CKM and flavour physics
at
LHCb

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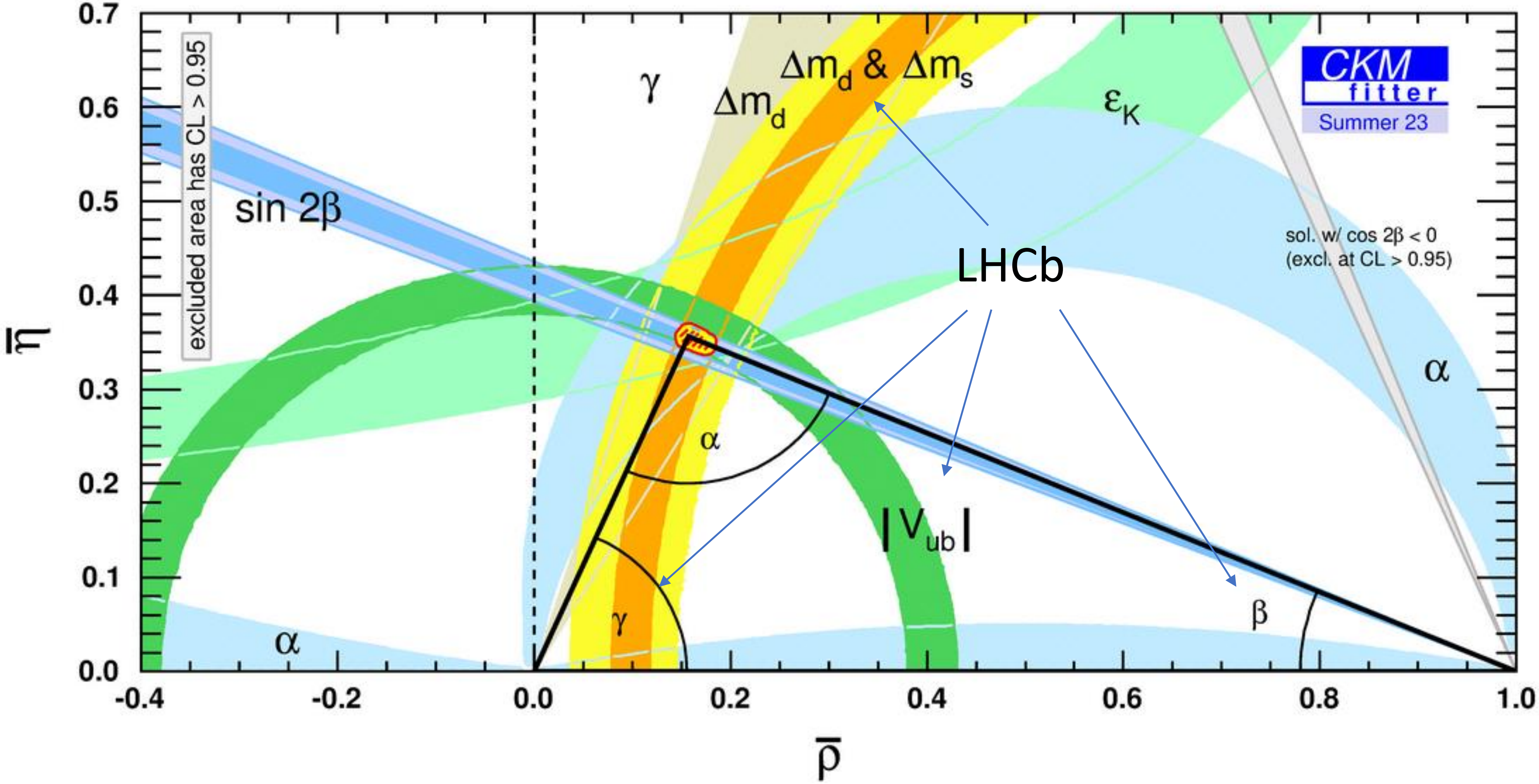
IJCLab Orsay

BABAR symposium

Talk outline

- What I will cover
  - **CKM physics: angles and sides**
  - **Lepton Flavour Universality**
- What I will not cover
  - Charm Physics
  - Rare decays
  - Hadron Spectroscopy
  - …
- Some **recent results** and **some retrospective**
- **Some projections for the future Run3 and beyond**



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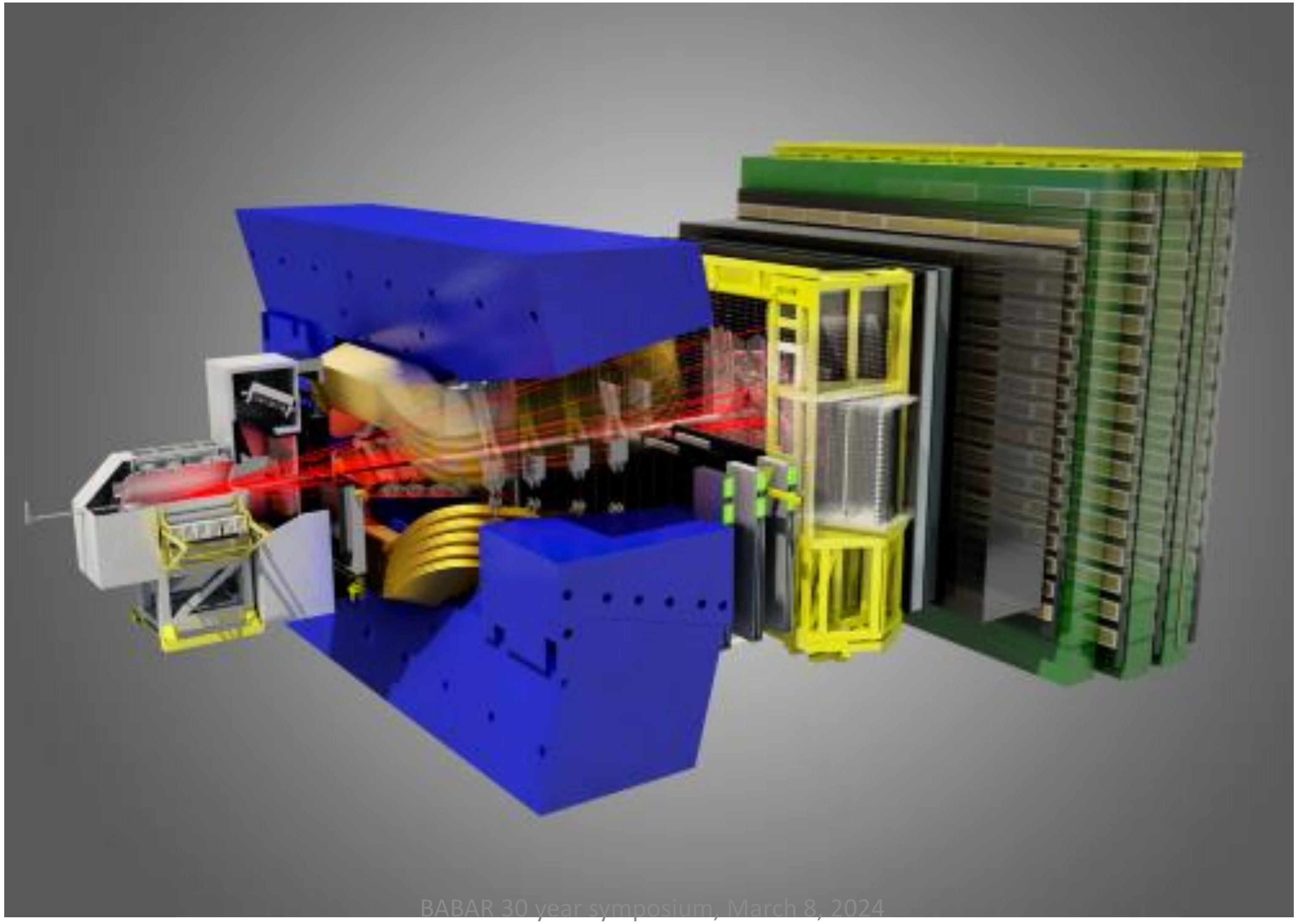
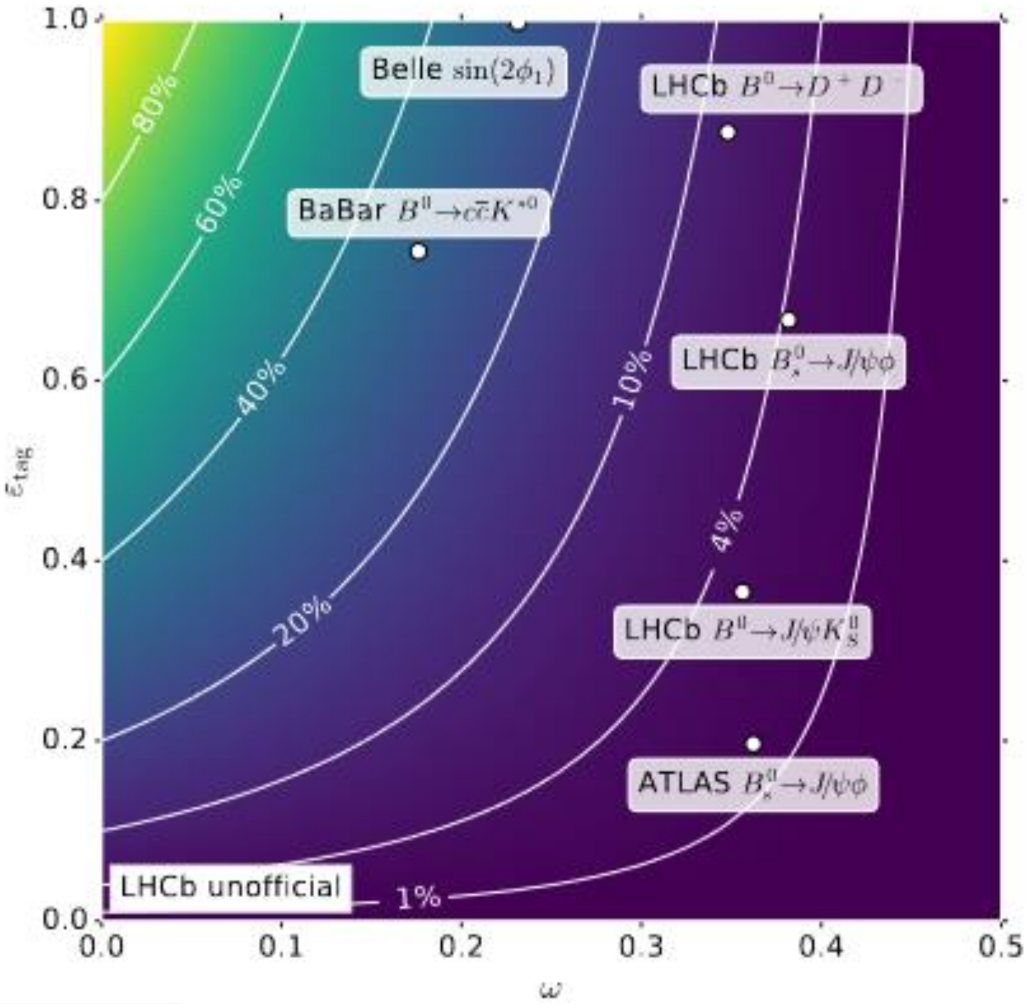
The LHCb detector

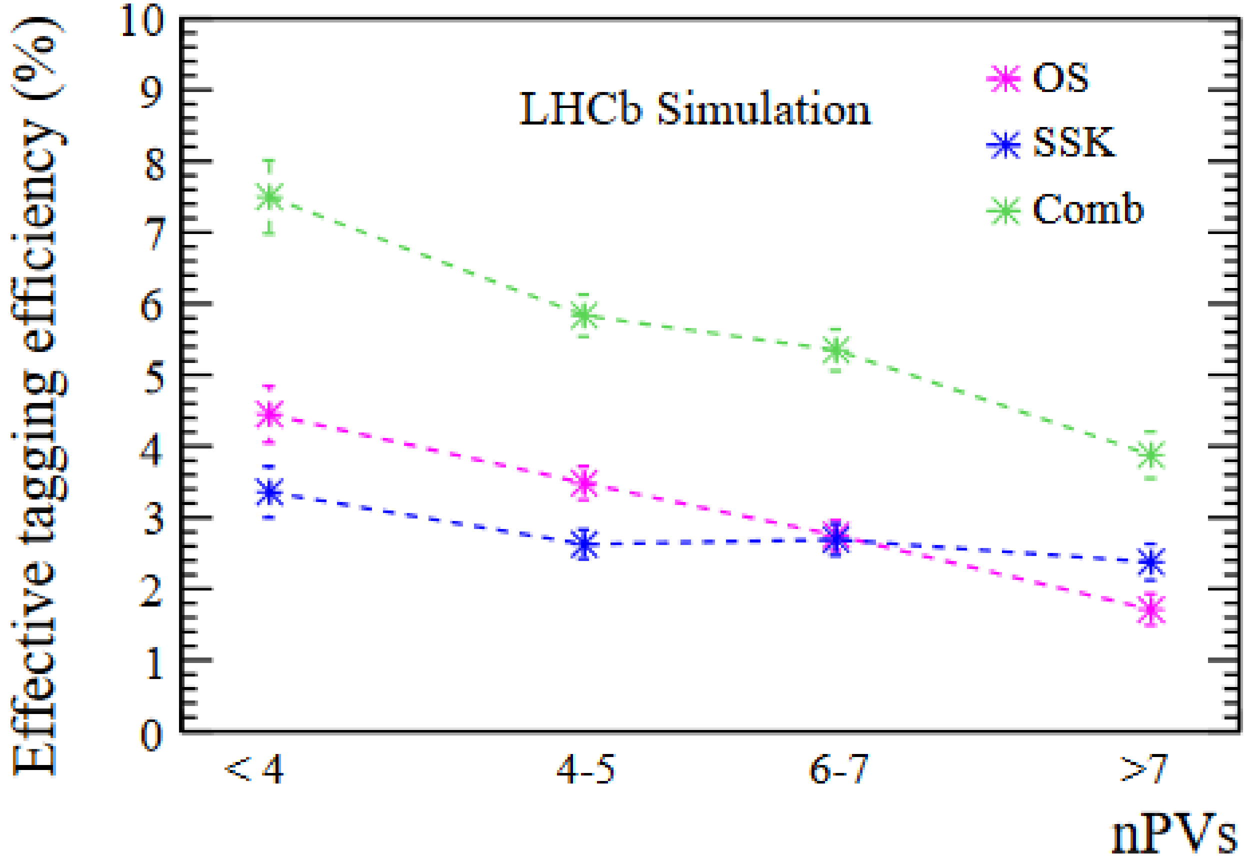


CKM physics at LHCb: What was expected

- Regarding angles
  - B_s CP violation studies:
    - **Φ_s LHCb-PAPER-2023-016 ($B_s \to J/\psi KK$)**, (LHCb-PAPER-2019-003, $B_s \to J/\psi\pi\pi$)
    - Φ_{sss} LHCb-PAPER-2023-001 ($B_s \to \phi\phi$), (LHCb-PAPER-2017-048, $B_s \to (K\pi)(K\pi)$)
  - **Measurement of γ angle LHC-CONF-2023-004 LHCb-CONF-2022-003**
  - Sub-dominant contribution to β determination
- Regarding sides
  - **B_s mixing** (PAPER-2023-025, **PAPER-2022-010**).
  - Sub-dominant contributions to V_{cb} and V_{ub}

Tagging at LHCb (CERN-PUB-2018-019)

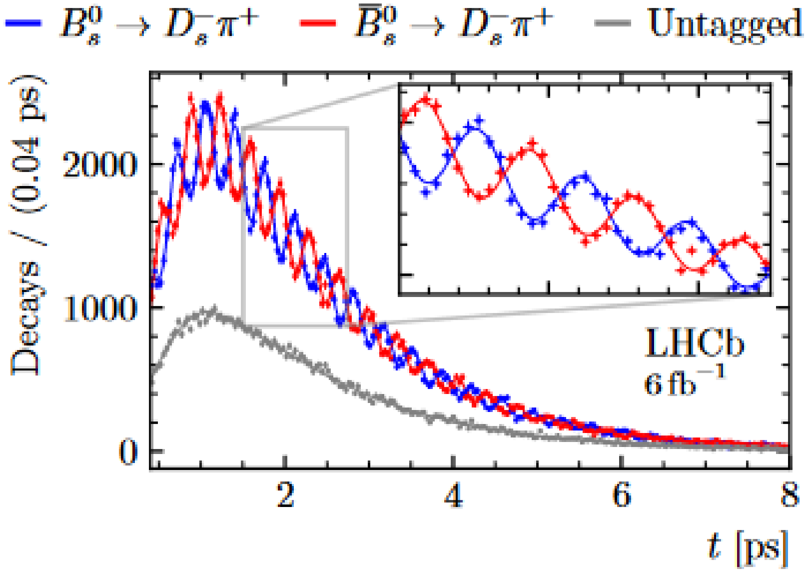


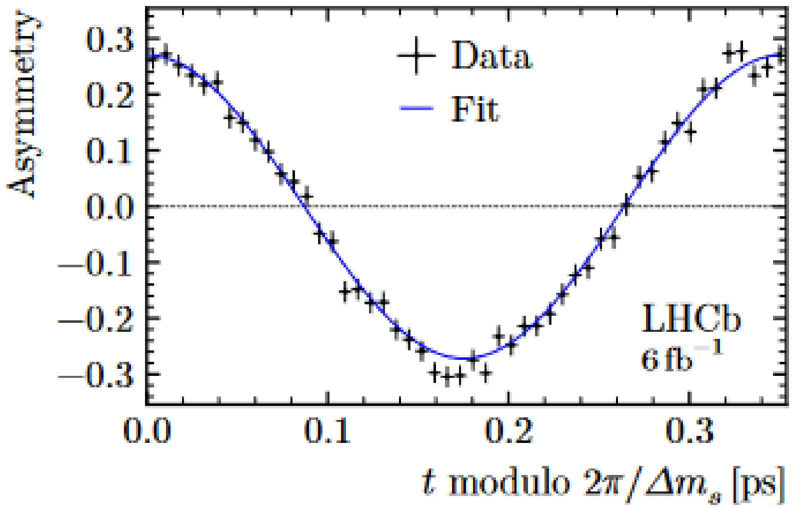


The most « textbook-like » measurement
B_s mixing frequency measurement

LHCb-PAPER-2021-005

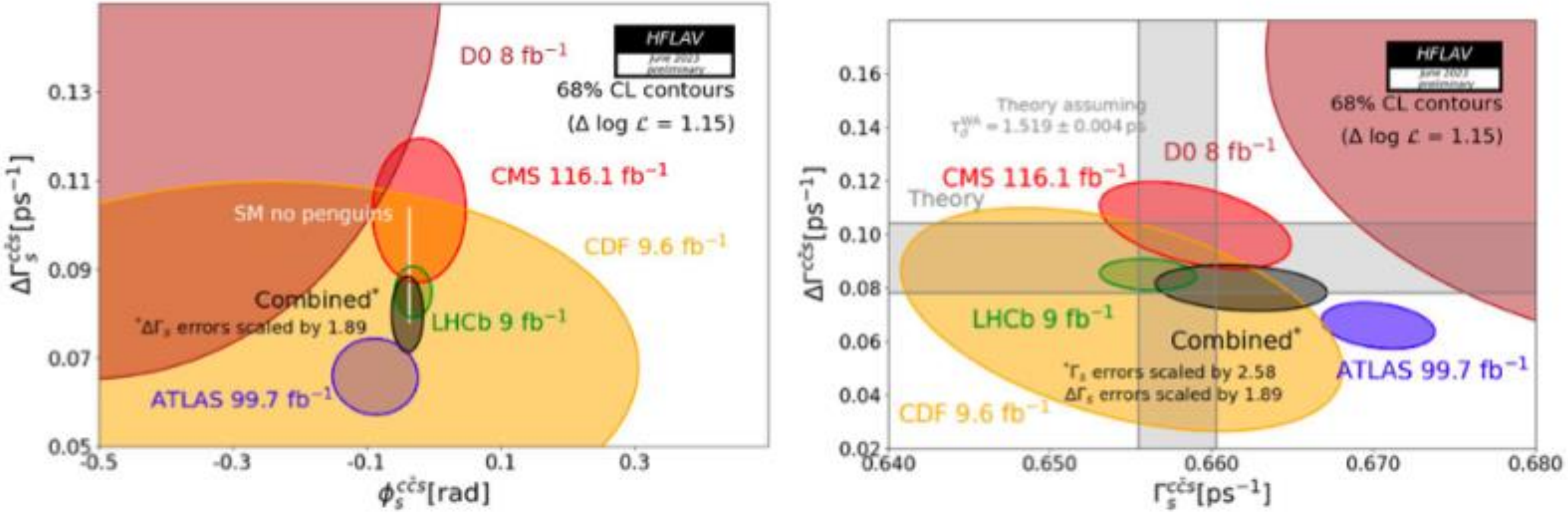
σ_t = 45 fs!





CP violation in the B_s system

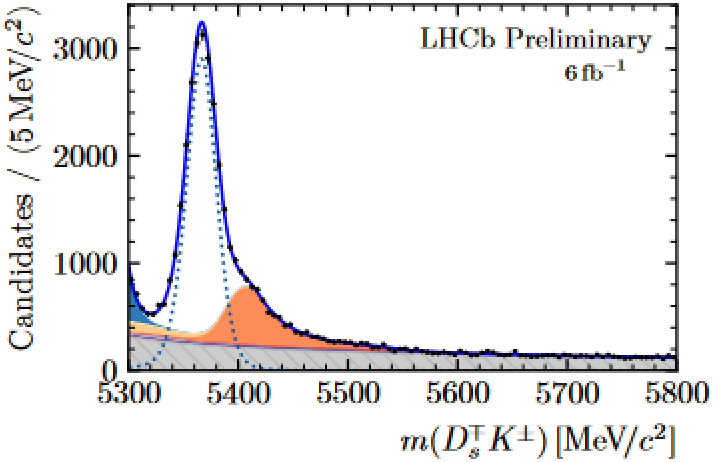
Measurement of ϕ_s in $B_s^0 \to J/\psi K^+ K^-$ arXiv: 2308.01468

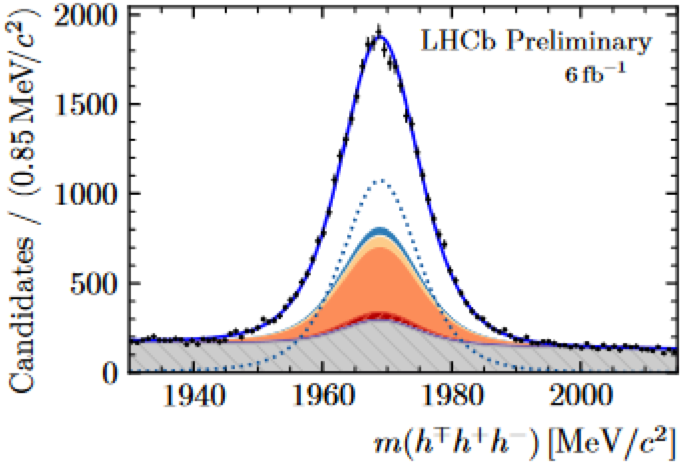


ϕ_s world average:

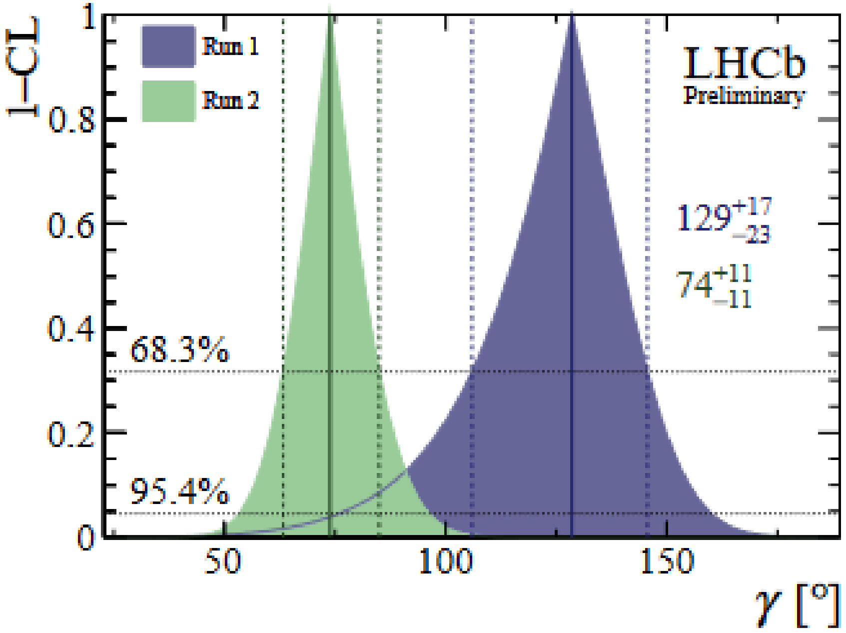
$$\phi_s = -0.039 \pm 0.016 \text{ rad}$$
$$\phi_s(J/\psi KK) = -0.050 \pm 0.017 \text{ rad}$$

γ measurement using B_s to D_sK

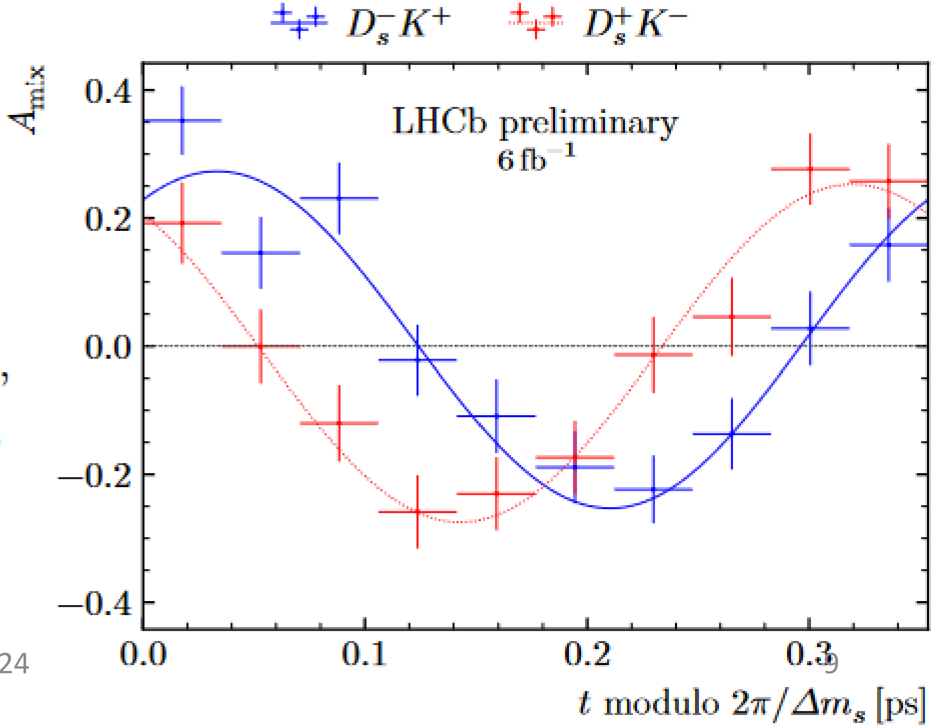




LHCb-PAPER-2023-004



$$\gamma = (74 \pm 11)^\circ\,,$$
$$\delta = (346.9 \pm 6.6)^\circ\,,$$
$$r_{D_sK} = 0.327 \pm 0.038\,,$$



CKM Physics at LHCb : What was not expected!

- Angles
  - (CP violation in charm LHCb-PAPER-2019-006)
  - **Huge CP violation effects in binned phase-space approach : PAPER-2022-017**
  - **Dominant contribution to β LHCb-PAPER-2023-013**
  - **So many modes for γ measurements !**

  PAPER-2023-040, PAPER-2023-029 and PAPER-2023-012
  - Measurement with neutrals in the final state LHCb-PAPER-2020-040
- Sides
  - **Important contributions to Vcb and Vub**

LHCb-CONF-2022-003,

γ measurement- List of inputs !

B decay	D decay	Ref.	Dataset	Status since Ref. [14]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[30]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	[18]	Run 1&2	**New**
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[19]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[31]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[32]	Run 1&2	As before
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[33]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[34]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[36]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[37]	Run 1	As before
$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	[38]	Run 1	As before
$B^0_s \to D_s^\mp K^\pm\pi^+\pi^-$	$D_s^+ \to h^+h^-\pi^+$	[39]	Run 1&2	As before

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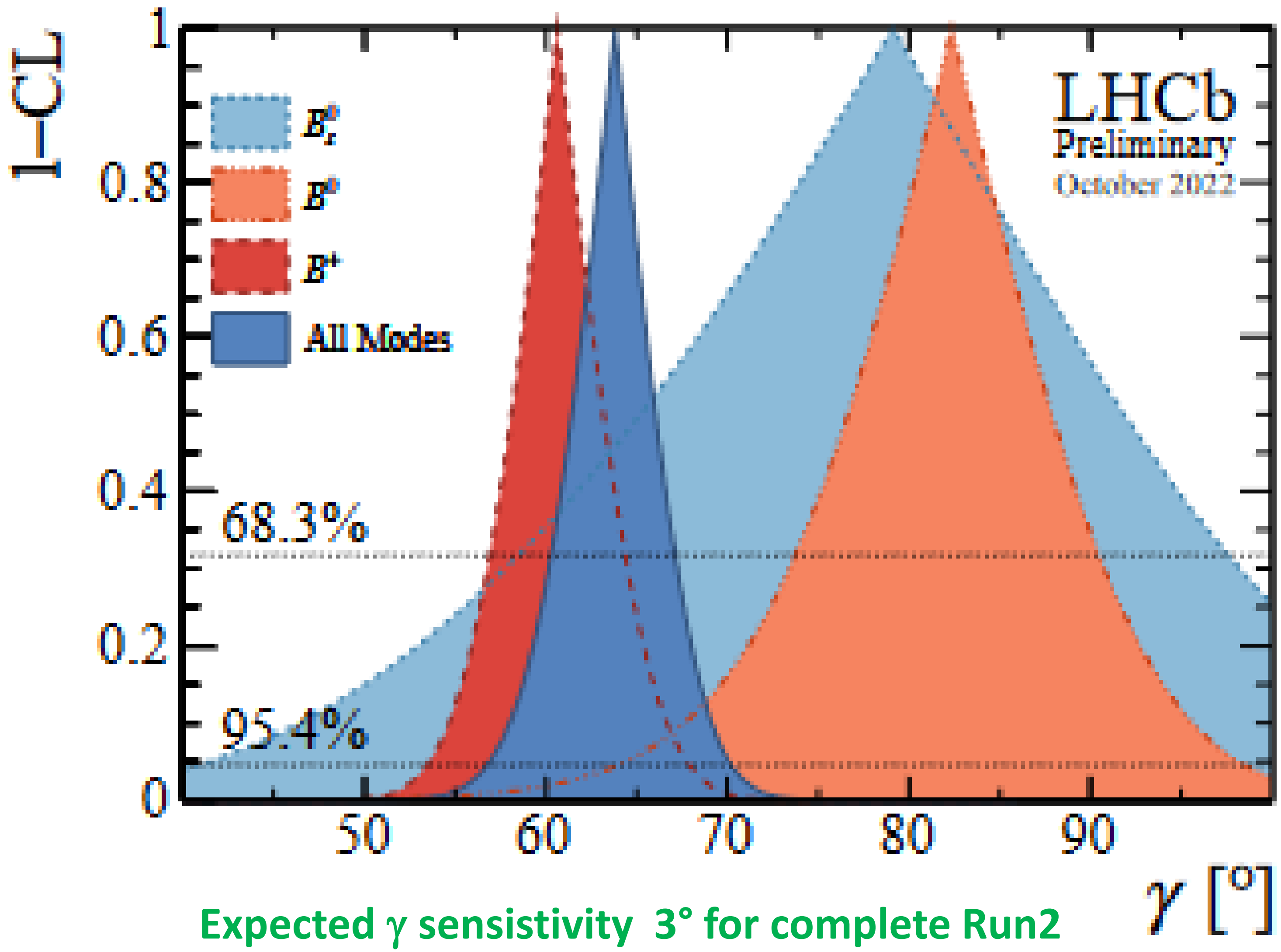
LHCb-CONF-2022-003,



Expected γ sensistivity 3° for complete Run2
1° with Run3/Run4

Direct measurement

$$\gamma = (63.8\,^{+3.5}_{-3.7})^\circ$$

in very good agreement with but still less precise than the indirect prediction from CKM triangle

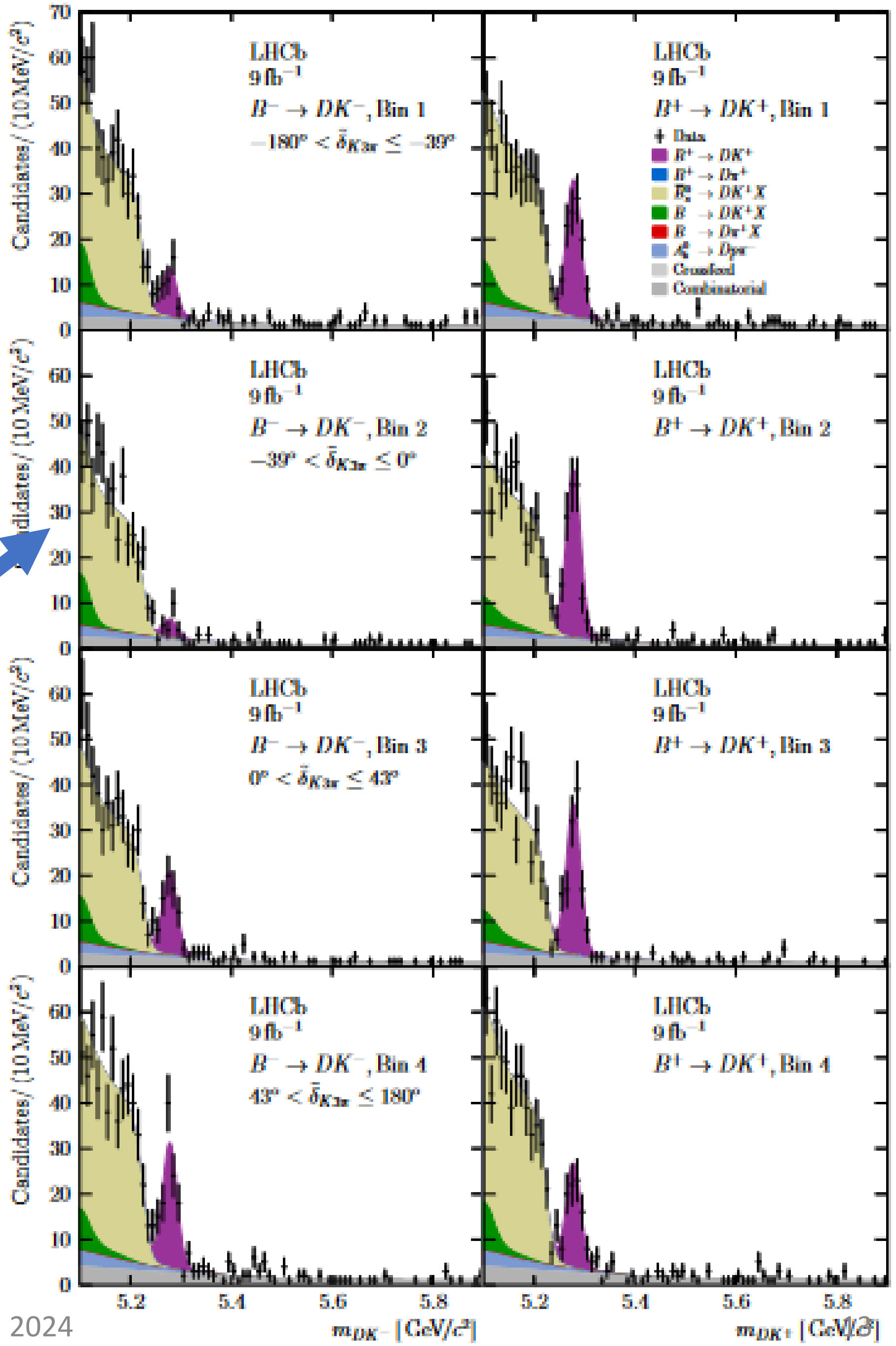
$$\gamma[^\circ] = 66.29^{+0.72}_{-1.86}\ [\text{ind.}]$$

$B^{\pm} \to D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]h^{\pm}$

LHCb- PAPER-2022-017

Bin	Limits $(\bar{\delta}_{K3\pi})$	$R^{i}_{K3\pi}$	$\delta^{i}_{K3\pi}$
1	$-180^\circ < \bar{\delta}_{K3\pi} \le -39^\circ$	$0.66\,^{+0.18}_{-0.21}$	$(117\,^{+14}_{-19})^\circ$
2	$-39^\circ < \bar{\delta}_{K3\pi} \le 0^\circ$	$0.85\,^{+0.14}_{-0.21}$	$(145\,^{+23}_{-14})^\circ$
3	$0^\circ < \bar{\delta}_{K3\pi} \le 43^\circ$	$0.78\,^{+0.12}_{-0.12}$	$(160\,^{+19}_{-20})^\circ$
4	$43^\circ < \bar{\delta}_{K3\pi} \le 180^\circ$	$0.25\,^{+0.16}_{-0.25}$	$(288\,^{+15}_{-29})^\circ$

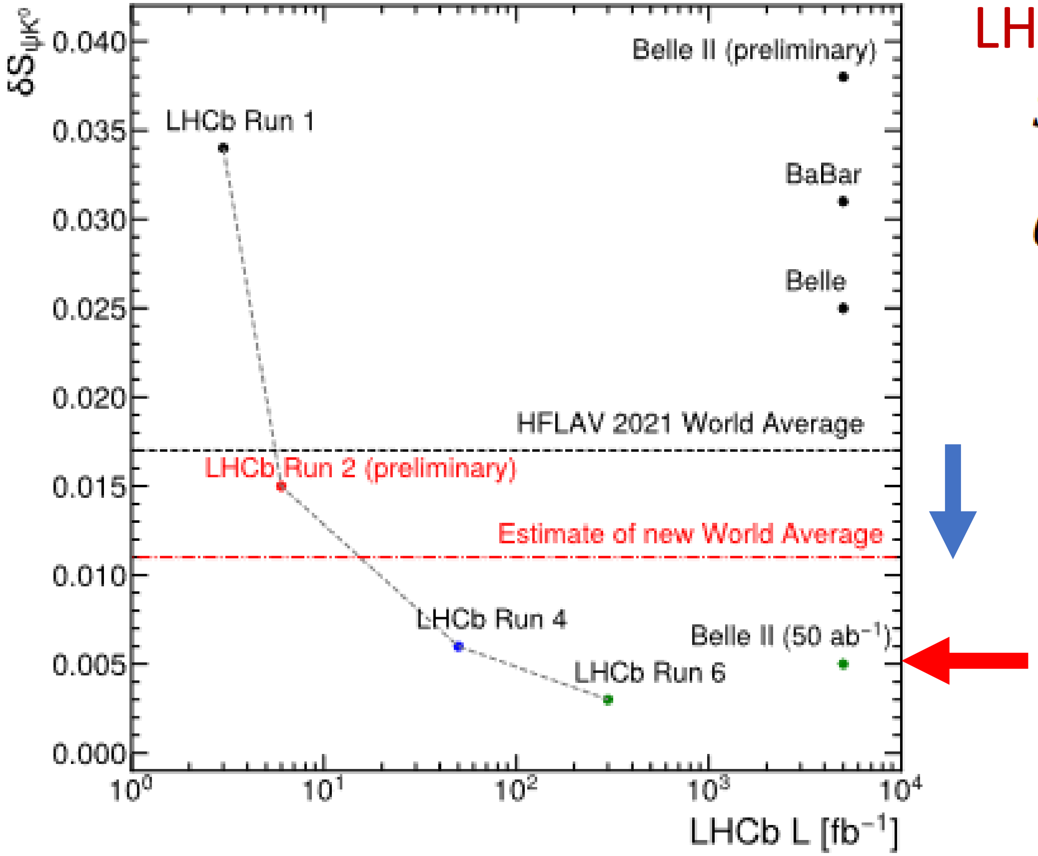
The largest (direct) CP violation effect ever observed !



sin2β status ans prospects

→ Important change in $\sin(2\beta)$, following preliminary LHCb results

from $\sin 2\beta = 0.699 \pm 0.017$ to $\sin 2\beta = 0.708 \pm 0.011$ [HFLAV]



LHCb-PAPER-2023-013

$$S_{\psi K_S^0} = 0.724 \pm 0.014$$

$$C_{\psi K_S^0} = 0.004 \pm 0.012$$

$$\rho = 0.40$$

V_{cb} and V_{ub}: profit of the B_s and Λ_b semileptonic decays !

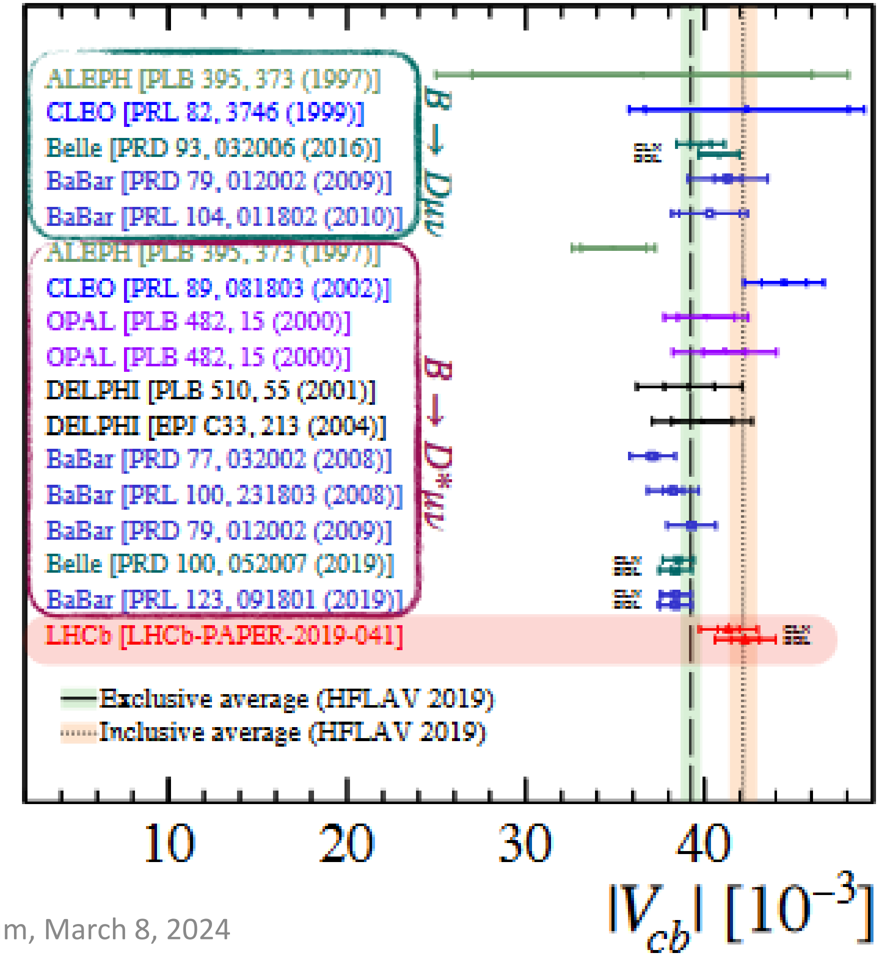
First exclusive $|V_{cb}|$ extraction at a hadron collider *and* first determination using B_s^0 decays

$$|V_{cb}|_{\mathrm{CLN}} = (41.6 \pm 0.6(\mathrm{stat}) \pm 0.9(\mathrm{syst}) \pm 1.2(\mathrm{ext})) \times 10^{-3}$$

$$|V_{cb}|_{\mathrm{BGL}} = (42.3 \pm 0.8(\mathrm{stat}) \pm 0.9(\mathrm{syst}) \pm 1.2(\mathrm{ext})) \times 10^{-3}$$

- Both extractions are compatible with each other
- Agreement with **exclusive** via $B^{0/+}$ and **inclusive** $|V_{cb}|$ determinations.

[PRD **101**, 072004 supplementary material]



Extraction of $|V_{ub}|/|V_{cb}|$

Phys. Rev. Lett. **126** (2021), 081804

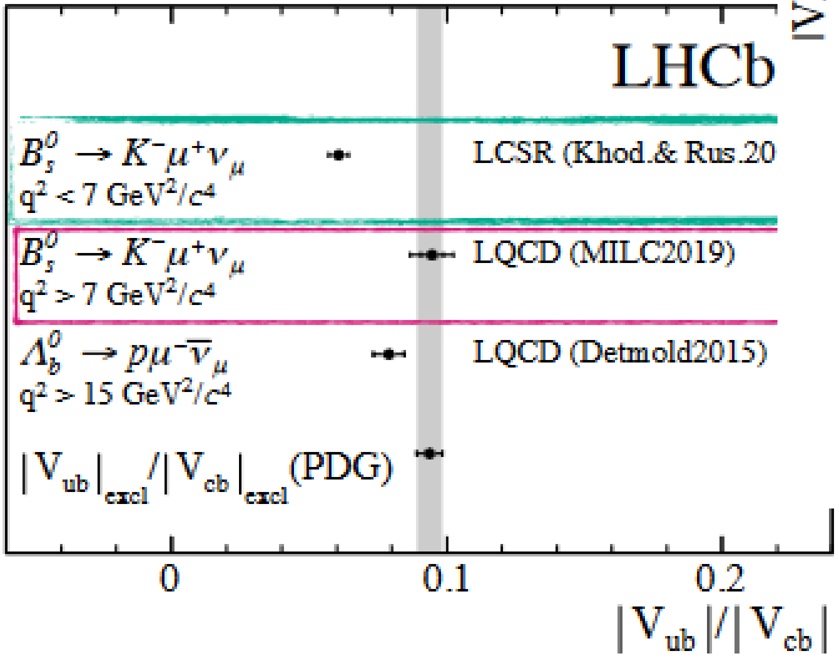
Low q^2: $\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)} = 1.66 \pm 0.08(\text{stat}) \pm 0.07(\text{syst}) \pm 0.05(D_s) \times 10^{-3}$

High q^2: $\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)} = 3.25 \pm 0.21(\text{stat})^{+0.16}_{-0.17}(\text{syst}) \pm 0.09(D_s) \times 10^{-3}$

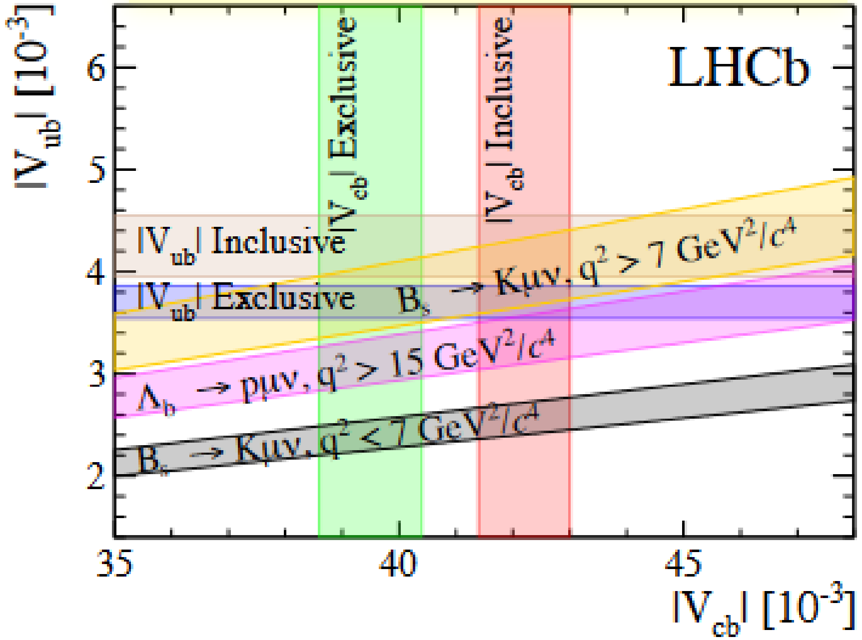
→ with FF predictions from **LCSR** [JHEP 112 (2017)] and **LQCD** [PRD 100, 034501]

$$|V_{ub}|/|V_{cb}|_{\text{low}} = 0.0607 \pm 0.0015(\text{stat}) \pm 0.0013(\text{syst}) \pm 0.0008(D_s) \pm 0.0030(\text{FF})$$

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



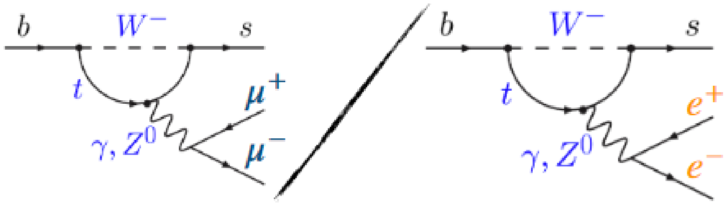
[PRL **126**, 081804 supplementary material]



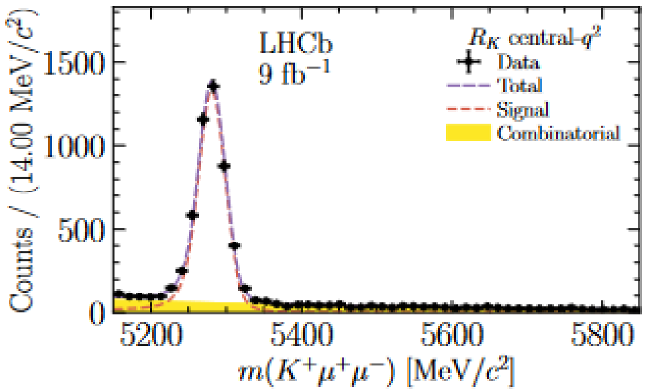
Lepton Flavour Universality at LHCb

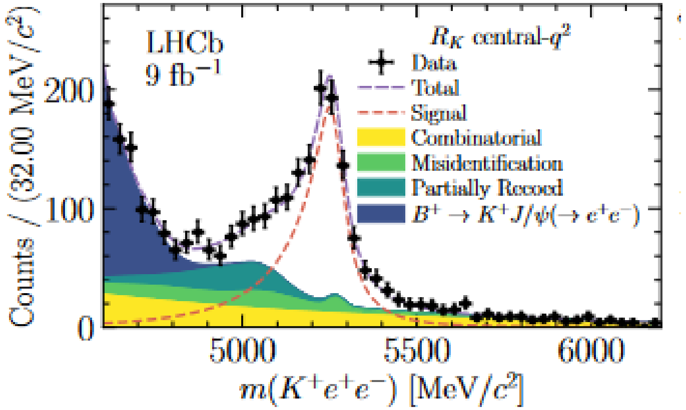
- In neutral currents, b➔se$^+$e$^+$ vs b➔sμ$^+$μ$^-$

(many modes investigated : K,K*,Λ,pK,ϕ,..)

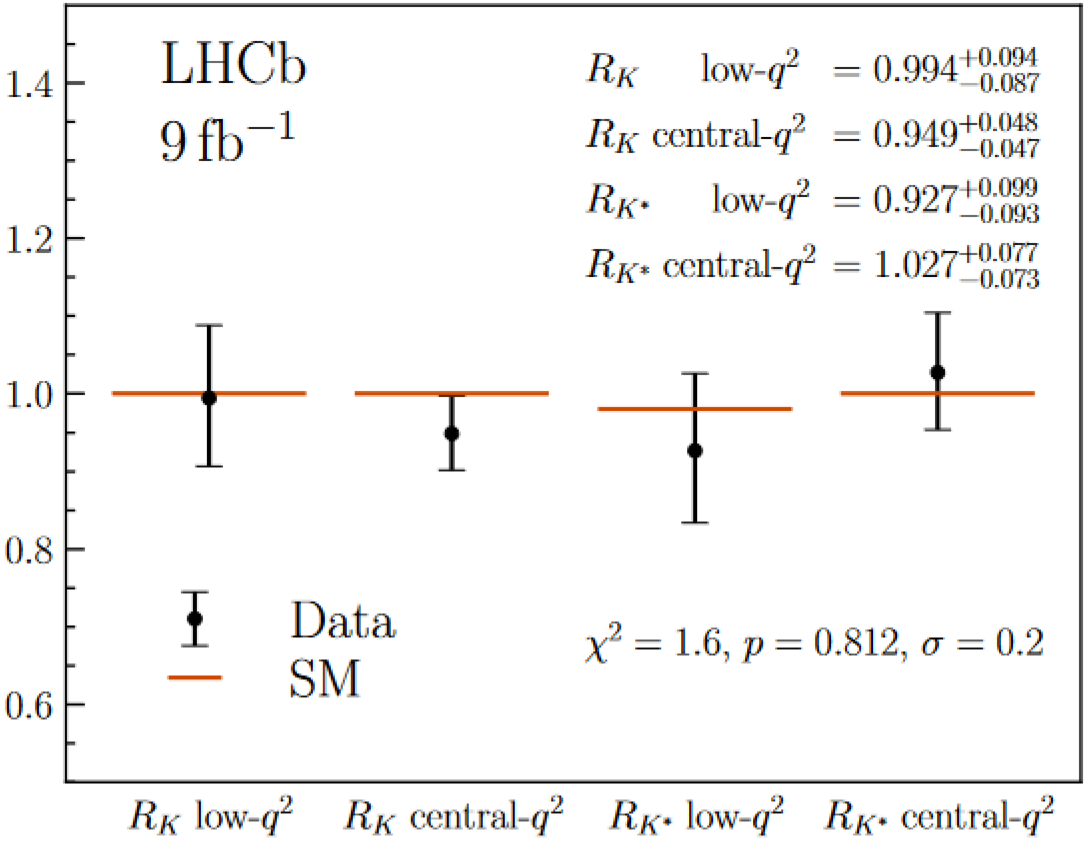


central-q^2





LHCb-PAPER-2022-046



$R(D^{(*)})$ measurements in LHCb

$R(D)=BR(B\to D\tau\nu)/BR(B\to D\mu\nu)$

$\tau^- \to \mu^- \nu_\tau \nu_\mu$

- Pros
  - Direct measurement of R(D,D*)
  - High statistics
- Cons
  - Double charm background control must be very good (mostly D^+)
  - Sensitive to D** $\mu^-\nu_\mu$

$\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$

- Pros
  - The possibility to measure the τ vertex is the key to reject the background and obtain a high purity sample
  - The 3π dynamics of the τ decay is very specific : possible to distinguish τ decays from the main double charm background from D_s decays
- Cons
  - Access to R(D) requires an external BR
  - Lower statistics

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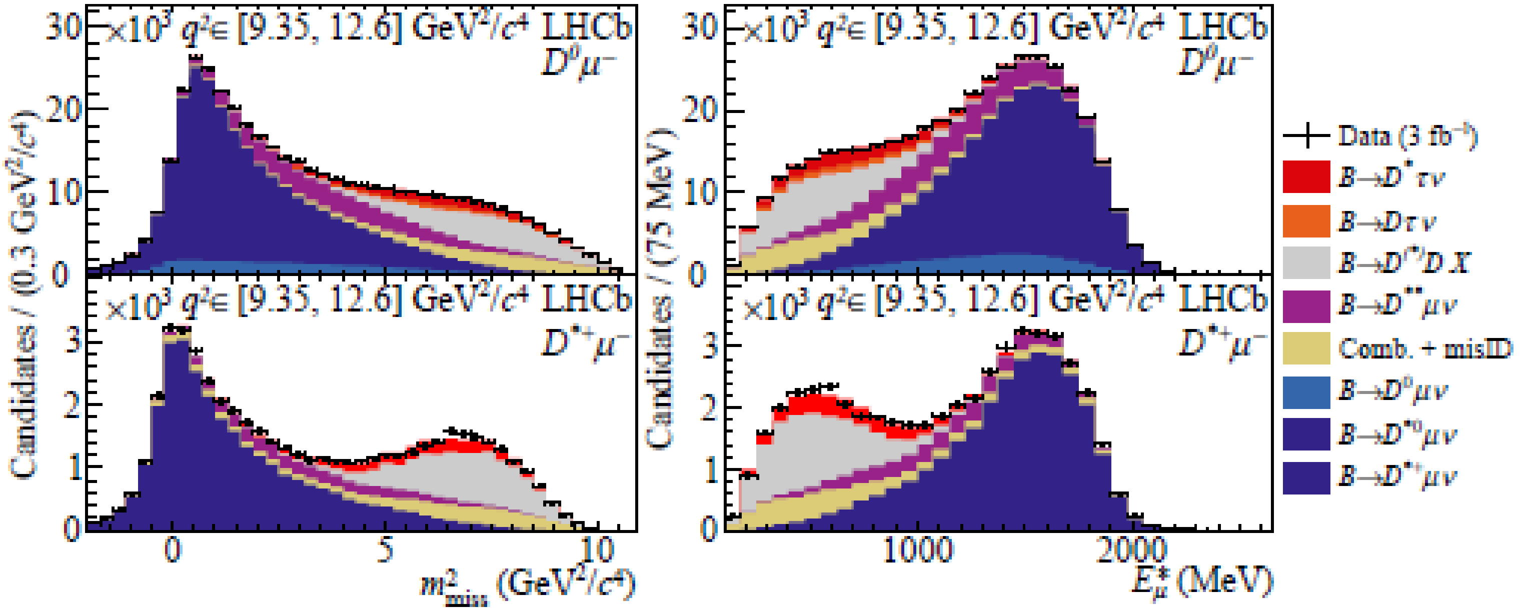
$R(D^{(*)})$ with muonic τ decays

LHCb-PAPER-2022-039

- Simultaneous measurement of $R(D)$ and $R(D^*)$ with Run 1 data using muonic $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$

3D template fit to

- $q^2 \equiv (p_B - p_{D^{(*)}})^2$
- $m^2_{\rm miss} \equiv (p_B - p_{D^{(*)}} - p_\mu)^2$
- E^*_μ energy of μ

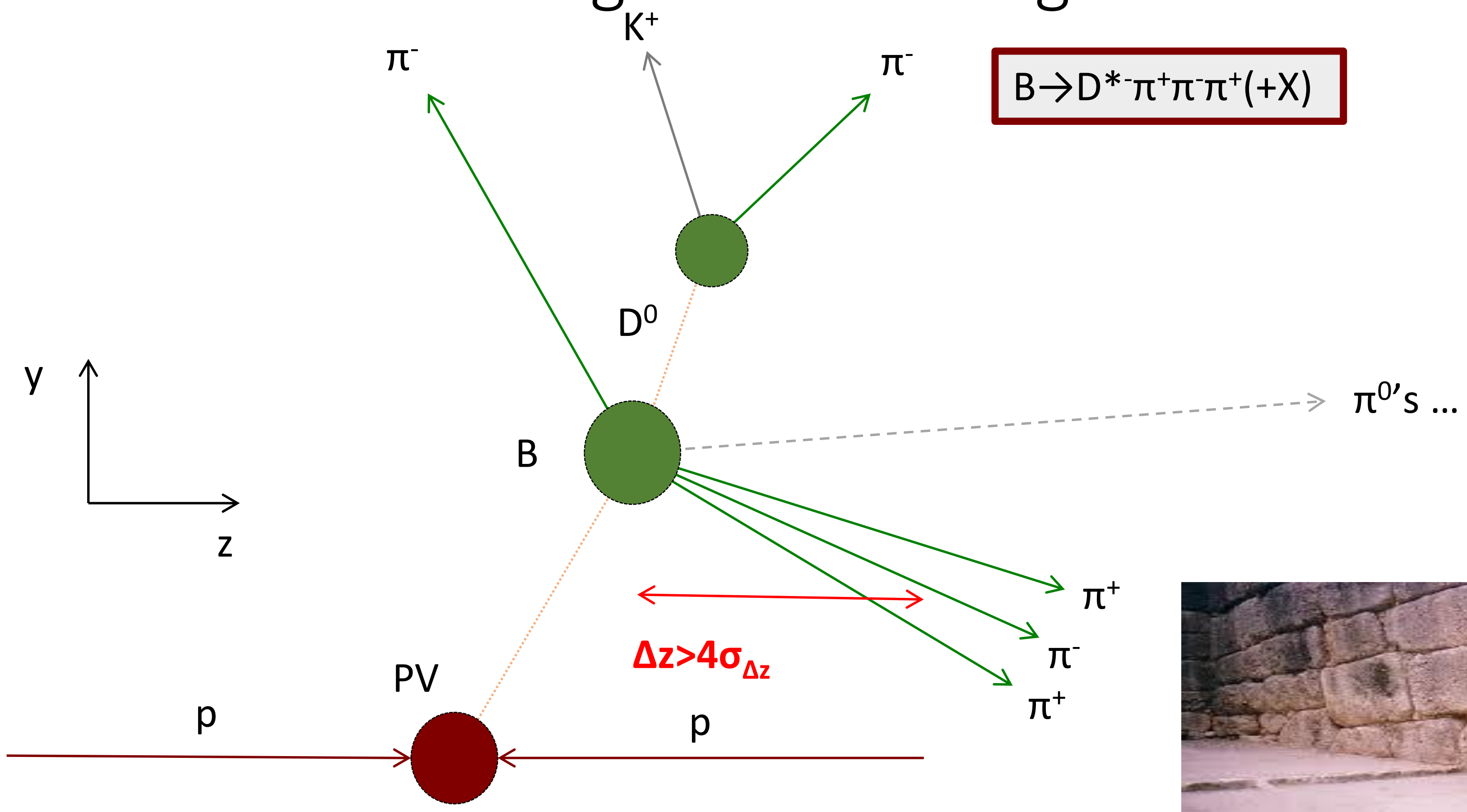


$$R(D) = 0.441 \pm 0.060(\text{stat}) \pm 0.066(\text{syst})$$
$$R(D^*) = 0.281 \pm 0.018(\text{stat}) \pm 0.023(\text{syst})$$

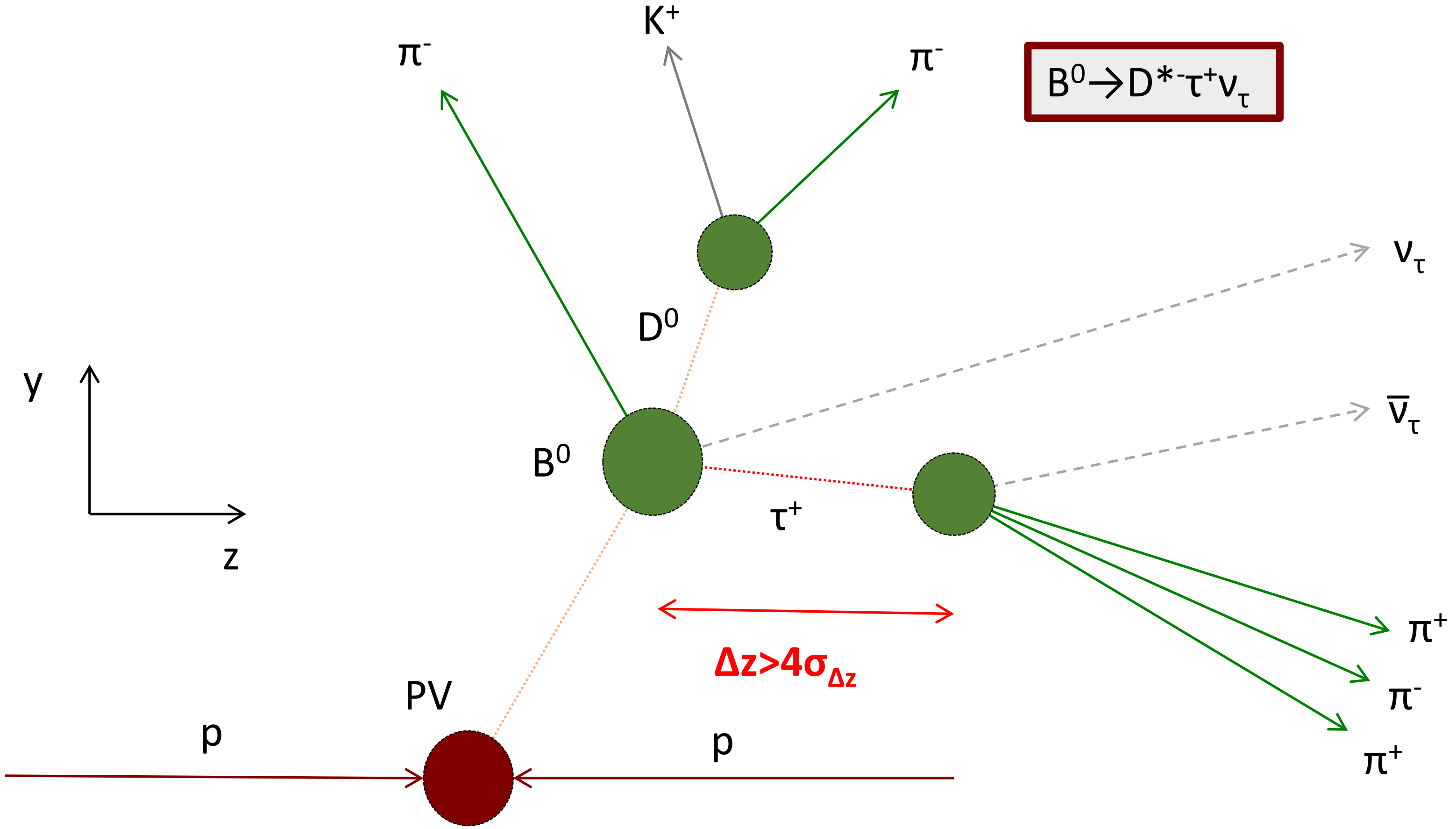
Agreement with SM at 1.9σ

R(D*) measurement with hadronic τ decays

Vertex topology of the usual B decay
100 times larger than the signal



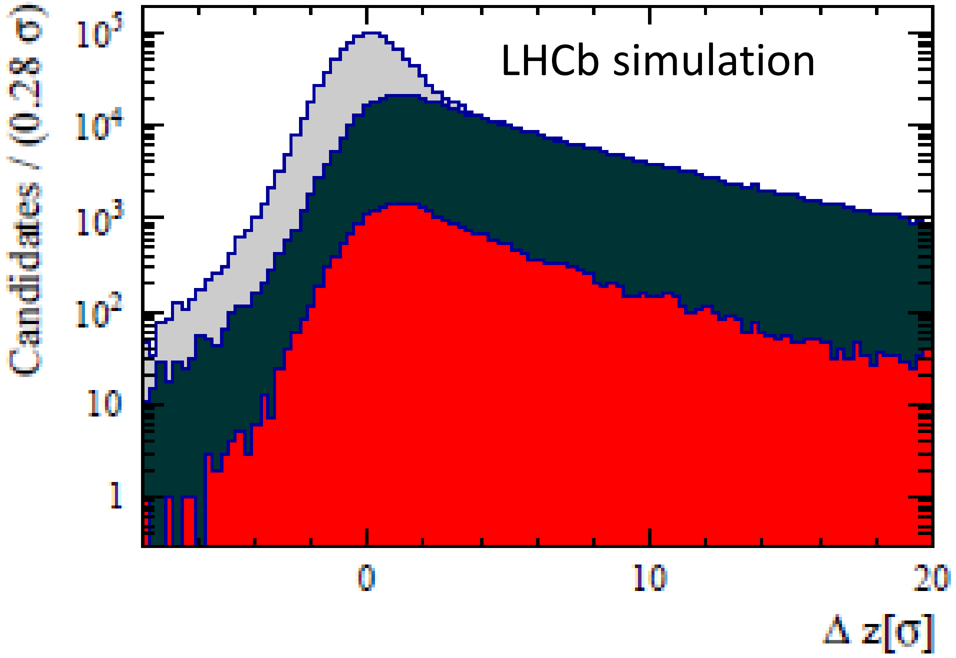
Selection: detached vertex



$B \to D^{*-}3\pi^{\pm}X$ backgrounds

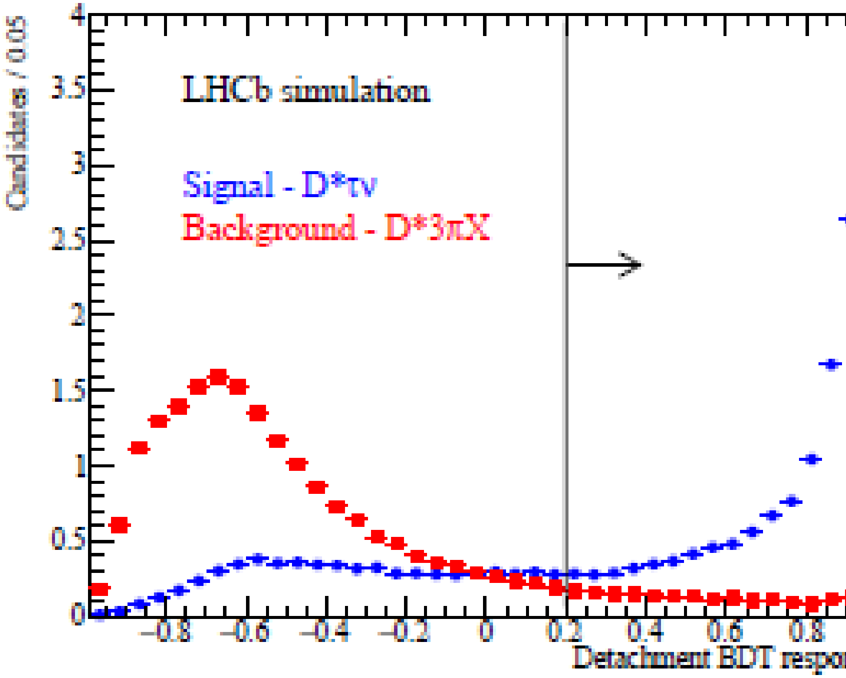
- Suppressed by requiring the τ vertex to be downstream w.r.t. the B vertex along the beam direction - detachment criteria
- A BDT classifier is used along with the vertex separation variables

LHCb-PAPER-2022-052
arxiv:2305.01463

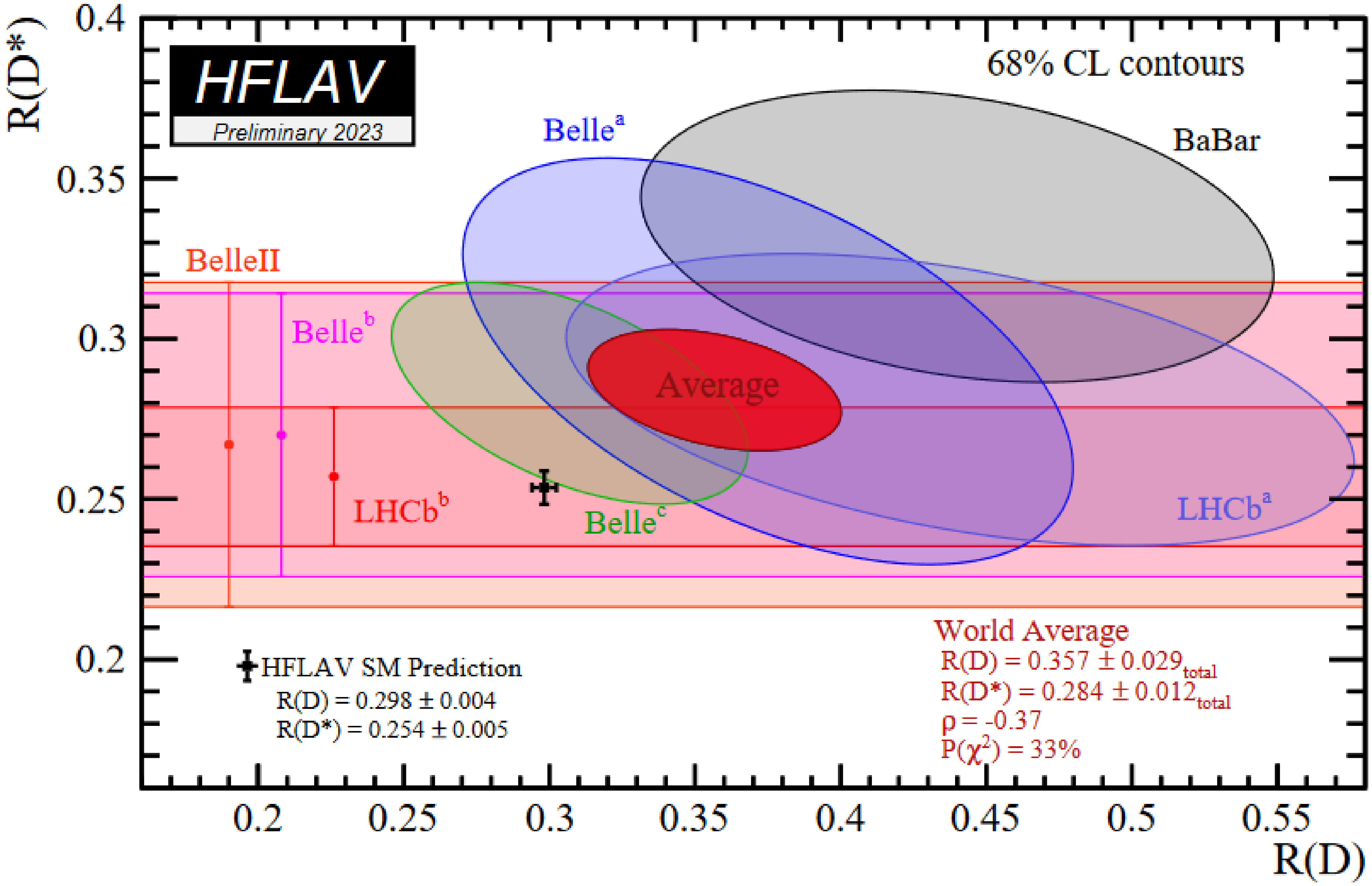


Prompt D*3πX
Double Charm
Signal

+



Background rejection >99,9% !



Deviation from SM : 3.3 σ

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D* polarization LHCb results LHCb-PAPER-2023-020 arXiv:2311.05224

- Signal yields from a 4D-binned template fit:
  - τ^+ lifetime (first row)
  - q^2 & $\cos\theta_D$ (second row)
  - anti-D_s BDT output (third row)
- Fit performed simultaneously on Run 1 and Run 2
- Results are integrated over Run 1 and Run 2

$F_L^{D^*}$ value extracted for the 3 q^2 region

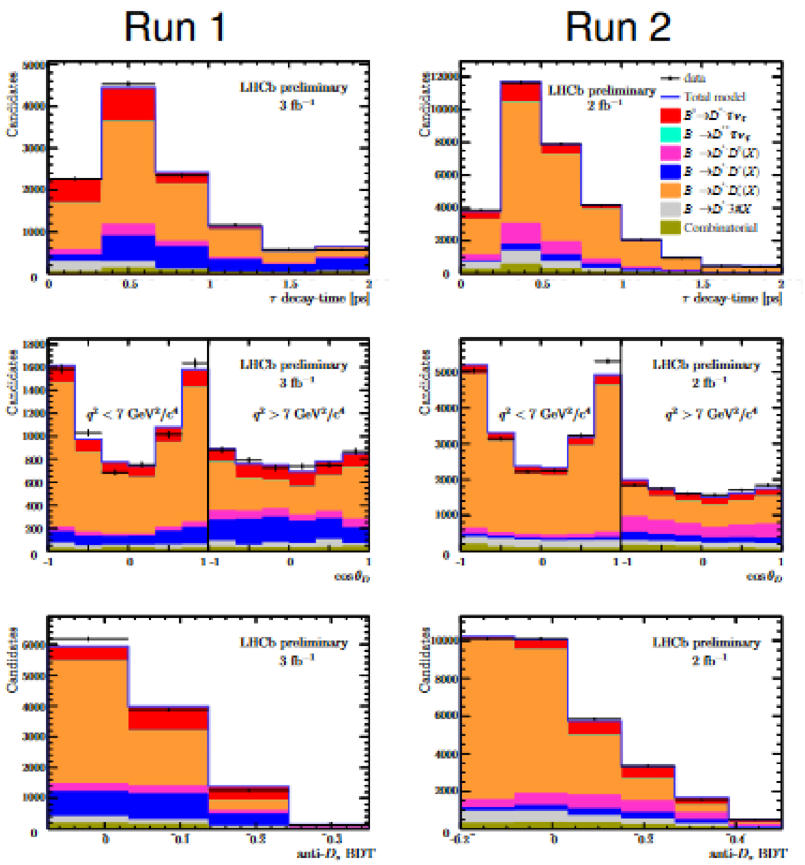
$q^2 < 7\,\mathrm{GeV}^2/c^4$: $0.51 \pm 0.07(stat) \pm 0.03(syst)$

$q^2 > 7\,\mathrm{GeV}^2/c^4$: $0.35 \pm 0.08(stat) \pm 0.02(syst)$

q^2 integrated : $0.43 \pm 0.06(stat) \pm 0.03(syst)$

- All values are found to be compatible with the SM within 1σ
  - expected value in the integrated region ~ 0.44

[arXiv:1808.03565, arXiv:1805.08222, arXiv:1907.02257]

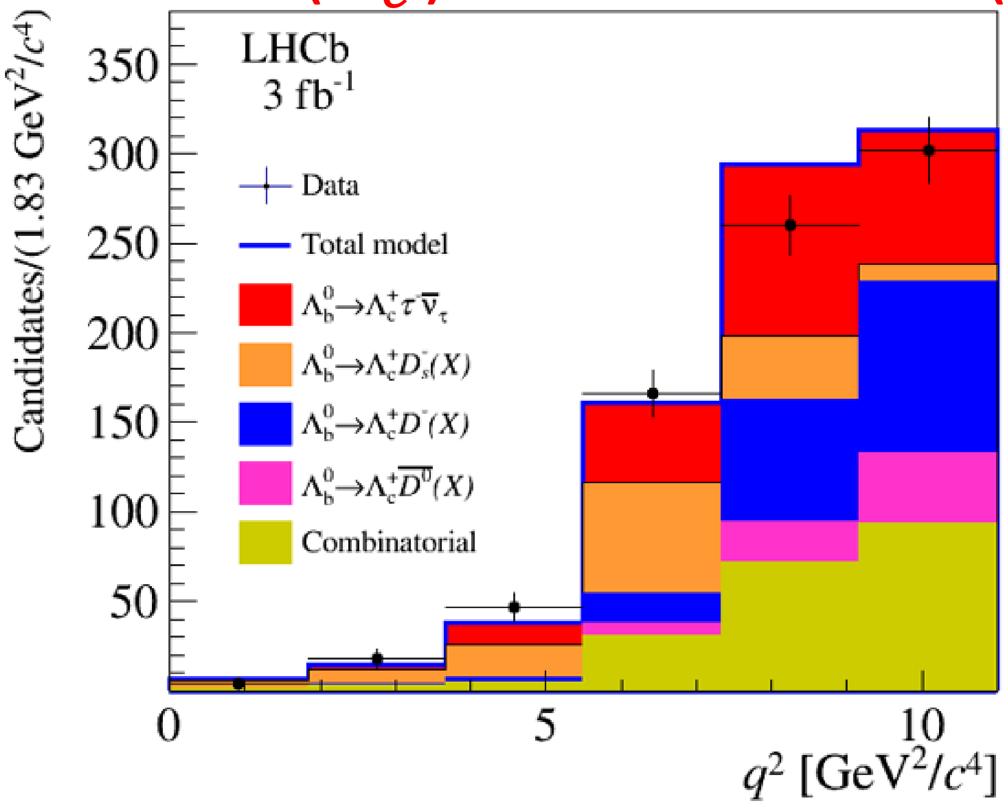


Reminder Belle Unpublished : F_L D*=0.60 ± 0.09 arXiv:1903.03102

LHCb measurement of R(Λ_c) with hadronic τ decays

LHCb-PAPER-2021-044
arxiv:2201:03497

$\mathcal{R}(\Lambda_c^+)$=0.242 ± 0.026 (stat) ± 0.040 (syst) ± 0.059 (ext)

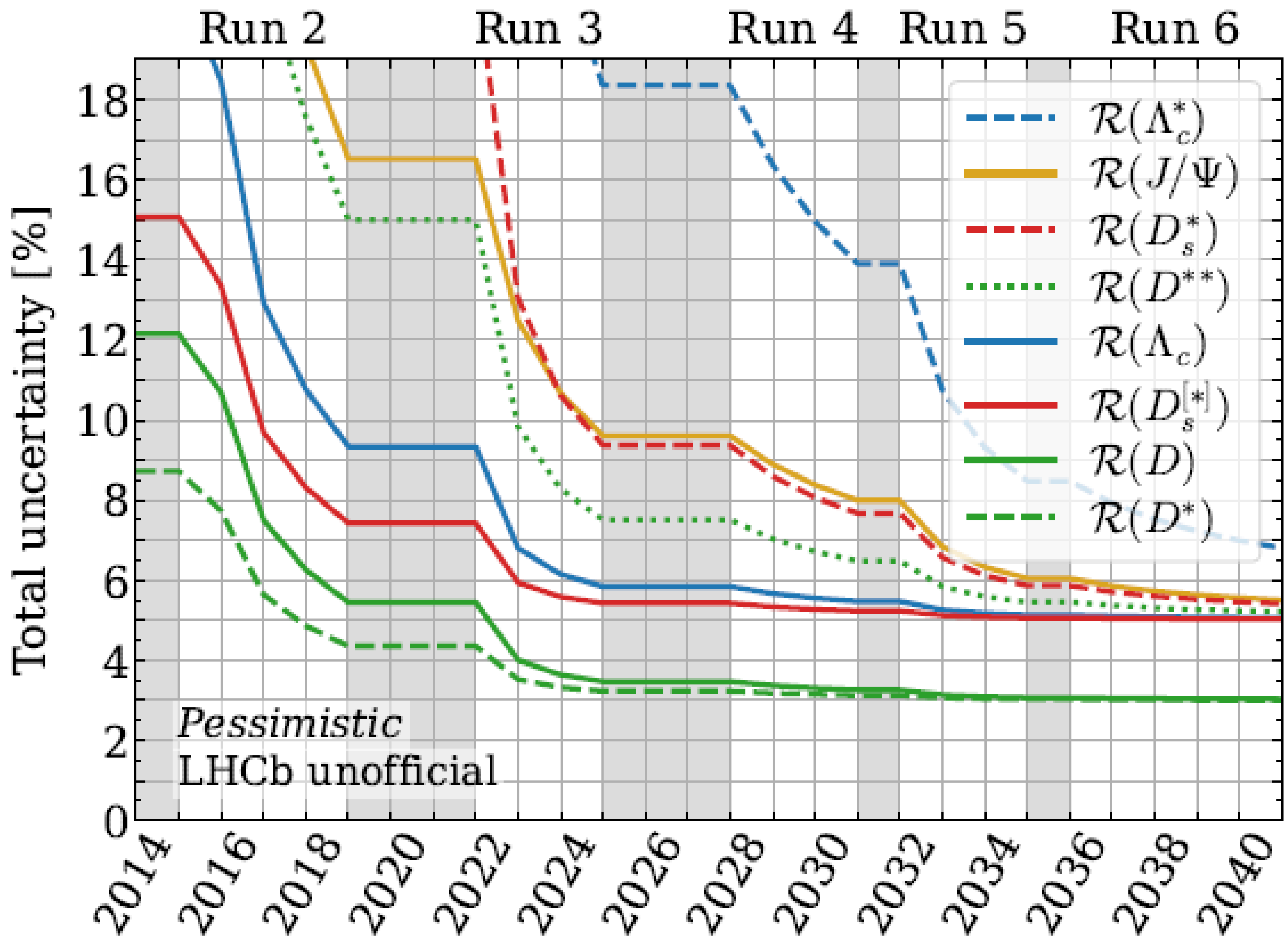


(SM expectation=0.324 ± 0.004)

F. Bernlochner et al., Physical Review D 99 055008 (2019)
with input from W. Detmold, C. Lehner, S. Meinel,
Physical Review D 92 034503 (2015)

Semitauonic prospects

(Rev. Mod. Phys. 94, 015003)

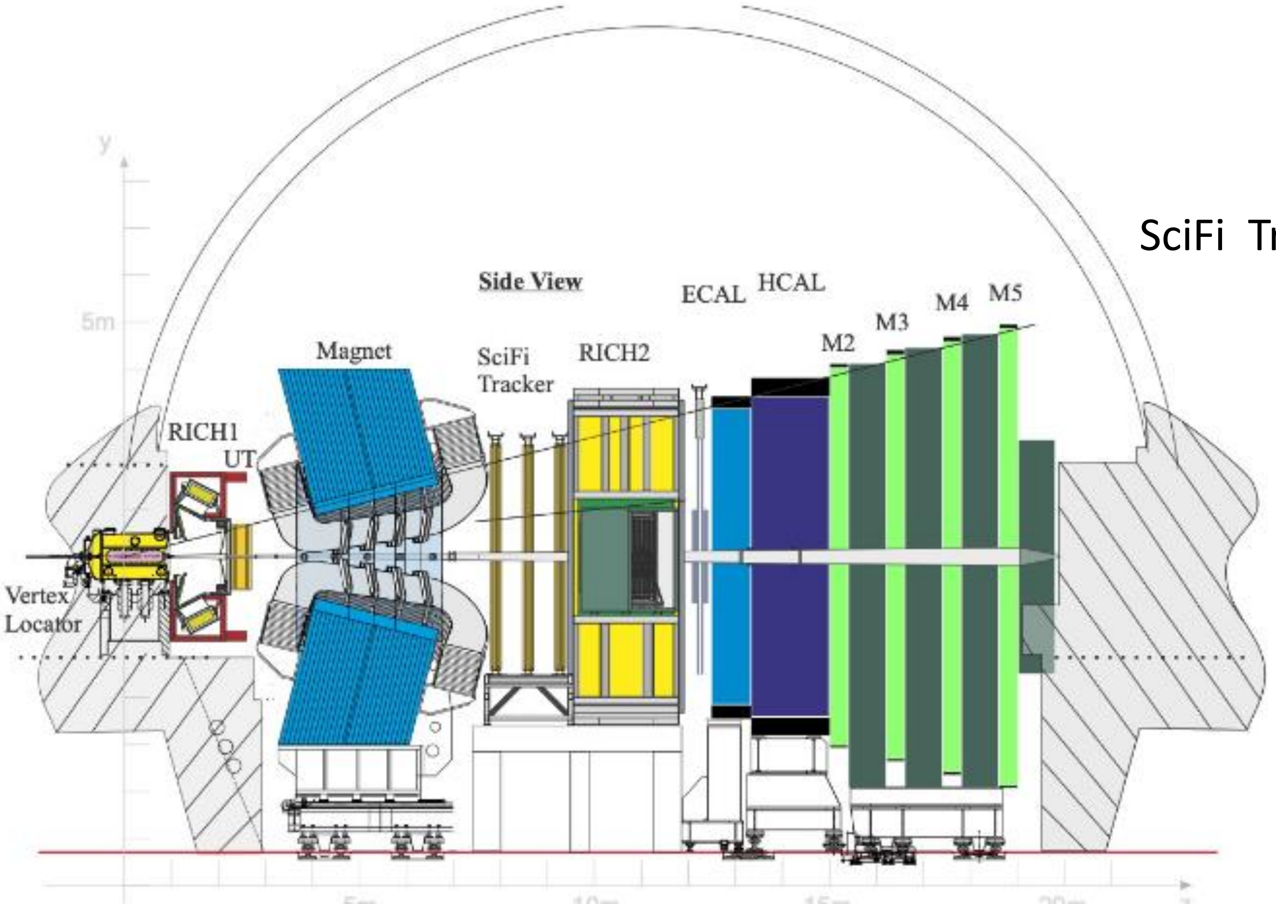


LHCb Upgrade 1 (LHCb-DP-2022-002)

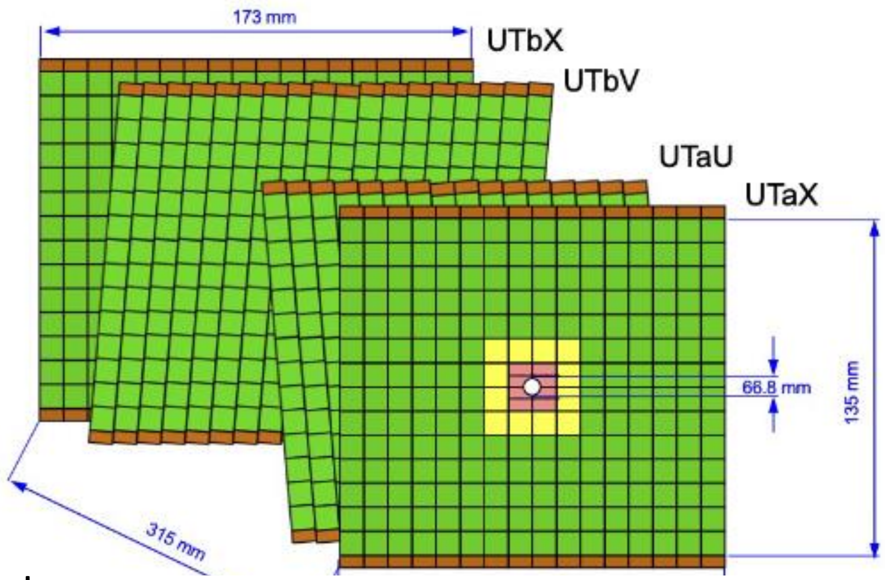
- Goal :
  - Luminosity jump 2 10^{32} to 10^{33}
  - Get rid of L0 trigger (hardware-based)
- Consequences : DAQ running at 40 MHz -> all front-electronics changed!
- Other improvments :
  - UT and SciFi trackers
  - VELO pixels instead of strips, closer to the beam
- Commissioned in 2023 to a great extent but no significant luminosity integrated up to now. (delays, Modest LHC running, VELO RF box incident).

Running successfully in 2024 is really mandatory!

LHCb present design



UT Si Tracker



SciFi Tracker

Conclusion

- LHCb is making unique contributions to all areas of CKM physics :
  - Angles β and γ
  - Sides : V_{ts},V_{td},V_{ub},V_{cb}

  and in Lepton Universality tests
  - In rare FCNC modes
  - In semitauonic decays
- LHCb is now the world leader in many areas, even those where it was not expected to contribute !
- **Prospects are bright !**
- In all these domains, the input from the other experiments, especially BES-III and Belle-II, will be essential to beat down the systematics!

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$R(D^*)$ with hadronic τ decays

$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)} = 1.700 \pm 0.101(\text{stat})^{+0.105}_{-0.100}(\text{syst})$$

- The absolute branching fraction of $B^0 \to D^{*-}\tau^+\nu_\tau$ decays

$$\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau) = (1.23 \pm 0.07\ (\text{stat}) \pm 0.08\ (\text{syst}) \pm 0.05(\text{ext})) \times 10^{-2}$$

$$R(D^*) = \mathcal{K}(D^*)\frac{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

- The BFs of $B^0 \to D^{*-}3\pi^\pm$ and $B^0 \to D^{*-}\mu^+\nu_\mu$ - external inputs

$$R(D^*) = 0.247 \pm 0.015(\text{stat}) \pm 0.015(\text{syst}) \pm 0.012(\text{ext})$$

In agreement with Run 1 result

- Combining with the Run 1 result

LHCb-PAPER-2022-052
arxiv:2305.01463

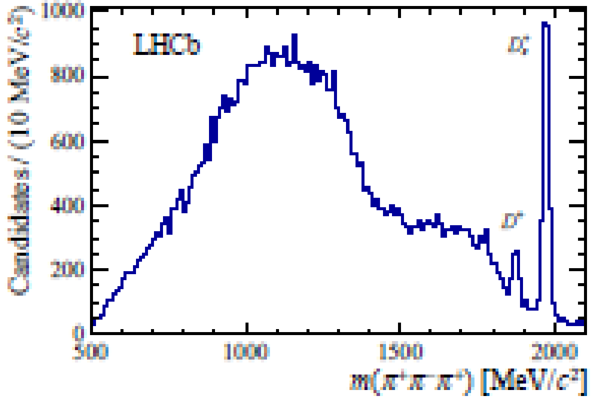
$$R(D^*)_{2011-2016} = 0.257 \pm 0.012\ (\text{stat}) \pm 0.014\ (\text{syst}) \pm 0.012\ (\text{ext})$$

Agreement within 1σ to SM

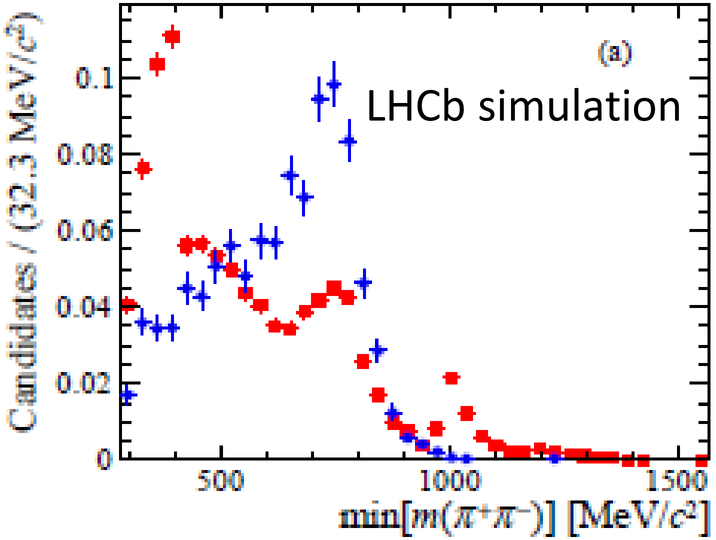
$R(D^*)_{\text{SM}} = 0.254 \pm 0.005$ [HFLAV]

Double-charm backgrounds

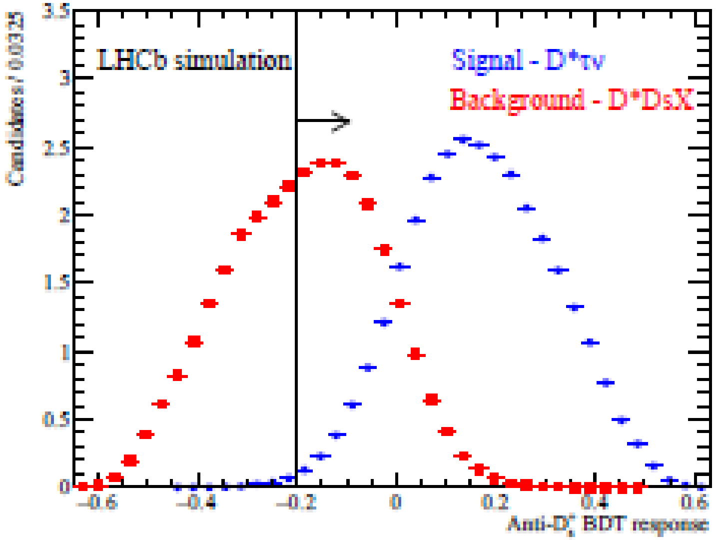
- $B \to D^{*-}(D_s^+, D^+, D^0)X$ backgrounds
- $B \to D^{*-}D_s^+X$ the largest contributor
- A BDT classifier based on kinematics and resonant structure to separate signal from $B \to D^{*-}D_s^+X$



[PRD 97, 072013 (2018)]



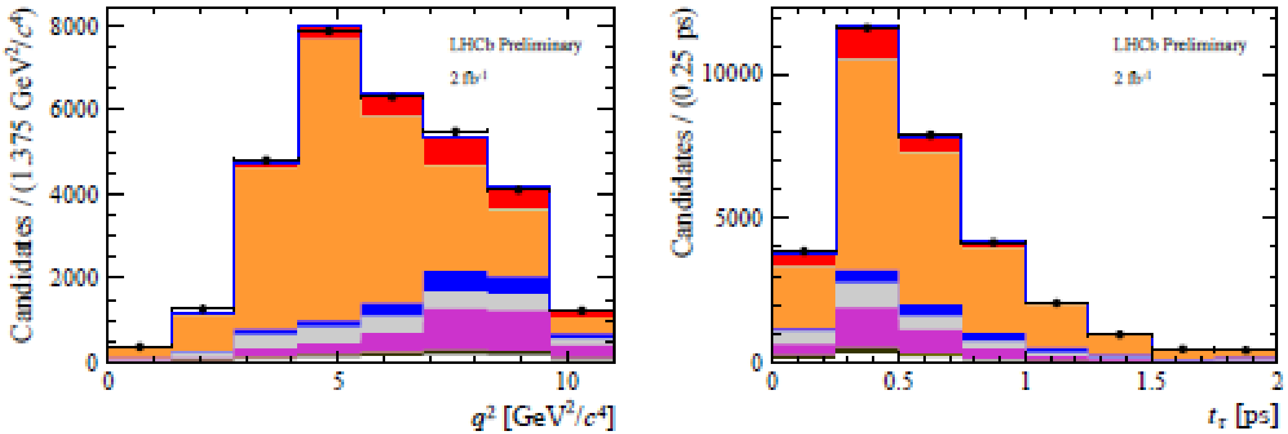
[PRD 97, 072013 (2018)]



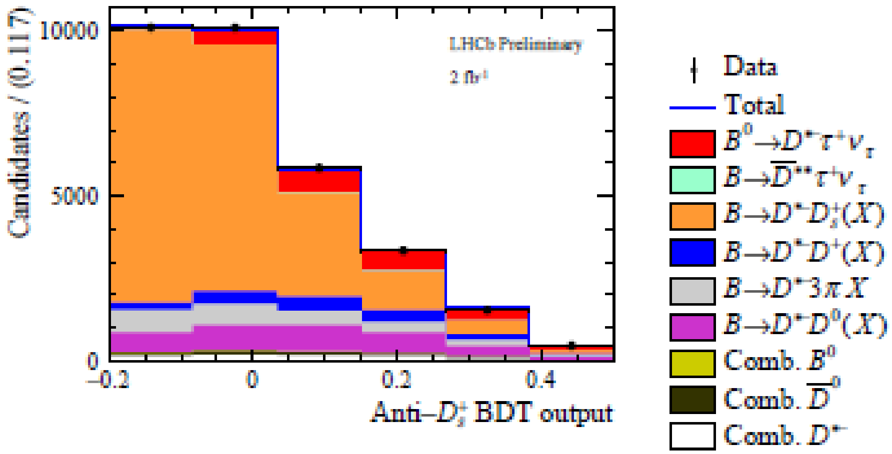
BR(D_s→3πX)=32.8% ± 0.9%
BES-III arxiv:2212.13072

- This BDT output is one of the fit variables for signal extraction

Signal extraction



LHCb-PAPER-2022-052
arxiv:2305.01463



$$N(B^0 \to D^{*-}\tau^+\nu_\tau) = 2469 \pm 154$$

Run 1 yield $= 1296 \pm 86$

- Larger dataset
- Improved selection