\nu_\tau}$	-0.0040 ± 0.0021	$-0.033C_T - 0.043C_S$
$\lvert g^W_\tau/g^W_\ell\rvert$	1.00097 ± 0.00098	$1 - 0.084C_T$
$\mathcal{B}(\tau\to 3\mu)$	$(0.0 \pm 0.6)\times 10^{-8}$	$2.5\times 10^{-4}(C_S - C_T)^2(\lambda^\ell_{\tau\mu})^2$



- Step 2: Simplified models



$SU(2)_L$-singlet vector leptoquark, $U^\mu_1 \equiv (\mathbf{3},\mathbf{1},2/3)$

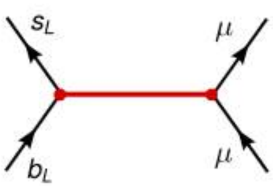
$$\mathcal{L}_U = -\frac{1}{2}U^\dagger_{1,\mu\nu}U^{1,\mu\nu} + M^2_U U^\dagger_{1,\mu}U^\mu_1 + g_U(J^\mu_U U_{1,\mu} + \text{h.c.})$$

$$J^\mu_U \equiv \beta_{i\alpha}\,\bar{Q}_i\gamma^\mu L_\alpha\ .$$

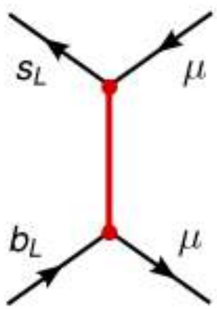
Model building

- Many models! See e.g.:

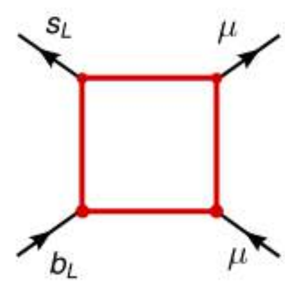
➢ Possible BSM models



- Heavy Z' model
- $SU(2)_L$ singlet or triplet
- arXiv:1403.1269, 1501.00993, 1503.03477, 1611.02703, ...



- Leptoquark model
- Spin 0 or 1
- arXiv:01511.01900, 1503.01084, 1704.05835, 1512.01560, 1511.06024, 1408.1627, ...



- Other new heavy scalars/vectors also leptoquark possible
- arXiv:01509.05020, 1608.07832, 1704.05438, 1607.01659, 1704.07845, hep-ph/0610037, ...

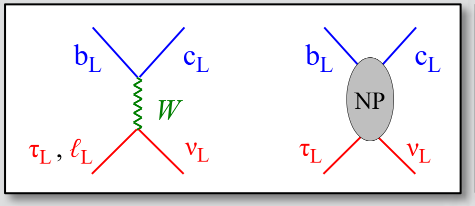
arXiv:1706.07808

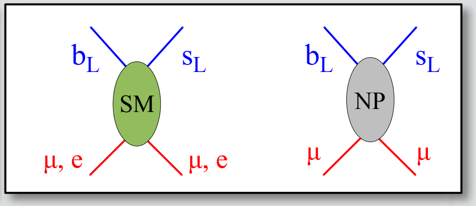
ICHEP 2018 @Seoul

4

Courtesy, Geng CHEN, ICHEP 2018 , 7 July 2018

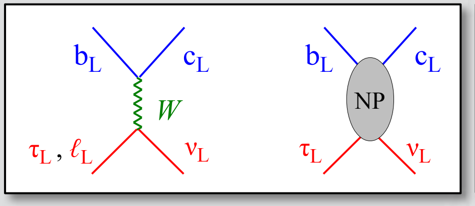
Model building

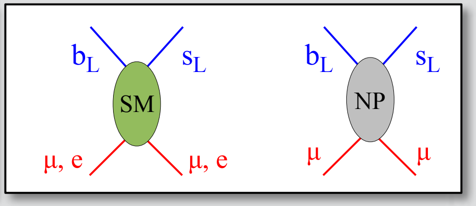




- Ingredients
  - NP: large coupling $b \rightarrow c\tau\nu$
    - Large coupling to 3rd gen leptons
    - Left-handed coupling (no RH neutrino)
  - NP: small (non-vanishing) coupling $b \rightarrow s\mu\mu$
    - Small coupling to 2nd gen leptons
    - Left-handed coupling (from C_9)

Model building





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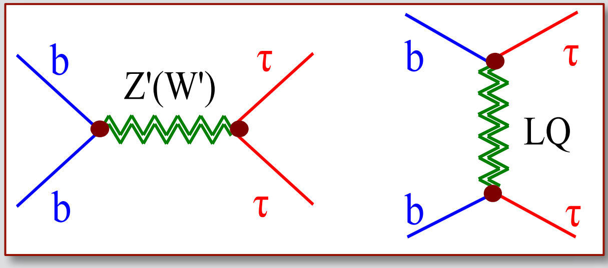
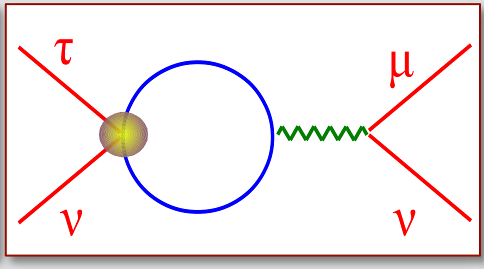
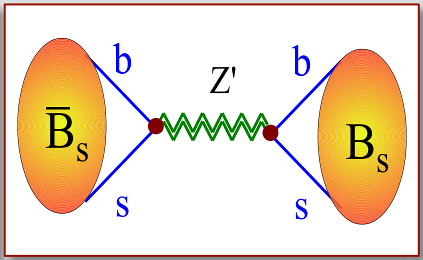
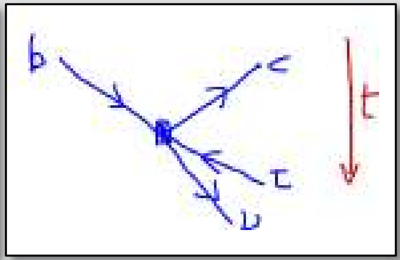






G.Isidori



J.M.Camalich

- Experimental constraints
  - High p_T searches (No $\tau\tau$ resonance: no s-channel Z′)
  - Radiative constr. $\tau \to \mu\nu\nu$
  - B_s^0 mixing (No tree level NP: small bs implies large $\tau\nu$)
  - B_c^+ lifetime (Scalar LQ increases BR($B_c^+ \to \tau^+\nu$))

Vector LQ favoured over Scalar LQ or Z′

Model building

$SU(2)_L$-singlet vector leptoquark emerges as a particularly simple and successful framework.

Buttazzo, Greljo, Isidori, Marzocca, B-physics anomalies: a guide to combined explanations JHEP 1711 (2017) 044

- Many more experimental handles; predictions can be checked!
- Universal for all b→cτν:
  - Accurate R(D*), R(J/ψ), …

$$\frac{R_D}{(R_D)_{SM}} = \frac{\Gamma(B\to D^*\tau\nu)/\Gamma_{SM}}{\Gamma(B\to D^*\mu\nu)/\Gamma_{SM}} = \frac{\Gamma(B_c\to\psi\tau\nu)/\Gamma_{SM}}{\Gamma(B_c\to\psi\mu\nu)/\Gamma_{SM}} = \frac{\Gamma(\Lambda_b\to\Lambda_c\tau\nu)/\Gamma_{SM}}{\Gamma(\Lambda_b\to\Lambda_c\mu\nu)/\Gamma_{SM}} = \dots$$

- Strong coupling to *tau's:*
  - Measure e.g. *$B^0\to K^*\tau\tau$*
- LFNU linked with LFV:
  - Look for e.g. *$B^0\to K^*\tau\mu$*
  - *$BR(\tau\to\mu\mu\mu)\sim10^{-9}$*

	μμ (ee)	ττ	νν	τμ	μe
b → s	R_K, R_{K^*} O(20%)	$B\to K^{(*)}\tau\tau$ → 100×SM	$B\to K^{(*)}\nu\nu$ O(1)	$B\to K\tau\mu$ → ~10^{-6}	$B\to K\mu e$???
b → d	$B_d\to\mu\mu$ $B\to\pi\mu\mu$ $B_s\to K^{(*)}\mu\mu$ O(20%) [$R_K=R_\pi$]	$B\to\pi\tau\tau$ → 100×SM	$B\to\pi\nu\nu$ O(1)	$B\to\pi\tau\mu$ → ~10^{-7}	$B\to\pi\mu e$???

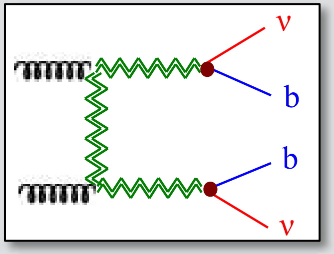
- c, u symmetry:
  - Study suppressed semileptonic

$$\frac{\Gamma(B\to\pi\tau\nu)/\Gamma_{SM}}{\Gamma(B\to\pi\mu\nu)/\Gamma_{SM}} = \frac{\Gamma(\Lambda_b\to p\,\tau\nu)/\Gamma_{SM}}{\Gamma(\Lambda_b\to p\,\mu\nu)/\Gamma_{SM}} = \frac{\Gamma(B_s\to K^*\tau\nu)/\Gamma_{SM}}{\Gamma(B_s\to K^*\mu\nu)/\Gamma_{SM}} = \dots = \frac{R_D}{(R_D)_{SM}}$$

- B_s mixing
  - O(1-10%) effect on Δm_s

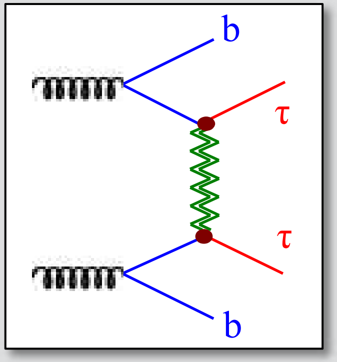
Model building

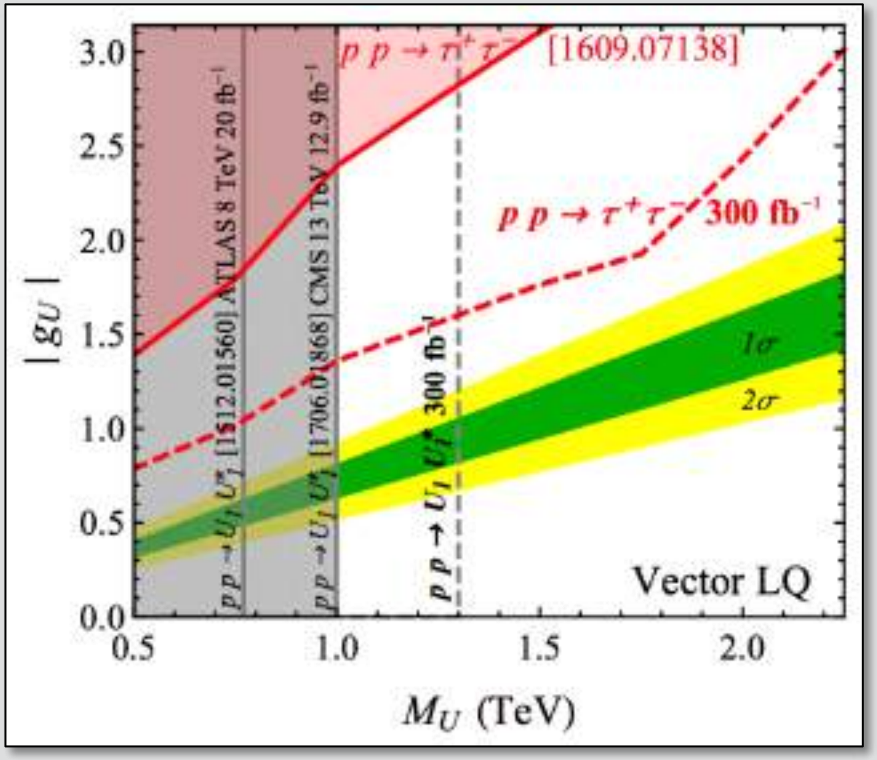
- Many more experimental handles; predictions can be checked!
- High p_T signatures?
  - LQ pairs



  - LQ t-channel in $bb \rightarrow \tau\tau$

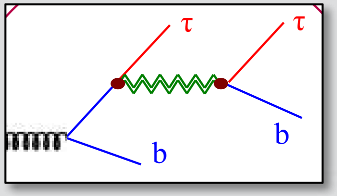
Reachable during HL-LHC





Buttazzo, Greljo, Isidori, Marzocca, B-physics anomalies: a guide to combined explanations, JHEP 1711 (2017) 044

  - Single production channel (dominant?)



The need for more precision

Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed”

– A.Soni

- “A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L^0 \to \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the lab. The group was unlucky.”

– L.Okun

(remember: $B(K_L^0 \to \pi^+\pi^-) \sim 2\ 10^{-3}$)