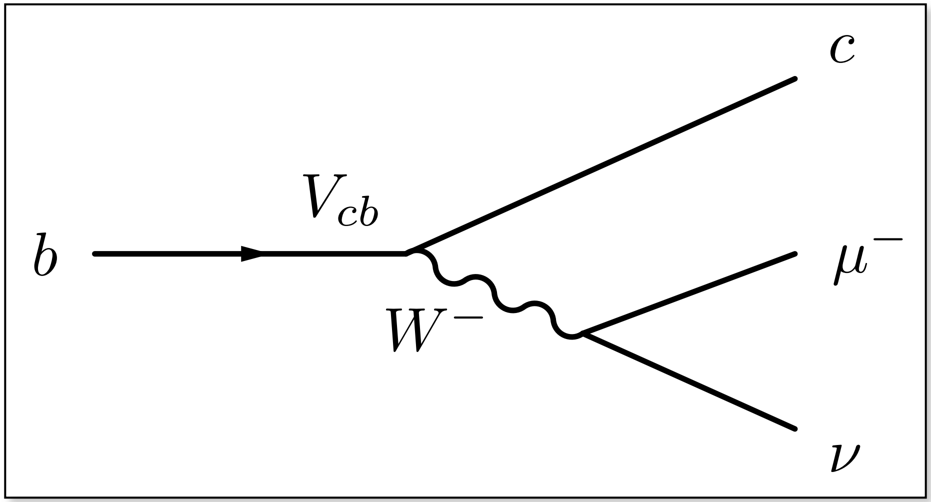
Anomalies with muons at LHCb

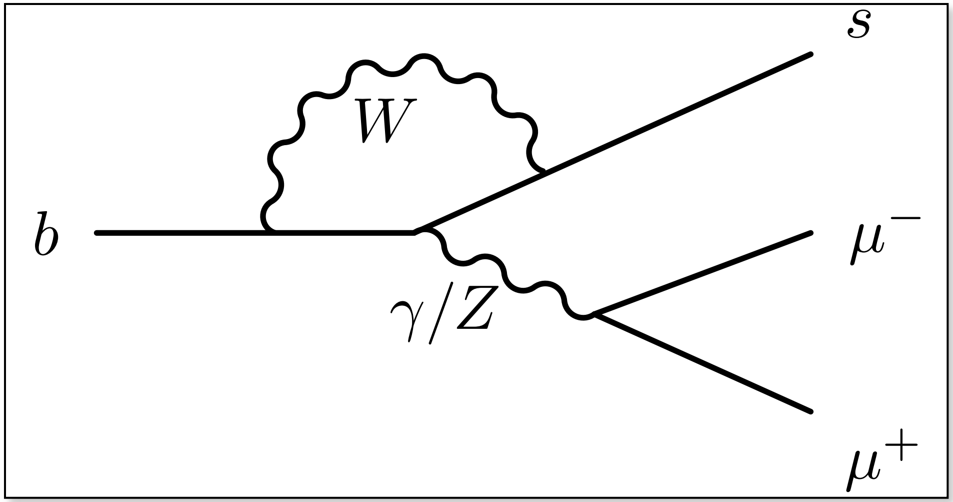
7 Nov 2022

Niels Tuning (LHCb, Nikhef)

Muon Precision Physics Workshop, Liverpool

CC and FCNC





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

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

Back in the days... (1995)

CERN/LHCC 95-5
LHCC/ I 8
25 August 1995

Last update
28 March 1996

LHC-B

LETTER OF INTENT

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

University of Liverpool, Liverpool, U.K.
S. Biagi, T. Bowcock

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- *"Non-CP-violating physics could be attempted with such an apparatus"*
- *"of considerable interest in theories with leptoquarks"*

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The purely leptonic decays of B_d^0 and B_s^0 mesons are of considerable interest in theories with leptoquarks[24]. In the leptoquark sce-

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Parameterization	A	B
$BR(B \to K\ell^+\ell^-)$	$6.0 \cdot 10^{-7}$	$2.7 \cdot 10^{-7}$
$R(B \to Ke^+e^-)$	4%	2%
$R(B \to K\mu^+\mu^-)$	7%	3%
$BR(B \to K^*e^+e^-)$	$5.6 \cdot 10^{-6}$	$4.1 \cdot 10^{-6}$
$R(B \to K^*e^+e^-)$	37%	28%
$BR(B \to K^*\mu^+\mu^-)$	$2.9 \cdot 10^{-6}$	$2.5 \cdot 10^{-6}$
$R(B \to K^*\mu^+\mu^-)$	34%	29%

Table 2.2: Rates and branching fractions[19, 20, 21] for the decays $B \to K\ell^+\ell^-$, and $B \to K^*\ell^+\ell^-$ with $m_t = 150$ GeV. A and B are two different param-

Back in the days… (1998)

LHCb

CERN LHCC 98-4
LHCC/P4
20 February 1998

Technical Proposal

A Large Hadron Collider Beauty Experiment for Precision Measurements of CP Violation and Rare Decays

University of Liverpool, Liverpool, U.K.
S.Biagi, T.Bowcock, P.Hayman, M.McCubbin, G.Patel

Back in the days… (1998)

- Little mention of rare decays
  - *"K*$\mu\mu$ should also be possible"*
  - *"allow for surpising effects"*
- No mention of semileptonic

LHCb

CERN LHCC 98-4
LHCC/P4
20 February 1998

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process, such as $B^0_d \to K^{**}\gamma^5$ and $B^0_s \to \phi\gamma$. Reconstruction of $B^0_d \to K^{*0}\mu^+\mu^-$ should also be possible. The large numbers of reconstructed events expected allow searches to be made for surprising effects in these rare decay modes. Events needed to


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November 2015
Tensions in the Standard Model

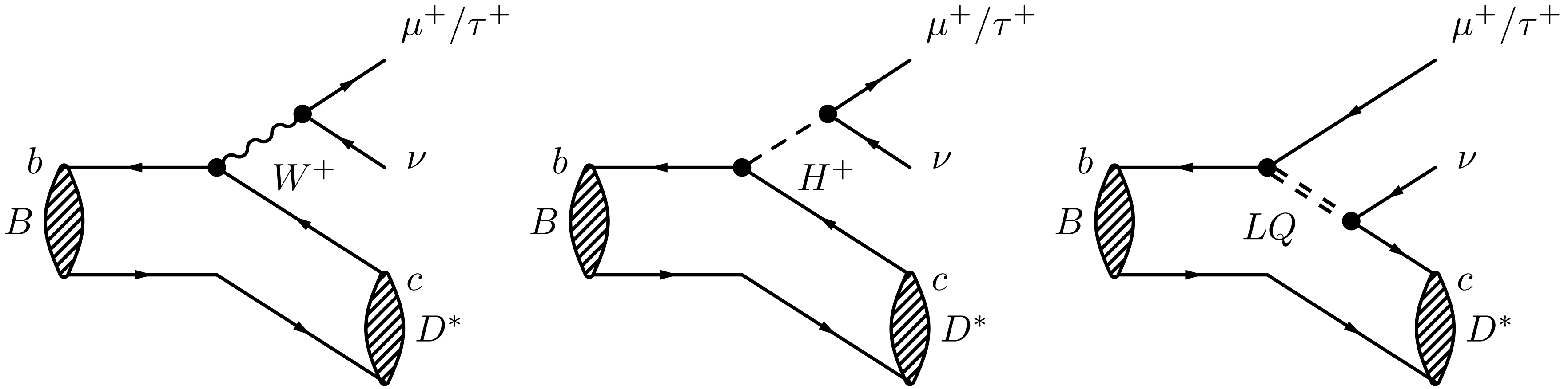
It's not new

Outline

- CC: $b \rightarrow c l^- \nu$
  - $R(D^{(*)})$
- FCNC: $b \rightarrow s l^+ l^-$
  - $B_s^0 \rightarrow \mu^+ \mu^-$
  - Decay rates
  - Angular analyses
  - Lepton flavour ratios
- Effective couplings
- Prospects

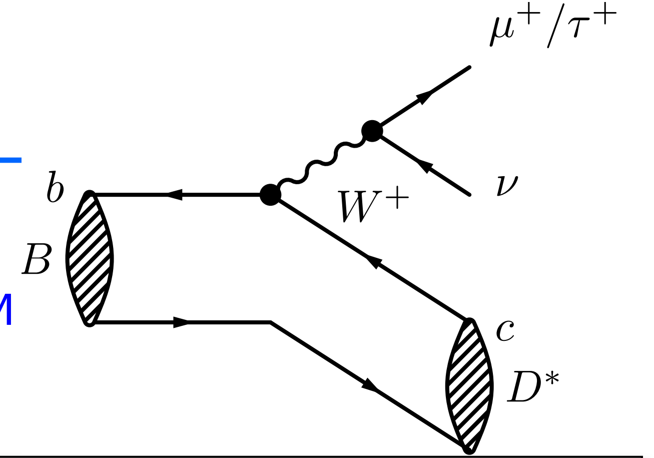
Back in the days: look for 2HDM

- Higgs couples to 3rd generation

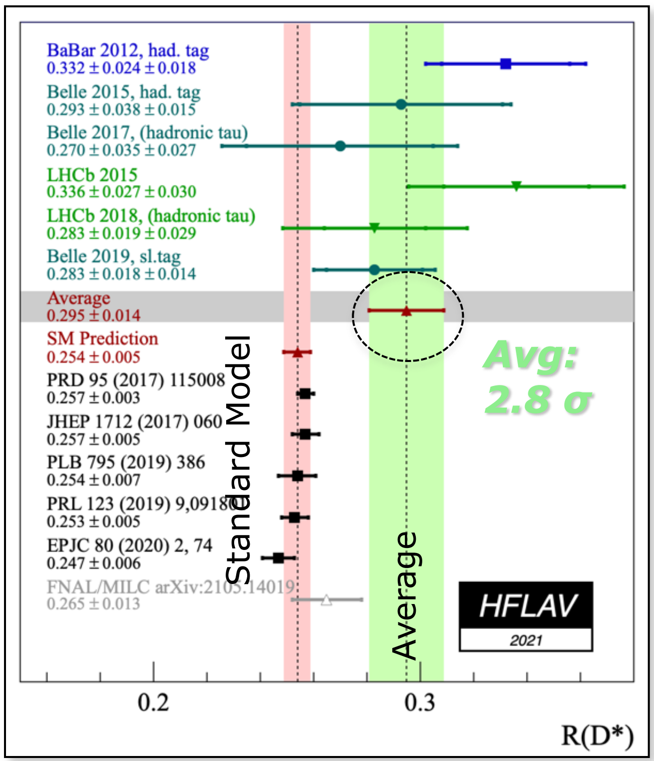


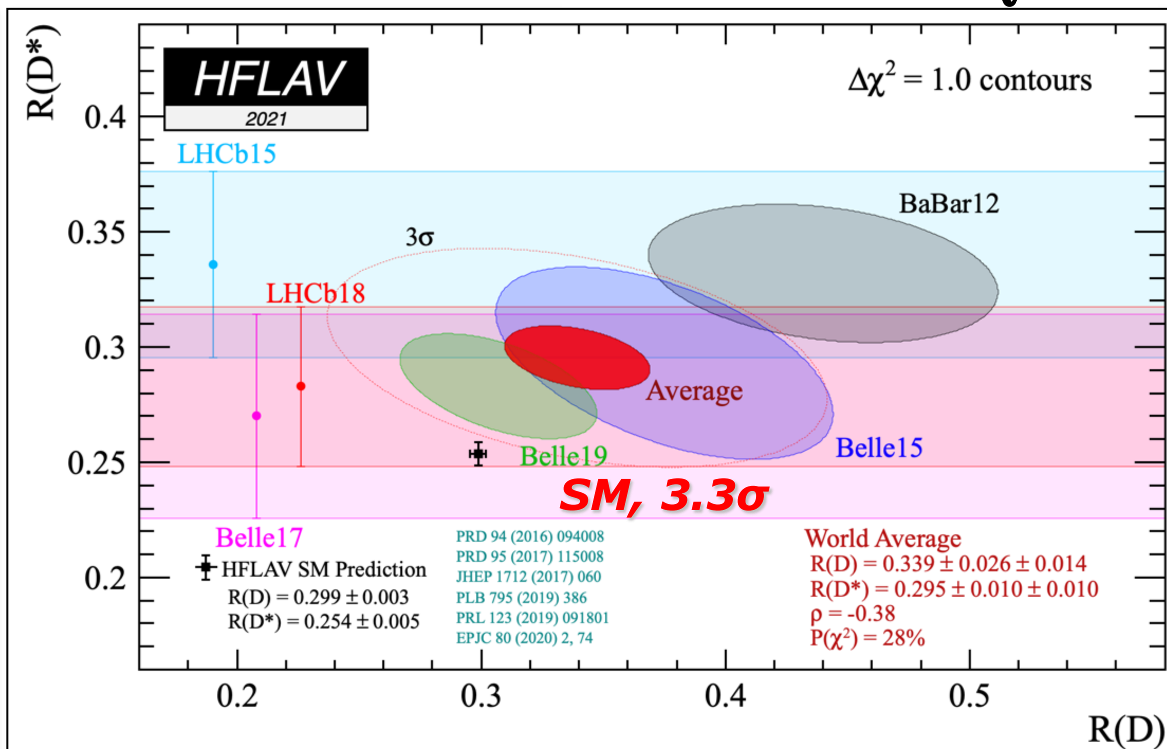
b→cl⁻ν : $R(D^{(*)})$

- LFNU in CC tree decays?
  - τ-excess in b→c transitions, sensitive to TeV BSM



2021:





$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\, \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\, \mu^+ \nu_\mu)} \qquad \mathcal{R}(J/\psi) = 0.71 \pm 0.17\,(\text{stat}) \pm 0.18\,(\text{syst})$$

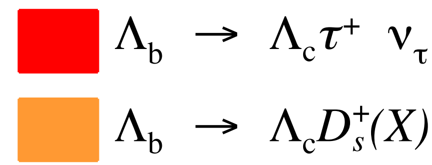
LHCb Coll. arXiv:1711.05623

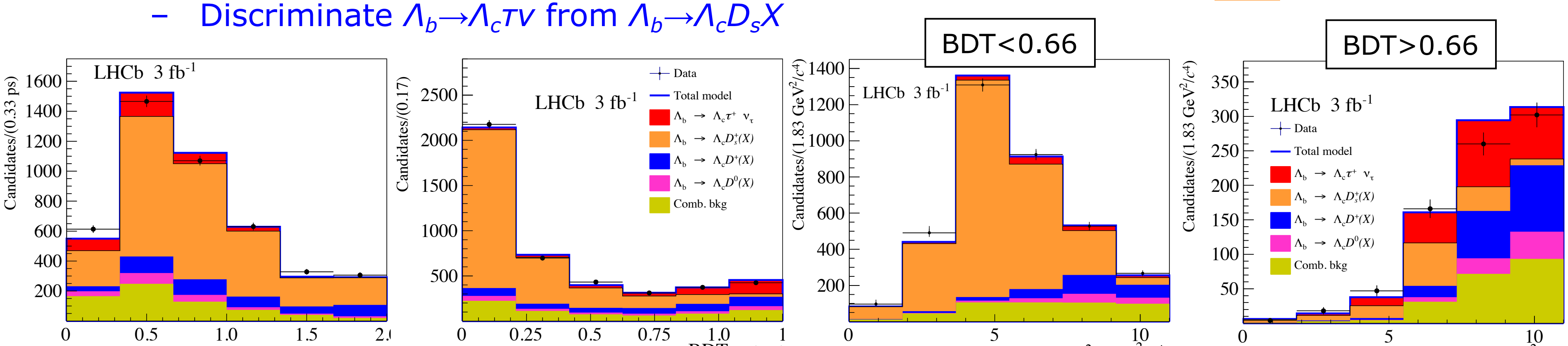
Recent measurement of $B(\Lambda_b \to \Lambda_c \tau \nu)$

- New result on semileptonic anomalies
  - Hadronic tau decays
- Measure

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)} = \frac{N_{\text{sig}}}{N_{\text{norm}}} \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \frac{1}{\mathcal{B}(\tau^- \to 3\pi(\pi^0)\overline{\nu}_\tau)}$$

- Simultaneous 3D fit to: τ, BDT, q^2
  - Discriminate $\Lambda_b \to \Lambda_c \tau \nu$ from $\Lambda_b \to \Lambda_c D_s X$





LHCb Coll. arXiv:2201.03497

- **First observation of $\Lambda_b \to \Lambda_c^+ \tau^- \nu$ at 6.1σ**
  - Using BR($\Lambda_b \to \Lambda_c \pi\pi\pi$):
  - Using BR($\Lambda_b \to \Lambda_c \tau\mu$):

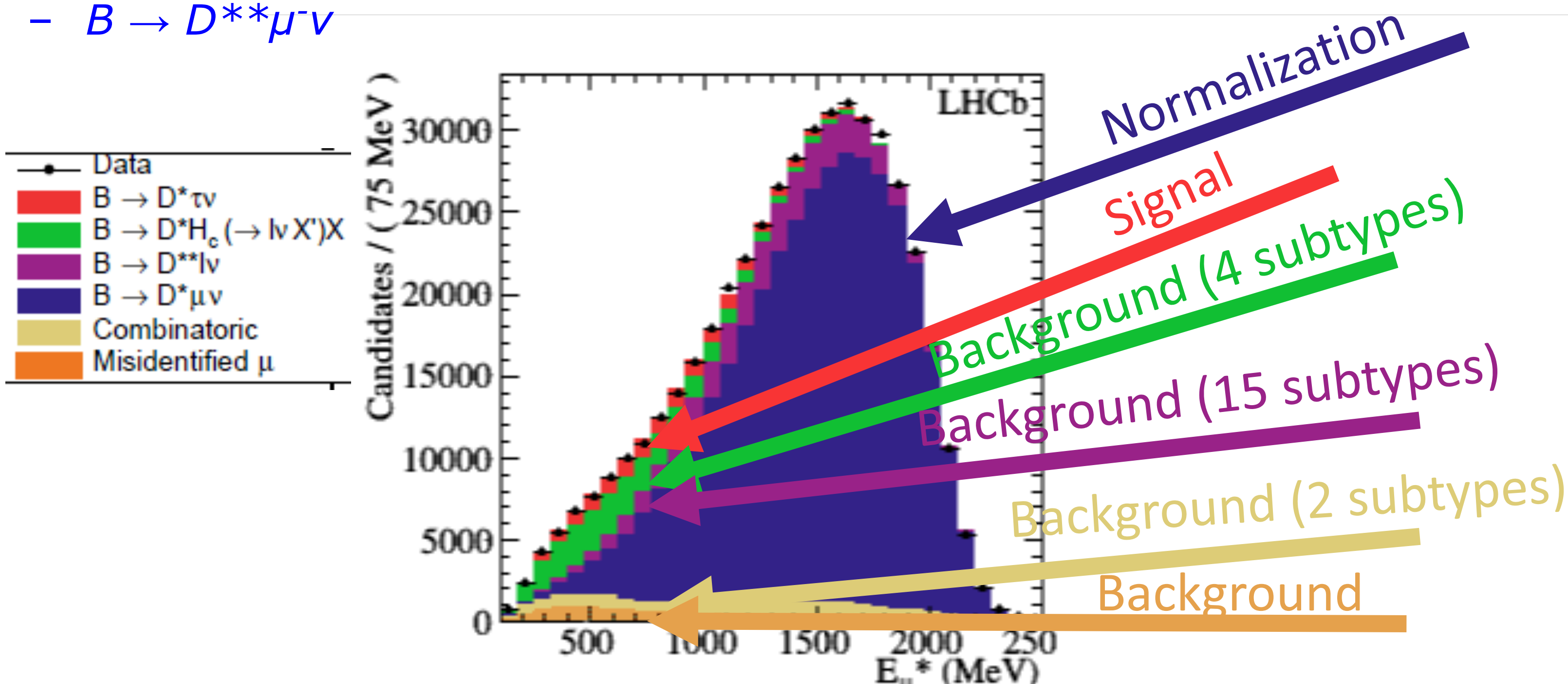
$$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau) = (1.50 \pm 0.16 \pm 0.25 \pm 0.23)\%$$
$$\mathcal{R}(\Lambda_c^+) = 0.242 \pm 0.026 \pm 0.040 \pm 0.059$$

SM: $R(\Lambda_c) = 0.333 \pm 0.010$ (Detmold, Lehner, Meinel arXiv:1503.01421)

LHCb, arXiv:2201.03497
PRL128 (2022) 191803

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

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

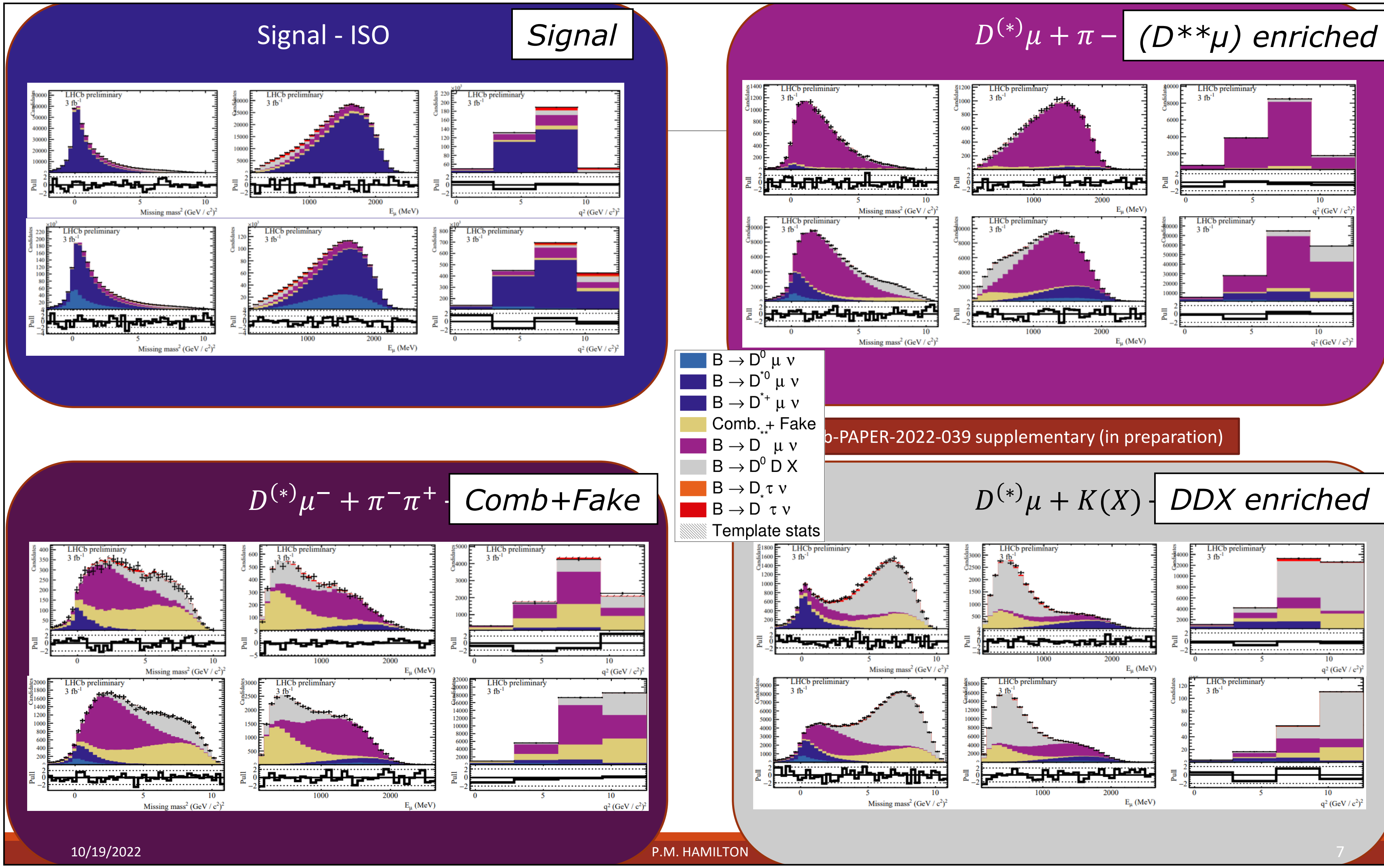


PRL 115 (2015) 111803

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

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

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

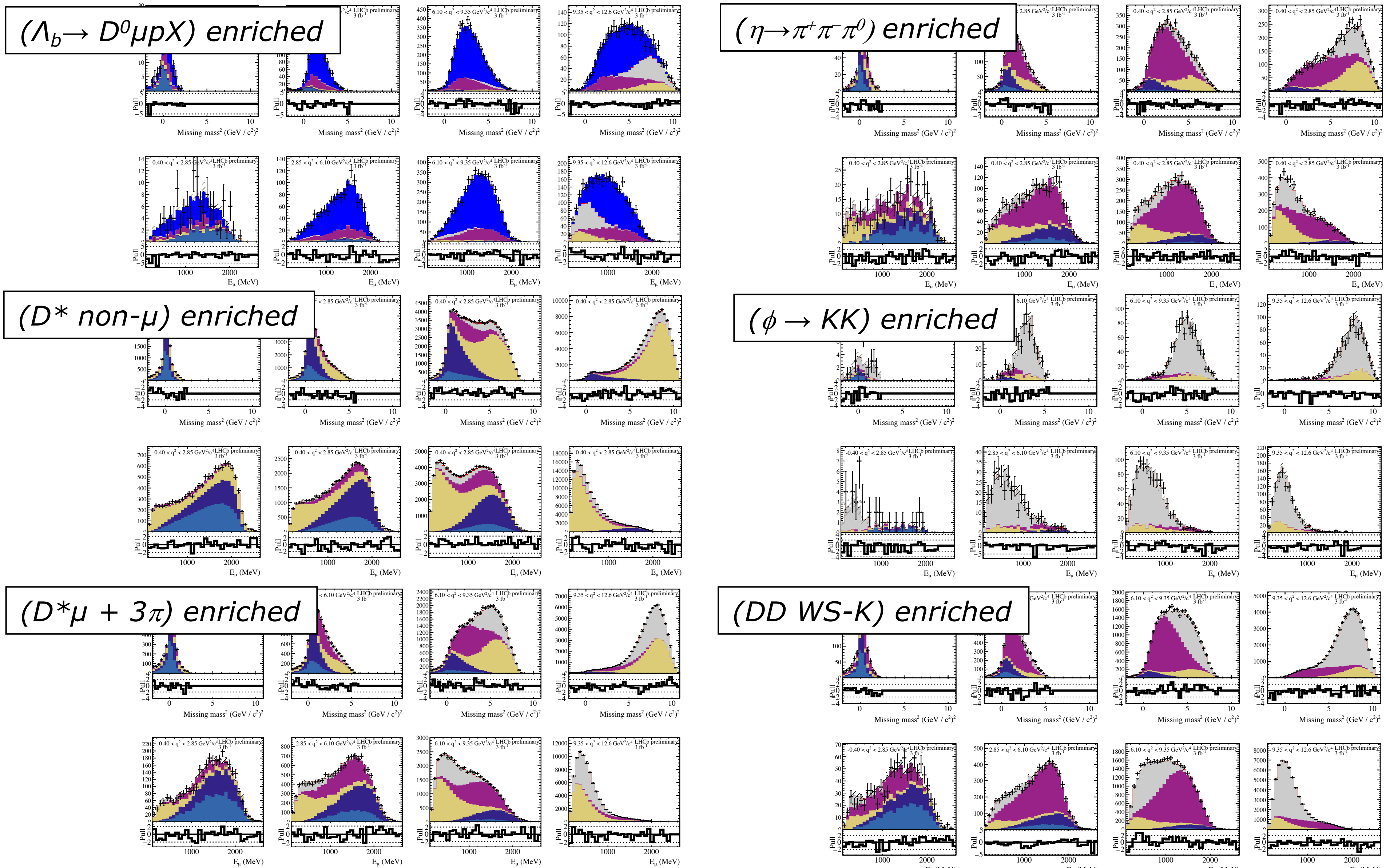


Courtesy: P.Hamilton, Impl.Workshop, 19 Oct 2022, LHCb-PAPER-2022-039, in preparation

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

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

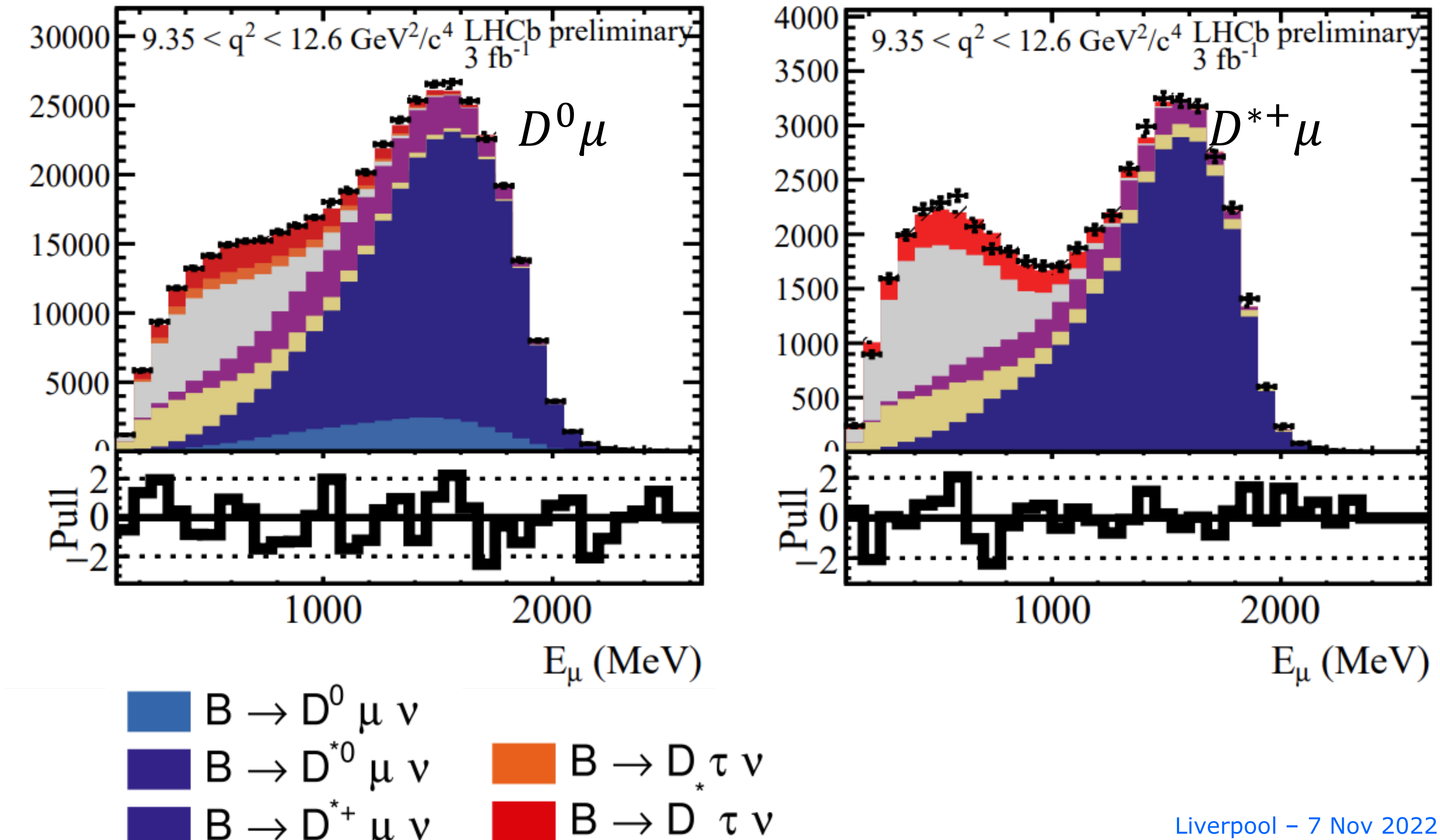
- Fit was checked on specific subsamples:



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

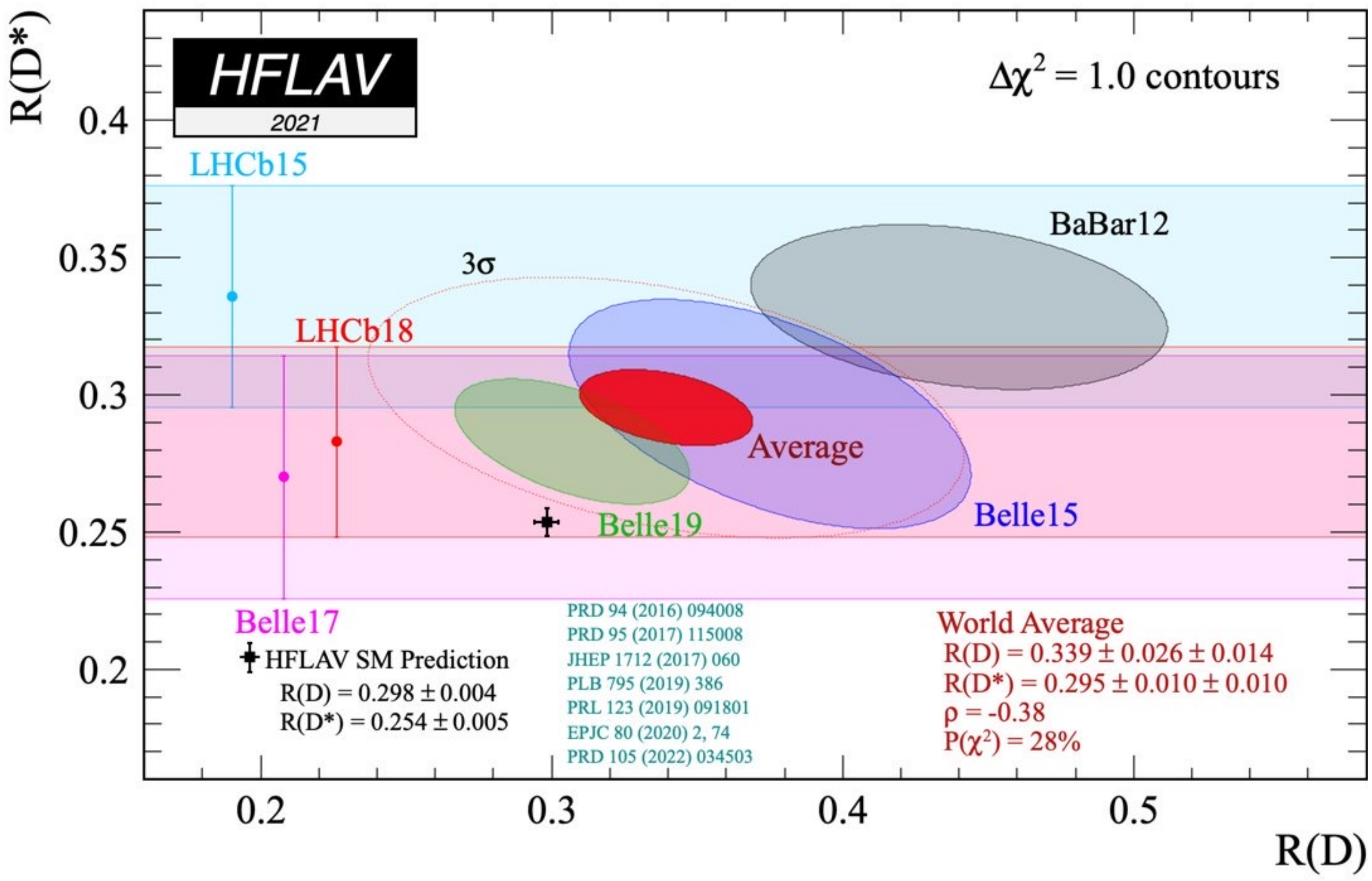
New measurement of R(D*) vs R(D) !

- Lots of ingredients in fit:



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

- World average 3.3σ to 3.2σ



NB: contours contain less than 68% CL…

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

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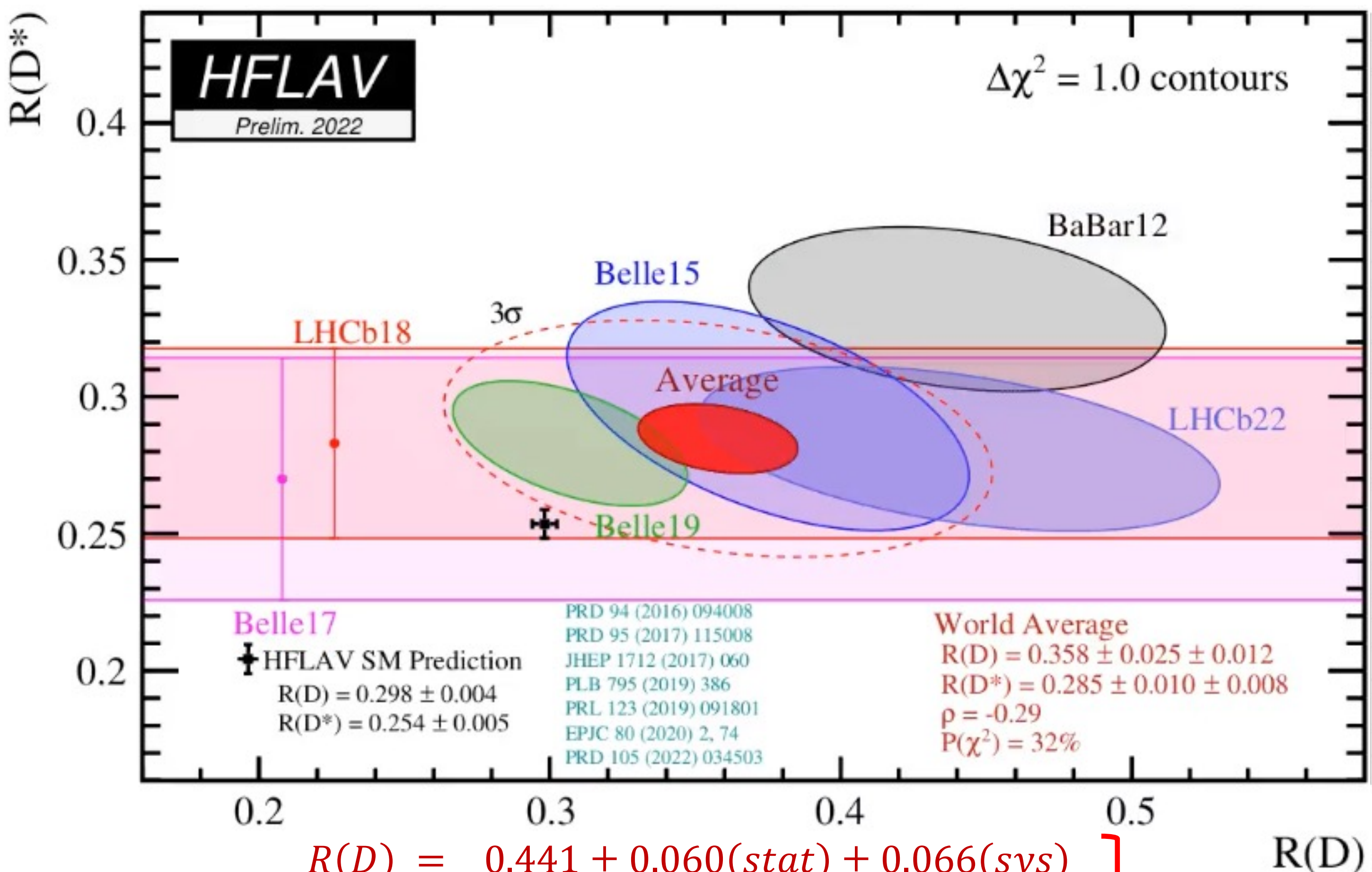


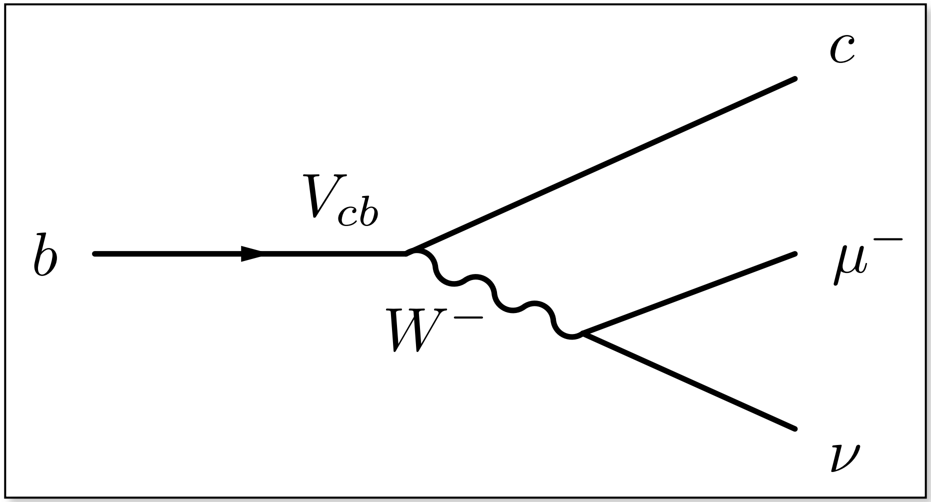
https://hflav-eos.web.cern.ch/hflav-eos/semi/fall22/html/RDsDsstar/RDRDs.html

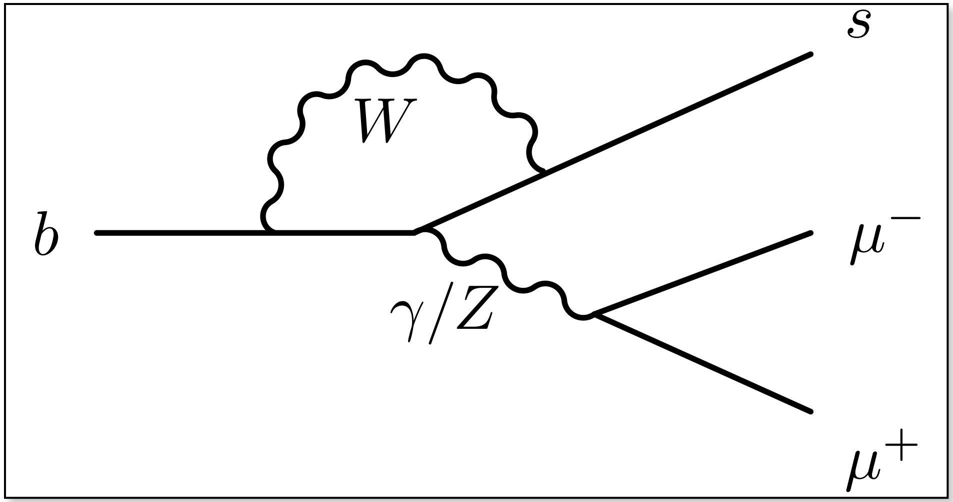
$$R(D) = 0.441 \pm 0.060(stat) \pm 0.066(sys)$$
$$R(D^*) = 0.281 \pm 0.018(stat) \pm 0.023(sys)$$
$$\rho = -0.49(stat)/-0.40(sys)/-0.43(tot)$$

1.9σ

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

CC and FCNC





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FCNC EWP Penguin
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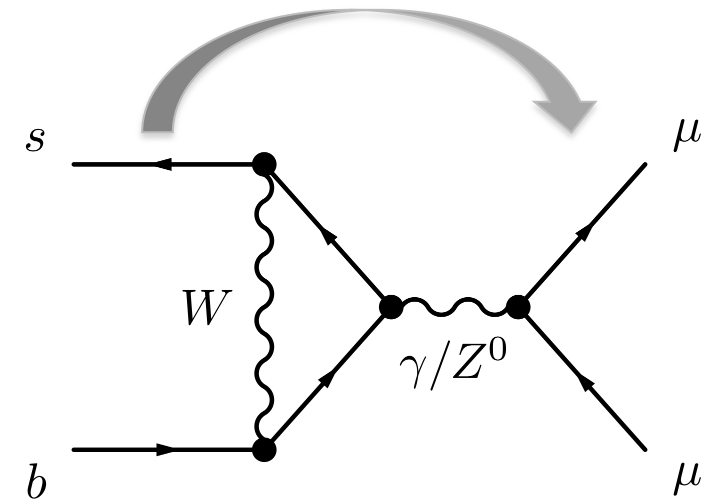
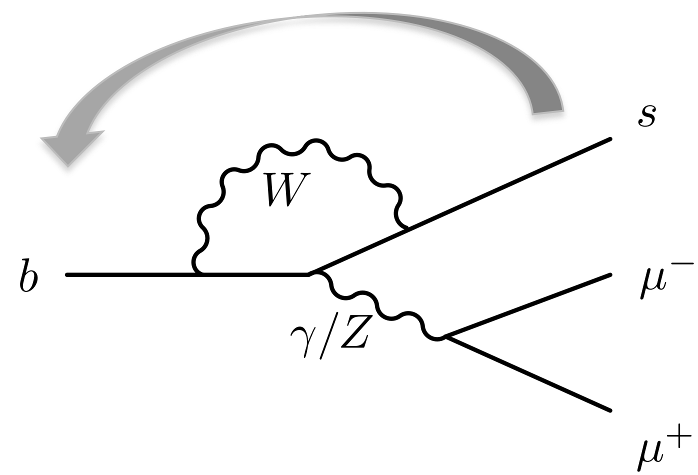
Rich laboratory:

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

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

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

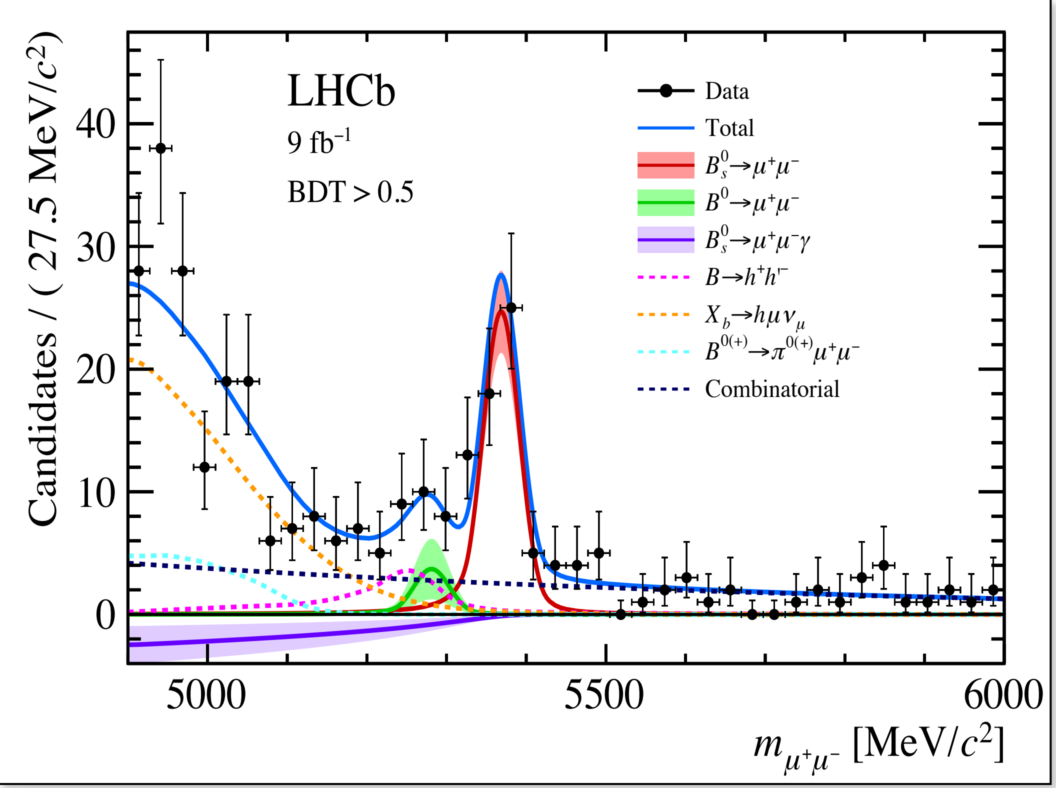




+ $B_s^0 \to e^+e^-$ (LHCb, arXiv:2003.03999)

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

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



LHCb Coll. arXiv:2108.09284

Theory:

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

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

Beneke, Bobeth, Szafron, arXiv:1908.07011

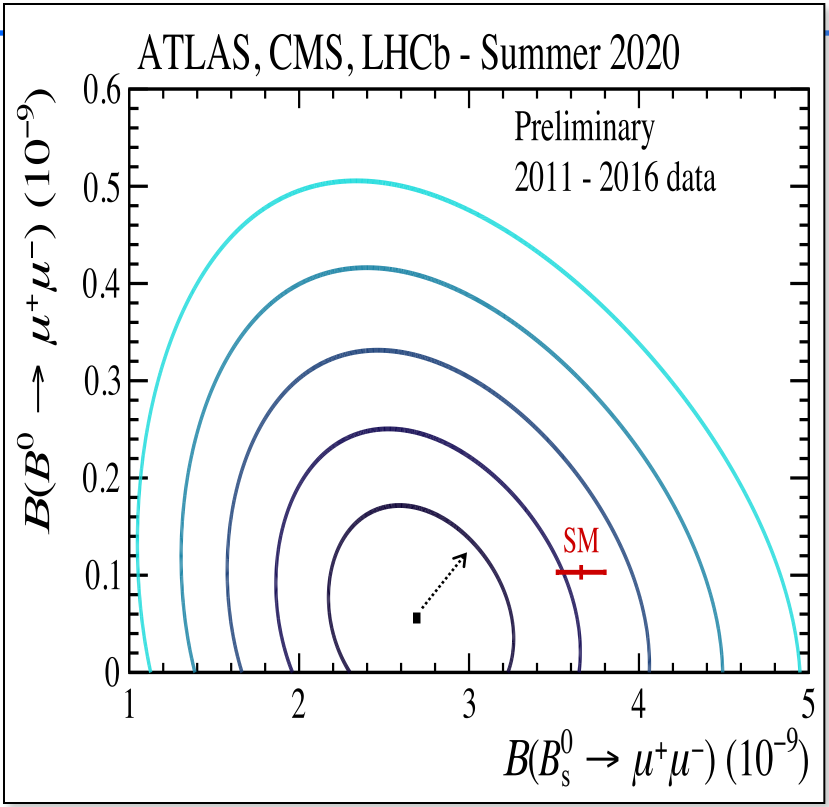
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}\right) \times 10^{-9}$$

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

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

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

- Including B^0:



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

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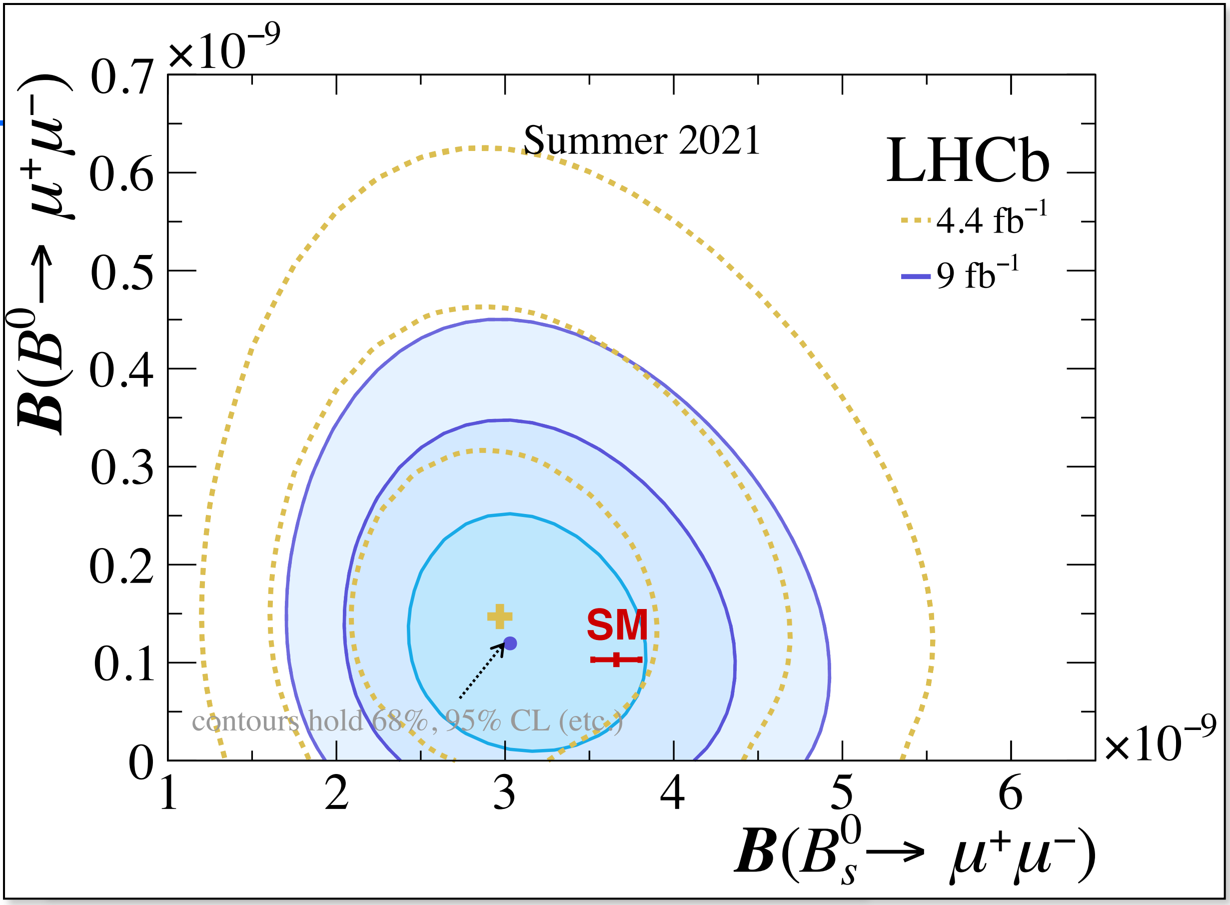


LHCb Coll. arXiv:2108.09284

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

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

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

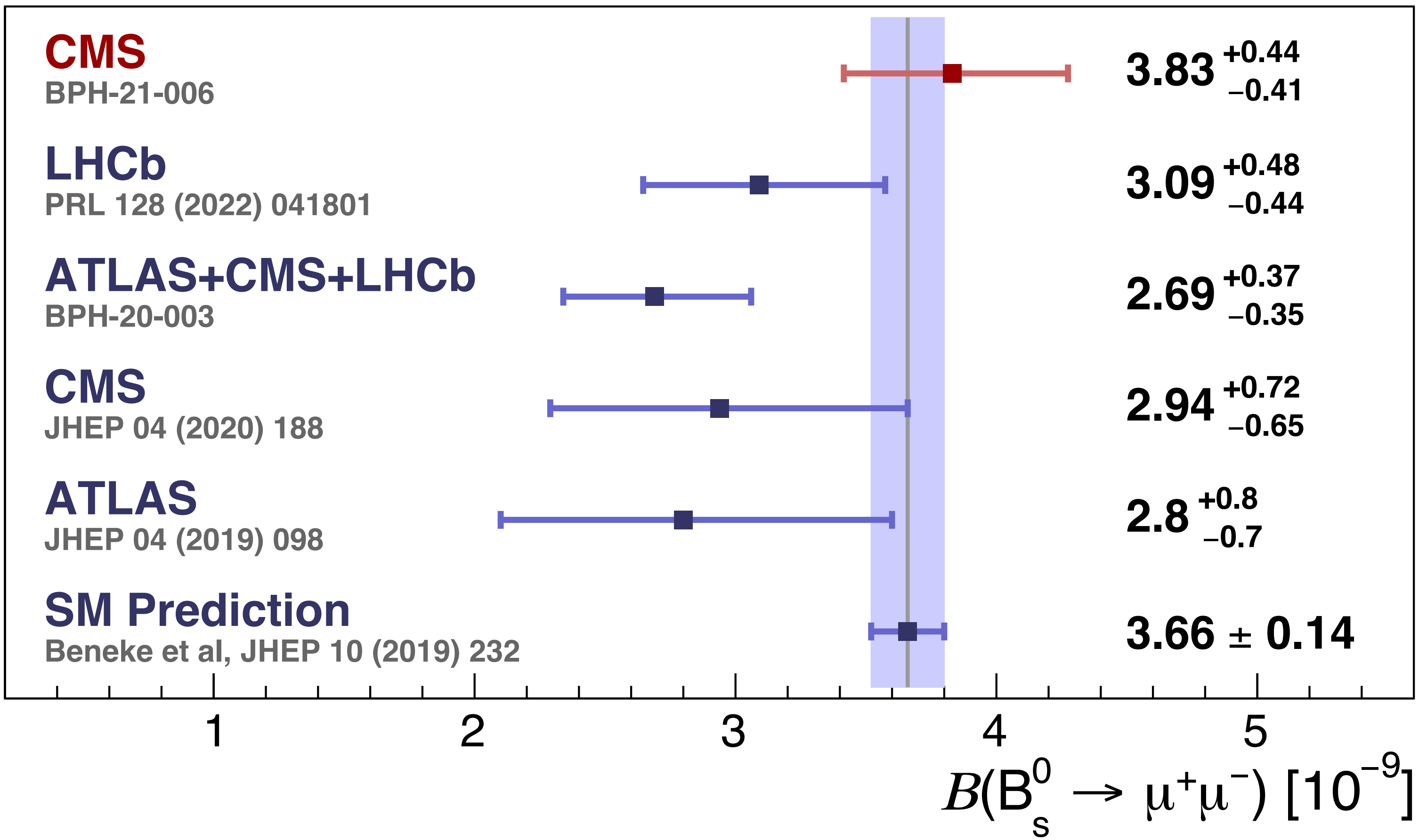
(Integrated, p_T [0.5,40] GeV/c, η [2.6,4])

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

LHCb Coll, arXiv:2103.06810

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

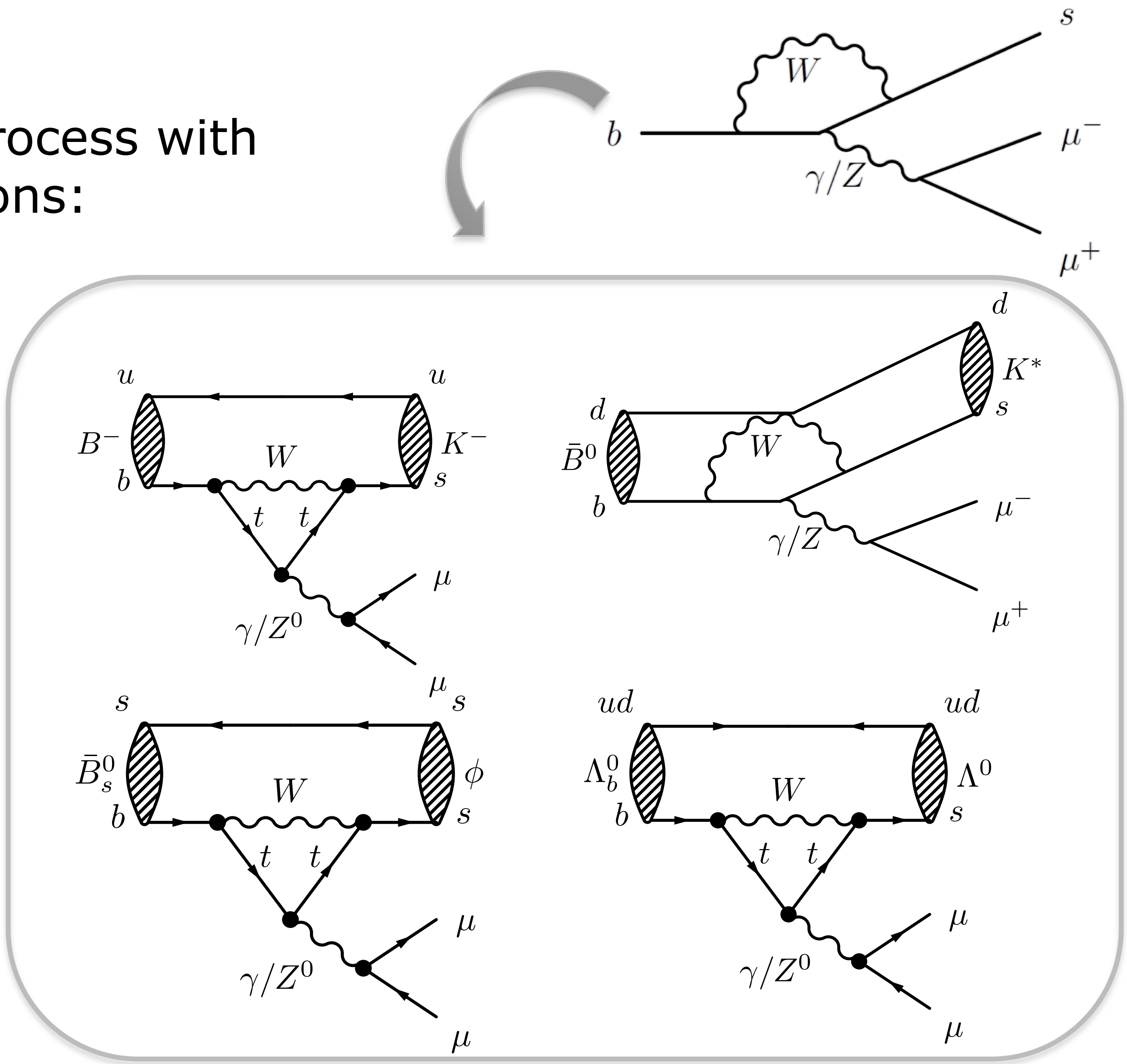
Summer 2022



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

Decay rates

- Study same process with different hadrons:

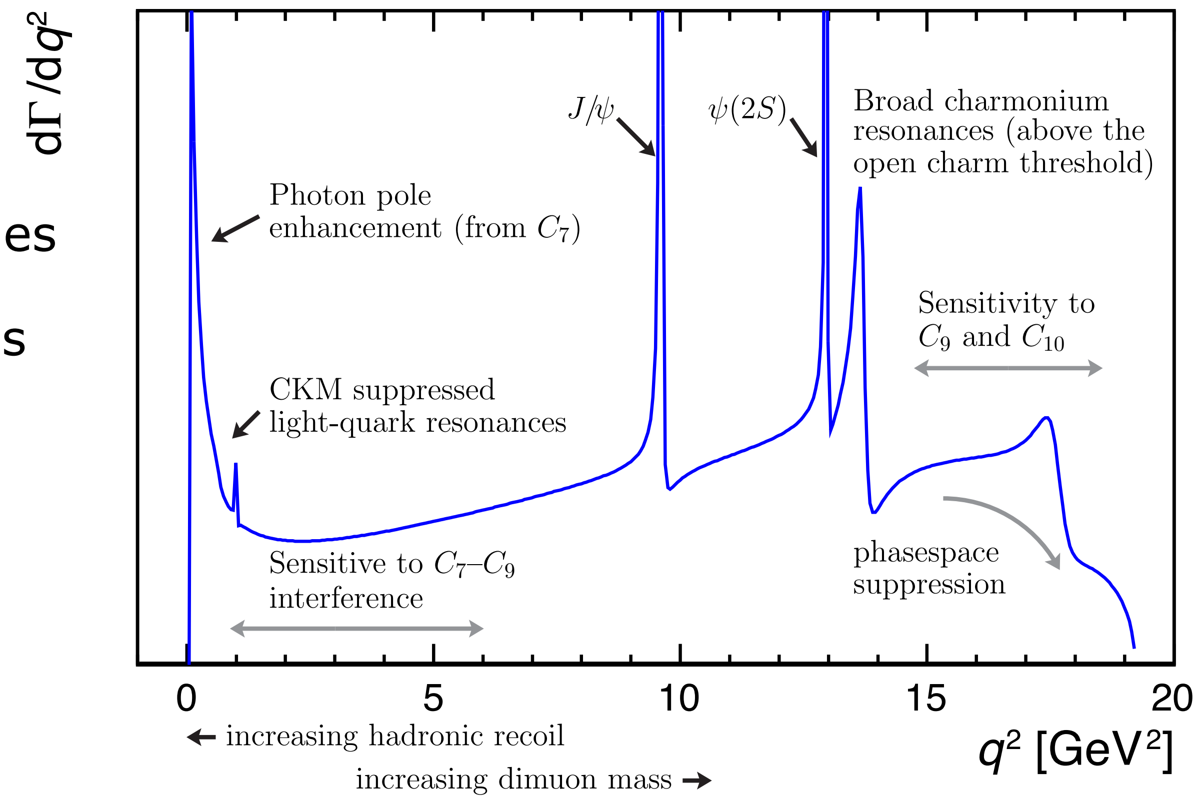


$b \to s l^+ l^-$

Rich laboratory:

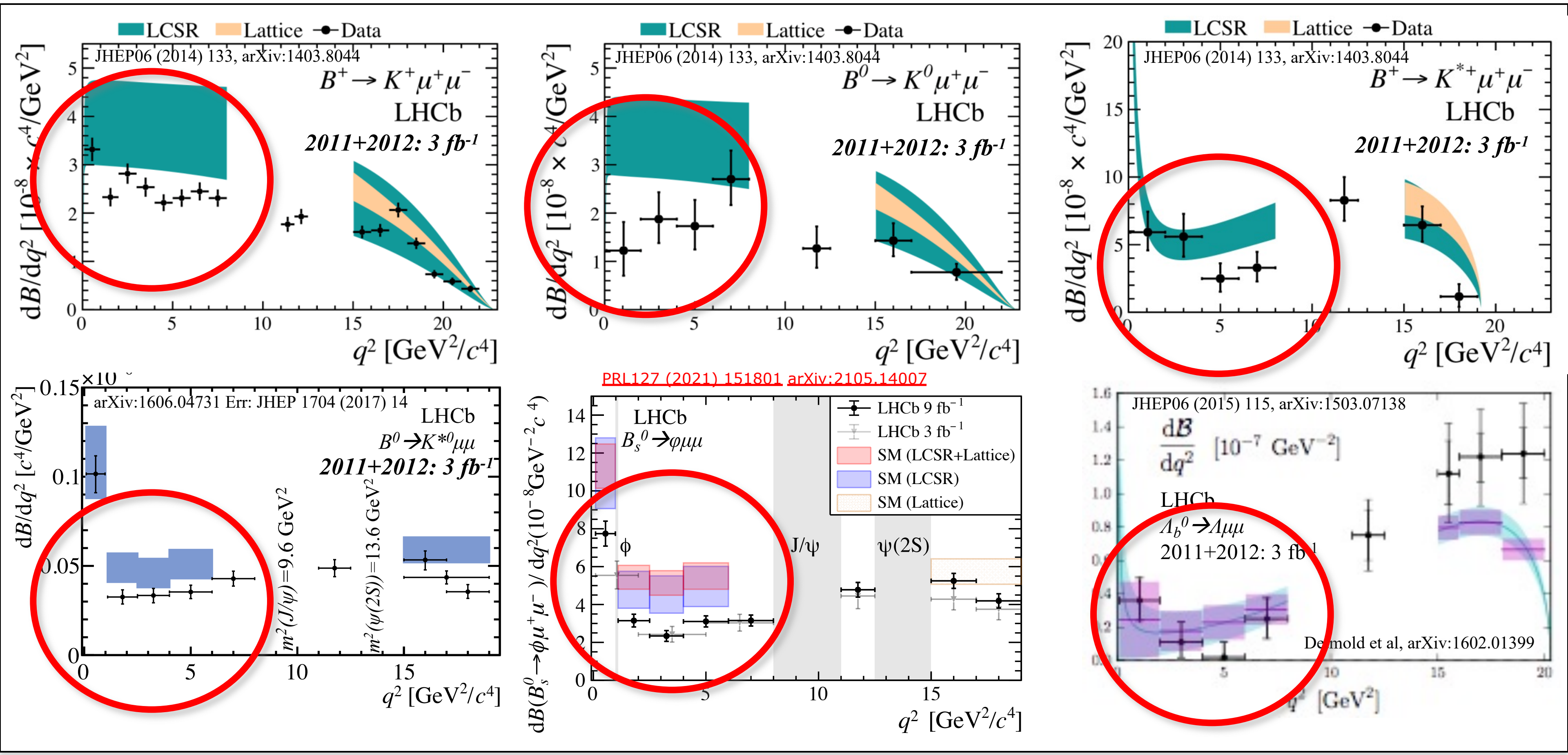
1) Purely leptonic
2) Decay rates
3) Angular asymmetries
4) Ratio of decay rates

T.Blake et al. arXiv:1606.00916



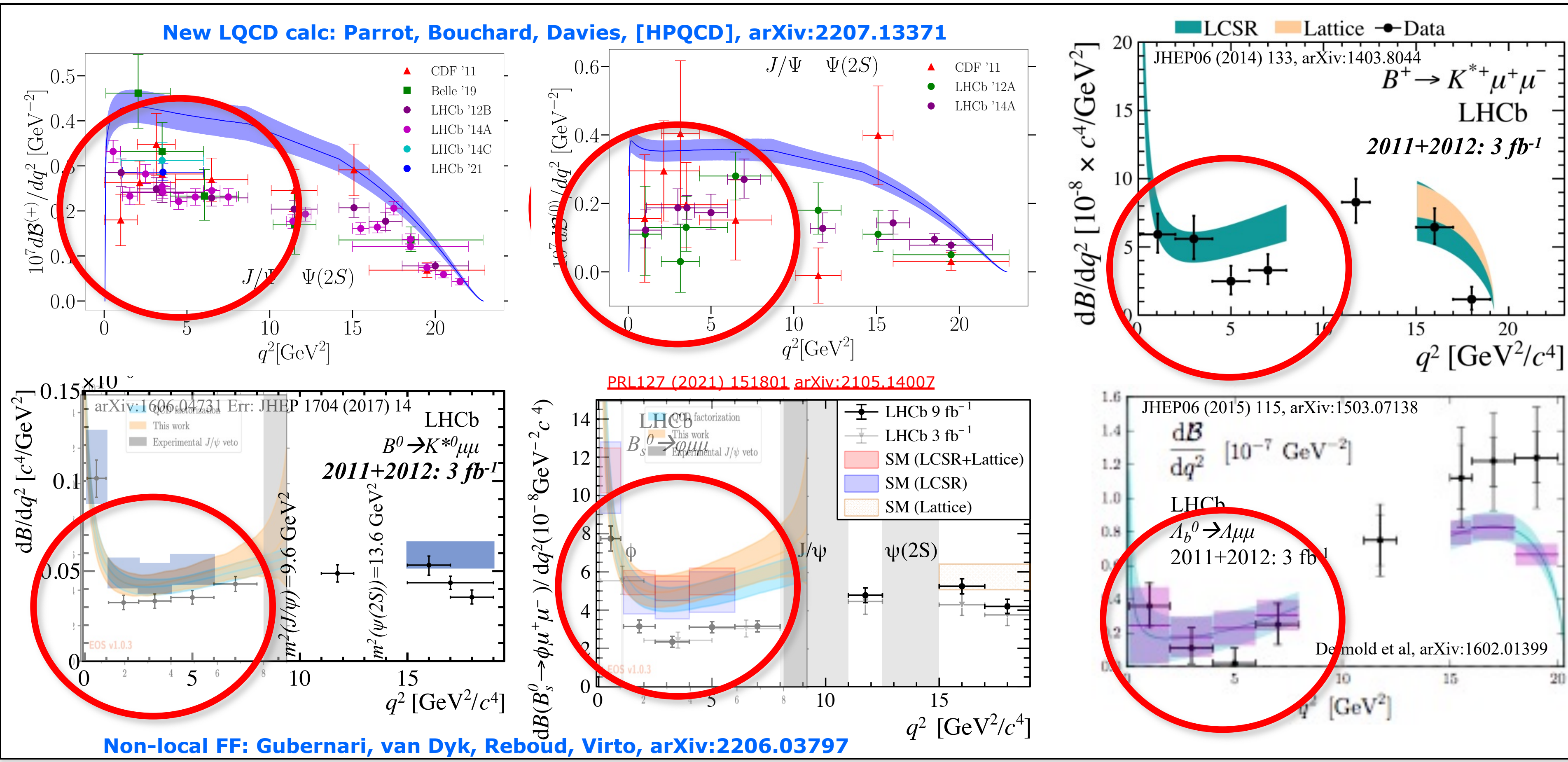
Decay rates

- Decay rate with muons in final state consistently low:

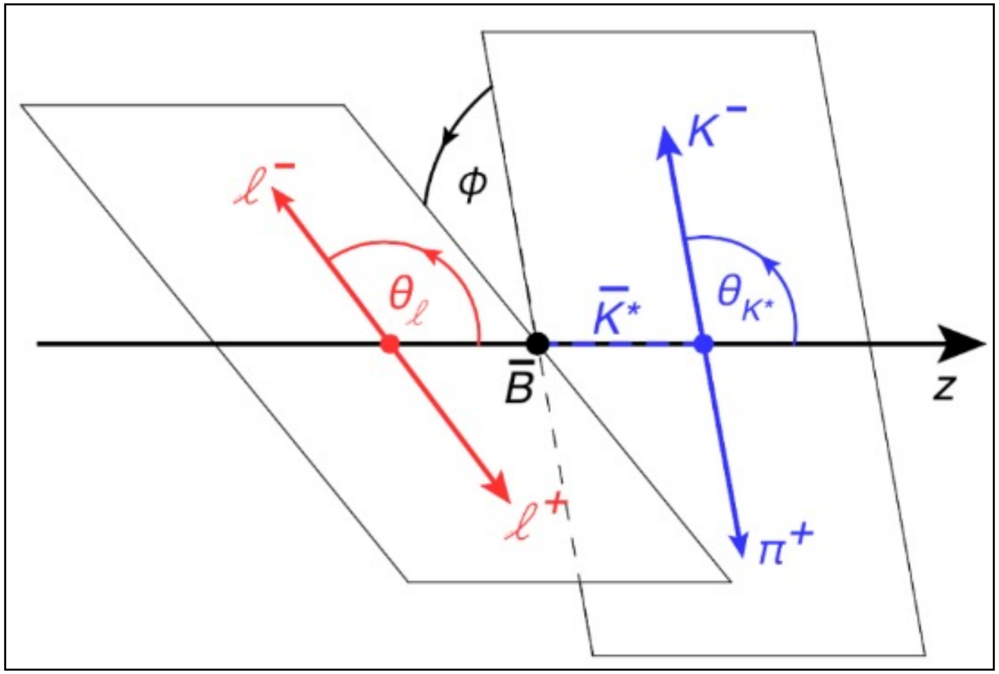


Decay rates

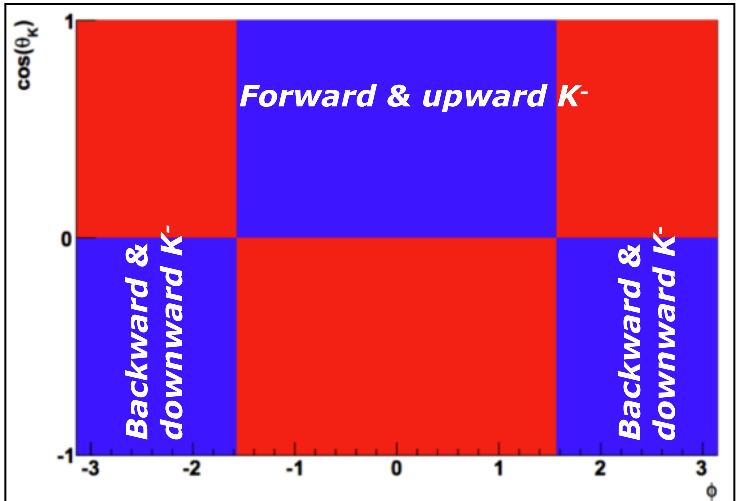
- Lots of theoretical develpoments:



Angular asymmetries



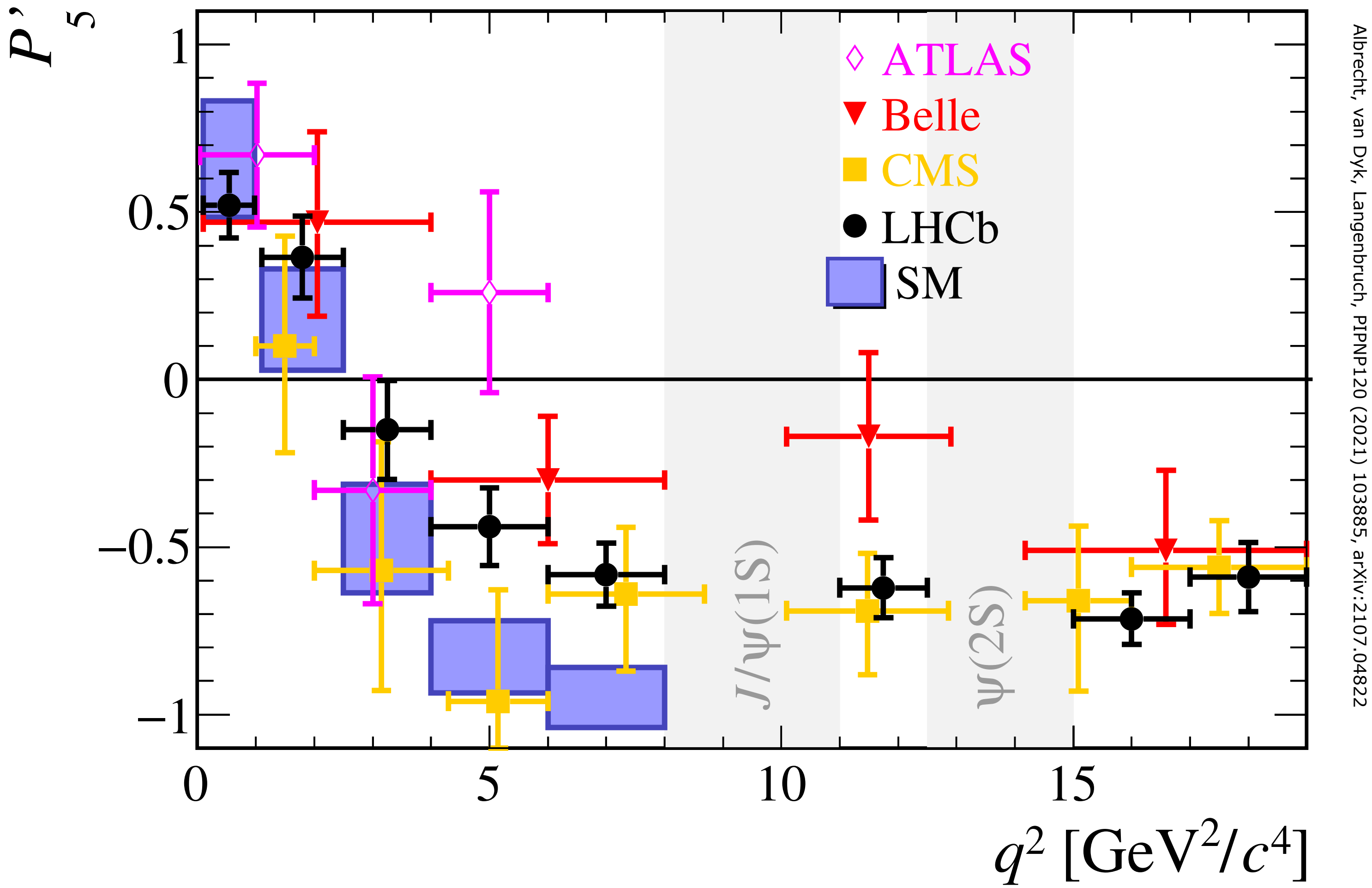
P_5':



Counting S_5: blue minus red

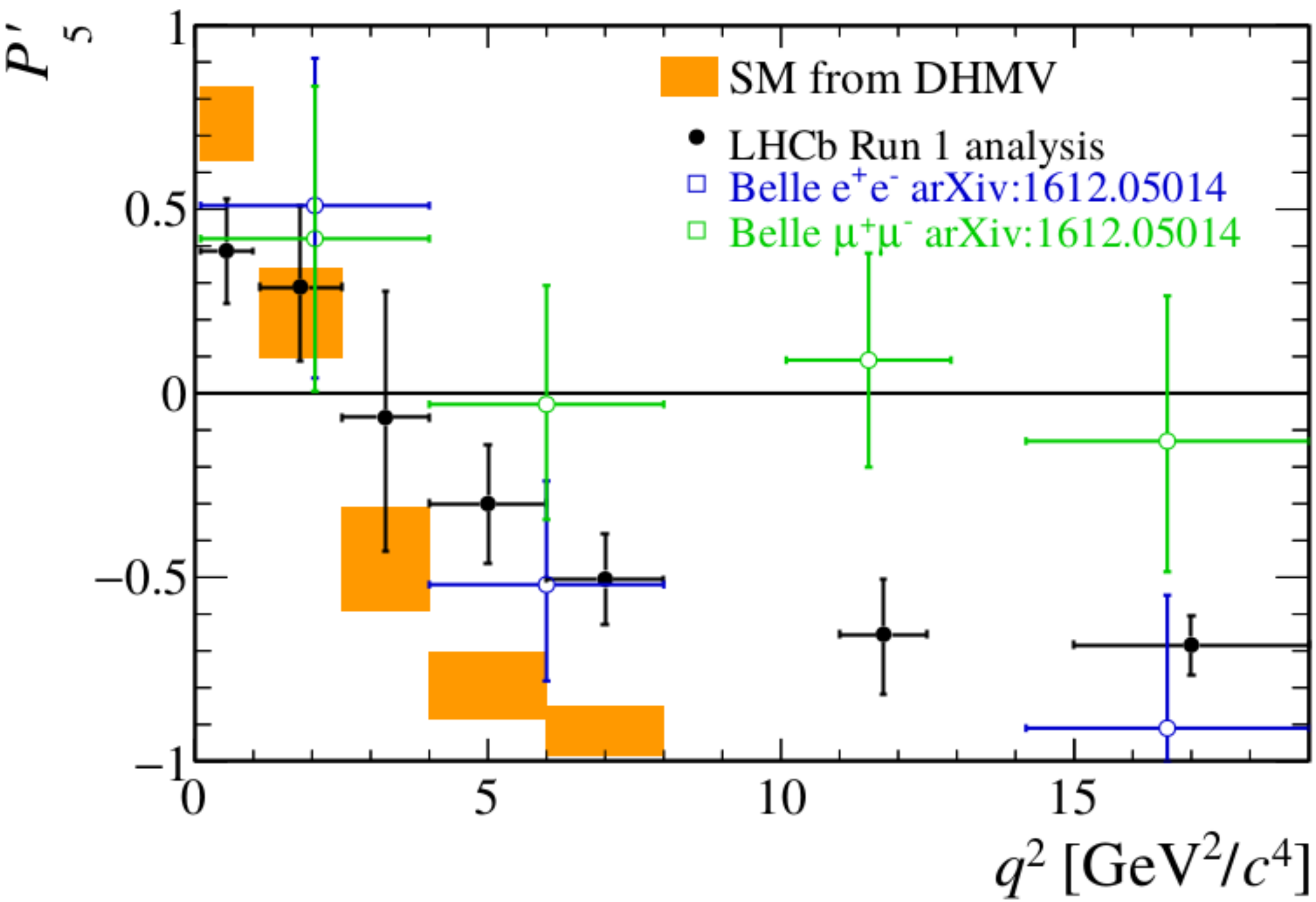
Angular asymmetries: eg. P_5'

- Compilation:



Angular asymmetries

- Interesting to compare angular asymmetries for μ and e

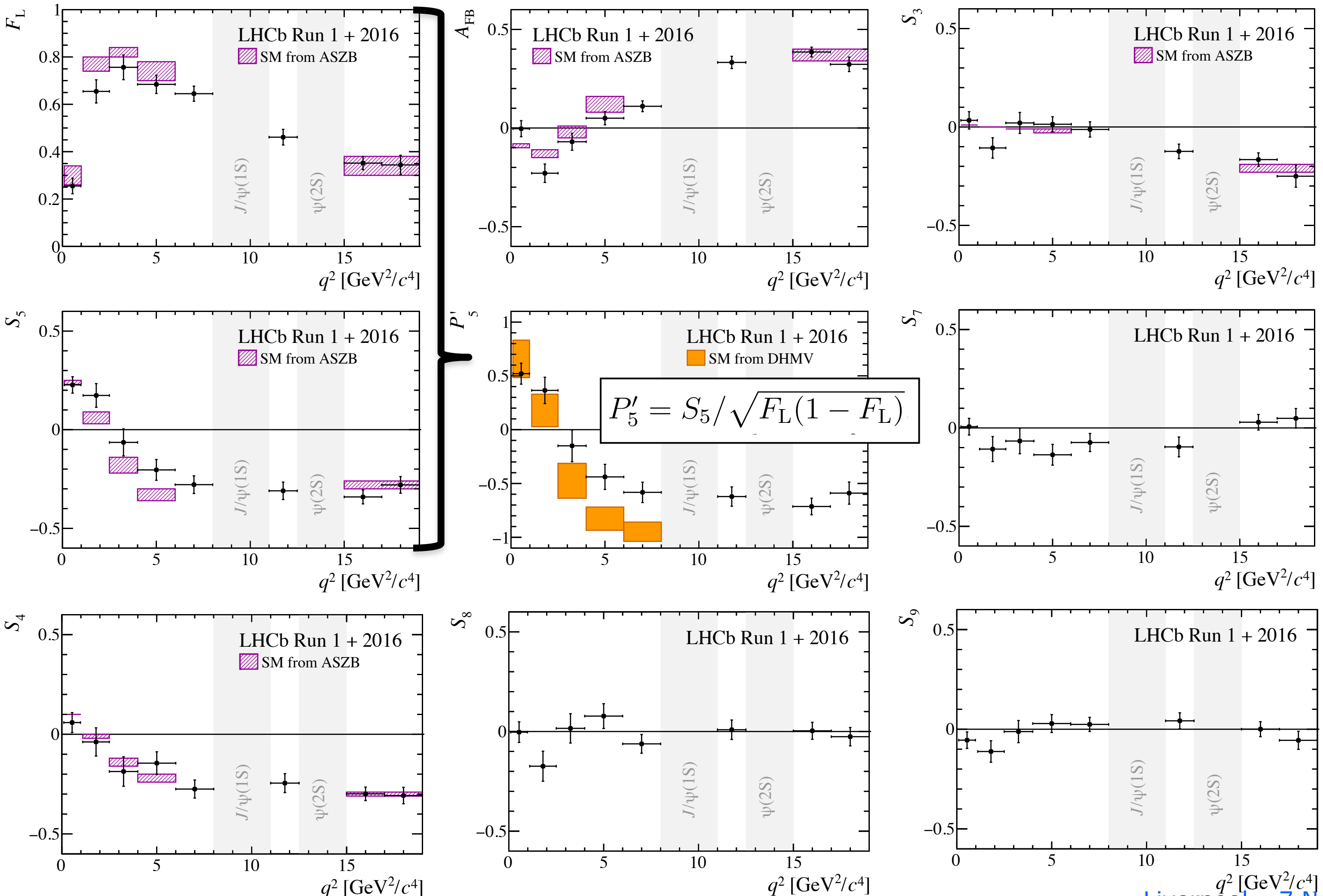


LHCb, arXiv:1512.04442

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

- Many measurements:

LHCb Coll, arXiv:2003.04831



Outline

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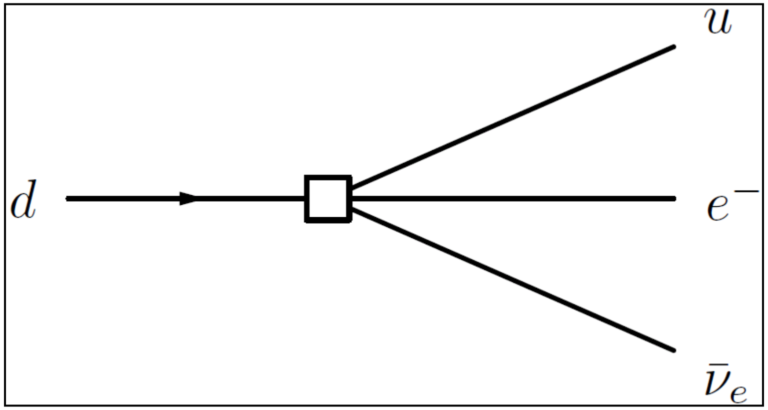
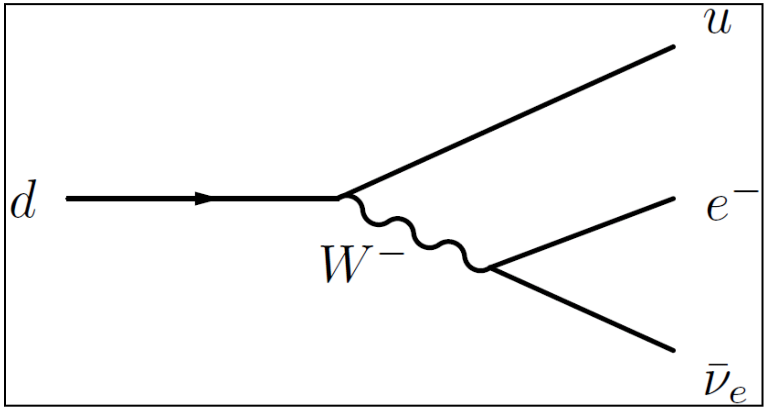
  - $R(D^{(*)})$
- FCNC: $b \to s l^+ l^-$
  - $B_s^0 \to \mu^+ \mu^-$
  - Decay rates
  - Angular analyses
  - Lepton flavour ratios
- Effective couplings
- Prospects

Intermezzo: Effective couplings

- Historical example



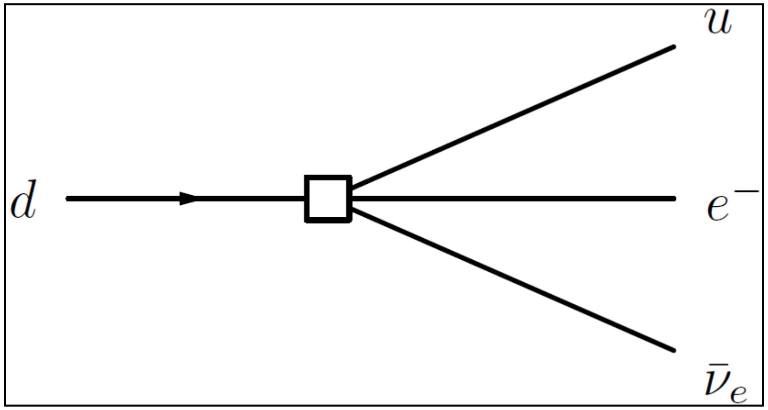


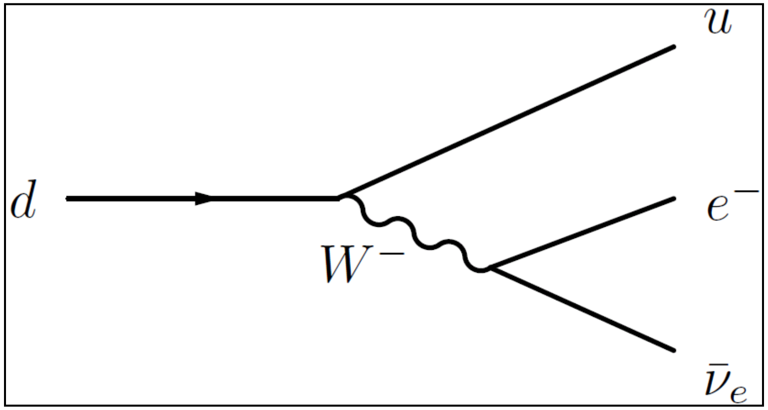
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

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

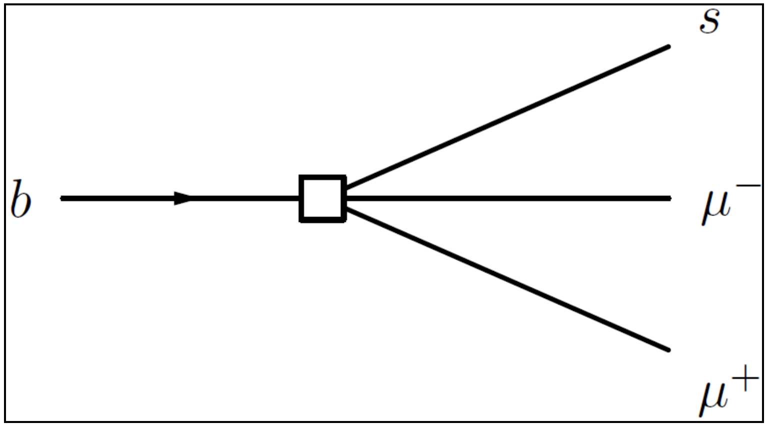
Intermezzo: Effective couplings

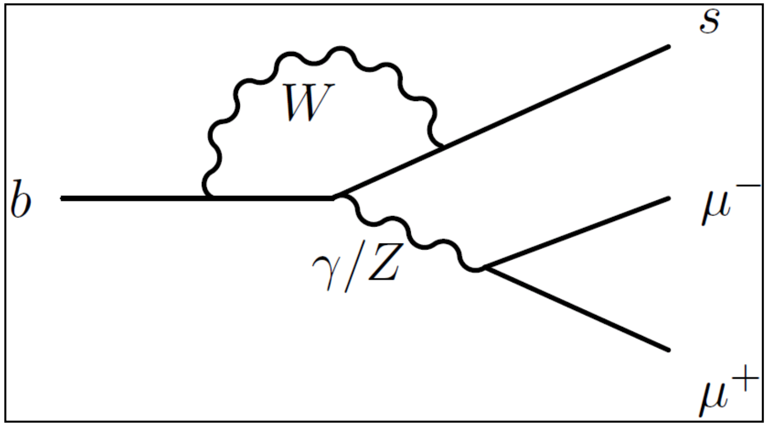
- Historical example





- Analog: *Flavour-changing neutral current*

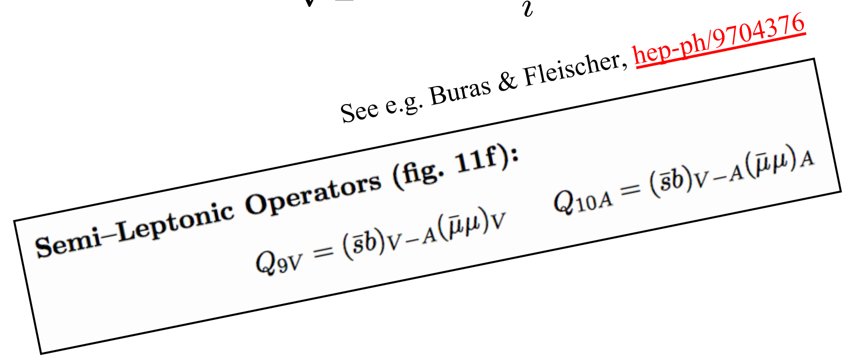




Intermezzo: Effective couplings

- 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}', …
  - …

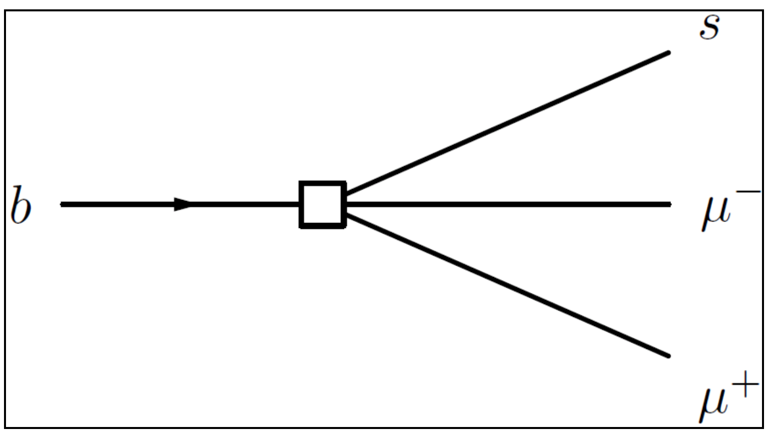
$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{\text{CKM}} \sum_i C_i(\mu) Q_i$$

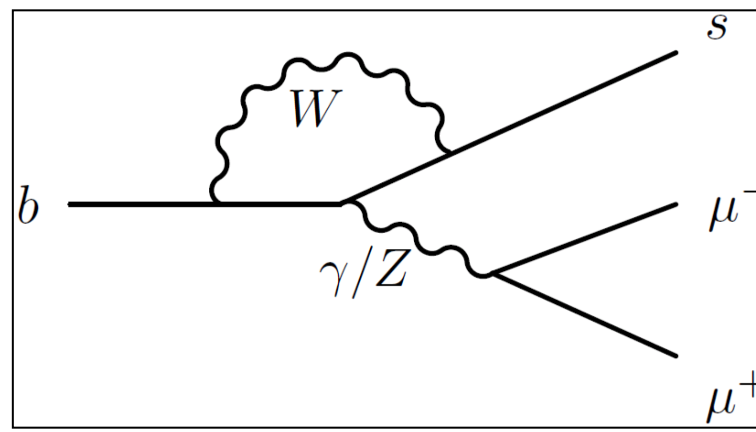

See e.g. Buras & Fleischer, hep-ph/9704376

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:

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

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

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

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

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

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

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

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

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

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

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

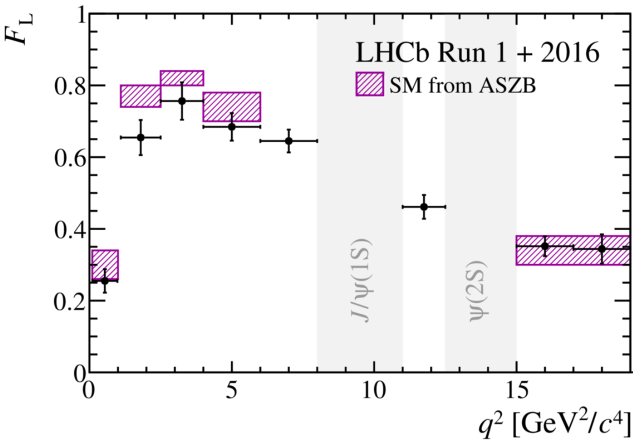
$$\frac{1}{\Gamma}\frac{d^3(\Gamma + \bar{\Gamma})}{d\cos\theta_\ell \, d\cos\theta_K \, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1 - F_L)\sin^2\theta_K + F_L \cos^2\theta_K + \frac{1}{4}(1 - F_L)\sin^2\theta_K \cos 2\theta_\ell$$
$$- F_L \cos^2\theta_K \cos 2\theta_\ell +$$
$$S_3 \sin^2\theta_K \sin^2\theta_\ell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

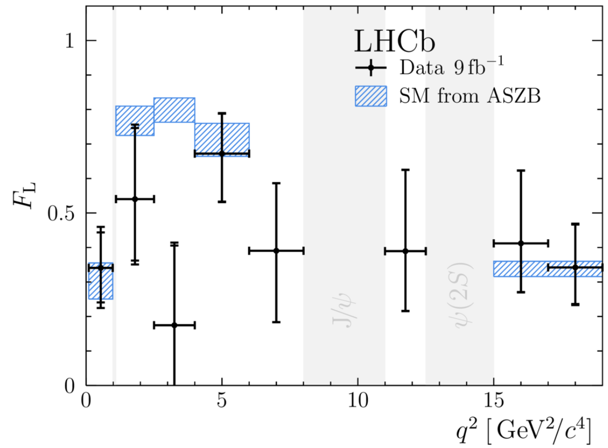
Coherent pattern

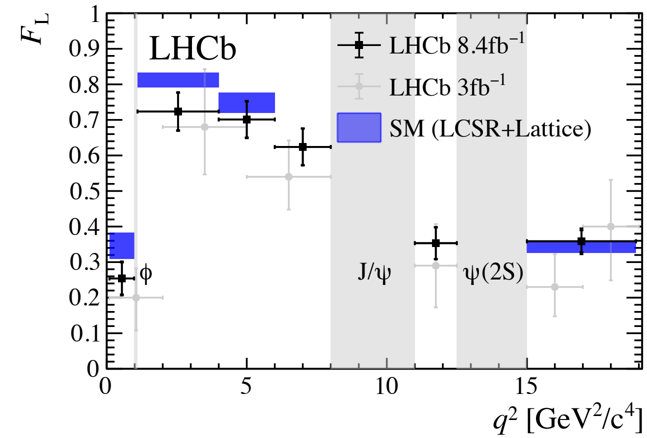
arXiv:2003.04831: $B^0 \to K^{*0}\mu^+\mu^-$

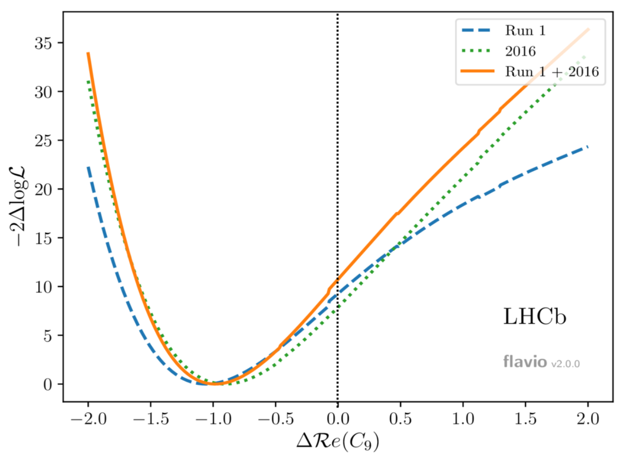
arXiv:2012.13241: $B^+ \to K^{*+}\mu^+\mu^-$

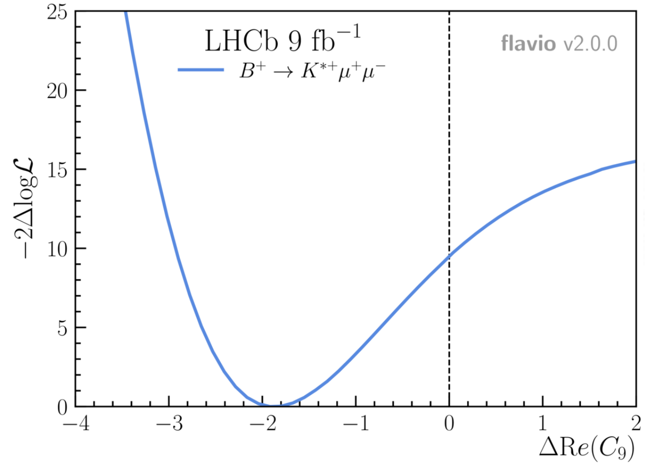
arXiv:2107.13428: $B^0_s \to \phi\mu^+\mu^-$

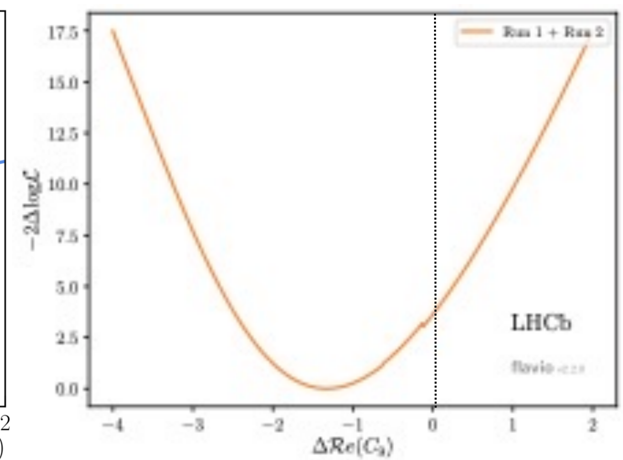


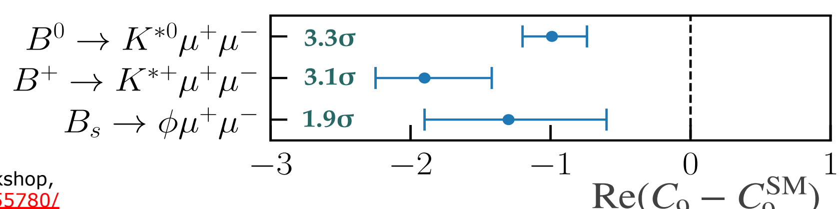












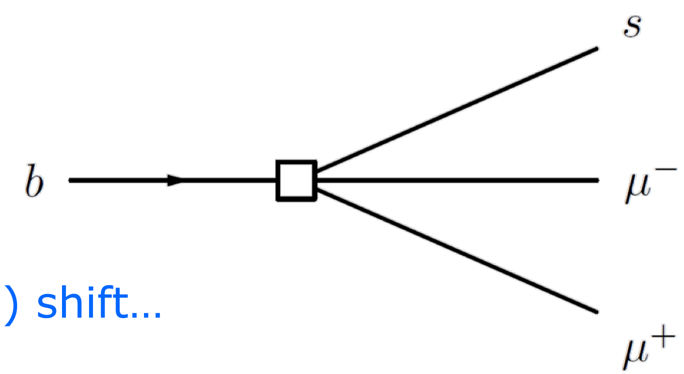
From: Martino Borsato, Flavour Anomaly Workshop, 20 Oct 2021, https://indico.cern.ch/event/1055780/

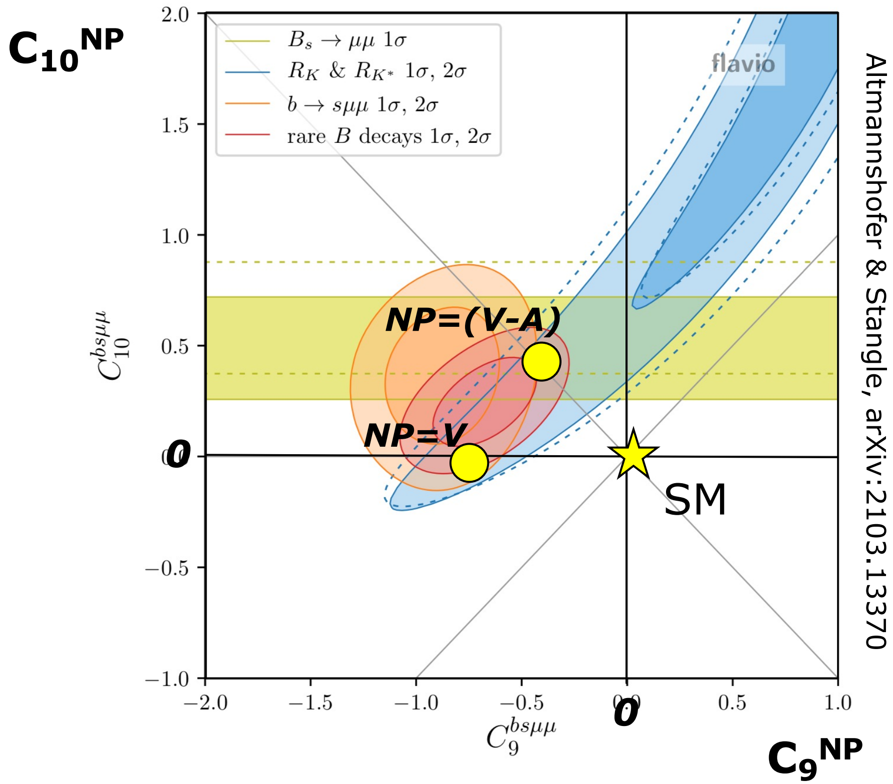
Coherent pattern

Model independent fits:

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

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





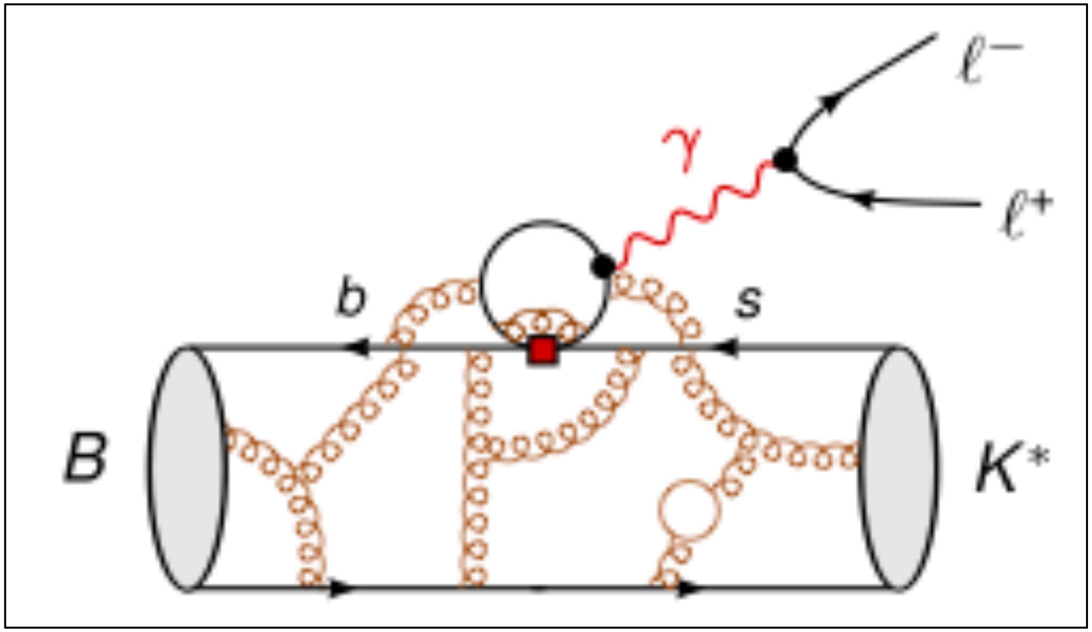
Wilson coefficient	all rare B decays best fit	pull
$C_9^{bs\mu\mu}$	$-0.82^{+0.14}_{-0.14}$	6.2σ
$C_{10}^{bs\mu\mu}$	$+0.56^{+0.12}_{-0.12}$	4.9σ
$C_9'^{bs\mu\mu}$	$-0.09^{+0.13}_{-0.13}$	0.7σ
$C_{10}'^{bs\mu\mu}$	$+0.01^{+0.10}_{-0.09}$	0.1σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$-0.06^{+0.11}_{-0.11}$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

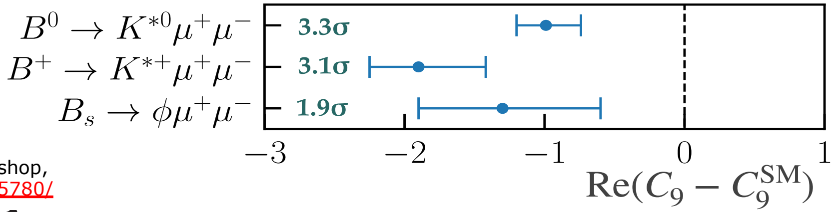
Similar improvement of fit for both scenario's

NB: p-value SM hypothesis ~0.5%

Coherent pattern

- Charm loop effects could also cause a shift in C_9



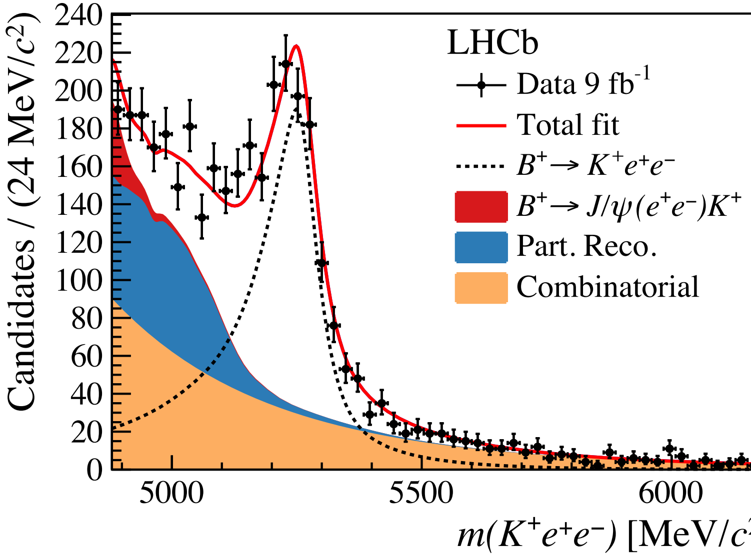


From: Martino Borsato, Flavour Anomaly Workshop, 20 Oct 2021, https://indico.cern.ch/event/1055780/

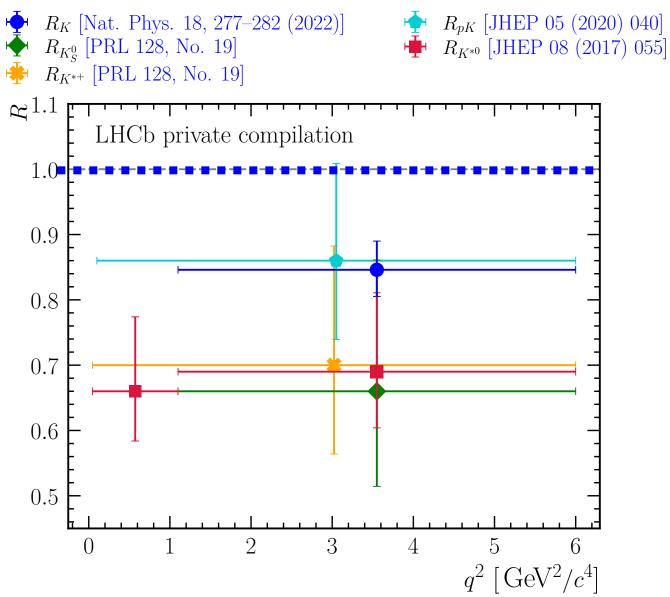
Ratio of decay rates

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

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



Ratio of decay rates



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

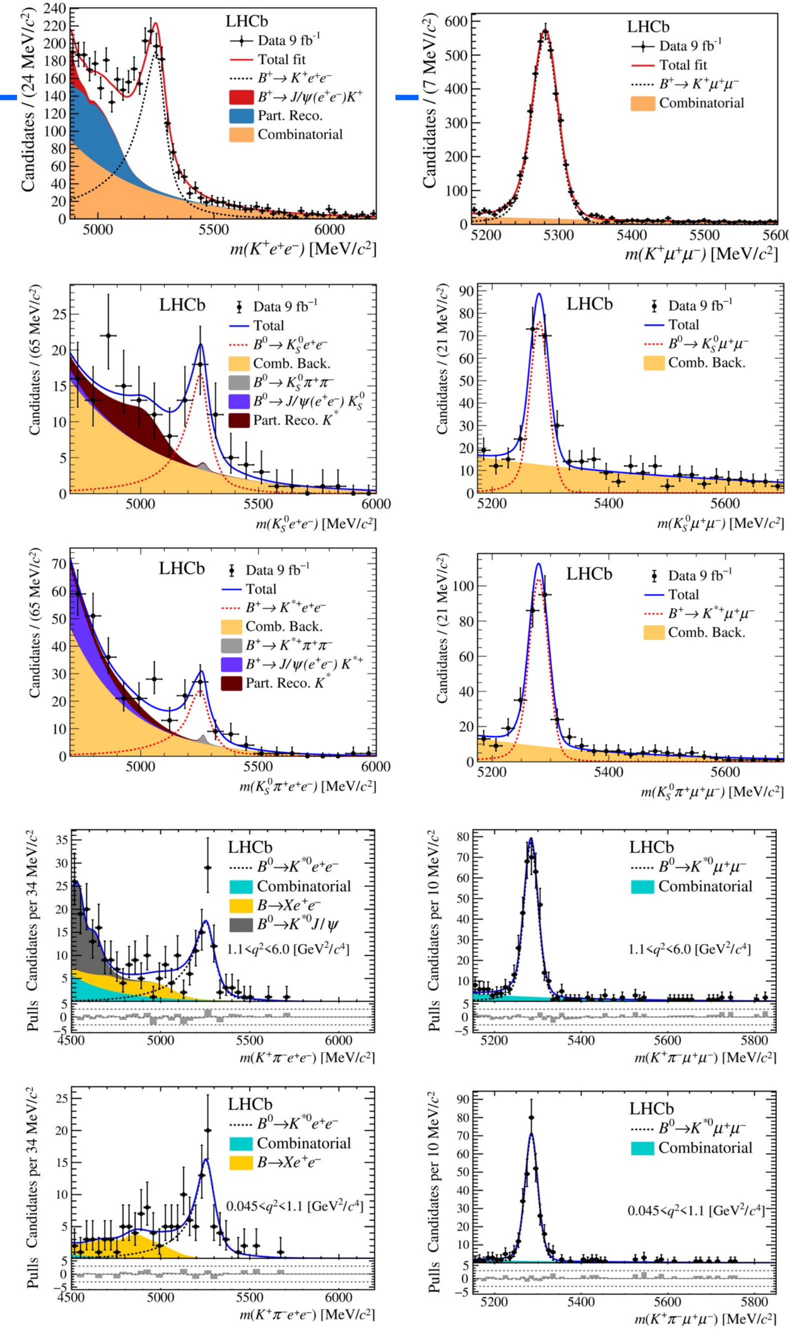
$B^0 \to K_S{}^0\mu^+\mu^-$

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

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

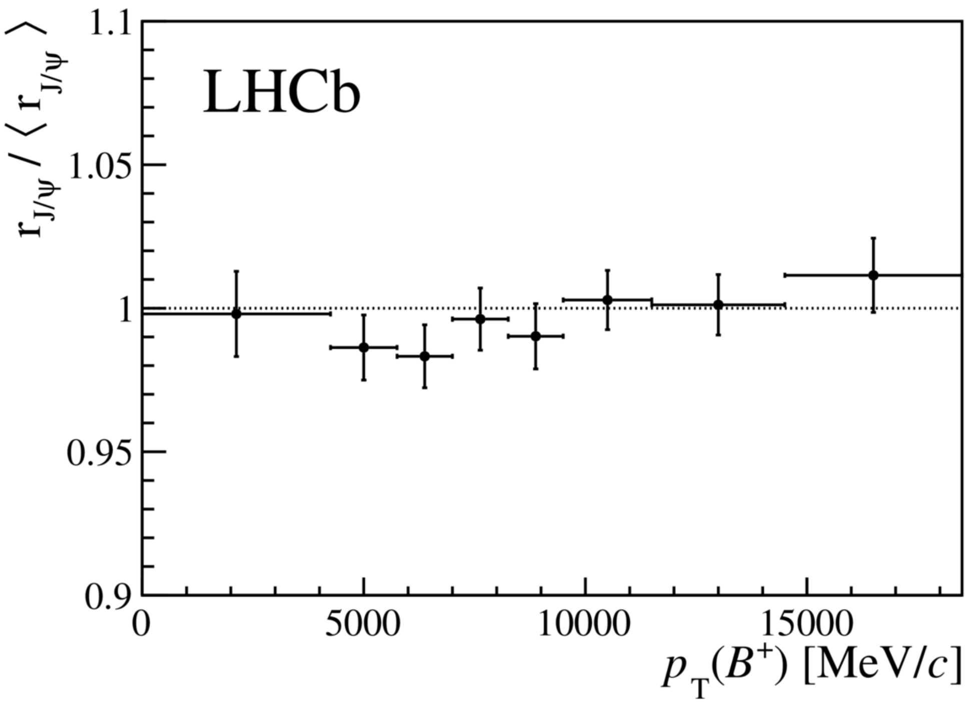
$B^0 \to K^{*0}\mu^+\mu^-$

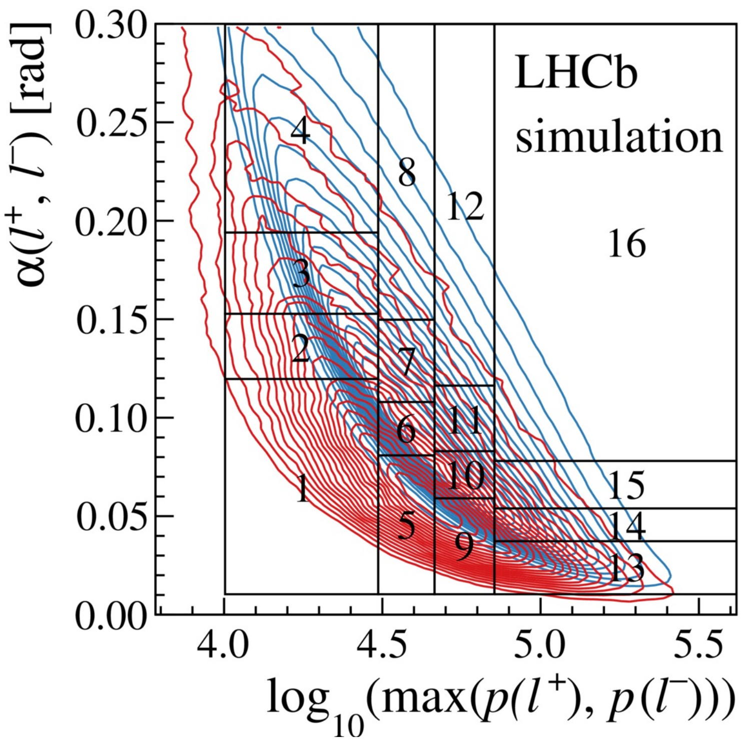
Kee ***Kμμ***



$r_{J/\psi}$

- Test efficiencies are understood in all kinematic regions by checking $r_{J/\psi}$ is flat
- Flatness of $r_{J/\psi}$ 2D plots gives confidence that efficiencies are understood





$$r_{J/\psi} = 0.981 \pm 0.020\ (\text{stat} + \text{syst})$$

LHCb Coll, arXiv:2103.11769

Analyses – where are we?

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

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

Outline

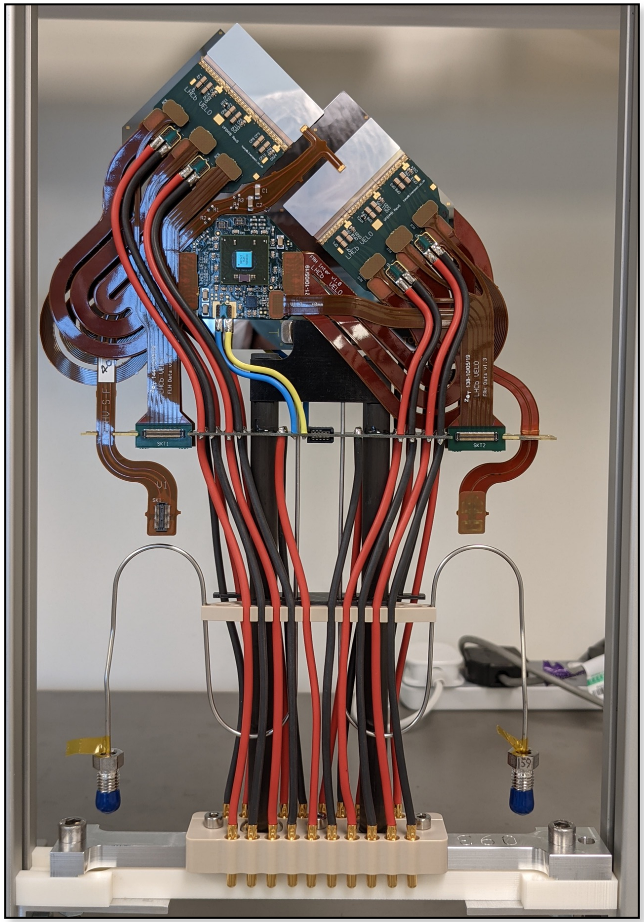
- CC: $b \to c l^- \nu$
  - $R(D^{(*)})$
- FCNC: $b \to s l^+ l^-$
  - $B_s^0 \to \mu^+ \mu^-$
  - Decay rates
  - Angular analyses
  - Lepton flavour ratios
- Effective couplings
- Prospects
  - Belle-II
  - LHCb Upgrade 1
  - LHCb Upgrade 2

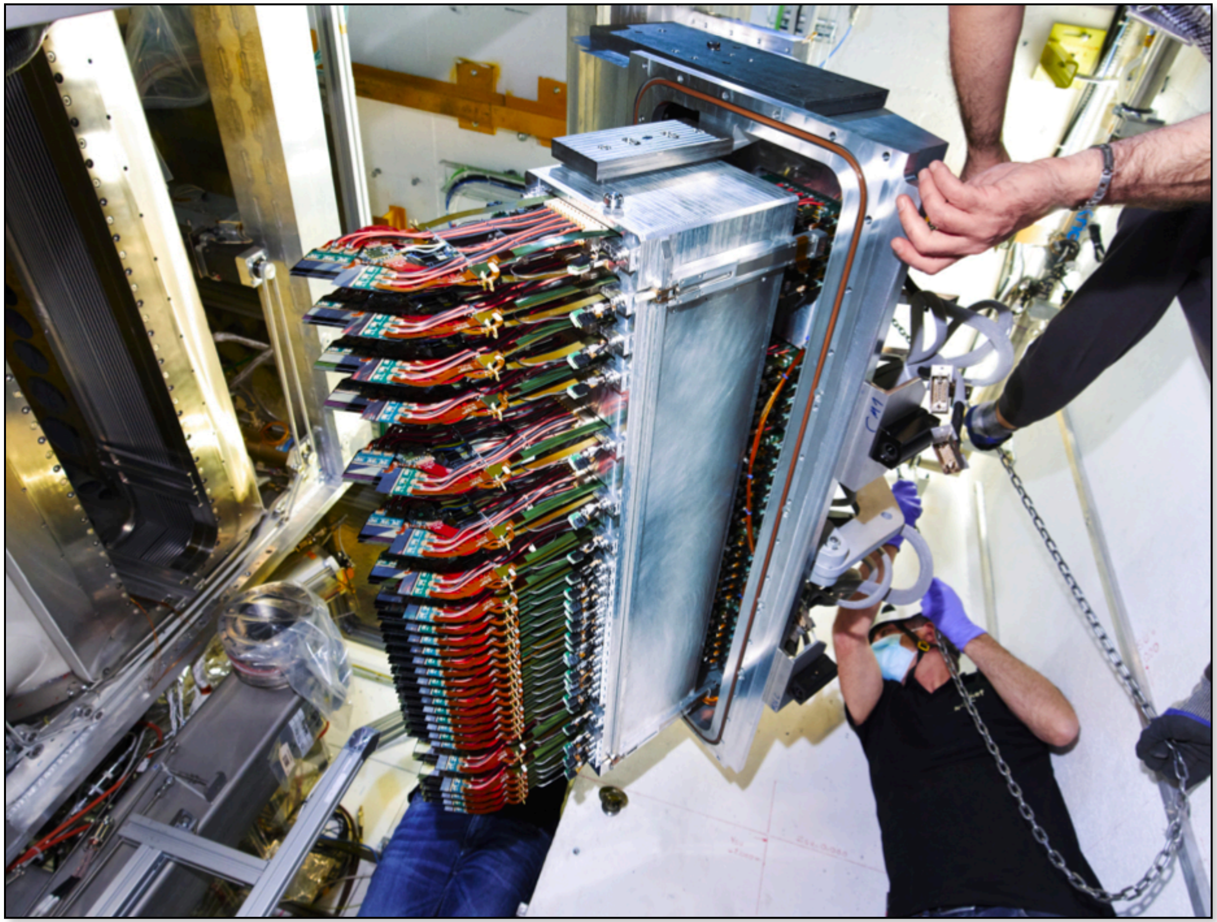
Future Plans

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035+
Run				Run III					Run IV						Run V
Shutdown	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			$L = 3 \times 10^{35}$				$7\ ab^{-1}$					$L = 6 \times 10^{35}$		$50\ ab^{-1}$	

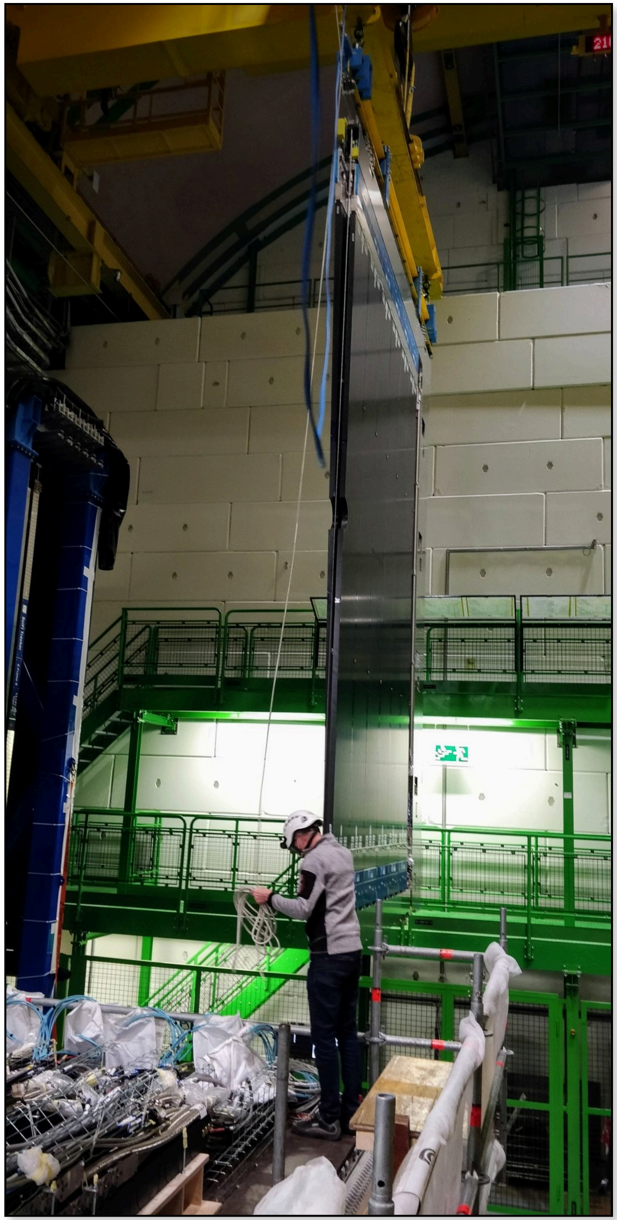
LHC schedule:
https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

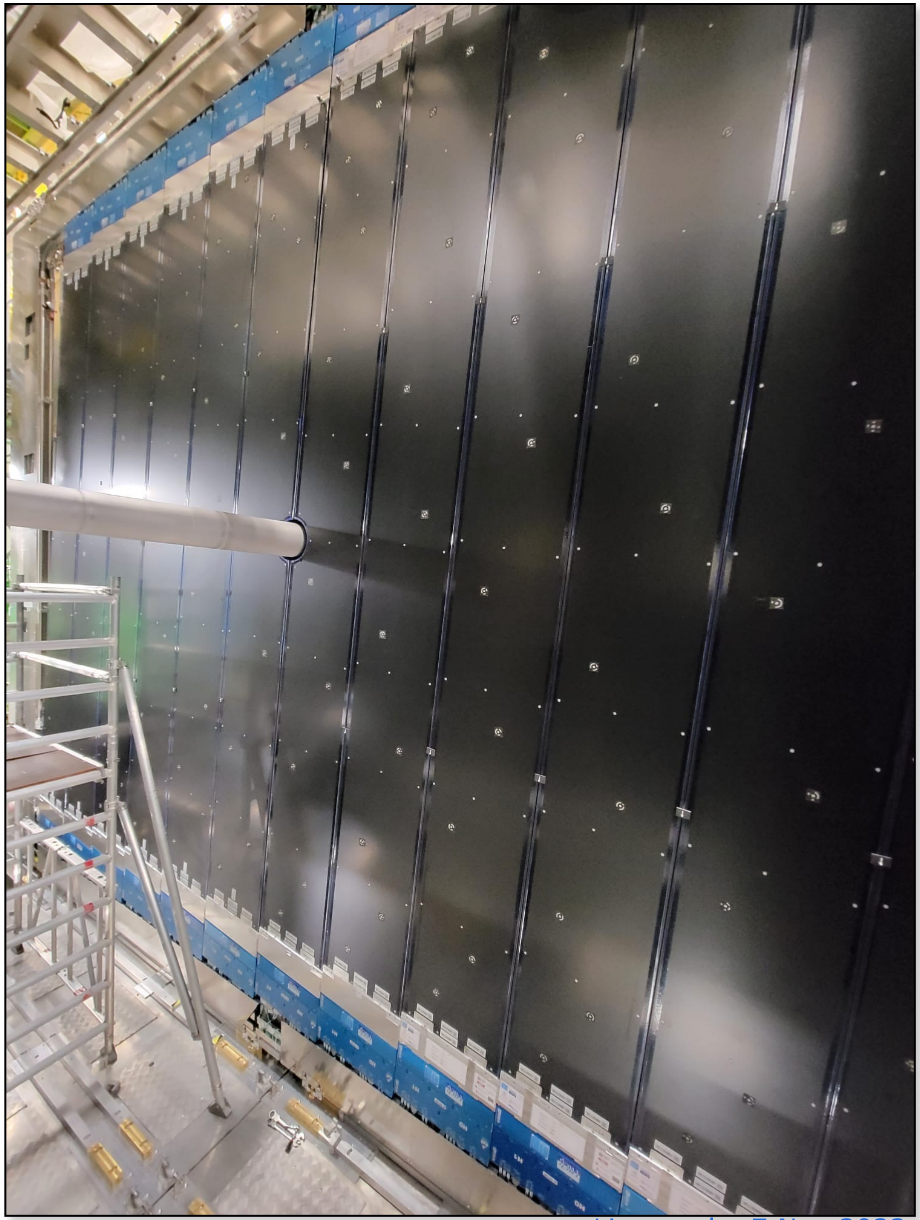
LHCb: VELO



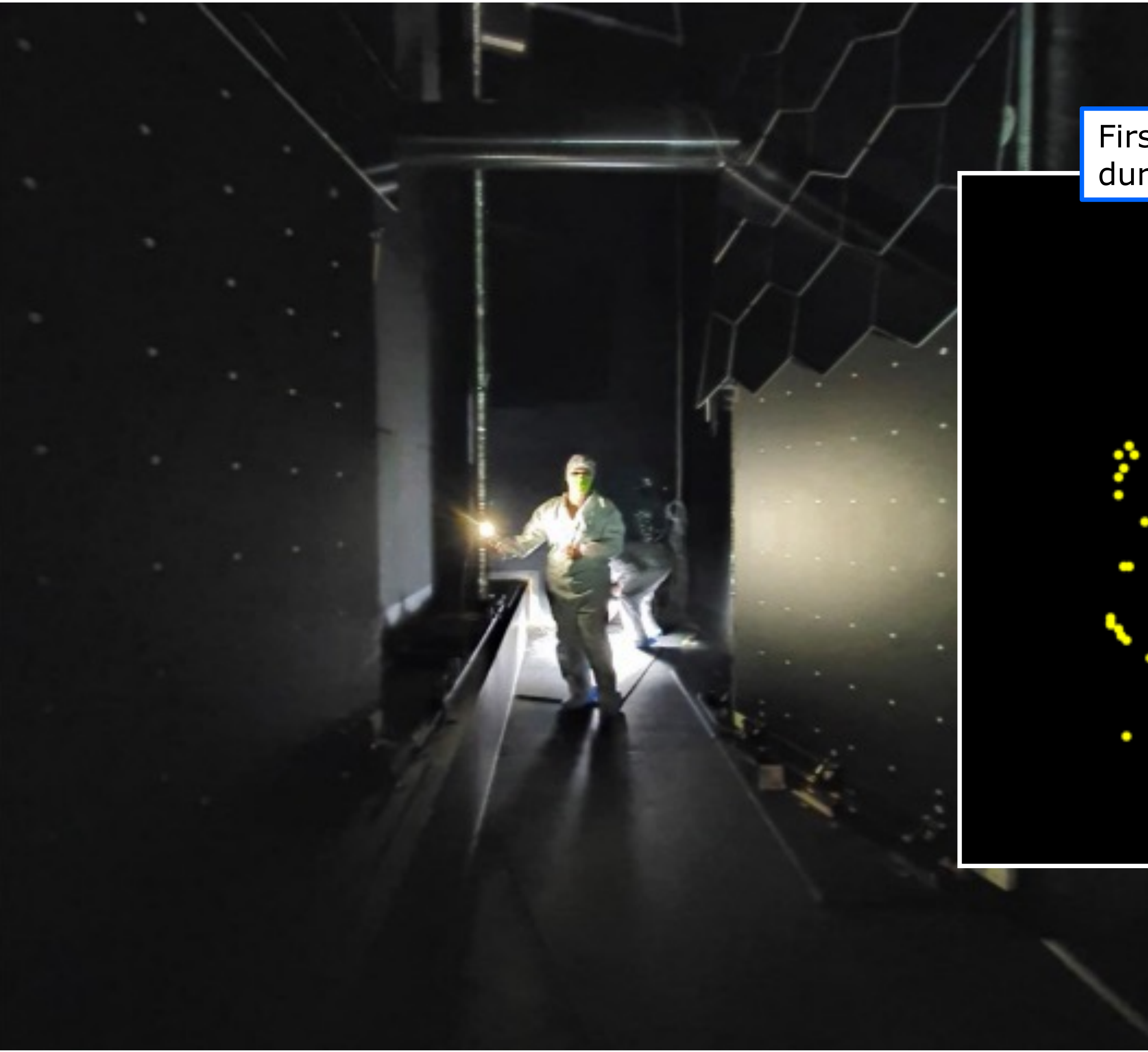


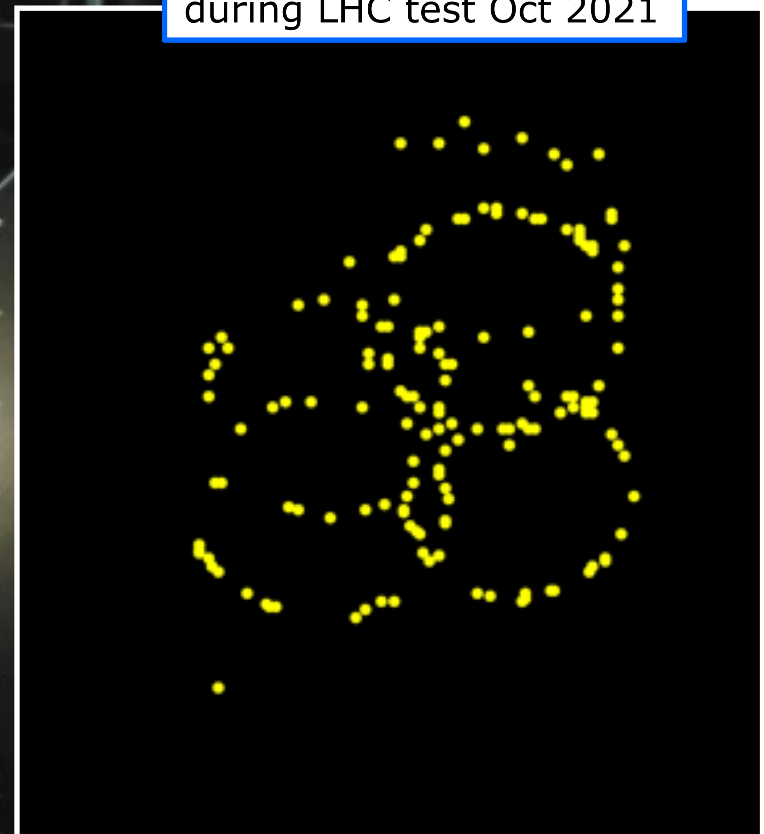
LHCb: Tracker





LHCb: Ring Imaging Cherenkov

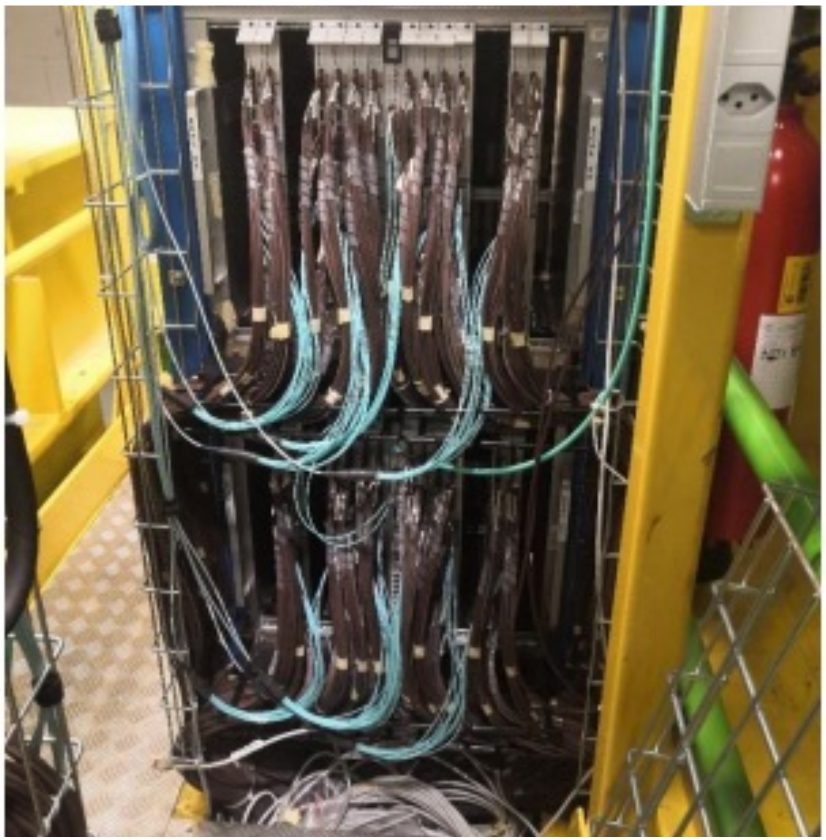




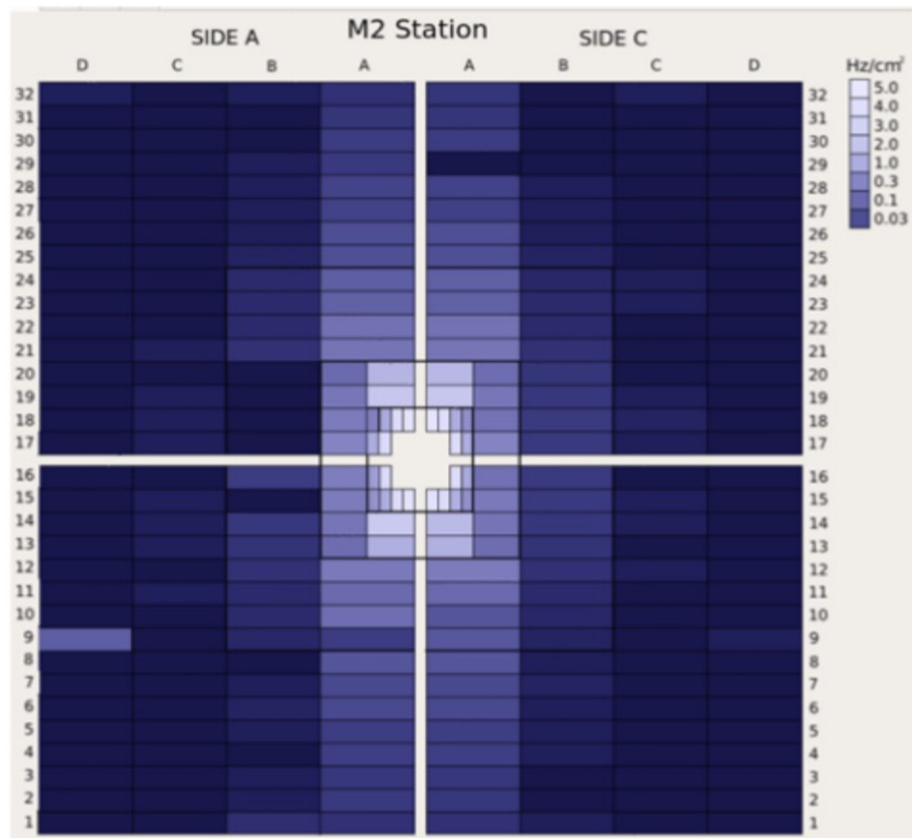
First rings in RICH2 during LHC test Oct 2021

LHCb: Calorimeter & Muon detector

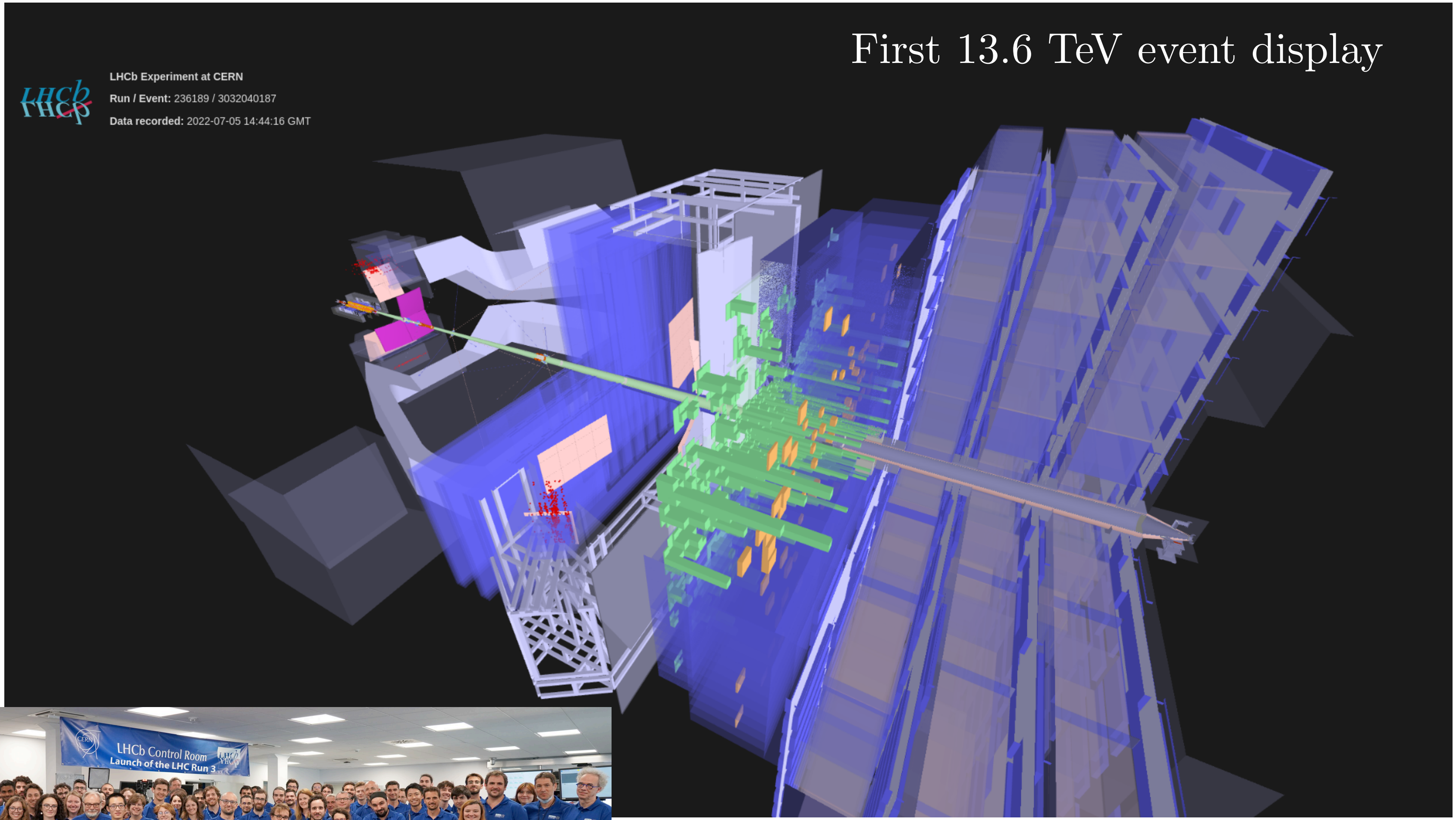
New CALO frontend and control boards



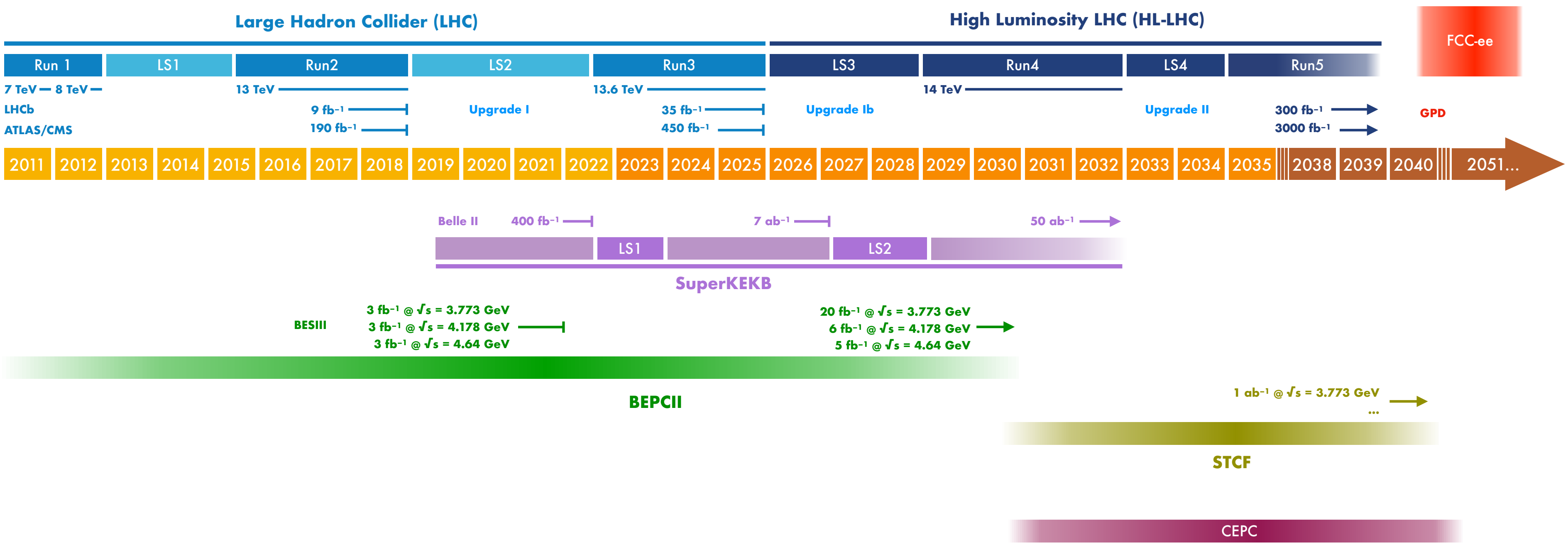
MUON Station 2 Hit map during machine test Oct 2021



First data at 13.6 TeV

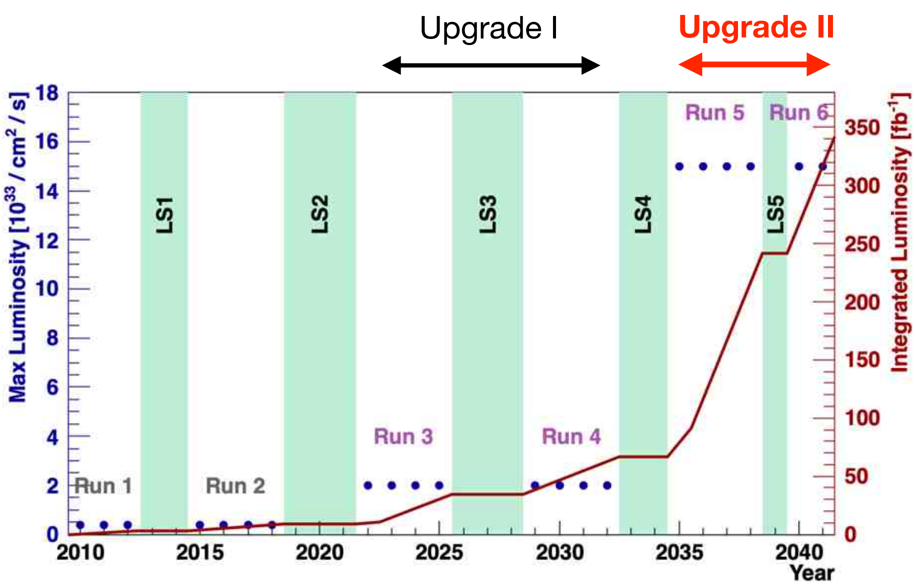


Future Plans



Archilli, Altmannshofer, arXiv:2206.11331

Future Plans



LHCb-TDR-023

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-LHCC-2021-012
LHCb TDR 23
24 February 2022

Framework TDR for the LHCb Upgrade II
Opportunities in flavour physics, and beyond, in the HL-LHC era

The LHCb collaboration

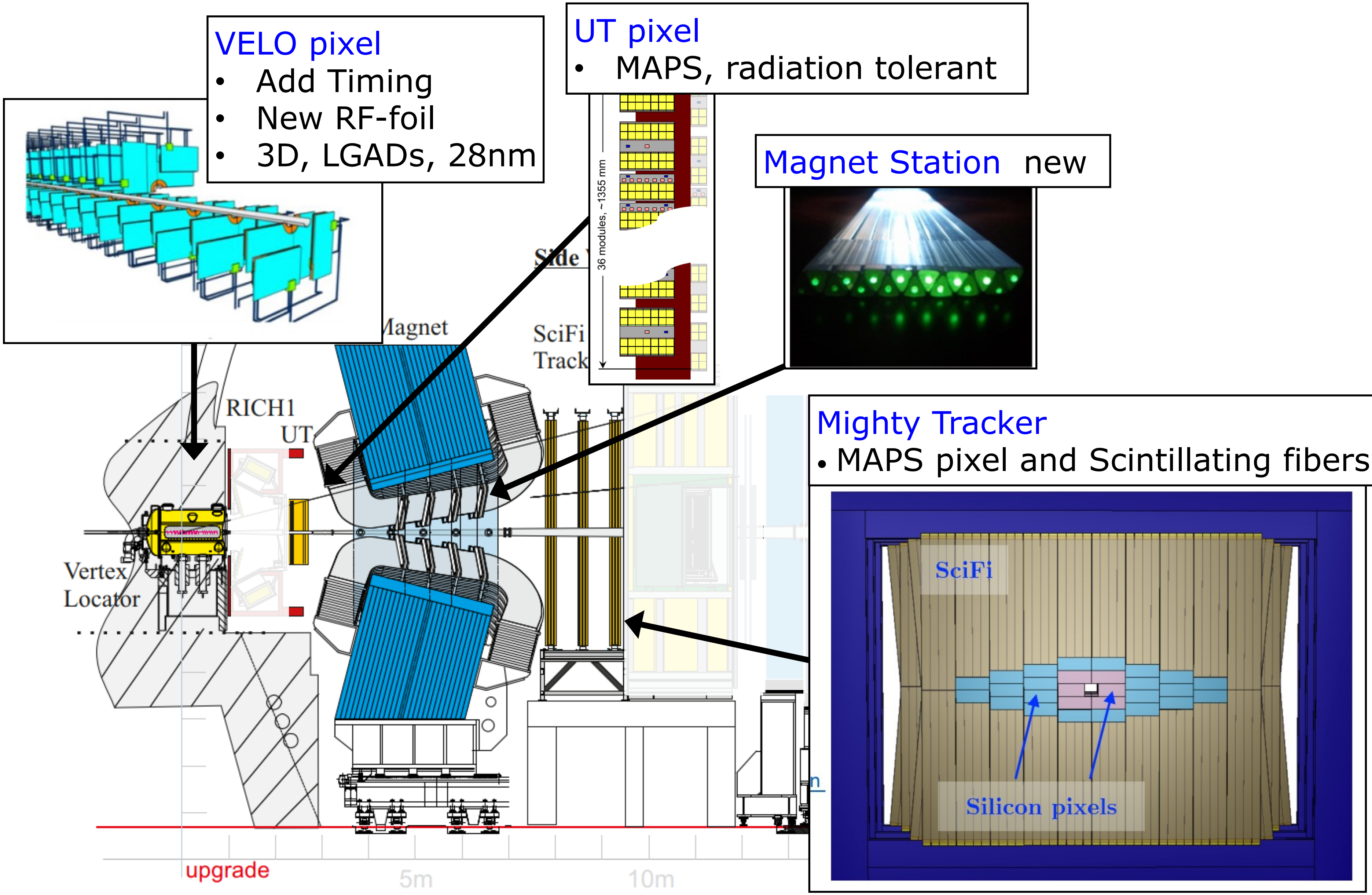
Abstract

This document is the Framework Technical Design Report for the Upgrade II of the LHCb experiment, which is proposed for the long shutdown 4 of the LHC. The upgraded detector will operate at a maximum luminosity of $1.5 \times 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$, with the aim of integrating $\sim 300\,\text{fb}^{-1}$ through the lifetime of the high-luminosity LHC (HL-LHC). The collected data will allow to fully exploit the flavour-physics opportunities of the HL-LHC, probing a wide range of physics observables with unprecedented accuracy. In particular, the new physics mass scale probed, for fixed couplings, will almost double as compared with the pre-HL-LHC era.

The accomplishment of this ambitious programme will require that the current detector performance is maintained at the maximum expected pile-up of ~40, and even improved in certain specific domains. To meet this challenge, it is foreseen to replace all of the existing spectrometer components to increase the granularity, reduce the amount of material in the detector and to exploit the use of new technologies including precision timing of the order of a few tens of picoseconds. The design options for each sub-detector are discussed, and the ongoing efforts to face the associated technology challenges. For the first time, elements of the environmental impact of the project are considered. Finally, details are given about the project schedule, the cost envelope and the participating institutes.

Approved by LHCC, 2022

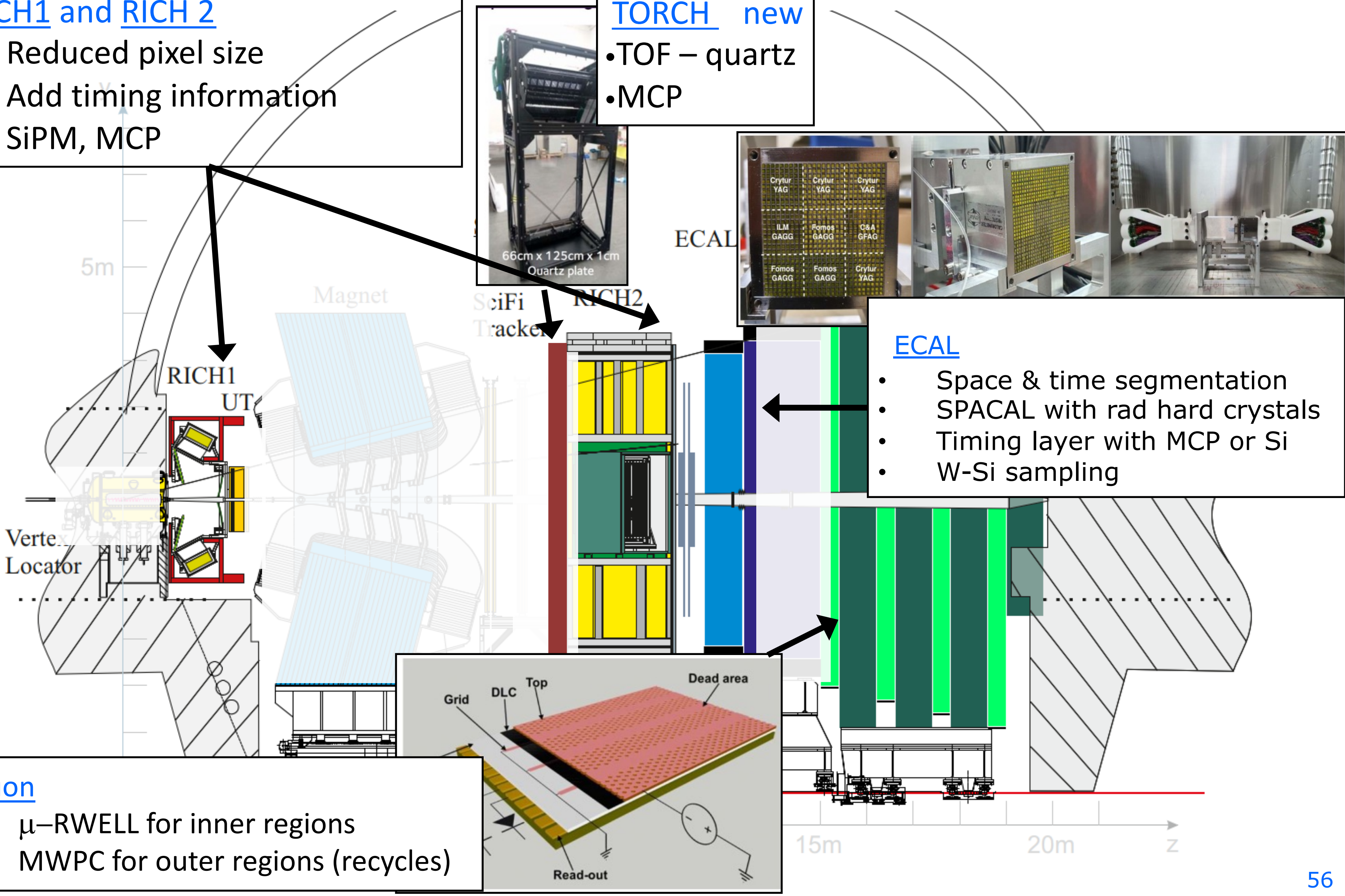
Planning for Upgrade II: Tracking



Planning for Upgrade II: PID detectors

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

TORCH new
- •TOF – quartz
- •MCP



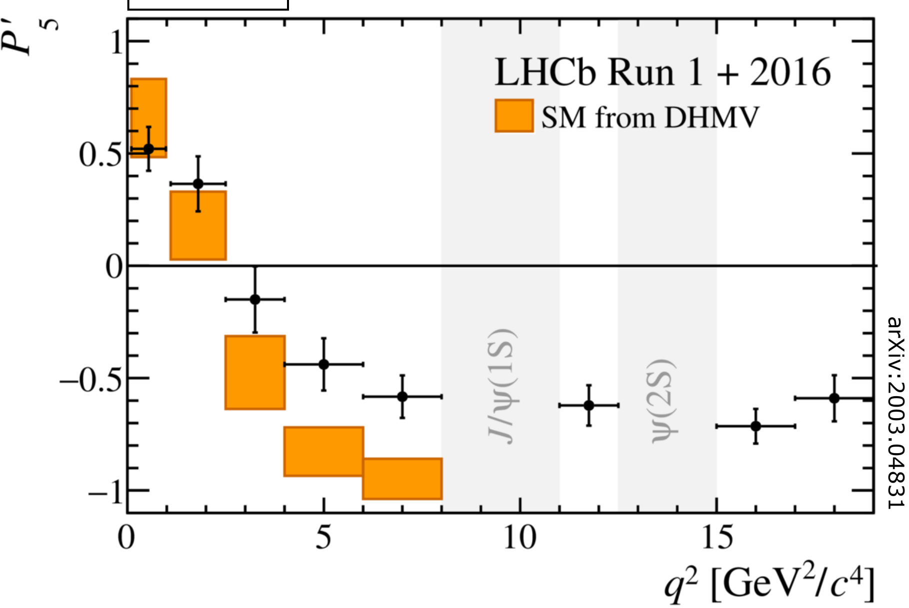
ECAL
- Space & time segmentation
- SPACAL with rad hard crystals
- Timing layer with MCP or Si
- W-Si sampling

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

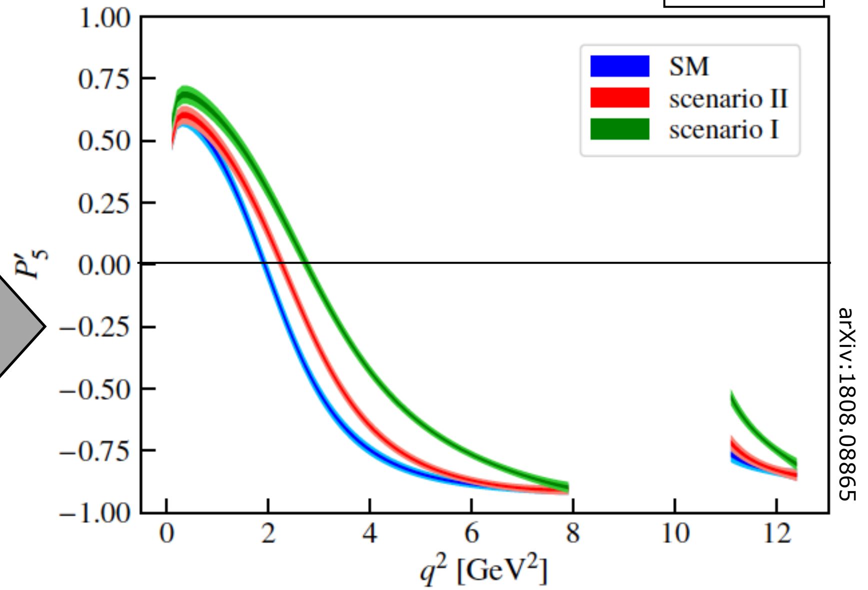
Summary

- Precision measurements to scrutinize the Standard Model
- Precision measurements reach very high mass scales
- Precision measurements are statistically limited
- Lots of opportunities to contribute to R&D

2020

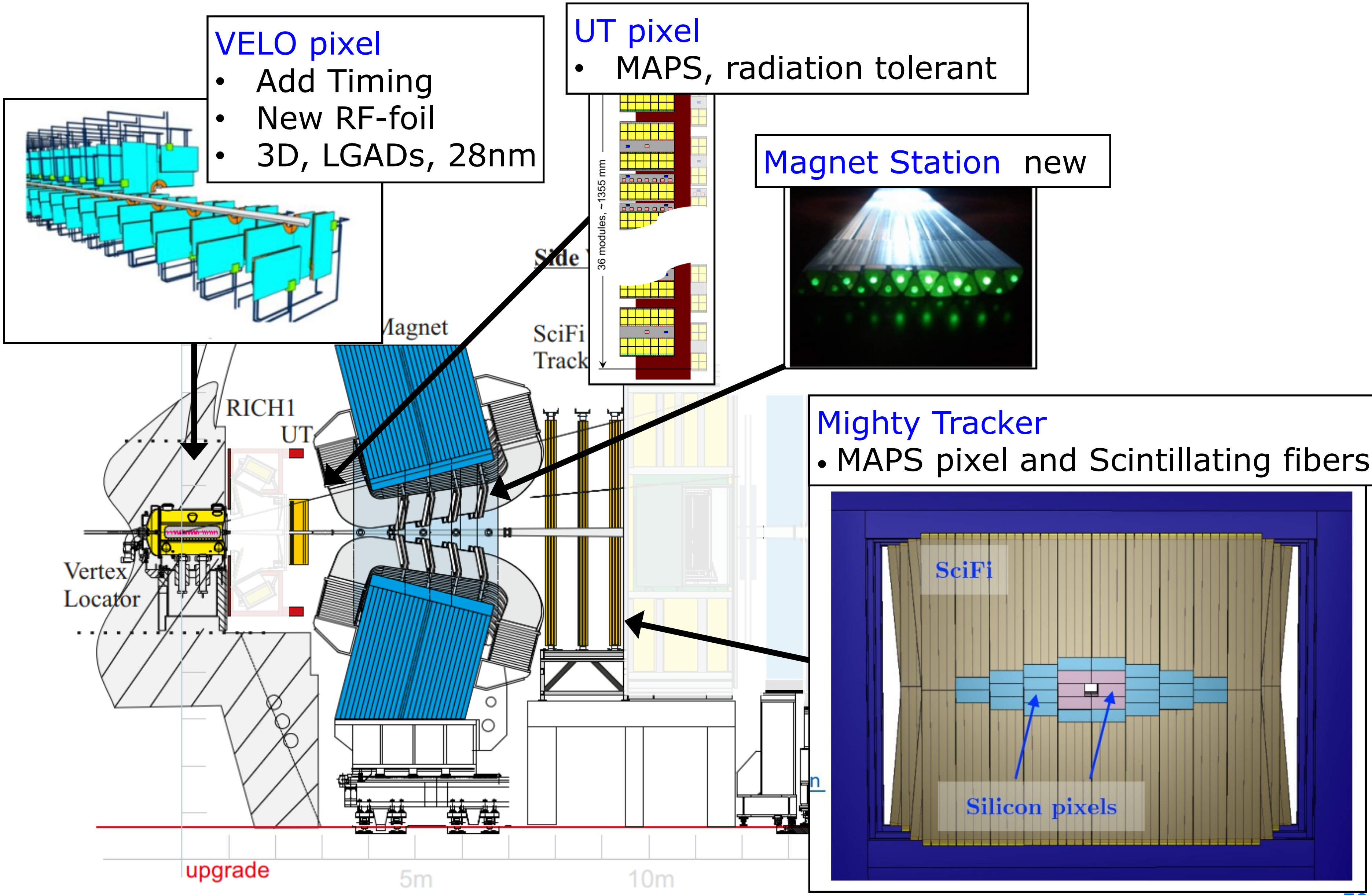


2040



Backups

Planning for Upgrade II: Tracking



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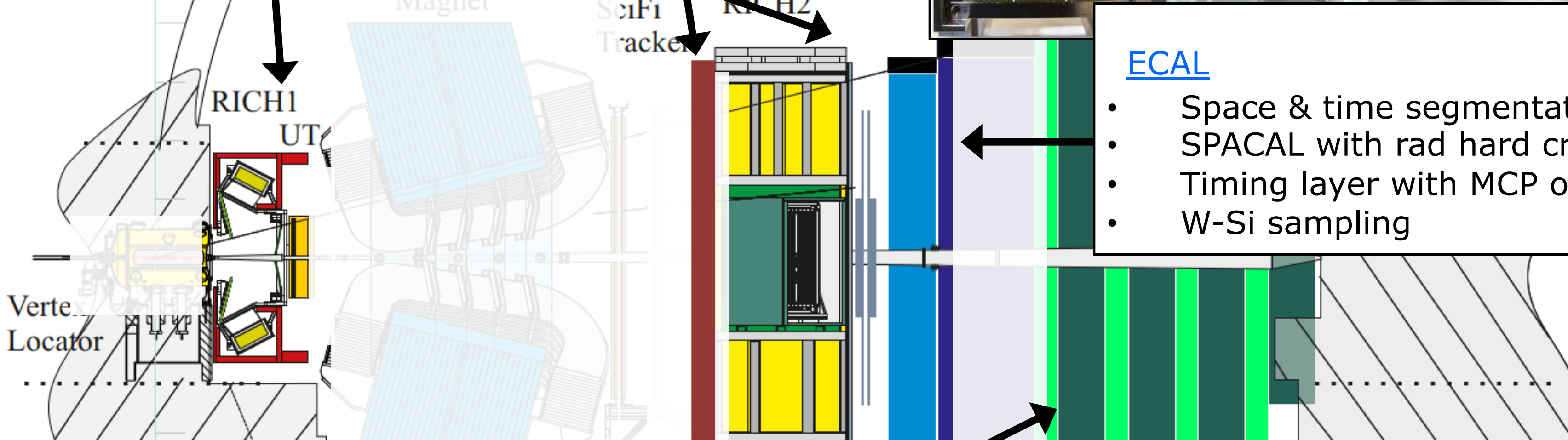

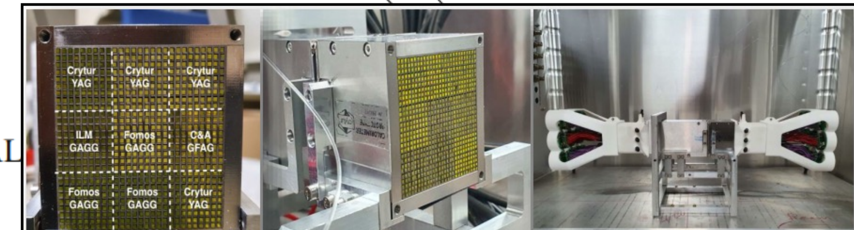

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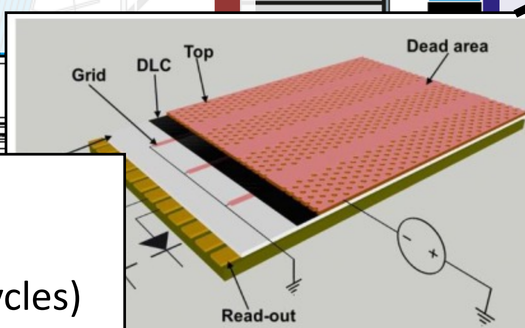
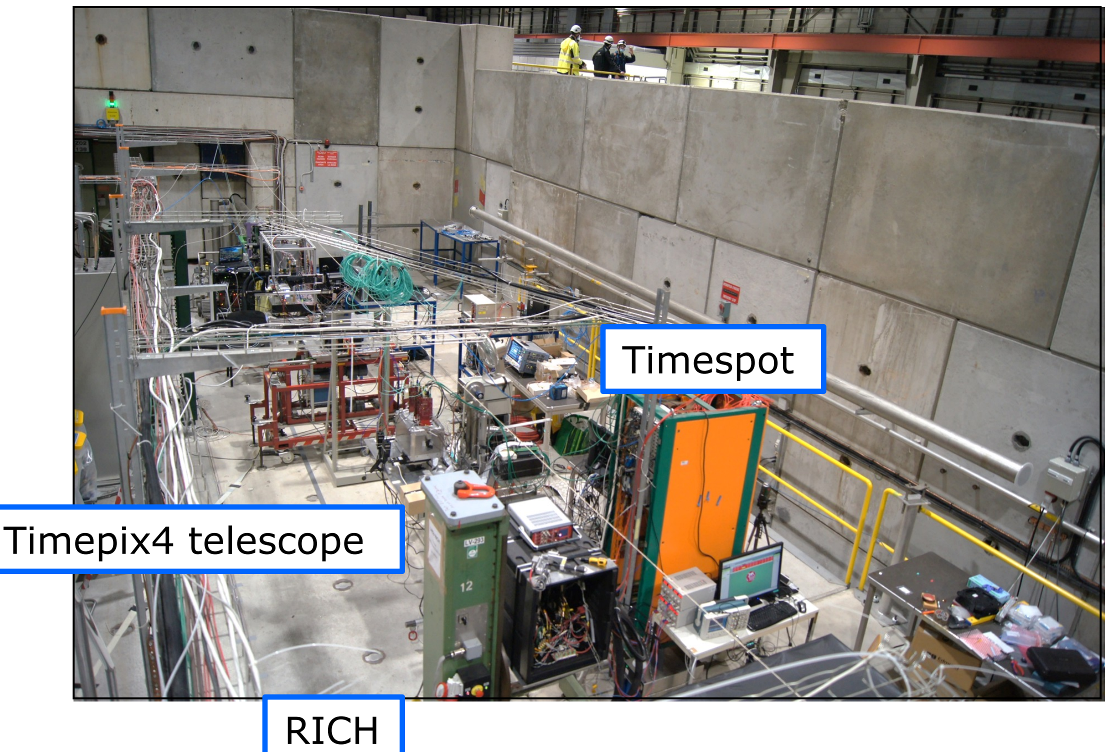
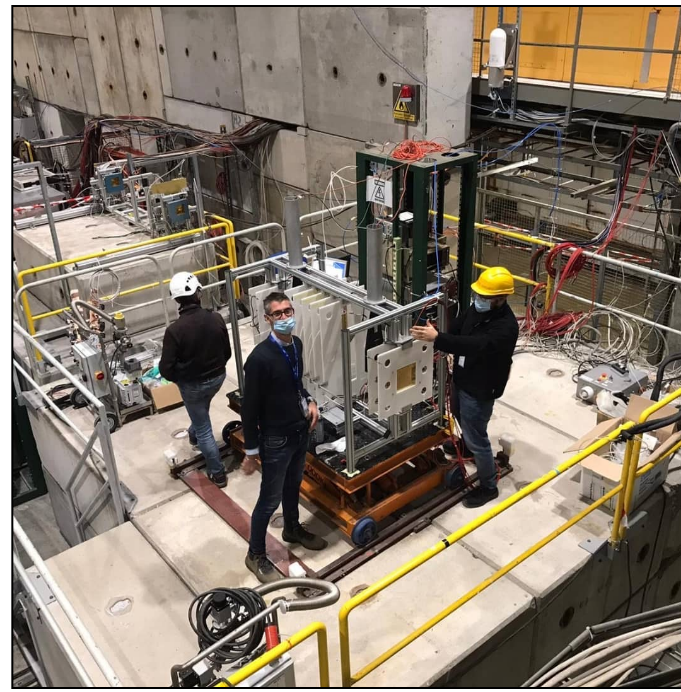


Planning for Upgrade II: Testbeam

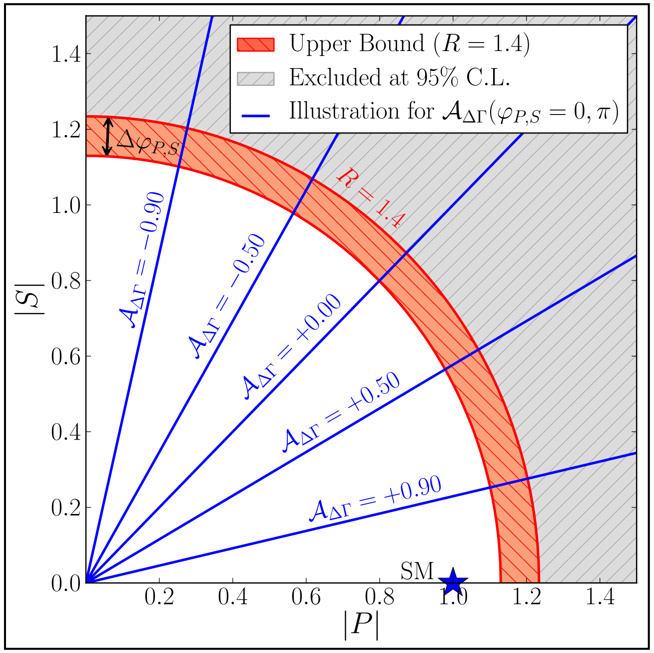
- Activities for RICH, VELO, ECAL, MUON
- Lots of opportunities for R&D in coming decade!



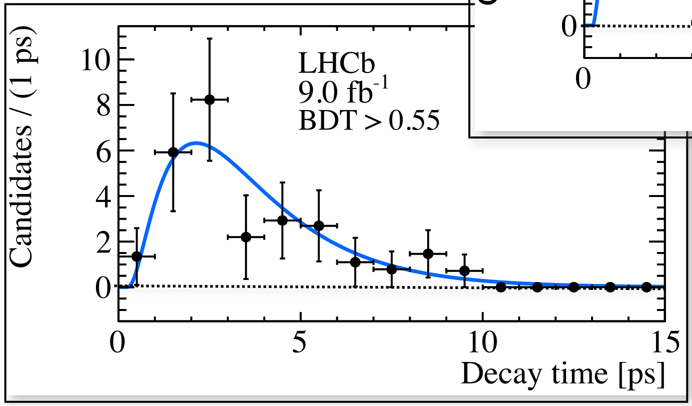


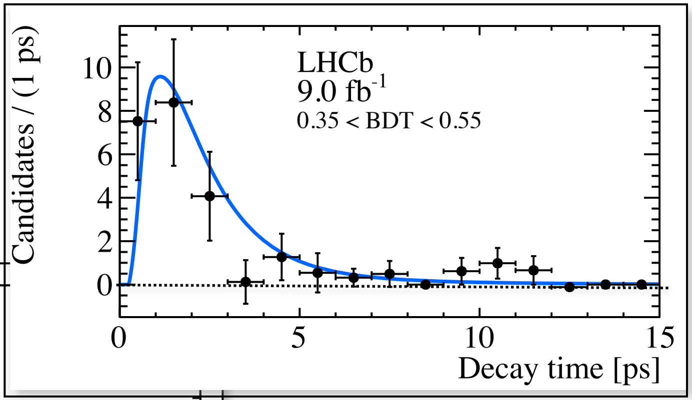
$B_s^0 \to \mu^+\mu^-$ (LHCb)

- More observables accessible
- New Physics can lead to different CP structure of final state
  - Affects the mix of long and short-living B_s^0 mesons



De Bruyn, Fleischer, NT, et al., PRL109 (2012) 041801





LHCb Coll. arXiv:2108.09284

$$\tau(B_s^0 \to \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03\,\mathrm{ps}$$

Historical record of indirect discoveries

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

Weak Interactions with Lepton-Hadron Symmetry*

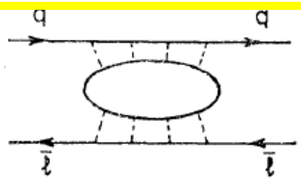
S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

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

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

27 July 1964

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

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

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

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

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

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

(Received September 1, 1972)

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

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

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

DESY 87-029
April 1987

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

The ARGUS Collaboration

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

Parameters	Comments
$r > 0.09$ 90%CL	This experiment
$x > 0.44$	This experiment
$B^{\frac{1}{2}} f_B \approx f_\pi < 160$ MeV	B meson (≈ pion) decay constant
$m_b < 5\text{GeV}/c^2$	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]
$m_t > 50\text{GeV}/c^2$	t quark mass

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

"Discovery" of charm

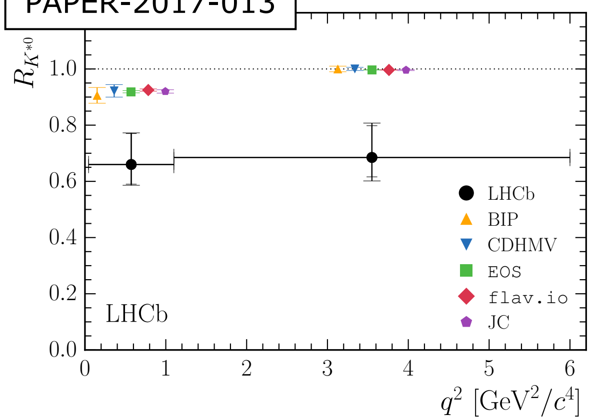
"Discovery" of beauty

"Discovery" of top

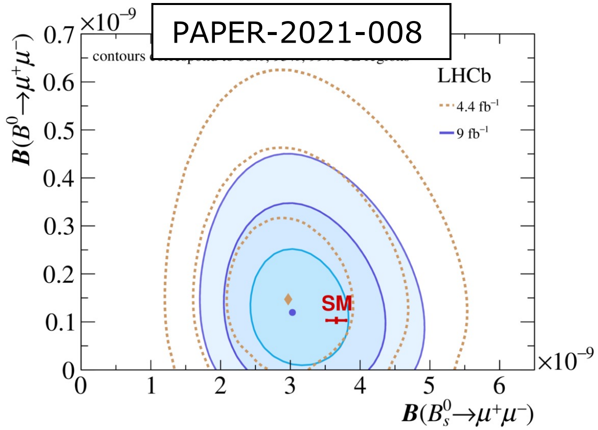
Anomalies

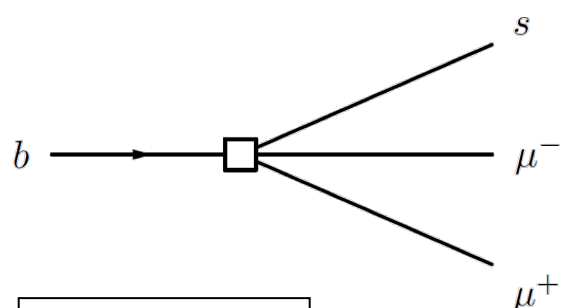
- What is the overall picture? Combination statistically not simple

PAPER-2017-013

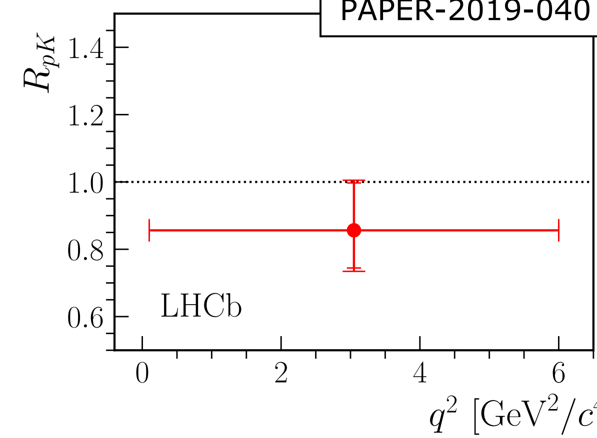


PAPER-2021-008

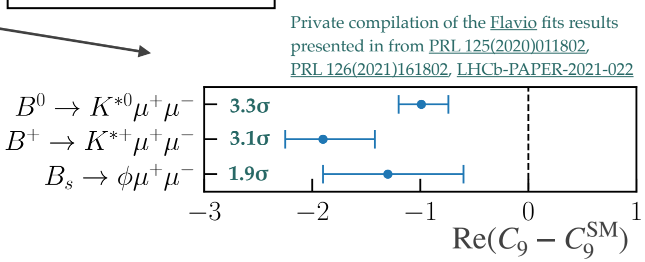




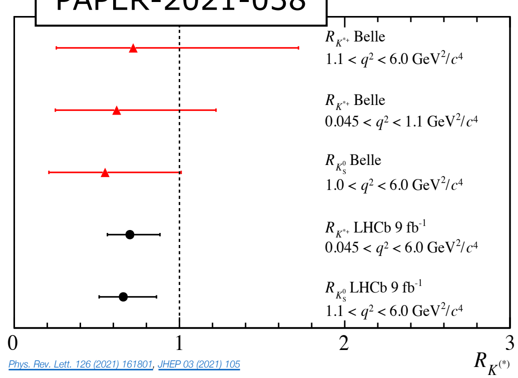
PAPER-2019-040



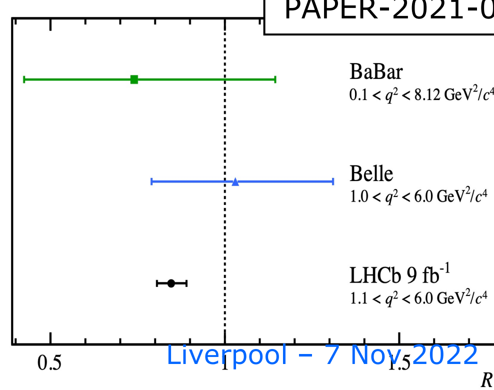
+ Angular Fits?



PAPER-2021-038



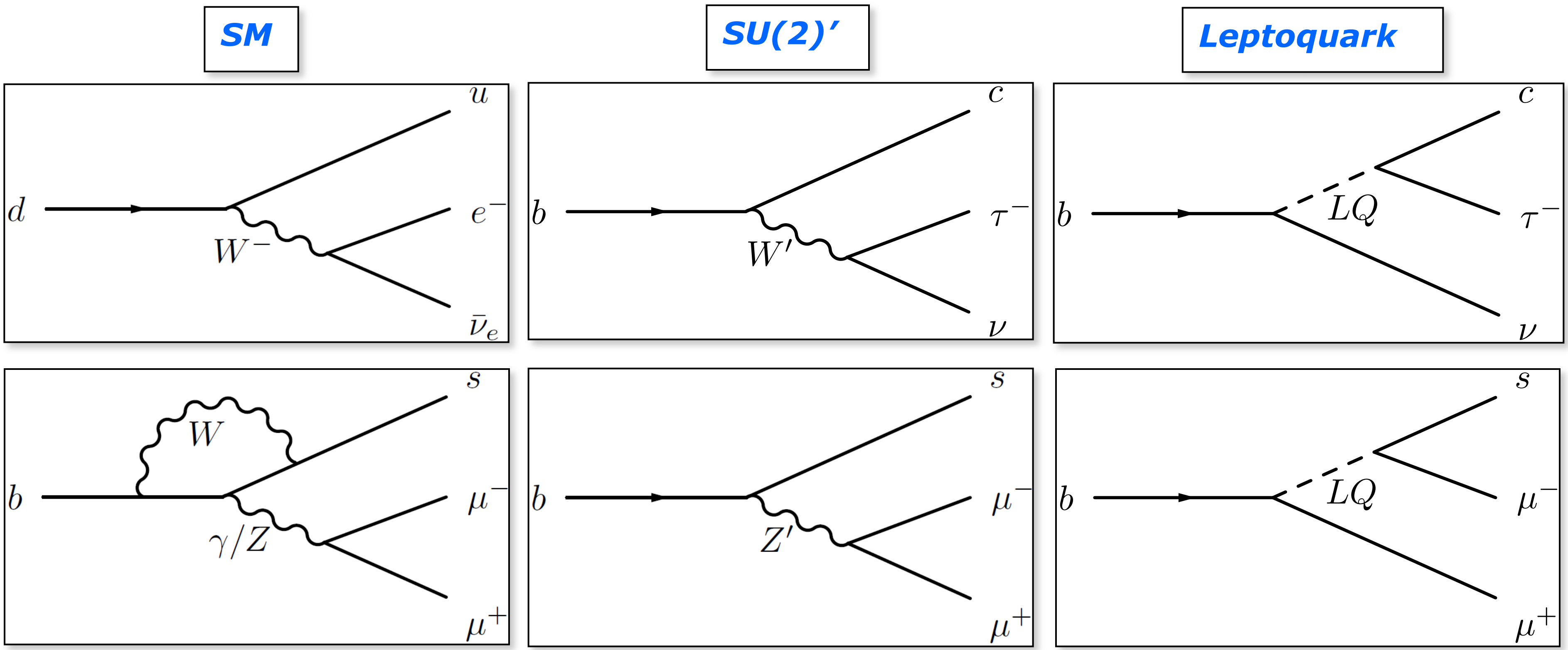
PAPER-2021-004



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

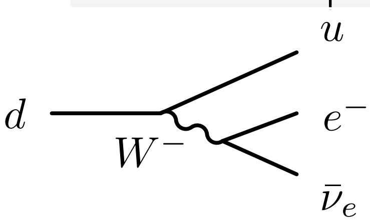
Model building

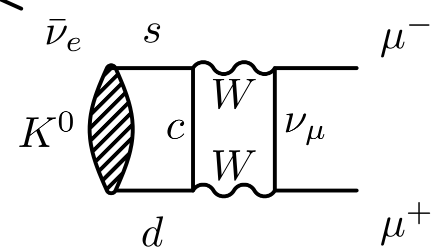
- Most popular models: Z′ or Leptoquark

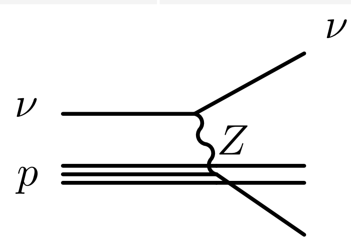


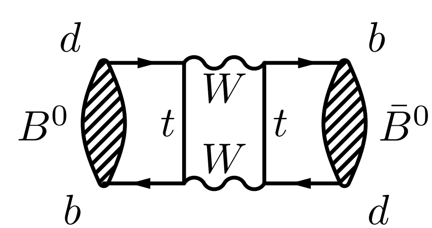
Historical record of indirect discoveries

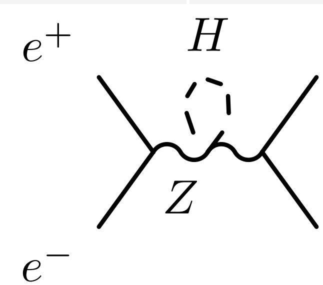
Particle	Indirect			Direct		
ν	β decay	Fermi	1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay	Fermi	1932	$W \rightarrow e\nu$	UA1, UA2	1983
c	$K^0 \rightarrow \mu\mu$	GIM	1970	J/ψ	Richter, Ting	1974
b	CPV $K^0 \rightarrow \pi\pi$	CKM, 3rd gen	1964/72	Υ	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z \rightarrow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





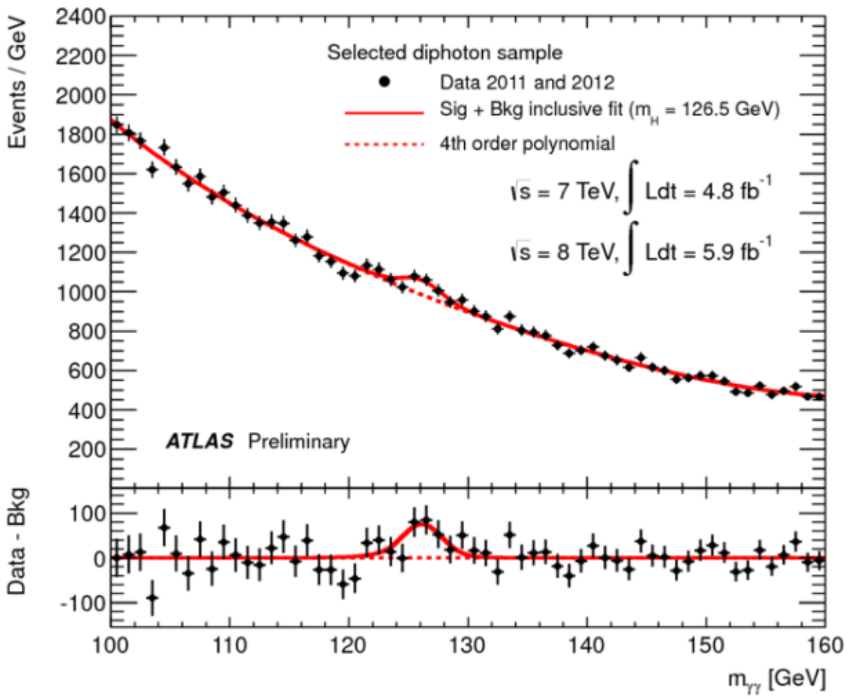


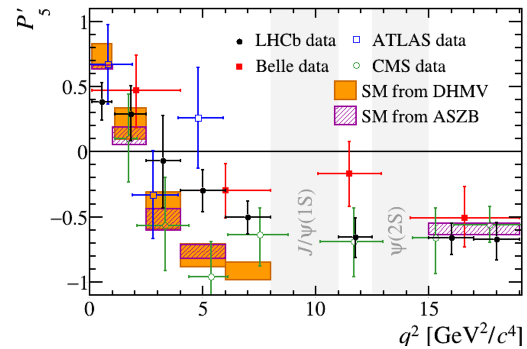


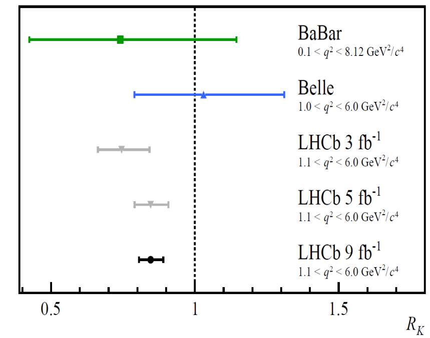


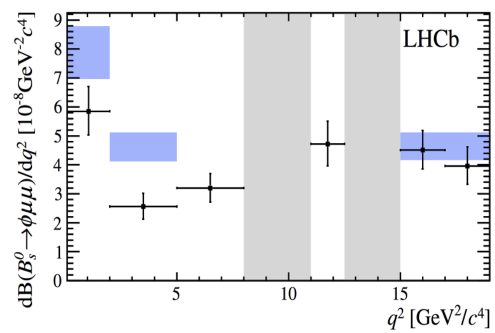
Quantifying significance

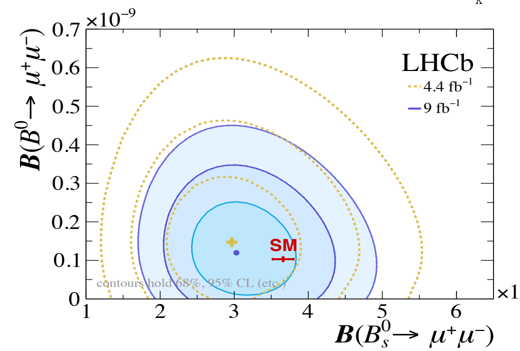
Higgs vs $b \to s l^+ l^-$











χ^2 of null hypothesis?

Good | Good

$\Delta\chi^2$ vs discovery hypothesis *(coherent pattern)* ?

Favour Gauss | Favour $(C_9,C_{10})^{NP}$

Look-elsewhere effect *(arXiv:2104.05631)* ?

Mass range | Wilson space