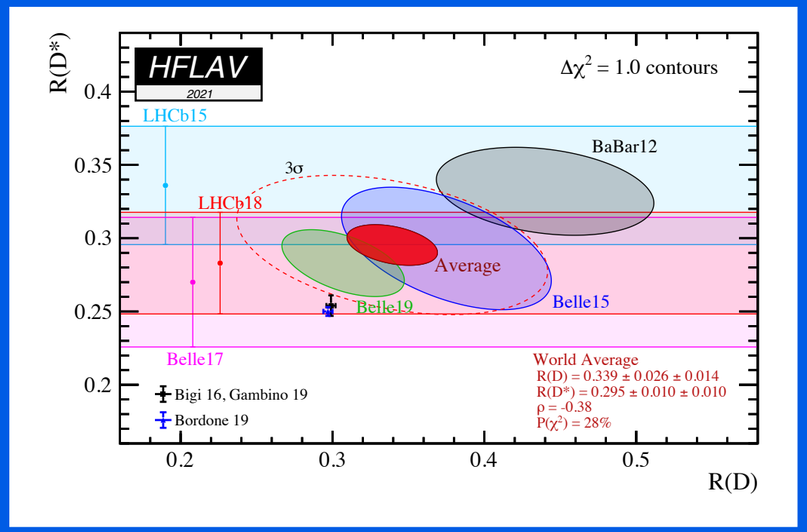
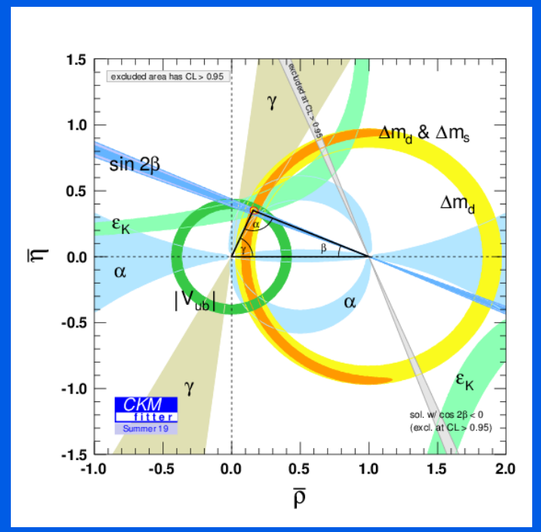
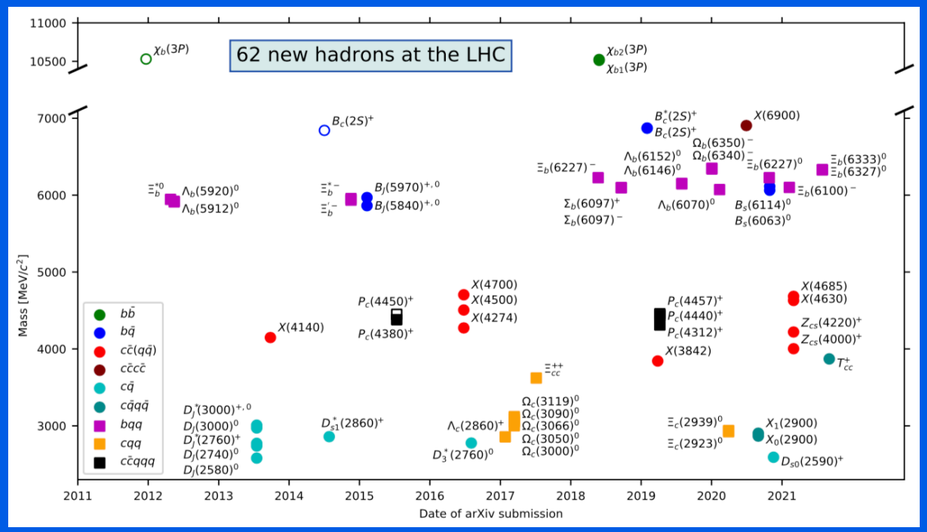
Review of flavour physics experimental results





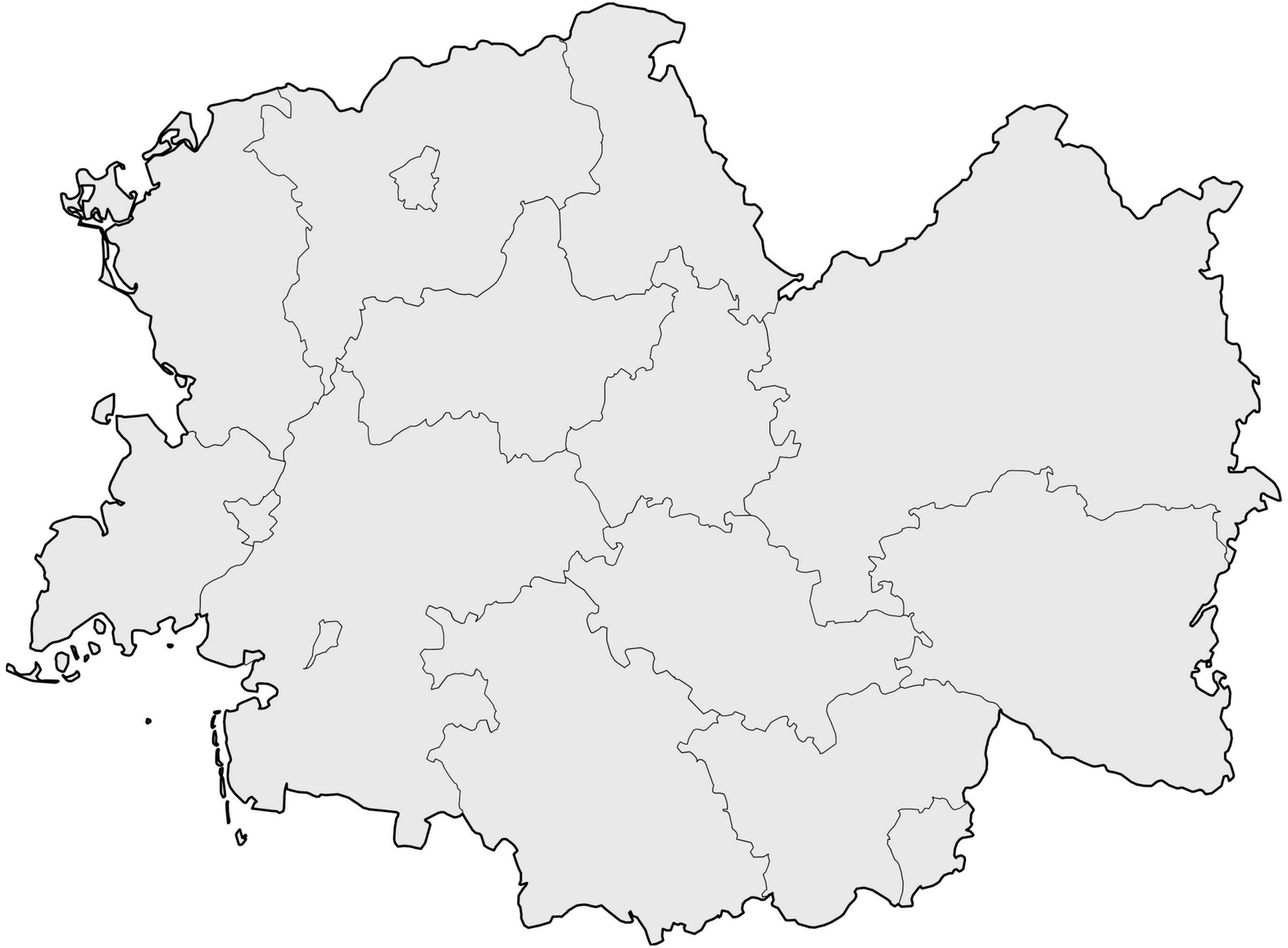


Vladimir V. Gligorov, CNRS/LPNHE

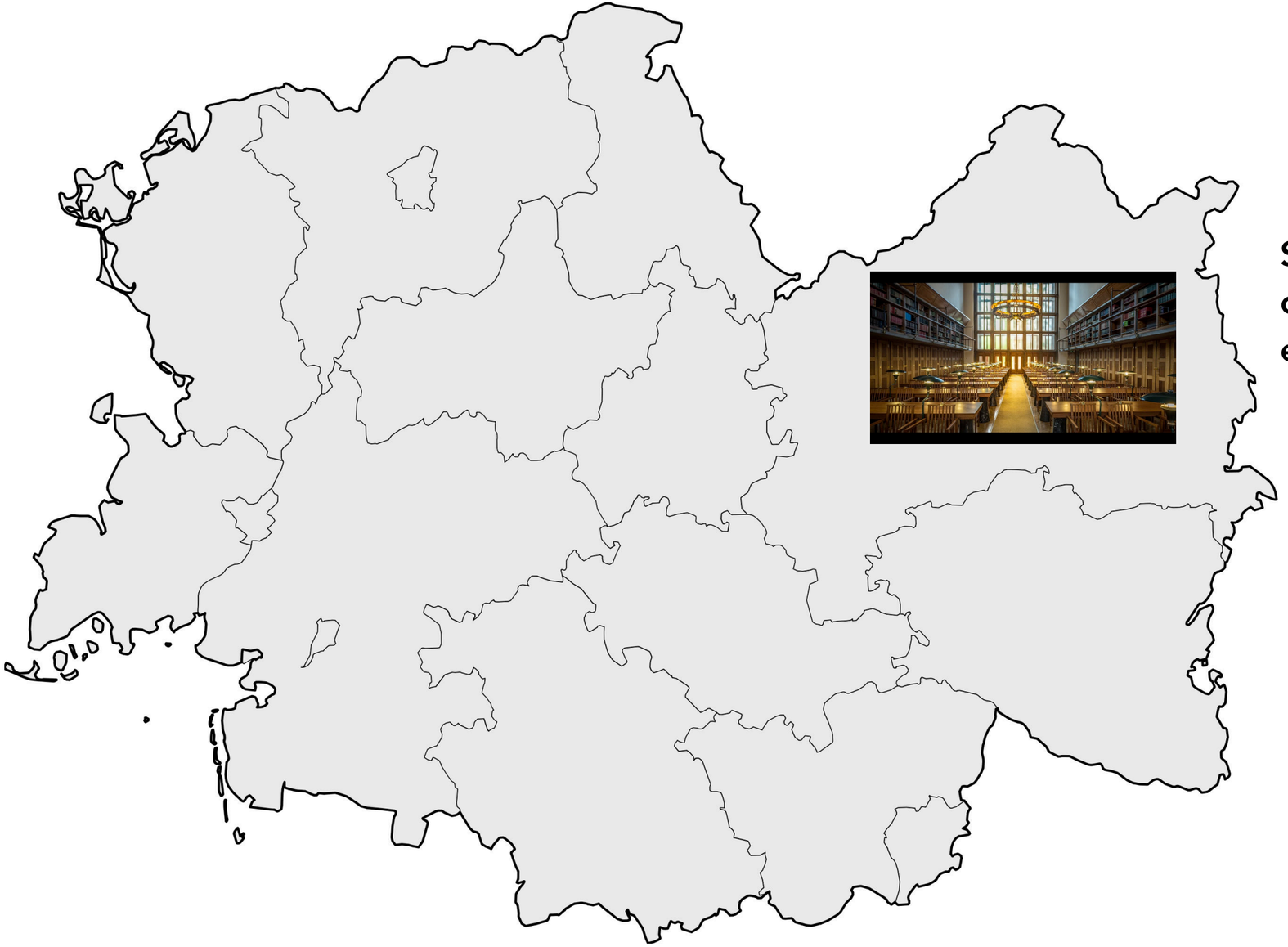
In a personal capacity with material from the LHCb, CMS, ATLAS, BES III, NA62, BaBar, Belle/Belle II experimental collaborations as well as the HFLAV, CKMFitter, and UTFit averaging groups

Portorož 2021, Slovenija, 22.09.2021

2020s flavour physics, a federative entity



2020s flavour physics, a federative entity



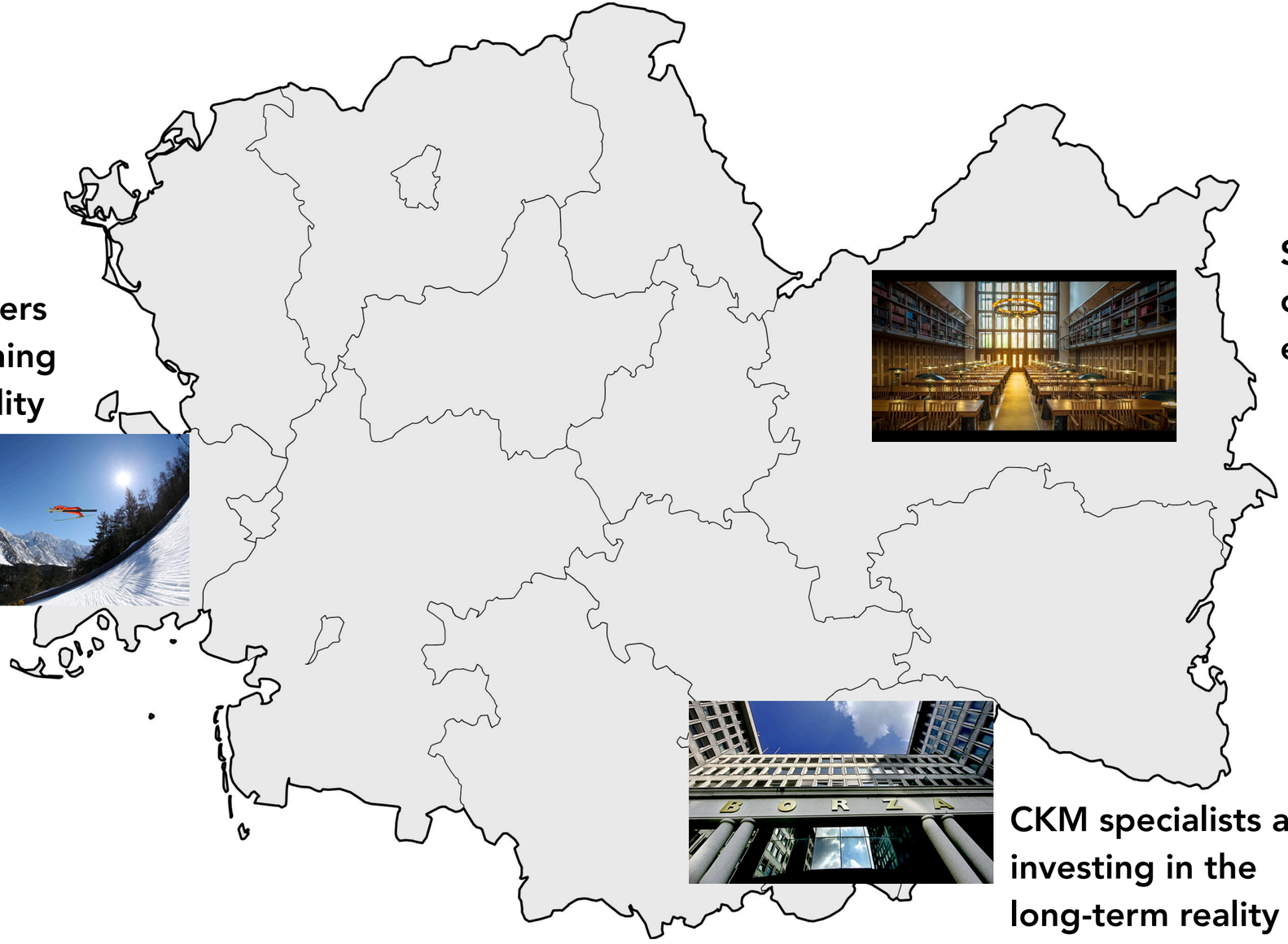
Spectroscopists like cataloguing actually existing reality

2020s flavour physics, a federative entity

Anomaly believers dream of returning to a former reality

Spectroscopists like cataloguing actually existing reality

2020s flavour physics, a federative entity

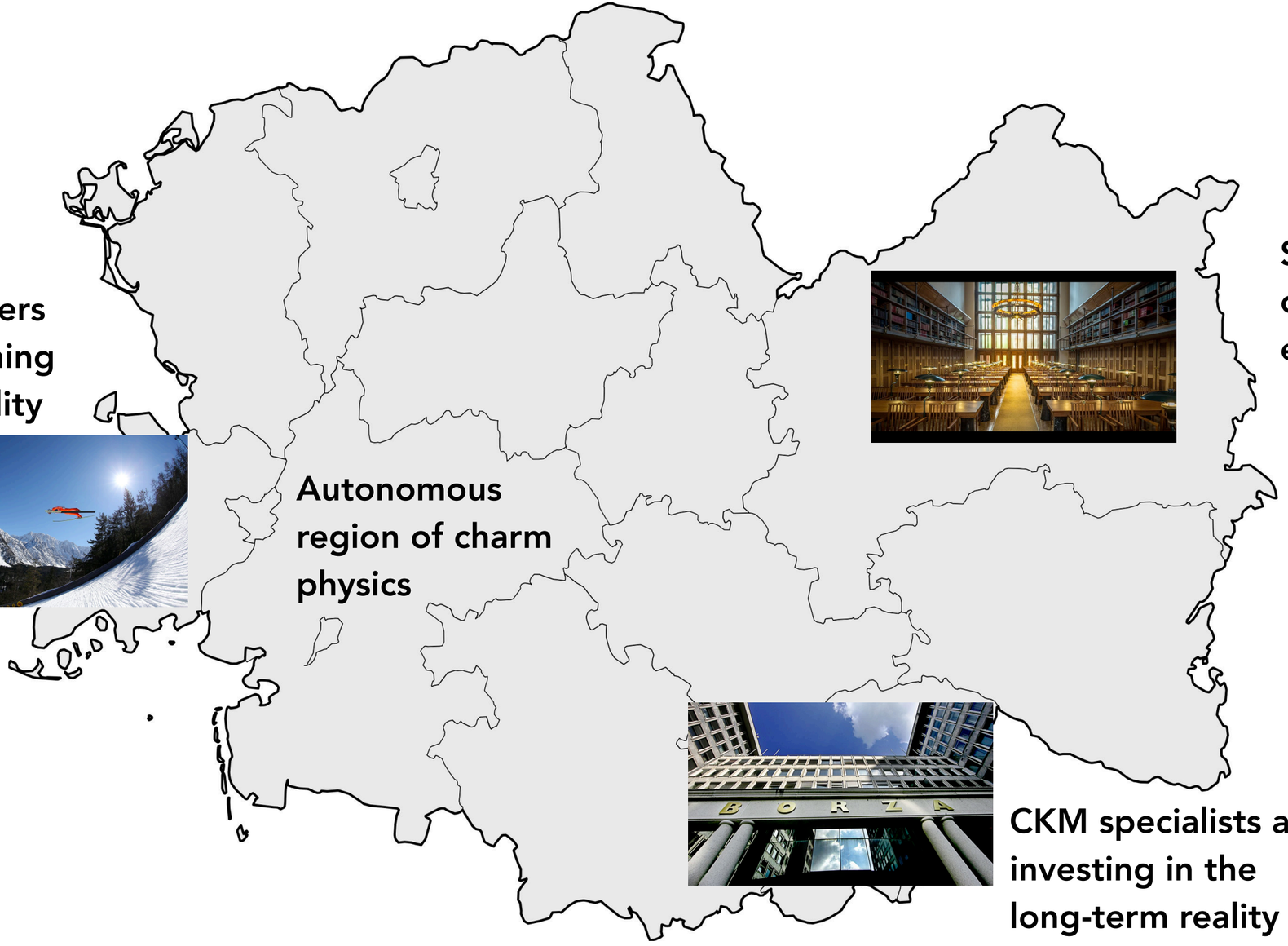


Anomaly believers dream of returning to a former reality

Spectroscopists like cataloguing actually existing reality

CKM specialists are investing in the long-term reality

2020s flavour physics, a federative entity



Anomaly believers dream of returning to a former reality

Autonomous region of charm physics

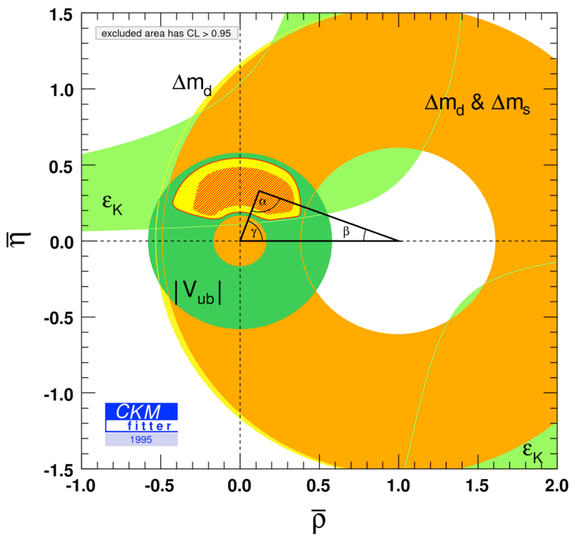
Spectroscopists like cataloguing actually existing reality

CKM specialists are investing in the long-term reality

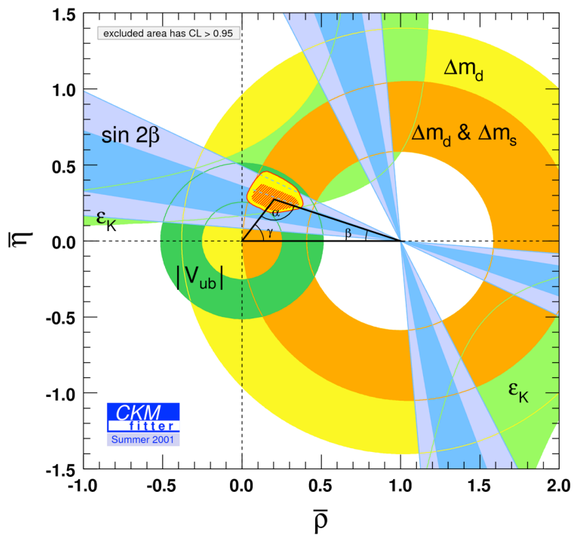
Hunt for the apex

Three decades of immense progress...

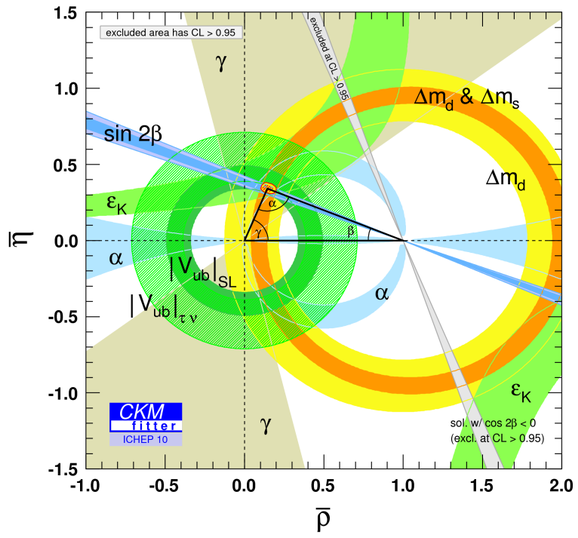
1995



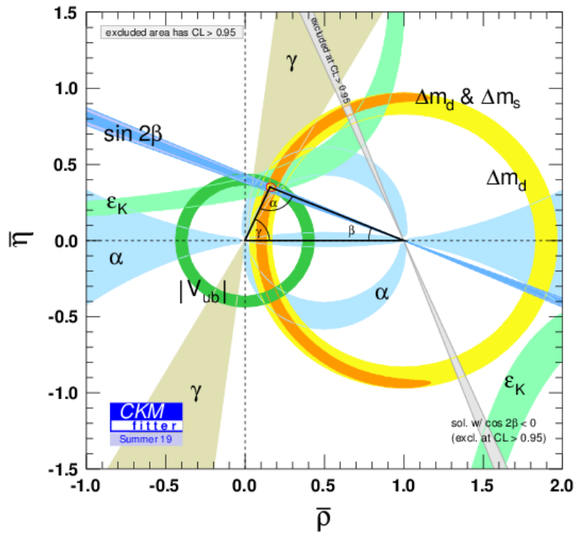
2001



2010

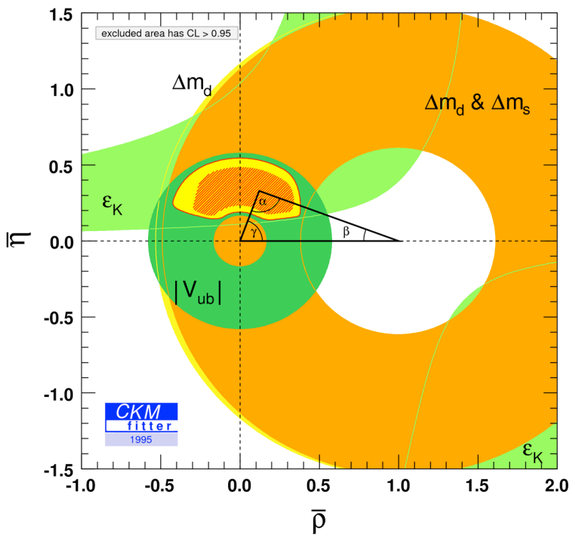


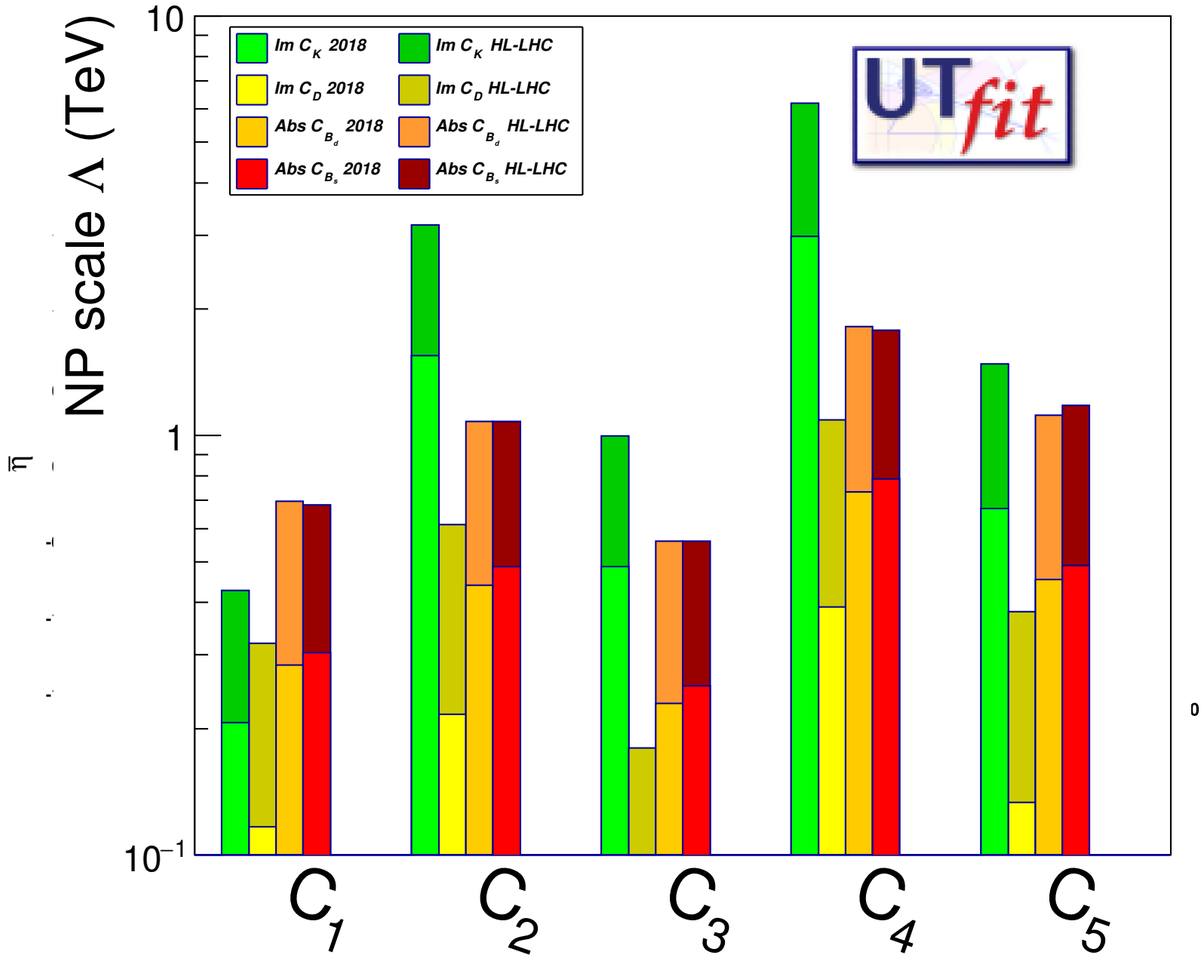
2019



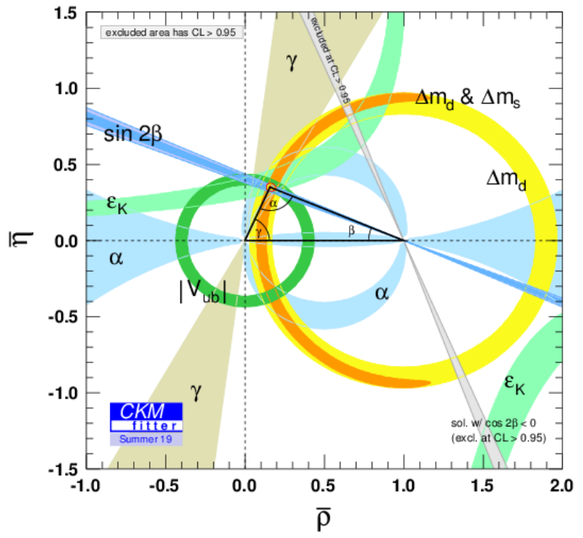
...and motivation for at least two more

1995





2019



The apex of the CKM triangle remains one of the safest long-term bets for constraining generic NP models

The road to a permille knowledge of γ

The road to a permille knowledge of γ

The charged B decays with 2/4-body D decays give the tightest overall constraints, but with ambiguities

The road to a permille knowledge of γ

Charged B decays with $D \to K_S hh$ and $B_s \to D_s K(hh)$ can resolve the ambiguities (up to a twofold one)

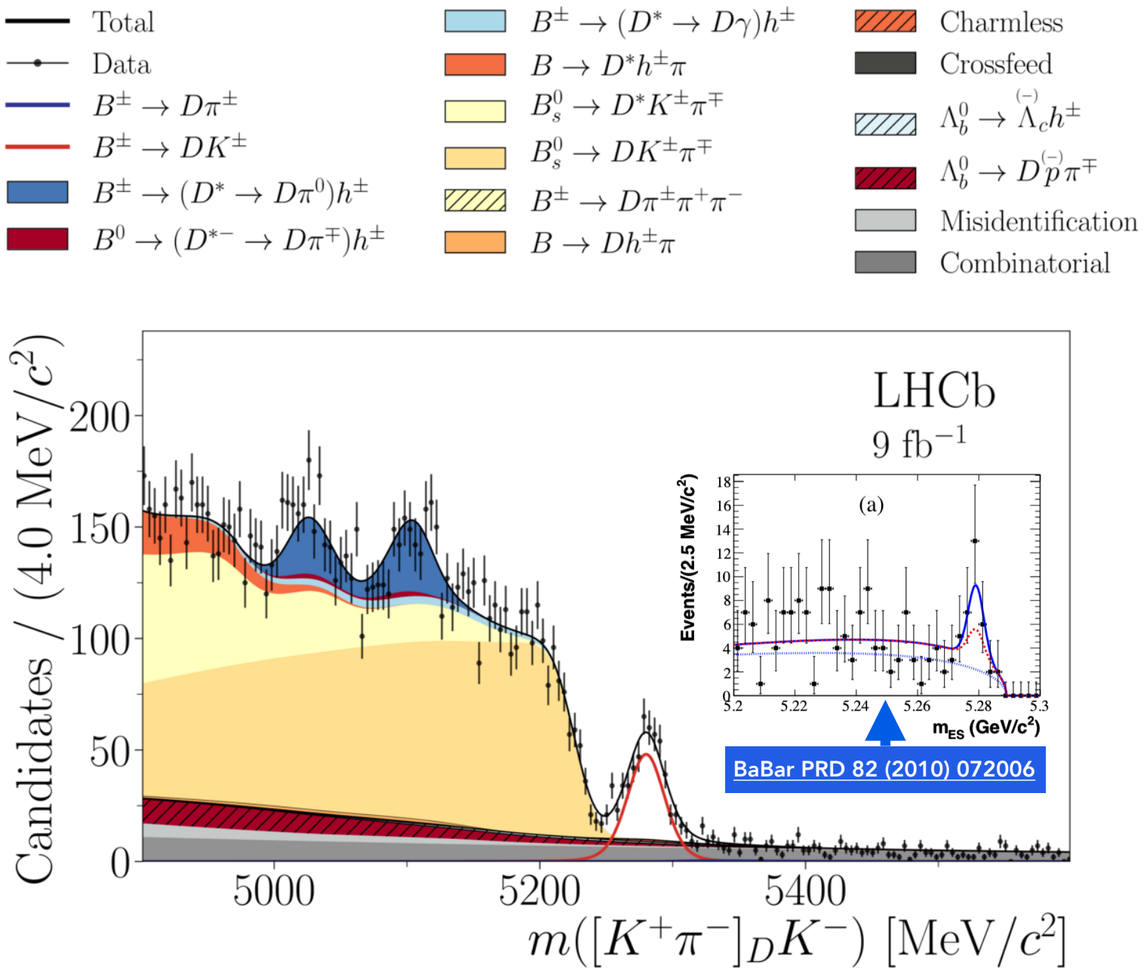
The road to a permille knowledge of γ

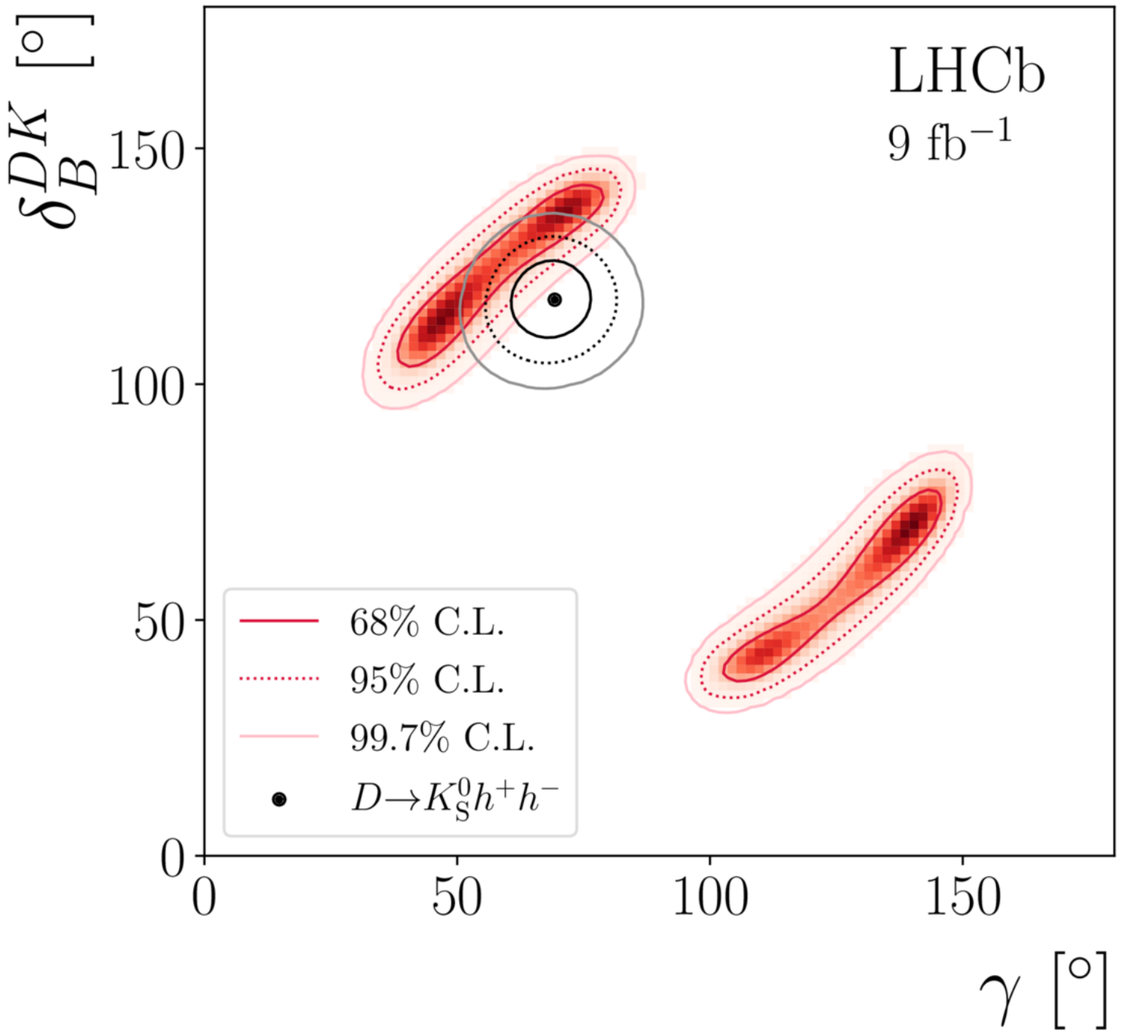
Resonant charm data, particularly input from BES III, is vital to keeping systematics down long-term

The road to a permille knowledge of γ

Baryon decays, multi-body B decays, and double-dalitz decays crucial to push precision into permille region

Suppressed modes are abundant now

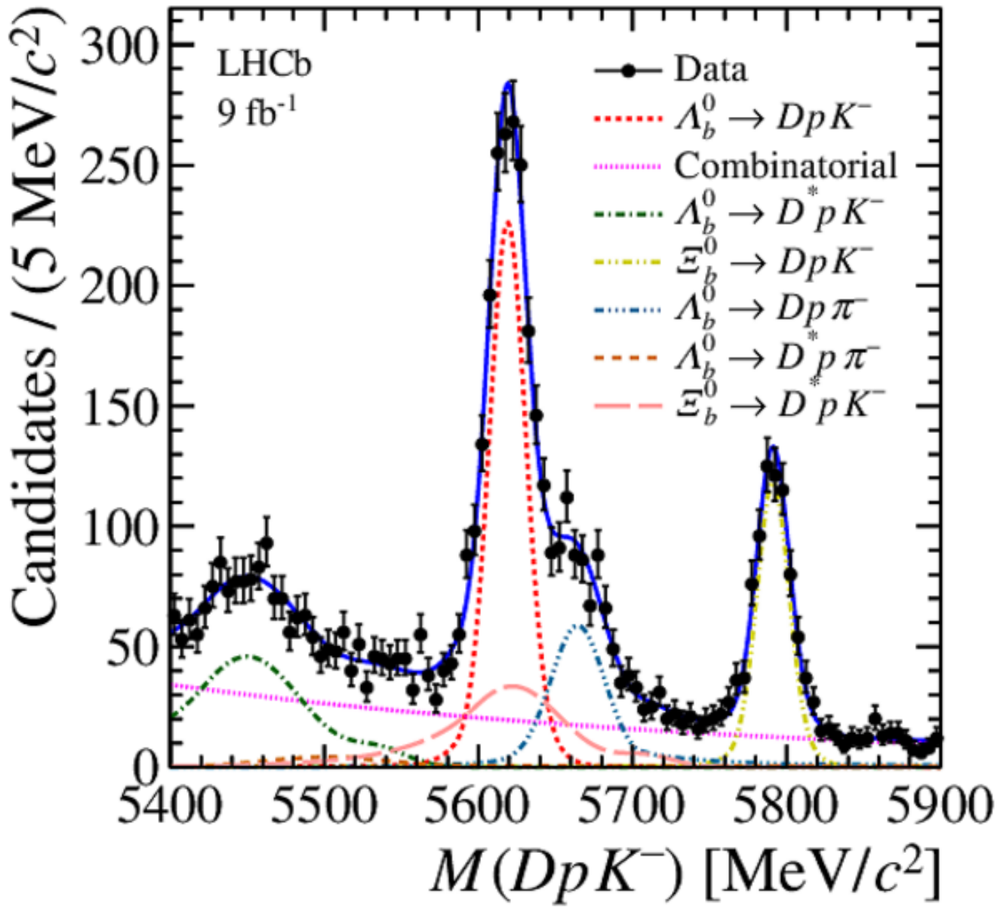




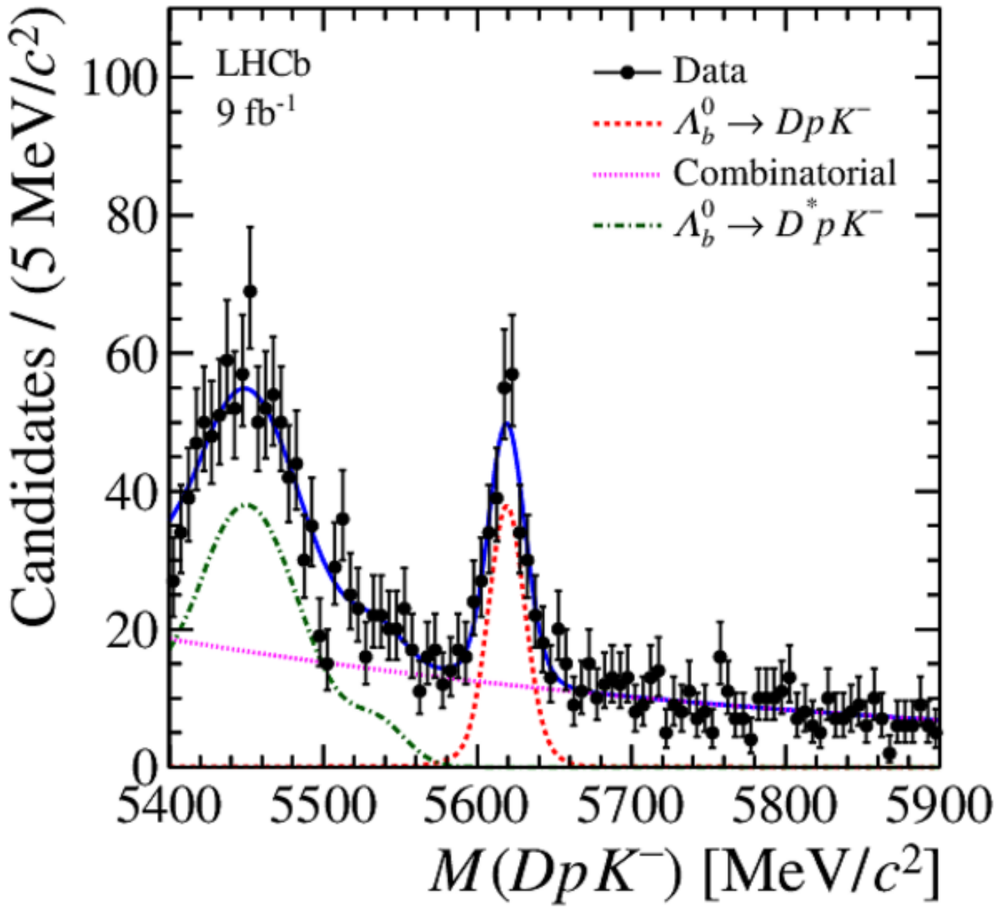
Remarkable precision from LHCb legacy ADS/GLW measurement (JHEP 04 (2021) 081)

Baryons are entering the game

Favoured



Suppressed



Fav to suppressed ratio ⟶

$$R = 7.1 \pm 0.8\,(\text{stat.})^{+0.4}_{-0.3}\,(\text{syst.}),$$

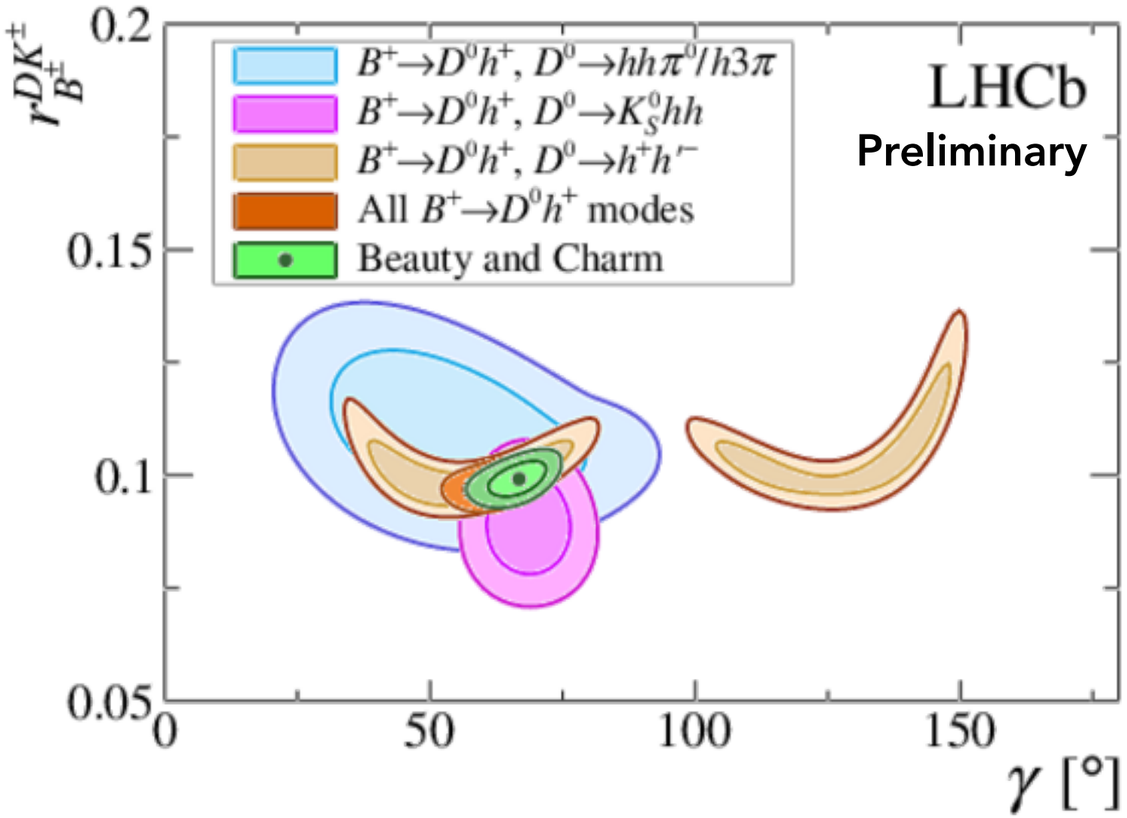
$$A = 0.12 \pm 0.09\,(\text{stat.})^{+0.02}_{-0.03}\,(\text{syst.}),$$

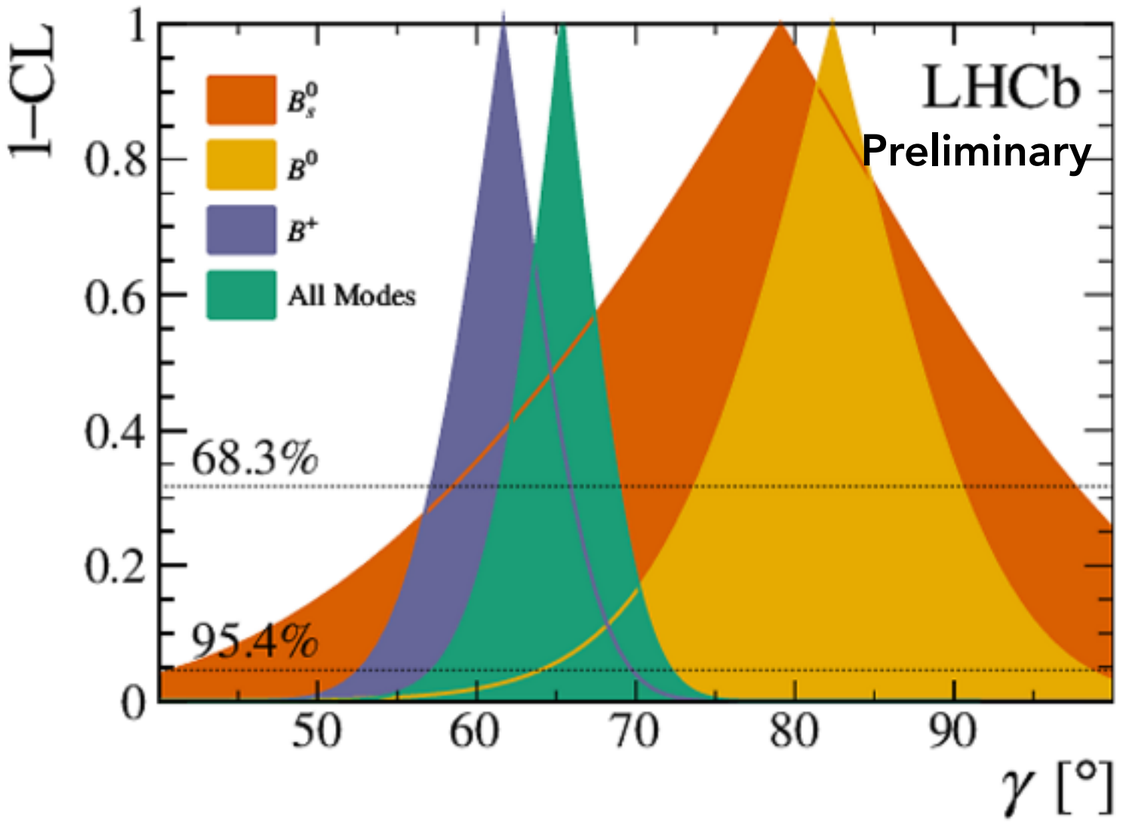
⟵ **Suppressed mode asymmetry**

CP asymmetry in $\Lambda_b \to DpK$ sensitive to γ measured for the first time (arXiv 2109.02621)

Global γ fits in the 2020s

LHCb combination for EPS 2021
LHCb-PAPER-2021-033, in preparation





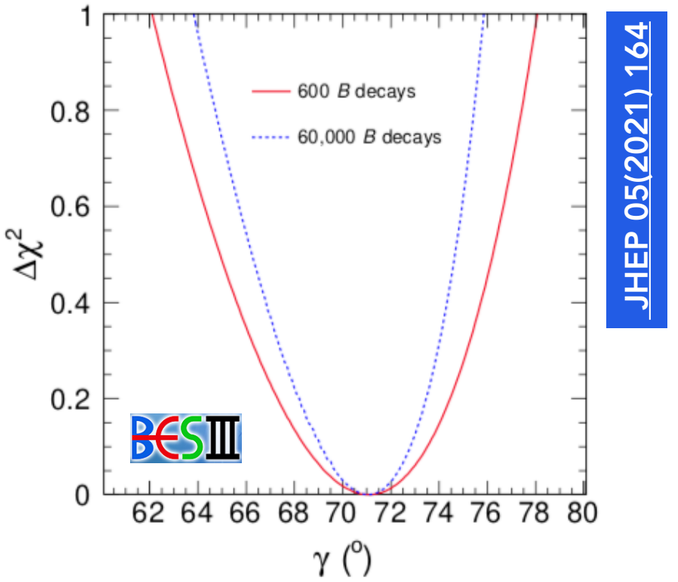
A diagnostic tool as much as a tool for improving precision — sharing between collaborations essential

The continued importance of BES III input

$B^{\pm} \to D(hh,4h)K^{\pm}$:

ADS (hh) mode limited by knowledge of $\delta^{K\pi}$

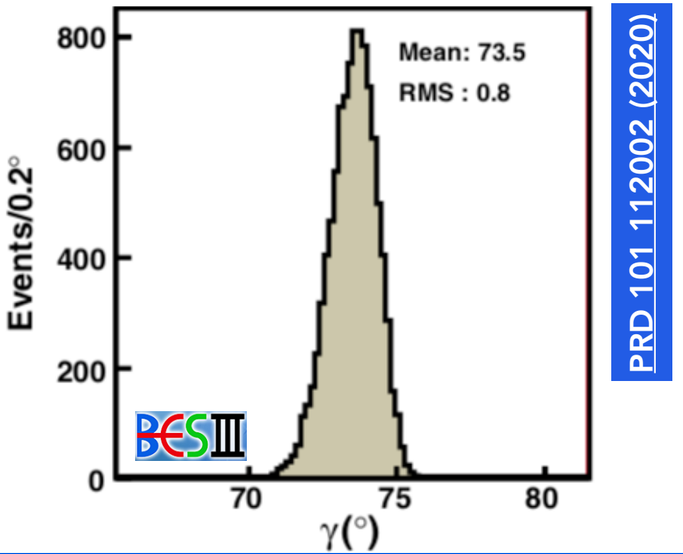
4h modes could eventually rival $K_S HH$ (!!) if strong phases would be measured better, but will be limited very quickly if they cannot!



JHEP 05(2021) 164

$B^{\pm} \to D(K_S hh)K^{\pm}$:

Will eventually be limited at 1 degree level by current BES III measurements, therefore vital that BES III goes ahead and collects 10x the dataset!

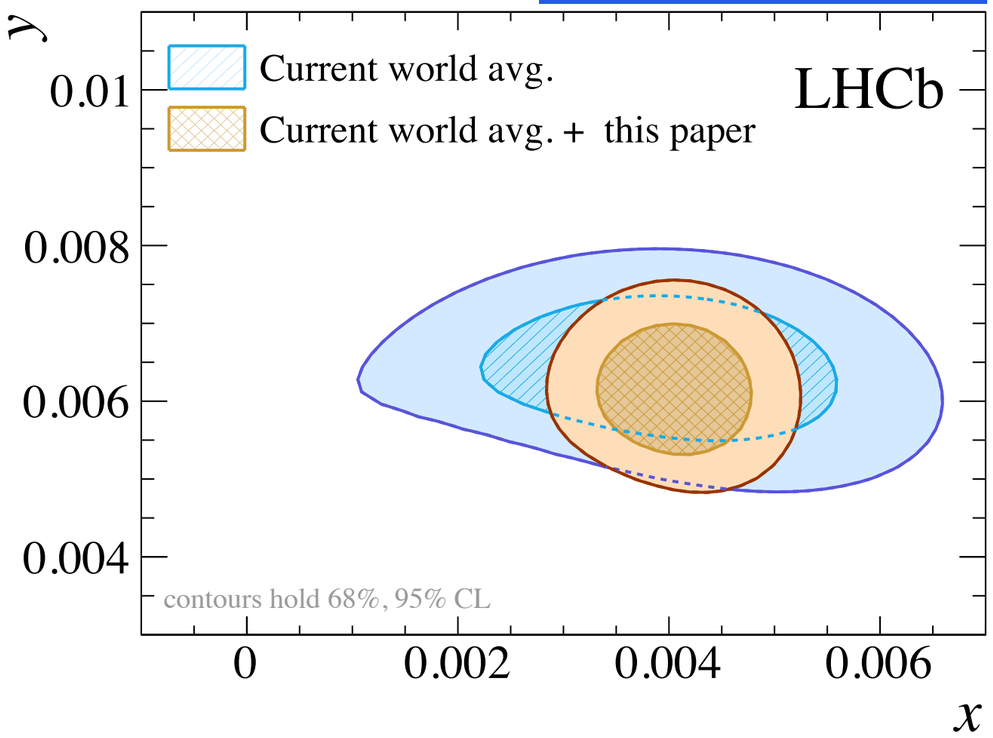


PRD 101 112002 (2020)

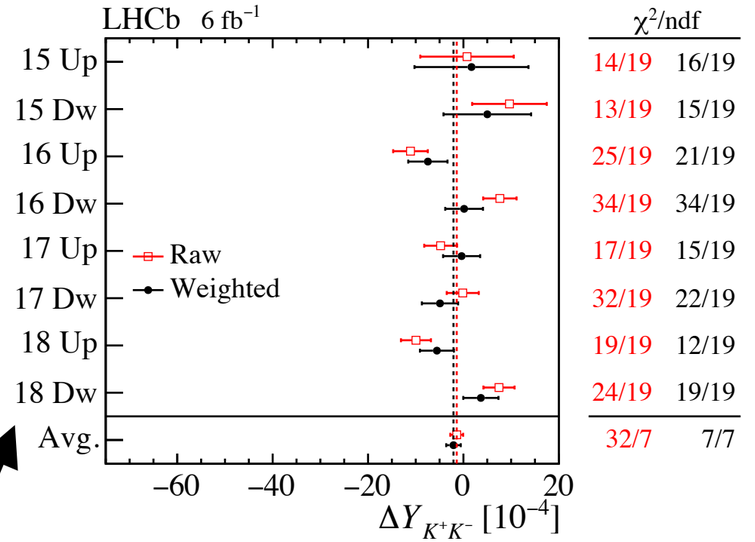
Of course on top of this BES III will also help through usual uncorrelated systematics etc.
A diverse experimental flavour programme is a healthy experimental flavour programme!

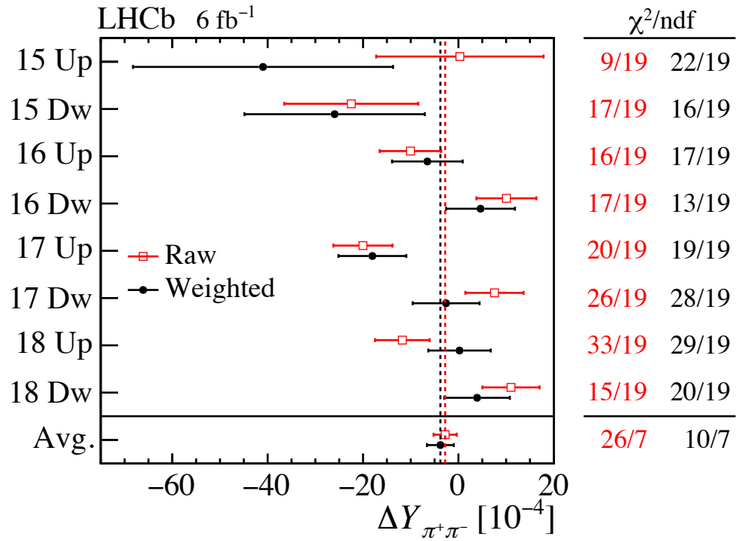
Progress on charm CPV and mixing

Phys. Rev. Lett. 127, 111801



$$\Delta Y_{K^+K^-} = (-2.3 \pm 1.5 \pm 0.3) \times 10^{-4},$$
$$\Delta Y_{\pi^+\pi^-} = (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4},$$

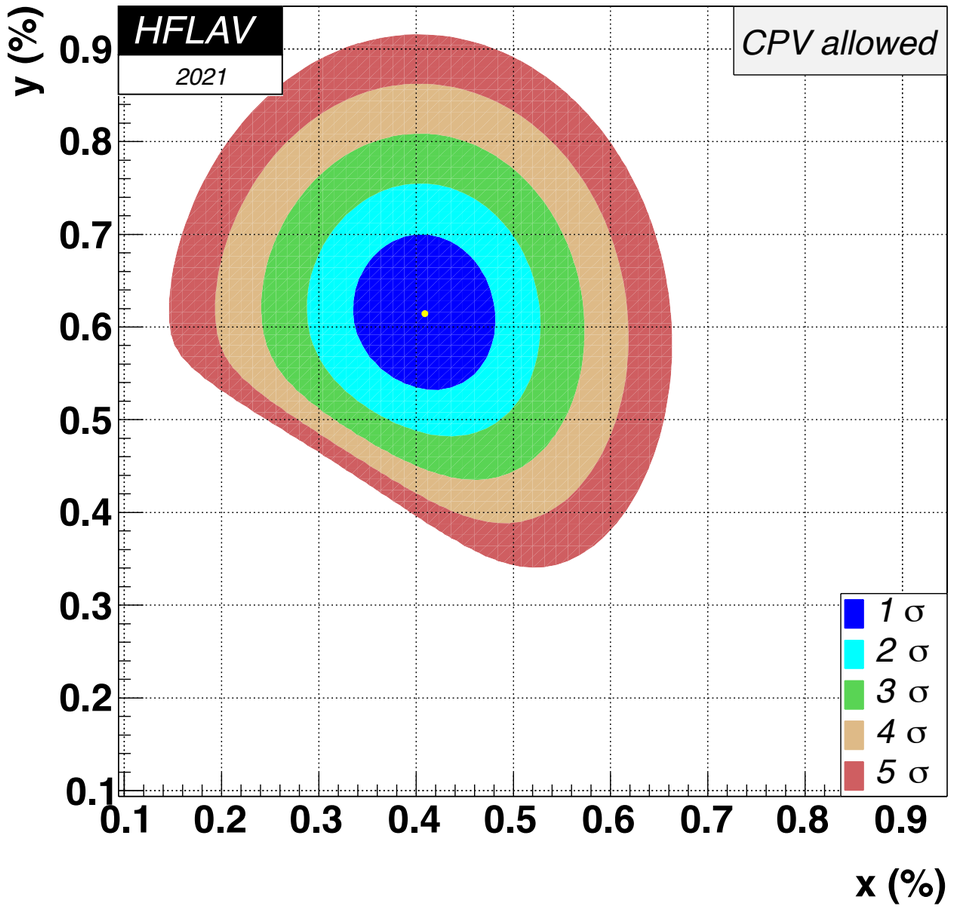


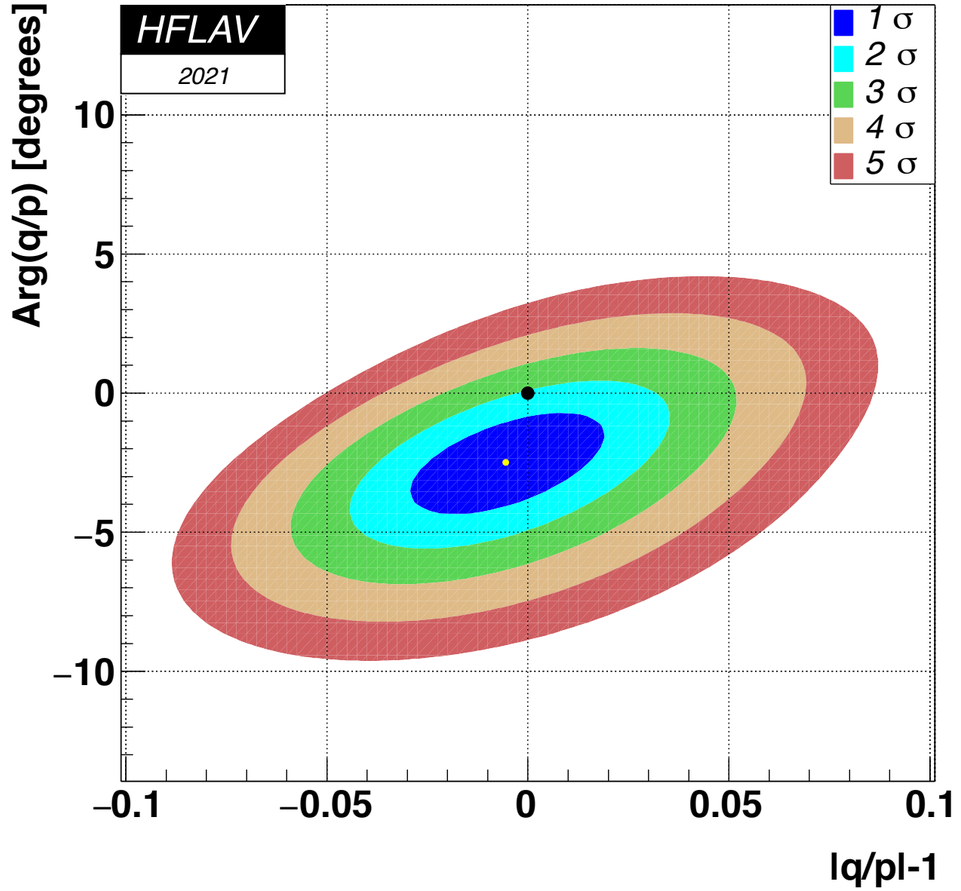


arXiv 2105.09889

Here I hope I can be forgiven for highlighting two LHCb results in particular the amazing 10^{-5} systematic uncertainty on the time-dependent CP asymmetry in D^0 decays.

Progress on charm CPV and mixing

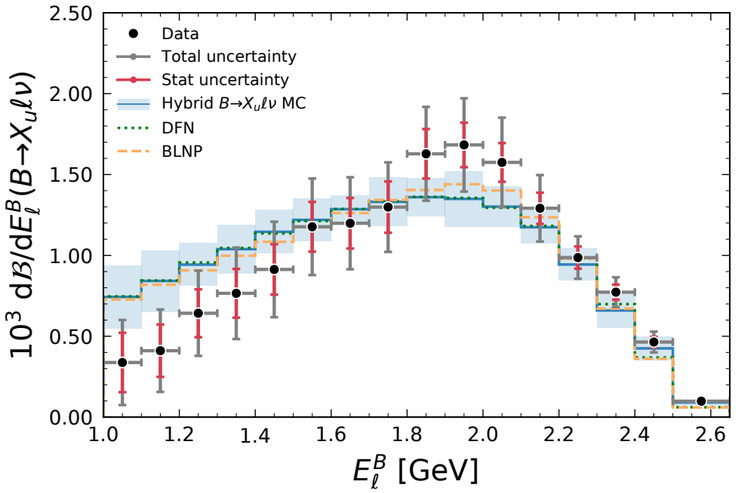




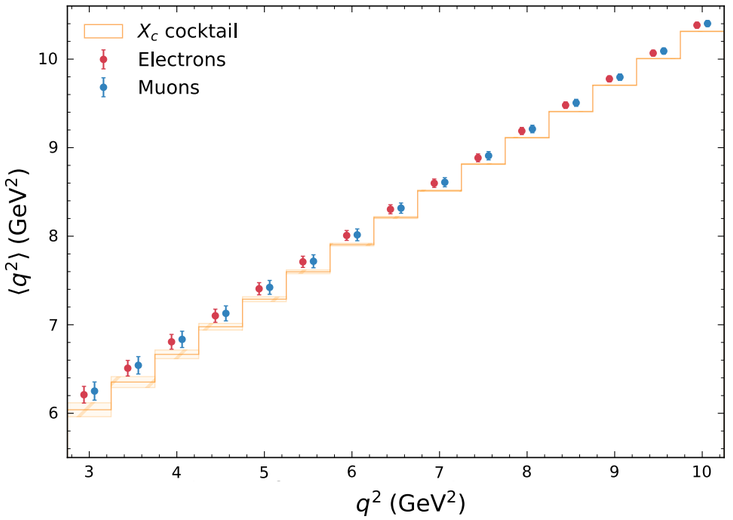
Charm mixing parameters are now measured to better than the 1 permille level. Meanwhile a small global 2σ deviation from the no-CPV hypothesis appears (of course CPV in decay has been observed).

V_{ub} and V_{cb}

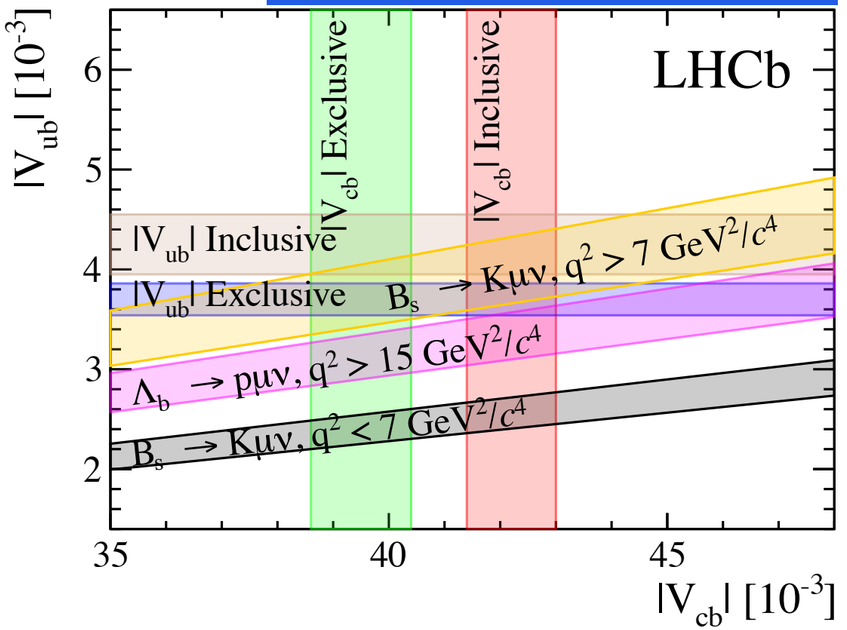
Belle Preprint 2021-015

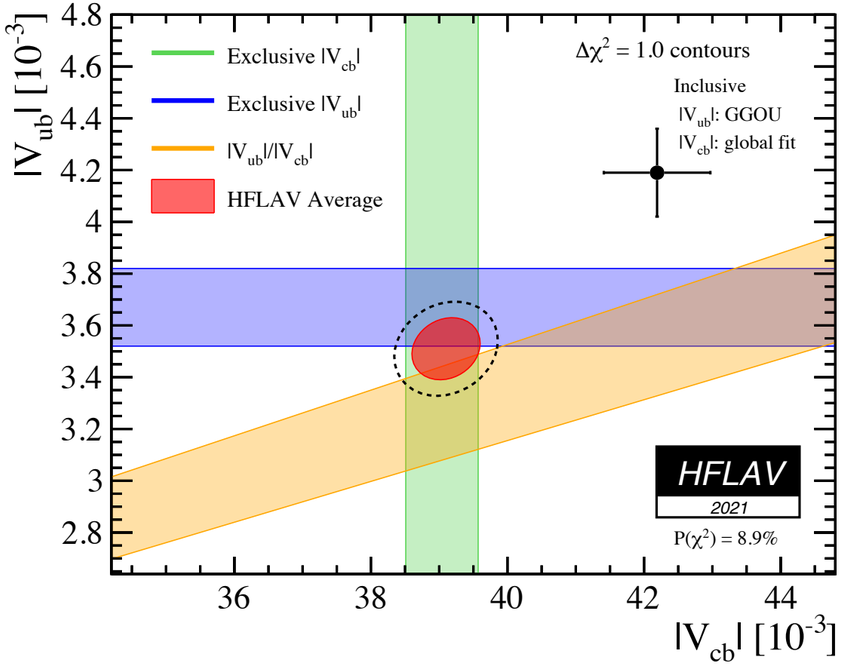


Belle Preprint 2021-018



PHYS. REV. LETT. 126 (2021) 081804



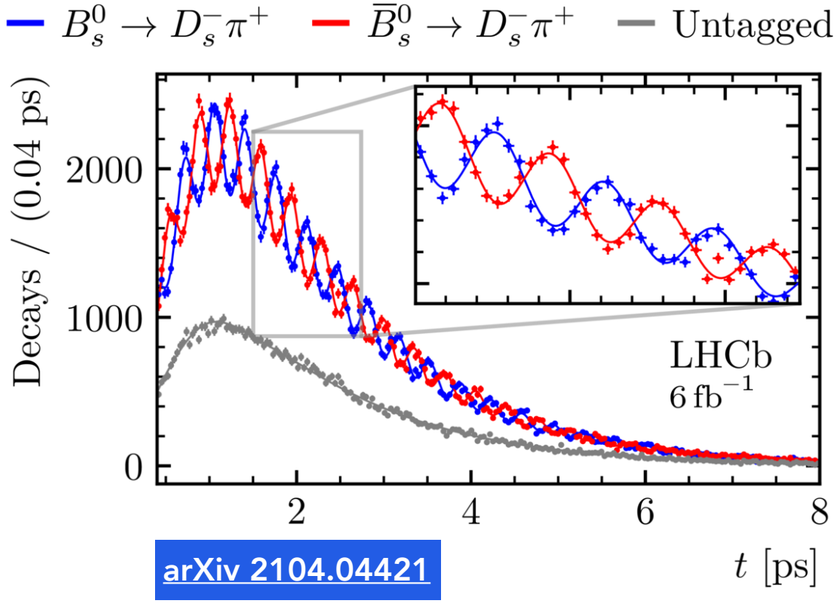


New measurements by Belle shed light on V_{ub} & V_{cb}

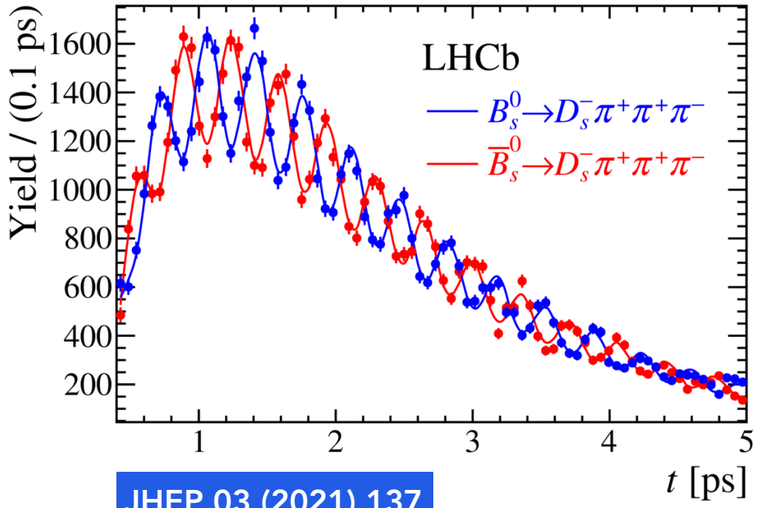
Inclusive-exclusive tensions remain in V_{cb}, are reduced in V_{ub}
Tension in Vub from 2-3 sigma depending on inputs
V_{cb} remains at 3 sigma, further experimental input must be matched by progress in theory/lattice calculations

Discrepancy in V_{ub}/V_{cb} from $B\to K\mu\nu$ at low/high q^2 needs to be understood better, implication for calculation of form-factors

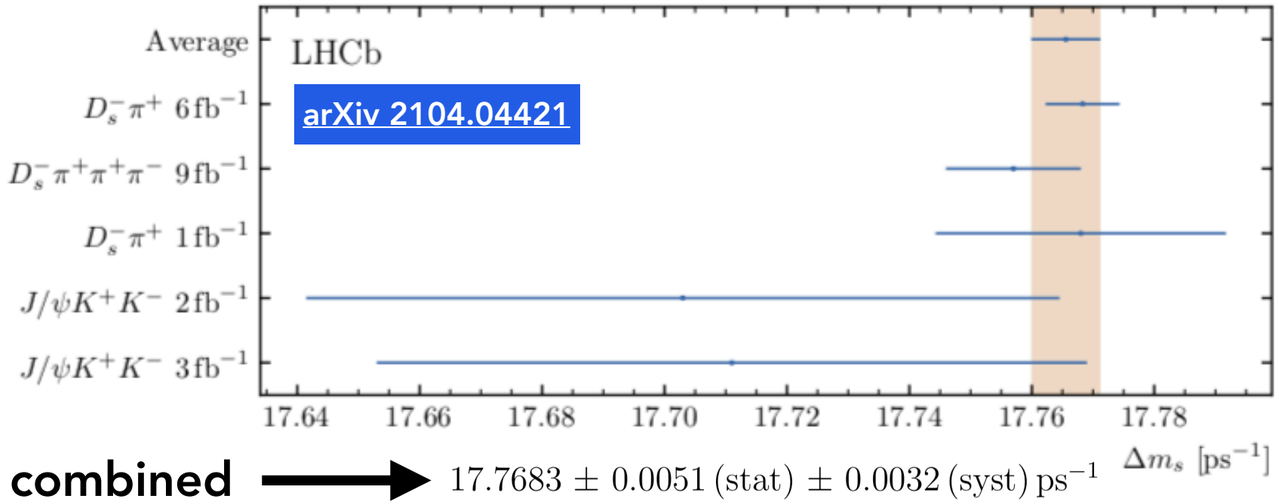
$\Delta m_{d,s}$ — no systematics limit in sight?



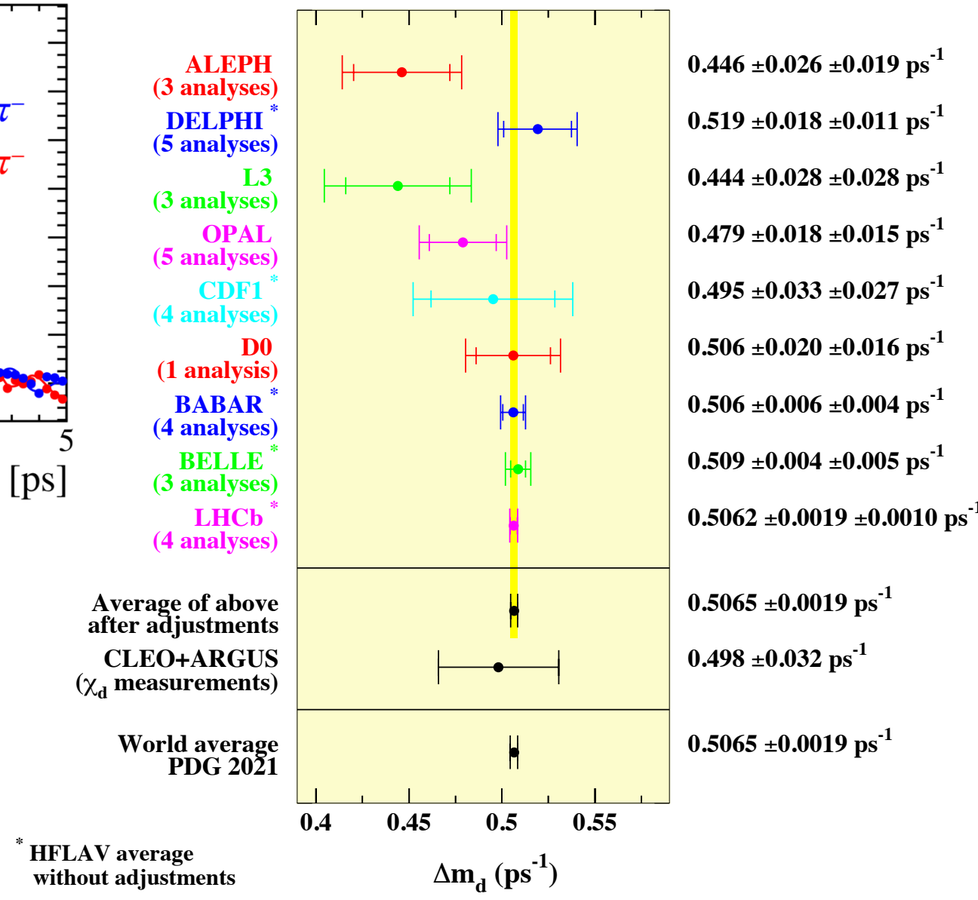
arXiv 2104.04421



JHEP 03 (2021) 137



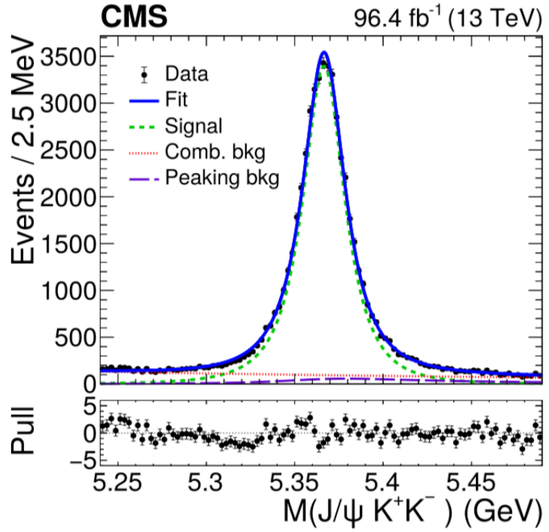
LHCb combined → $17.7683 \pm 0.0051\,(\text{stat}) \pm 0.0032\,(\text{syst})\ \text{ps}^{-1}$

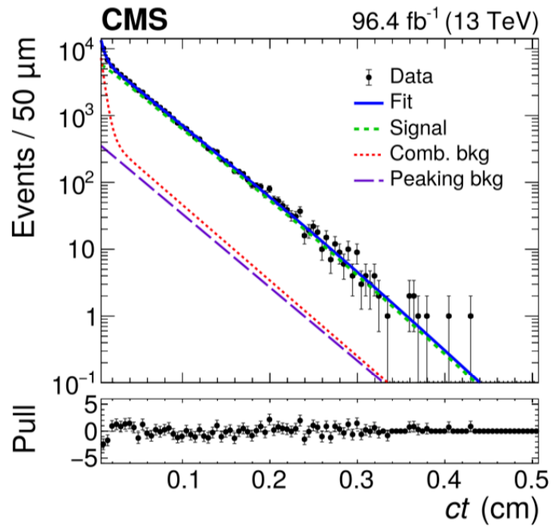


Eagerly awaiting the full Run 1+2 LHCb update on $B_s \to D_s K$ for γ of course

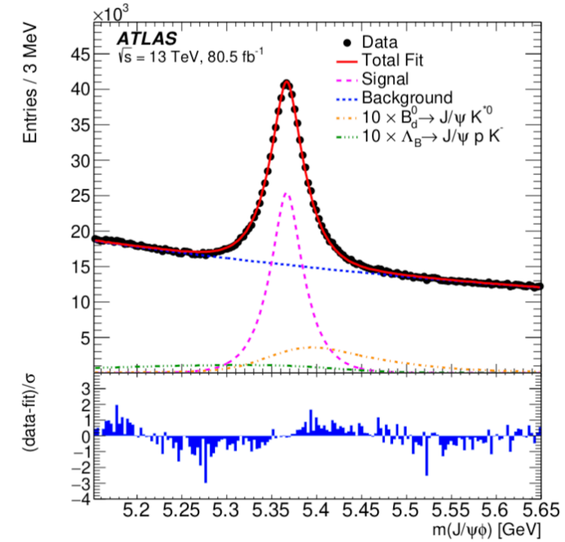
φ_s — the forgotten golden mode?

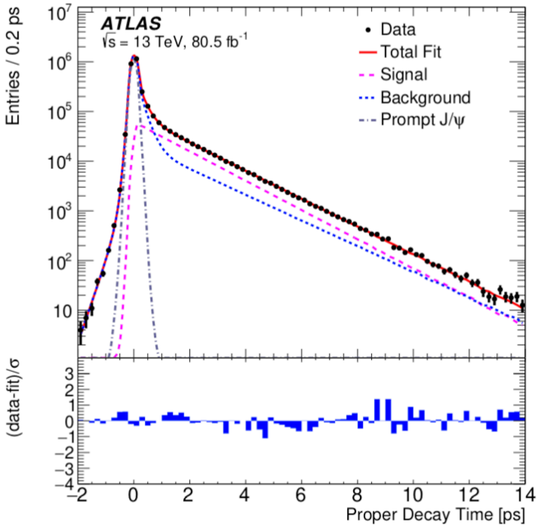
Phys. Lett. B 816 (2021) 136188

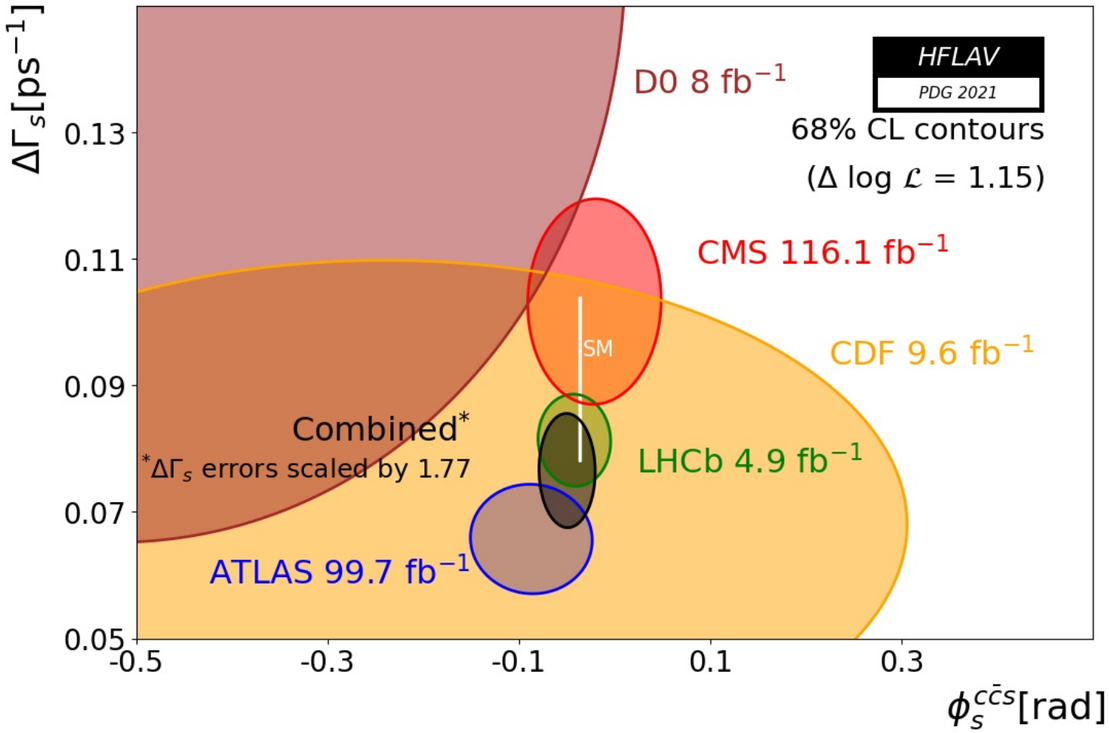




Eur. Phys. J. C 81 (2021) 342



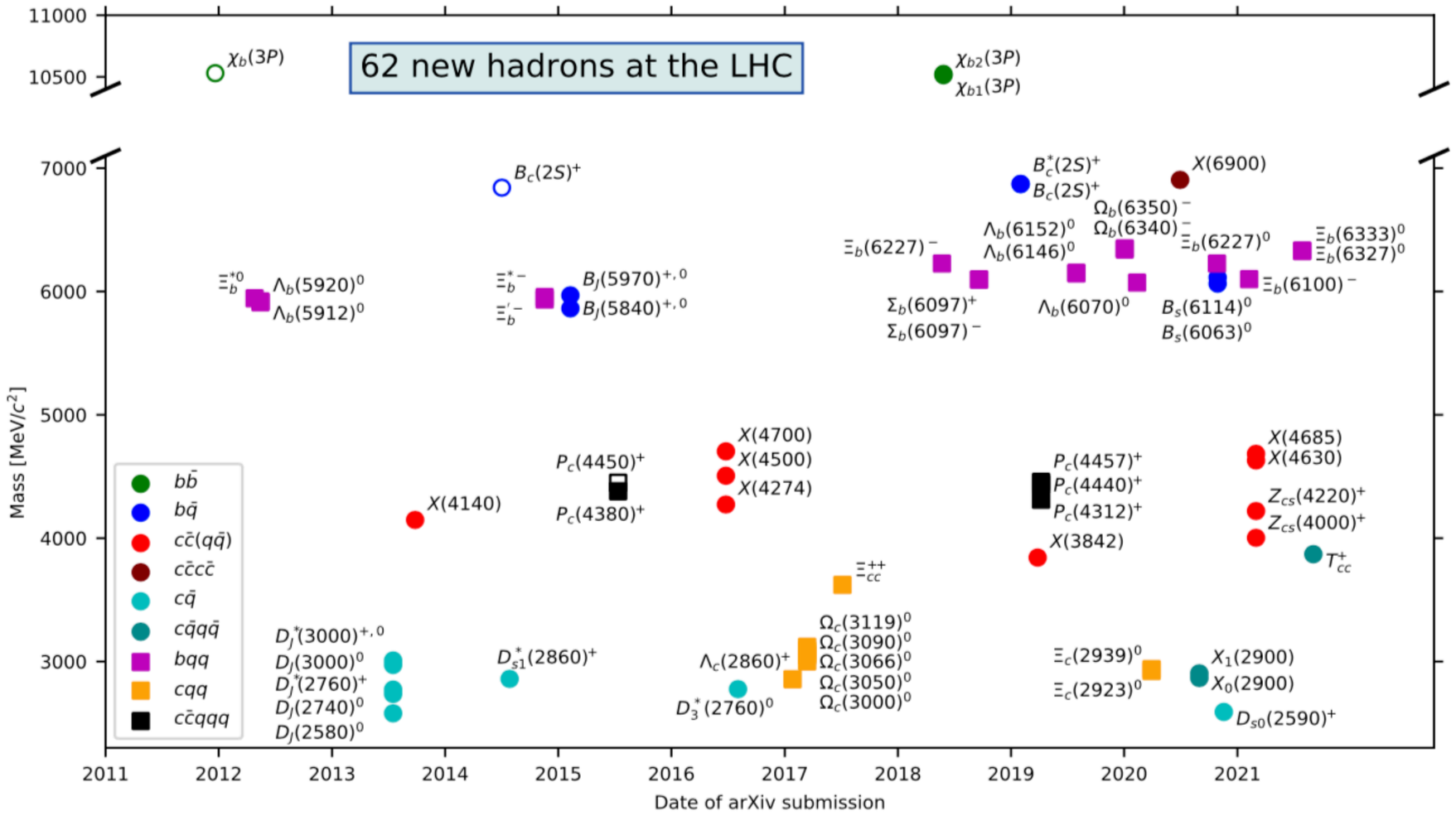




World average still dominated by LHCb but discrepancy in $\Delta\Gamma_s$ deserves careful attention

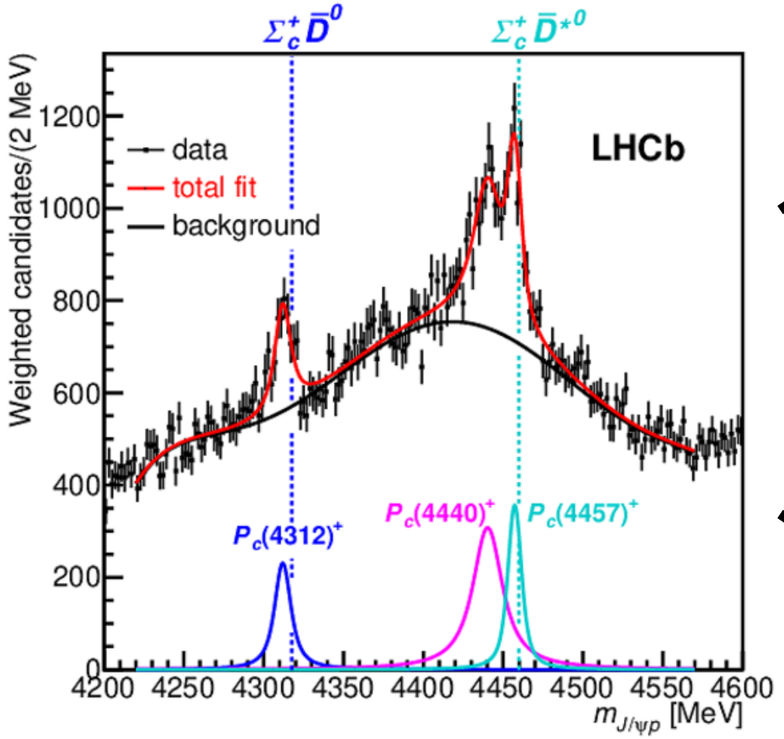
Cataloguing hadrons

The LHC as a hadron factory

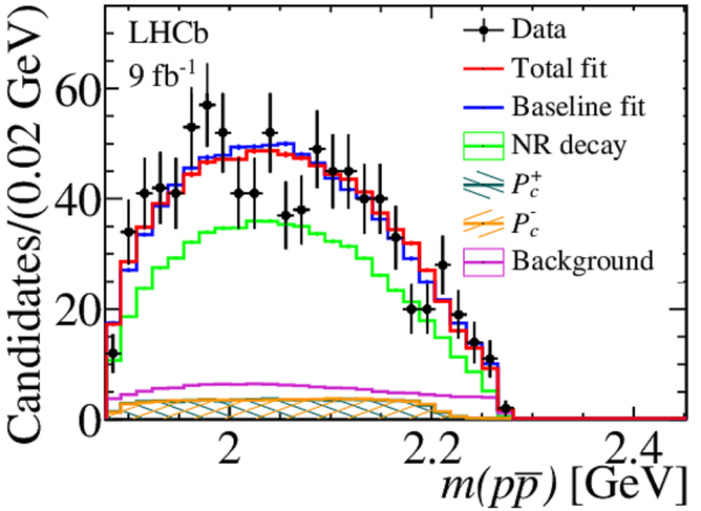


Credit to Patrick Koppenburg https://www.nikhef.nl/~pkoppenb/particles.html

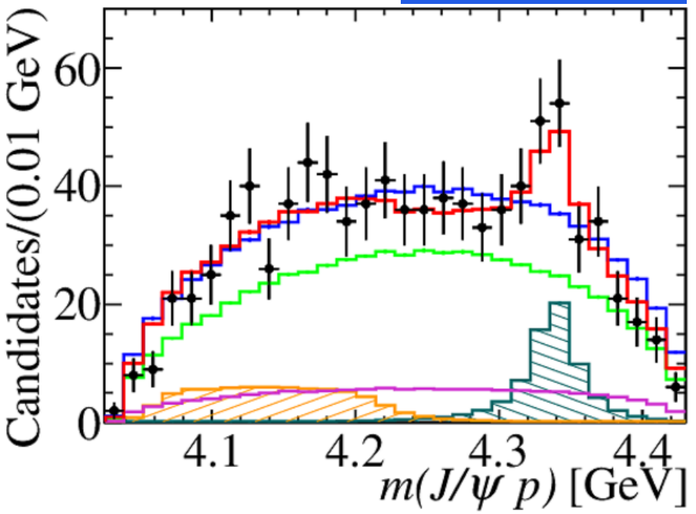
5-quark states: from exotic to routine

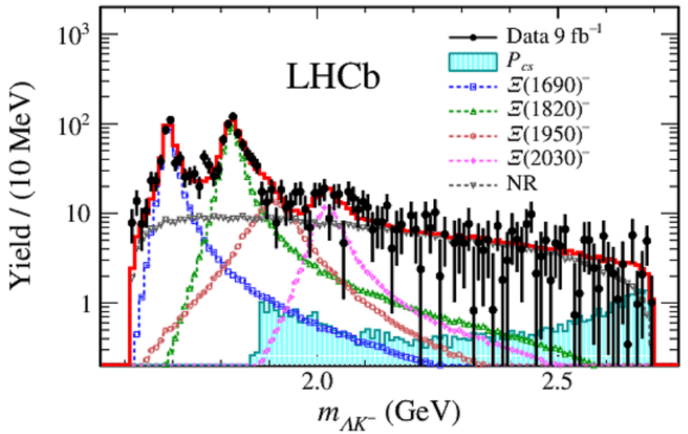


PHYS. REV. LETT. 122 (2019) 222001

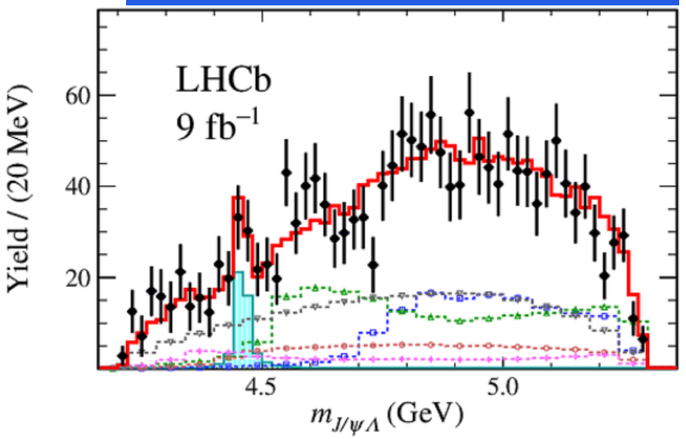


arXiv 2108.04720



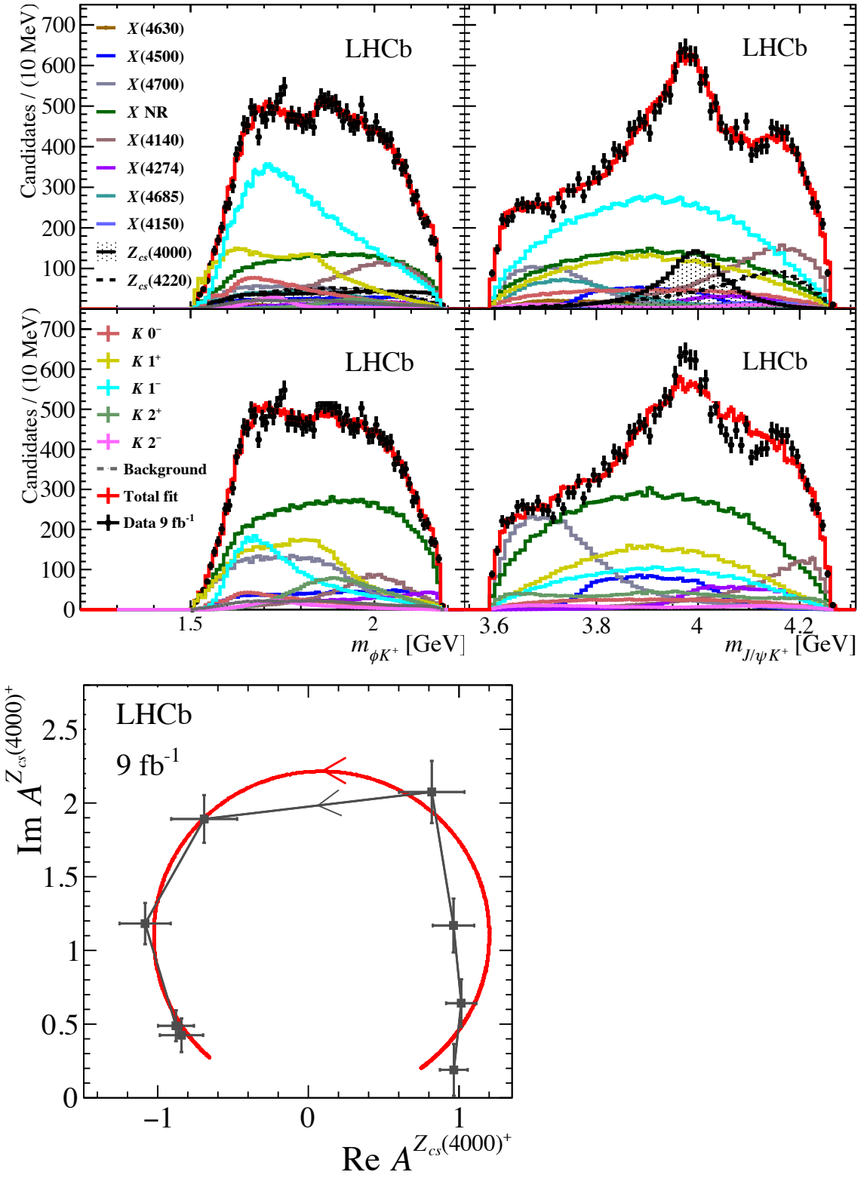


SCIENCE BULLETIN 66 (2021) 1278

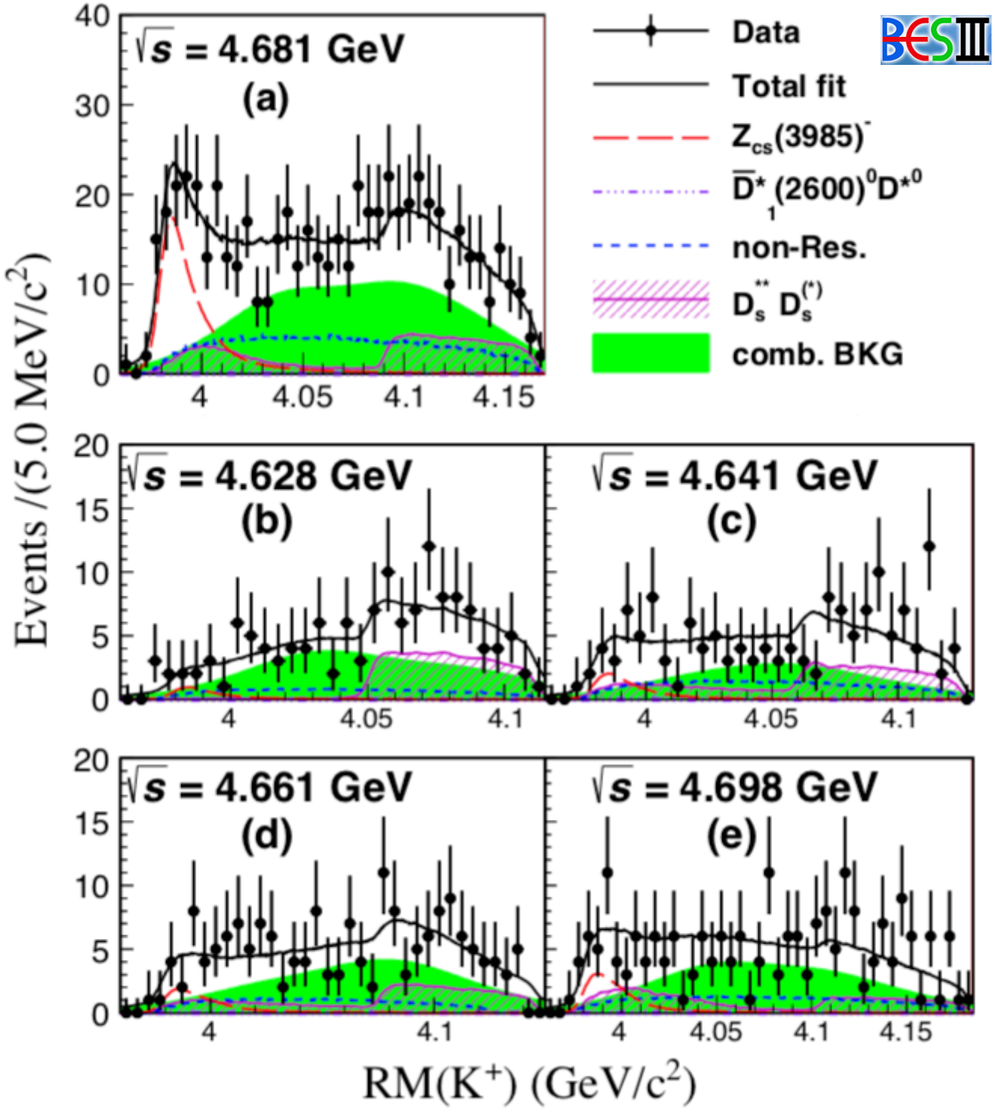


For now the nature of these pentaquarks remains unclear — Run 3 will have much to say about it

4-quark states with charm & strangeness



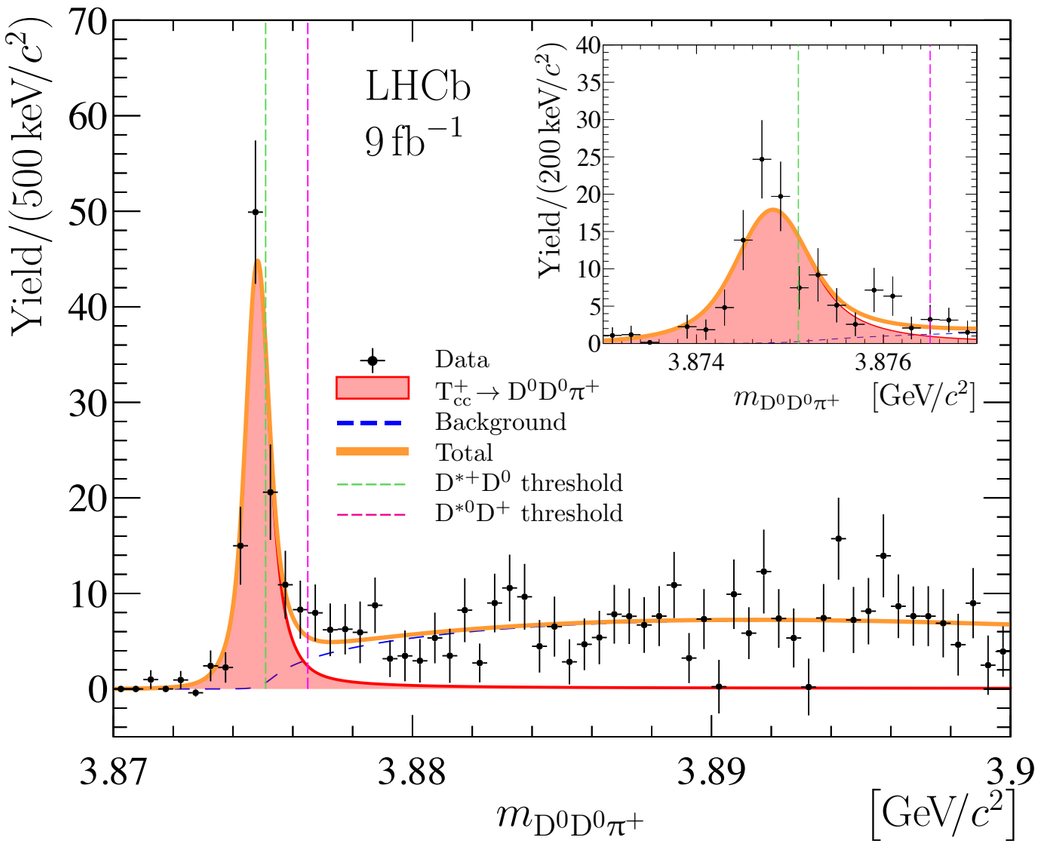
PHYS. REV. LETT. 127 (2021) 082001



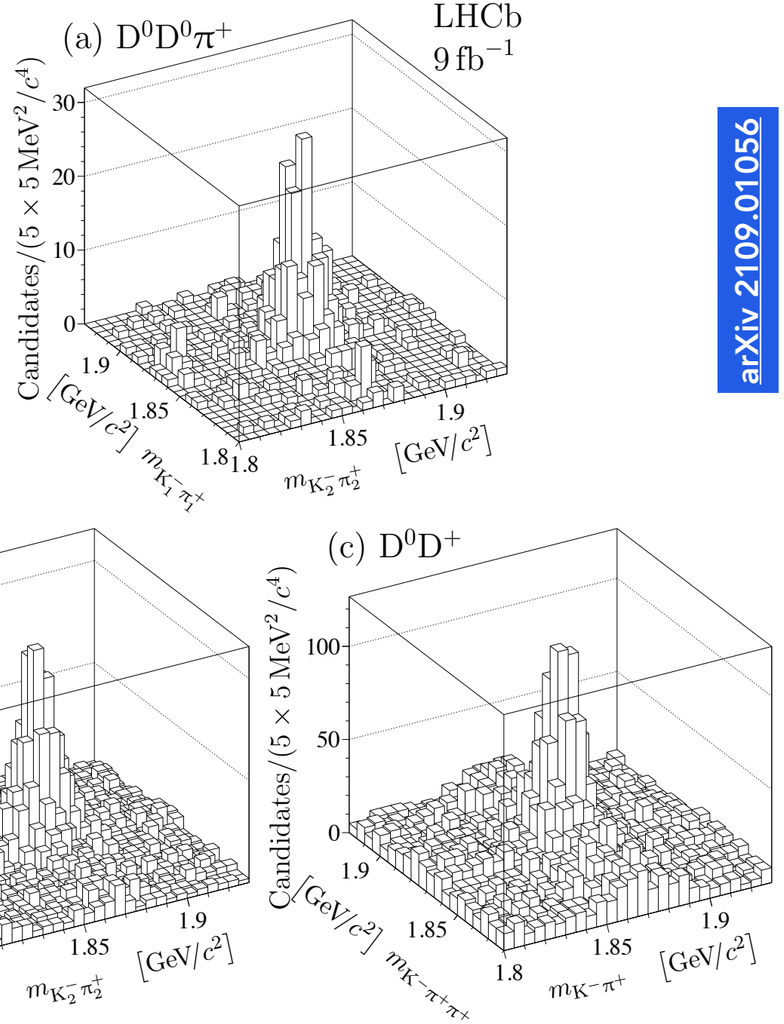
Phys. Rev. Lett. 126, 102001 (2021)

Evidence of such states from LHCb and BES III, but more data needed to confirm properties

Another doubly-heavy 4-quark state



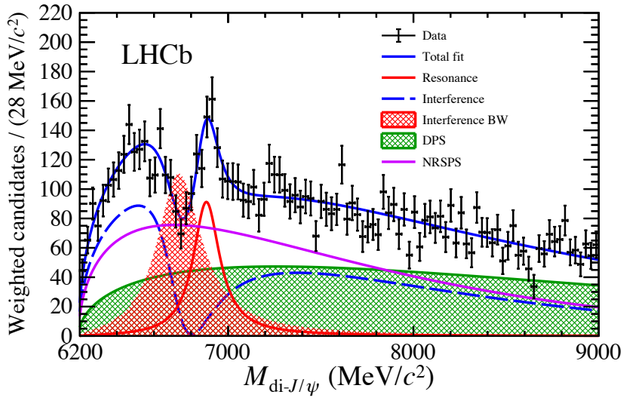
arXiv 2109.01038

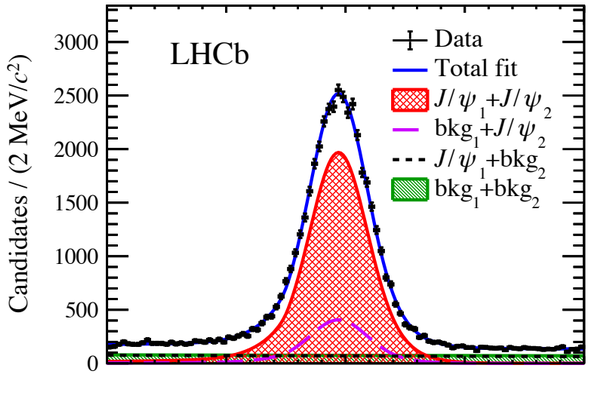


arXiv 2109.01056

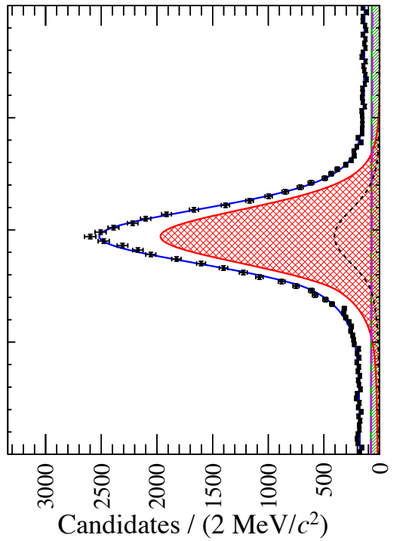
Mass and width consistent with T_c^{++} expectations — motivates searches for stable doubly-bottom states

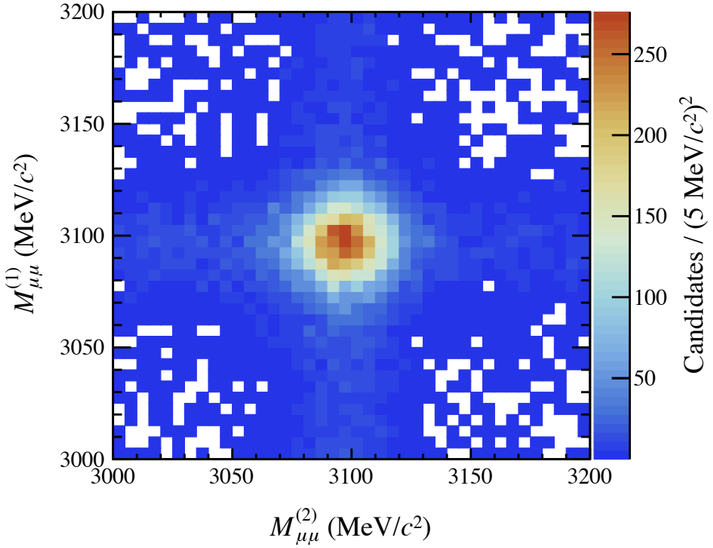
Searches for further 4-quark states

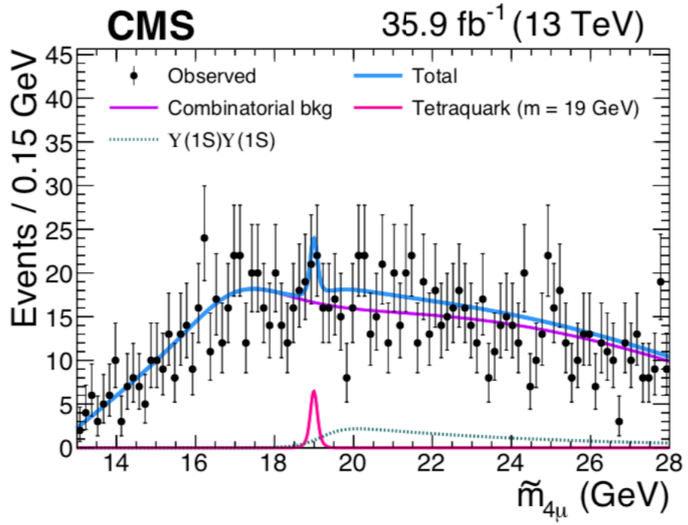




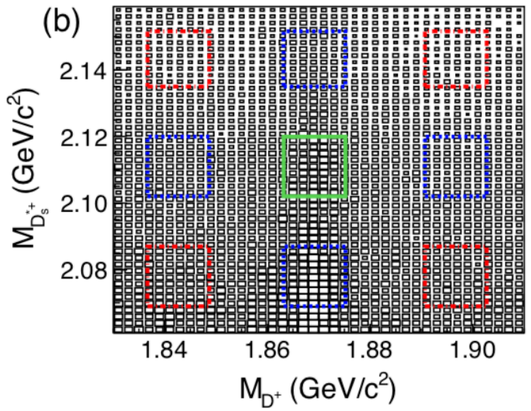
SCIENCE BULLETIN 65 (2020) 1983

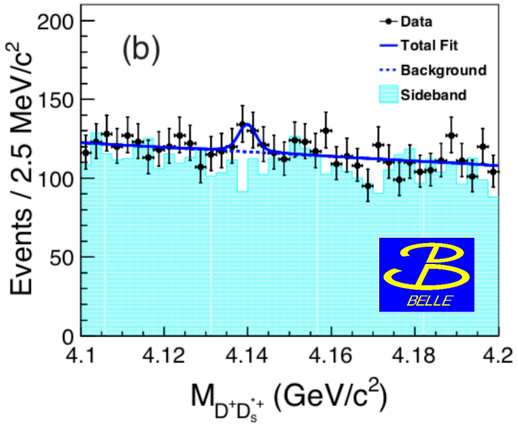






Phys. Lett. B 808 (2020) 135578



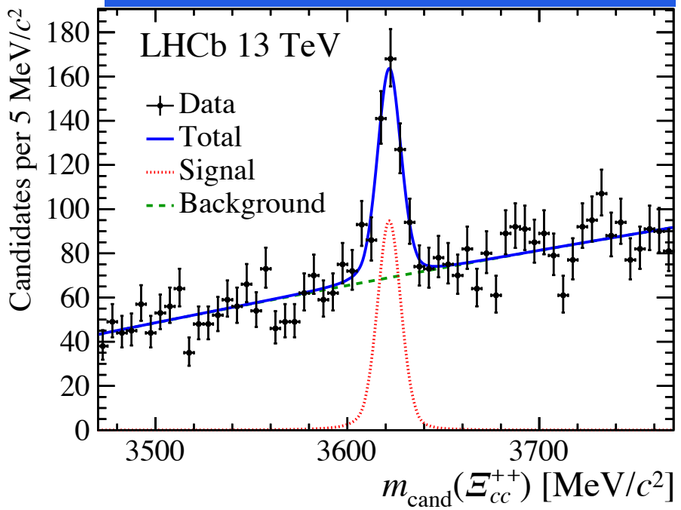


PRD 102, 112001 (2020)

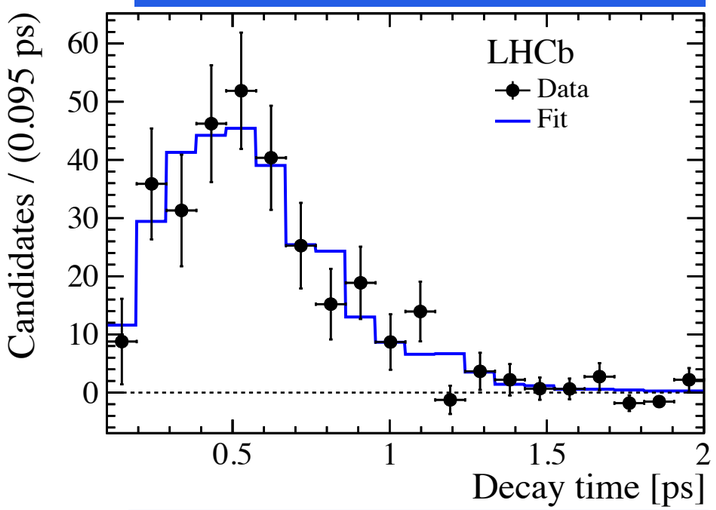
LHCb di-J/ψ signal is compatible with both tetraquark & rescattering hypotheses — more data needed to establish spin-parity in particular. For very heavy tetraquarks CMS & ATLAS datasets play a crucial role.

Precision studies of hadron properties

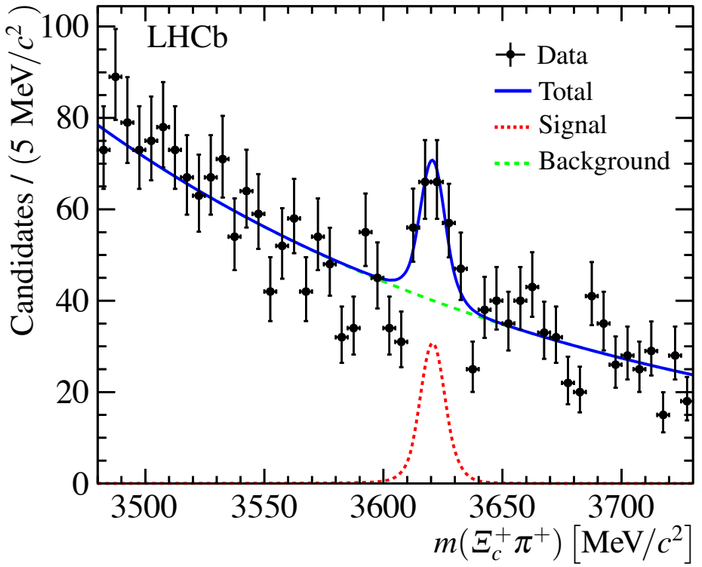
PHYS. REV. LETT. 119 (2017) 112001



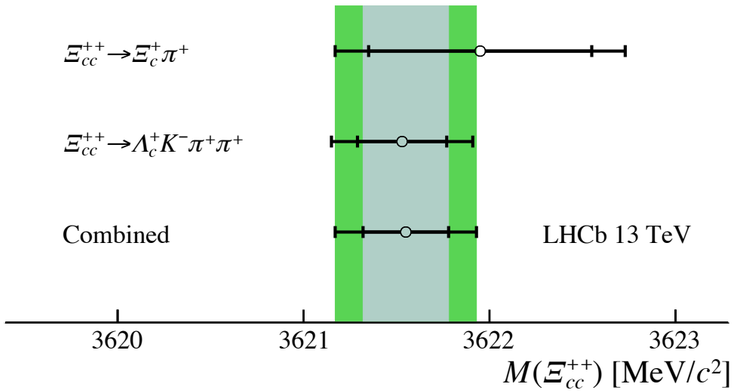
PHYS. REV. LETT. 121 (2018) 052002



PHYS. REV. LETT. 121 (2018) 162002



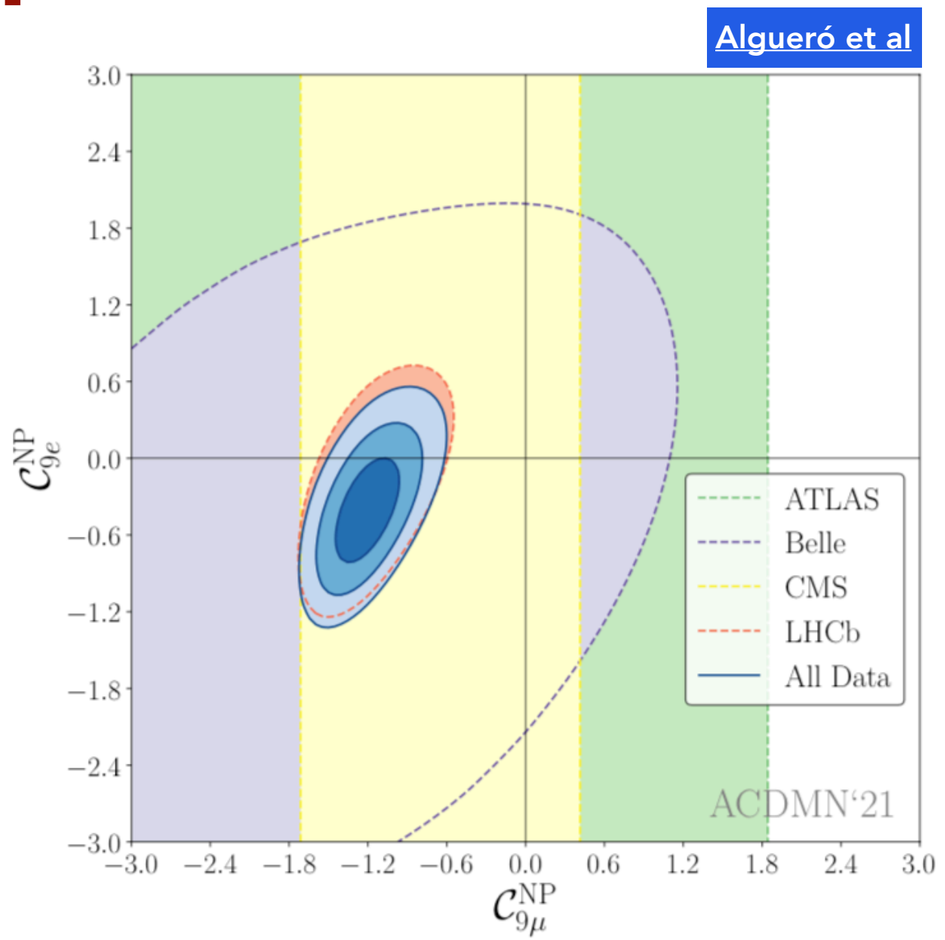
JHEP 02 (2020) 049

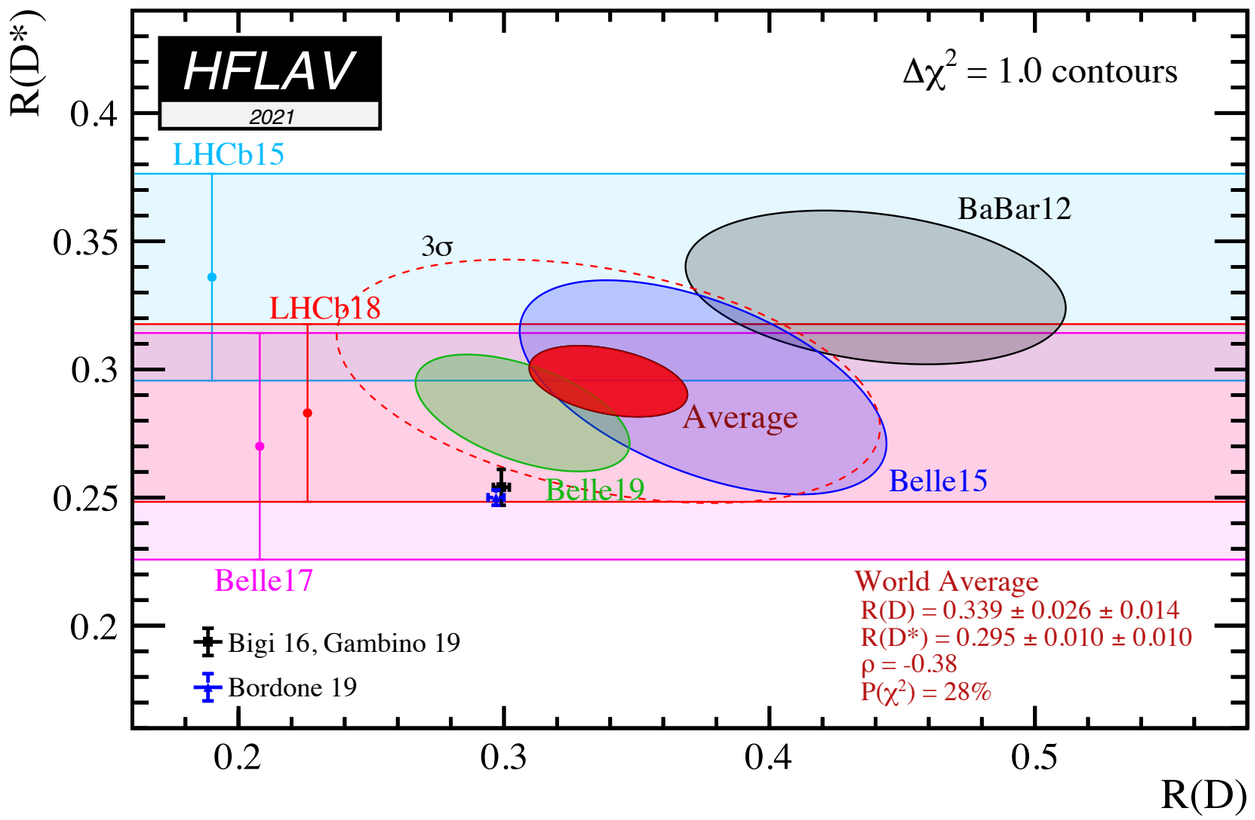


A nice example of how in a few years we've gone from observation to precision studies

Anomalous couplings

Experimental status of the anomalies





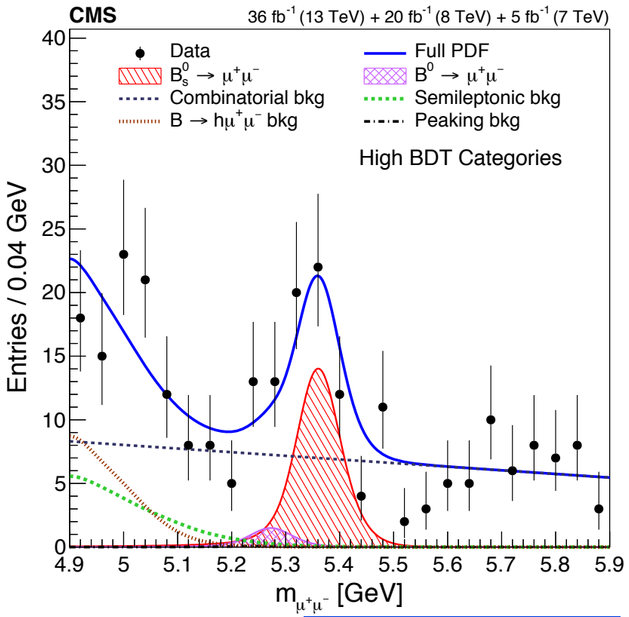
The Einsteinian constant is not a constant, is not a center. It is the very concept of variability -- it is, finally, the concept of the game. (Jacques Derrida)

The 5σ criterion is not a criterion, it is not a constant. It is the very… (V.V. Gligorov)

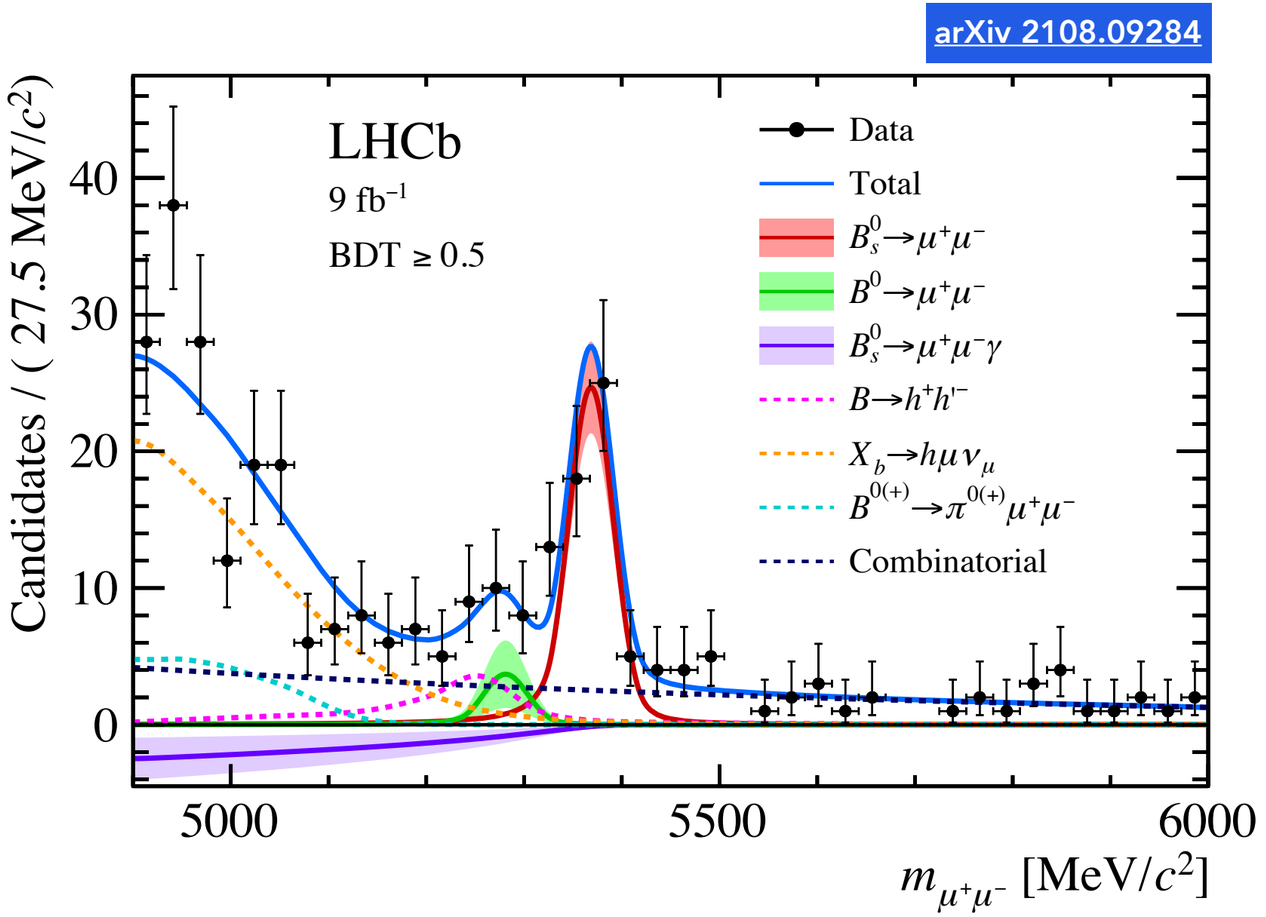
Apologies to teams whose b→sll results were omitted: blame HFLAV for not making a b→sll plot!

b→$\mu\mu$ legacy LHC measurements

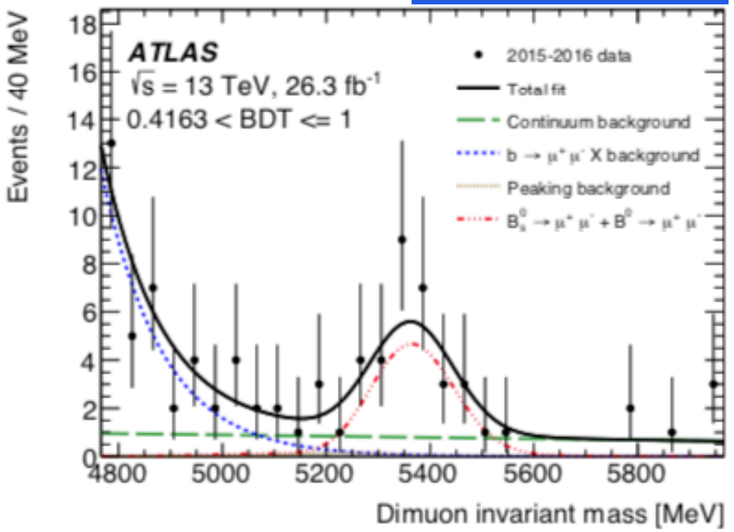
JHEP 04 (2020) 188



arXiv 2108.09284

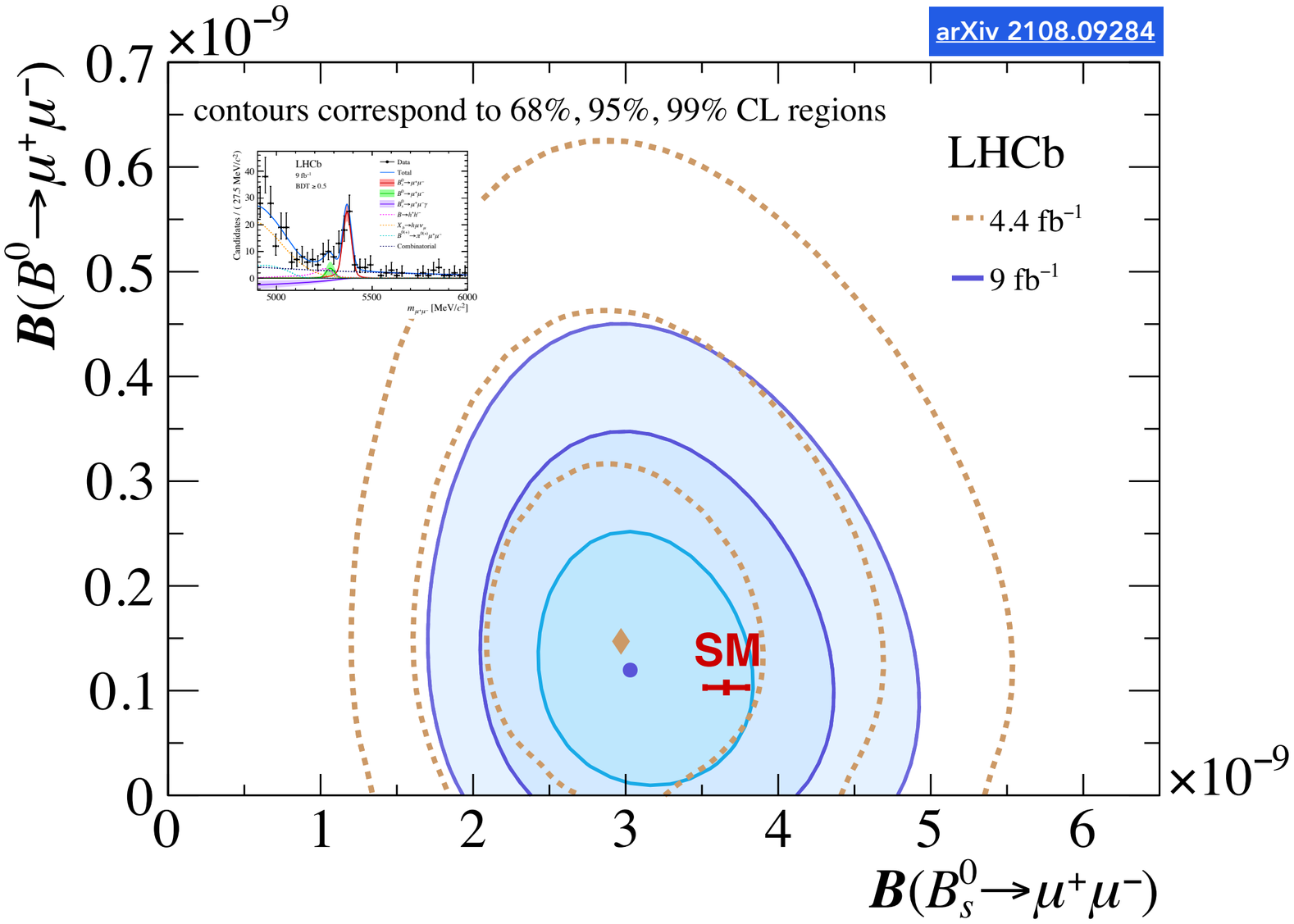


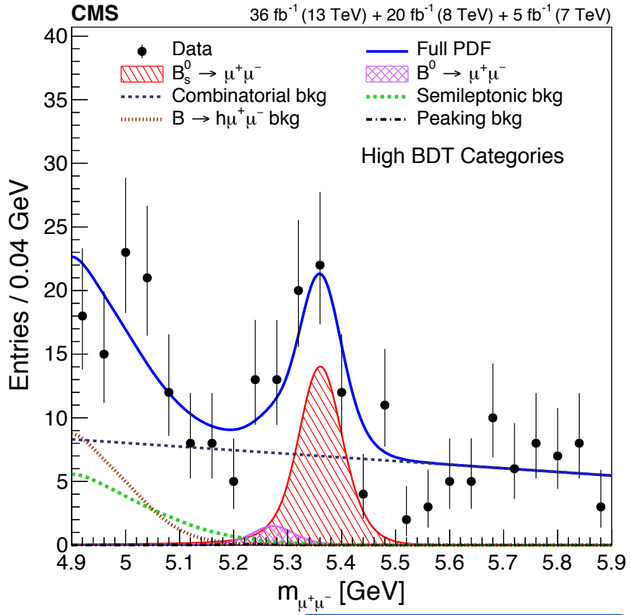
JHEP 04 (2019) 098



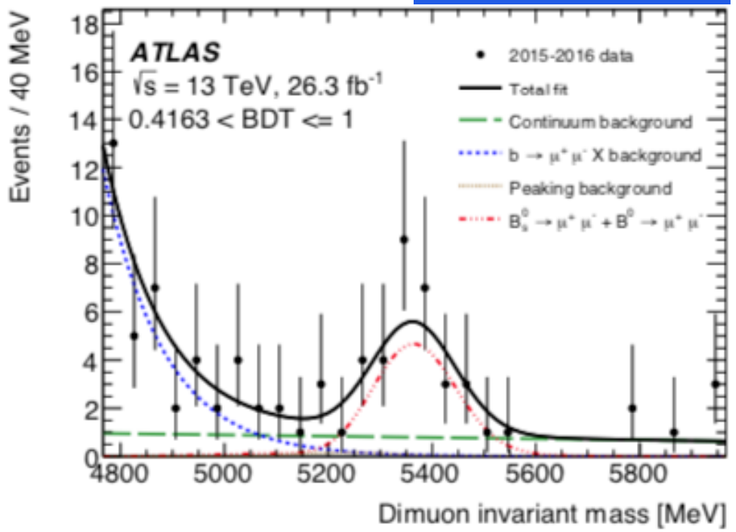
b→$\mu\mu$ legacy LHC measurements

JHEP 04 (2020) 188





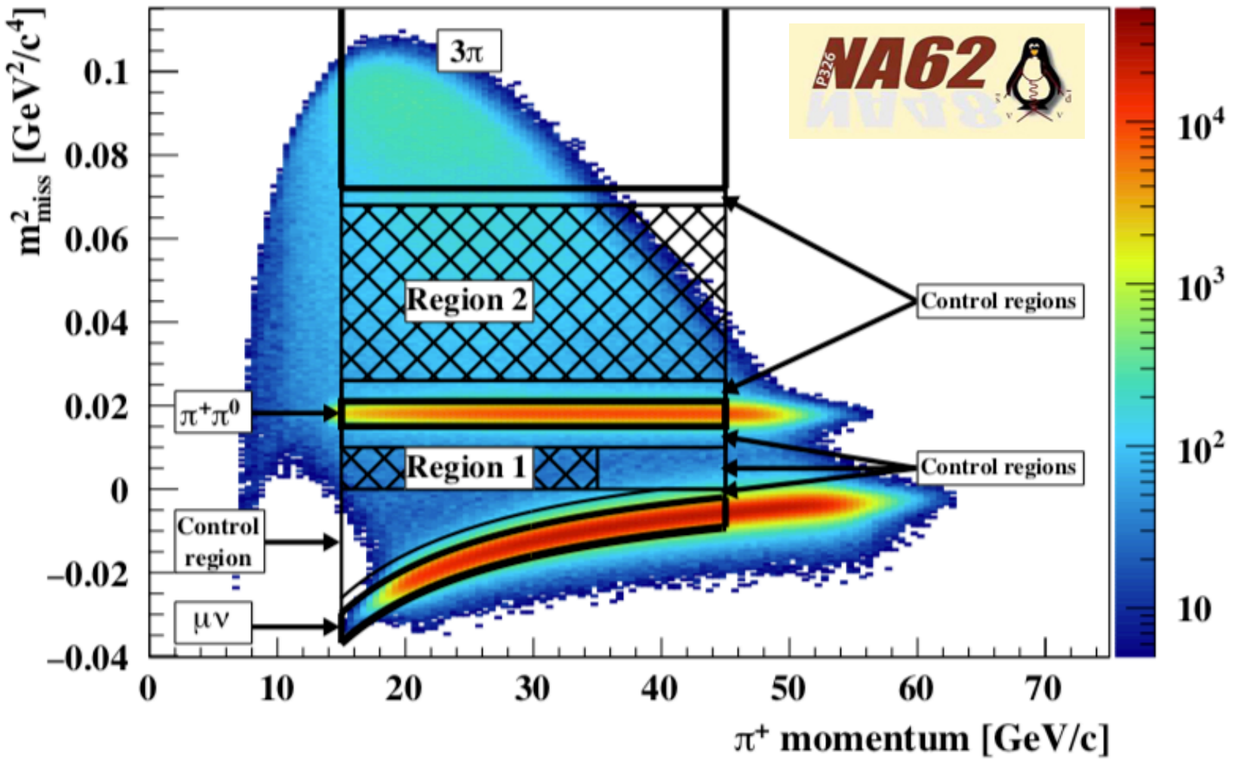
JHEP 04 (2019) 098

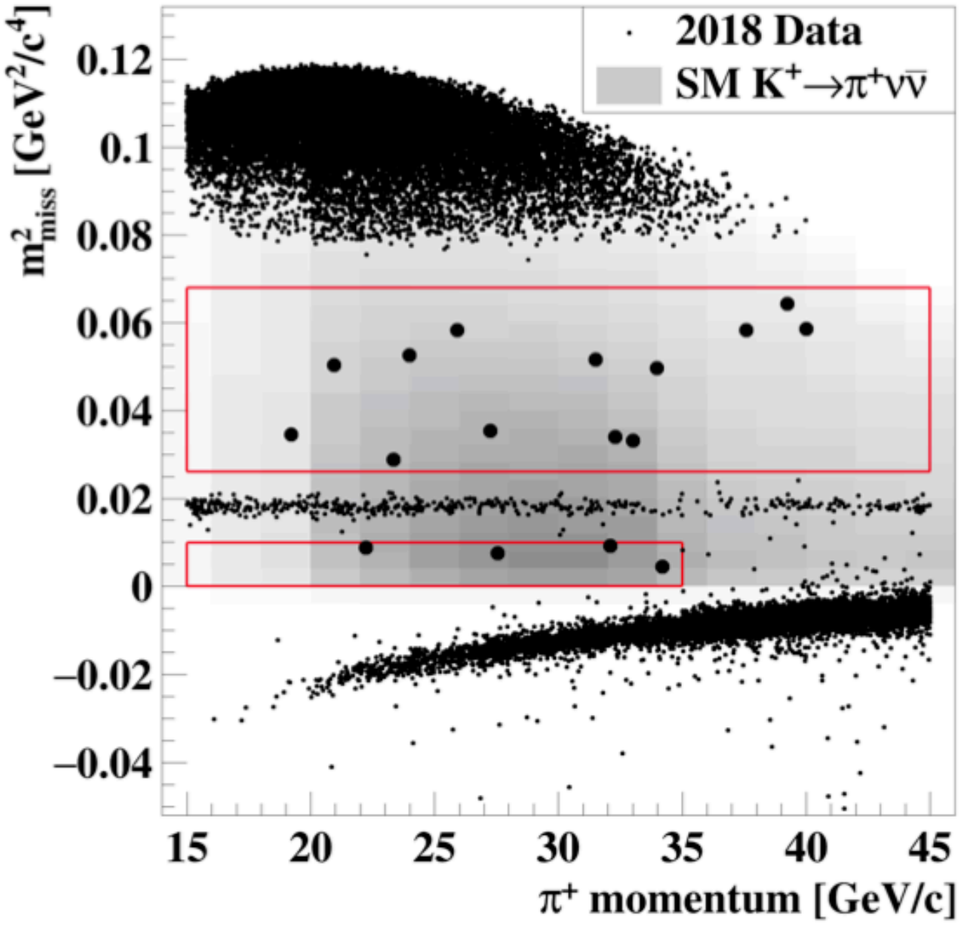


A beautiful (and SM-compatible) legacy of Runs 1 and 2

s→ννd steps towards discovery

JHEP 06 (2021) 093





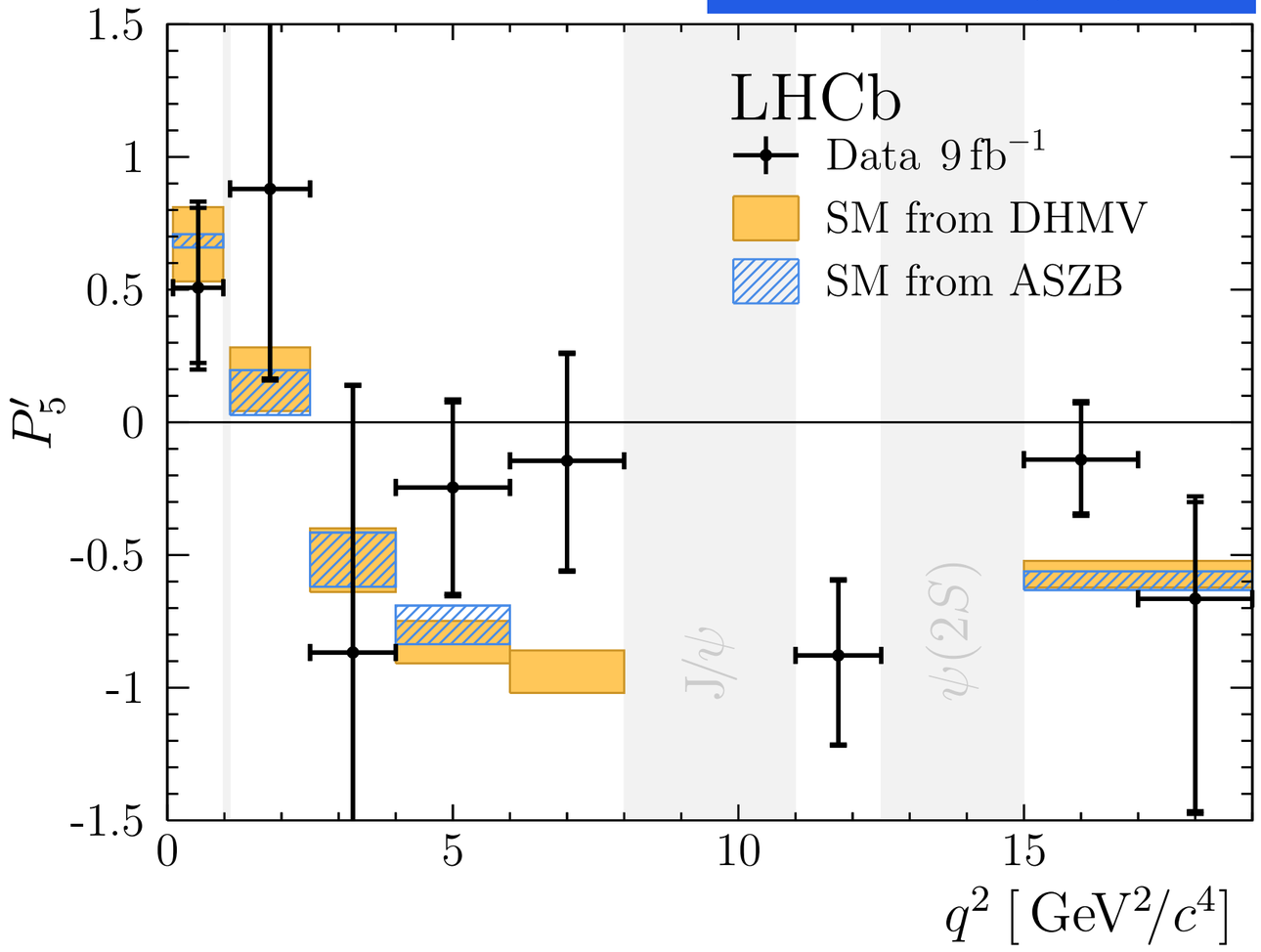
$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$$

Evidence of the decay and good agreement with the SM. A tremendous achievement for NA62!

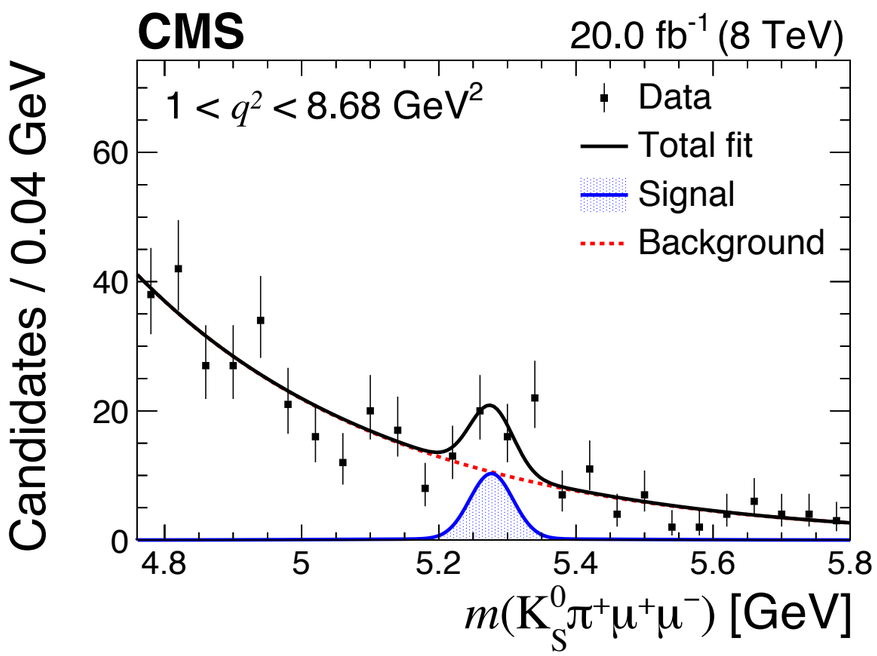
A future observation of $K^0 \to \pi^0 \nu\nu$ opens a fifth way to constrain the apex of the CKM Unitarity Triangle

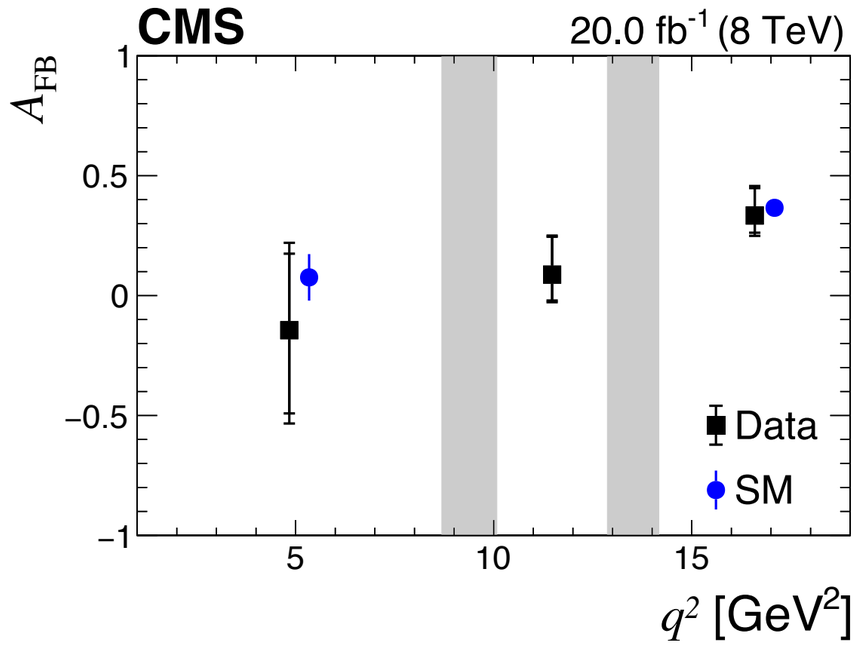
K*$^{+}\mu\mu$ angular analyses

PHYS. REV. LETT.126 (2021) 161802



JHEP 04 (2021) 124



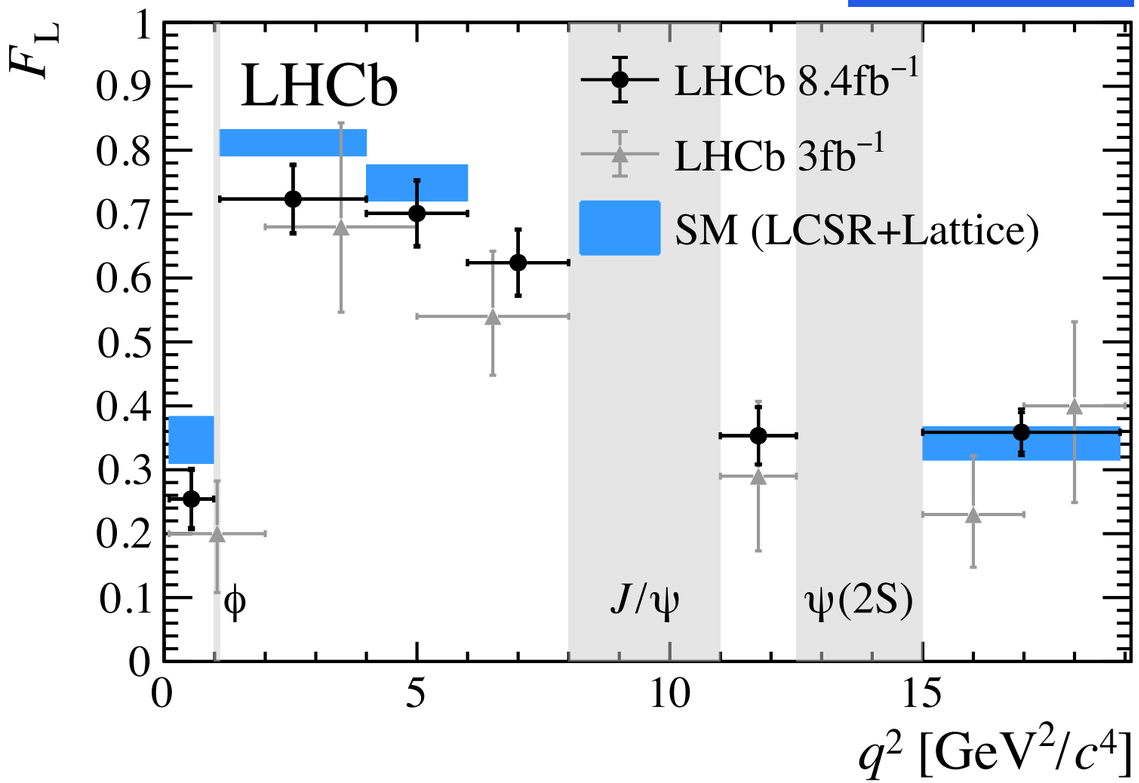


Amazing to see CMS entering the K*+ game — this is what we need as a field!

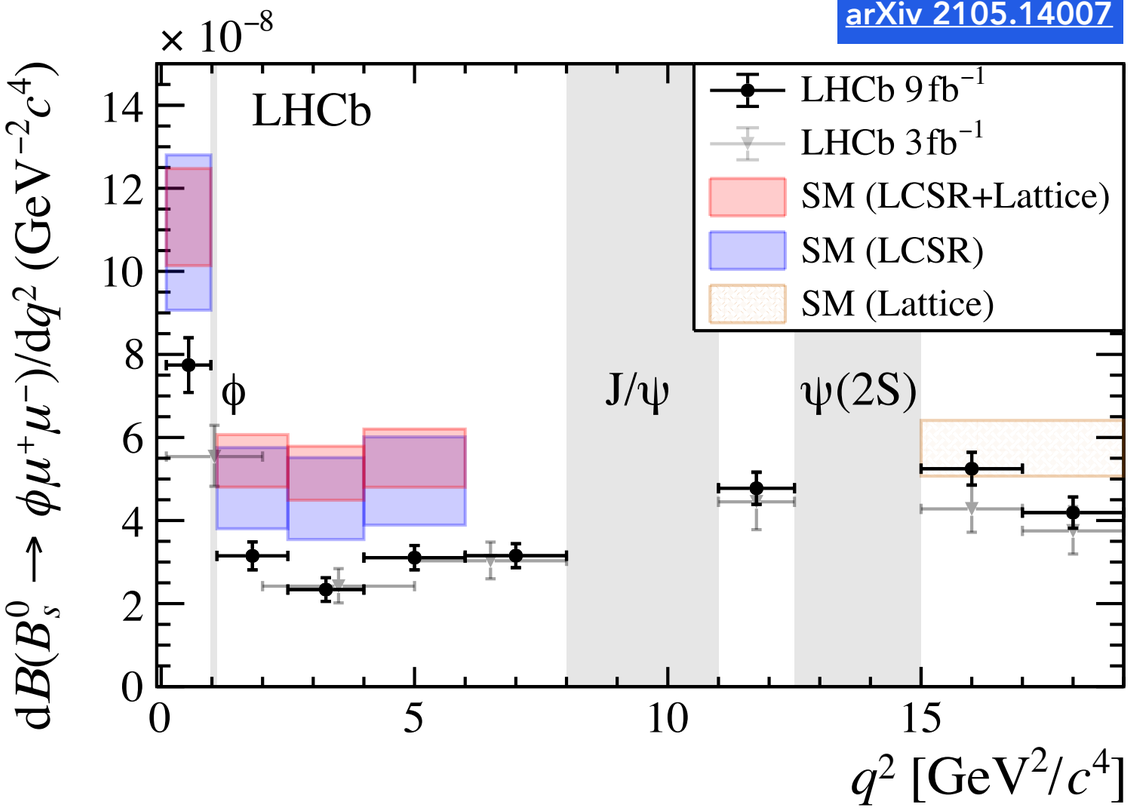
Results in very nice agreement with the picture observed in the neutral K* meson analyses

$\varphi\mu\mu$ angular analysis + branching fraction

arXiv 2107.13428



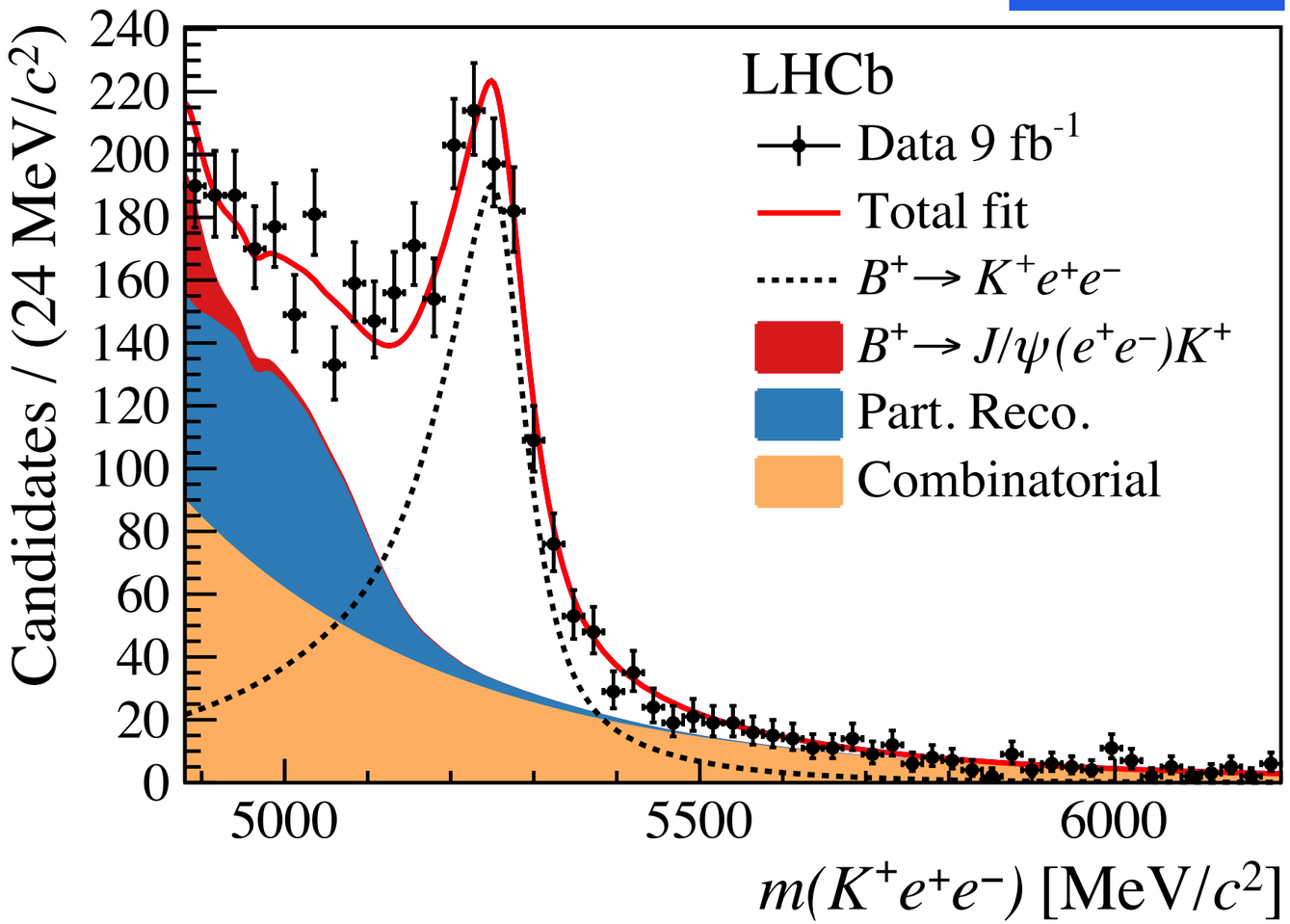
arXiv 2105.14007



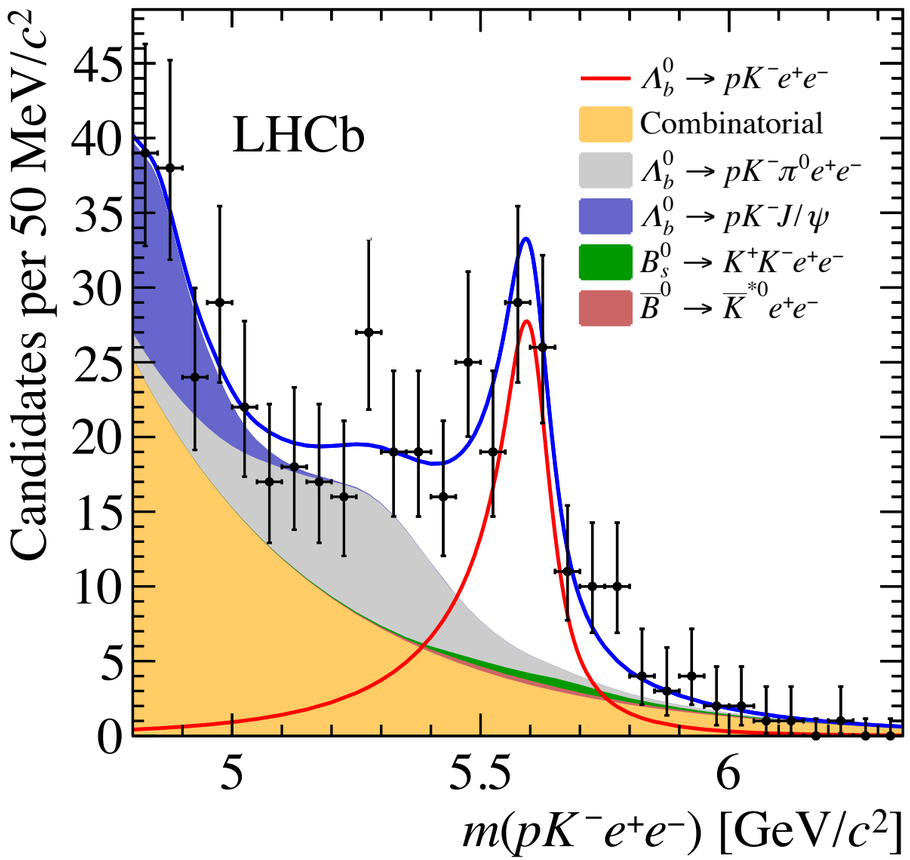
Pattern again consistent with other b→sll angular analyses. At this point fair to say that nobody really thinks these are a pure fluctuation — but more data is needed to determine what they are.

b→sll lepton universality tests

arXiv 2103.11769



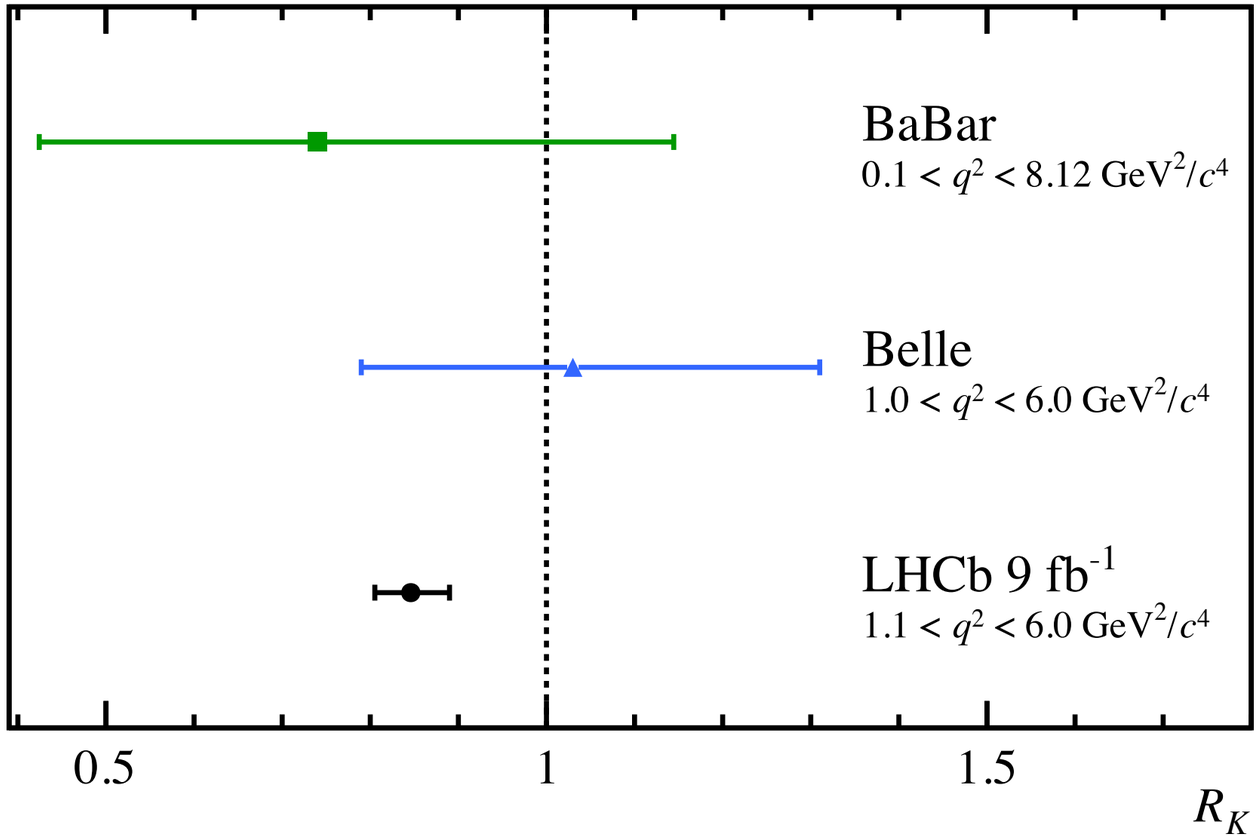
JHEP 05 (2020) 040



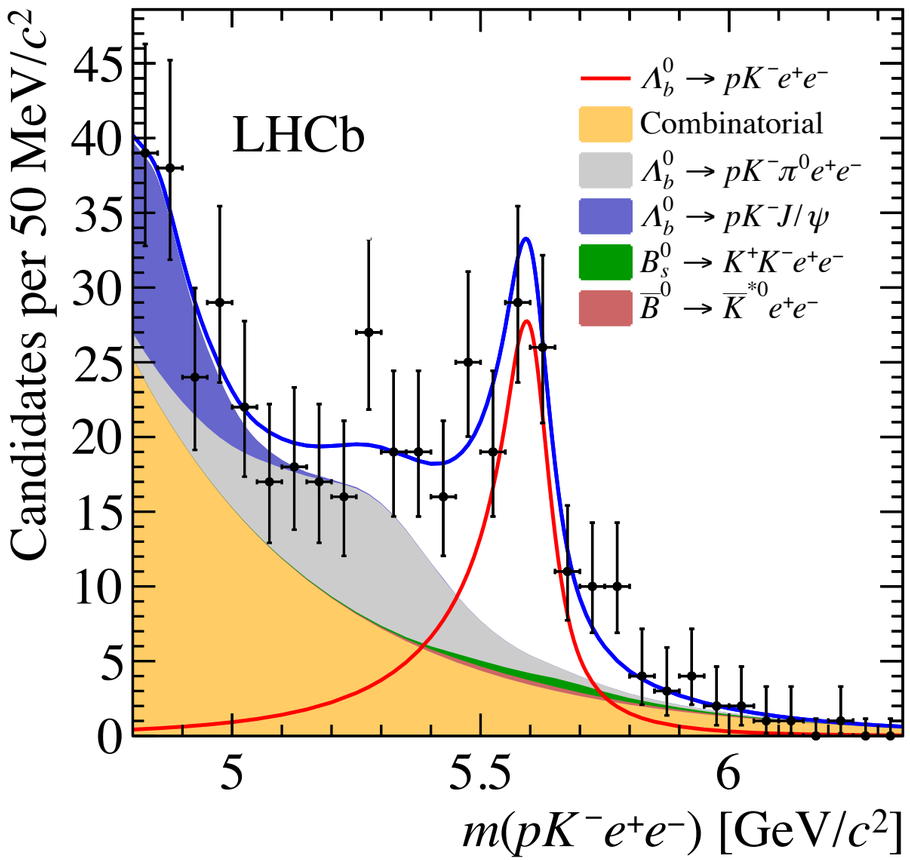
The data is mounting… almost entirely in one direction. Even baryon modes are entering the game.
The latest LHCb analysis of RK provides the first single-measurement evidence for LU in b→sll decays!

b→sll lepton universality tests

arXiv 2103.11769



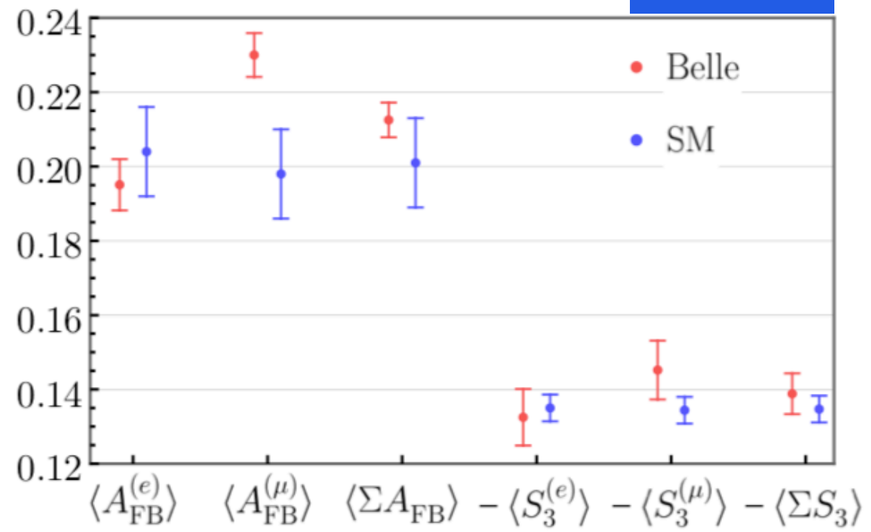
JHEP 05 (2020) 040

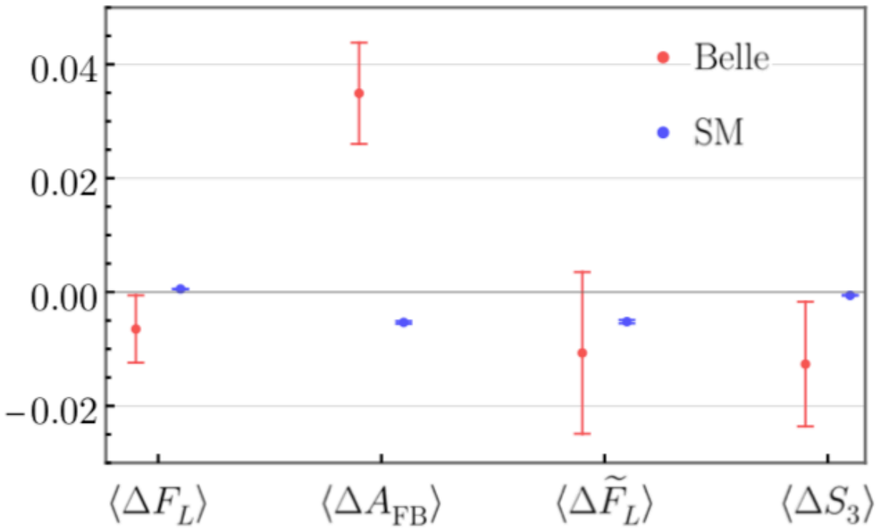


Nevertheless could still be a fluctuation — fascinating to see what CMS (and ATLAS?) can do in this sector

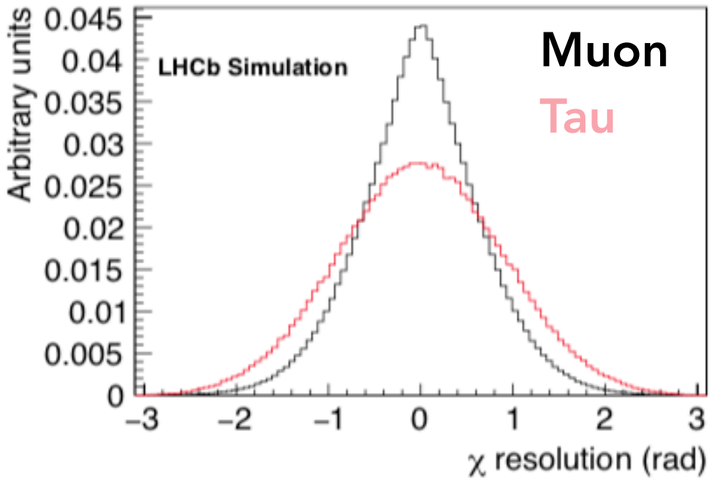
b→clν LU: we need more observables

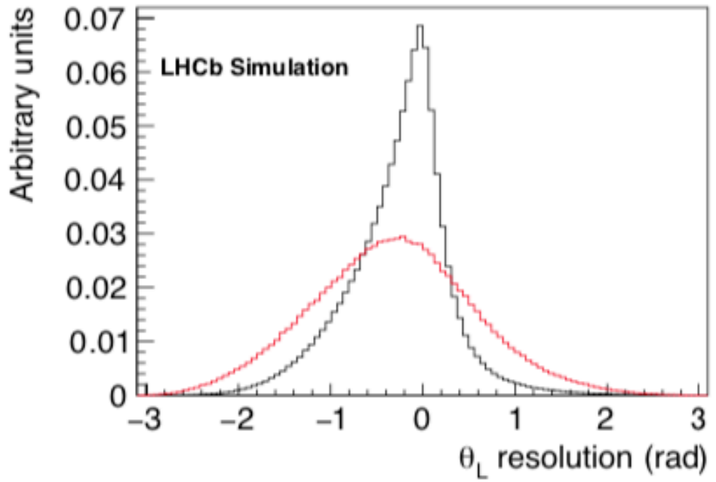
Bobeth et al

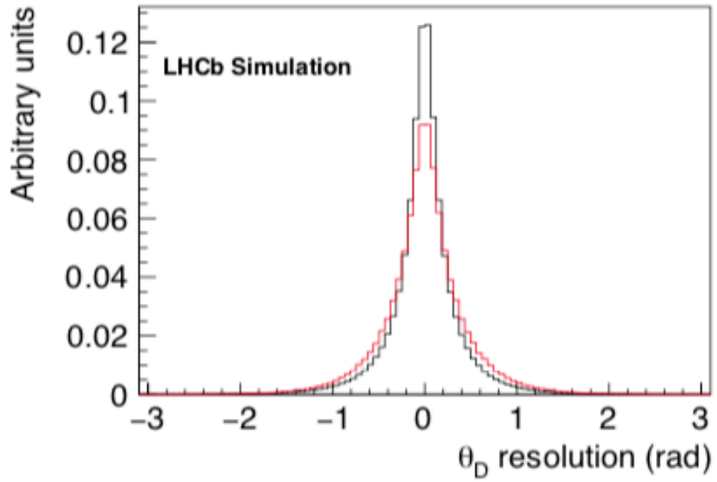




HL-LHC Yellow Report

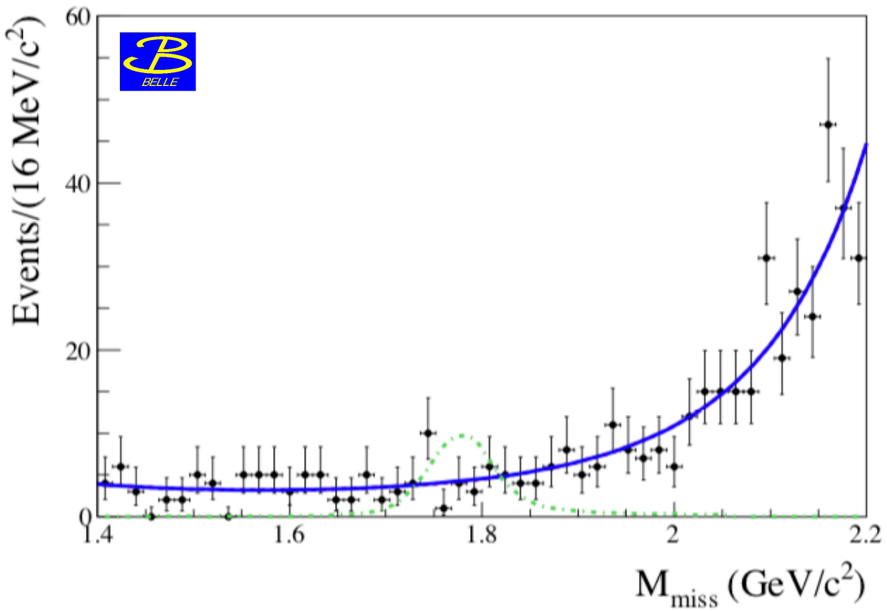






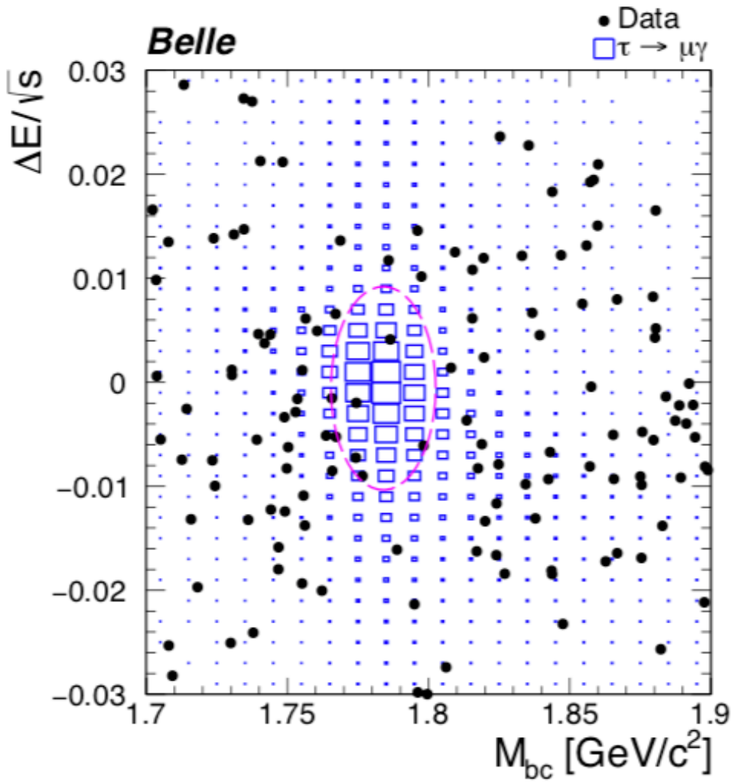
Angular b→sll and b→clν lepton universality tests are slowly starting, despite the difficulties. Post-hoc analysis of Belle data by theory colleagues provides a strong motivation to publish our data in more detail!

Searches for LFV



Mode	ε $(\times 10^{-4})$	$N_{\rm sig}$	$N_{\rm sig}^{\rm UL}$	$\mathcal{B}^{\rm UL}$ $(\times 10^{-5})$
$B^0 \to \tau^\pm \mu^\mp$	11.0	$1.8\,^{+8.2}_{-7.6}$	12.4	1.5
$B^0 \to \tau^\pm e^\mp$	9.8	$0.3\,^{+8.8}_{-8.2}$	11.6	1.6

Belle Preprint 2021-23

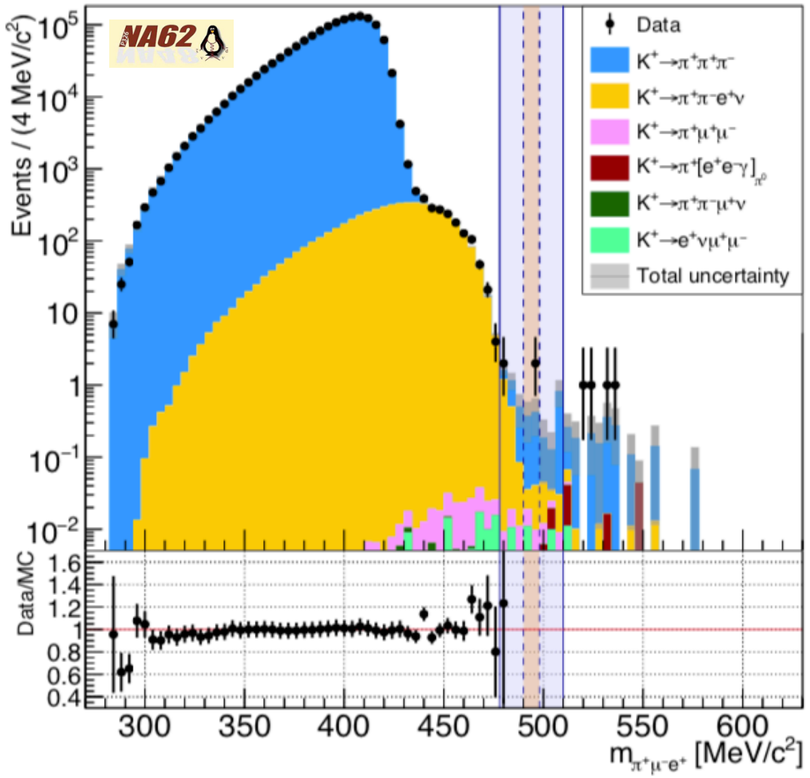


(a) $\tau^\pm \to \mu^\pm \gamma$

$$\mathcal{B}(\tau^\pm \to \mu^\pm \gamma) < \frac{\tilde{s}_{90}}{2\epsilon N_{\tau\tau}} = 4.2 \times 10^{-8},$$

$$\mathcal{B}(\tau^\pm \to e^\pm \gamma) < \frac{\tilde{s}_{90}}{2\epsilon N_{\tau\tau}} = 5.6 \times 10^{-8},$$

Belle Preprint 2021-09



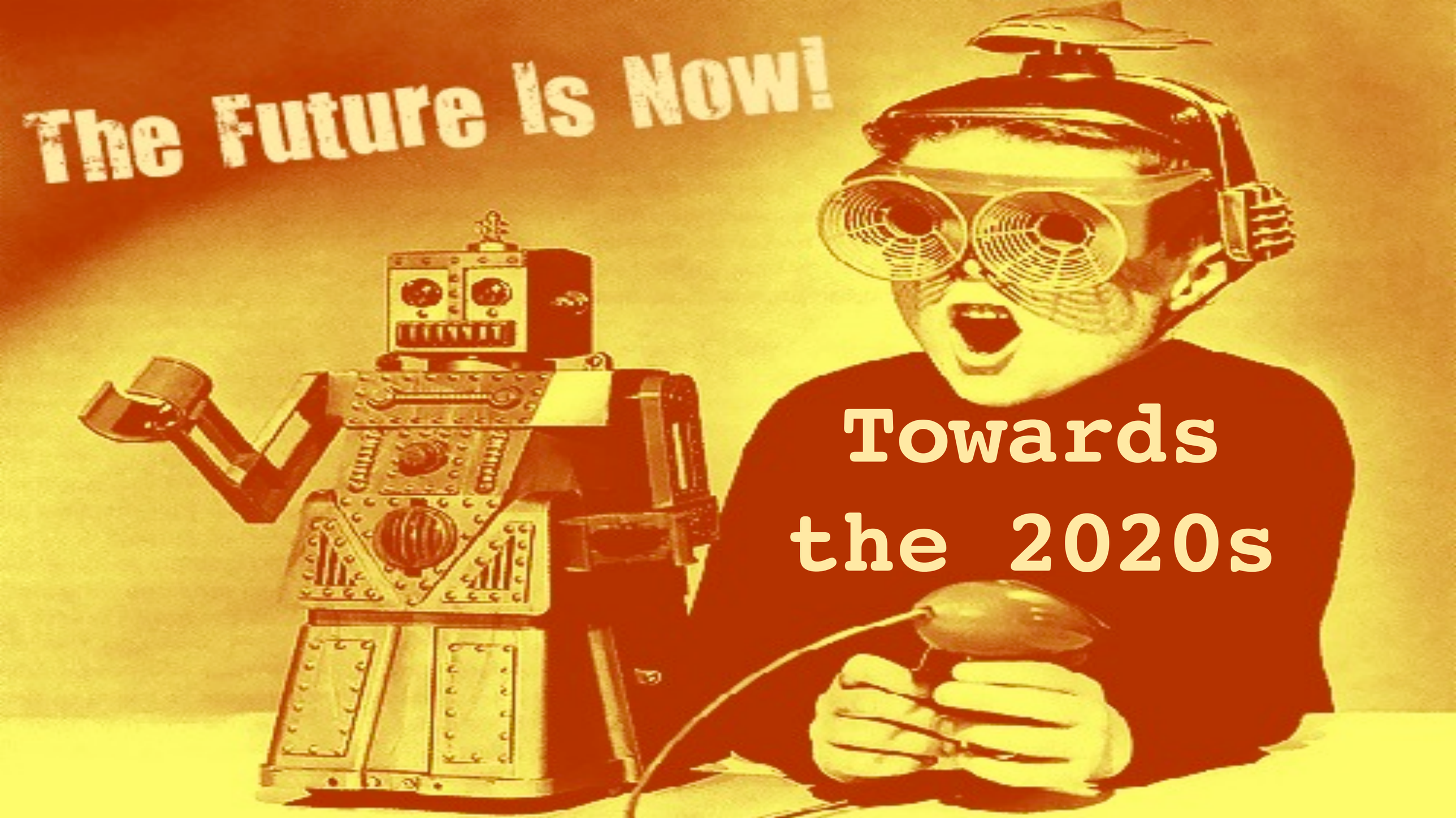
$$\mathcal{B}(K^+ \to \pi^- \mu^+ e^+) < 4.2 \times 10^{-11};$$

$$\mathcal{B}(K^+ \to \pi^+ \mu^- e^+) < 6.6 \times 10^{-11};$$

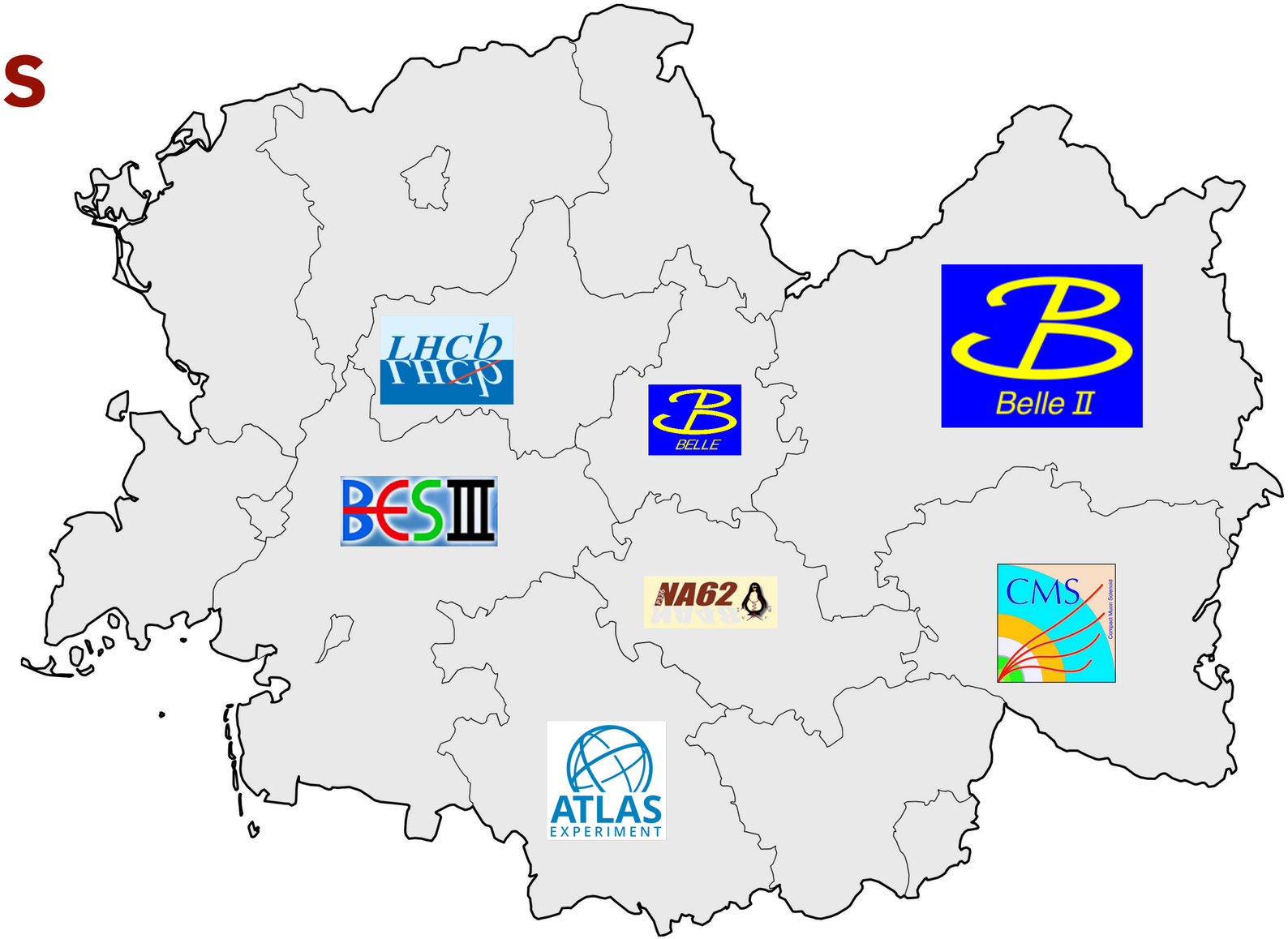
$$\mathcal{B}(\pi^0 \to \mu^- e^+) < 3.2 \times 10^{-10}.$$

NA62 -- CERN-EP-2021-090

Many searches going on across the full range of hadron/lepton decays...


The Future Is Now!
Towards
the 2020s

Final thoughts



All eyes on Belle 2 — vital sociologically and scientifically to have an e^+e^- flavour factory in business

CMS has a potentially amazing HL-LHC detector&trigger. Can they make the most of it?

Vital to ensure LHCb upgrade 2 is the best detector possible, with a much bigger budget than previous ones.

BES III and NA62 will continue to play unique and crucial roles in the experimental landscape

Backup