Results from LHCb

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XXX Cracow Epiphany Conference
on Precision Physics at High Energy Colliders

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Outline

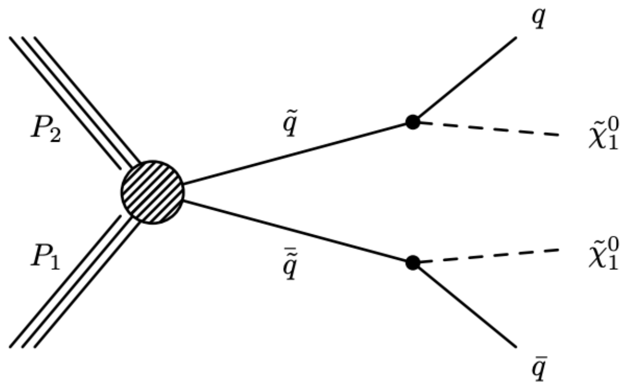
- Flavour physics and LHCb
- Selected recent precision *B*-physics results
  - $\sin 2\beta$
  - ϕ_s and $\Delta\Gamma_s$
  - γ
  - A^{CP} in $B^- \to D^{(*)0} D_{(s)}^{(*)-}$ decays
  - $B^0 \to K^{*0}\mu^+\mu^-$
- Status of upgrade I
- Plans for upgrade II

Direct vs indirect searches

Searching for **New Physics** at high energy scales

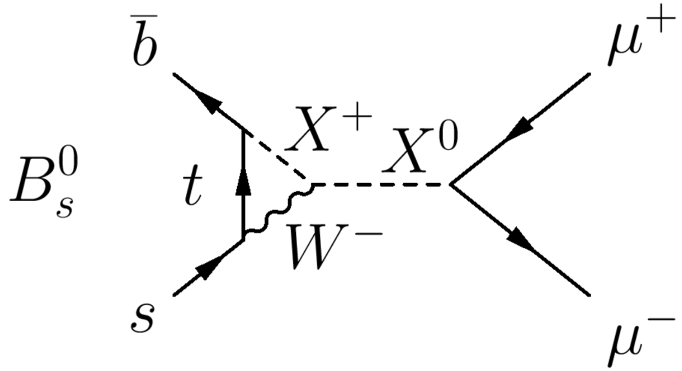
Direct effects from **real** particle production

*clear **signal**,*
*but hard **ceiling** at $\sqrt{s}$*



Indirect effects through **virtual** particles

*subtle **deviations** from theory,*
*but **unlimited** mass range*

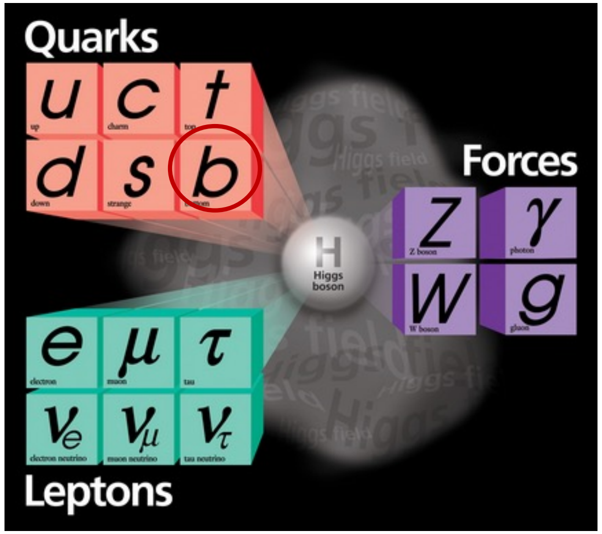


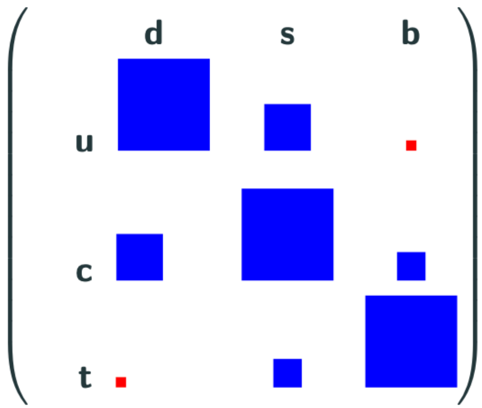
Heavy flavour physics

Quarks **change flavour** through coupling with the $W^{\pm}$ boson

The **CKM matrix** describes the amplitude of these transitions

Very-off-diagonal elements V_{ub} and V_{td} have a large **complex phase** → $O(1)$ *CP* violation

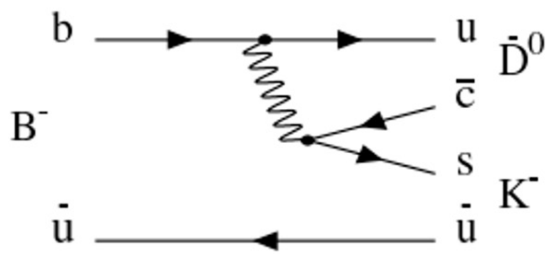


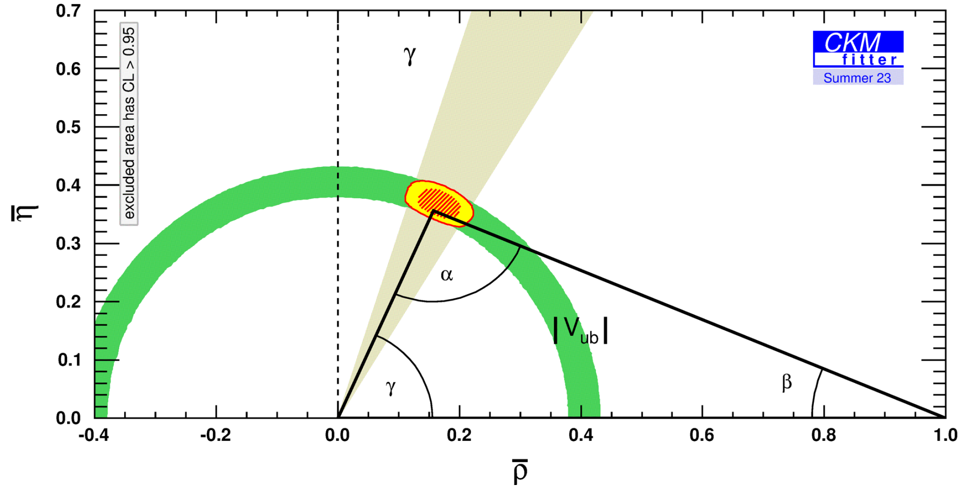


$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

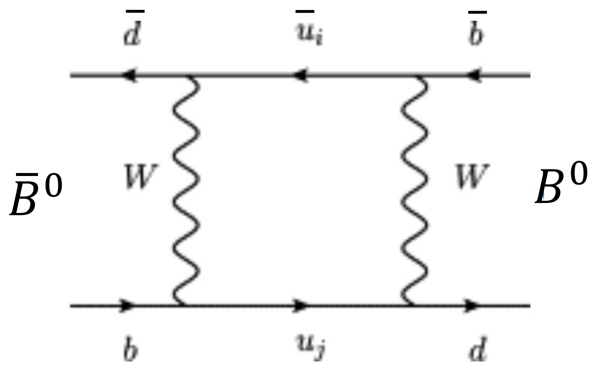
Trees and loops

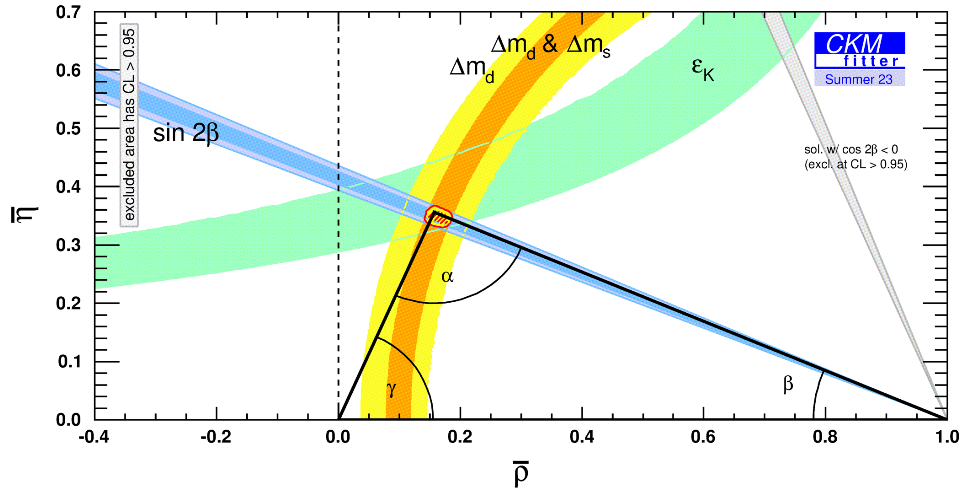
Determination of $\bar{\rho}$ and $\bar{\eta}$ from decays **without** loops (trees)





Determination of $\bar{\rho}$ and $\bar{\eta}$ from processes **with** loops





Inconsistencies between the two methods indicates **new particles in loops**.
So far: **CONSISTENT**.

Producing B hadrons

e^+e^- collisions at $\Upsilon(4S)$

PEPII (Babar),
KEKB (Belle, Belle II)

- Small background
- Coherent production
- Fixed boost

Hadron collisions

Tevatron (CDF, D0),
LHC(LHCb, ATLAS,CMS)

- Large yield
- Produce B^0, B^+, B_s, B_c, B baryons
- Strongly boosted

The LHCb experiment at CERN

(2011-2018 version) $2 < \eta < 5\ (10 < \theta < 300\text{mrad})$

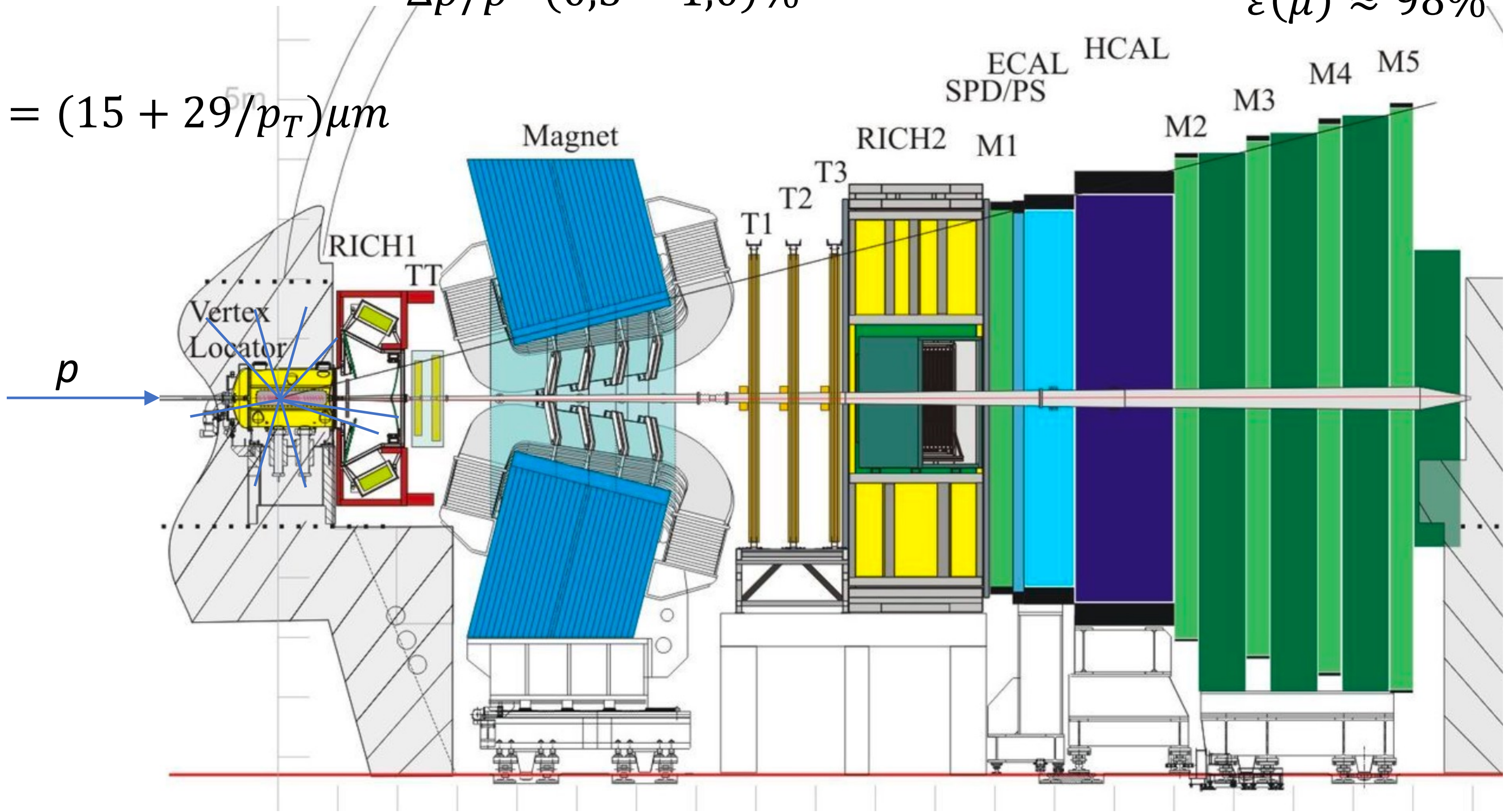
The LHCb Dectector
JINST 3 (2008) S08005

LHCb Detector Performance
Int. J. Mod. Phys. A30
1530022 (2015)

$\Delta p/p \sim (0{,}5 - 1{,}0)\%$

$\varepsilon(\mu) \approx 98\%$

$\sigma_{IP} = (15 + 29/p_T)\mu m$

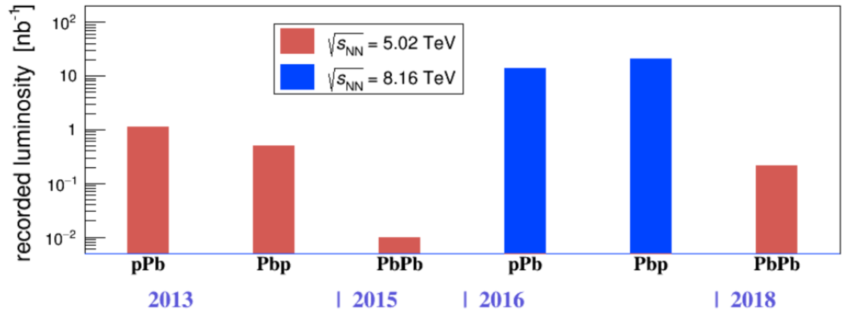


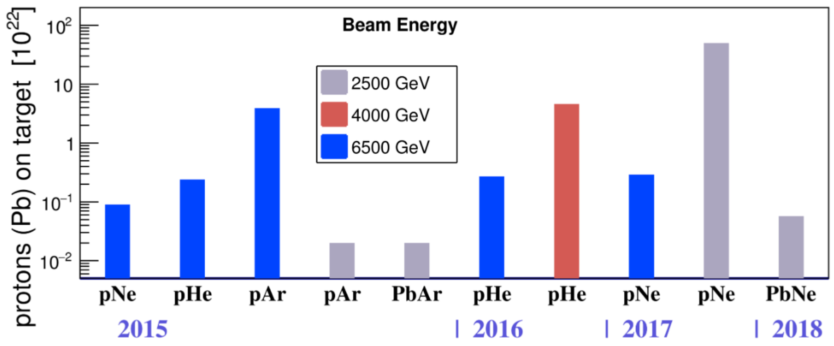
PID for $2 < p < 100$ GeV

ECAL $\frac{\sigma(E)}{E} \approx 6\%$
For $E > 20$ GeV

More on the present upgraded detector later!

LHCb physics program





Heavy ions

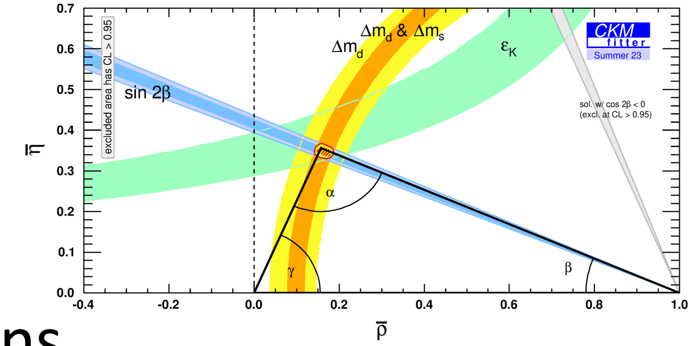
Fixed target

'regular' *pp* running:

- ***CP* violation**
- **rare *B* decays**
- **charm*** and strange physics
- production cross-sections
  - *heavy flavor, EW, QCD*
- spectroscopy
  - *traditional, exotic*

** See talks by Alessia Anelli and Aleksei Chernov on Thursday*

Results: $\sin 2\beta$



Classic: First observation of CPV in B mesons

Belle, Babar, 2001, using $B^0 \to J/\psi K_S$ decays

Theoretically **clean** observable:

little nonperturbative 'pollution'

Mixed and non-mixed decays **interfere**

time-dependent asymmetry:

$$\mathcal{A}^{CP}(t) = \frac{\Gamma(\overline{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\overline{B}^0(t) \to f) + \Gamma(B^0(t) \to f)} = \frac{S \sin(\Delta m_d t) - C \cos(\Delta m_d t)}{\cosh\left(\frac{1}{2}\Delta\Gamma_d t\right) + \mathcal{A}_{\Delta\Gamma}\sinh\left(\frac{1}{2}\Delta\Gamma_d t\right)}$$

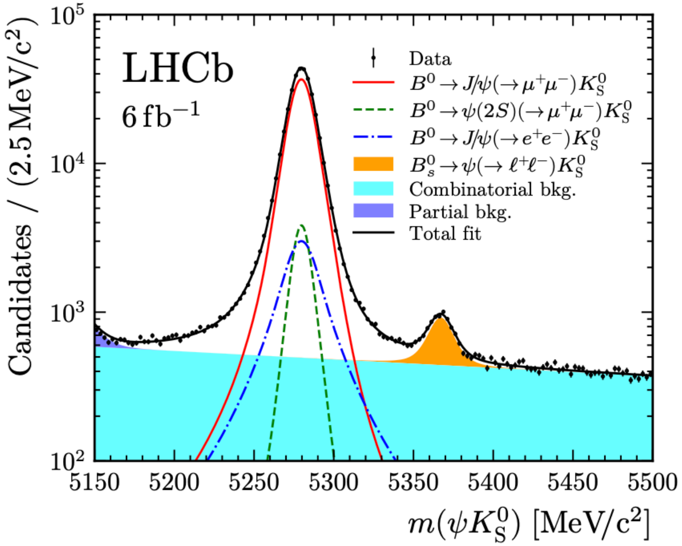
Requires knowledge of initial state: **flavor tagging**

Same-side, from fragmentation tracks

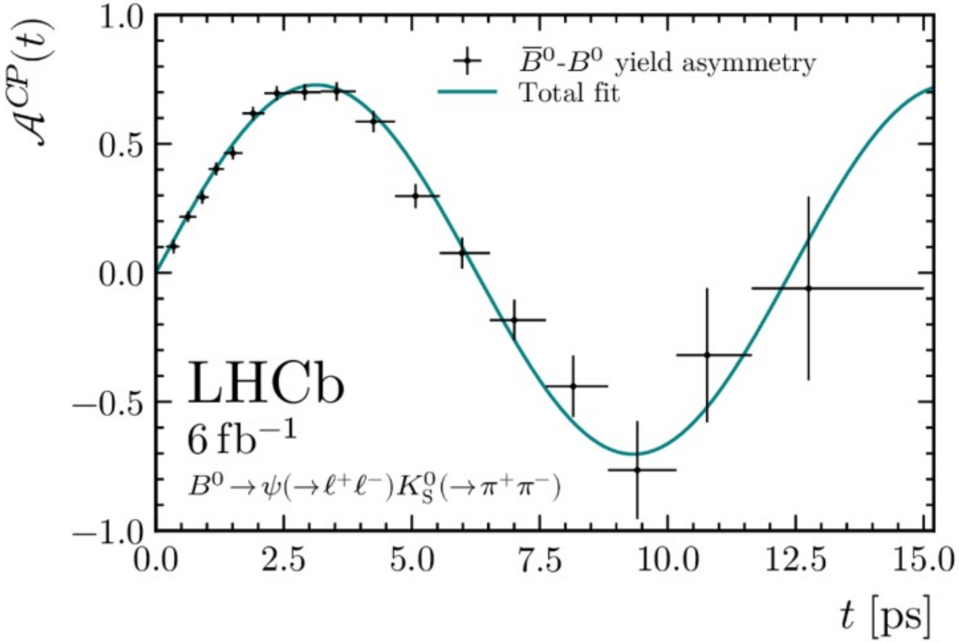
Opposite-side, from leptons, Kaons, charm of other B

Statistical efficiency $\varepsilon D^2 \approx 4\%$

Results: $\sin 2\beta$



$$\mathcal{A}^{CP}(t) = \frac{S\sin(\Delta m_d t) - C\cos(\Delta m_d t)}{\cosh\left(\frac{1}{2}\Delta\Gamma_d t\right) + \mathcal{A}_{\Delta\Gamma}\sinh\left(\frac{1}{2}\Delta\Gamma_d t\right)}$$



$B^0 \to J/\psi(\to \mu^+\mu^-)K_s^0$	~306K
$B^0 \to \psi(2S)(\to \mu^+\mu^-)K_s^0$	~24K
$B^0 \to J/\psi(\to e^+e^-)K_s^0$	~43K

$$S_{\psi K^0_S} = 0.717 \pm 0.013\,(\text{stat}) \pm 0.008\,(\text{syst}),$$
$$C_{\psi K^0_S} = 0.008 \pm 0.012\,(\text{stat}) \pm 0.003\,(\text{syst}).$$

- Best single measument
- More precise than previous HFLAV world-average (0.699 ± 0.017)
- Consistent with global fit

arXiv:2308.01468

Result: ϕ_s and $\Delta\Gamma_s$

Similar decay as $B^0 \to J/\psi K_S$: $B_s \to J/\psi\phi$

Expect **small asymmetry** from V_{ts} : $\phi_s = 36.8^{+0.9}_{-0.6}$ mrad

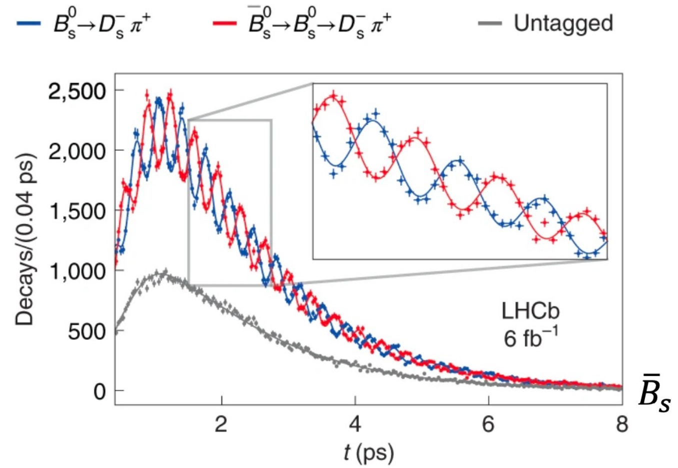
Modulated by **fast** B_s oscillations

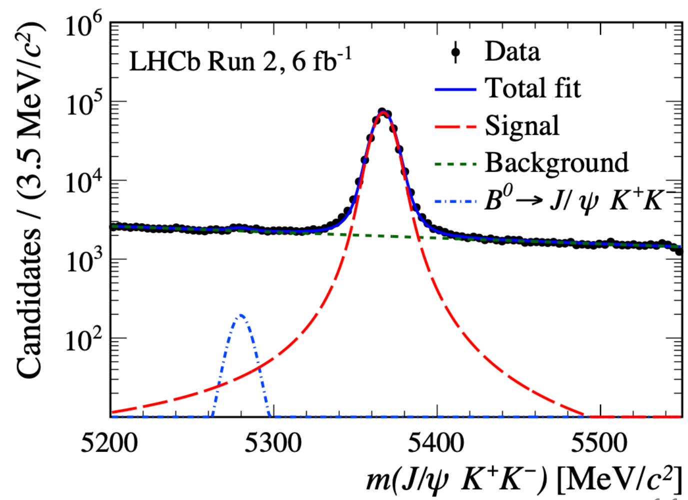
$P \to VV$ decays require **angular analysis** to disentangle CP-odd, CP-even

349k signal events

6 $m(KK)$ bins near $\phi(1020)$

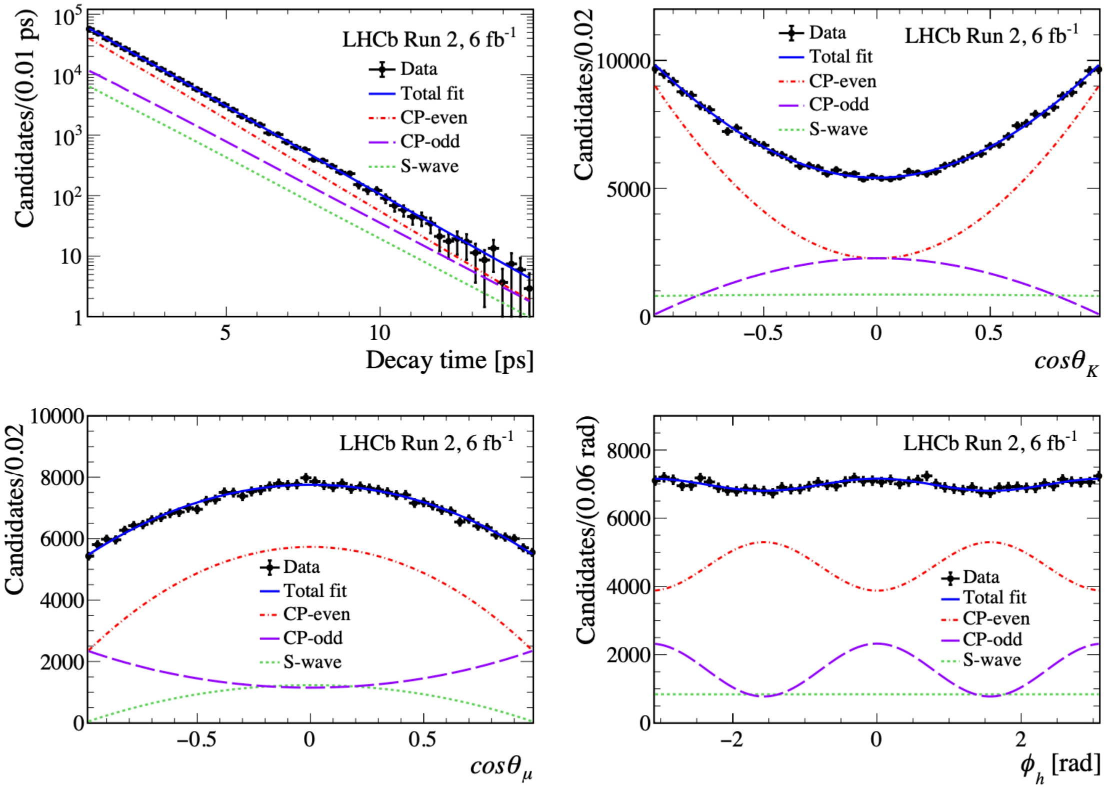
Nature Physics 18, (2022) 1





ϕ_s fit

Simultaneous fit with similar $B^0 \to J/\psi K^{*0}$

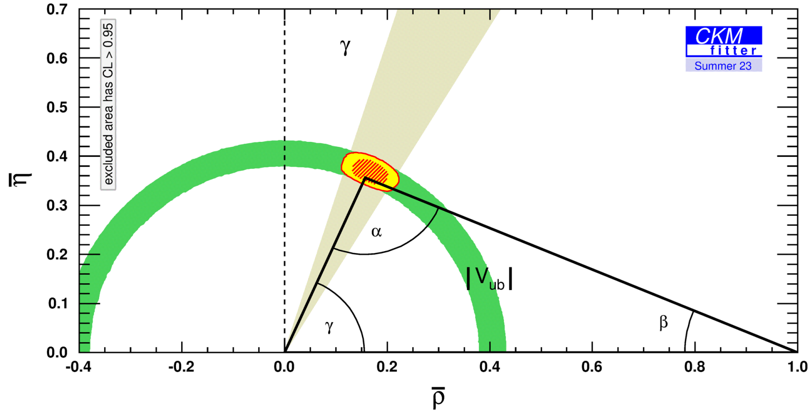


Measure 9 physics parameters:

Parameter	Values		
ϕ_s [rad]	-0.039	± 0.022	± 0.006
$\lvert\lambda\rvert$	1.001	± 0.011	± 0.005
$\Gamma_s - \Gamma_d$ [ps^{-1}]	-0.0056	$^{+0.0013}_{-0.0015}$	± 0.0014
$\Delta\Gamma_s$ [ps^{-1}]	0.0845	± 0.0044	± 0.0024
Δm_s [ps^{-1}]	17.743	± 0.033	± 0.009
$\lvert A_\perp\rvert^2$	0.2463	± 0.0023	± 0.0024
$\lvert A_0\rvert^2$	0.5179	± 0.0017	± 0.0032
$\delta_\perp - \delta_0$ [rad]	2.903	$^{+0.075}_{-0.074}$	± 0.048
$\delta_\parallel - \delta_0$ [rad]	3.146	± 0.061	± 0.052

- Consistent with other measurements
- Consistent with no CP violation
- Consistent with SM CP violation

γ with $B^- \to DK$



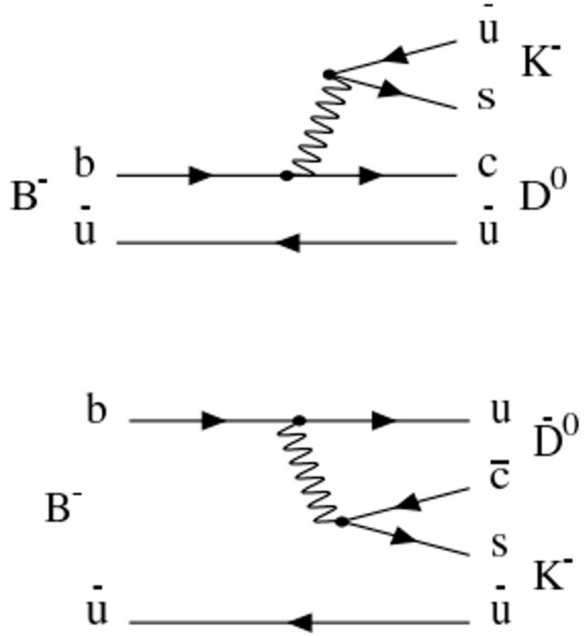
$B^- \to D^0 K^-$ and $B^- \to \overline{D}^0 K^-$ **interfere** through common decay modes of D^0 and $\overline{D}^0$.

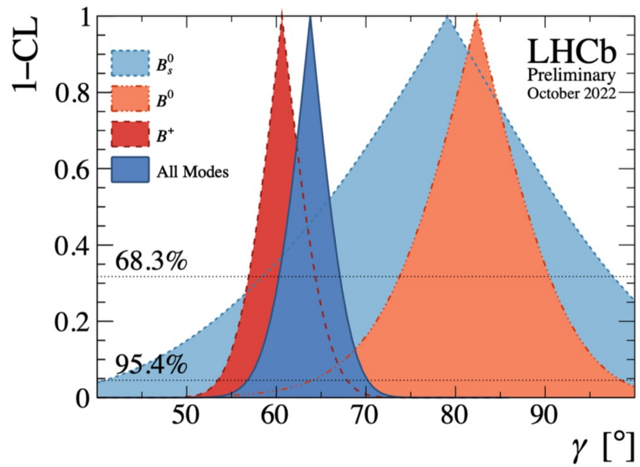
Results in nonzero $A^{CP} = \frac{\Gamma(B^-)-\Gamma(B^+)}{\Gamma(B^-)+\Gamma(B^+)}$

- GLW: CP eigenstates: $\pi^+\pi^-$, K^+K^-, $K_S\pi^0$
- ADS: CF&DCS: π^+K^-, $\pi^+K^-\pi^0$
- BPGGSZ: Self-conjugate: $K_S\pi^+\pi^-$, $K_SK^+K^-$

Theory uncertainty $O(10^{-7})$

Dominates LHCb average γ





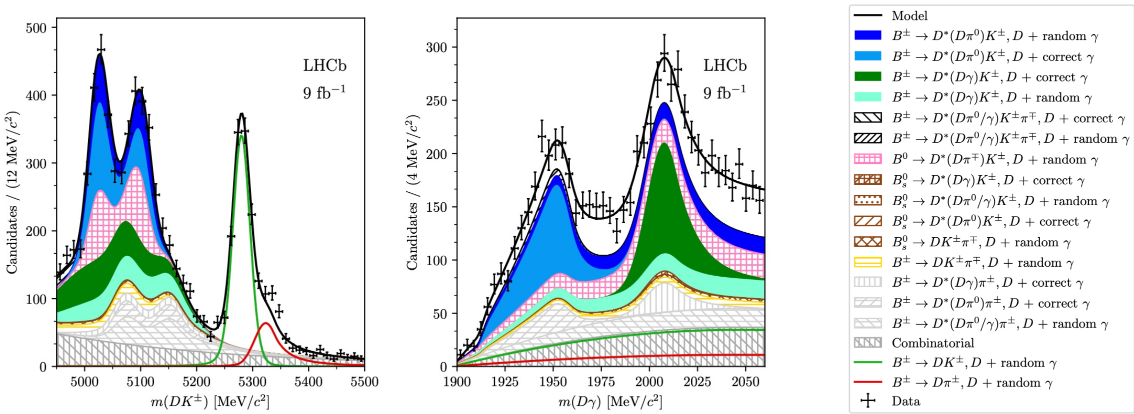
$\gamma = \left(63.8^{+3.5}_{-3.7}\right)^\circ$

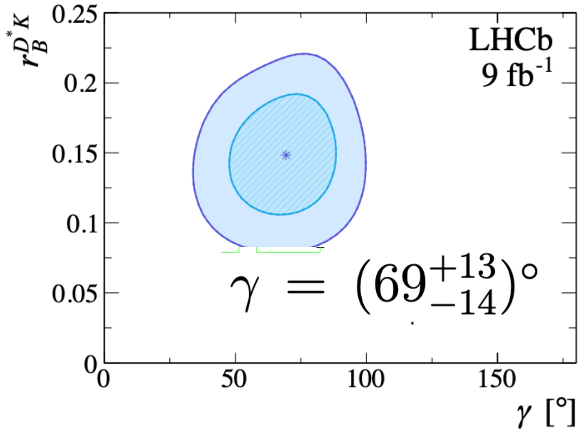
Agrees with fit to indirect observables $\gamma = (65.7^{+1.3}_{-1.2})^\circ$
CKMfitter

Result: $B^- \to D^* K$

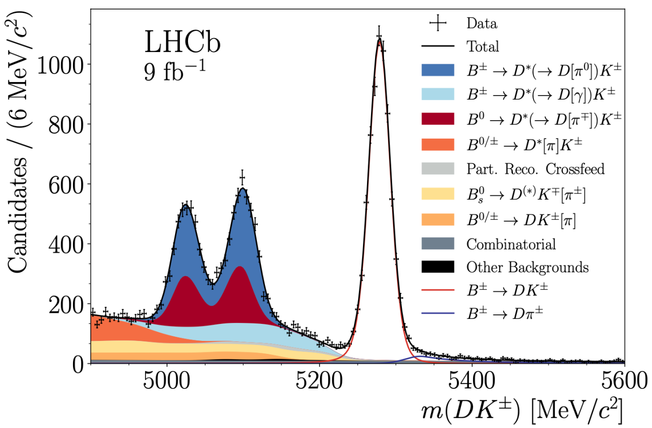
Two recent measurements use $B^- \to D^* K$ decays, with $D \to K_S \pi^+ \pi^-, K_S K^+ K^-$

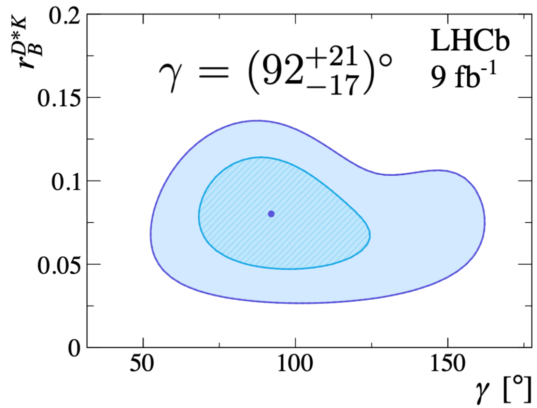
Fully reconstructed $D^{*0} \to D^0 \gamma / \pi^0$ arXiv:2310.04277 JHEP12(2023)013





Partially reconstructed $D^{*0} \to D^0 \gamma / \pi^0$ arXiv:2311.10434





CPV in $B^- \to D_{(s)}^{(*)-} D^{(*)0}$

arXiv:2306.09945
JHEP 09 (2023) 202

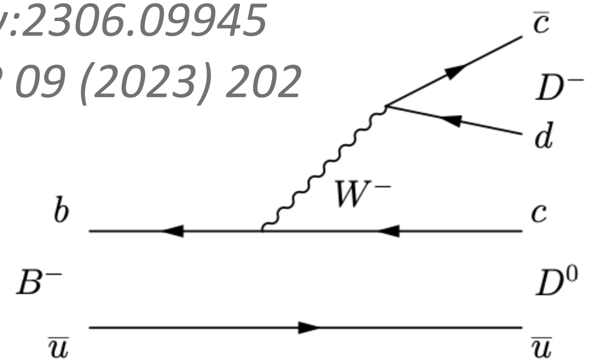
SM: $A^{CP}(B^- \to D^- D^0) \sim 10^{-2}$

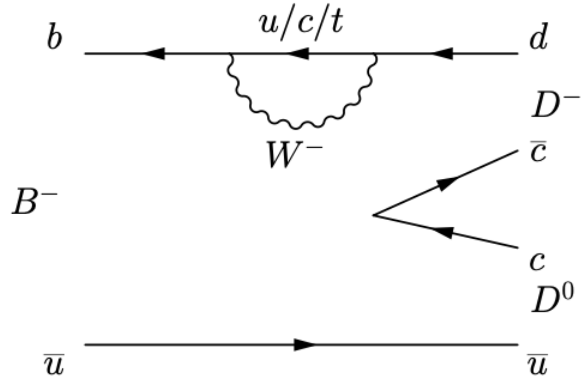
New physics can enhance to $O(10^{-1})$

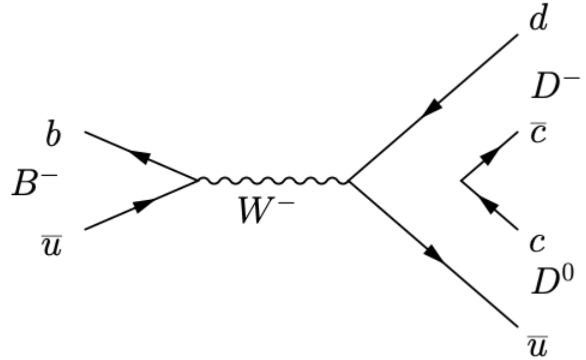
IJTP 55 5290, PRD 79 055004

QCD penguin amplitudes affect present theory prediction

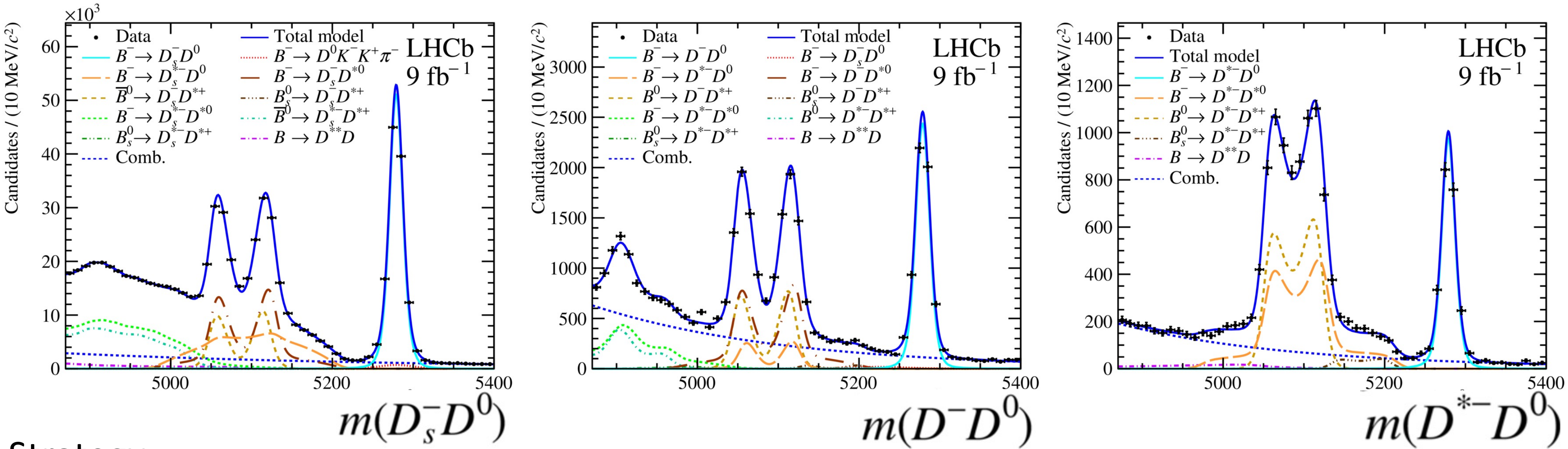
Combined *CP* and *BF* of B^-, B^0, $B_s \to DD$ can reduce this *PRD 91 034027*







CPV in $B^- \to D_{(s)}^{(*)-} D^{(*)0}$



Strategy:

measure **raw asymmetries**

$$A_{\text{raw}} \equiv \frac{N(B^-) - N(B^+)}{N(B^-) + N(B^+)}$$

Subtract **production asymmetry**

measured in $B^+ \to J/\psi K^+$

Subtract **detection asymmetry**

- trigger
- PID
- offline reconstruction
- material interaction

Decay	$\mathcal{A}_{\text{raw}}$	$\mathcal{A}_{\text{P}}$	$\mathcal{A}_{\text{D}}$
$D_s^- D^0$	$-1.3 \pm 0.2 \pm 0.1$	$-1.1 \pm 0.3 \pm 0.3$	-0.7 ± 0.2
$D_s^{*-} D^0$	$-2.4 \pm 1.1 \pm 0.9$	$-1.1 \pm 0.4 \pm 0.3$	-0.8 ± 0.2
$D_s^- D^{*0}$	$-0.8 \pm 0.8 \pm 0.4$	$-1.1 \pm 0.4 \pm 0.3$	-0.8 ± 0.2
$D^- D^0$	$1.5 \pm 1.0 \pm 0.2$	$-1.1 \pm 0.4 \pm 0.3$	0.1 ± 0.2
$D^- D^{*0}$	$-1.3 \pm 2.0 \pm 1.3$	$-1.1 \pm 0.4 \pm 0.3$	0.1 ± 0.2
$D^{*-} D^0$	$2.4 \pm 1.6 \pm 0.2$	$-1.2 \pm 0.4 \pm 0.3$	0.2 ± 0.3
$D^{*-} D^{*0}$	$1.3 \pm 2.1 \pm 1.6$	$-1.1 \pm 0.5 \pm 0.3$	0.1 ± 0.2

CPV in $B^- \to D_{(s)}^{(*)-} D^{(*)0}$

Results:

Decay	$\mathcal{A}^{CP}$	World average [PDG]
$B^- \to D_s^- D^0$	$(0.5 \pm 0.2 \pm 0.5 \pm 0.3)\%$	$(-0.4 \pm 0.7)\%$
$B^- \to D_s^{*-} D^0$	$(-0.5 \pm 1.1 \pm 1.0 \pm 0.3)\%$	-
$B^- \to D_s^- D^{*0}$	$(1.1 \pm 0.8 \pm 0.6 \pm 0.3)\%$	-
$B^- \to D^- D^0$	$(2.5 \pm 1.0 \pm 0.4 \pm 0.3)\%$	$(1.6 \pm 2.5)\%$
$B^- \to D^{*-} D^0$	$(3.3 \pm 1.6 \pm 0.6 \pm 0.3)\%$	$(-6 \pm 13)\%$
$B^- \to D^- D^{*0}$	$(-0.2 \pm 2.0 \pm 1.4 \pm 0.3)\%$	$(13 \pm 18)\%$
$B^- \to D^{*-} D^{*0}$	$(2.3 \pm 2.1 \pm 1.7 \pm 0.3)\%$	$(-15 \pm 11)\%$

Consistent with **zero**

Consistent with **SM**

Huge improvement over previous results

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

Rare decay ($\mathcal{B} \approx 10^{-6}$) only possible through loops

highly sensitive to new physics

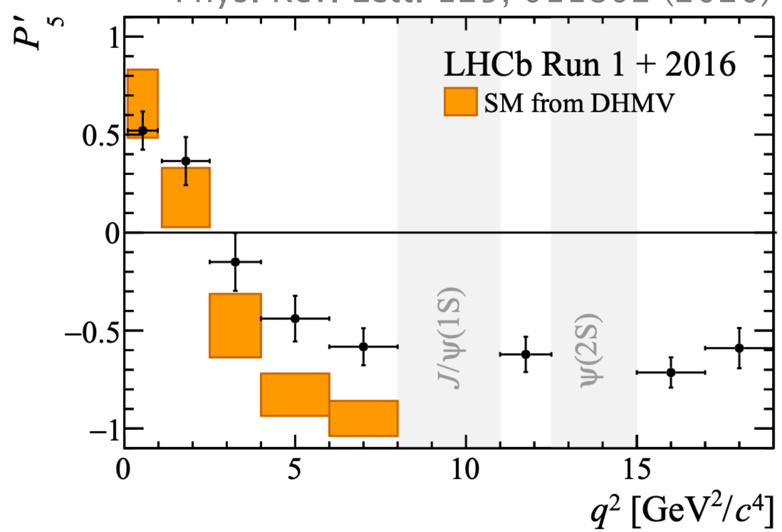
Five observables per decay: $q^2, k^2, \theta_l, \theta_K, \varphi$

Earlier analyses indicate discrepancy for $P'_5 \equiv S_5/\sqrt{F_L(1-F_L)}$

3,3σ discrepancy in $Re(C_9)$

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

Phys. Rev. Lett. 125, 011802 (2020)



But long-distance hadronic effects can mimic NP

arXiv:2312.09102
arXiv:2312.09115

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

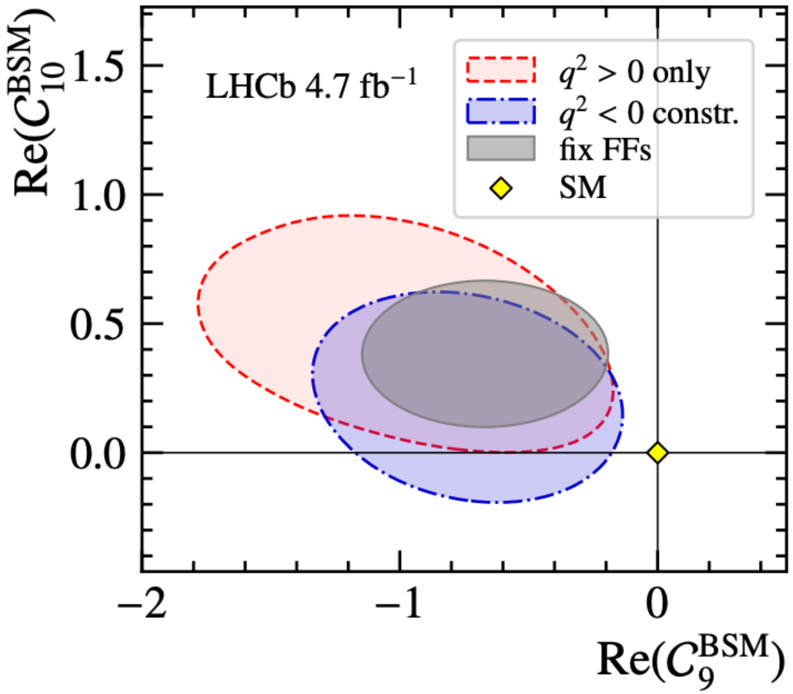
New analysis without q^2 binning

same dataset: Run1+2016 = 4,7 fb^{-1}

Control long-distance terms from $B^0 \to K^{*0}J/\psi, \psi'$

polynomial expansion in $z(q^2)$

Include (or ignore) long-distance predictions at $q^2 < 0$

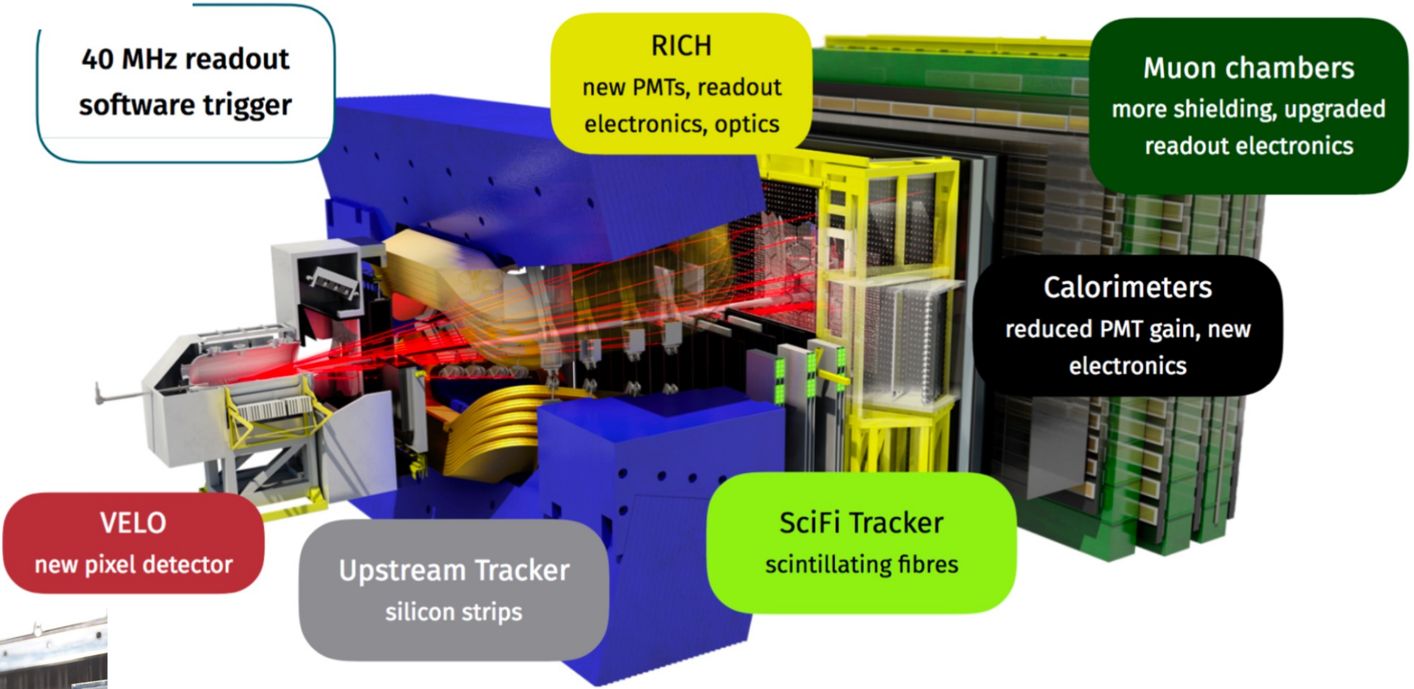


Discrepancy on $Re(C_9)$ reduced to less than 2σ

arXiv:2305.10515

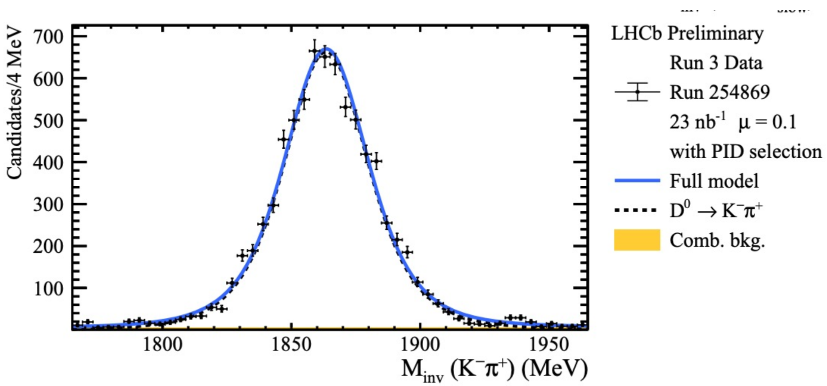
The LHCb upgrade

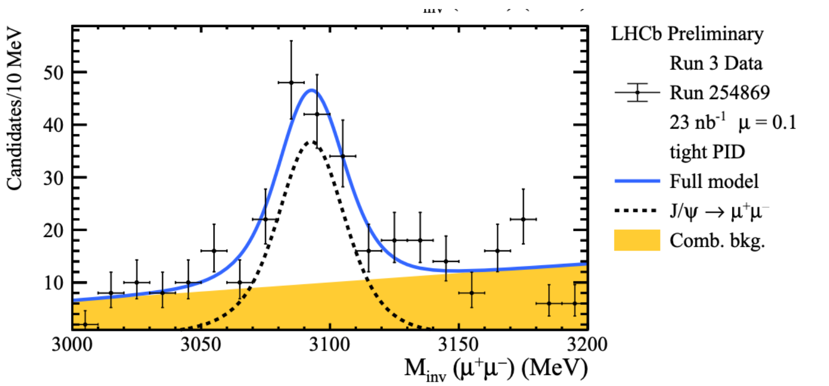
- Full software trigger
- Raise $\mathscr{L}$ to 2x10^{33}cm^{-2}s^{-1}(5x Run2) but maintain current reconstruction performance
- Major redesign of all sub-detectors and ambitious readout upgrade



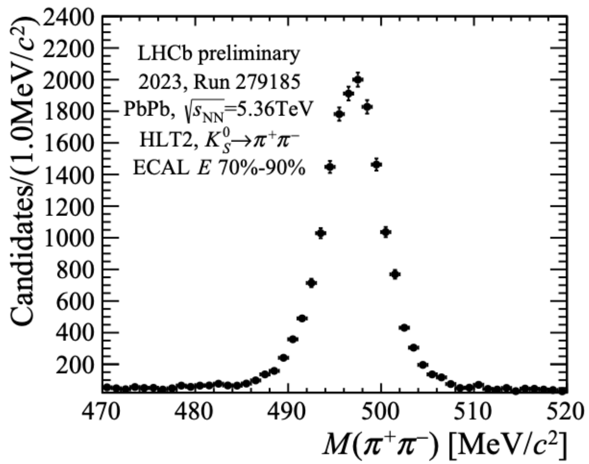
Reconstructed Run 3 events

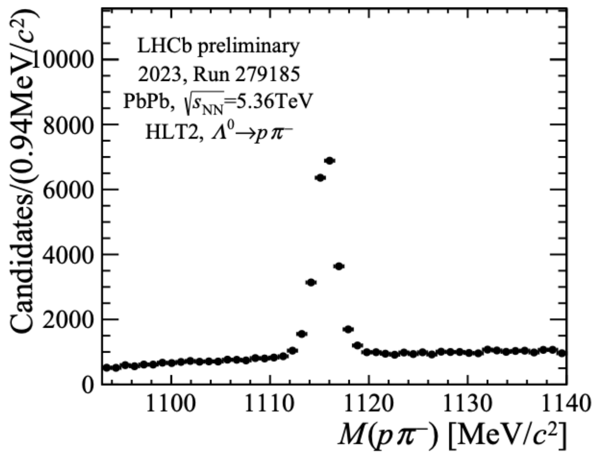
2022 pp





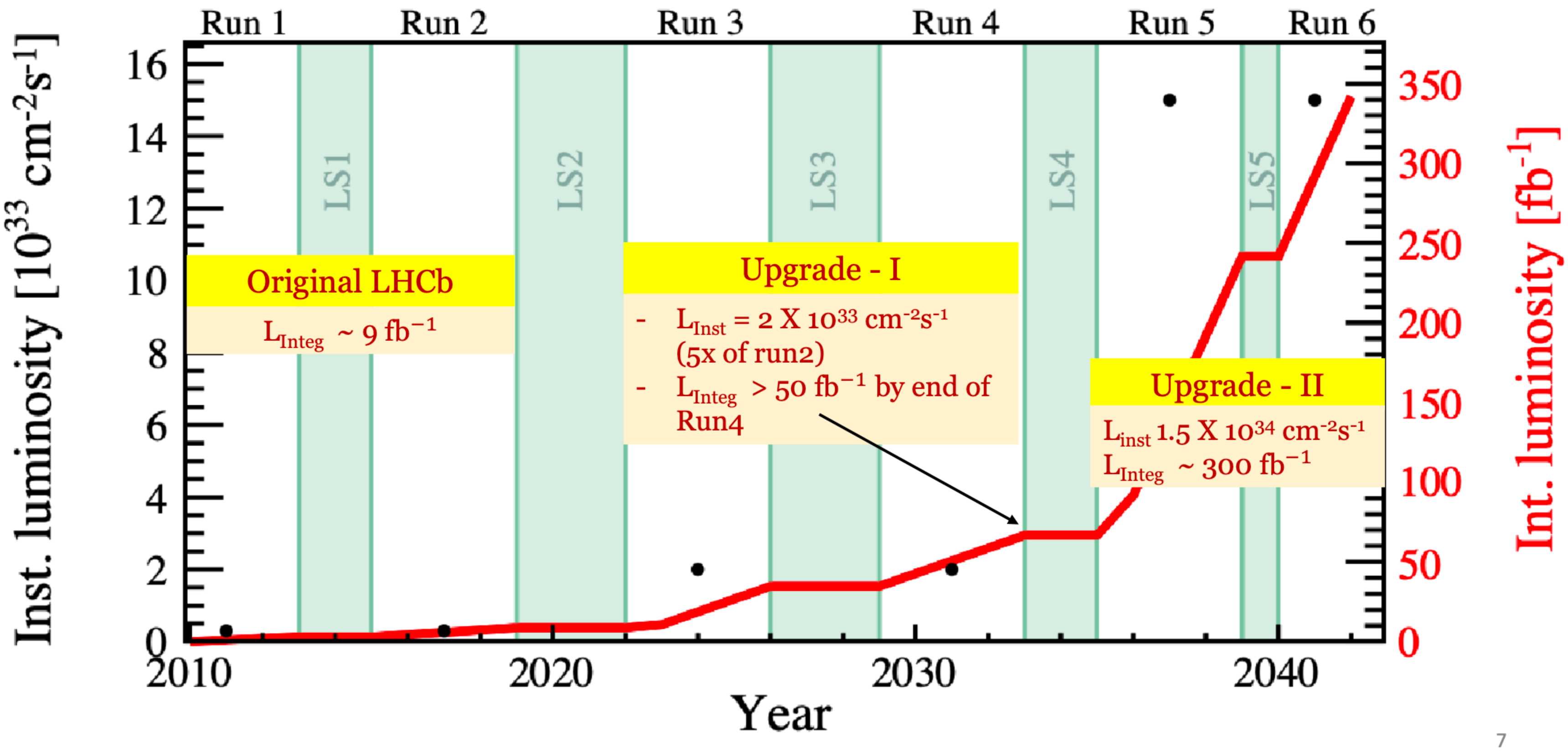
2023 PbPb





Aim for physics quality data starting 2024

LHCb schedule



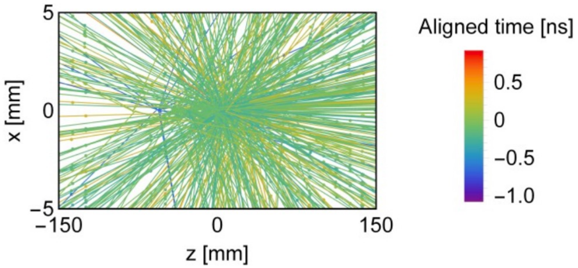
Plans for upgrade 2

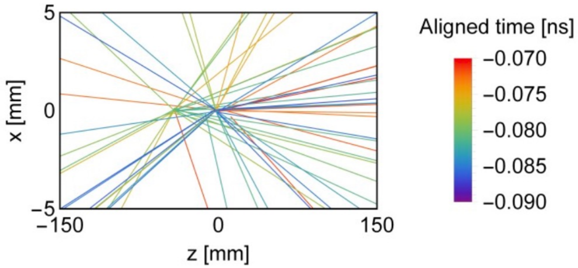
Goal is to reach 300 fb^{-1}

$L_{inst} \approx 1{,}5 \cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Pileup of 40

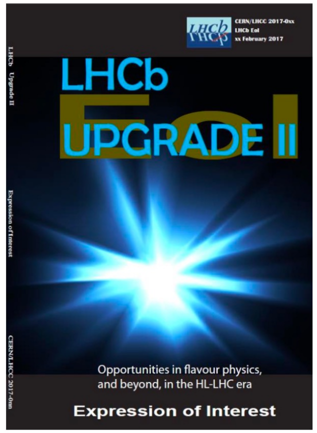
Separate collisions with $O(10\mathrm{ps})$ timing



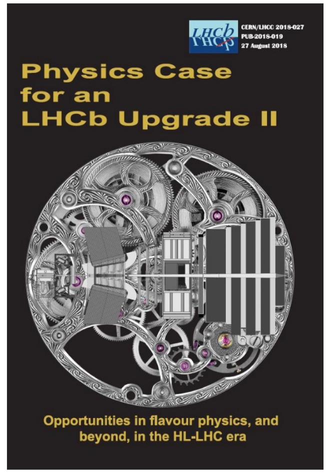


First enhancements in LS3,

Full installation in LS4



[CERN-LHCC-2017-003]



[CERN-LHCC-2018-027]

[CERN-LHCC-2021-012]

Conclusions

Analysis of Run1 and Run2 data **ongoing**

Many unique and world-best measurements

Upgraded detector complete for **physics in 2024**

Welcome fresh competion with Belle-II

Viable plans for high luminosity with **Upgrade II**

*Major **challenge**: high pile-up in forward region*
*Very high **reward** in precision flavour measurements*