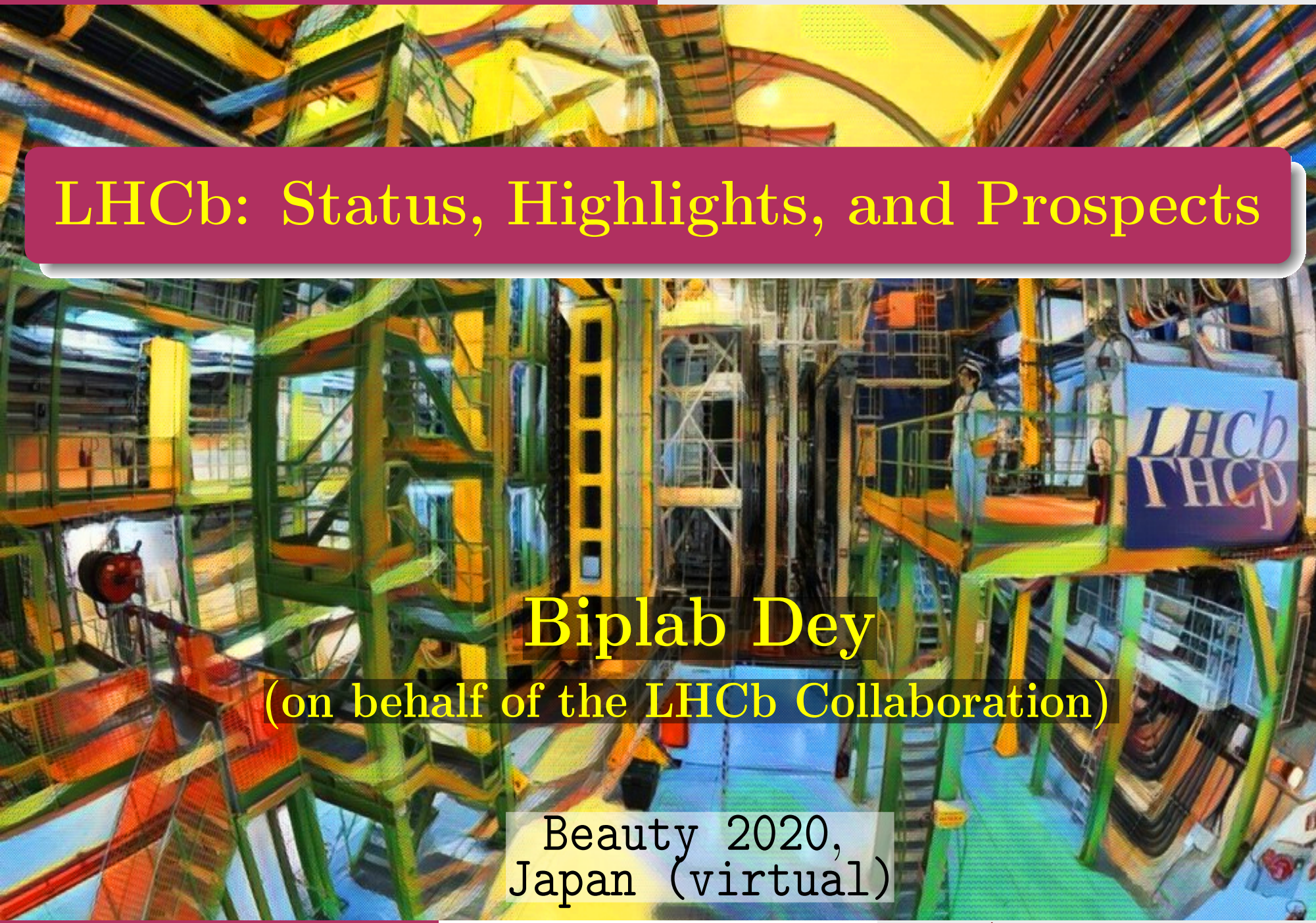
LHCb: Status, Highlights, and Prospects



Biplab Dey

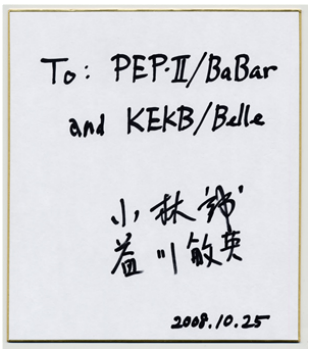
(on behalf of the LHCb Collaboration)

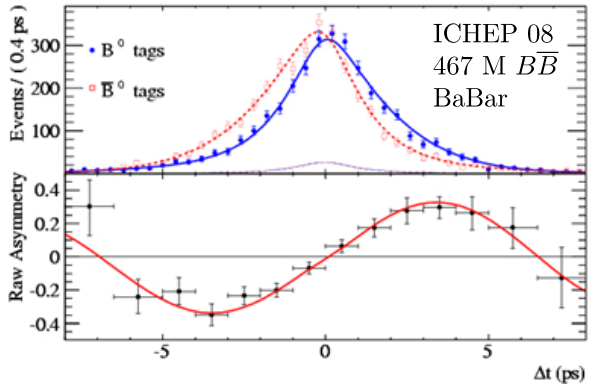
Beauty 2020,
Japan (virtual)

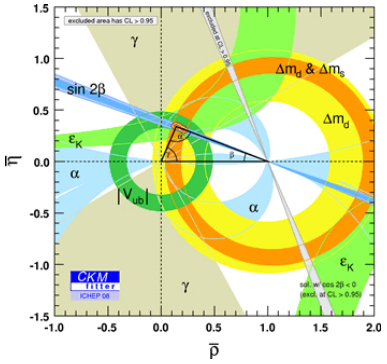
The Flavor paradigm

- *BABAR*/Belle [2000-10]: established the CKM CPV framework.





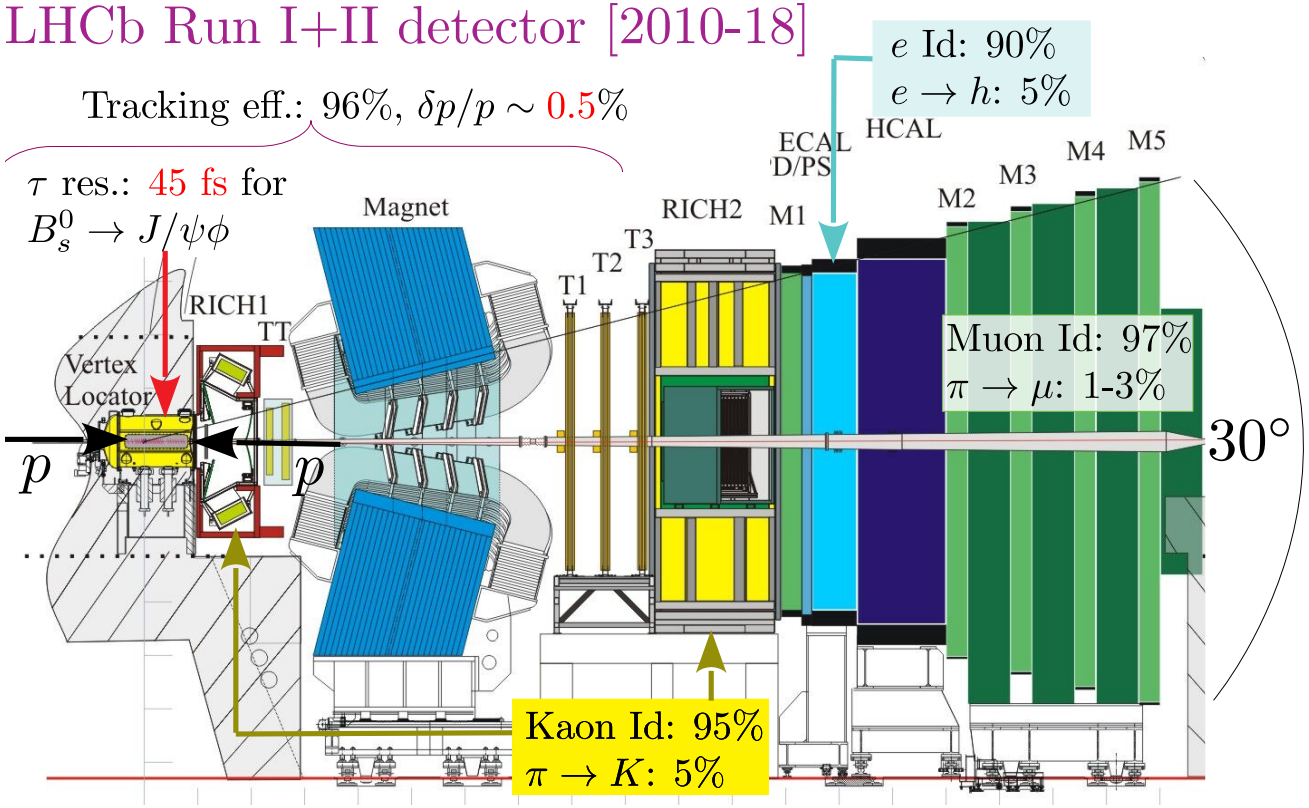


- $\sigma_{b\bar{b}}^{\Upsilon(4S)} \sim \mathcal{O}(\text{nb})$. For precision physics: super-flavor factory.
- @LHC: *huge* cross-sections $\sigma_{b\bar{b}} \sim \mathcal{O}(\text{mb})$, but harsh environment.
- Folklore: *hadron colliders are discovery machines, while lepton colliders are precision machines.*
- To harness $\sigma_{b\bar{b}}^{\text{LHC}}$, needed a special detector...

Flavor-factory at a hadron collider

- LHCb: $\frac{m_b}{\sqrt{s}} \sim 10^{-3}$. Highly boosted b's $\Rightarrow$ forward spectrometer.

LHCb Run I+II detector [2010-18]



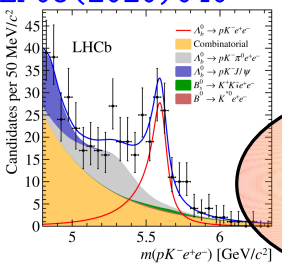
- *Primed for flavor physics at the LHC*
- Excellent tracking and vertexing. RICH(PID) unique at LHC.

[JINST14(2019)P11023, JINST14(2019)P04013, Int.J.Mod.Phys.A30(2015)1530022, JINST3(2008)S08005]

But, also a general purpose detector...

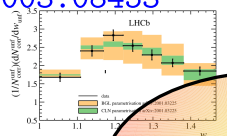
- Rich haul of physics (> 530 publications). Broad program.

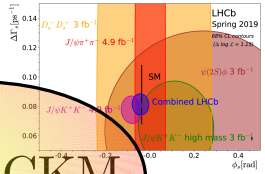
JHEP05(2020)040



Lepton universality

arXiv:2003.08453



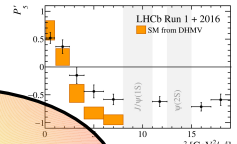


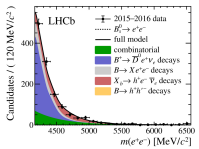
CPV & CKM

EPJC79(2019)706

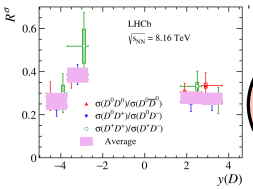
Rare decays

PRL125,011802(2020)





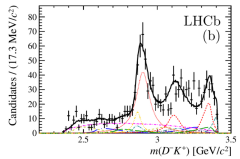
PRL124(2020)211802



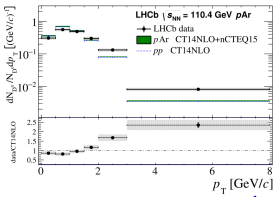
Heavy Ions

arXiv:2007.06945

Hadron spectroscopy



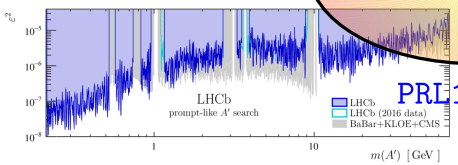
arXiv:2009.00026



Fixed target

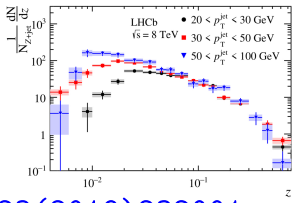
PRL122,132002(2019)

Dark sectors



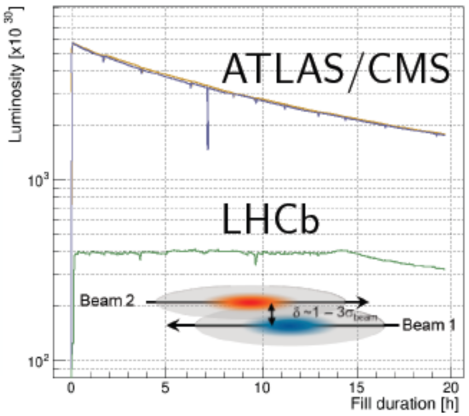
PRL124,041801(2020)

Electroweak & forward QCD



PRL123(2019)232001

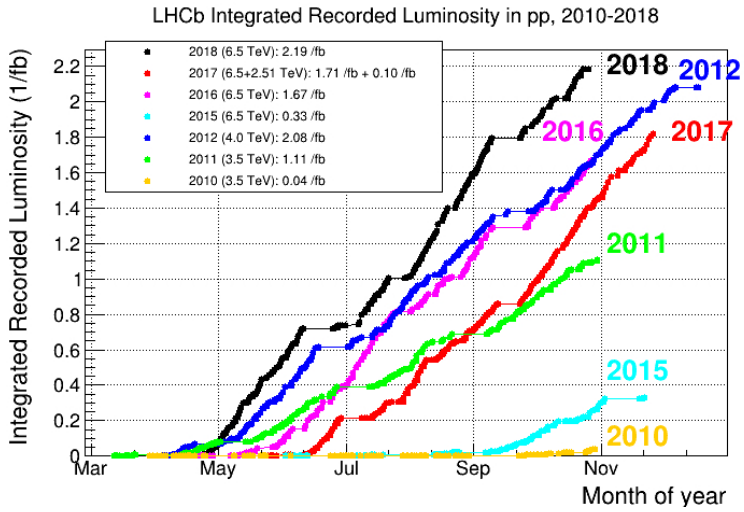
Run I/II operations and luminosities



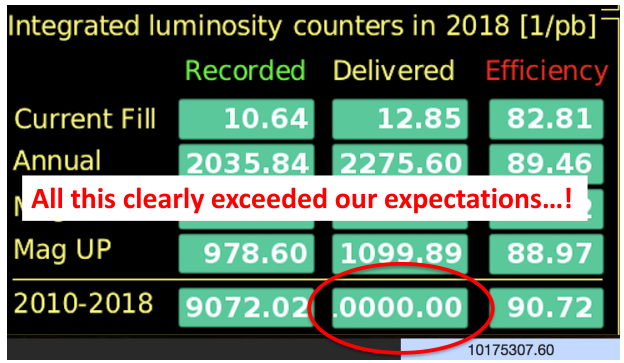
- 10-15× lower lumi than ATLAS/CMS to limit occupancies in sub-detectors (lumi-levelling).
- LHCb design lumi was 2×10^{32} cm^{-2}s^{-1}. We were able to run at twice of that. Mainly due to innovations in the trigger.
- Thanks to excellent performance of the LHC as well!

Run I: 2011-12, 3/fb @7,8 TeV

Run II: 2015-18, 6/fb @13 TeV



23^{rd} October, 2018:



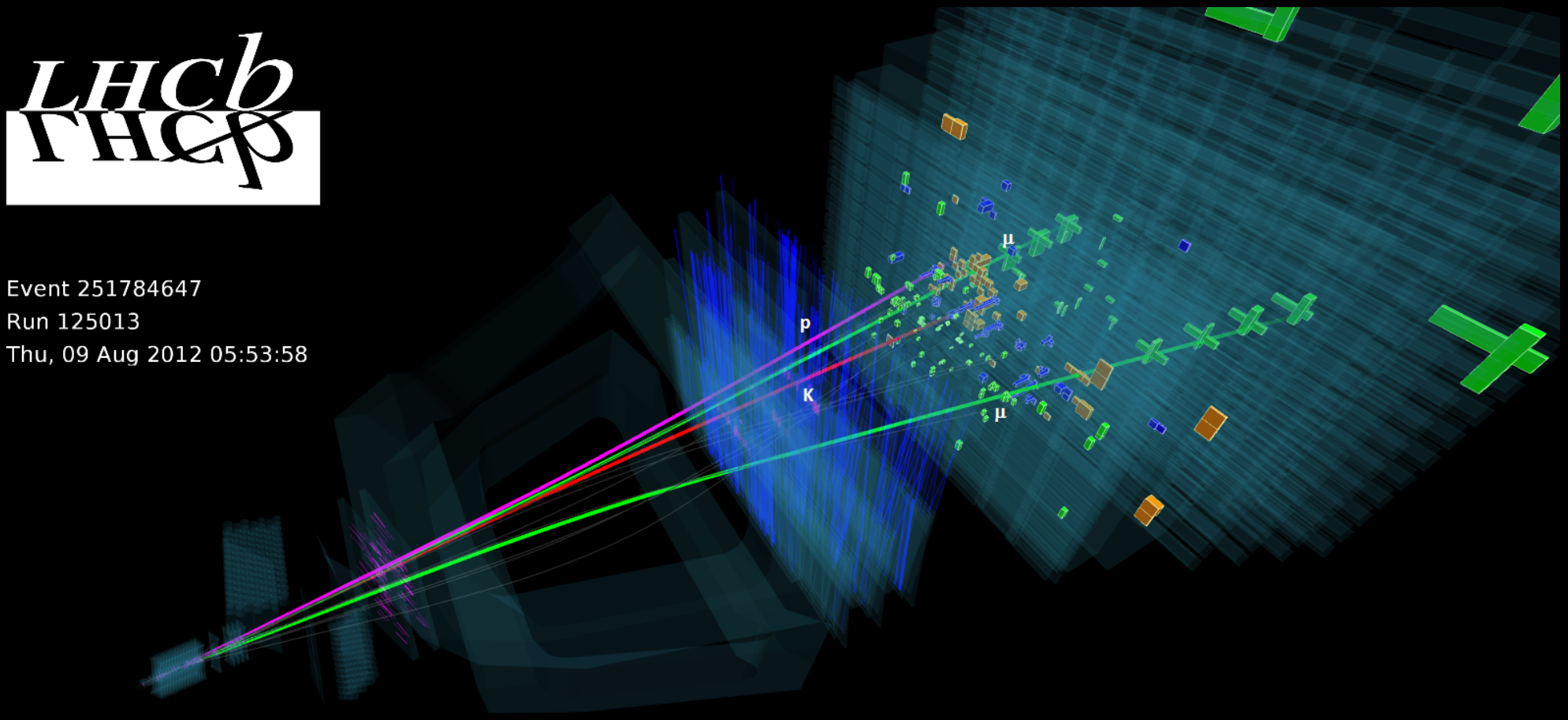
Takeaways from Run I+II till now...

- Gained huge experience in triggering for precision flavor physics in harsh LHC enviroment $\Rightarrow$ lessons for Hi-Lumi LHC.
- Significantly sharpened CKM picture. Charm CPV, B_s^0 mixing...
- Access to all b-hadron species ($B^{\pm,0}$,B_s^0,Λ_b^0,...) has been critical.
- LHCb can do neutrals, semileptonics, once thought to be near-impossible ($|V_{ub}|$, $\Lambda_b^0 \to \Lambda\gamma$,...).
- $\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-)$ consistent with SM, but evolution of B-anomalies among the most promising topics in HEP today. $\hookrightarrow$[Adlene's talk]
- Revolutionized exotic hadron spectroscopy.

Run I/II physics highlights

- I will cover:
  - Hadron Spectroscopy
  - New measurements for γ and CPV in B_s^0
  - Dark sector searches

- Adlene's talk (next session) will cover *anomalies* in:
  - Semileptonics
  - $b \to s$ FCNC decays

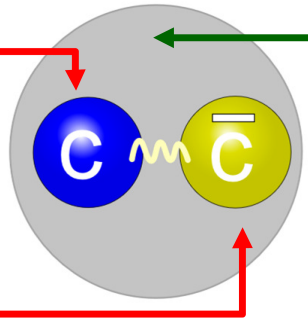


Hadron spectroscopy

Making sense of the "zoo"...

- 1974 J/ψ discovery: could be immediately interpreted.

These quarks are much heavier than the QCD scale Λ_{QCD}, & hence are discernable, nonrelativistic entities within the hadron



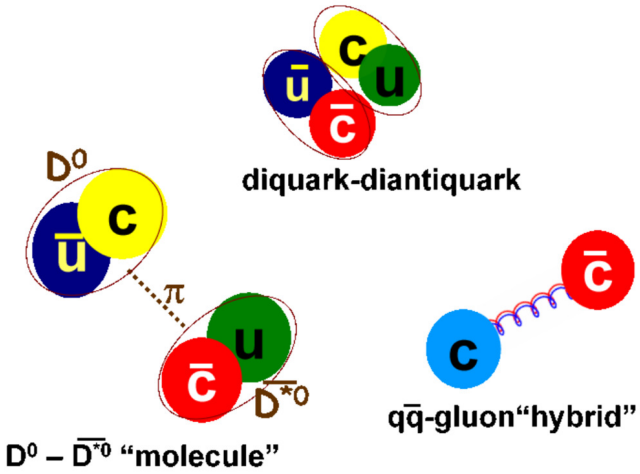
This part consists of innumerable gluons and sea $q\bar{q}$ pairs, but in the hadrons of lowest mass it just has $J^{PC} = 0^{++}$

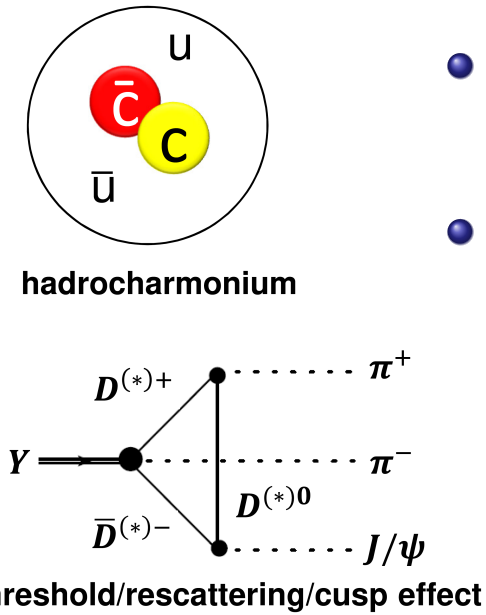
[R. Lebed]

- NR potential model predicted the $c\bar{c}$ spectrum...

[eg., PRD17(1978)3090]

- Till Belle discovered the $X(3872)$ exotic candidate in 2003.



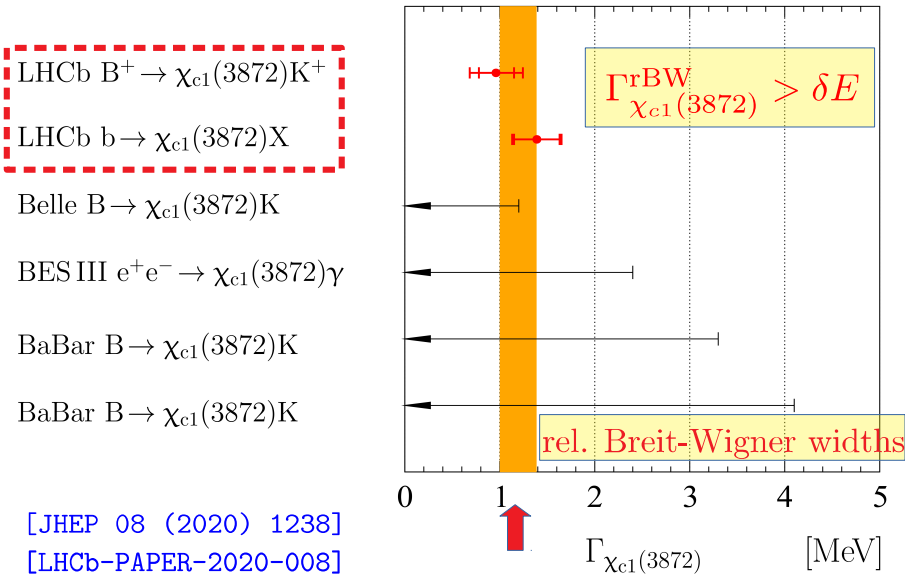


- ~ 40 exotic candidates since then.
- No single theory picture that fits all cases, though $\Lambda_{\rm QCD}/m_c \ll 1$ is a common thread.

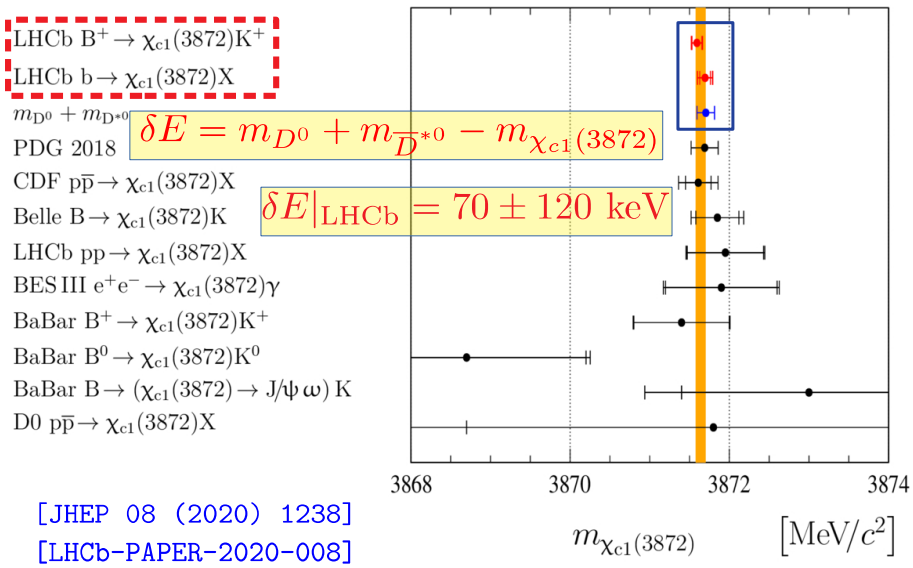
The $\chi_{c1}(3872)$ lineshape puzzle

[JHEP 08(2020) 123]
[LHCb-PAPER-2020-008]

- LHCb established the $\chi_{c1}(3872)$ ($X(3872)$) as 1^{++} [PRL110, 222001 (2013) PRD92, 011102 (2015)], but its nature still not understood. Molecule or tetraquark?
- Key features: narrow width, mass right *at* the $D^0\overline{D}^{*0}$ threshold.



[JHEP 08 (2020) 1238]
[LHCb-PAPER-2020-008]



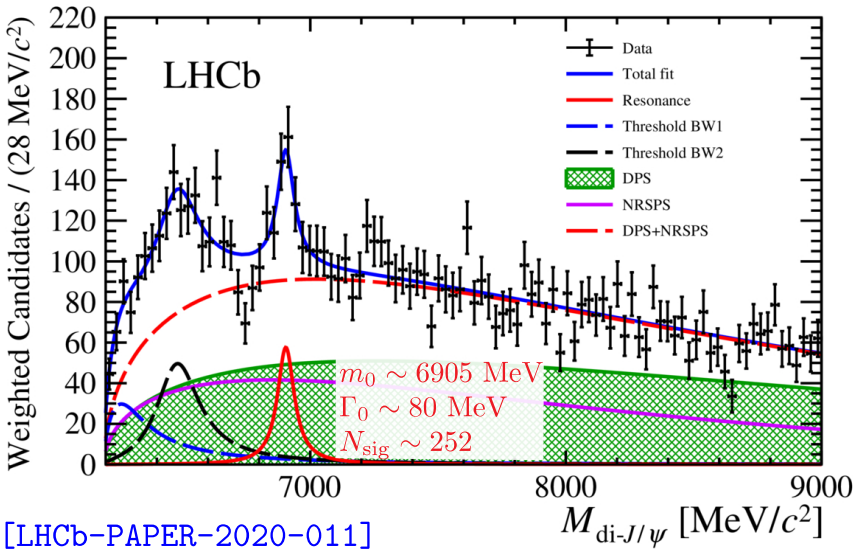
[JHEP 08 (2020) 1238]
[LHCb-PAPER-2020-008]

- Flatté with couplings to $D\overline{D}^*$, $\rho^0 J/\psi$, $\omega J/\psi$: FWHM ~ 0.22 MeV, $< \Gamma^{\rm rBW} \Rightarrow$ rBW lineshape inadequate.

First $|cc\bar{c}\bar{c}\rangle$ tetraquarks

[LHCb-PAPER-2020-011]
(Science Bulletin (2020))

- $T_{QQ\bar{Q}\bar{Q}}$, $Q \in \{c, b\}$, in many QCD models [1803.02522, 1911.00960].
- $T_{bb\bar{b}\bar{b}}$ searched at LHCb [JHEP10(2018),086] and CMS [2002.06393].
- LHCb prompt di-J/ψ: peak at 6900 MeV + other structures.



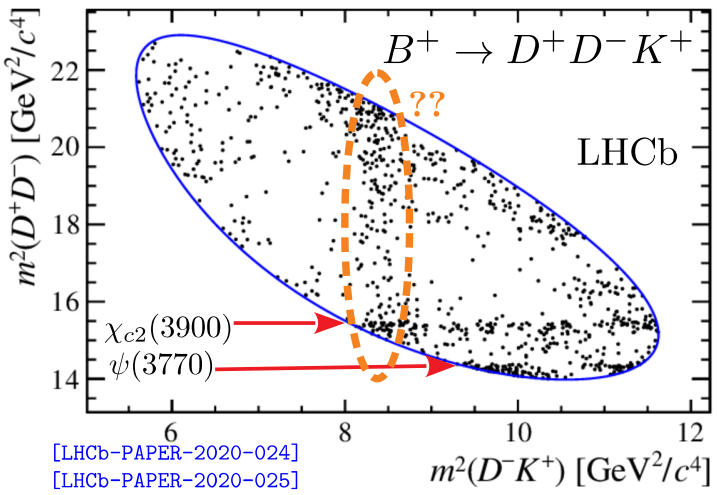
[LHCb-PAPER-2020-011]

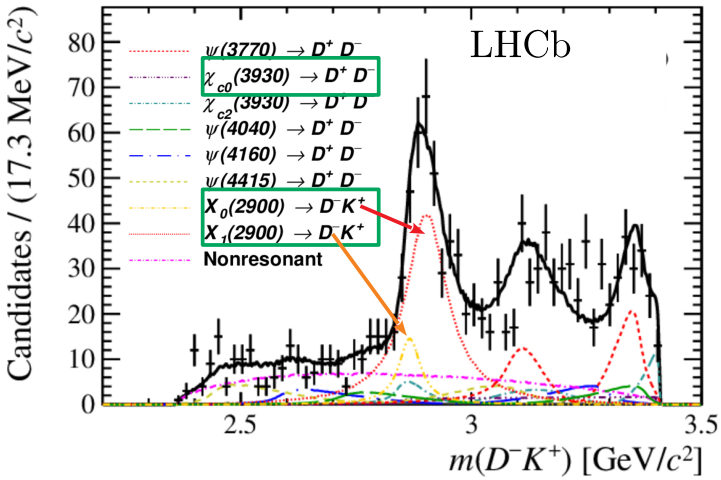
- Diquark models: $[cc]_{S=1}[\bar{c}\bar{c}]_{S=1}$.
- Karliner *et al.* [2009.04429]: $0^{++}(2S)$. "Dip": opening of S-wave di-η_{c0}.
- Becchi *et al.* [2006.14388]: 2^{++}.

- Spin-parity determination (as $X \to 4\ell$) with Run 3 data [2007.05501] .

First $|cs\bar{u}\bar{d}\rangle$ tetraquarks

[LHCb-PAPER-2020-024]
[LHCb-PAPER-2020-025]

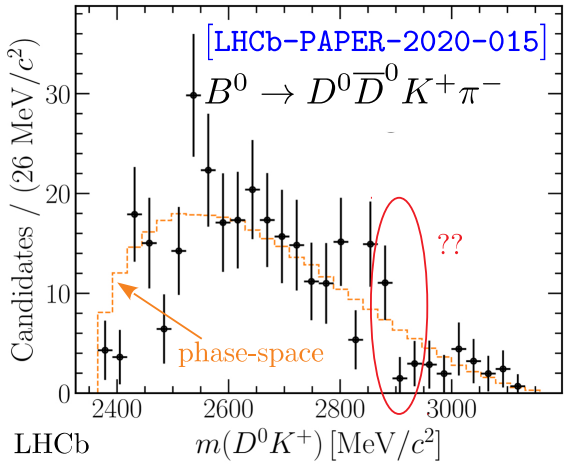




$0^+ X_0(2900)$:
$m_0 \sim 2866$, $\Gamma_0 \sim 57$
$1^- X_1(2900)$:
$m_0 \sim 2904$, $\Gamma_0 \sim 110$

$\chi_{c0}(3930)$:
$m_0 \sim 3923$, $\Gamma_0 \sim 17$
$\chi_{c2}(3930)$:
$m_0 \sim 3923$, $\Gamma_0 \sim 34$

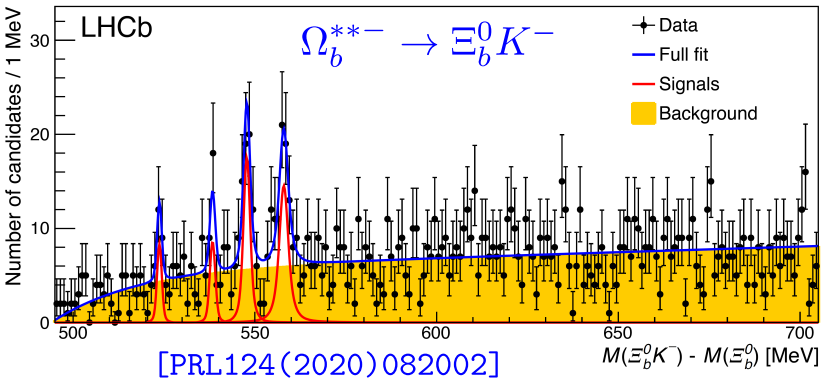
- "Model-independent" analysis: $c\bar{c}$ reflections can't mimic $m(D^-K^+)$ band.
- Karliner *et al.* [2008.05993]: X_0(compact tetraquark), X_1 ($D^*\overline{K}^*$ molecule?).
- $B^0 \to D^0\overline{D}^0K^+\pi^-$: no isospin-partner $[D^0K^+]$.



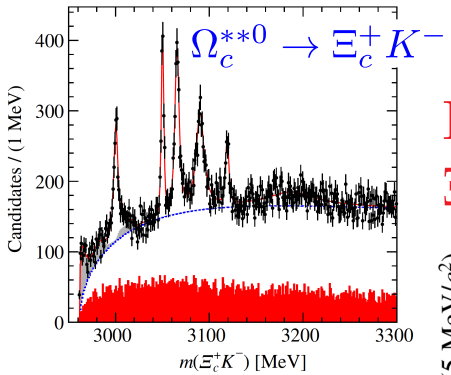
Excited b/c-hadrons

↪ [see Arvind's talk]

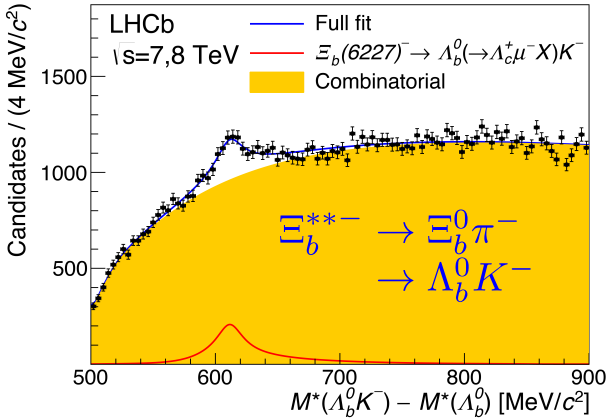
- Major strides in conventional (heavy-flavor) baryon spectroscopy...



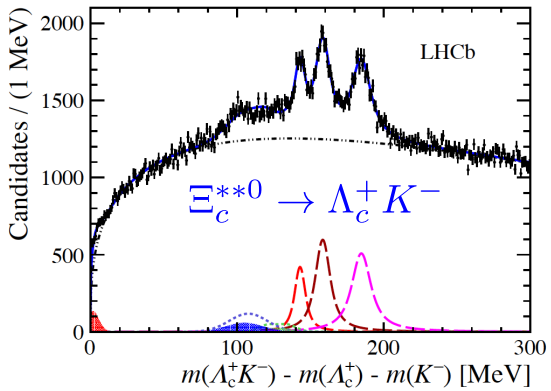
[PRL124(2020)082002]



[PRL118(2017)182001]

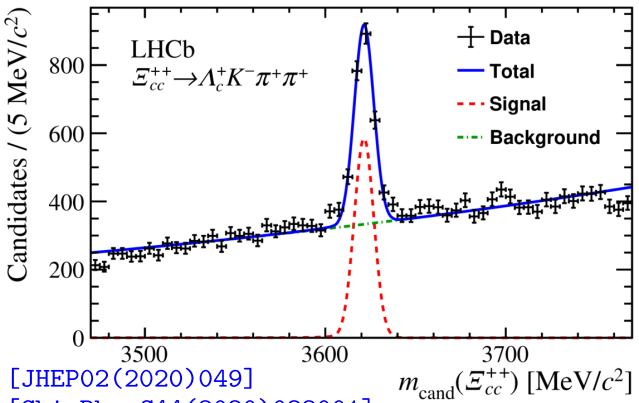


[PRL121(2018)072002]



PRL124(2020)222001]

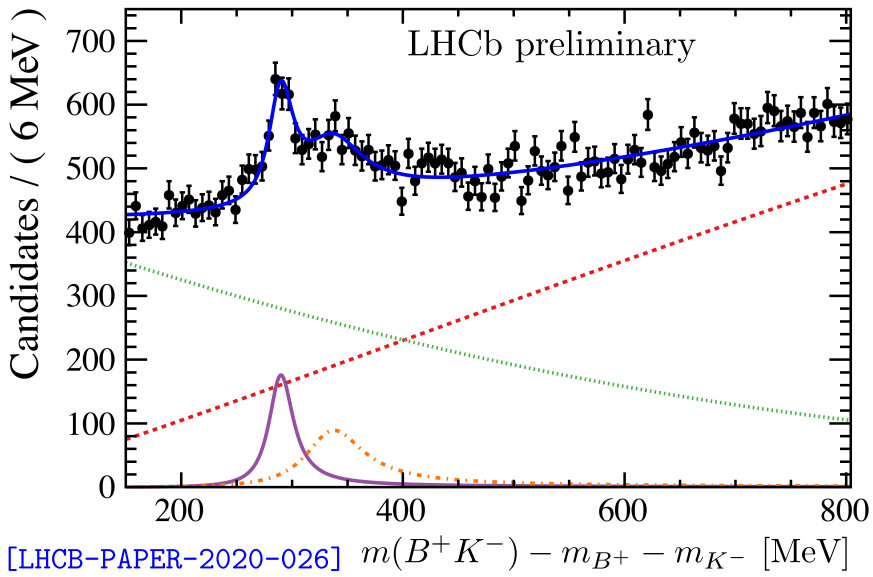
Discovery of Ξ_{cc}^{++} by LHCb.
Ξ_{cc}^+ not seen yet.



[JHEP02(2020)049]
[ChinPhysC44(2020)022001]
[PRL121(2018)162002]
[PRL119 (2017)112001]
[PRL121(2018)052002]

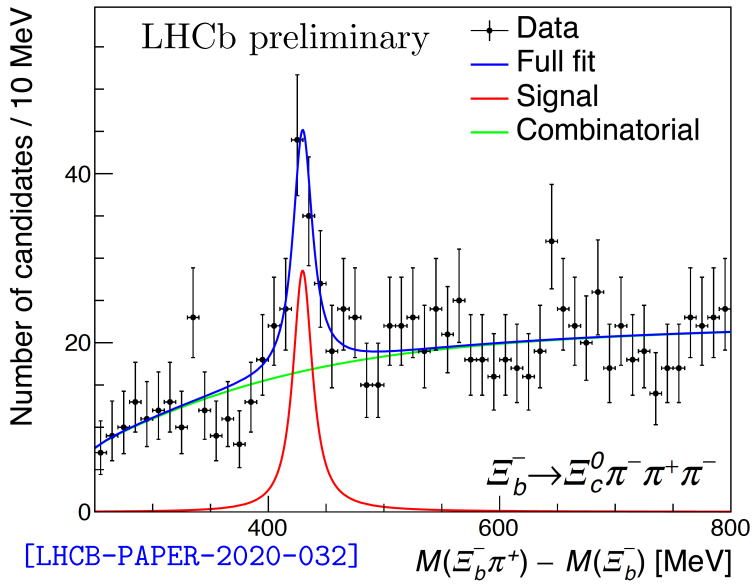
...AND MORE A COMING (NEW!)

- New B^+K^- structures from B^{**0} decays.



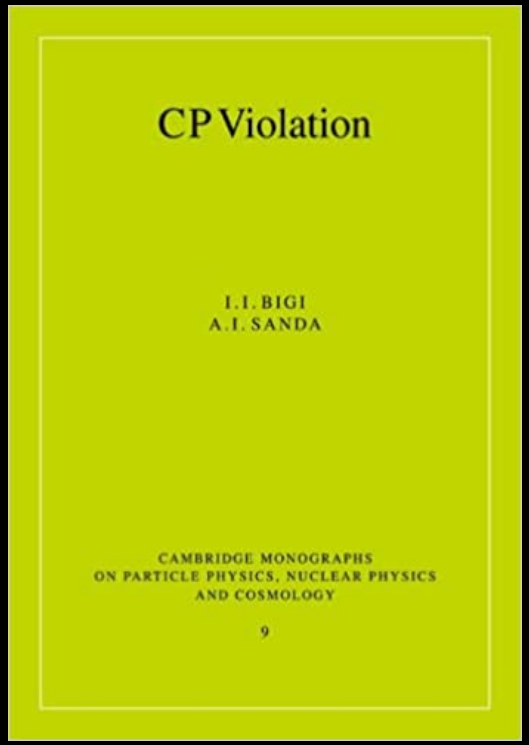
[LHCB-PAPER-2020-026]

- New $\Xi_b(6227)^0 \to \Xi_b^-\pi^+$: likely isospin partner of the $\Xi_b(6227)^-$.



[LHCB-PAPER-2020-032]

- See Arvind's talk on Wed for details.

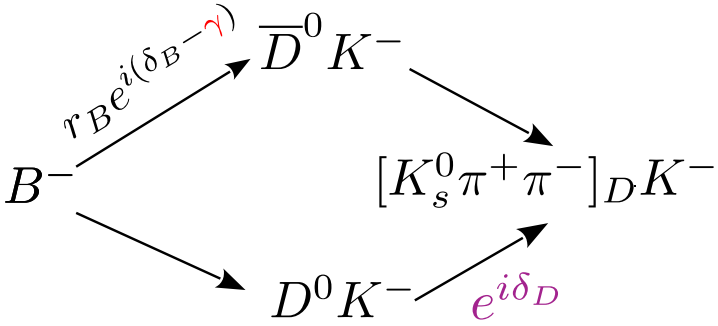


CKM angle γ and CPV in B_s^0

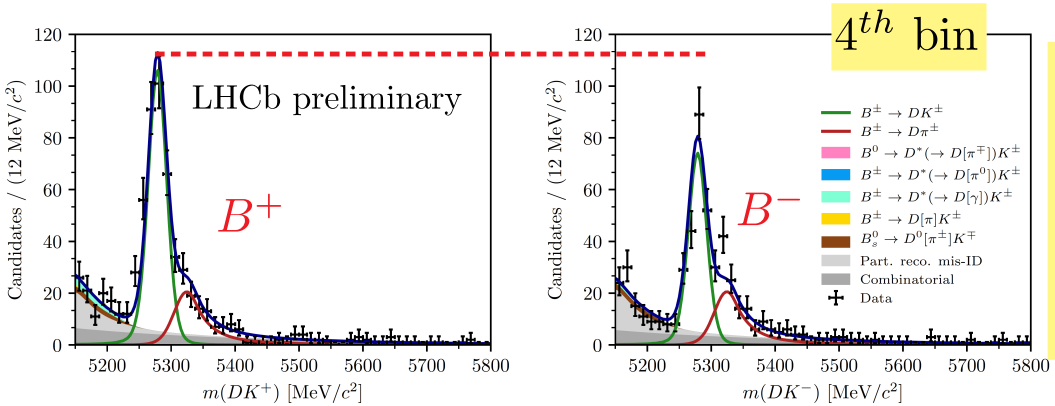
γ FROM $B^{\mp} \to D(\to K^0_S\pi^+\pi^-)K^{\pm}$

[LHCb−CONF−2020−001]
"BPGGSZ" method

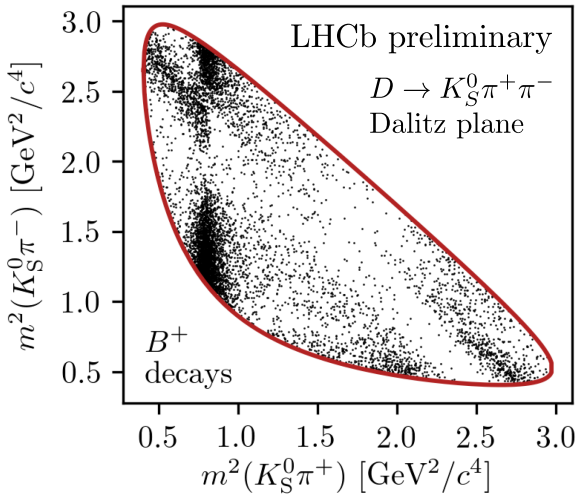
- SM benchmark: γ accessible in tree decays. $V_{ub} \sim e^{-i\gamma}$.
- $\gamma = (72.1^{+4.1}_{-4.5})^\circ$ from trees [HFLAV]; $(65.7^{+0.1}_{-2.7})^\circ$ from loops [CKMFitter].
- Model-independent method (inputs from BESIII on D decay).



[LHCb-CONF-2020-001]

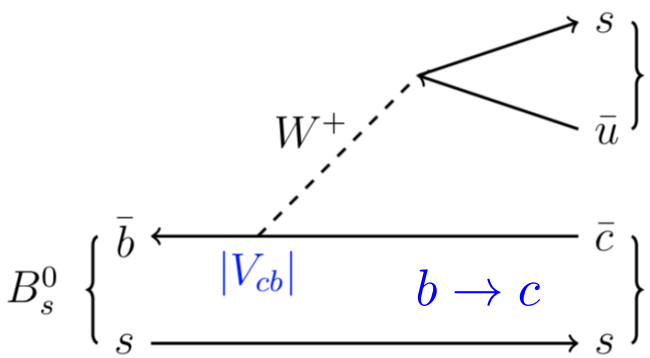


$N_i^\pm$ in i^{th} D-decay Dalitz bin gives δ_B^{DK}, γ

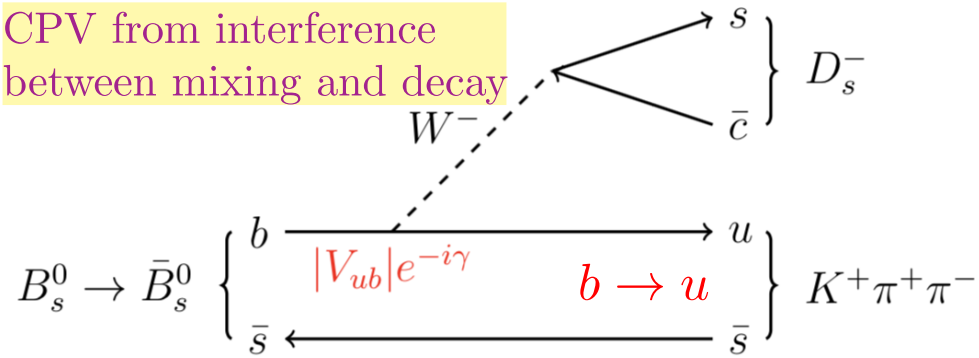


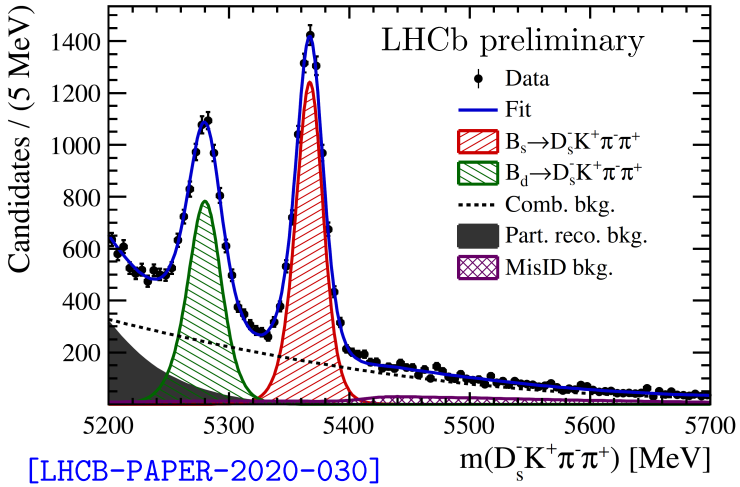
- $B \to D\pi$ as control mode. $\gamma = (69 \pm 5)^\circ$. Most precise single measurement.
- Combined $\gamma|_{\text{LHCb}}$ precision at 4° level on target. $\Rightarrow$ see Anton's talk on Wed

γ FROM $B_s^0 \to D_s^{\mp} K^{\pm}\pi^+\pi^-$ (NEW!) [LHCb−PAPER−2020−030]



CPV from interference between mixing and decay





[LHCB-PAPER-2020-030]

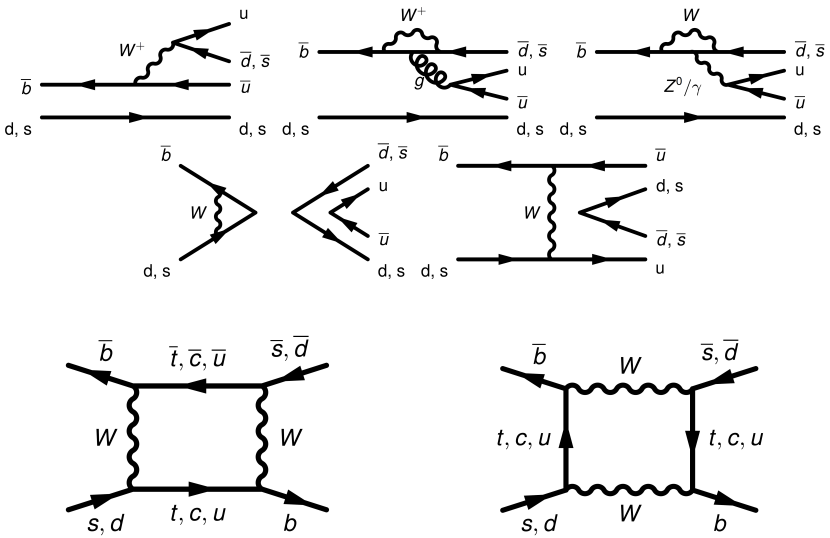
- Similar to $B_s^0 \to D_s^{\mp} K^{\pm}$ [JHEP03(2018)059], except complicated $K\pi\pi$ system.
- Time-dep. flavor-tagged 5D amplitude analyis! $N_{\text{sig}} \sim 7500$.

- Most precise measurement of Δm_s and a new measurement of γ from B_s^0 decays $\Rightarrow$ see Stefano's talk tomorrow.

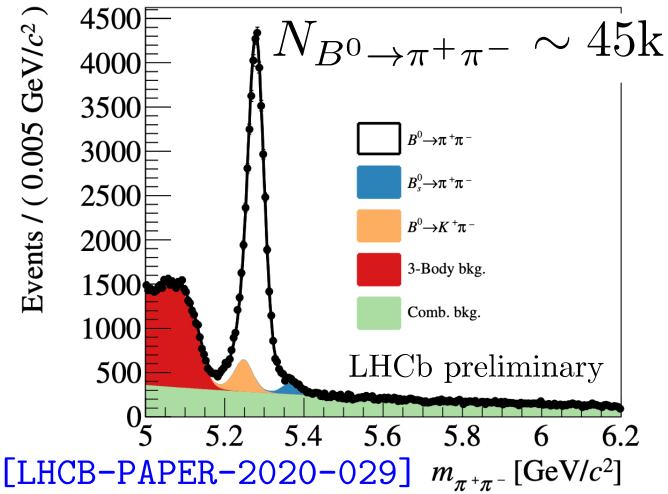
CPV IN $B^0_{(s)} \to h^+h'^-$ (NEW!)

[LHCb−PAPER−2020−029]

- 2-body $B^0_{(s)}$ decays: rich set of diagrams (tree, penguin, mixing).



- TD-CPV: $B^0 \to \pi^+\pi^-$, $B^0_s \to K^+K^-$.
  TI-CPV: $B^0 \to K^+\pi^-$, $B^0_s \to K^-\pi^+$
- Results dominated by Run I LHCb analysis [PRD98(2018)032004] $\Rightarrow$ *evidence* for TD-CPV in $B^0_s \to K^+K^-$.



[LHCB-PAPER-2020-029]

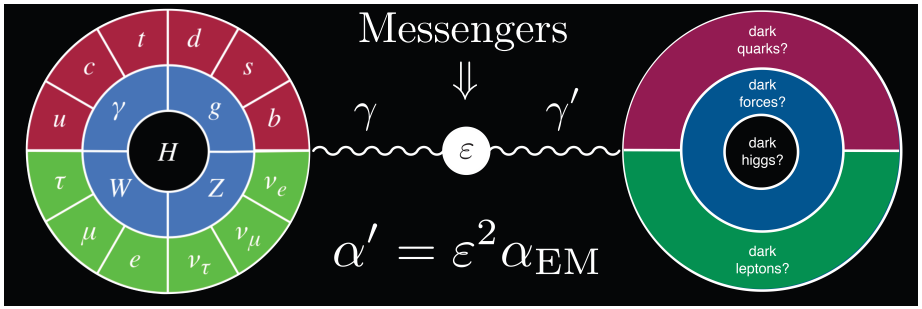
- Update to 2015+16 (2.2/fb) data. Results compatible w/ Run I analysis.
- First *observation* of TD-CPV in $B^0_s \to K^+K^-$ $\Rightarrow$ see Stefano's talk tomorrow.

Dark sector searches

Dark sectors: a different paradigm for NP

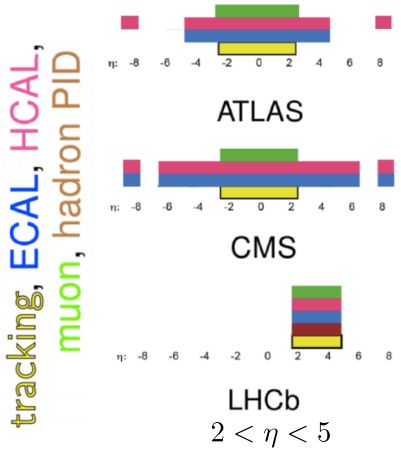
- DM charged under its own (dark) gauge sector ⇒ SM talks to DM via messengers. Messengers can be at any (GUT?) scale.

- Low energy EFT ⇒ four portals.
- LHCb sensitive to all: scalar (Higgs), neutrino (HNL), vector (dark photons), axions (ALPs).



- Complementary to ATLAS/CMS: LHCb has ×15 lower $\mathcal{L}_{\rm int}$ and forward coverage only.

- LHCb: low pileup, soft triggers ($p_T > 1$ GeV for muons, $p_T > 3$ GeV for calo), exotica from B decays.



- Run II (2015) onwards: offline quality selection (PID, vertexing, calo) in trigger. No pre-scale for dimuons. Non-standard searches.

A sample of exotica searches at LHCb

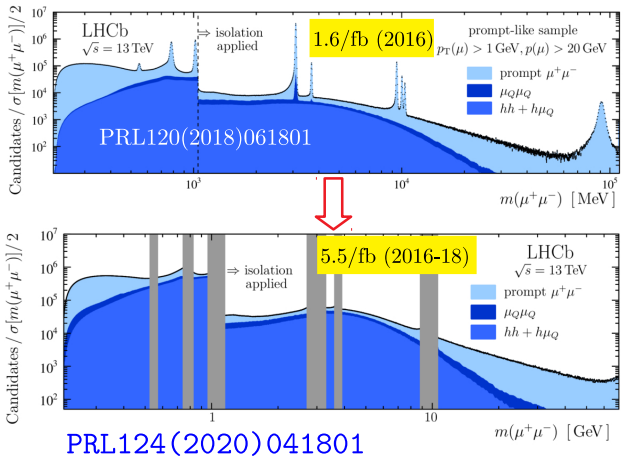
- Many dark photon, Majorana neutrinos, dark scalar searches...

PRL 124 (2020) 041801	Search for $A' \to \mu^+\mu^-$
EPJC78 (2018) 1008	Search for lepton-flavour-violating decays of Higgs-like bosons
JHEP 09 (2018) 147	Search for a dimuon resonance in the Υ mass region
PRL 120 (2018) 061801	Search for dark photons produced in 13 TeV pp collisions
EPJC 77 (2017) 812	Updated search for long-lived particles decaying to jet pairs
EPJC 77 (2017) 224	Search for massive long-lived particles decaying semileptonically in the LHCb detector
EPJC76 (2016) 664	Search for Higgs-like bosons decaying into long-lived exotic particles
PRL 112 (2014) 131802	Search for Majorana Neutrinos in $B^- \to \pi^+\mu^-\mu^-$ Decays
PRL 115 (2015) 161802	Search for Hidden-Sector Bosons in $B^0 \to K^{*0}\mu^+\mu^-$
PRD 95 (2017) 071101(R)	Search for long-lived scalar particles in $B^+ \to K^+\chi(\mu^+\mu^-)$
PRL 116 (2016) 251803	Proposed Inclusive Dark Photon Search at LHCb
PRD 92 (2015) 115017	Dark photons from charm mesons at LHCb (for Run 3)

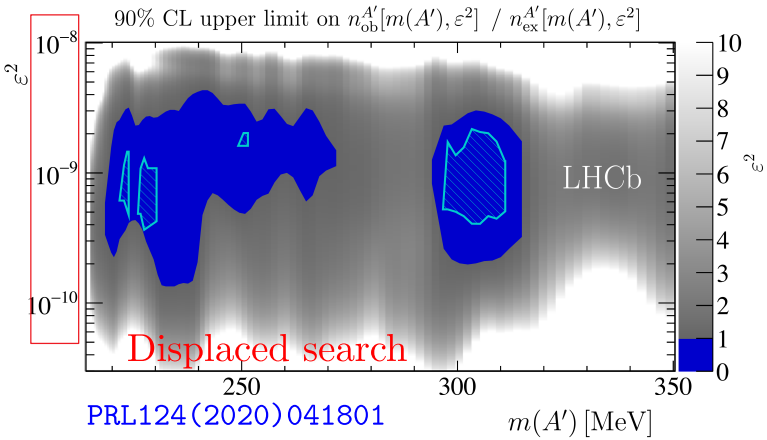
Low mass A' with dimuons

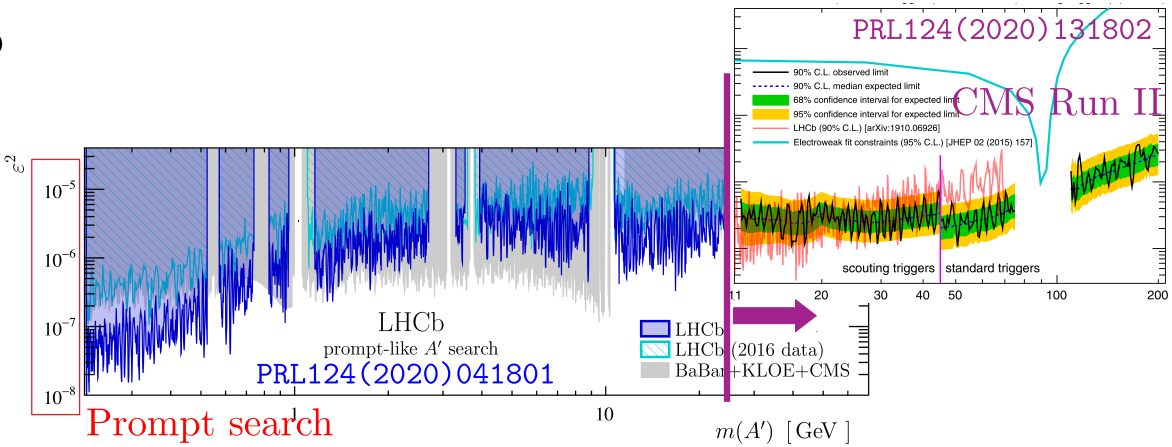
[PRL124(2020)041801]

- Low mass dark photon ($A' \to \ell^+\ell^-$): $\mu^+\mu^-$ easiest at LHCb



Run II onwards, high-level reco available in the trigger (Turbo stream), allowing for these searches



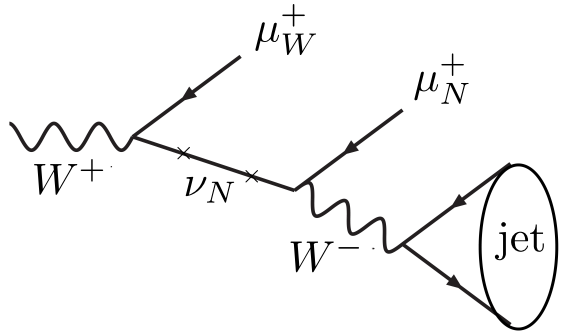


- Run 3 proposal: e^+e^- in with $D^* \to DA'$, $\pi^0, \eta \to \gamma A'$.

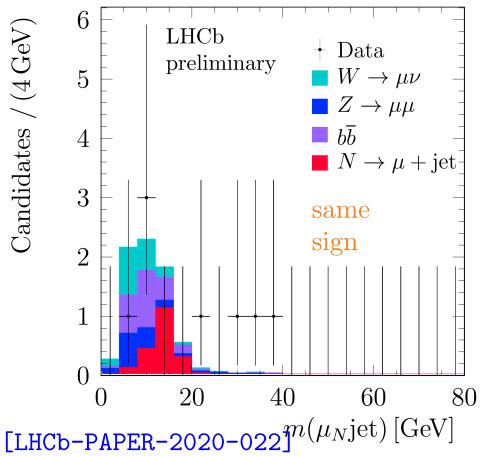
HNL IN $W^+ \to \mu^+\mu^\pm$JET

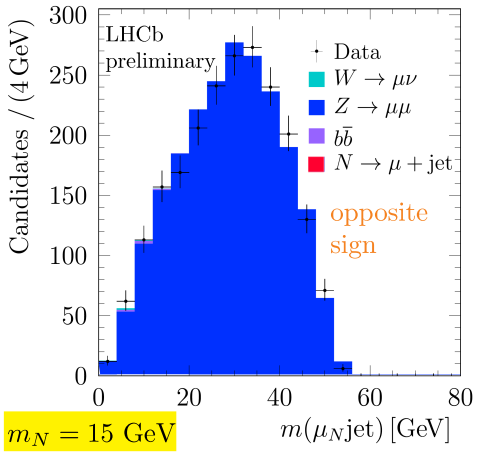
[LHCb−PAPER−2020−022]

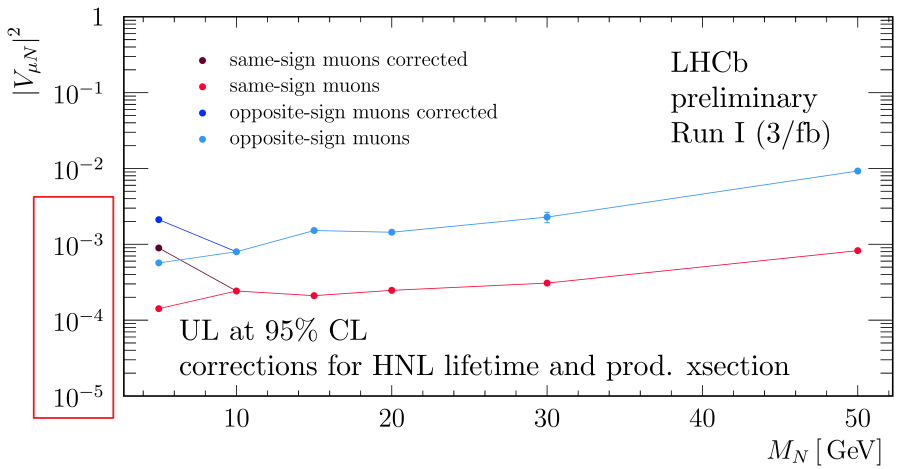
- Heavy right-handed ("sterile") neutrinos can solve DM, ν mass. Mixing w/ active ν ($|V_{\nu M}|$).
- Run I search of on-shell $W^\pm \to \mu^\pm N$. Prompt decay of HNL, and $m_N \in [5, 50]$ GeV.



- Both same-sign(LNV) and opp.-sign(LNC, 1^{st} time!) $\mu\mu$ probed.







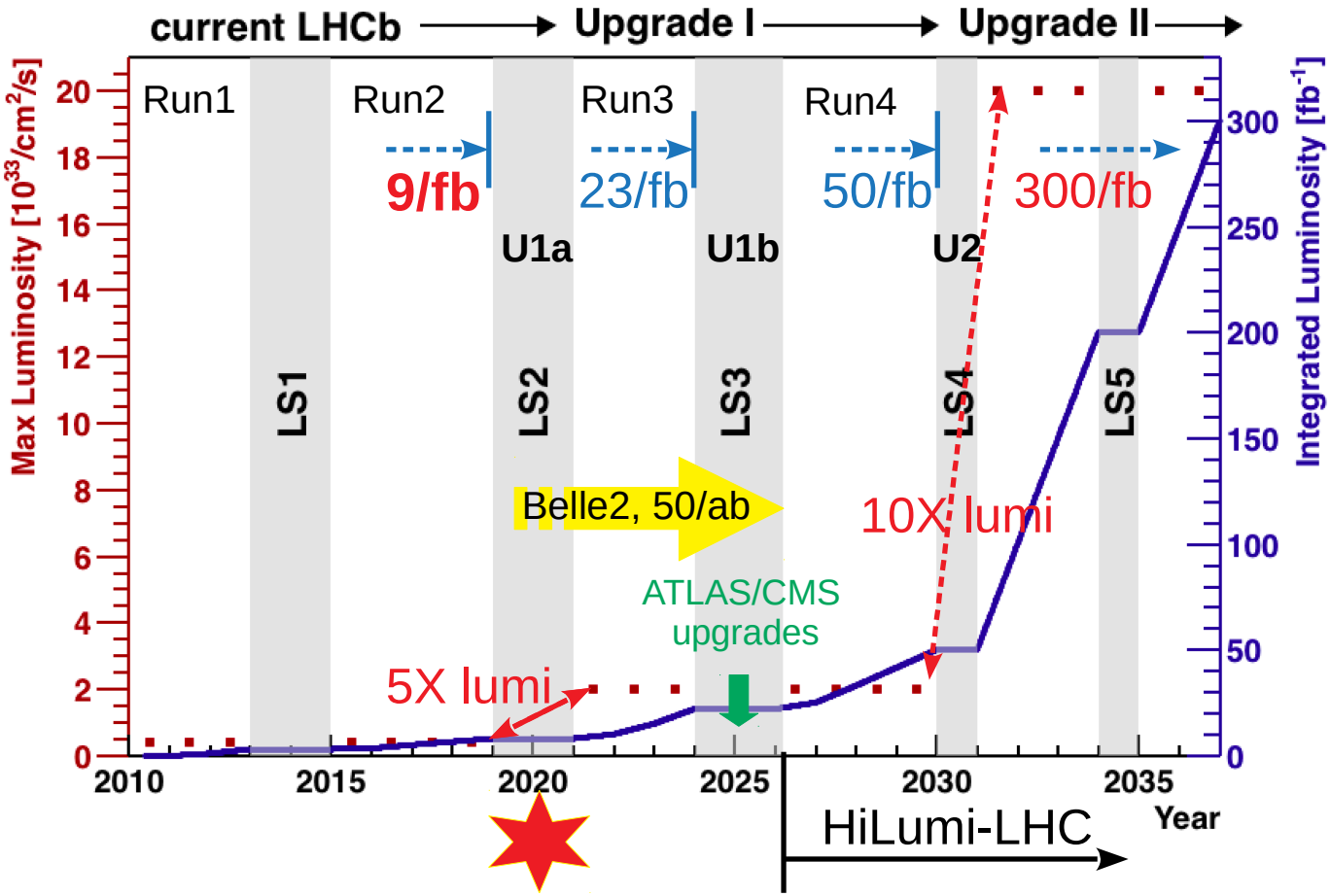
- Sensitivity still statistics-limited (compared to ATLAS/DELPHI limits). Can be competitive after the upgrade.


Looking ahead...

LHCb UPGRADES

[CERN-LHCC-2017-003
LHCB-PUB-2018-009]

- Aim to collect $\times 100$ data, improving upon 1-2 fb^{-1}/year.



- Staged upgrade towards 300 fb^{-1}
- Upgrade Ia(now)
- Entire detector R/O at 40MHz
- Versatile online s/w trigger

↪ [see Laurent's talk on Thu]

LHCb UPGRADES

[CERN-LHCC-2017-003 LHCB-PUB-2018-009]

- No departures from CKM picture yet, but 20% NP still allowed.

Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

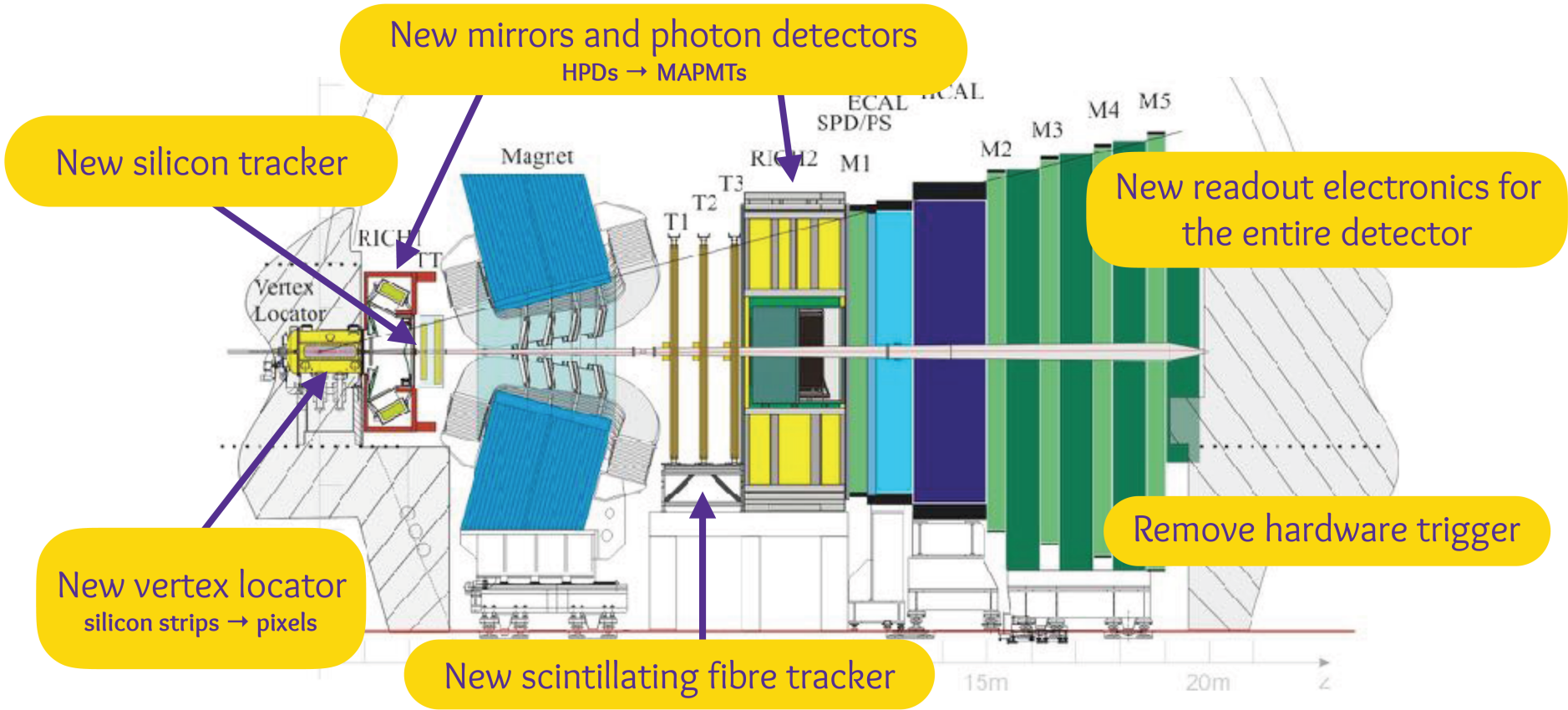
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K^0_S$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a^s_{sl}	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B^0_s, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B^0_s \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K^0_S\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

$> 5\sigma$ in PRL122(2019)211803

[Upgrade II Physics case document]

LHCb Upgrade Ia

- *An almost new detector for Run 3 in 2021.* Commisioning hit by COVID. Nevertheless, all sub-detectors progressing well.



- HLT w/ hybrid technology: HLT1 in GPU's, HLT2 in CPU's.

Summary

- Run I/II LHCb has been a fantastic success – core flavor physics, spectroscopy, dark sectors, heavy ions...
- Only way to increase data collection rate was to remove L0 hardware trigger (1 MHz bottleneck).
- Versatile software HLT seen the way out $\Rightarrow$ major uphaul of code-base for analysis flow as well.
- Updates with Run I+II data coming up for our theory colleagues.
- Looking forward to Run 3...

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Thank you!