LHCb: where color meets flavor

Flavored particles as lab to understand fundamental interactions

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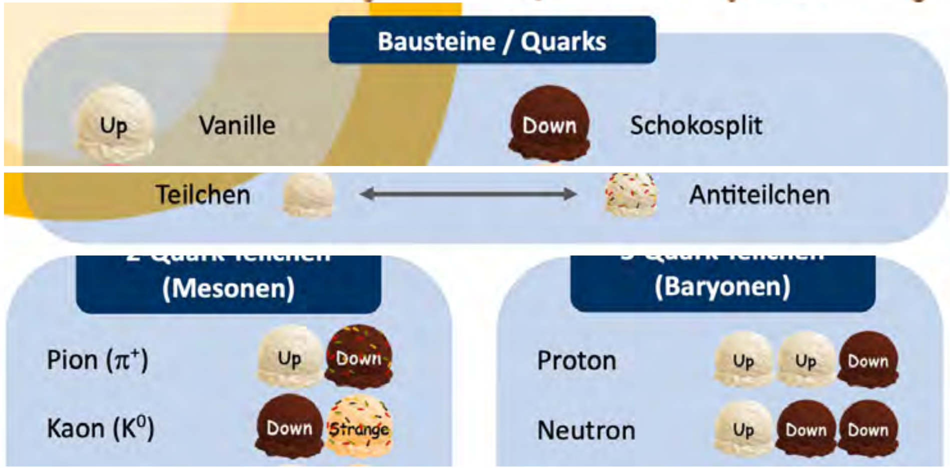
color meets flavor

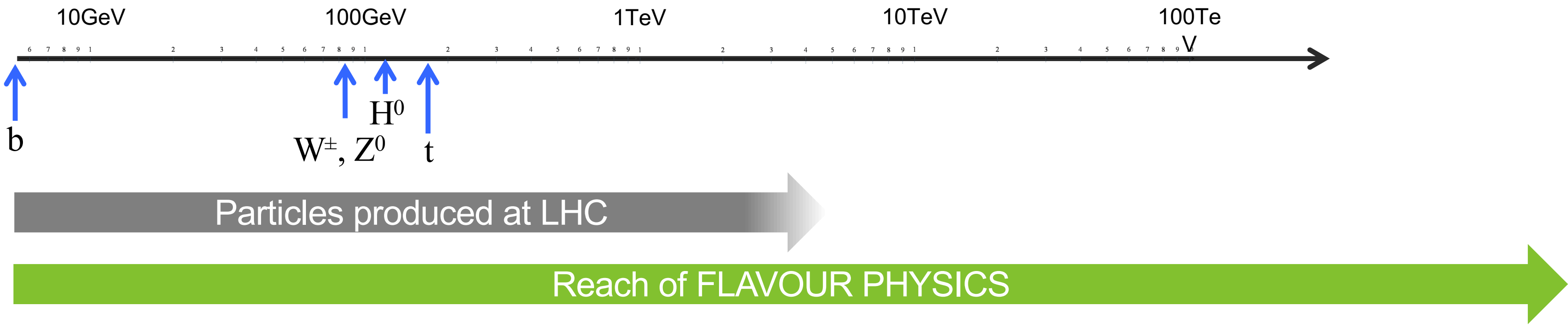
FSP LHCb
Erforschung von
Universum und Materie

Coined by Gell-mann and Fritsch on visit to ice cream parlour (Pasadena, 1971)
"Just as ice cream has both color and flavor so do quarks."

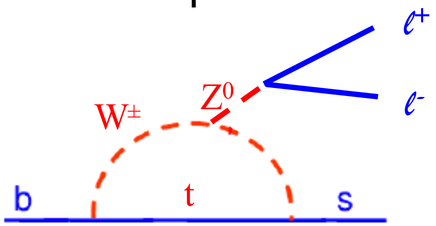


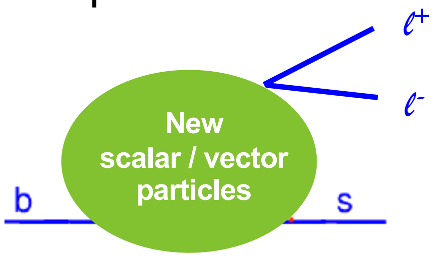
Some plots / drawings borrowed from Y. Amhis @ M60

Searches for New Physics in Flavour



Flavour physics: Search for new heavy particles
in precision measurements of quantum effects

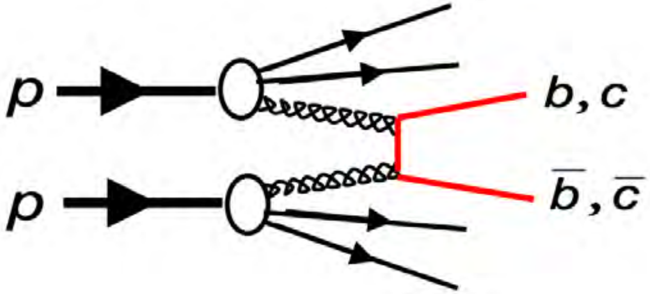


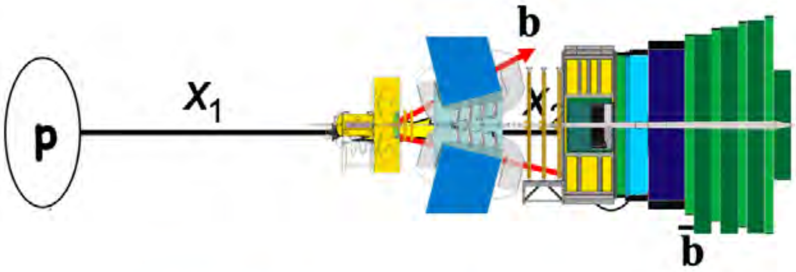


Flavor: Sensitive to new particles with masses of **100 – 10^7 TeV**
(but dependent on assumed couplings)

[ESPPU:1910.11775]

Flavor from proton collisions – forward physics





25% bb in accept ance

Facility	#B per year	Total #B
LHC (Run 1-3)	5×10^{13}	2×10^{14}
LHCb-U1	1×10^{12}	5×10^{12}
Belle 2	6×10^{9}	6×10^{11}
LHCb-U2	$2,5 \times 10^{13}$	$> 10^{14}$

Relevant: total #B times efficeincy (trigger!)

→ e^+e^- make up here

LHCb: a story in three generations

LHCb (original): Run 1
Forward beauty experiment concept established

LHCb (original): Run 2
Align and calibrate detector in quasi-real time, full detector reconstruction and pileup suppression in trigger

LHCb-U1: Run 3
Greatly improved tracker & PID granularity, 30 MHz detector readout & GPU trigger performing a near-full detector reconstruction

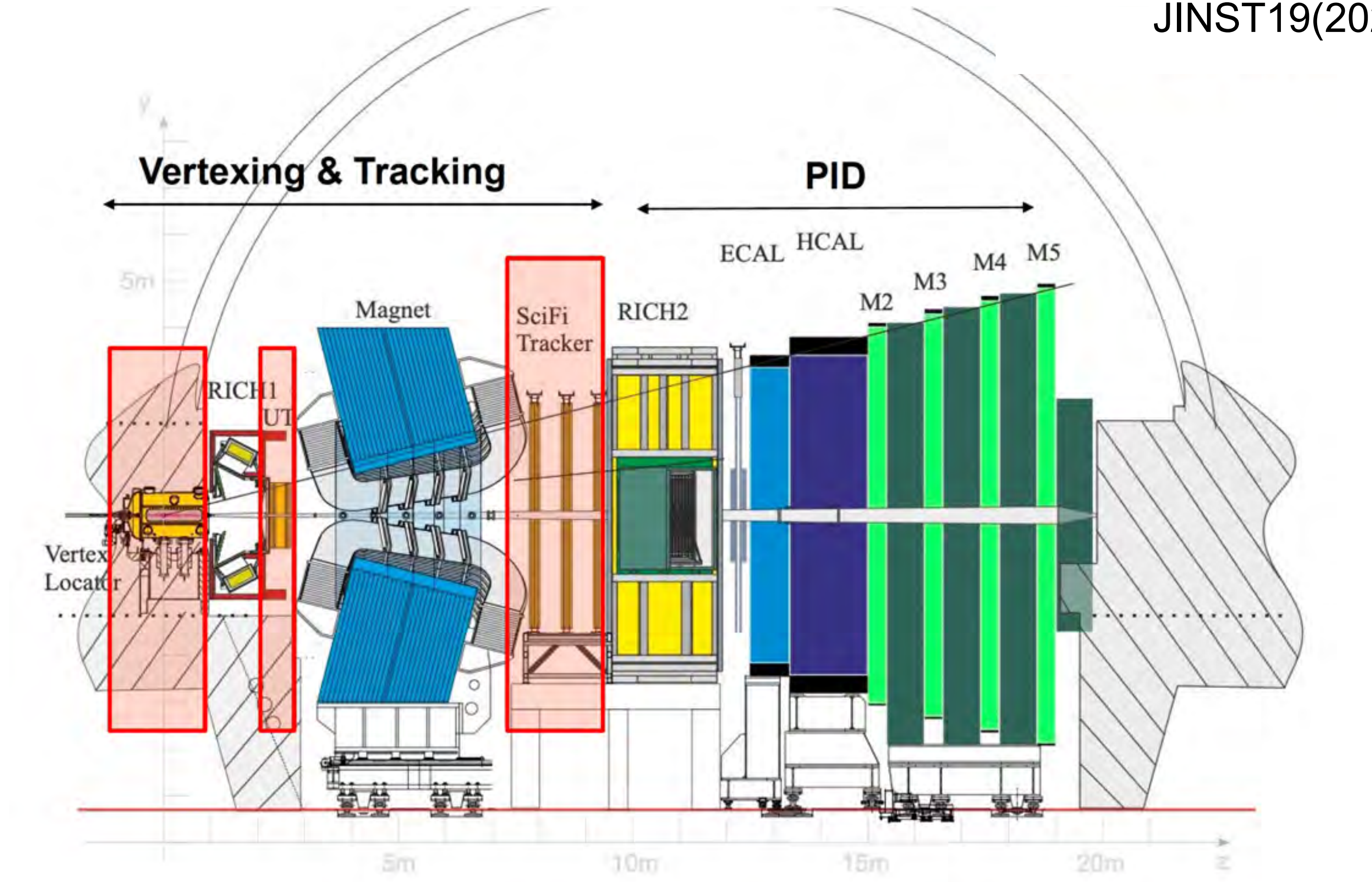
LHCb-U1b: Run 4
Enhance PID, explore enhanced readout boards

LHCb-U2: Run 5
Deploy 4D tracking, PID, and calorimetry + a highly granular pixel tracker to be processed by a heterogenous trigger

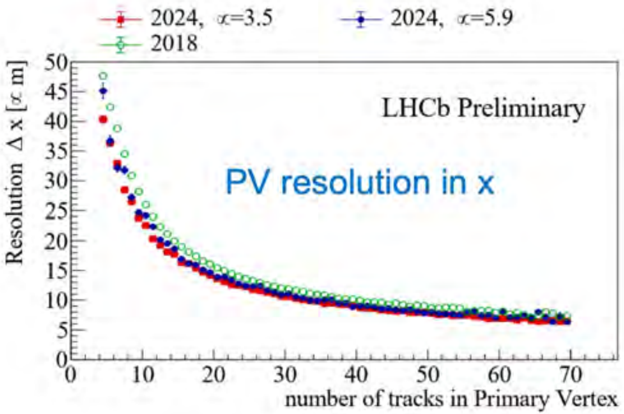
Inspiration for slide from Vava Gligorov

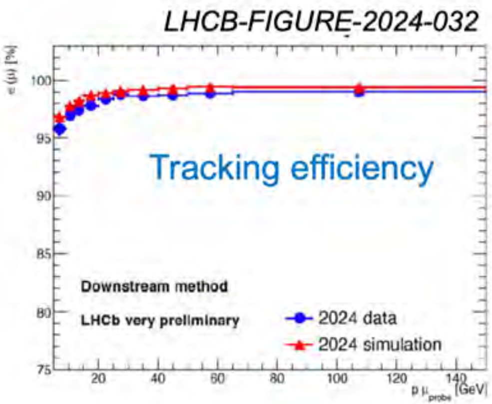
Re-built detector in Run 3

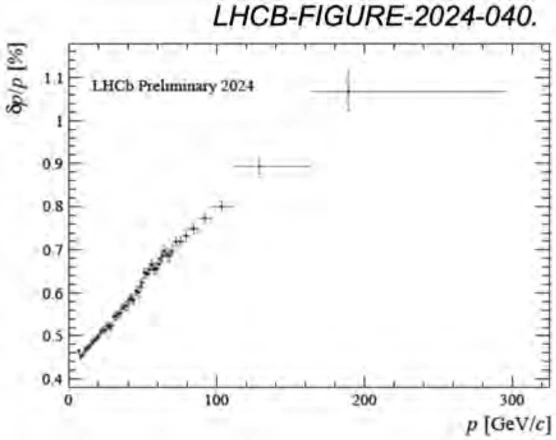
JINST19(2024)P05065

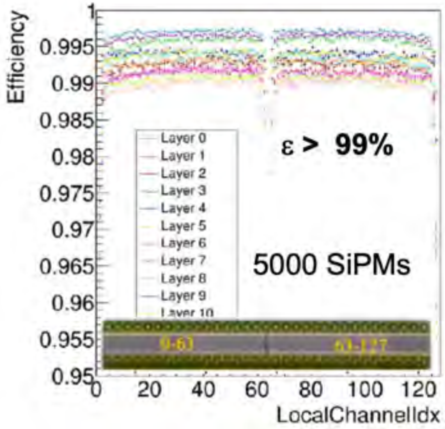


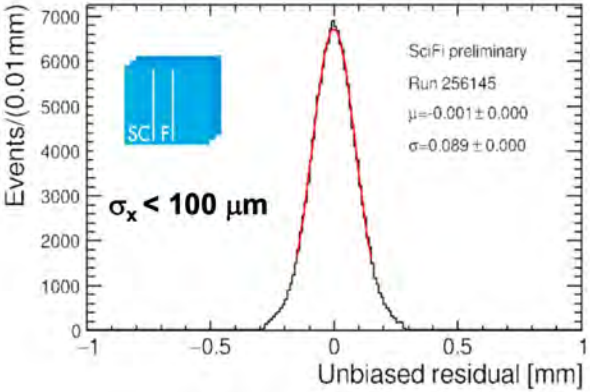
Run 3 status: lets only talk about 2024+

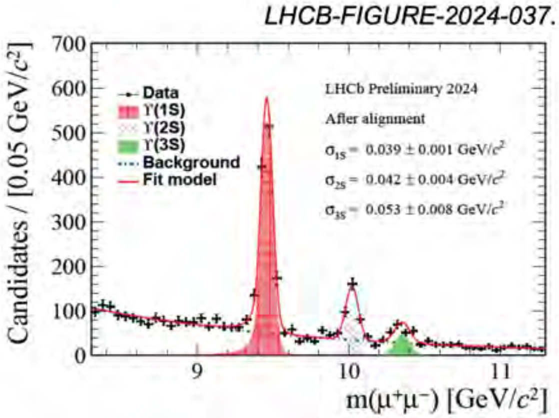




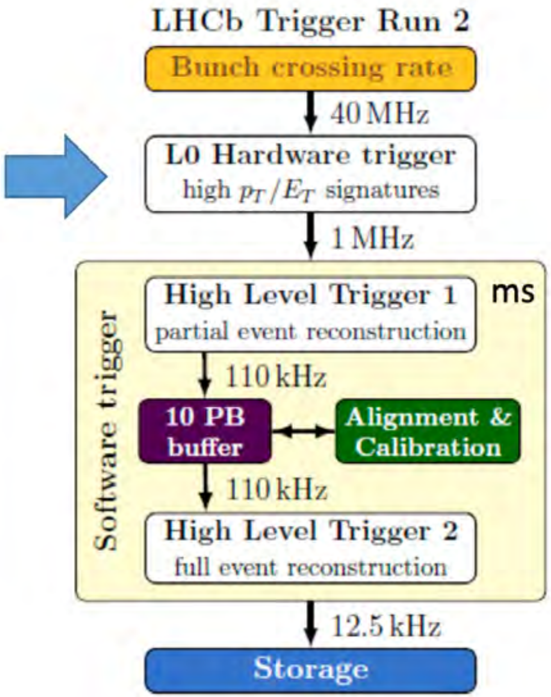




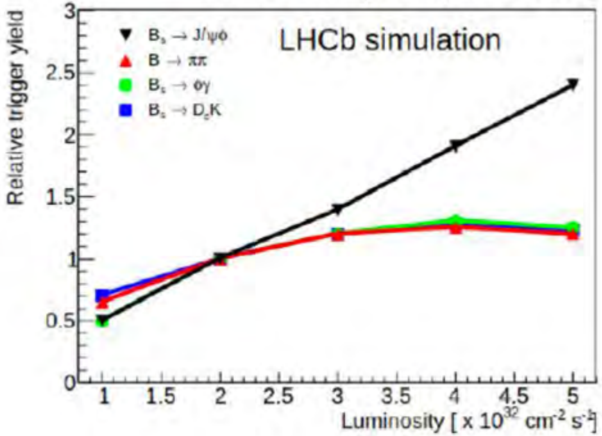




Trigger: LHCb-original



JINST 19 (2024) P05065



L0-Trigger: Bottleneck for hadronic decays

LHCb-U1: full software trigger

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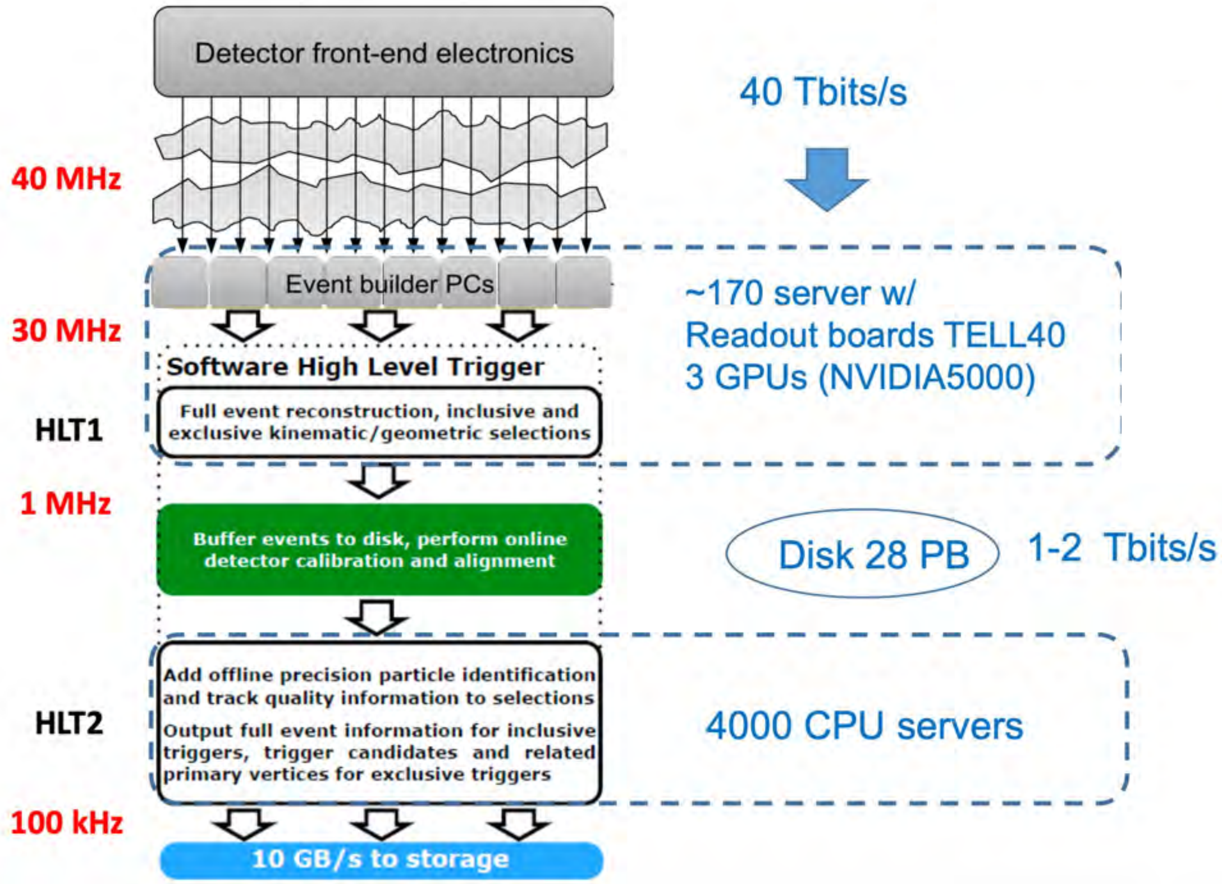
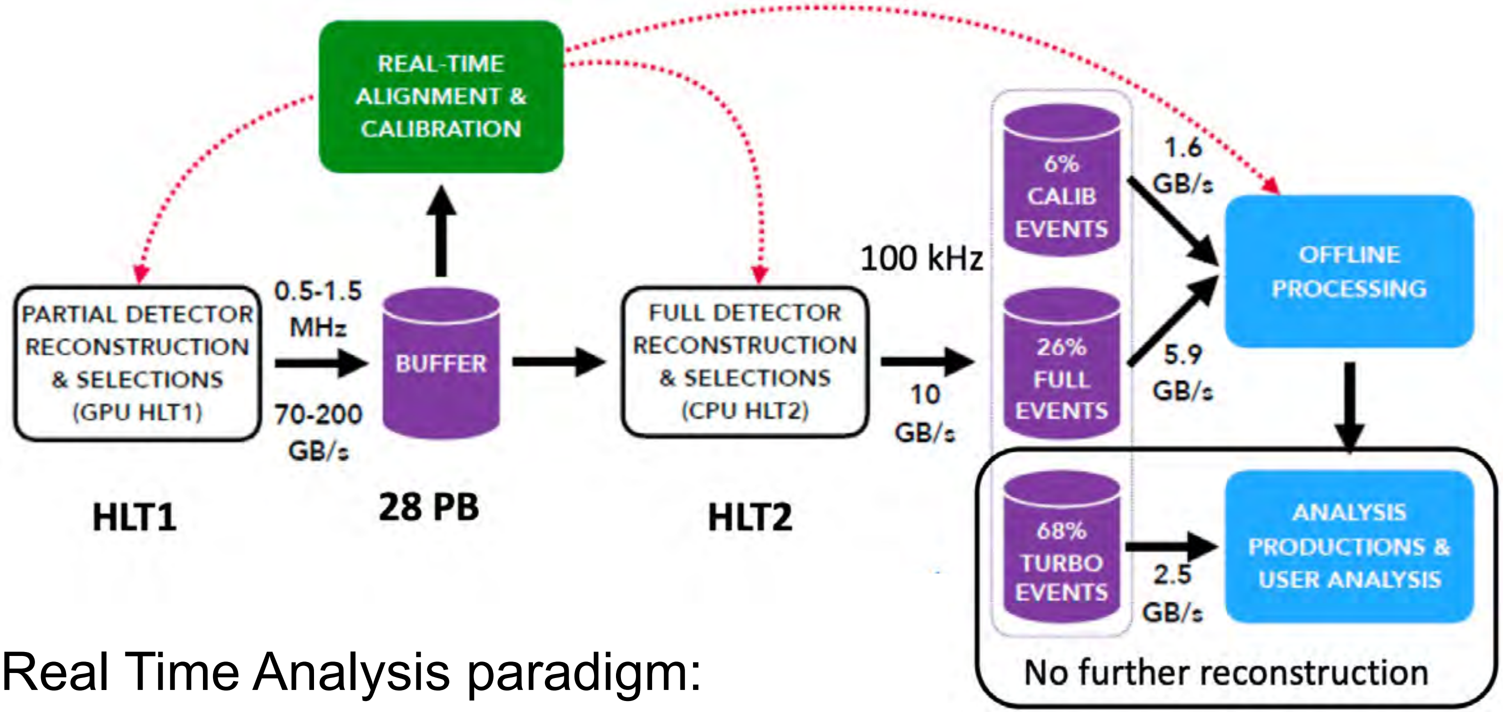


HEP novelty:

Triggerless readout and event reconstrution @ 40MHz

Real Time Analysis

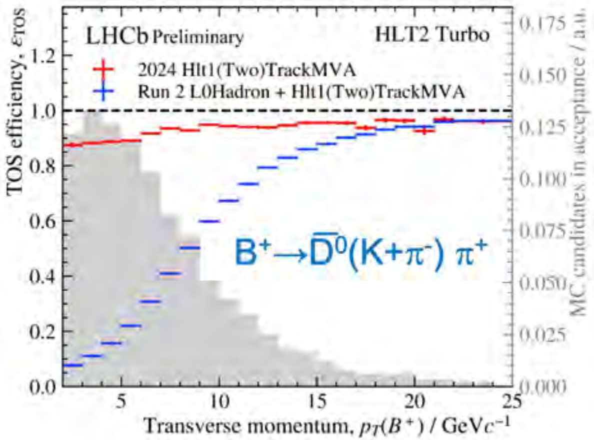
Data processing path

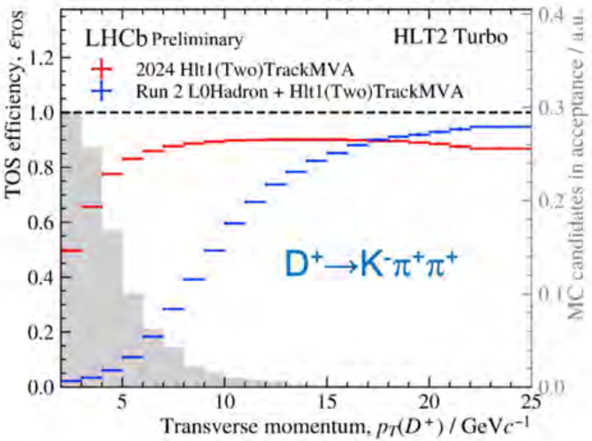


Real Time Analysis paradigm:
Almost ¾ of all events are saved with “only signal info”, not possible to re-reconstruct

.. and it does work ..

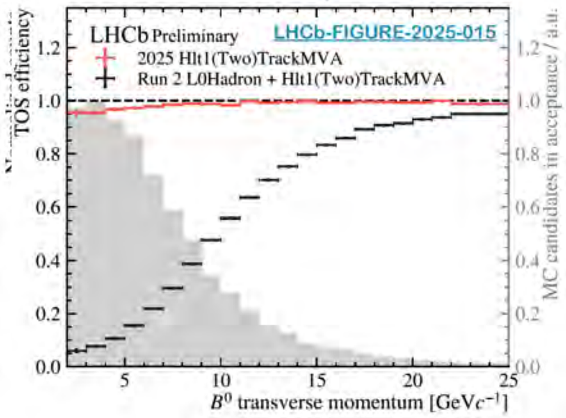
LHCb-FIGURE-2024-030

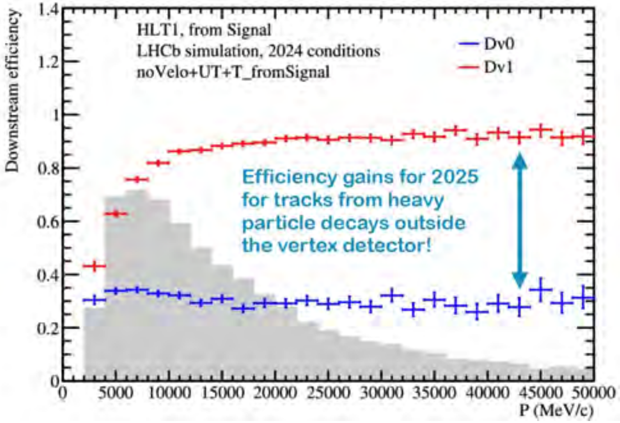




Trigger in Run 3:

Yield increase /fb
factor 2-3 hadronic b
facctor 2-4 hadronic c





2025 is again much better

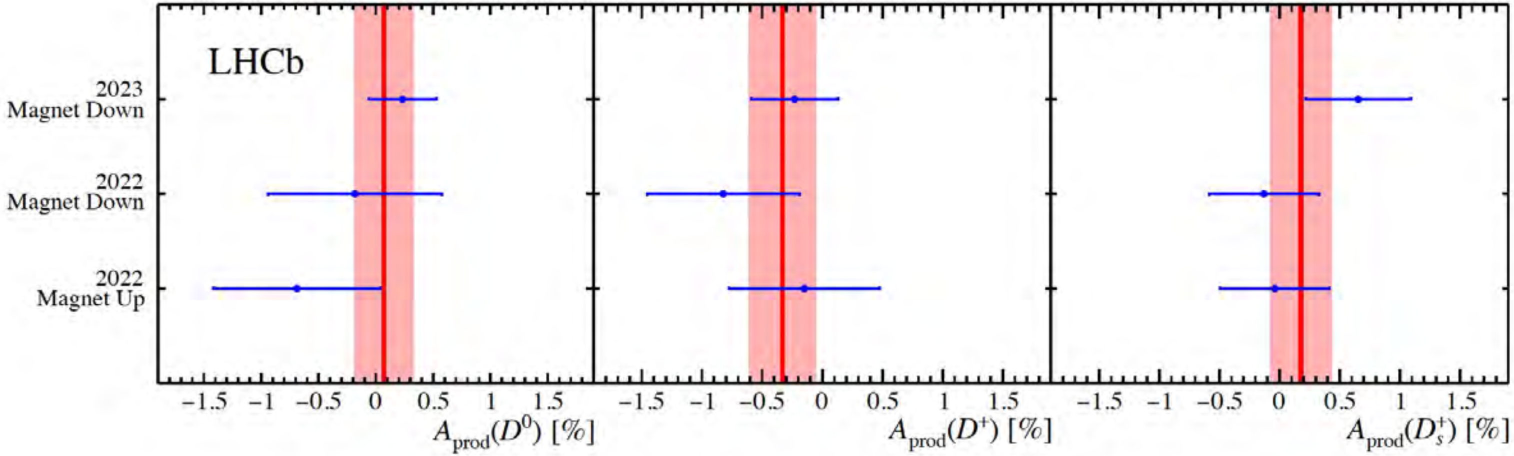
Reconstruct all tracks and
Kalman fit at 30 MHz

Also improved Calo &
muon PID

Run 3: Charm production asymmetries

JHEP 10 (2025) 050

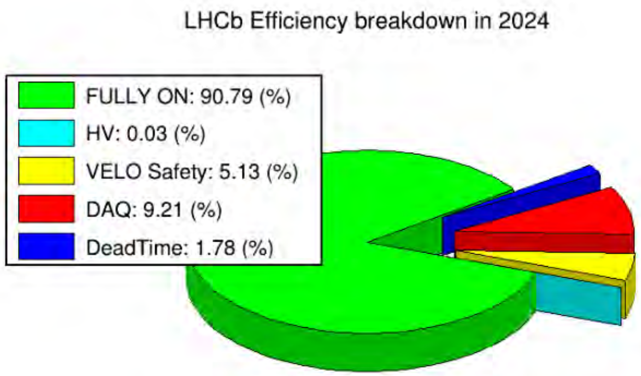
Important to understand possible asymmetries of detector for CPV

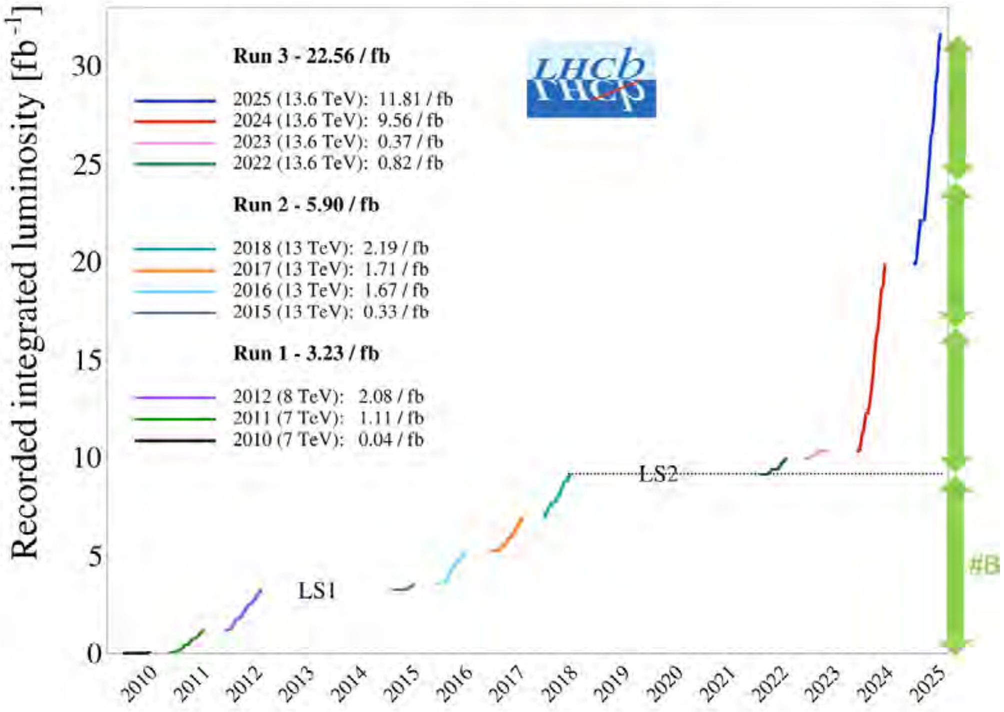


$$A_{\rm prod}(D^0) = (0.07 \pm 0.26\,({\rm stat}) \pm 0.10\,({\rm syst}))\%,$$
$$A_{\rm prod}(D^+) = (-0.33 \pm 0.29\,({\rm stat}) \pm 0.14\,({\rm syst}))\%,$$
$$A_{\rm prod}(D_s^+) = (0.18 \pm 0.26\,({\rm stat}) \pm 0.08\,({\rm syst}))\%.$$

Compatible with TH → asymmetries of new detector are under control

Run 3 finally became a success for LHCb



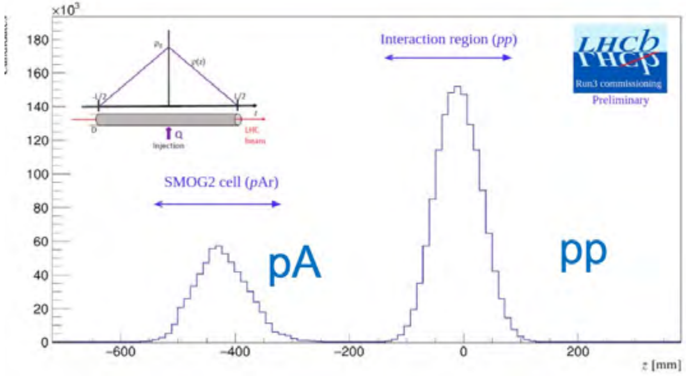


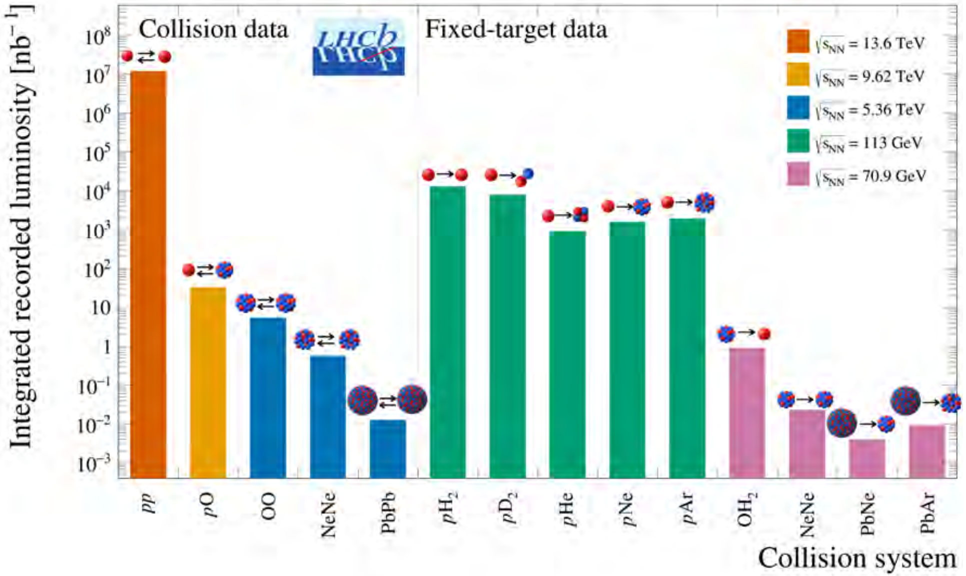
Lumionosity recorded (#B) increased by factor 4

Trigger: additonal factor 1 (muon) – 4 (hadron multibody) on top

LHCb – also a fixed target experiment

- SMOG2:
  Insert different gases into the vertex tank (beam vacuum) at ~400 mm up-stream of the pp interaction point.





LHCb physics program

Quark Flavor

CKM Metrology:
B-mixing
CP violation
β, γ, ϕ_s

Rare b,c-decay:
$b \to sll$
$B_s \to \mu\mu$

Charm:
Mixing and CPV

Semi-leptonic B:
$|V_{cb}|, |V_{ub}|$
R(D), R(D*)

Production

Heavy flavor production in pp
QCD

Electroweak:
W, Z, $\sin^2\theta_w$

Fixed Target
Astro-QCD

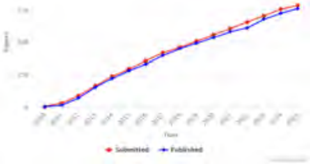
Heavy Ion
Astro-QCD

Hadron Physics

Spectroscopy

Tetra & Penta-Quarks,
Exotics

>800 papers

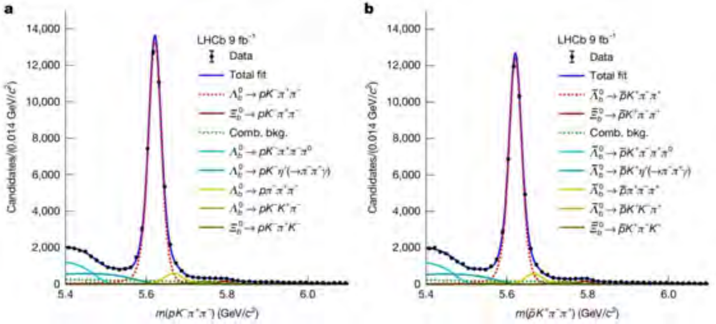


- I will not (try to) go through all these beautiful physics areas & results
- Instead, I will give my subjective view on two questions:
  - What are we at LHCb up to these days?
  - Are there any signs for New Physics at LHCb?
- **Focus on areas with special timeliness**

U. Uwer, Bormio 25

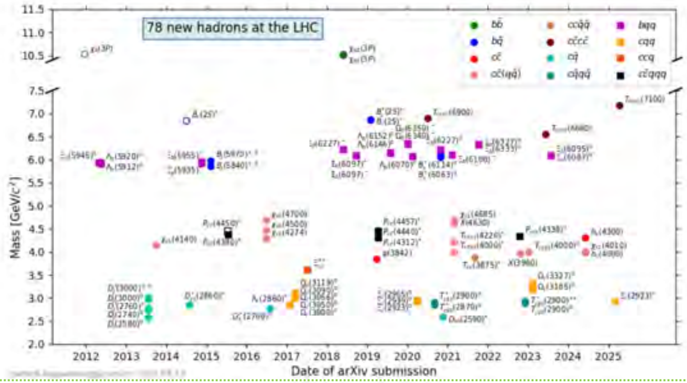
Some selected highlights

Precision studies of unexplored territory



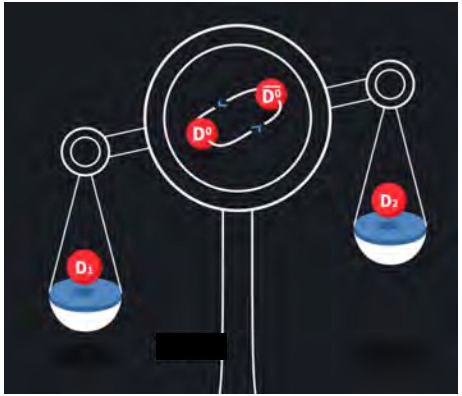
2025:
CPV in baryons discovered

Spectroscopy program



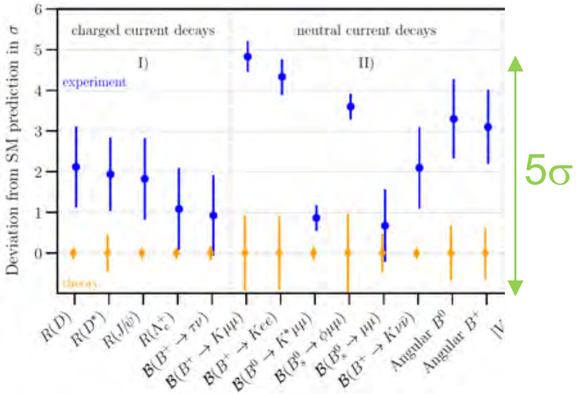
24 new exotic hadrons measured

Charm physics



CPV discovered 2019, still not clear if
SM or not ?

Flavor anomalies



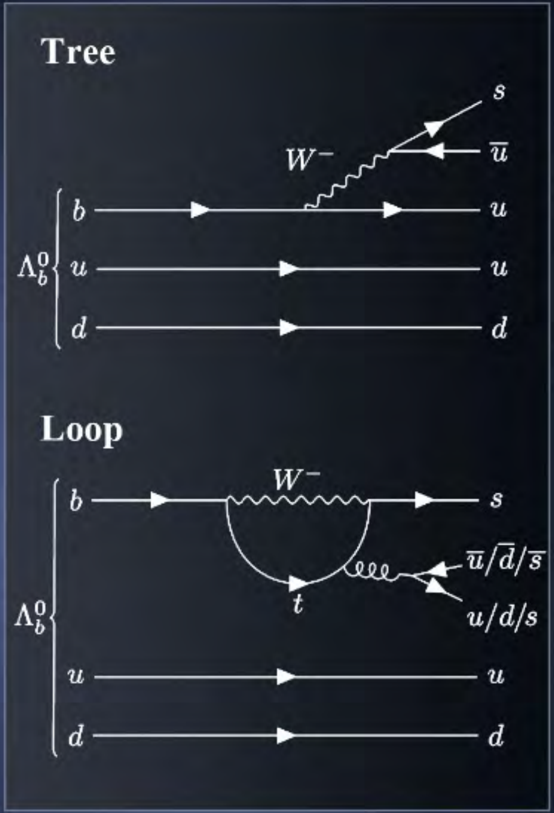
TH issues or BSM?

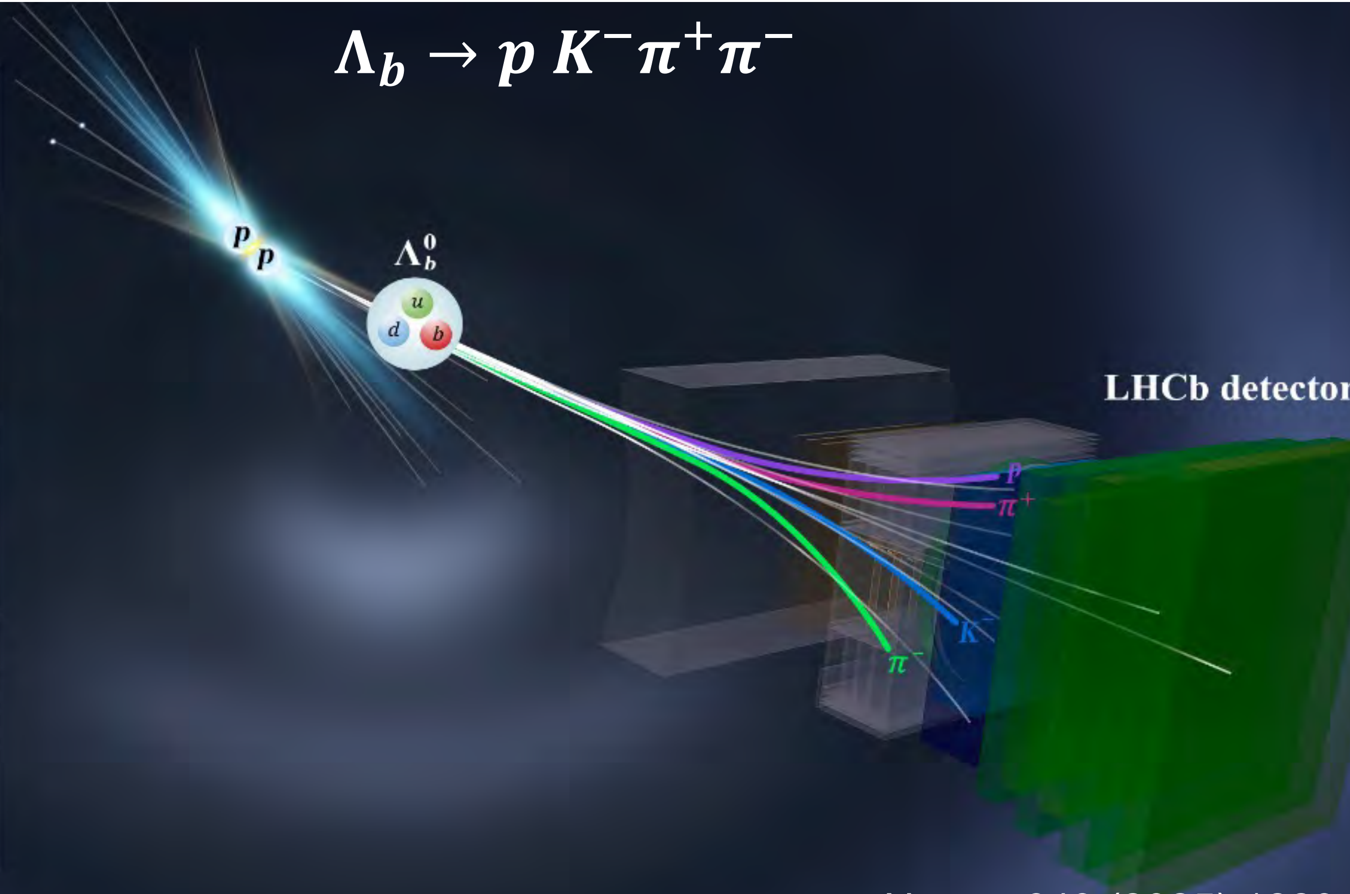
Precision studies of unexplored territory

- **2025: discovery of CPV in baryons → SM or not ?**
- b→d ll system becomes accessible → new or like b→s ?
- Rare charm: new Null-Tests for BSM searches
- …

First observation of CP violation in baryons

$$\Lambda_b \to p\, K^- \pi^+ \pi^-$$



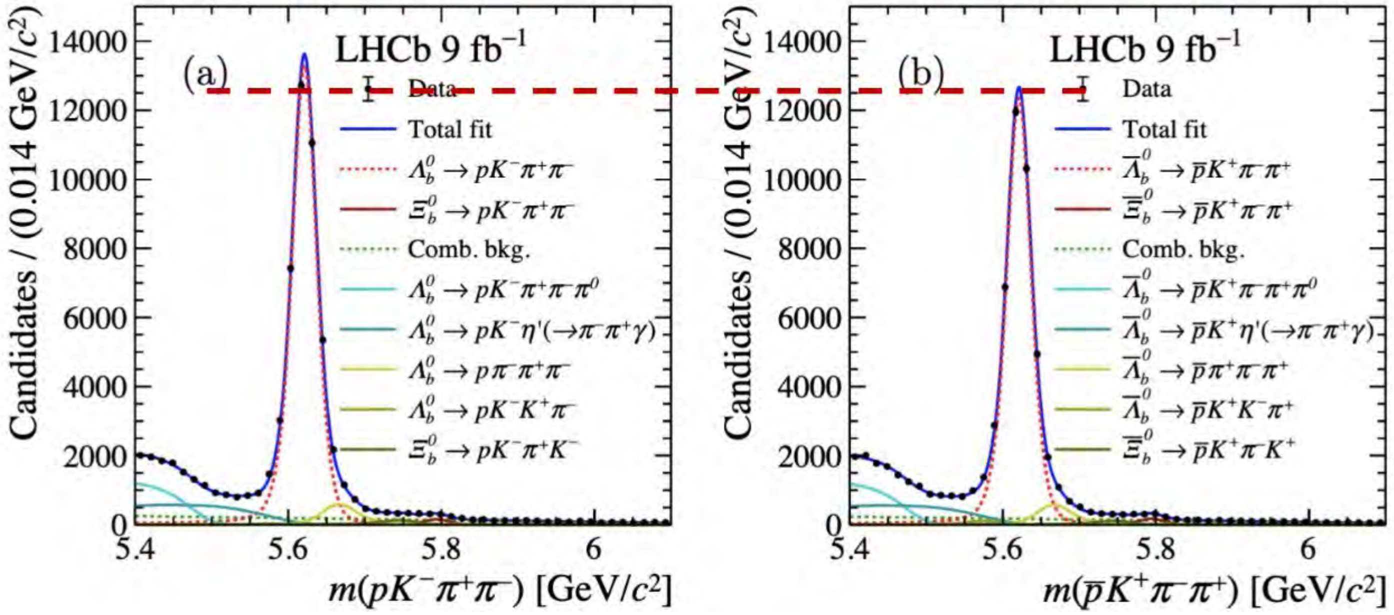


Nature 643 (2025) 1223

CP Violation in Baryons observed

Nature 643 (2025) 1223

$\Lambda_b^0 \to pK^-\pi^+\pi^-$ $\qquad$ $\overline{\Lambda}_b^0 \to \bar{p}K^+\pi^-\pi^+$



- First observation of CPV in baryonic decays (5.2σ)

$$A_{CP} = (\,2.45 \pm 0.46 \pm 0.01\,)\%$$

Fingerprint: Complex analysis of resonances

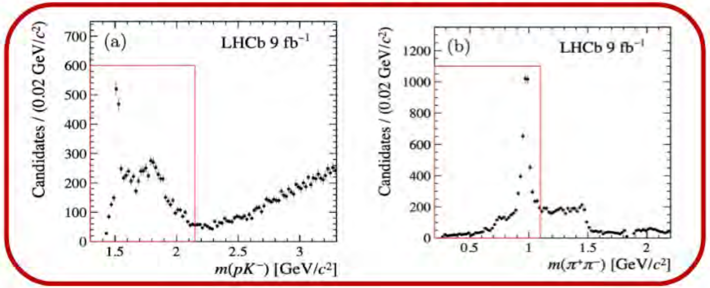
Nature 643 (2025) 1223

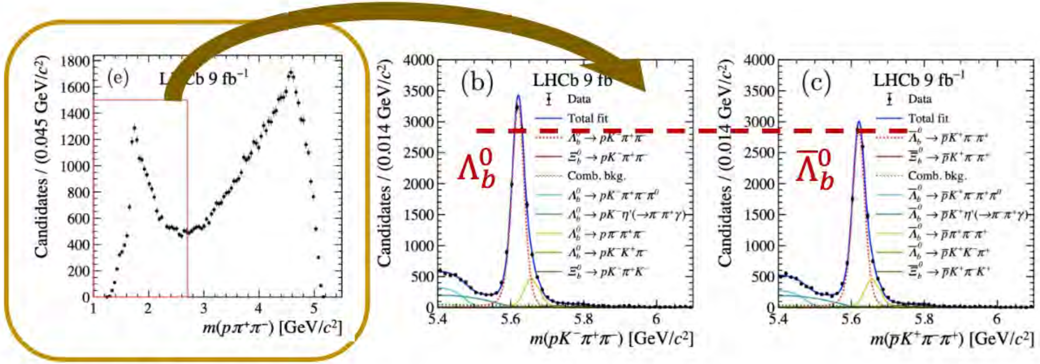
- Interference between resonance states induces CPV depending detailed decay topology

- Local A_{CP} reaching 6σ
  - Most significant CPV in N^+ resonances region

Decay topology	Mass region (GeV/c^2)	$\mathcal{A}_{CP}$	
$\Lambda_b^0 \to R(pK^-)R(\pi^+\pi^-)$	$m_{pK^-} < 2.2$ $m_{\pi^+\pi^-} < 1.1$	$(5.3 \pm 1.3 \pm 0.2)\%$	**4σ**
$\Lambda_b^0 \to R(p\pi^-)R(K^-\pi^+)$	$m_{p\pi^-} < 1.7$ $0.8 < m_{\pi^+K^-} < 1.0$ or $1.1 < m_{\pi^+K^-} < 1.6$	$(2.7 \pm 0.8 \pm 0.1)\%$	
$\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$	$m_{p\pi^+\pi^-} < 2.7$	$(5.4 \pm 0.9 \pm 0.1)\%$	**6σ**
$\Lambda_b^0 \to R(K^-\pi^+\pi^-)p$	$m_{K^-\pi^+\pi^-} < 2.0$	$(2.0 \pm 1.2 \pm 0.3)\%$	

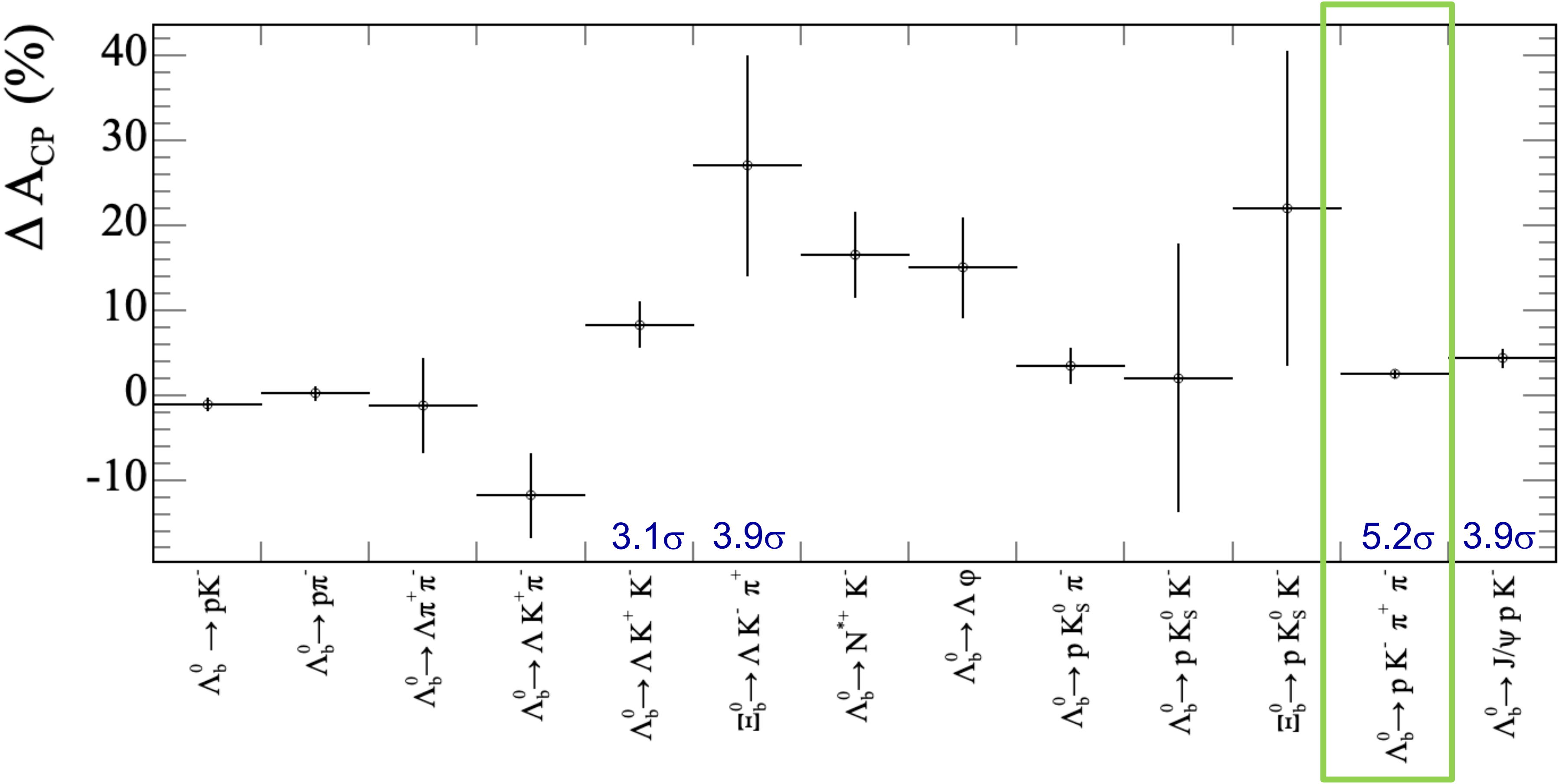
❖ Λ resonances ❖ $f_0(980)$ resonances





❖ N^+ resonances

New territory: Baryon CPV

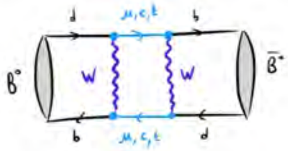


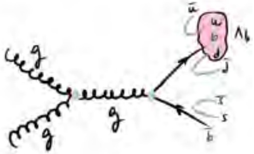
Uncharted territory

- LHCb: unique environment to study CP violation in baryon decays
  - Numerous new results from Run 1 & 2 data:
    - First observation of CPV in baryonic decays!
    - Many first observations of decays modes, evidences of CPV in some
  - Run 3: improved hadronic trigger can be game changer

- A major step forward in understanding CP violation
  - While generally smaller than in mesons, baryonic CPV can be significant under specific conditions
  - Complex dynamics of baryon decays call for innovative analysis techniques
  - New and wide area to make precision tests opens up

History of CP violation





__1956__
Parity violation
T. D. Lee,
C. N. Yang,
C. S. Wu *et al.*

__1963__
Cabibbo Mixing
N. Cabibbo

__1964__
Strange mesons:
***CP* violation in K^0**
decays
J. W. Cronin,
V. L. Fitch *et al.*

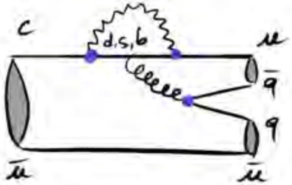
__1973__
The CKM matrix
M. Kobayashi,
T. Maskawa

__2001__
Beauty mesons:
***CP* violation in B^0**
decays
BaBar and Belle
collaborations

__2019__
Charm mesons:
***CP* violation in D^0**
decays
LHCb collaboration

__2025__
Beauty baryons:
***CP* violation in Λ_b^0**
decays
LHCb collaboration

TODAY



Drawings borrowed from Y. Amhis @ M60

CP violation in charm

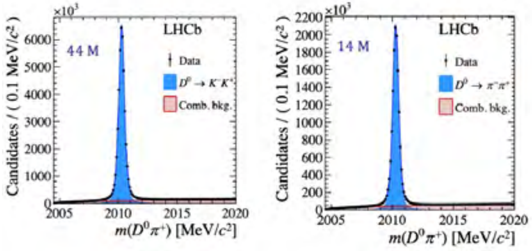
- CPV discovered 2019,
  still not clear if SM or not ?

CP violation in charm

In the SM there is very little room for CPV in the charm system → powerful null tests

The strength of the LHC

$\sigma(c\bar{c}) \sim 20 \times \sigma(b\bar{b})$



Charm CPV discovered "at"
Moriond EW 2019

First observation of CP violation in Charm !

The question is if this can be accommodated within the SM or is a sign of NP?

Direct CPV state of the art

- **2019:** First observation of **direct CPV** in *D0→h+h*

$$\Delta A_{CP} = A_{CP}(D^0 \to K^- K^+) - A_{CP}(D^0 \to \pi^- \pi^+) = (-15.4 \pm 2.9) \times 10^{-4}$$

- *Comparison with theory*
  - *Before 2019: "everything above 10^{-4} is a smoking gun for NP"*
  - *Now: predictions range from below 10^{-4} to the measured values*

→ A lot to measure and discover in this field!

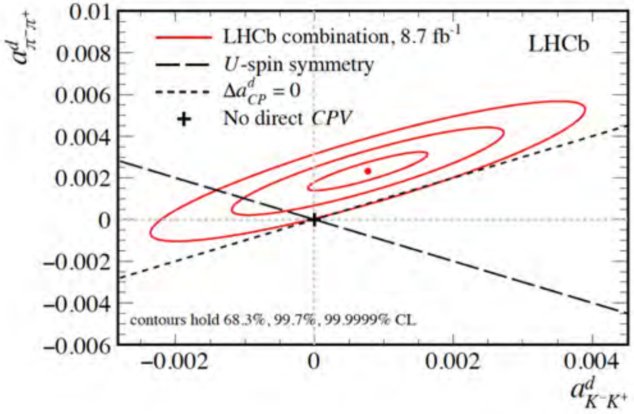
Precise fingerprint

PRL131(2023) 091802

- **2022:** CPV mainly coming from $D^0 \to \pi^- \pi^+$ decays

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

with $\rho(a^d_{KK}, a^d_{\pi\pi}) = 88\%$

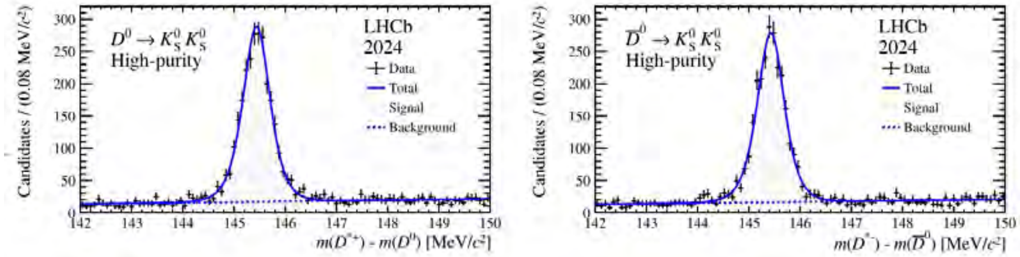


- Significant program to clarify picture
  - Precision measurement of CPV and mixing in various charm decays
  - Also hadronic parameters, e.g. from BESIII give important inputs

Example: CPV in $D^0 \to K_S K_S$

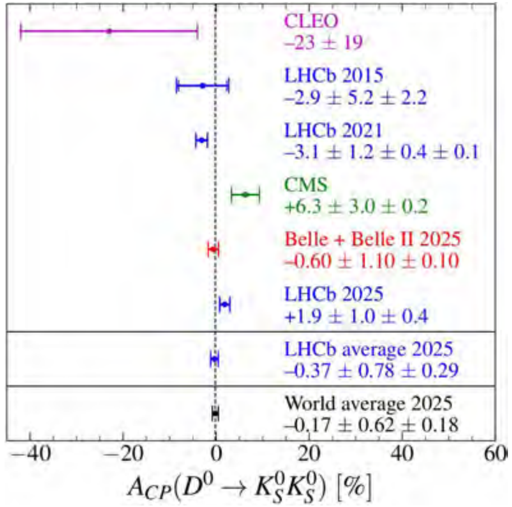
arXiv:2510.14732

- Predictions:
  - A_{CP} could be as large as 1%
  - Other models predict $A_{CP}(K_S K_S) = 0.35 * A_{CP}(\pi^-\pi^+) \sim 10^{-4}$
- Measurement with Run 3 data
  - Better than Run 2 precision with just few months of Run 3 data

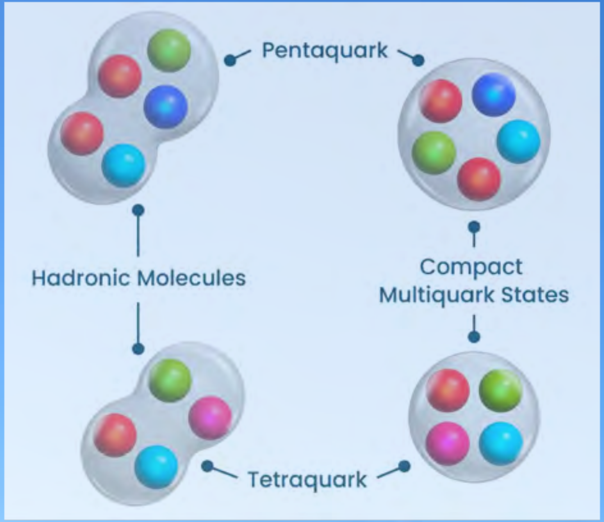


- Result: $A_{CP} = (1.86 \pm 1.04 \pm 0.41)\%$
  - Compatible with no CPV
  - Marginal agreement with previous LHCb results

Comparison of results



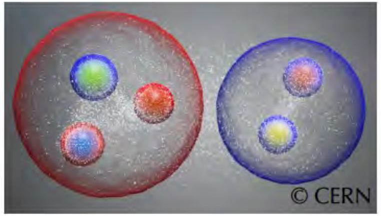
Spectroscopy program



A look at the strong interaction

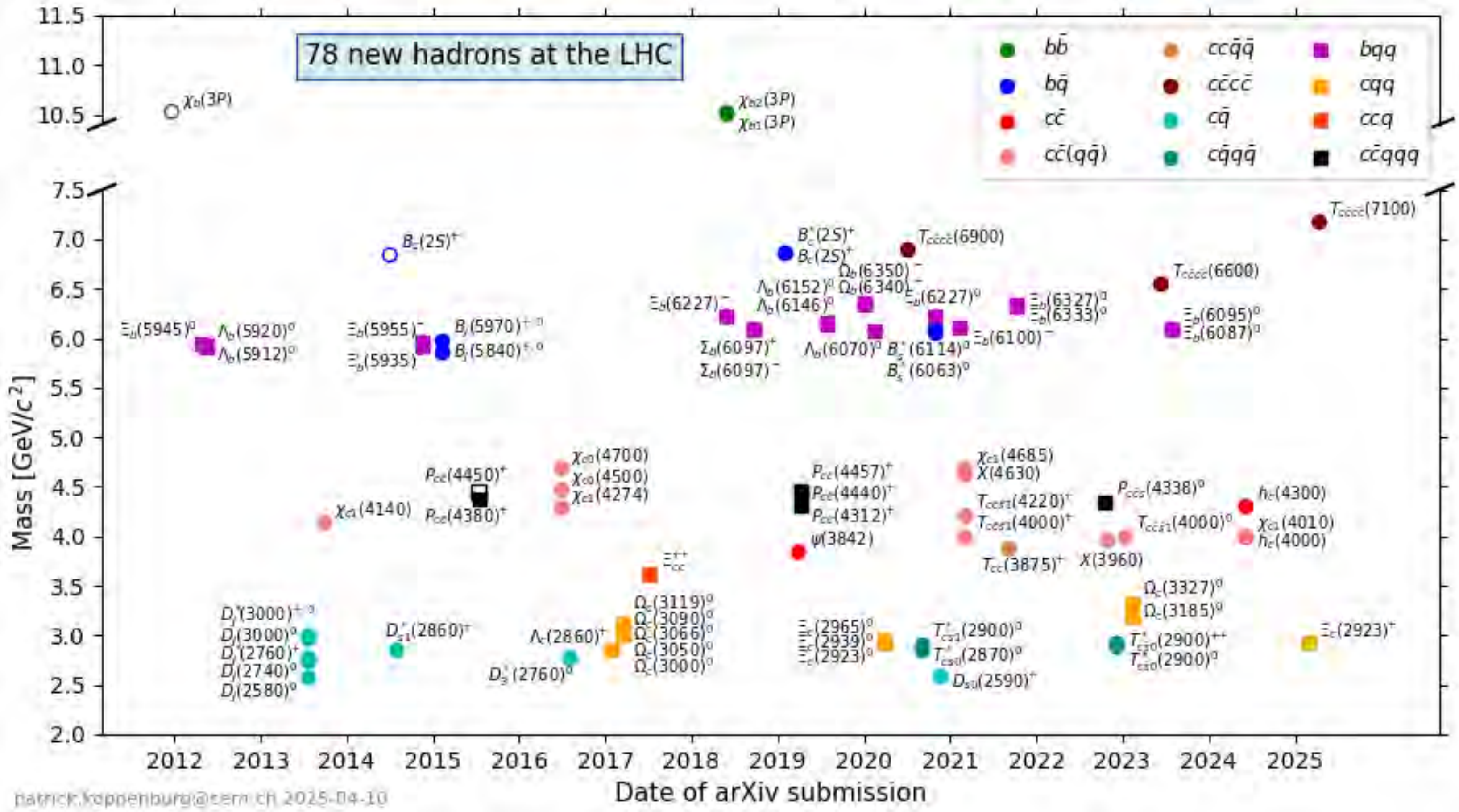
- **Strong Interaction (QCD)** describes interaction of quarks and gluons
  - QCD predicts a **hadron spectrum**, but non-perturbative regime
- **Quark Model** classifies hadrons according to their valence quarks
  - 1. **Conventional: meson or baryon**

  - 2. **Exotic states: tetraquark , pentaquark , glueball, …**



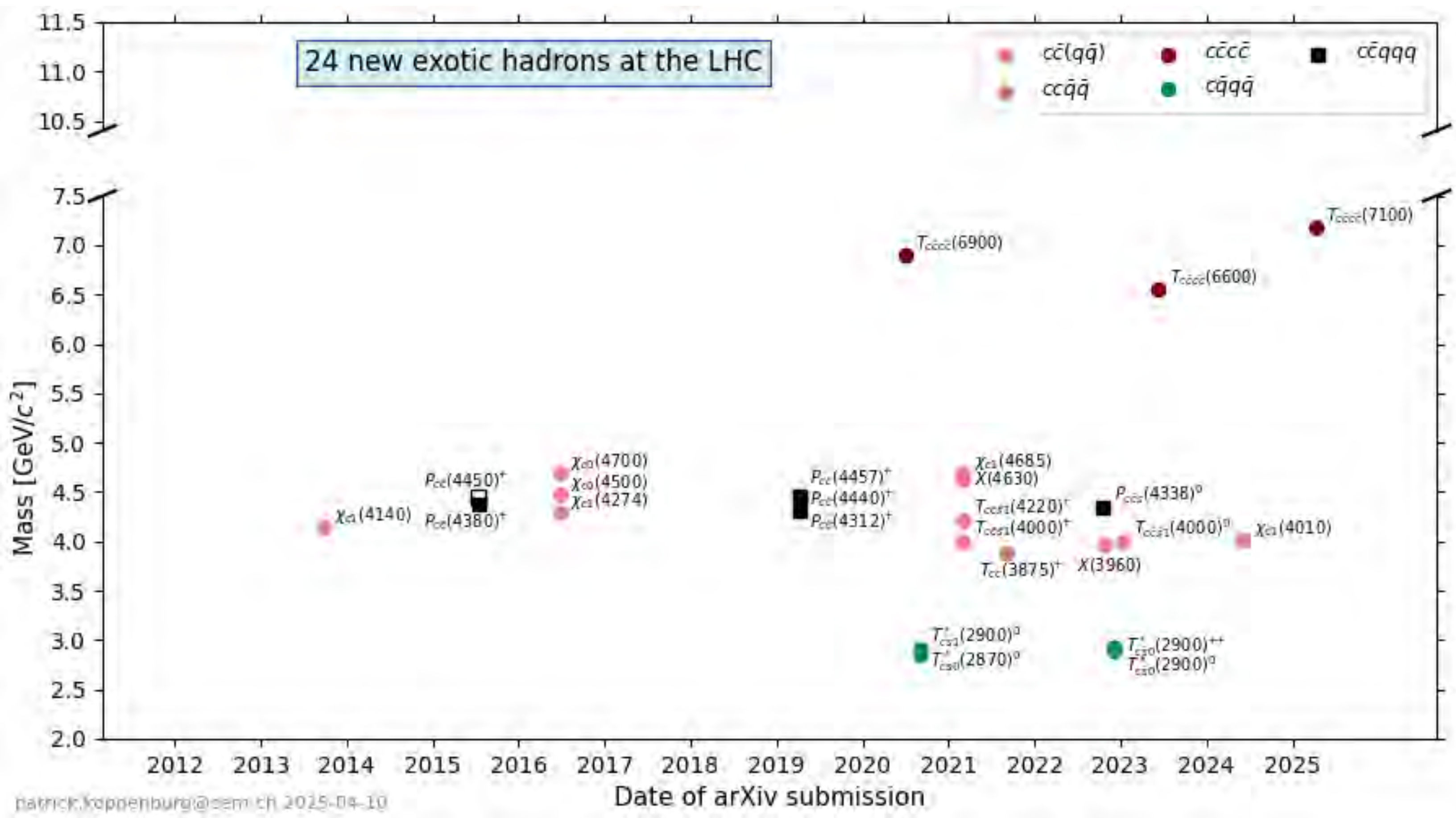
- **Exotic states offer a beautiful lab to study QCD**

A fantastic lab to understand QCD



70 out of 79 discovered by LHCb

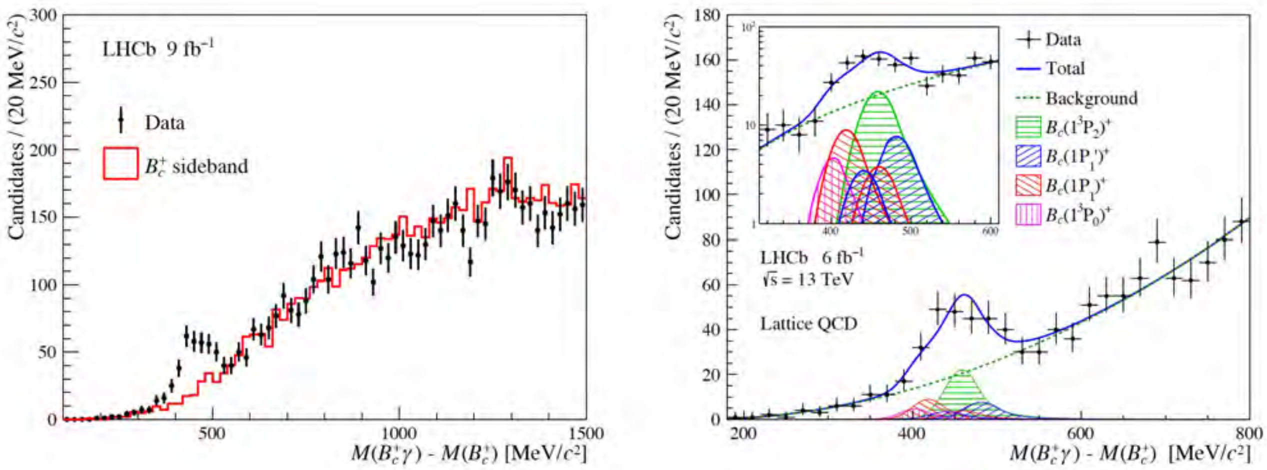
A fantastic lab to understand QCD



Only one recent highlight: New B^+_c states

PRL135(2025)231902

- B_c^+ system: Heavy quarkonium: ideal to probe QCD both TH & EXP
  - Unique features to extract information on both QCD dynamics and weak interactions
  - Challenge: $N(J/\psi) : N(\Upsilon(1S)) : N(B_c^+) = 100\text{k} : 0.4\text{k} : 1$ @ LHCb
- Recent highlight: Observation of orbitally excited B^+_c states

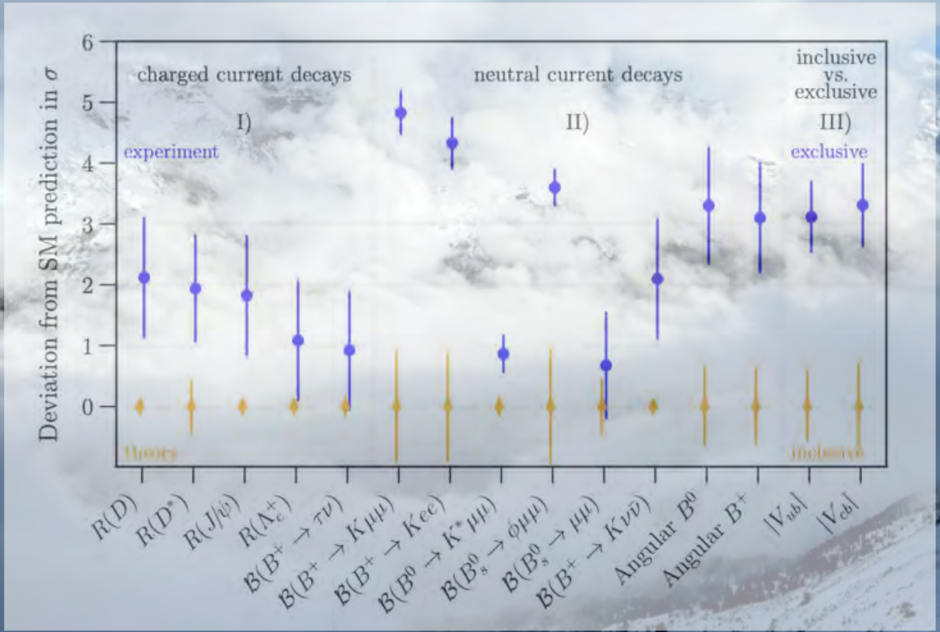


Structure confirmed with > 7σ

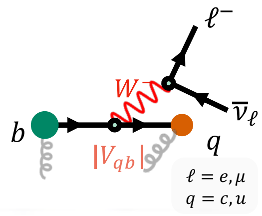
Expected origin: superposition of multiple decays: $B_c(1P)^+ \rightarrow B_c^{*+}\gamma$

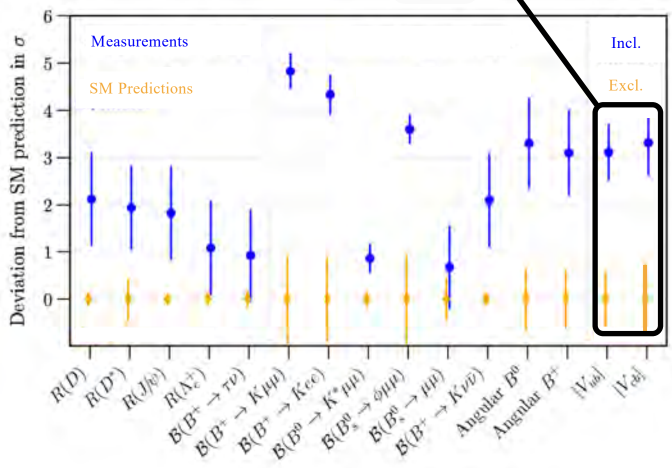
- Larger datasets and angular analyses needed to understand system

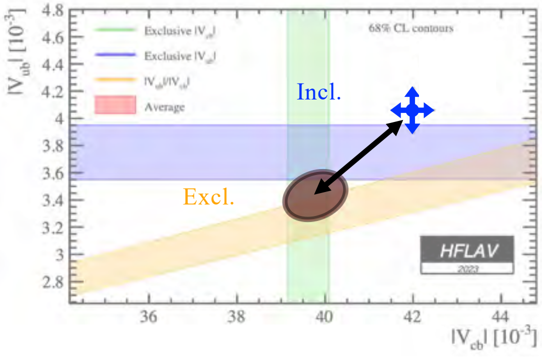
Flavor anomalies

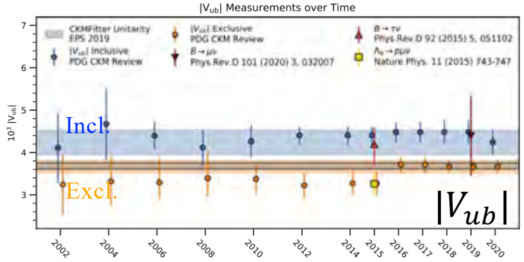


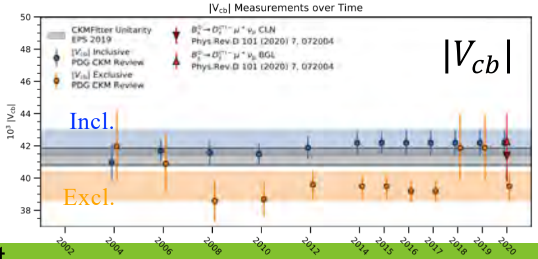
Flavor anomalies: Inclusive vs. exclusive



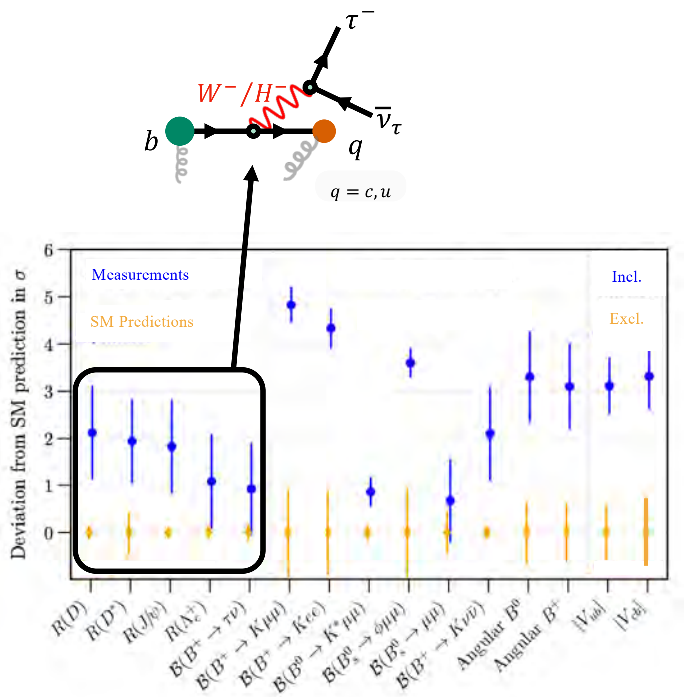


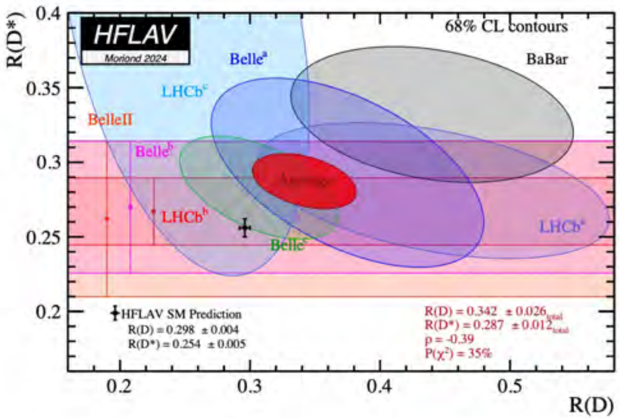




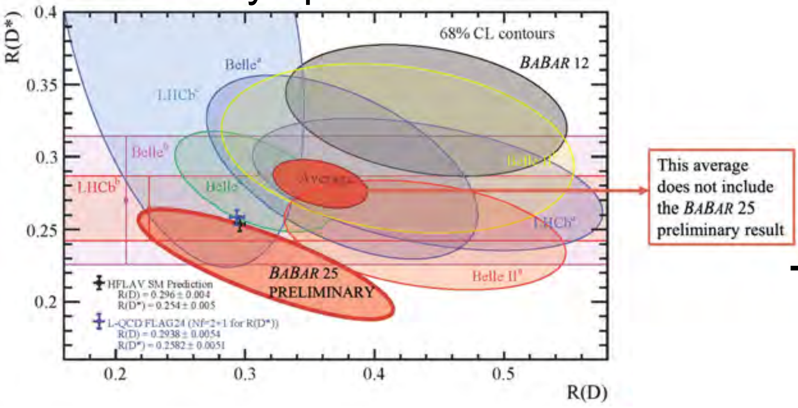


Flavor anomalies: Charged currents



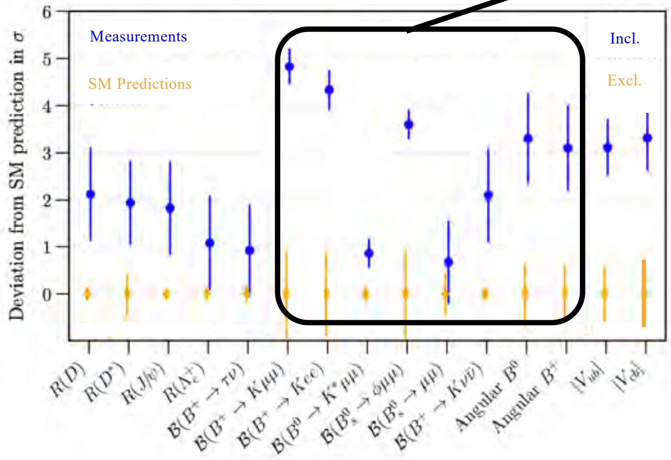


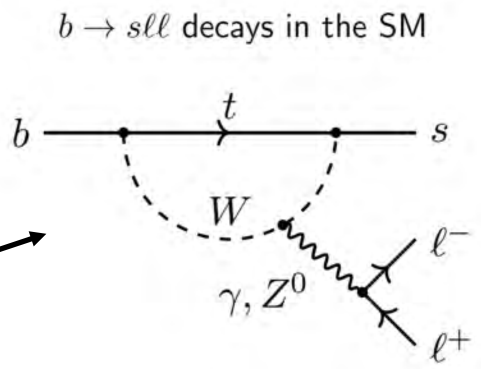
Preliminary update from Babar

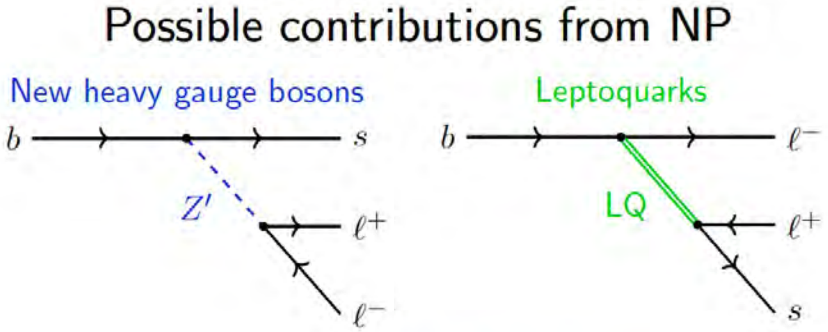


Hitlin, Dec25, Fermilab workshop

Flavor anomalies: $b \to s\,\ell^+\ell^-$

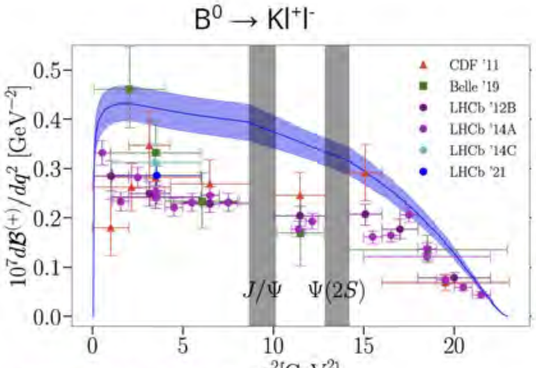




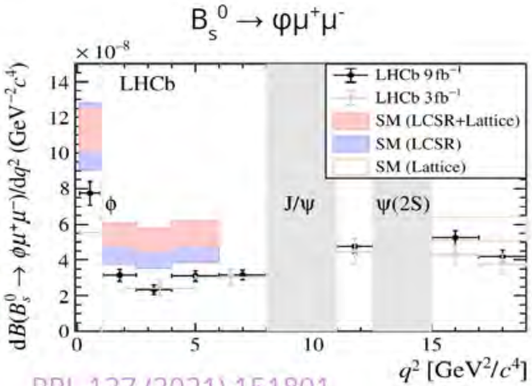


Flavor anomalies: $b \to s\, \ell^+ \ell^-$

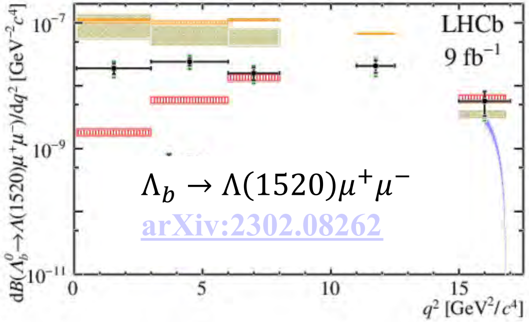
- *Hints for deviations wrt SM in b → sμ+μ- BR and angular observables*
- *A lot of interest due to coherence and combined significance*

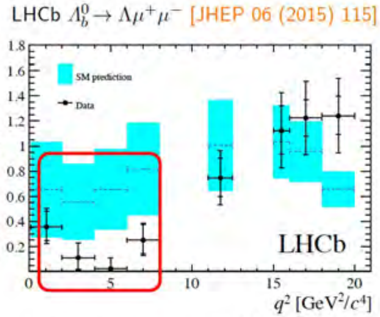


PRD.107.014511



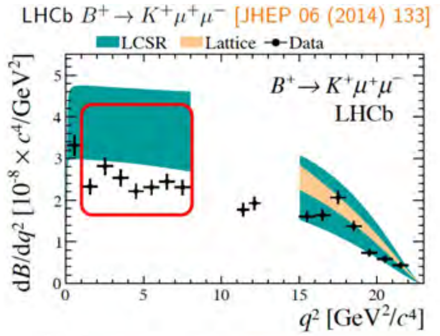
PRL 127 (2021) 151801

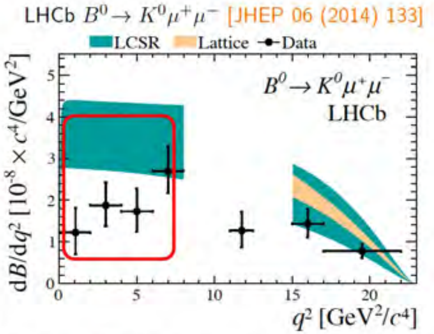




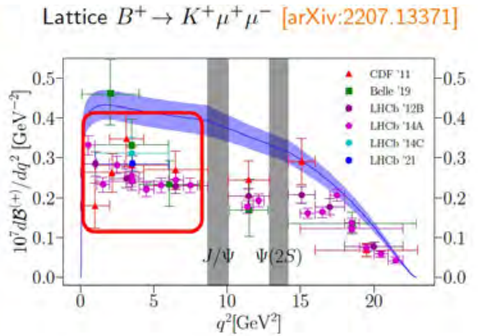
$b \rightarrow s\, \ell^+\ell^-$ branching fraction measurements

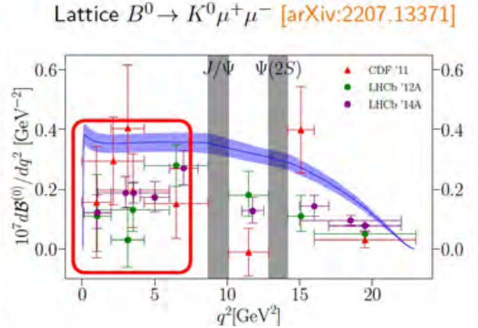
- Recent developments on non-local corrections [JHEP 09 (2022) 133] and new results from Lattice QCD [HPQCD, arXiv:2207.13371]





TH developments

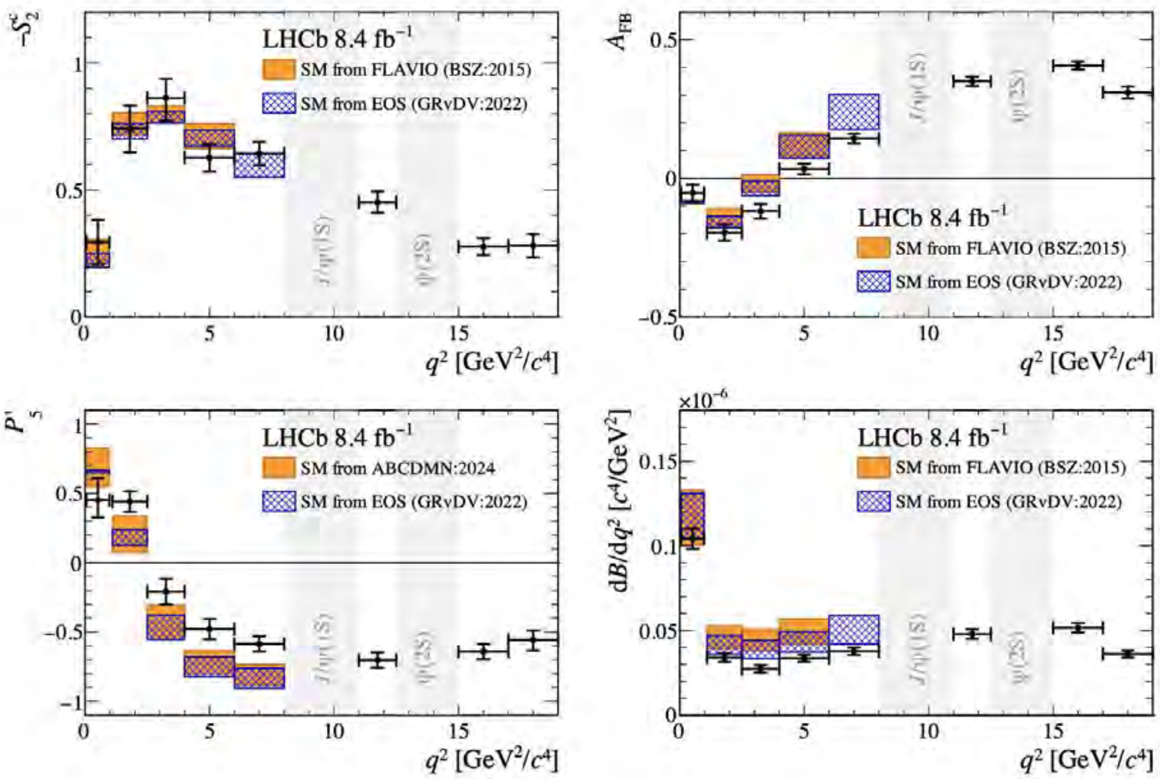




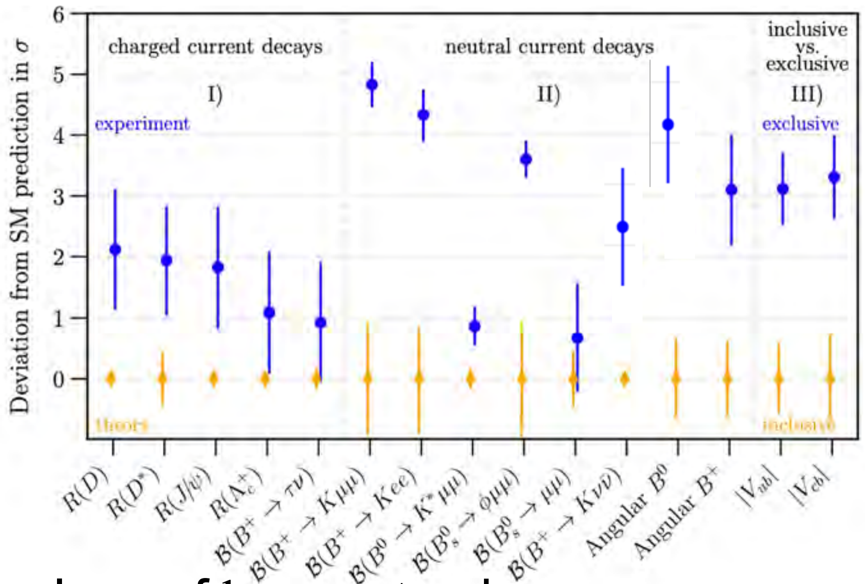
New analysis: $B^0 \to K^{*0} \mu^+\mu^-$

2512.18053

- *Comprehensive analysis of full Run 1+2 data*
- *5-dimensional fit to full set of angular observables and BR*
- *Results: local tension increased*
  - *P'_5 (2.1-2.7σ)*
  - *A_{FB} (1.7-2.5σ)*
  - *BR (1.5-2.1σ)*
- Consistent tension remains with increased significance



Branching fractions of $b \rightarrow s \mu^+\mu^-$



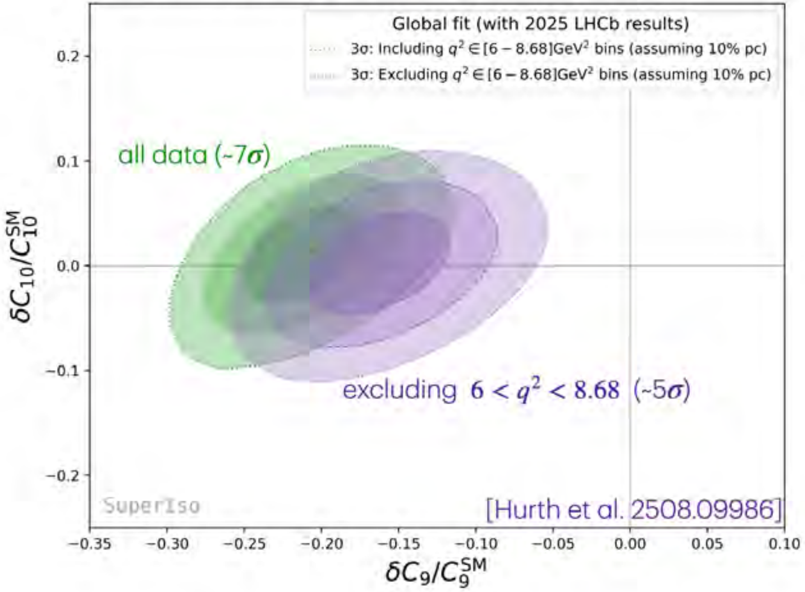
- Analysis of large class of $b \rightarrow s \mu^+\mu^-$ decays
  - Several tensions seen, but individual significance is moderate
  - Tendency to undershoot prediction of differential x-sections
    → **intriguing hint or theoretical issue in prediction?**

→ **TH developments needed as well as more measurements**

What does this mean? Global fits

Exclusive: global fits

- Global fits show a strong tension with the SM:



- This fit includes an O(10%) estimate of nonlocal power corrections
- With and without the inclusion of the $q^2 \in [6,8.68]$ GeV^2 bins the fit result is:

$$\delta C_9 = -0.69 \pm 0.12 \quad (4.8\sigma)$$
$$\delta C_9 = -0.89 \pm 0.11 \quad (7.1\sigma)$$

- This is an enormous NP effect:

$$C_9^{NP} \sim -\frac{1}{4} C_9^{SM}$$

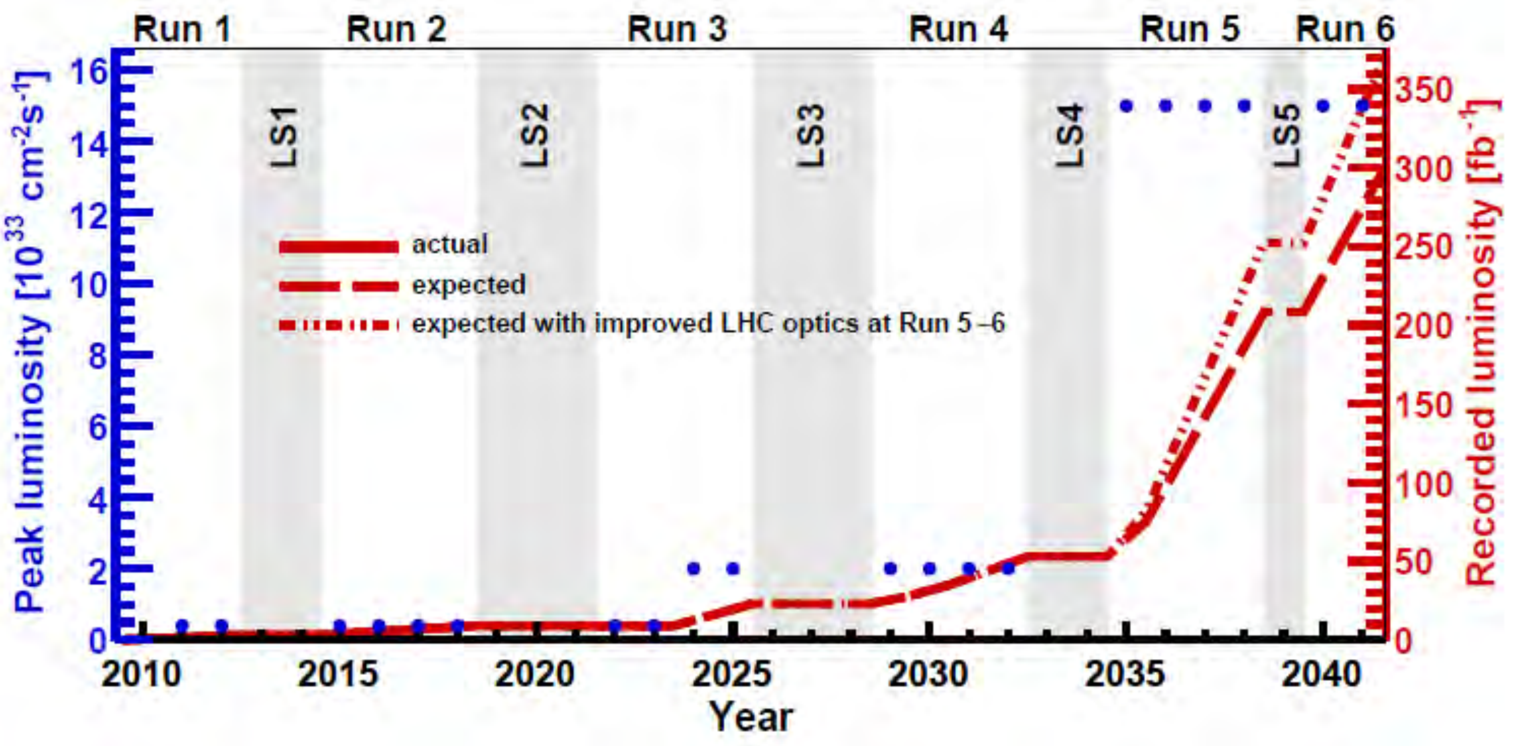
- Good agreement across many fitters:
  - ABCDMN [Algueró et al, 2304.07330]
  - AS/GSSS [Altmannshofer et al, 2212.10497]
  - CFFPSV [Ciuchini et al, 2212.10516]
  - HMMN [Hurth et al, 2104.10058]
  - GRvDV [Gubernari et al, 2206.03797]

Enrico Lunghi, IU   4/24   Fermilab, December 2025

E. Lunghi, Fermilab workshop 12/25

Quo vadis ?
Outlook

LHCb lifespan



LHCb-U2 currently under scientific review by the LHC committee.

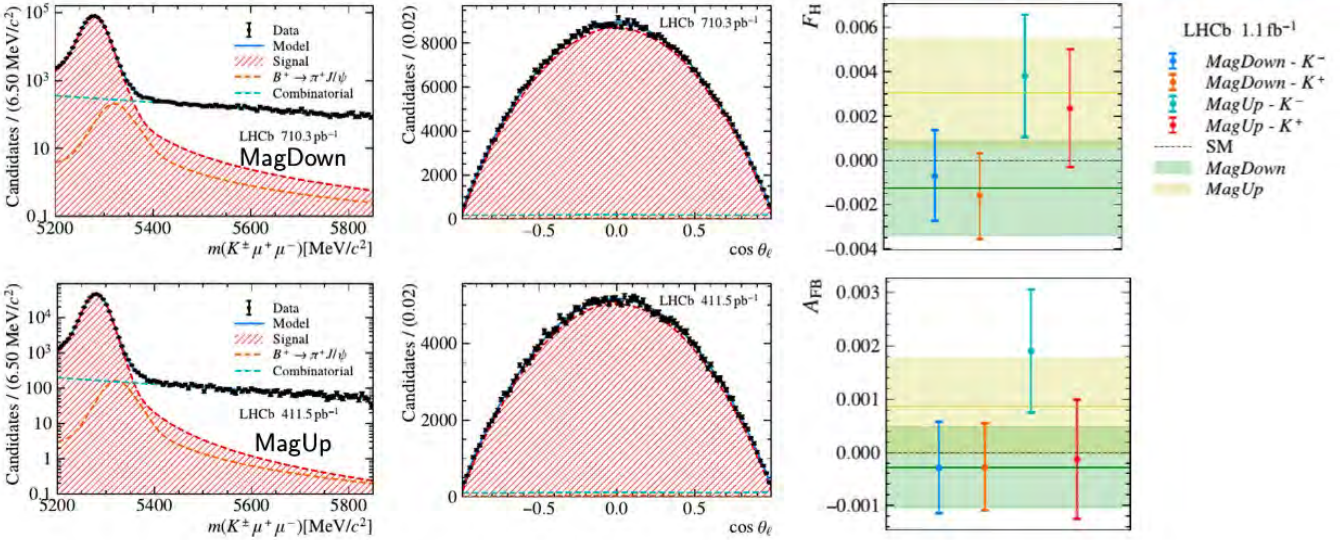
Summary & Conclusion

- Run 1 and 2 data still provide a continuous stream of results
- Exceptional two years for LHCb: Upgrade-1 fulfils expectation
  - Increased dataset by factor 4
  - Additional factor 2-4 due to new trigger for some modes
- Data analysis has just started!
- Several interesting patterns emerge, all need
  - More data to clarify patterns
  - Theory effort and close collaboration between color and flavor


WE'RE ALL VERY EXCITED BY YOUR RESEARCH, BUT WE DON'T HAVE TIME TO READ THE PAPER, SO WE'D LIKE YOU TO SUMMARISE YOUR FINDINGS WITH ONE OF THESE EMOJIS.

Run 3 angular analysis

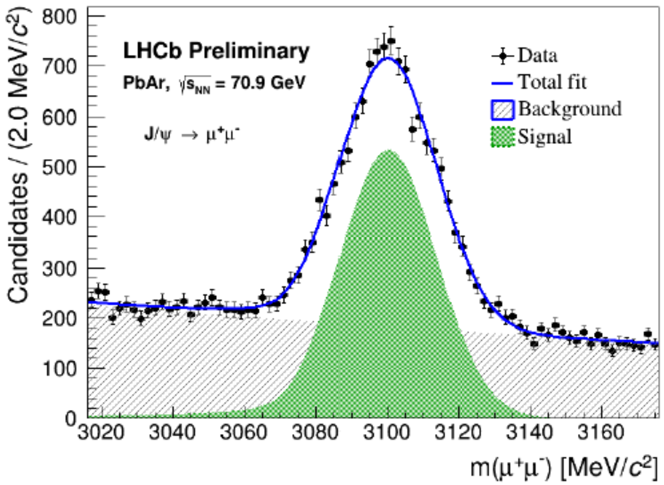
LHCb-PAPER-2025-040, in preparation

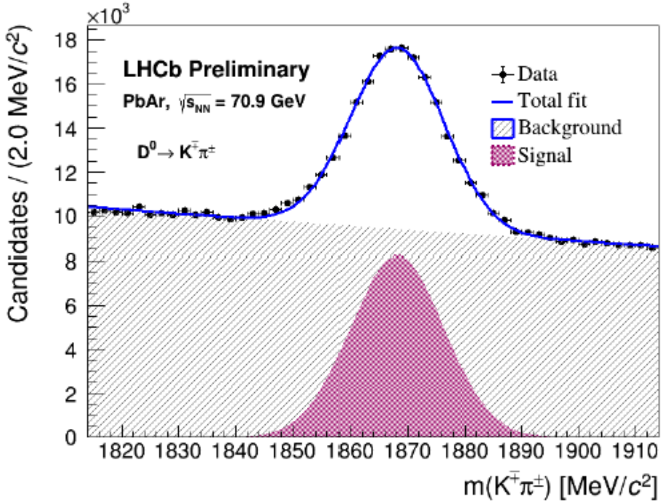


- Differential angular fit of
  $$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{3}{4}(1 - F_H) + \frac{1}{2}F_H + A_{FB}\cos\theta_\ell$$
- Using 1 fb^{-1} of 2024 data excellent agreement with SM prediction of 0:
  $A_{FB} = 0.00019 \pm 0.00048_{stat} \pm 0.00033_{syst}$, $F_H = 0.0005 \pm 0.0011_{stat} \pm 0.0014_{syst}$
- Consistent results for MagnetUp/Down and Kaon charge

Some glimpses to Run 3 performance

LHCb-FIGURE-2025-014

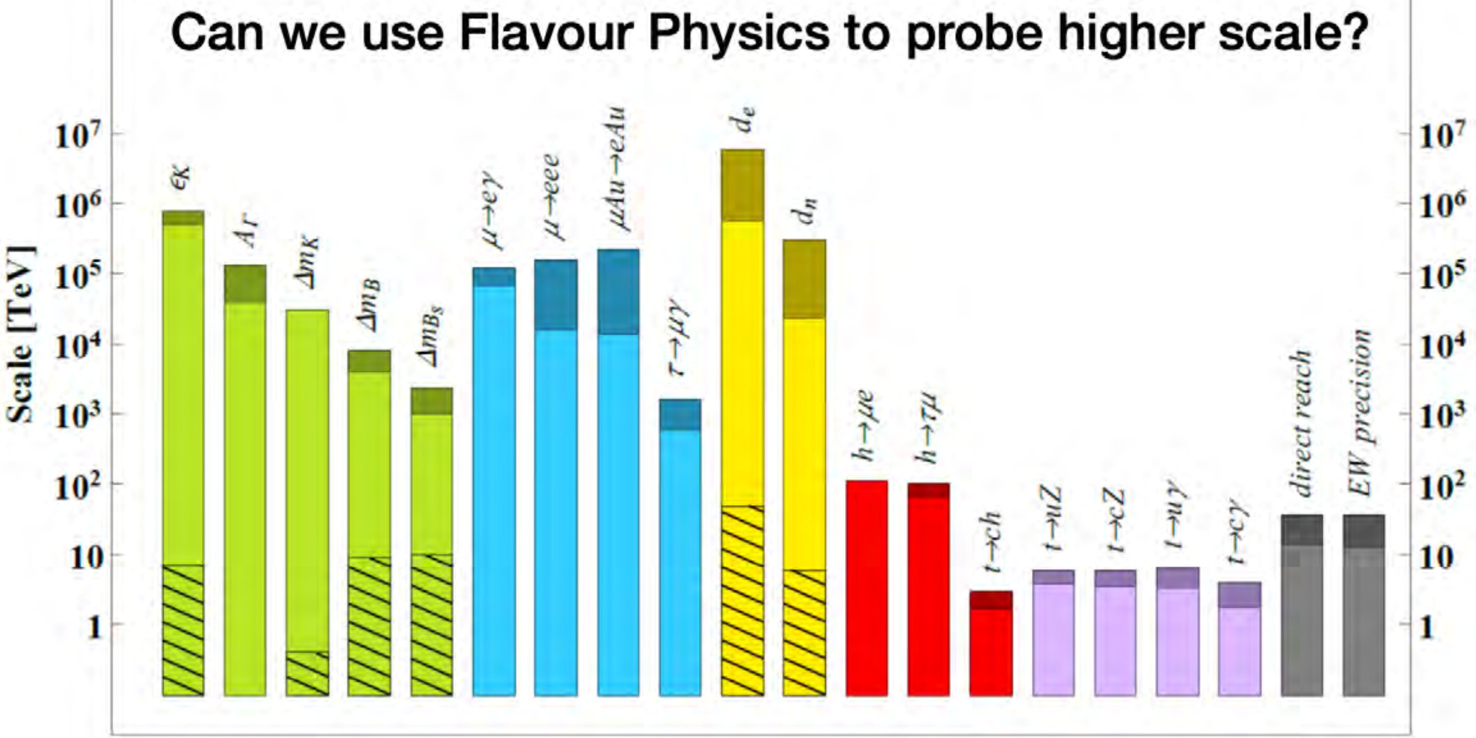




- Efficient reconstruction of PbAr signals at $\sqrt{s}$=70.9 GeV
- Cross-section measurements with this and other configurations are on their way

NP scale tested

ESPPU:1910.11775



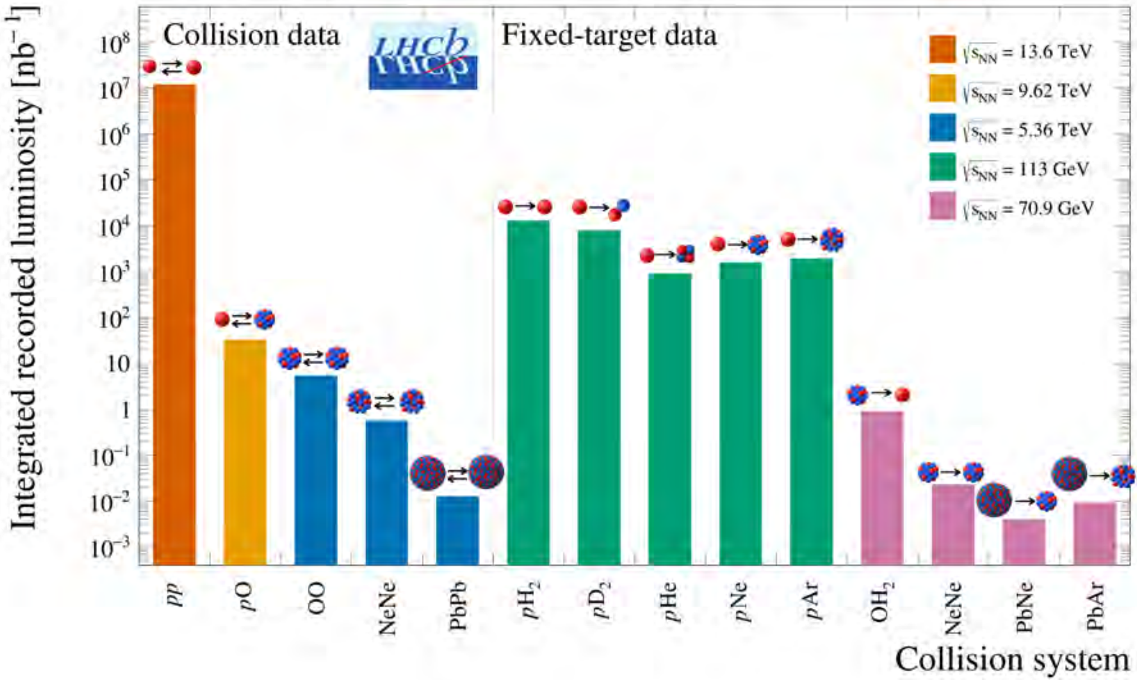
Assuming unit couplings for effective coefficients

Flavor machines (Marina Artuso et al)

Facility	Luminosity ($cm^{-2}s^{-1}$)	B pair cross section	luminosity per year	B pairs per year	Lumi so far (fb^{-1})	Expected final lumi (fb^{-1})
FNAL Tevatron through Run 2	$2x10^{32}$	100 μb	2 fb^{-1}	$2x10^{11}$	~10	~10
e^+e^- B factory - (4S) (KEKB)	$3x10^{34}$	1.15 nb	300 fb^{-1}	$3.45x10^{8}$	1040	1040
LHC (Run 1,2,3)	$1x10^{34}$	500 μb	100 fb^{-1}	$5x10^{13}$	~500	~500
LHCb upgrade 1	$2x10^{32}$	500 μb	>10.0 fb^{-1}	$1x10^{12}$	22	>50
SuperKEKB	5.0 x 10^{35}	1.15 nb	5 ab^{-1}	$5.8x10^{9}$	500	30000-50000
HL-LHC	5 (7.5) $x10^{34}$	500 μb	300 fb^{-1}	$15x10^{13}$	----	3000
LHCb upgrade 2	1.0(1.5)$x10^{34}$	500 μb	42-49 fb^{-1}	$2.5x10^{13}$		300
FCC-ee (Z pole)	1.82 $x10^{36}$(IP)	9.1 nb	87 ab^{-1}(4IP)	3.6x 10^{12}(4IP)	----	150000 (4IP/4yrs)

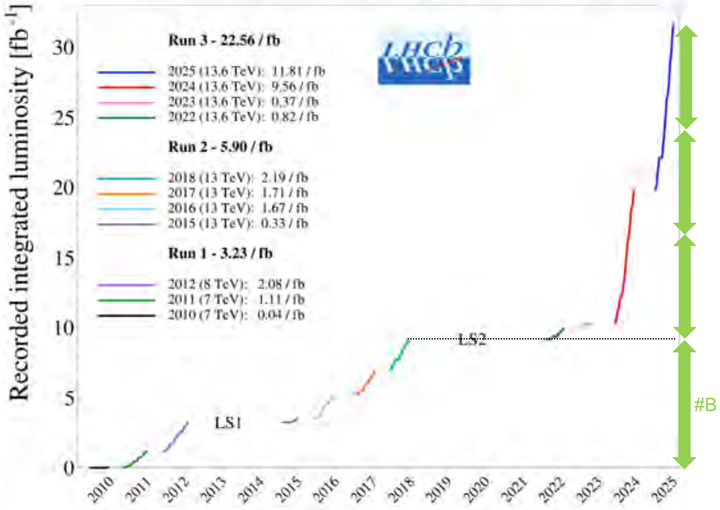
What counts is efficiency x # of b produced=$N_{Bdetected}$. This makes the gap between e^+e^- and hadron colliders smaller, but still leaves a large advantage to hadron colliders for many types of studies. Also, e^+e^- running on $\Upsilon(4S)$, only studies B_d and B_u pairs

LHCb – Collider and fixed target experiment



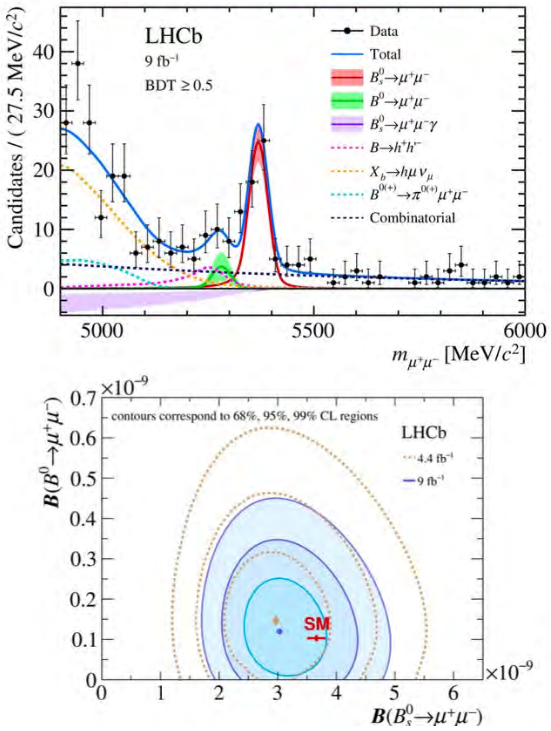
- SMOG2 system allows parallel data taking in collider and fixed target mode

Zoom in to proton collisions

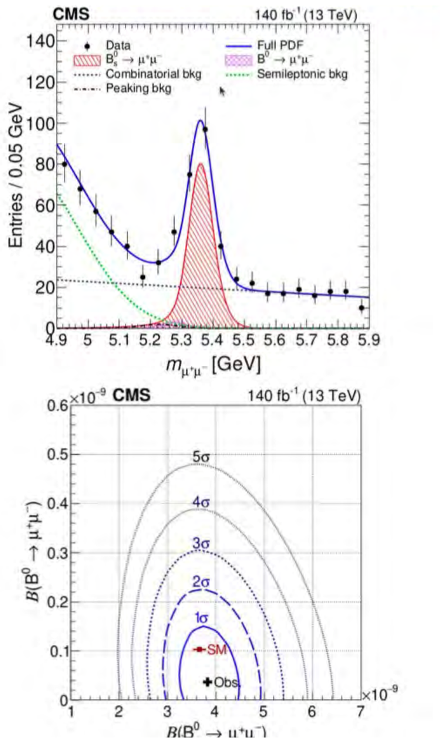


- Very successful Run 3 data taking, recorded #B increased by factor 4

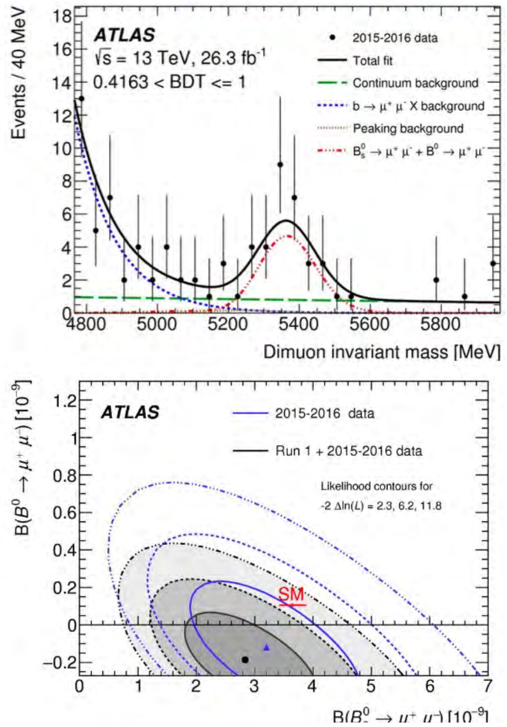
Golden channel: $B_{s,d} \to \mu^+\mu^-$ seen around the ring



LHCb, PRL 128(2022)041801



CMS, PLB842(2023)137955

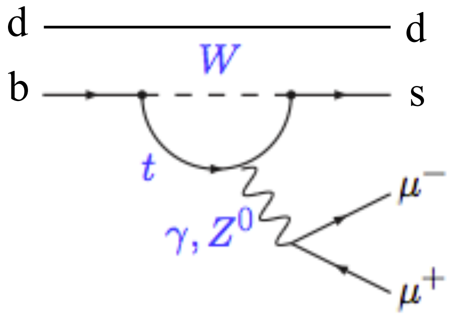


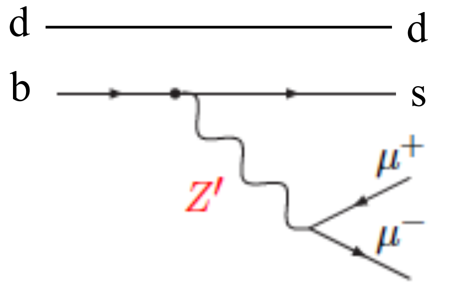
ATLAS, JHEP04(2019)098

$B_s \to \mu^+\mu^-$ measured compatible with SM, B^0 might come in reach in Run 3

→ stringent constraint on SUSY and other scalar SM extensions

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



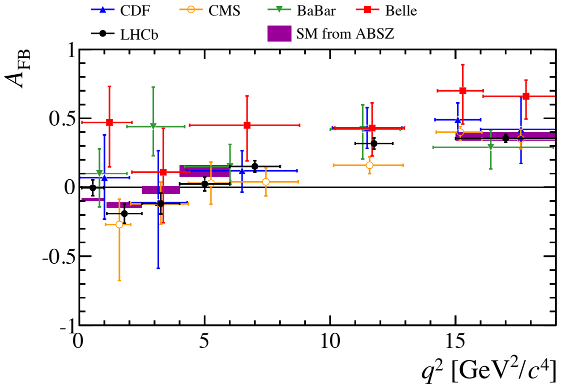


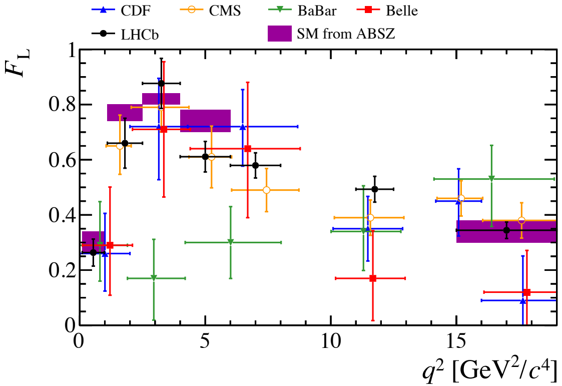
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\Bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l - F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi + \tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi + S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

fraction of longitudinal polarisation of the K*

forward-backward asymmetry of the dilepton system

Observables depend on B→K* form factors and on short distance physics





- Situation unclear. Clean up by smarter observables

$P_i^{(\prime)}$ **basis**: ***Reparameterise the fit to obtain optimised observables:***
form factor uncertainties cancel at first order

JHEP 12 (2014) 125, JHEP 09 (2010) 089

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}}$$