Overview of LHCb

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Large Hadron Collider

Proton energy: up to 7 TeV (10^{12} eV)
speed: 0.999999991 c

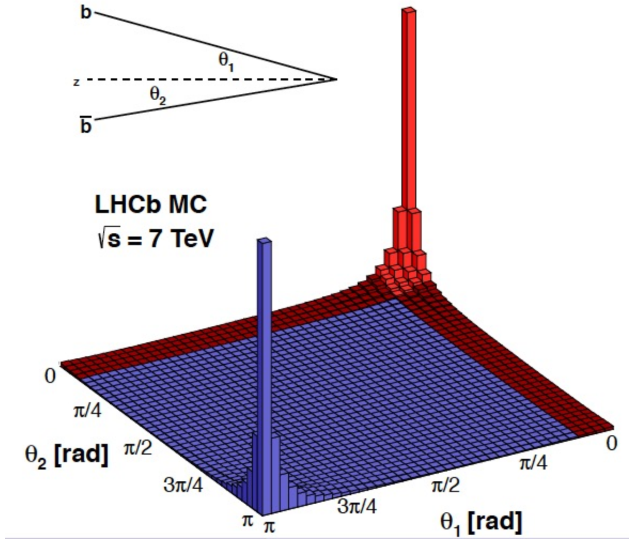
Beauty/charm production

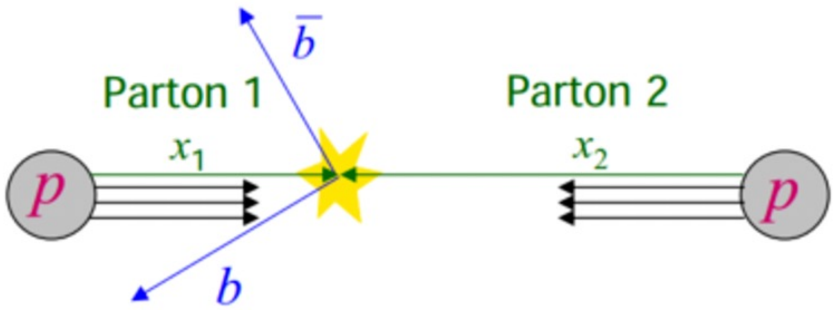
- Large production cross-section @ 7 TeV
  - Minibias ~60 mb
  - Charm ~6 mb
  - Beauty ~0.3 mb c.f. 1nb @$\Upsilon(4S)$

Flavour factory!

All b-hadrons:
$B^+, B^0, B_s^0, \Lambda_b^0, B_c^+, \ldots$

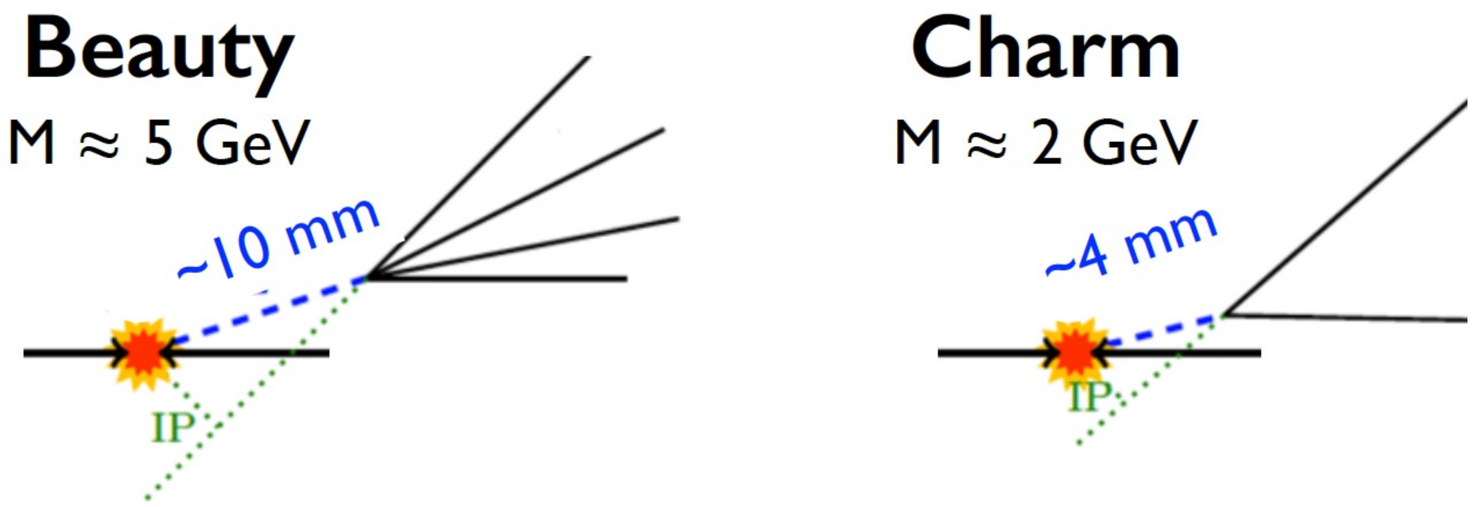
- Predominantly in forward/backward cones





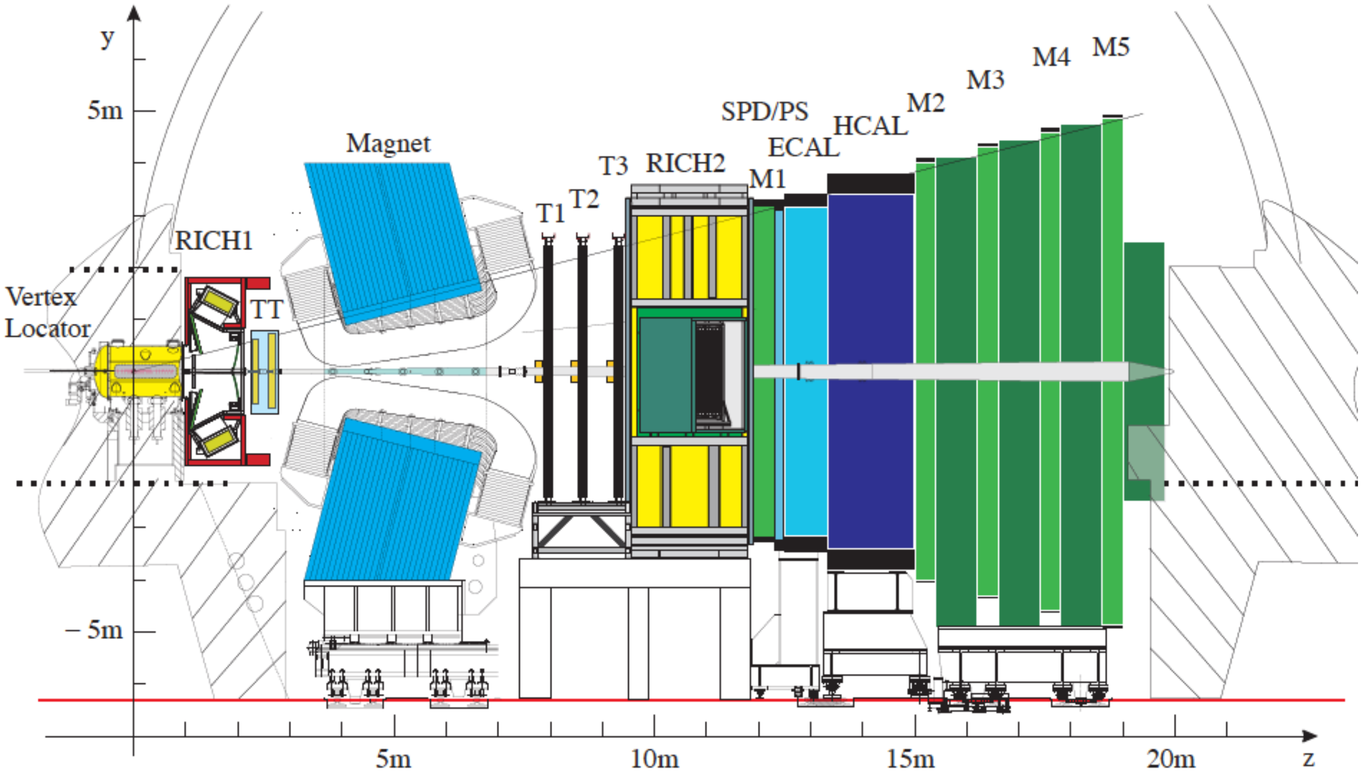
Initial energy of $b\bar{b}$ not known

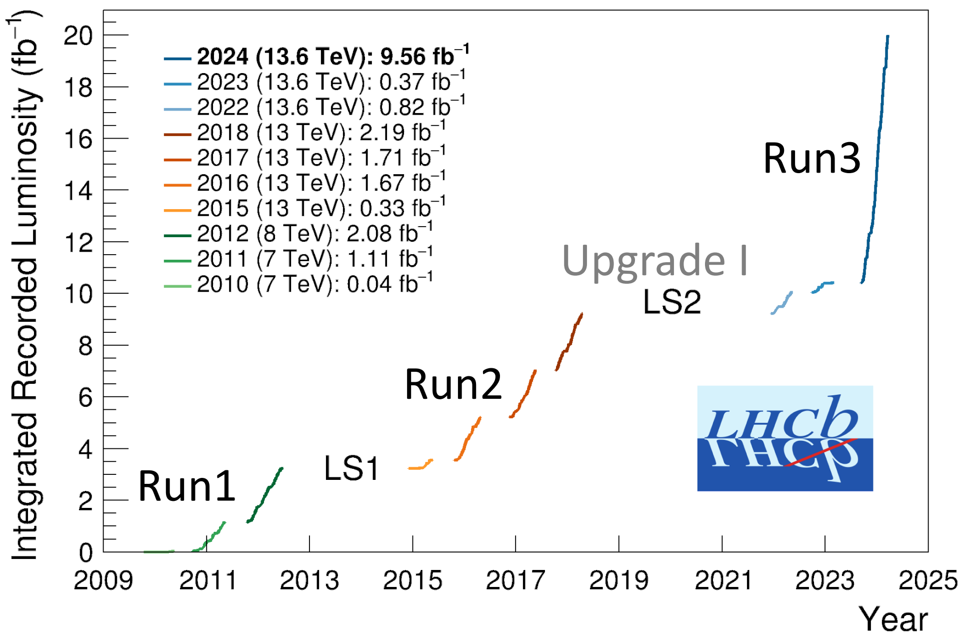
Beauty/charm signature



- Compared to minimum bias (background)
  - Relatively high mass → high *transverse momentum*
  - Relatively long lifetime → large impact parameter (IP)
- Requires excellent vertexing, tracking, particle-identification

The LHCb experiment

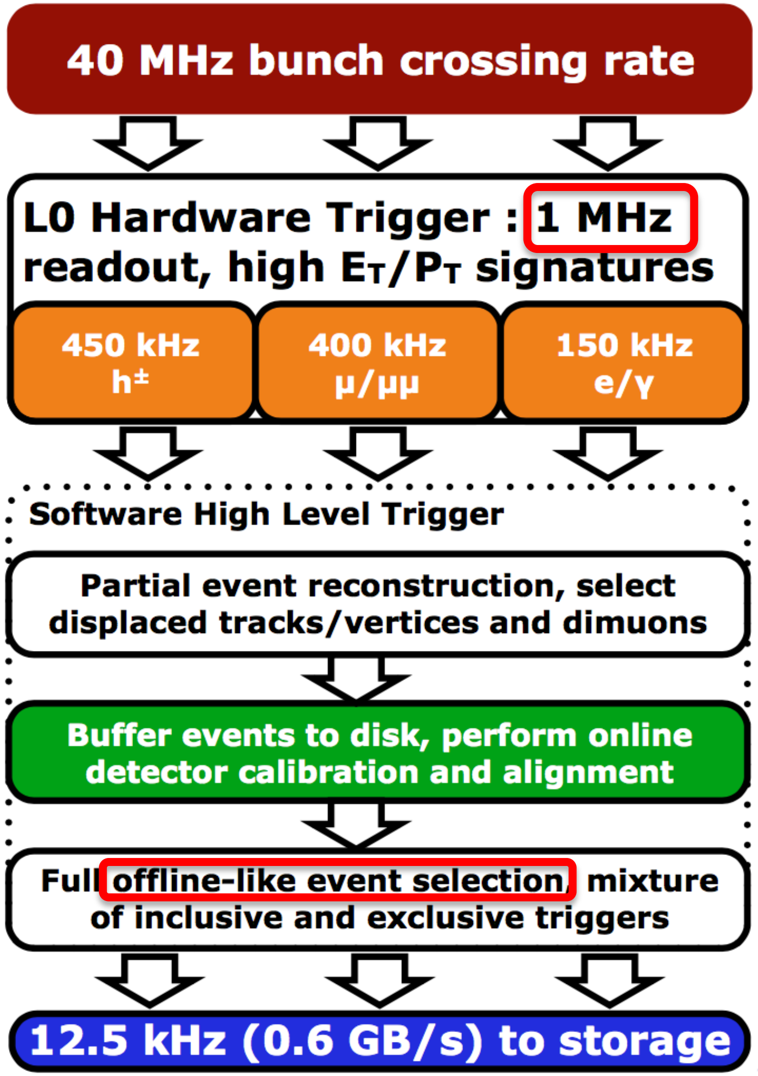




Vertex Locator	$\sigma_{\mathrm{PV},x/y} \sim 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{PV},z} \sim 60\ \mu\mathrm{m}$
Tracking (TT, T1-T3)	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system (M1-M5)	$\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID rate $(\pi \to \mu) = 1 - 3\%$
ECAL	$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\%$ (E in GeV)
HCAL	$\sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\%$ (E in GeV)

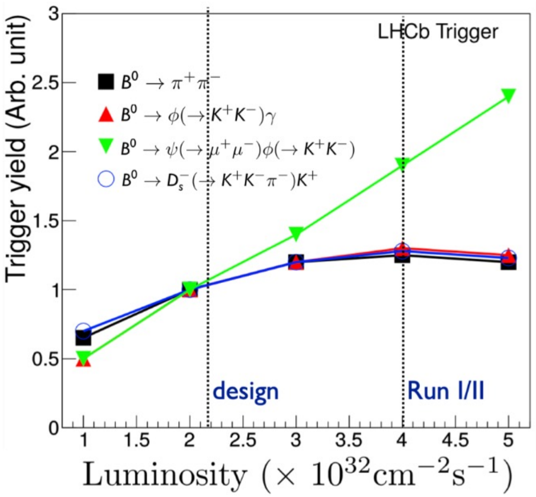
- Run3 (2022-2026)
  - Luminosity: ~25 fb^{-1}
  - Yields, compared to Run 1+2
    - Muon modes ~3
    - Hadronic modes ~6 (higher trigger eff.)

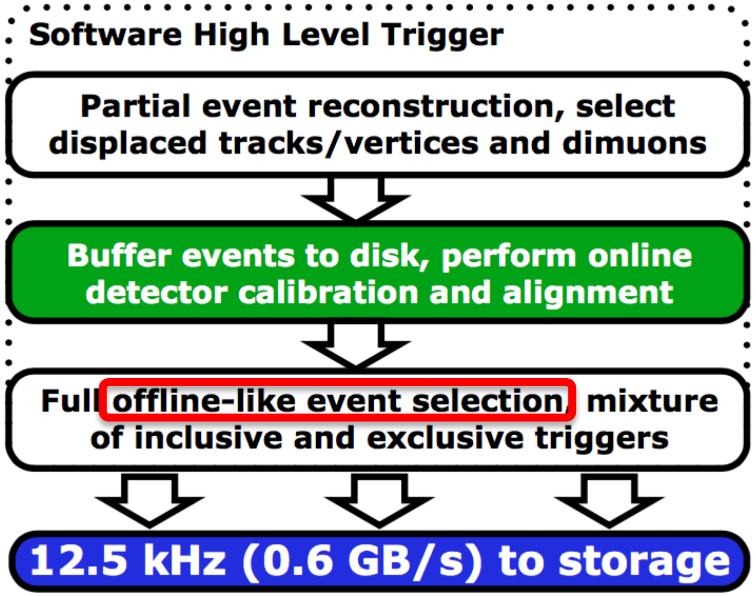
The LHCb trigger (2018)



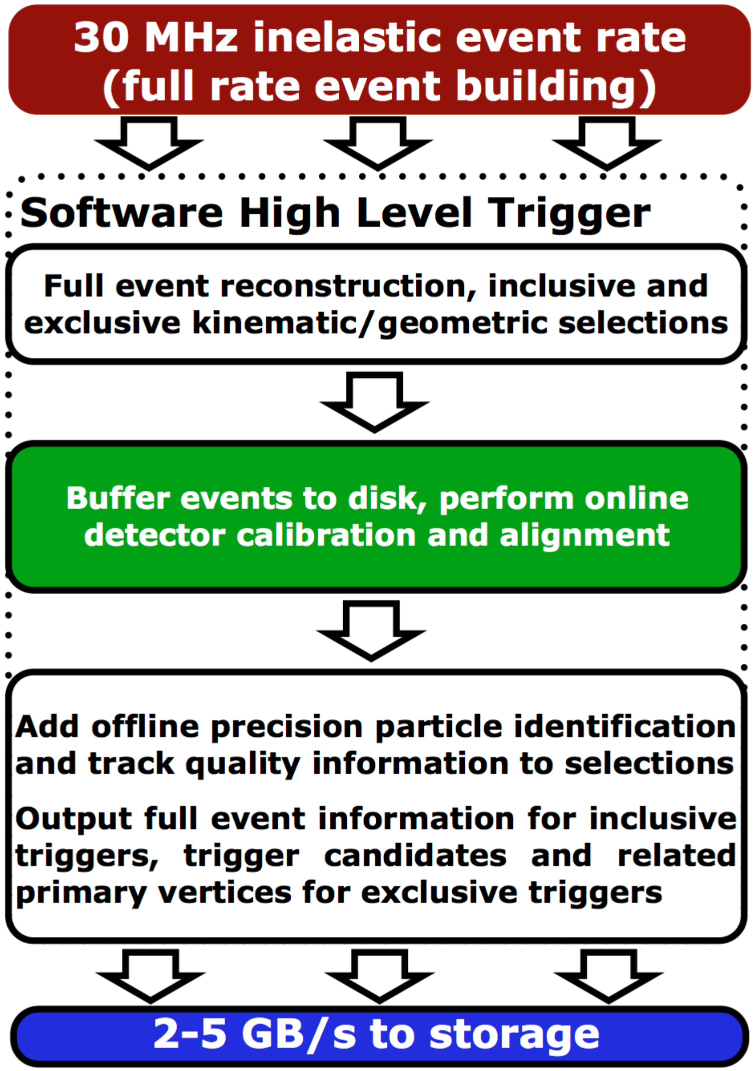
- L0, Hardware
  - $p_T(\mu_1)\times p_T(\mu_2) >$ (1.5 GeV)^2
  - $p_T(\mu) >$ 1.8 GeV
  - $E_T(e) >$ 2.4 GeV
  - $E_T(\gamma) >$ 3.0 GeV
  - $E_T(h) >$ 3.7 GeV
- High Level Trigger
  - Stage1, p_T, IP
  - Stage2, full selection

The LHCb trigger (Run3)



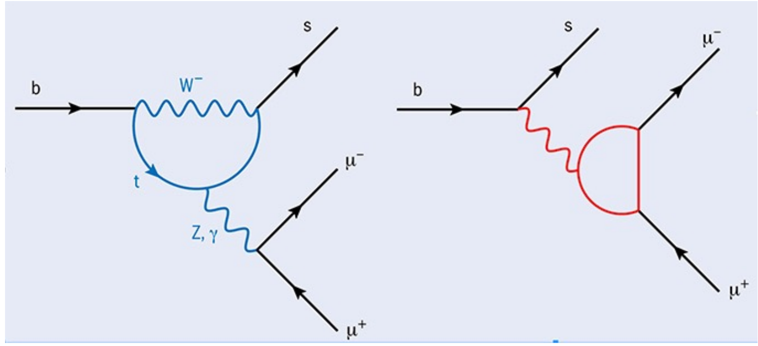


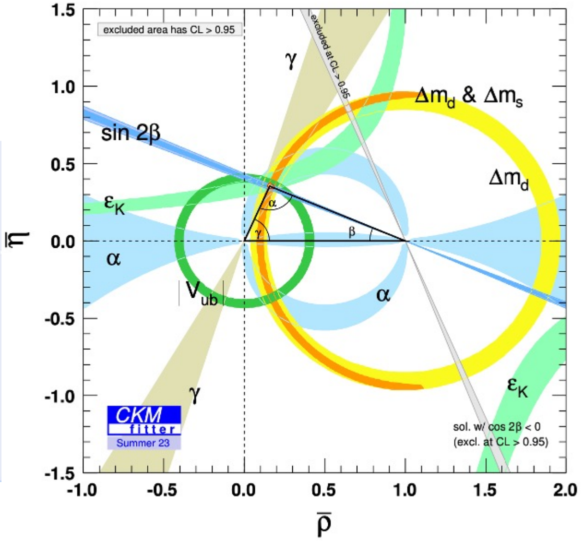
L0 removed

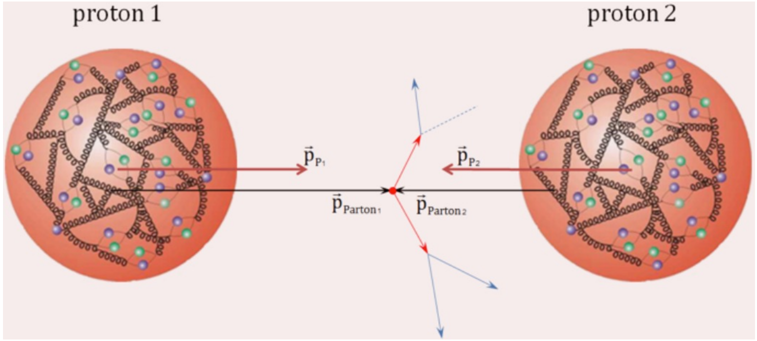


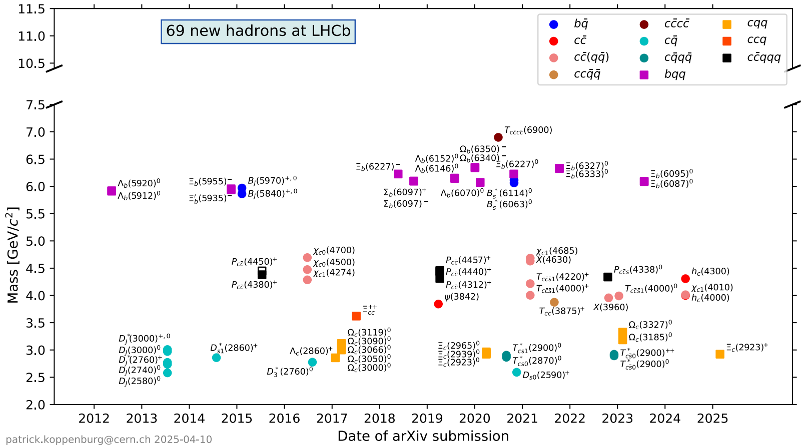
Physics programs at LHCb

- Indirect search for New Physics
  - CP Violation
  - Rare decays
- Quantum Chromodynamics
  - Spectroscopy (Quark model + strong interaction)
  - Production (PDF, hard scattering, fragmentation)
- Heavy Ions
- Electroweak





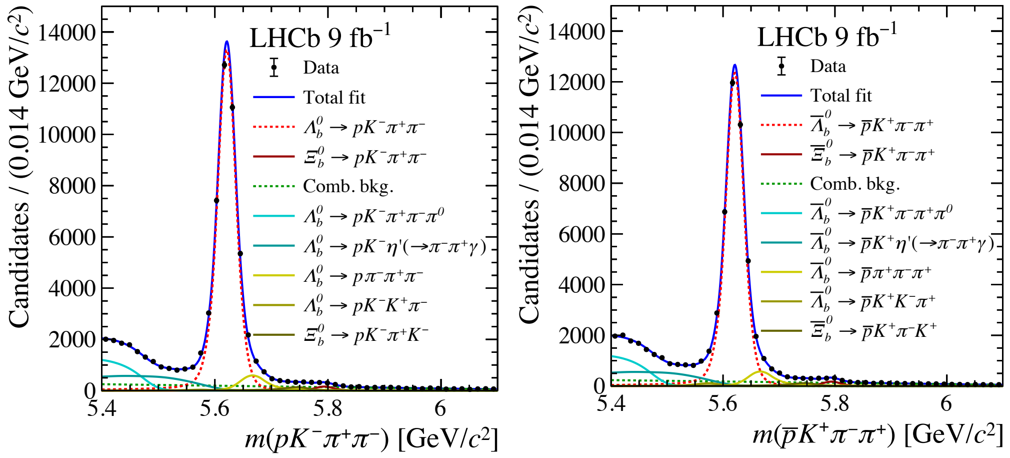




CPV in baryon decays

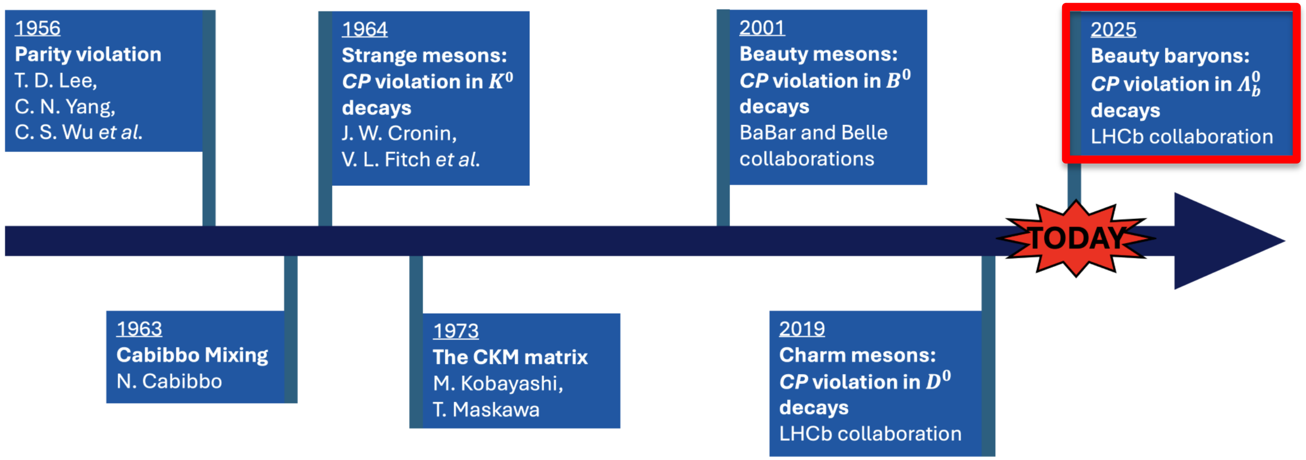
- First observation!

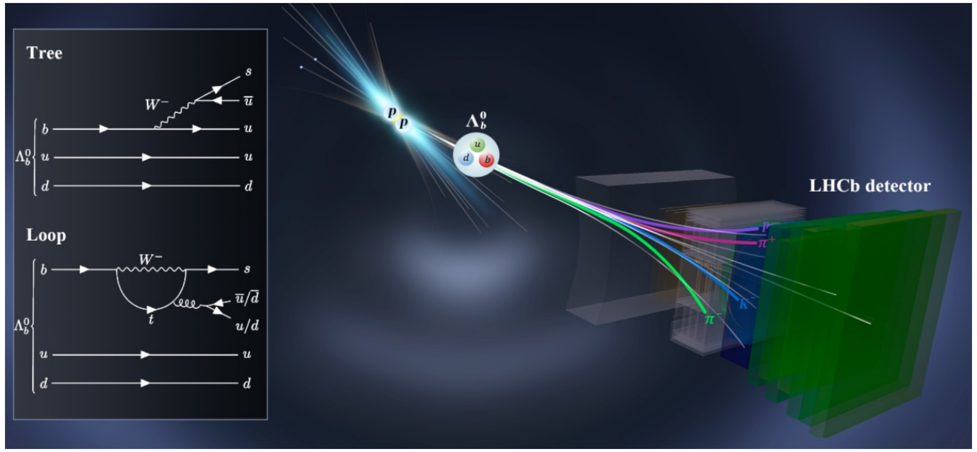
[arXiv:2503.16954]



$$A_{CP} \equiv \frac{\Gamma(\Lambda_b^0 \to pK^-\pi^+\pi^-) - \Gamma(\bar{\Lambda}_b^0 \to \bar{p}K^+\pi^-\pi^+)}{\Gamma(\Lambda_b^0 \to pK^-\pi^+\pi^-) + \Gamma(\bar{\Lambda}_b^0 \to \bar{p}K^+\pi^-\pi^+)}$$

$$= (2.45 \pm 0.46 \pm 0.10)\% \quad 5.2\sigma$$





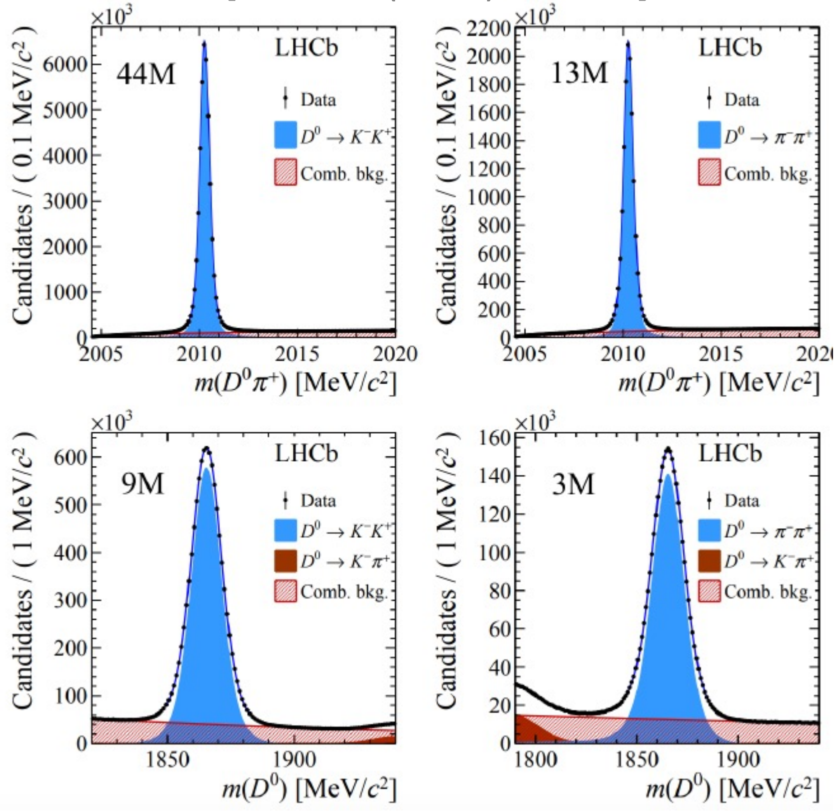
- Evidence also found in $\Delta A_{CP}(\Lambda_b^0 \to \Lambda K^+K^-)$

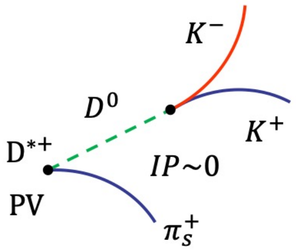
[PRL 134 (2025) 101802]

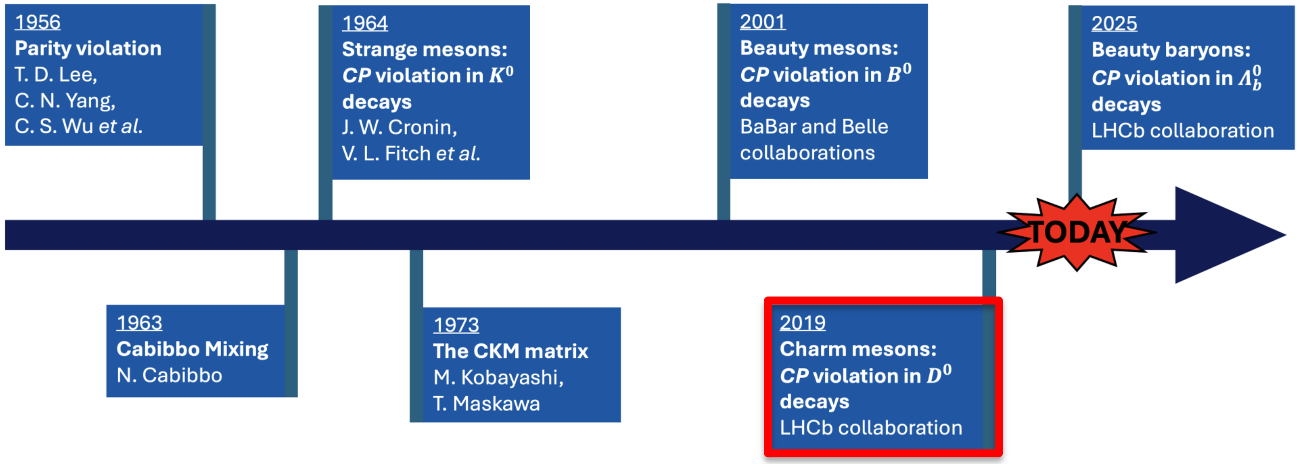
CPV in charm decays

- First observation!

[PRL 122 (2019) 211803]







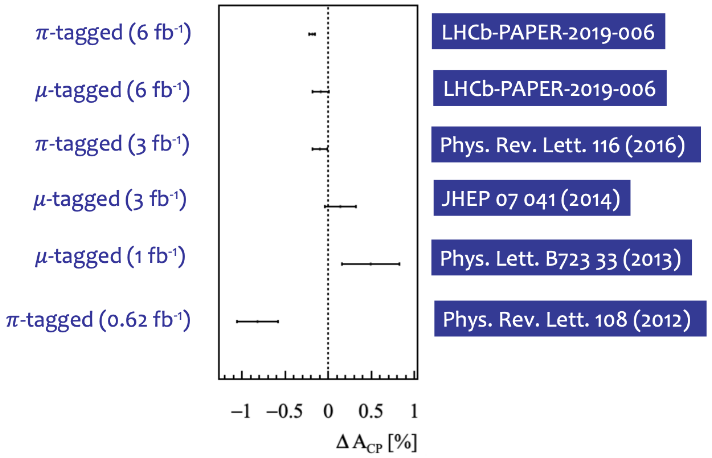
$$A_{CP}(f) = \frac{\Gamma(M \to f) - \Gamma(\bar{M} \to \bar{f})}{\Gamma(M \to f) + \Gamma(\bar{M} \to \bar{f})}$$

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

$$\Delta A_{CP}^{\pi\text{-tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4},$$
$$\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}.$$

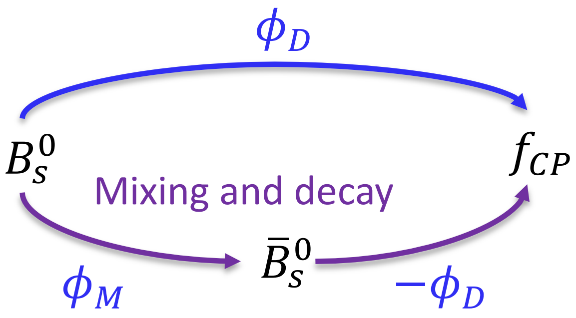
Combined one:

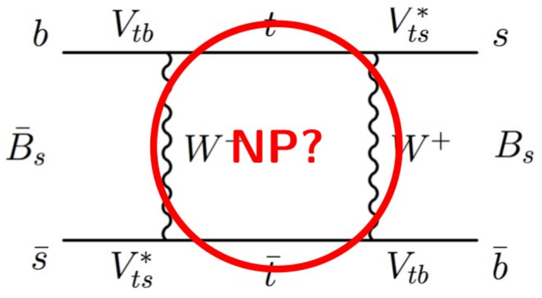
$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$



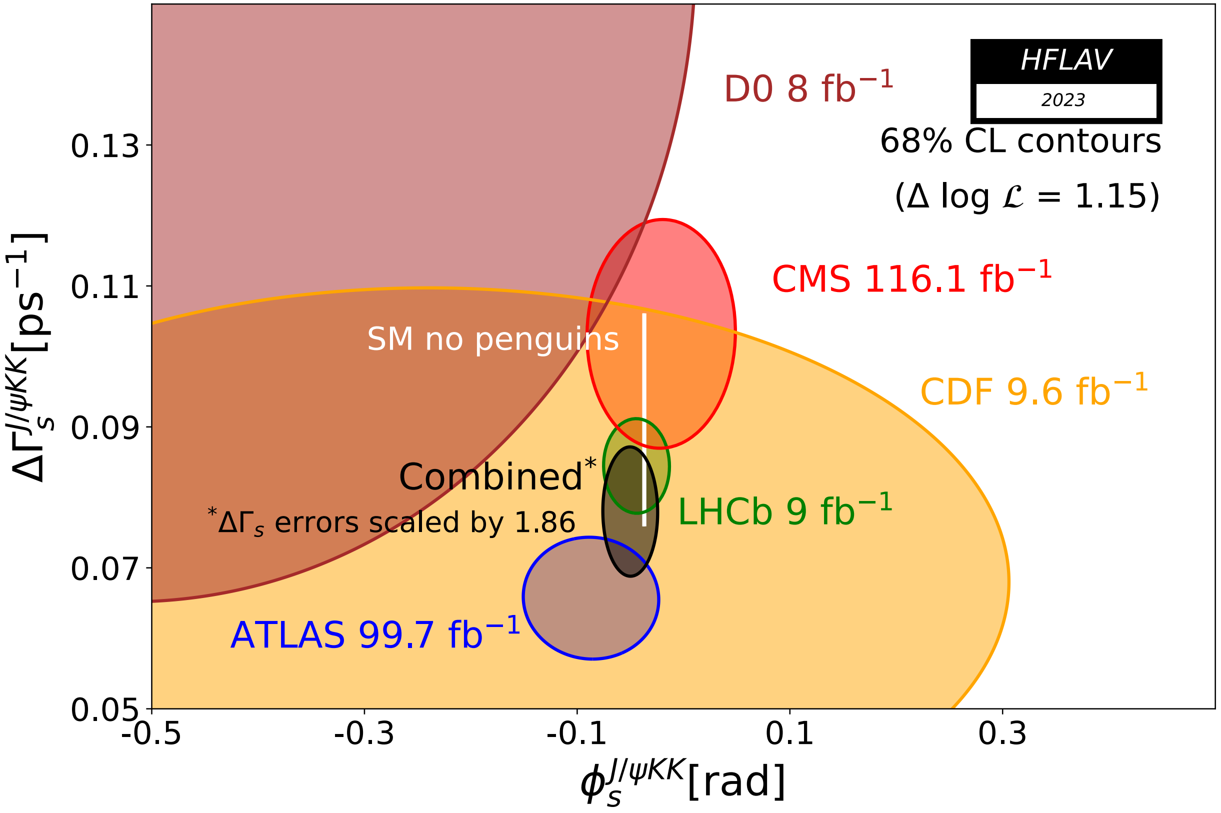
CPV in mixing

- $\phi_s = \phi_M - 2\phi_D$, small in SM
- $B_s^0 \to J/\psi h^+ h^-$



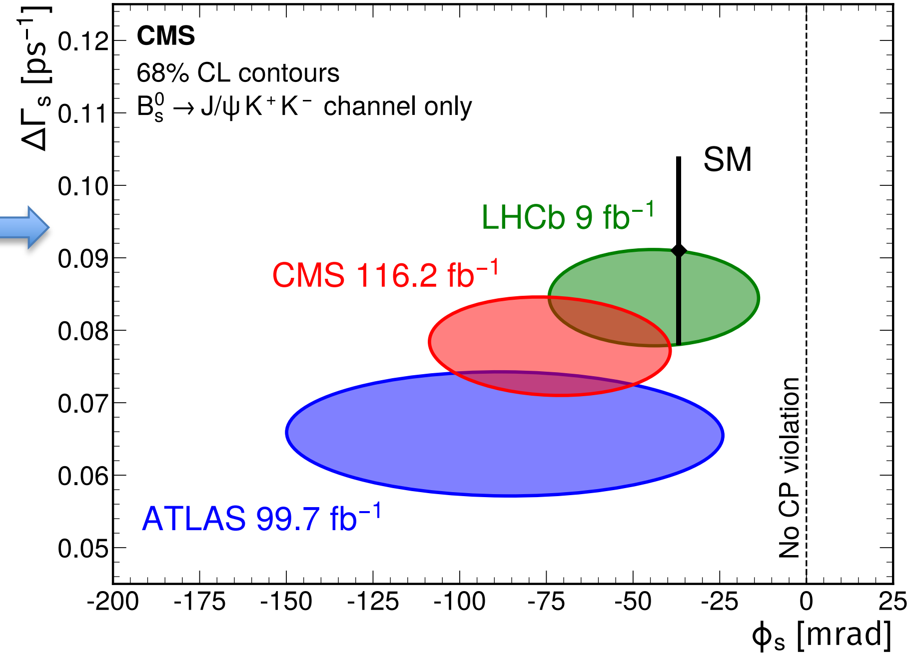


[PRL 132 (2024) 051802]



Flavour tagging?

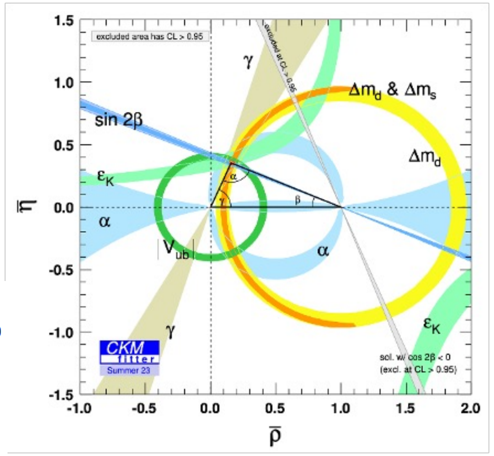
[CMS, arXiv:2412.19952]

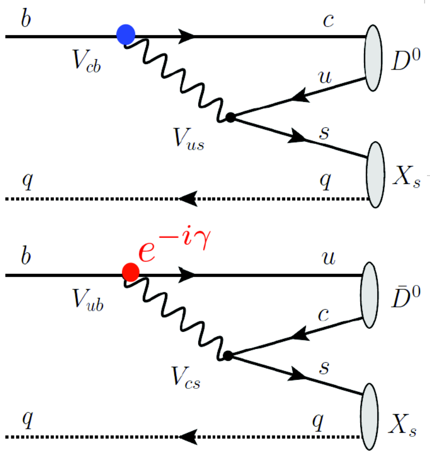


CKM-γ combination

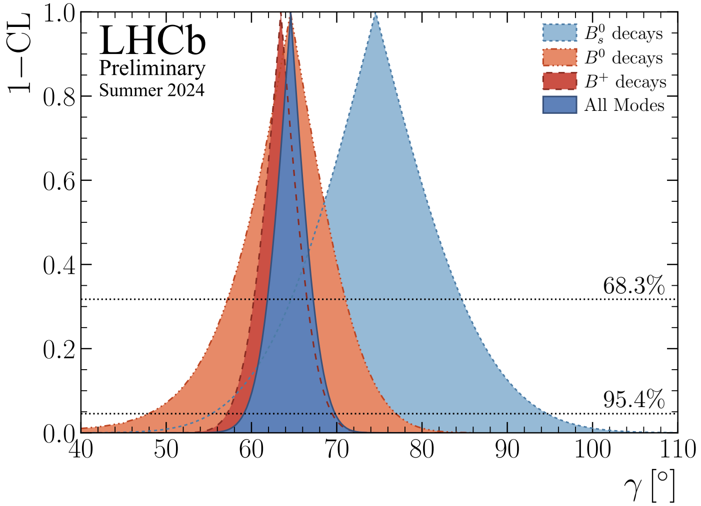
- Simultaneous determination of CKM-γ & charm mixing parameters
  - CKM $\gamma = (64.6 \pm 2.8)^\circ$
  - Charm mixing $x = (0.41 \pm 0.05)\%$,

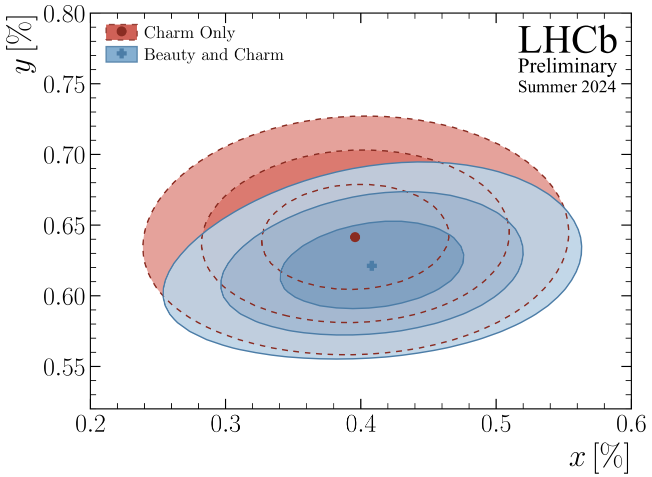
    $y = (0.621^{+0.022}_{-0.021})\%$

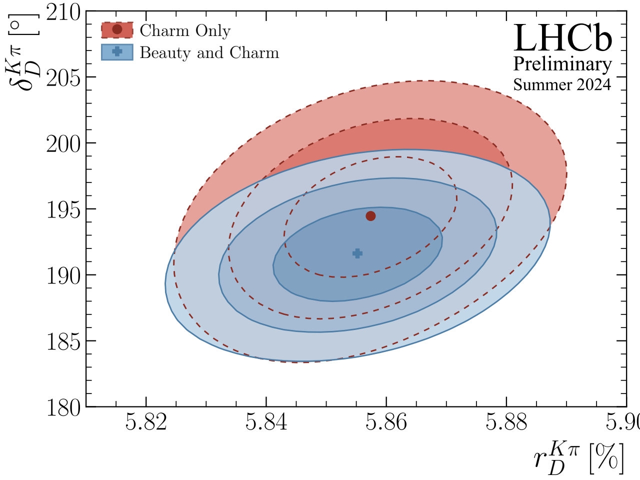




Inputs from BESIII/STCF needed soon

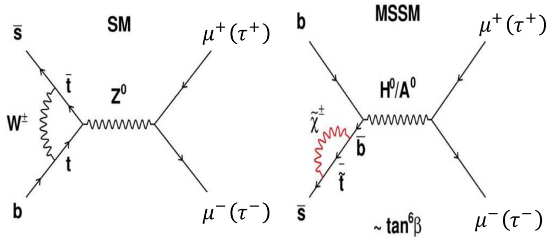






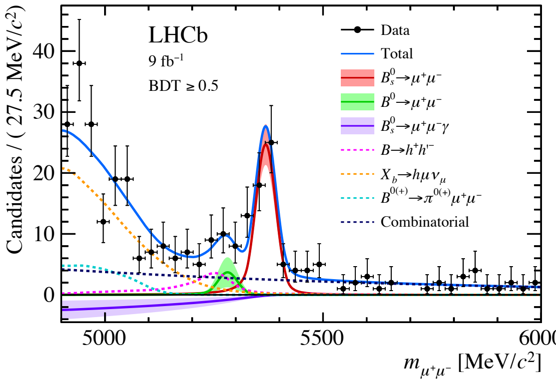
[LHCb-Conf-2024-004]

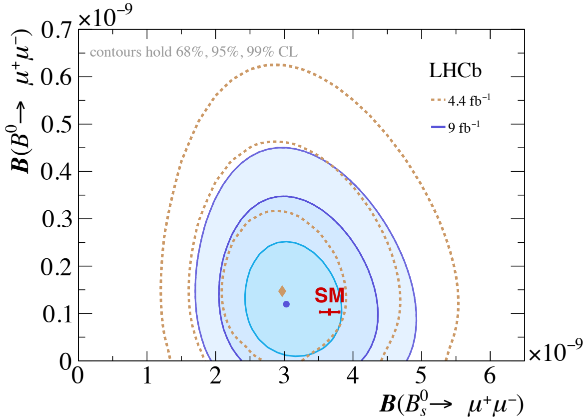
$B^0_{(s)} \to \mu^+\mu^-$

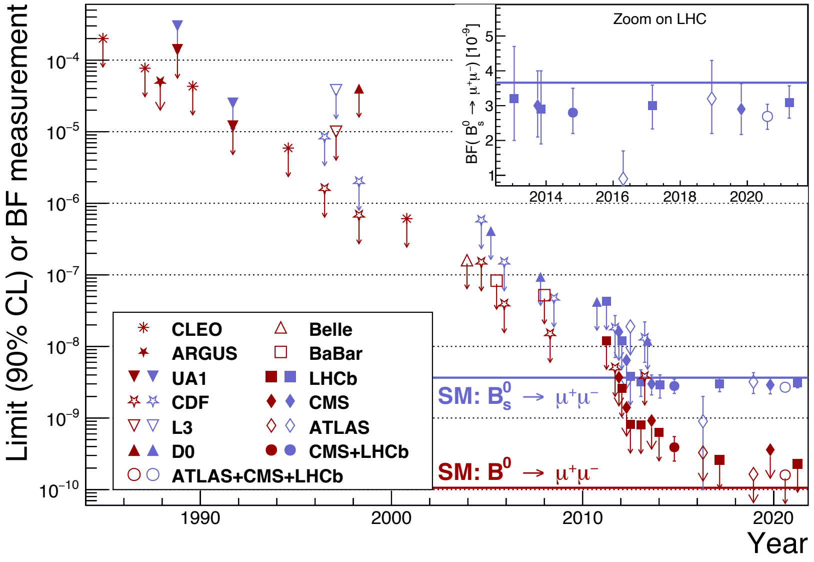


- Suppressed in SM, could be enhanced by New Physics

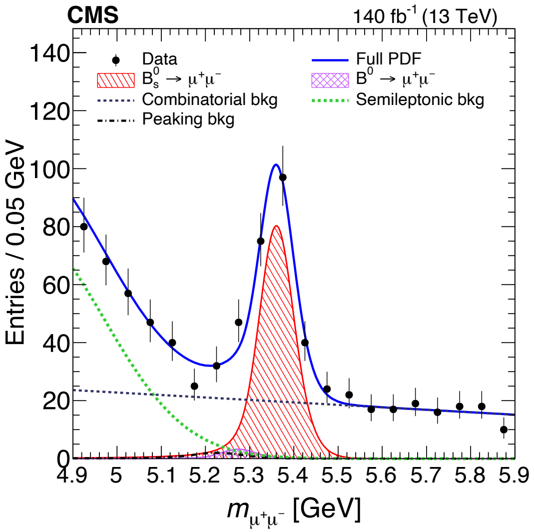
PRL 128 (2022) 041801

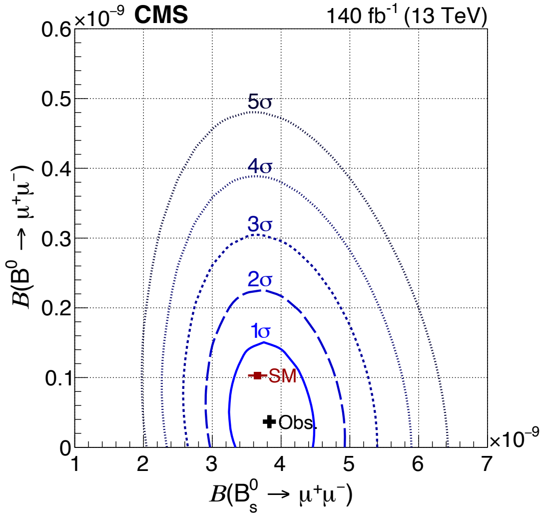


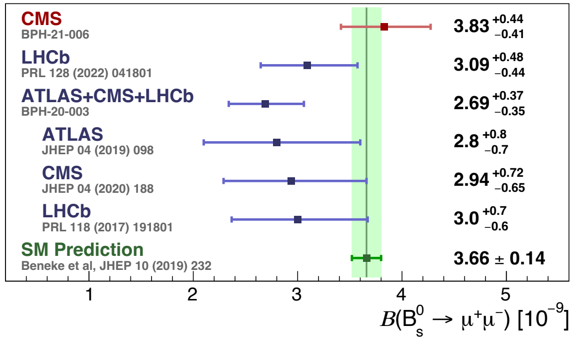




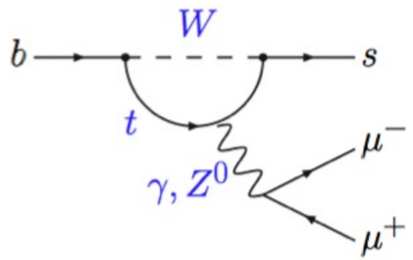
PLB 842 (2023) 137955



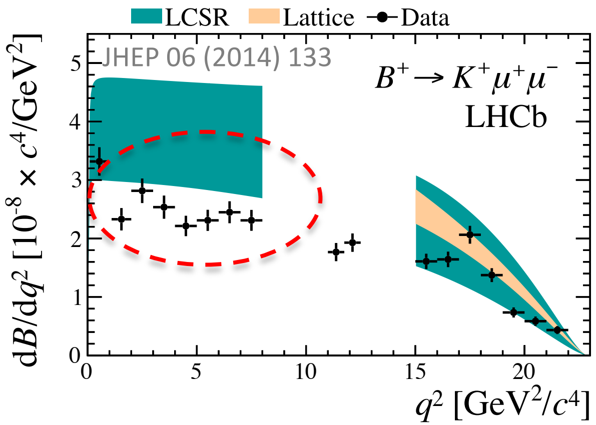


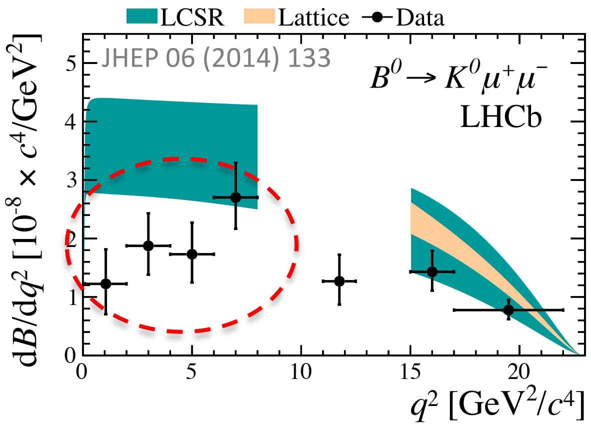


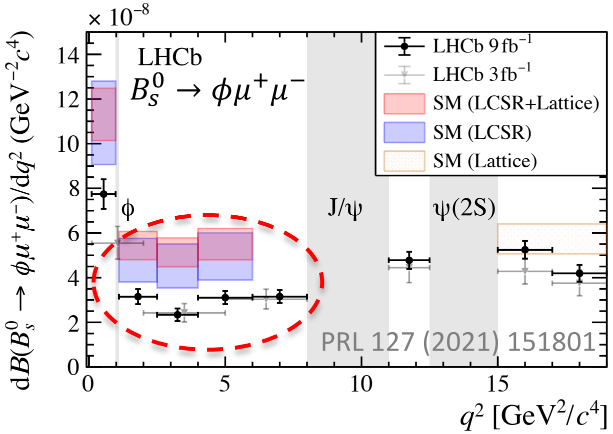
Branching fraction of $b \to s\mu^+\mu^-$

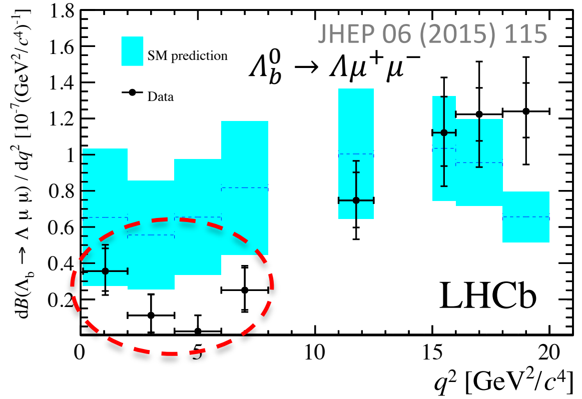


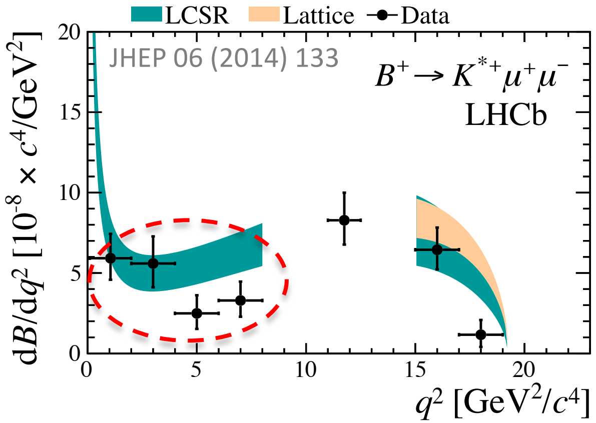
- Pattern of tensions seen, theoretical uncertainty?

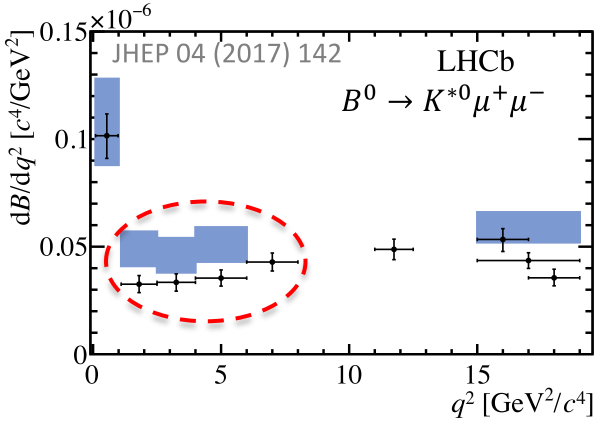


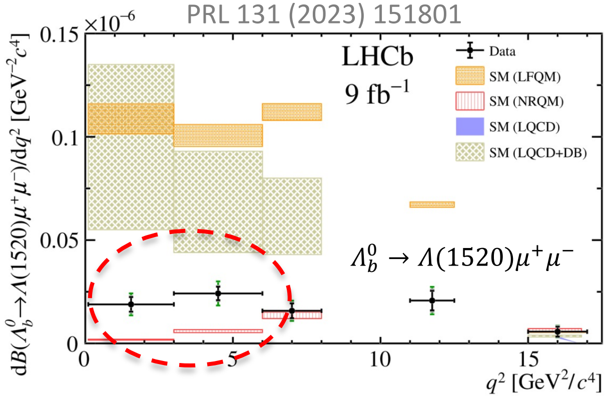




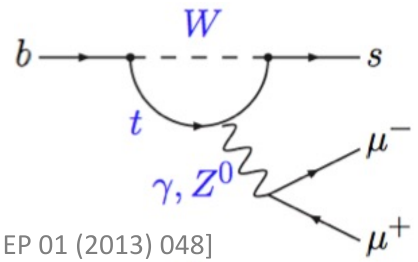








P_5' with $B^0 \to K^{*0}\mu^+\mu^-$

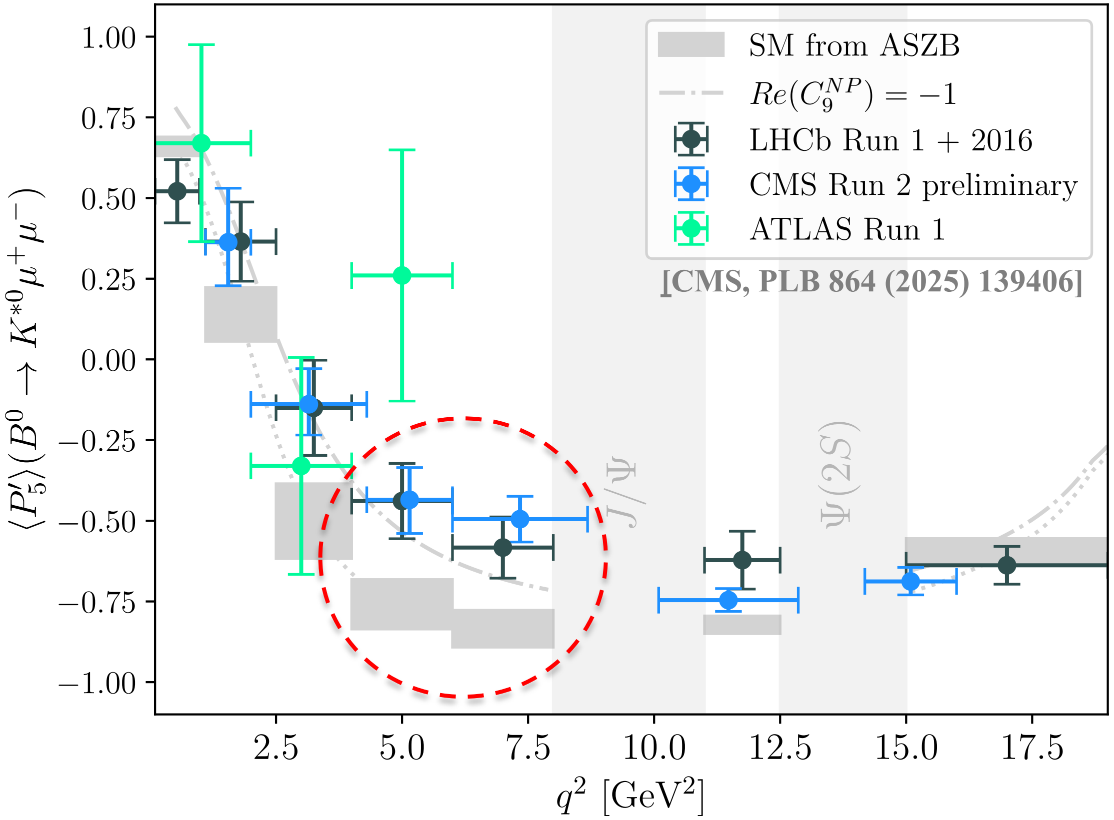


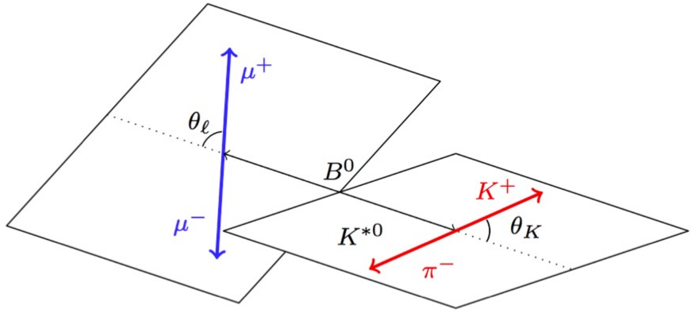
- $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$, less form-factor dependent

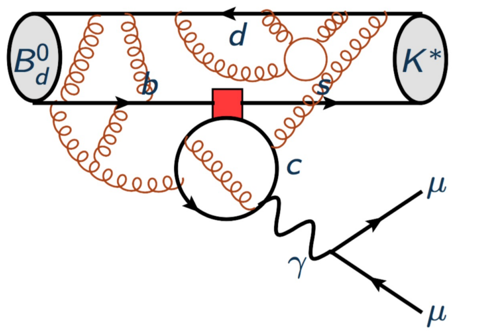
[S. Descotes-Genon, *et al.*, JHEP 01 (2013) 048]

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

[PRL 125 (2020) 011802]

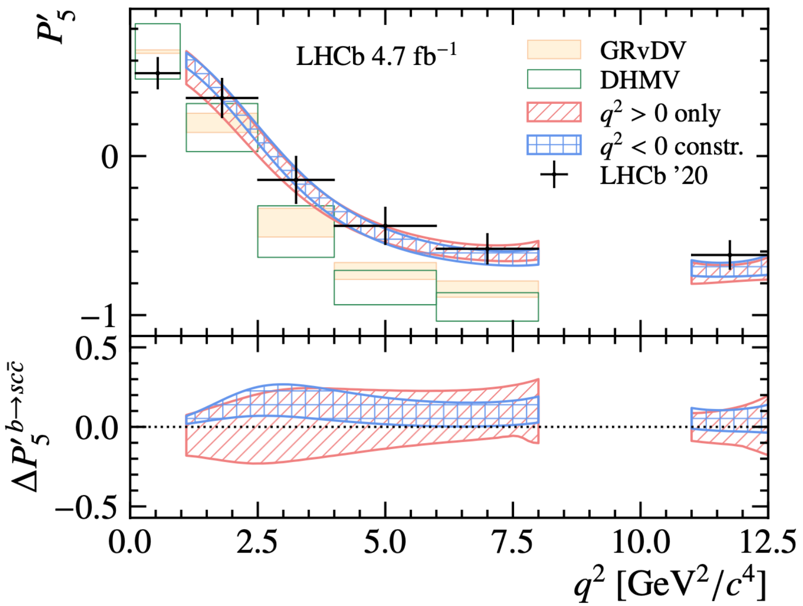


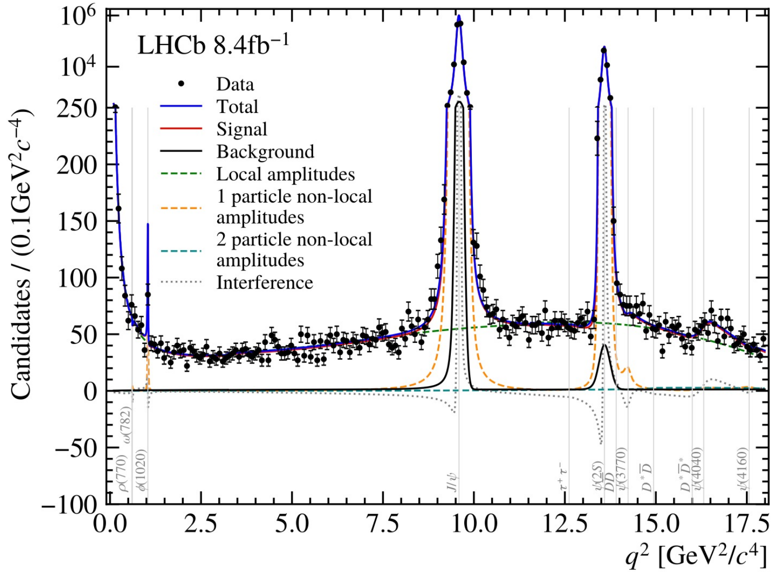


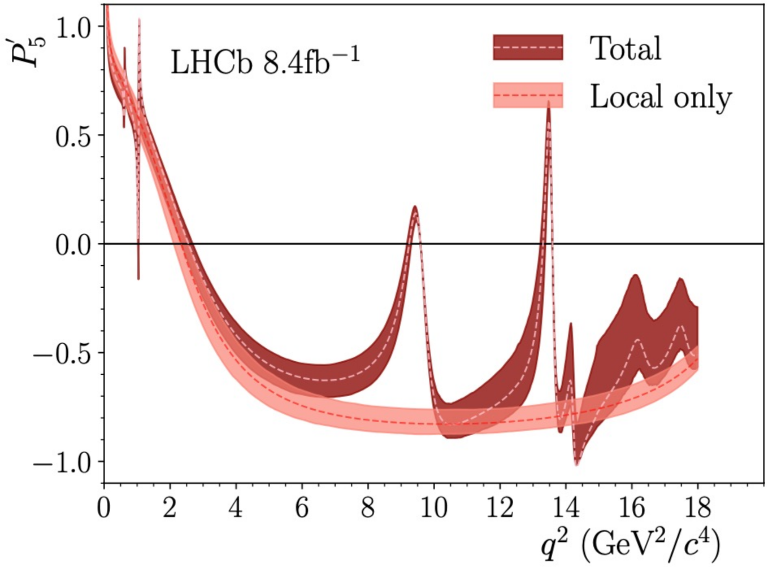


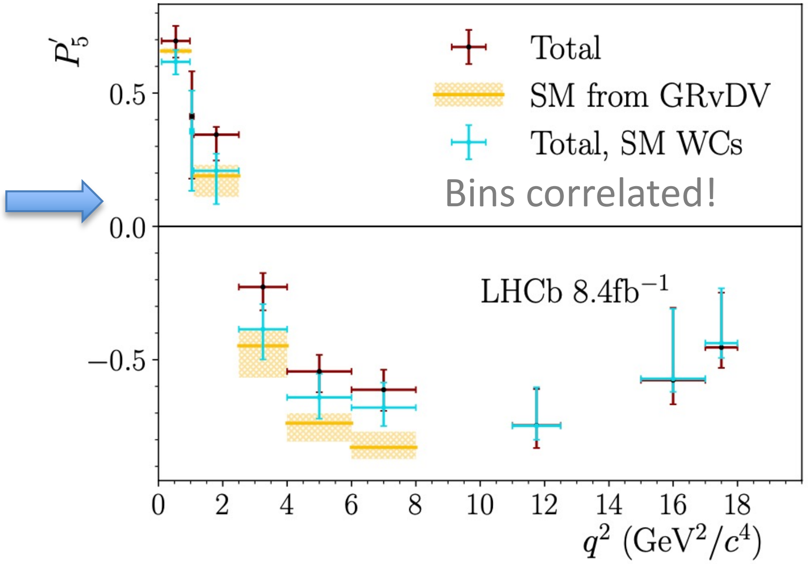
Charm loop

- Model of local and nonlocal contributions to extract Wilson co-efficiency [PRL 132 (2024) 131801]
- Model of both 1-(2-) particle amplitudes, whole dimuon region [JHEP 09 (2024) 026]



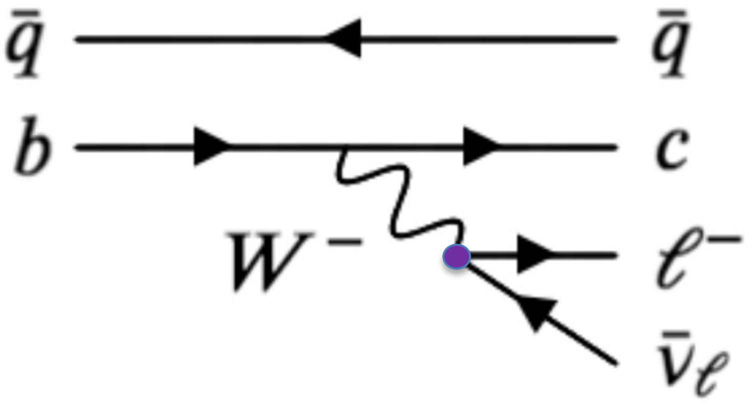


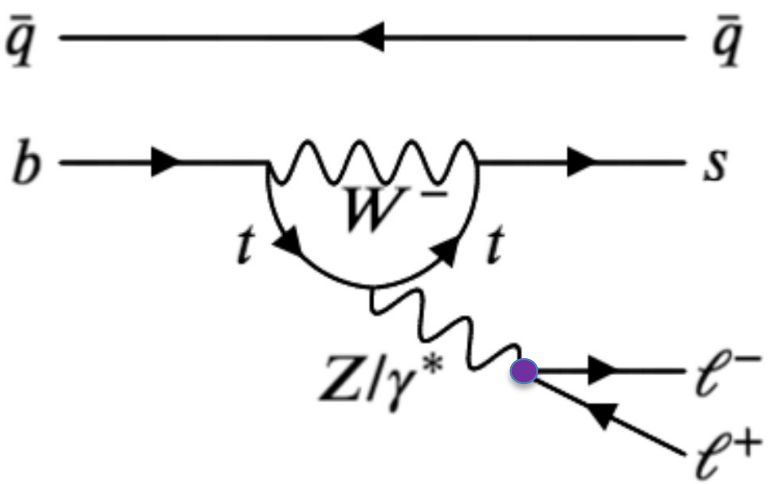




Lepton flavour universality

- Leptons (e, μ, τ) have identical coupling to gauge bosons





  – which means, e.g.,

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \cong 1$$

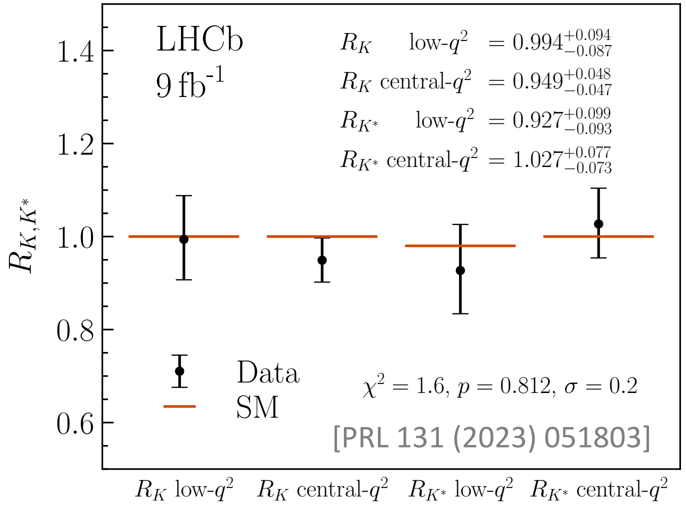
$\mathcal{O}(10^{-4})$ uncertainty
[C. Bobeth *et al.*, JHEP 12 (2007) 040]

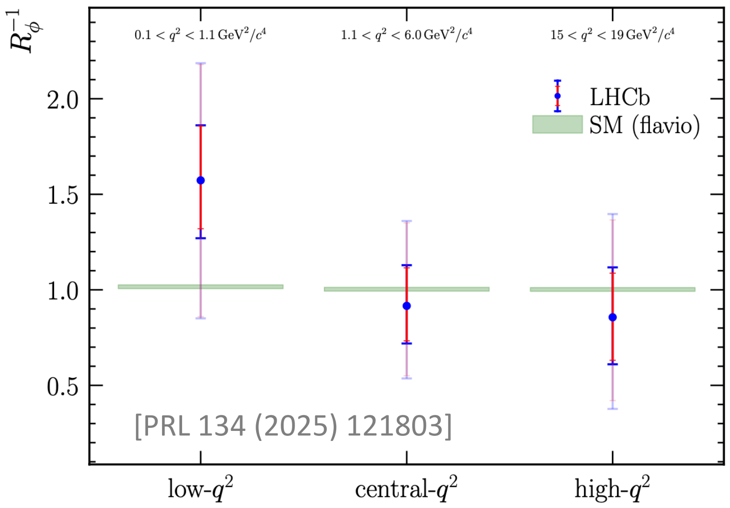
$\mathcal{O}(1\%)$ QED correction
[M. Bordone *et al.*, EJPC 76 (2016) 440]

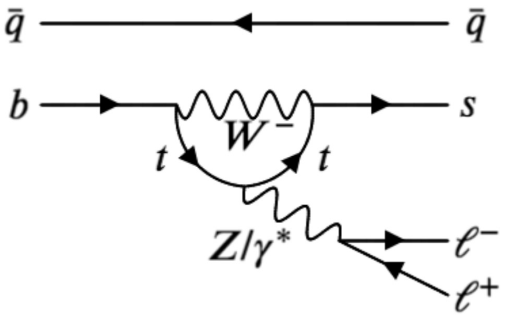
- Lepton flavour universality violation? New Physics!

LFU in $b \to s\ell^+\ell^-$ decays

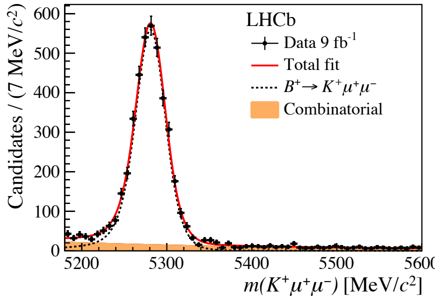
- All consistent with Standard Model for now

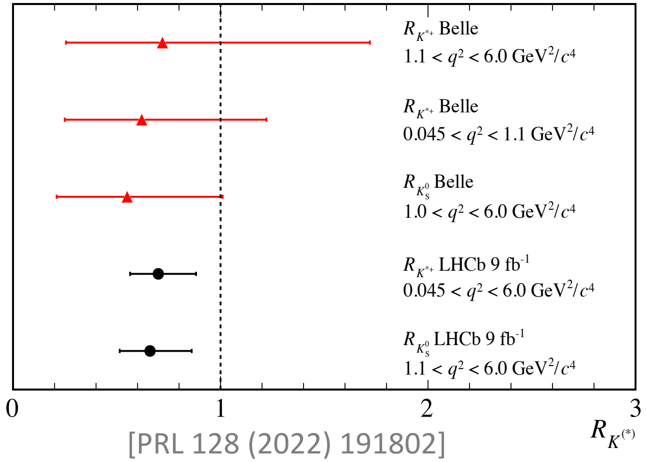


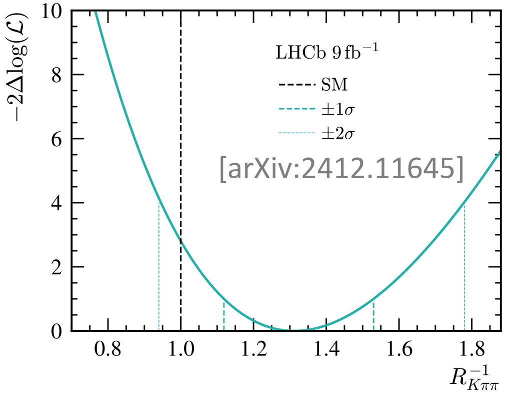


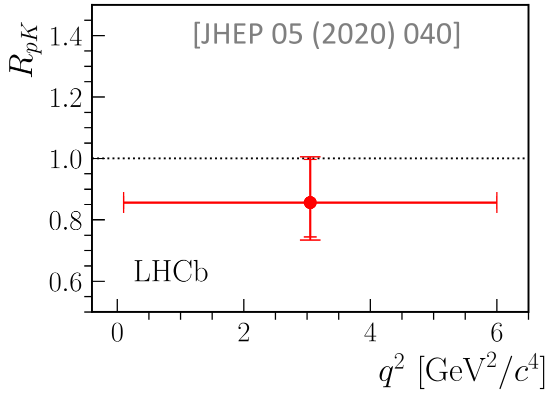


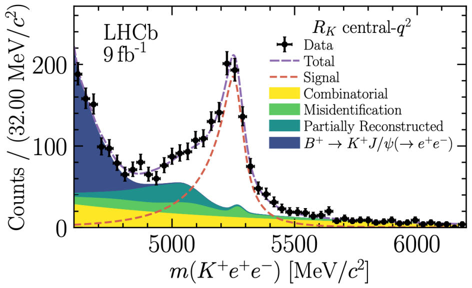
$$R_X = \frac{\mathcal{B}(H_b \to X\mu^+\mu^-)}{\mathcal{B}(H_b \to Xe^+e^-)}$$





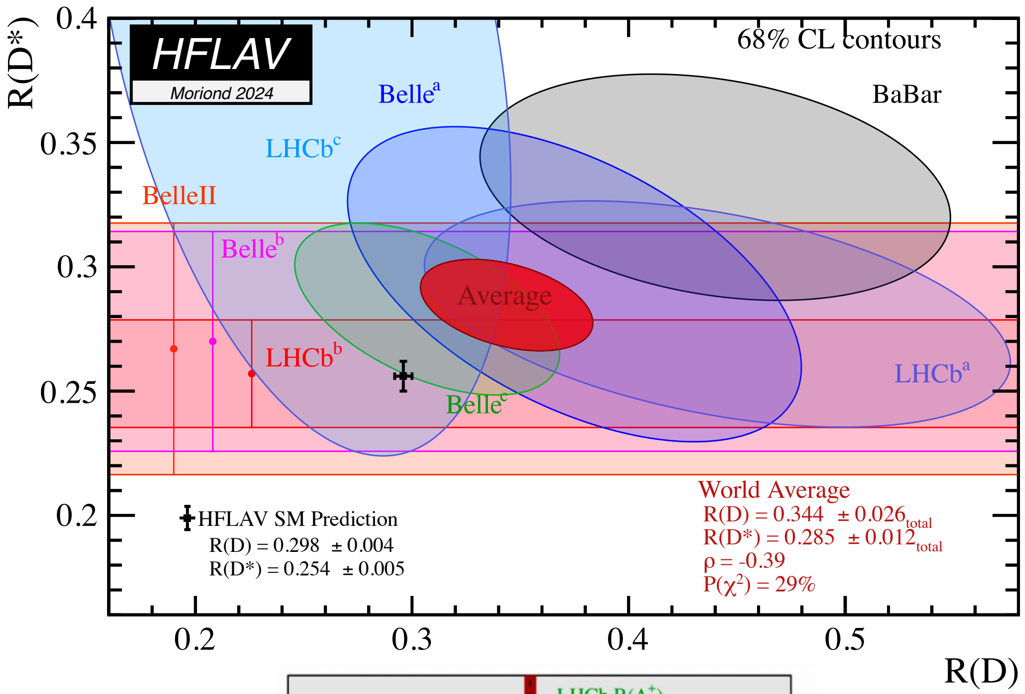


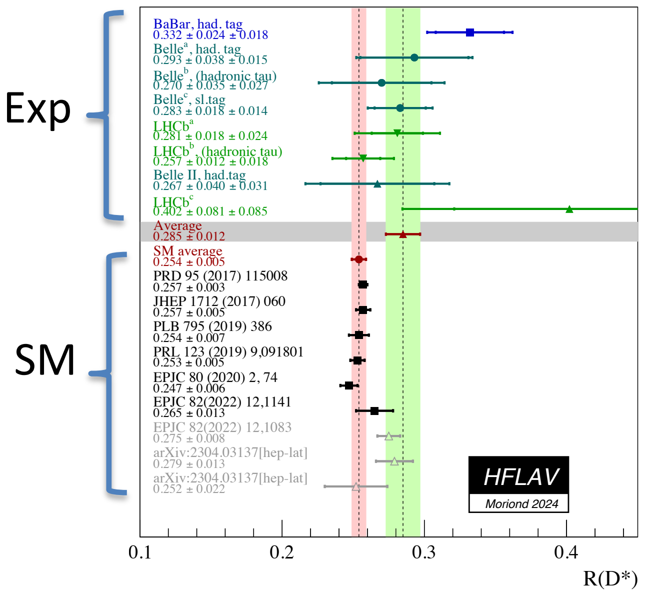


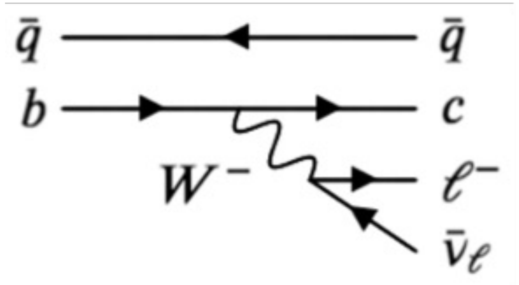


LFU in $b \to c\ell\nu$ decays

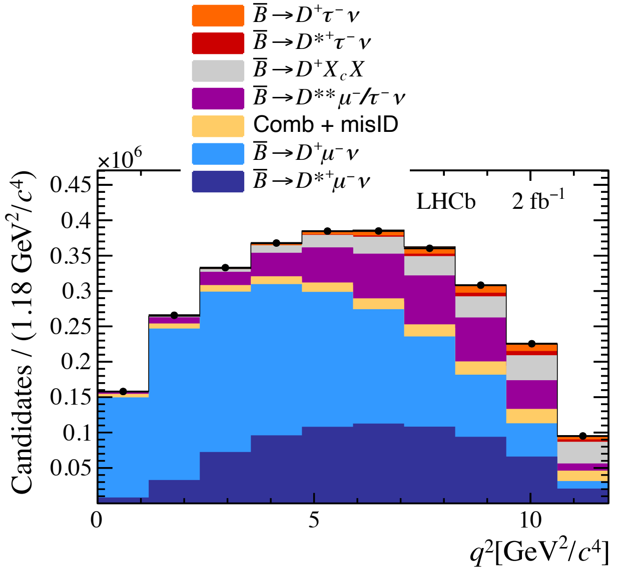
- Deviations from SM seen by Babar/Belle/LHCb

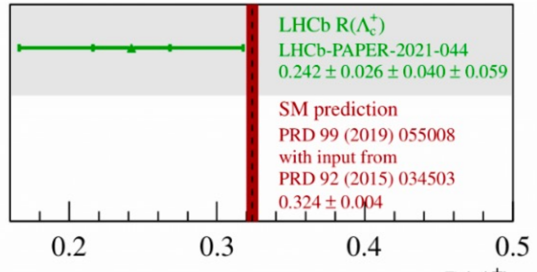




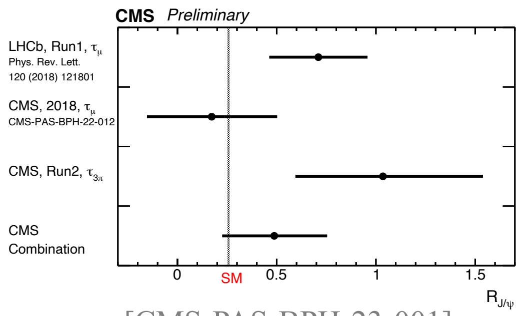


$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c\tau^-\bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c\mu^-\bar{\nu}_\mu)}$$



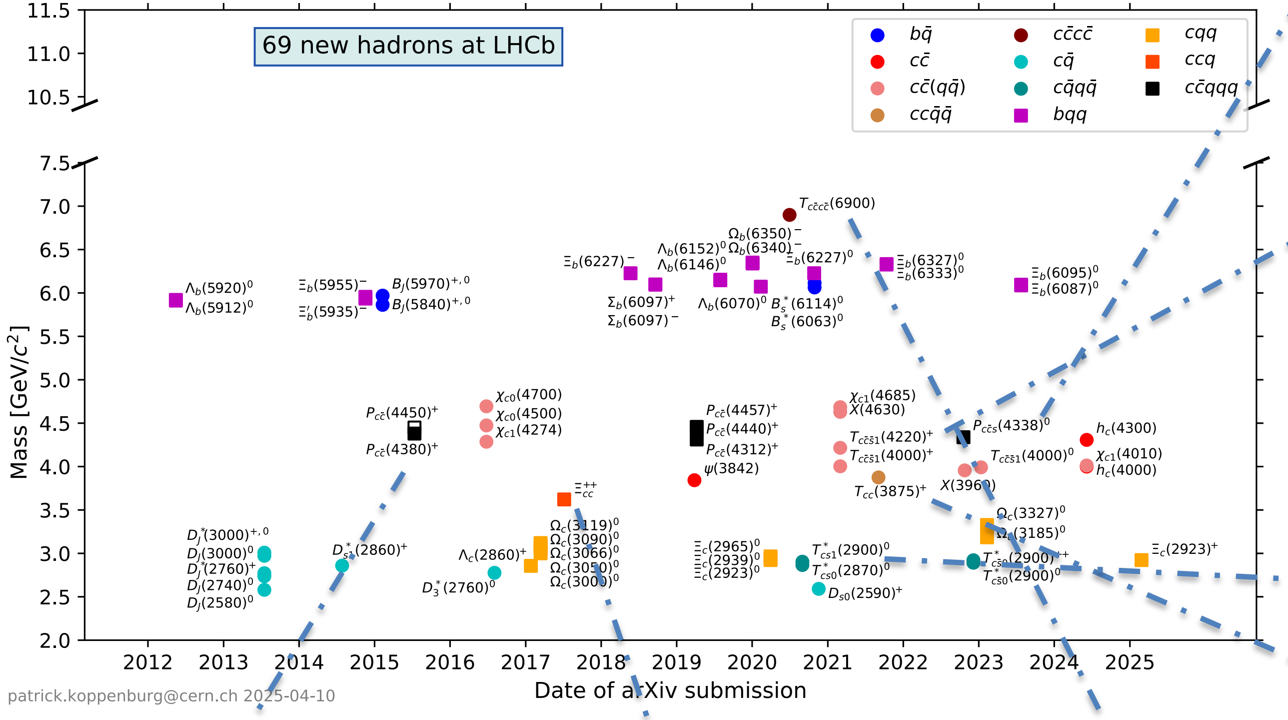


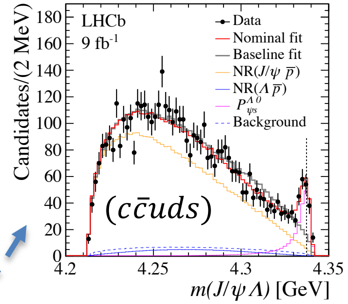
[PRL 128 (2022) 191803]

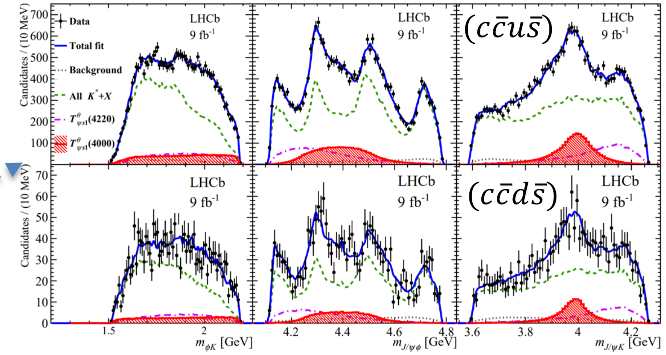


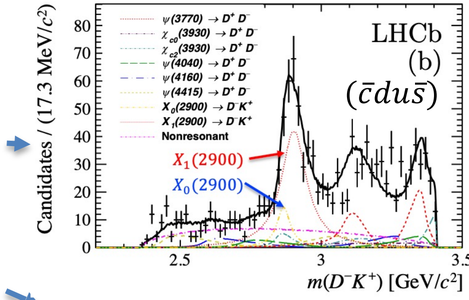
[CMS-PAS-BPH-23-001]

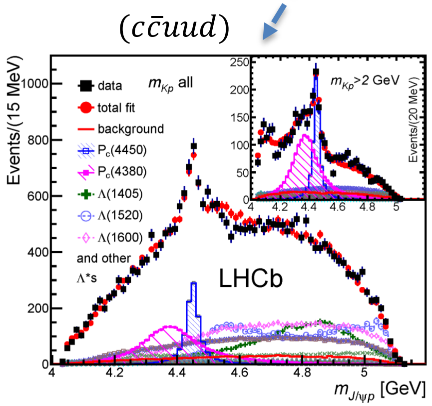
Spectroscopy

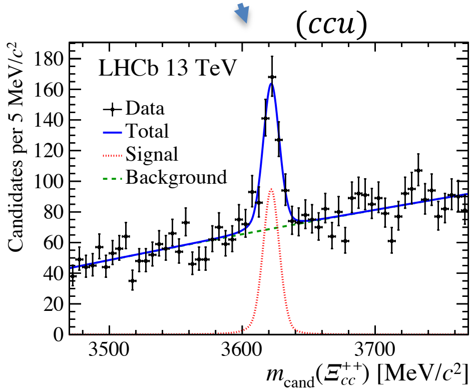


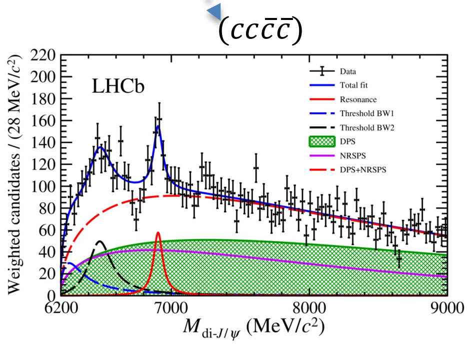


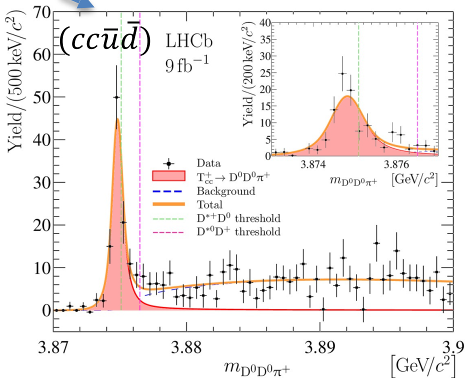




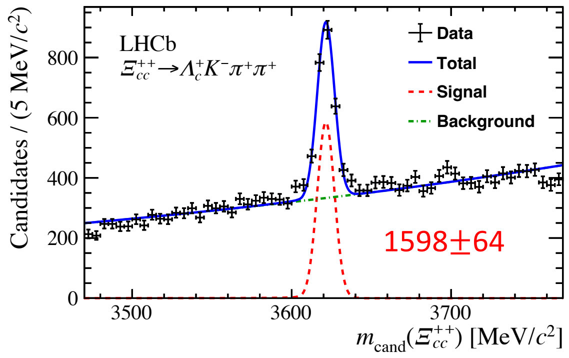


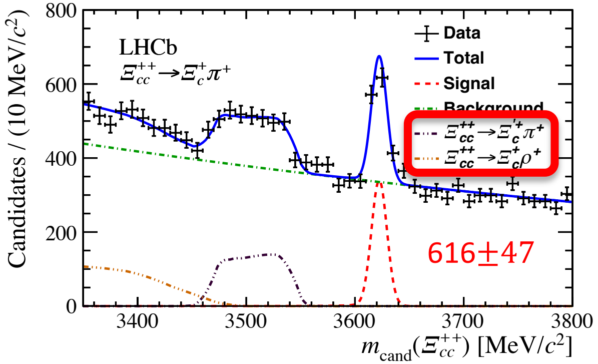


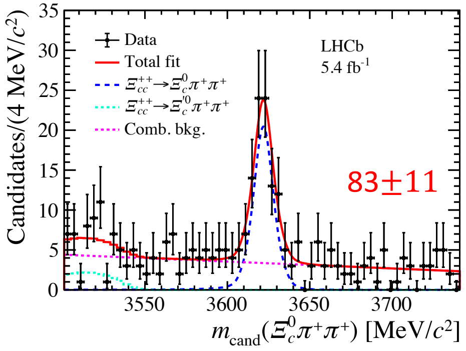




Doubly charmed baryons

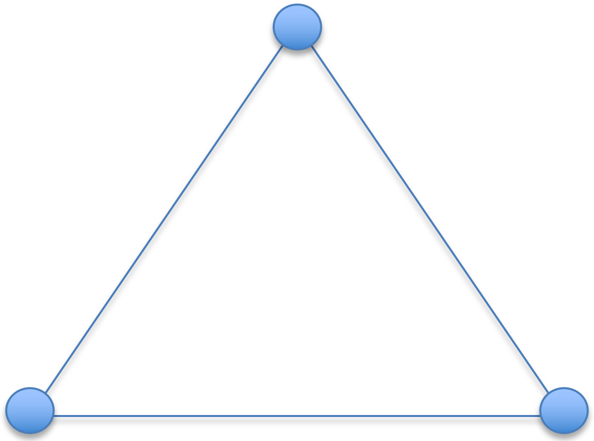






First search, Hint [SCPMA 64 (2021) 101062]

$\Omega_{cc}^{+}\ (ccs)$



$\Xi_{cc}^{++}\ (ccu)$

$\Xi_{cc}^{+}\ (ccd)$

Observation [PRL 119 (2017) 112001]

Mass [JHEP 02 (2020) 049]

Lifetime [PRL 121 (2018) 052002]

Production [CPC 44 (2020) 022001]

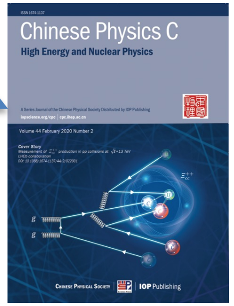
Decay $\Xi_c^+\pi^+$ [PRL 121 (2018) 162002]

$\Xi_c'^+\pi^+$ [JHEP 05 (2022) 038]

$\Xi_c^0\pi^+\pi^+$ [arXiv:2504.05063]

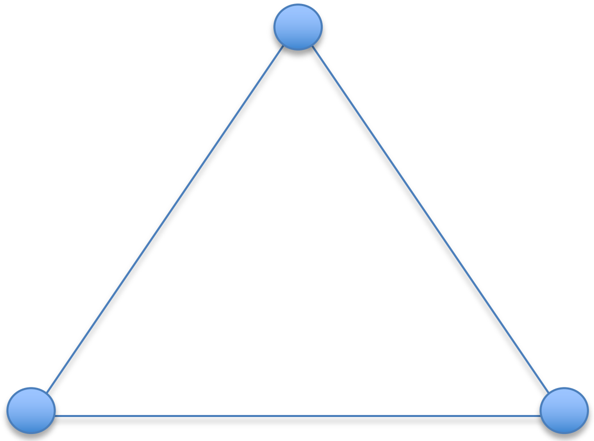
Hint/Evidence

[SCPMA 63 (2020) 221062, JHEP 12 (2021) 107]



First search [CPC 45 (2021) 093002]

$\Omega_{bc}^{0}\ (bcs)$



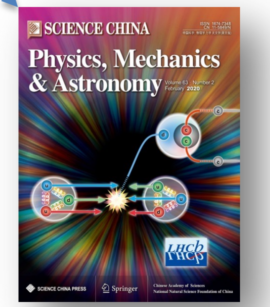
$\Xi_{bc}^{+}\ (bcu)$

$\Xi_{bc}^{0}\ (bcd)$

First search

Hint

[CPC 47 (2023) 093001]



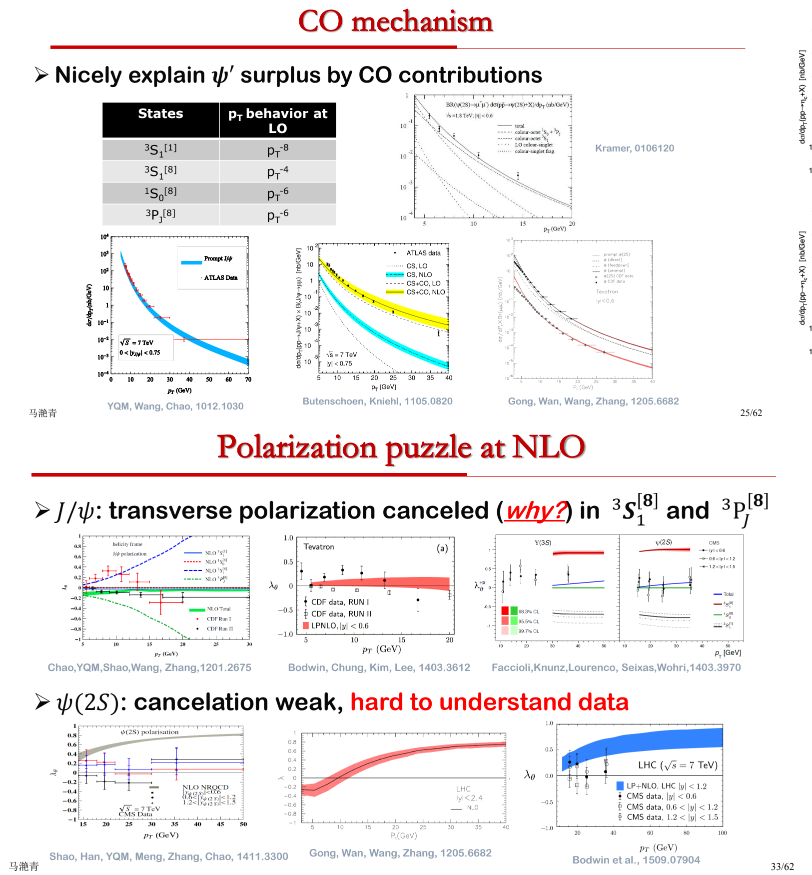
First search

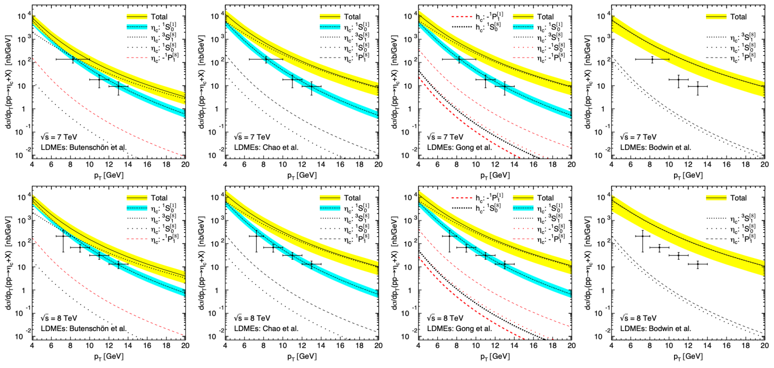
[JHEP 11 (2020) 095]

η_c production

- 50 years after J-particle's discovery, hadroproduction mechanism?

[EPJC 84 (2024) 1274]





[M. Butenschoen, et al., PRL 114 (2015) 092004]

- **LHCb data + HQSS helps to constrain** $\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$

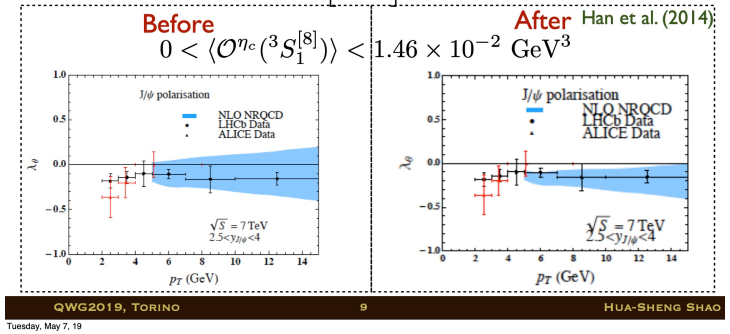
$$\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle = \langle \mathcal{O}^{\eta_c}(^3S_1^{[8]})\rangle$$

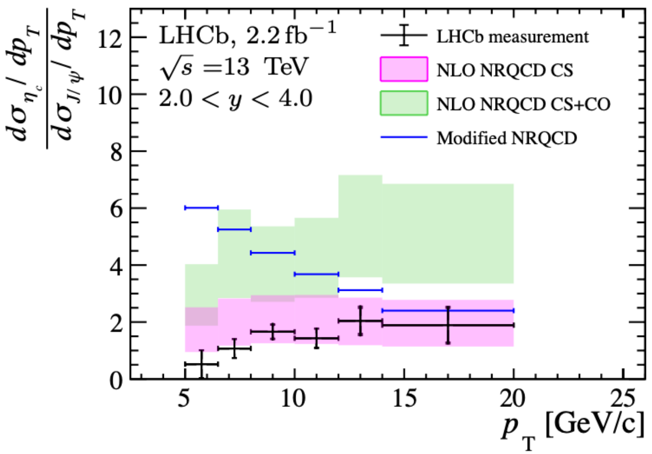
- **A conservative upper limit was set via**

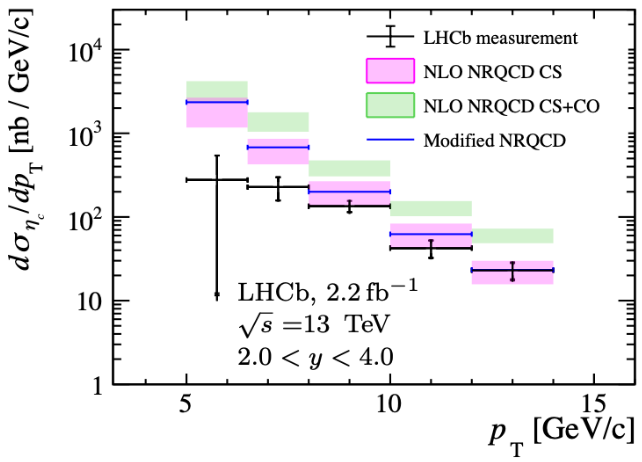
$$\langle \mathcal{O}^{\eta_c}(^3S_1^{[8]})\rangle \hat{\sigma}(c\bar{c}\left[^3S_1^{[8]}\right]) = \sigma_{\text{LHCb data}}$$

Before — After — Han et al. (2014)

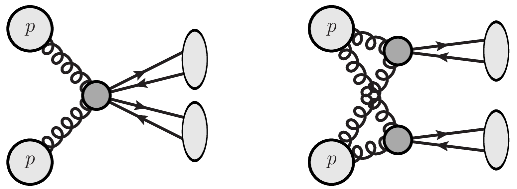
$$0 < \langle \mathcal{O}^{\eta_c}(^3S_1^{[8]})\rangle < 1.46 \times 10^{-2}\ \text{GeV}^3$$





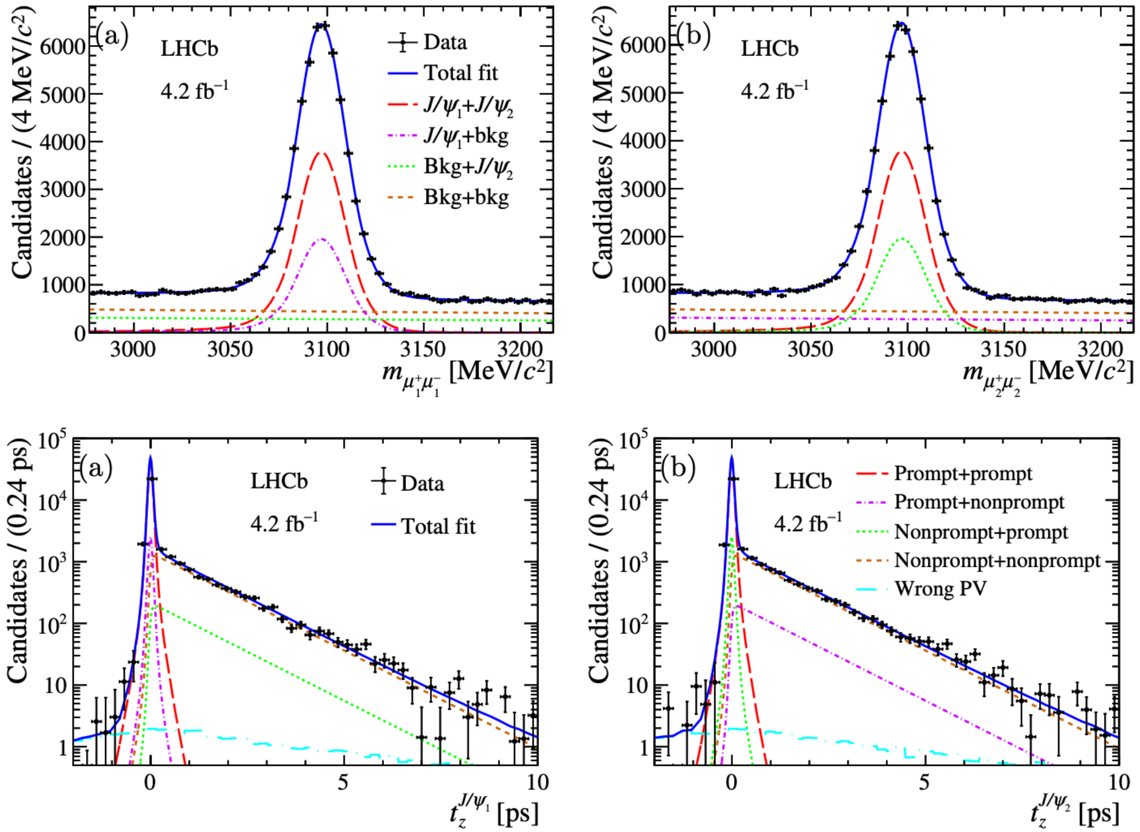


Double parton scattering

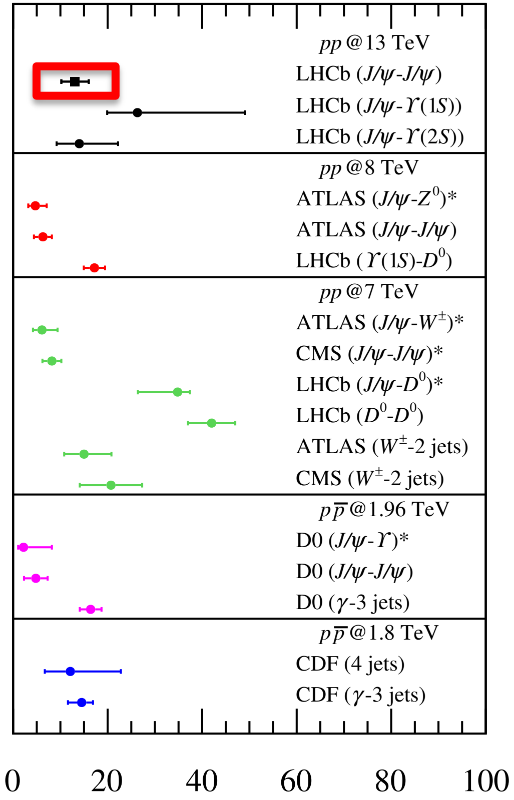


- Δy used to separate DPS from SPS,

  J/ψ+J/ψ, $(2.187 \pm 0.020)\times 10^4$



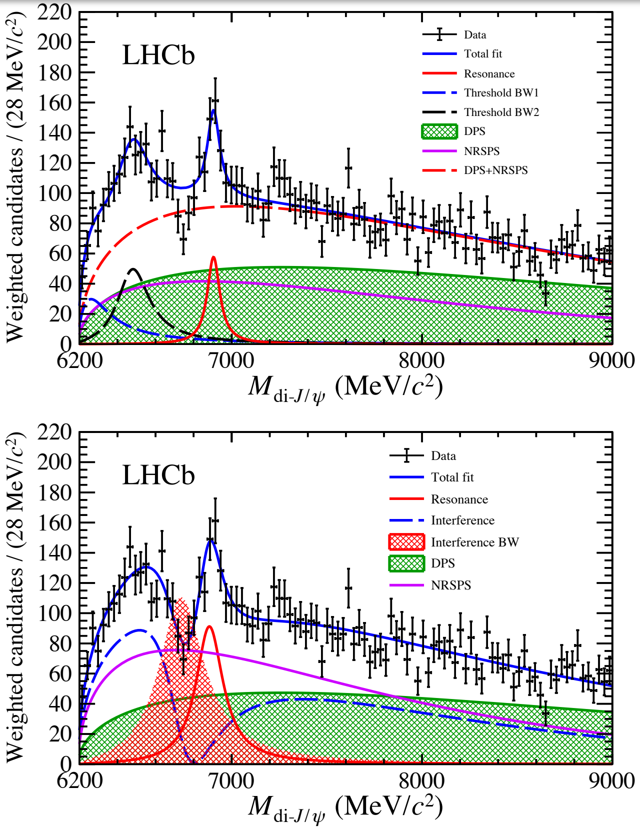
[JHEP 03 (2024) 088]



$\sigma_{\rm eff}$ [mb]

$$\sigma_{\rm eff} = \frac{\sigma_S^{(A)}\sigma_S^{(B)}}{\sigma_D^{(A,B)}}$$

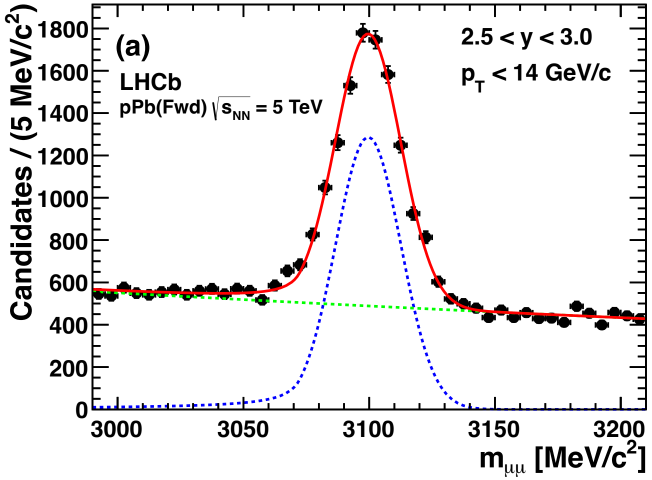
Inputs needed for $X(6900)$ studies

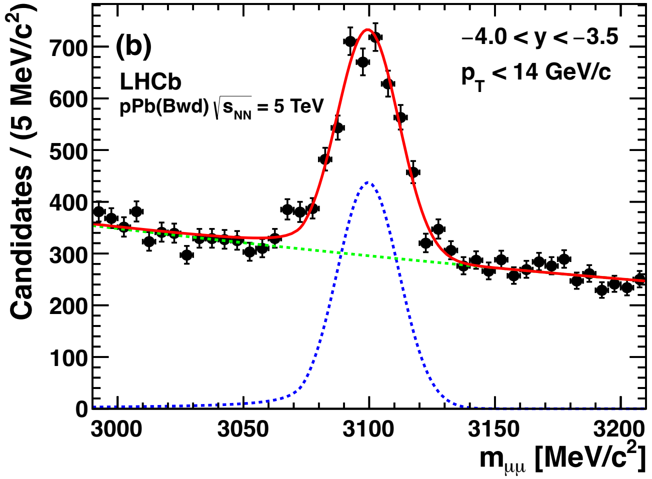


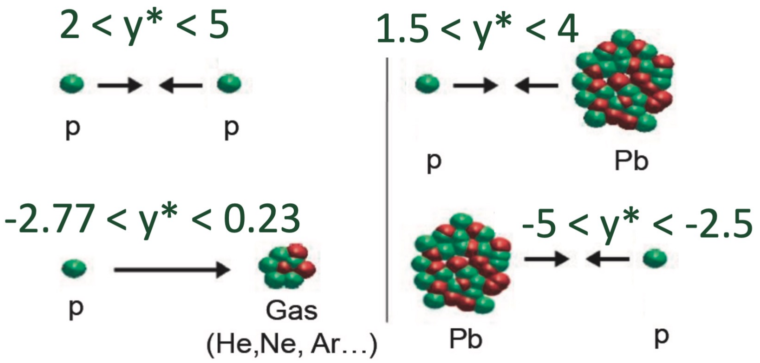
[Science Bulletin 65 (2020) 1983]

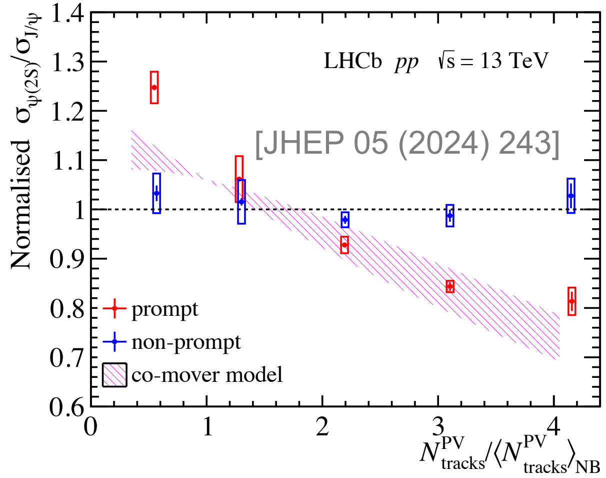
Charmonium suppression

- In 2013 LHCb joined heavy-Ion run for the 1st time

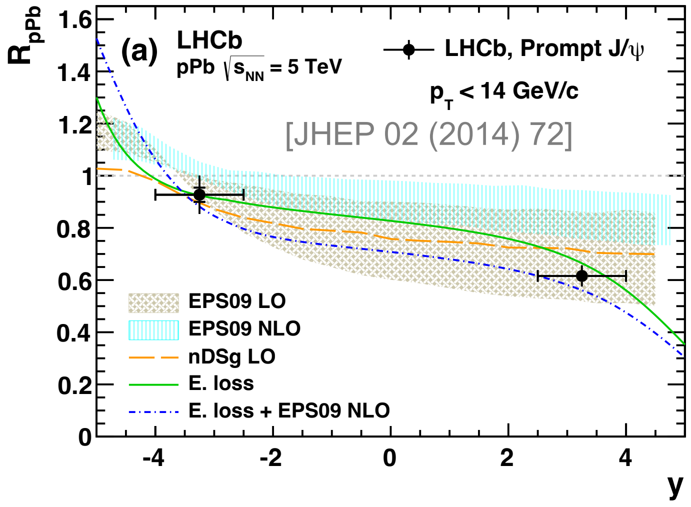




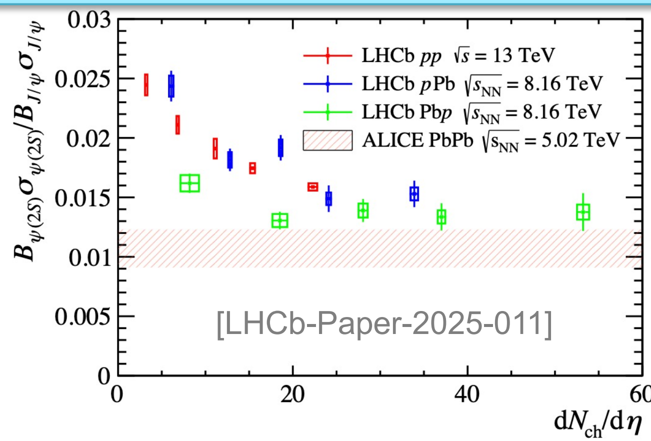




Clear suppression wrt *pp*

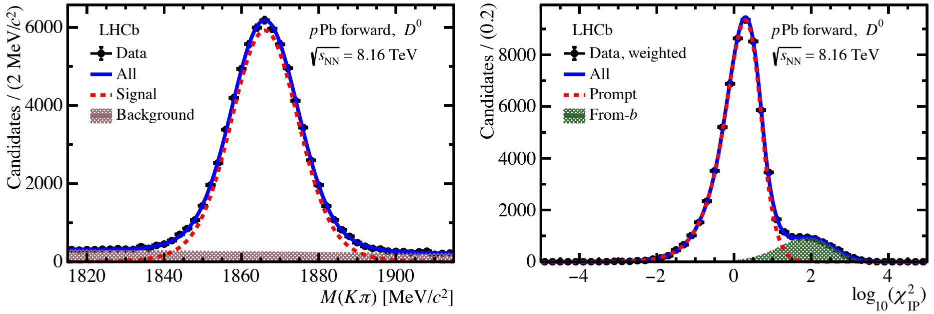


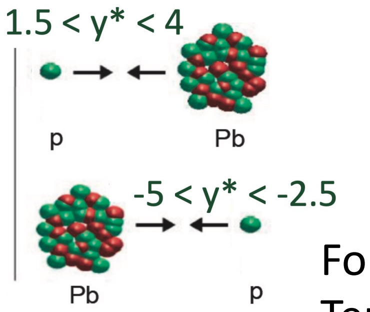
Stronger suppression in Pb-going direction, similar to PbPb, not entirely from comovers?



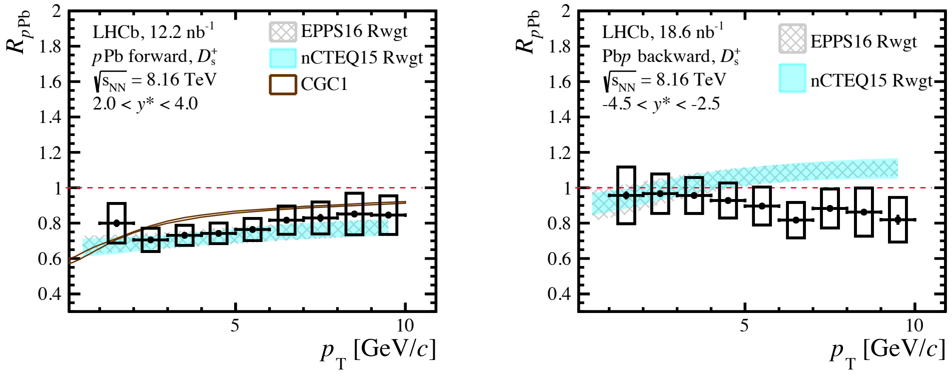
Open charm in *p*Pb

- Provides constraints on nPDF…



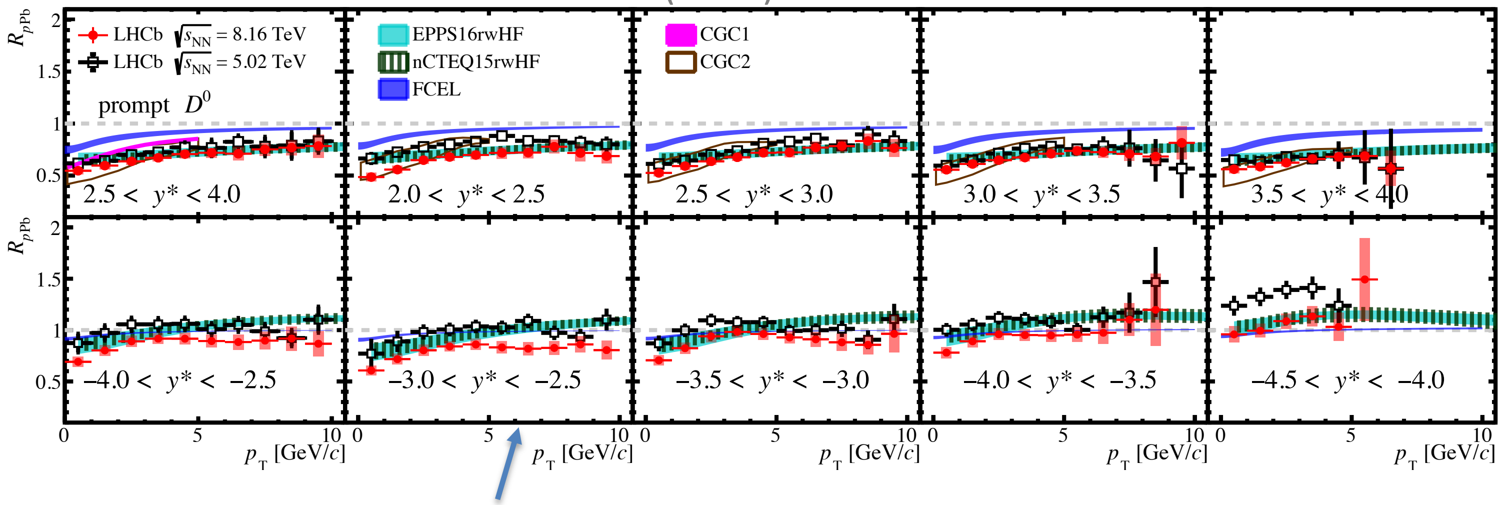


PRD 110 (2024) L031105

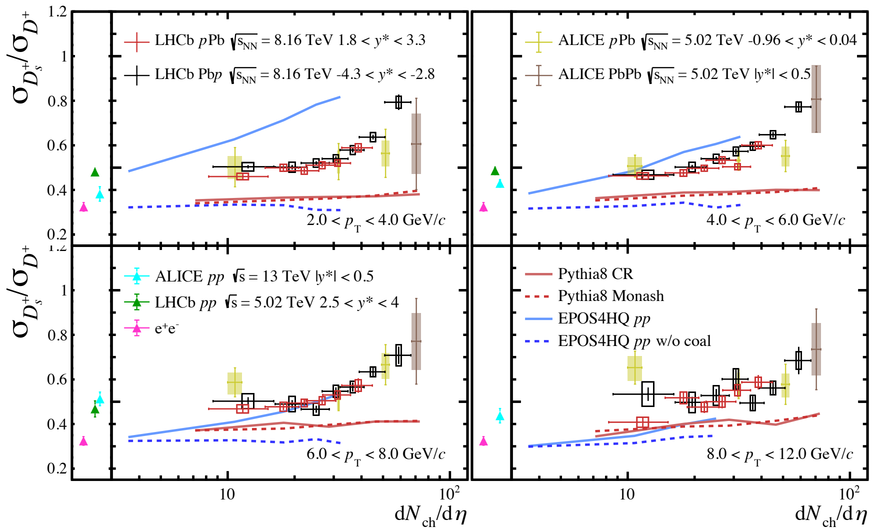


Forward D_s^+ consistent with updated nPDF calculation,
Tension at backwards rapidity, additional effects?

PRL 131 (2023) 102301



Some tension at backward rapidity

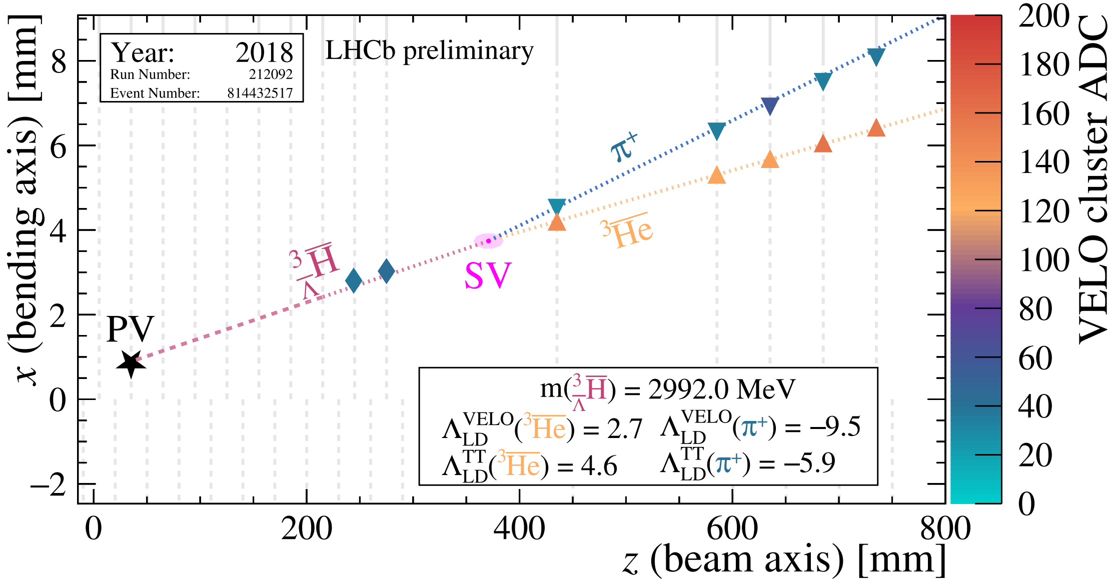


Clear strangeness enhancement

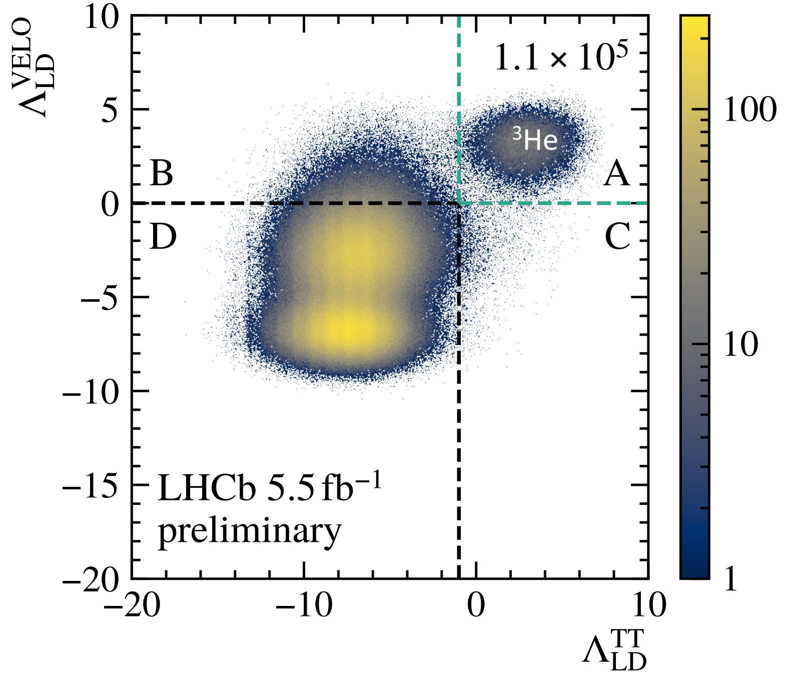
Nuclei production

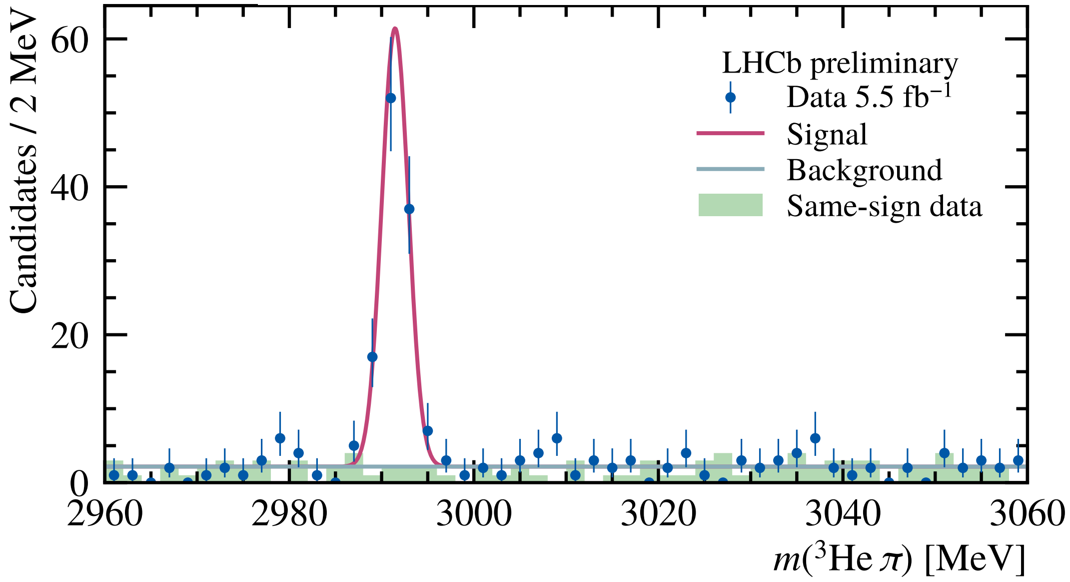
- New method to identify *d* and ^{3}He
- Clean sample of (anti)hypertritons

[LHCb-Conf-2023-002]



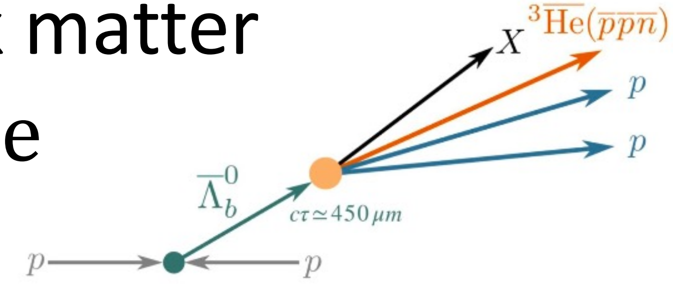
Event display of hypertriton candidate – ^{3}He identified by dE/dx in silicon layers



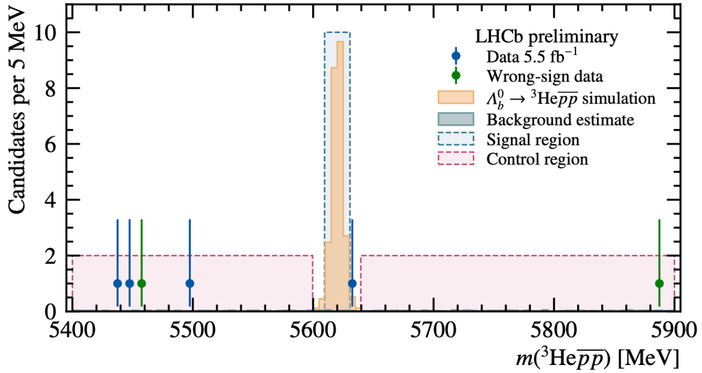


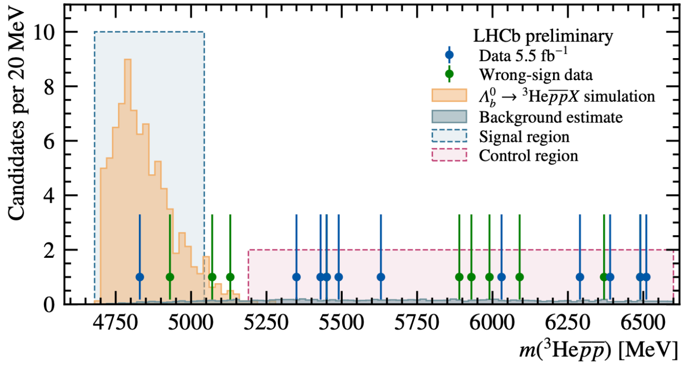
Antihelium production in $\bar{\Lambda}_b^0$ decays

- Antihelium in cosmic rays, "Smoking gun" for new physics
- One explanation of antihelium by AMS02, dark matter annihilations to $b\bar{b}$, $\bar{\Lambda}_b^0$ has significant BR to $^3\overline{\mathrm{He}}$

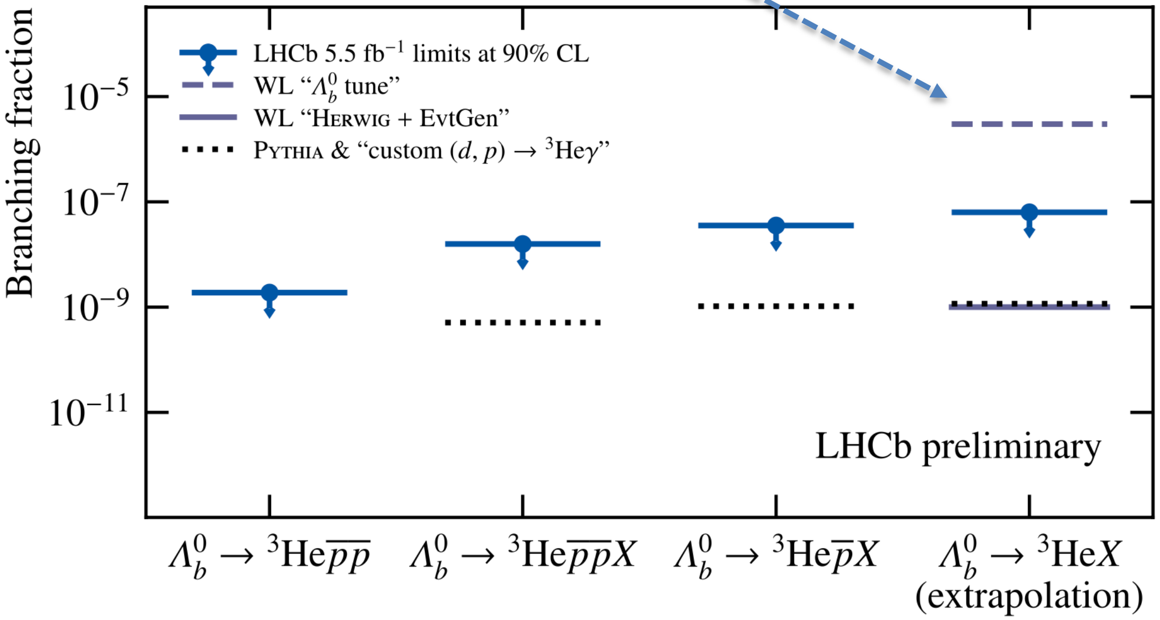


[LHCb-Conf-2024-005]





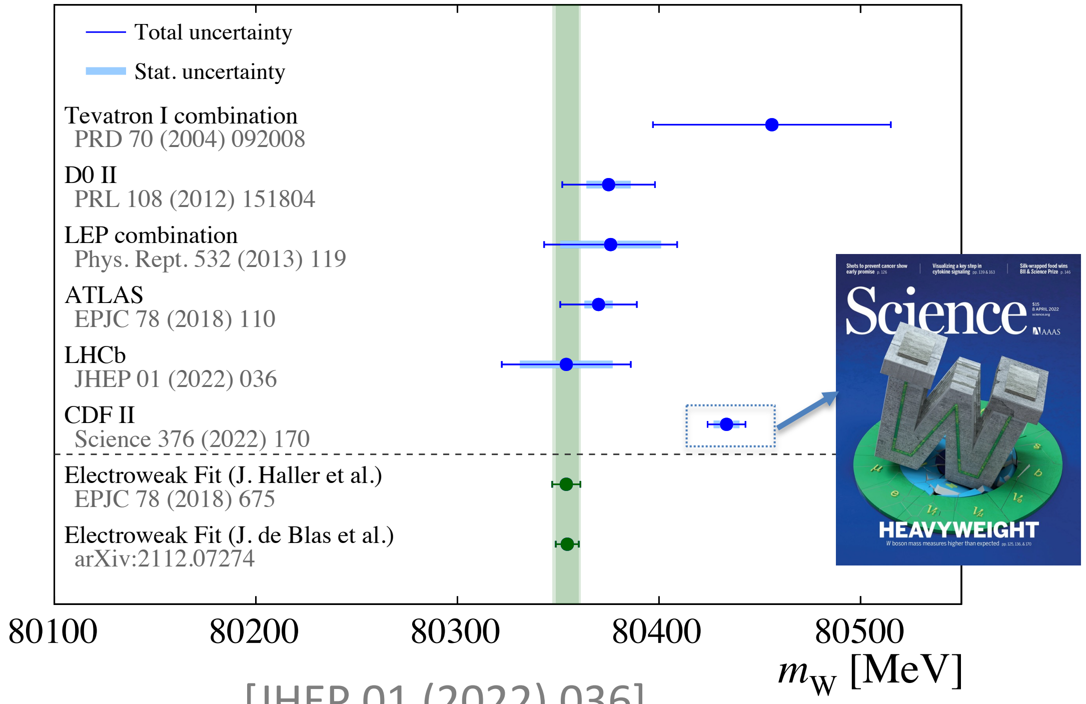
[PRL 126 (2021) 101101]



W/Z boson mass

- CDF results on W mass demand more measurements at LHC

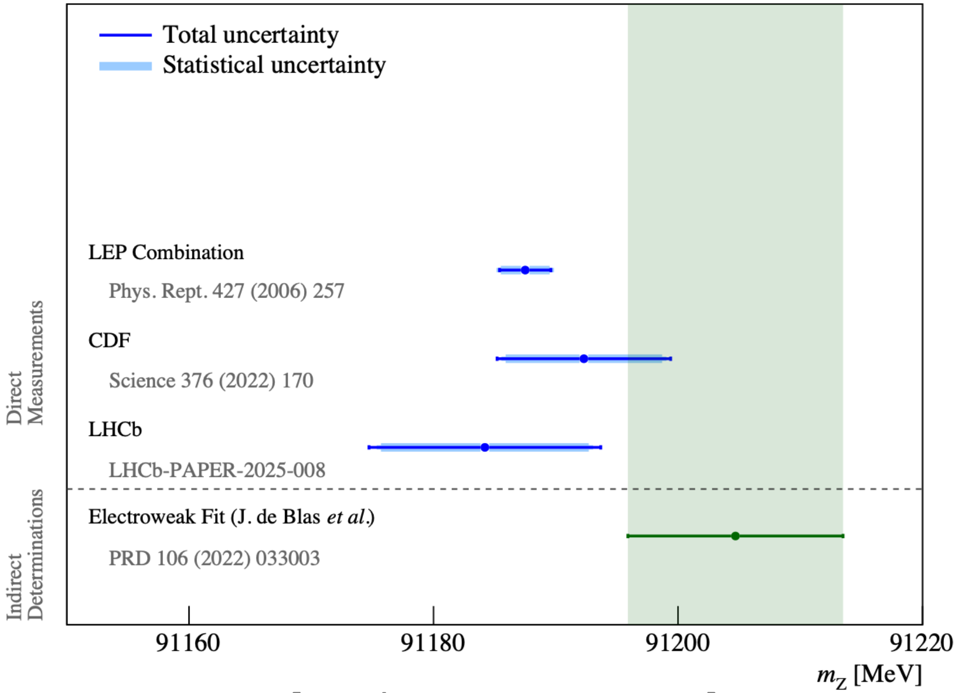
$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{th}} \pm 9_{\text{PDF}}$ MeV



[JHEP 01 (2022) 036]

- First direct measurement of m_Z at LHC

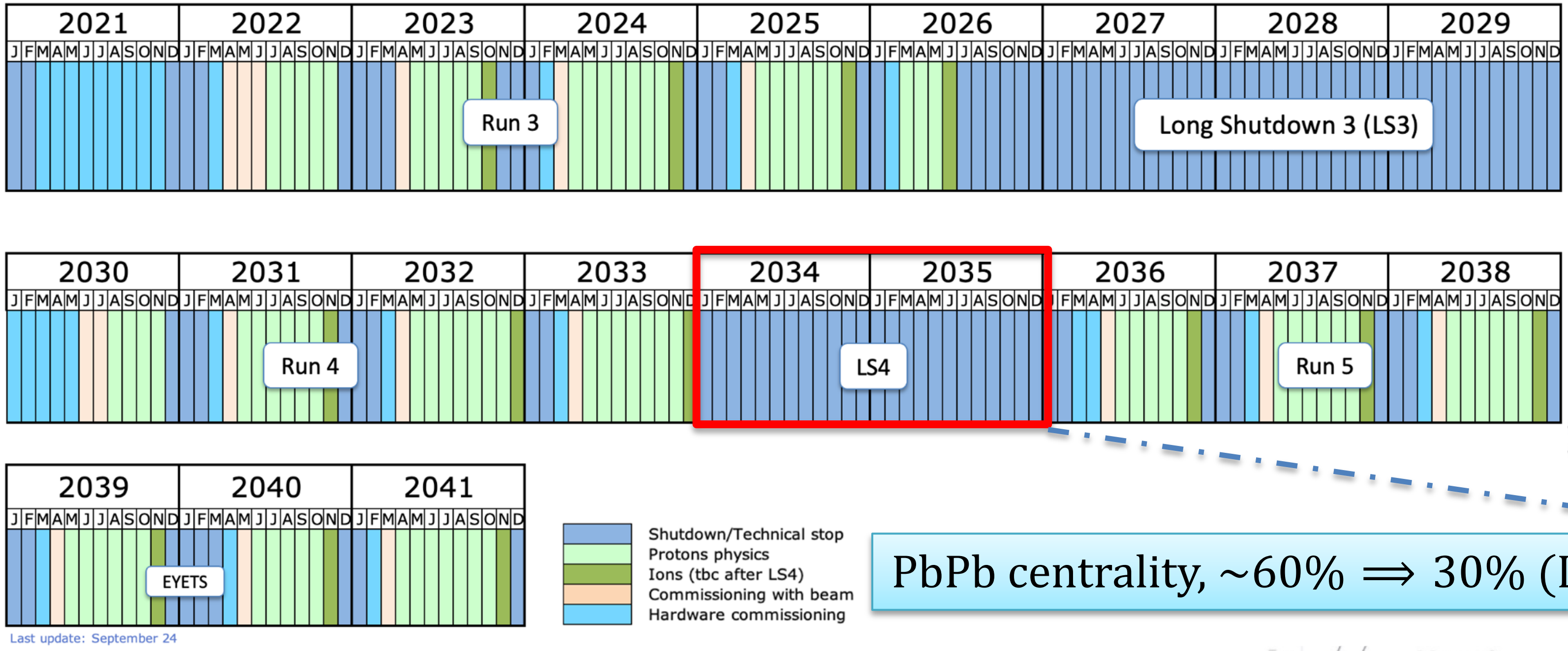
$m_Z = 91184.2 \pm 8.5 \pm 4.3$ MeV

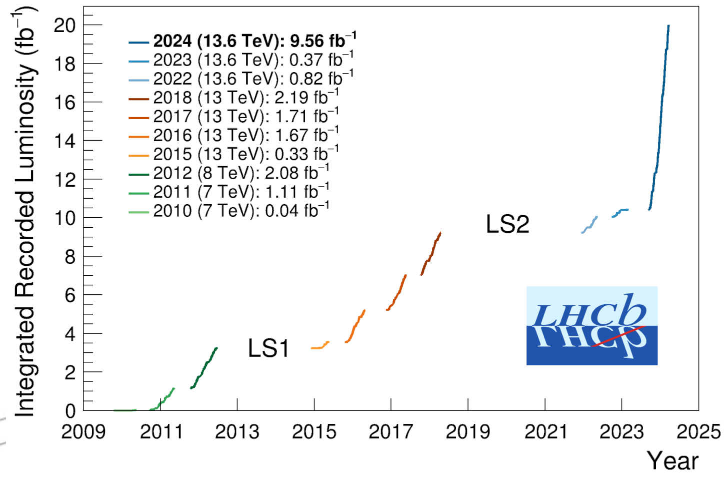


[LHCb-Paper-2025-08]

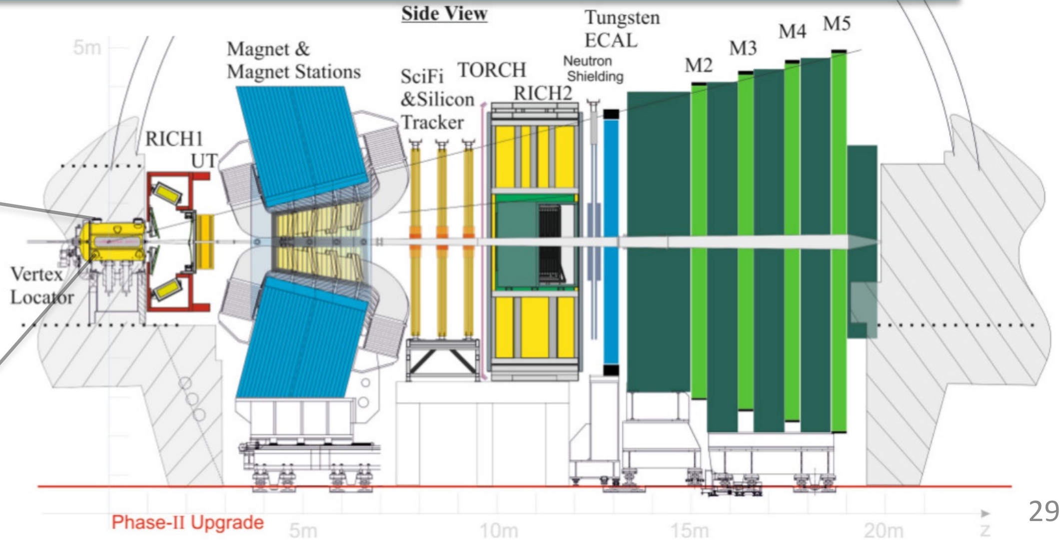
The LHCb upgrades

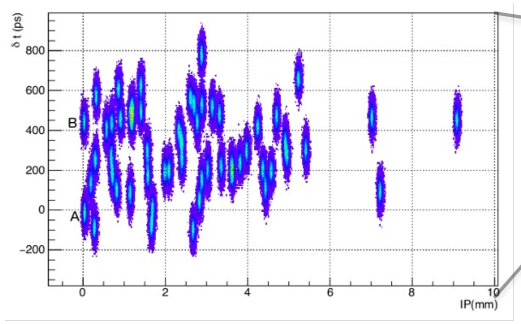
[CERN-LHCC-2018-027, 2021-012]





PbPb centrality, ~60% $\Longrightarrow$ 30% (LHCb-UI) $\Longrightarrow$ 0% (LHCb-UII)

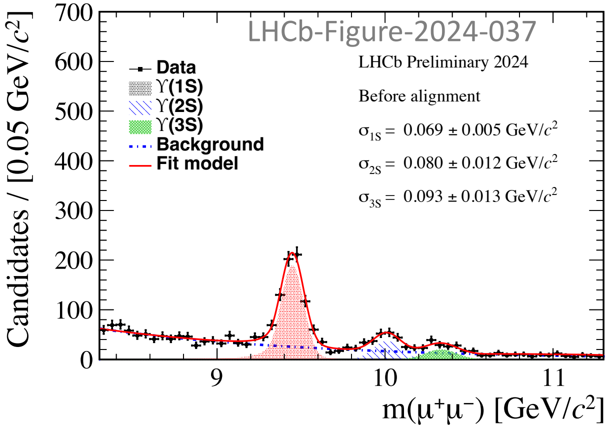


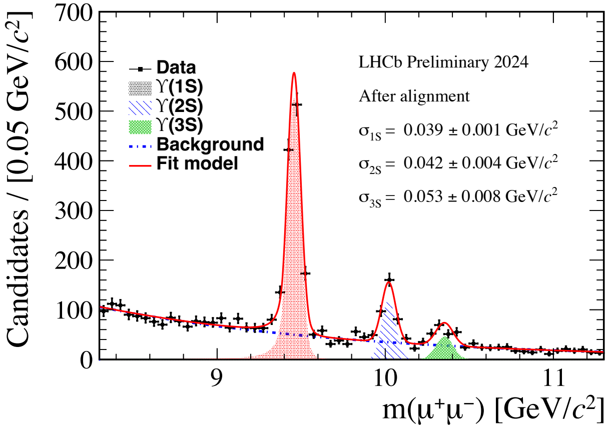


Upgrade II, 4D detector , Timing, $\mathcal{O}(10\text{ ps})$, is essential

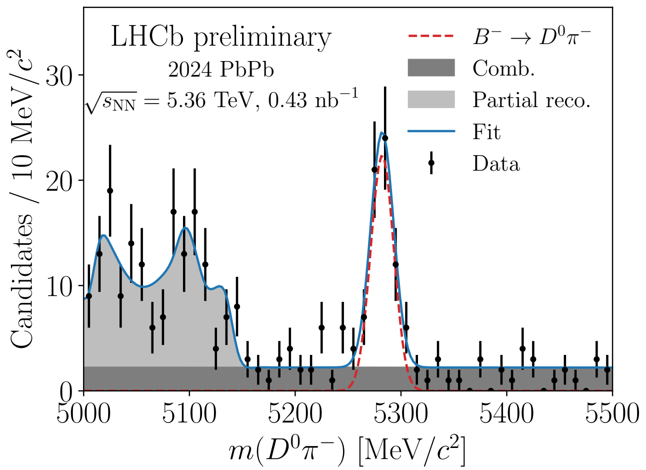
Data-taking in 2024

- Calibration / alignments much improved



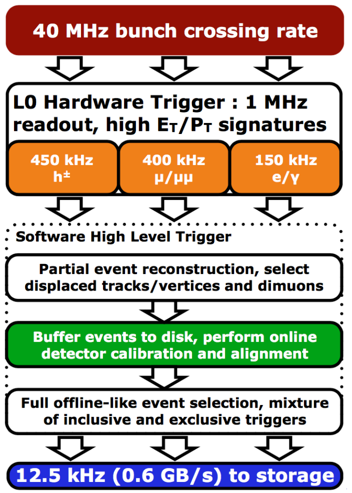


LHCb-Figure-2025-004

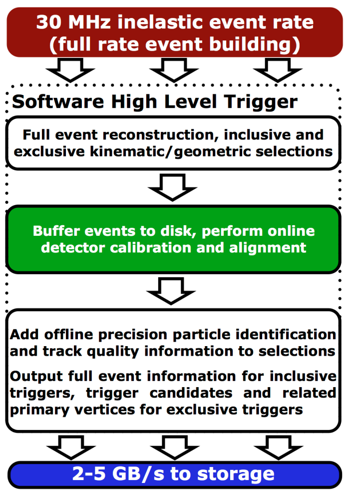


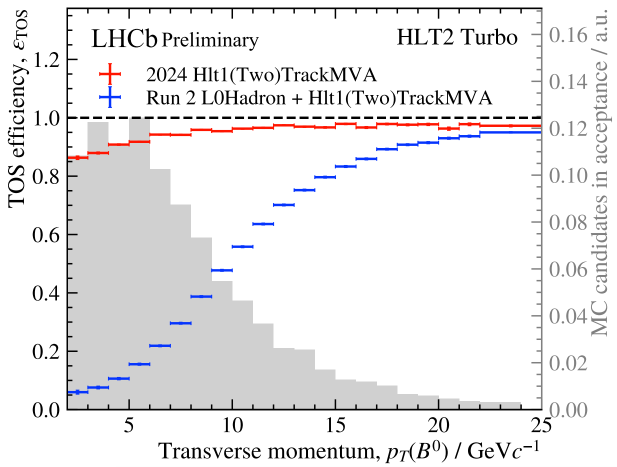
Fully hadronic B decays in PbPb

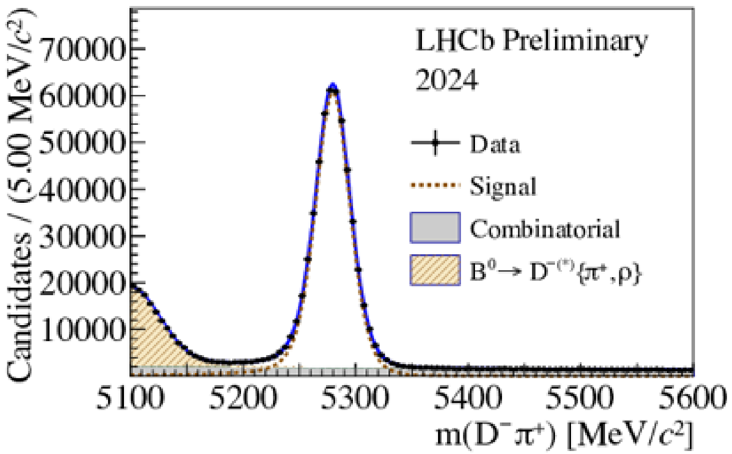
2018



2024



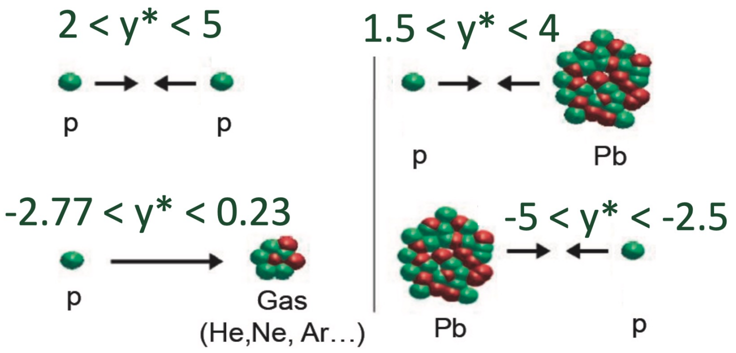


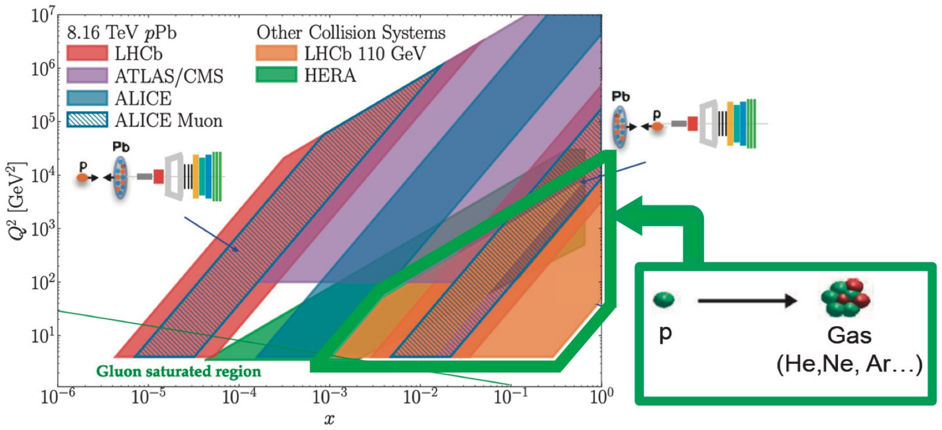


Trigger efficiency for hadronic modes improved by ~2

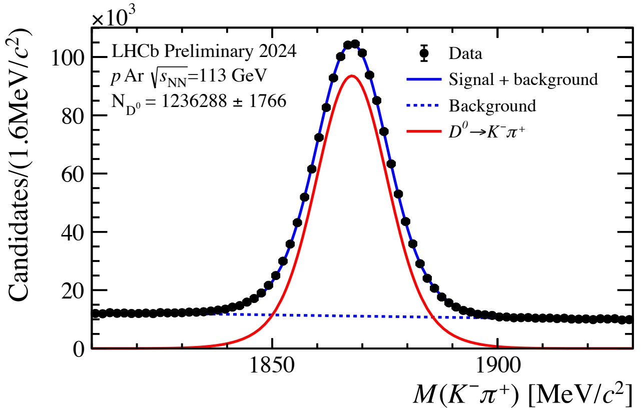
SMOG (System for Measuring Overlap with Gas)

[LHCb-Figure-2023-008]

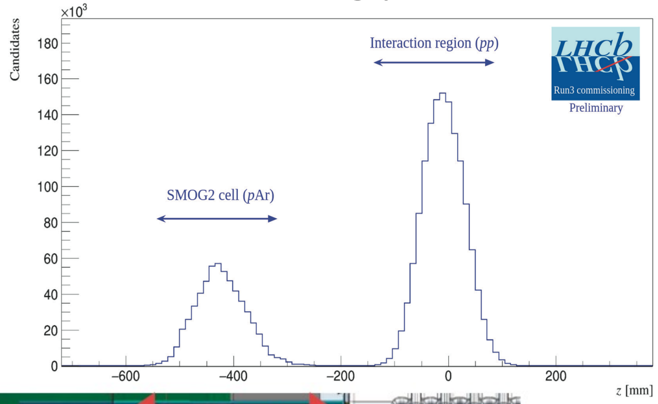


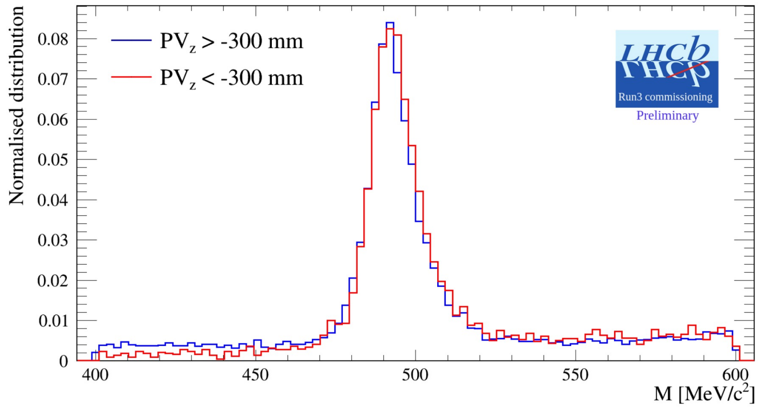


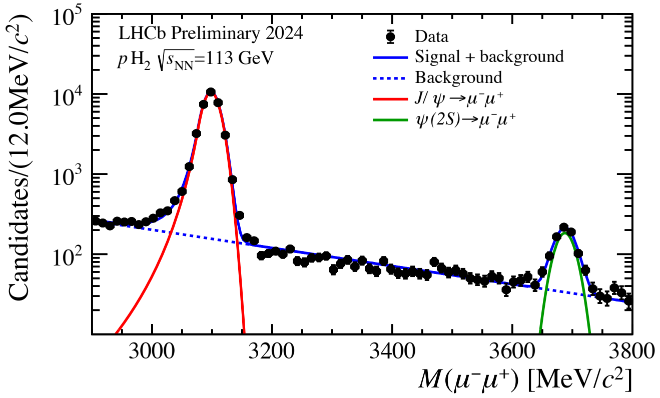
[LHCb-Figure-2024-003]

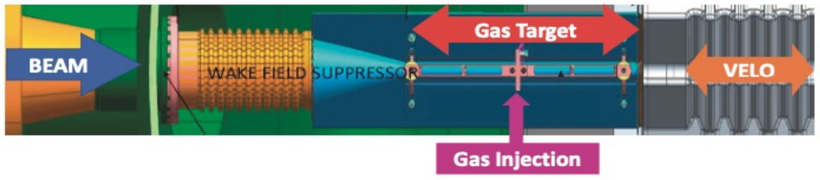


Simultaneous data-taking possible







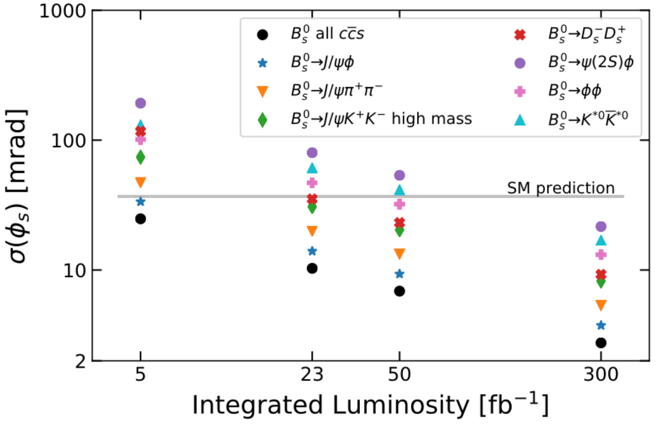


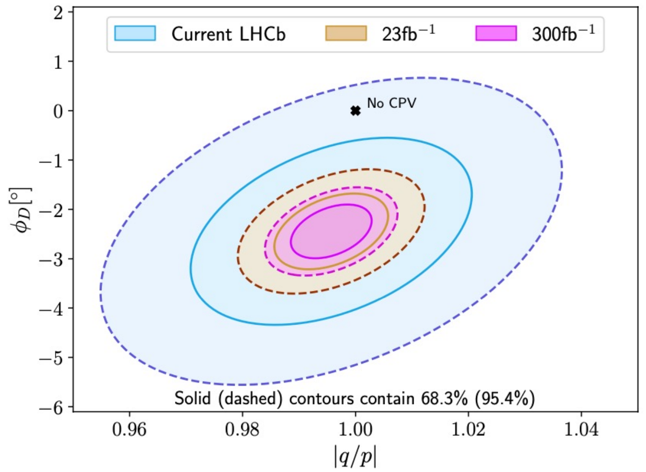
Prospects

[CERN-LHCC-2018-027, 2021-012]

- **LHCb upgrades** (2025: 23 fb^{-1}, Upgrade-II: 300 fb^{-1})

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	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 $B^0 \to J/\psi K_S^0$	0.04 [606]	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 [607]
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 [608]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [609]
$\tau_{B_s^0 \to \mu^+\mu^-}$	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} [610]	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}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–





Summary

- Many interesting results from LHCb
  - Baryon CPV, ϕ_s; $B_s^0 \to \mu^+\mu^-$, $b \to s\mu^+\mu^-$; Exotic hadrons, charmonium production in *pp* and in *p*A, antihelium; W/Z mass

  collaboration between theory and experiments essential
- Stay tuned w/ LHCb upgrade (50 fb^{-1}) & upgrade-II (300 fb^{-1})
  - Trigger efficiency for hadronic modes improved by factor of ~2
  - Improving calibration & alignment essential for precision
- Your suggestions are always appreciated!