Prospects of charm physics at LHCb

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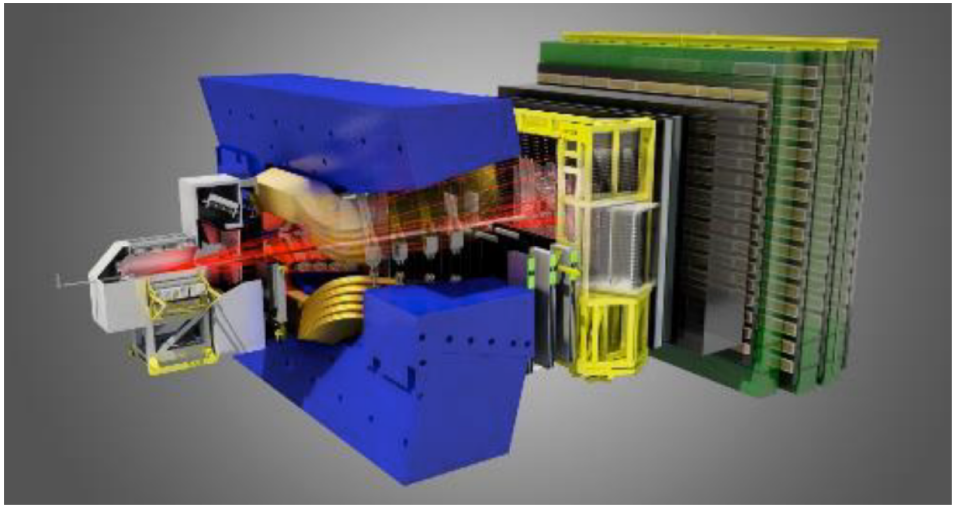
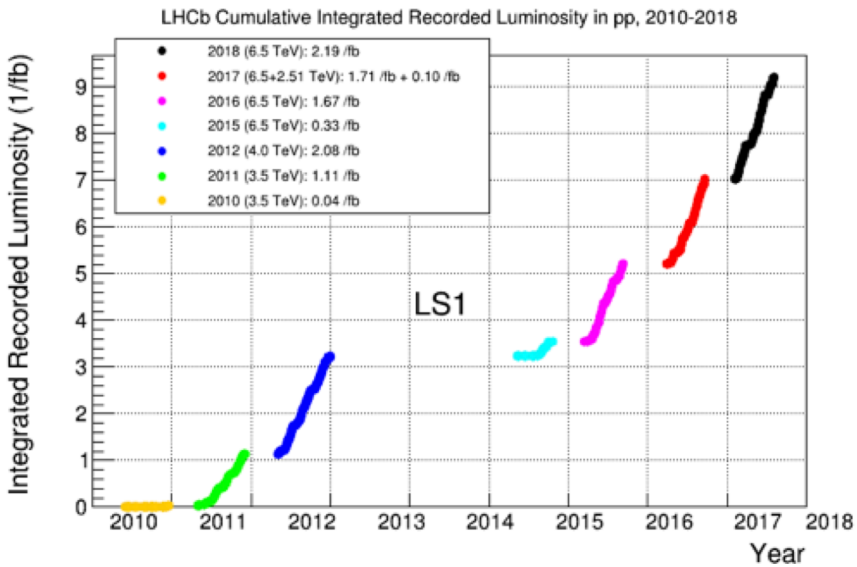
Outline

- LHCb detector and its upgrade plan
- Charm physics @ LHCb
- Prospects on charm mixing and CP violation
- Prospects on rare charm decays
- Conclusion

LHCb experiment before 2019

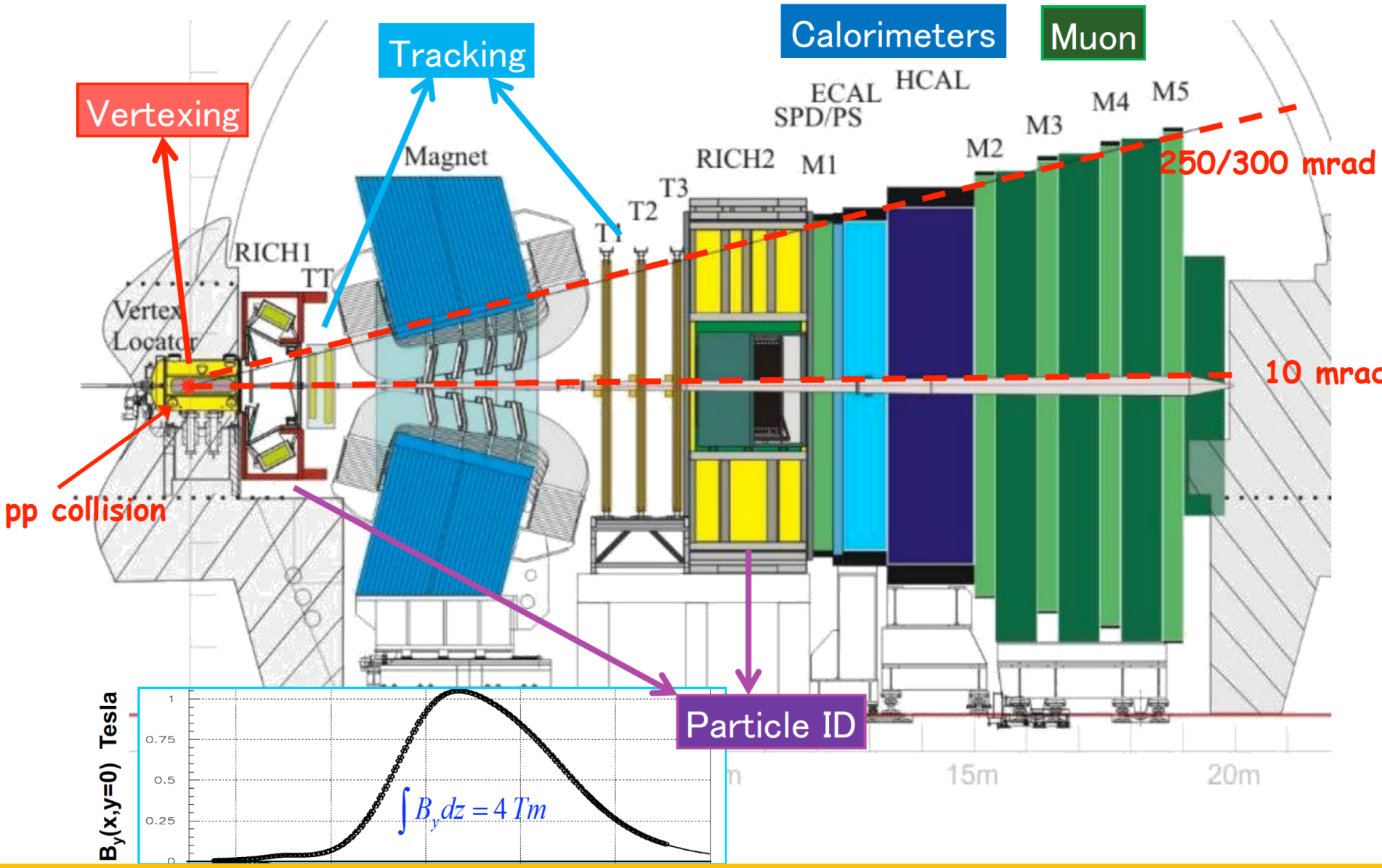




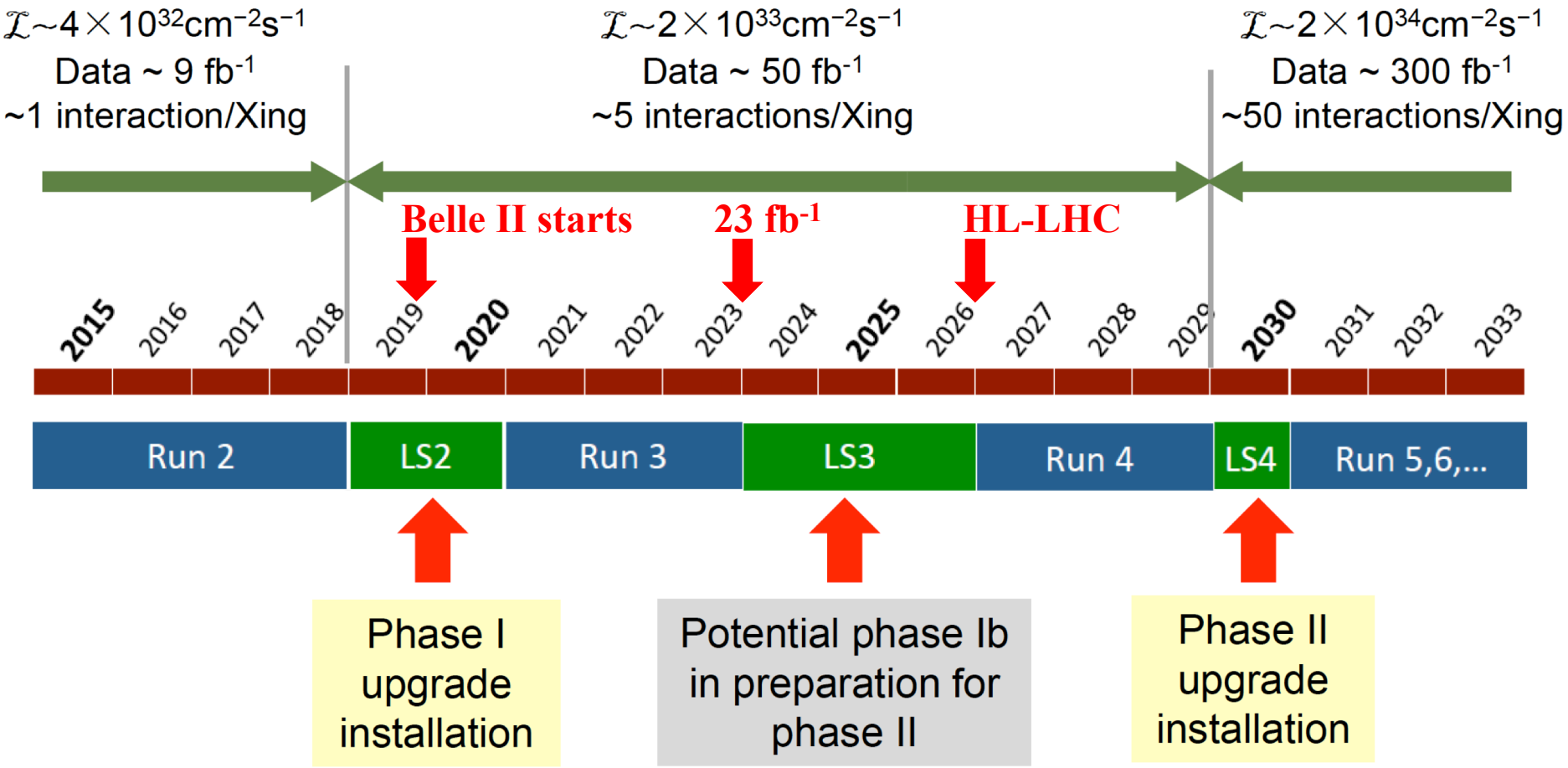
- Forward spectrometer dedicated for flavor physics studies
  - Excellent primary and secondary vertex measurements;
  - Very good PID performance on K/π/p
  - Excellent momentum resolution

- Wonderful performance with the LHCb detector:
  - Run1: 3 fb^{-1} pp data at 7 and 8 TeV
  - Run2: 6 fb^{-1} data at 13 TeV, effectively 4-6 times more than Run1

The retired detector

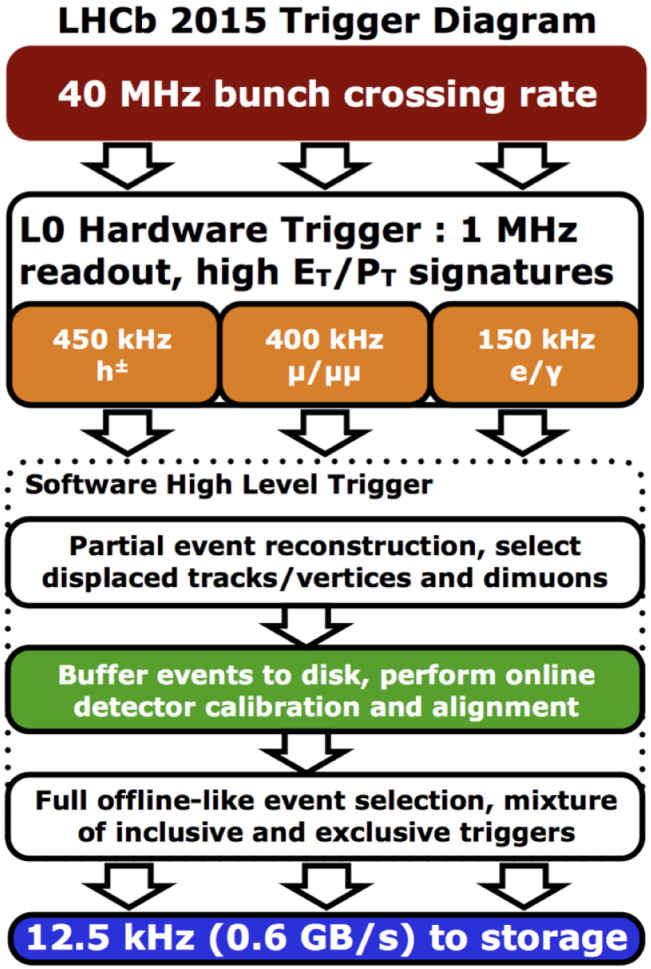


The LHCb upgrade plans

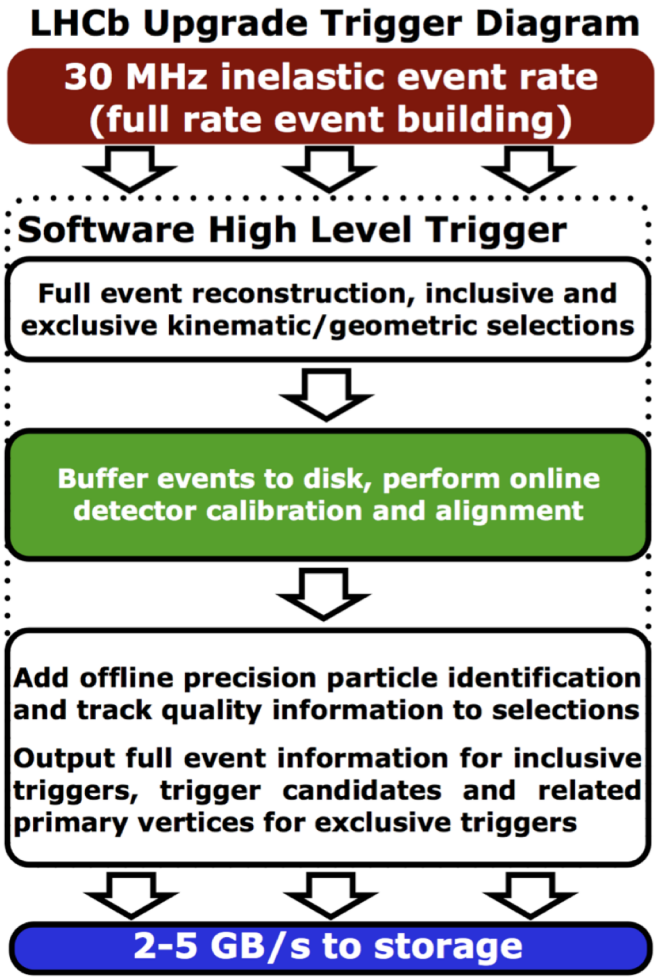


Data acquisition situation in Upgrade I

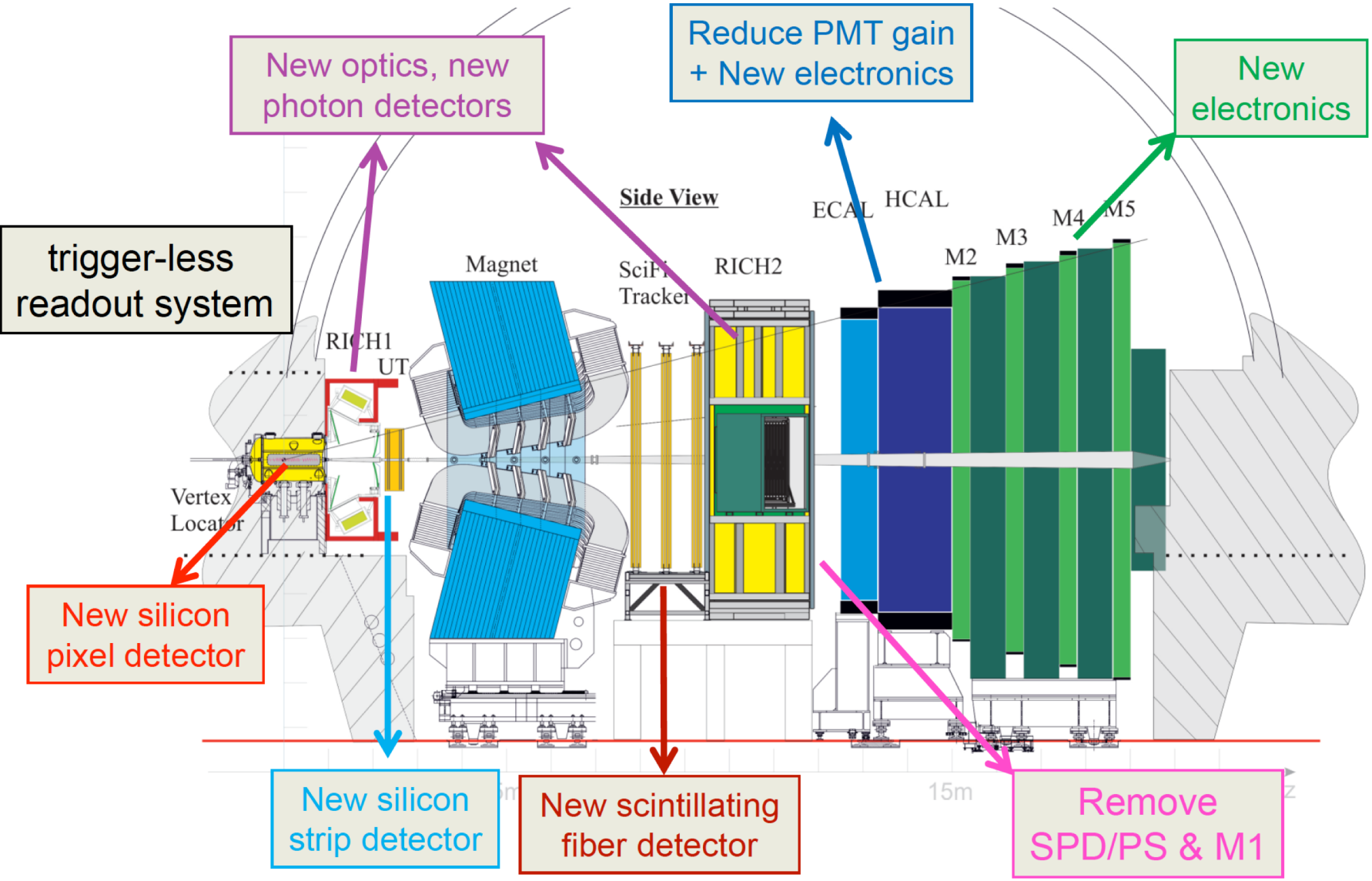
- 1-2 fb^{-1} per year
- ~1 interaction per Xing
- Hardware + software trigger



- 9-10 fb^{-1} per year
- ~5 interaction per Xing
- Software only trigger



A new LHCb detector from 2021



A next LHCb detector from 2030

$\mathcal{L} \sim 2 \times 10^{34} cm^{-2} s^{-1}$
Data ~ 300 fb^{-1}

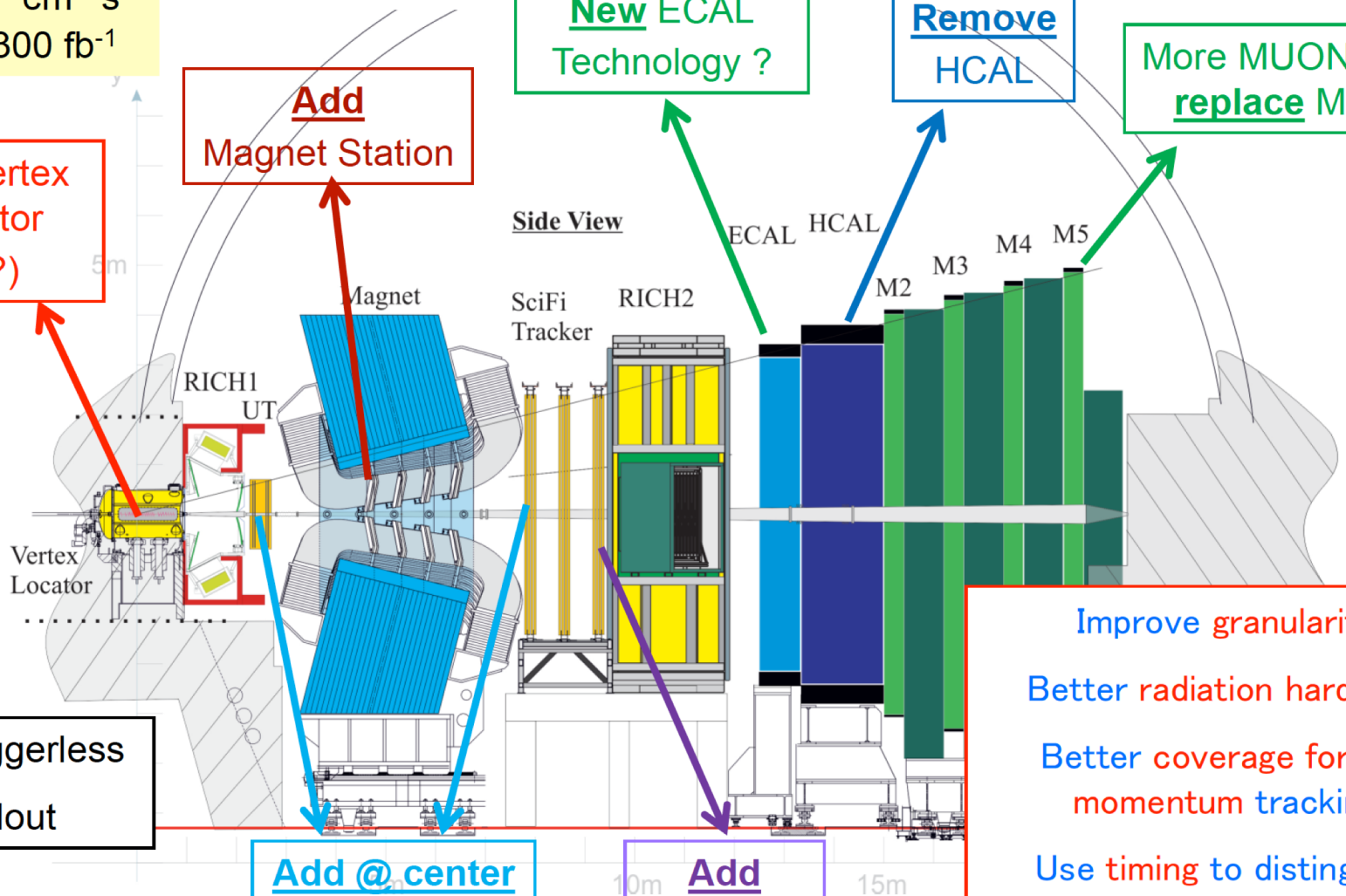
New Vertex Detector (4D?)

Add Magnet Station

New ECAL Technology ?

Remove HCAL

More MUON filter + **replace** MWPC



Keep triggerless readout

Add @ center Mighty Tracker

Add TORCH ?

Improve granularity

Better radiation hardness

Better coverage for low momentum tracking

Use timing to distinguish vertices (high-pileup)

Charm physics @ LHCb

CERN-LHCC-2018-027

- Charm physics is a core part of the LHCb upgrade physics program

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

Observable	Cu	Upgrade II	ATLAS & CMS
EW Penguins			
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$		0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$		0.008	–
R_ϕ, R_{pK}, R_π		.02, 0.02, 0.05	–
CKM tests			
γ, with $B_s^0 \to D_s^+ K^-$		1°	–
γ, all modes		0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$		0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$		4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	1	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	1	11 mrad	Under study [611]
a_{sl}^s	33	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$		1%	–
$B_s^0, B^0 \to \mu^+\mu^-$			
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$		10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$		2%	–
$S_{\mu\mu}$		0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies			
$R(D^*)$	0.0	0.002	–
$R(J/\psi)$		0.02	–
Charm			
$\Delta A_{CP}(KK - \pi\pi)$	8.5	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays		$3\pi)$ 8.0×10^{-6}	–

Charm (D^0/D^+) production

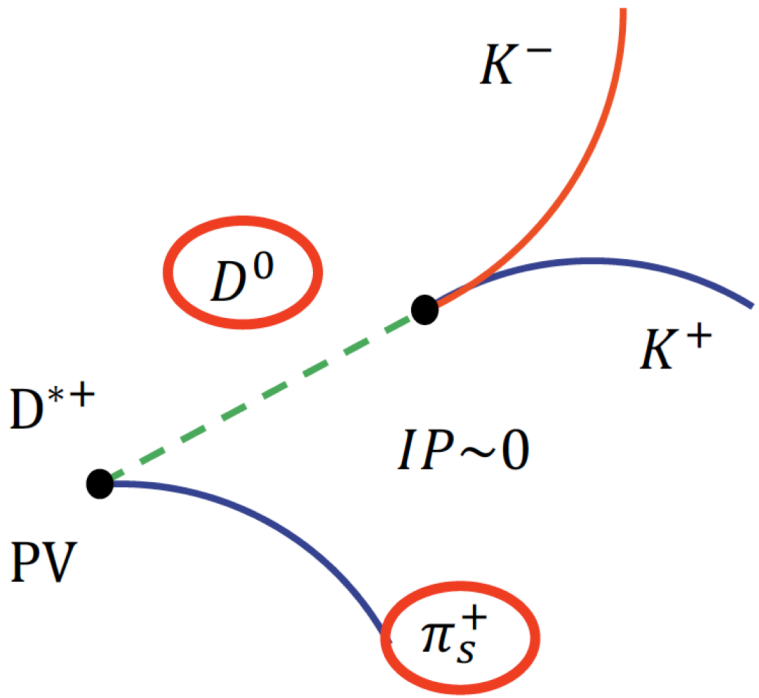
Experiments	Production	Efficiency
LHCb (50 fb^{-1})	~200 x 10^{12}	<0.1%
BelleII	~0.1 x 10^{12}	few%
CEPC	~0.26 x 10^{12}	few%
BESIII	~0.25 x 10^{8}	> 10%
Super tau-charm	~25 x 10^{8}	> 10%

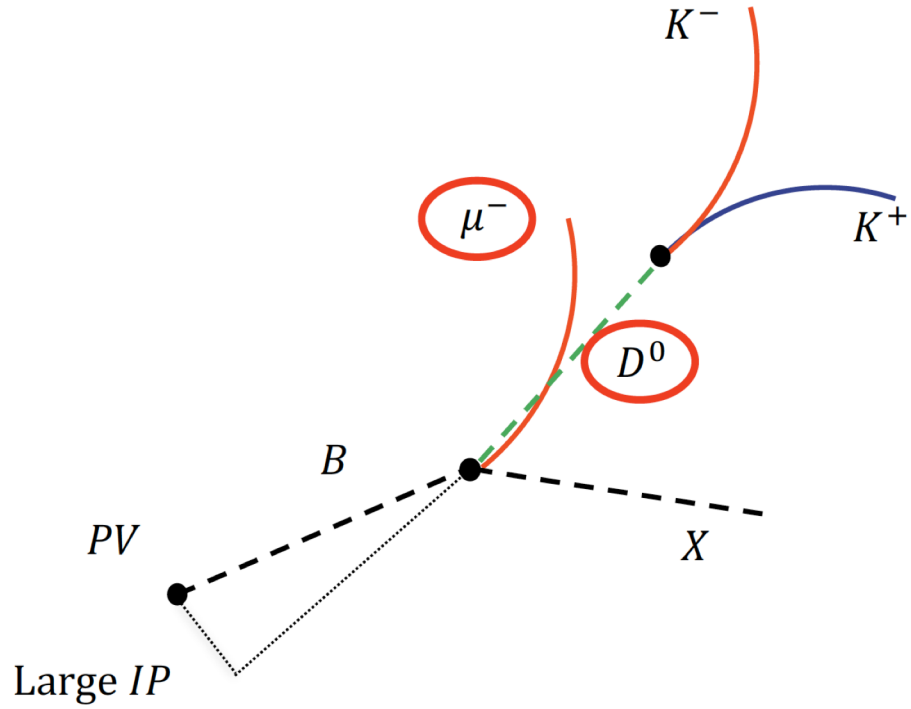
- LHCb: decays into charged final states; charmed baryons; time-dependent measurements
- Belle II (CEPC): decays into final states containing neutrals, i.e. γ, π^0,$\eta^{(,)}$, K^0, neutrinos; absolute branching fraction measurements
- BES III (super tau-charm): Quantum-coherent production； absolute branching fraction measurements

See W. Yan and H. Li's talk for more details

Charm sources @ LHCb

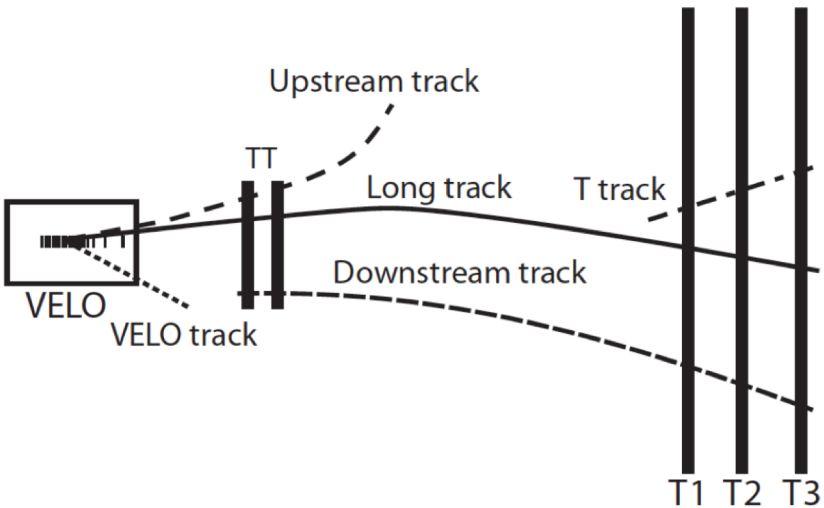
- Direct prompt production: large background; not possible for flavor tagging
- $D^{*+} \to D^0\pi^+$: large yield, high purity, $\sigma(t) \sim 0.1\tau$
- $\bar{B} \to D^0\mu^- X$: 1/6 of D^{*+} tagged, lower purity, $\sigma(t) \sim 0.3\tau$
- $\bar{B} \to D^{*+}(D^0\pi^+)\mu^- X$: 1/40 of D^{*+} tagged, highest purity, $\sigma(t) \sim 0.3\tau$

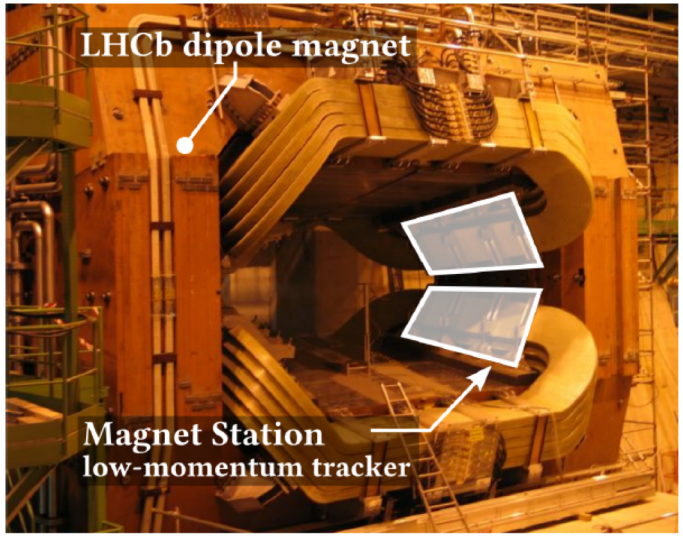




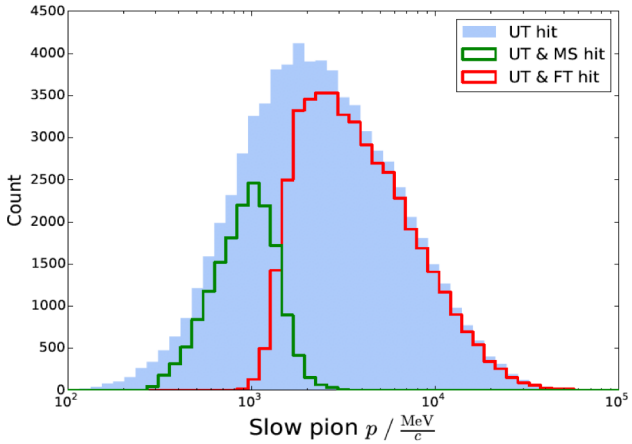
We can get more

- Low detection efficiency for soft pion



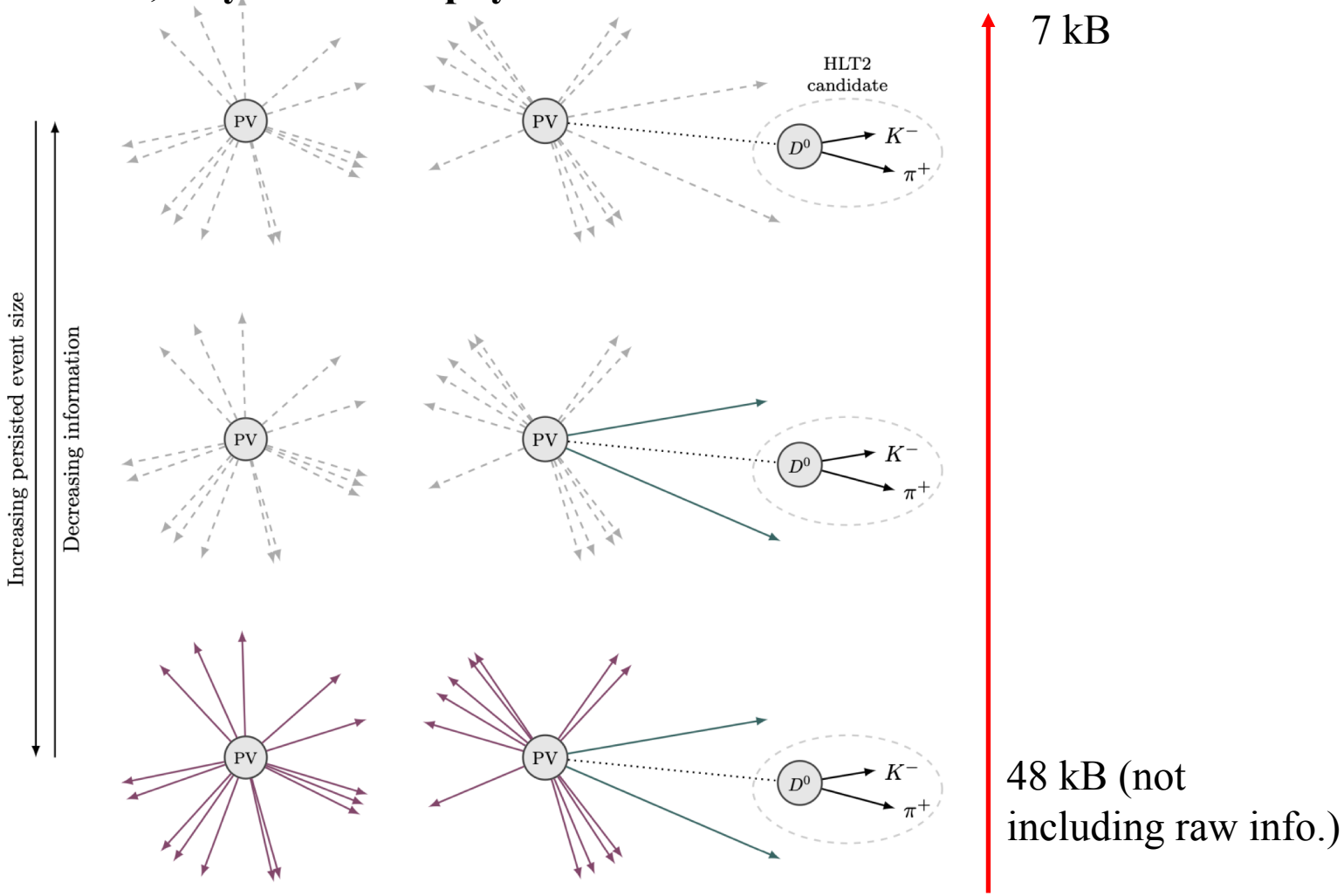


- By adding a new detector inside magnet give **~40% increase** in yields



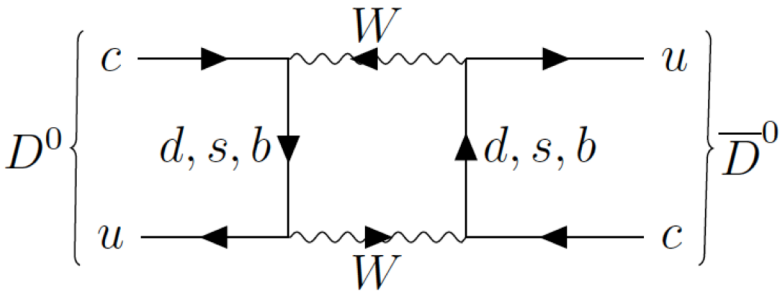
Turbo technique

- **Storage limits bandwidth; by storing selective part of an event increase number of signals stored; Key for charm physics**

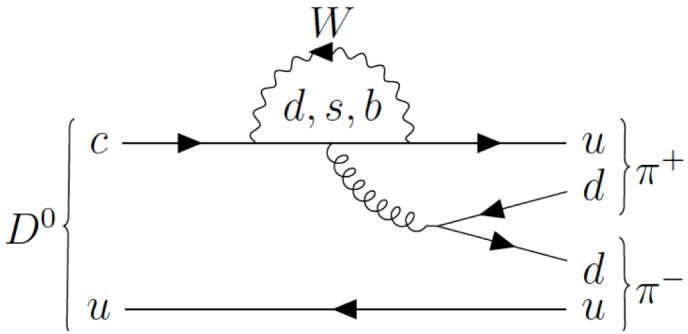


Charm physics overview @ LHCb

- **Charm mixing and CP violation**
  - **Complementary to K and B system**
  - **Direct CP violation in charm found recently**
  - **Indirect CP violation not yet**



- **Rare charm decays**
  - **Unique access to up-type FCNC with down-type quarks in loops**
  - **Very rare in SM, though long-distance dynamics can enhance; still room for new physics searches**



- **Charm hadron spectrum and properties**
- **Charm baryons**

Charm mixing notation

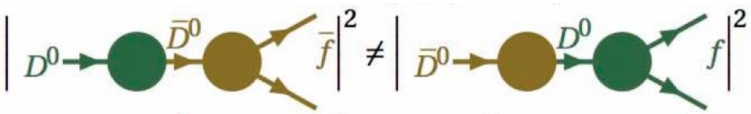
- Neutral charm meson mixes with its anti-particle

$$|D_{1,2}\rangle \equiv p|D^0\rangle \pm q|\overline{D^0}\rangle \ (\text{CPT: } p^2+q^2=1)$$

- Mass and decay width different for the two eigenstates

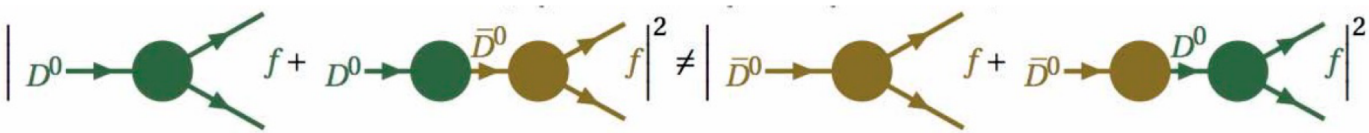
$$x \equiv 2\frac{M_1 - M_2}{\Gamma_1 + \Gamma_2}, \quad y \equiv \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$$

- CP violation in mixing



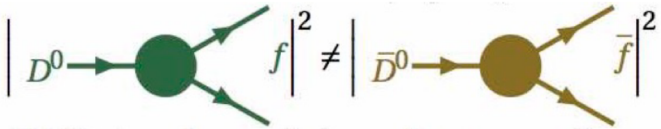
or $\left|\frac{p}{q}\right| \neq 1$

- CP violation in mixing and decay



$$\phi = \arg\left(\frac{q\overline{A_f}}{pA_f}\right) \neq 0$$

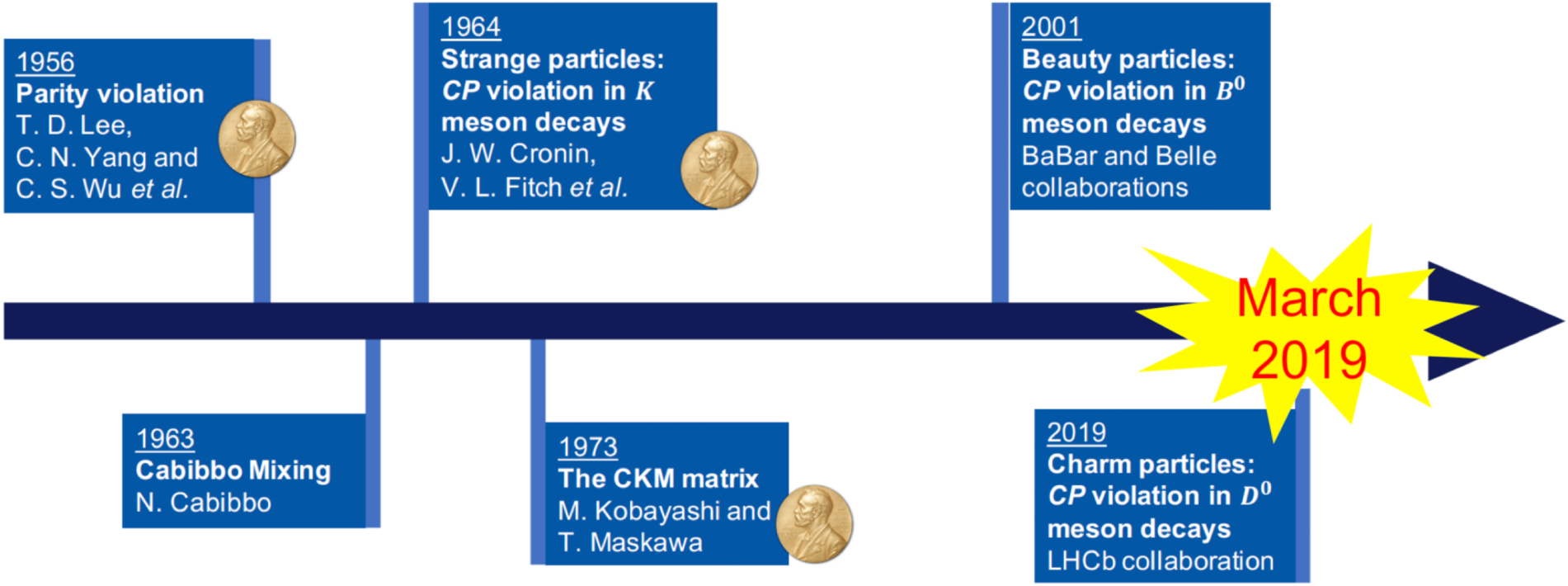
- Direct CP violation



$$A_{CP}^{\text{decay}} \equiv \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}$$

Year of direct Charm CP violation

Phys. Rev. Lett. 122 (2019) 211803



See L. Sun's talk for more details

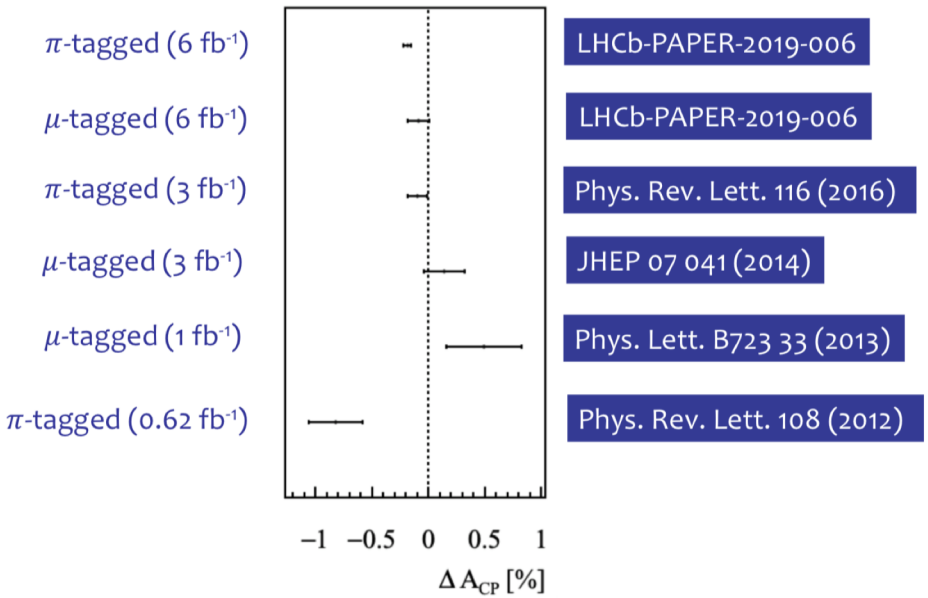
A. Carbone, CERN seminar, March 19, 2019

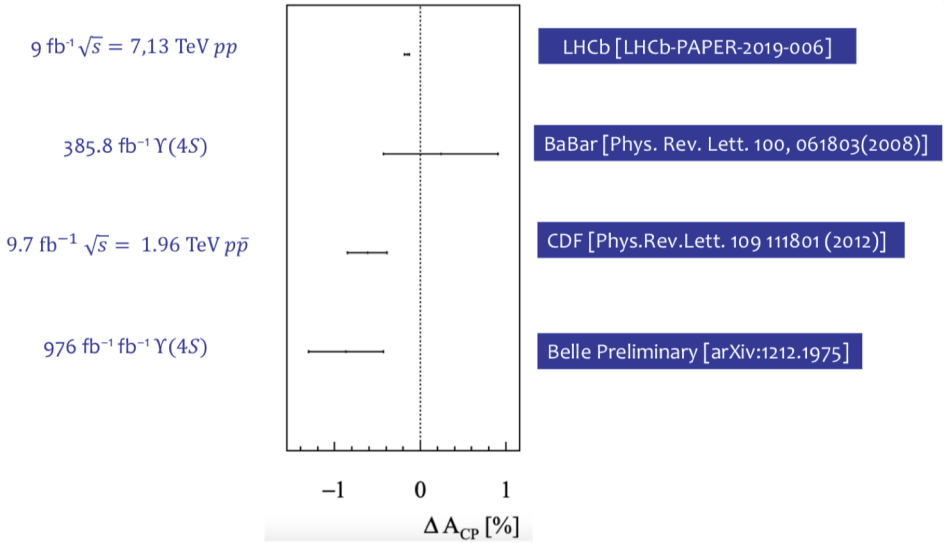
$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

CP violation in charm observed at 5.3σ

Why luminosity matters

Phys. Rev. Lett. 122 (2019) 211803





Statistics is the name of the game

To probe a value of 10^{-4}, you need 10^{8} events

Prospects (units of 10^{-3})

CERN-PUB-LHCC-2018-027
BELLE2-PUB-PH-2018-001

	Current best (stat. + sys)		LHCb U1 (50 fb^{-1}) (2029) (stat. only)	LHCb U2 (300 fb^{-1}) (≈2037) (stat. only)	Belle II (50 ab^{-1}) (2027) (stat. + sys.)
ΔA_{CP}	LHCb (9 fb^{-1})	0.29	0.07	0.03	(0.6)
$A_{CP}(D^0 \to K^+ K^-)$	LHCb (3 fb^{-1})	1.8	0.17	0.07	0.3
$A_{CP}(D^0 \to \pi^+ \pi^-)$	LHCb (3 fb^{-1})	1.8	0.17	0.07	0.5
$A_{CP}(D^0 \to \pi^0 \pi^0)$	Belle (1 ab^{-1})	6.5	–	–	0.9
$A_{CP}(D^0 \to K^+ \pi^-)$	LHCb (5 fb^{-1})	9.1	0.9	0.35	(4.0)
$A_{CP}(D^0 \to K_S K_S)$	Belle (1 ab^{-1})	15	7	2.8	2.3
$A_{CP}(D^0 \to K_S K^{*0})$	LHCb (9 fb^{-1})	4.0	3.7	1.5	(?)
$A_{CP}(D^+ \to \pi^+ \pi^0)$	Belle (1 ab^{-1})	12.6	–	–	1.7
$A_{CP}(D^+ \to \phi \pi^+)$	LHCb (4.8 fb^{-1})	0.49	0.15	0.06	0.4
$A_{CP}(D^+ \to K_S K^+)$	LHCb (6.8 fb^{-1})	0.76	0.29	0.12	0.4
$A_{CP}(D^+_s \to K_S \pi^+)$	LHCb (6.8 fb^{-1})	1.8	0.78	0.32	2.9
$A_{CP}(D^+ \to \eta' \pi^+)$	LHCb (3 fb^{-1})	8.9	0.9	(0.35)	1.4

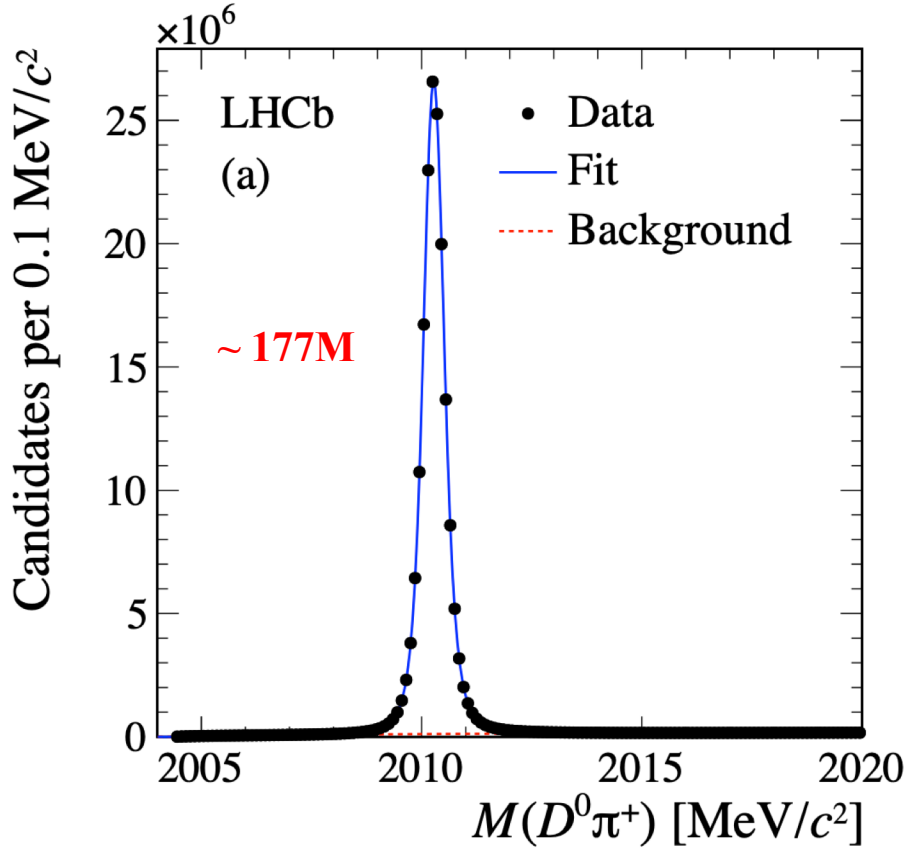
Indirect CP violation

Phys. Rev. D 97 (2018) 031101

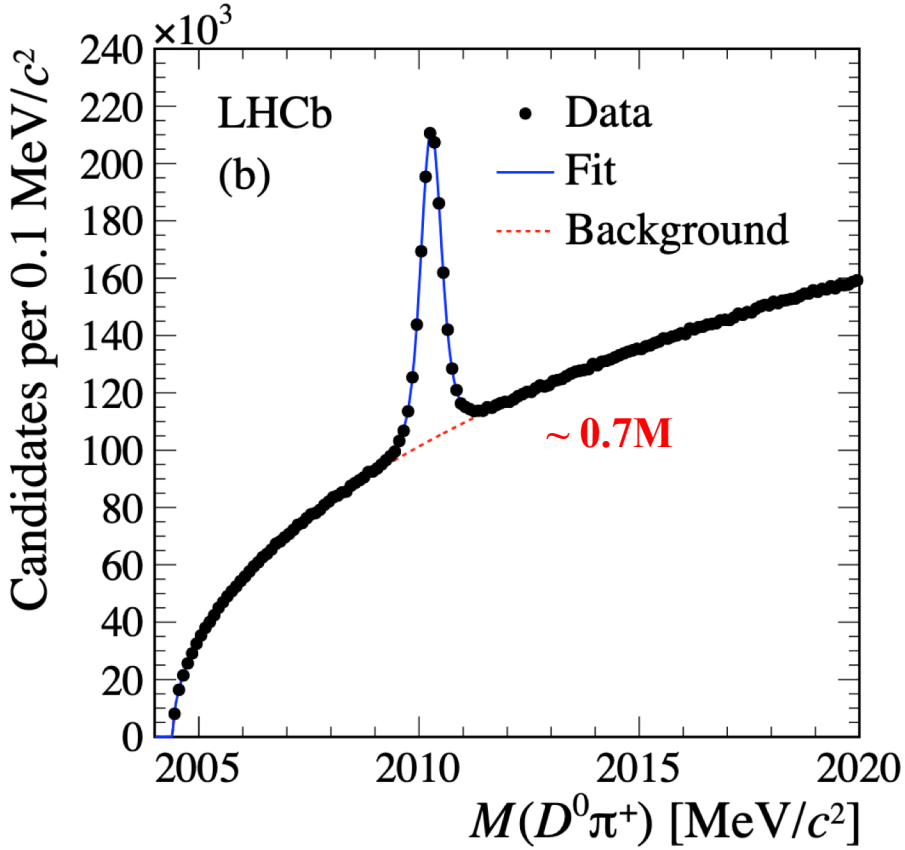
- One of the golden channels: $D \to K\pi$

5 fb^{-1}, 2011-2016

Right sign: $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$



Wrong sign: $D^{*+} \to D^0(\to K^+\pi^-)\pi^+$



Methodology

Phys. Rev. D 97 (2018) 031101

$$R_{K\pi}(t) \approx R_D^{K\pi} + \sqrt{R_D^{K\pi}}\, y'_{K\pi}\,(\Gamma t) + \frac{x'^2_{K\pi} + y'^2_{K\pi}}{4}(\Gamma t)^2\,,$$

Direct CP violation

$$x'_{K\pi} \equiv x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$$

$$y'_{K\pi} \equiv y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$$

$$A_D^{K\pi} = \frac{R_D^{K\pi+} - R_D^{K\pi-}}{R_D^{K\pi+} + R_D^{K\pi-}}$$

Link to x, y through $\delta_{K\pi}$ (measured by BESIII)

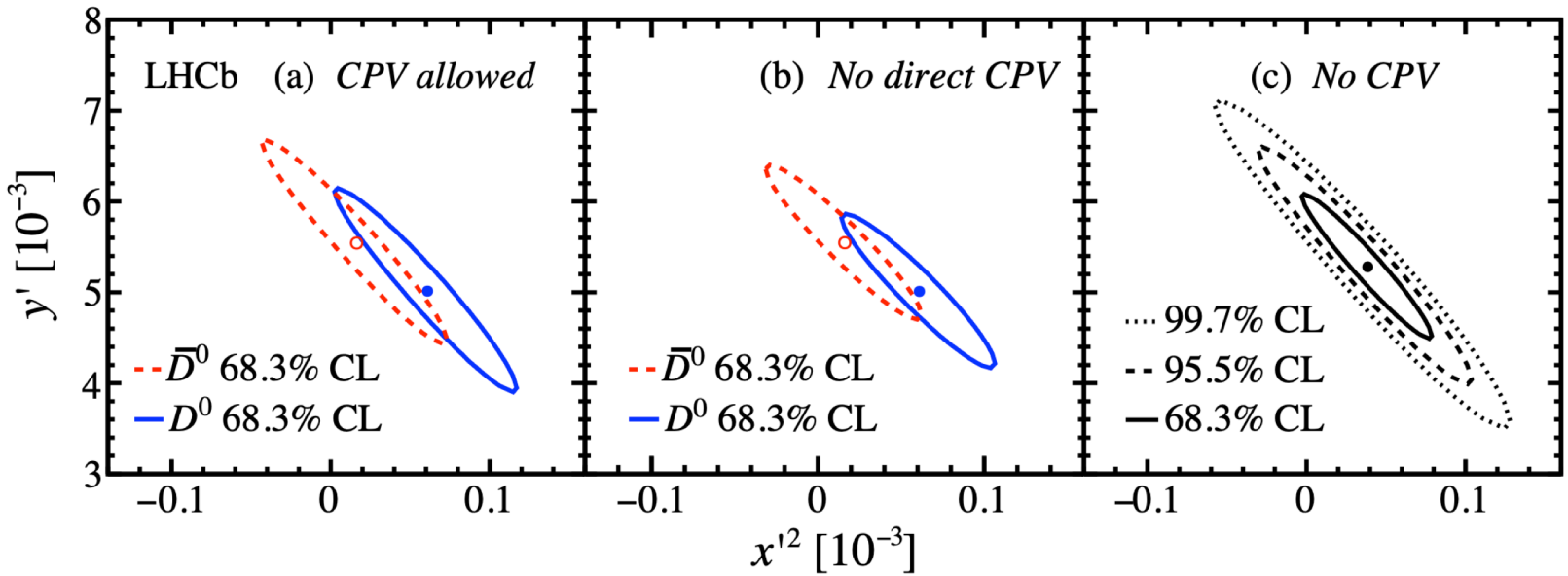
- Can also access to CP violation in mixing and decays

$$(x'^{\pm}_{K\pi})^2 = \left|\frac{q}{p}\right|^{\pm 2}(x'_{K\pi}\cos\phi \pm y'_{K\pi}\sin\phi)^2 \qquad y'^{\pm}_{K\pi} = \left|\frac{q}{p}\right|^{\pm}(y'_{K\pi}\cos\phi \mp x'_{K\pi}\sin\phi)$$

Results

Phys. Rev. D 97 (2018) 031101

- The results give constrain on mixing parameters:



- And also CP violating parameters:

$$A_D = (-0.1 \pm 9.1) \times 10^{-3} \qquad 1.00 < |q/p| < 1.35$$

Prospects

- Prospects for $D \to K\pi$:

Uncertainties depend on central values

Sample ($\mathcal{L}$)	Yield ($\times 10^6$)	$\sigma(x'^2_{K\pi})$	$\sigma(y'_{K\pi})$	$\sigma(A_D)$	$\sigma(\lvert q/p\rvert)$	$\sigma(\phi)$
Run 1–2 ($9\,\mathrm{fb}^{-1}$)	1.8	1.5×10^{-5}	2.9×10^{-4}	0.51%	0.12	10°
Run 1–3 ($23\,\mathrm{fb}^{-1}$)	10	6.4×10^{-6}	1.2×10^{-4}	0.22%	0.05	4°
Run 1–4 ($50\,\mathrm{fb}^{-1}$)	25	3.9×10^{-6}	7.6×10^{-5}	0.14%	0.03	3°
Run 1–5 ($300\,\mathrm{fb}^{-1}$)	170	1.5×10^{-6}	2.9×10^{-5}	0.05%	0.01	1°

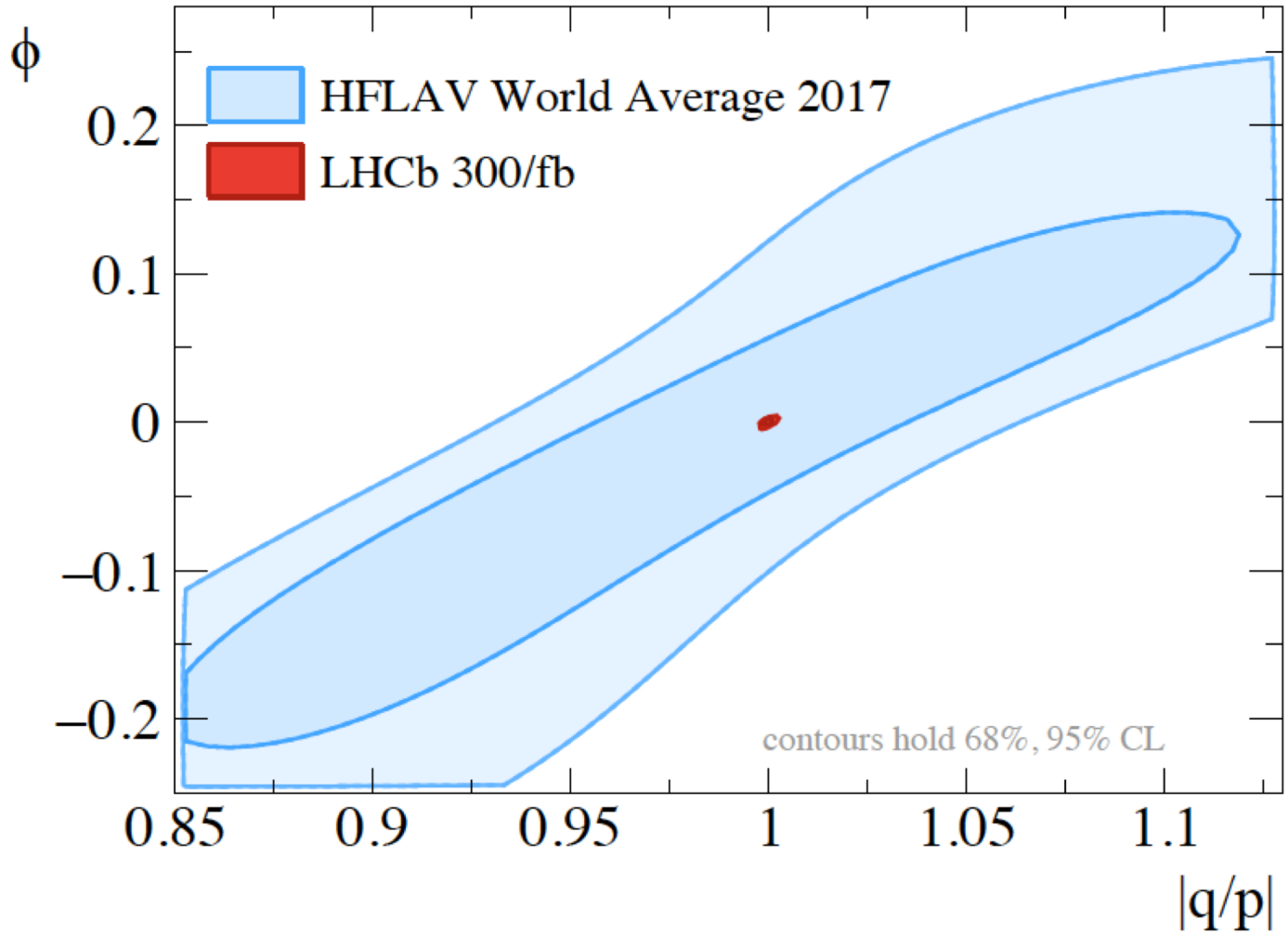
- Similar analysis also for $D \to K\pi\pi\pi$;
- Variation of strong phase over phase space allows direct measurement of x', y' and thus provide higher sensitivity to CP violating variables $\phi, |\frac{q}{p}|$

Sample ($\mathcal{L}$)	Yield ($\times 10^6$)	$\sigma(x'_{K\pi\pi\pi})$	$\sigma(y'_{K\pi\pi\pi})$	$\sigma(\lvert q/p\rvert)$	$\sigma(\phi)$
Run 1–2 ($9\,\mathrm{fb}^{-1}$)	0.22	2.3×10^{-4}	2.3×10^{-4}	0.020	1.2°
Run 1–3 ($23\,\mathrm{fb}^{-1}$)	1.29	0.9×10^{-4}	0.9×10^{-4}	0.008	0.5°
Run 1–4 ($50\,\mathrm{fb}^{-1}$)	3.36	0.6×10^{-4}	0.6×10^{-4}	0.005	0.3°
Run 1–5 ($300\,\mathrm{fb}^{-1}$)	22.5	0.2×10^{-4}	0.2×10^{-4}	0.002	0.1°

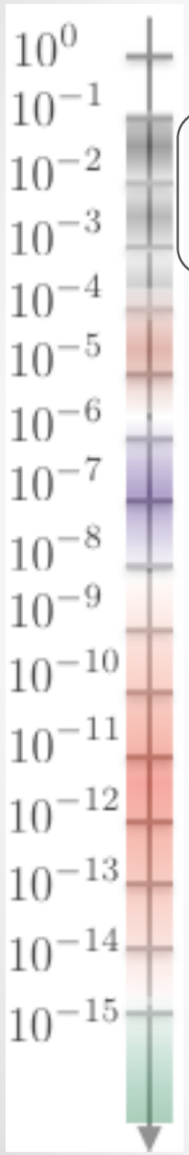
- Similar sensitivities also from $D \to K_s\pi\pi$

An overall picture

- Summary of potential precision on CP-violating parameters



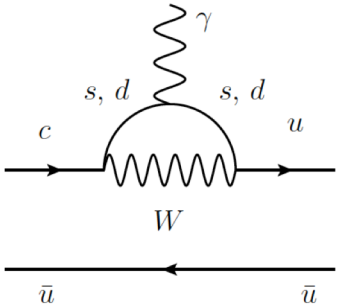
Fingerprint of charm decays



Mixing and CPV

Cabibbo Favoured

Cabibbo Suppressed

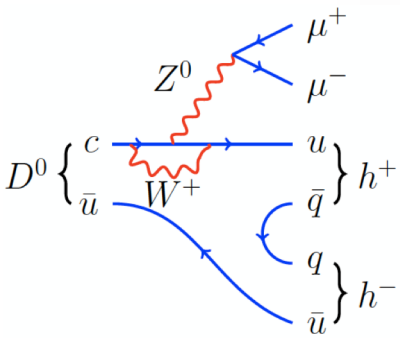


Radiative $D^0 \to \phi\gamma, \rho\gamma$

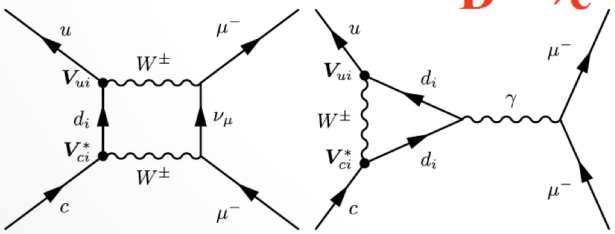
Vector-Meson Dominance $D^0 \to \pi^+\pi^- V(\to l^+l^-)$ $D^+ \to \pi^+ V(\to l^+l^-)$ $\Lambda_c \to pV(\to l^+l^-)$

$D^0 \to \gamma\gamma$

Flavour Changing Neutral Current $D^0 \to \pi^+\pi^- l^+l^-$ $D^+ \to \pi^+ l^+l^-$ $\Lambda_c \to pl^+l^-$



$D^0 \to e^+e^-$ $D^0 \to \mu^+\mu^-$



Lepton Number Violating $D^+ \to \pi^-\mu^+\mu^+$ $D^0 \to K^-\pi^-\mu^+\mu^+$

Lepton Flavour Violating $D^+ \to \pi^+e^+\mu^-$ $D^0 \to e^+\mu^-$ $D^0 \to K^-\pi^+e^+\mu^-$

$\Lambda_c^+ \to p\mu^+\mu^-$

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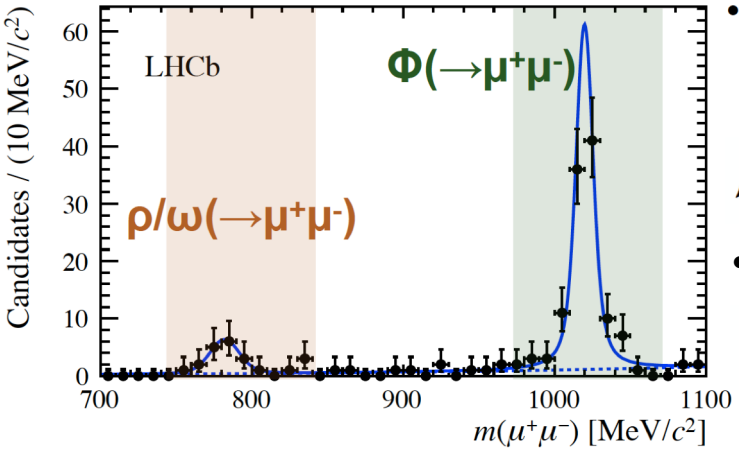
Run 1, 3 fb^{-1}

- Rare charmed baryon decays with FCNC process



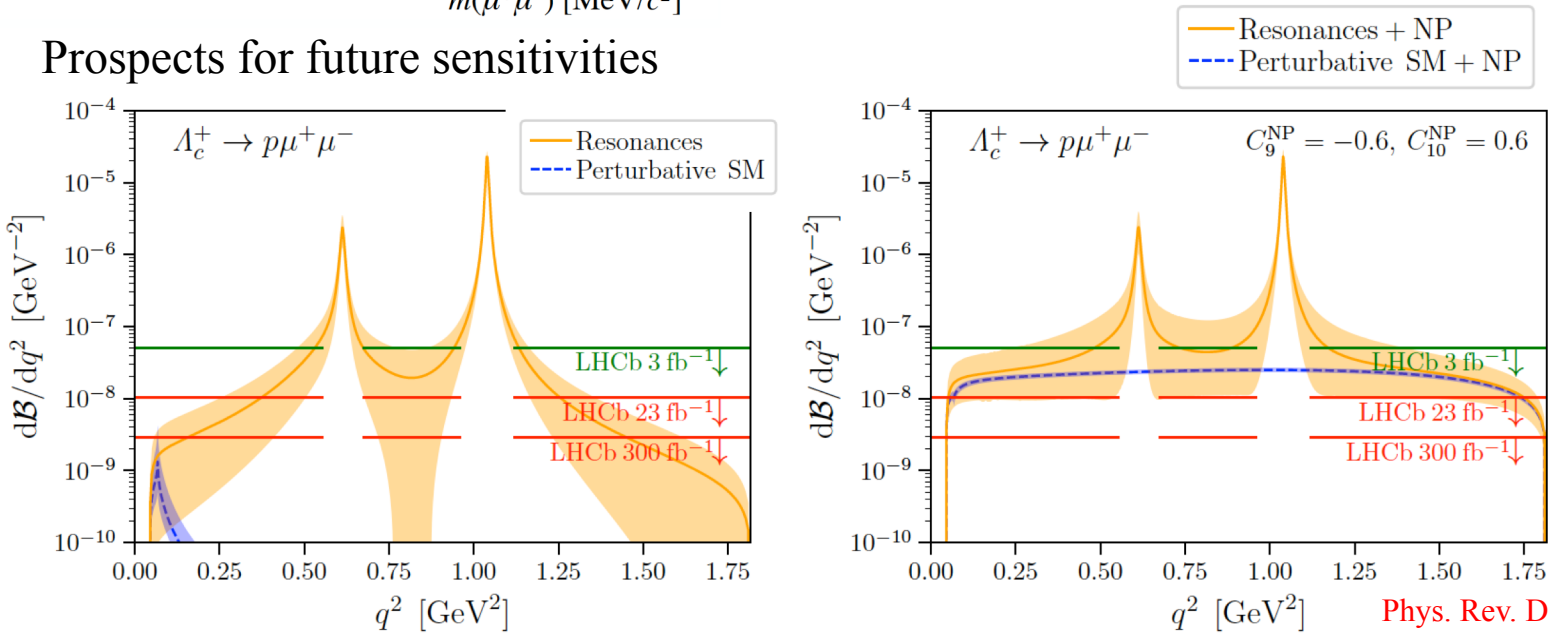
- Long distance contributions (ϕ, ρ, ω) dominated; first observation of decays to ρ/ω final states

$$\mathcal{B}(\Lambda_c^+ \to p[\mu^+\mu^-]_{\rho/\omega}) = (9.4 \pm 3.2 \pm 1.0 \pm 2.0) \times 10^{-8}$$

- Upper limits on non-resonant (short-distance)

$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 9.6 \times 10^{-8} \text{ at } 95\% \text{ CL}$$

- Prospects for future sensitivities



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More clever way…

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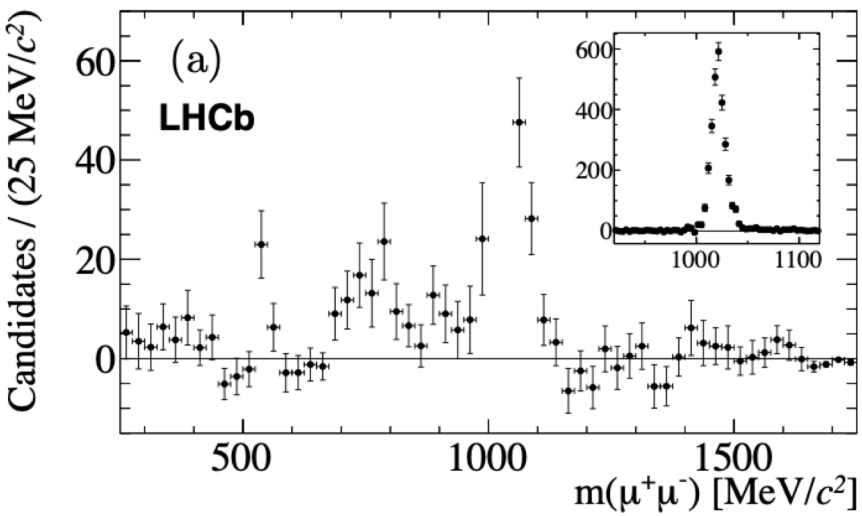


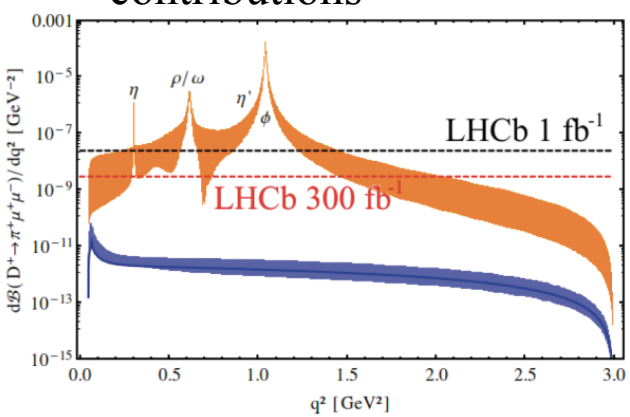
Run 1, 1 fb^{-1}

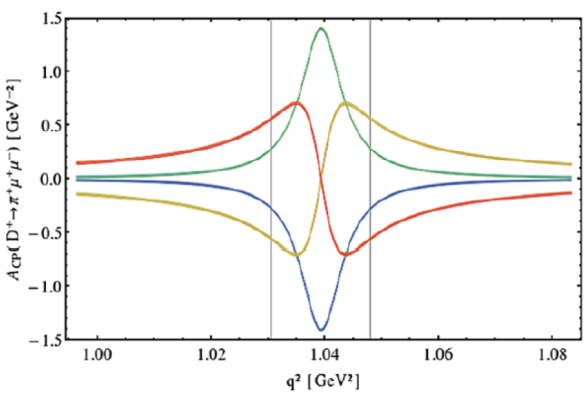
- Run 1 analysis with 2011 data on $D^+ \to \pi^+\mu^+\mu^-$ decays shows no significant contribution from short-distance contribution

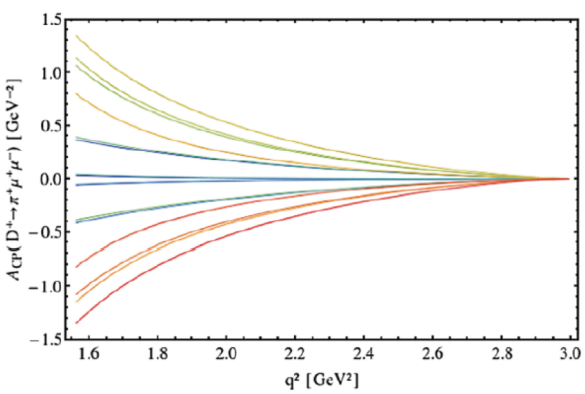
$$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 7.3\,(8.3) \times 10^{-8},$$

@ 90(95)%

- Short-distance contribution from SM far below LHCb limits;
- Angular distributions like A_{FB} or A_{CP} may help to distinguish short- and long- distance contributions







An example: $D^0 \to \pi^+\pi^-(K^+K^-)\mu^+\mu^-$

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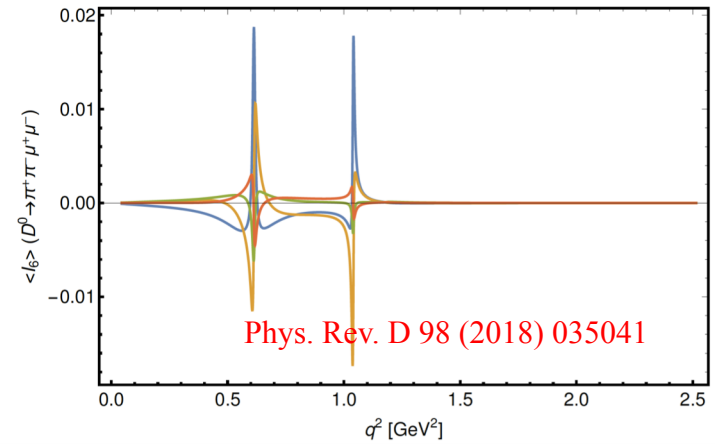
- Asymmetries sensitive to short-distance through short- and long- distance interference
- Observables null for SM, but few% for some NP models

Run 1+2, 5 fb^{-1}



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- angular asymmetries
  - forward backward asymmetry

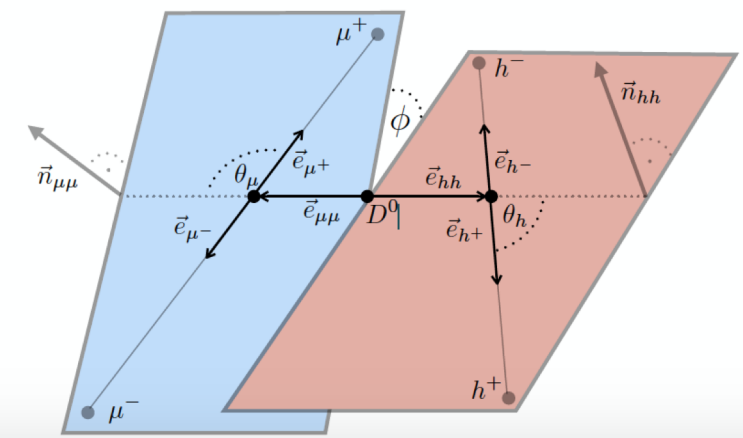
$$A_{\rm FB} = \frac{\Gamma(\cos\theta_\mu > 0) - \Gamma(\cos\theta_\mu < 0)}{\Gamma(\cos\theta_\mu > 0) + \Gamma(\cos\theta_\mu < 0)}$$

  - triple product asymmetry

$$A_{2\phi} = \frac{\Gamma(\sin 2\phi > 0) - \Gamma(\sin 2\phi < 0)}{\Gamma(\sin 2\phi > 0) + \Gamma(\sin 2\phi < 0)}$$

- CP asymmetry

$$A_{CP} = \frac{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) - \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) + \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}$$



Results

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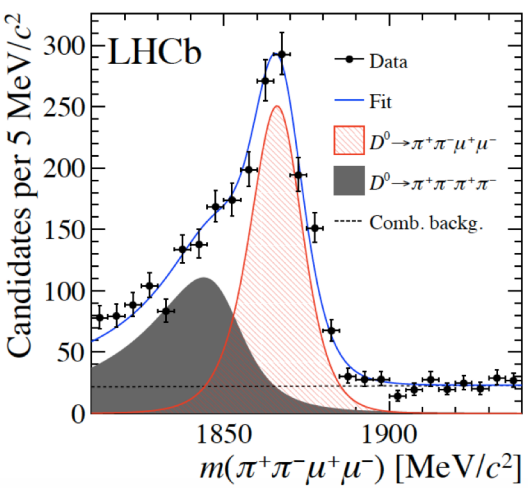
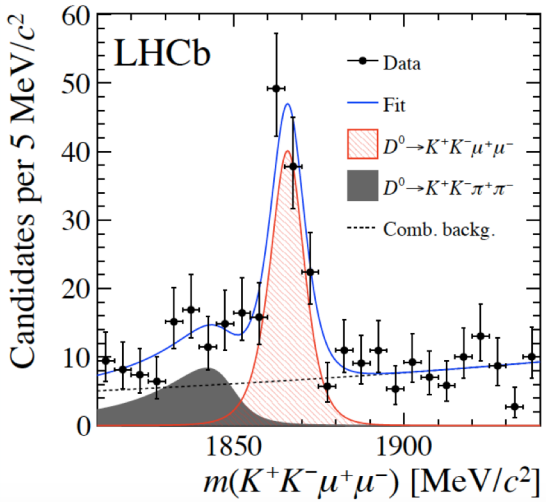
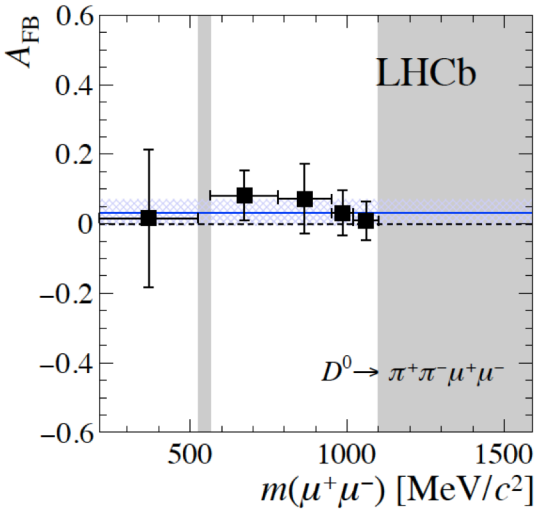
Run 1+2, 5 fb^{-1}

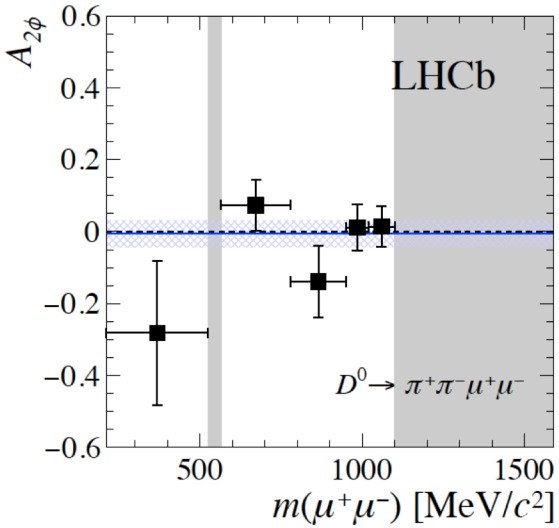


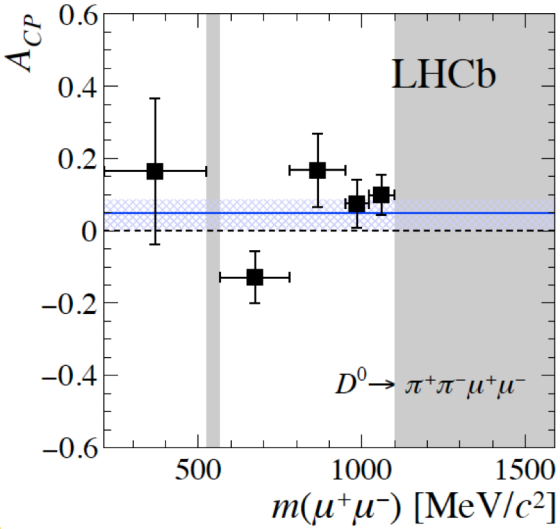


- $D^0 \to \pi^+\pi^-\mu^+\mu^-$: 1.1k
- $D^0 \to K^+K^-\mu^+\mu^-$: 110

- All asymmetries consistent with zero (null as predicted by SM)
- More interesting results with 300 fb^{-1}

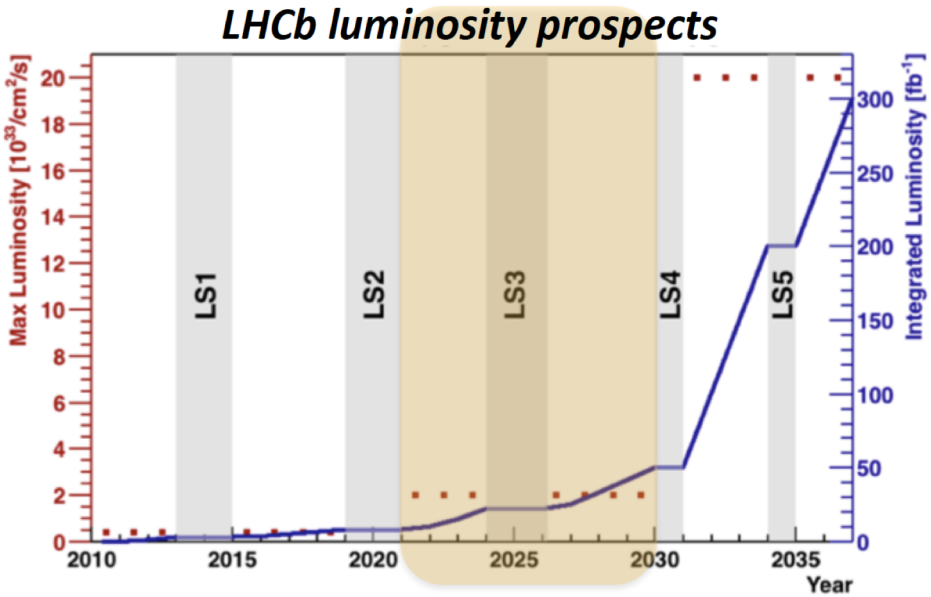






Conclusion

- The LHCb experiment, dedicated for b- and c-quark physics, has a rich upgrade program (on charm)
- The tremendous charm samples collected by the LHCb experiment will help ping down precisions on many key physics variables and probe for new physics
- Stay tuned for more charming results in the future



Thank you for your attention