# Probing new horizons with flavour at the LHCb experiment

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technische universität dortmund

European Research Council
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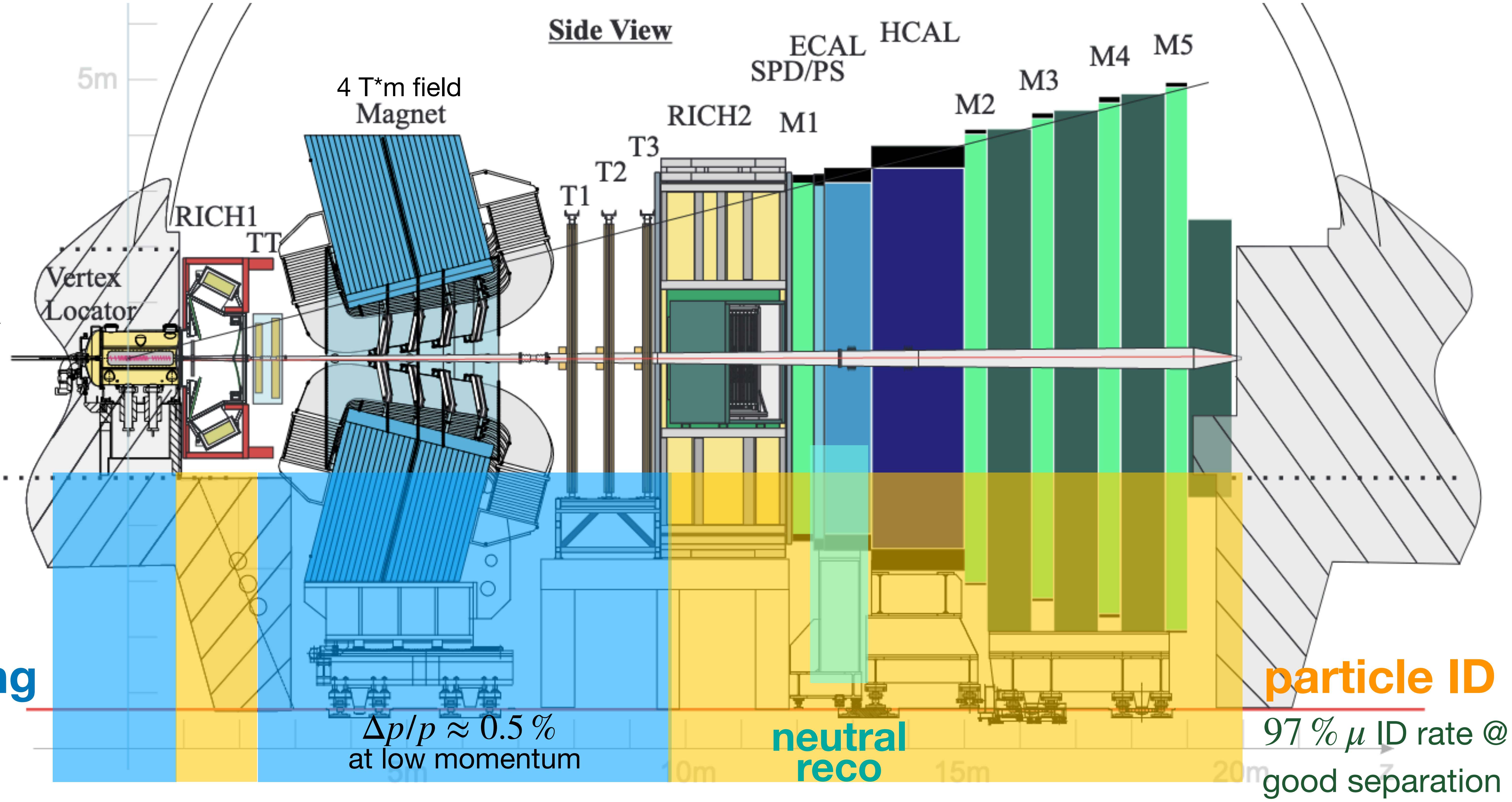
LHCb

# Why LHCb?



- Original motivation: precision measurements of CP violation and rare decays in beauty and charm
- Today: **the ultimate flavour factory at the LHC**, and a general-purpose forward detector
  - Study not only $pp$ collisions, but also heavy-ion ($pPb$, $PbPb$) and fixed-target ($p$-gas)

$\sigma_{IP} \approx 20\mu m$
at high pT




tracking

$\Delta p/p \approx 0.5\,\%$
at low momentum

neutral
reco

particle ID

$97\,\%$ $\mu$ ID rate @ 1-3% pion misID;
good separation of hadrons $\pi/K/p$

2011–2018 (Runs 1-2):
Collected ~9 fb$^{-1}$ integrated luminosity
in 7, 8, 13 TeV pp collisions
with >90% data-taking efficiency

2022– (Run 3):
starting now!

- Highly complementary to $e^+e^-$ "B-factory" experiments:
  - Produce **all types** of b,c-**mesons** and **baryons**
  - Huge **cross-section** and large **boost**
  - But weaker capabilities with neutral particles and lack of beam-energy constraint

# The menu for today

note: I had to cherry-pick results to fit in time.

**First course:**
heavy-flavour spectroscopy
- classical
- exotic

**See also:** Wednesday & Friday plenary
and numerous parallel talks

**Second course:**
weak decays of heavy flavour
- mixing and CPV
- rare semileptonic decays

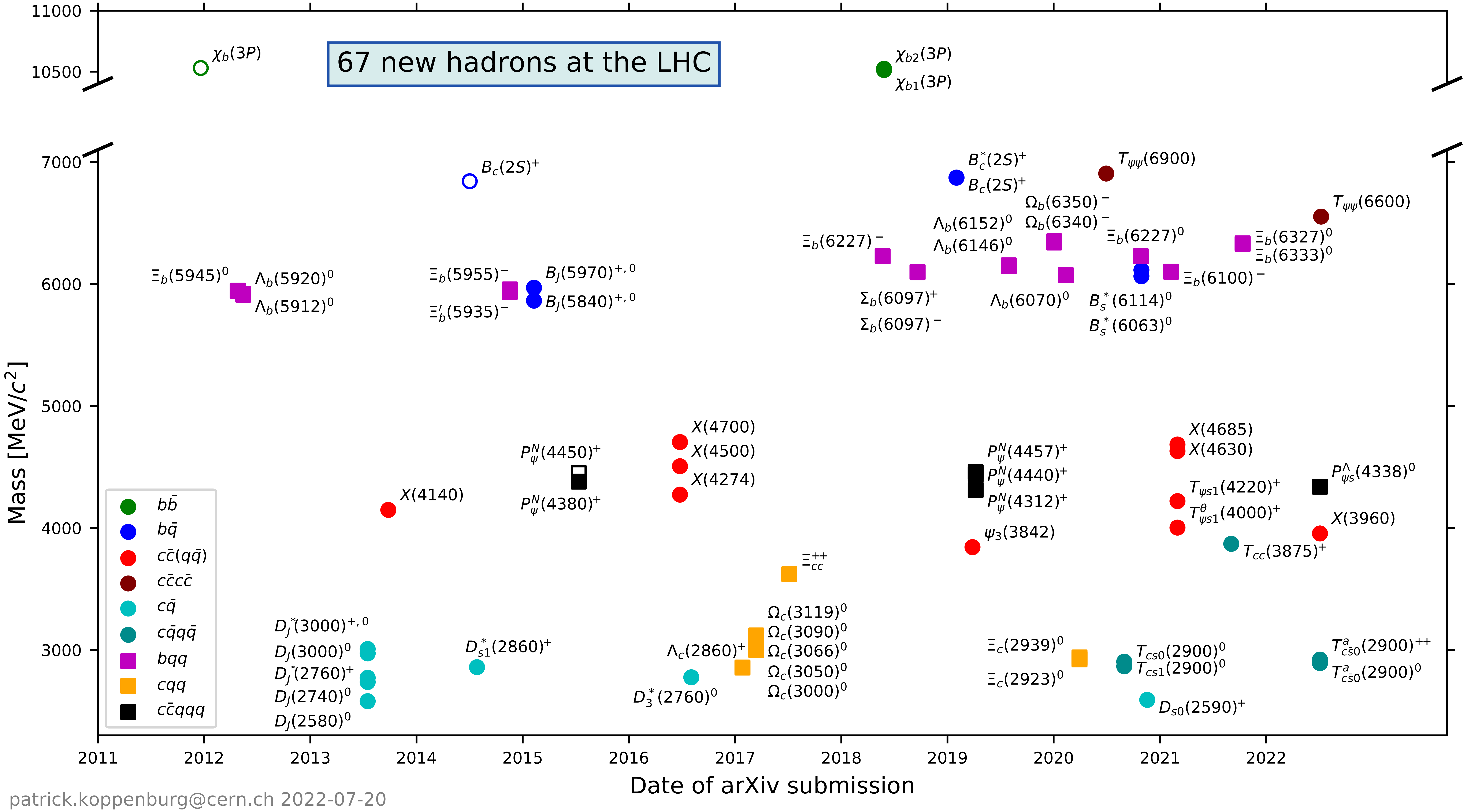
**See also:** Tuesday plenary
and numerous parallel talks

**Dessert:**
dreams on the bright future of flavour physics

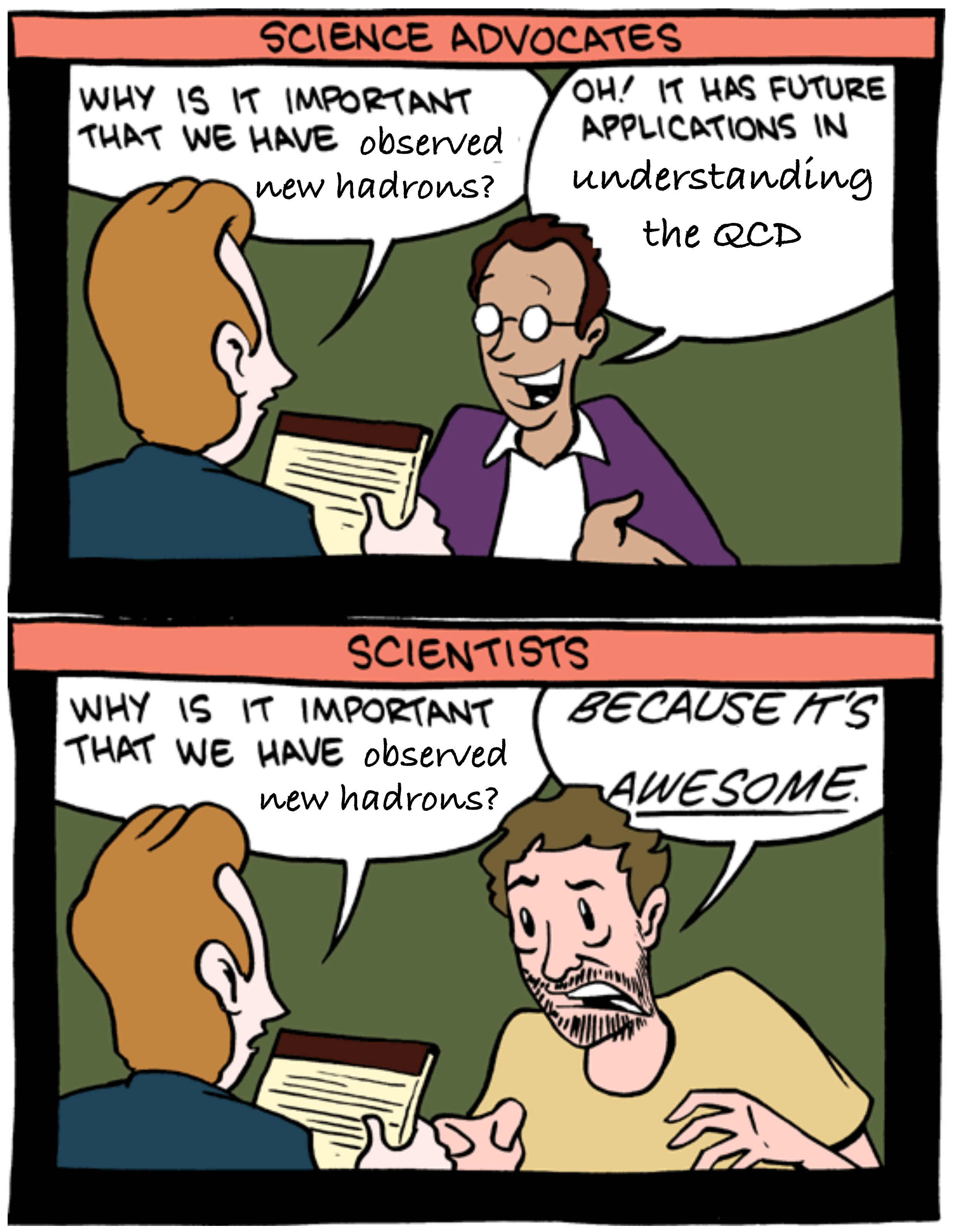
# Fantastic beasts…

## The LHC experiments steadily deliver new discoveries of conventional and exotic hadrons

LHCb-FIGURE-2021-001 and updates in https://www.nikhef.nl/~pkoppenb/particles.html



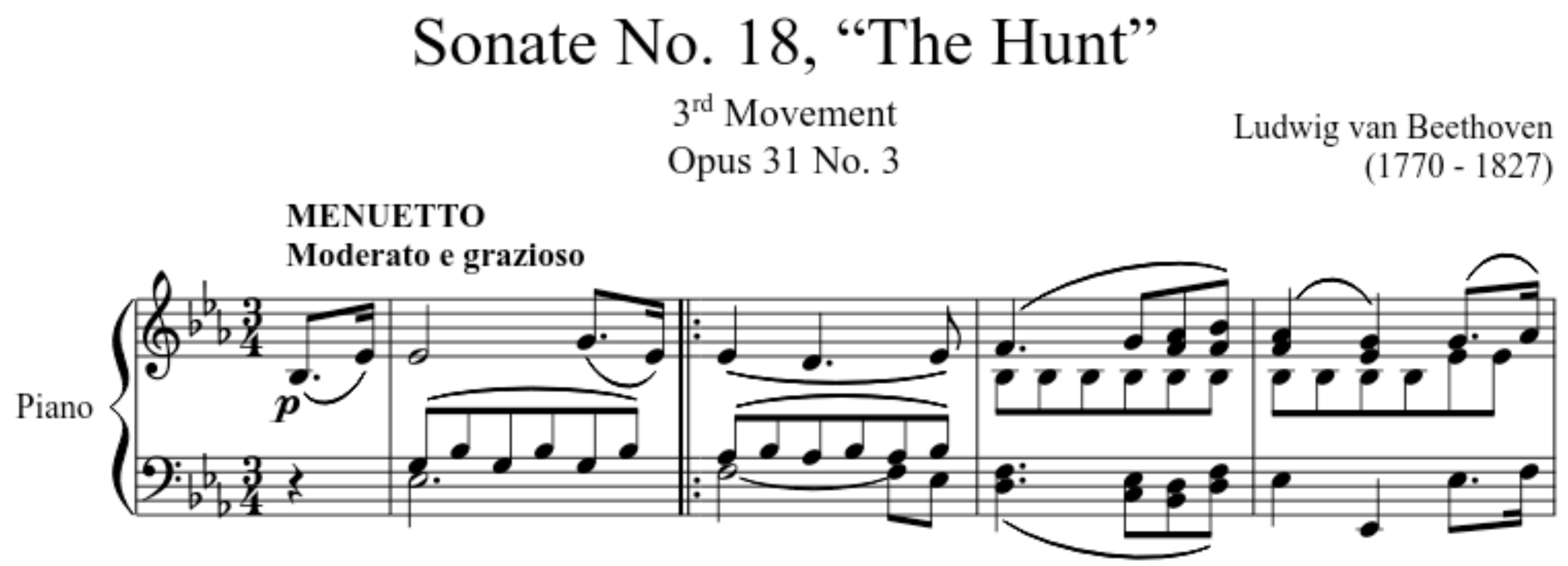


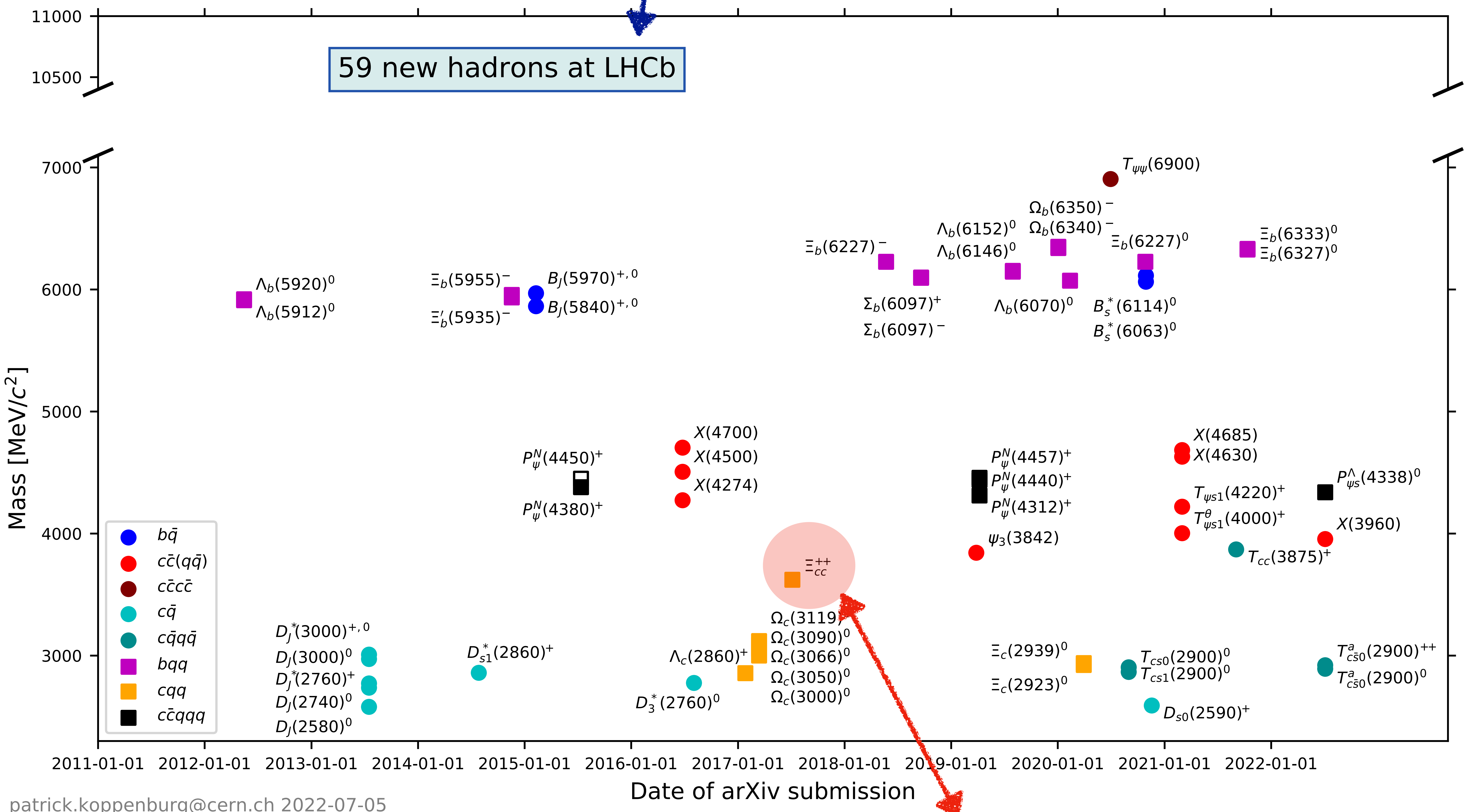

https://www.smbc-comics.com/?id=2088

# Fantastic beasts… and where to find them






## Majority at LHCb!




weakly-decaying

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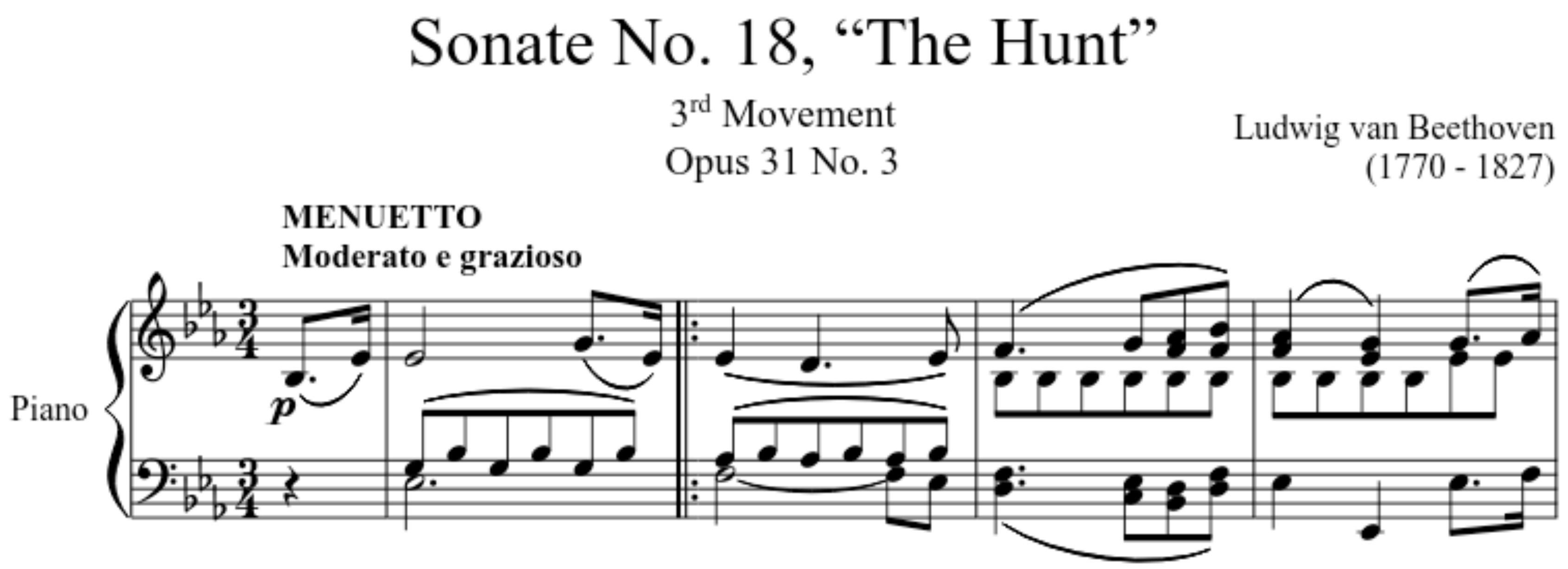
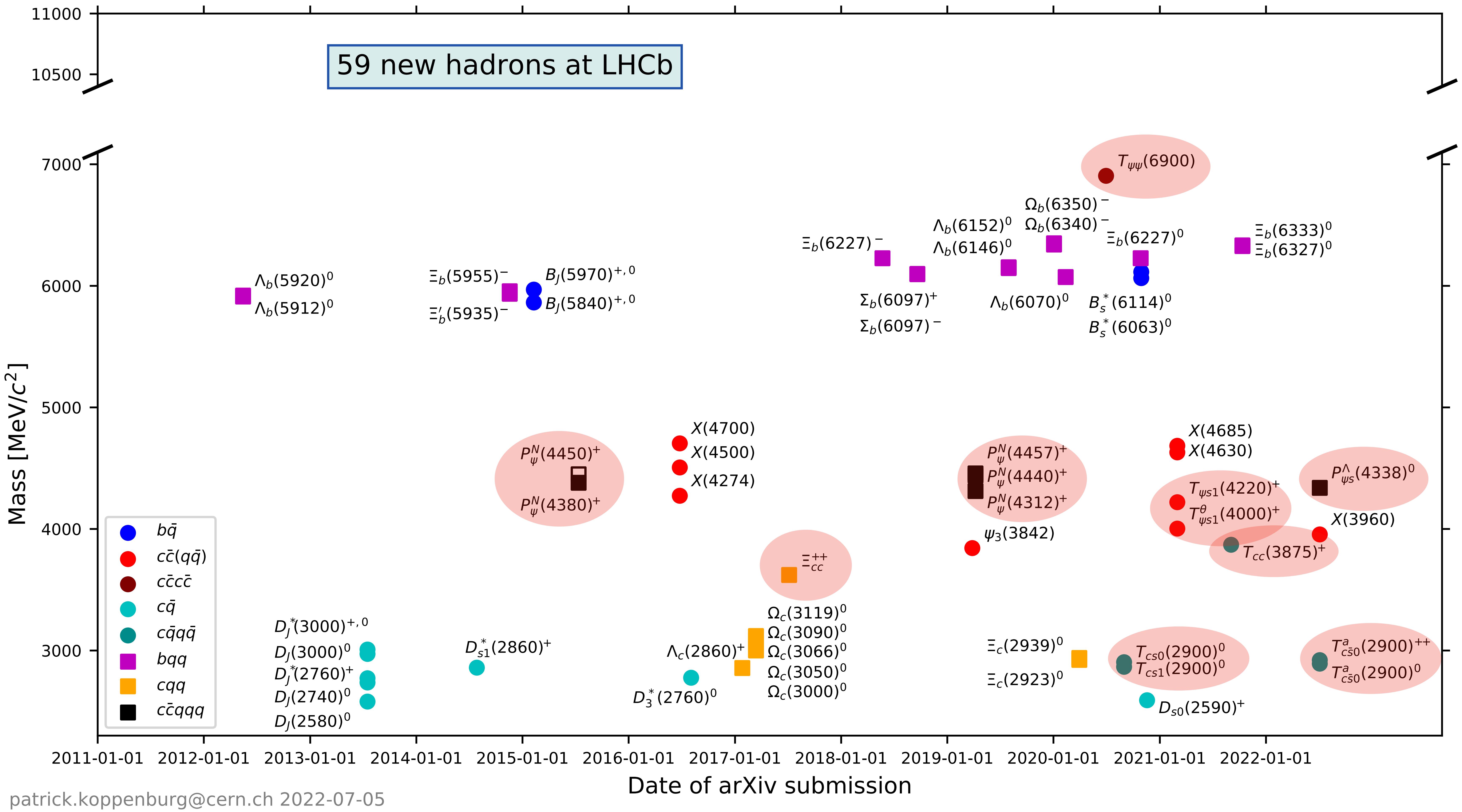
# Fantastic beasts… and where to find them






**How to systematise the new beasts?**

LHCb proposed a new naming scheme for exotic hadrons: 2206.15233

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new quark combinations

# What are the biggest missing pieces in our conventional spectroscopy puzzle?

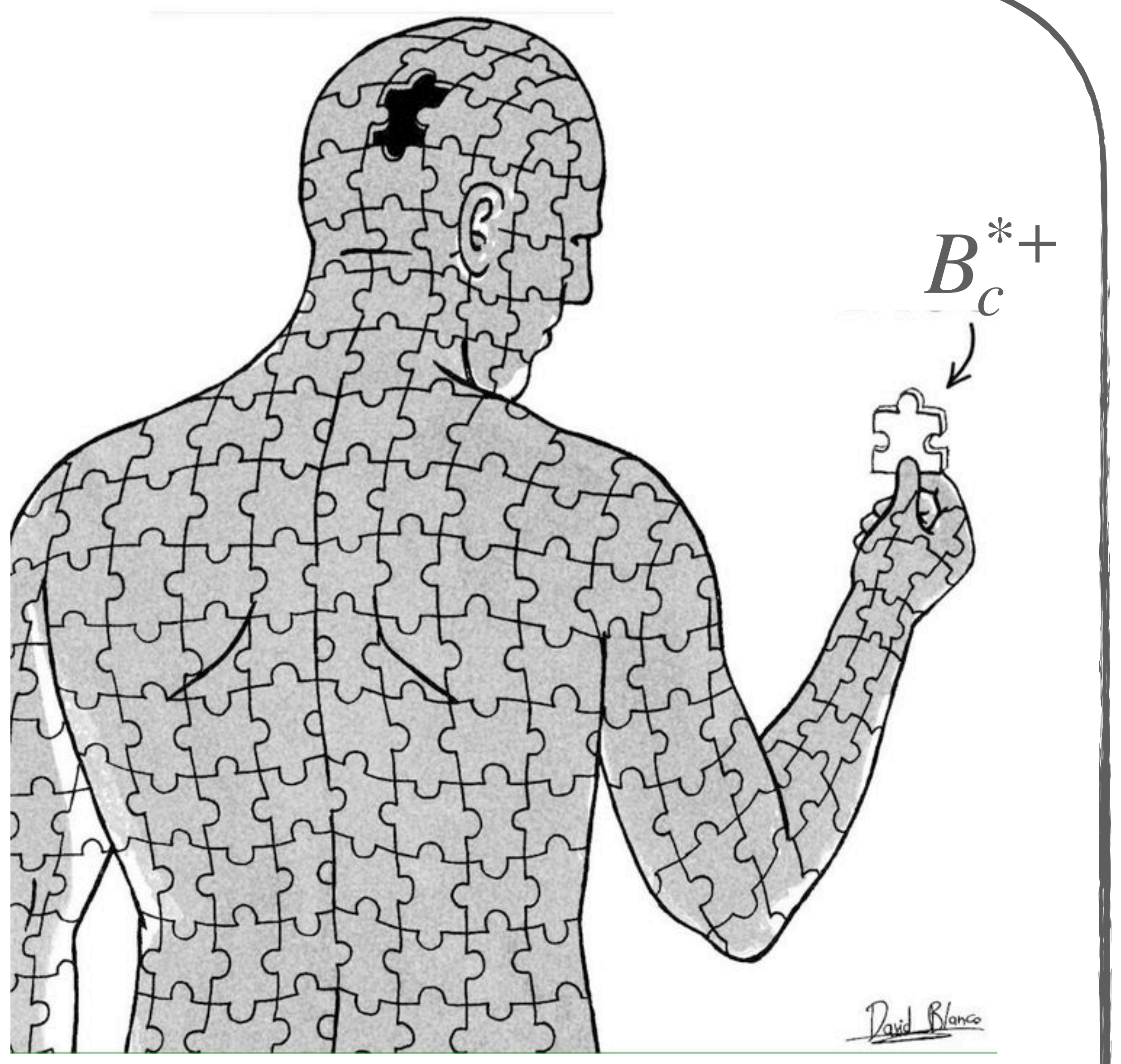
## Mesons:

All possible combinations of $u, d, s, c, b$ quarks+antiquarks are known!

All pseudoscalar ground L=0 states ($q_\uparrow \bar{q}_\downarrow$) are known

One vector ground L=0 state ($q_\uparrow \bar{q}_\uparrow$), namely, $B_c^{*+} = (c_\uparrow \bar{b}_\uparrow)$, not yet discovered

Much work to do for excited states ($L > 0$).




Ground-State Meson Man
(not your average superhero)

## Baryons:

Most combinations with >1 heavy quark (c/b) not observed yet, except for $\Xi_{cc}^{++} = (ccu)$.

All possible combinations with (0, 1) heavy quarks are known.

**Four** ground states (L=0) with one heavy quark not yet discovered:

$\Sigma_b^0(udb)$ and $\Xi_b^{\prime 0}(usb)$ – spin 1/2,
$\Sigma_b^{*0}(udb)$ and $\Omega_b^{*-}(ssb)$ – spin 3/2.

note:
lighter states with these quark contents are known

Much work to do for excited states ($L > 0$).

**Q1:** What is the problem for the missing L=0 states?
**A:** Their decay modes are $B_c^{*+} \to B_c^+ \gamma$ or $\Sigma_b^0 \to \Lambda_b^0 \pi^0$, with very low Q values.
Soft photons or $\pi^0$ are challenging at a hadron collider.

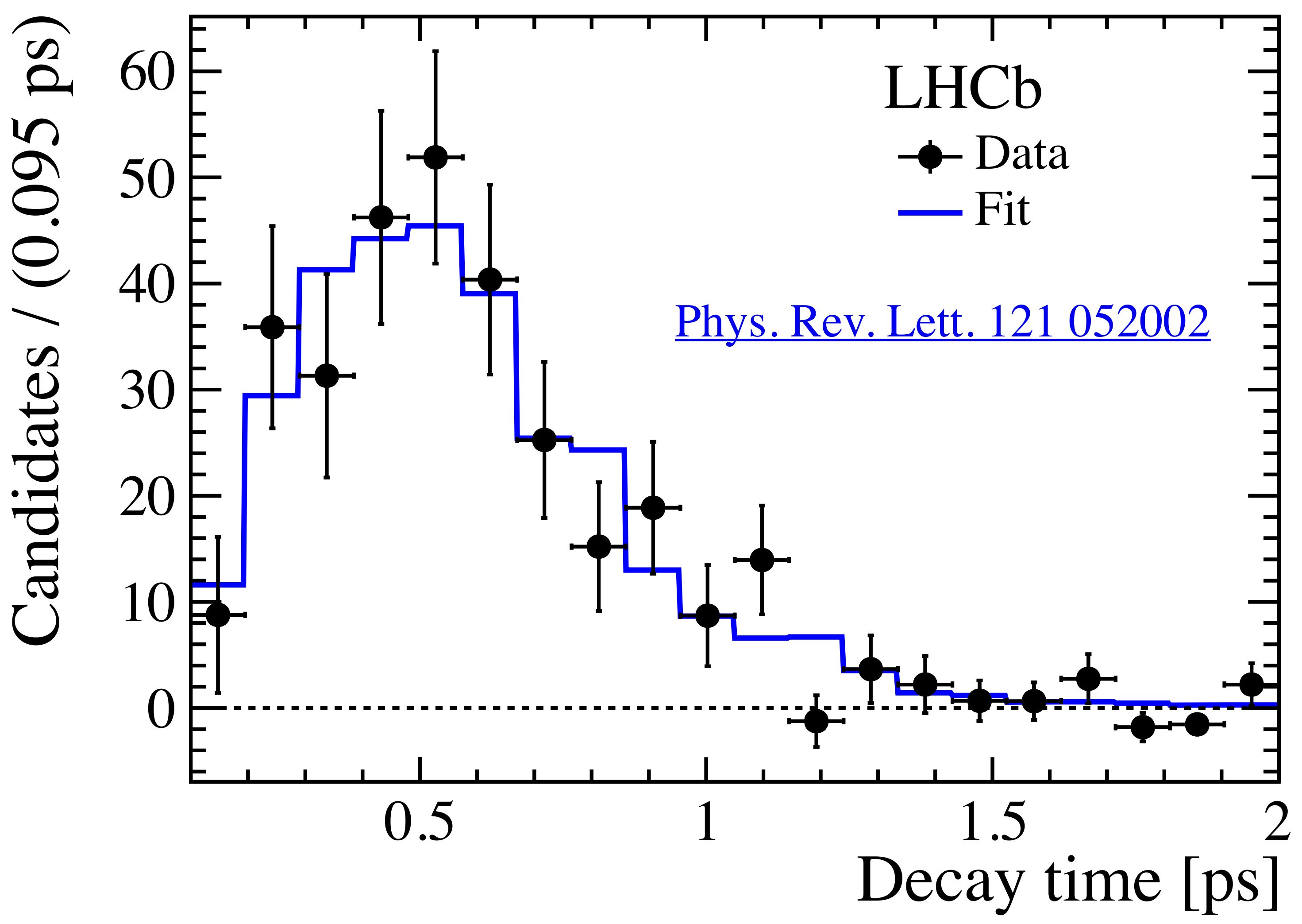
**Q2:** What is the problem for baryons with >1 heavy quark?
**A:** Tiny production rate at the LHC and small BF for individual fully-reconstructed decay modes. For many of them, short lifetime (= large background).

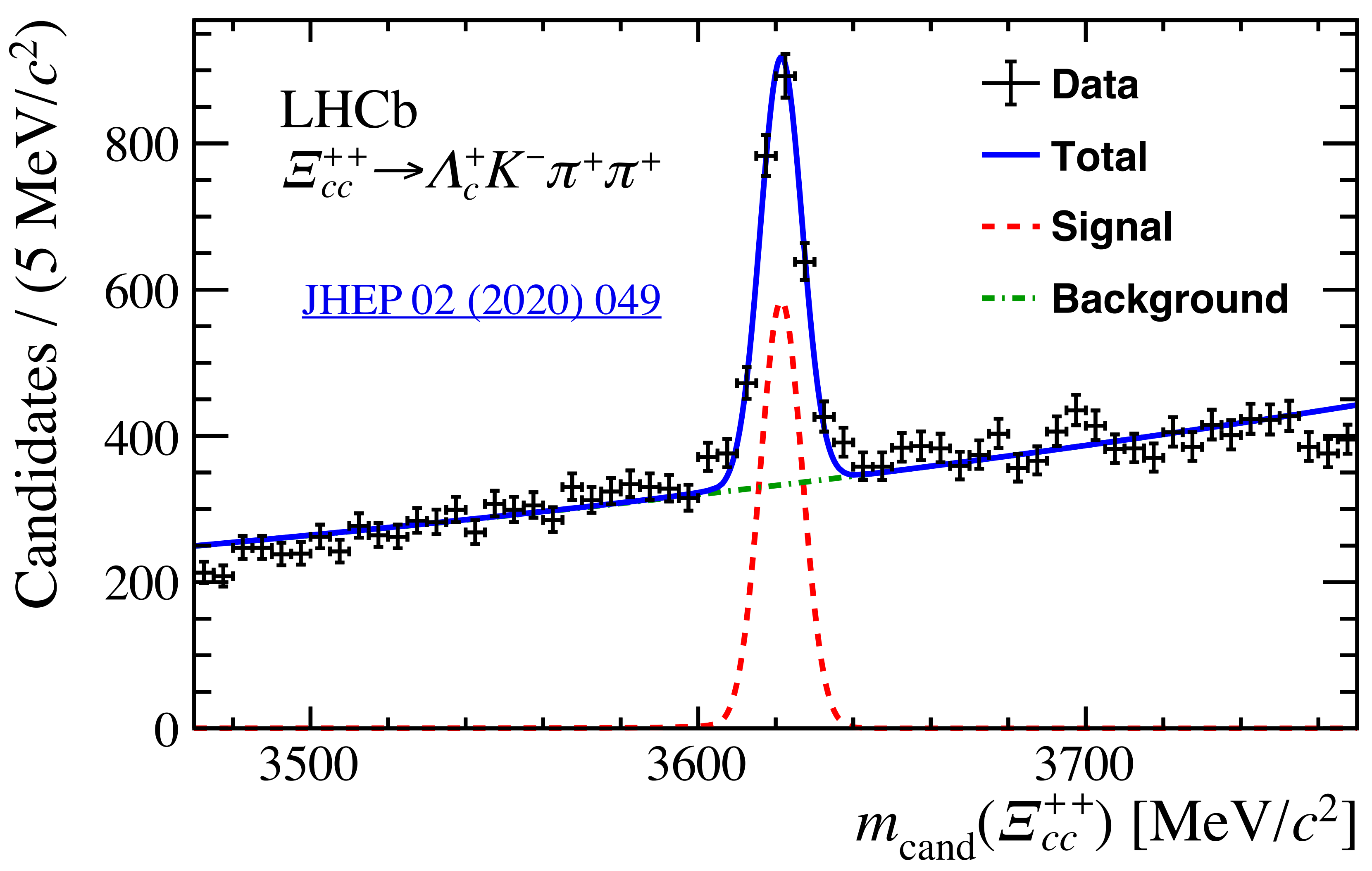
Need a lot more data, and clever ideas.

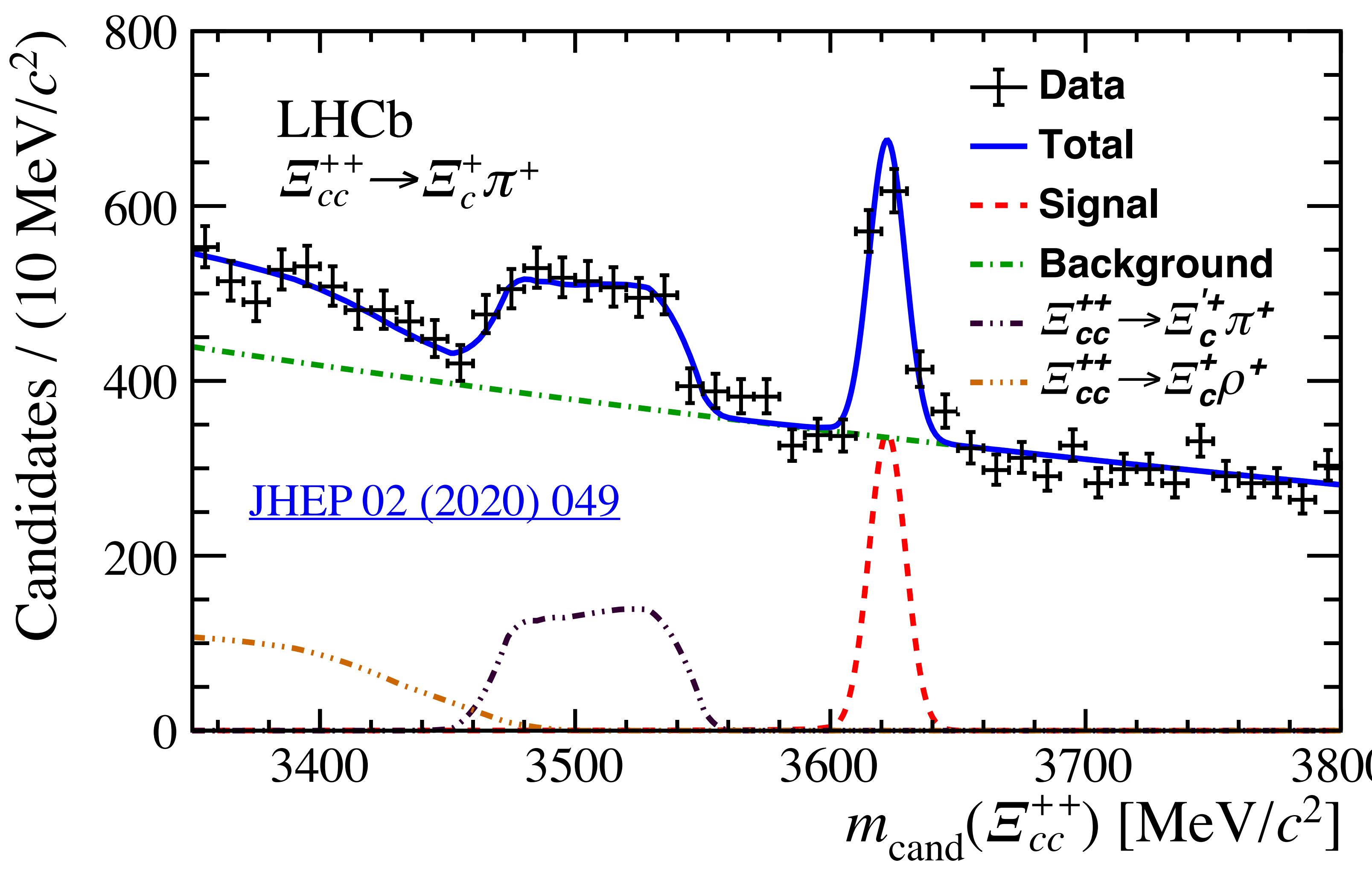
# Doubly charming: first taste



- LHCb has discovered the $\Xi_{cc}^{++}$ baryon (ccu) in 2017.
- Since then: precise measurements of its mass, lifetime, production rate and several decay channels!




$$m = 3621.55 \pm 0.23(\mathrm{stat.}) \pm 0.30(\mathrm{syst.})\ \mathrm{MeV/c^2}$$

$$\tau = 0.256^{+0.024}_{-0.022}(\mathrm{stat.}) \pm 0.014(\mathrm{syst.})\ \mathrm{ps}$$

Relative branching fractions measured for:

$$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$$
$$\Xi_{cc}^{++} \to \Xi_c'^{+} \pi^+$$
$$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$$

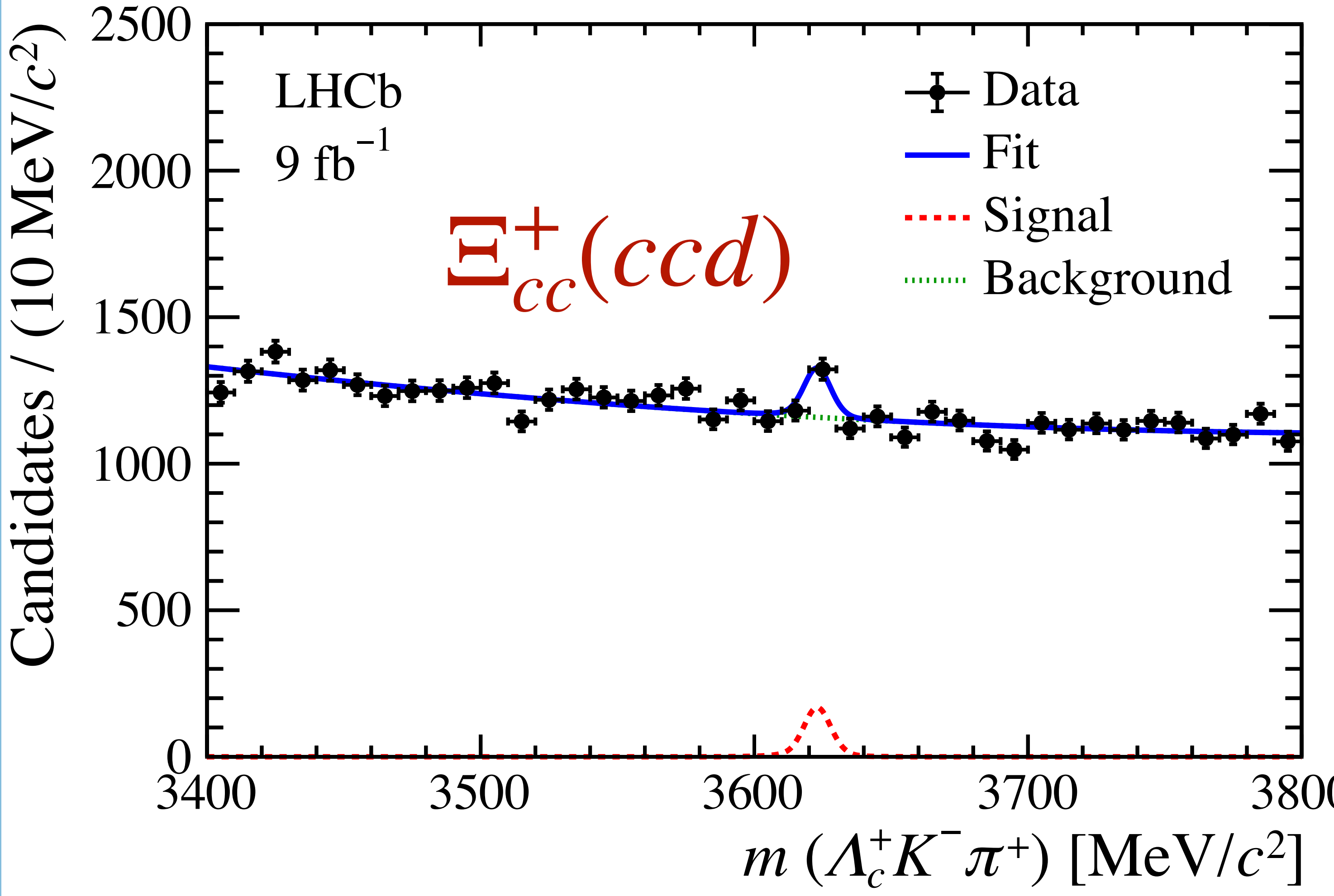
(times the production cross-section)

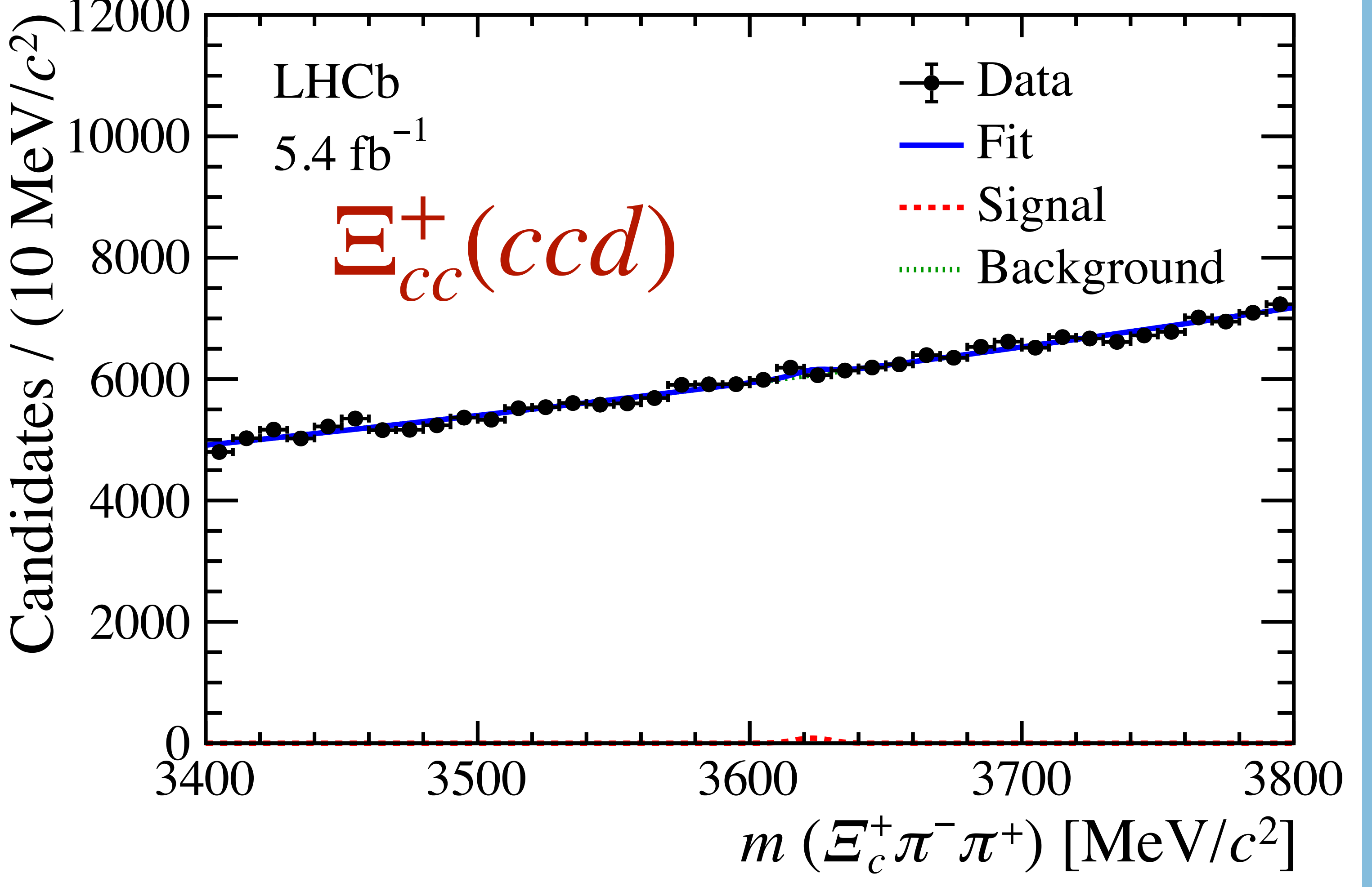
**Quest for Run 3: excited states and new decay modes.**
**Guidance by theory is always welcome.**

# Catch me if you can

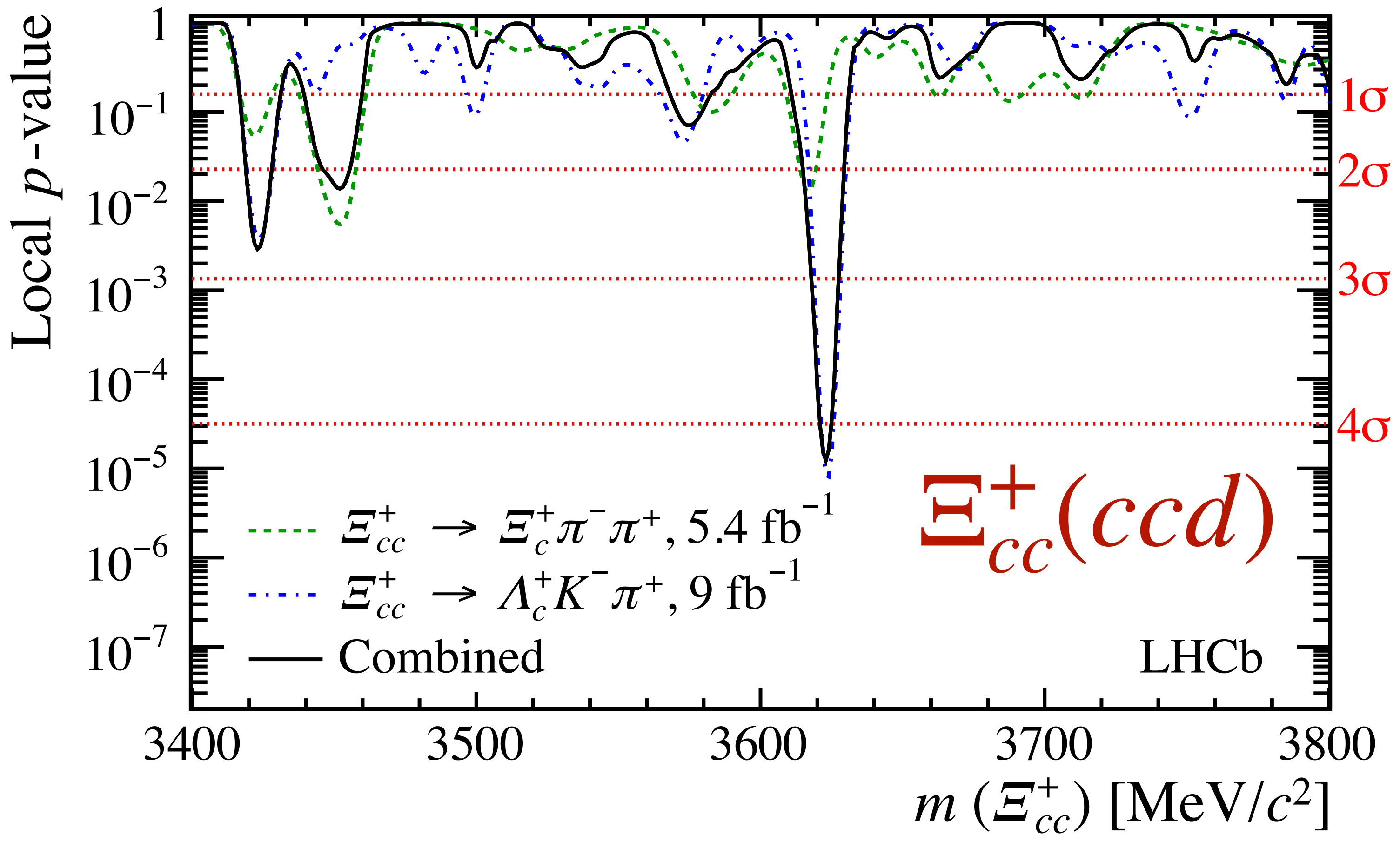


- Numerous searches for other doubly-heavy baryons at LHCb

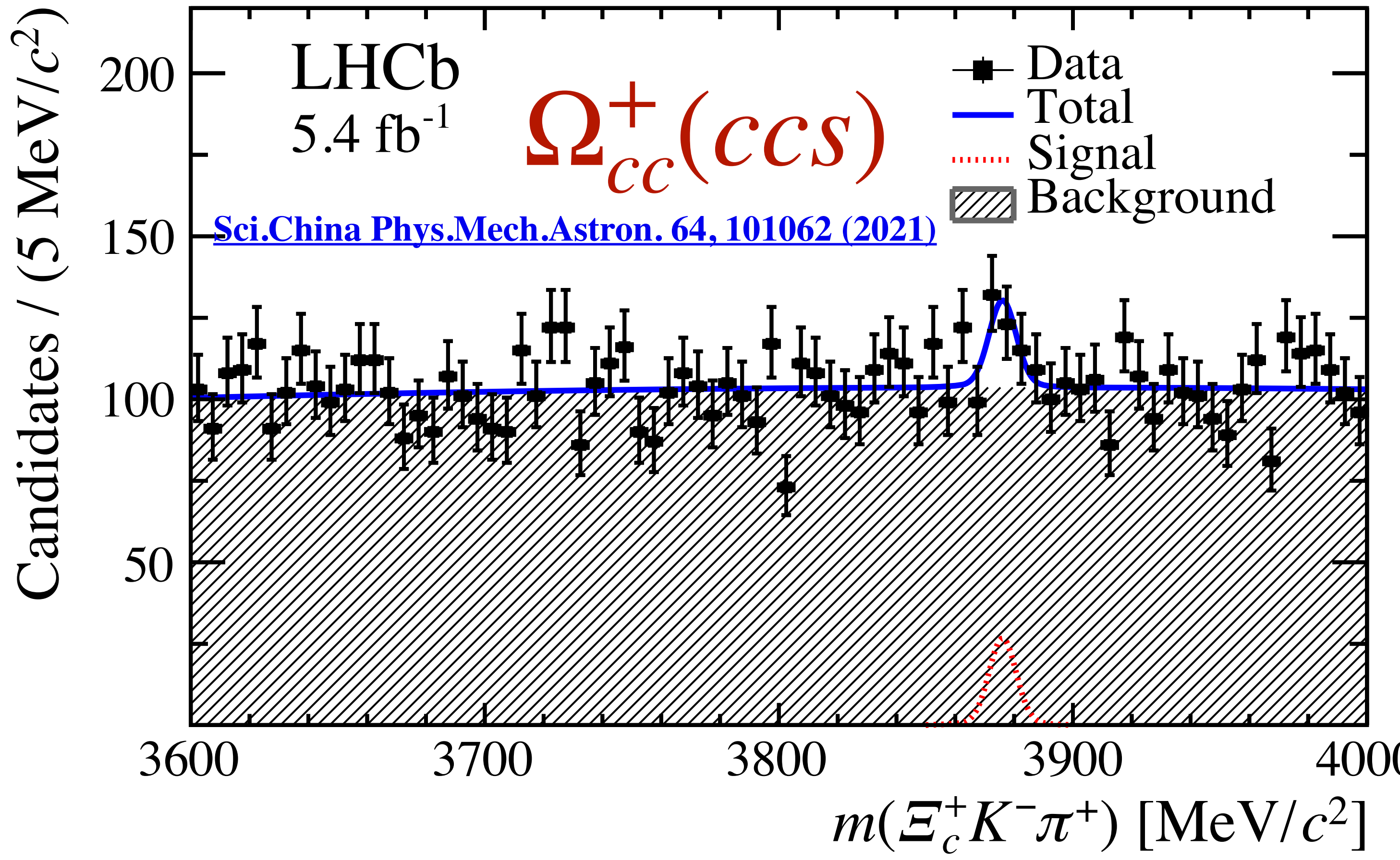


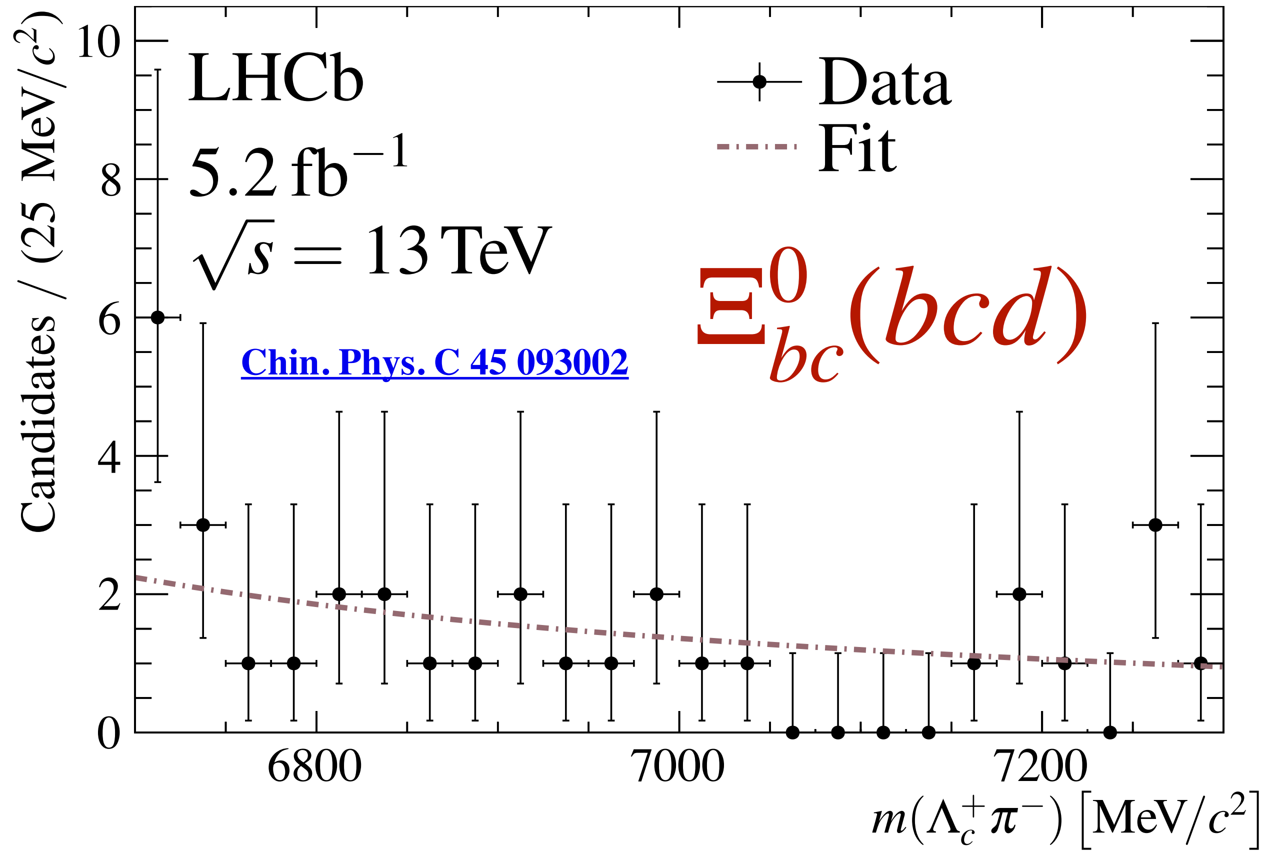



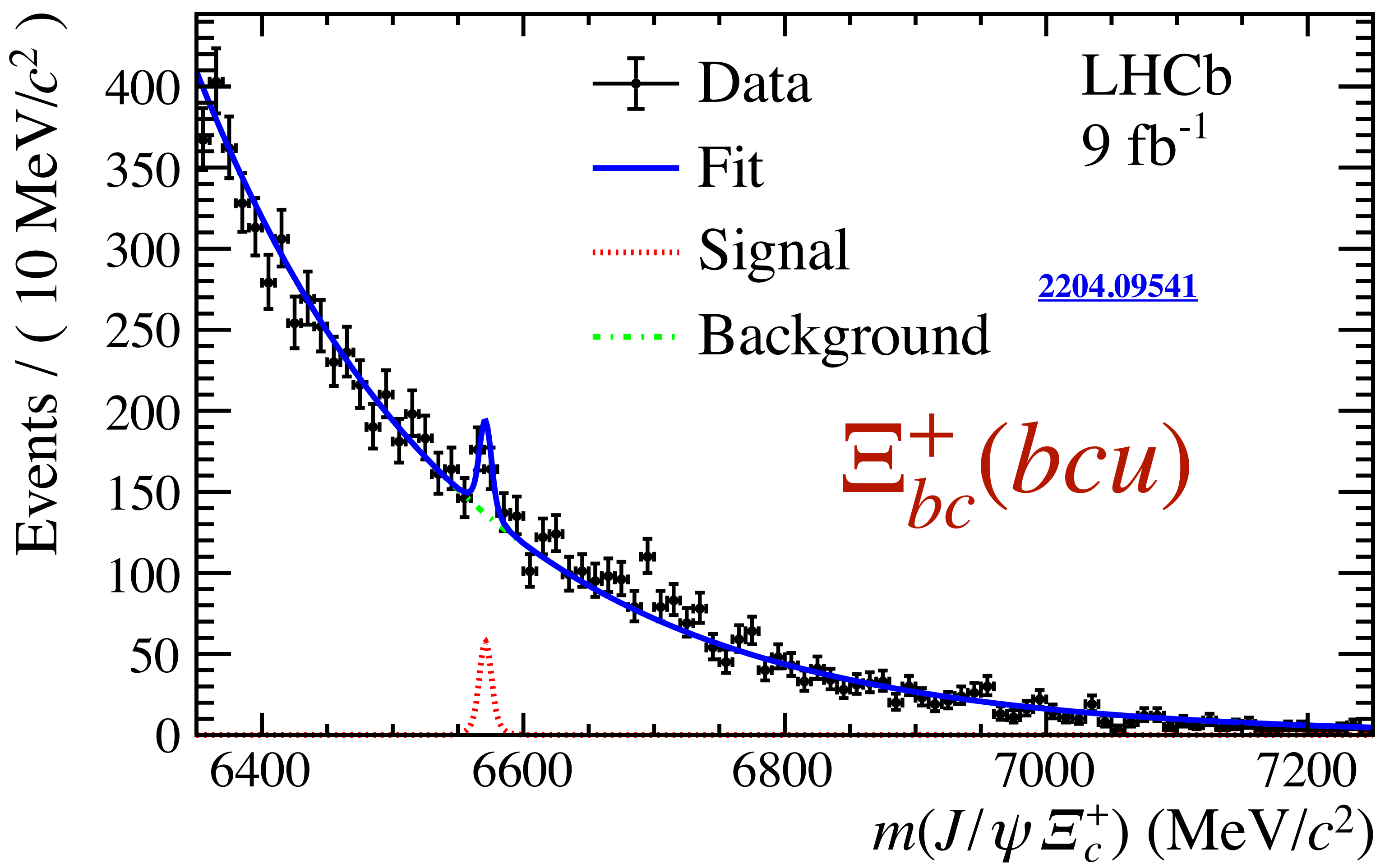

JHEP 12 (2021) 107




preferred mass value consistent with being isospin partner of $\Xi_{cc}^{++}$



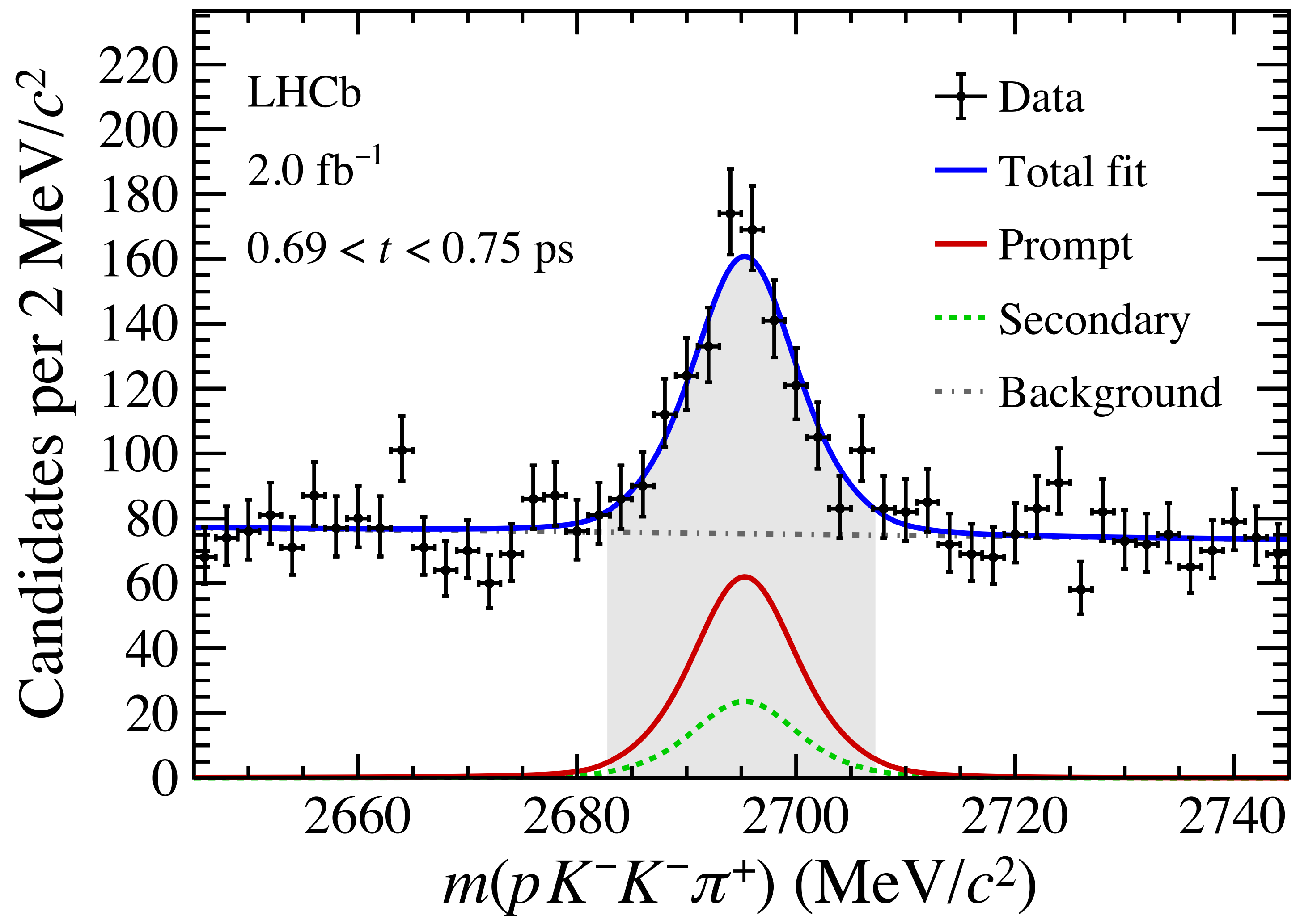

The isospin partner, $\Xi_{cc}^{+}$ (ccd), around the corner?

Other species need the full Run 3 dataset at least.

# Decay another day

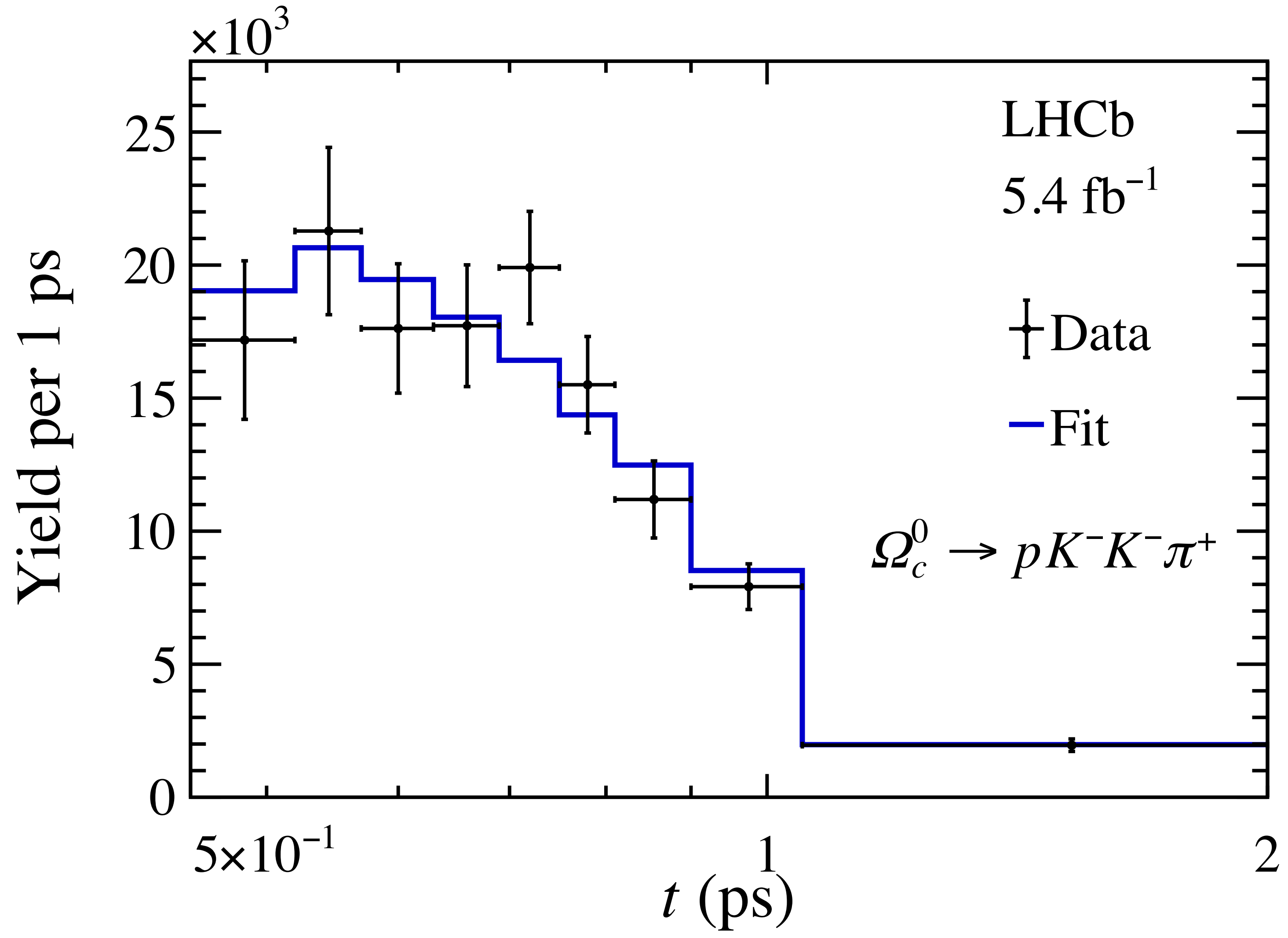
Science Bulletin 67 (2022) 479
Phys. Rev. Lett. 121 (2018) 092003

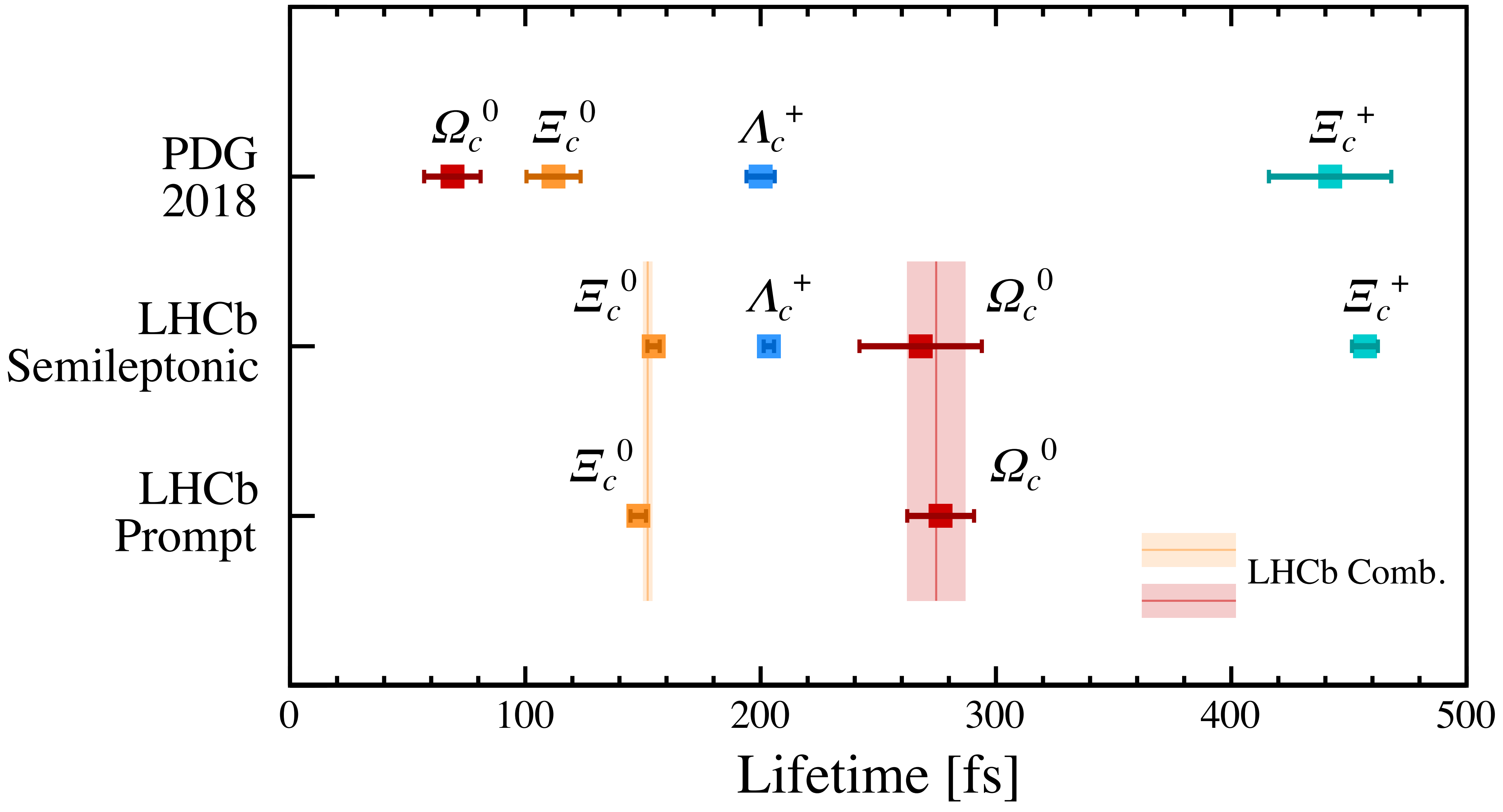
- LHCb measured the lifetime of the $\Omega_c^0$ baryon $\tau = 274.5 \pm 12.4$ fs; **four times larger** than the 2018 PDG average of $\tau = 69 \pm 12$ fs.
  - We use both prompt $\Omega_c^0$ baryons, and $\Omega_c^0$ from semileptonic decays of $\Omega_b^-$.
  - Decay channel $\Omega_c^0 \to pK^-K^-\pi^+$: all tracks from the same vertex.




- Charm baryon lifetime hierarchy changes from $\underset{(usc)}{\tau_{\Xi_c^+}} > \underset{(udc)}{\tau_{\Lambda_c^+}} > \underset{(dsc)}{\tau_{\Xi_c^0}} > \underset{(ssc)}{\tau_{\Omega_c^0}}$ to $\underset{(usc)}{\tau_{\Xi_c^+}} > \underset{(ssc)}{\tau_{\Omega_c^0}} > \underset{(udc)}{\tau_{\Lambda_c^+}} > \underset{(dsc)}{\tau_{\Xi_c^0}}$

can be explained theoretically in HQE $\sim 1/m_c^4$ (?)



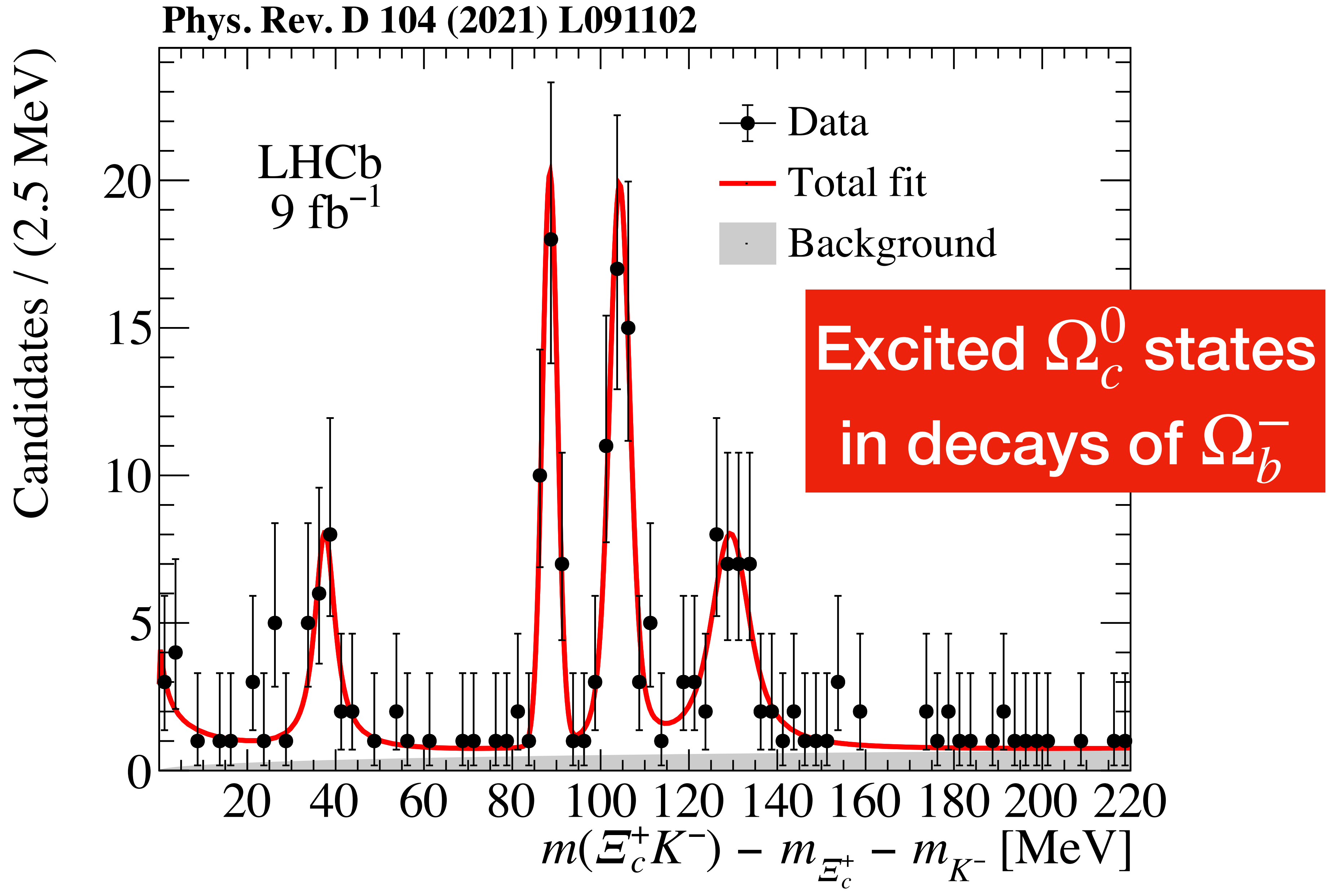



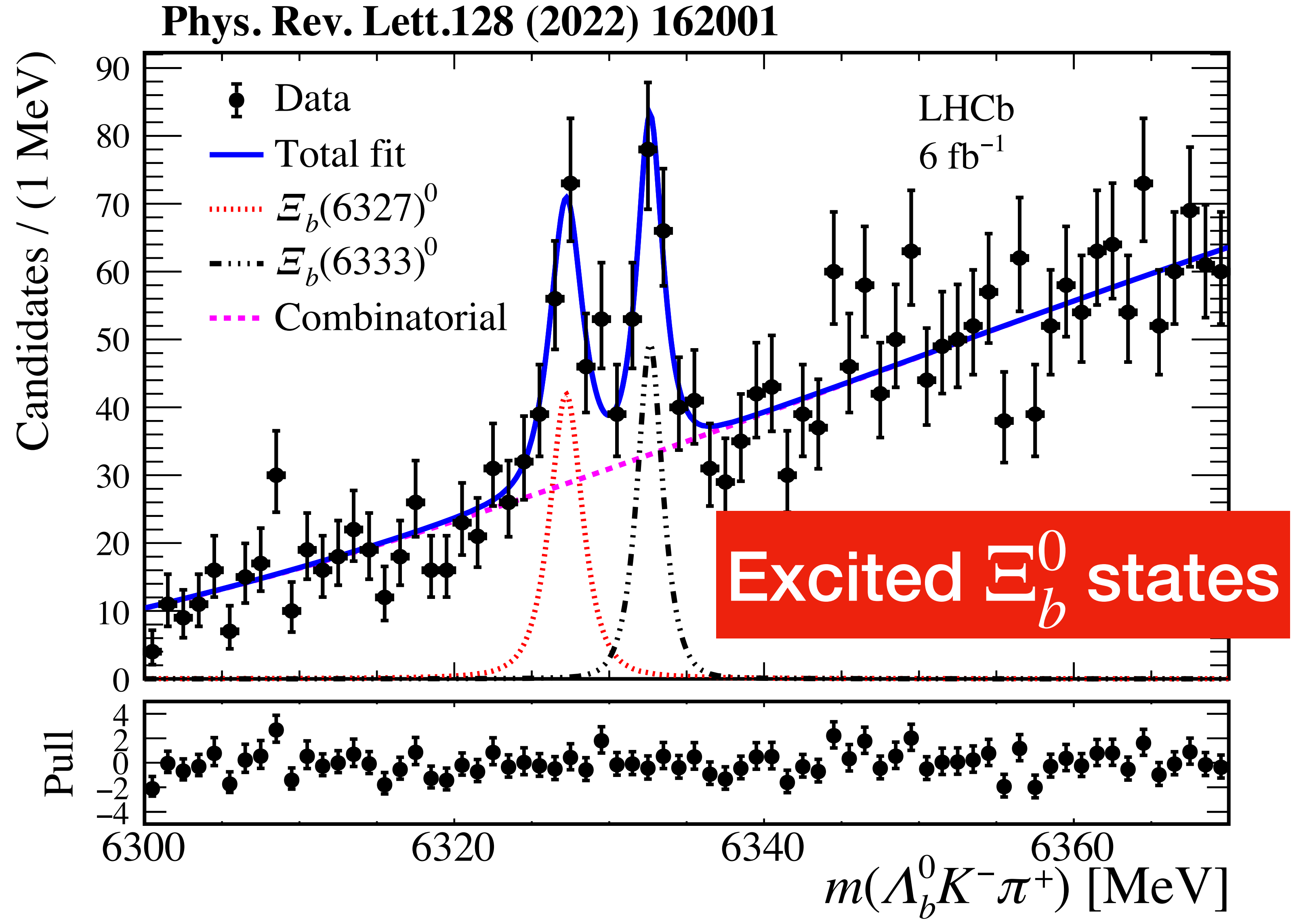

"This is the first time in the history of particle physics that the lifetime of a hadron measured in a new experiment was so drastically different from the old one."
[H-Y Cheng, 2109.01216]

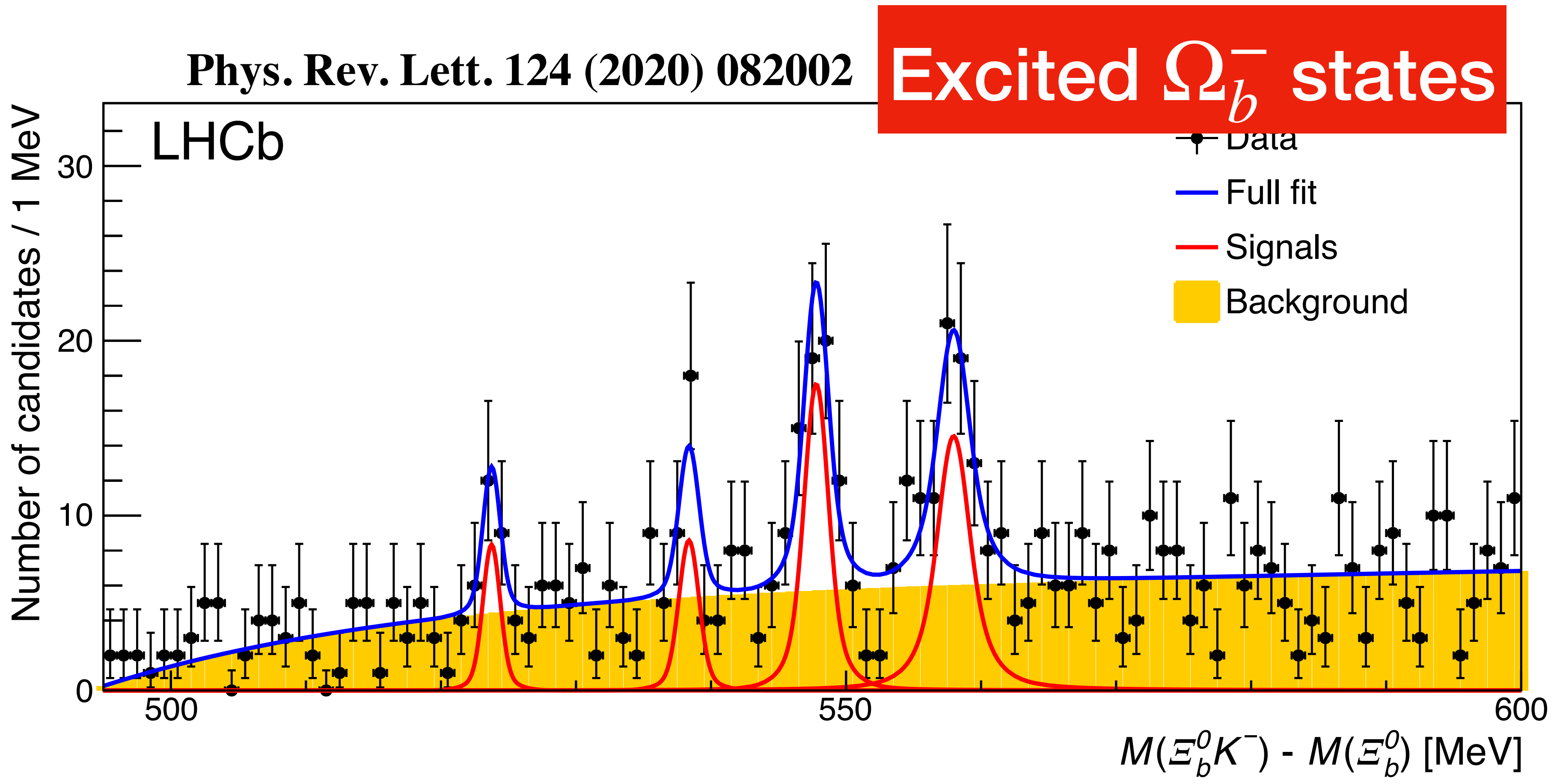
**News at ICHEP'2022: Belle II measures $\tau_{\Omega_c^0} = 243 \pm 49$ fs, consistent with the LHCb findings.**

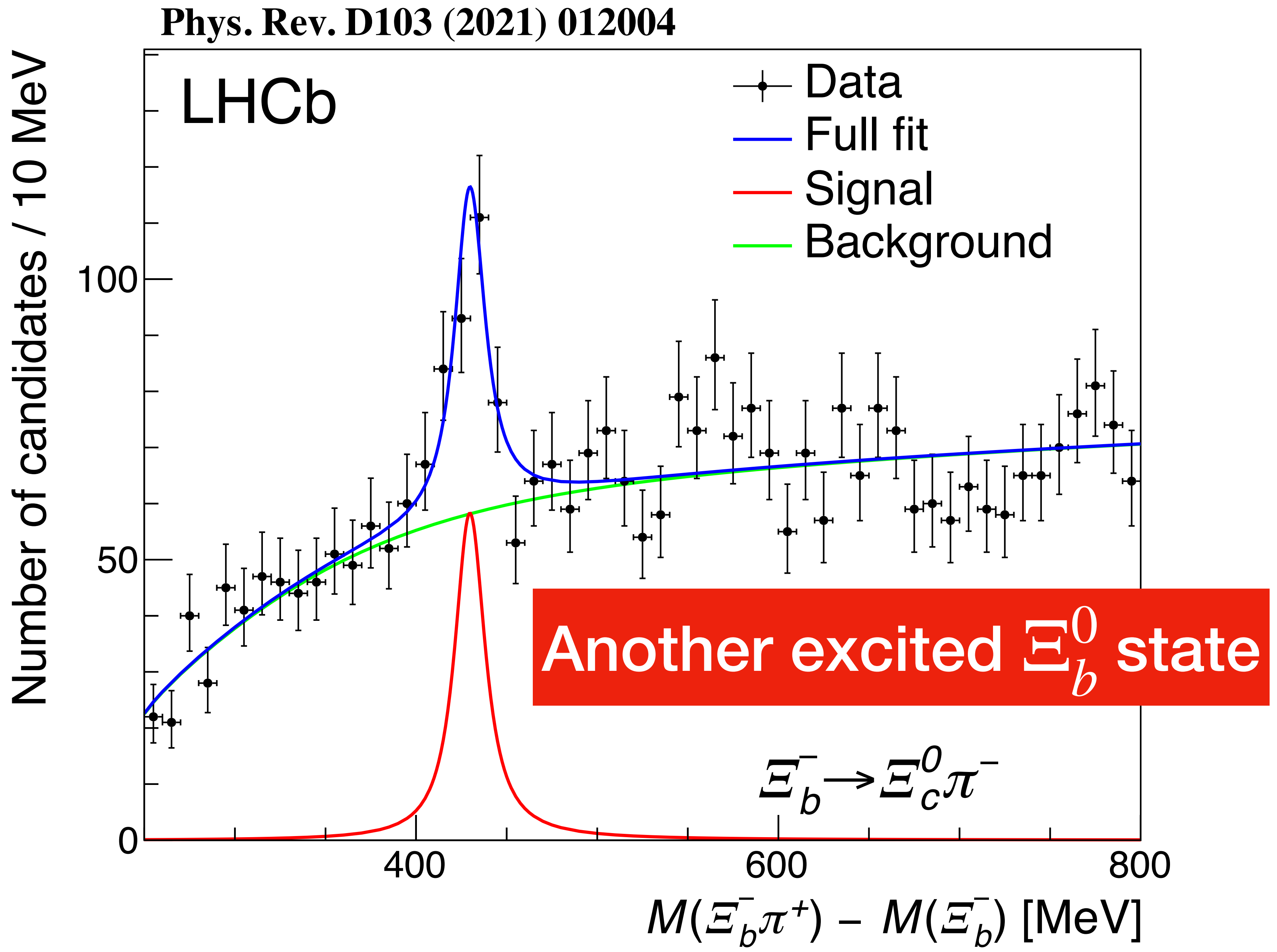
# Three quarks in a boat, to say nothing of the dog

- Some recent discoveries / confirmations of charm and beauty baryons (L > 0 states)



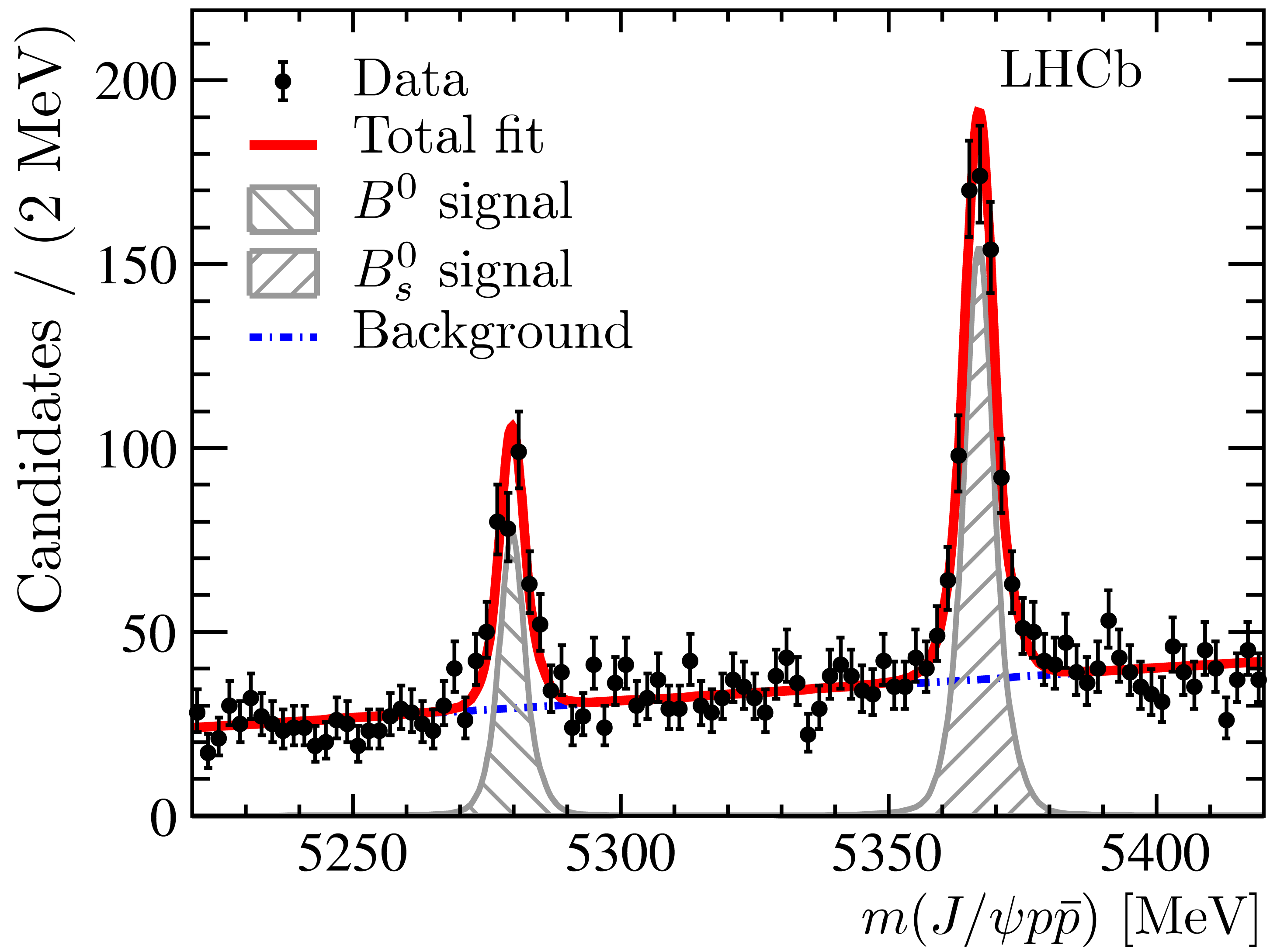



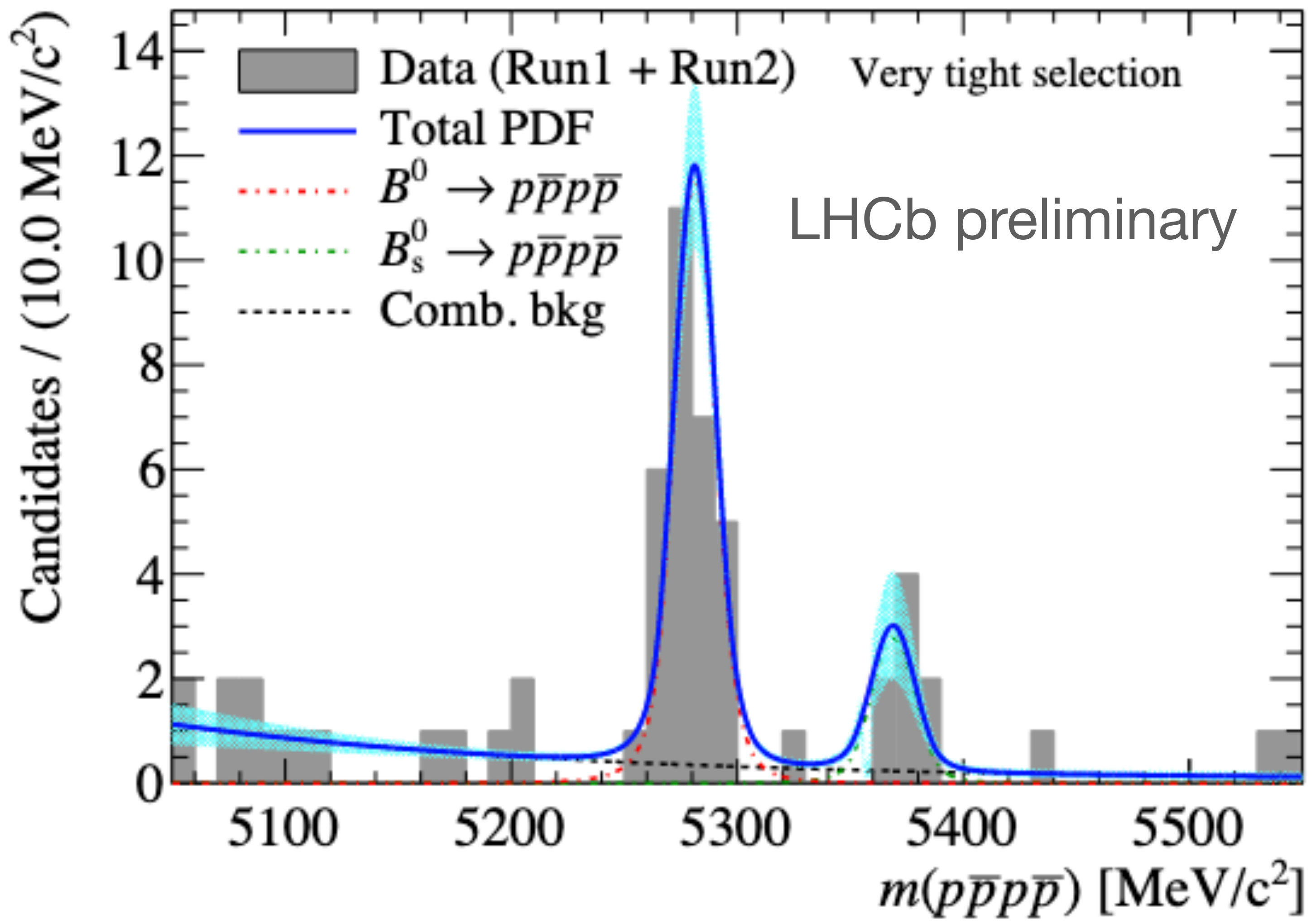
# The $p\bar{p}$ puzzle?



- 2019: LHCb measures **Phys. Rev. Lett. 122 (2019) 191804**
  $\mathscr{B}(B^0 \to J/\psi p\bar{p}) = (4.5 \pm 0.6) \times 10^{-7}$ and
  $\mathscr{B}(B_s^0 \to J/\psi p\bar{p}) = (3.6 \pm 0.4) \times 10^{-6}$
  - Naive expectation: $\mathscr{B}(B_s^0 \to J/\psi p\bar{p}) \sim 10^{-9}$: OZI suppression
  - Potential resonances in $m(p\bar{p})$? Not seen by LHCb **PRL 128 (2022) 062001**
    *Eur.Phys.J.C* 75 (2015) 3, 101



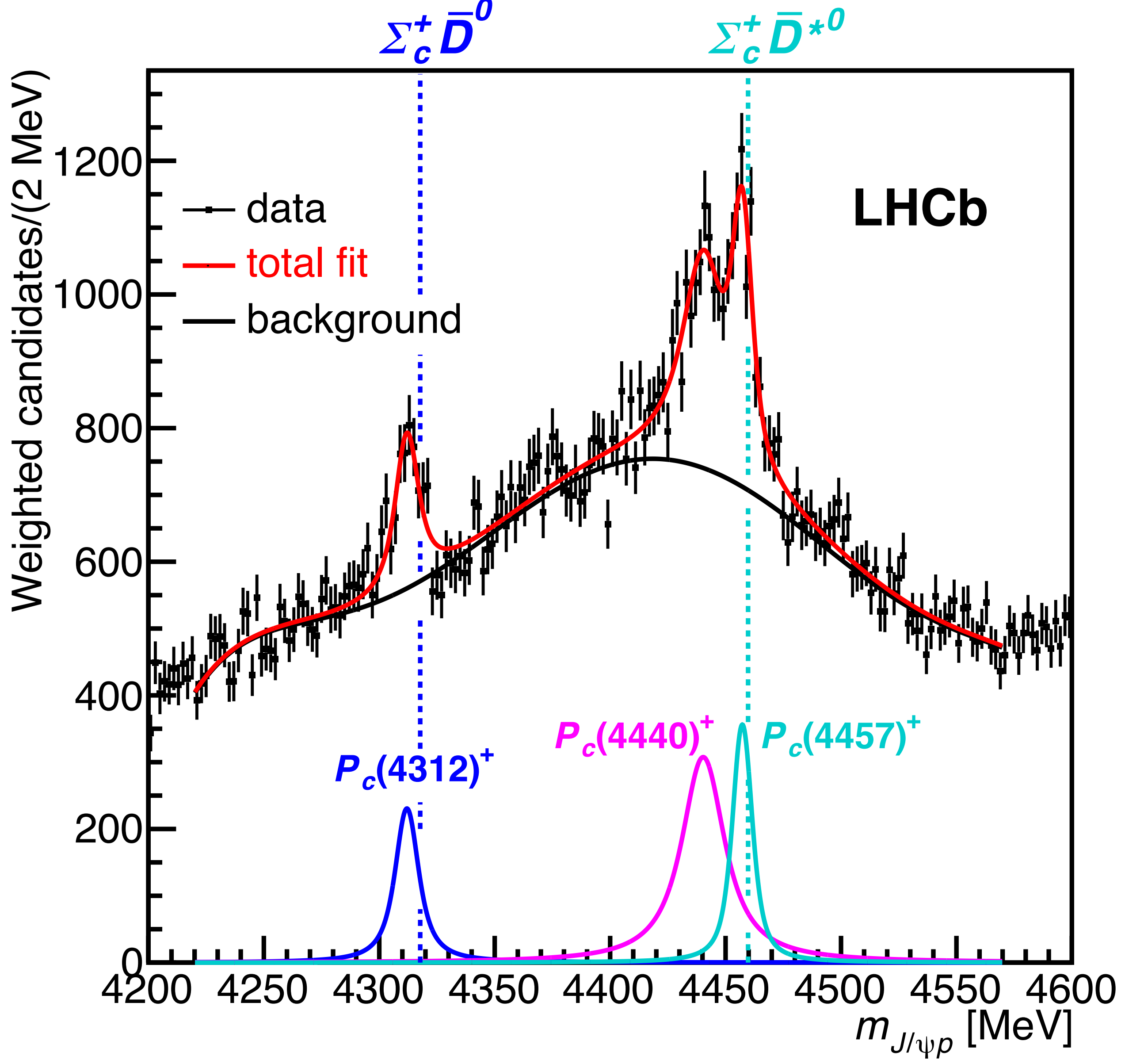

- **NEW:** LHCb measures $\mathscr{B}(B_s^0 \to p\bar{p}p\bar{p}) = (2.3 \pm 1.0) \times 10^{-8}$ and
  $\mathscr{B}(B^0 \to p\bar{p}p\bar{p}) = (2.2 \pm 0.4) \times 10^{-8}$ **LHCb-PAPER-2022-032, preliminary**
  - Naive expectation: $\mathscr{B}(B_s^0 \to p\bar{p}p\bar{p}) < \mathscr{B}(B^0 \to p\bar{p}p\bar{p})$ (CKM suppression)
  - Note the low statistical significance of the $B_s^0$ signal, though.




**Is there something interesting happening in the $B_s^0$ decays with a $p\bar{p}$ system?**

We need theoretical predictions more robust than “naive expectations”.

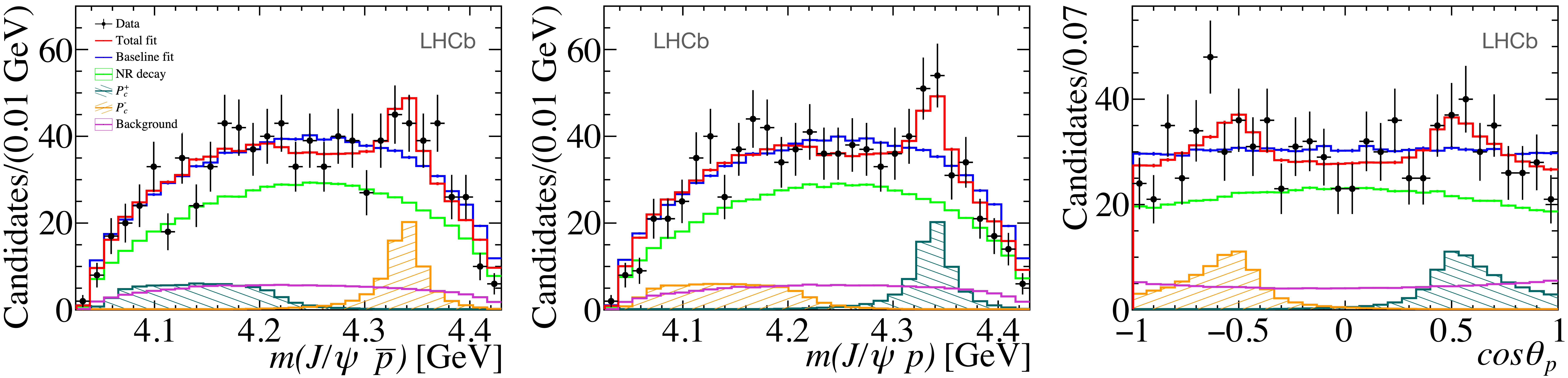
# **Five quarks in a boat**, to say nothing of the dog




- The beasts we know since a while… **Phys. Rev. Lett. 122 (2019) 222001**
  seen in $\Lambda_b^0 \to J/\psi p K^-$ decays as peaks in $m(J/\psi p)$

- … are joined by a new arrival from baryonic B-meson decays
- Amplitude analysis of $B_s^0 \to J/\psi p \bar{p}$ decays: evidence for a new $P_\psi^N(4337)^+$
  - Does this really explain the large branching fraction of $B_s^0 \to J/\psi p \bar{p}$?

**Phys. Rev. Lett. 128 (2022) 062001**



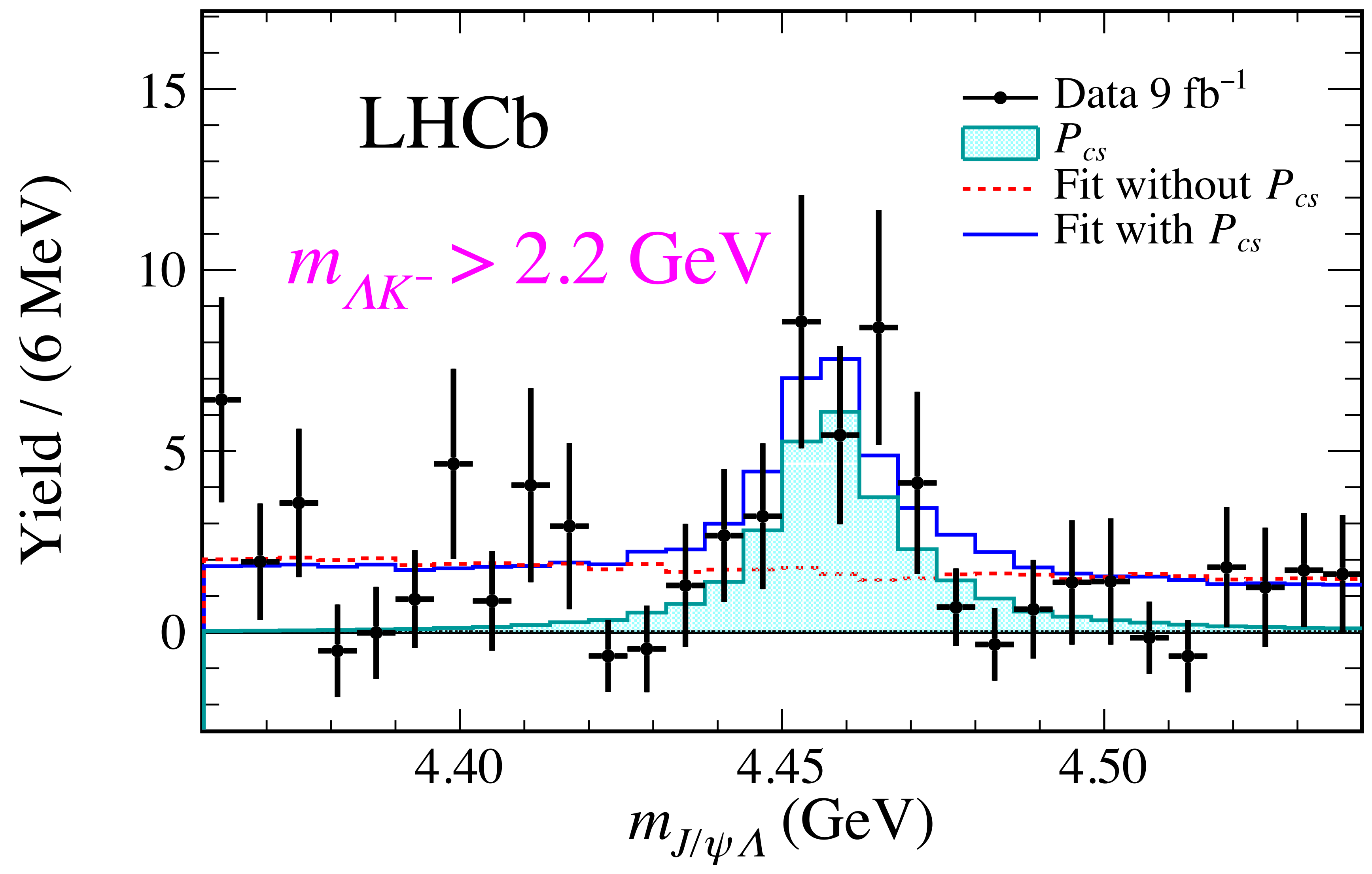

**Who ordered that?** Do we understand why is this state not seen in $\Lambda_b^0 \to J/\psi p K^-$?

# They can also be strange

- We also spot some strange beasts… and again in **baryonic B-meson decays**

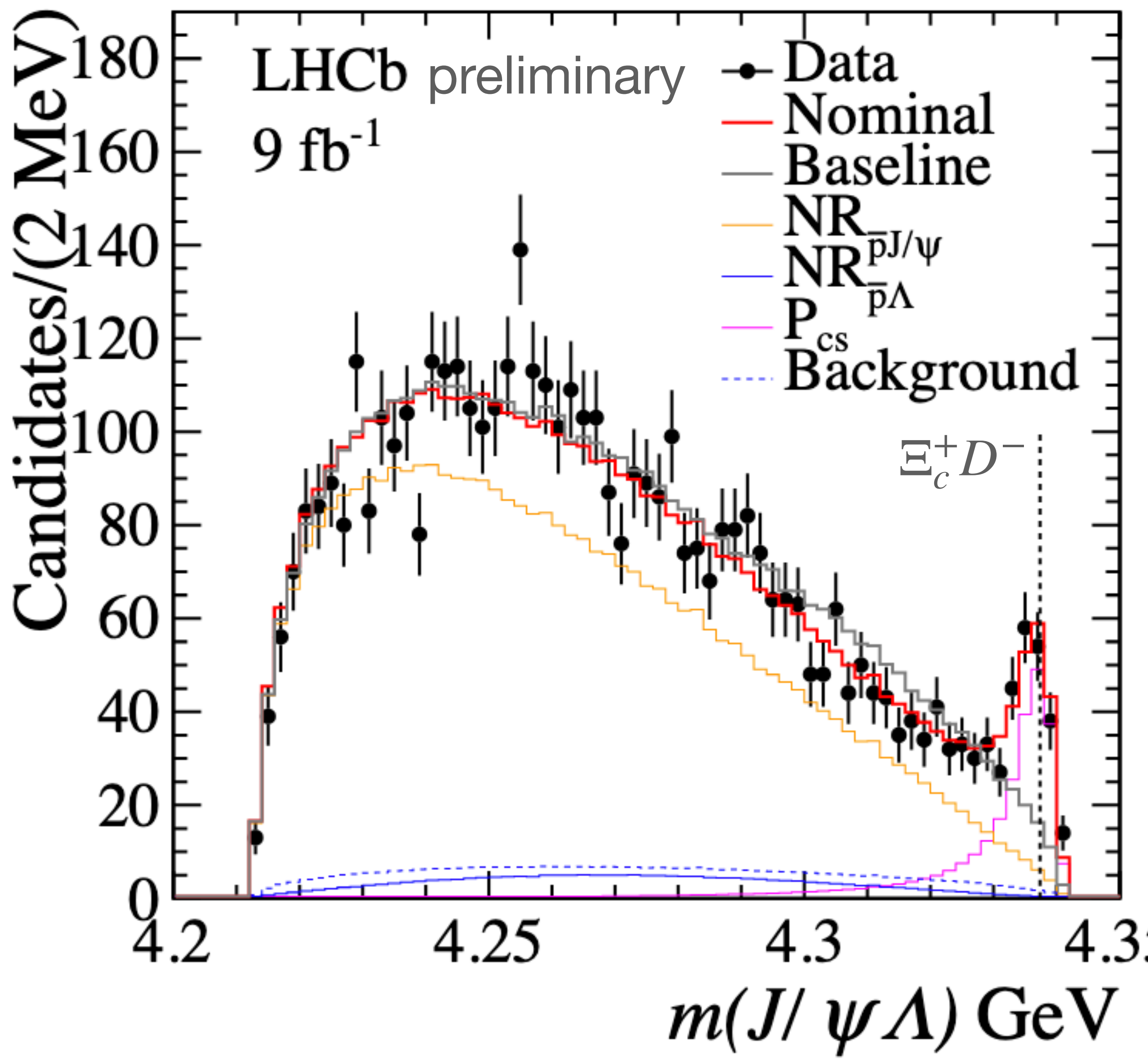
Evidence for $P^{\Lambda}_{\psi s}(4459)^0$ in $\Xi_b^- \to J/\psi \Lambda K$ decays

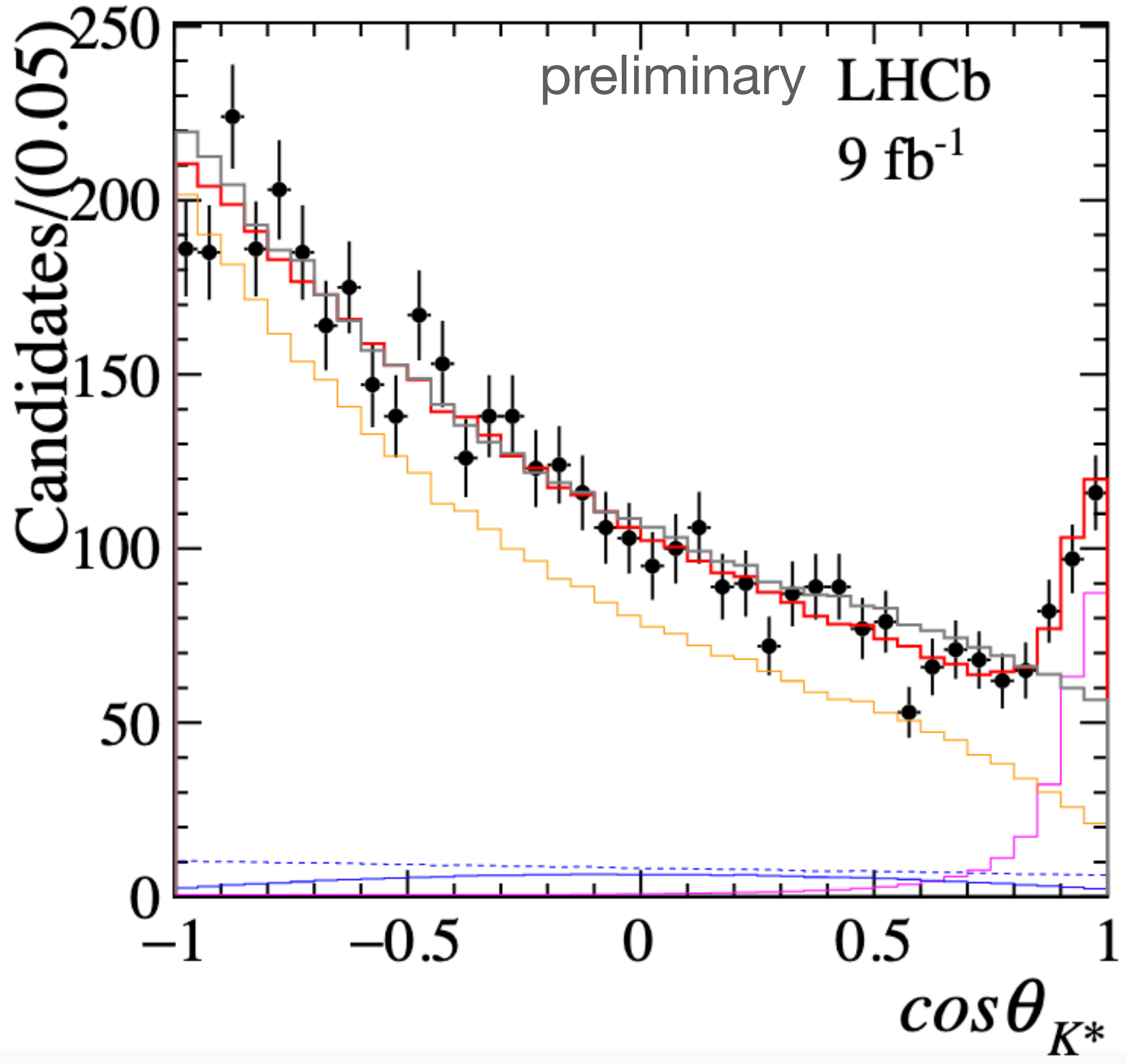
Science Bulletin 66 (2021) 1278

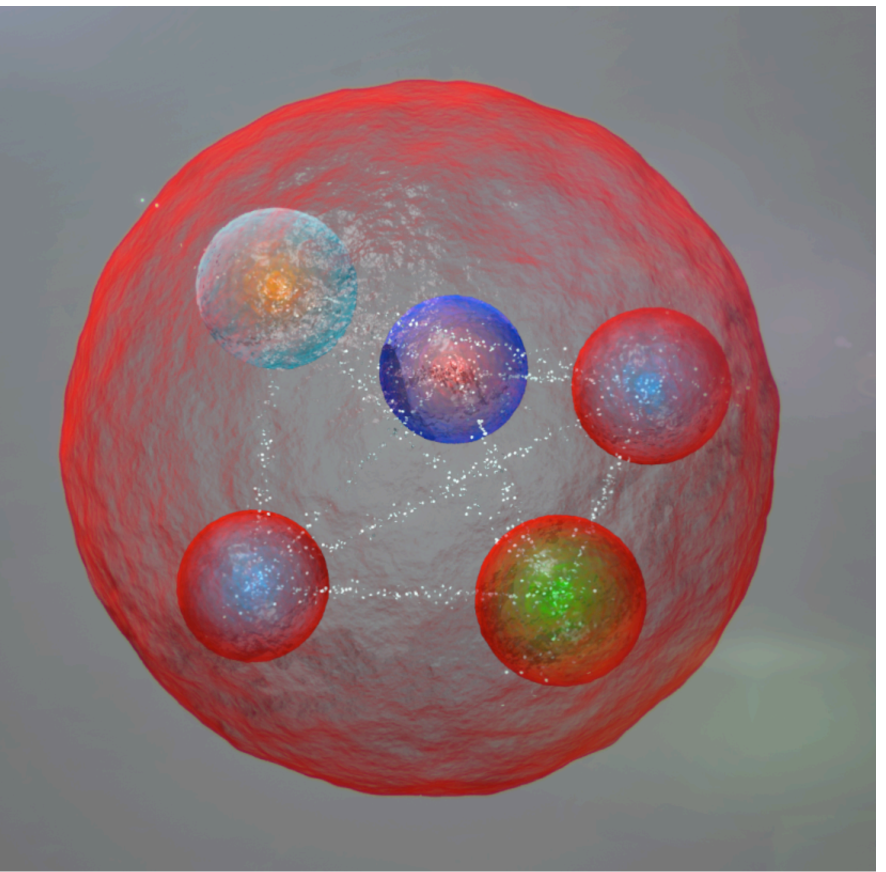



**NEW:** Observation of $P^{\Lambda}_{\psi s}(4338)^0$ in $B^- \to J/\psi \Lambda \bar{p}$ decays

LHCb-PAPER-2021-031 Preliminary

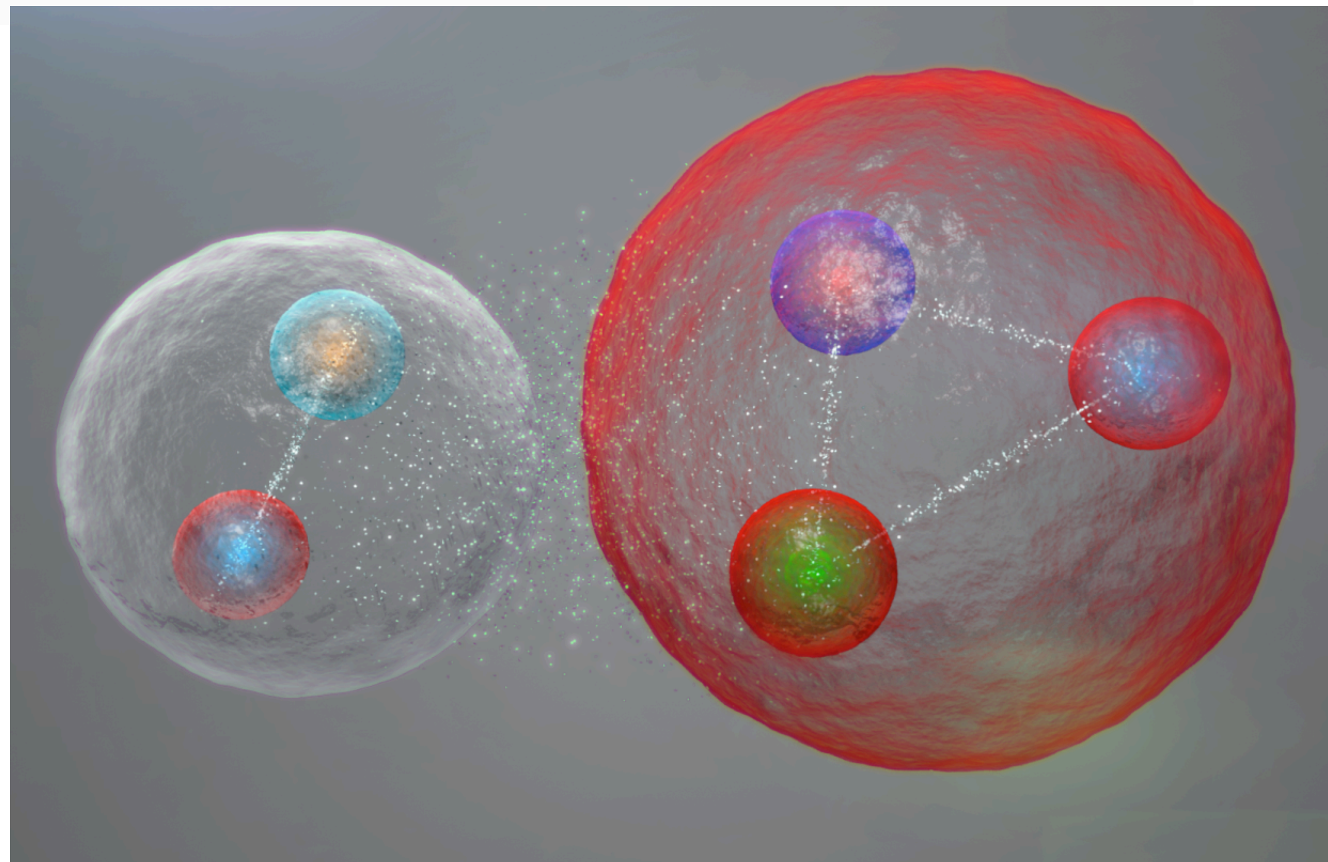


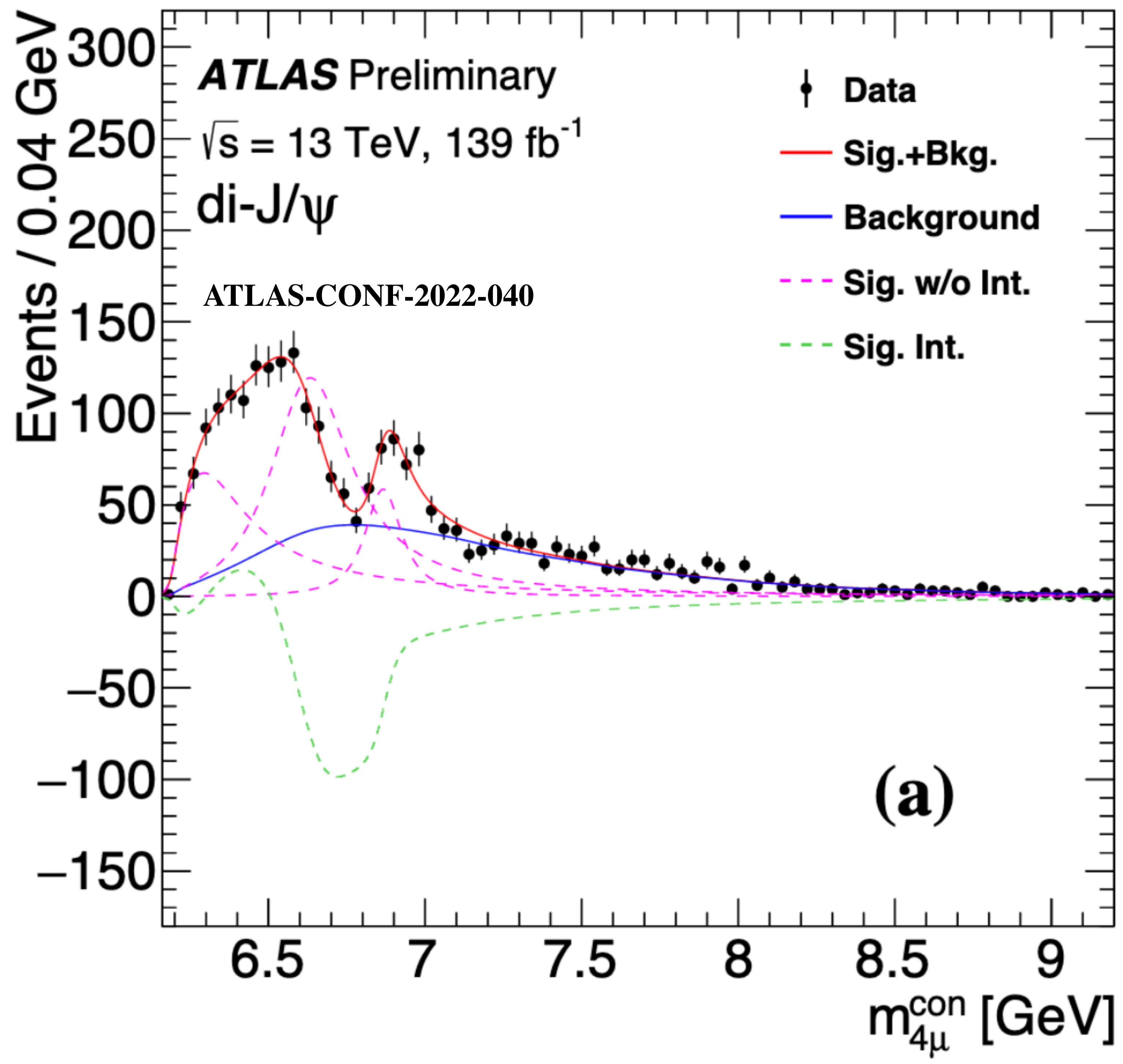
**Interpretation(s): tightly bound? meson+baryon "molecules"? kinematic effects?**

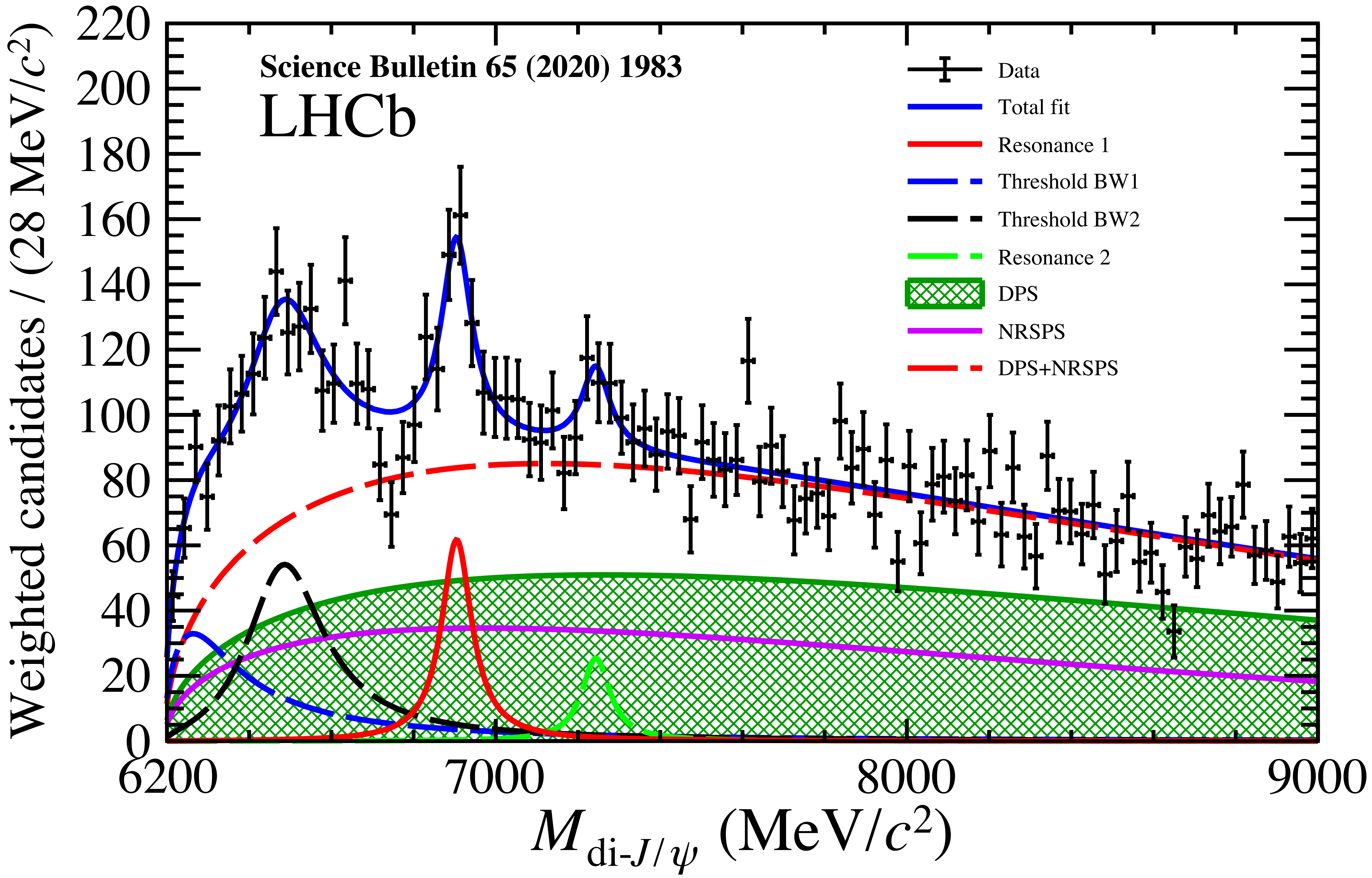
Proximity to meson+baryon thresholds might be the clue.

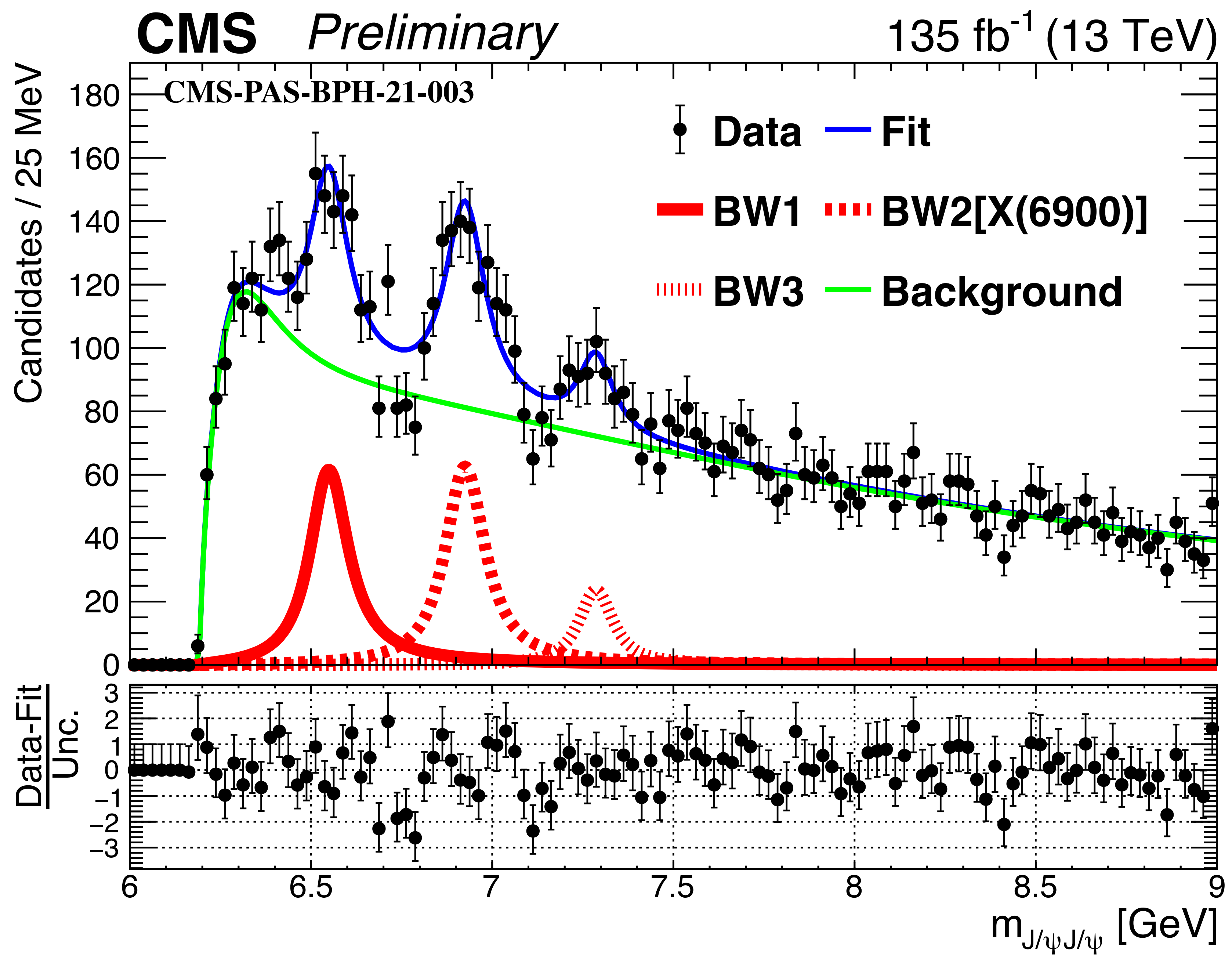


# Ultimately charming

- In 2020, LHCb reported a structure in $J/\psi J/\psi$ spectrum: $X(6900) = (cc\bar{c}\bar{c})$; now $T_{\psi\psi}(6900)$
- Recently confirmed by ATLAS and CMS!
  - Strengthened evidence for additional structures
    - 3 peaks, or 2 peaks and feeddown from decays via higher charmonium states?
- What is the binding mechanism? Are there beauty analogs?



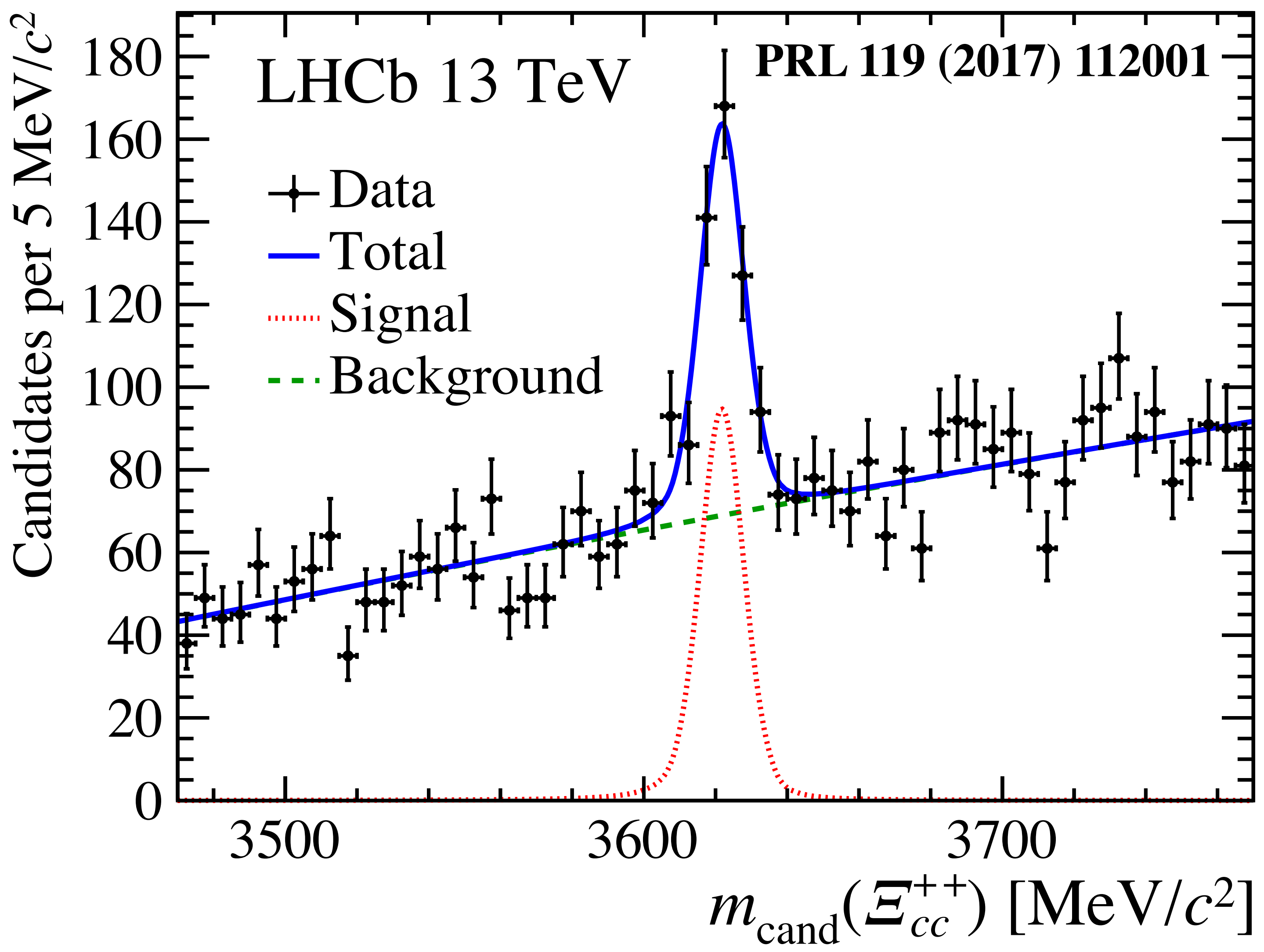



# Ultimately charming



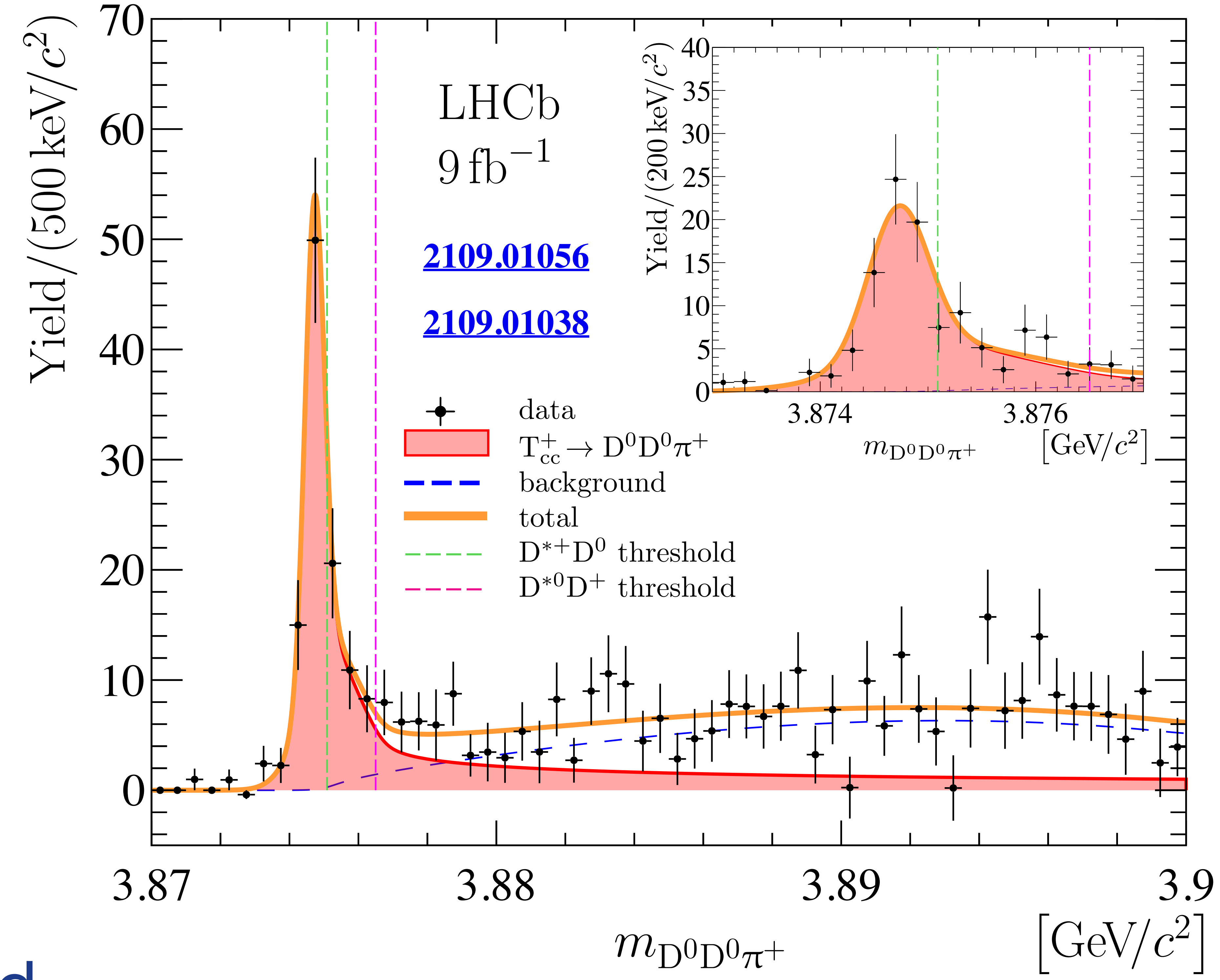
- Most exotic candidates have a $(c\bar{c})$ in their quark content. Can we have a $(cc)$ instead?

*2017*




$\Xi_{cc}^{++}\,(ccu)$ → $T_{cc}(3875)^{+}\,(cc\bar{u}\bar{d})$

*2021*




- A manifestly exotic state observed in $m(D^0D^0\pi^+)$ at the threshold
  - decays via off-shell $D^{*+}$, properties consistent with $J^P = 1^+$ and isospin 0
  - the longest-living exotic state known to date

several talks on Tue & posters in this conference!

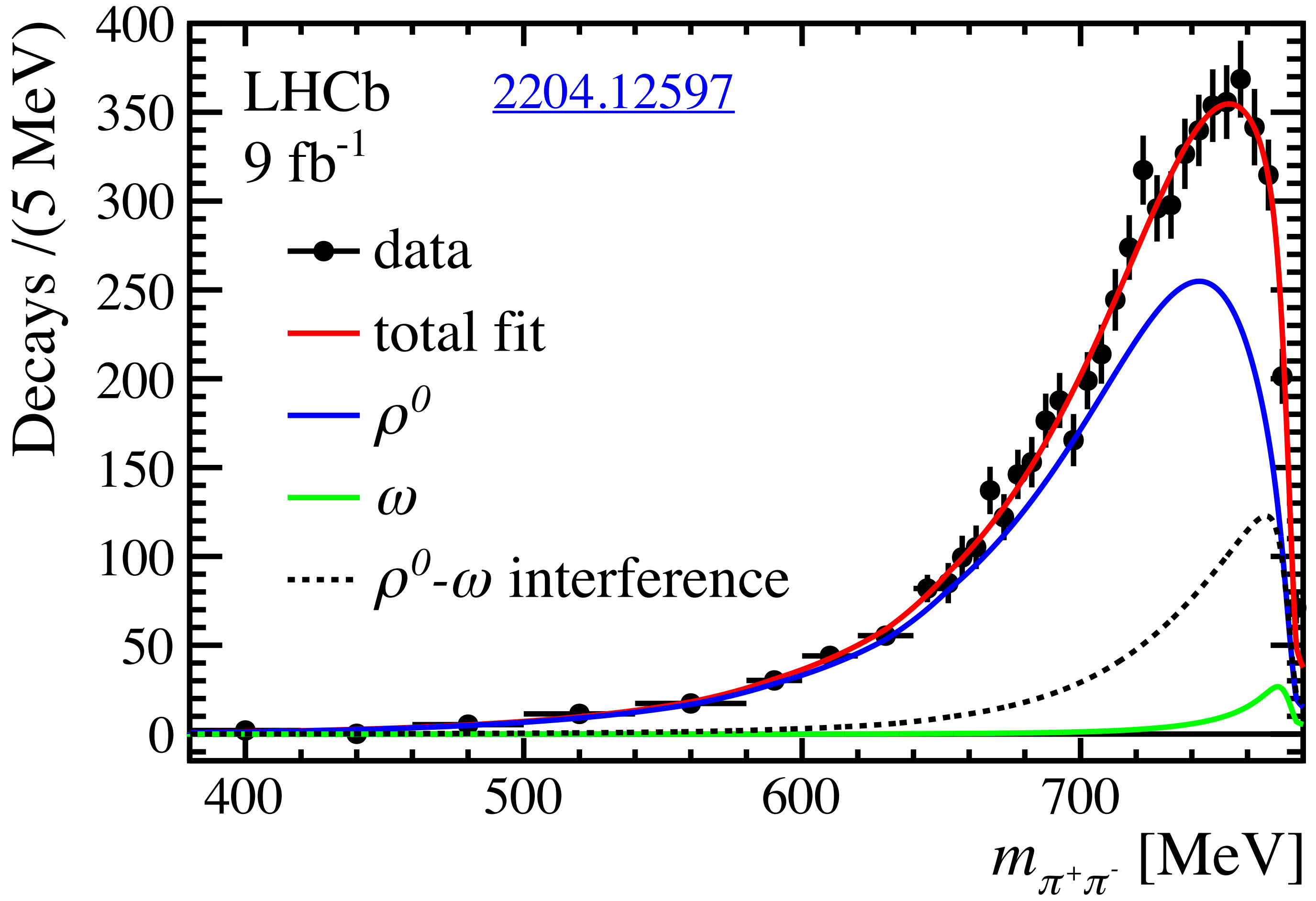
**This result supports predictions of a *weakly-decaying* $bb\bar{u}\bar{d}$ state: a tetraquark flying some mm before decay?**

1505.00613
1704.02383
1904.04197
and many more

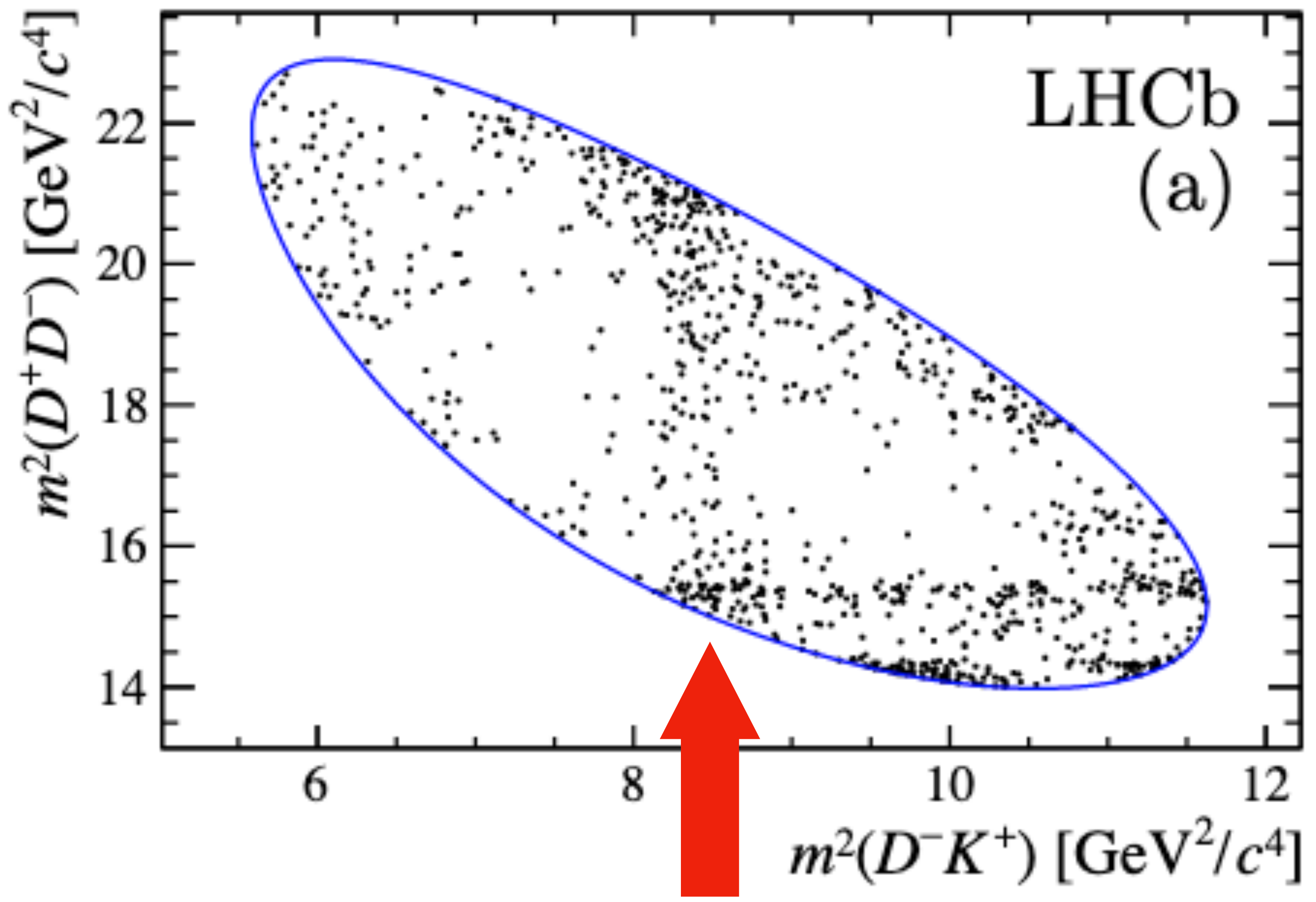
# More tetraquarks



- Detailed studies of the $X(3872)$: “below-threshold” decay to $J/\psi\omega$ seen in $J/\psi\pi^+\pi^-$ final state
  - Allowed for precise determination of the **isospin-violating $J/\psi\rho$ decay rate: factor ~6 too large** for a conventional charmonium state!
- Recent new tetraquarks: seen as **manifestly exotic** structures in Dalitz plot of B decays; **established** through **amplitude analysis**

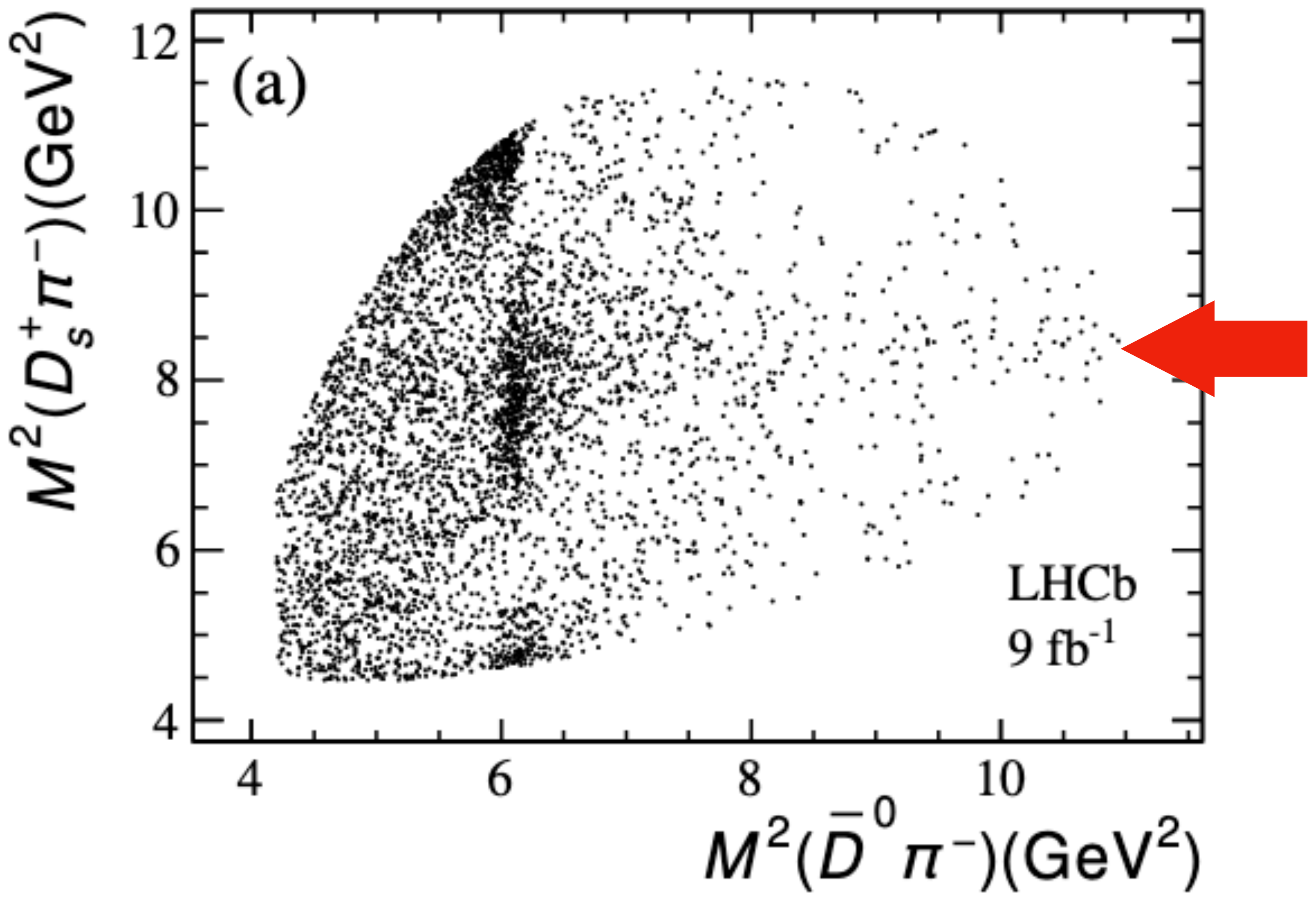



Unexpected structure in $m(D^-K^+)$ in $B^+ \to D^+D^-K^+$ decay



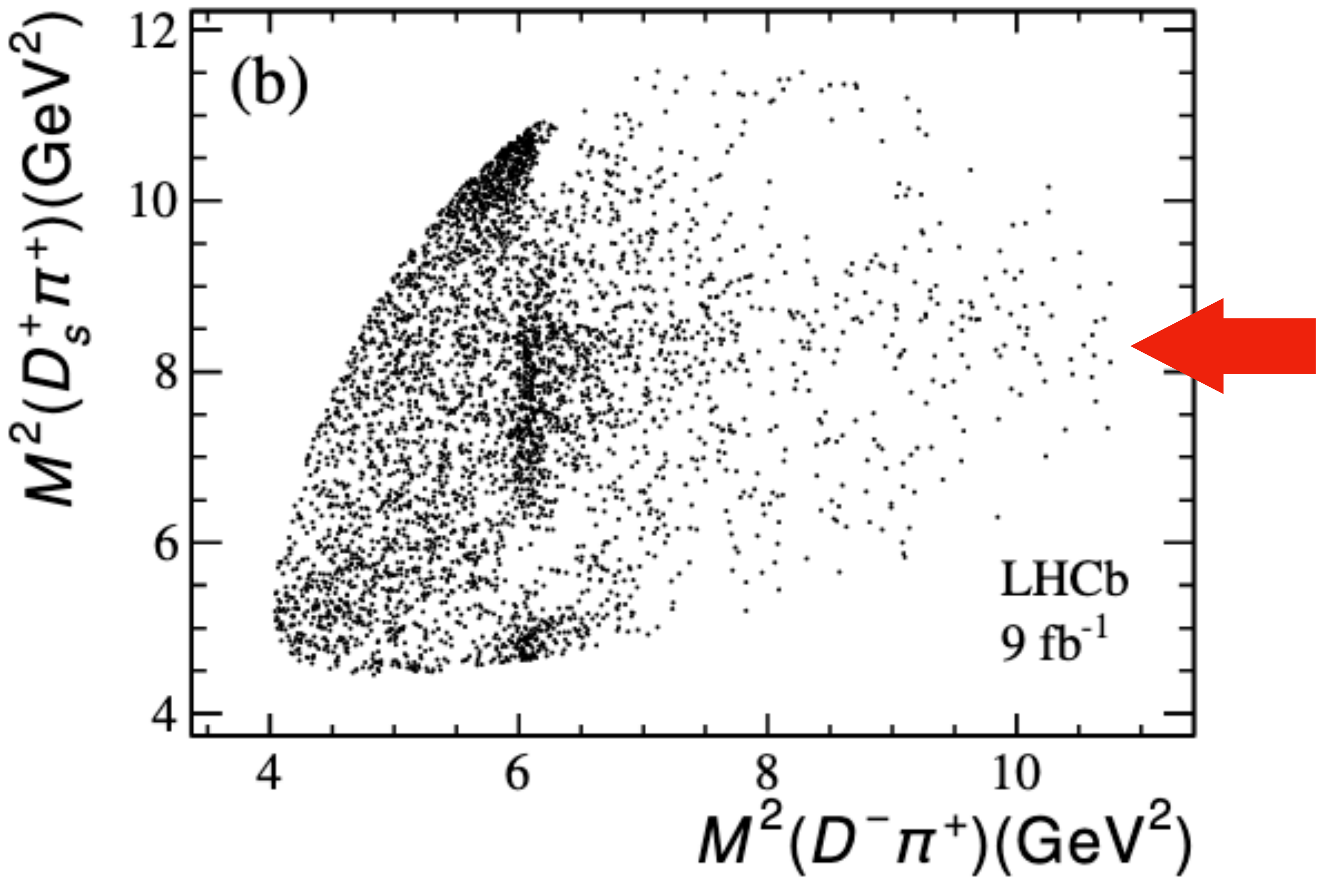

$T_{cs0}(2900)^0$

Unexpected structure in $m(D_s^+\pi^-)$ in $B^0 \to \overline{D}^0 D_s^+\pi^-$ decay




$T^a_{c\bar{s}0}(2900)^0$

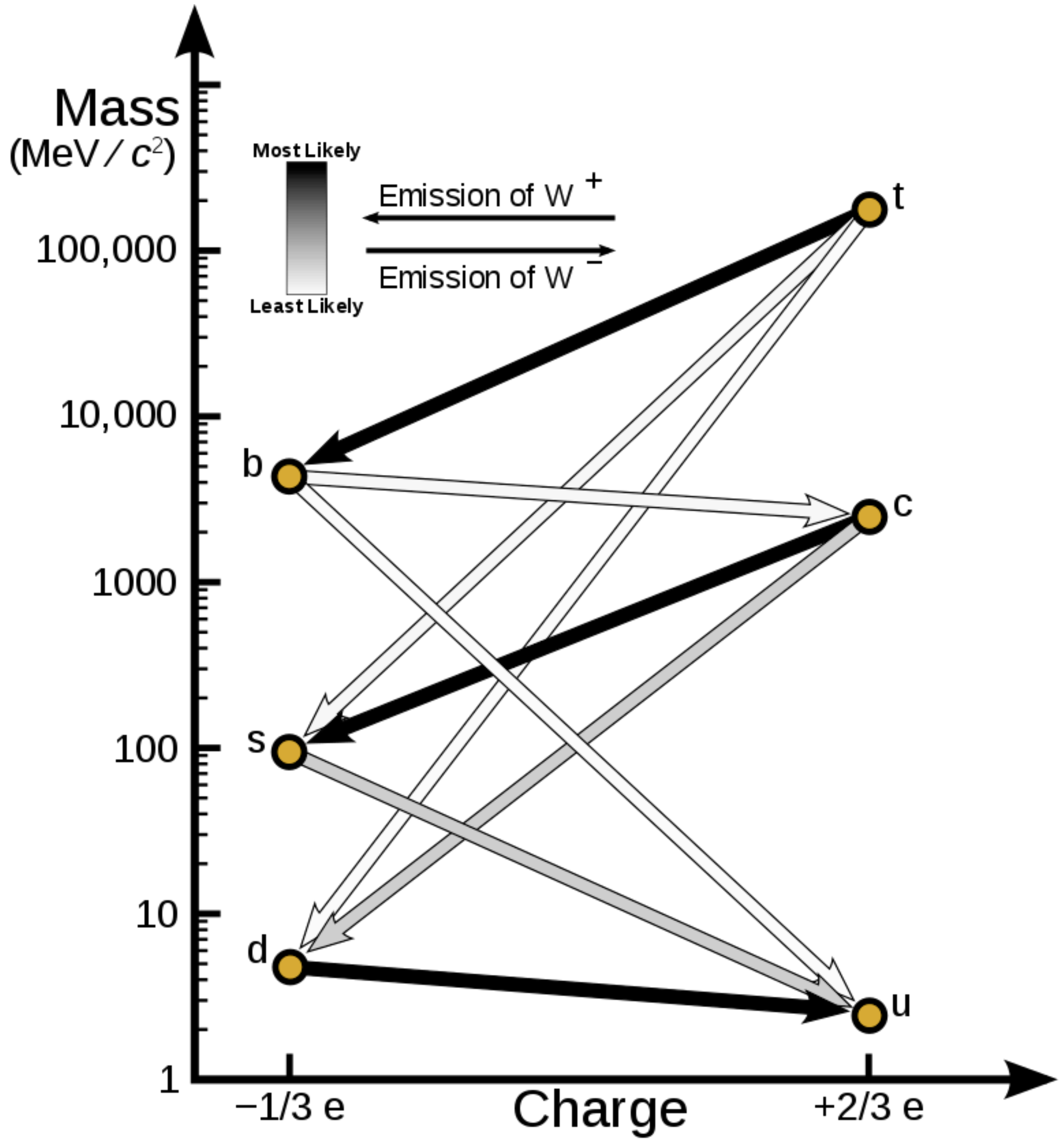
Unexpected structure in $m(D_s^+\pi^+)$ in $B^+ \to D^-D_s^+\pi^+$ decay




$T^a_{c\bar{s}0}(2900)^{++}$

first tetraquark with charge 2

# Weak decays of heavy hadrons




**Expansion over $\lambda \sim |V_{us}| \sim 0.2$**

CP violation in $b$ sector

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} \sim \begin{bmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4) \, .$$

**Higher-order expansion needed to see small CPV effects in charm**

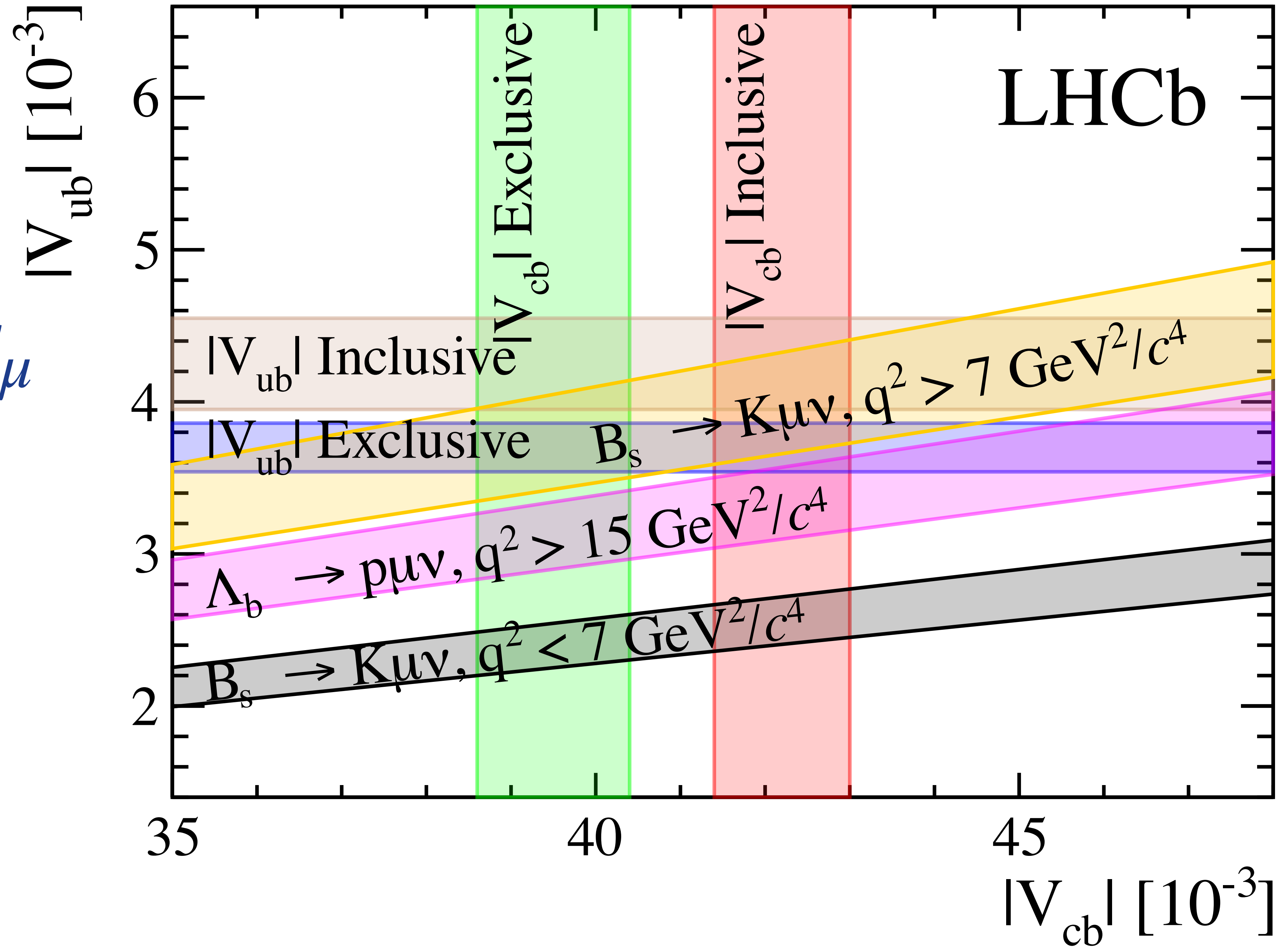
CP violation in $c$ sector

$$\begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+A^2\lambda^5[1-2(\rho+i\eta)]/2 & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\lambda^3[1-(1-\lambda^2/2)(\rho+i\eta)] & -A\lambda^2+A\lambda^4[1-2(\rho+i\eta)]/2 & 1-A^2\lambda^4/2 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

# Stalking b-quarks decays

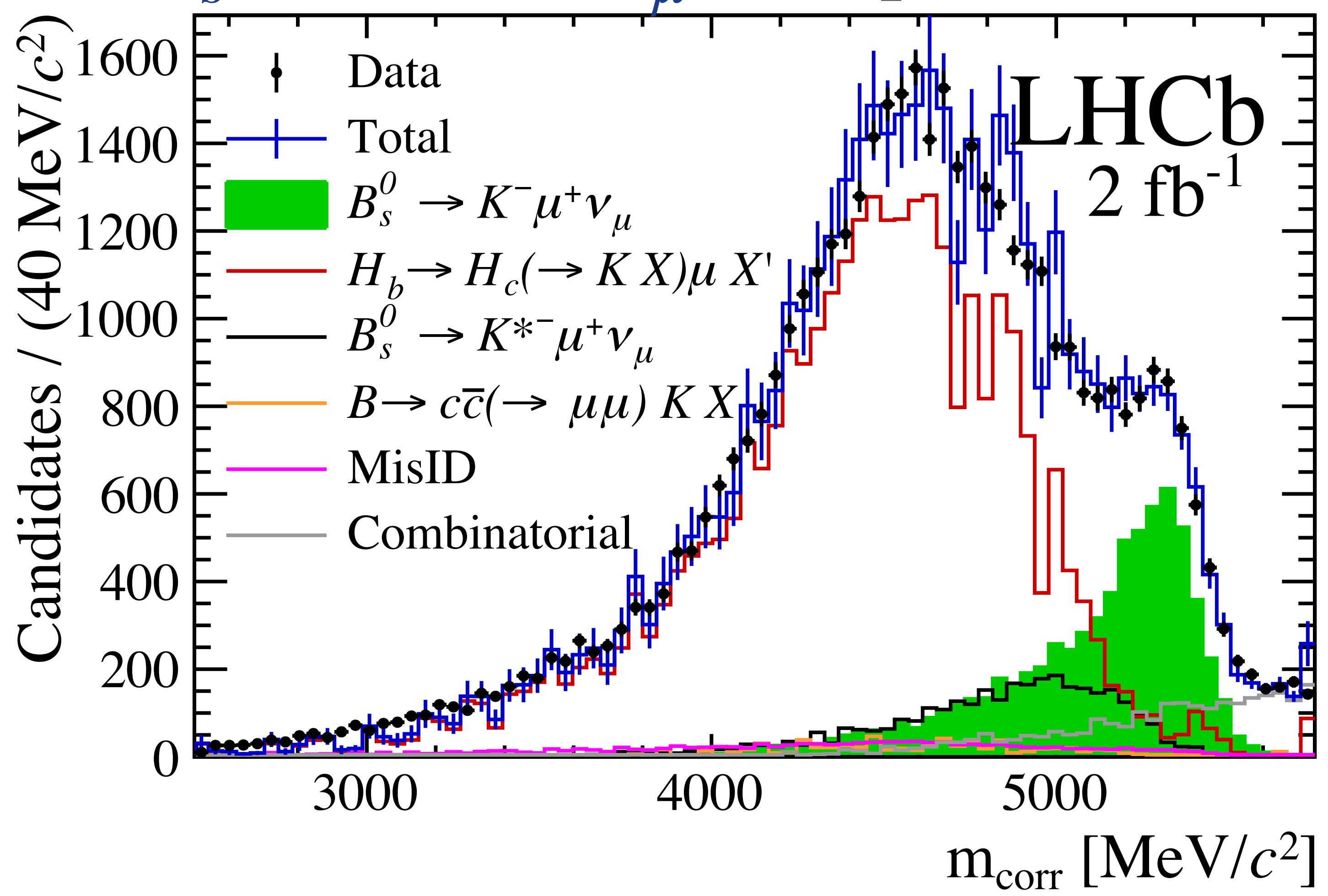
Phys. Rev. Lett. 126 (2021) 081804

- Sizes of CKM matrix elements $V_{ub}$ and $V_{cb}$ measured with semileptonic B decays
- Disagreement between the past experimental results: inclusive vs exclusive

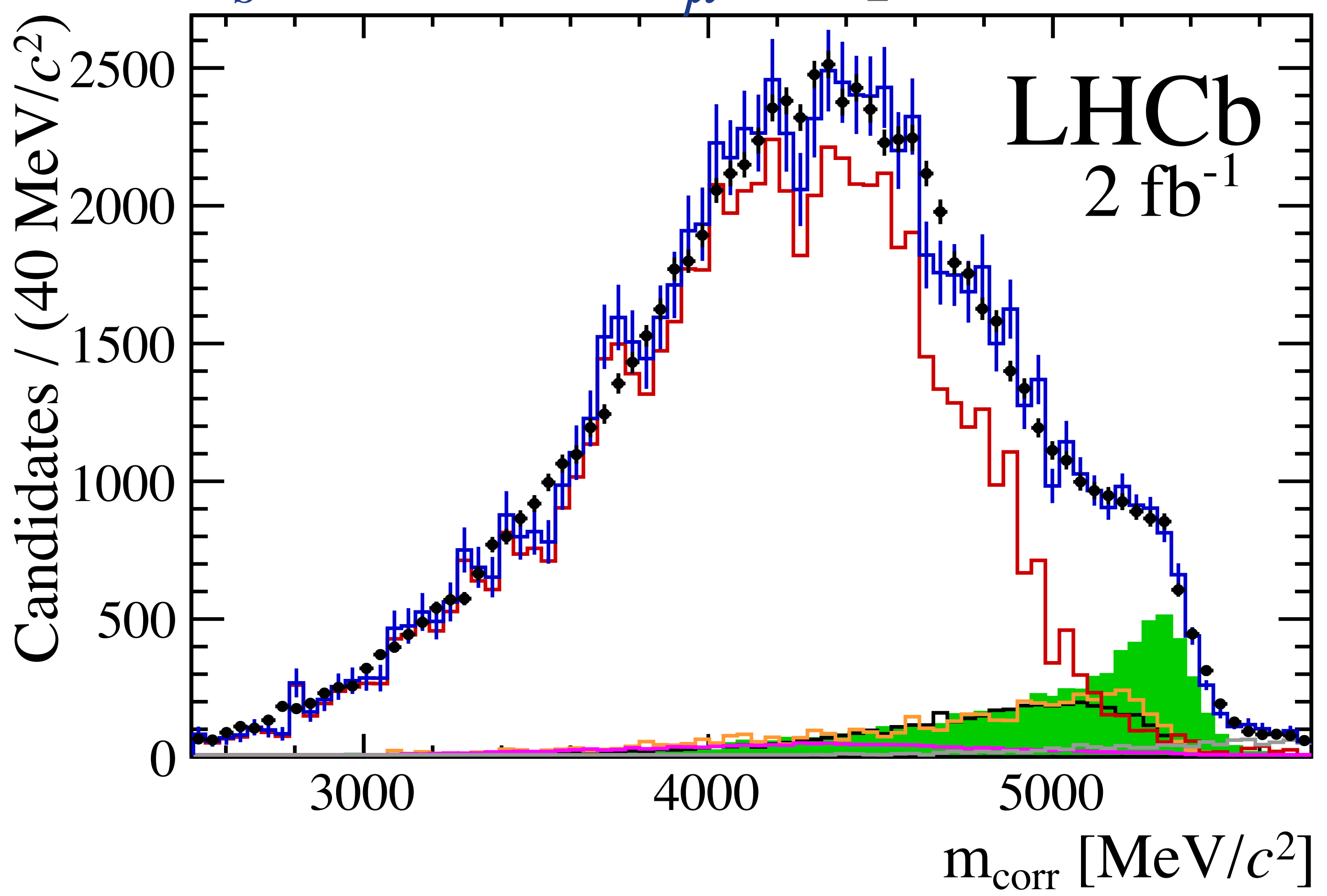



- LHCb: measure the ratio of BF $B_s^0 \to K^-\mu^+\nu_\mu$ and $B_s^0 \to D_s^-\mu^+\nu_\mu$

$B_s^0 \to K^-\mu^+\nu_\mu$ $q^2 < 7GeV^2$




$B_s^0 \to K^-\mu^+\nu_\mu$ $q^2 > 7GeV^2$




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

$$|V_{ub}|/|V_{cb}|(\mathrm{low}) = 0.0607 \pm 0.0015\,(\mathrm{stat}) \pm 0.0013\,(\mathrm{syst}) \pm 0.0008\ (D_s) \pm 0.0030\ (\mathrm{FF}),$$
FF from LCSR (1501.05373)

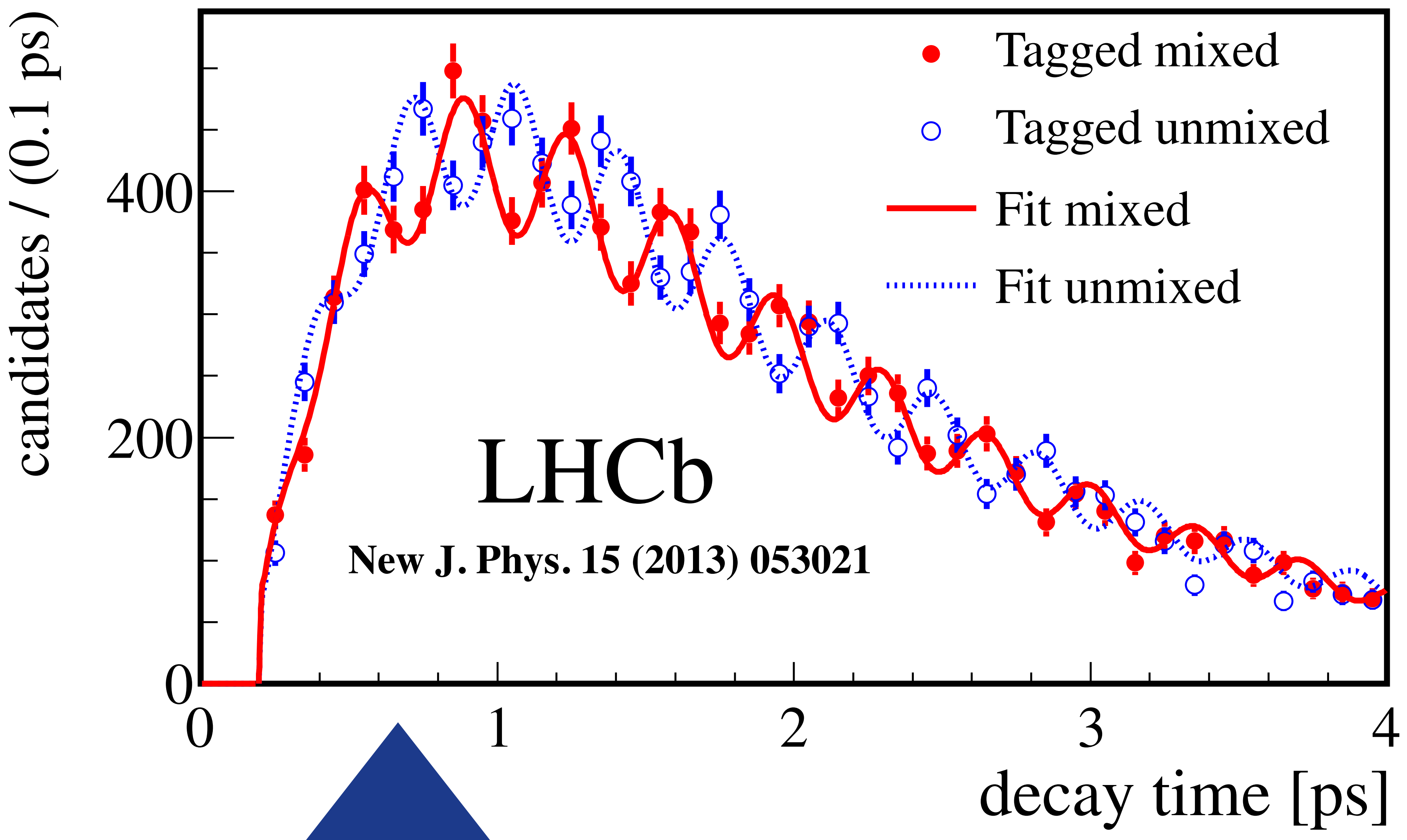
$$|V_{ub}|/|V_{cb}|(\mathrm{high}) = 0.0946 \pm 0.0030\,(\mathrm{stat})^{+\ 0.0024}_{-\ 0.0025}\,(\mathrm{syst}) \pm 0.0013\ (D_s) \pm 0.0068\ (\mathrm{FF}),$$
FF from LQCD (FerMILC, 1901.02561)

**The discrepancy needs to be understood.**

# Meson life is beautiful

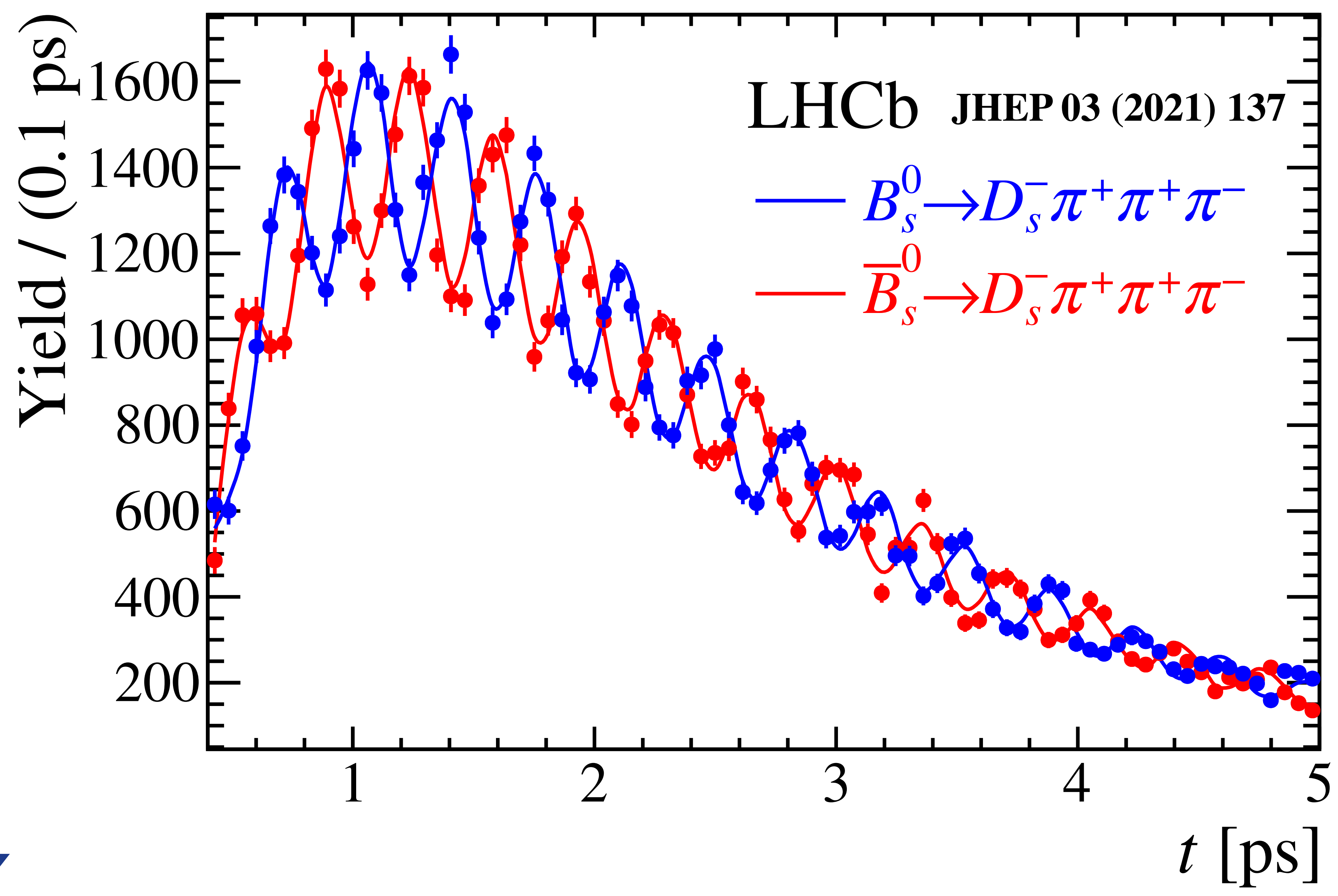


- The textbook plot: oscillations of $B_s^0$ mesons

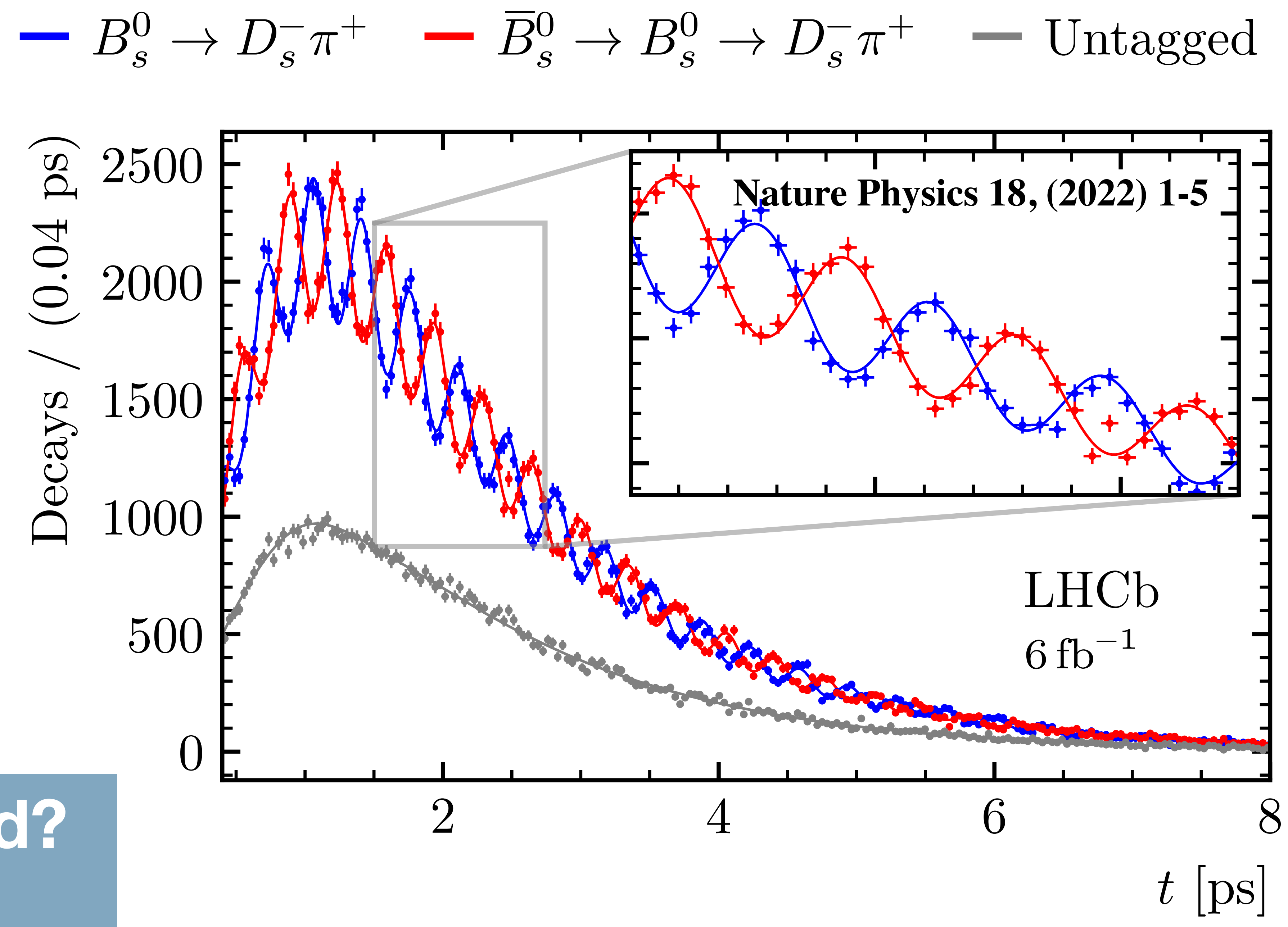



2013

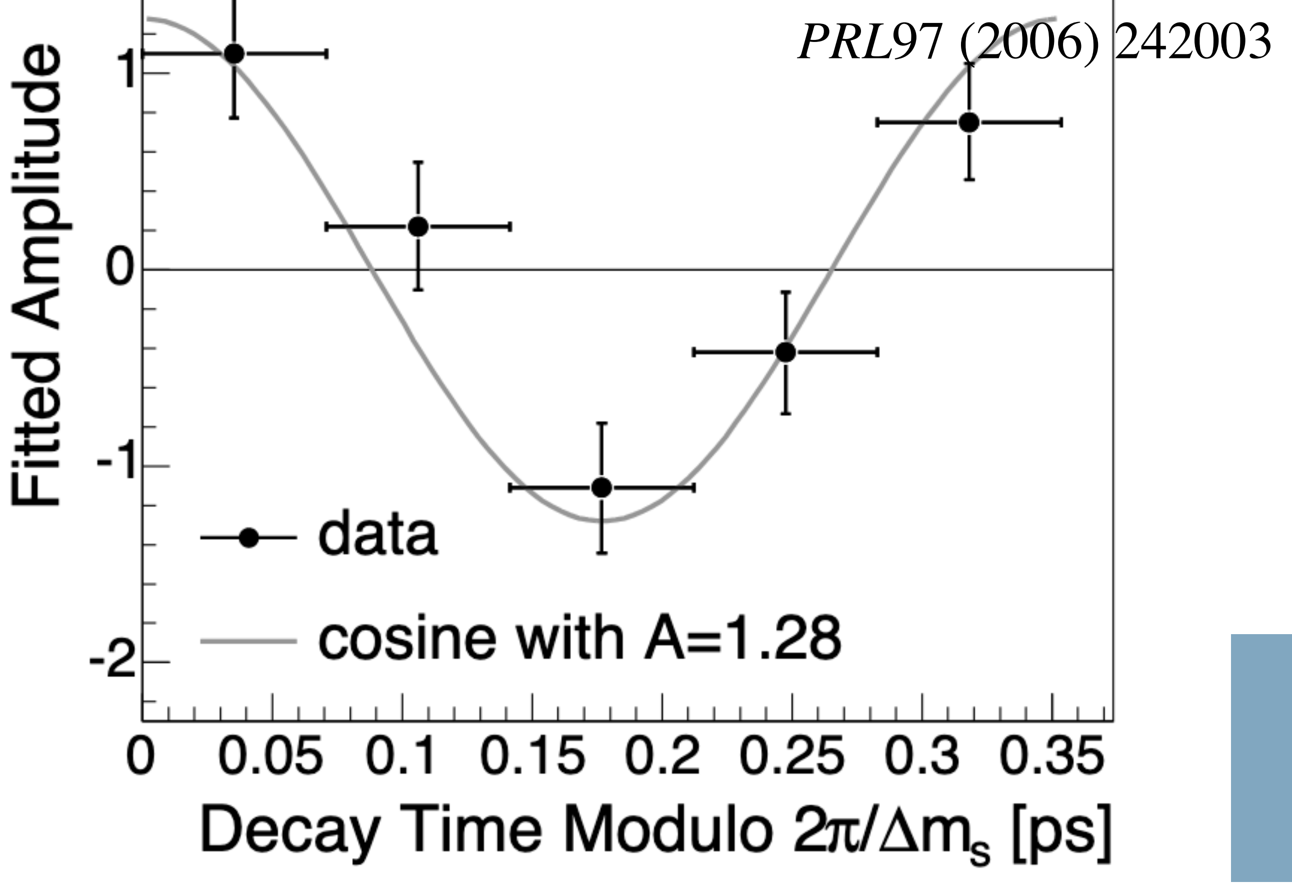
2020




2021




CDF, 2006




**oscillation frequency (LHCb average):**

$$\Delta m_s = 17.7656 \pm 0.0057\ \mathrm{ps}^{-1}$$

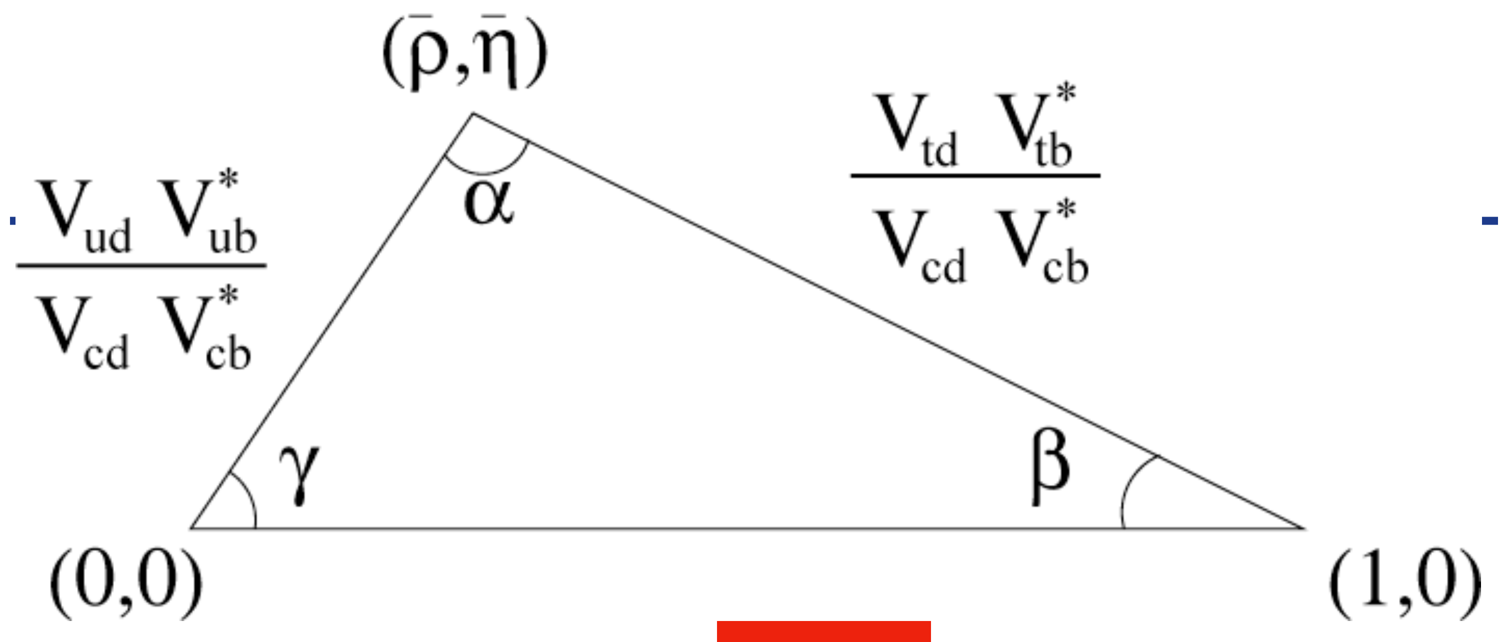
$$\Delta m_s(\mathrm{SM}) = 18.4^{+0.7}_{-1.2}\ \mathrm{ps}^{-1}$$ 1909.11087

relies heavily on lattice inputs!

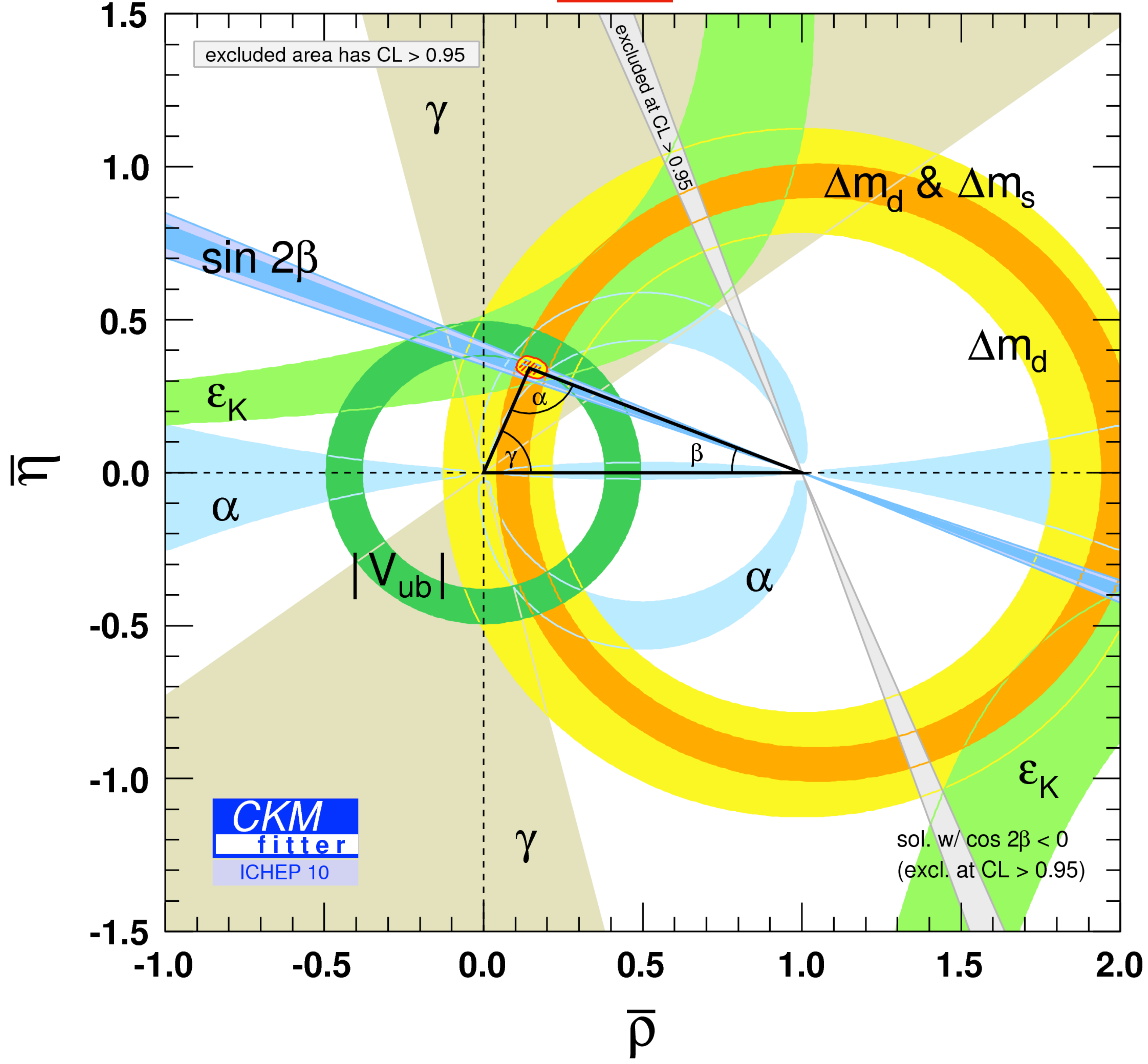
**Can theoretical precision be improved?**
**Powerful constraint on BSM?**

# CP violation in beauty

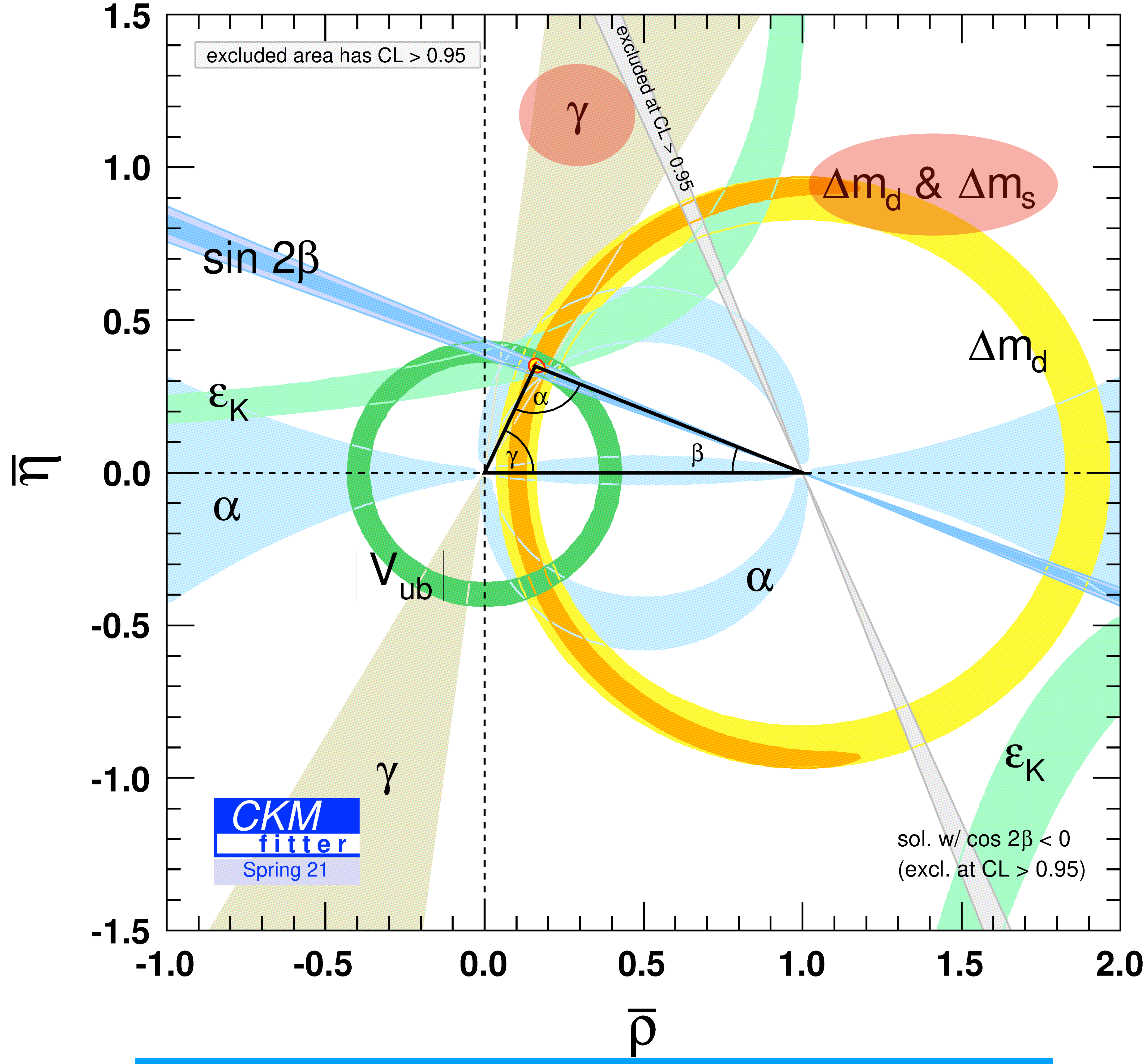
- Immense progress in our knowledge of the **unitarity triangle** since LHCb started taking data




2010




2021




LHCb combination (2021): $\gamma = \left(65.4^{+3.8}_{-4.2}\right)^\circ$

JHEP 12 (2021) 141

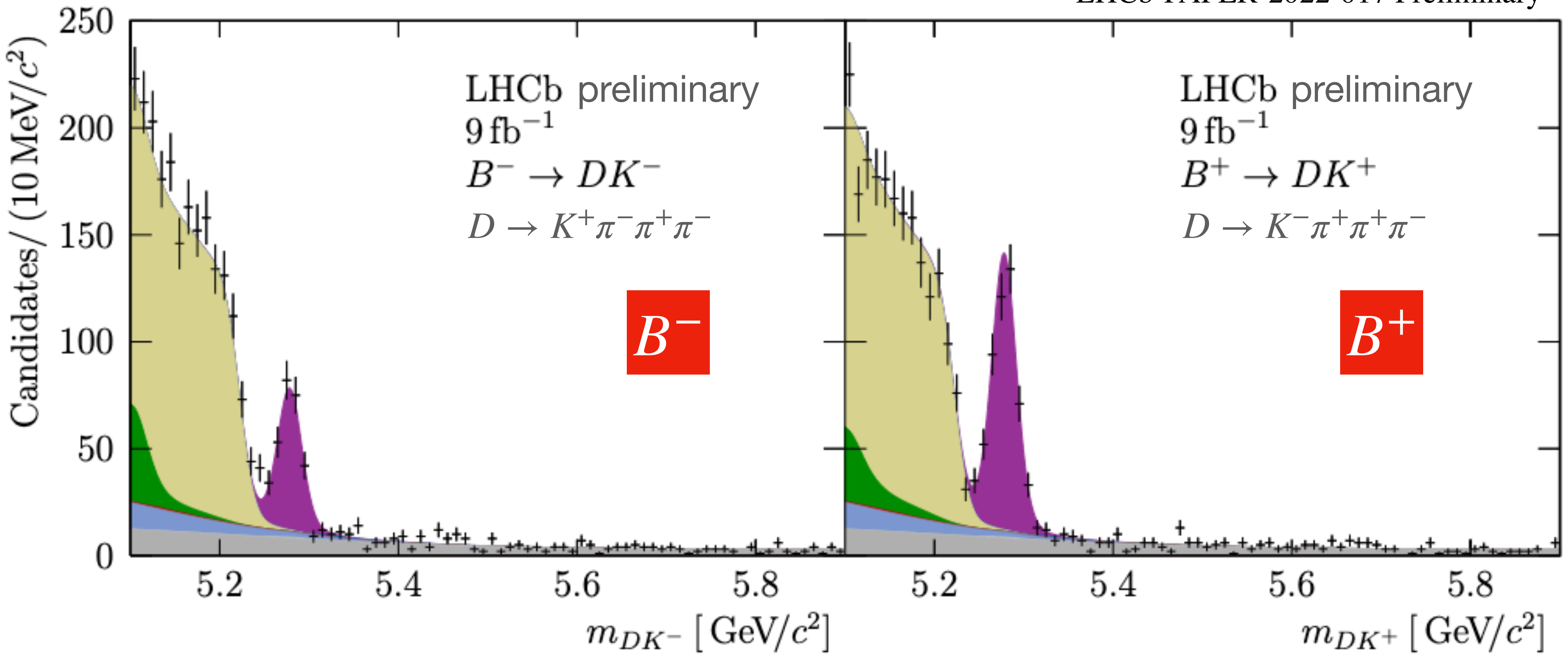
# CP violation in beauty



- Legacy measurements with Run 1+2 dataset are still arriving

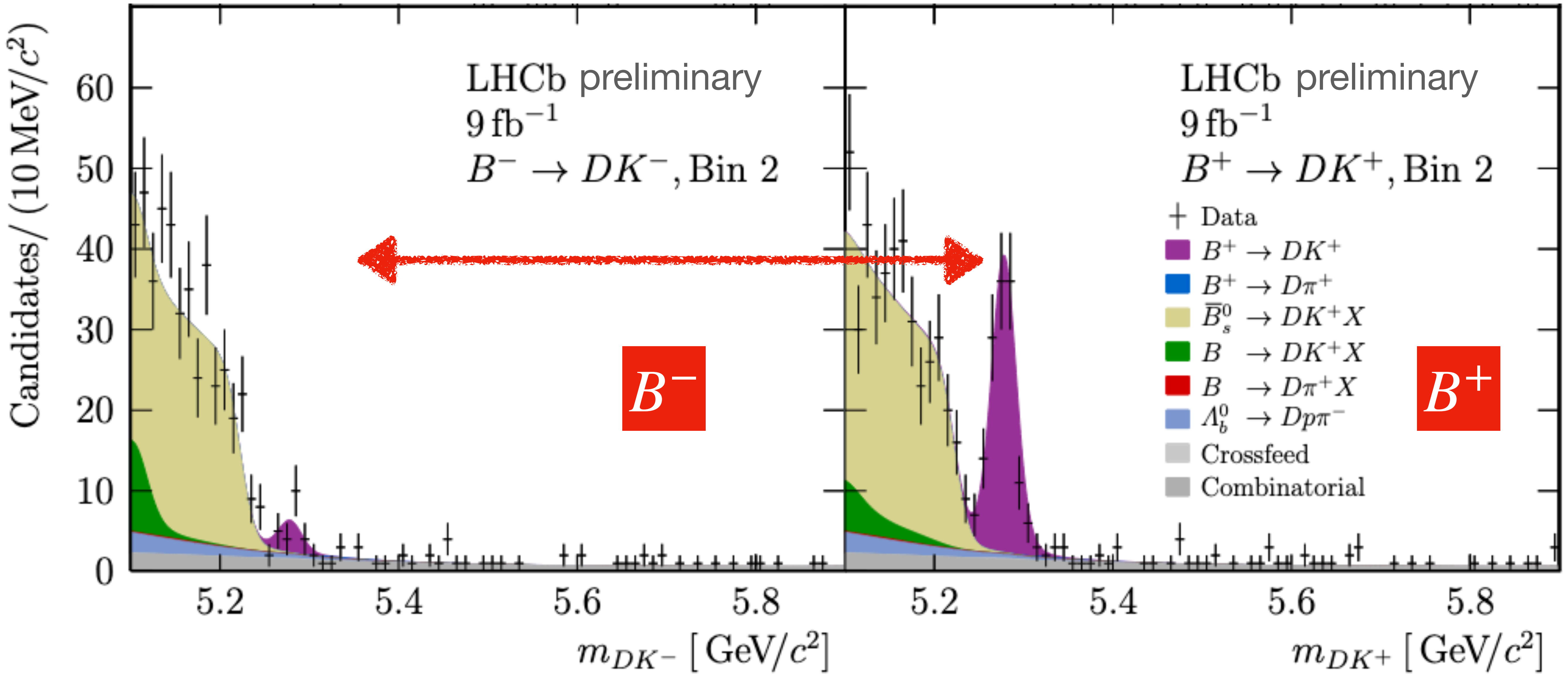
LHCb-PAPER-2022-017 Preliminary

full dataset




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

one region of $D$-meson decay phase space




CP asymmetry enhanced in certain regions of $D$-meson decay phase space

$$\mathscr{A}_{CP} \sim 85\,\%$$

# CP violation in charm

- 2019: LHCb measures $\Delta\mathcal{A}_{CP} \equiv \mathcal{A}_{CP}(K^+K^-) - \mathcal{A}_{CP}(\pi^+\pi^-)$
  - difference of time-integrated CP asymmetries in two Cabibbo-suppressed $D^0$ decays
    - interference of penguin and tree → CPV?
    - near-cancellation of systematic uncertainties due to production and detection asymmetries
  - $\Delta\mathcal{A}_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$: first observation of CPV in charm [PRL 122 (2019) 211803]
- **NEW**: we also measure the individual asymmetry $\mathcal{A}_{CP}(K^+K^-)$

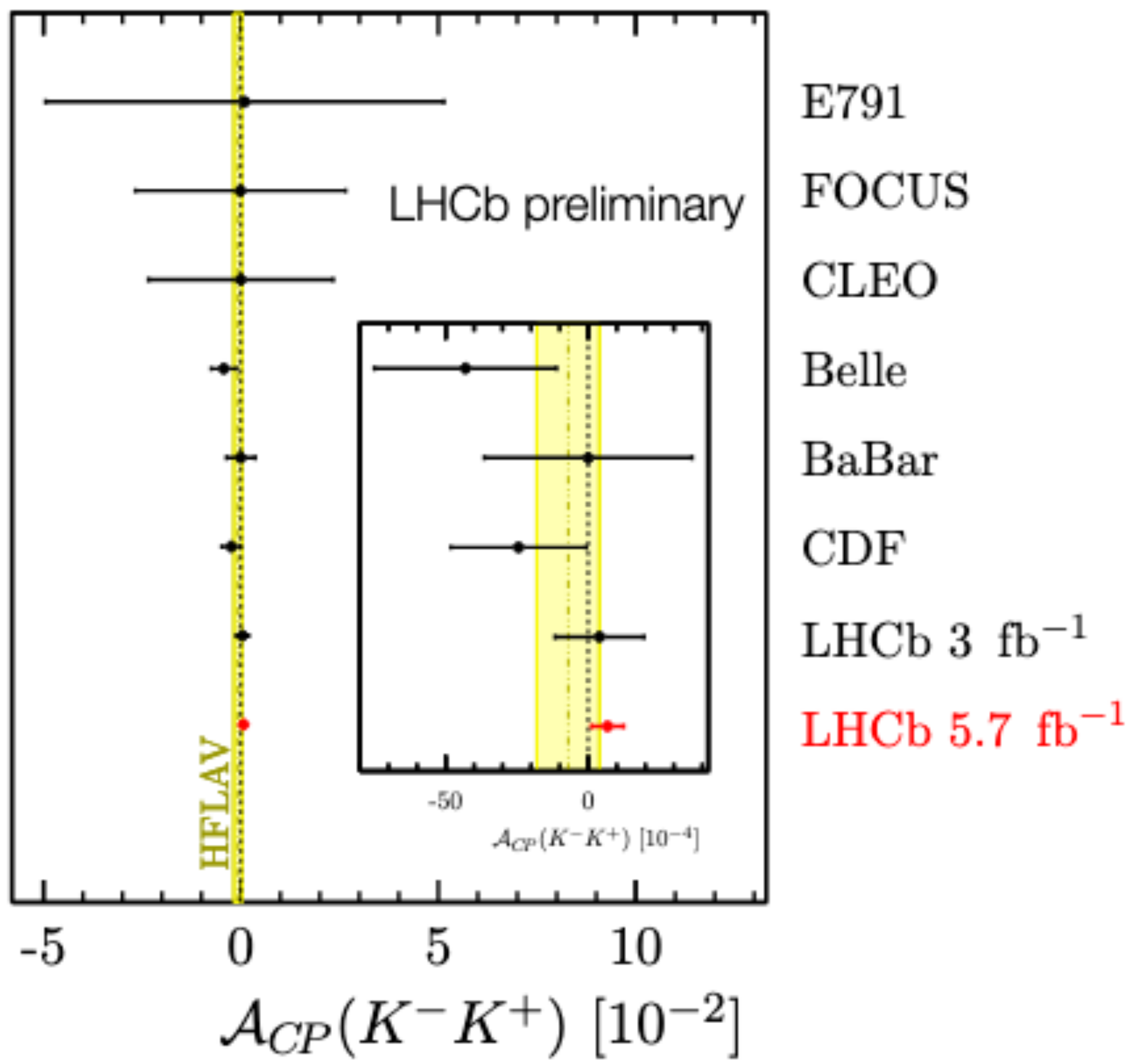
$$\mathcal{A}_{CP}(K^+K^-) = \big(6.8 \pm 5.4(\text{stat}) \pm 1.6(\text{syst})\big) \times 10^{-4}$$

- Why is this interesting? $\mathcal{A}_{CP} \sim a_{direct}$ + terms due to D mixing
- Combination of LHCb results on $\mathcal{A}_{CP}(K^+K^-)$, $\Delta\mathcal{A}_{CP}$ and mixing parameters leads to

$$a_{direct}(K^+K^-) = (\ 7.7 \pm 5.7) \times 10^{-4}$$
$$a_{direct}(\pi^+\pi^-) = (23.2 \pm 6.1) \times 10^{-4}$$

$> 3\sigma$ evidence for CPV in $D^0 \to \pi^+\pi^-$

LHCb-PAPER-2022-024, Preliminary




**LHCb has power to probe CPV in charm.**
**Time for theory to catch up!**

**Do our measurements agree with SM?**
**It's for you to tell us.**

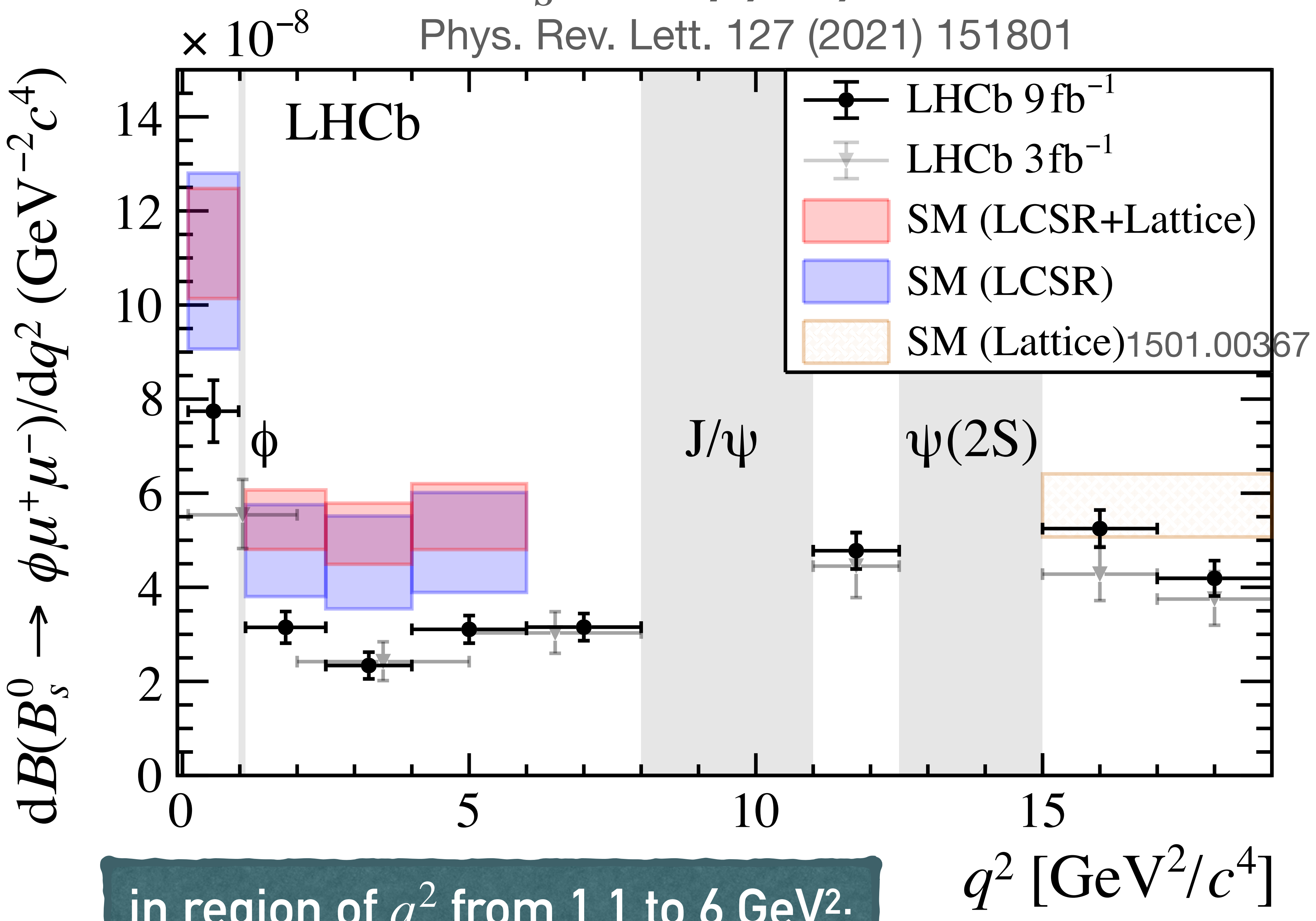
# Rare decays: $b \to s\ell^+\ell^-$



- Loop-level processes $b \to s\ell^+\ell^-$: rather clean theoretically, rare ( $\sim 10^{-7}$)
- Differential branching fraction measurements consistently lower compared to the SM expectations

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

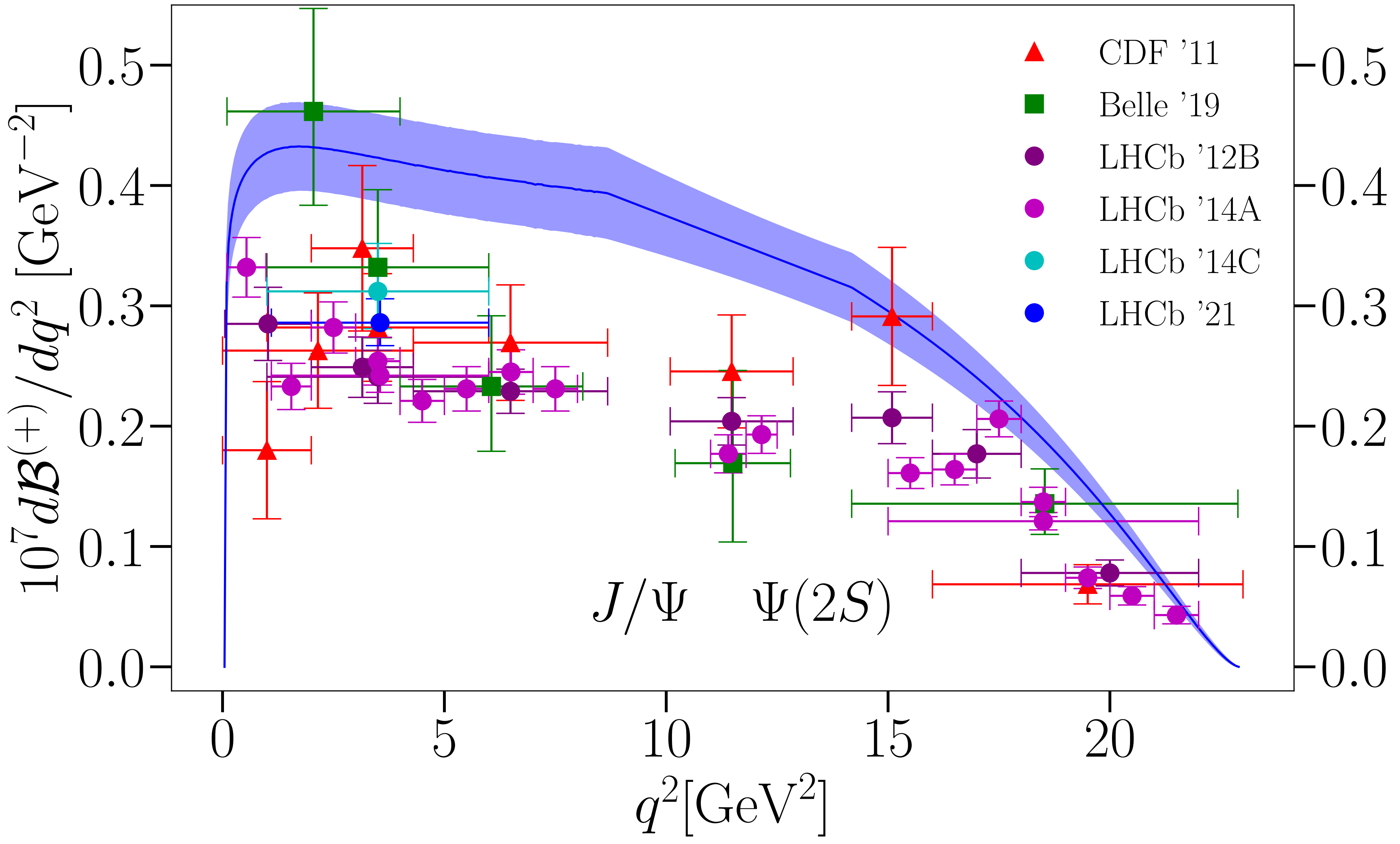
Phys. Rev. Lett. 127 (2021) 151801




in region of $q^2$ from 1.1 to 6 GeV²:
3.6σ below SM (lattice+LCSR)
1.8σ below SM (LCSR)

$B^+ \to K^+\mu^+\mu^-$ 2207.13371; LHCb: JHEP 06 (2014) 133

talk by W.Parrott (Mon parallel)




**This does not look like statistical fluctuations. Is there still room for the SM prediction to accommodate our measurements?**

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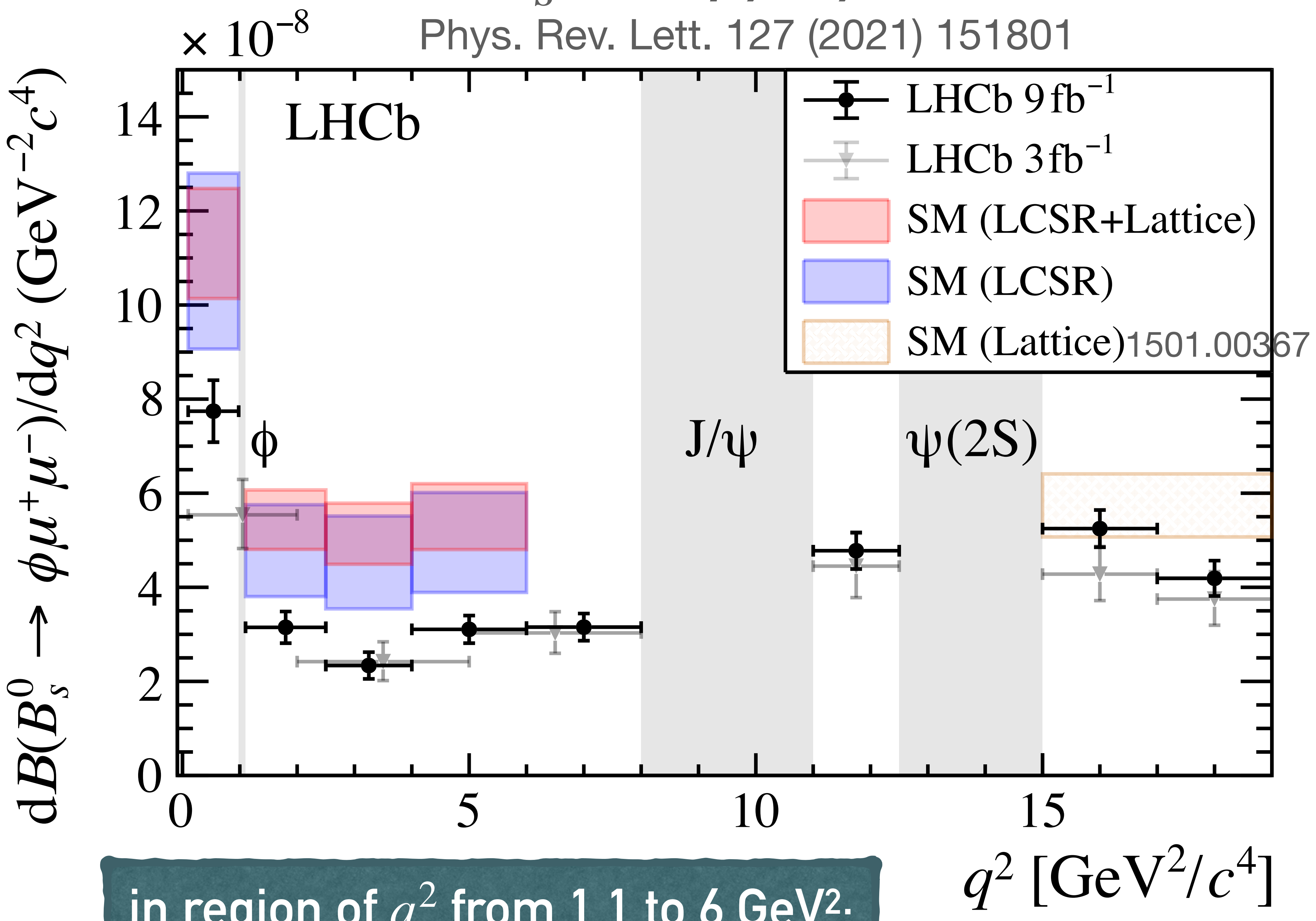
Phys. Rev. Lett. 127 (2021) 151801

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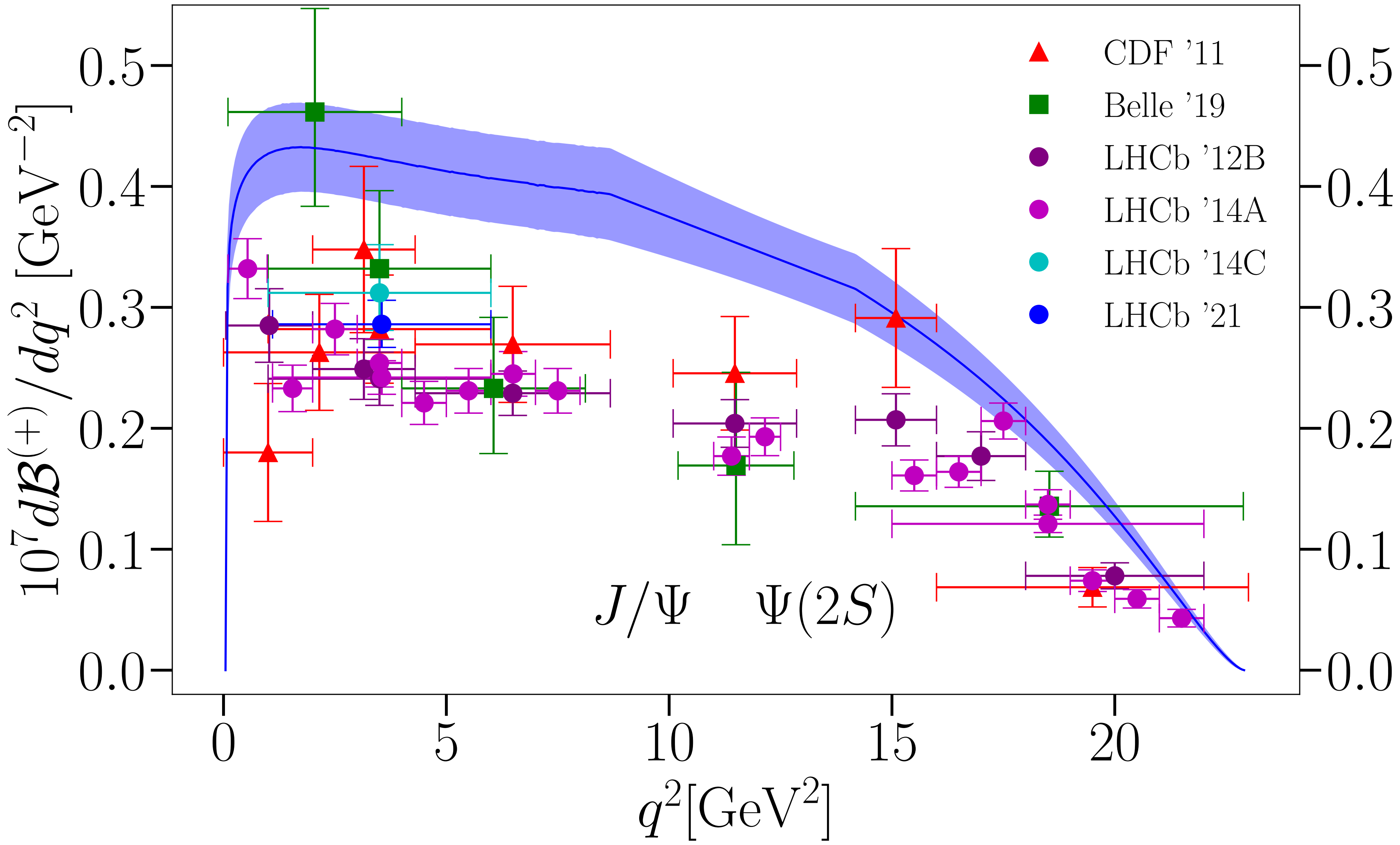



Note that LHCb measures ratios like

$$\frac{B_s^0 \to \phi\mu^+\mu^-}{B_s^0 \to J/\psi\phi}$$

**Improved knowledge of the $b \to sJ/\psi$ channels needed.**

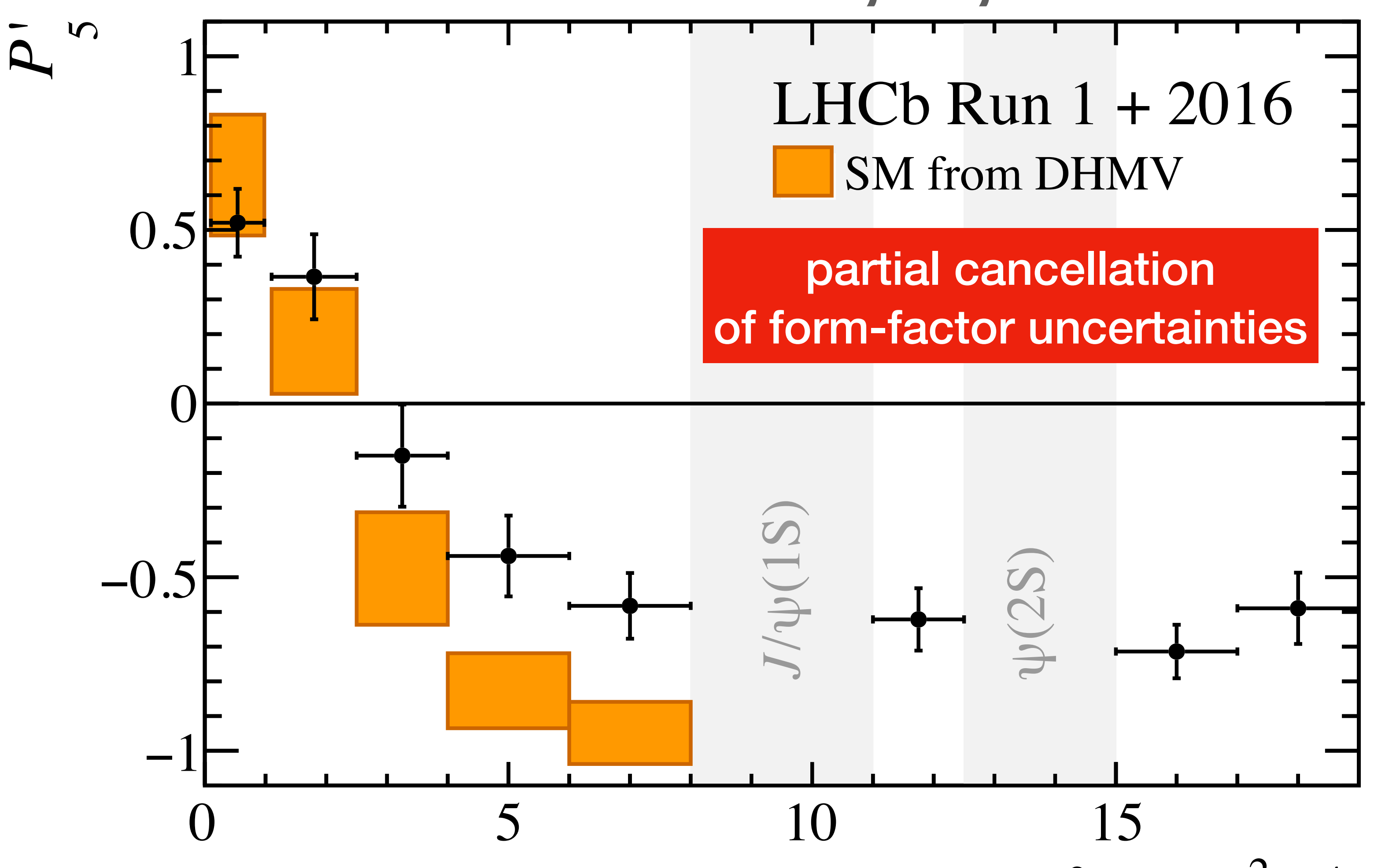
**This does not look like statistical fluctuations. Is there still room for the SM prediction to accommodate our measurements?**

- LHCb's **unique** reach is in ability to perform similar measurements for **b-baryon** decays: $\Lambda_b^0 \to \Lambda\mu^+\mu^-$, $\Xi_b \to \Xi\mu^+\mu^-$, $\Omega_b^- \to \Omega^-\mu^+\mu^-$ etc. However, there is very few theoretical predictions (especially for $\Xi_b, \Omega_b^-$). **We would encourage theoretical activity on baryonic channels.**

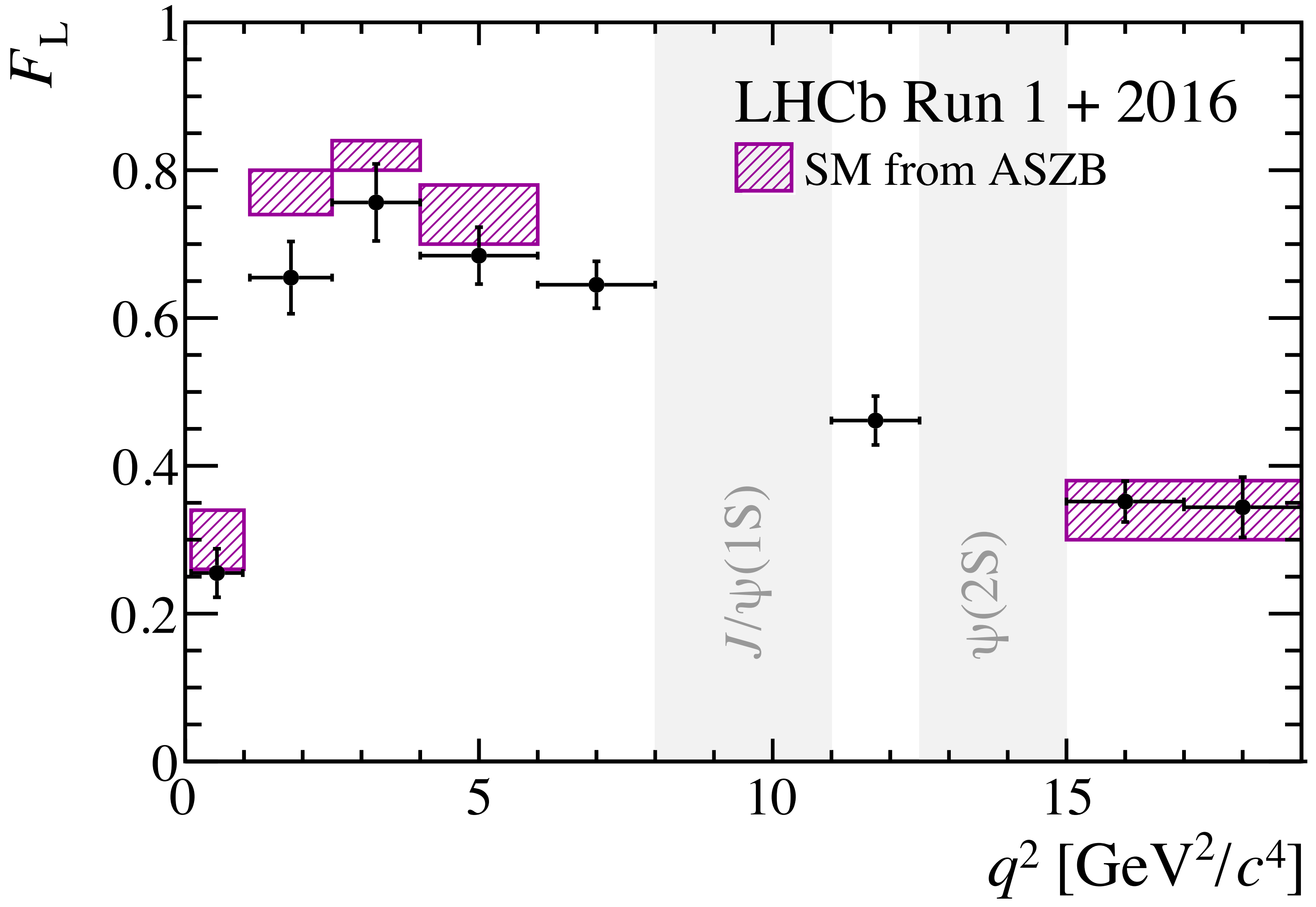
# Rare decays: $b \to s\ell^+\ell^-$

- Intriguing discrepancies with the SM in angular observables persist; more data always welcome

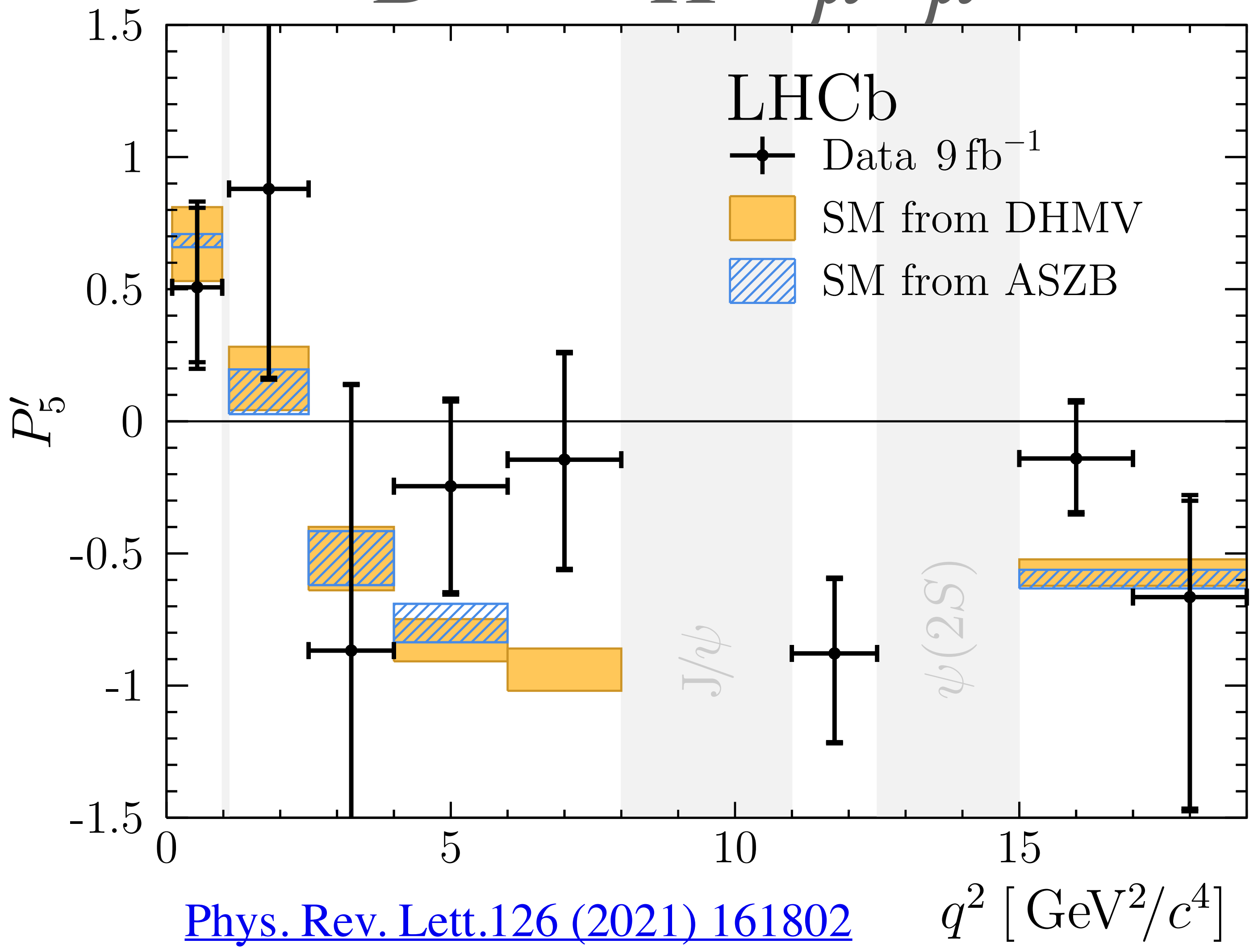
$B^0 \to K^{*0}\mu^+\mu^-$



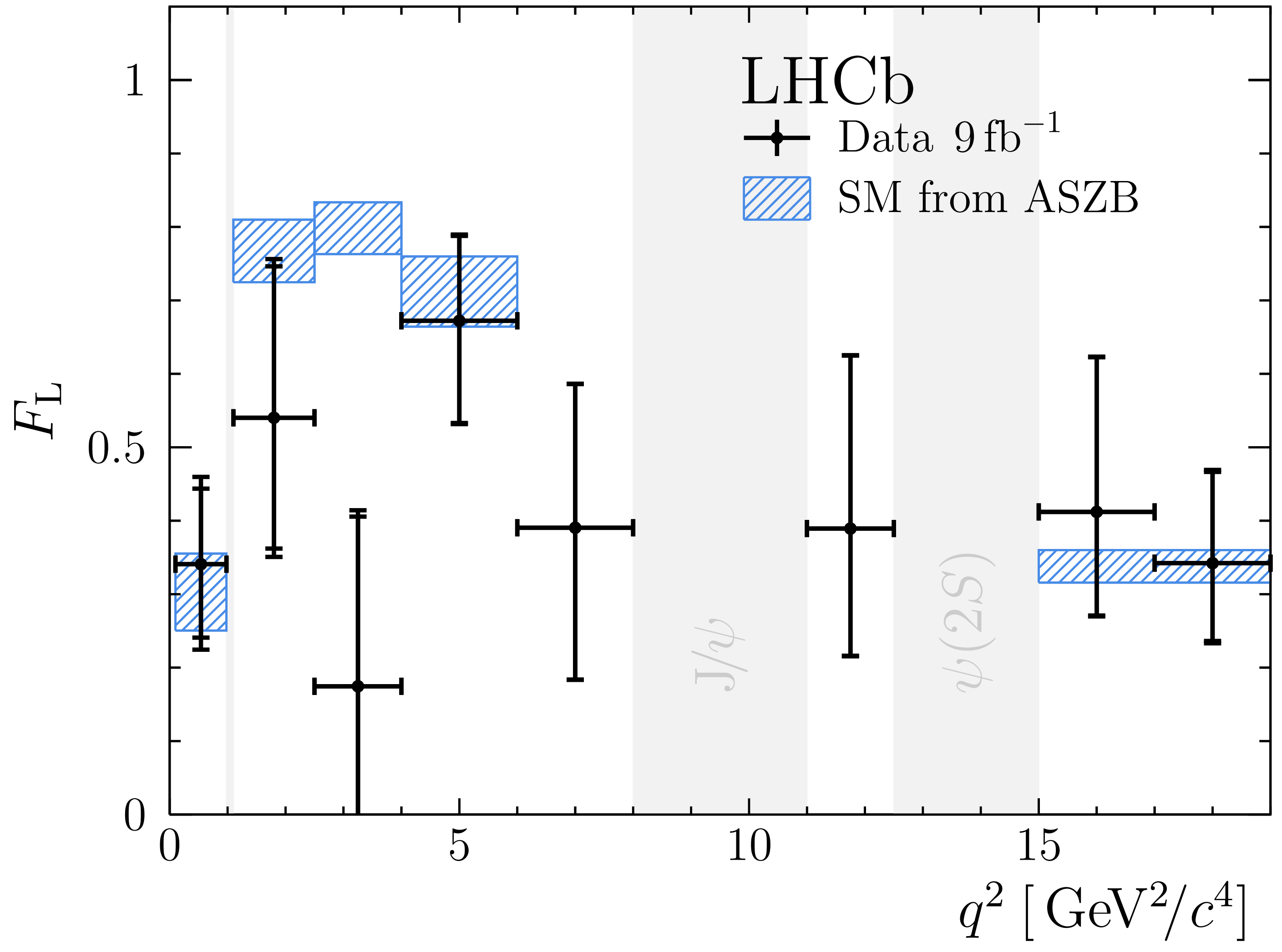

Phys. Rev. Lett. 125 (2020) 011802




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



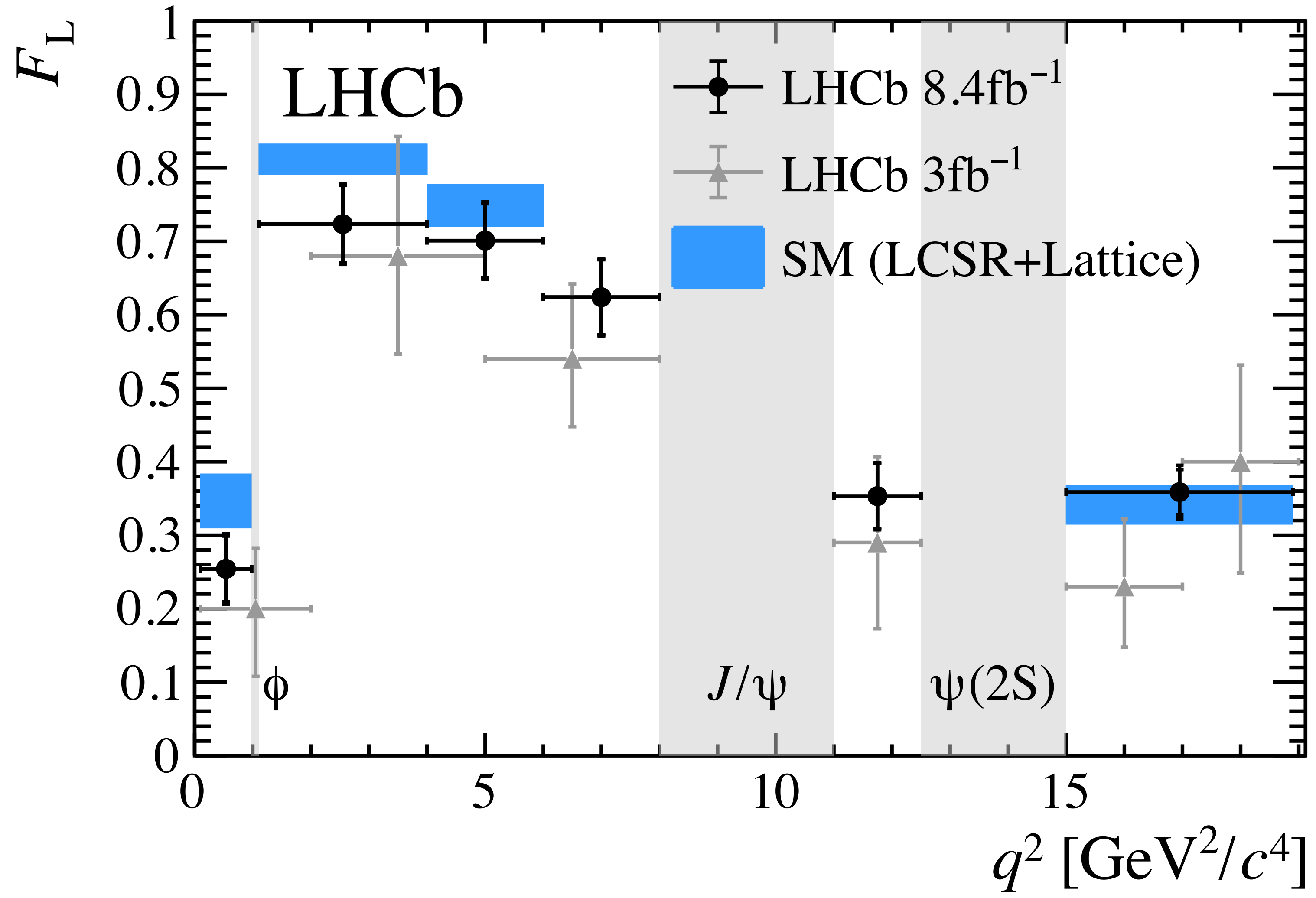

Phys. Rev. Lett.126 (2021) 161802




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

(untagged analysis)

JHEP 11 (2021) 043



# All leptons are equal



- SM: the $\ell$ in $b \to s\ell^+\ell^-$ can be **electron** or **muon** with **equal** probability (modulo tiny phase-space effects ~$m_\mu/m_b$)
- We are testing this in a plethora of decay modes: mesons $B^+ \to K^{(*)+}\ell^+\ell^-$, $B^0 \to K^{(*)0}\ell^+\ell^-$ or baryons $\Lambda_b^0 \to pK^-\ell^+\ell^-$
- **What we want to measure:** "tests of Lepton Universality"

$$R_X = \frac{\mathcal{B}(B \to X\mu^+\mu^-)}{\mathcal{B}(B \to Xe^+e^-)}$$

in a given region of $q^2 = m^2(\ell^+\ell^-)$

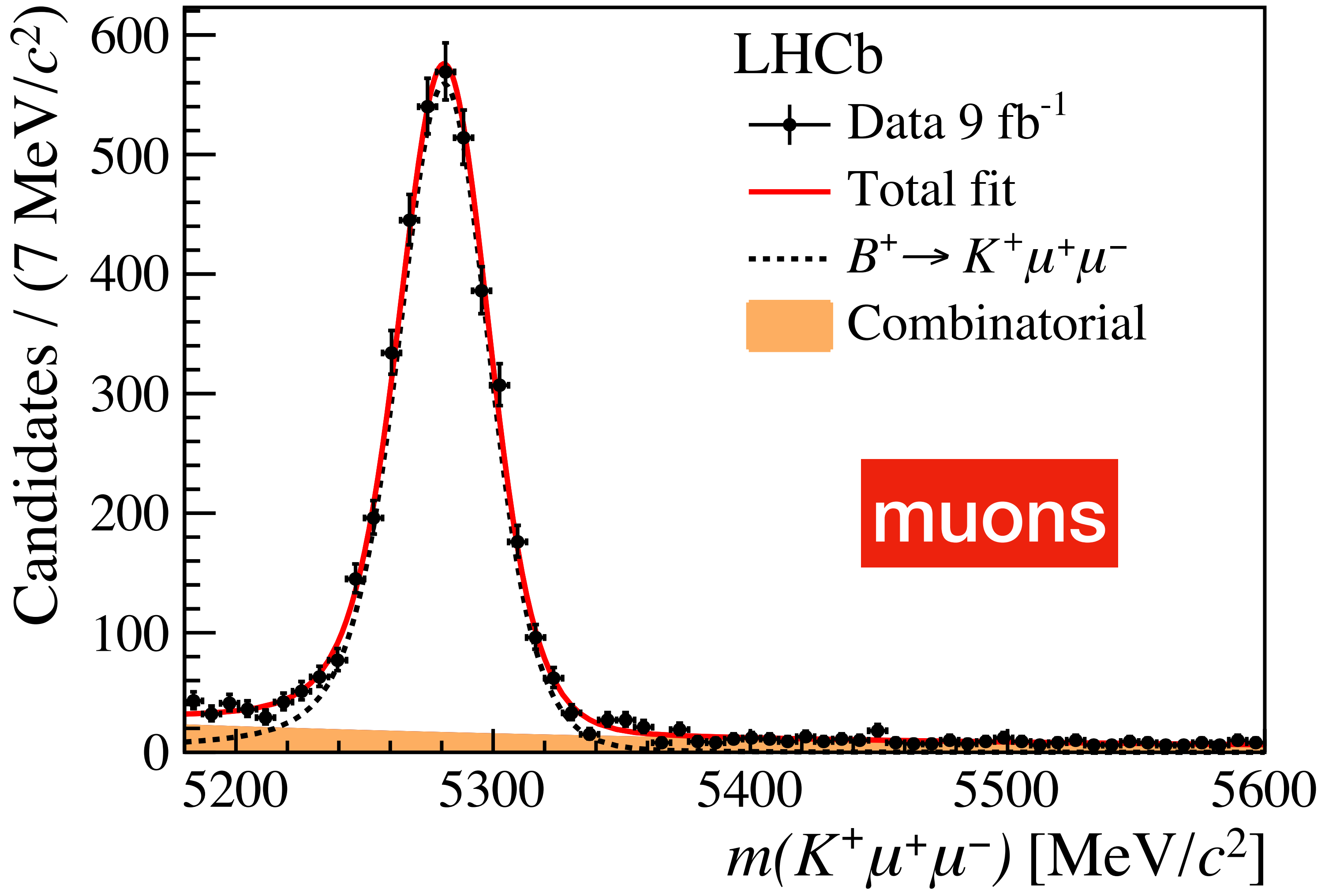
clean theoretically

- Main complexity: muons and electrons behave very differently in the detector.
- **What we really measure:**

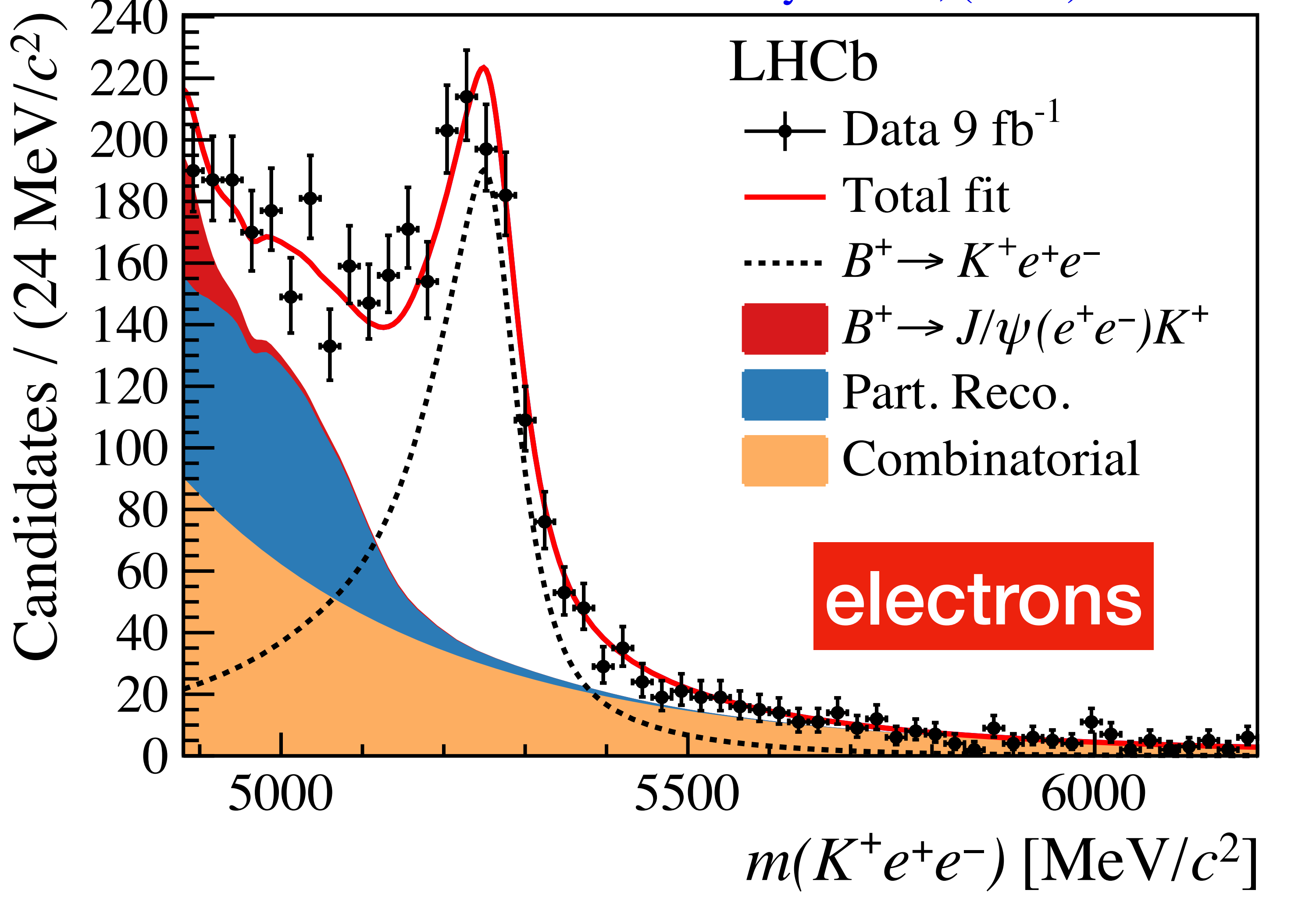
$$R_X = \frac{\mathcal{B}(B \to X\mu^+\mu^-)}{\mathcal{B}(B \to Xe^+e^-)} \times \frac{\mathcal{B}(B \to XJ/\psi(e^+e^-))}{\mathcal{B}(B \to XJ/\psi(\mu^+\mu^-))}$$

relies on well-tested LU in $J/\psi \to \ell^+\ell^-$

- Allows to cancel many systematic uncertainties.

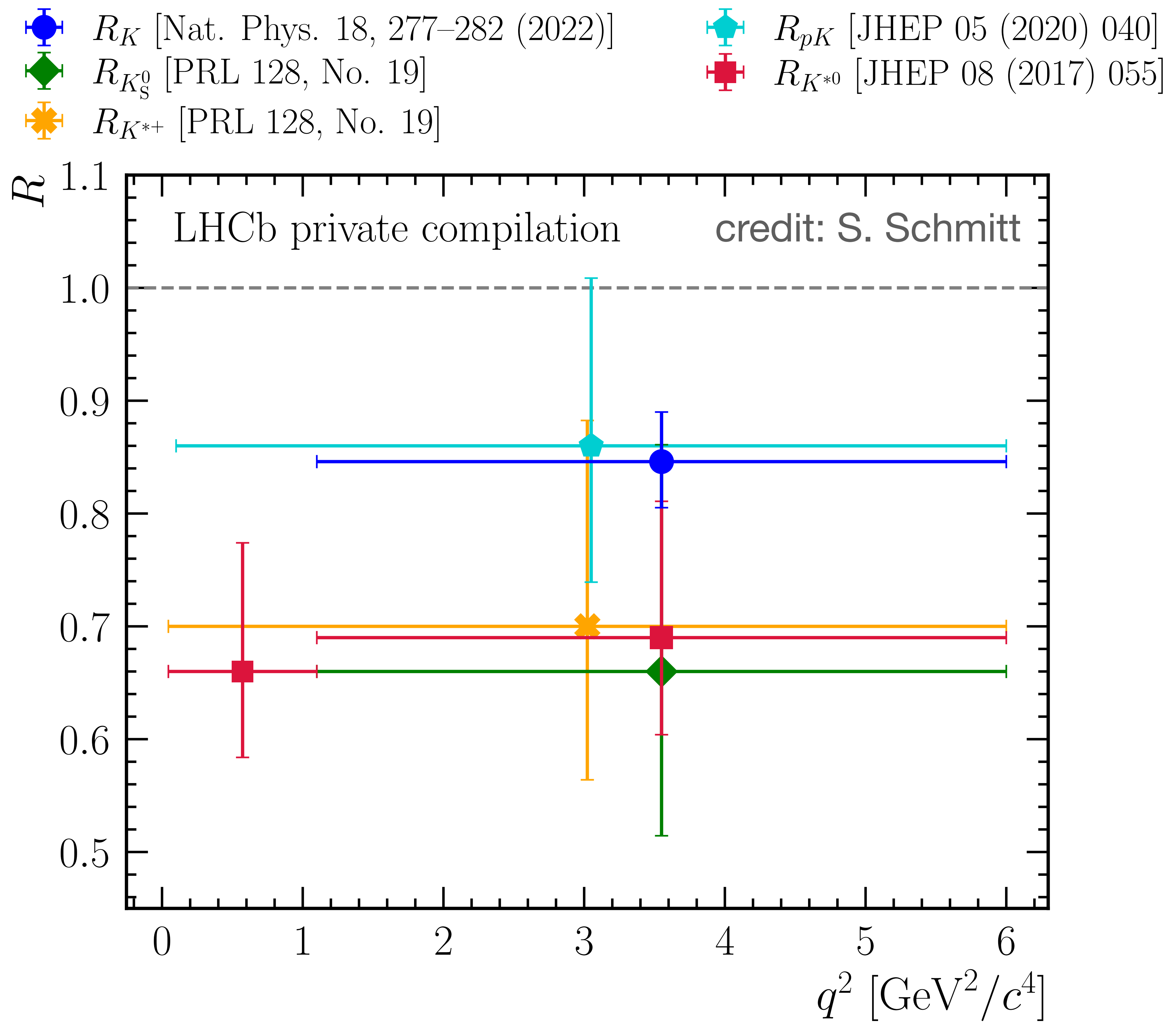



Nature Physics 18, (2022) 277-282




resolution due to bremsstrahlung emission & recovery

# All leptons are equal, but some leptons are more equal than others?




Do we have a consistent picture from different measurements?
Needs confirmation with a larger dataset.

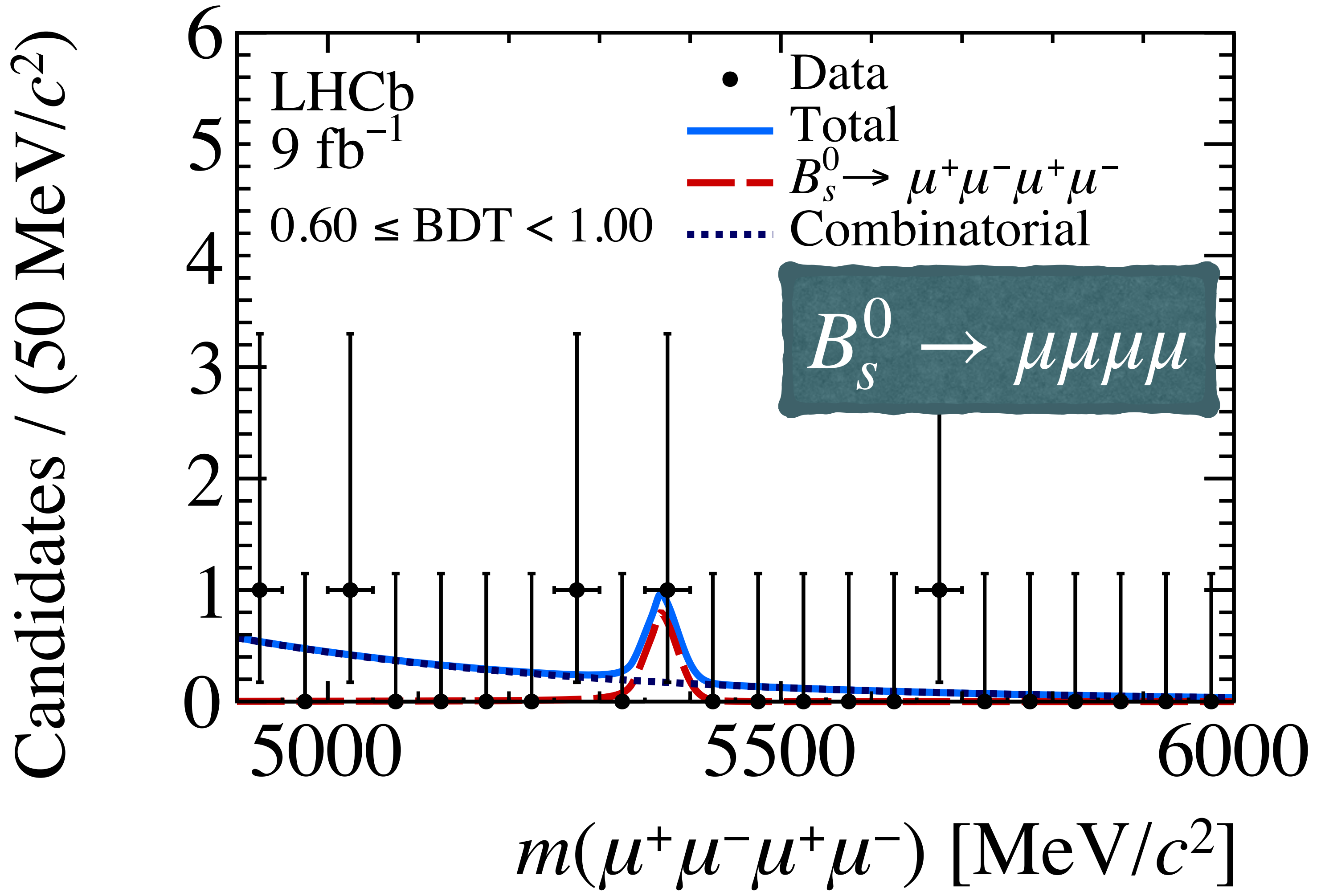
**Inputs from independent experiments are also crucial.**

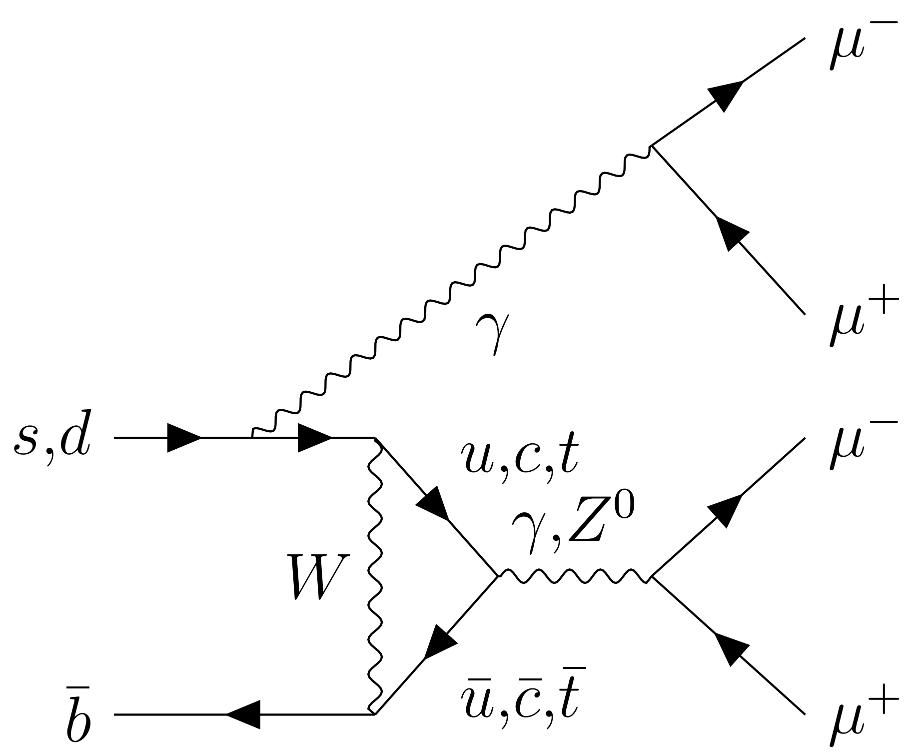
- Most results are from analysis of the **partial** LHCb dataset
- In particular, LHCb is currently focused on a combined measurement of $R_{K^+}$ and $R_{K^{*0}}$ with the Run 1+2 legacy dataset
  - This leads to a deeper understanding of systematic effects which will be reflected in the final result.
  - **Please be patient for the final results!**
- We also work on LU tests with $B_s^0 \to \phi \ell^+ \ell^-$, baryons, and other processes.

# Rare decays: $b \to s\ell^+\ell^-\ell^+\ell^-$

JHEP 03 (2022) 109

- Four muons are better than two!
- Lift the helicity suppression of $B_s^0 \to \mu^+\mu^-$ decays by emitting a virtual photon going to dimuon

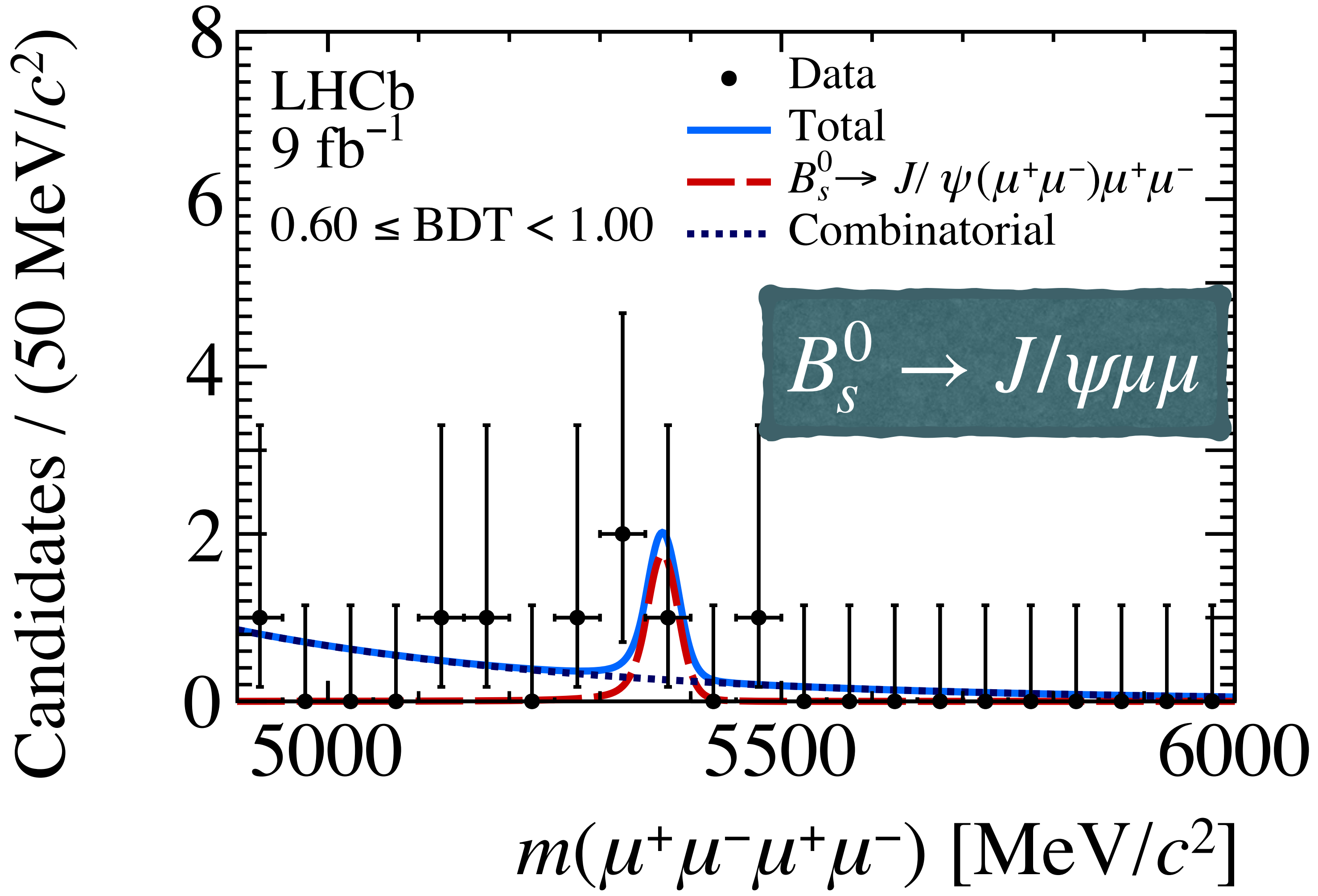


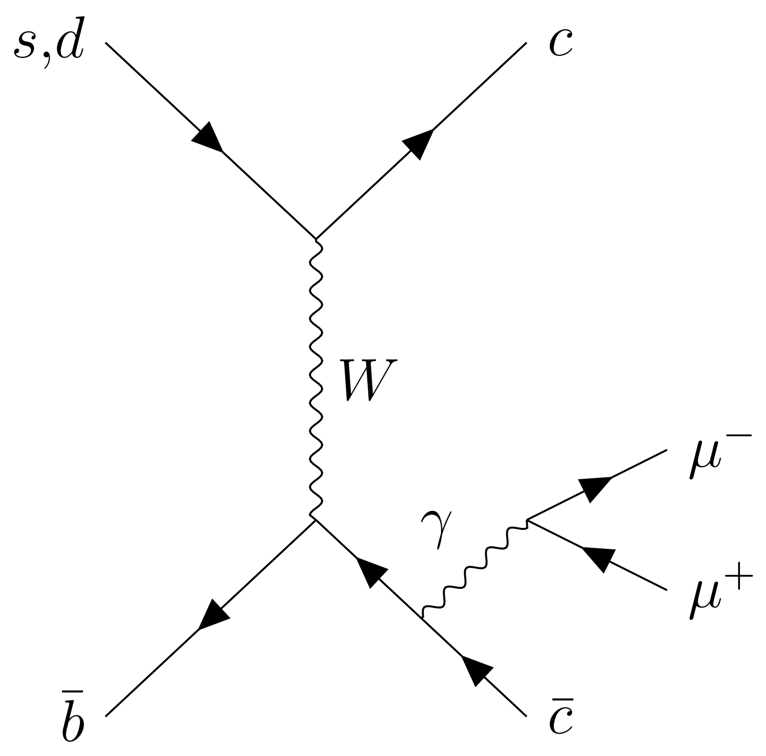




$\mathscr{B}(B_s^0 \to \mu\mu\mu\mu) < 8.6 \times 10^{-10}$ @ 95% CL

SM expectation: $\sim 10^{-10}$

- Same final state can be used to probe W-exchange processes:



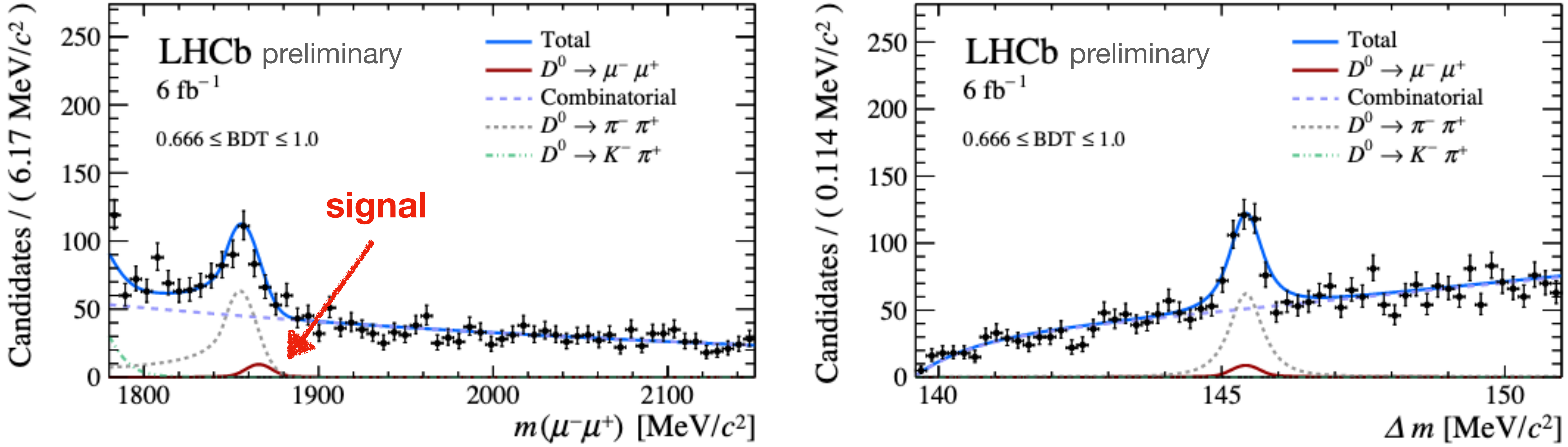

$\mathscr{B}(B_s^0 \to J/\psi(\mu\mu)\mu\mu) < 2.6 \times 10^{-9}$ @ 95% CL

**Multilepton decays will become a hot topic in Run 3 of LHCb. However, reliable theoretical predictions are highly desired.**

# Rare decays: $c \to u\ell^+\ell^-$

- **NEW**: search for $D^0 \to \mu^+\mu^-$, SM short-distance rate $\sim 10^{-18}$ (helicity suppression) but $\sim 10^{-13}$ due to $D^0 \to \gamma\gamma \to \mu^+\mu^-$

LHCb-PAPER-2022-029 Preliminary




$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 2.94\,(3.25) \times 10^{-9} \text{ at } 90\ (95)\%\ \text{CL}$$

[Phys. Rev. Lett. 128 221801]

- LHCb also studied processes like $D^+ \to \pi^+\pi^-\mu^+\mu^-$, dominated by resonances in dimuon mass
  - Interferences between resonances and NR are sensitive to BSM, but compatible with the SM so far

**LHCb reach in rare charm is similar to that in rare beauty.**
**Maintaining reliable PID performance at low momentum is a key for success.**
**Reliable theoretical predictions are important to have.**

# All leptons are equal, but some leptons are more equal than others?

- Anomalies in tree-level $b \to c\tau\nu$ transitions: not rare (~1%) but experimentally challenging
- The ratios of tau/mu universality, $R_D, R_{D*}, R_{J/\psi}$ are above the SM predictions
  - Lattice QCD crucial for form-factor inputs! talk by Alejandro Vaquero, Tue plenary

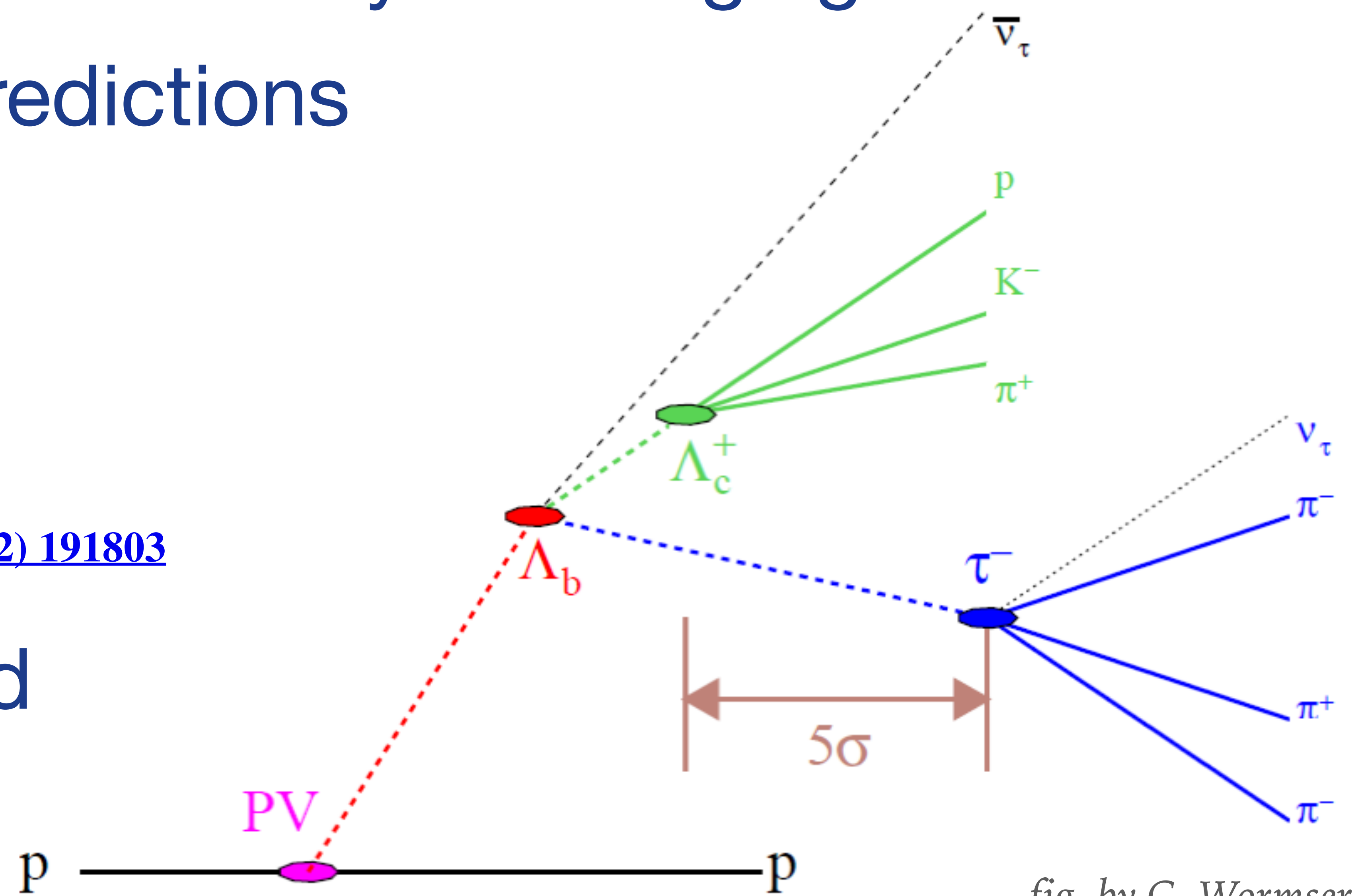


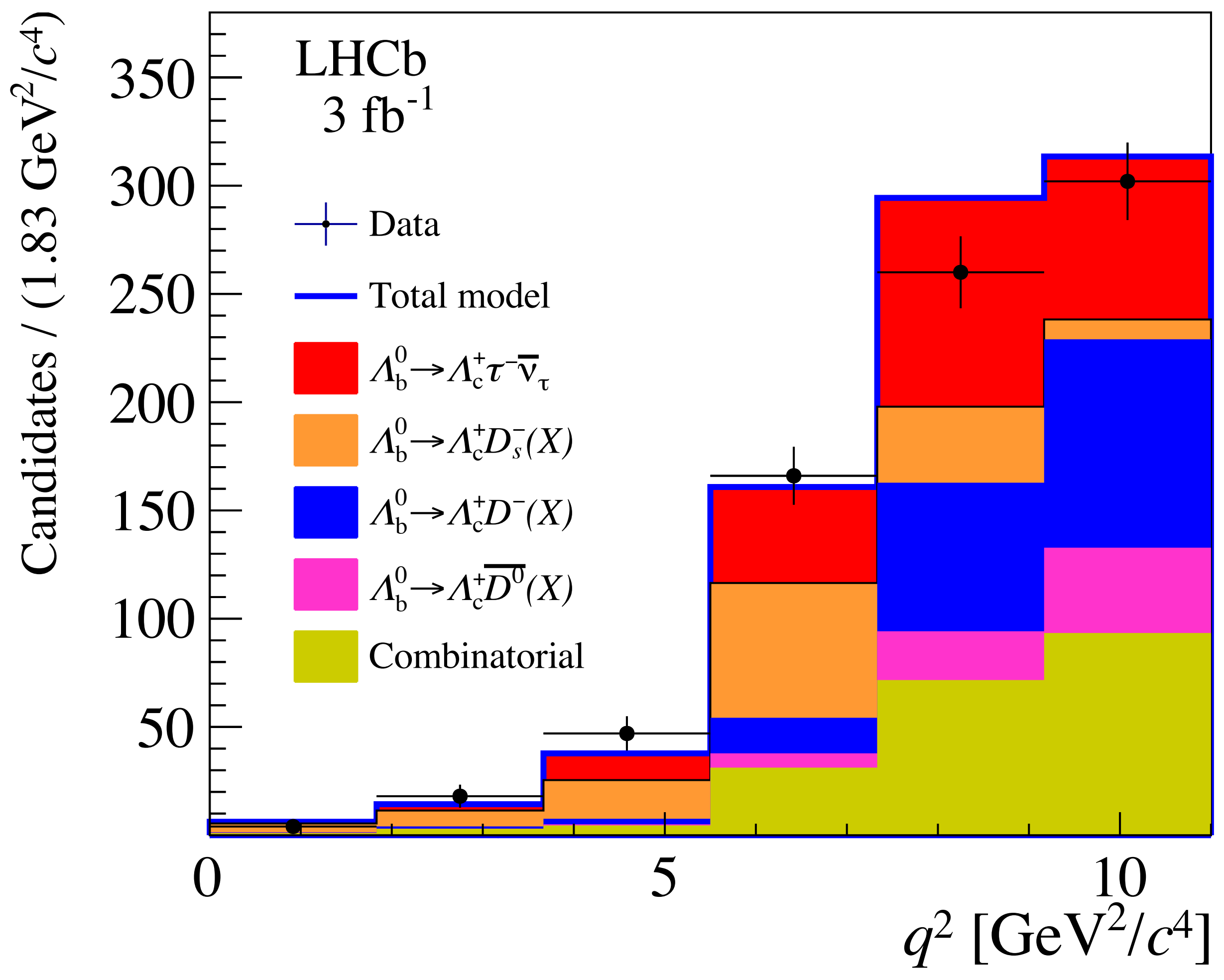
fig. by G. Wormser

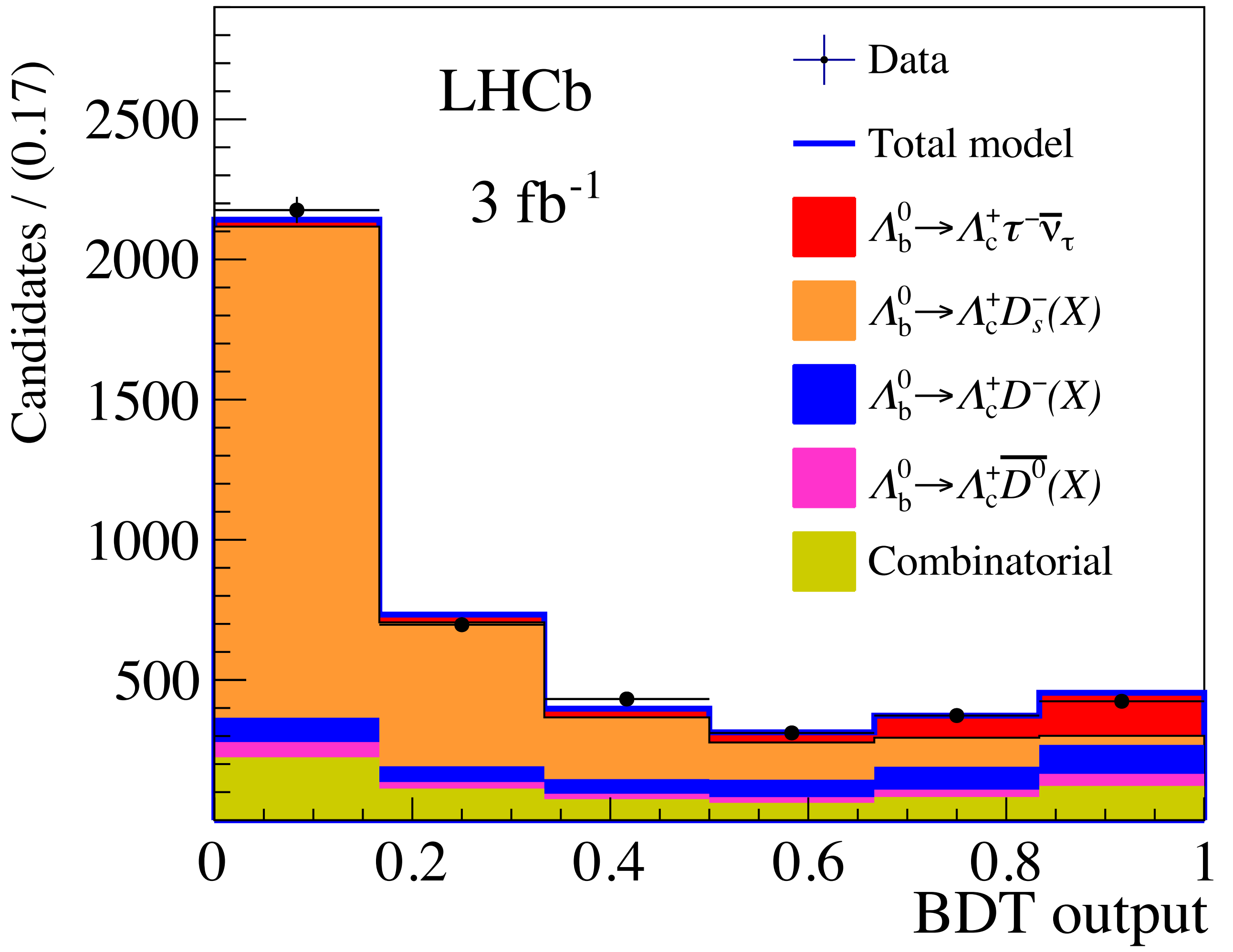
- Baryonic decays offer complementary insight
- Search for $\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau$ with $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$ Phys. Rev. Lett. 128 (2022) 191803
- Physics background suppressed by a combination of geometry and kinematics
- Normalised to $\Lambda_b^0 \to \Lambda_c^+\pi\pi\pi$ (same final state) and use the DELPHI value of $\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+\mu\nu)$

$$R(\Lambda_c^+) = 0.242 \pm 0.026\,(\text{stat}) \pm 0.040\,(\text{syst}) \pm 0.059\,(\text{ext.BF})$$

vs SM prediction: 0.324±0.004 Phys. Rev. D99 (2019) 055008
using lattice inputs:
1503.01421, 1702.02243

**Poor knowledge of baryonic BFs is the main limitation!**

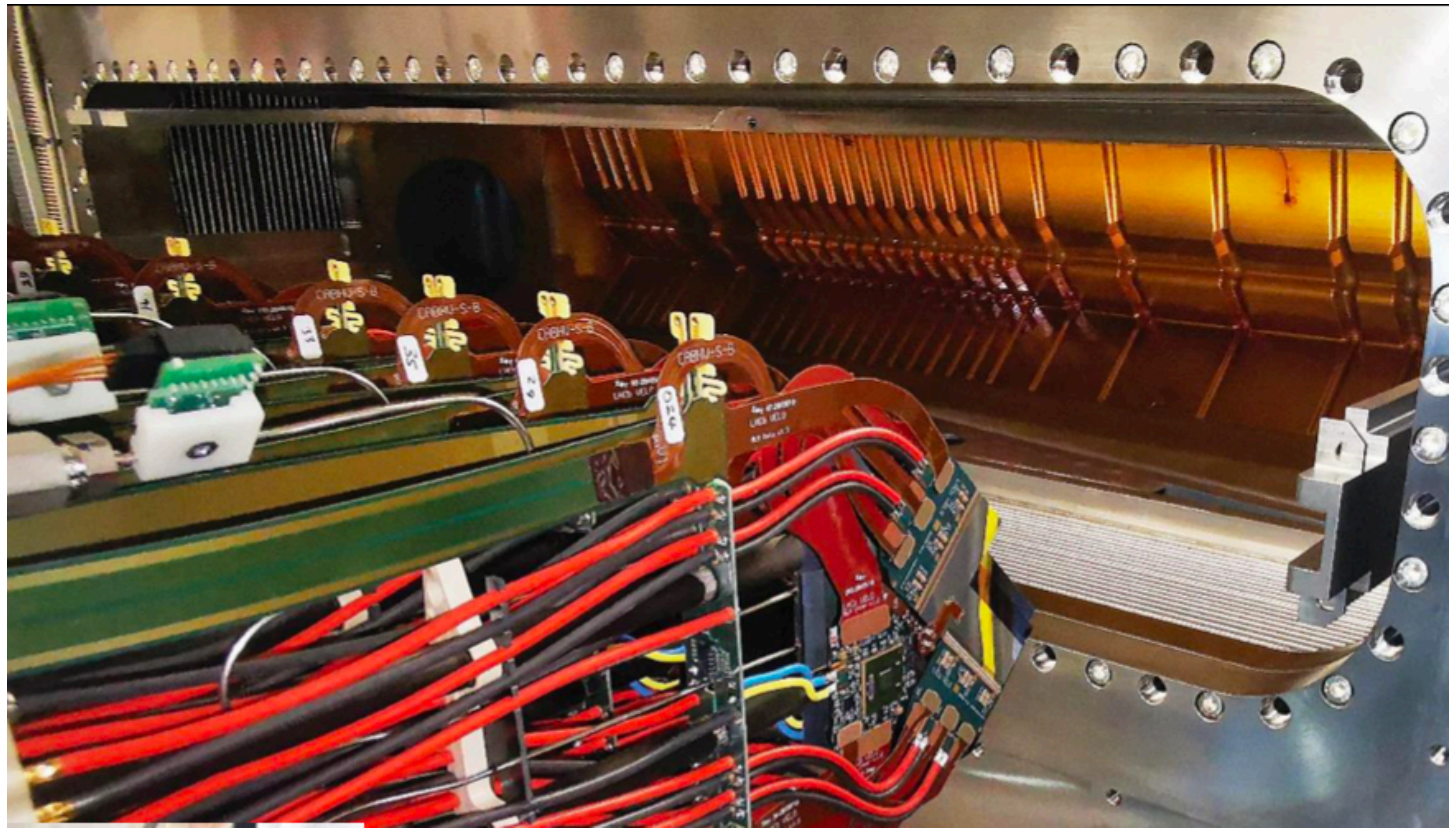


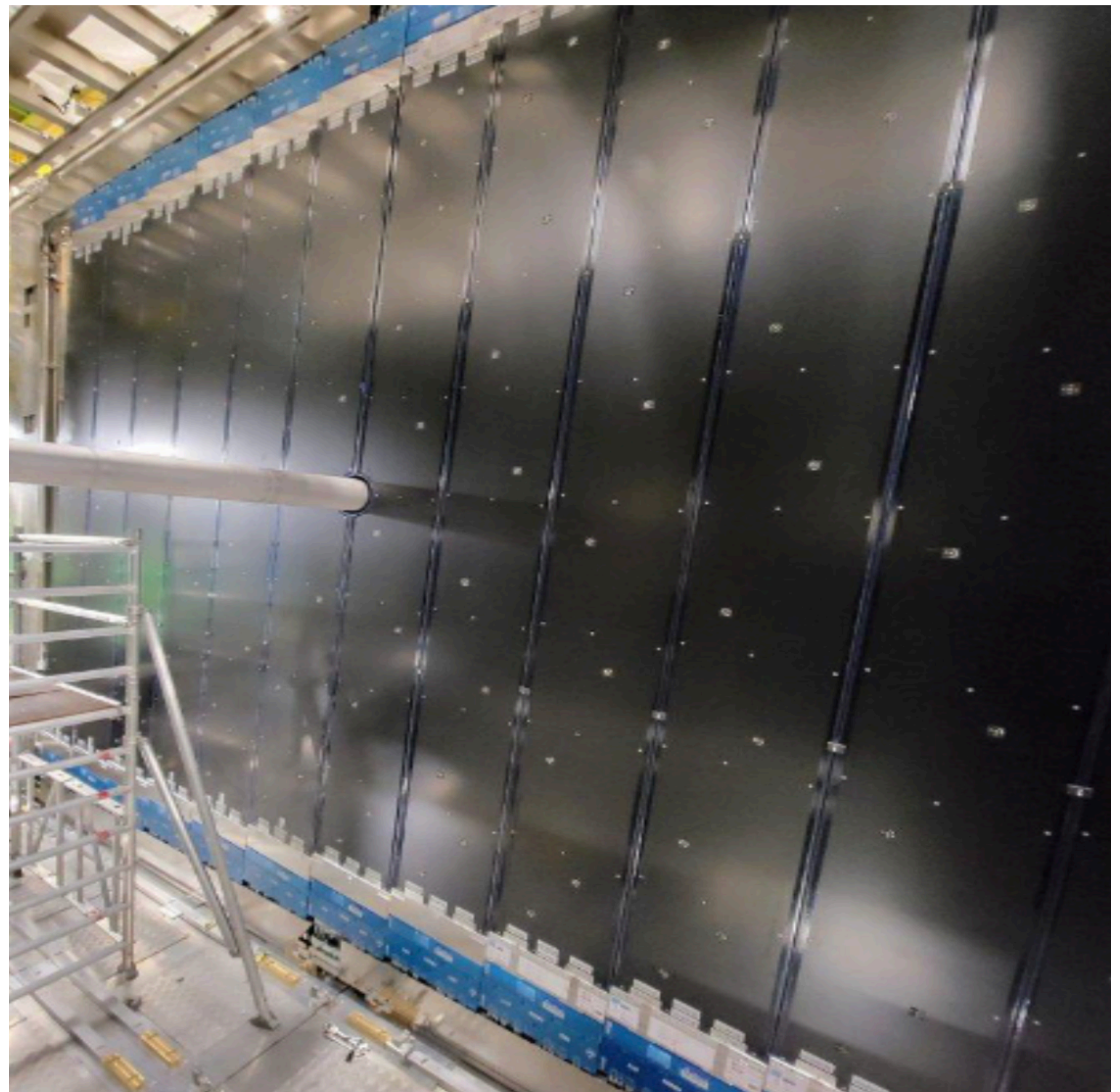



# LHCb upgrade(s)



- All results shown today were prepared using the data collected in 2010-2018
- **Right now, we are commissioning a shiny new detector!**
  - Collect data at ~factor 5 increased pile-up
  - **Full detector readout at 40 MHz + fully-software trigger (1st stage running on GPUs)**
    - The highest throughput among HEP experiments
    - Large boost in efficiency for hadronic channels
  - Completely new tracking system: pixel-based vertex locator and scintillating-fibre tracker
    - another tracking detector going live in winter
  - Improved Cherenkov detectors, refurbished calorimeter & muon electronics

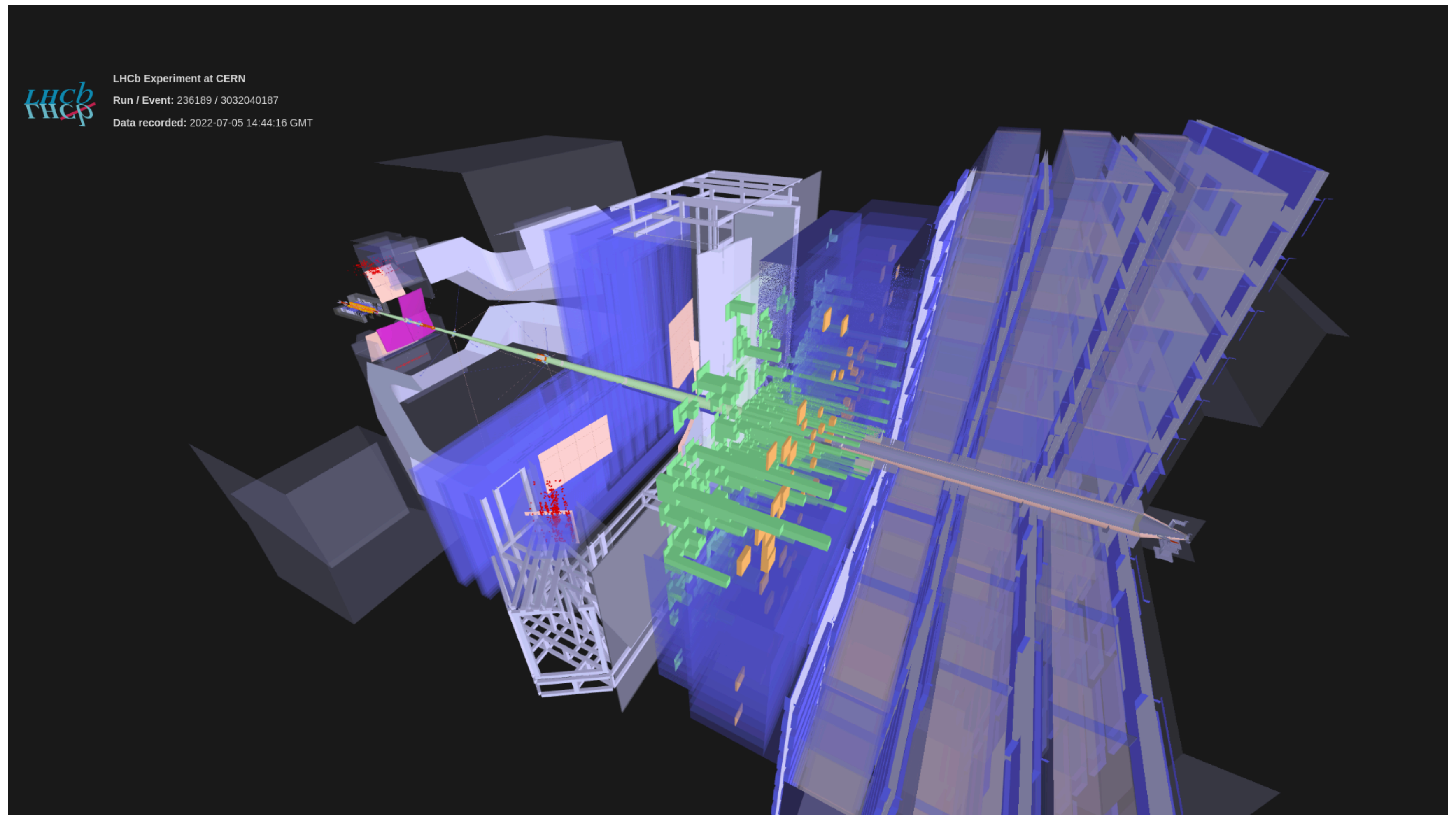


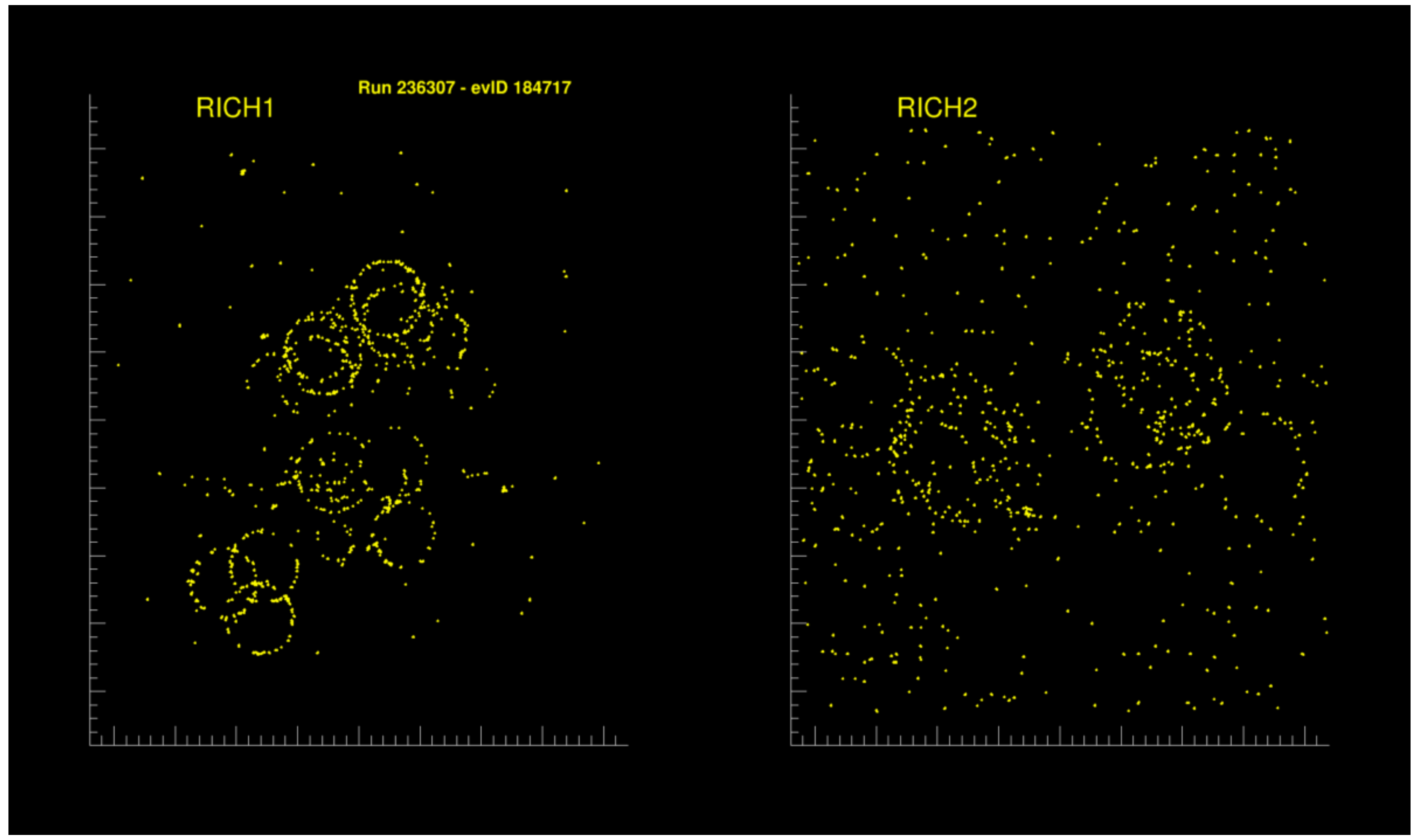


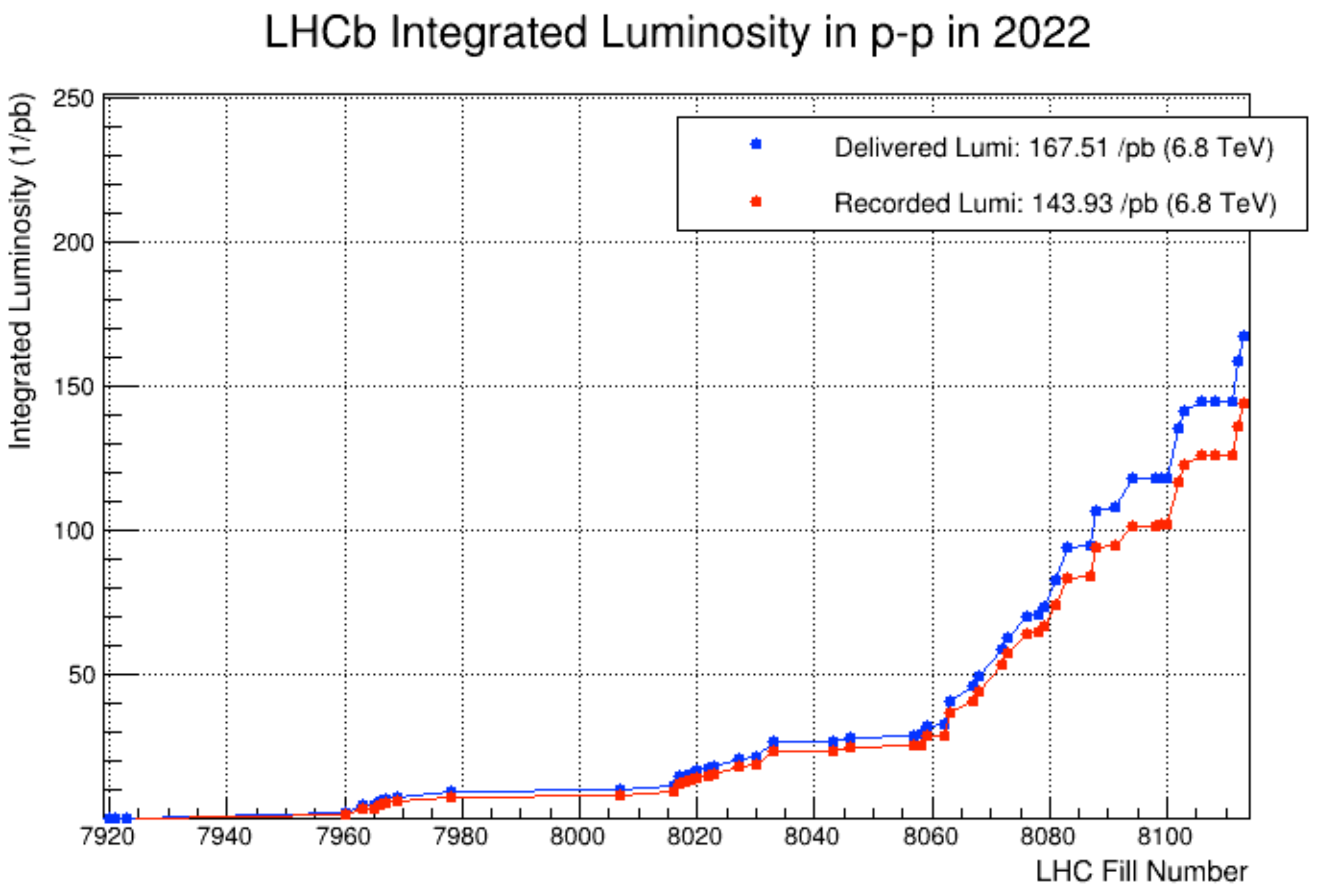
# LHCb upgrade(s)



- Our new detector is being calibrated and aligned




- But we already plan for the next upgrade! See our TDR [LHCC-2021-012]
- Extensive R&D ongoing for needed technologies

$\leftarrow$ 9 fb$^{-1}$ $\rightarrow$ $\quad$ $\leftarrow$ Goal: 50 fb$^{-1}$ $\rightarrow$ $\quad$ $\leftarrow$ Goal: 300 fb$^{-1}$ $\rightarrow$

Upgrade I — Consolidation — Upgrade II

| Run 1 | LS1 | Run 2 | LS2 | | Run 3 | LS3 | Run 4 | LS4 | Run 5 | LS5 | Run 6 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2011 2012 | 2013 2014 | 2015 2016 2017 2018 | 2019 2020 2021 | 2022 | 2023 2024 2025 | 2026 2027 2028 | 2029 2030 2031 2032 | 2033 2034 | 2035 2036 2037 2039 | 2040 | 2041 2042 |

- Pushing the sensitivity to flavour observables to unprecedented levels!
- Getting ready for new surprises in hadron spectroscopy and decays!

# Summary



- The particle zoo keeps growing, with LHCb steadily supplying new beasts
- Routine measurements of properties of heavy hadrons and their decays sometimes yield surprises
- LHCb Upgrade will provide the desired dataset to explore the intriguing anomalies observed in our data
- There are measurements where LHCb has unique reach, e.g. systematic studies of b-baryon decays
- Strong synergy with theory colleagues needed as ever!
- Developments in lattice QCD crucial for LHCb precision measurements: form-factors, decay constants, predictions of hadron properties and many more…


LHCb collaboration, summer 2022

Questions?
Feel free to contact me:
vitalii.lisovskyi@cern.ch

# Extras

# $B^+ \to D_s^+ D_s^- K^+$



- Amplitude analysis performed for the first time


| Component | $J^{PC}$ | $M_0$ [MeV] | $\Gamma_0$ [MeV] | $\mathcal{F}$ [%] | $\mathcal{S}$ [$\sigma$] |
|---|---|---|---|---|---|
| $X(3960)$ | $0^{++}$ | $3955 \pm 6 \pm 12$ | $48 \pm 17 \pm 10$ | $24.2 \pm 7.6 \pm 7.9$ | 12.6 (14.3) |
| $X_0(4140)$ | $0^{++}$ | $4133 \pm 7 \pm 11$ | $69 \pm 17 \pm 7$ | $17.7 \pm 4.9 \pm 7.7$ | 3.7 (3.9) |
| $\psi(4260)$ | $1^{--}$ | 4230 [58] | 55 [58] | $3.7 \pm 0.4 \pm 3.0$ | 3.1 (3.3) |
| $\psi(4660)$ | $1^{--}$ | 4633 [31] | 64 [31] | $2.2 \pm 0.2 \pm 0.5$ | 2.9 (3.2) |
| NR | $S$-wave | - | - | $46.6 \pm 13.3 \pm 11.3$ | 3.1 (3.4) |

Probably the same as $\chi_{c0}(3930)$? Candidate for $c\bar{c}s\bar{s}$

Possible rescattering from $J/\psi\phi \to D_s^+D_s^-$?

2011.02542 etc

- Precise measurements by LHCb and (new!) CMS