University of Chinese Academy of Sciences

LHCb prospects

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Outline

- ➢ **LHCb running status and upgrade plans/studies**
- ➢ **CKM physics @ upgrade scenario**
- ➢ **Spectroscopy and other interesting physics @ upgrade scenario**
- ➢ **Conclusion**

LHCb detector

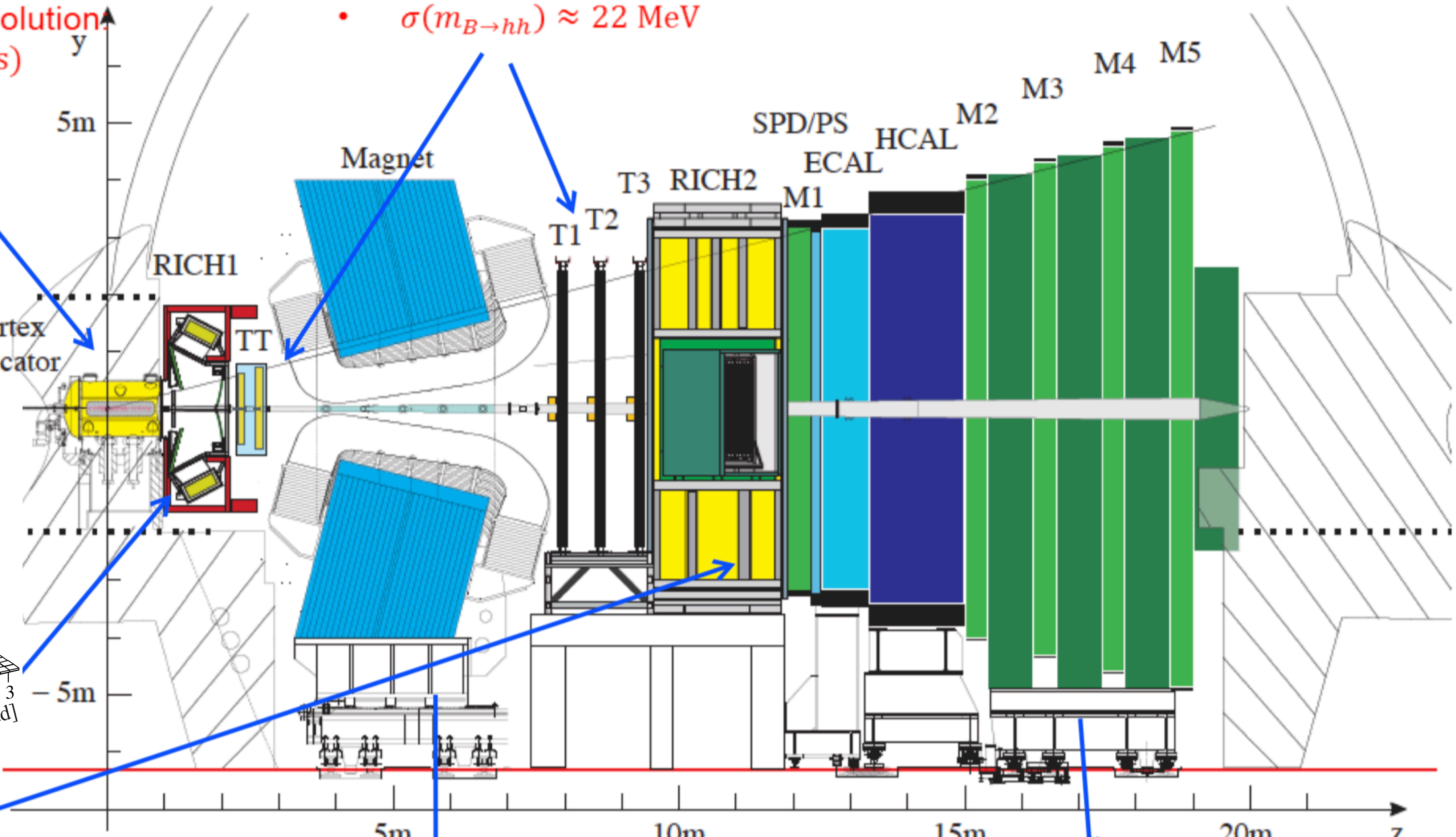
➢ **Forward spectrometer @ collider, acceptance: 1.9<η<4.9**

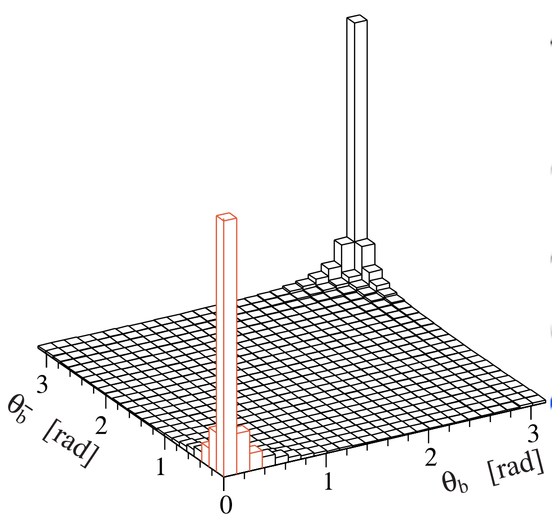
$$\eta = \frac{1}{2}\ln\frac{p+p_z}{p-p_z}$$

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

Vertex Locator(vertex reconstruction)
- Impact parameter resolution: 20 μm
- Decay time resolution: 45 fs (τ_B~1.5 ps)

Tracking system(particle reconstruction)
- ϵ(Tracking) ~96%
- $\delta p/p$ ~0.5%-1%(5-200 GeV)
- $\sigma(m_{B\to hh}) \approx 22$ MeV





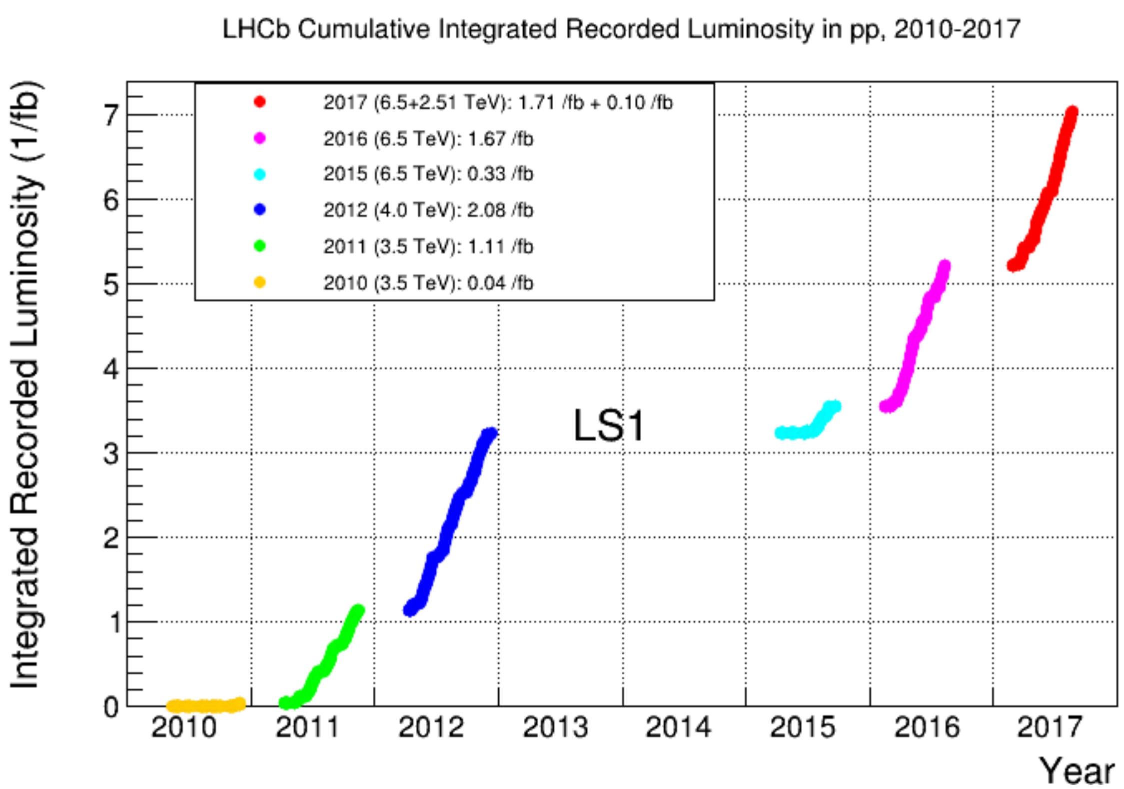
RICH: particle ID
- $\varepsilon(K\to K)$ ~95%
- Mis-ID: $\varepsilon(\pi\to K)$ ~5%

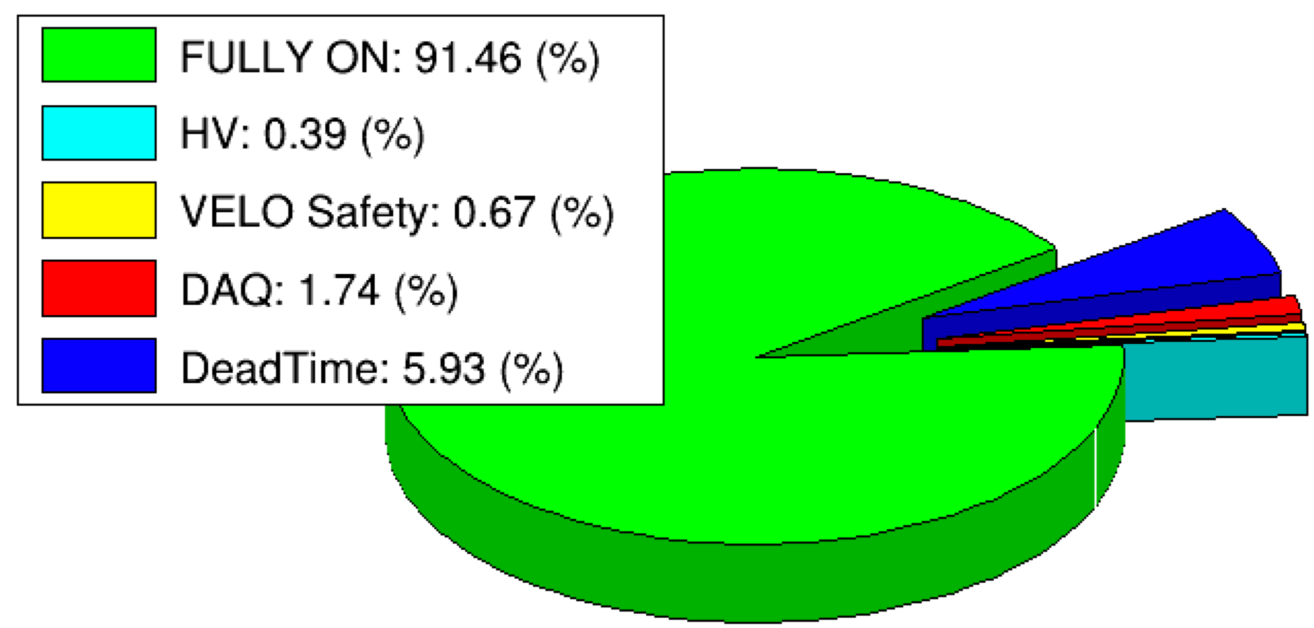
Magnet
- Bending power: 4 Tm

Muon system
- μ ID: $\varepsilon(\mu\to\mu)$ ~97%
- Mis-ID: $\varepsilon(\pi\to\mu)$ ~1-3%

LHCb operation status

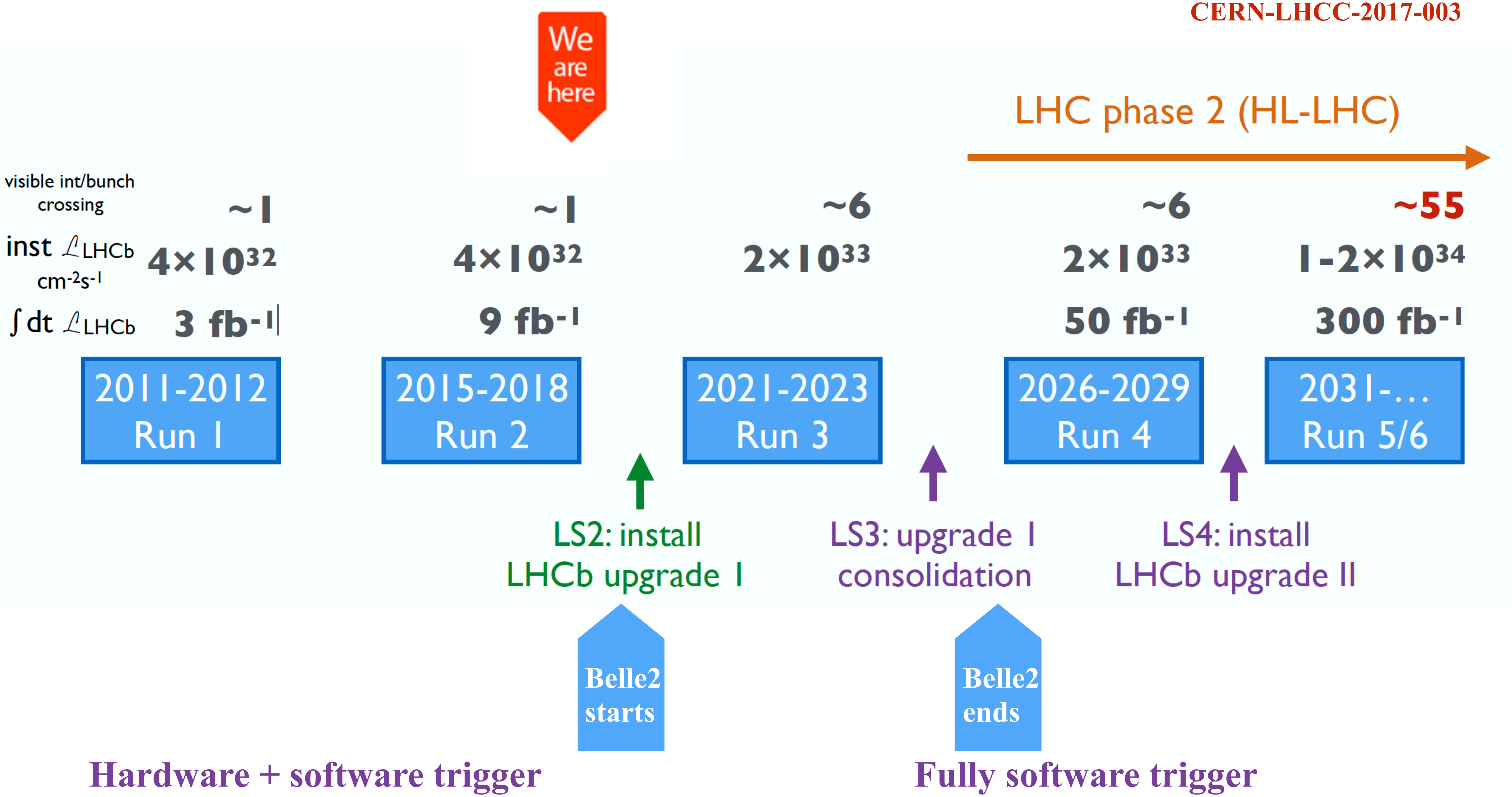
- Wonderful performance with the LHCb detector
- In total, we have already collected 7 fb^{-1} data (1 fb^{-1} with 3.5 TeV, 2 fb^{-1} with 4 TeV and 4 fb^{-1} with 6.5 TeV)
- Expected 2 fb^{-1} more data in 2018
- More than 90% overall efficiency





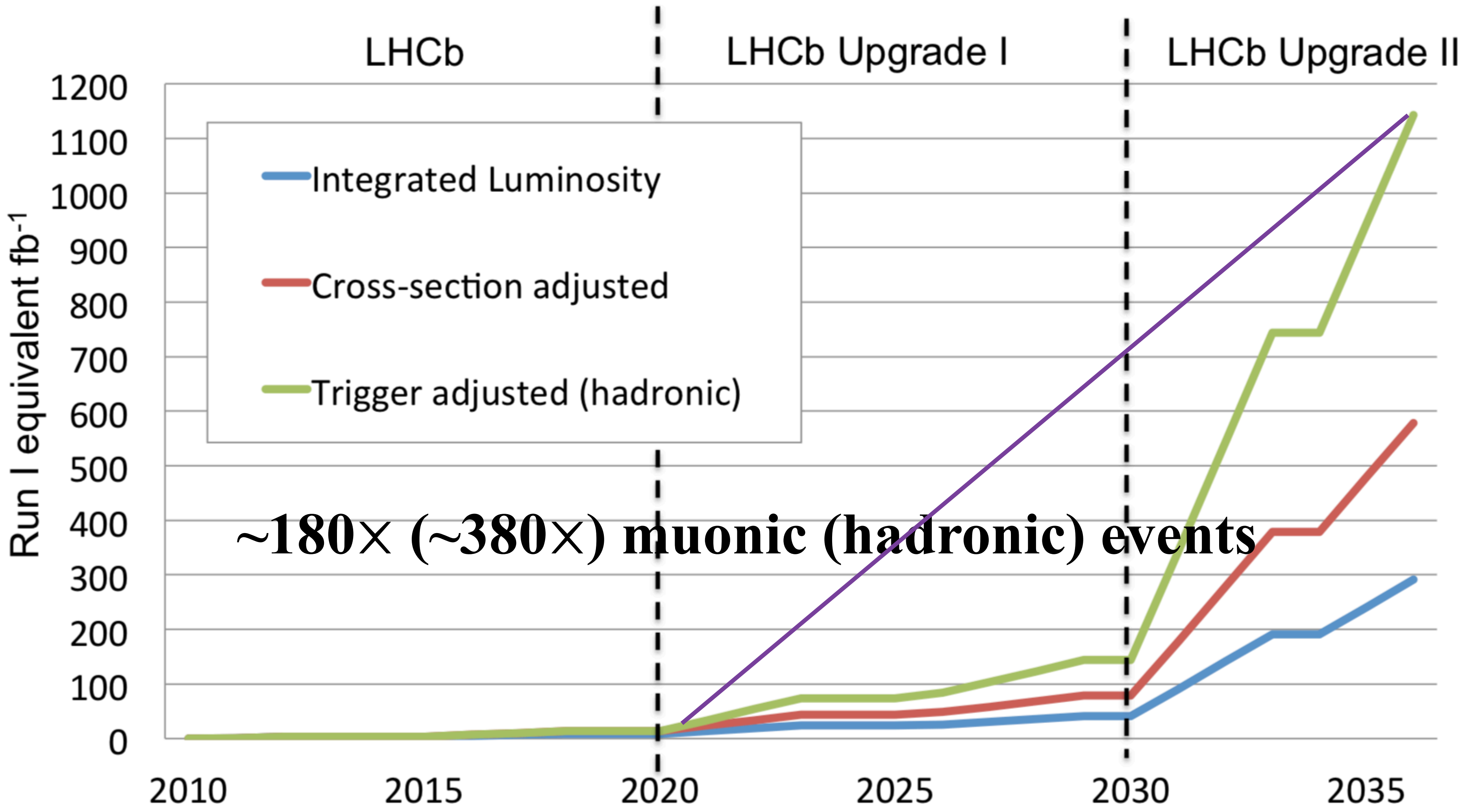
LHCb upgrade plans

CERN-LHCC-2017-003



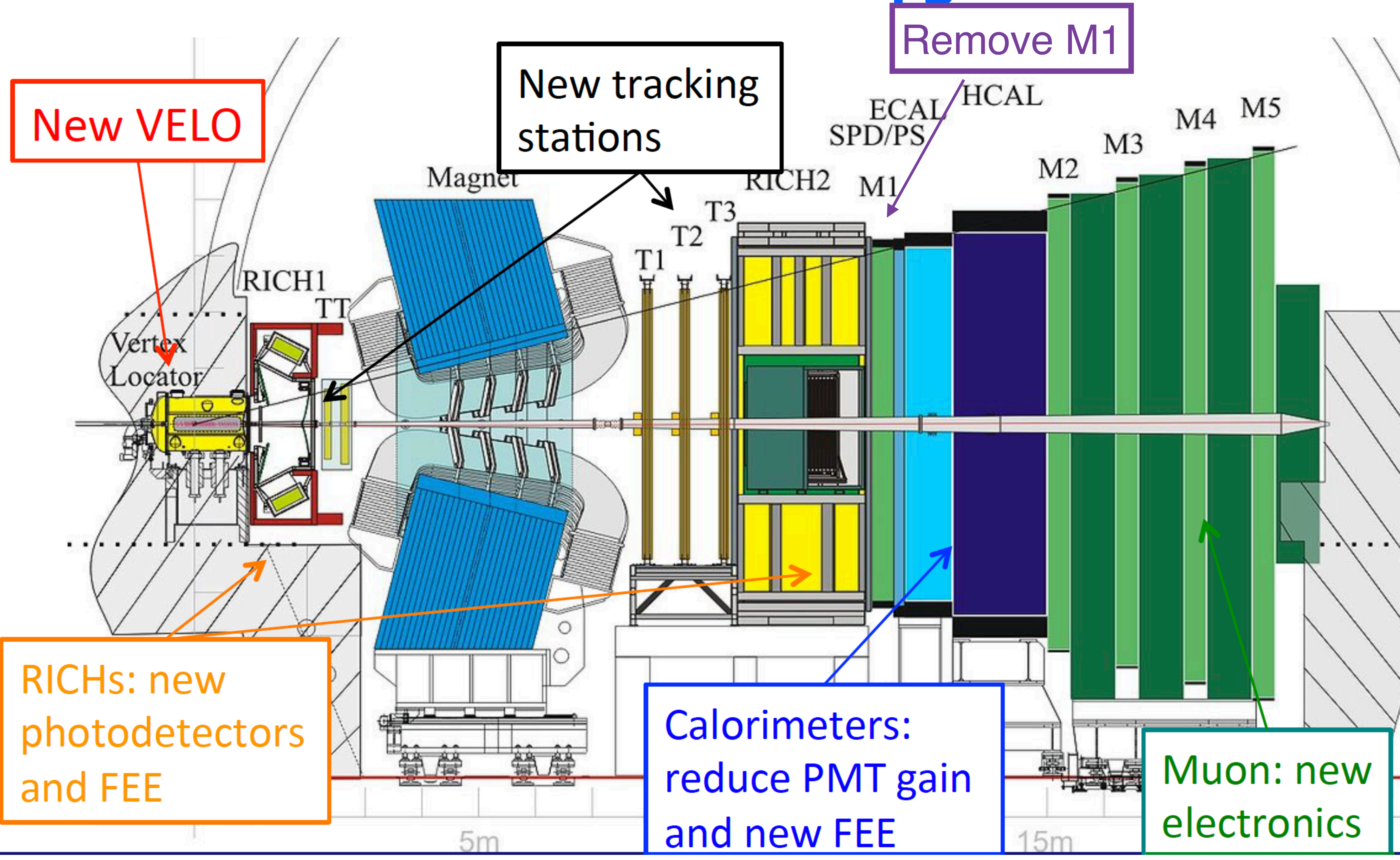
- ➢ **Upgrade I: several detector replaced; 40 MHz readout with fully software trigger**
- ➢ **Upgrade II: new ideas under study on tracking, calorimeter, adding timing info etc**

Statistics



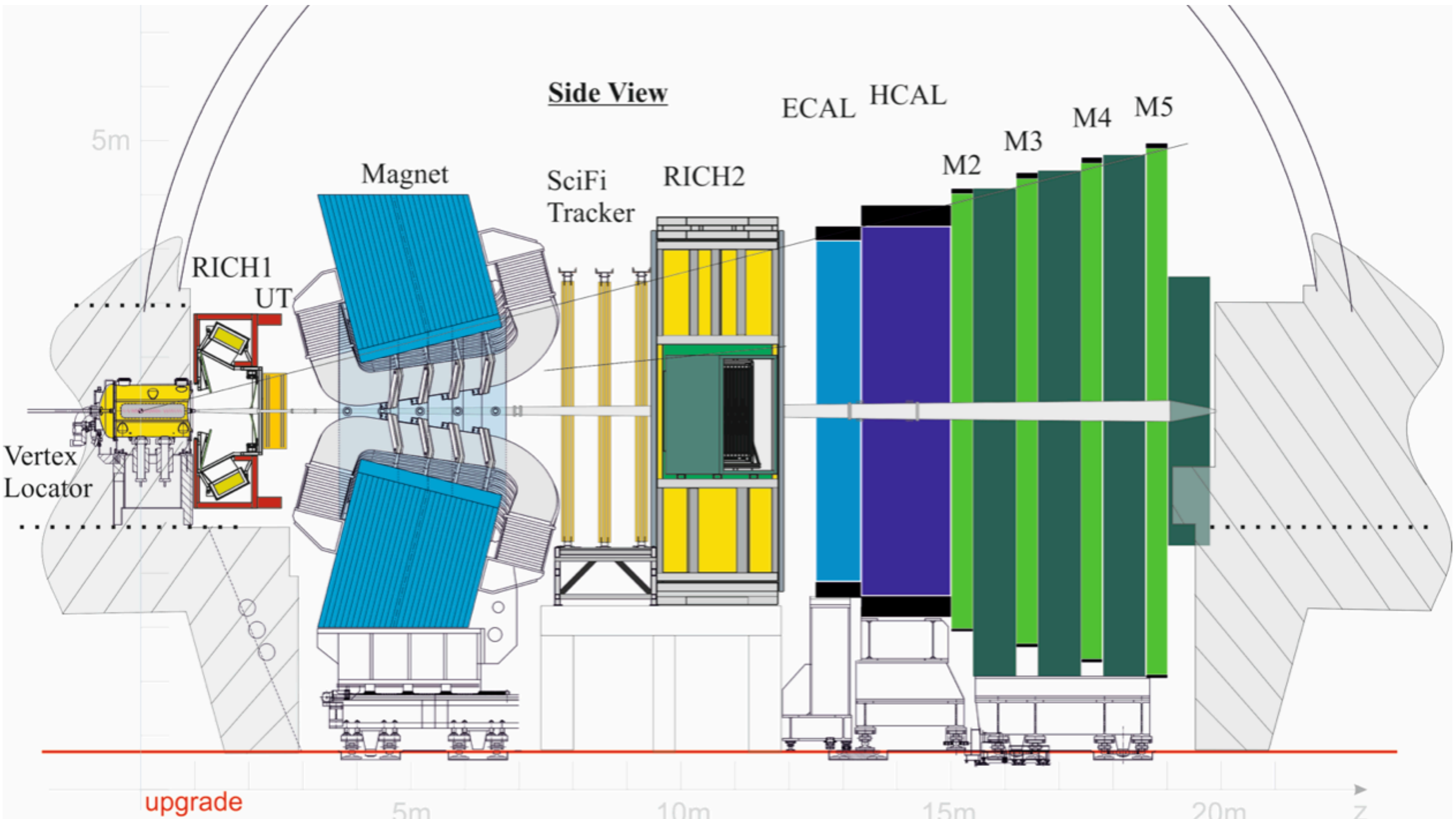
- ➢ **Cross section adjusted according to collision energy (7/8/13/14 TeV)**
- ➢ **Trigger improvement has large uncertainties, hope we can do better**
- ➢ **Great scenario for physics, but very challenging for detector**
- ➢ **Open questions: how to cope with much larger occupancy? Can we broaden LHCb physics?**

Phase I detector upgrade

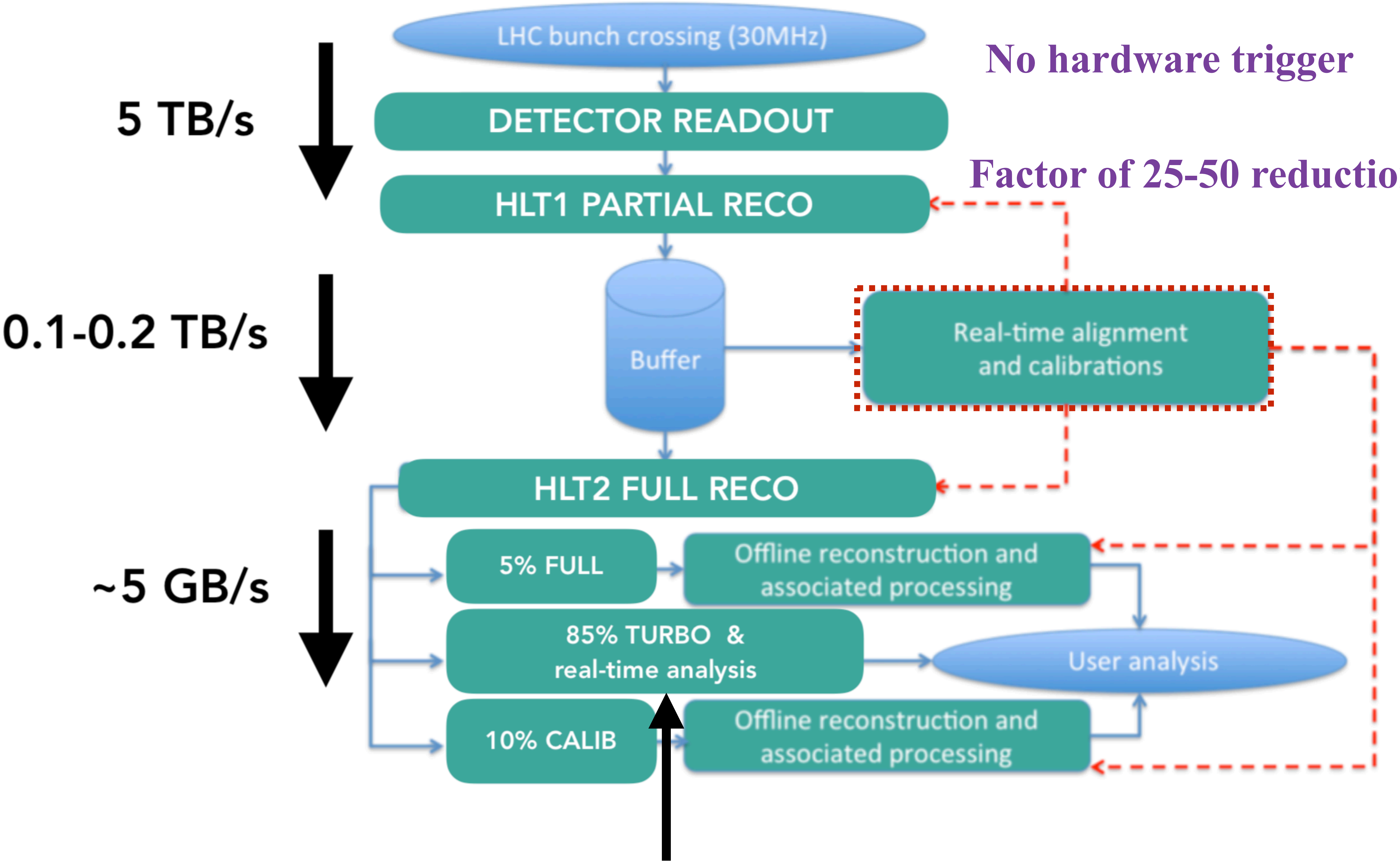


➢ **Reduce occupancy and change FEE to 40 MHZ**

New detector for Run 3 + 4



Upgrade 1 trigger

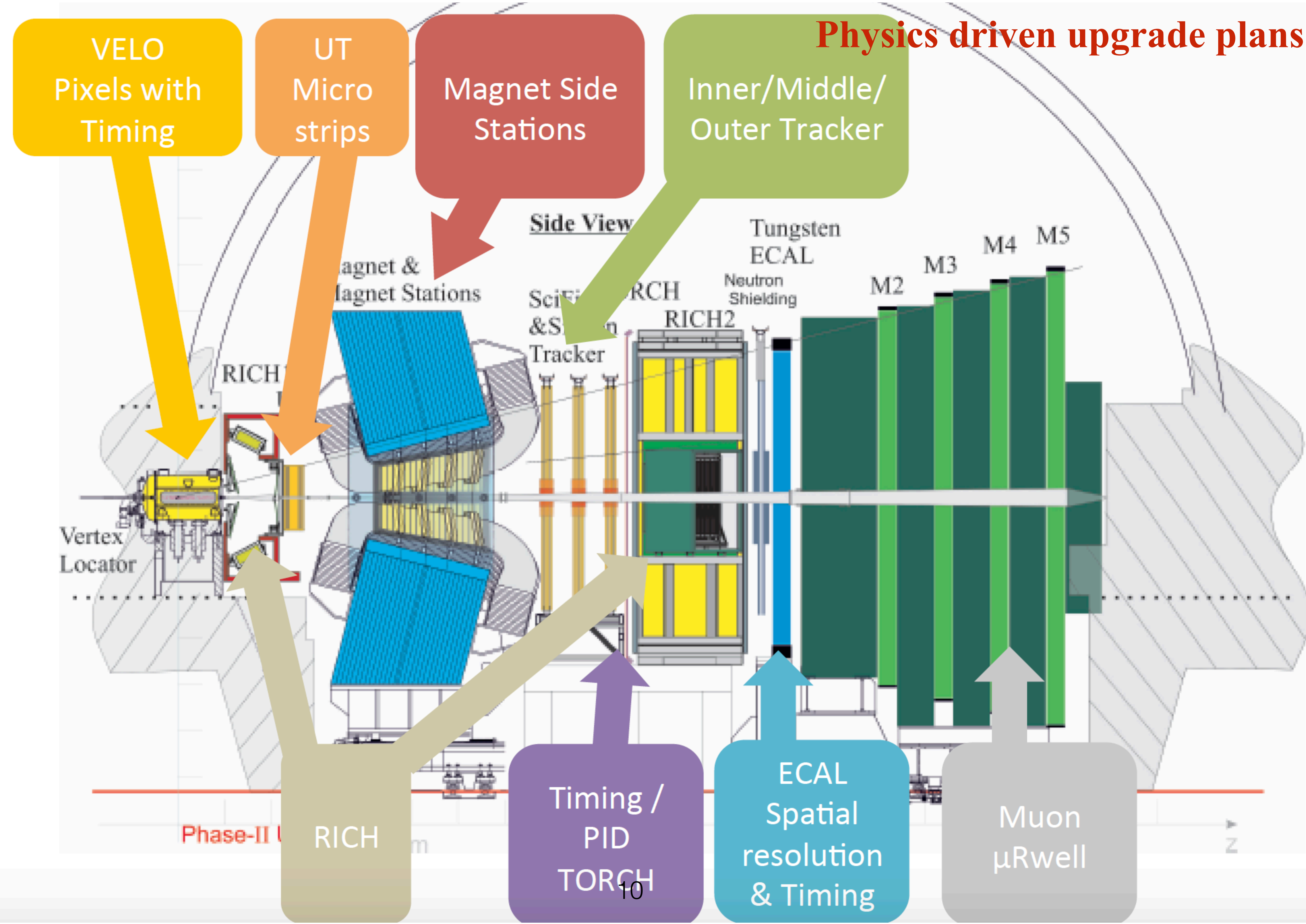


No hardware trigger

Factor of 25-50 reduction

Raw data will not be kept for these analyses

Phase II upgrade

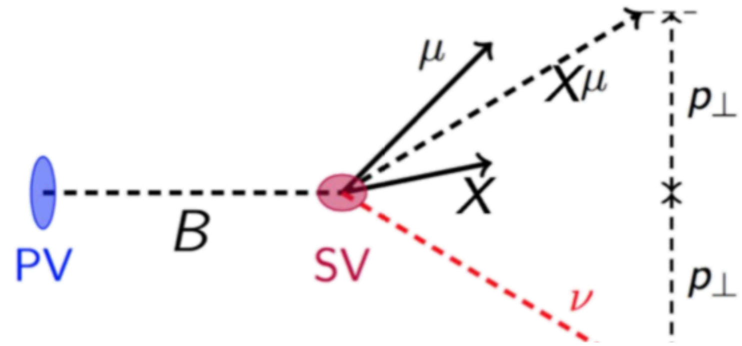


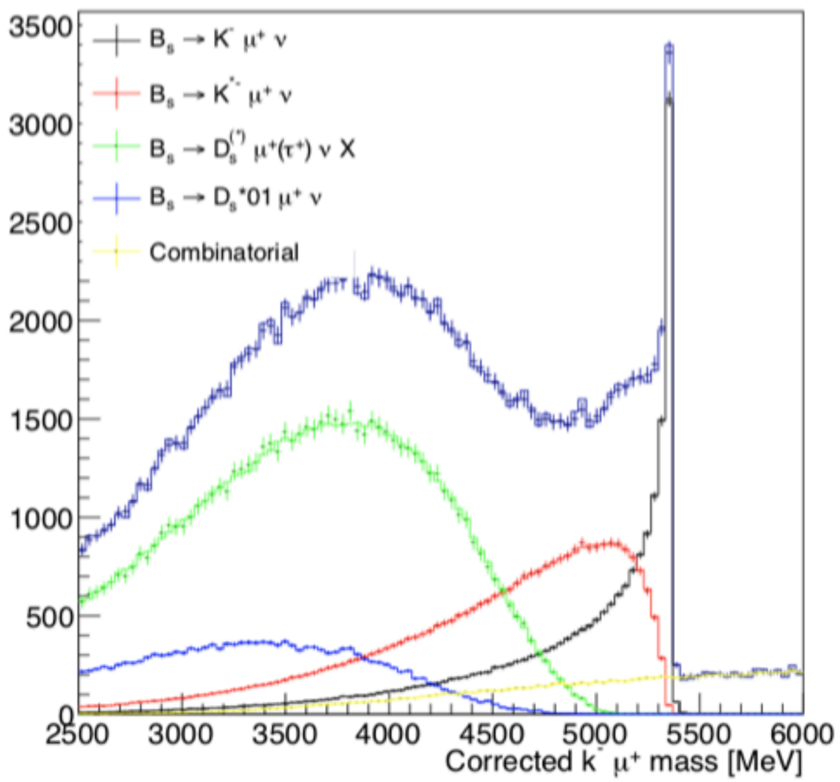
Needs for better vertex resolution

➢ **SV resolution directly related to lifetime resolution→TD CPV measurements**

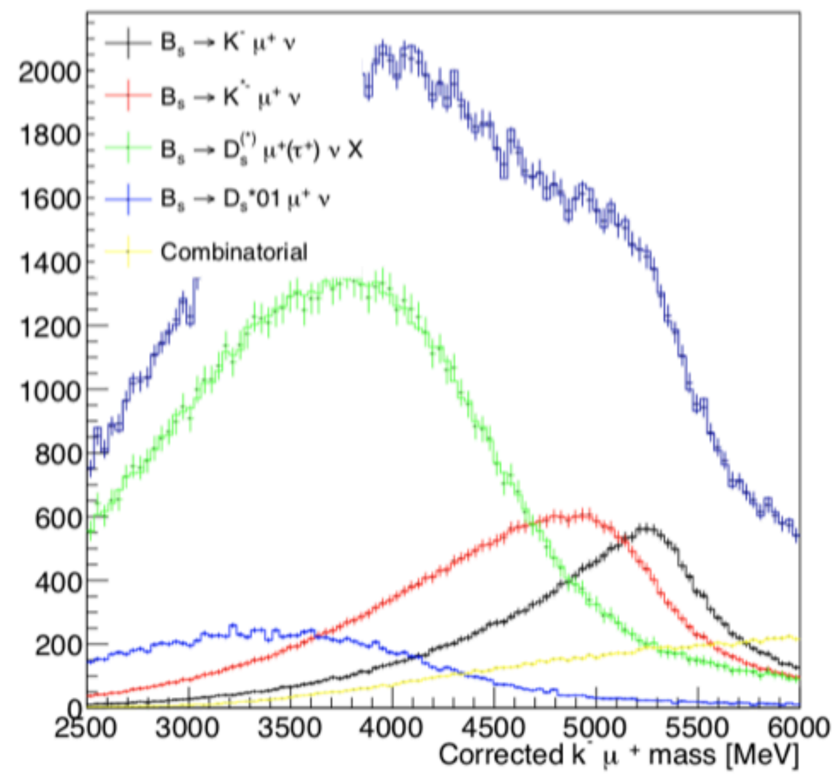
➢ **SV resolution also important for SL analyses: B momentum direction from SV-PV**

$$m_{corr} = \sqrt{m_{X\mu}^2 + p_\perp^2} + p_\perp$$





Perfect resolution

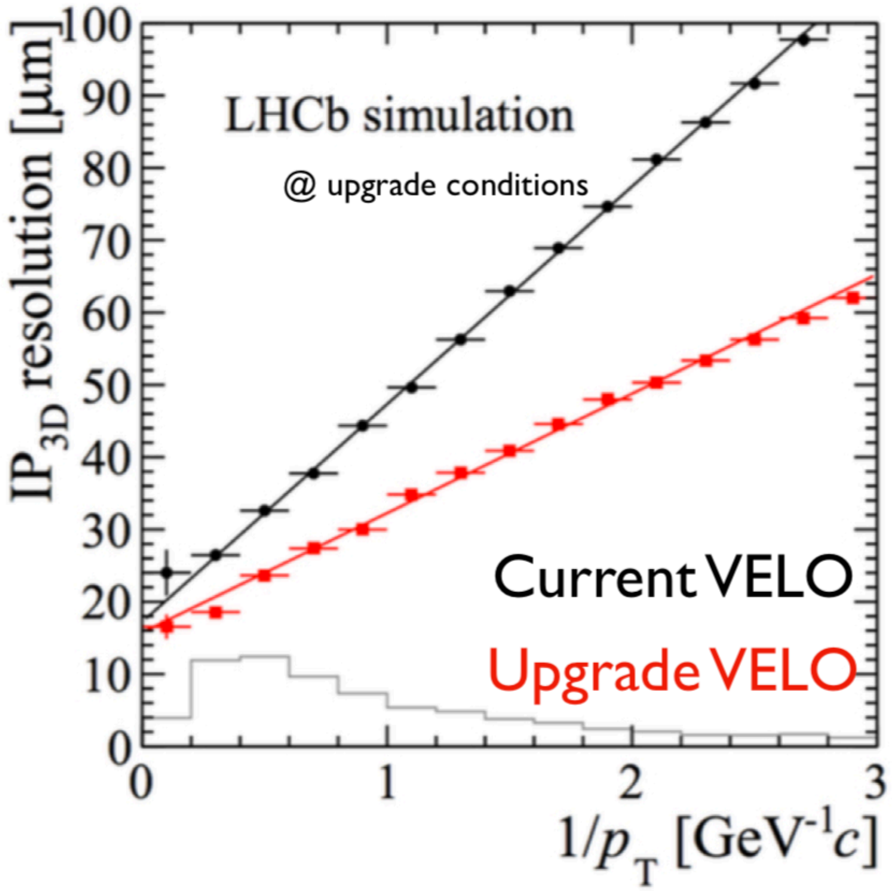


LHCb resolution

➢ **Better SV resolution→ better VELO (i.e. granularity), removing RF foil (upgrade II?) etc.**

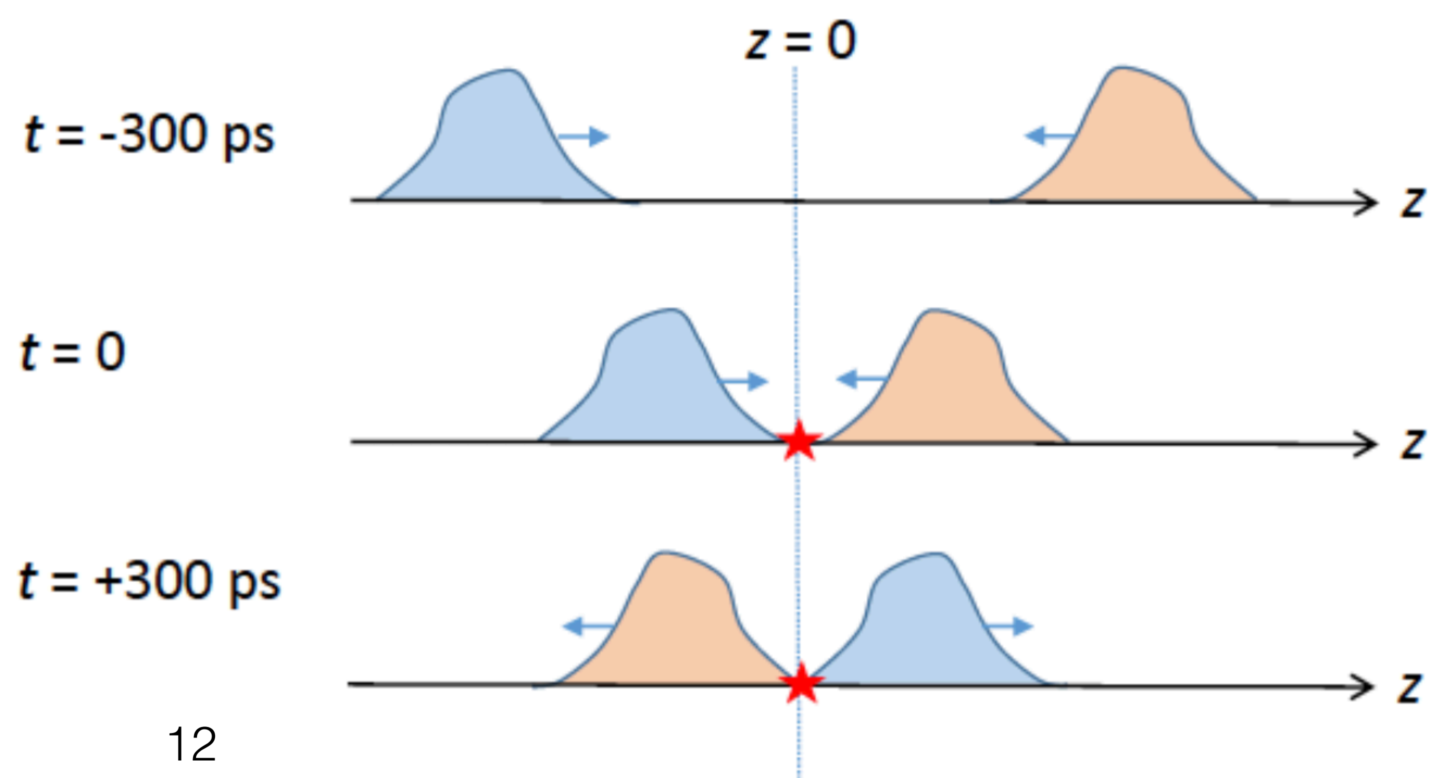
VELO

➢ **Pixel (now striped) silicon detector as close to beam pipe as 5.1 mm (now 8.1 mm)**



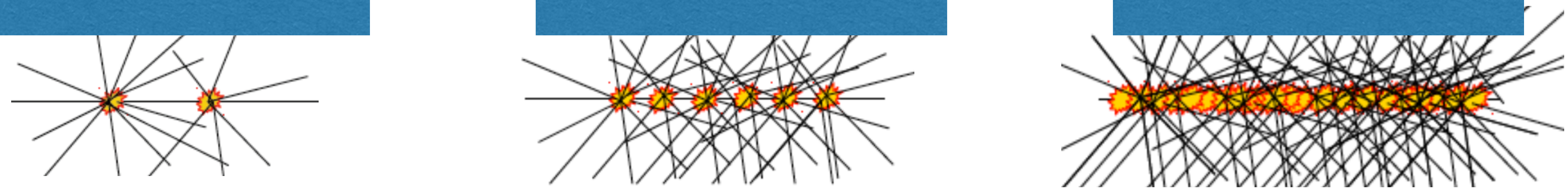
Decay time resolution [fs]		
	$B_s^0 \to \phi\phi$	$B^0 \to K^{*0}\mu^+\mu^-$
Current VELO	48.3 ± 0.5	41.2 ± 0.5
Upgraded VELO	43.4 ± 1.6	35.3 ± 0.3

➢ **Timing considered to further separate PV to reduce wrong association**

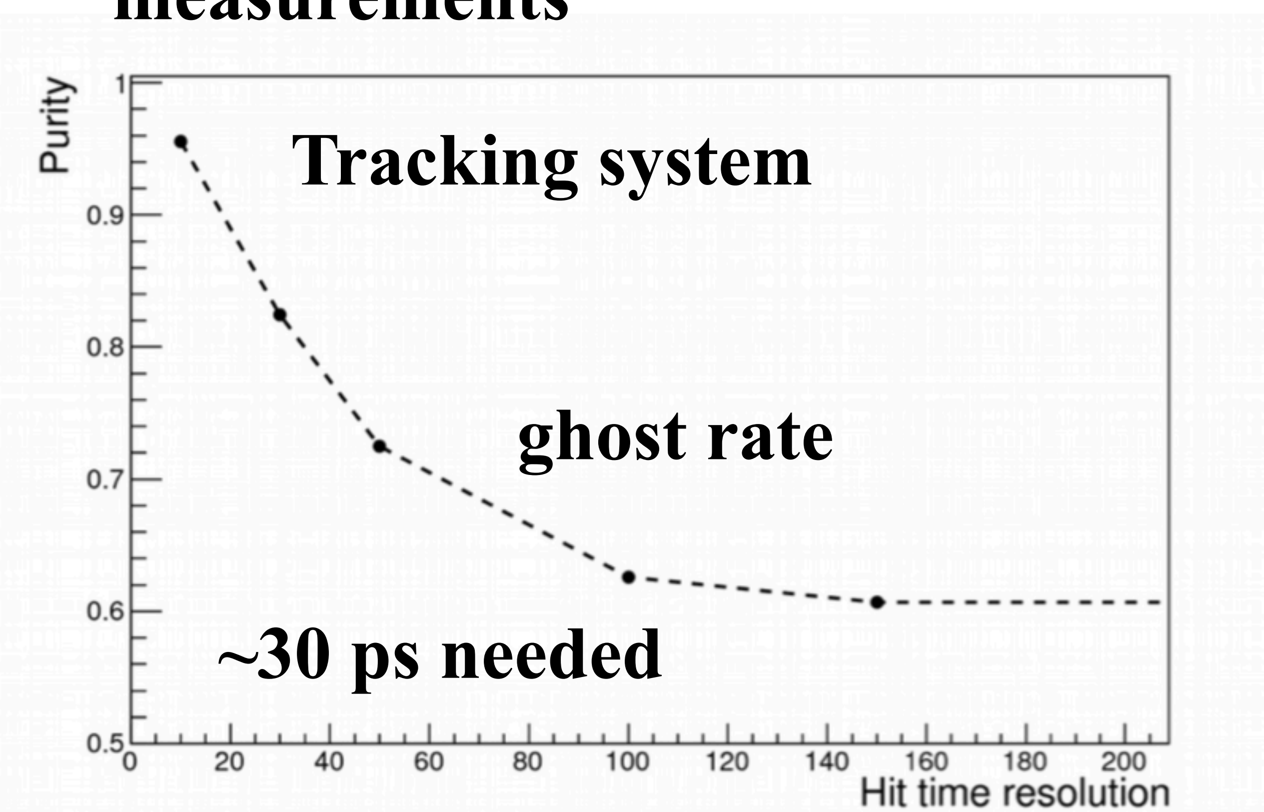


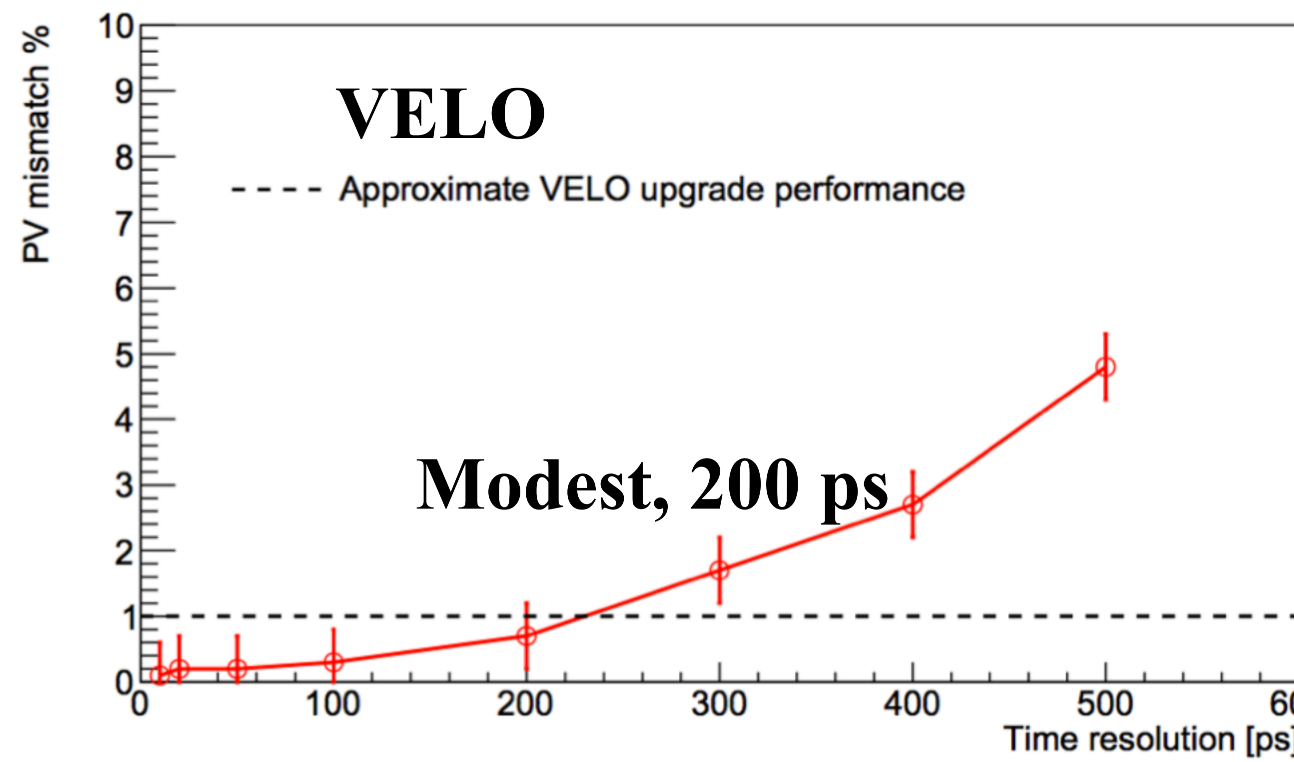
Timing in tracking

Current Run 1 + Run 2 1.1 vis. interaction	Upgrade I Run 3 + Run 4 5.5 vis. interaction	Upgrade II Run 5 + Run x 55 vis. interaction



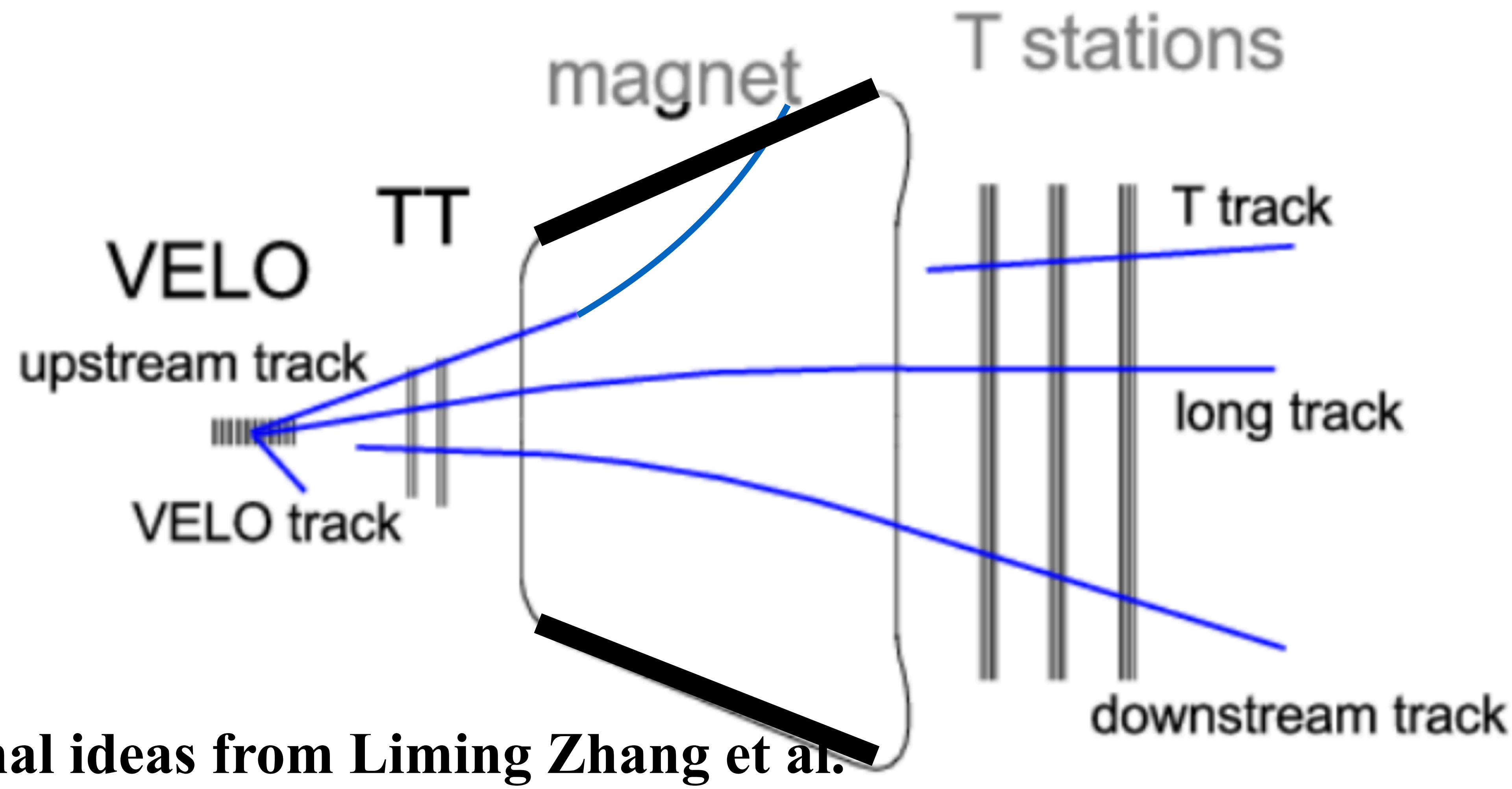
- Very high ghost rate; very high wrong PV association; crucial for lifetime measurements





- Timing info. considered for tracking system: VELO, T-station etc.

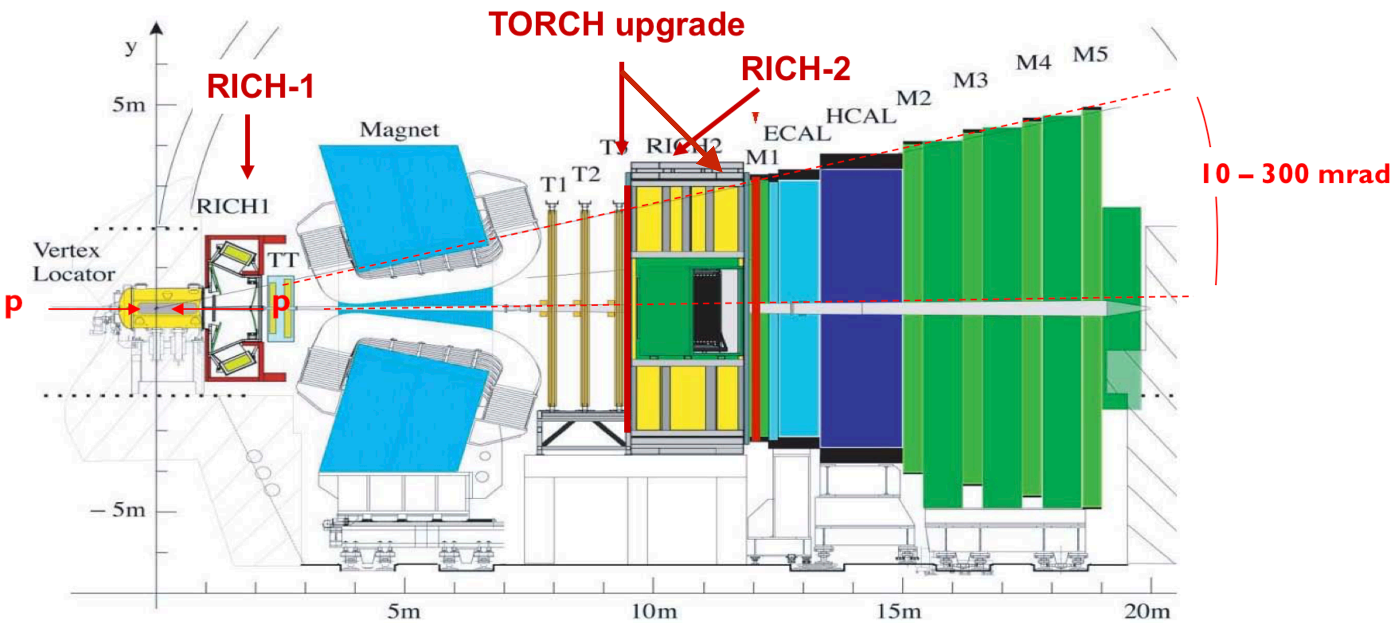
Low momentum tracks

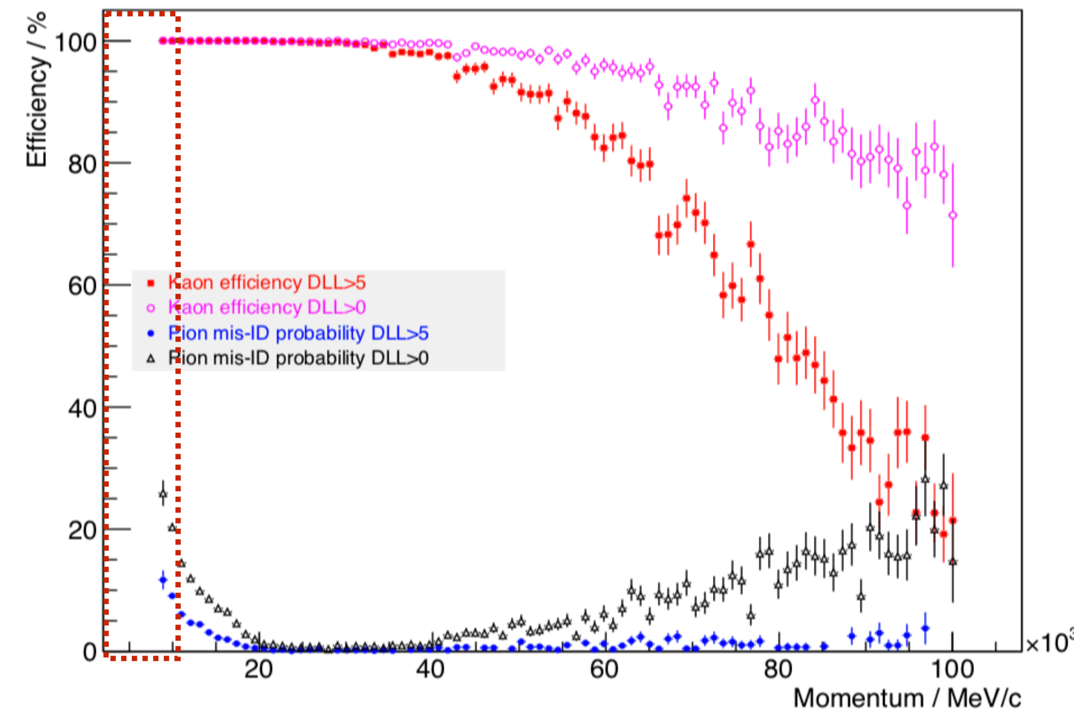


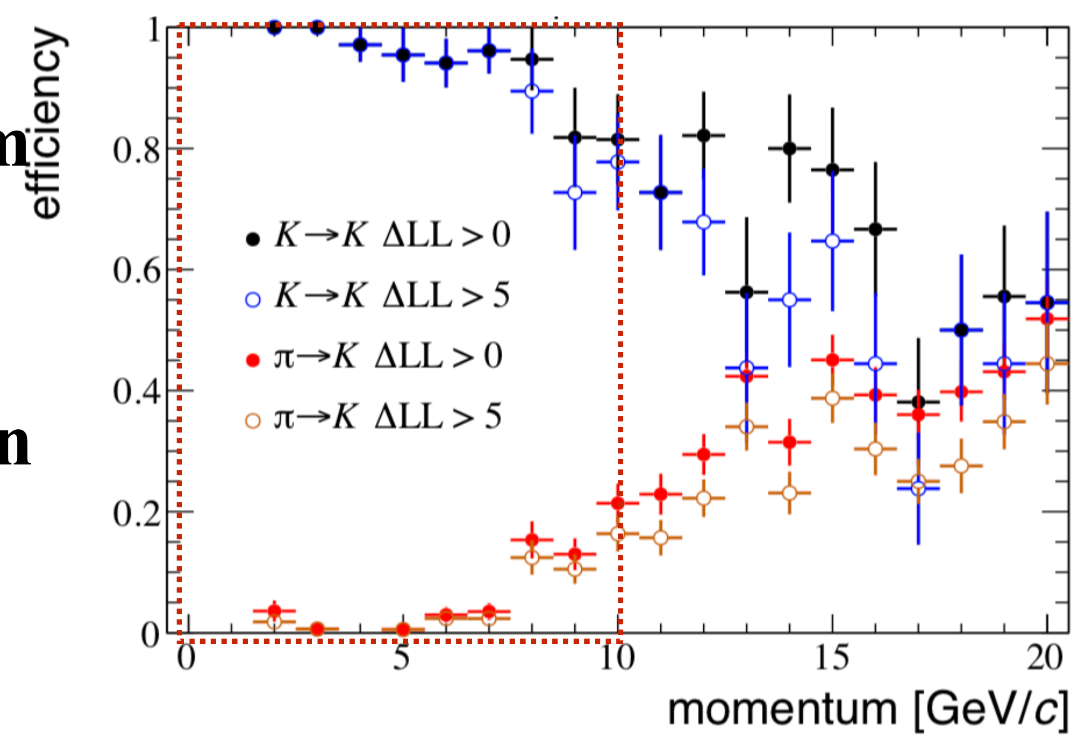
- Original ideas from Liming Zhang et al.
- Little momentum info. from VELO+TT: momentum resolution around 20% to 1% with 1 mm z-segmentation
- Improvement on efficiencies: 20%-60% depending on channels
- Interesting channels are $D^* \to D\pi_{slow}$, τ channels ($R(D^*)$ etc), $Bc^* \to Bc\pi_{slow}\pi_{slow}$, $\Sigma_b \to \Lambda_b\pi_{slow}$ etc.

RICH detector and TORCH

- Main ideas for upgrade: reduce occupancy, reduce single photon resolution, add timing information and wider PID distinguishing range
- Focus on TORCH, a new sub-detector for LHCb upgrade







- Improve PID coverage to low momentum tracks
- Also ideas on offering timing information for calorimeter particles

Physics with electrons, π^0, γ

$B \to \eta' X$
$B^+ \to K^+\pi^0$, $B^+ \to \rho^+\rho^0$
$\Lambda_b \to pK\eta^{(\prime)}$, $B^0 \to K^*\eta^{(\prime)}$
$B^0, B_s \to h^+h^-\pi^0$

$D^0 \to e\mu$
$D^+ \to \pi^+\pi^0(\to \gamma e^+e^-)$
$D^0 \to \Phi\gamma$, $K^*\gamma$, $\rho/\omega\gamma$

$B^+ \to D(hh\pi^0)K$
$B_s \to D_s{}^*K$
$B^+ \to D^*K$

$B^0 \to J/\psi\pi^0$
$B^0 \to J/\psi\omega$
$B^+ \to J/\psi\rho^+$

$B_s \to \Phi\gamma$
$B \to K^*\gamma$
$B_s \to \gamma\gamma$
$B \to K^*e+e-$

$Z \to e^+e^-$
$W \to e\nu$
WW,ZZ,WZ
Top (l^+l^-b)
γ + jet

$B_{s,1} \to B_s\gamma$
$\Lambda_b{}^{**} \to \Lambda_b\gamma$
$B_c{}^* \to B_c\gamma/\pi^0$
χ_c, χ_b polarisation
Pentaquarks $\to \chi_{c,b}X$

$B \to D^{**}(\to D^0\pi^0X)\mu\nu$
$B \to De\nu$ vs. $B \to D\mu\nu$

- **Improvement to ideal calorimeter: better energy resolution, better sensitivity to low energy particles, wider energy coverage, better position resolution, timing to reduce background**

Calorimeter upgrade plans

Slides from Andreas Schopper at Annecy upgrade meeting

LS2 in 2019/20: → LHCb Upgrade I

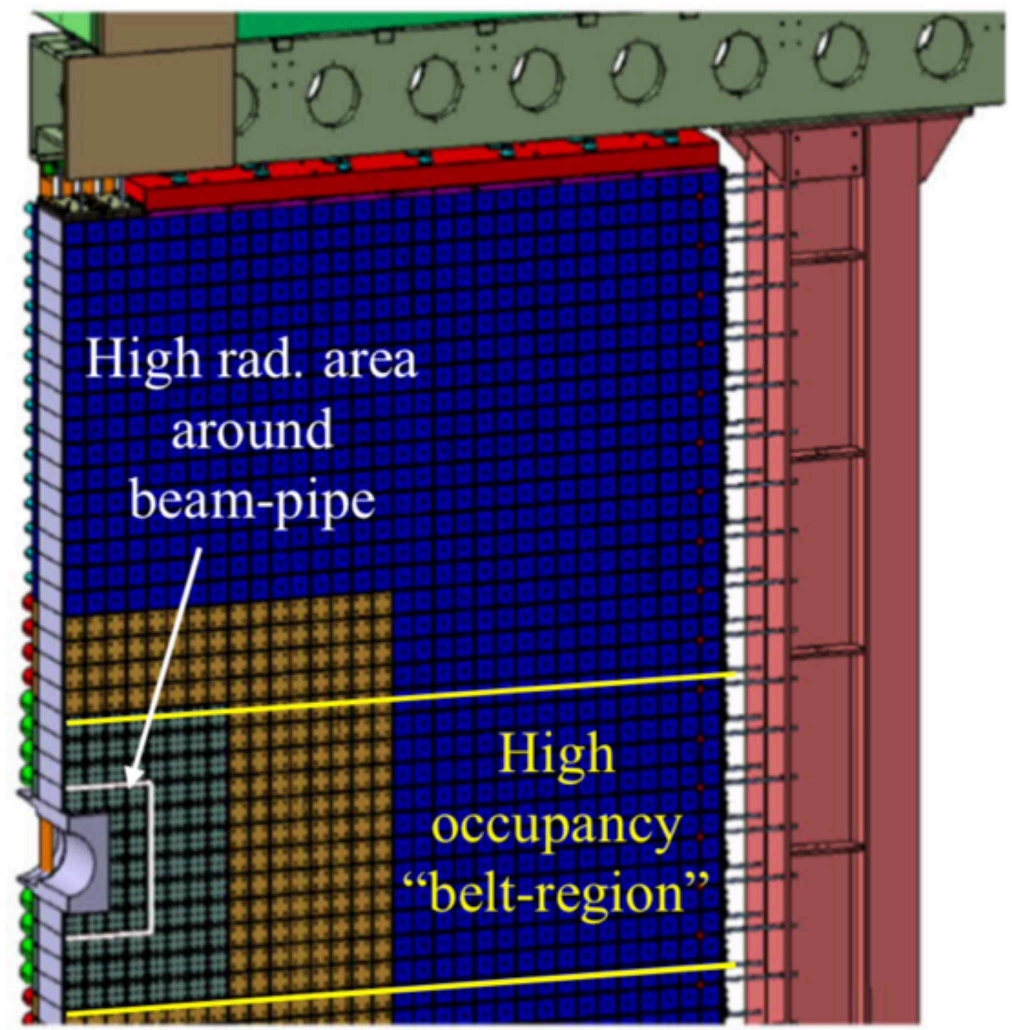
- Keep current ECAL Shashlik modules but **upgrade electronics to full 40 MHz readout**

LS3 in 2024/25: → Consolidation (1b)

- **Replace modules around beam-pipe** ($\geq$ 32 modules) compatible with **$L=2 \times 10^{33}$ cm^{-2}s^{-1}**

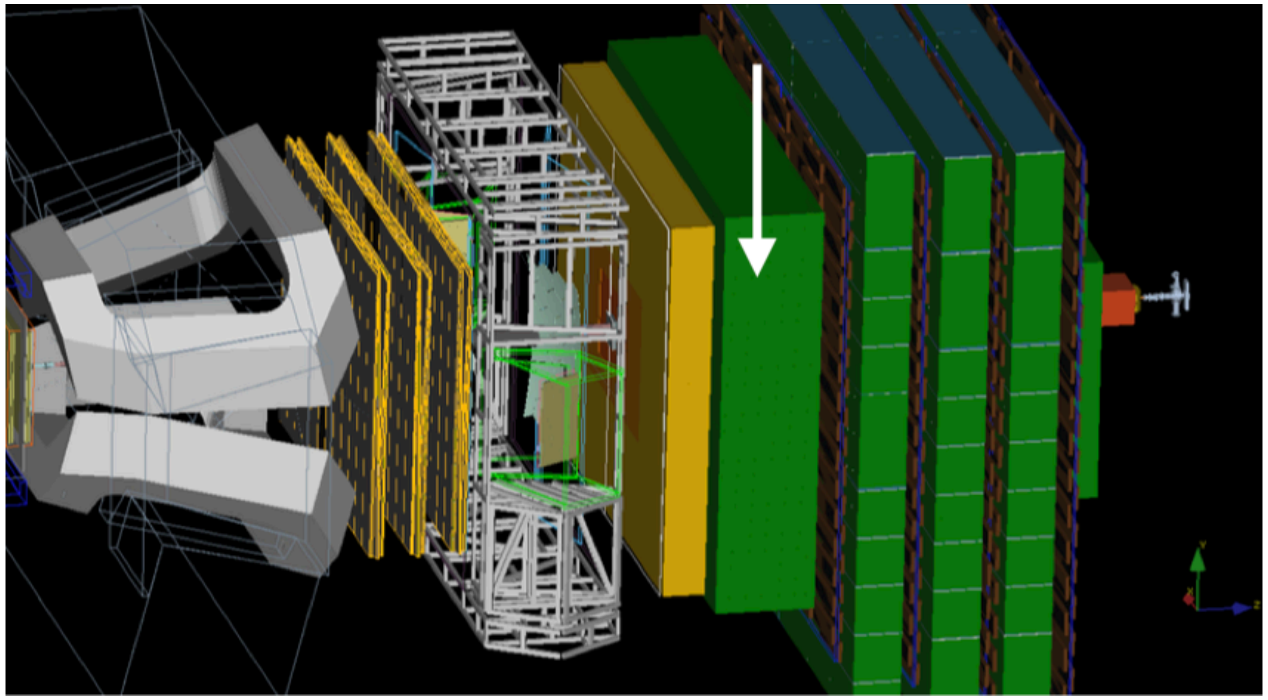
LS4 in 2030/31: → LHCb Upgrade II

- **Rebuilt ECAL in high occupancy "belt-region"** compatible with luminosity up to **$L=2 \times 10^{34}$ cm^{-2}s^{-1}**
- Include **timing information** to mitigate multiple interactions/crossing



Muon detector

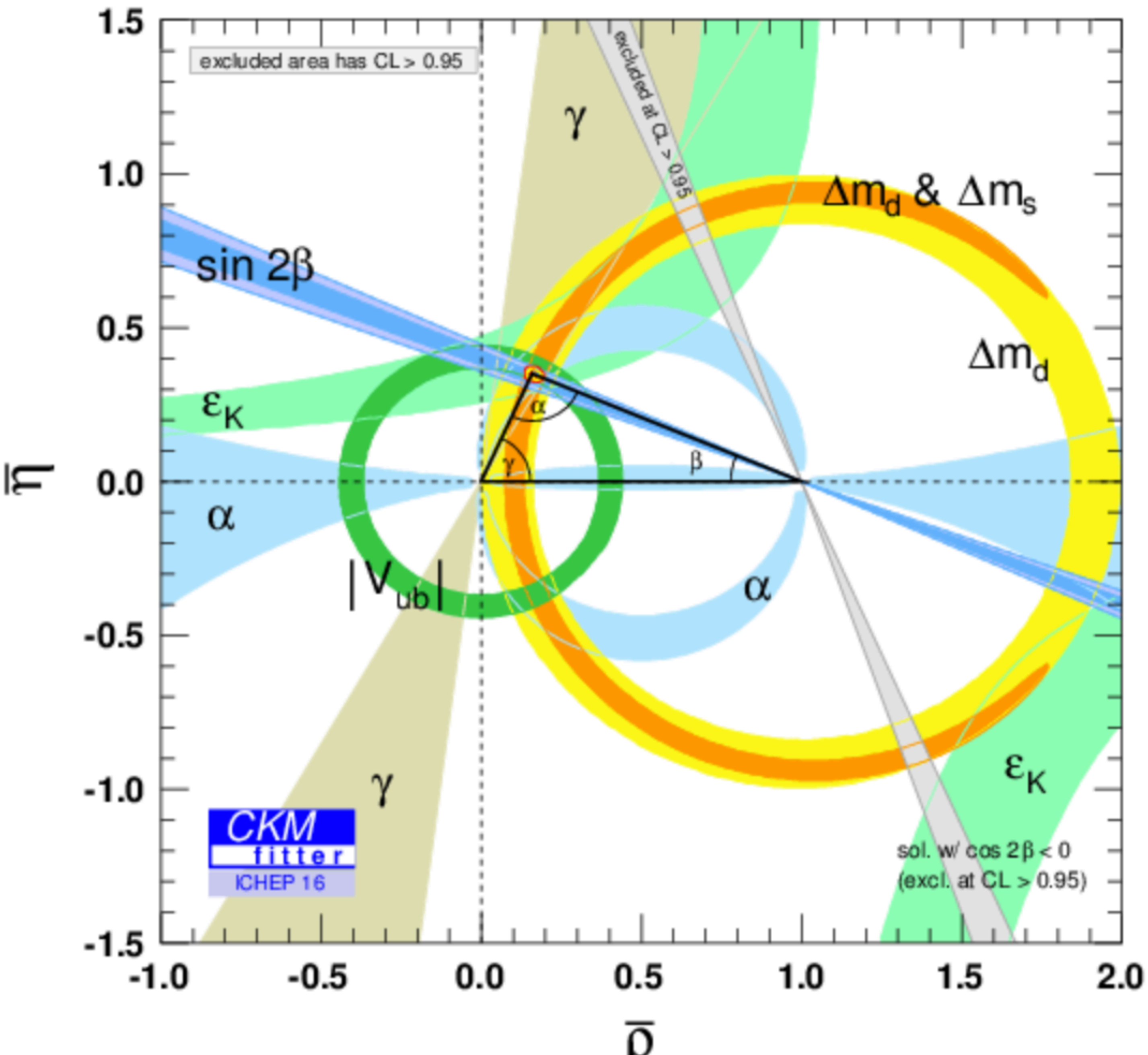
- ➢ Wonderful performance of muon detector in Run 1 and Run 2: tracking inefficiencies from dead time 1% in Run 1 and 2.6% in Run 2
- ➢ Need to maintain similar performance with 5×(50×) more occupancy
- ➢ Phase I upgrade: new MWPC with PAD readout keeps similar performance as Run 2



- ➢ Phase II upgrade: adding iron shielding wall (replacing HCAL) to reduce rate
- ➢ New detector R&D ongoing: μ-RWELL appear to be promising (others like MWPC, GEM also possible)

CKM Physics

➢ Looking for inconsistencies in CKM matrix → extra CPV sources



➢ Key variables for LHCb physics programs:

γ, $\beta_{(s)}$, α, $|V_{ub}|$, $|V_{cb}|$, Δm_d, Δm_s …

➢ Important to measure same quantities in different processes to check for deviations from new physics

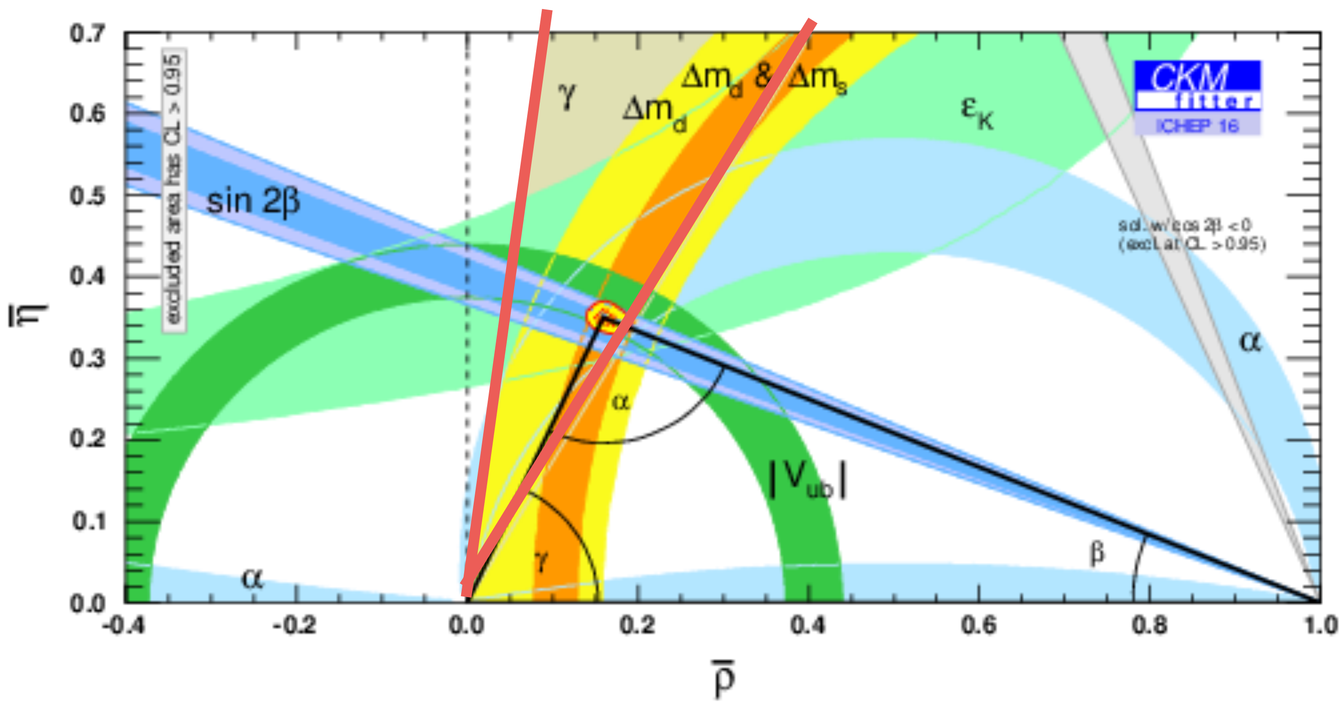
➢ Inputs from Lattice QCD etc are also important for CKM constrain

➢ New physics still possible at 10%-15% level

➢ Prospects for selected key CKM observables are given for 300 fb^{-1}

CKM angle γ

- ➢ **Least well known CKM parameters** $\gamma = \arg\left[-V_{ud}V_{ub}^{*}/(V_{cd}V_{cb}^{*})\right]$



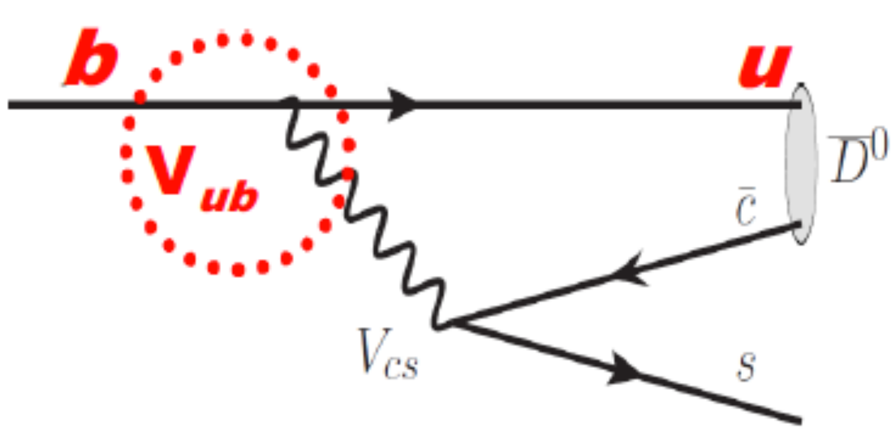
Direct: $\gamma = (73.5^{+4.3}_{-5.0})^\circ$

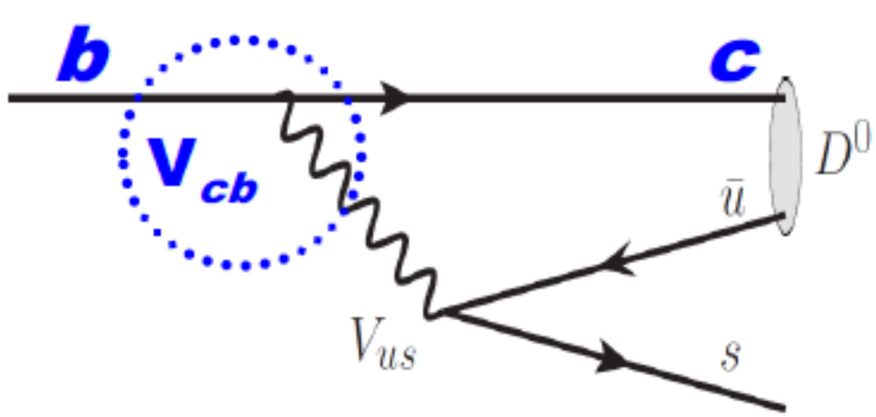
VS

Indirect: $\gamma = (65.3^{+1.0}_{-2.5})^\circ$

New Physics?

- ➢ **γ at tree level: clean theory prediction δγ/γ ~ 10^{-7}** JHEP 1401 (2014) 051





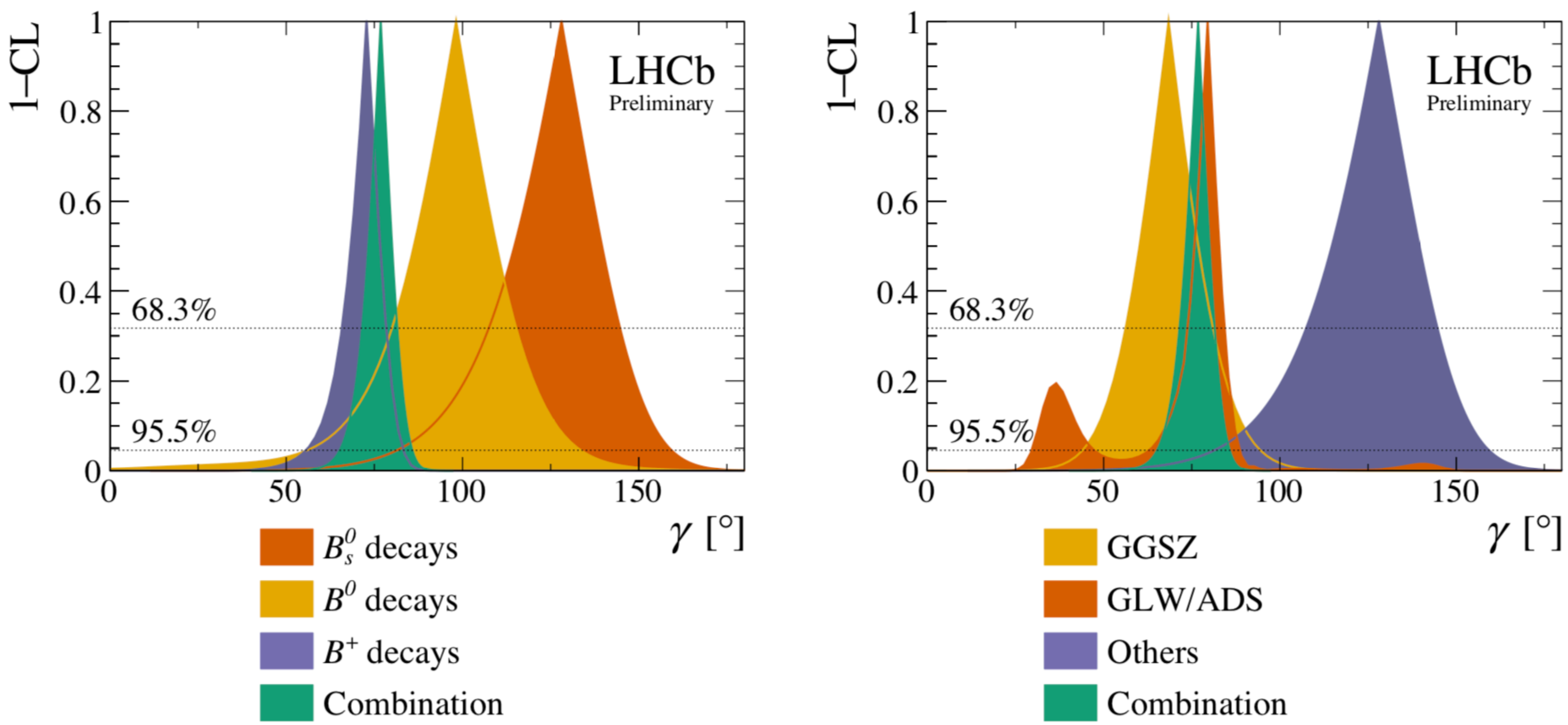
- ➢ **Sensitive channels with small BFs: need to combine many channels**

$B_s \to D_s K$, $B^+ \to DK^+$ with D to hh, Kshh etc

γ average

➢ **Combining all LHCb measurements, we have** LHCb-CONF-2017-004

$$\gamma \in [71.1, 81.9]^\circ \quad \text{at } 68.3\% \text{ CL}\,, \qquad \textbf{or} \qquad \gamma = (76.8\,^{+5.1}_{-5.7})^\circ\,,$$
$$\gamma \in [64.3, 86.6]^\circ \quad \text{at } 95.5\% \text{ CL}\,.$$



➢ **Some tension exists and may be interesting to follow-up**

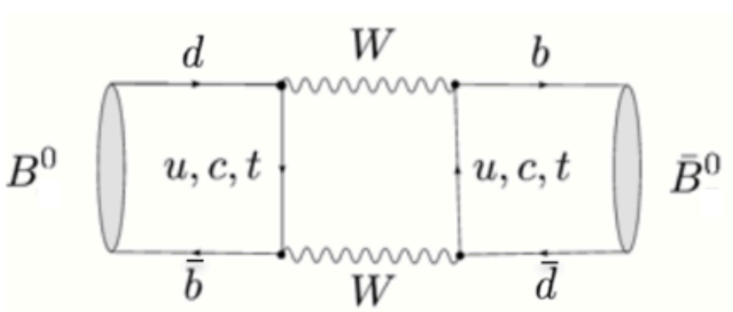
➢ **Future sensitivities (scaled according to statistical uncertainties)**

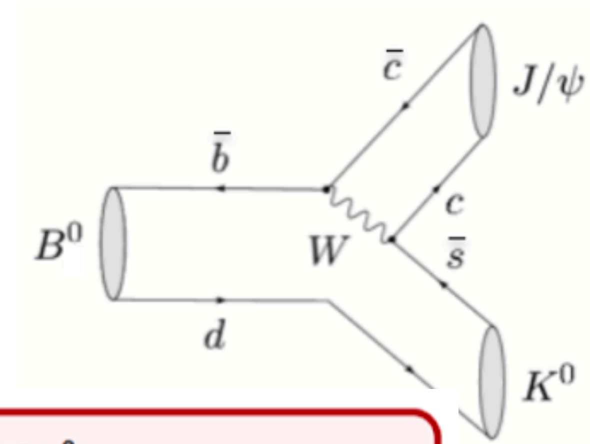
Run 1	Run 2	Upgrade 1	Upgrade 2
5.5°	2.8°	0.71°	0.28°

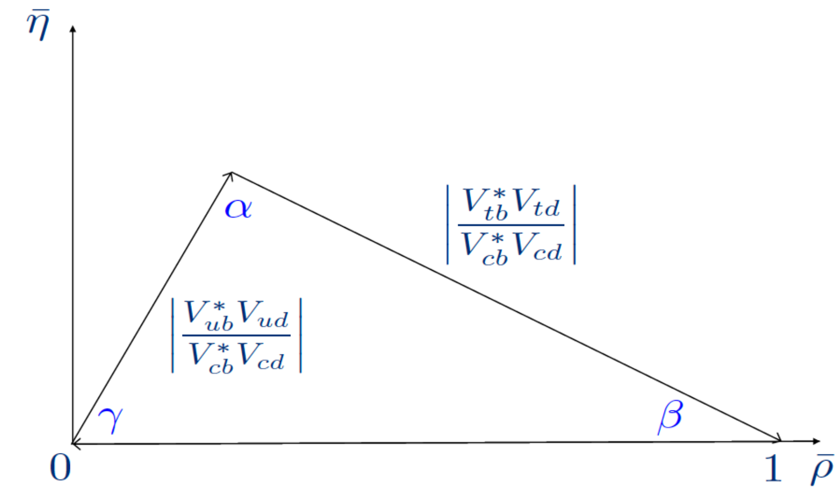
➢ **More channel can be explored including those with π^0 and γ if we have better calorimeter**

sin2β

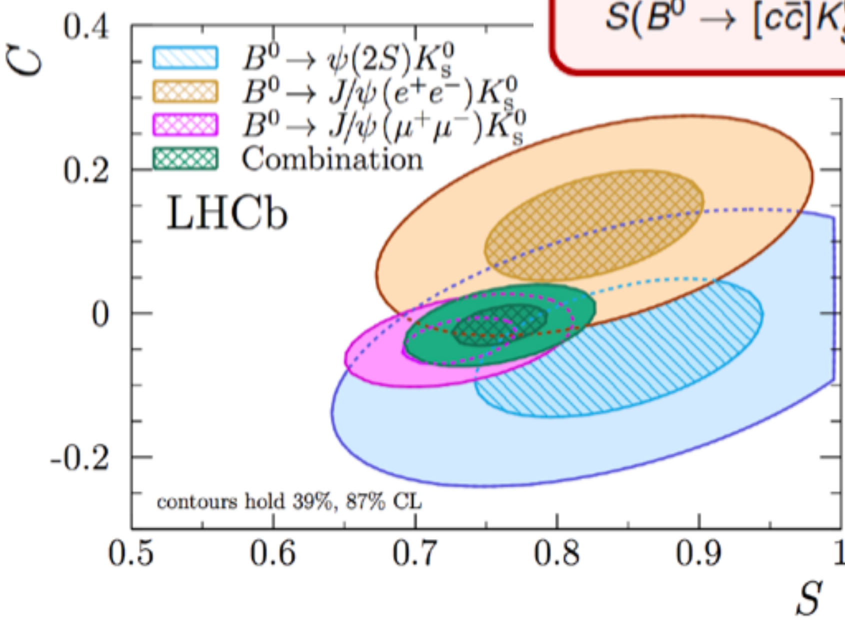
- ➢ CPV through interference between mixing and $b \to c\bar{c}s$ in B^0 decays gives access to sin2β

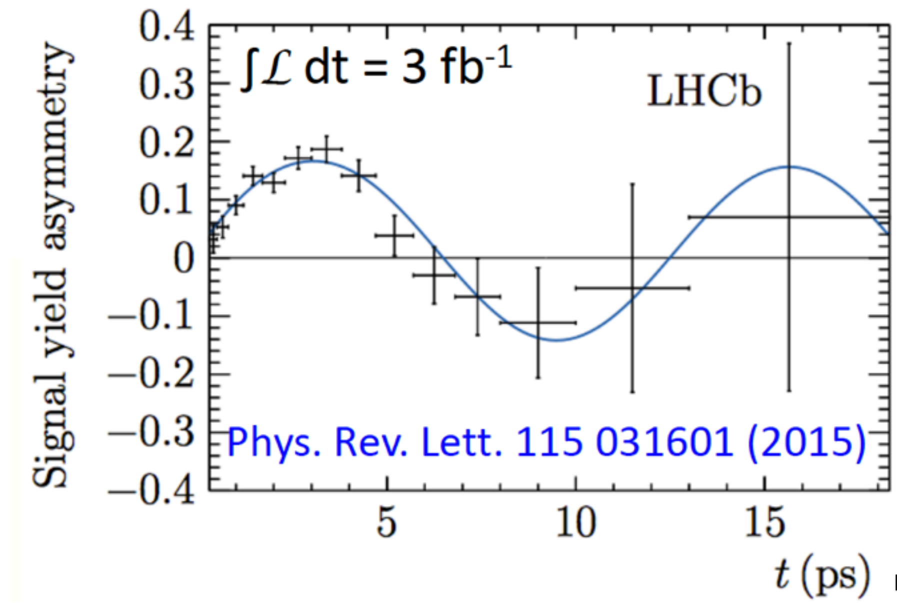






$C(B^0 \to [c\bar{c}]K_S^0) = -0.017 \pm 0.029$
$S(B^0 \to [c\bar{c}]K_S^0) = 0.760 \pm 0.034$





- ➢ Run 1 sensitivity already reaches B-factories

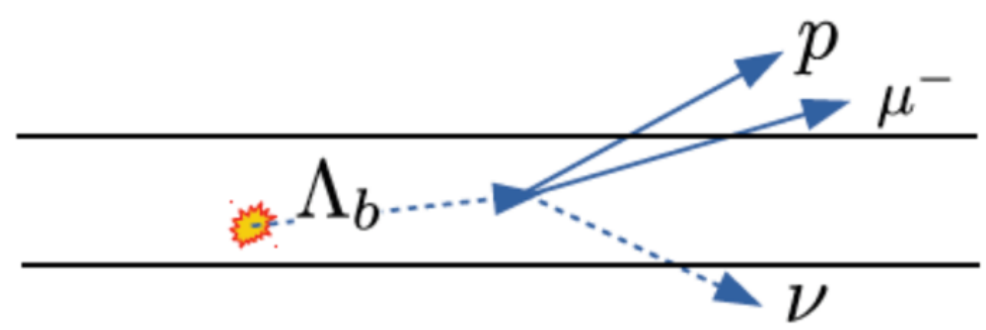
Run 1	Run 2	Upgrade I	Upgrade II
0.034	0.017	0.004	0.002

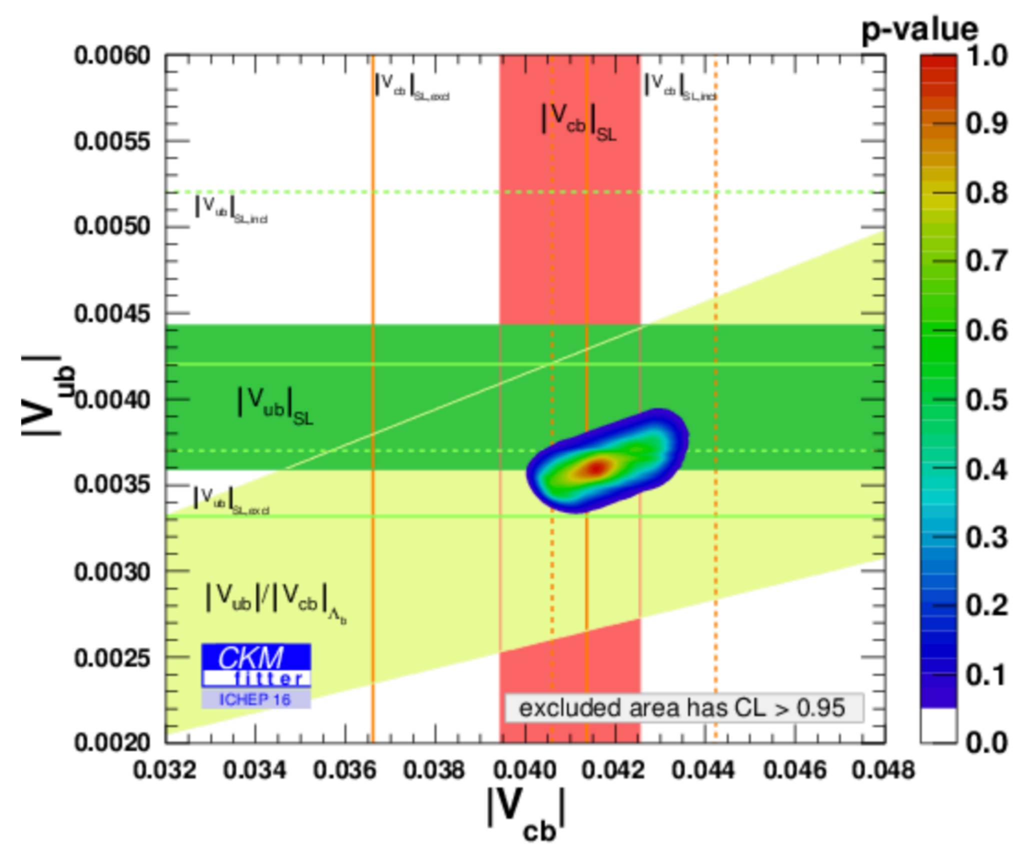
- ➢ Upgrade statistics also gives sensitivity to the non-zero $\Delta\Gamma_d$ predicted in SM

$|V_{ub}/V_{cb}|$ and α

Nature Phys. 11 (2015) 743-747

➢ LHCb has proved the ability to do $|V_{ub}|/|V_{cb}|$ measurement at hadron collider





➢ Similar measurements can also be done via SL decays of Bs, Bc

➢ SV resolution crucial for the game

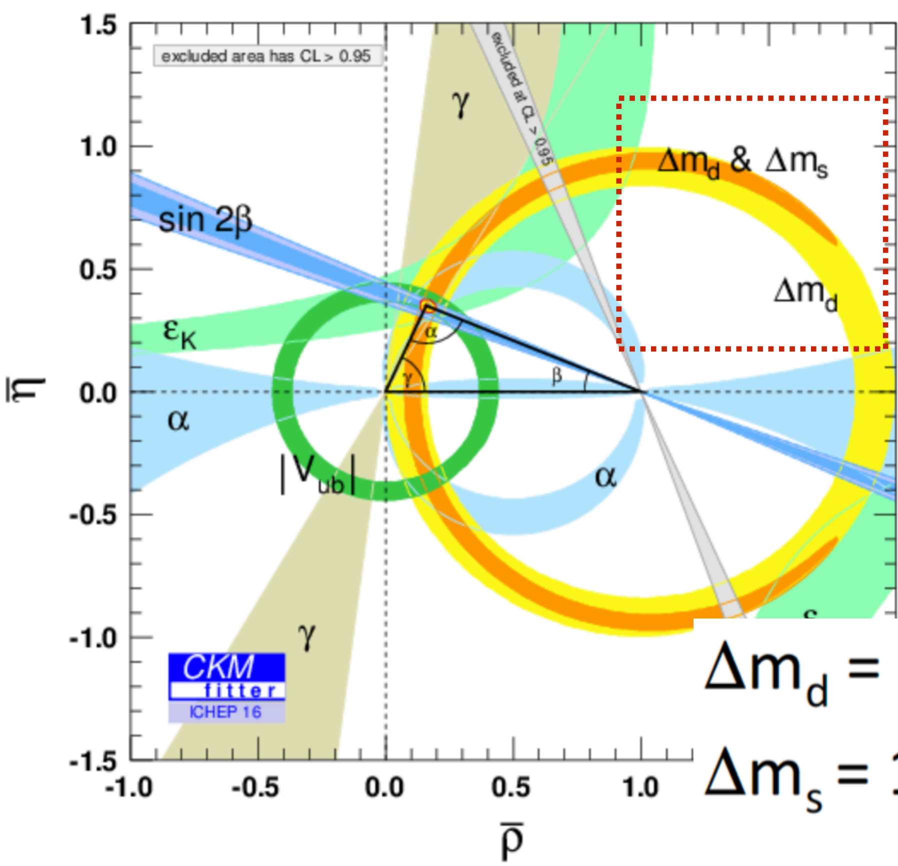
➢ Future sensitivity will be driven by Belle II

➢ LHCb has limited access to CKM angle α, extract using $B\to\pi\pi$, $\rho\pi$, $\rho\rho$; though LHCb has good sensitivity to $B^0\to\pi^+\pi^-$, $B^0\to\rho^0\rho^0$; sensitivity driven by inputs from B-factories

➢ Hopefully we can do more with better calorimeter in upgrade

Δm_d and Δm_s

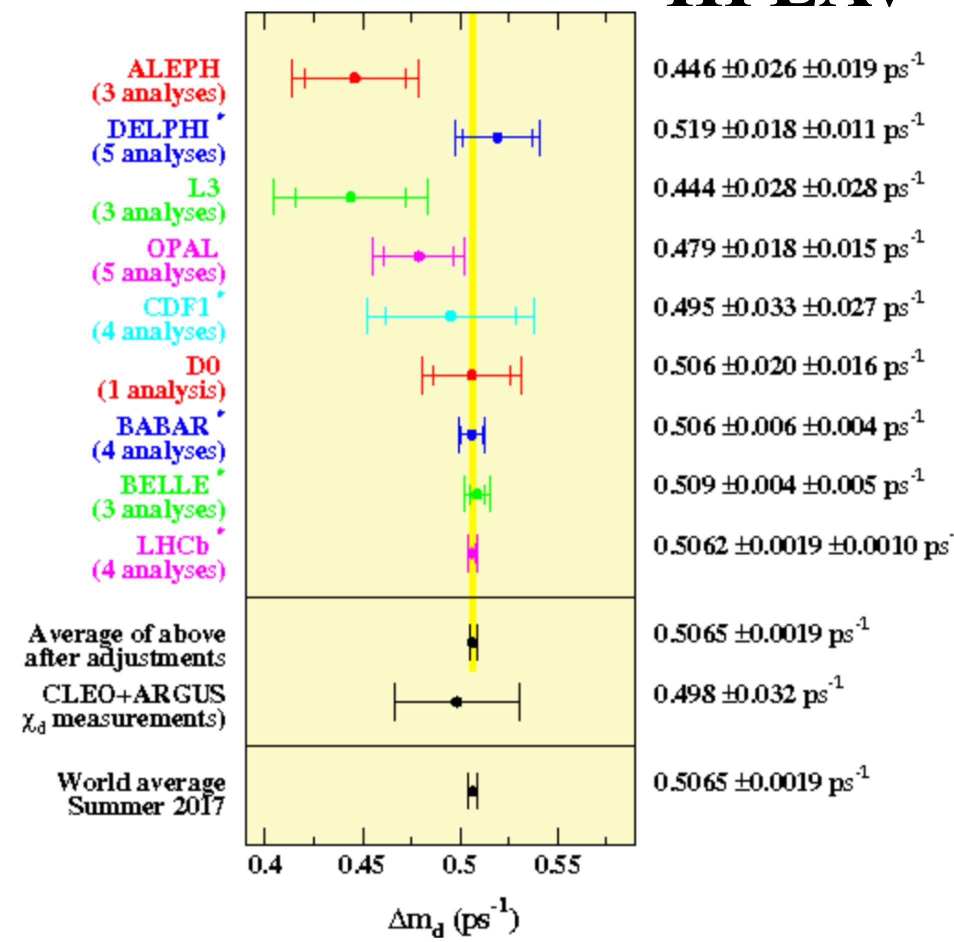
➢ Combinations of oscillation frequency Δm_d and Δm_s are dominated by LHCb and may continue to be dominated by LHCb



$\Delta m_d = 0.5065 \pm 0.0019\ \mathrm{ps}^{-1}$

$\Delta m_s = 17.757 \pm 0.021\ \mathrm{ps}^{-1}$

HFLAV



➢ However, interpreting are limited by Lattice inputs

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2\ \eta_c S(x_t)\ A^2\lambda^6\ [(1-\bar{\rho})^2+\bar{\eta}^2]\ m_{B_d} f_{B_d}^2 \hat{B}_{B_d}$$

~7%

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \left(\frac{\lambda}{1-\frac{\lambda^2}{2}}\right)^2 [(1-\bar{\rho})^2+\bar{\eta}^2]$$

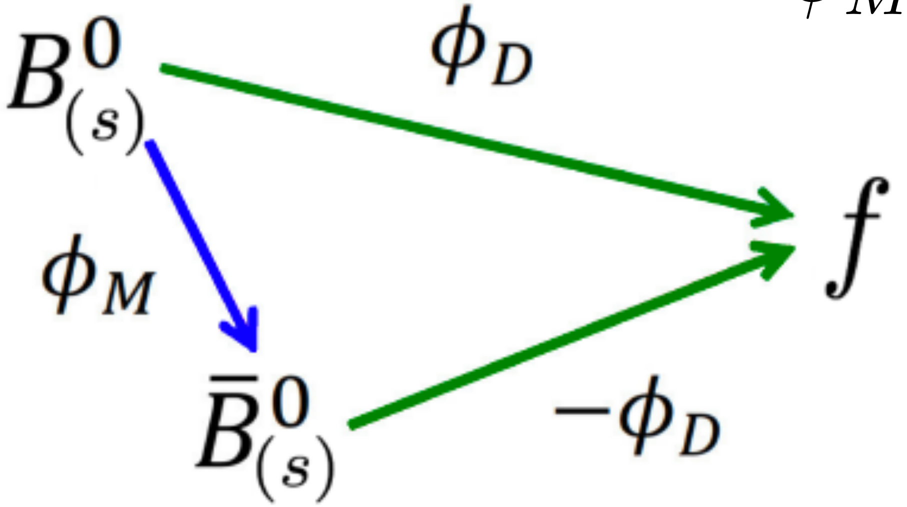
~4%

Efforts from Lattice community needed to further reduce uncertainty by a factor of 10 more

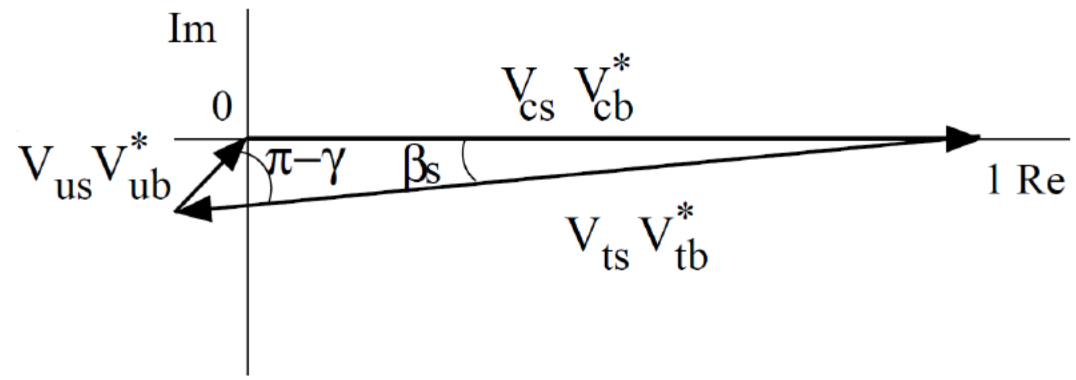
ϕ_s

- **CPV through interference between mixing and decays for B$_s$ decays**

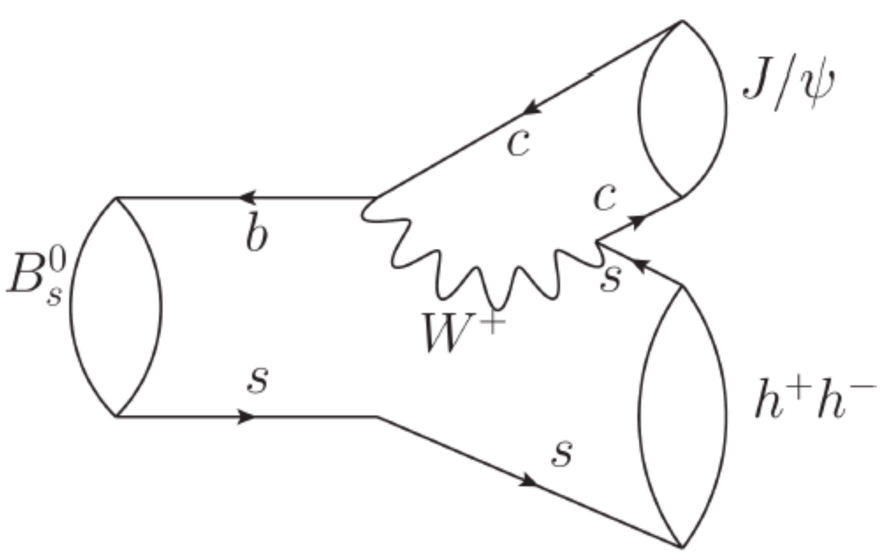
$$\phi_M = -2\beta_s$$

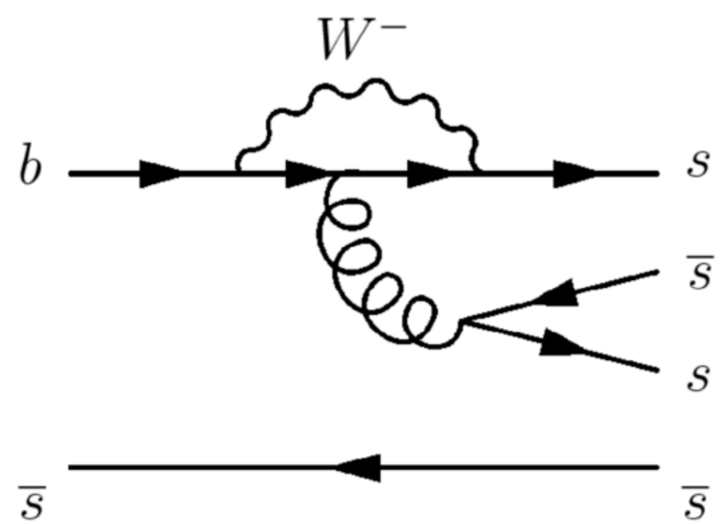


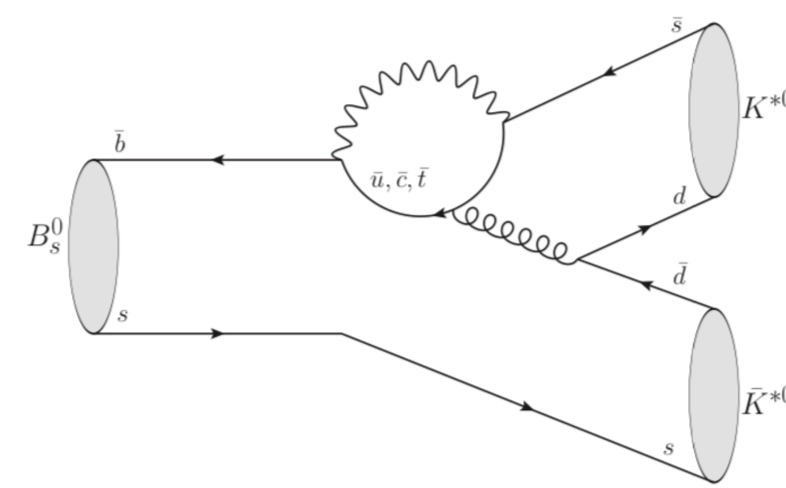
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$



- **Ignoring sub-leading penguin contribution:**



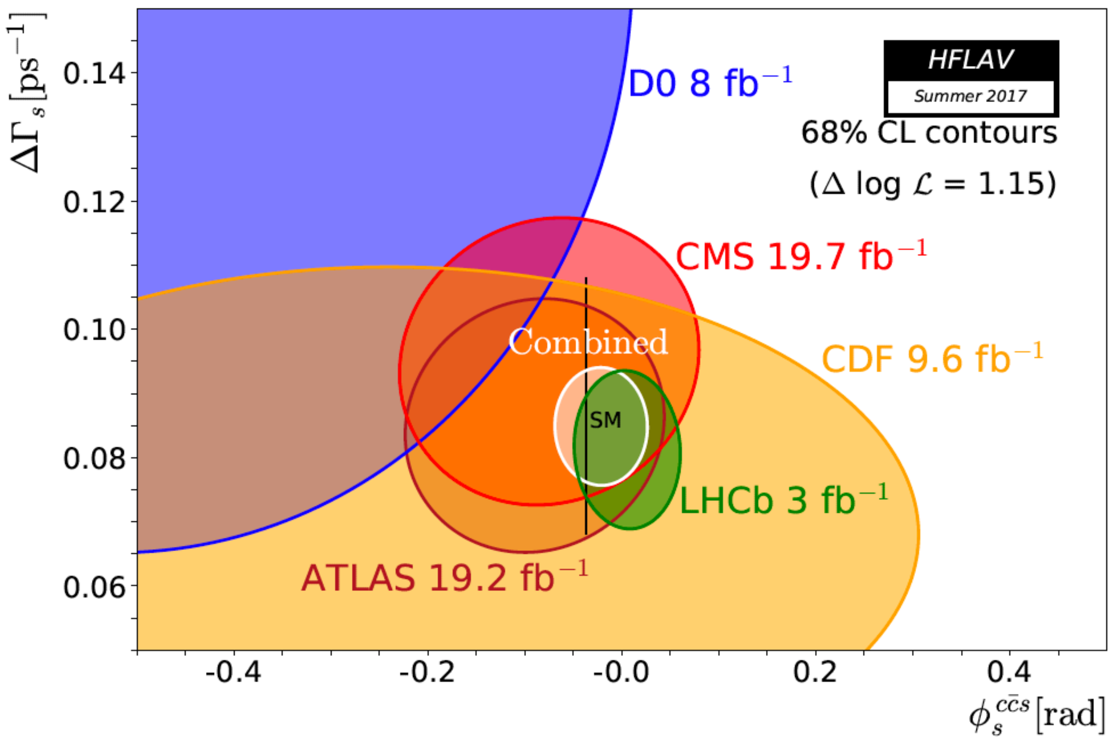




$$\phi_s^{c\bar{c}s} = -2\beta_s \qquad \phi_s^{s\bar{s}s} \sim 0 \qquad \phi_s^{d\bar{d}s} \sim 0$$

ϕ_s measurements and prospects

➢ **LHCb dominated combination; currently consistent with SM** $\phi_s^{c\bar{c}s}$



HFLAV combination

$$\phi_s^{c\bar{c}s} = -0.021 \pm 0.031 \text{ rad}$$
$$\Delta\Gamma_s = 0.085 \pm 0.006 \text{ ps}^{-1}$$
$$\Gamma_s = 0.6640 \pm 0.0020 \text{ ps}^{-1}$$

Penguin effects under control

$\Delta\phi_s \sim 0.001 \pm 0.020$ rad

$\phi_s^{c\bar{c}s} \stackrel{\text{SM}}{=} -0.0370 \pm 0.0006$ rad **[CKMFitter, PRD 84 (2011) 033005]**

$\Delta\Gamma_s \stackrel{\text{SM}}{=} 0.088 \pm 0.020$ ps^{-1} **[M. Artuso et al, arXiv:1511.09466]**

➢ **Similar (much harder) analyses performed for Bs→ϕϕ and Bs→KπKπ for** $\phi_s^{s\bar{s}s}$ **and** $\phi_s^{d\bar{d}s}$

$\phi_s^{s\bar{s}s} = -0.17 \pm 0.15 \pm 0.03$ rad $\quad\quad$ $\phi_s^{s\bar{d}d} = -0.10 \pm 0.13 \pm 0.14$ rad,

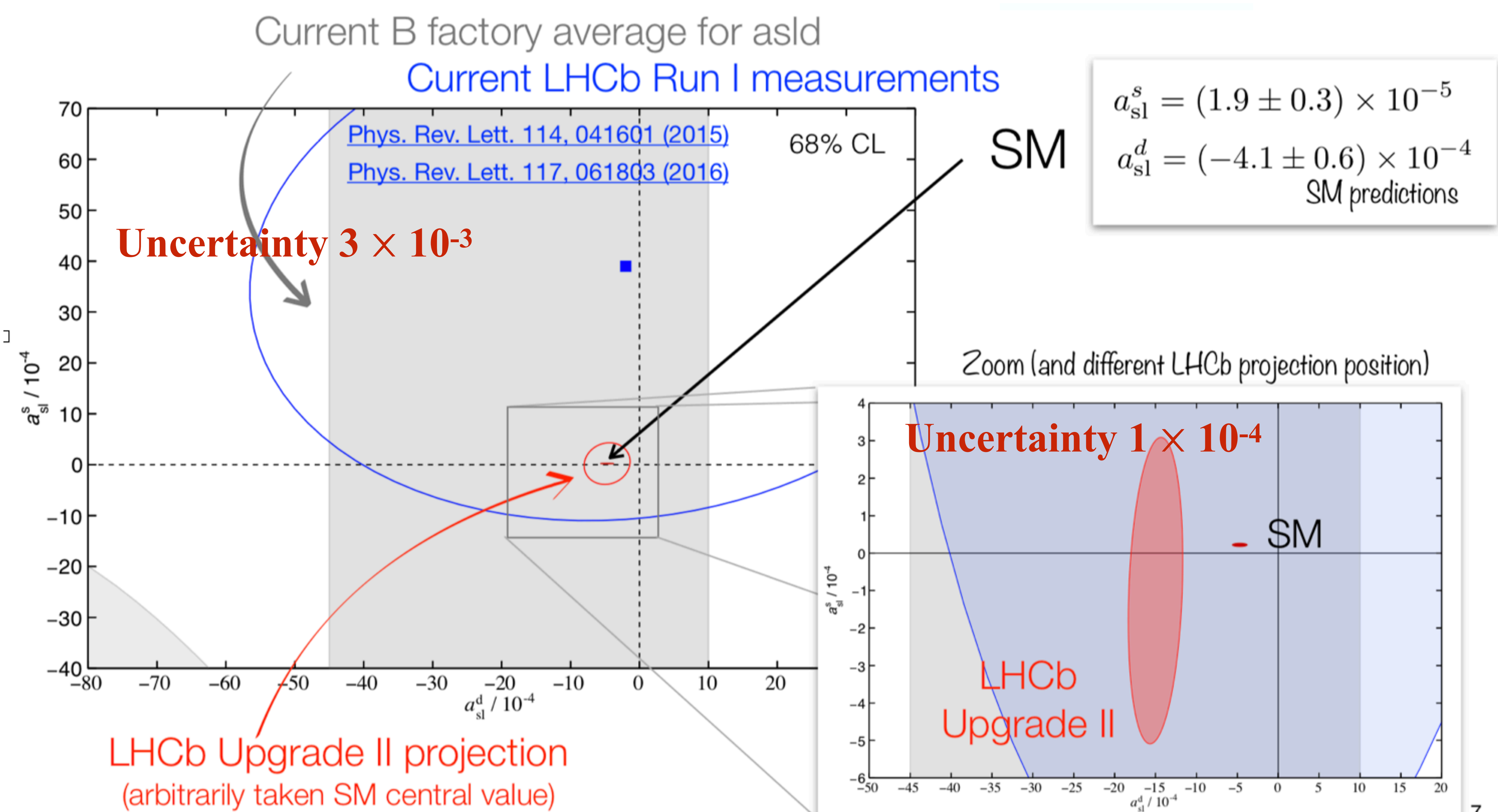
	Run 1	Run 2	Upgrade I	Upgrade II
$\phi_s^{c\bar{c}s}$	31 mrad	15 mrad	4 mrad	2 mrad
$\phi_s^{d\bar{d}s}$	180 mrad	90 mrad	22 mrad	10 mrad
$\phi_s^{s\bar{s}s}$	150 mrad	75 mrad	19 mrad	8 mrad

CPV in mixing

$$|\frac{q}{p}| = 1$$

- **Access through flavor specific final states (i.e. SL decays)** $B^0_{(s)} \to \bar{B}^0_{(s)} \overset{?}{=} \bar{B}^0_{(s)} \to B^0_{(s)}$

$$a_{\rm sl} = \frac{\Gamma(\overline{B} \to B \to f) - \Gamma(B \to \overline{B} \to \bar{f})}{\Gamma(\overline{B} \to B \to f) + \Gamma(B \to \overline{B} \to \bar{f})} \approx {\rm Im}\left(\frac{\Gamma_{12}}{M_{12}}\right) \approx \frac{\Delta\Gamma}{\Delta m}\tan\phi_M$$



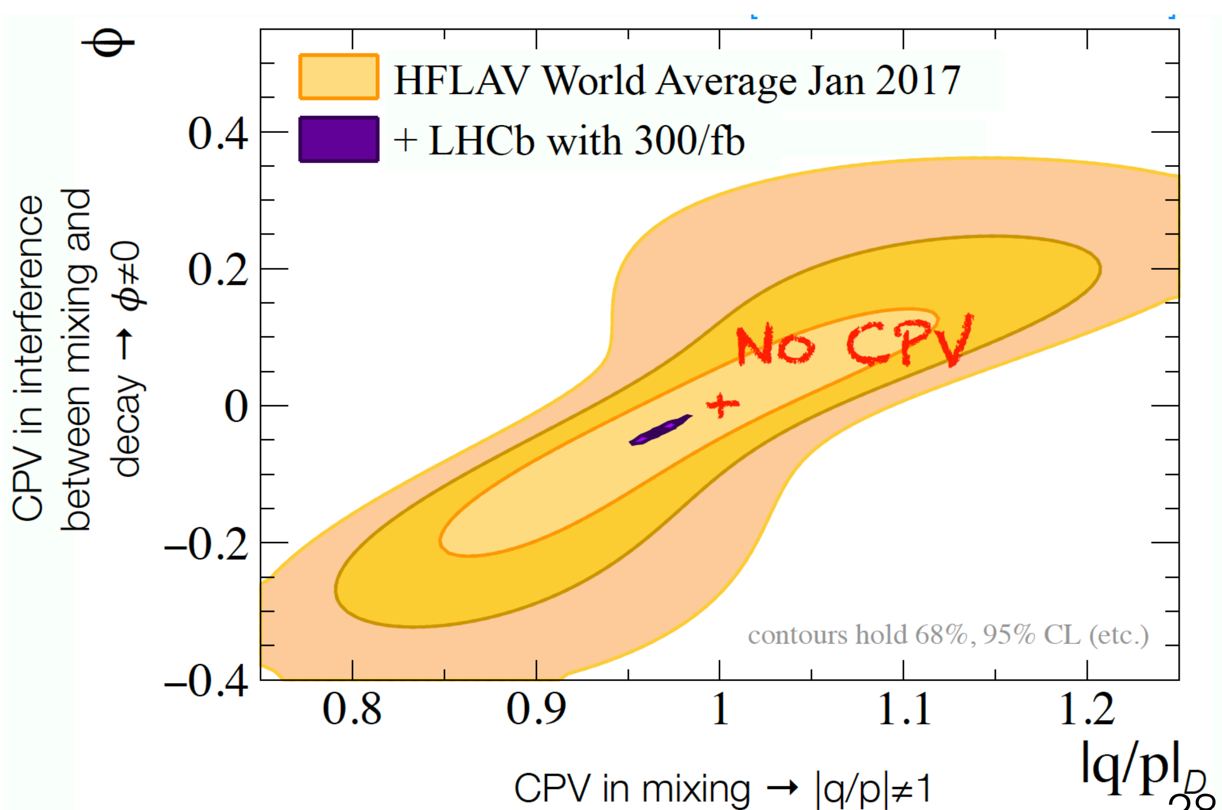
CPV in charm

- Charm CPV predicted in SM at level of 10^{-4}
- Sensitivity already at this level, very interesting with more data collected

ΔA_{CP} measurements: direct CPV

Sample ($\mathcal{L}$)	Yield ($\times 10^9$) $D^0 \to K^+K^-$	$D^0 \to \pi^+\pi^-$	$\sigma(\Delta A_{CP})$	$\sigma(A_{CP})$
Run 1-2 ($9\,\text{fb}^{-1}$)	0.08	0.03	0.03%	0.07%
Run 1-4 ($50\,\text{fb}^{-1}$)	1.0	0.31	0.01%	0.03%
Run 1-6 ($300\,\text{fb}^{-1}$)	5.7	1.8	0.005%	0.01%

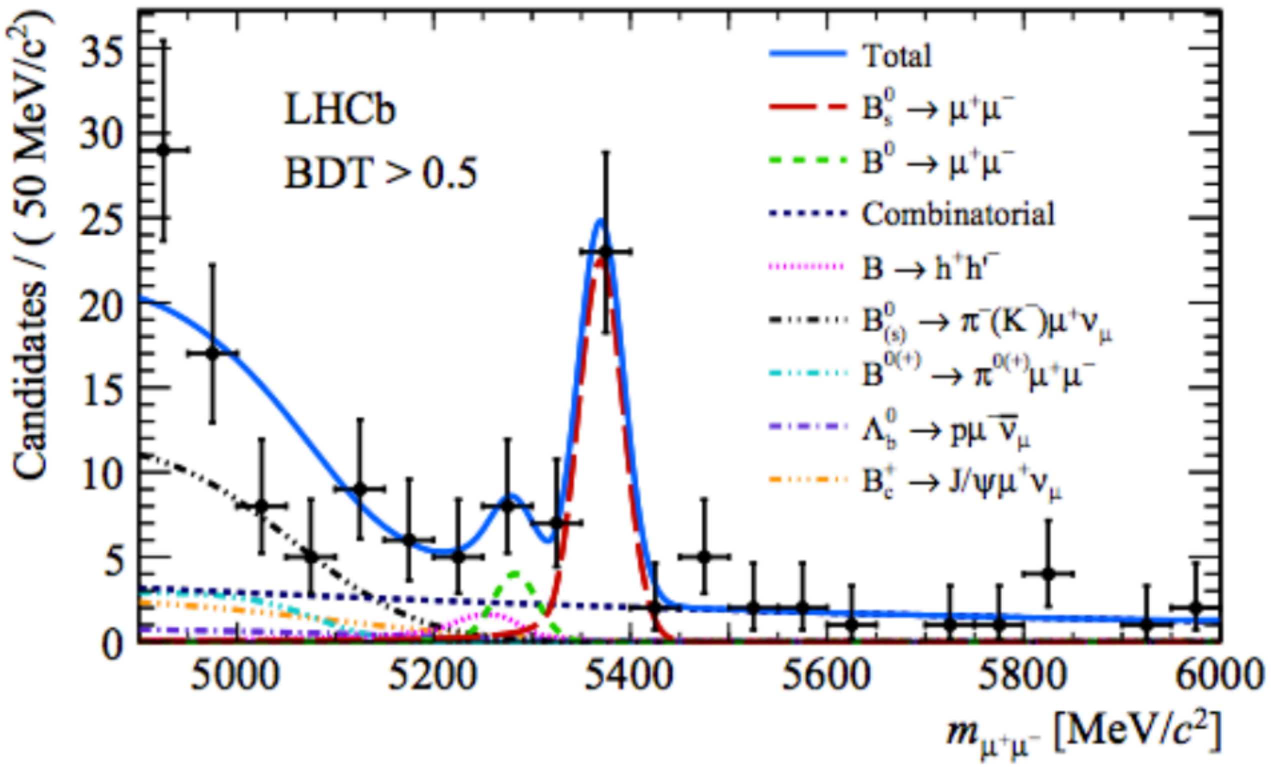
CPV in mixing and decays



- Most sensitive channels: TD measurements with $D^0 \to K^+\pi^-$, $D^0 \to K_S hh$, $D^0 \to hh$
- Time to measure or predict: which channel should we look at

$B_{(s)} \to \mu\mu$

➢ **Highly suppressed FCNC mode, sensitive to new physics**



$$BF_{SM}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

$$BF_{SM}(B_s^0 \to \mu^+\mu^-) = (3.60 \pm 0.18) \times 10^{-9}$$

Bobeth et al. [PRL 112(2014)101801] **Altmannshofer et al.** [arXiv:1702.05498]

➢ **First single experiment observation by LHCb**

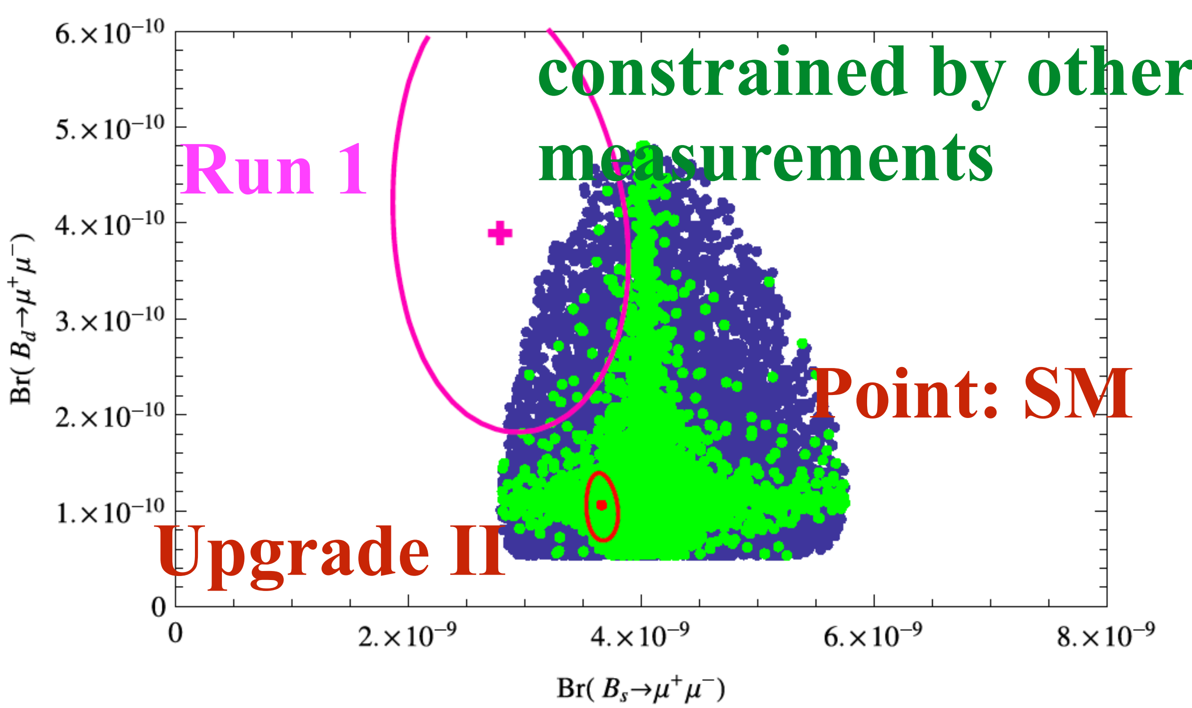
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0^{+0.7}_{-0.6}) \times 10^{-9} \ (S = 7.8\sigma)$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ at 95\% CL}$$

➢ **In upgrade II, we may expect 10% precision on the ratio between two modes and 0.03 ps on effective lifetime**

➢ **CPV will also be interesting**

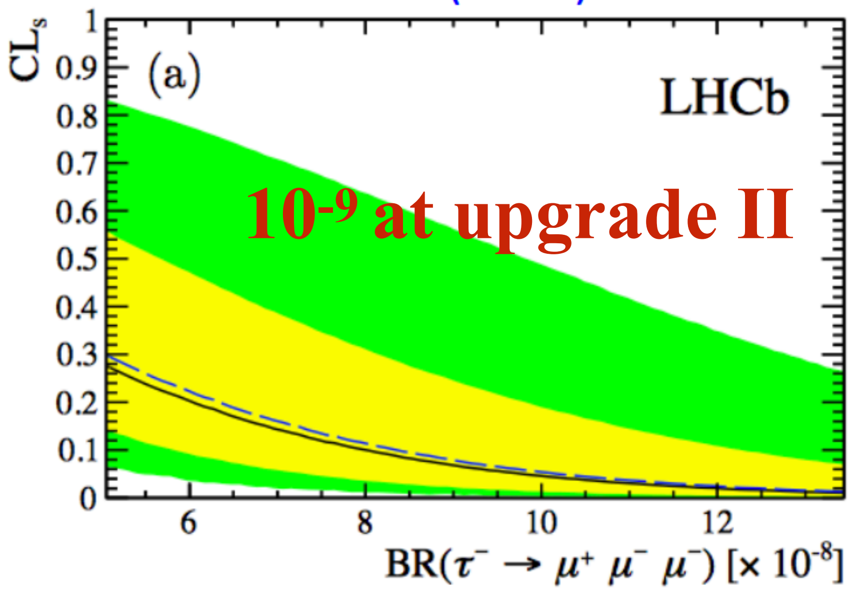
A new physics model



Other rare decays

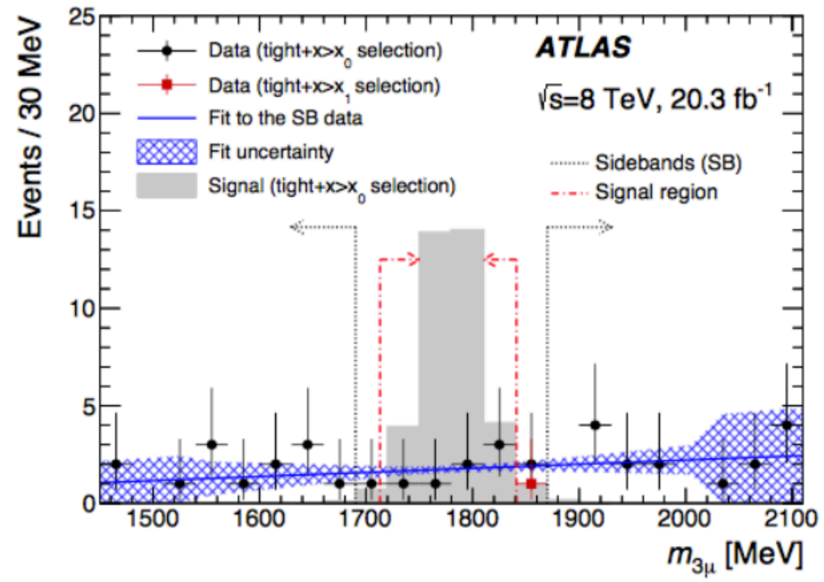
- ➢ **Statistics is the name of the game;**
- ➢ **Sensitivity scaled according to 1/√N**

JHEP 02 (2015) 121



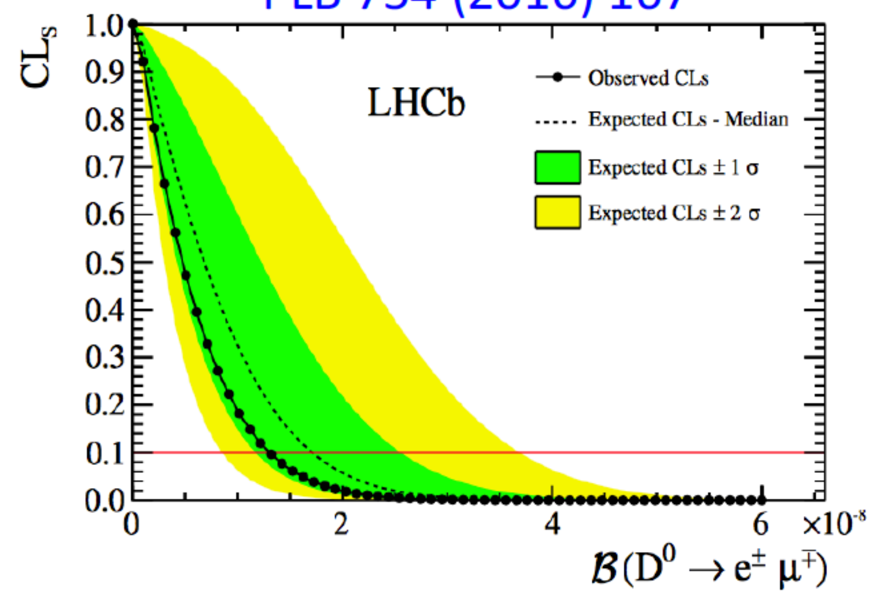
$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 4.6\ (5.6) \times 10^{-8}$

EPJC 76 (2016) 232



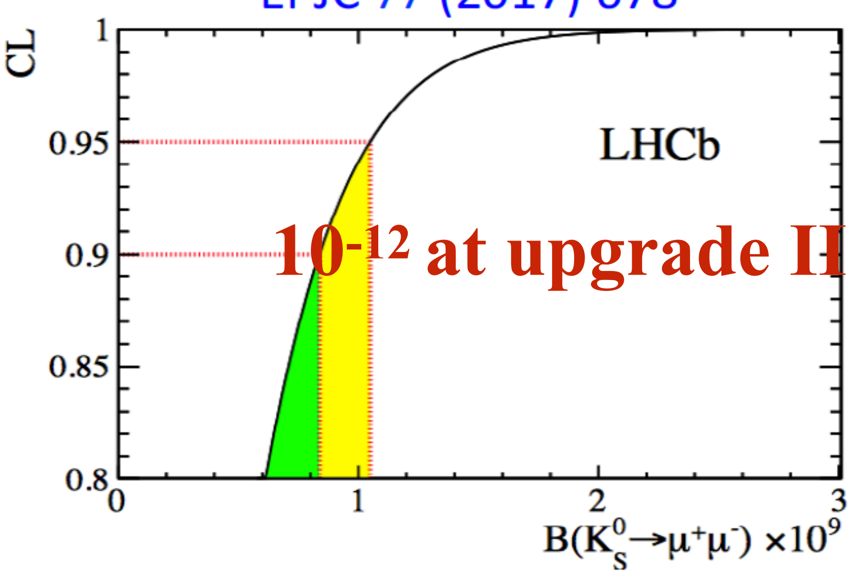
$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 3.76\times 10^{-7}$

PLB 754 (2016) 167



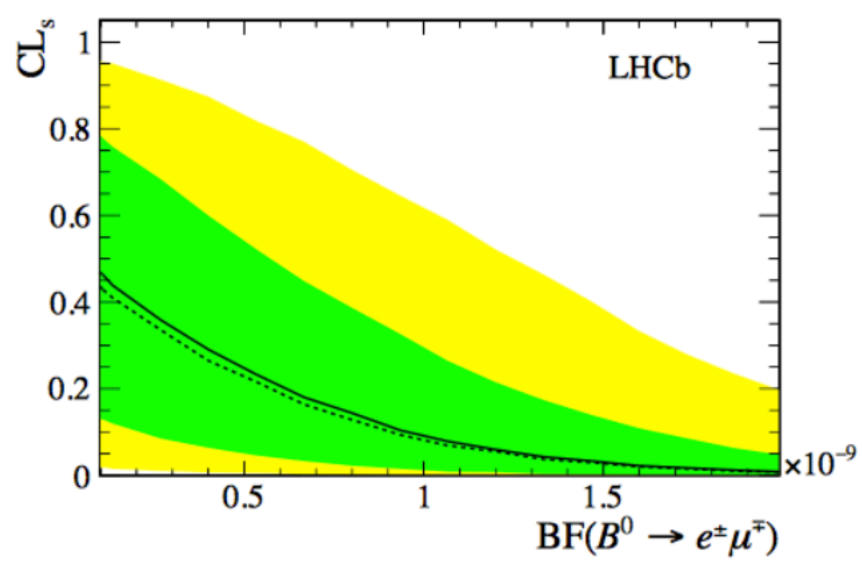
$\mathcal{B}(D^0 \to e^\pm\mu^\mp) < 1.3(1.6)\times 10^{-8}$

EPJC 77 (2017) 678



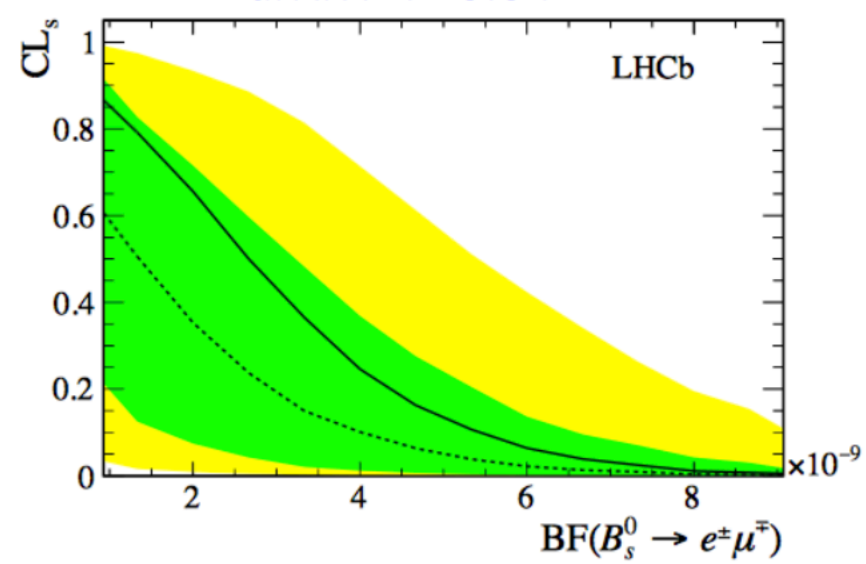
$\mathcal{B}(K^0_S \to \mu^+\mu^-) < 0.8\ (1.0) \times 10^{-9}$

arXiv:1710.04111



$\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 1.0\ (1.3) \times 10^{-9}$

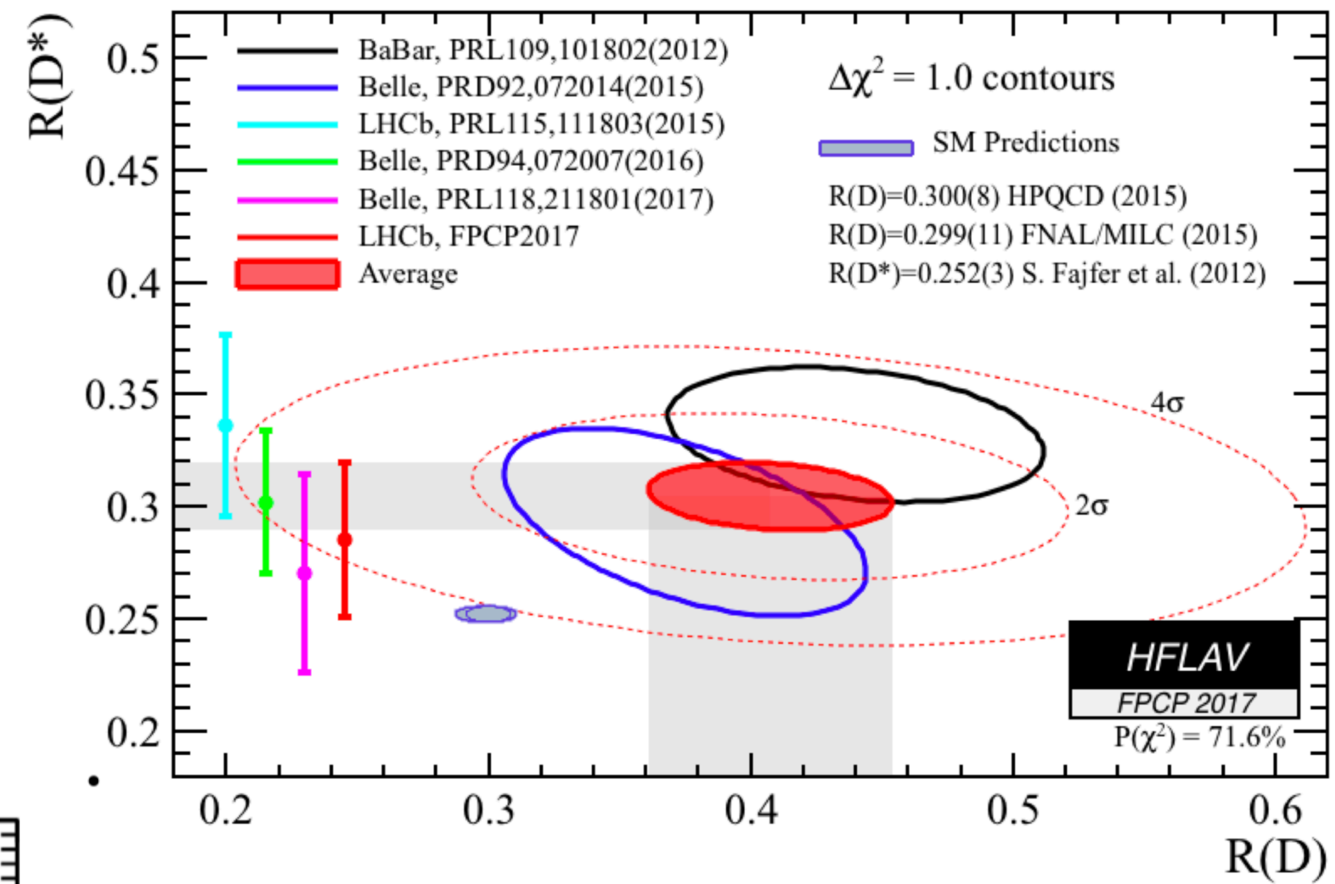
arXiv:1710.04111



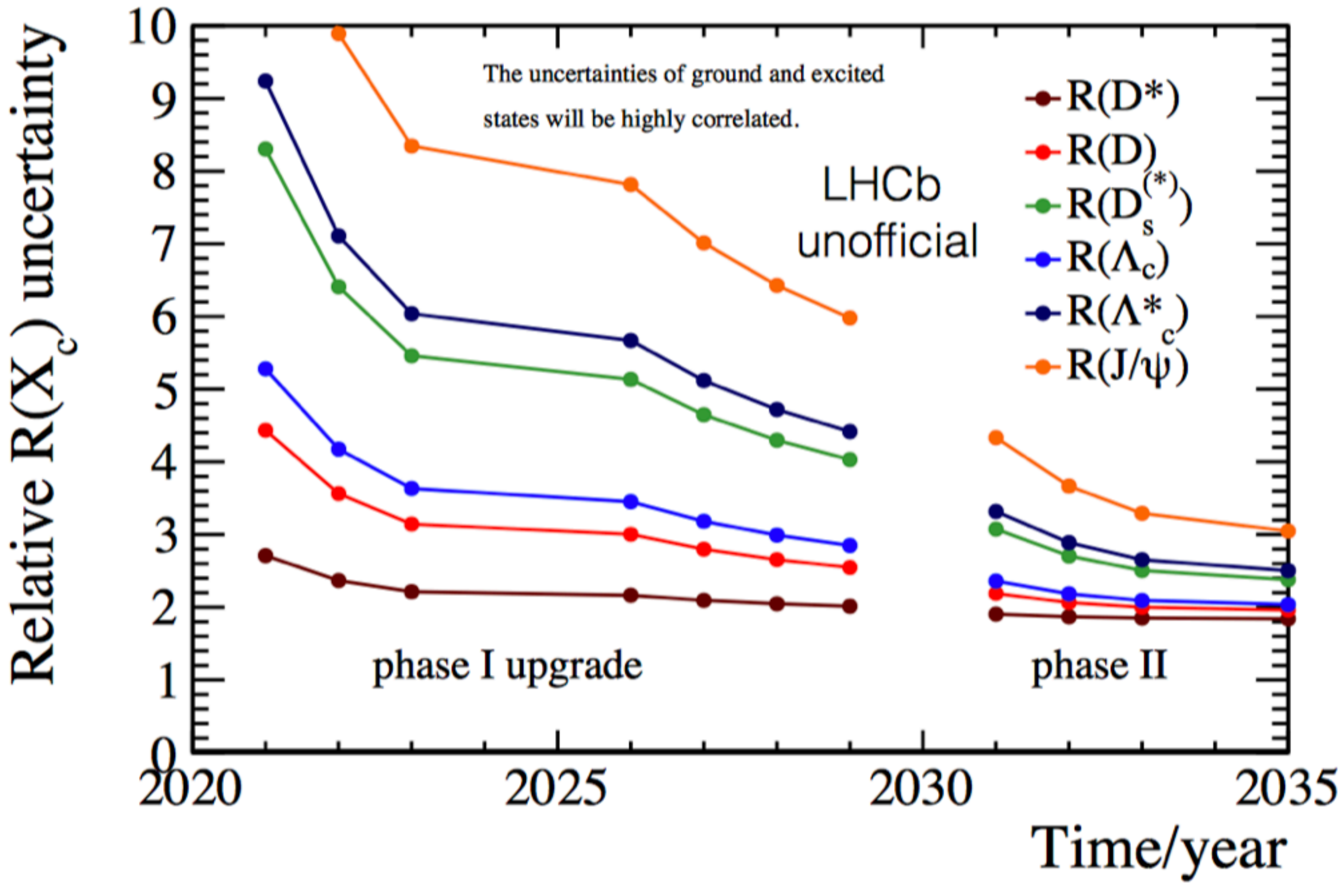
$\mathcal{B}(B^0_s \to e^\pm\mu^\mp) < 5.4\ (6.3) \times 10^{-9}$

Lepton flavor universality measurements

➢ Lepton flavor universality test becomes a hot topic after many deviations seen from B-factories and LHCb measurements (see Jibo's talk)



➢ Sensitivities estimated for muonic + pionic channels



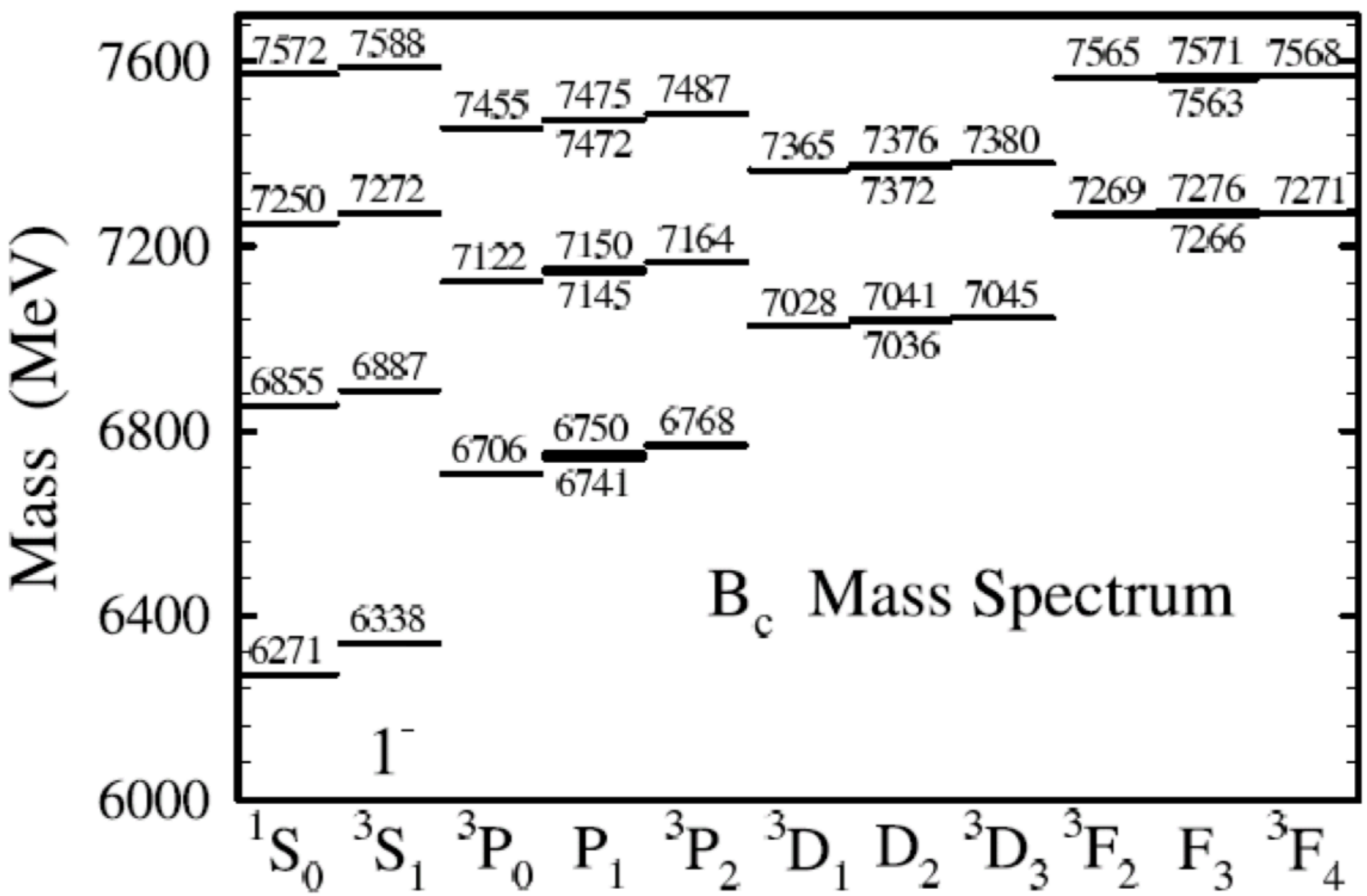
➢ Assumes that all the systematic uncertainties scale w.r.t. statistic except those can't or reply on external inputs

Bc physics (1)

PRL 113 (2014) 212004
JHEP 01 (2018) 138

➢ Though several new decay channels have been observed by LHCb, a large set of Bc physics have not been touched due to limited statistics

➢ With about ~180× (~380×) more statistics for muonic (hadronic) final states, interesting studies on Bc excited states, $Bc \to D_{(S)}^{(*)} D^{(*)}$ and $Bc \to Bs\pi$ etc.

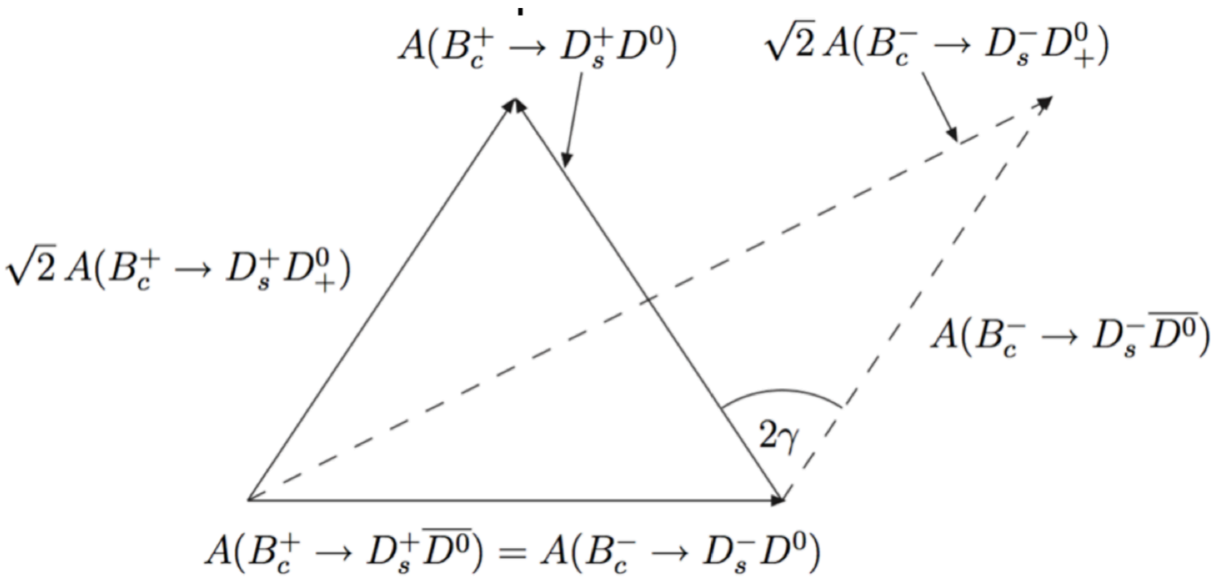


➢ Currently, only ATLAS claims a observation of excited Bc state with a mass of 6842 ± 6 MeV, possibly Bc(2S), but not confirmed by other experiments

➢ Bc excited states with $Bc^* \to Bc\pi\pi$, $Bc\gamma$, $Bc\mu\mu$ with interested to look at

Bc physics (2)

➢ $B_c \to D_{(S)}^{(*)} D^{(*)}$ supposed to be sensitive to CKM angle γ; though yields are much smaller than golden modes, r_{Bc}~1 for Ds mode and 0.1 for D mode (amplitude between b→u and b→c) and thus large CPV



LHCb unofficial

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D_s^+ \bar{D}^0)}{\mathcal{B}(B^+ \to D_s^+ \bar{D}^0)} < 7.0 \times 10^{-4},$$
$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D_s^+ D^0)}{\mathcal{B}(B^+ \to D_s^+ \bar{D}^0)} < 7.2 \times 10^{-4},$$

Ds: 7×10^{-4}

$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D^+ \bar{D}^0)}{\mathcal{B}(B^+ \to D^+ \bar{D}^0)} < 1.3 \times 10^{-2},$$
$$\frac{f_c}{f_u}\frac{\mathcal{B}(B_c^+ \to D^+ D^0)}{\mathcal{B}(B^+ \to D^+ \bar{D}^0)} < 9.1 \times 10^{-3},$$

D: 1×10^{-2}

➢ With the upgrade II statistic, these channels can start to appear

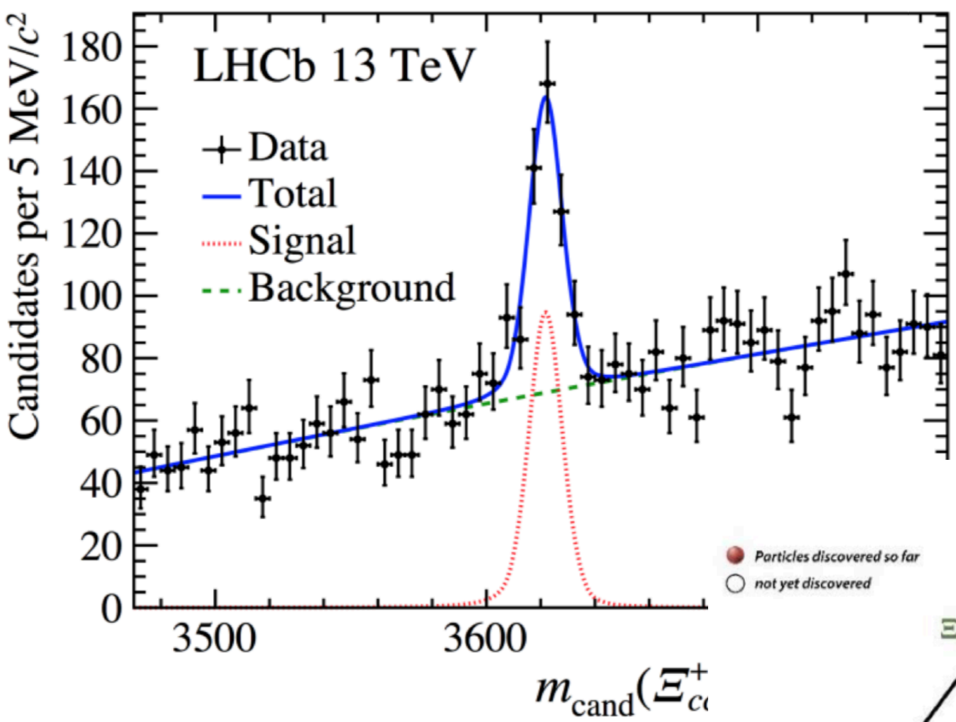
Cai-Dian Lü et al. , PRD 86 (2012) 074019

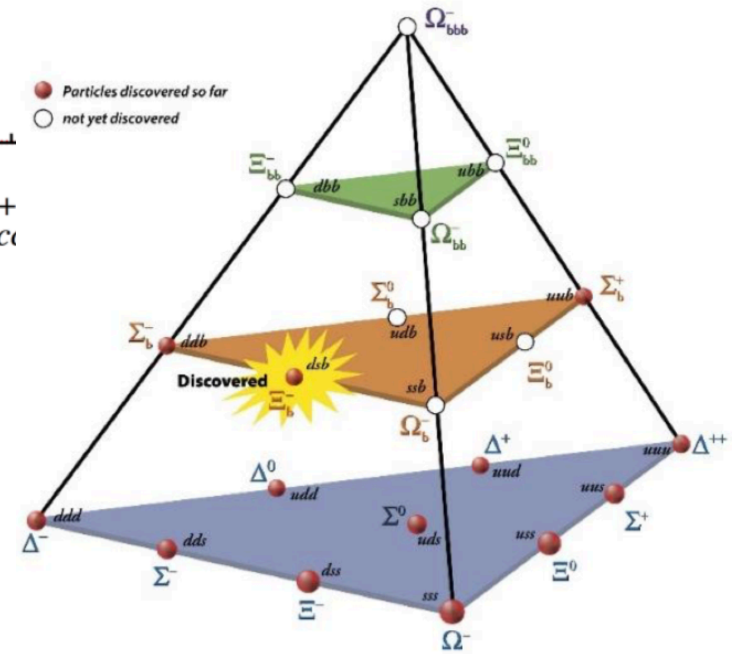
Channel	$\mathcal{B}$	yield ratio
$B_c^+ \to D_s^+ \bar{D}^0$	$(2.3 \pm 0.5) \times 10^{-6}$	$(3.1 \pm 0.9) \times 10^{-7}$
$B_c^+ \to D_s^+ D^0$	$(3.0 \pm 0.5) \times 10^{-6}$	$(4.0 \pm 1.1) \times 10^{-7}$
$B_c^+ \to D^+ \bar{D}^0$	$(32 \pm 7) \times 10^{-6}$	$(1.0 \pm 0.3) \times 10^{-4}$
$B_c^+ \to D^+ D^0$	$(0.10 \pm 0.02) \times 10^{-6}$	$(3.2 \pm 0.9) \times 10^{-7}$

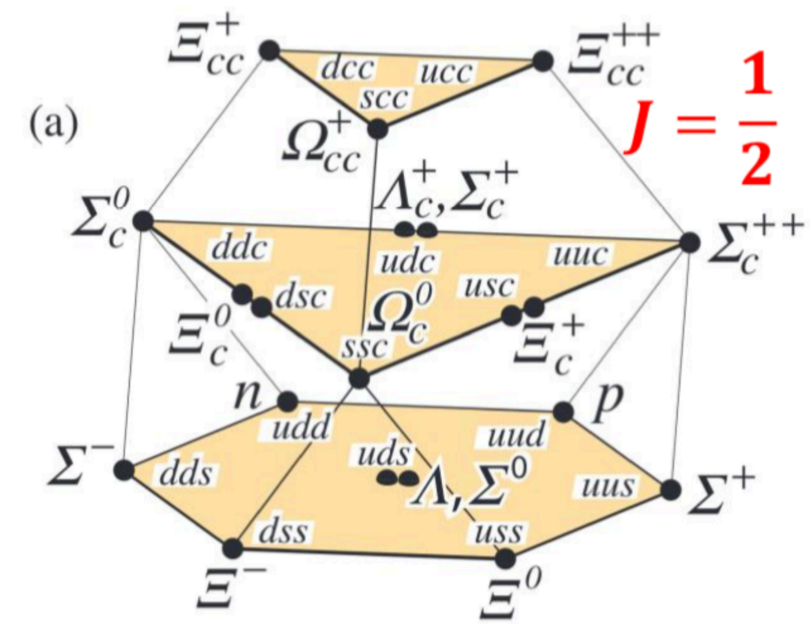
Large difference on BR between different theoretical calculations (theoretical uncertainties)

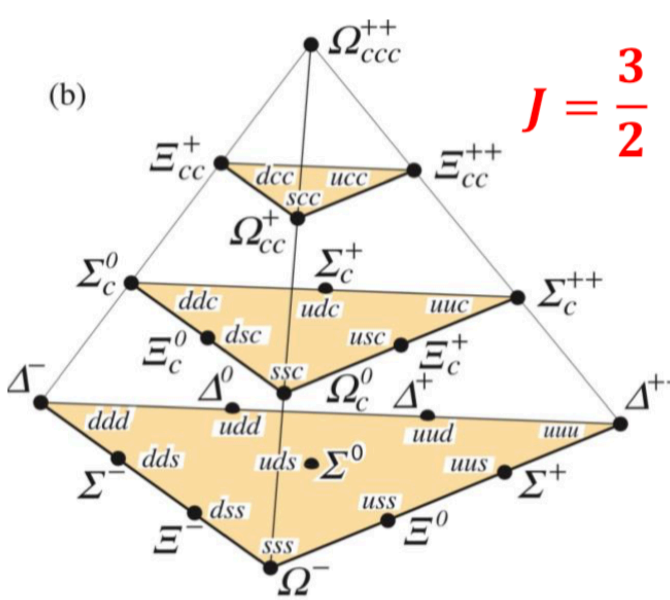
Baryons with 2 or 3 heavy quarks

➢ **One of the most excited results last year: Ξ_{cc}^{++}; wonderful collaboration between theorists and experimentalists in China**







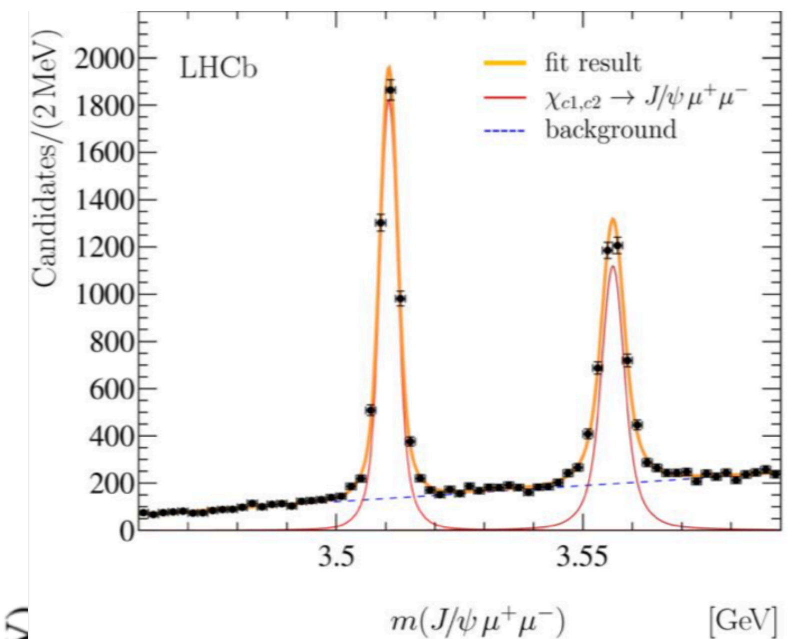


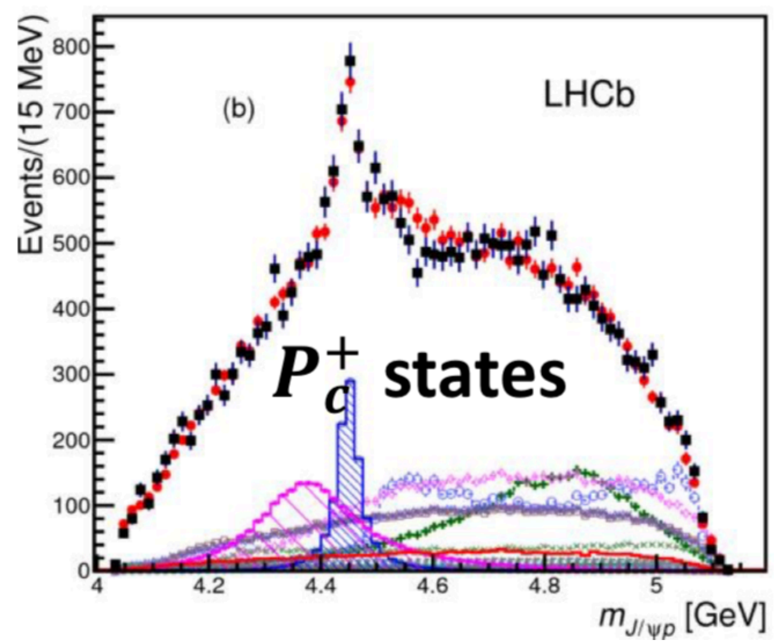
➢ **See Yuehong's talk for more details**

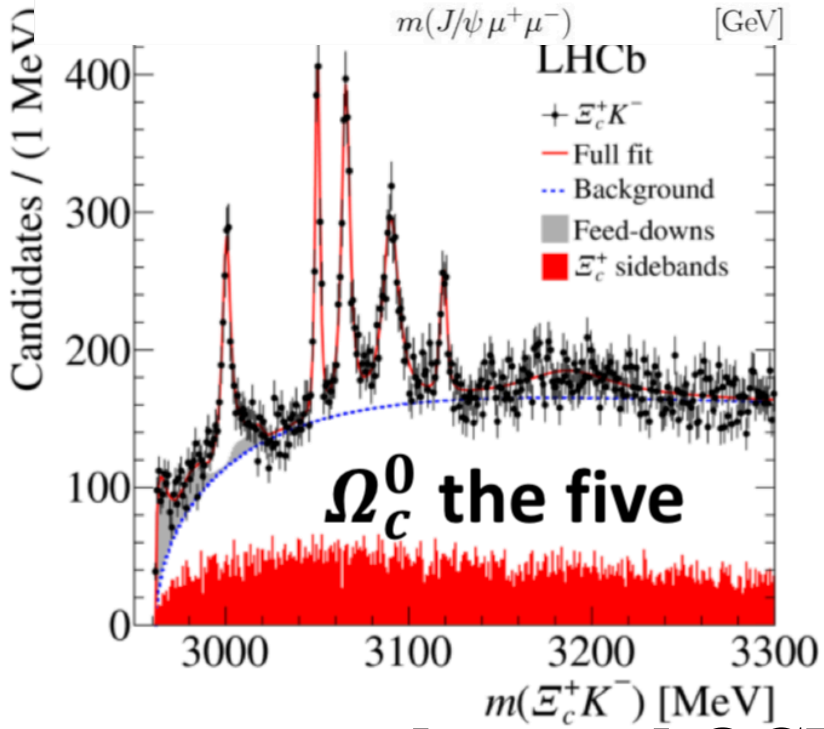
➢ **More baryon states can be found with upgrade data; further collaborations with theoretical community is important**

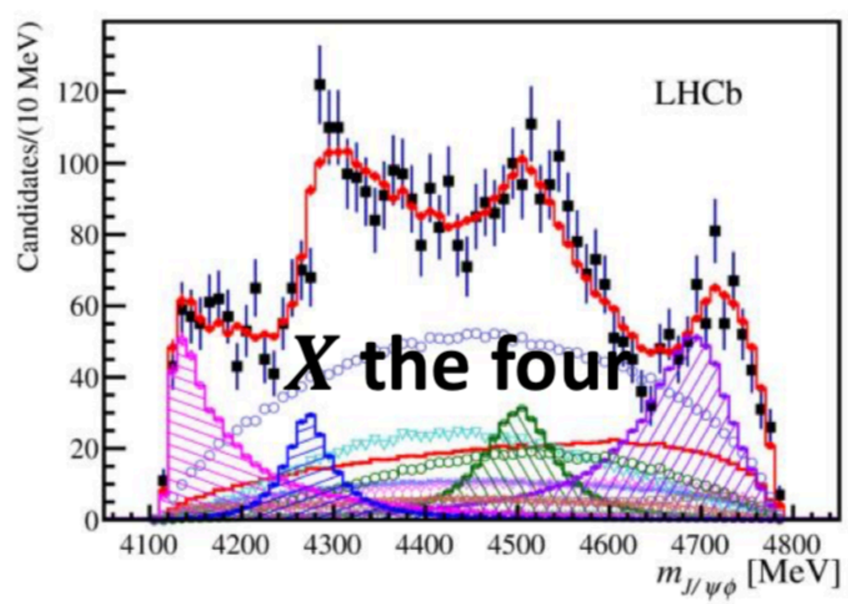
Unexpected discoveries

➢ **One of the most charming part of experiments is to discover unexpected physics (see Yuanning's talk)**







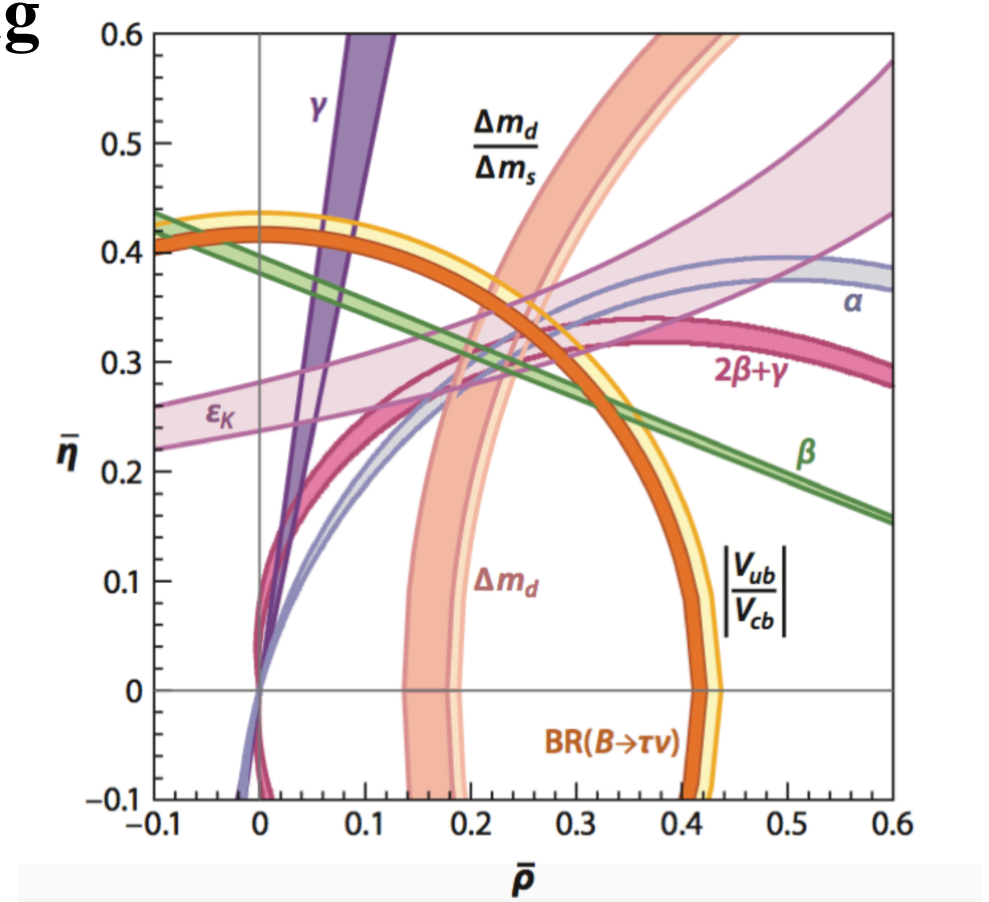


➢ **Spectroscopy: understand QCD at low energy; fill gap between Lagrangian to real resonances**

➢ **For sure, we may have more with upgrade statistics**

Conclusion

- **Physics driven detector upgrade:**
  - **Maintain detector performance in upgrade conditions (50× visible collisions), reduce effects due to 50× tracks**
  - **Broaden LHCb physics reach based on Run 1 + 2 experience**
- **LHCb continues to produce very interesting physic results and try to search for new physics in a broad range of final states**



- **Prospects given mostly based on scaling w.r.t statistic increase**
- **Future is challenging and difficult to predict, but hopefully it is better than prospects**
- **Global scenarios of flavor physics may change with upgrade statistics → collaborations with (Chinese?) theorists are always needed to make sure we are leading these changes**

Backup slides

Physics prospects with upgrade I

Type	Observable	LHCb 2018	**Upgrade** (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s(B_s^0 \to J/\psi\phi)$	0.025	0.008	$\sim$0.003
	$2\beta_s(B_s^0 \to J/\psi\, f_0(980))$	0.045	0.014	$\sim$0.01
	a_{sl}^s	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\overline{K}^{*0})$	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	0.09	0.02	$<$0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.025	0.008	0.02
	$s_0 A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08	0.025	$\sim$0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	8 %	2.5 %	$\sim$10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$\sim$100 %	$\sim$35 %	$\sim$5 %
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	4°	0.9°	negligible
	$\gamma(B_s^0 \to D_s K)$	11°	2.0°	negligible
	$\beta(B^0 \to J/\psi K_S^0)$	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	0.65×10^{-3}	0.12×10^{-3}	–

Upgrade II physics prospects

Topics and observables	Experimental reach	Remarks
EW Penguins		
Global tests in many $b \to s\mu^+\mu^-$ modes with full set of precision observables; lepton universality tests; $b \to dl^+l^-$ studies	*e.g.* 440k $B^0 \to K^*\mu^+\mu^-$ & 70k $\Lambda_b^0 \to \Lambda\mu^+\mu^-$; Phase-II $b \to d\mu^+\mu^-$ $\approx$ Run-1 $b \to s\mu^+\mu^-$ sensitivity.	Phase-II ECAL required for lepton universality tests.
Photon polarisation		
$\mathcal{A}^{\Delta}$ in $B_s^0 \to \phi\gamma$; $B^0 \to K^*e^+e^-$; baryonic modes	Uncertainty on $\mathcal{A}^{\Delta} \approx 0.02$; $\sim 10k$ $\Lambda_b^0 \to \Lambda\gamma$, $\Xi_b \to \Xi\gamma$, $\Omega_b^- \to \Omega\gamma$	Strongly dependent on performance of ECAL.
$b \to cl^-\bar{\nu}_l$ lepton-universality tests		
Polarisation studies with $B \to D^{(*)}\tau^-\bar{\nu}_\tau$; τ^-/μ^- ratios with B_s^0, Λ_b^0 and B_c^+ modes	*e.g.* 8M $B \to D^*\tau^-\bar{\nu}_\tau$, $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ & $\sim 100k$ $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$	Additional sensitivity expected from low-p tracking.
$B_s^0, B^0 \to \mu^+\mu^-$		
$R \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$; $\tau_{B_s^0 \to \mu^+\mu^-}$; CP asymmetry	Uncertainty on $R \approx 20\%$ Uncertainty on $\tau_{B_s^0 \to \mu^+\mu^-} \approx 0.03\,\mathrm{ps}$	
LFV τ decays		
$\tau^- \to \mu^+\mu^-\mu^-$, $\tau^- \to h^+\mu^-\mu^-$, $\tau^- \to \phi\mu^-$	Sensitive to $\tau^- \to \mu^+\mu^-\mu^-$ at 10^{-9}	Phase-II ECAL valuable for background suppression.
CKM tests		
γ with $B^- \to DK^-$, $B_s^0 \to D_s^+K^-$ *etc.*	Uncertainty on $\gamma \approx 0.4°$	Additional sensitivity expected
ϕ_s with $B_s^0 \to J/\psi K^+K^-$, $J/\psi\pi^+\pi^-$	Uncertainty on $\phi_s \approx 3\,\mathrm{mrad}$	in CP observables from Phase-II
$\phi_s^{s\bar{s}s}$ with $B_s^0 \to \phi\phi$	Uncertainty on $\phi_s^{s\bar{s}s} \approx 8\,\mathrm{mrad}$	ECAL and low-p tracking.
$\Delta\Gamma_d/\Gamma_d$	Uncertainty on $\Delta\Gamma_d/\Gamma_d \sim 10^{-3}$	Approach SM value.
Semileptonic asymmetries $a_{\mathrm{sl}}^{d,s}$	Uncertainties on $a_{\mathrm{sl}}^{d,s} \sim 10^{-4}$	Approach SM value for a_{sl}^{d}.
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ with Λ_b^0, B_s^0 and B_c^+ modes	*e.g.* 120k $B_c^+ \to D^0\mu^-\bar{\nu}_\mu$	Significant gains achievable from thinning or removing RF-foil.
Charm		
CP-violation studies with $D^0 \to h^+h^-$, $D^0 \to K_S^0\pi^+\pi^-$ and $D^0 \to K^\mp\pi^\pm\pi^+\pi^-$	*e.g.* 4×10^9 $D^0 \to K^+K^-$; Uncertainty on $A_\Gamma \sim 10^{-5}$	Access CP violation at SM values.
Strange		
Rare decay searches	Sensitive to $K_S^0 \to \mu^+\mu^-$ at 10^{-12}	Additional sensitivity possible with downstream trigger enhancements.