Highlights and perspectives from the LHCb experiment

Mat Charles (Sorbonne Université/LPNHE)

representing the LHCb collaboration

v3

Thank you to the organisers

- I know it's not the same as an in-person conference in Paris*, but this is an important event for our community.
- Really, a big thank-you to the organisers. This can't have been easy to prepare.
- ... and good luck for LHCP 2021, which I look forward to attending in person.

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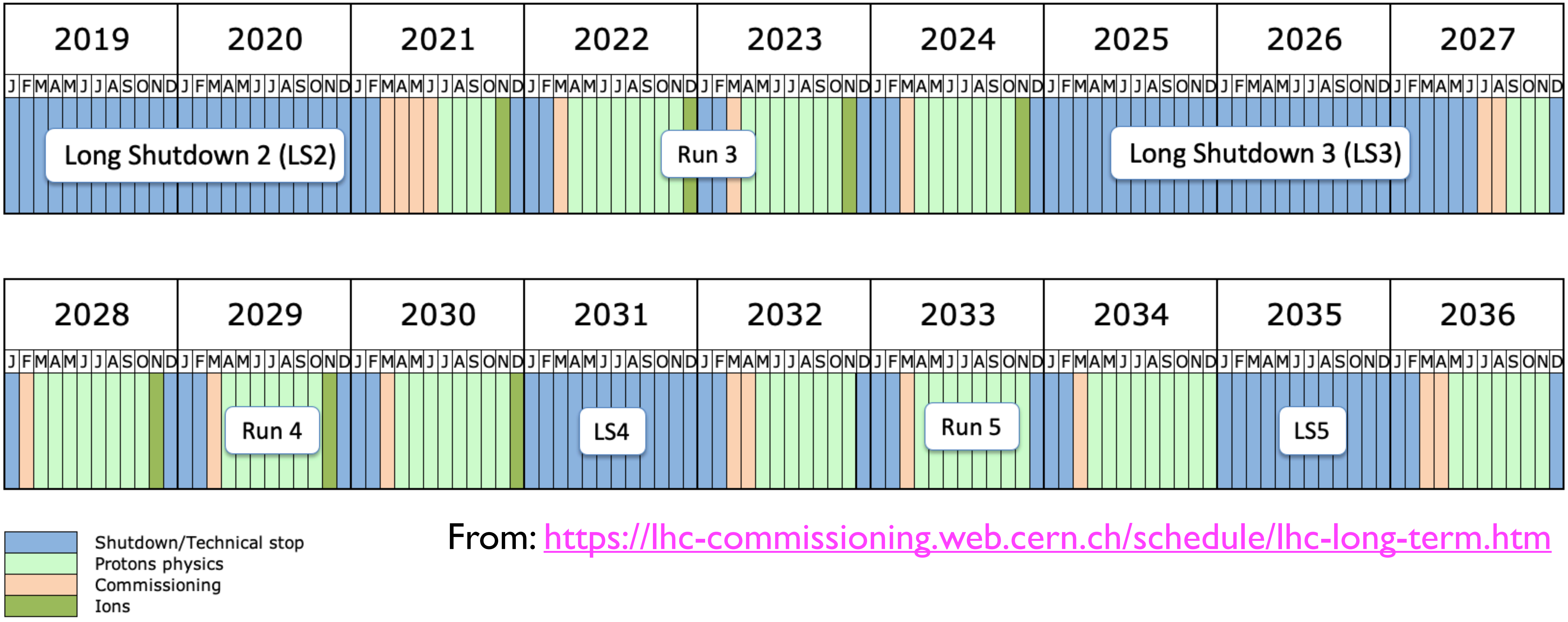
* e.g. less traffic

Highlights and perspectives

- It's been a rough few months, but I'm pleased to say that LHCb has some nice new results to report.
- These include some that are brand new for this conference. No spoilers here: you'll have to go to the talks to find out more.
- First, a few words on our status and the ongoing upgrade.

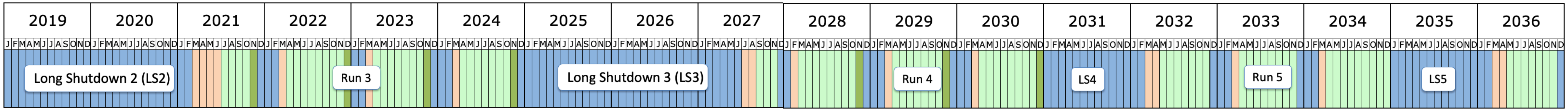
Reminder: LHC schedule (as of 2019)



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

- Clearly, details will change (especially for 2021).
  - See this morning's talk by Jose.
  - See also talk by F. Bordry on 5 May (Indico, slides)
- But looking at the big picture...

LHCb plan



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

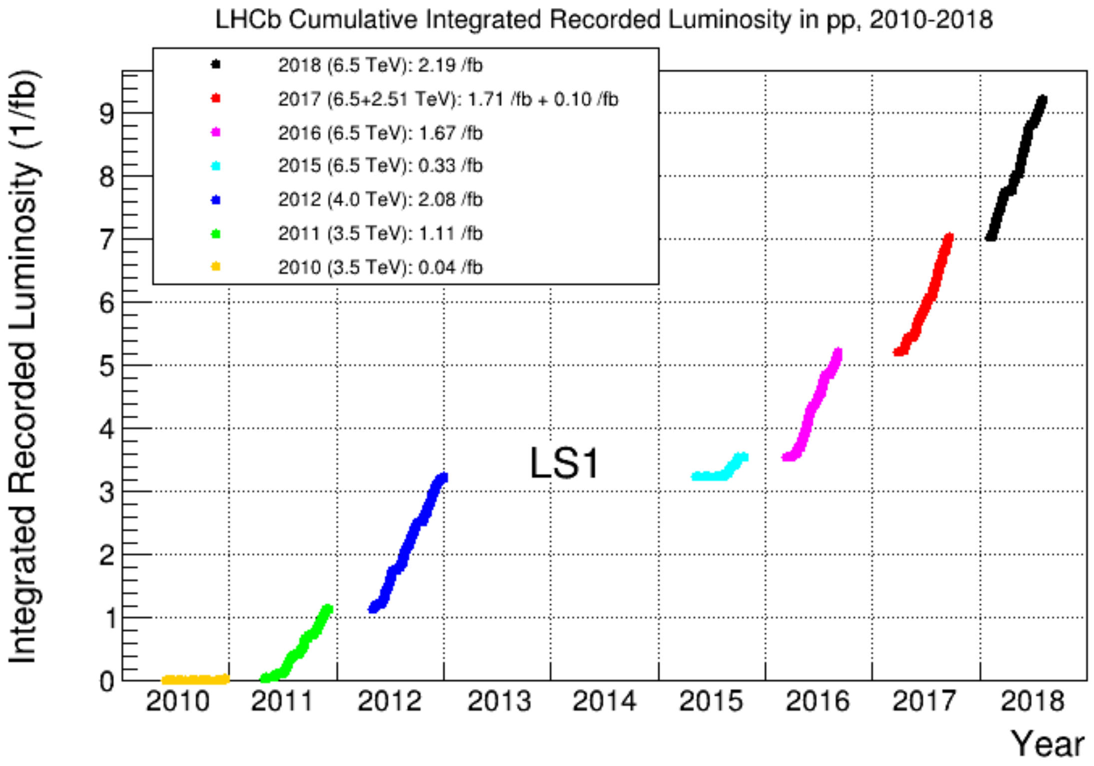
Run 3
LHCb upgrade I

Run 4
LHCb upgrade Ib

Run 5 and beyond
LHCb upgrade II

In Run1+2, we accumulated about 9/fb of data. Most LHCb physics scales with $\sigma(b\bar{b})$ or $\sigma(c\bar{c})$, which is roughly linear in the CM energy. In units of "one Run1", the data sample is about:

1 Run1 for Run1
4 Run1 for Run2
=> total: 5 Run1 units so far.



Mark Tobin, Mon 18:00, plenary
Vava Gligorov, Tue 15:03, Tools
Dorothea vom Bruch, Wed 15:21, Performance

LHCb plan

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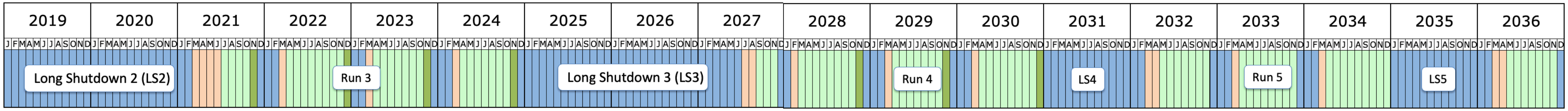


Run 3
LHCb upgrade I

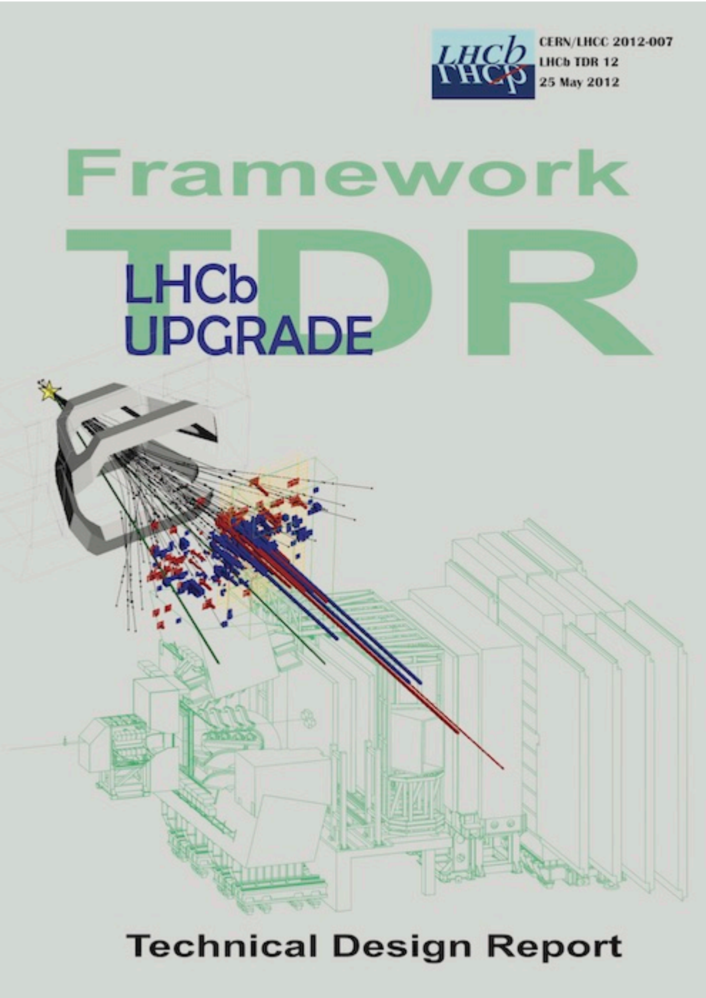
Run 4
LHCb upgrade Ib

Run 5 and beyond
LHCb upgrade II

During LS2, we've been doing a major upgrade to the LHCb detector.

- All subdetectors updated, and:
- Many subdetectors overhauled or replaced.
- Completely new trigger strategy: all-software.
- Big jump in instantaneous lumi and in trigger efficiency => much higher signal rates
- Increase in output bandwidth, but smarter computing model to swallow it.

Few words on current status shortly.



CERN/LHCC 2012-007
LHCb TDR 12
25 May 2012

Framework TDR
LHCb UPGRADE

Technical Design Report

CERN-LHCC-2012-007

Mark Tobin, Mon 18:00, plenary

LHCb plan

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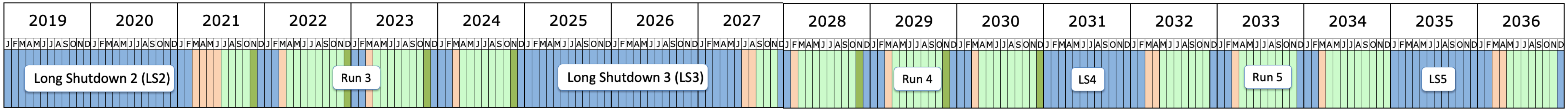


Run 3
LHCb upgrade I

Run 4
LHCb upgrade Ib

Run 5 and beyond
LHCb upgrade II

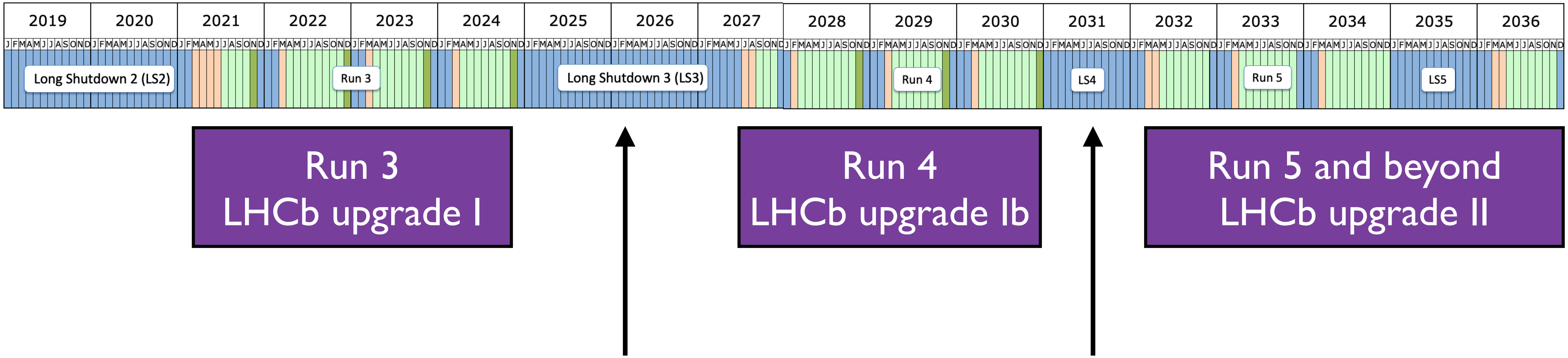
With the new trigger and higher lumi, we expect to take data
- at a higher rate
- with a higher efficiency
- with better alignment and calibration (real-time analysis)

Original assumption: 5/fb per year after upgrade, total of 50/fb.
With a crude factor of 2 for removing the hardware trigger, this means:
- Run3: about 15-20/fb => about 20-25 Run1 units (total 25-30)
- Run4: about 20-25/fb => about 30-35 Run1 units (total ~ 60)

Mark Tobin, Mon 18:00, plenary
Nicola Neri, Tue 15:21, Upgrades

LHCb plan

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



Run 3
LHCb upgrade I

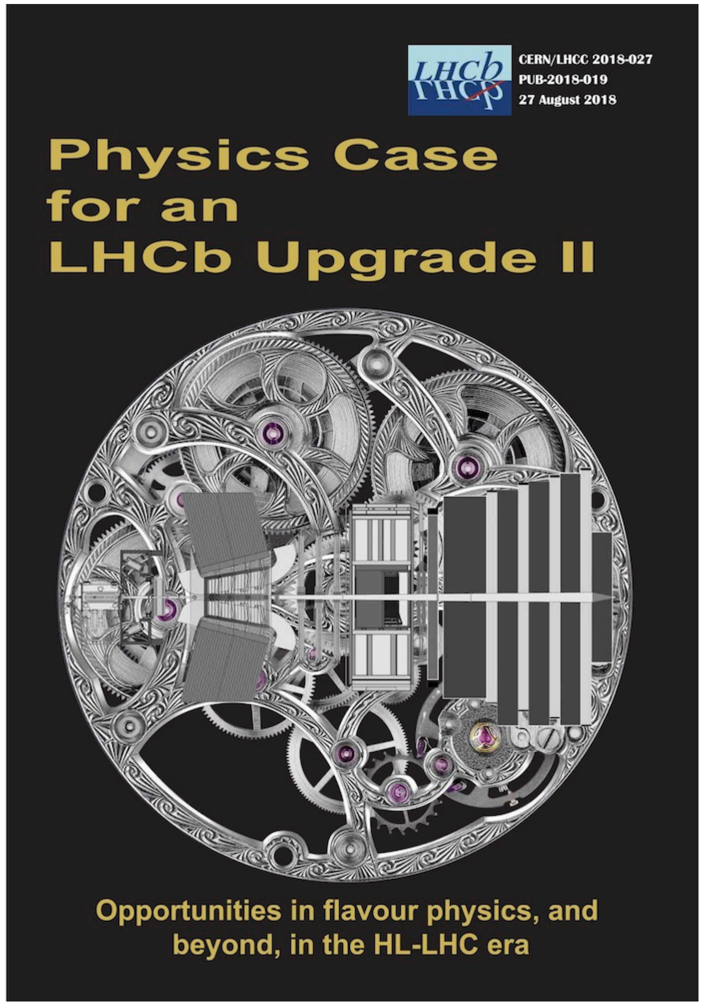
Run 4
LHCb upgrade Ib

Run 5 and beyond
LHCb upgrade II

Run2 multiplied previous (Run1) stats by about 5.
Run3 will multiply prev. (Run1-2) stats by about 5.
Run4 will double previous (Run1-3) stats.

Keep lumi doubling time short => plan for a second upgrade in LS4, perhaps with some parts pre-installed to take advantage of longer LS3.
Currently preparing a framework TDR.

Goal: 300/fb by Run 6 (i.e. 5x Run1-4 stats)


CERN/LHCC 2018-027
PUB-2018-019
27 August 2018

Physics Case
for an
LHCb Upgrade II

Opportunities in flavour physics, and beyond, in the HL-LHC era

CERN-LHCC-2018-027

Mark Tobin, Mon 18:00, plenary

Ongoing upgrade work

- COVID19* situation has caused, and is still causing, delays.
  - Assembly work at CERN halted during shutdown.
  - But also delays to work at other labs worldwide, and to transport of components, and to movement of experts to/from CERN.
- Work is now resuming, starting with pilot projects. Scope will increase as CERN re-opens.
- We do not yet know what the overall impact will be.
- For more on the LHCb upgrades, see talk by Mark Tobin this afternoon.
- Next slides: a few illustrations of restarted work.
- First, new news: decision made that the initial online reconstruction will be done with a farm of GPU systems (ALLEN project). Some key work done right here in Paris!

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* L'académie française aurait préféré « la covim ».

Mark Tobin, Mon 18:00, plenary

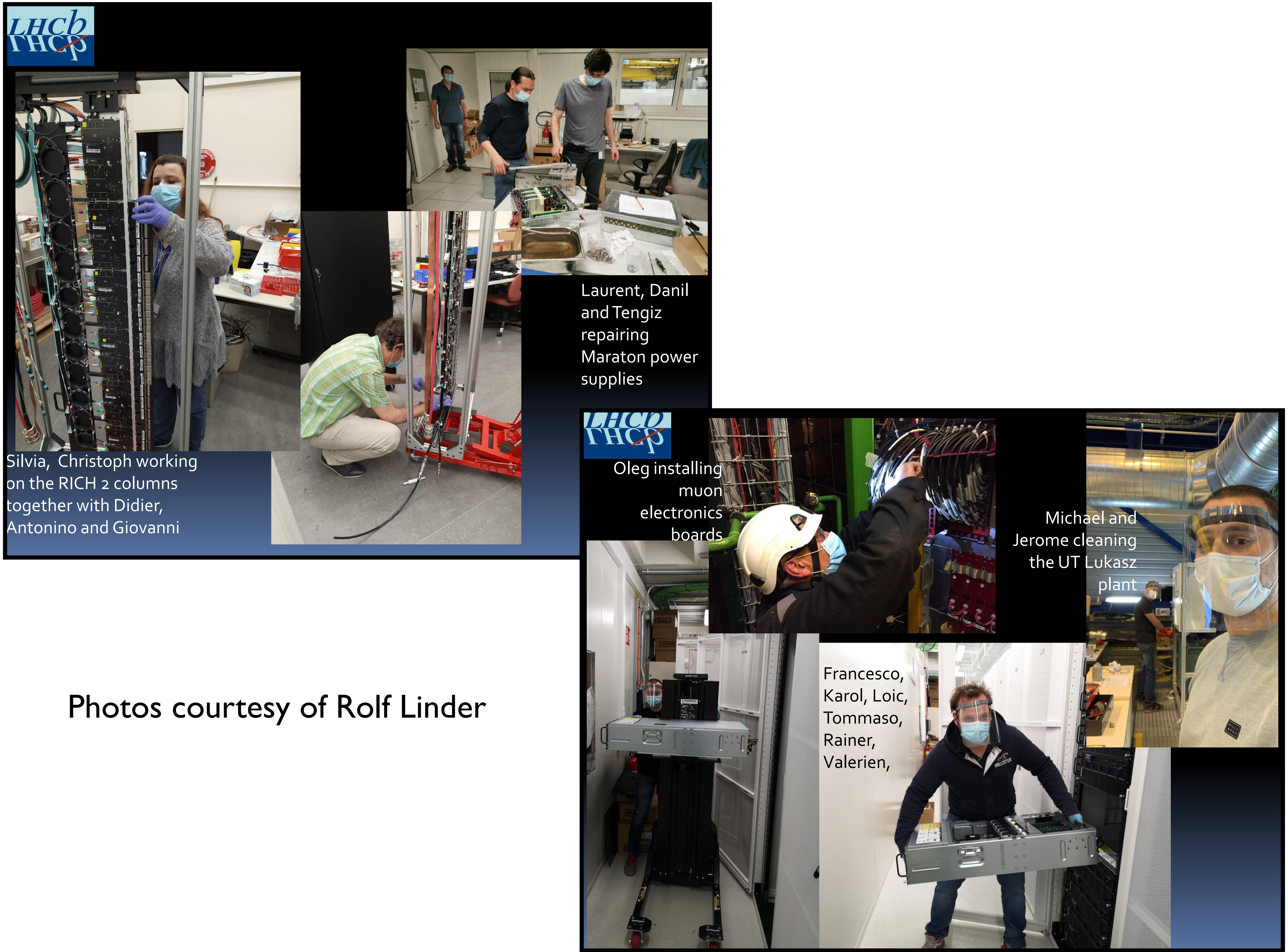
Ongoing upgrade work

Freek, Raphael, vacuum group and transport started to install the Velo RF boxes.

Photos courtesy of Rolf Linder

Mark Tobin, Mon 18:00, plenary

Ongoing upgrade work



Laurent, Danil and Tengiz repairing Maraton power supplies

Silvia, Christoph working on the RICH 2 columns together with Didier, Antonino and Giovanni

Oleg installing muon electronics boards

Michael and Jerome cleaning the UT Lukasz plant

Francesco, Karol, Loic, Tommaso, Rainer, Valerien,

Photos courtesy of Rolf Linder

LHCb at LHCP

A probably incomplete list of talks by LHCb speakers:

- Vava Gligorov: Triggering and online calibration with machine learning techniques*
- Charlotte Barbara Van Hulse: Soft QCD and Exclusive processes with LHCb
- Sook Hyun Lee: Charged hadron production in Z-tagged jets (fragmentation of light quarks)
- Jana Crkovská: Multiplicity dependent production of X(3872)
- Dorothea Vom Bruch: Performance of the real-time reconstruction, alignment, and calibration in Run 3 at LHCb
- Alex Seuthe: PID performance in Run2 at LHCb
- Renata Kopecna: Tracking and vertexing performance and developments over Run2 at LHCb
- Benjamin Audurier: Recent results on heavy flavor in small and large systems from LHCb (Wed, Heavy ions)
- Mirco Dorigo: CKM metrology and B decays
- Guillaume Pietrzyk: CP-violation in charm
- Jinlin Fu: CP violation in B decays
- Miriam Lucio Martinez: Lepton flavour violation and universality tests at LHCb
- Jacco de Vries: Electroweak penguin decays
- Marcin Kucharczyk: Search for long-lived particles in LHCb
- Constantin Weisser: Search for dark photon in LHCb (Fri, Dark sectors & BSM)
- Menglin Xu: EWK physics: Measurements and prospects from LHCb
- Nicola Neri: Physics perspectives for LHCb beyond Run4
- Christopher Betancourt: Timing at LHCb post LS4
- Liupan An: CINCO: Study of exotic states* (Fri, joint QCD+Flavour)
- Mark Tobin: LHCb upgrades
- Mark Whitehead: CPV in B-Hadron decays*
- Maurizio Martinelli: Charm physics*
- William Barter: Precision QCD measurements*

Red indicates upcoming result
that I will not talk about
* = CINCO talk

New since LHCP 2019...

LHCb-PAPER-2019-023: Observation of the $\Lambda_b^0 \to \chi_{c1}(3872)pK^-$ decay

LHCb-PAPER-2019-024: Measurement of the $\eta_c(1S)$ production cross-section in pp collisions at $\sqrt{s} = 13$ TeV

LHCb-PAPER-2019-025: Observation of new resonances in the $\Lambda_b^0\pi^+\pi^-$ system

LHCb-PAPER-2019-027: Determination of quantum numbers for several excited charmed mesons observed in $B^- \to D^{*+}\pi^-\pi^-$ decays

LHCb-PAPER-2019-028: Search for CP violation and observation of P violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays

LHCb-PAPER-2019-029: Search for the doubly charmed baryon Ξ_{cc}^+

LHCb-PAPER-2019-030: Measurement of the shape of the $B_s^0 \to D_s^*\mu\nu_\mu$ differential distribution

LHCb-PAPER-2019-031: Search for $A' \to \mu^+\mu^-$ decays

LHCb-PAPER-2019-032: Updated measurement of decay-time-dependent CP asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

LHCb-PAPER-2019-033: Measurement of the B_c^- production fraction and asymmetry in 7 and 13 TeV pp collisions

LHCb-PAPER-2019-034: Observation of the semileptonic decay $B^+ \to p\bar{p}\mu^+\nu_\mu$

LHCb-PAPER-2019-035: Measurement of Ξ_{cc}^{++} production in pp collisions at $\sqrt{s} = 13$ TeV

LHCb-PAPER-2019-036: Measurement of CP violation in $B^0 \to D^{*\pm}D^{\mp}$ decays

LHCb-PAPER-2019-037: Precision measurement of the Ξ_{cc}^{++} mass

LHCb-PAPER-2019-038: Strong constraints on the $K_S^0 \to \mu^+\mu^-$ branching fraction

LHCb-PAPER-2019-039: Isospin amplitudes in $\Lambda_b^0 \to J/\psi\Lambda(\Sigma^0)$ and $\Xi_b^0 \to J/\psi\Xi^0(\Lambda)$ decays

LHCb-PAPER-2019-040: Test of lepton universality with $\Lambda_b^0 \to pK^-\ell^+\ell^-$ decays

LHCb-PAPER-2019-041: Measurement of $|V_{cb}|$ with $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$ decays

LHCb-PAPER-2019-042: First observation of excited Ω_b^- states

LHCb-PAPER-2019-043: Search for the lepton flavour violating decay $B^+ \to K^+\mu^-\tau^+$ using B_{s2}^{*0} decays

LHCb-PAPER-2019-044: Measurement of CP observables in $B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$ with $D \to K_S^0K\pi$ decays

LHCb-PAPER-2019-045: Observation of a new baryon state in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum

LHCb-PAPER-2019-046: Measurement of the shape of the $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ differential decay rate

LHCb-PAPER-2020-001: Search for the rare decays $B_s^0 \to e^+e^-$ and $B^0 \to e^+e^-$

LHCb-PAPER-2020-002: Measurement of CP-averaged observables in the $B^0 \to K^{*0}\mu^+\mu^-$ decay

LHCb-PAPER-2020-003: Precise measurement of the B_c^+ meson mass

LHCb-PAPER-2020-004: Observation of new Ξ_c^0 baryons decaying to $\Lambda_c^+K^-$

LHCb-PAPER-2020-005: Measurement of the $\Lambda_b^0 \to J/\psi\Lambda$ angular distribution and the Λ_b^0 polarisation in pp collisions

LHCb-CONF-2019-003: Measurement of the Z production cross-sections in pPb collisions at $\sqrt{=}8$ TeV

LHCb-CONF-2019-004: Study of prompt D^0 meson production in pPb at $\sqrt{s_{NN}} = 8.16$ TeV at LHCb

LHCb-CONF-2019-005: Multiplicity-dependent modification of $\chi_{c1}(3872)$ and $\psi(2S)$ production in pp collisions at $\sqrt{s} = 8$ TeV

Will just pick out some recent highlights.

Rare & electroweak penguin decays

arXiv:2003.04831: Measurement of CP-averaged observables in the $B^0 \to K^{*0}\mu^+\mu^-$ decay
arXiv:2003.03999: Search for the rare decays $B_s^0 \to e^+e^-$ and $B^0 \to e^+e^-$
arXiv:2001.10354: Strong constraints on the $K_S^0 \to \mu^+\mu^-$ branching fraction
JHEP 2020, 40 (2020): Test of lepton universality with $\Lambda_b^0 \to pK^-\ell^+\ell^-$ decays

Why rare decays?

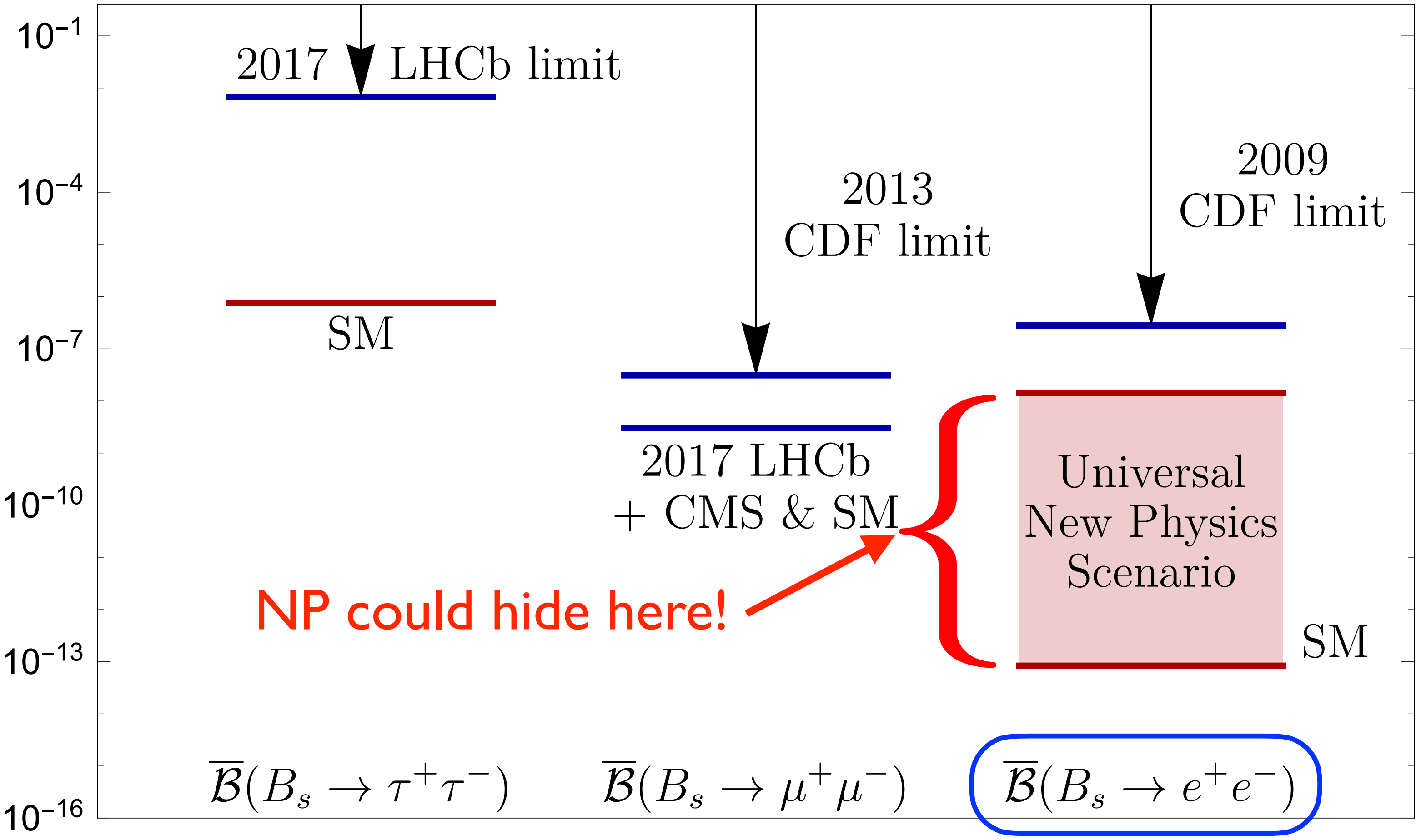
- Look at processes where NP could plausibly enter.
- If suppressed in the SM: NP could enter at a rate that's comparable.
  - If NP smaller but not vastly smaller, can show up in interference effects
- If forbidden in the SM: immediate smoking gun
- Focus particularly on processes that are theoretically and experimentally clean.
  - no good if uncertainty on SM prediction > experimental precision

$B^0_{(s)} \rightarrow e^+e^-$

Giacomo Fedi, Fri 18:00, plenary
Jacco De Vries, Tue 15:03, Flavour
Miriam Lucio Martinez, Tue 15:21, Flavour

- Classic rare decays for which the SM predicted BF is very small => any signal would be a sign of NP.
- Conceptually similar to, but more suppressed than, $B^0_s \rightarrow \mu^+\mu^-$
- Let's start with $B^0_{(s)} \rightarrow e^+e^-$...

Fleischer et al, JHEP 05 (2017) 156



arXiv:2003.03999: Search for the rare decays $B^0_s \rightarrow e^+e^-$ and $B^0 \rightarrow e^+e^-$

arXiv:2001.10354: Strong constraints on the $K^0_S \rightarrow \mu^+\mu^-$ branching fraction

$B^0_{(s)} \to e^+e^-$

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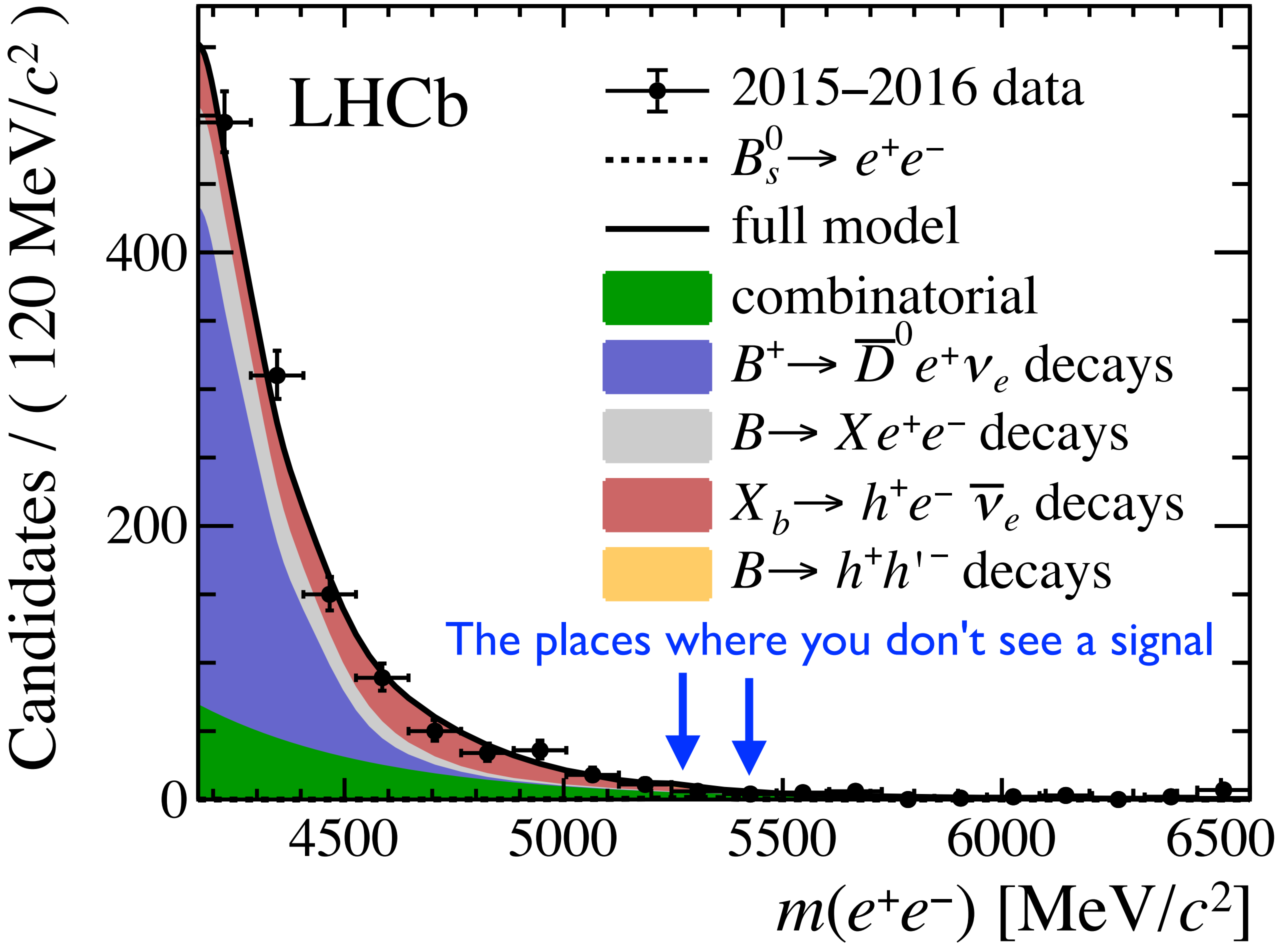
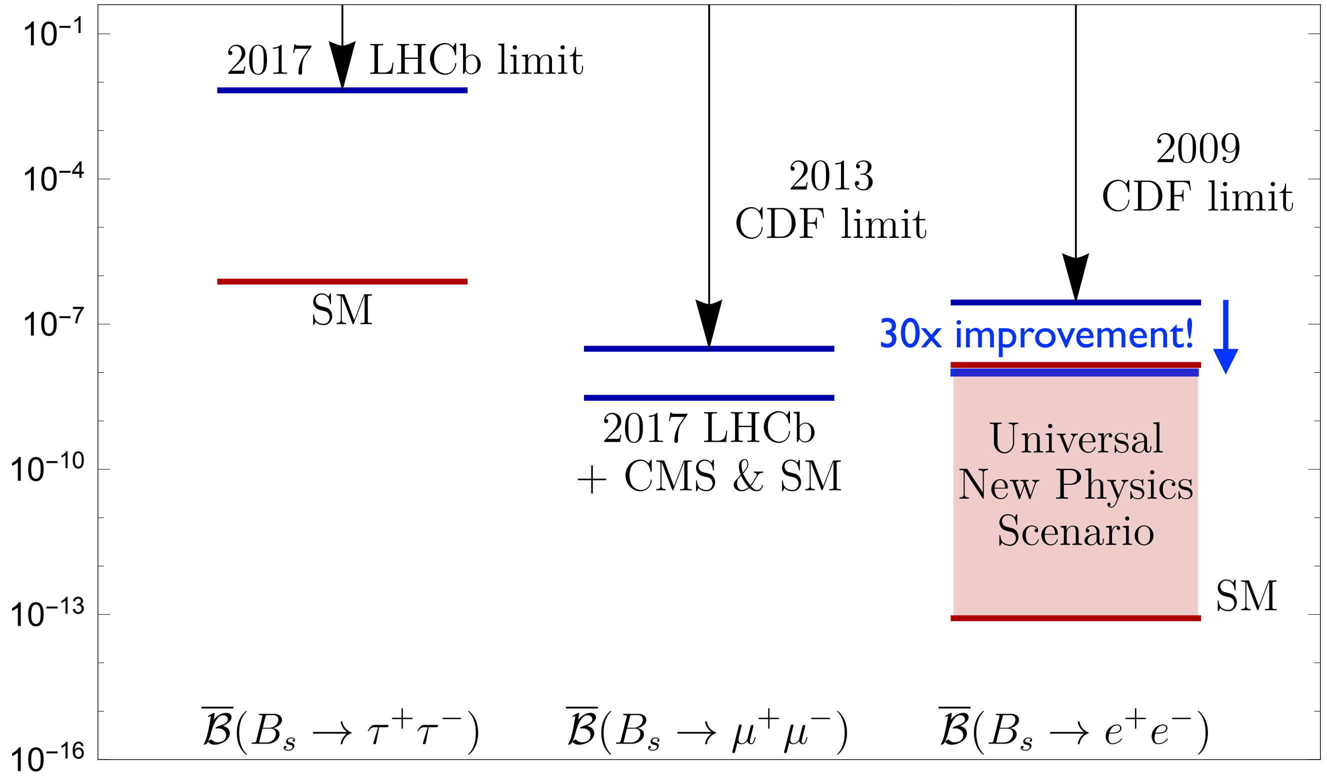
- Apply reconstruction (incl. brem. recovery), selection
- Simultaneous fit by dataset, bremsstrahlung category
- No signal => set upper limit (CL$_s$) at 95% CL:



The places where you don't see a signal

Fleischer et al, JHEP 05 (2017) 156



30x improvement!

$$\mathscr{B}(B^0_s \to e^+e^-) < 11.2 \times 10^{-9}$$

Similar story for B^0: $\mathscr{B}(B^0 \to e^+e^-) < 2.5\,(3.0) \times 10^{-9}$

arXiv:2003.03999: Search for the rare decays $B^0_s \to e^+e^-$ and $B^0 \to e^+e^-$

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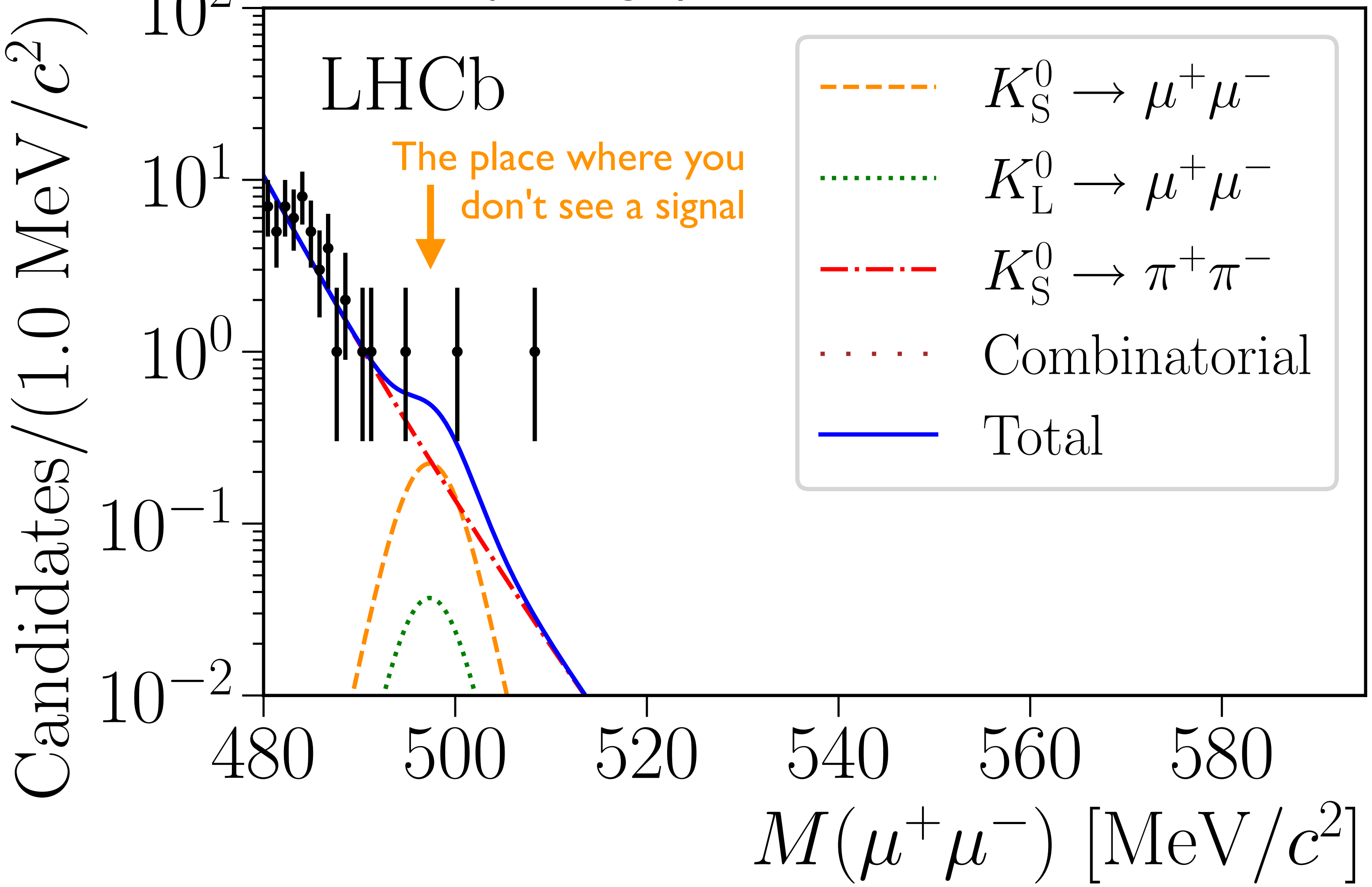
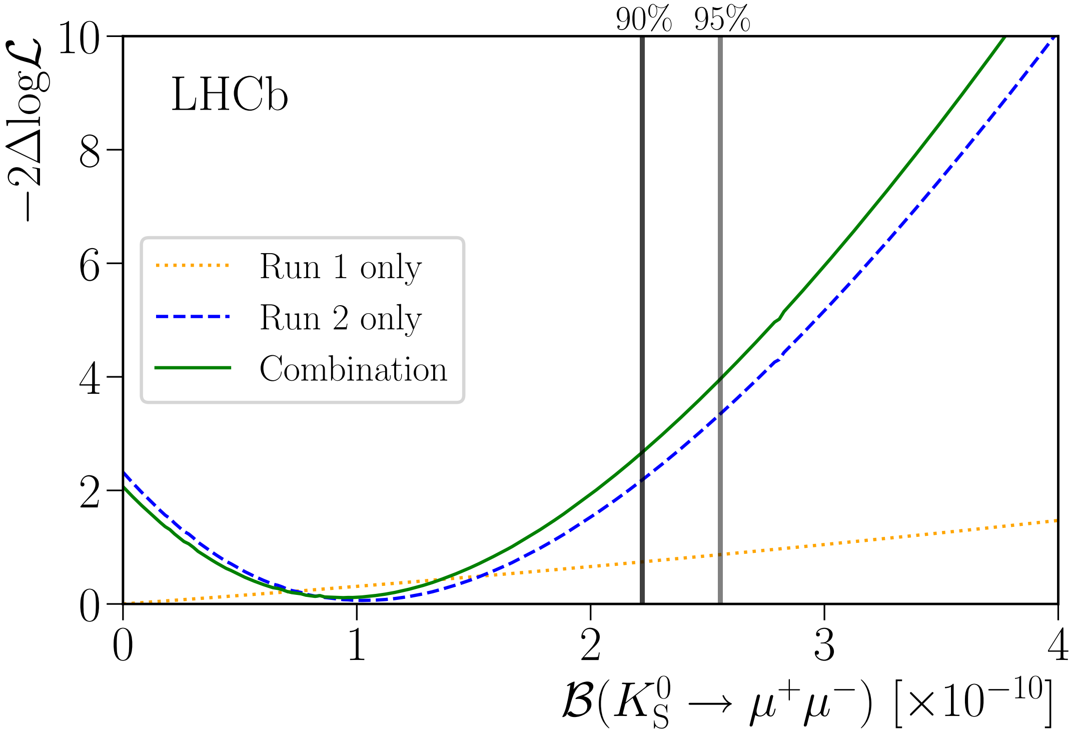
$K^0_S \to \mu^+\mu^-$

- $K^0_S \to \mu^+\mu^-$ is even cleaner, and we make a lot of Ks
- Veto background from material interactions in VELO
- Simultaneous fit across bins of BDT, trigger category:


One example category in simultaneous fit

The place where you don't see a signal



$\mathcal{B}(K^0_S \to \mu^+\mu^-) < 2.1 \times 10^{-10}$

at 90% CL (world-best)

Room for NP: 10^2 from SM prediction: $(5.18 \pm 1.50 \pm 0.02) \times 10^{-12}$

D'Ambrosio & Kitahara, PRL 119, 201802 (2017)

arXiv:2001.10354: Strong constraints on the $K^0_S \to \mu^+\mu^-$ branching fraction

The anomalies

- Various curious effects seen in electroweak penguin decays
  - and in semileptonic decays; not discussed here
- First showed up in angular and q^2 distributions of $b \to s\mu^+\mu^-$ decays -- but these have significant theory uncertainties.
  - Solution 1: look at ratios of lepton flavours, e.g. $B \to K\mu^+\mu^-/B \to Ke^+e^-$
  - Solution 2: develop optimised observables to reduce theory errors
- No single result is significant -- but we keep seeing small effects, mostly 2-3σ.
  - And these days, even 2-3σ effects represent hope
- Will cover one recent result from each class.
- Work ongoing to update other measurements.

arXiv:2003.04831: Measurement of CP-averaged observables in the $B^0 \to K^{*0}\mu^+\mu^-$ decay
JHEP 2020, 40 (2020): Test of lepton universality with $\Lambda_b^0 \to pK^-\ell^+\ell^-$ decays

R_{pK} $(\Lambda_b^0 \to pK^-\ell^+\ell^-)$

Giacomo Fedi, Fri 18:00, plenary
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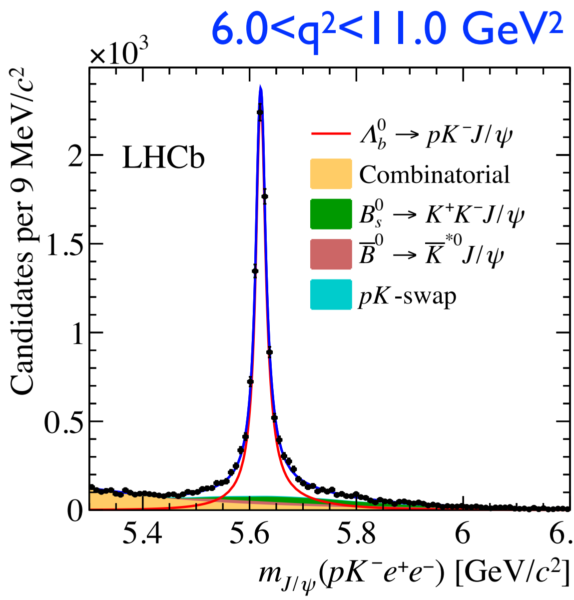
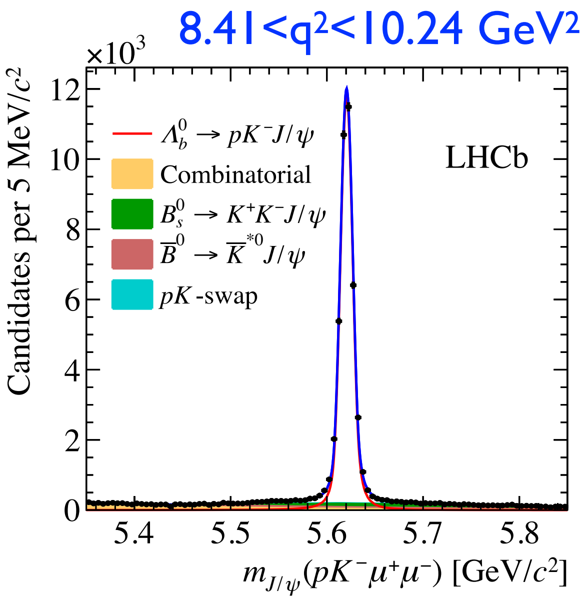
Miriam Lucio Martinez,
Tue 15:21, Flavour

Measure double ratio to suppress detector effects:

$$R_{pK}^{-1} = \frac{\mathscr{B}(\Lambda_b^0 \to pK^-e^+e^-)}{\mathscr{B}(\Lambda_b^0 \to pK^-J/\psi(\to e^+e^-))} \Bigg/ \frac{\mathscr{B}(\Lambda_b^0 \to pK^-\mu^+\mu^-)}{\mathscr{B}(\Lambda_b^0 \to pK^-J/\psi(\to \mu^+\mu^-))}$$



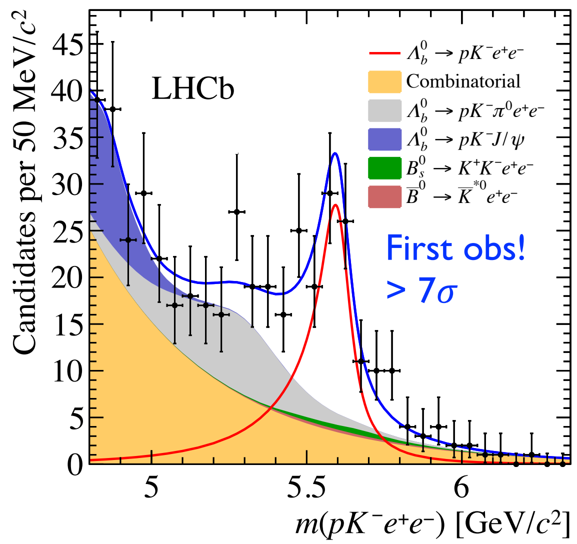


J/ψ

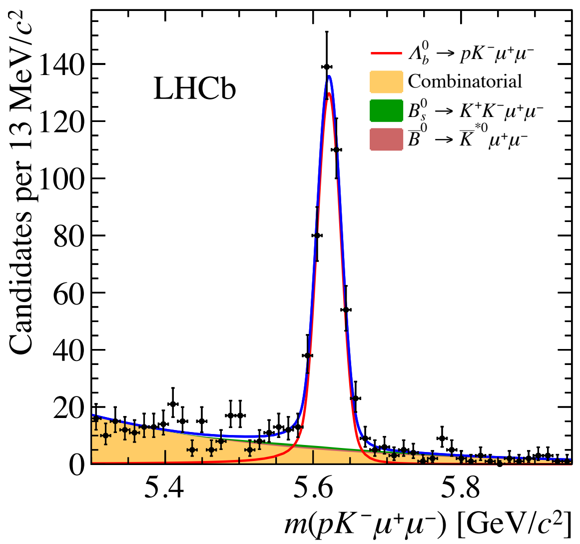
Double ratio R_{pK}^{-1} cancels many systematic effects.

Powerful crosscheck: measure efficiency-corrected ratio of J/ψ yields, which doesn't benefit from this cancellation.

$$r_{J/\psi}^{-1} = 0.96 \pm 0.05$$



Electrons



Muons

Rare mode (0.1<q²<6.0 GeV²)

$$R_{pK}^{-1} = 1.17^{+0.18}_{-0.16} \pm 0.07$$

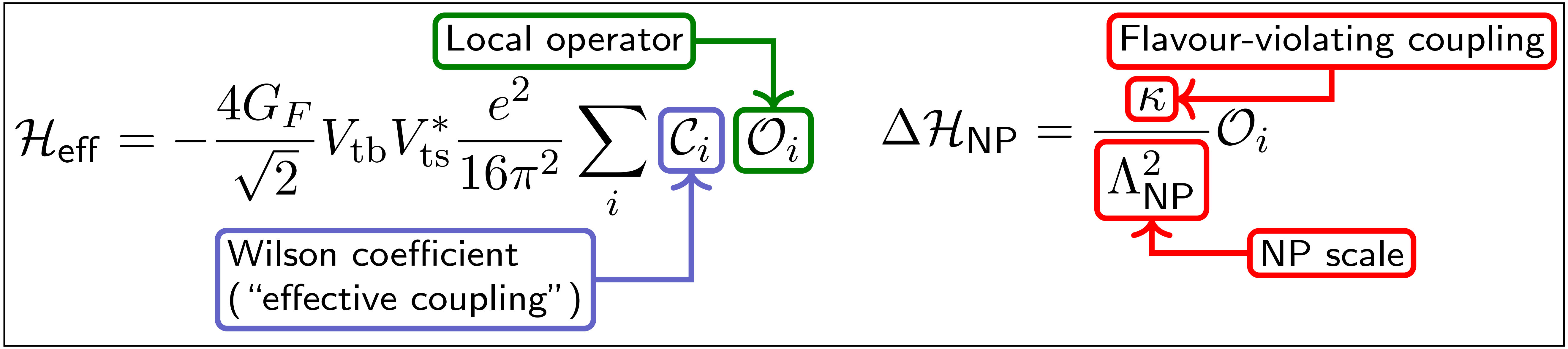
$$(R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05 < 1)$$

JHEP 2020, 40 (2020): Test of lepton universality with $\Lambda_b^0 \to pK^-\ell^+\ell^-$ decays

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

Giacomo Fedi, Fri 18:00, plenary
Jacco De Vries, Tue 15:03, Flavour
Miriam Lucio Martinez, Tue 15:21, Flavour

- Look at angular observables vs q^2
  - Use "optimised" variables to help cancel hadronic effects, e.g. P'_5
- To pull the information together, use Wilson coefficients:



$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V^*_{\text{ts}} \frac{e^2}{16\pi^2} \sum_i \boxed{\mathcal{C}_i} \boxed{\mathcal{O}_i}$$

$$\Delta\mathcal{H}_{\text{NP}} = \frac{\boxed{\kappa}}{\boxed{\Lambda^2_{\text{NP}}}} \mathcal{O}_i$$

Local operator

Wilson coefficient
("effective coupling")

Flavour-violating coupling

NP scale

- Main interest in EW penguin operators: C_9, C'_9, C_{10}, C'_{10}
- New this March: Run1+2016 update with $B^0 \to K^{*0}\mu^+\mu^-$

Optimised variables: Descotes-Genon et al,
JHEP, 1301:048, 2013, JHEP, 1305:137, 2013

arXiv:2003.04831: Measurement of CP-averaged observables in the $B^0 \to K^{*0}\mu^+\mu^-$ decay

Thanks to C. Langenbruch

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

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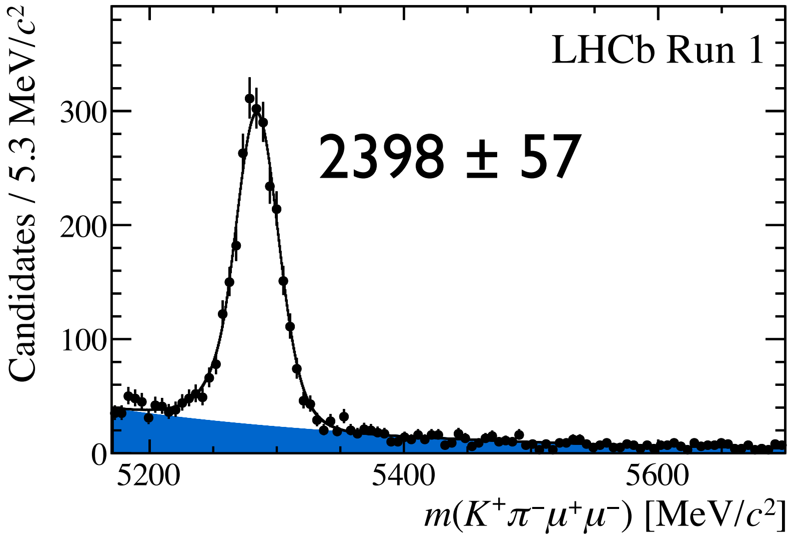
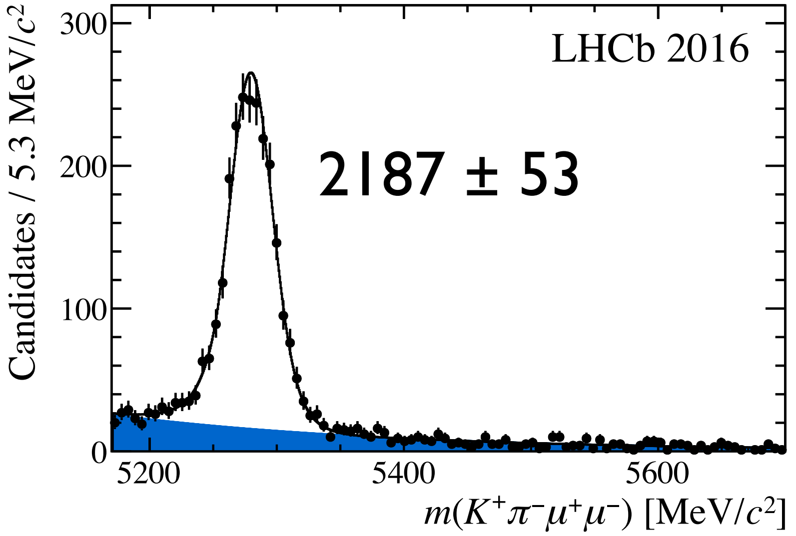
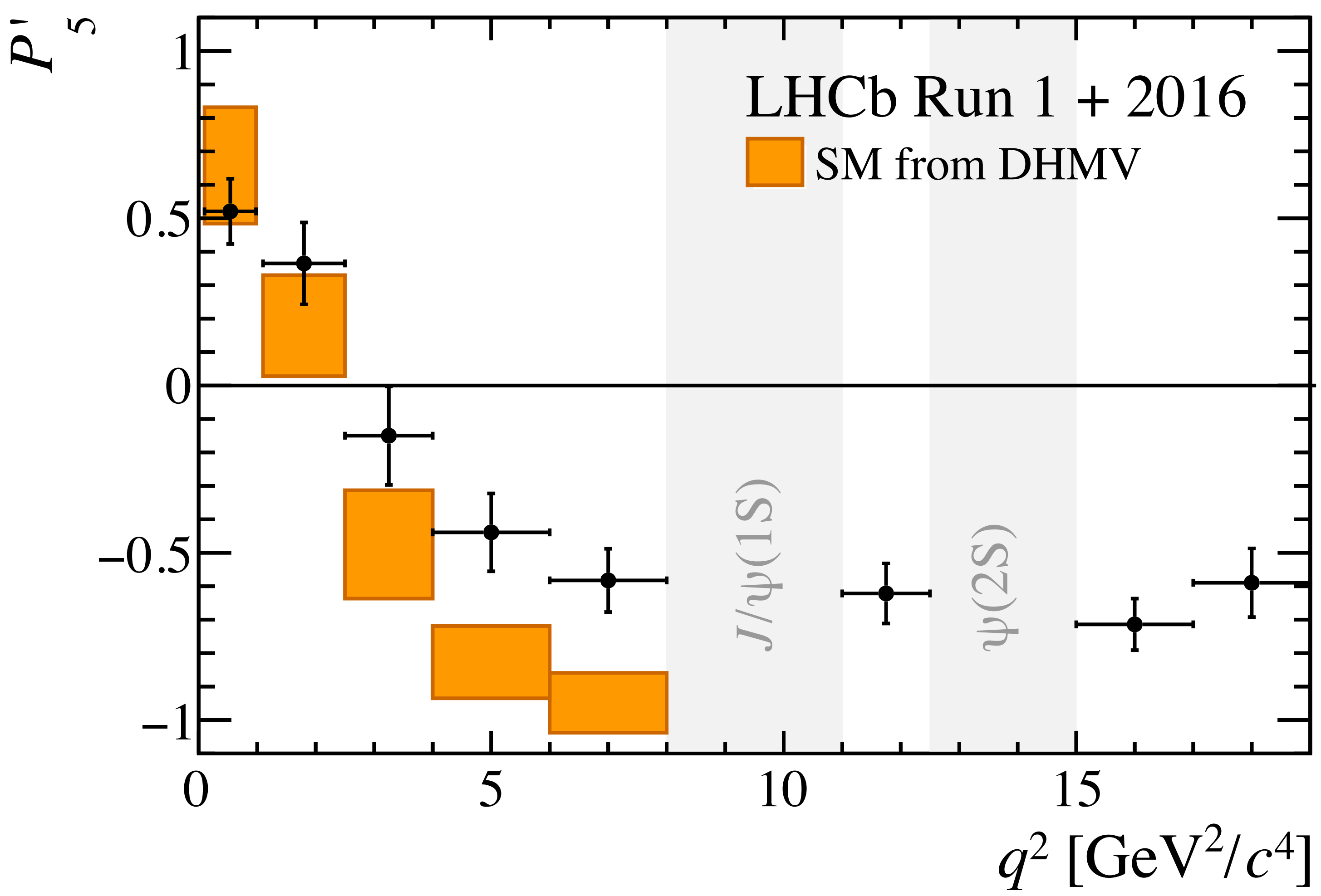
- Fit to angular distribution in bins of q^2
  - Work with two different parameterisations
  - Correct for efficiency
  - Model background, incl. S-wave under the K^{*0}
- Fit results to full set of angular observables in paper. Illustrating with just one:







... but one observable alone is not the full story. What is the overall picture?

arXiv:2003.04831: Measurement of CP-averaged observables in the $B^0 \to K^{*0}\mu^+\mu^-$ decay

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

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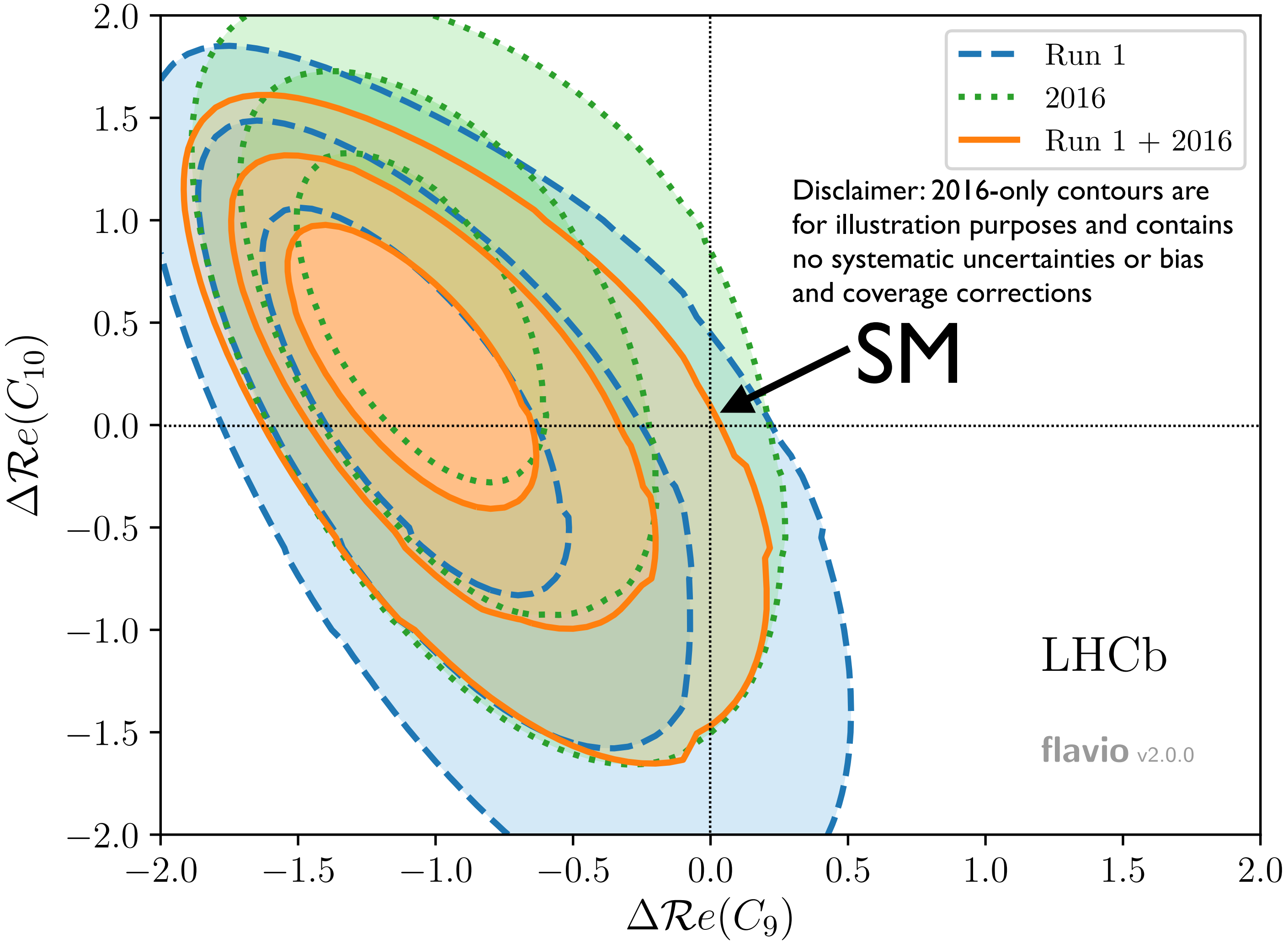
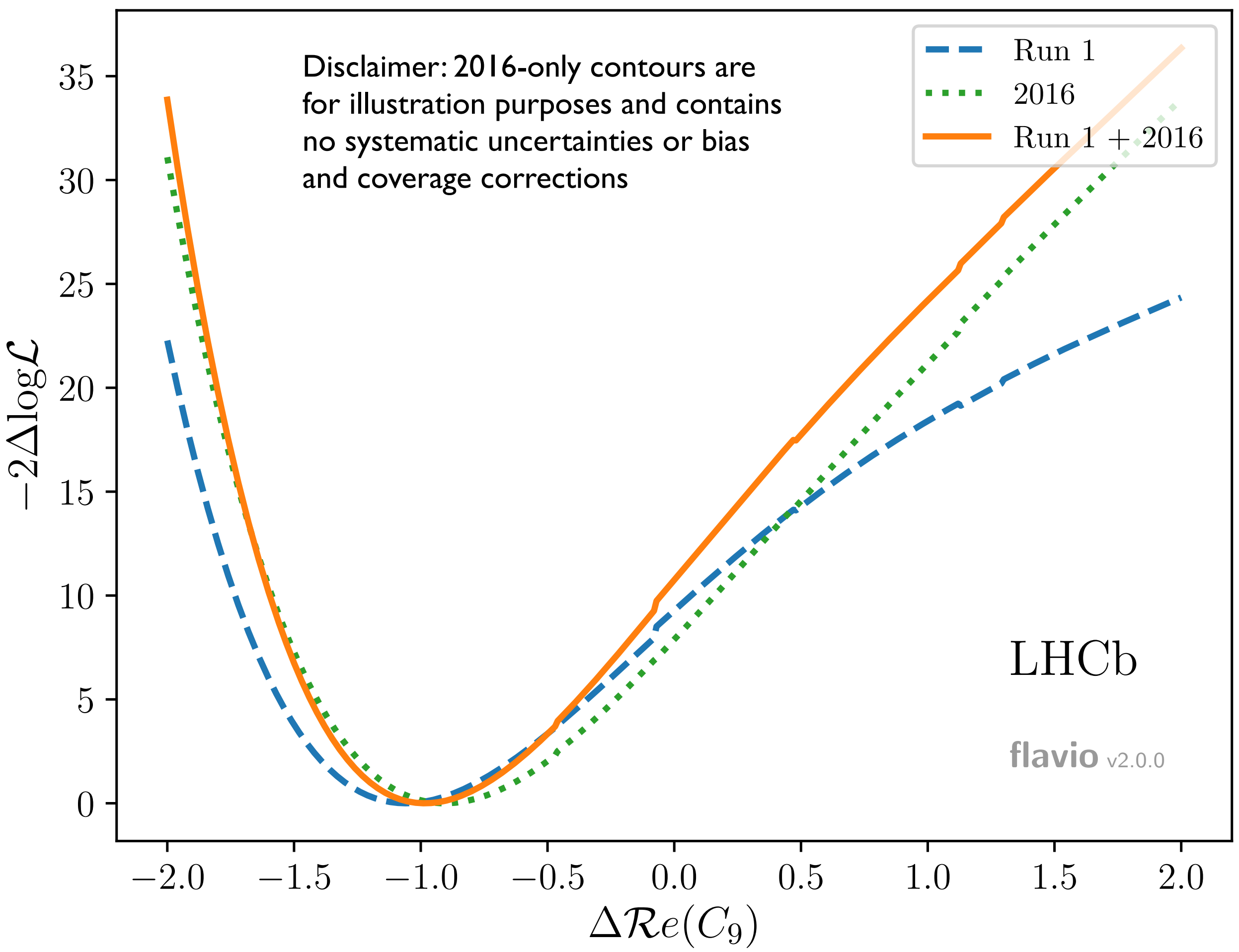
- "What is the overall picture?"

  Caution:
  - Depends on your "SM" model and its theory uncertainties
  - Depends on what variations you consider (what degrees of freedom).



Disclaimer: 2016-only contours are for illustration purposes and contains no systematic uncertainties or bias and coverage corrections

Varying $\mathrm{Re}(C_9)$ and $\mathrm{Re}(C_{10})$



Disclaimer: 2016-only contours are for illustration purposes and contains no systematic uncertainties or bias and coverage corrections

Varying only $\mathrm{Re}(C_9)$: 3.3σ

(or 2.7σ if excluding $6 < q^2 < 8\,\mathrm{GeV}/c^2$)

arXiv:2003.04831: Measurement of CP-averaged observables in the $B^0 \to K^{*0}\mu^+\mu^-$ decay

CKM & CPV

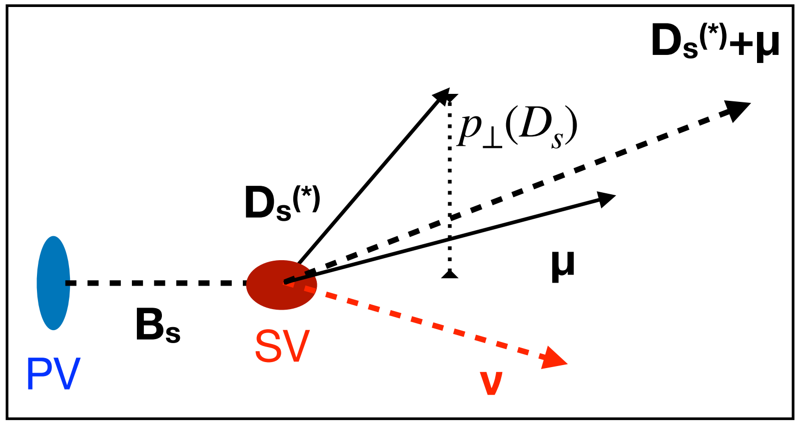
Mark Whitehead, Fri 17:30, plenary
Mirco Dorigo, Thu 15:25, Flavour

$|V_{cb}|$ in $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$

- Key idea: differential decay rate goes like:

$$\frac{\mathrm{d}^4\Gamma(B \to D^*\mu\nu)}{\mathrm{d}w\,\mathrm{d}\cos\theta_\mu\,\mathrm{d}\cos\theta_D\,\mathrm{d}\chi} = \frac{3m_B^3 m_{D^*}^2 G_F^2}{16(4\pi)^4}\eta_{\mathrm{EW}}^2 \boxed{|V_{cb}|^2} \boxed{|\mathcal{A}(w,\theta_\mu,\theta_D,\chi)|^2}$$

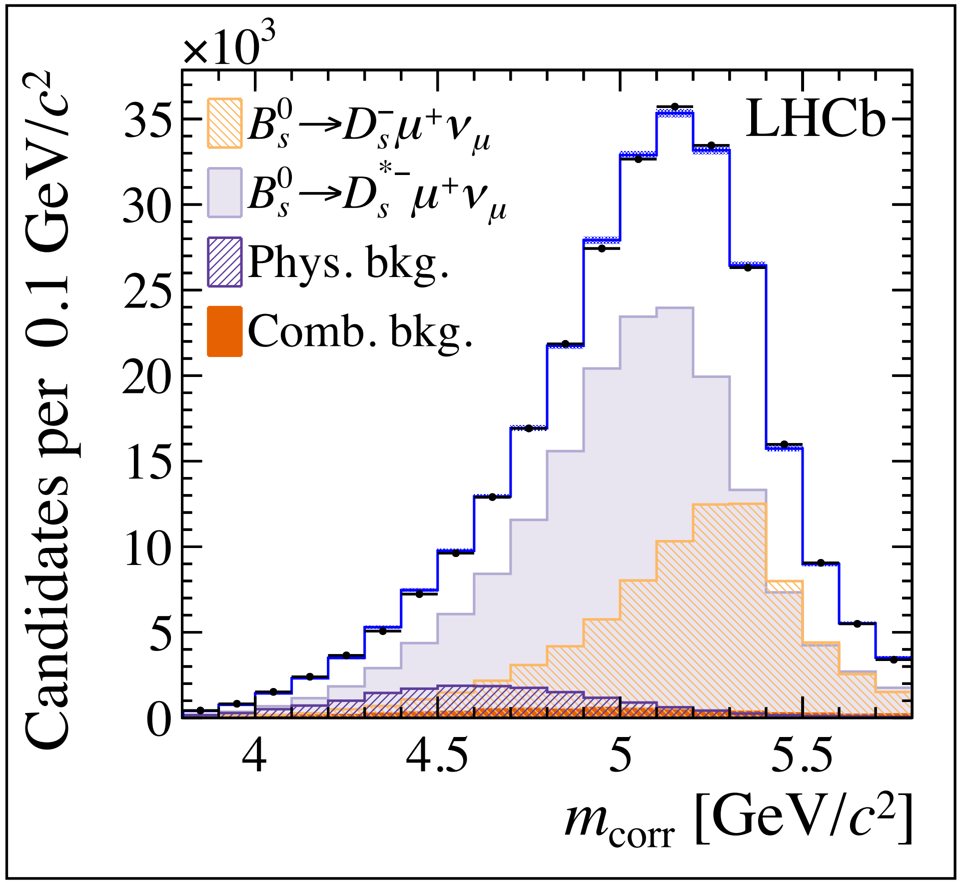
- Decay amplitude can be expressed as sum of helicity amplitudes $H_{+,-,0,t}$
- ... which can be expressed in terms of form factors that depend on q^2 (or w)
- ... whose evolution can be parameterised (CLN, BGL).
- So: assume FF parameterisation, fit yield as function of q^2 or w, deduce $|V_{cb}|$
  - in practice, measure relative to control modes $B^0 \to D^{(*)-}\mu^+\nu_\mu$
- Problem: $q^2 = m^2(\mu^+\nu_\mu)$ and w can't be measured directly.
- Solution: measure instead $p_\perp(D_{(s)})$: fully reconstructed and correlated with w

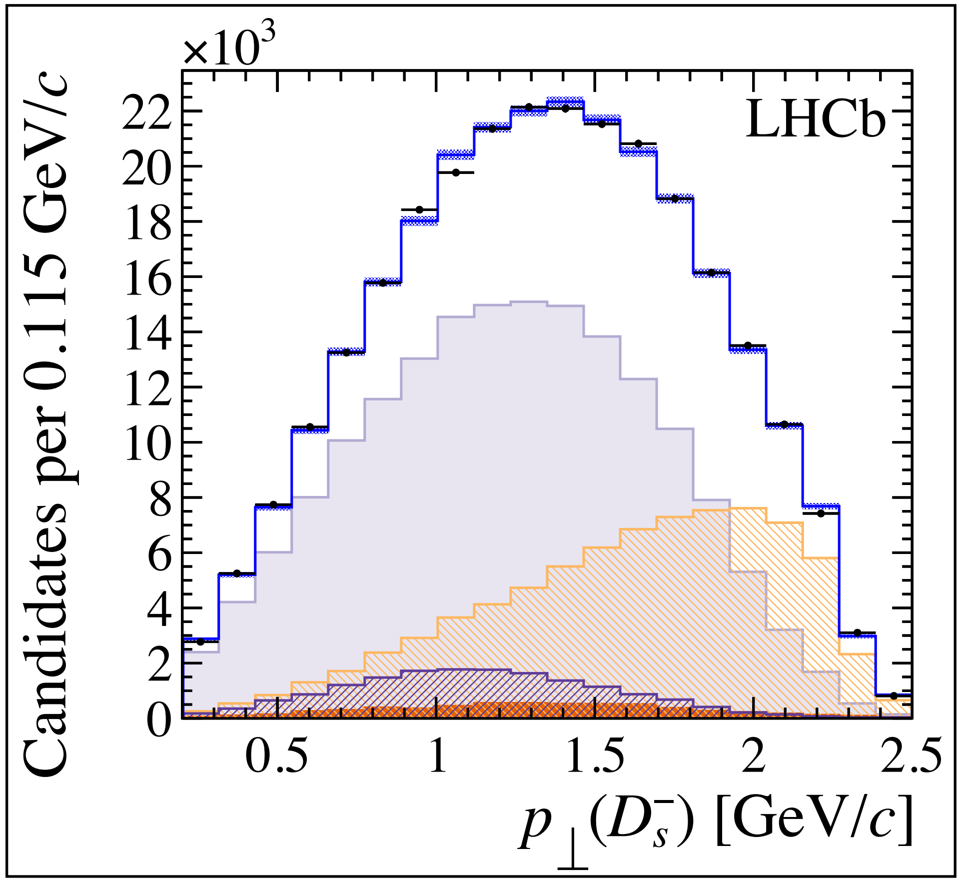


Mark Whitehead, Fri 17:30, plenary
Mirco Dorigo, Thu 15:25, Flavour

$|V_{cb}|$ in $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$

Multidimensional fit to $p_\perp(D_{(s)})$ and corrected mass m_{corr}

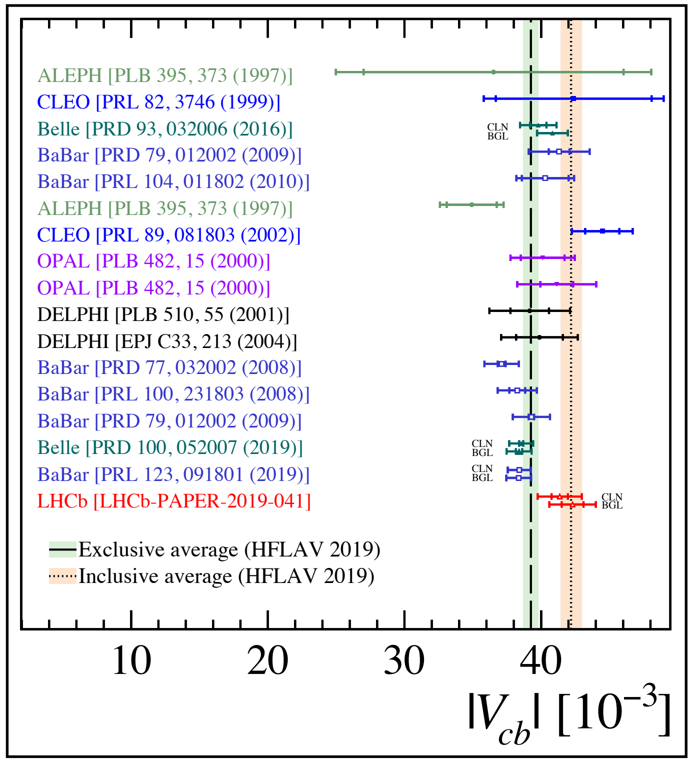




CLN: $|V_{cb}| = (41.4 \pm 0.6 \pm 0.9 \pm 1.2) \times 10^{-3}$

BGL: $|V_{cb}| = (42.3 \pm 0.8 \pm 0.9 \pm 1.2) \times 10^{-3}$

- First measurement of $|V_{cb}|$ with B_s^0 decays
- Novel method (use of $p_\perp$) can be applied more broadly, esp. to measure $|V_{cb}|$ in $B^{0,+}$ decays.



PRD 101, 072004 (2020): Measurement of $|V_{cb}|$ with $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$ decays

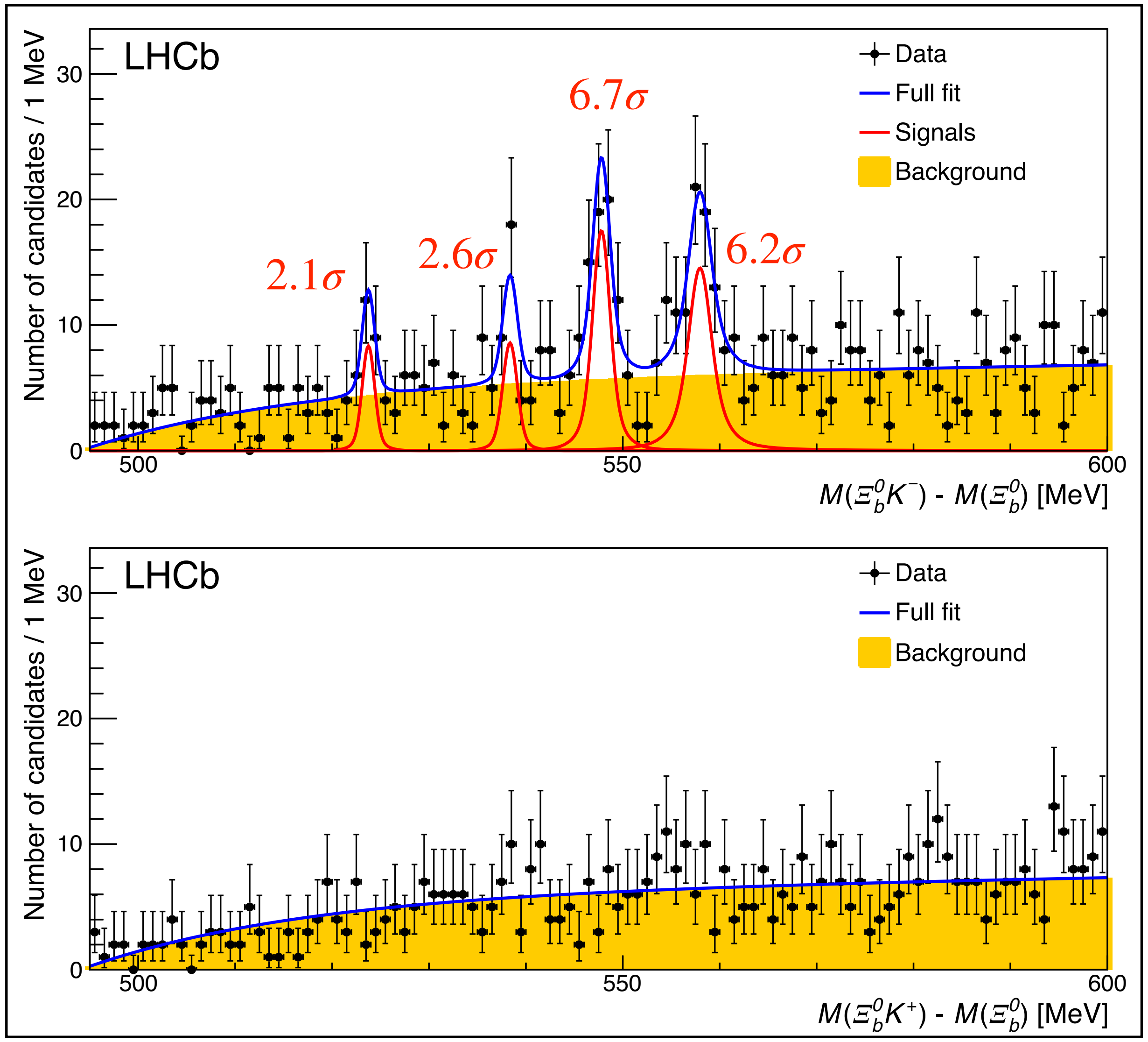
Spectroscopy

arXiv:2002.05112: Observation of a new baryon state in the $\Lambda_b^0 \pi^+\pi^-$ mass spectrum
PRL 124, 082002 (2020): First observation of excited Ω_b^- states
arXiv:2003.13649 : Observation of new Ξ_c^0 baryons decaying to $\Lambda_c^+ K^-$

Will Barter, Tue 17:30, plenary

Excited $\Omega_b^- \to \Xi_b^0 K^-$

- Reconstruct $\Xi_b^0 \to \Xi_c^+ \pi^-$, $\Xi_c^+ \to p K^- \pi^+$
- Study $m(\Xi_b^0 K^-) - m(\Xi_b^0)$ mass spectrum, identify several peaks
- Common fit to WS, RS samples to constrain background shape
- Accounting for LEE, two peaks have significance above 5σ
- All peaks narrow ($\Gamma < 3.1\,\mathrm{MeV}$ at 90% CL)



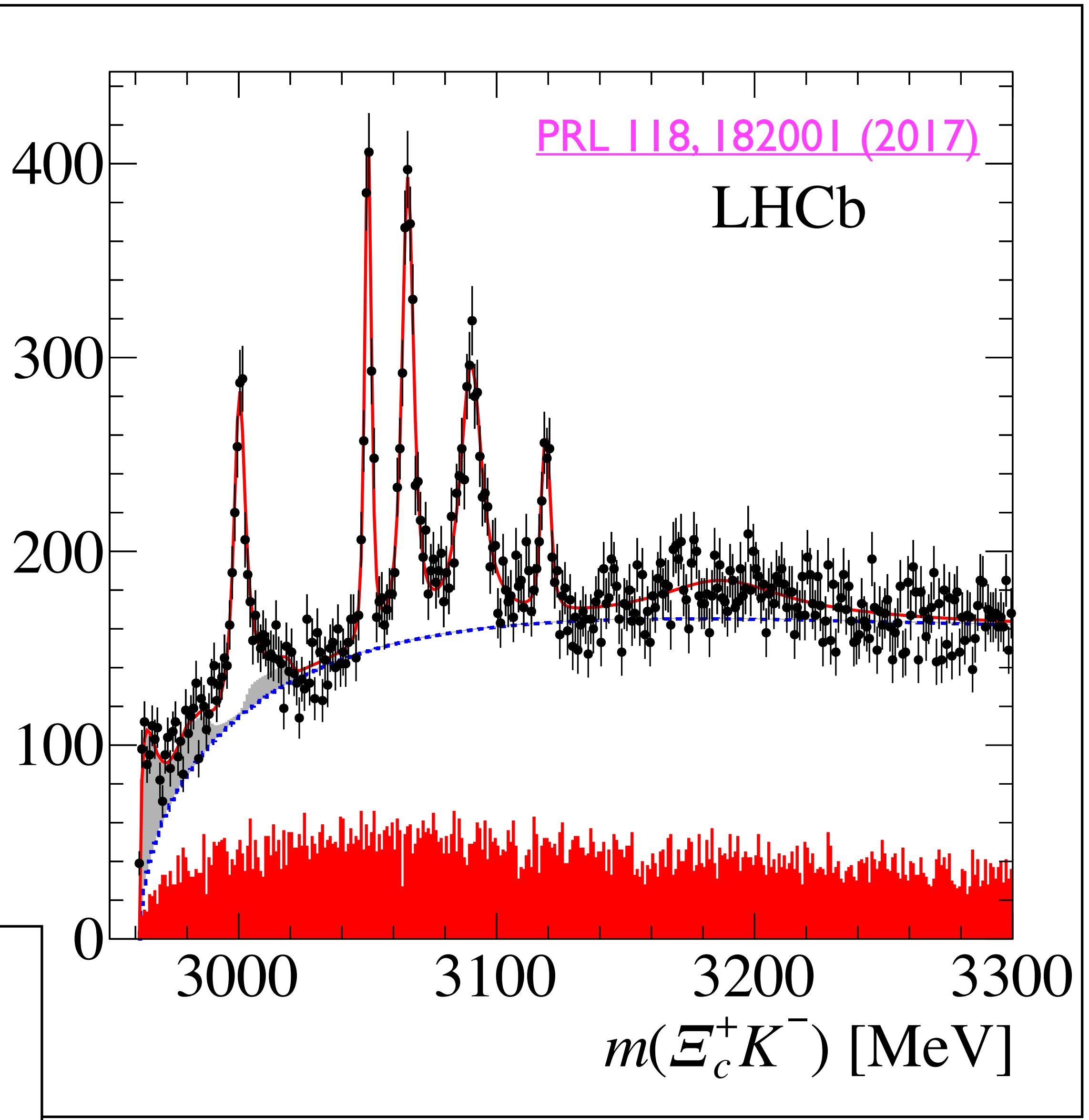
Peak of δM [MeV]	Width [MeV]	Signal yield	Significances $[\sigma]$ Local	Global
523.74 ± 0.31	$0.00\,^{+0.7}_{-0.0}$	$15\,^{+6}_{-5}$	3.6	2.1
538.40 ± 0.28	$0.00\,^{+0.4}_{-0.0}$	$18\,^{+6}_{-5}$	3.7	2.6
547.81 ± 0.26	$0.47\,^{+0.6}_{-0.5}$	$47\,^{+11}_{-10}$	7.2	6.7
557.98 ± 0.35	$1.4\,^{+1.0}_{-0.8}$	$57\,^{+14}_{-13}$	7.0	6.2

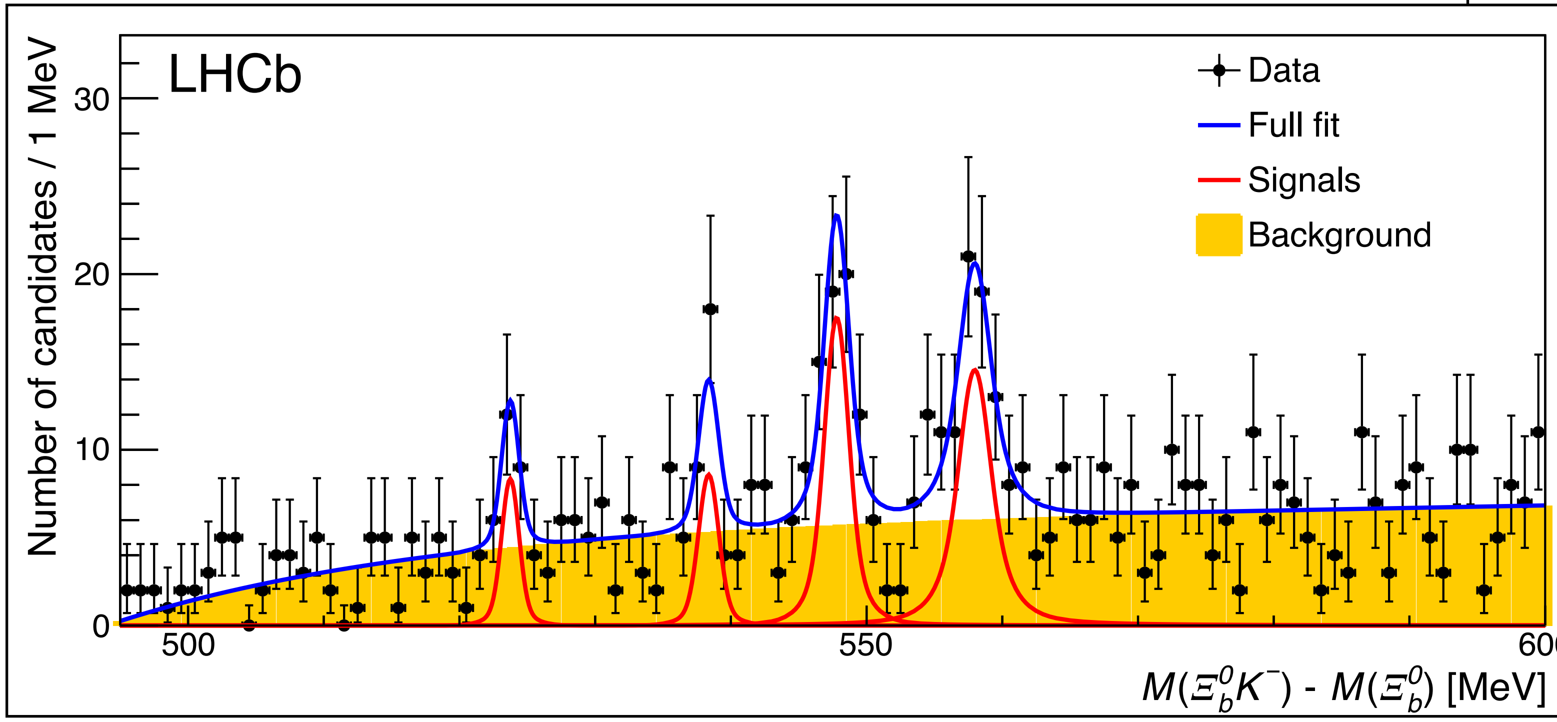
PRL 124, 082002 (2020): First observation of excited Ω_b^- states

Will Barter, Tue 17:30, plenary

Excited $\Omega_b^- \to \Xi_b^0 K^-$

- Note qualitative similarity: Ω_b^- spectrum in $m(\Xi_b^0 K^-)$ and Ω_c^0 spectrum in $m(\Xi_c^+ K^-)$.
- Properties consistent with low-lying L=1 resonances (but TBC)

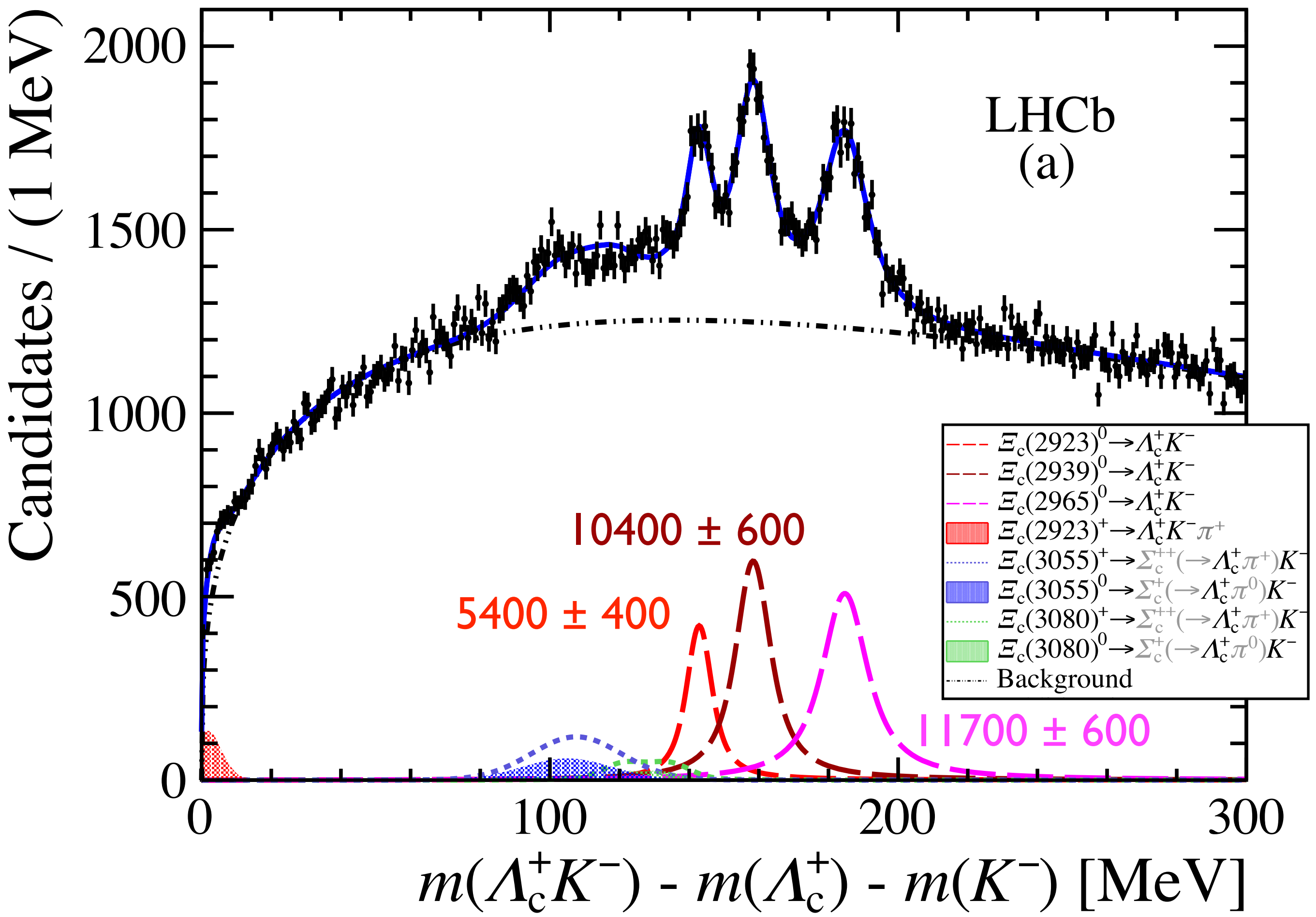




PRL 124, 082002 (2020): First observation of excited Ω_b^- states

Excited $\Xi_c^0 \to \Lambda_c^+ K^-$

Will Barter, Tue 17:30, plenary



$$m(\Xi_c(2923)^0) = 2923.04 \pm 0.25 \pm 0.20 \pm 0.14 \,\mathrm{MeV}/c^2$$
$$m(\Xi_c(2939)^0) = 2938.55 \pm 0.21 \pm 0.17 \pm 0.14 \,\mathrm{MeV}/c^2$$
$$m(\Xi_c(2965)^0) = 2964.88 \pm 0.26 \pm 0.14 \pm 0.14 \,\mathrm{MeV}/c^2$$

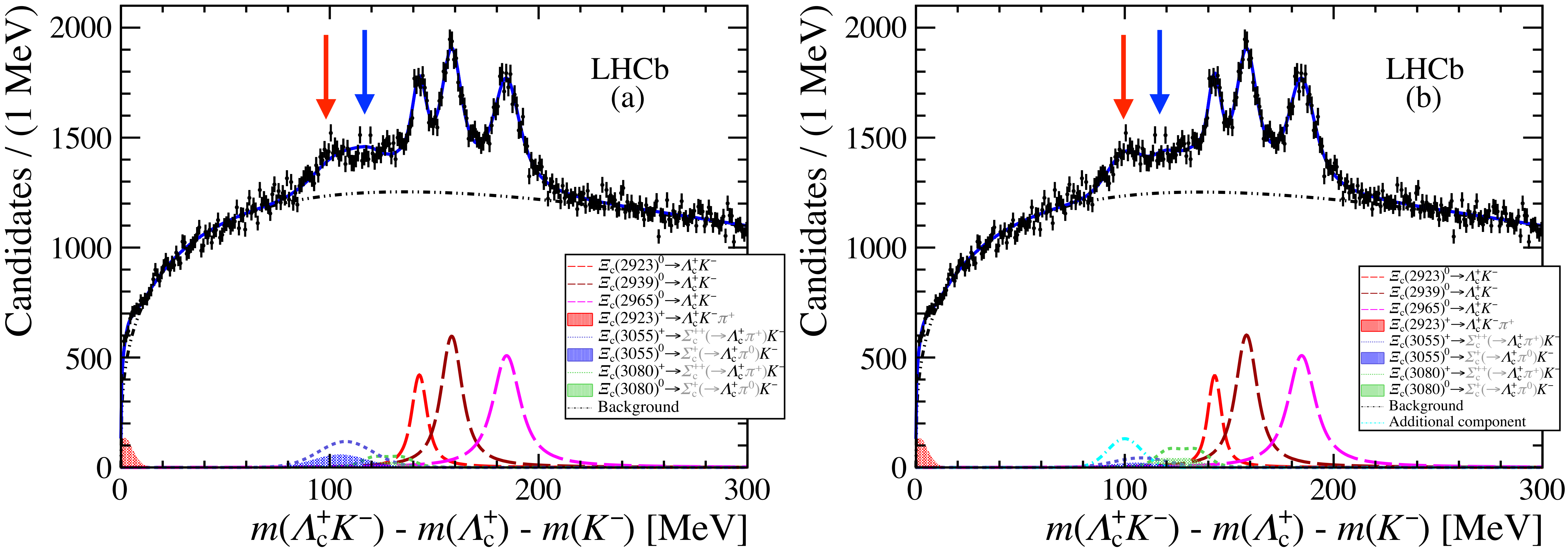
$$\Gamma(\Xi_c(2923)^0) = 7.1 \pm 0.8 \pm 1.8 \,\mathrm{MeV}$$
$$\Gamma(\Xi_c(2939)^0) = 10.2 \pm 0.8 \pm 1.1 \,\mathrm{MeV}$$
$$\Gamma(\Xi_c(2965)^0) = 14.1 \pm 0.9 \pm 1.3 \,\mathrm{MeV}$$

- Three states observed with high significance
- First two (2923, 2939) could be resolved peaks of $\Xi_c(2930)^0$ structure previously reported by BABAR (PRD 77:031101, 2008), Belle (EPJC 78, 252 (2018))... but needs further study.
- Third (2965) likely related to $\Xi_c(2970)$ previously reported by BABAR & Belle, but mass & width in tension; needs further study.

arXiv:2003.13649 : Observation of new Ξ_c^0 baryons decaying to $\Lambda_c^+ K^-$

Will Barter, Tue 17:30, plenary

Excited $\Xi_c^0 \to \Lambda_c^+ K^-$



- Also some curious structure at lower mass, ~100 MeV (red).
- Could be additional feed-downs; could be additional state(s).
- Described by empirical model (single Gaussian); effects on other peaks in the fit are small & included as systematic uncertainties.

arXiv:2003.13649 : Observation of new Ξ_c^0 baryons decaying to $\Lambda_c^+ K^-$

Last words

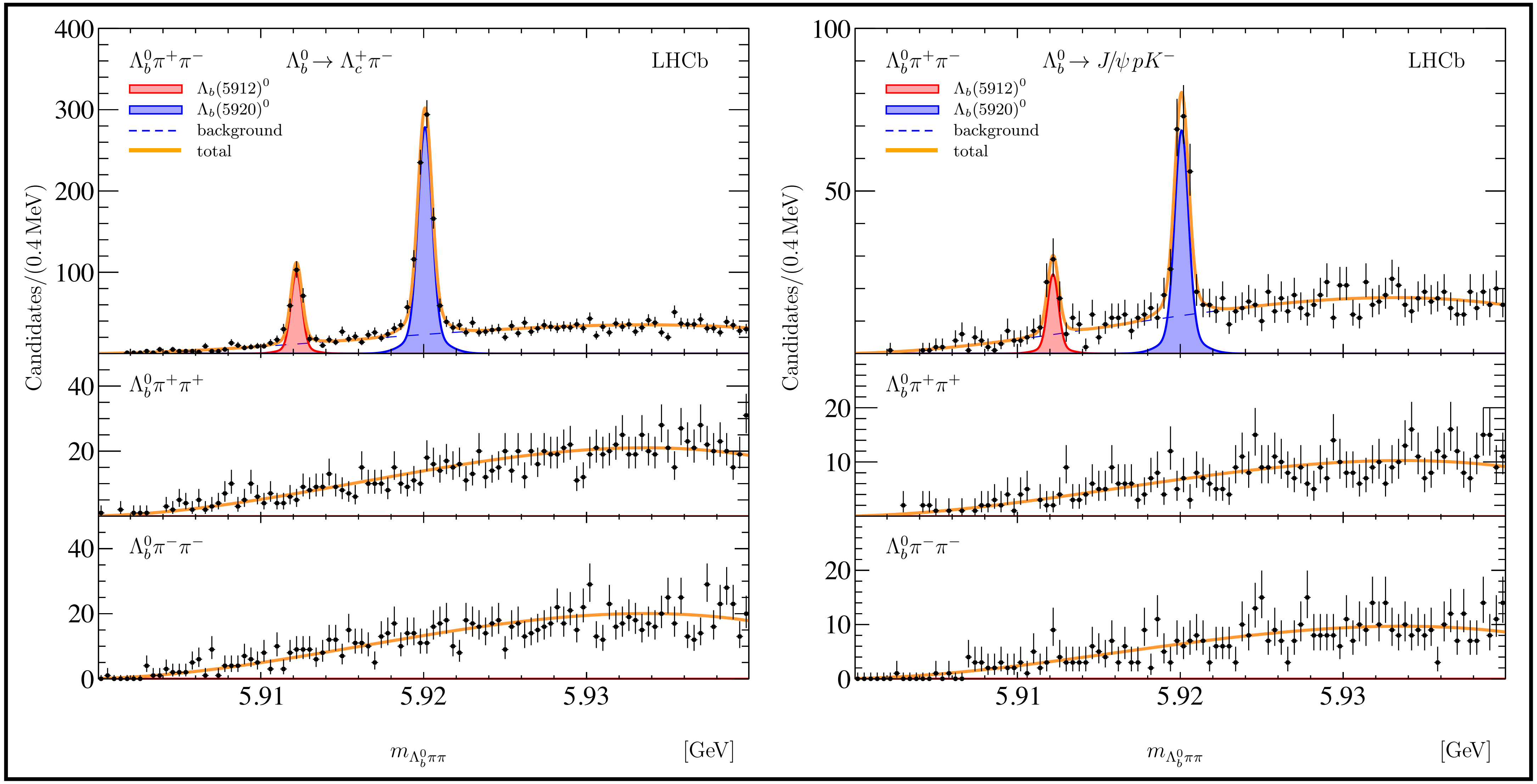
- Upgrade work has been paused, but is now ramping back up.
- Analysis work continuing
- Results presented in several areas:
    - Searches for NP with rare & electroweak penguin decays
    - Precision CKM & CPV studies
    - Spectroscopy
- ... and there is much more I did not have time for
    - ... heavy ions, electroweak, dark photon searches, isospin, ...
- Anomalies are still there, still tantalising, still not close to 5σ for individual tests of the SM.
- More details in LHCb talks throughout the conference!


$\tilde{t}$

Will Barter, Tue 17:30, plenary

Excited $\Lambda_b^0 \to \Lambda_b^0 \pi^+ \pi^-$

- Selection is key. Separate BDT classifiers for studying low-mass and high-mass regions.
  - Train with MC as signal, same-sign data as background
  - Also require $p_t(\pi^+\pi^-) > 250\,\mathrm{MeV}$ in high-mass region
- Low-mass region is straightforward. Simultaneous fit to 6 spectra:



See also PRL 109, 172003 (2012)

Known $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ observed, properties remeasured.

Natural widths of both states consistent with zero.

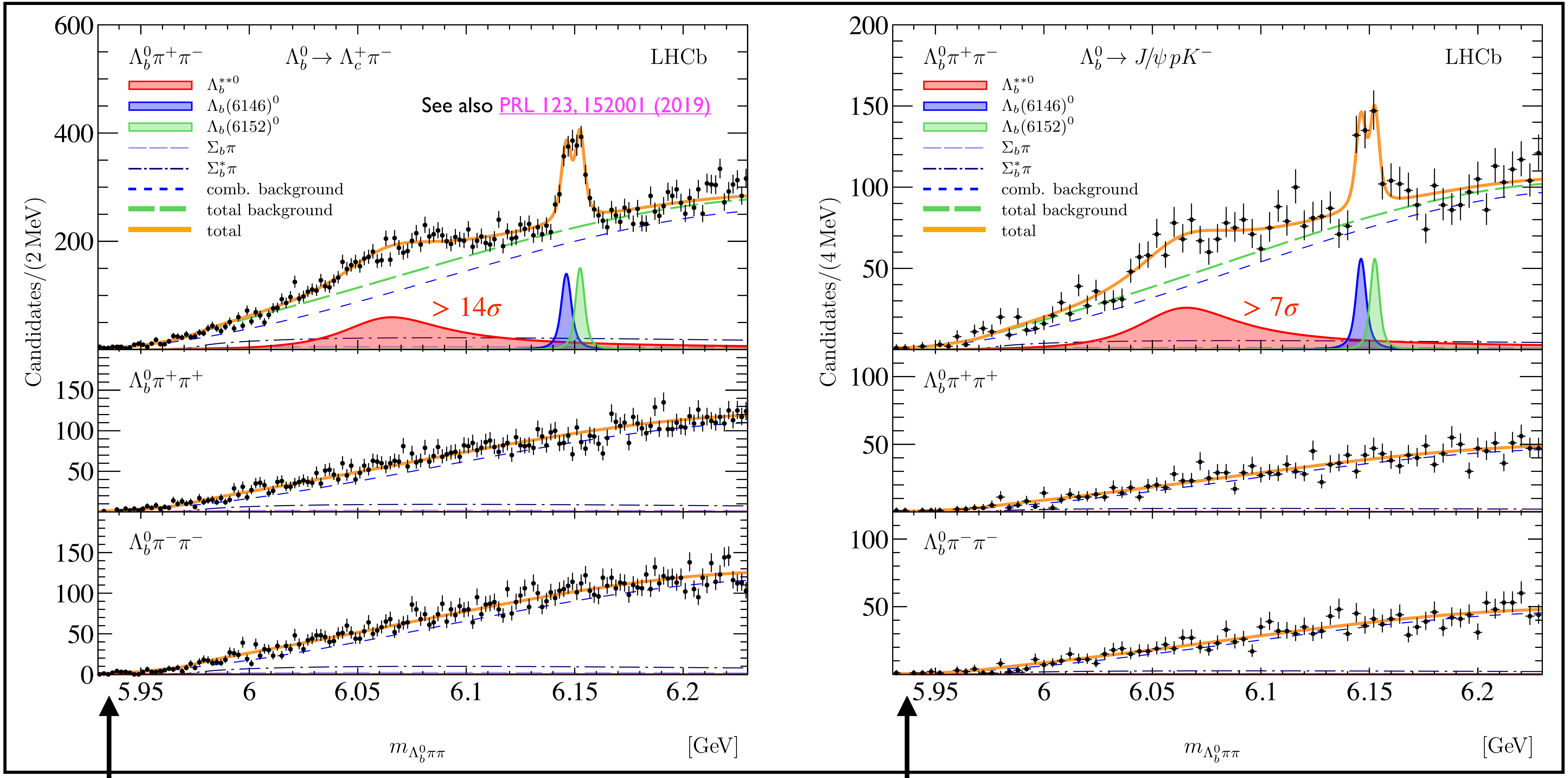
$$m_{\Lambda_b(5912)^0} = 5912.21 \pm 0.03 \pm 0.01 \pm 0.21\,\mathrm{MeV}$$
$$m_{\Lambda_b(5920)^0} = 5920.11 \pm 0.02 \pm 0.01 \pm 0.21\,\mathrm{MeV}$$
$$m_{\Lambda_b(5920)^0} - m_{\Lambda_b(5912)^0} = 7.896 \pm 0.034\,\mathrm{MeV}$$
$$\Gamma_{\Lambda_b(5912)^0} < 0.25\,(0.28)\,\mathrm{MeV}$$
$$\Gamma_{\Lambda_b(5920)^0} < 0.19\,(0.20)\,\mathrm{MeV}$$

arXiv:2002.05112: Observation of a new baryon state in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum

Excited $\Lambda_b^0 \to \Lambda_b^0\pi^+\pi^-$

Will Barter, Tue 17:30, plenary

- Now the high-mass region:



See also PRL 123, 152001 (2019)

$p_t(\pi^+\pi^-) > 250\,\mathrm{MeV}$ cut suppresses events at low mass

$$\begin{aligned}\Delta m_{\Lambda_b^{**0}} &= 452.7 \pm 2.9 \pm 0.5\,\mathrm{MeV}\\ \Gamma_{\Lambda_b^{**0}} &= 72 \pm 11 \pm 2\ \ \mathrm{MeV}\\ m_{\Lambda_b^{**0}} &= 6072.3 \pm 2.9 \pm 0.6 \pm 0.2\,\mathrm{MeV}\end{aligned}$$

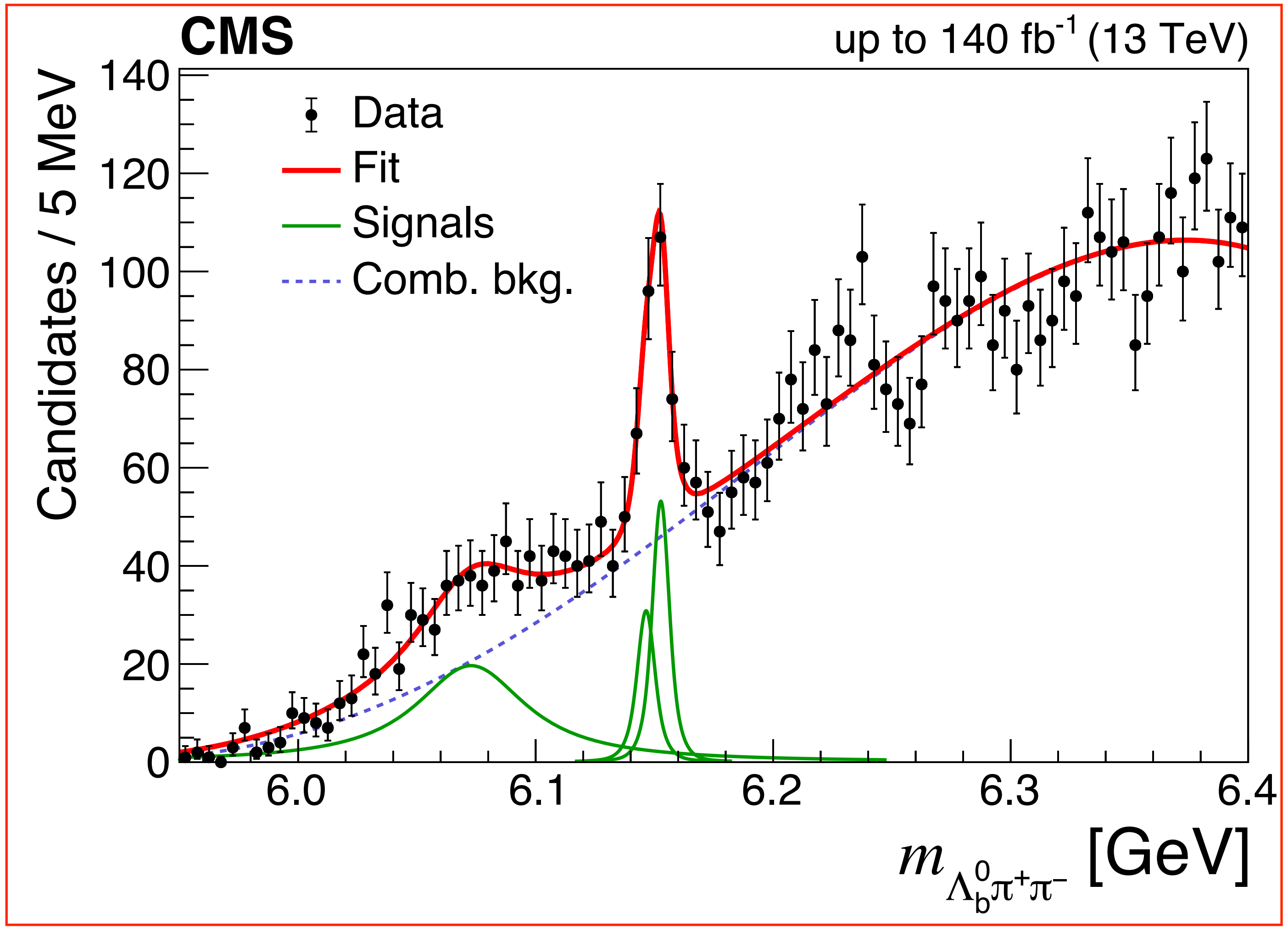
Broad Λ_b^{**0} structure interpreted as $\Lambda_b(2S)^0$ resonance.

arXiv:2002.05112: Observation of a new baryon state in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum

Will Barter, Tue 17:30, plenary

Excited $\Lambda_b^0 \to \Lambda_b^0 \pi^+ \pi^-$

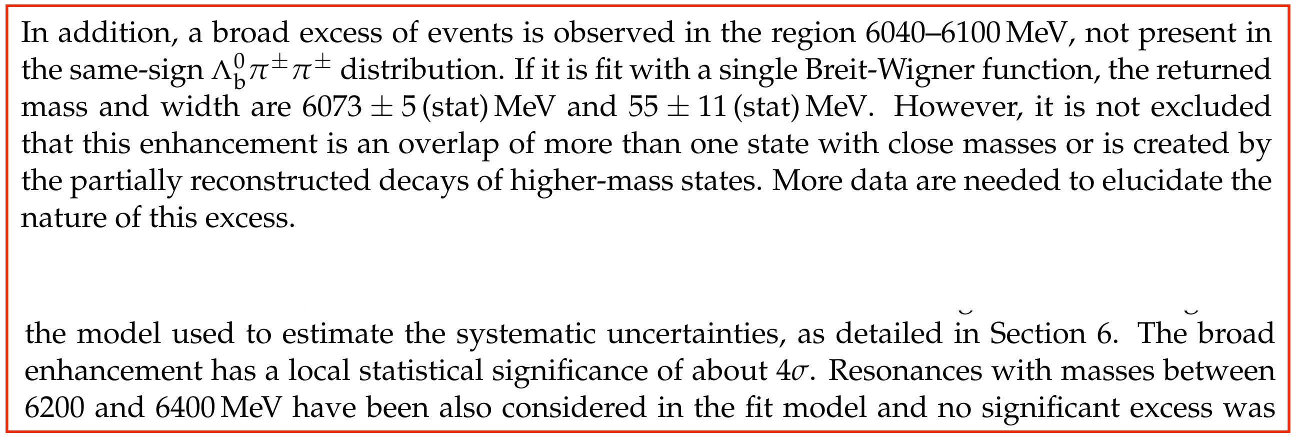
- Nice coincidence: on the same day* that this analysis was shown as a preliminary result (22 Jan 2020, Bormio), a related study by CMS appeared on the arXiv (PLB 803 (2020) 135345).



CMS results

$$M(\Lambda_b(5912)^0) = 5912.32 \pm 0.12 \pm 0.01 \pm 0.17\,\text{MeV}$$
$$M(\Lambda_b(5920)^0) = 5920.16 \pm 0.07 \pm 0.01 \pm 0.17\,\text{MeV}$$

$$M(\Lambda_b(6146)^0) = 6146.5 \pm 1.9 \pm 0.8 \pm 0.2\,\text{MeV}$$
$$M(\Lambda_b(6152)^0) = 6152.7 \pm 1.1 \pm 0.4 \pm 0.2\,\text{MeV}$$


In addition, a broad excess of events is observed in the region 6040–6100 MeV, not present in the same-sign $\Lambda_b^0\pi^\pm\pi^\pm$ distribution. If it is fit with a single Breit-Wigner function, the returned mass and width are 6073 ± 5 (stat) MeV and 55 ± 11 (stat) MeV. However, it is not excluded that this enhancement is an overlap of more than one state with close masses or is created by the partially reconstructed decays of higher-mass states. More data are needed to elucidate the nature of this excess.

the model used to estimate the systematic uncertainties, as detailed in Section 6. The broad enhancement has a local statistical significance of about 4σ. Resonances with masses between 6200 and 6400 MeV have been also considered in the fit model and no significant excess was

... i.e. CMS also sees excess with local significance of 4σ

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* CMS e-print submitted 17 Jan but due to weekend & holiday didn't appear until the early hours of 22 Jan.

CPV observables in $B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$ with $D \to K_S^0 K^\pm \pi^\mp$

Mark Whitehead, Fri 17:30, plenary
Mirco Dorigo, Thu 15:25, Flavour

- Uses CLEO model-independent input for $D \to K_S^0 K^\pm \pi^\mp$
- Reports several inputs for γ measurements
  - ... but not enough constraints in this analysis alone to get useful value of γ
- Several disjoint subsamples of events, splitting like:
  - $B \to DK$ vs $B \to D\pi$
  - B^+ vs B^-
  - Same-sign $B \to D(K_S^0 K^\pm \pi^\mp)\pi^\pm$ vs opposite-sign $B \to D(K_S^0 K^\mp \pi^\pm)\pi^\pm$
  - $m(K_S^0\pi)$ inside or outside K^{*+} region (±100 MeV around K^{*+} mass)
  - K_S^0 reconstructed from long vs downstream tracks

arXiv:2002.08858: Measurement of CP observables in $B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$ with $D \to K_S^0 K^\pm \pi^\mp$ decays

$B^\pm \to D(K/\pi)^\pm$ with $D \to K^0_S K^\pm \pi^\mp$

Yields (summed over charge)

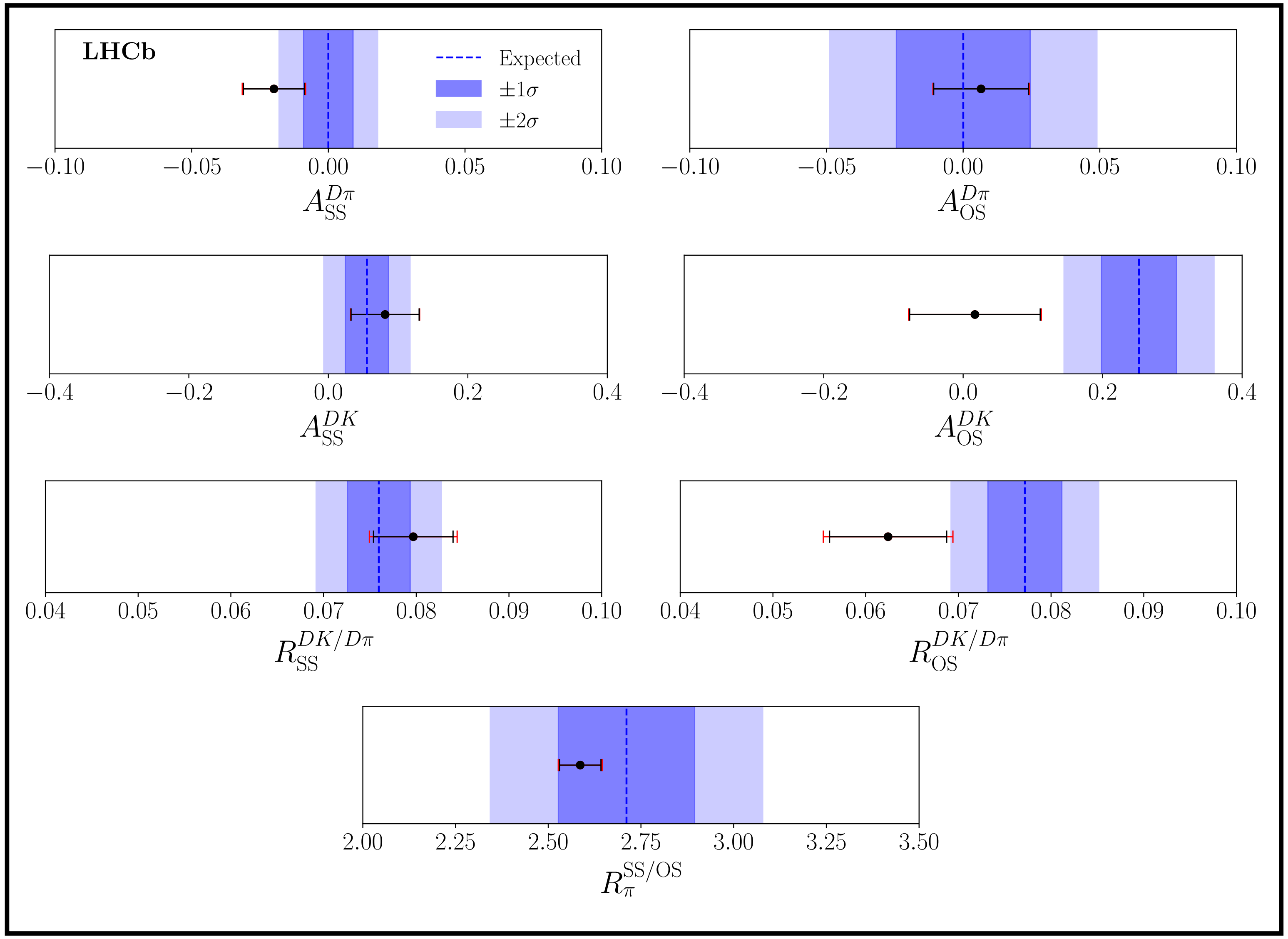
	non-K^{*+} region	K^{*+} region
$N^{DK^\pm}_{\mathrm{SS}}$	266 ± 27	715 ± 37
$N^{DK^\pm}_{\mathrm{OS}}$	336 ± 27	217 ± 22
$N^{D\pi^\pm}_{\mathrm{SS}}$	3304 ± 73	8977 ± 106
$N^{D\pi^\pm}_{\mathrm{OS}}$	4686 ± 76	3471 ± 66

$$\begin{aligned}
A^{D\pi}_{\mathrm{SS}} &= -0.020 \pm 0.011 \pm 0.003\,, \\
A^{D\pi}_{\mathrm{OS}} &= 0.007 \pm 0.017 \pm 0.003\,, \\
A^{DK}_{\mathrm{SS}} &= 0.084 \pm 0.049 \pm 0.008\,, \\
A^{DK}_{\mathrm{OS}} &= 0.021 \pm 0.094 \pm 0.017\,, \\
R_{\mathrm{SS/OS}} &= 2.585 \pm 0.057 \pm 0.019\,, \\
R^{DK/D\pi}_{\mathrm{SS}} &= 0.079 \pm 0.004 \pm 0.002\,, \\
R^{DK/D\pi}_{\mathrm{OS}} &= 0.062 \pm 0.006 \pm 0.003\,,
\end{aligned}$$

K^{*+} region

$$\begin{aligned}
A^{D\pi}_{\mathrm{SS}} &= -0.034 \pm 0.020 \pm 0.003\,, \\
A^{D\pi}_{\mathrm{OS}} &= 0.003 \pm 0.015 \pm 0.003\,, \\
A^{DK}_{\mathrm{SS}} &= 0.095 \pm 0.089 \pm 0.018\,, \\
A^{DK}_{\mathrm{OS}} &= -0.038 \pm 0.075 \pm 0.011\,, \\
R_{\mathrm{SS/OS}} &= 0.706 \pm 0.019 \pm 0.009\,, \\
R^{DK/D\pi}_{\mathrm{SS}} &= 0.081 \pm 0.008 \pm 0.004\,, \\
R^{DK/D\pi}_{\mathrm{OS}} &= 0.073 \pm 0.006 \pm 0.002\,.
\end{aligned}$$

non-K^{*+} region



Measured observables, compared to SM expectations (from world-avg inputs) for K^{*+} region

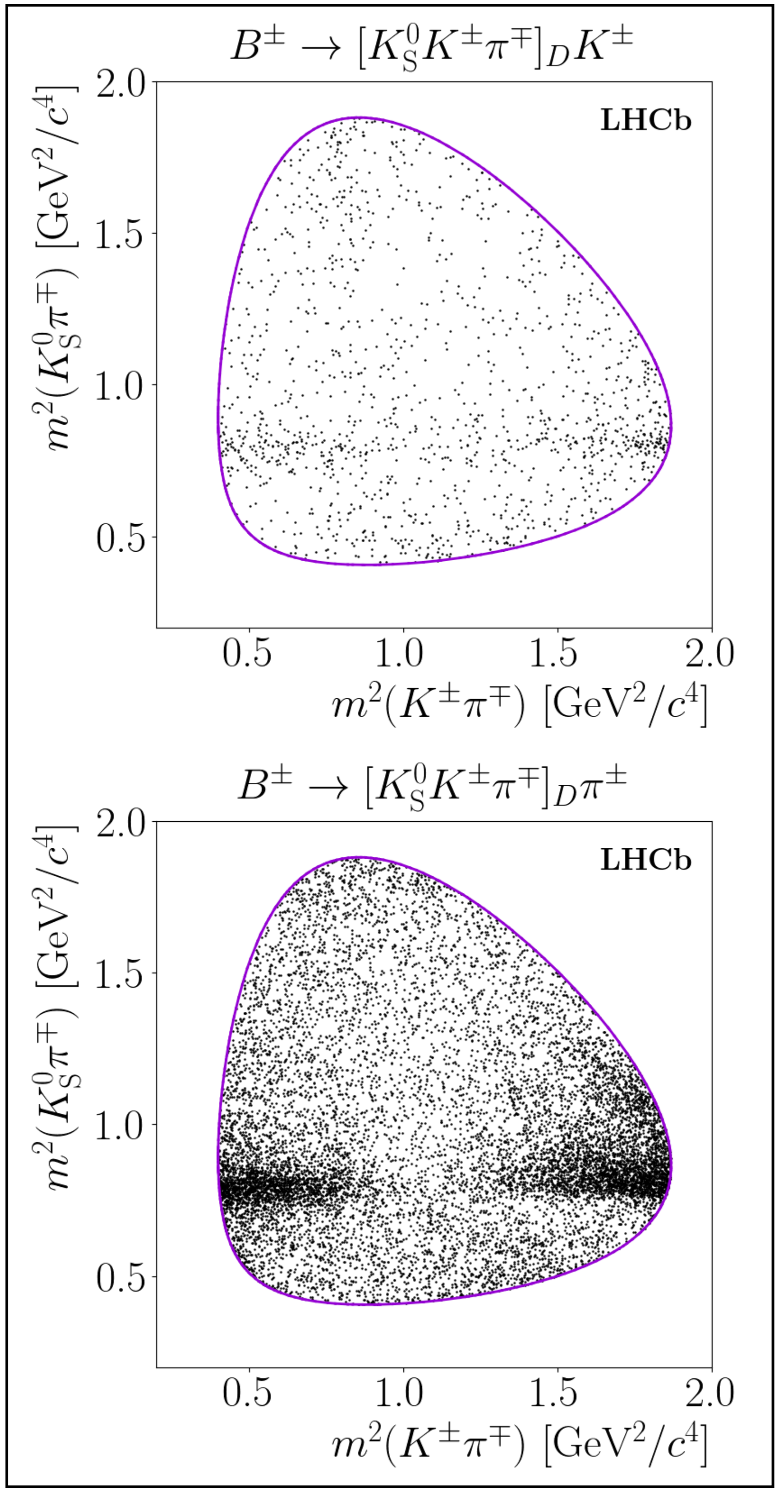
Mark Whitehead, Fri 17:30, plenary
Mirco Dorigo, Thu 15:25, Flavour

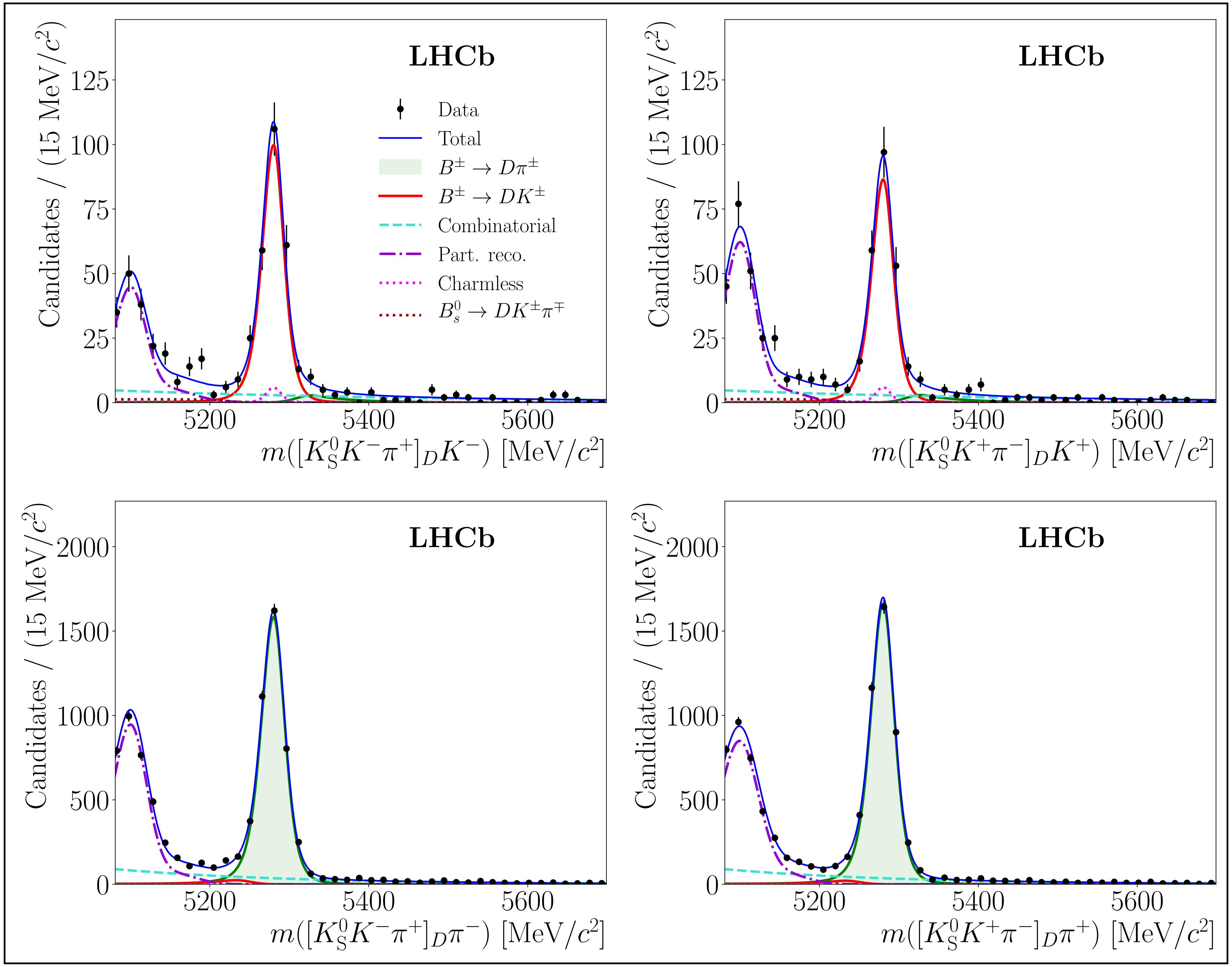
arXiv:2002.08858: Measurement of CP observables in $B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$ with $D \to K^0_S K^\pm \pi^\mp$ decays

$B^\pm \to D(K/\pi)^\pm$ with $D \to K^0_\mathrm{S}K^\pm\pi^\mp$

Mirco Dorigo, Thu 15:25, Flavour
Mark Whitehead, Fri 17:30, plenary

- Examples (just a subset!) for same-sign decays; fits inside K^{*+} region





arXiv:2002.08858: Measurement of CP observables in $B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$ with $D \to K^0_\mathrm{S}K^\pm\pi^\mp$ decays