Inter-University Research Institute Corporation
High Energy Accelerator Research Organization

Seminar, November 20th, 2018

LHCb Upgrade II

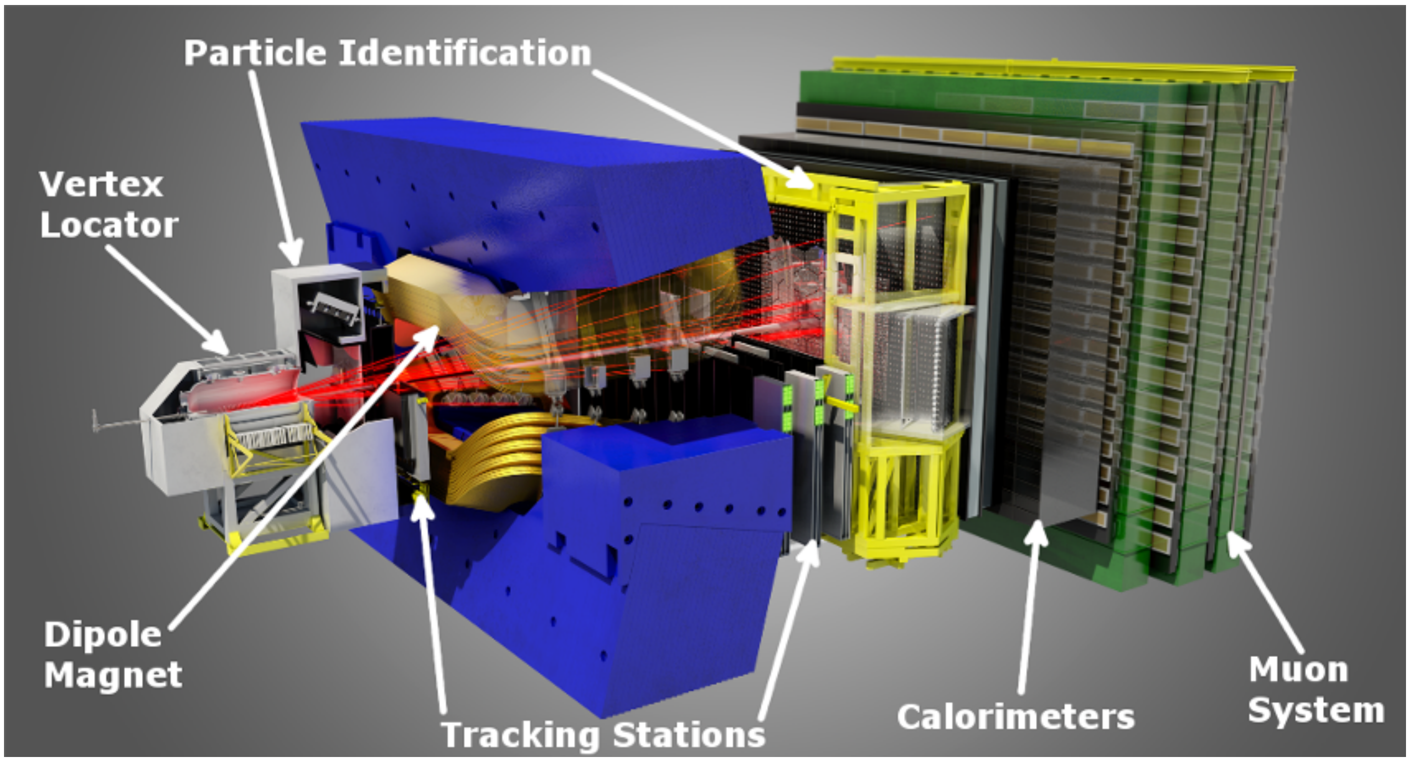
Eugeni Graugés
Universitat de Barcelona
LHCb collaboration

OUTLINE

- Introduction
  - Beauty production at LHC
  - LHCb experiment, dataset & performance
  - LHCb physics programme
- Imminent LHCb Upgrade
- LHCb Upgrade II
  - Physics Case
  - Future detector requirements, R&D and possible solutions
  - Calendar, timeline and global effort
- Summary & Conclusions

Introduction

LHCb: a general purpose spectrometer in the forward direction ($2<\eta<5$), optimized for high-precision heavy-flavor physics.



Performance between 2010-2018:

- Vtx $_{res.}$ 4µm
- $t_{res.}$ 45fs
- $p_{res.}$ 0.6% @ 100 GeV

LHCb Detector performance arXiv:1412.6352; VELO performance arXiv:1405.7808v2

Beauty production at LHC

- σ_{bb} = **154±14μb** @√s=13TeV,

Within the LHCb acceptance

PLB 118,052002 (2017)

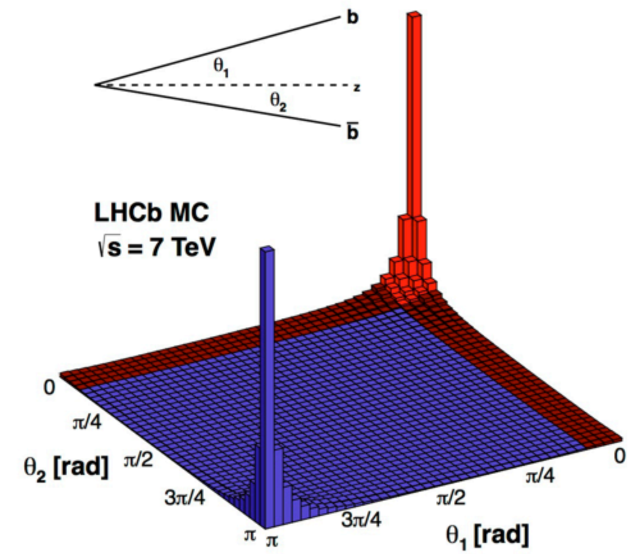
  – All b-hadron species produced at LHC

  B^0, B^+, B_s, B_c, Λ_b, …

  – **Charm: ~ beauty x 20**

JHEP 03(2016)159

gluon-gluon fusion



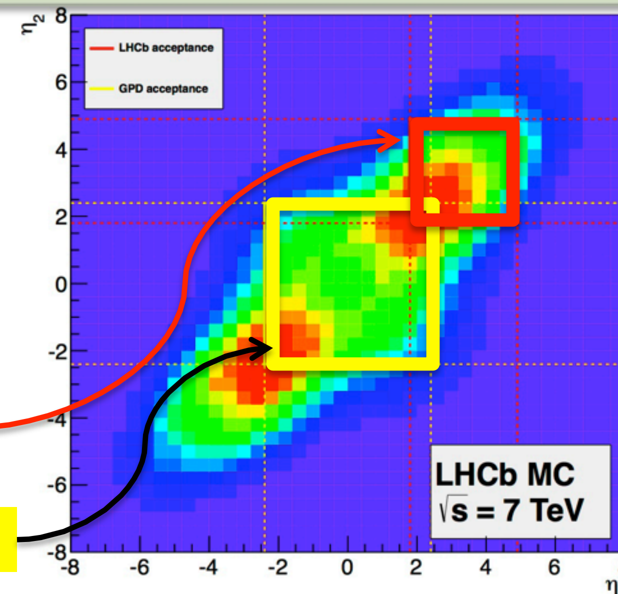
Covers 4% of solid angle (25% of heavy quark mesons).

- Operated since the end of 2011 at

  ~4 · $10^{32}/cm^2$ s (2x design lumi)

  ~ 60KHz (@13TeV) of bb pairs

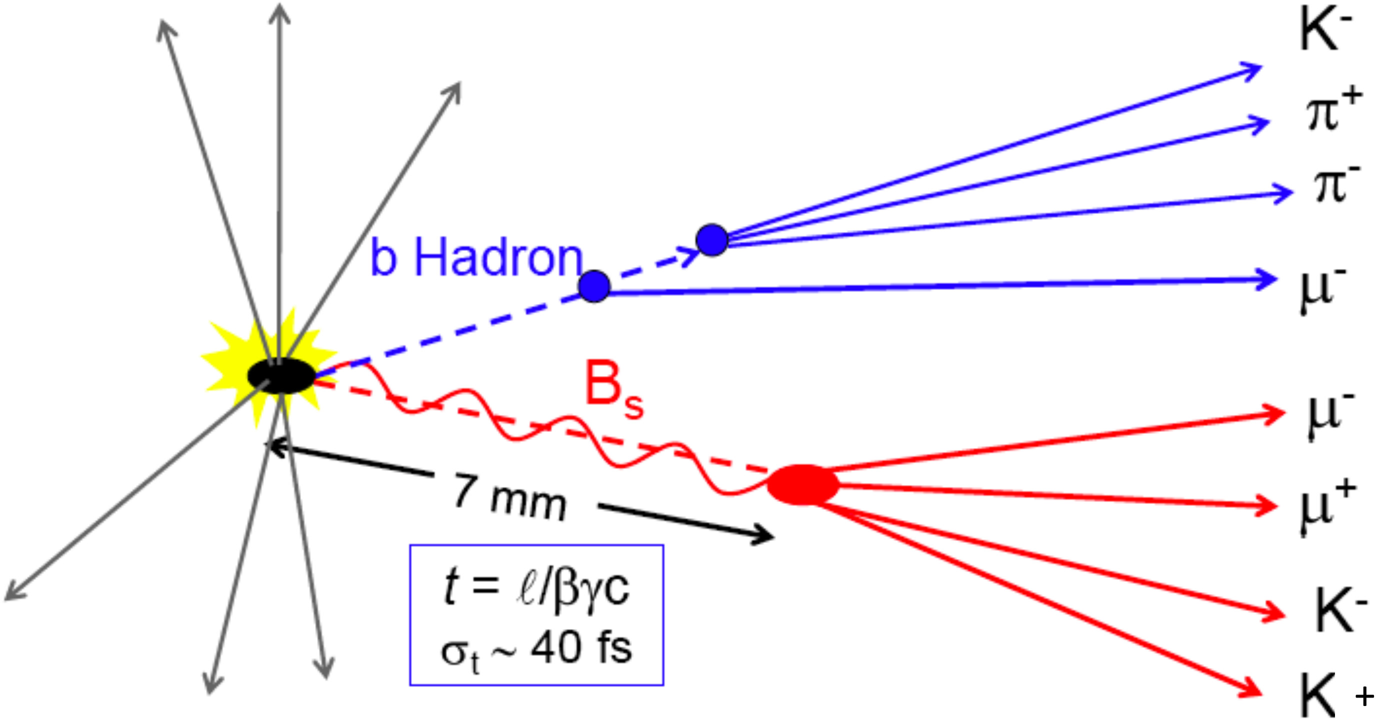
  (10^4 x B factories)



LHCb acceptance: 2<η<5

ATLAS/CMS acceptance: |η|<2.5

Beauty physics requirements @ LHC



- High Statistics: Need an efficient trigger to select hadronic and leptonic B meson decays, specially taking into account $\sigma_{bb}/\sigma_{inel} \sim o(10^{-3})$
- Excellent vertex resolution, to resolve a displaced secondary vertex
- Very good mass resolution, to reduce the background
- Very efficient particle identification (K/π), essential to do flavour physics

… and ALARA pile-up

LHCb dataset & performance

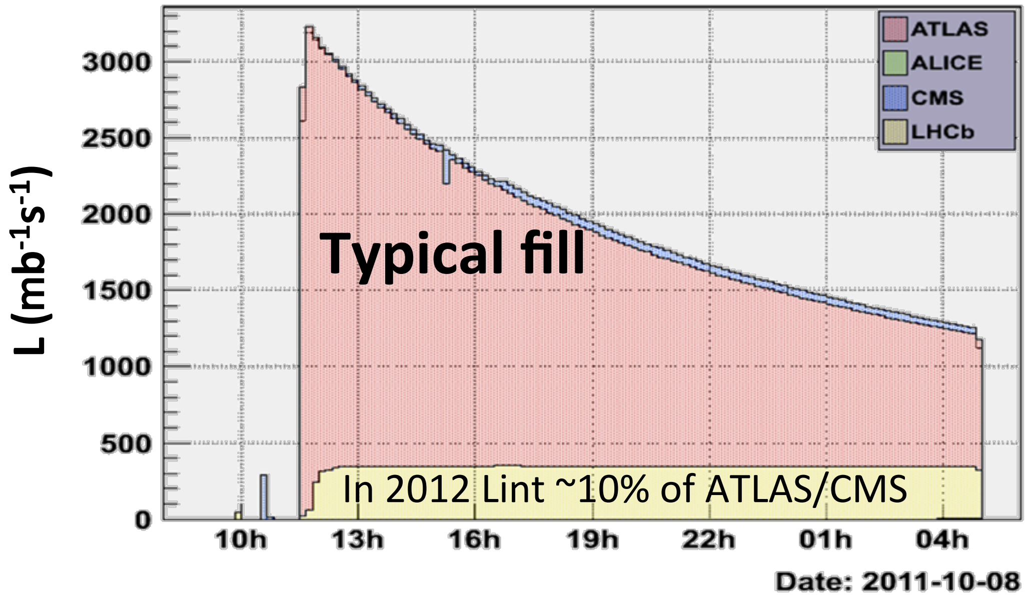
- Great LHC running with $\mathscr{L}$ leveling, with over 10 fb^{-1} delivered Run1+ Run2

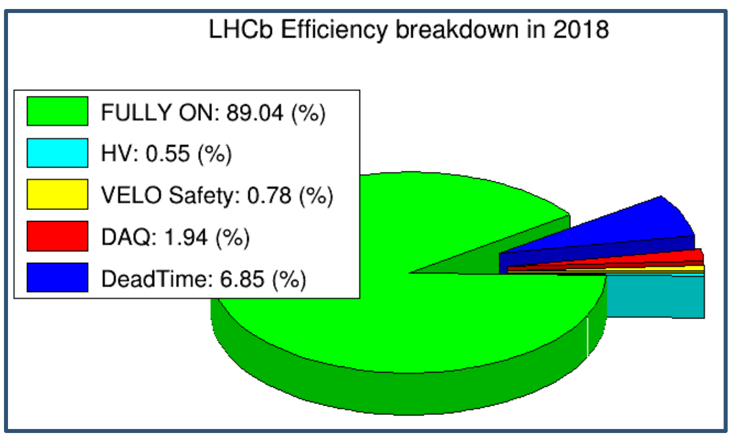
matched by …

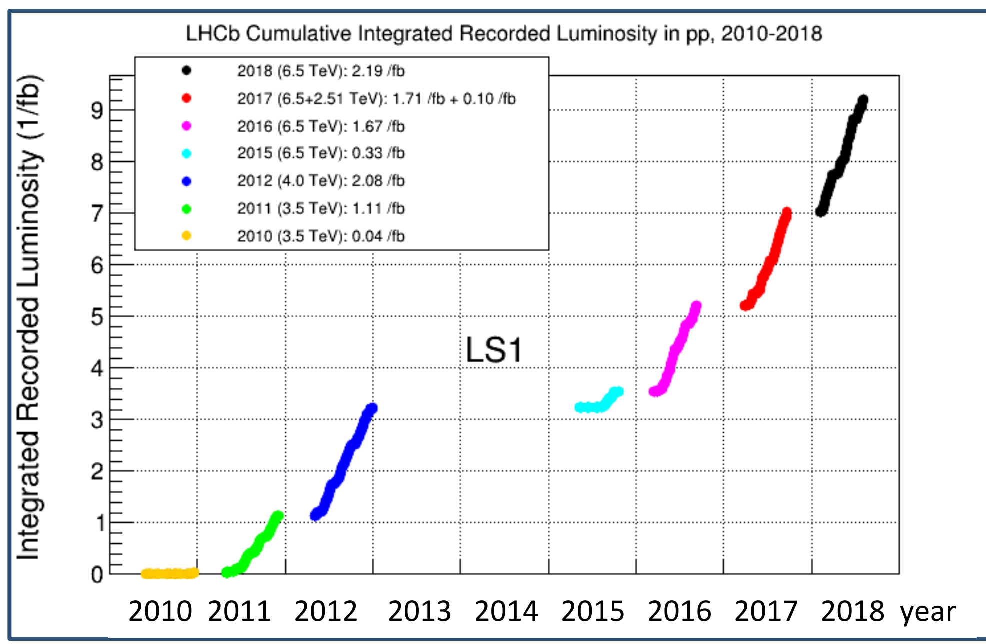
- an excellent performance of LHCb detectors
  - 9 fb-1 recorded

    Run1: 3fb^{-1} @7-8TeV.

    Run2: 6fb^{-1} @13TeV.

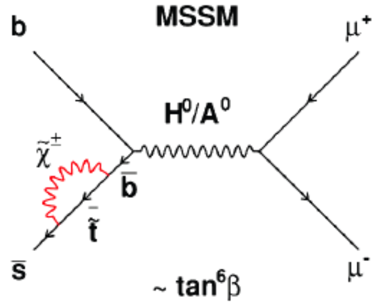


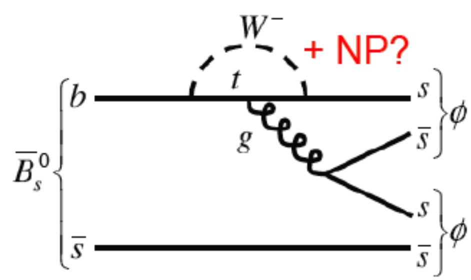


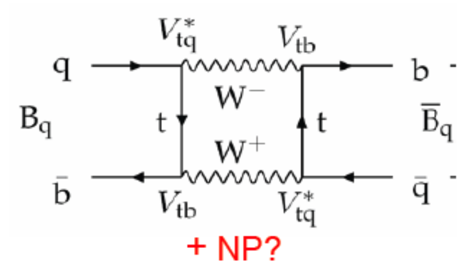


The LHCb physics programme

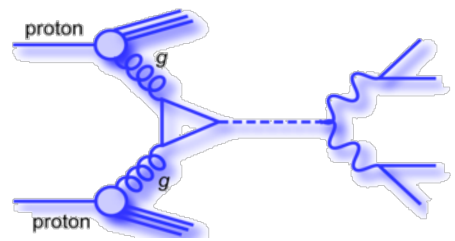
- **New Physics (NP)** evidence may appear both in measurements of CP violation and rare decays, mediated by new particles (via their contributions in loop diagrams); e.g.: Comparing CKM quantities determined in tree & loop process







- Complementary to **ATLAS & CMS** direct searches
  – If NP is discovered, its structure must be determined



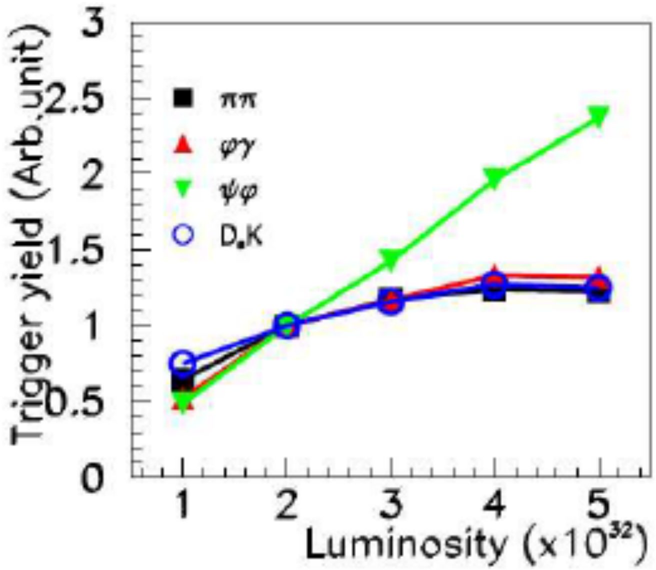
- **New particles would distort the SM (CKM) picture of B decays by modifying:**
  – **Phases** CP violation
  – **Amplitudes** ⇔ Branching ratios
  – **Lorentz Structure** Angular distributions

Imminent LHCb Upgrade

- Excellent results from Run-I and (partial) Run-II physics data analysis.

BUT….

- Precision limited by statistical uncertainties.
  – Hardware trigger at FE limited @ 1.1MHz rate.
  – Stern p_T and E_T cuts saturate hadronic channels.



in addition…

LHCB-TDR-012

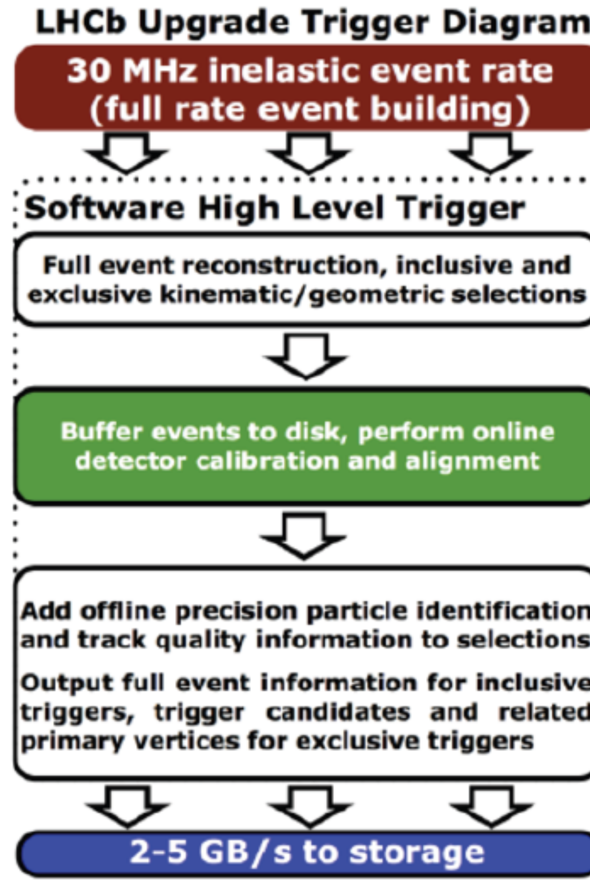
CERN-LHCC-2011-001

- At higher lumis the current LHCb could not perform successfully track reconstruction
  - Much higher track/primary vertex multiplicity
  - Processing time in the online farm too high
- Designed to survive **5y** (at ½ lumi), so radiation hardness would start to become an issue

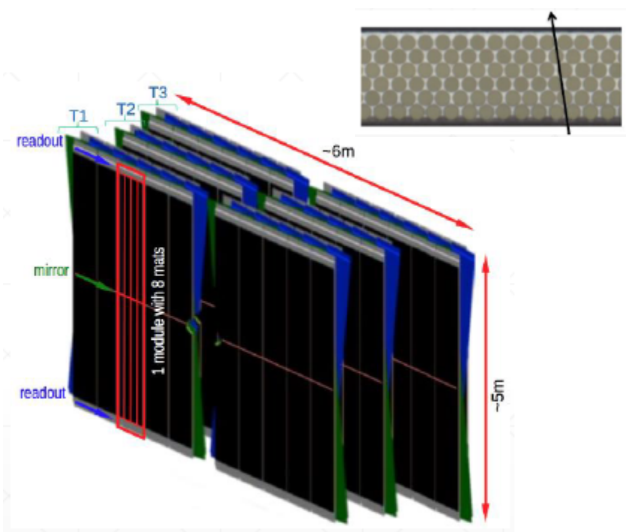
An Upgrade of the LHCb detector is the answer …

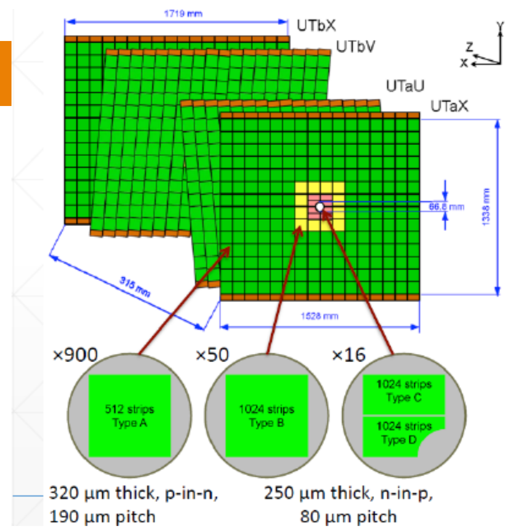
Imminent LHCb Upgrade

- Allows for a Factor 5 luminosity increase, by means of :
  - New flexible fully-software trigger system.
    – Trigger-less 40MHz readout in all sub-detectors.
    – Fully informed trigger with complete reconstruction.
  - New SciFi Tracker downstream from the magnet.
  - Finer sensors: VeLo(pixel), UT(strip), RICH(MaPMT).



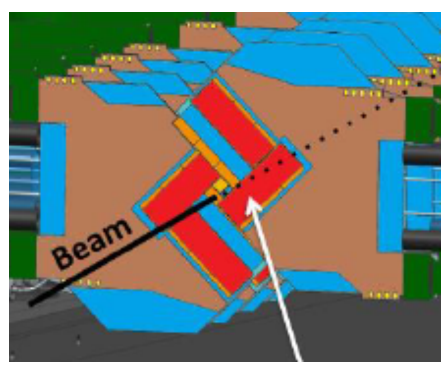
SciFi & UT (LHCB-TDR-015)





CERN-LHCC-2014-016

VELO-II (LHCB-TDR-013)



PID Upgrade(LHCB-TDR-014)

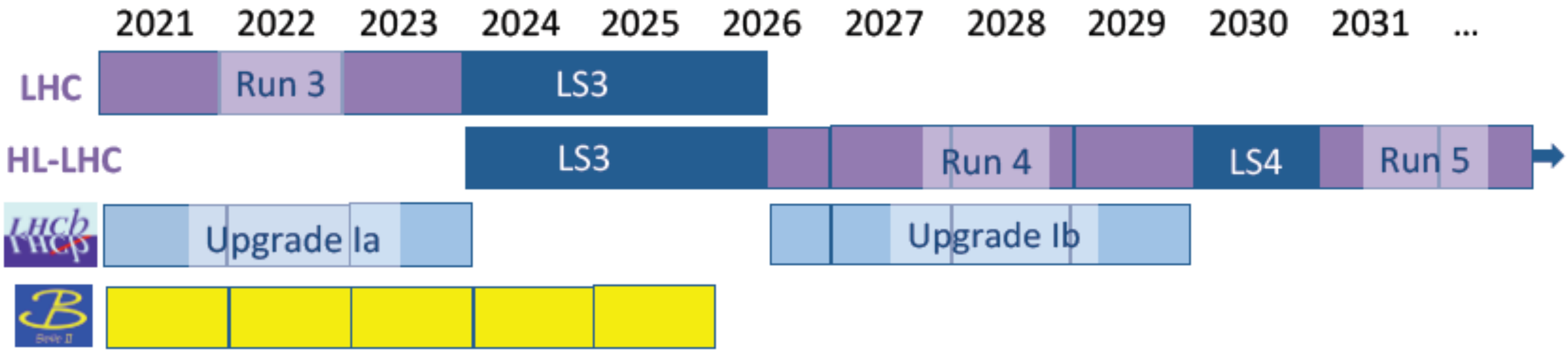
Imminent LHCb Upgrade

PHYSICS PROSPECTS (Table from the LHCB-TDR-012, current estimates are better)

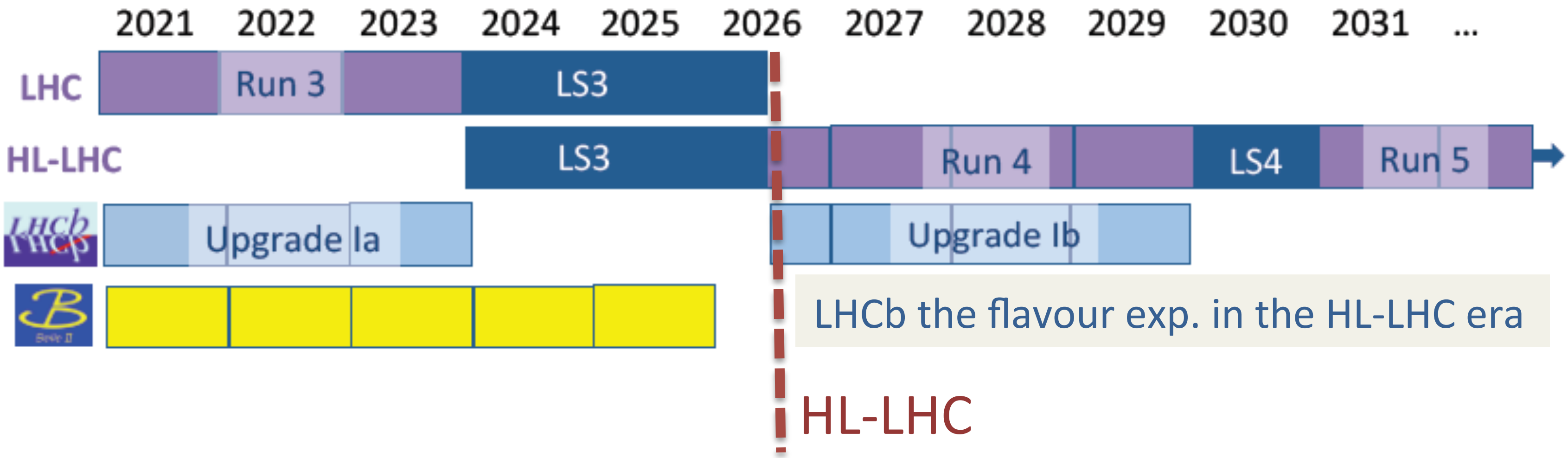
Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\text{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–$12°$ [19, 20]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [18]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

LHCb Upgrade to take data during LHC RUN3 & Run4 until LS4 in 2030

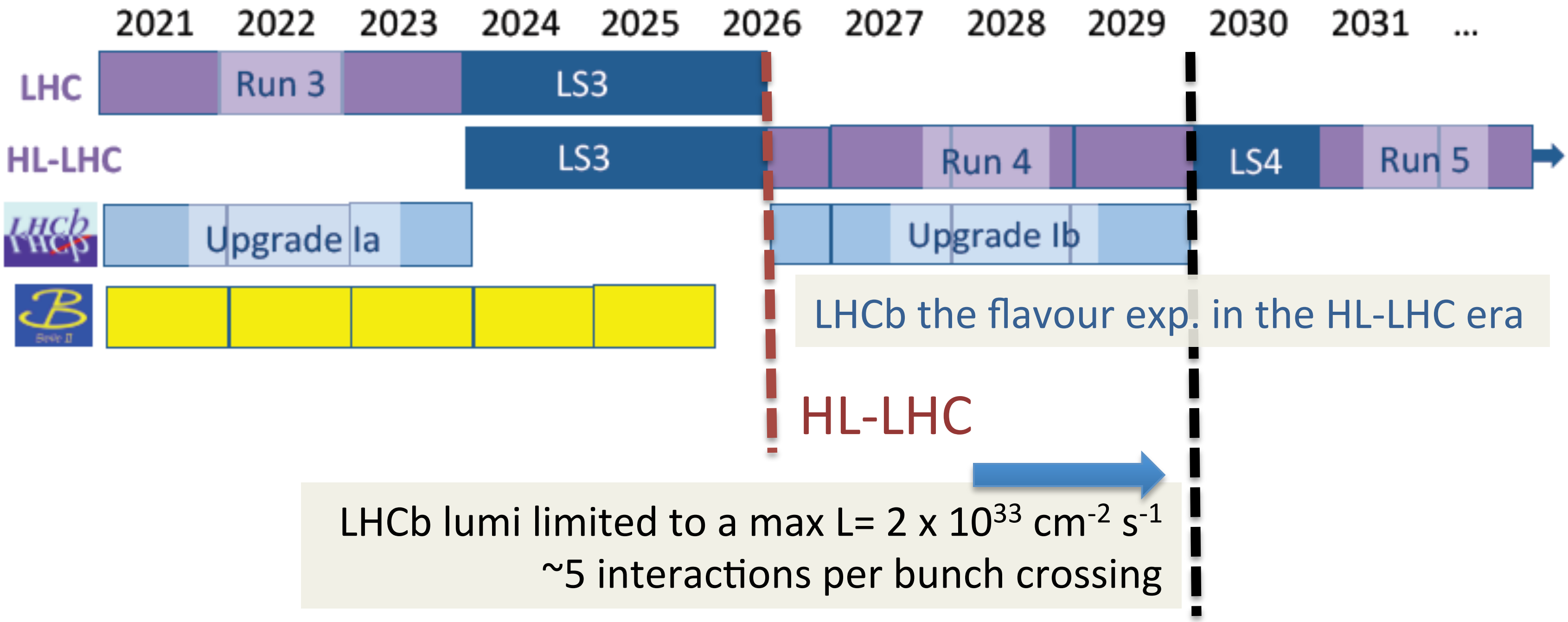
LHCb Calendar



LHCb Calendar

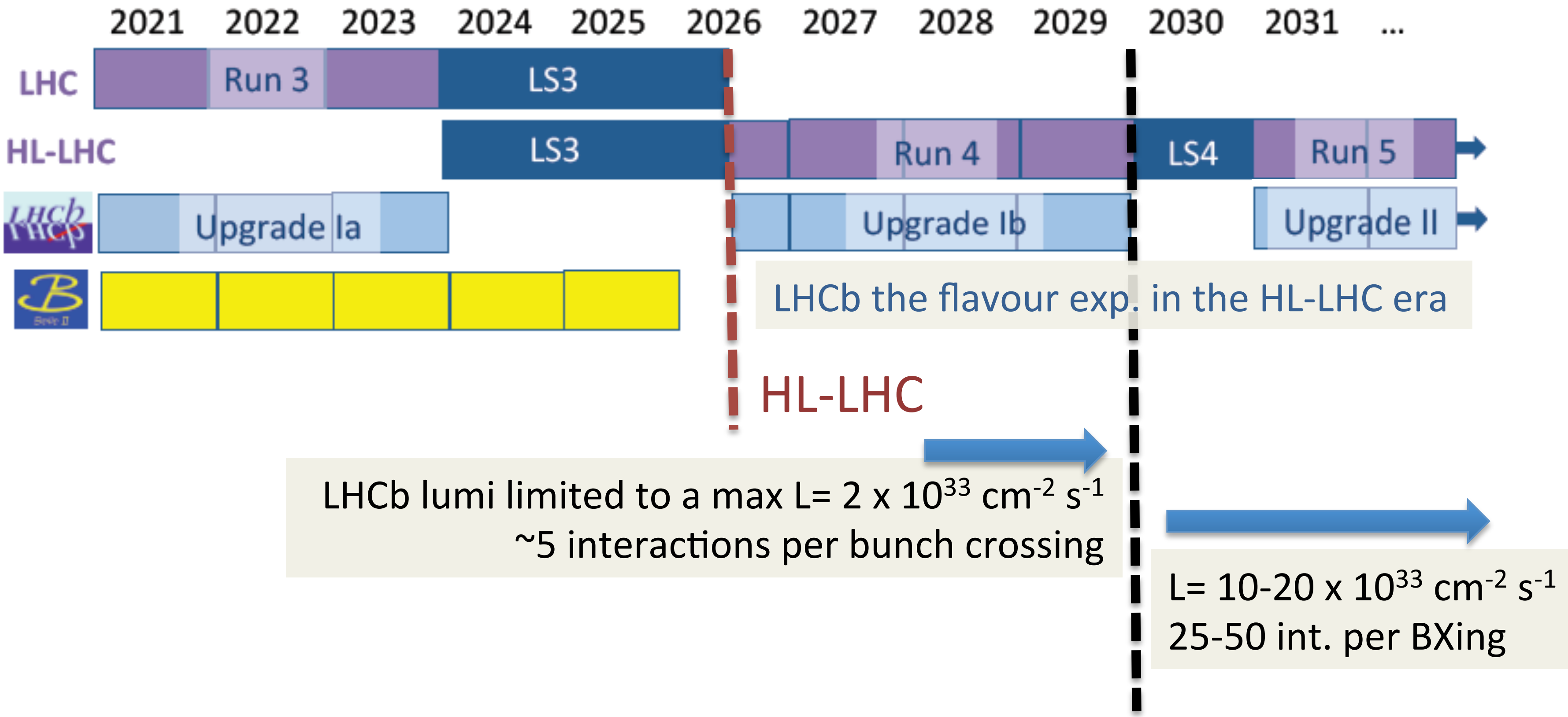


LHCb Calendar

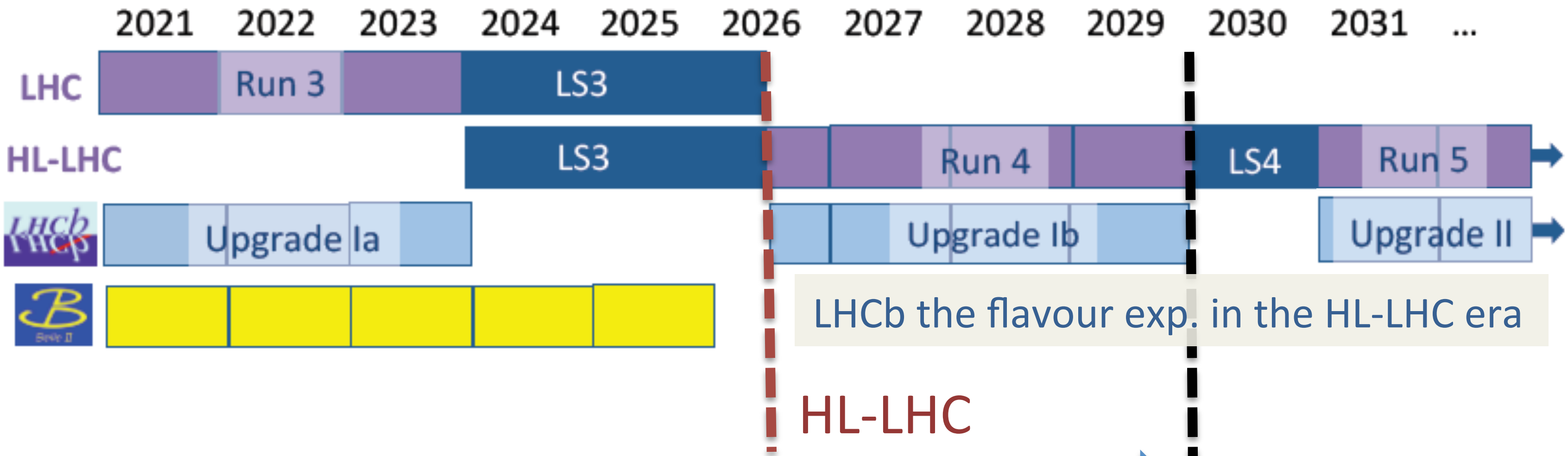


LHCb lumi limited to a max L= 2 x 10^{33} cm^{-2} s^{-1}
~5 interactions per bunch crossing

LHCb Calendar

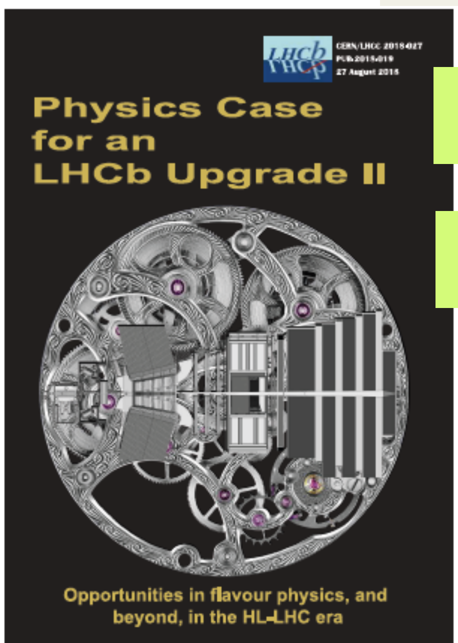


LHCb Calendar



LHCb lumi limited to a max L= 2 x 10^{33} cm^{-2} s^{-1}
~5 interactions per bunch crossing

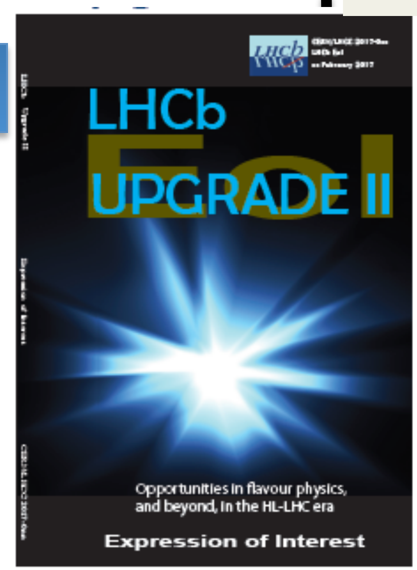
L= 10-20 x 10^{33} cm^{-2} s^{-1}
25-50 int. per BXing



PHYSICS CASE
[LHCB-PUB-2018-009]

HL-LHC machine study
CERN-ACC-NOTE-2018-0038

LHCC asked to address



Expression of Interest 2017
[CERN-LHCC-2017-003]

LHCb Upgrade II Physics Case

[LHCB-PUB-2018-009] arXiV:1808.08865

PHYSICS TOPICS ADDRESSED:

(assuming a sample of 300/fb of data)

- Time dependent CPV
- Time integrated CPV
- Unitarity Triangle & semi-lept.
- Mixing and CPV in Charm
- Rare Decays
- Forward and high p_T Physics
- Exotic hadrons and Spectroscopy

- Appendix on:

Heavy Ions, Fixed target, long-lived particles

LHCb Upgrade II Physics Case

Summary of Results:

[LHCB-PUB-2018-009] arXiV:1808.08865

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 detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0\to\mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Integrated Lumi 9/fb 23/fb 300/fb

LHCb Upgrade II Physics Case

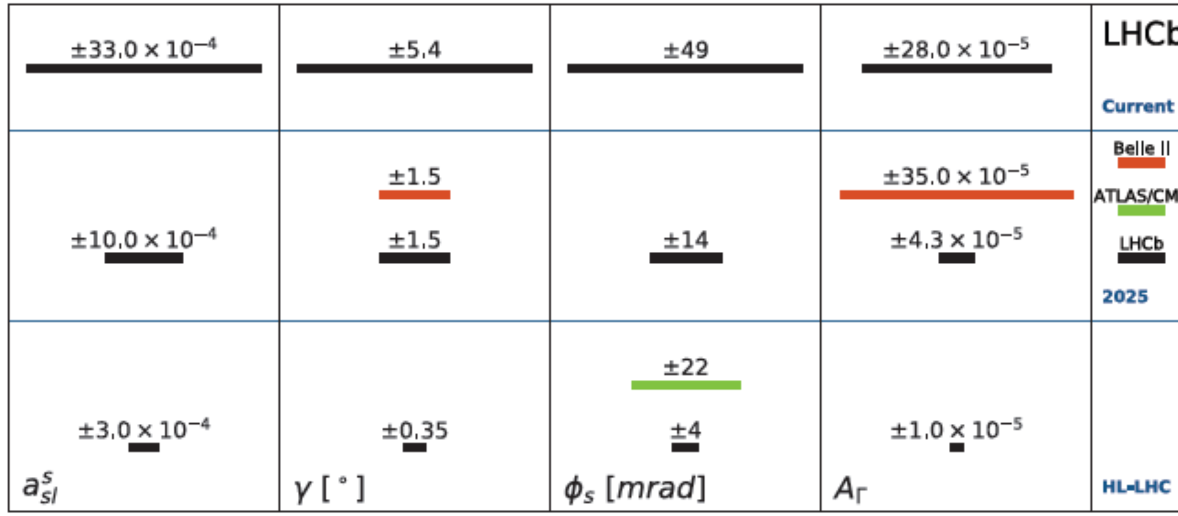
Summary of Results: [LHCB-PUB-2018-009] arXiV:1808.08865

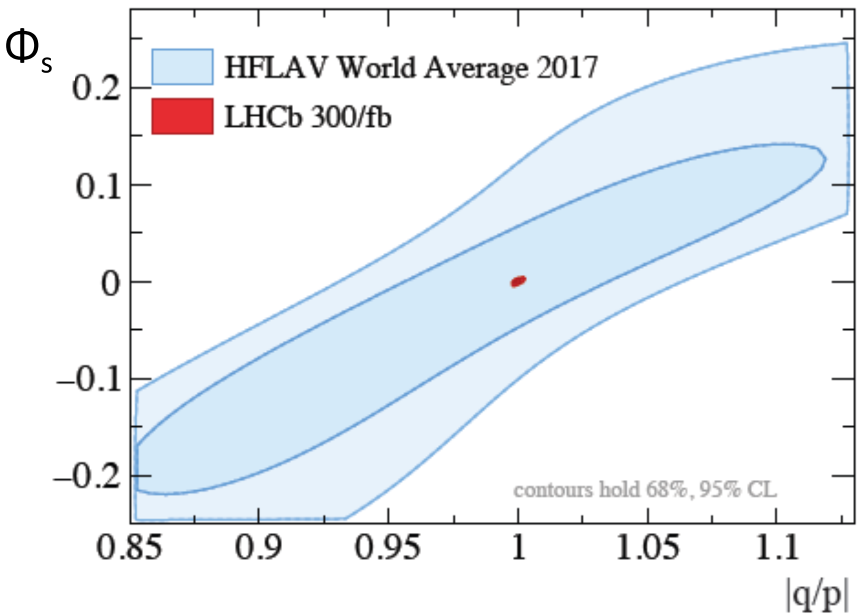
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\text{GeV}^2c^4)$	0.1 [274]	0.025	[illegible]	0.007	–
R_{K^*} $(1 < q^2 < 6\,\text{GeV}^2c^4)$	0.1 [275]	0.031	[illegible]	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	[illegible]	–	[illegible]	–
γ, all modes	[illegible]	1.5°	[illegible]	[illegible]	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	[illegible]	0.011	[illegible]	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	[illegible]	[illegible]	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	[illegible]	[illegible]	–	[illegible]	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	[illegible]	Under study [611]
a_{sl}^s	33×10^{-4} [211]	[illegible]	–	[illegible]	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	[illegible]	3%	[illegible]	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	[illegible]	–	2%	–
$S_{\mu\mu}$	–	[illegible]	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	[illegible]	0.0072	0.005	0.002	–
$R(J/\psi)$	[illegible]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

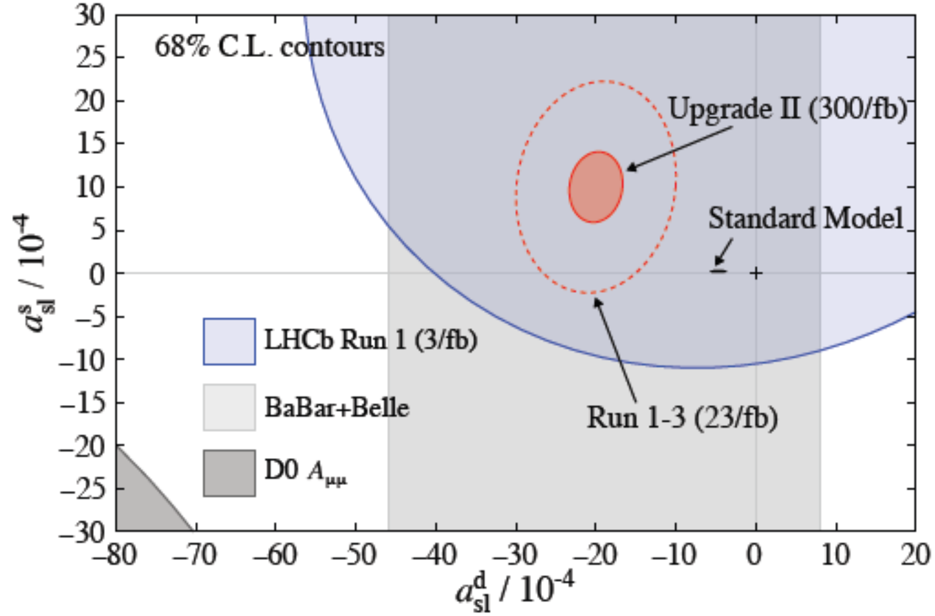
Let's review some of these channels with more details

Physics Case: CP Violation

- γ: 0.4°
- ϕ_s: 4 mrad
- Charm CPV: $O(10^{-5})$

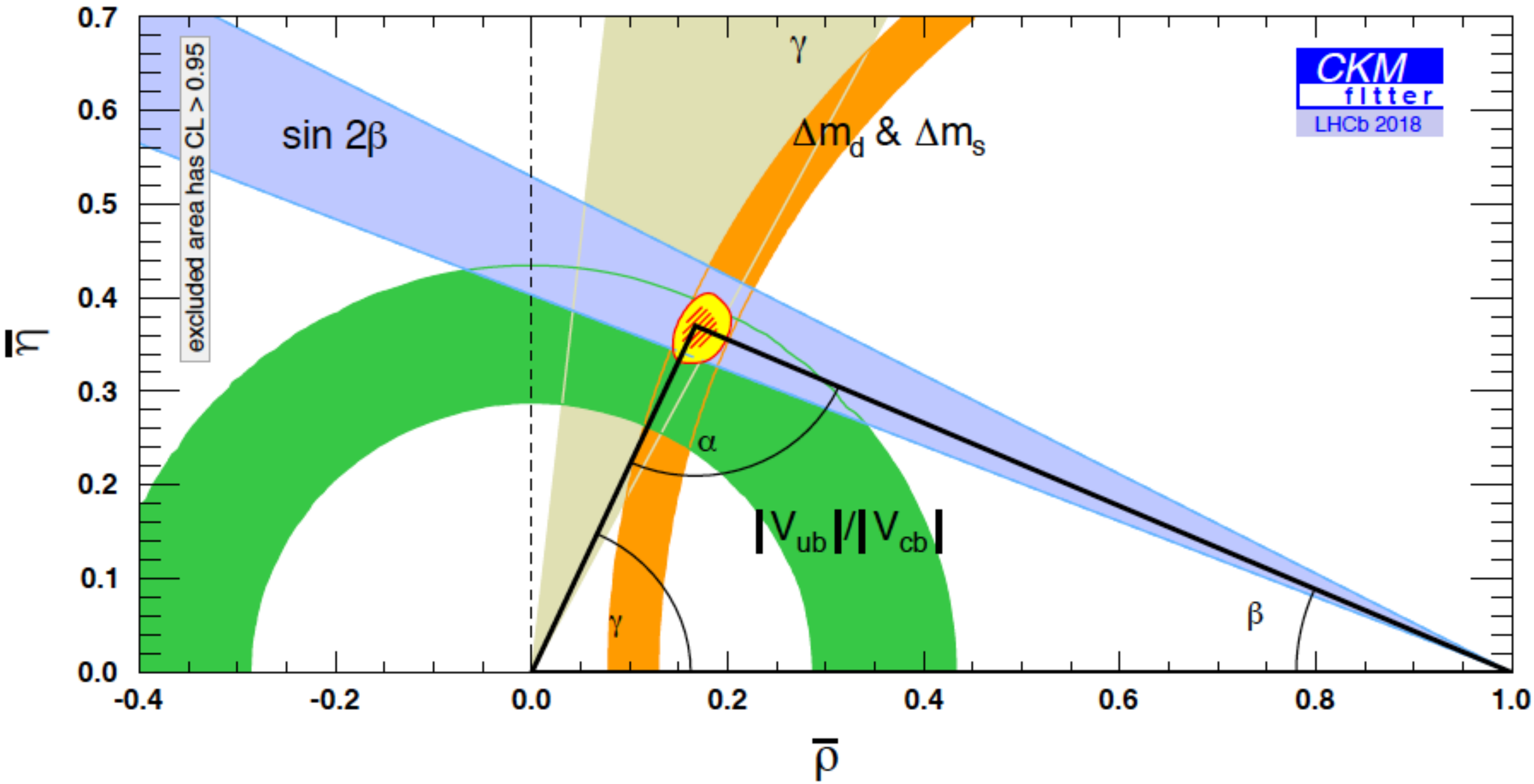






[LHCB-PUB-2018-009] arXiV:1808.08865

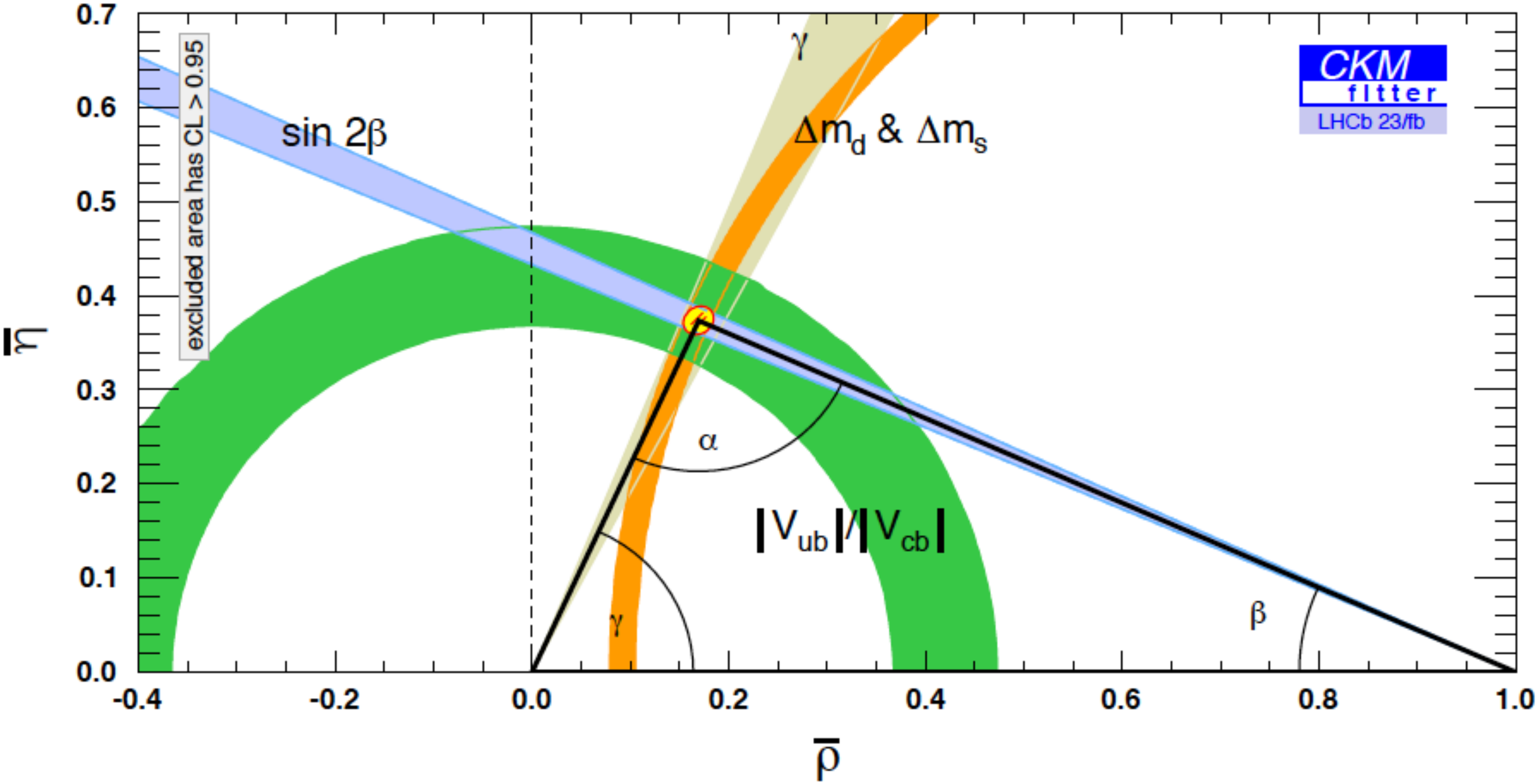
Current (LHCb only) Unitarity Triangle



[LHCB-PUB-2018-009] arXiV:1808.08865

Pre-HL-LHC (LHCb only) Unitarity Triangle

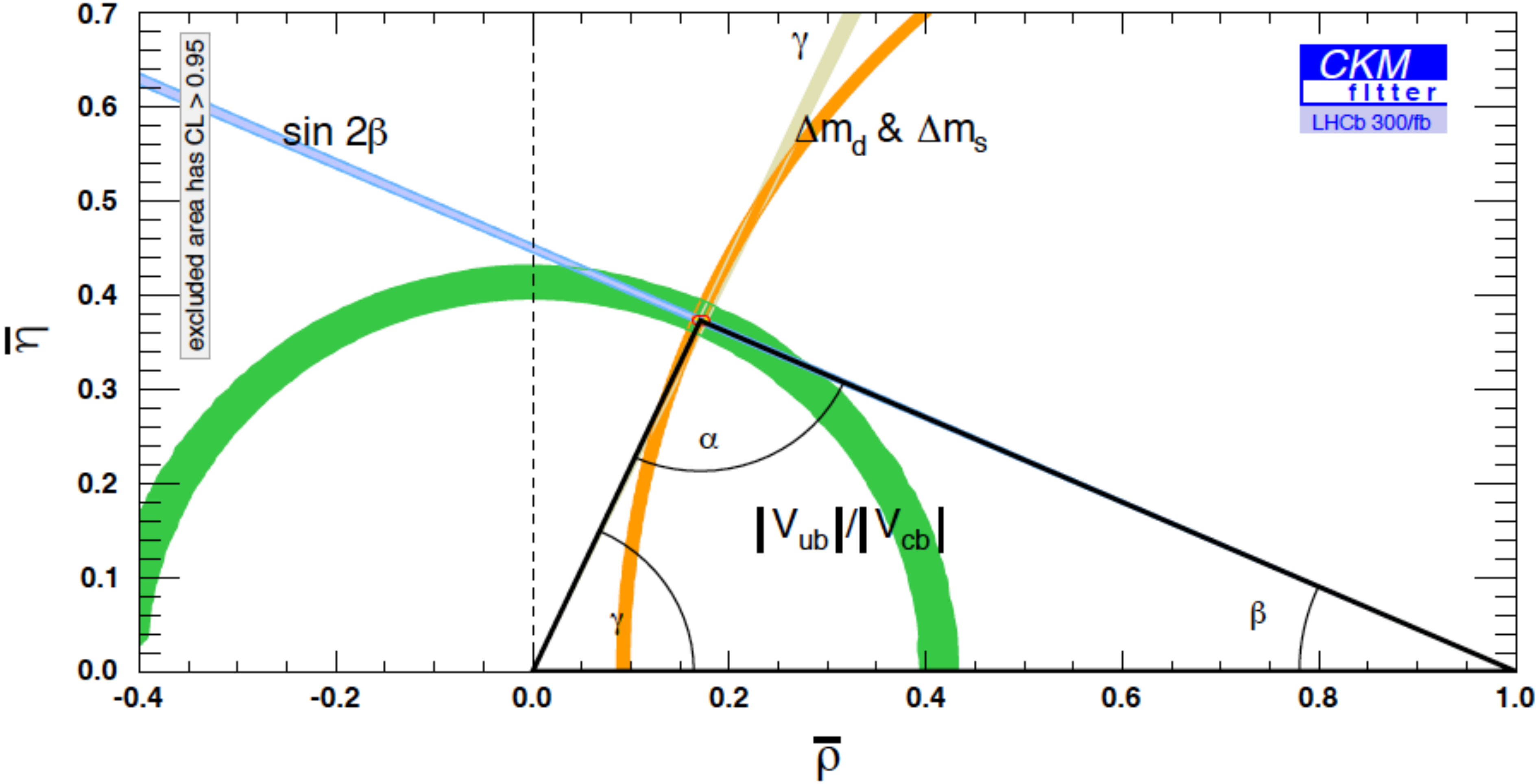
Lattice QCD assumptions from theory community



[LHCB-PUB-2018-009] arXiV:1808.08865

Post-HL-LHC (LHCb only) Unitarity Triangle

Lattice QCD assumptions from theory community



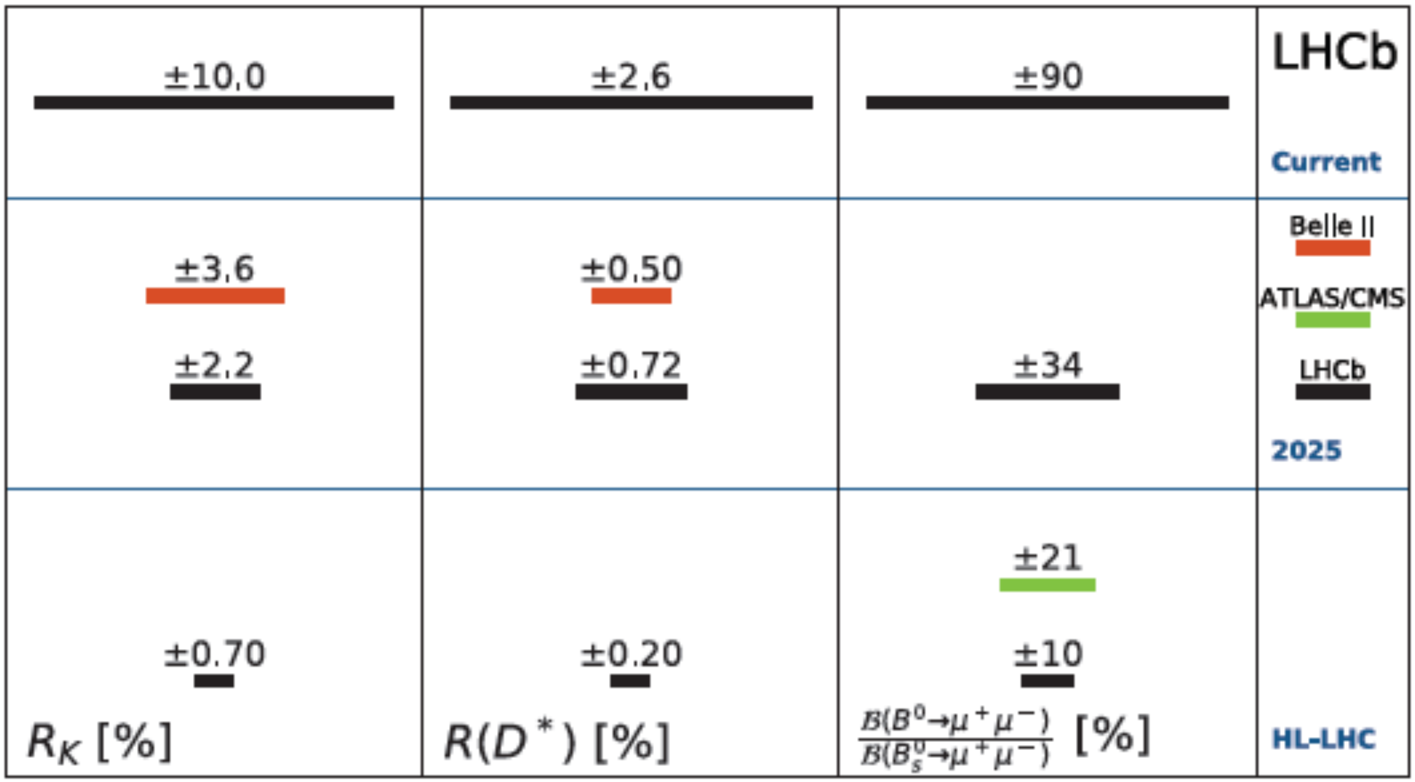
Permit tree-level observables (SM benchmarks) to be assessed against loop contributions (new physics sensitive)

[LHCB-PUB-2018-009] arXiV:1808.08865

Physics Case: Rare decays

- Wide range of observables in b→s/d l^+l^-
- Down to a 10% precision on

$$R \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$$



[LHCB-PUB-2018-009] arXiV:1808.08865

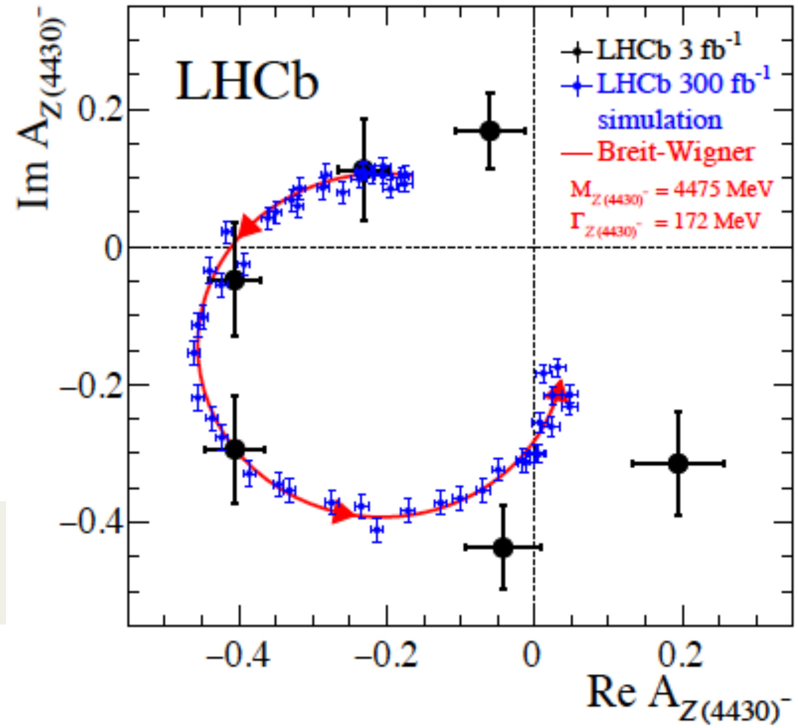
Physics Case: Forward GPD

- Spectroscopy:

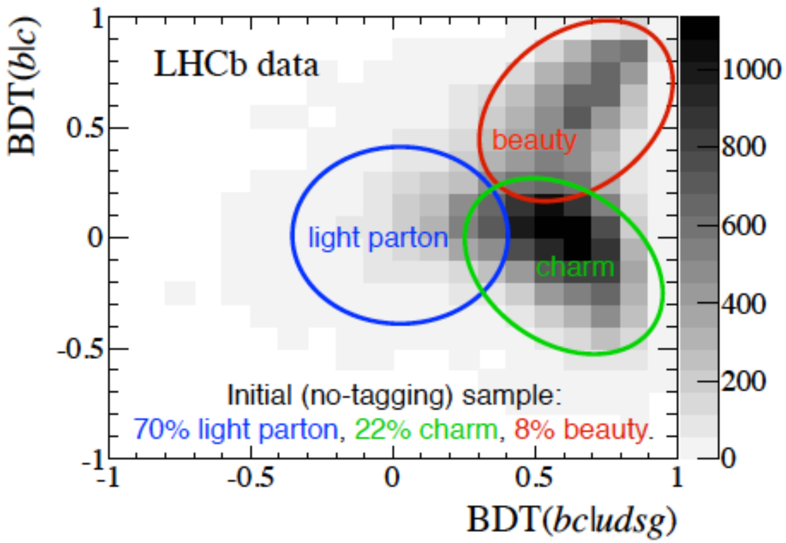
  New discovery opportunities

- Potential best Higgs to charm limits @ LHC

Argand plot $Z(4430)^-$ from $B \rightarrow \Psi(2s)\, K^+\pi^-$



SV-tagger BDT separates b and c for the sub-leading versus leading jet for $pp \rightarrow VH(bb,cc)$, where V=Z, W



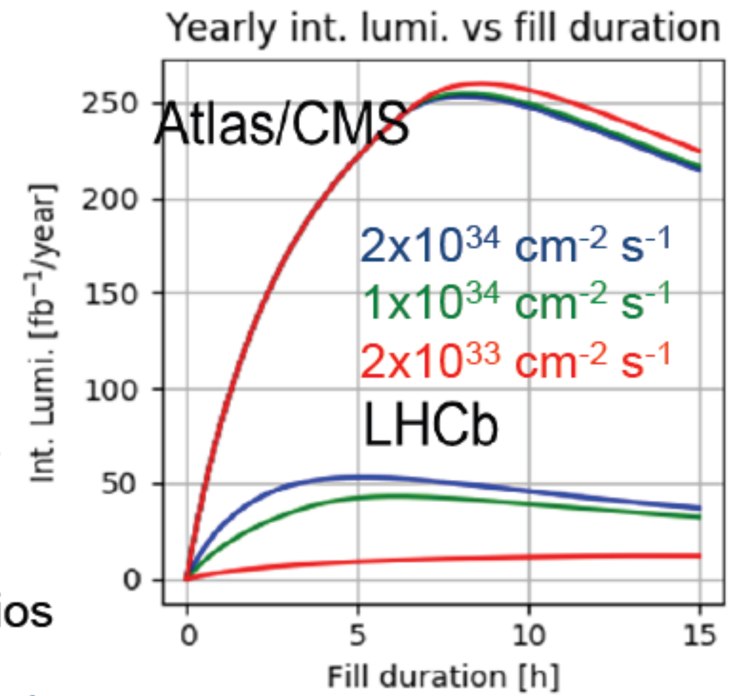
[LHCB-PUB-2018-009]
arXiV:1808.08865

HL-LHC machine consideration

- "LHCb Upgrades and operation at 10^{34} cm^{-2} s^{-1} luminosity –A first study":

"identified a range of potential **solutions**…permitting the collection of **300 fb^{-1}** or more"

Accelerator elements for modification:
Absorbers, Collimators, Cryogenics, Shielding…



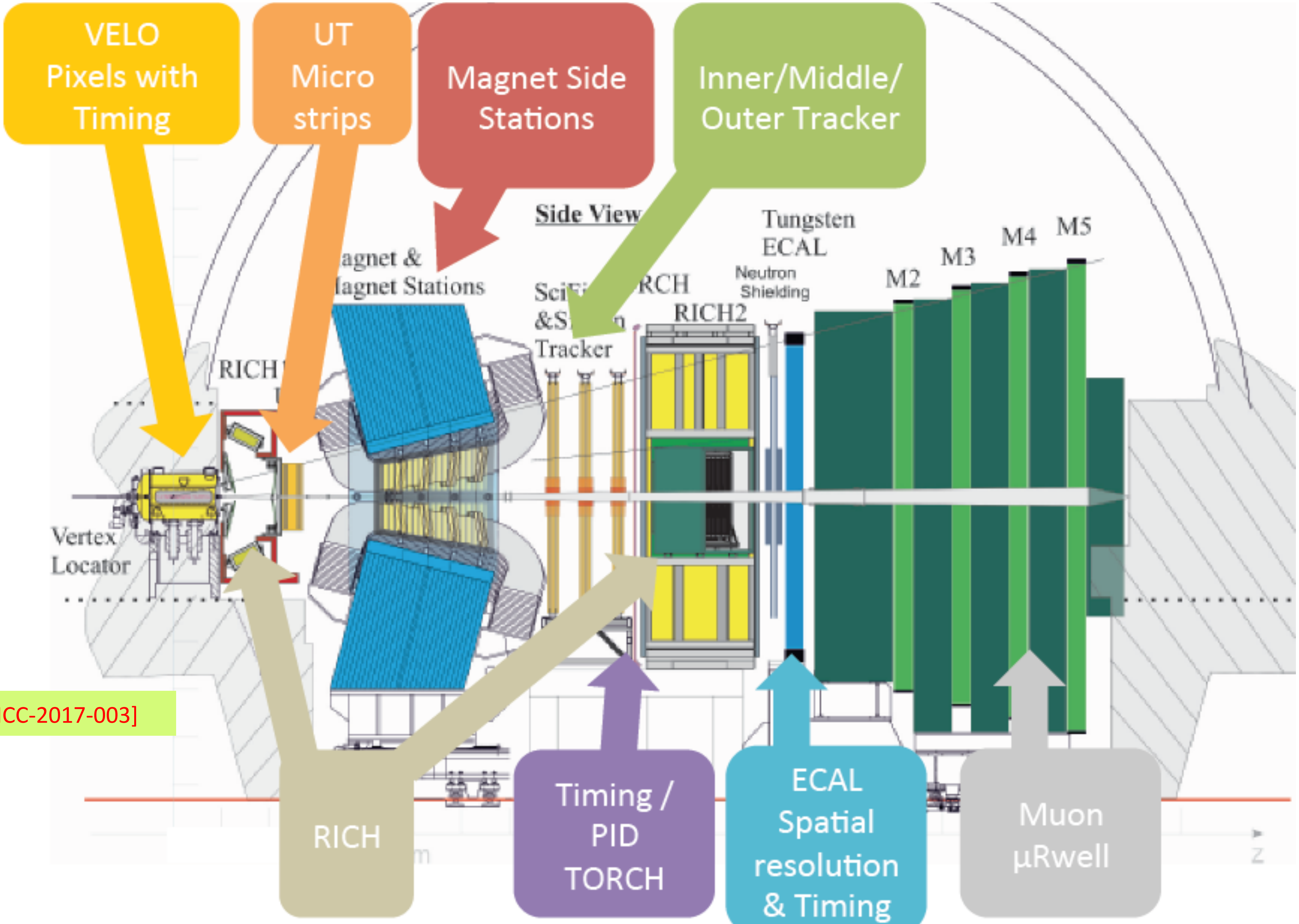
Examples of HL-LHC LHCb operational scenarios

L /yr LHCb	62	46	51	[fb^{-1}]
L /yr ATLAS/CMS	255	257	256	
Beta*	1.5	1.5	1.5	[m]
Crossing Plane	H	H	V	Horizontal/Vertical
Magnet Polarity	-	+	±	

- **2-3% effect on *L* at ATLAS-CMS**
- **Field reversal used for CPV systematics**

… and to do that a new detector is needed

LHCb Upgrade II detector



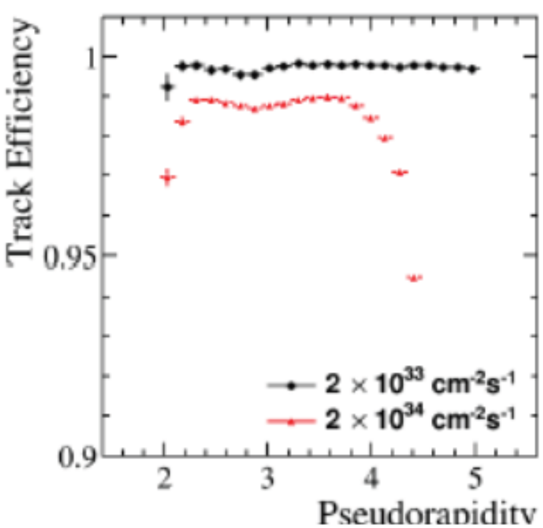
[CERN-LHCC-2017-003]

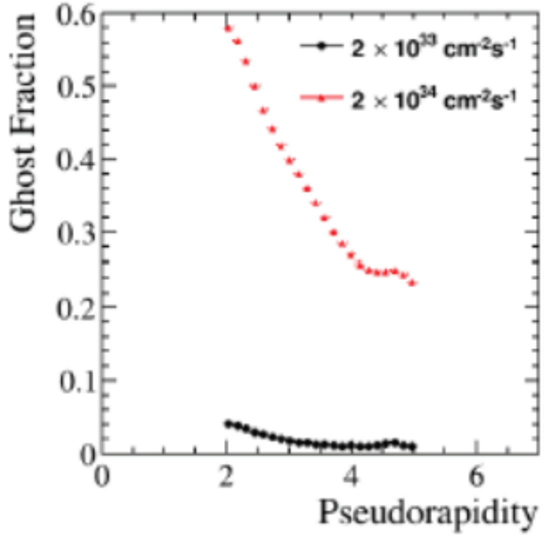
Upgrade II: VeLo Chanllenges

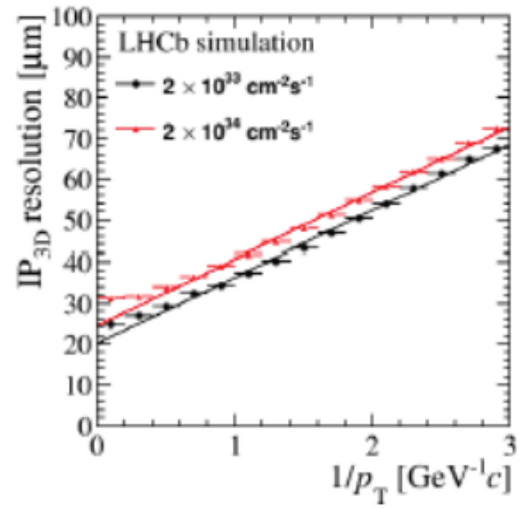
- Phase II Upgrade must deliver the same quality performance as Upgrade I, with
  - 10 x higher particle multiplicity
  - 10 x higher radiation damage
  - 10 x higher data-out rates
  - 10 x denser primary vertex environment

> This is the intensity frontier!
> The **only** potential viable solution lies with hybrid pixels; even before any considerations of timing/physics

- With no hardware intervention the detector will be unable to survive the rates or integrated doses at Phase II - upgrade of sensors, ASICs and mechanics are needed
- Additional improvements - in particular timing info - also needed to maintain physics performance at Phase II



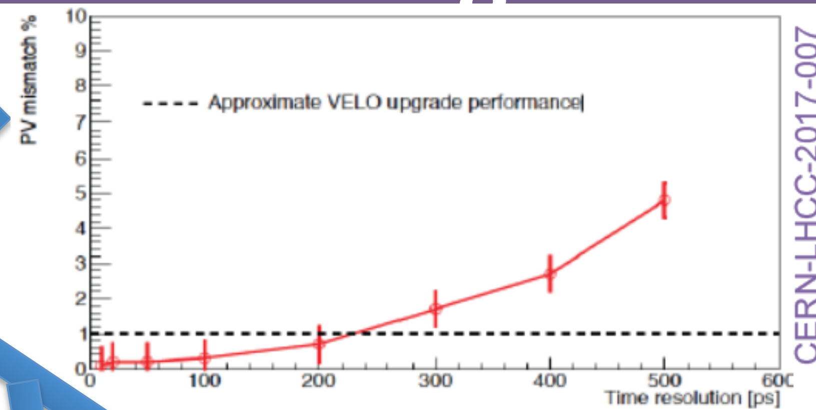




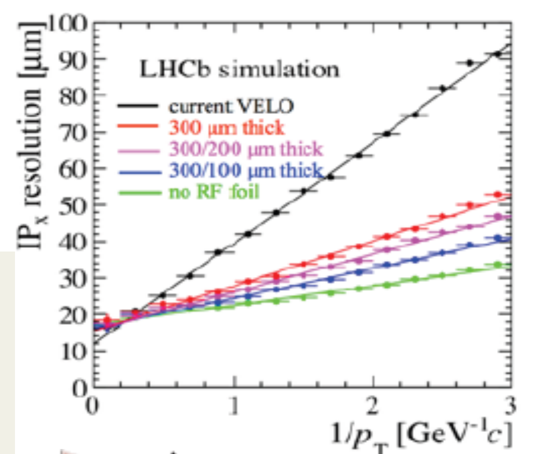
Upgrade II Vertex & Tracking

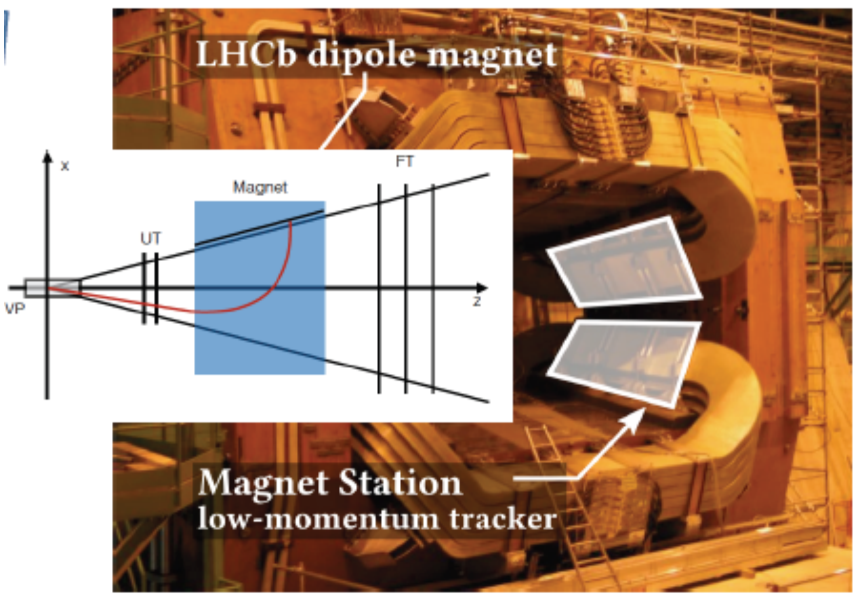
- Include timing detectors to improve PV reconstruction, decrease ghost probability
- Hybrid VELO pixel with increased radiation hardness and reduced material budget

• Magnet side stations could be added after LS3 (upgrade I consolidation) to improve momentum resolution of tracks upstream of the magnet



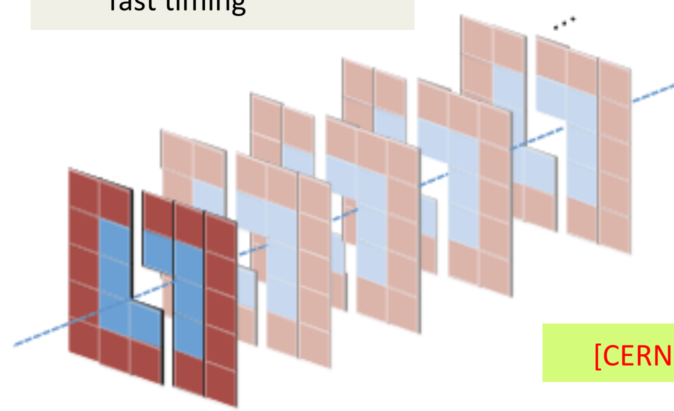
Reduced VELO material (RF shield)





Vertex Detector

- **Small-r**: small pixels, radiation hard
- **Large-r**: larger pixels, fast timing



[CERN-LHCC-2017-003]

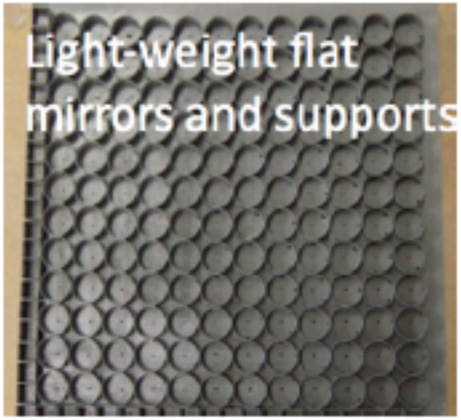
Upgrade II Particle ID

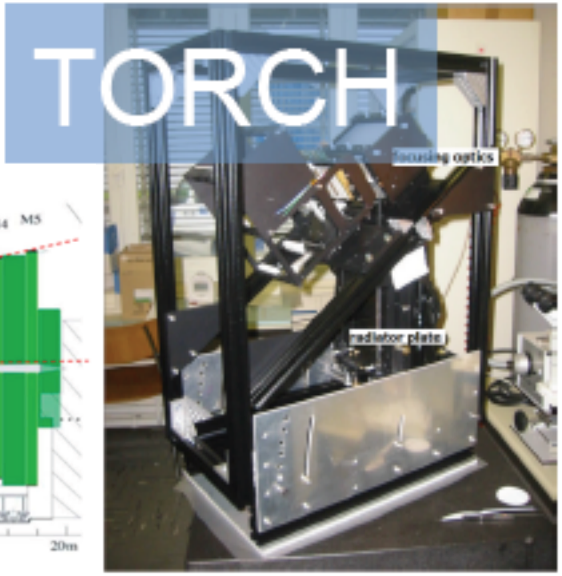
RICH detectors:

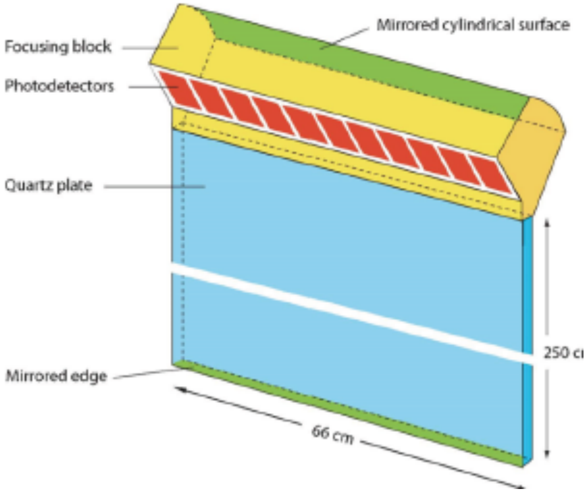
- Better coverage required at high & low momenta
- Better single photon resolution<5mrad
- Improvement of optical error by using flat mirrors
- Higher granularity plus timing info

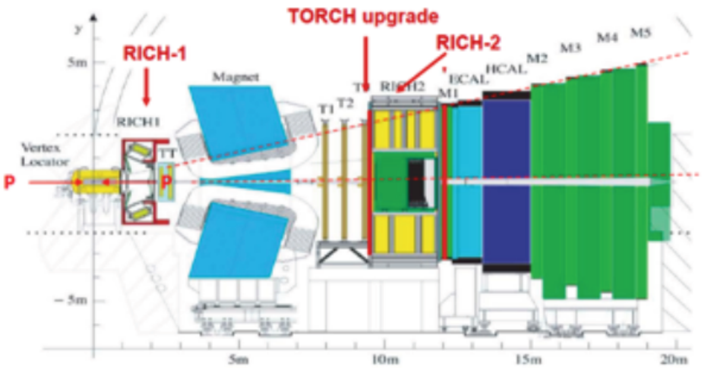
TORCH ToF detector:

- PID for low-momentum particles.
- Aim for 70ps single photon time resolution.
- Combine with VELO info for improved track matching.









[CERN-LHCC-2017-003]

**** Synergies with other CERN R&D projects UltraFast** (ASIC development for ultrafast RO electronics)

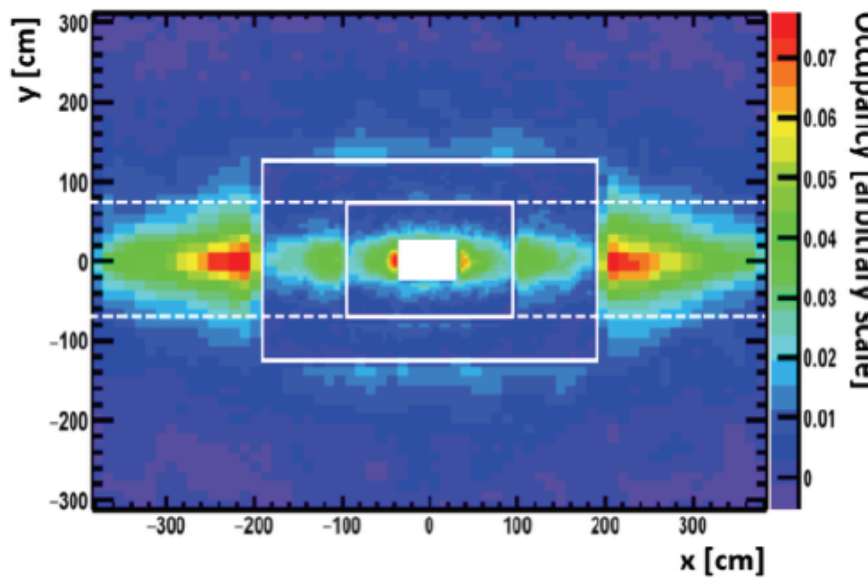
Upgrade II Calorimetry

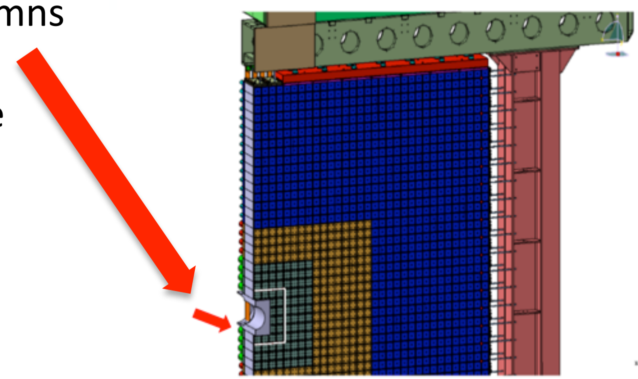
	S [GeV$^{1/2}$]	C	N [MeV]	Material
LHCb	~10%	~0.8%	~10-20	~1X_0
ATLAS	10-12%	~0.2%	~250	~0.5-1.5 X_0
CMS	3-6%	~0.5%	200-600	~0.5-2.0 X_0

ECAL Upgrade Ib (LS3 in 2025):

$$\frac{\delta E}{E} = \frac{S}{\sqrt{E}} \oplus C \oplus \frac{N}{E}$$

- Inner region of the ECAL most affected by radiation, pile-up
- According to the TDR "The performances should remain satisfactory up to 2.5Mrad"
  (C term ~<3%) → 20/fb or ~2023
- Degradation in performance would then be seen in Run 4 (2×10^{33} cm^{-2}s^{-1})
- Innermost modules need to be replaced during LS3
- Original plan was to replace with (identical) spare modules (32 modules already available)
  - Requires "only" dismantling the columns of modules above the central region
  - Other intervention would require the dismantling of a large fraction of the calorimeter → long task





Upgrade II Calorimetry

ECAL Upgrade Ib (LS3 in 2025, before RUN4):

ALTERNATIVE OPTION:

- Replace Innermost modules with a newer technology.
- Test for a full new ECAL in the LHCb Upgrade II
- Why: Lots of interesting physics are sometimes very demanding with the CALO syst.

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

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

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

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

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

$Z \to e^+e^-$
$W \to e\nu$
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 $\to \chi_{c,b}X$

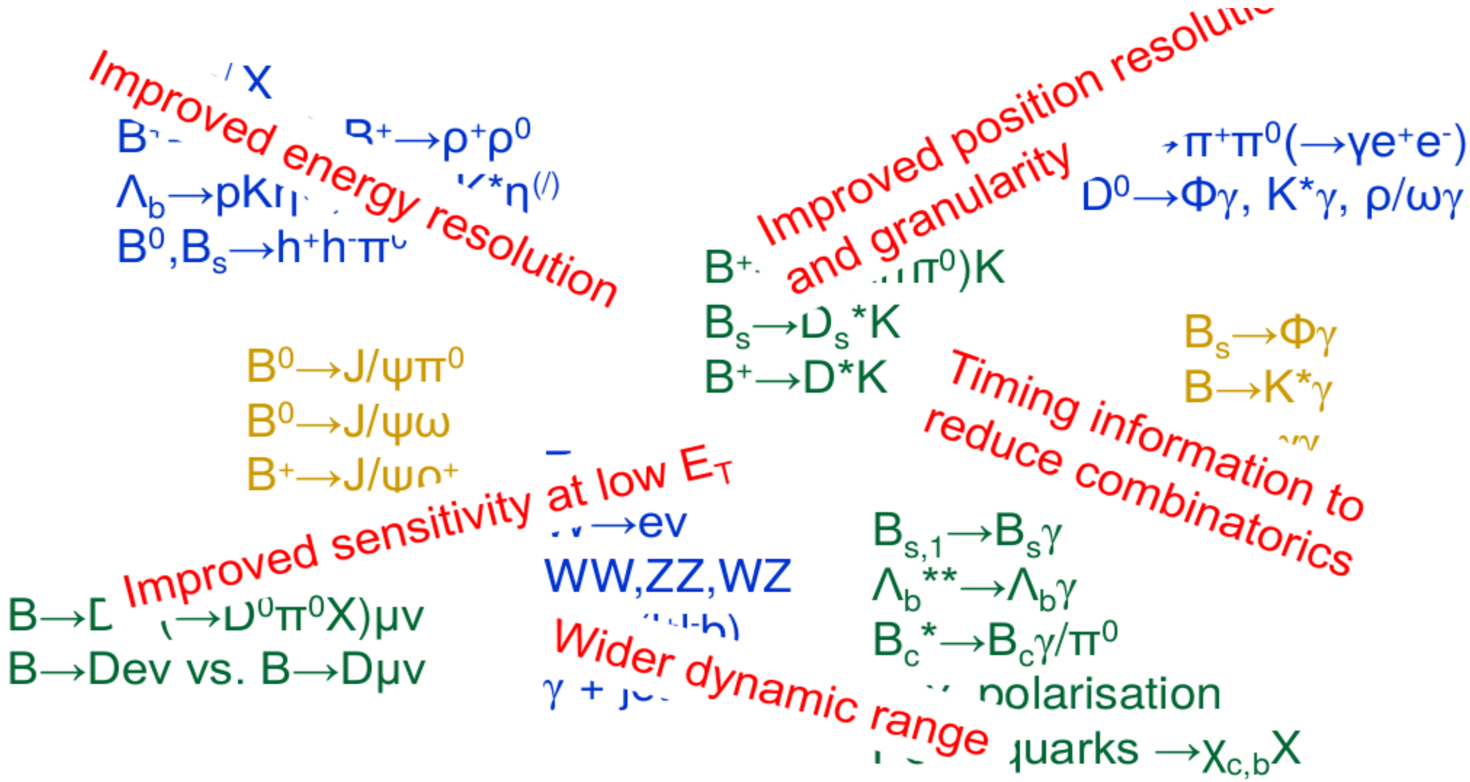
$B \to D^{**}(\to D^0\pi^0X)\mu\nu$
$B \to De\nu$ vs. $B \to D\mu\nu$

Upgrade II Calorimetry

ECAL Upgrade Ib (LS3 in 2025, before RUN4):

ALTERNATIVE OPTION:

- Replace Innermost modules with a newer technology.
- Test for a full new ECAL in the LHCb Upgrade II
- Why: Lots of interesting physics are sometimes very demanding with the CALO syst.



Upgrade II Calorimetry

ECAL Upgrade II :

Requirements to meet the demands:

- Improved energy & position resolution & Improved sensitivity to low ET
  - Reduce lateral and longitudinal shower size => new absorber (to get up to 25 X_0) & reduced cell size => New optimal geometry to be studied
- Wider dynamic range: New RO electronics
- Timing information to reduce the combinatorics, specially important in a HL-LHC regime ➔ New RO electronics but also NEW SIGNAL COLLECTION method: Fast Scintillators, Fibres, Silicon ?

** **Synergies w/ other CERN R&D projects UltraFast** (ASIC R&D for ultrafast RO electronics)

POSSIBLE OPTIONS:

1) Homogeneous crystal calorimeter (w/ longitudinal segmentation ?)

- Fast & Rad Hard crystal with high light yield

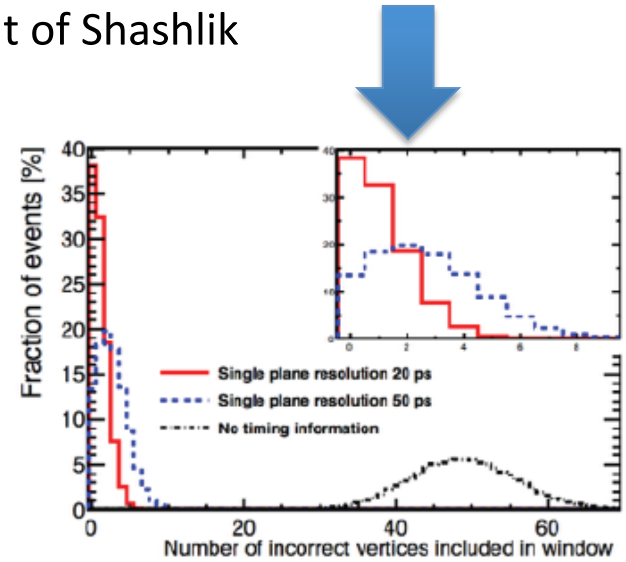
Upgrade II Calorimetry

2) Sampling calorimeter

-Converter material with typical R_M ~ 1-2cm (Lead, W or various alloys)
-Rad. hard crystal as scintillating medium w/ high light yield & fast response
-Radiation hard light-guide/fibre to transport light (for Shashlik type)
-Radiation hard photo-detector (in the corresponding spectral range)
-Include a very fast (crystal) component (~20ps) for pile-up mitigation into module or add "pre-shower timing layer" (Si based?) in front of Shashlik

R&D has started on:

- Performance studies of various sampling calorimeters: Shashlik, SpaCal, etc…
- Radiation hard scintillators of garnet type: i.e. YAG and GAGG crystals)
- Radiation hardness of GaAs photodiodes with epitaxial technology
- Tungsten alloys



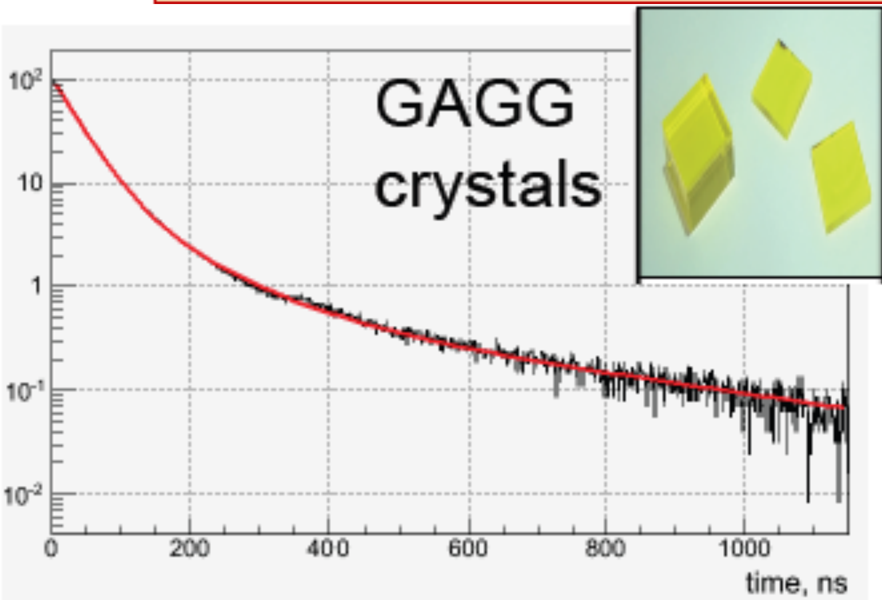
Remember: requirements in most inner region not the same as for middle or outer region →different technologies possible

→Current R&D concentrates on replacement of 32 modules in LS3

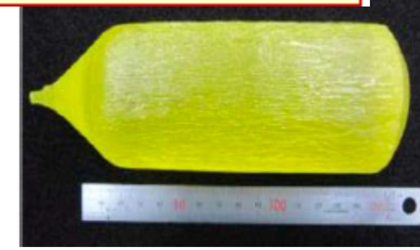
Upgrade Calo II: Homogeneous Calorimeter

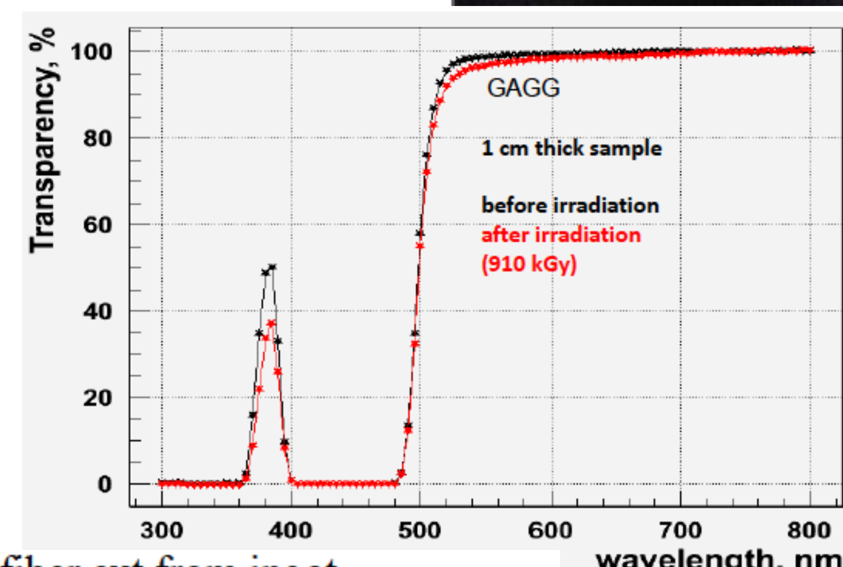
Generic R&D on radiation hard garnet type crystals:

→ GAGG crystals resist to radiation of ~1MGy (100 Mrad)

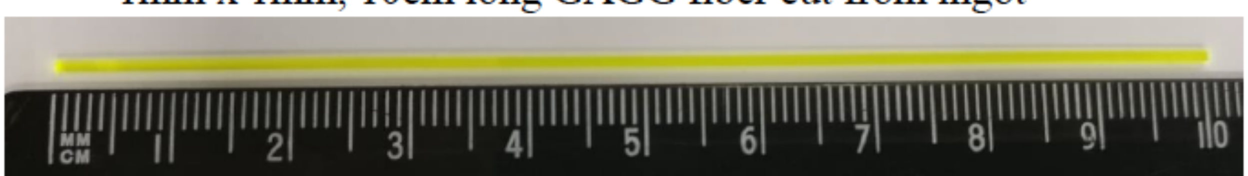


Samples of GAGG irradiated at CERN



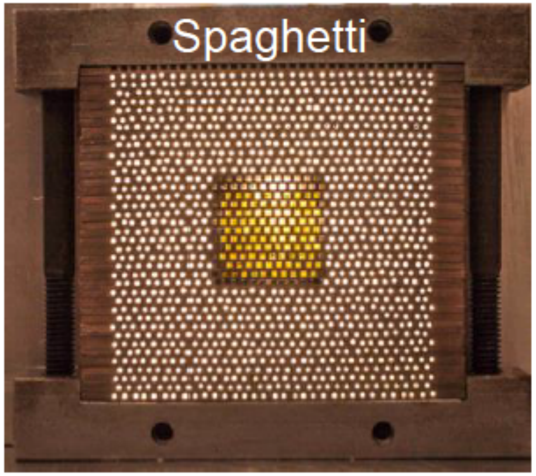


1mm x 1mm, 10cm long GAGG fiber cut from ingot



Upgrade Calo II: Calorimeter Options

…and even some ideas on accordion type modules…



Homogeneous Crystal:

- requires long crystal of ~40cm to contain 25 X_0
- "given" Moliere Radius
- very good homogeneity
- potentially very good E-resolution (<10%)
- large volume of crystal → high cost

Shashlik type module:

- can be made very compact ~15-20cm
- Moliere Radius "tunable"
- **no rad. hard WLS fibers (yet) to transport light!**
- challenging optimization to reach good E-resolution
- some cost optimization possible

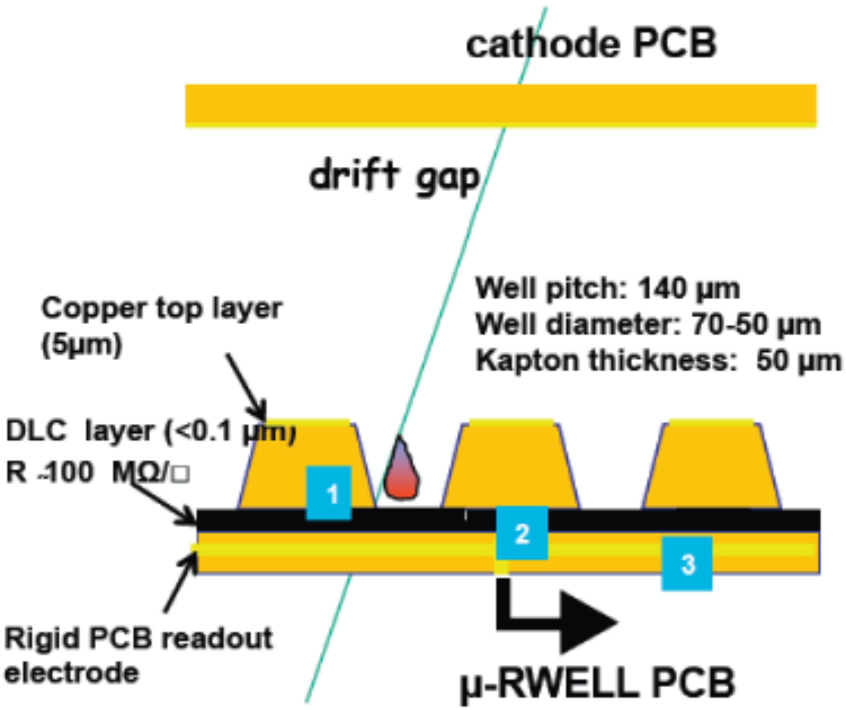
Spaghetti type module:

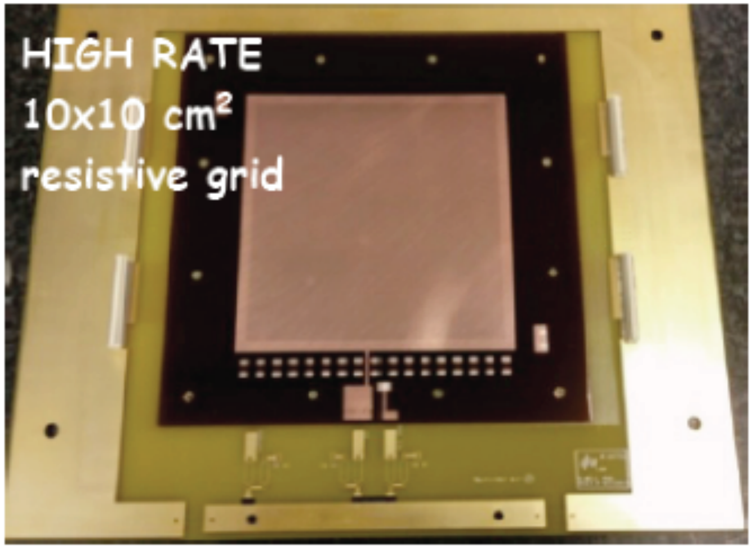
- can be made very compact ~15-20cm
- **fibers scintillate AND transports light!**
- Moliere Radius "tunable"
- challenging optimization to reach good E-resolution
- some cost optimization possible

Upgrade Calo II: Muon chambers

Prospective R&D started since NEW detectors are needed

G. Bencivenni et al., 2015_JINST_10_P02008

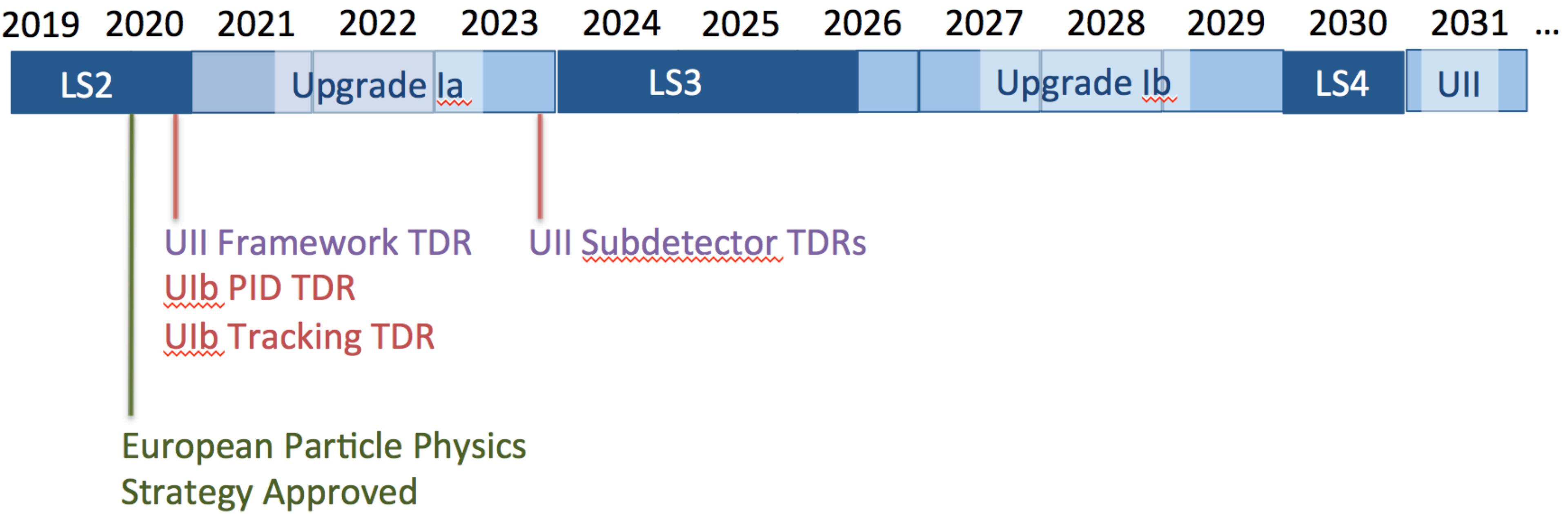




(*) DLC = Diamond Like Carbon
High mechanical & chemical resistant material

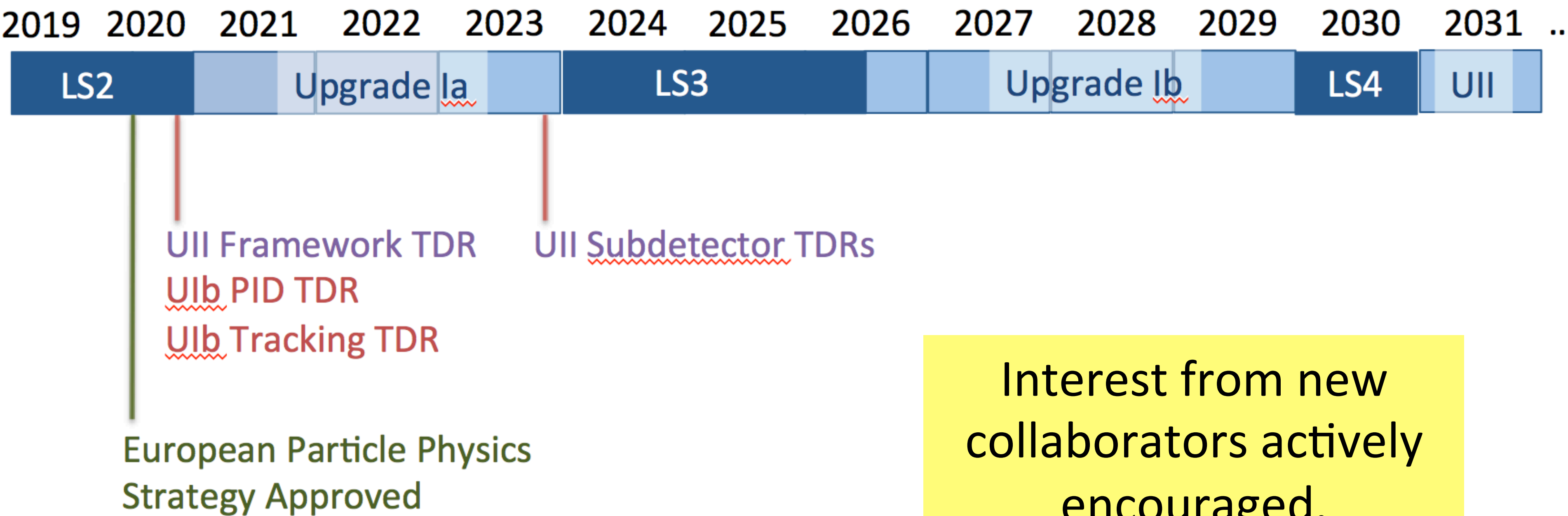
… and a new electronics too!

Detector R&D effort



- R&D active on sub-detectors
- Planning group set milestones & review progress
- Met with national representatives on funding steps
- The LHCC recently approved LHCb to proceed to a TDR on LHCb Upgrade II.

Detector R&D effort



Interest from new collaborators actively encouraged.

- R&D active on sub-detectors
- Planning group set milestones & review progress
- Met with national representatives on funding steps
- The LHCC recently approved LHCb to proceed to a TDR on LHCb Upgrade II.

Detector (Global) R&D effort

Interest from new collaborators actively encouraged.

- LHCb has amended its constitution to introduce the Technical Associate membership:

“**An Institute can be given the status of Technical Associated Member if it wishes to bring in technical, financial or human resources to a particular detector or computing related project. Technical Associate Members are not eligible to have LHCb authorship, nor have access to the LHCb data and internal physics results. Access to software for detector or software development is granted to Technical Associated Members.**

A Technical Associated Member must be hosted by an Institute of the LHCb Collaboration, called the Host Institute. The Host Institute will propose the Technical Associated Member candidature to the Collaboration Board.

The Host Institute must take the responsibility to ensure the long-term operation and maintenance of any hardware, or software, which the Technical Associated Member would produce and which would become part of the experiment. Otherwise, theTechnical Associates must apply for full membership.

The Technical Associated Members will not have a CB member or a vote in the CB, but will be represented in the CB through the Host Institute.”

Detector (Global) R&D effort

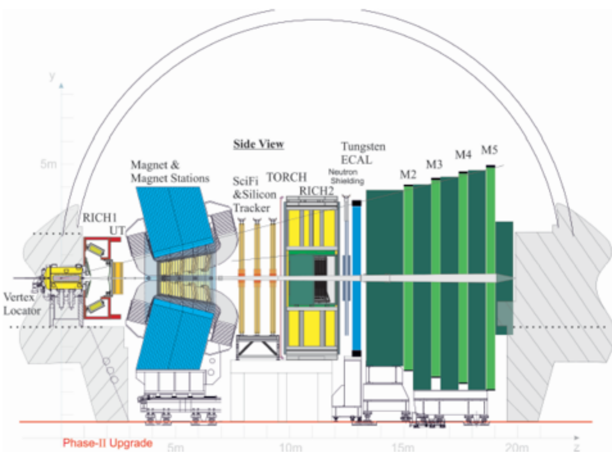
Interest from new collaborators actively encouraged.

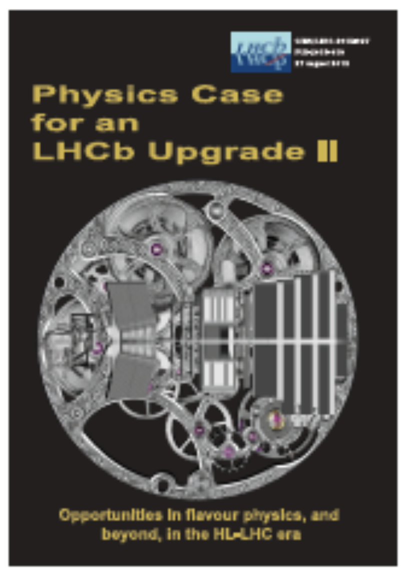
- Technical Associate membership is defined in a way that avoid any conflict of interest with other current ATLAS/CMS/Belle-II memberships.
- Resource optimization suggests that the LHCb Upgrade II might benefit greatly of a global effort on instrumentation R&D and on its ulterior physics data exploitation (from 2030 onwards); by the experimental flavour physics community as a whole.
- Interested parties are encouraged to contact any of the LHCb institutions to explore (in contact with the LHCb management) the possibility to become a Technical Associate Members
- Next LHCb Upgrade II open workshop on April 8th-10th, 2019 in Amsterdam is a great opportunity to explore how to get involved.

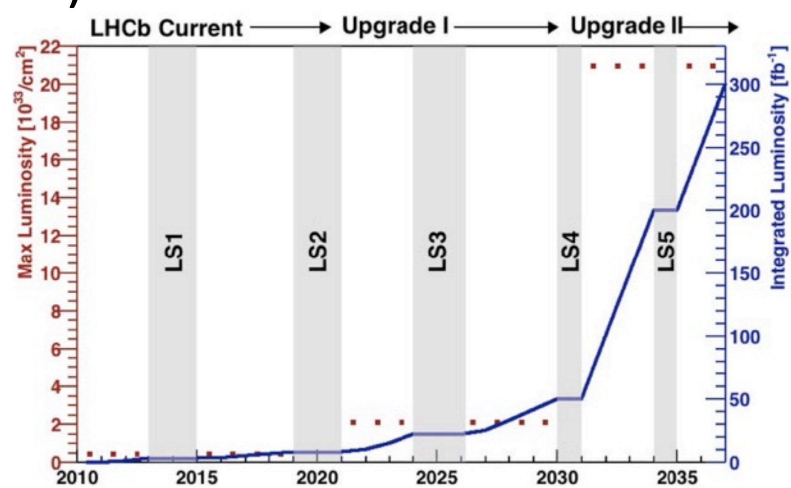
Summary & Conclusions

Physics Case Key messages

- Several **theoretically clean** observables whose statistical error can be drastically reduced (γ, $R_K(*)$, Bs➔μμ…)
- New Physics scale probed will be highly increased compared with pre-HL-LHC
- **Widen the set of observables** under study to search and characterise new physics (b➔sll, b➔clν…)
- Strong programme **beyond flavour** exploiting unique acceptance (spectroscopy, electroweak, dark sector)







Instrumentation Key messages

- The LHCb detector after 2030 should have the following features:
  - Radiation Hardness
  - Increase granularity to cope with increased multiplicity
  - Timing capabilities to cope with a pile-up of 25-50 hard (inelastic) interactions per BX

- A new procedure has been put in place for those groups, beyond the current LHCb, interested into the instrumentation R&D for a flavour experiment after 2030

END. Thanks!

Credits

Some of the material shown in the slides (figures, structures, etc...) have been taken from other talks from LHCb collaborators, mainly Chris Parkes, Preema Pais, José Mazorras, Xavier Vilasís-Cardona, Andreas Schopper, Alessandro Cardini & Paula Collins among others. I want to thank them all.

Back-up

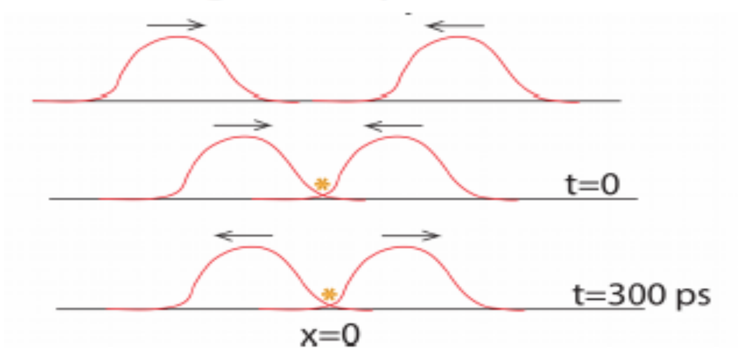
Upgrade II Calorimetry

ECAL Upgrade II :

TIMING is a new player in the game.

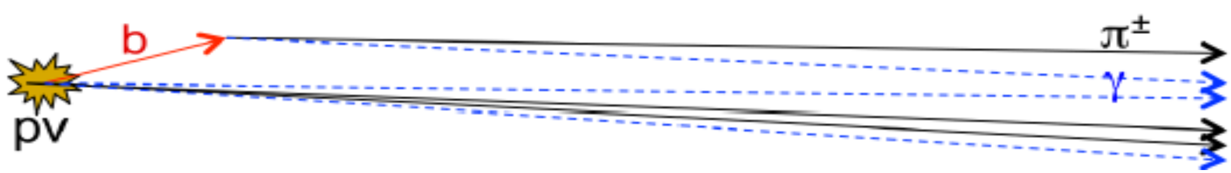
Why it is important at HL-LHC:

- To reduce shower overlap, one possibility consists in increasing the granularity (should also reduce the Moliere radius…)
- Background and combinatorics reductions can be achieved by using a new dimension → time
  - Ex:
    - 300 ps for beams to cross each other
    - Assuming 10 int/xing → 20 ps between collision (gauss. Distr.)



- Strategy :

  1) Sort the charged particles to the PV (timing info)
  2) Associate the photons to the charged tracks (highly relativistic)



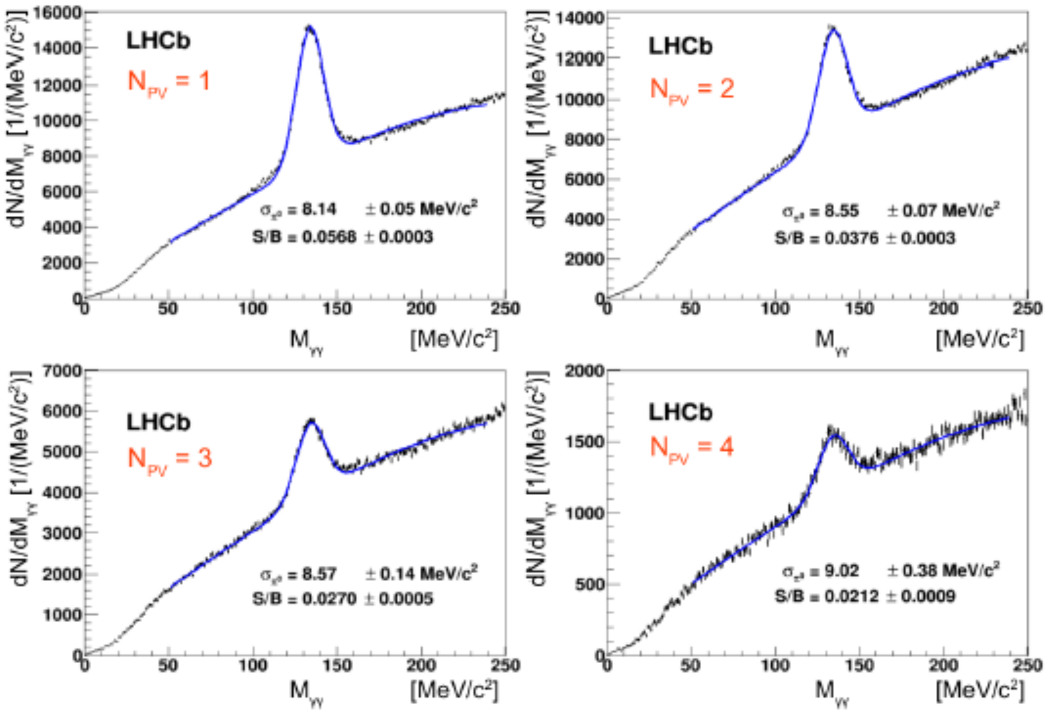
Upgrade II Calorimetry

ECAL Upgrade II :

TIMING is a new player in the game.

Why it is important at HL-LHC: If we can't disentangle different PVs (remember we assume 50 interactions per BX)

- The effect of the number of primary vertices is already obvious in the present reconstruction
  - Run 2 minimum bias data split wrt the number of PV
  - The selection applied is $p_T(\gamma)$>300MeV/c and $p_T(\pi^0)$>550MeV/c



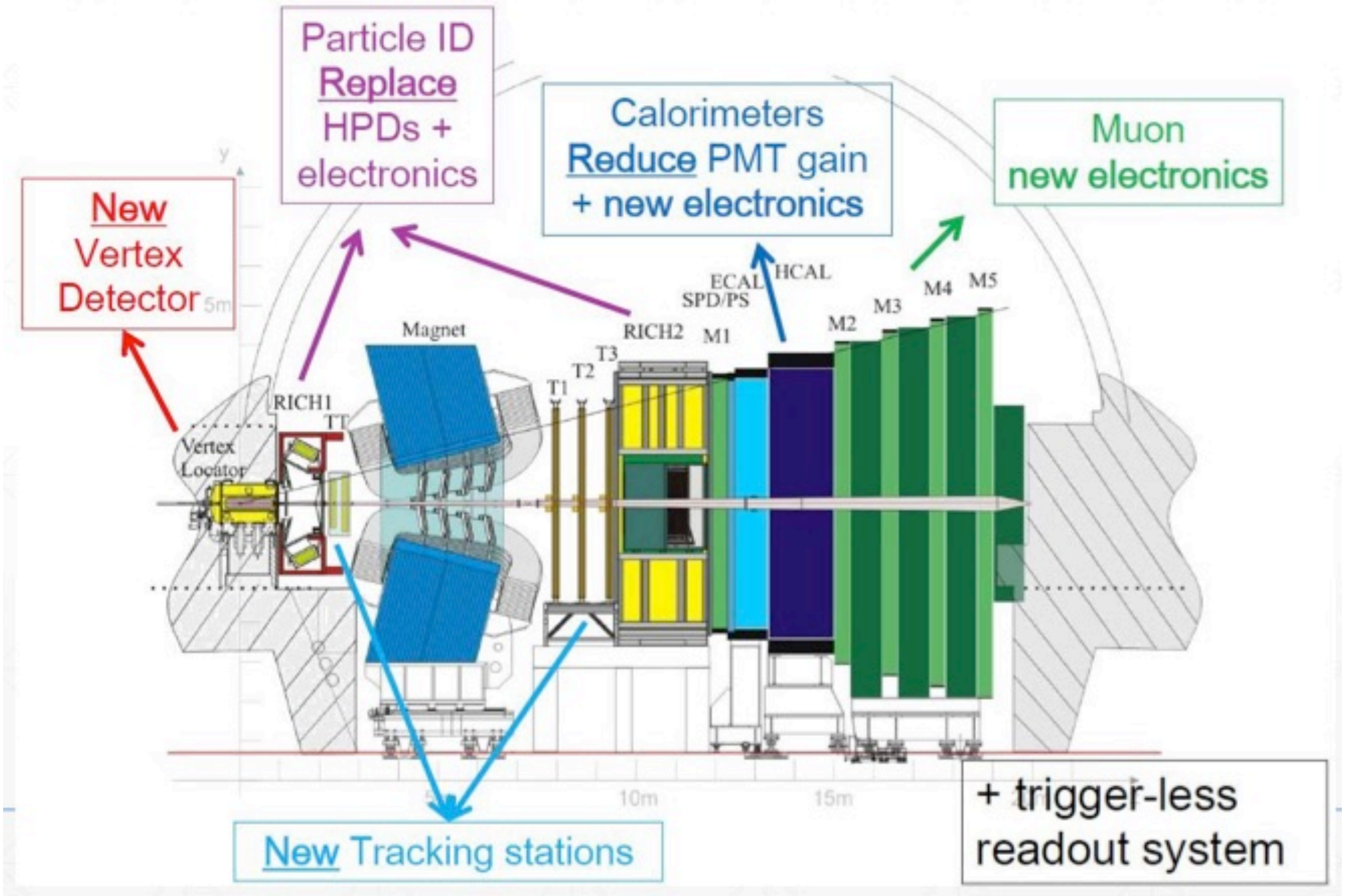
Upgrade II Calo: Cerenkov Calorimeter

- Ongoing radiation hardness studies and light yield measurements
- Why is this option interesting:
  - Cerenkov radiation is a prompt effect, and therefore very fast
  - Possible synergies with Ultra Fast medical imaging
- Caveats:
  - Is there enough light yield?
  - The materials are Rad-Hard, for the ECAL inner-most region?

Table 1. Properties of KRS, NBW and PWO crystals.

Crystal	KRS-15	NBW	PWO
Chemical composition	$TlCl(78\%)TlBr(22\%)$	$NaBi(WO_4)_2$	$PbWO_4$
Light emission	cherenkov	cherenkov	scintillation
Density $\rho(g/cm^3)$	7.65	7.57	8.3
Refractive index	2.2	2.15	2.2
Radiation length $X_0(mm)$	9.2	10.3	9.0
Moliere radius $R_m(mm)$	20.8	23.8	20.0
Melting temperature (^oC)	420	920	1123
Transmission edge $(nm) \geq$	410	380	350
Emission peak (nm)	-	-	480
Critical energy $E_c(MeV)$	8.95	9.75	-
Decay time $\tau(ns)$	-	-	2.1, 7.5, 26

Inminent LHCb Upgrade



Detector R&D effort

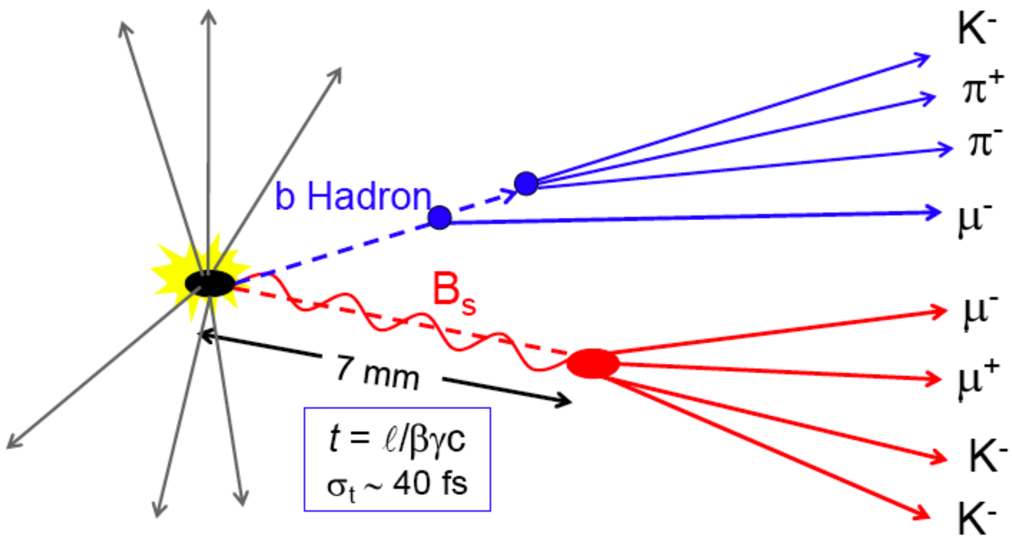
Enlarge beyond the current collaboration the interested number of institutions

- The amendment to the LHCb also addresses possible conflict of interest with other experiment membership:

“A Member or Associate Member of the LHCb Collaboration is not allowed to be a concurrent member of the Belle-II Collaboration unless they have been admitted as part of an institutes Technical Associate Membership or were a member of both collaborations prior to July 1st 2017. Any requests for joint collaboration on physics topics that would substantially benefit from the combination of data from both experiments need to be approved prior to commencement by the LHCb Spokesperson and Physics Coordinator.

This amendment to the LHCb Constitution will be reconsidered at the end of Belle-II data-taking.”

Beauty physics requirements @ LHC



At L0 trigger level (7 TeV)
min.bias : cc : bb
250 : 20 : 1

Excellent vertex resolution: to resolve fast B_s oscillation. → VELO

Background reduction: Very good mass resolution → Tracking
Good particle identification (K/π) → RICH, CALO, Muon

High statistics: Efficient trigger for hadronic and leptonic states → L0 x HLT

- VELO
- Tracking
- RICH
- CALO
- Muon
- L0 x HLT

B decays with *μμ*	$\varepsilon_{(\mathbf{L0\ x\ HLT})}$ ~ 70-90 %
B decays with *hadrons*	$\varepsilon_{(\mathbf{L0\ x\ HLT})}$ ~ 20-50 %
Charm decays :	$\varepsilon_{(\mathbf{L0\ x\ HLT})}$ ~ 10-20 %

(trigger efficiencies for off-line selected events)

Flavor tagging plays a key role

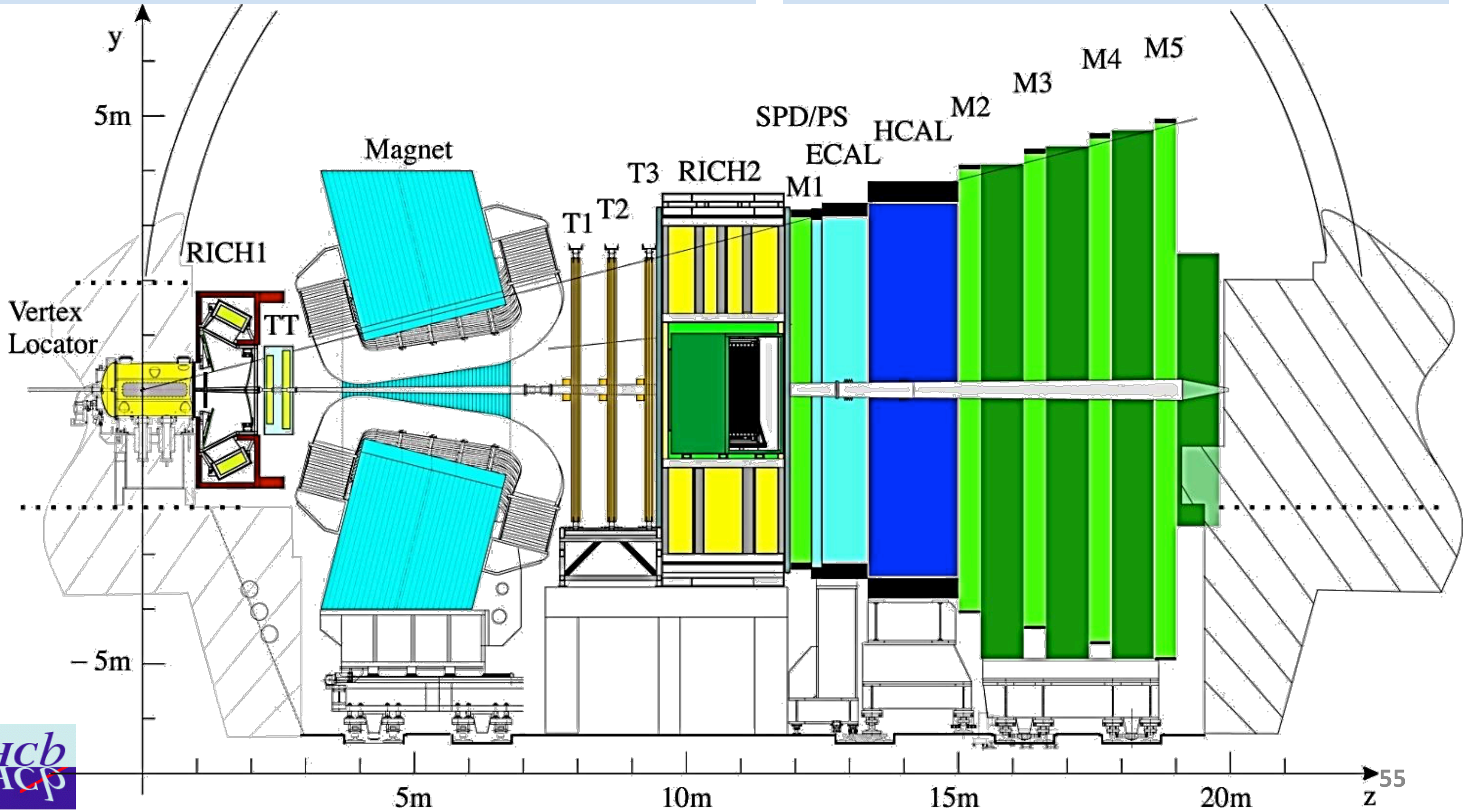
σ_{cc} ~ 6 mb (~1.7 mb in LHCb acceptance) : LHC is a charm factory !

LHCb

Pre-Upgrade LHCb detector

- VELO: 21 (R+φ) Si station
- RICH 1& 2: C_4F_{10} + Aerogel / CF_4
  π/K separation 2<p<100 GeV
- TRACKING: Si+Straw tubes + 4 Tm
  δp/p = 0.4 – 0.6%

- CALO: SPD/PS, ECAL, HCAL
  (Lead,Iron,Lead-Scintillator)
- MUON: MWPC + GEM
  π/μ separation



LHCb

Imminent LHCb Upgrade

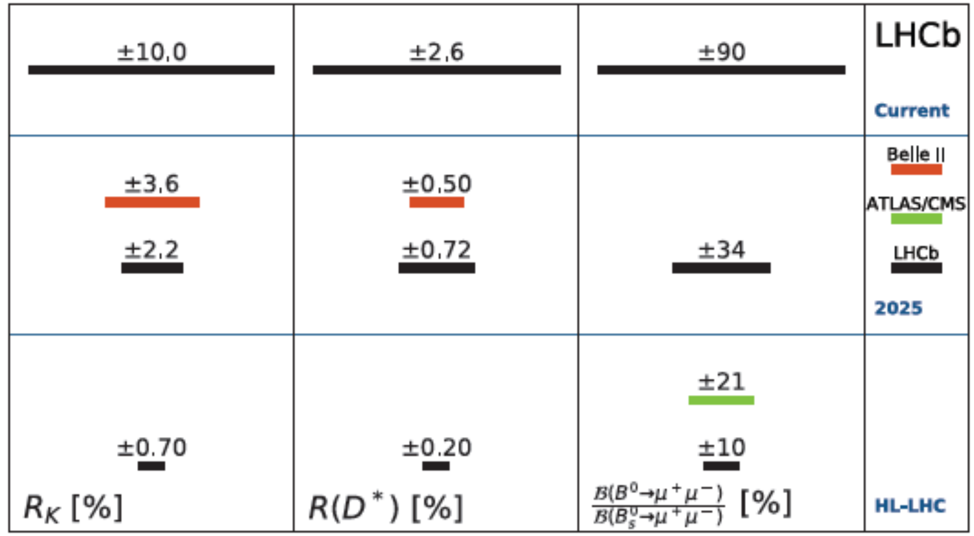
Excellent results from Run-I and (partial) Run-II physics data analysis. Latest results:

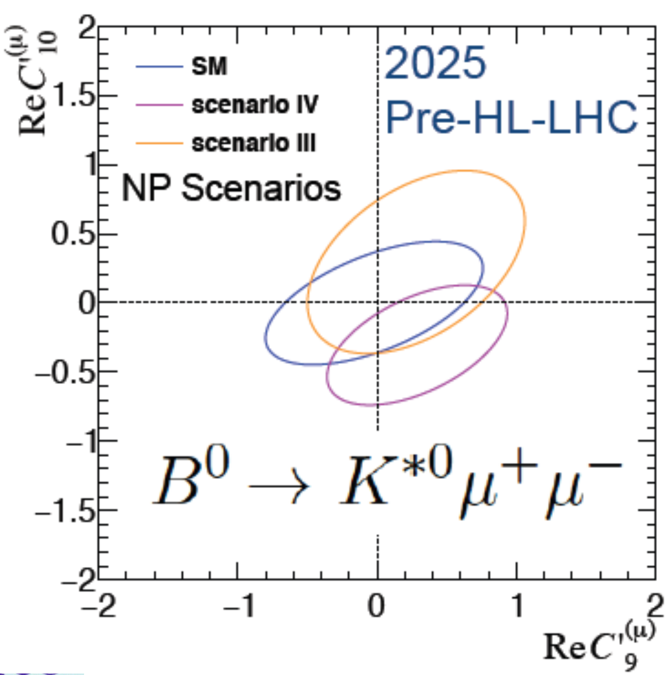
- Observation of $\Xi_{cc}^{++} \rightarrow \Xi_c^{+}\pi^{+}$ (LHCb-PAPER-2018-026)
- Ω_C^0 lifetime (LHCb-PAPER-2018-028)
- Observation of 2 resonances in the $\Lambda^0_b\pi^{\pm}$ systems (LHCb-PAPER-2018-032)
- Evidence of a $\eta_c(1S)\pi^-$ resonance in $B^0 \rightarrow \eta_c(1S)K^+\pi^-$ decays (LHCb-PAPER-2018-034)
- Anti-proton production in pHe collisions at $\sqrt{S_{NN}}$= 110 GeV (LHCb-PAPER-2018-031)
- Angular momenta of the decay $\Lambda^0_b \rightarrow \Lambda\mu^+\mu^-$ (LHCb-PAPER-2018-029)
- Observation of $B^0_s \rightarrow D^{*0}\phi$ and search for $B^0 \rightarrow D^0\phi$ decays (LHCb-PAPER-2018-15)

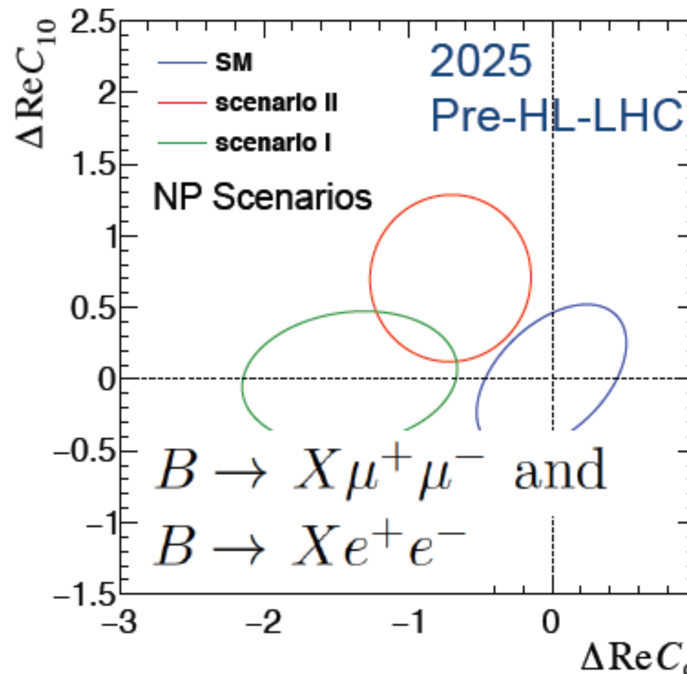
Physics Case: Rare decays

- Wide range of b➔sl⁺l⁻/dl⁺l⁻ observables
- 10 % precision on

$$R \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$$





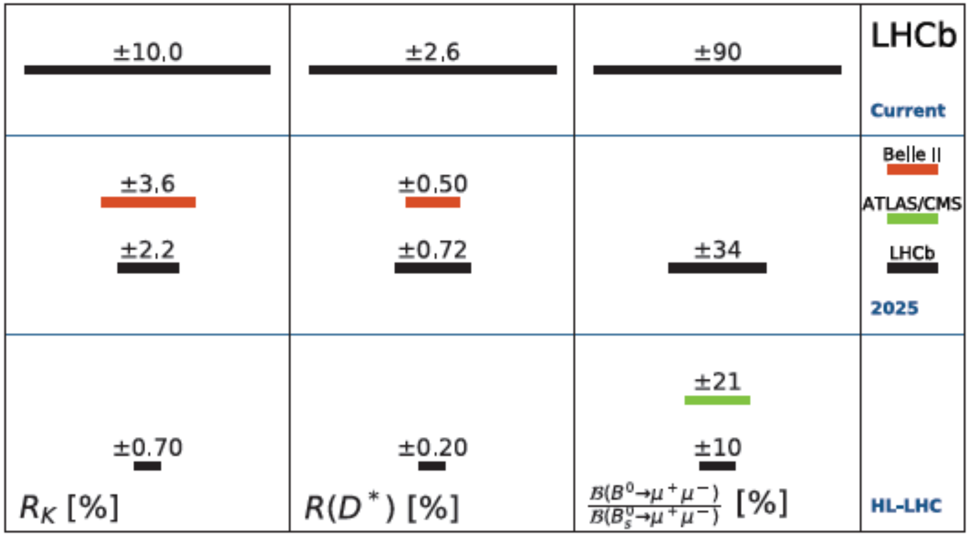


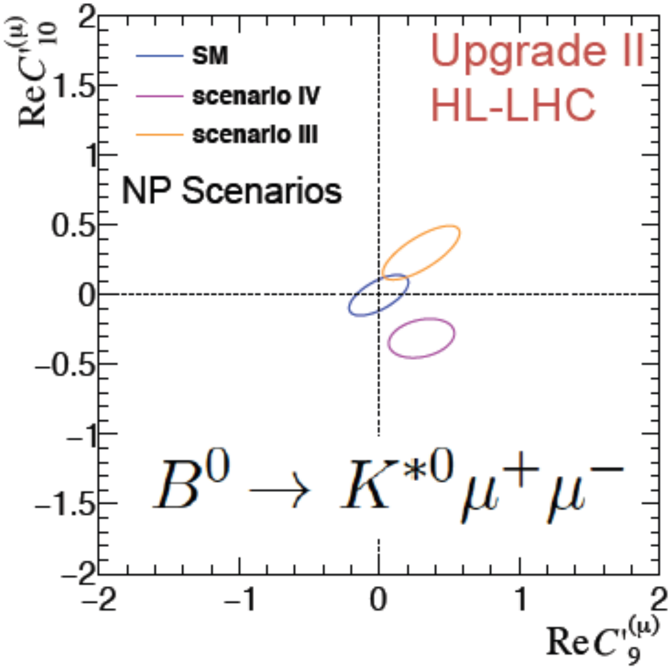
[LHCB-PUB-2018-009] arXiV:1808.08865

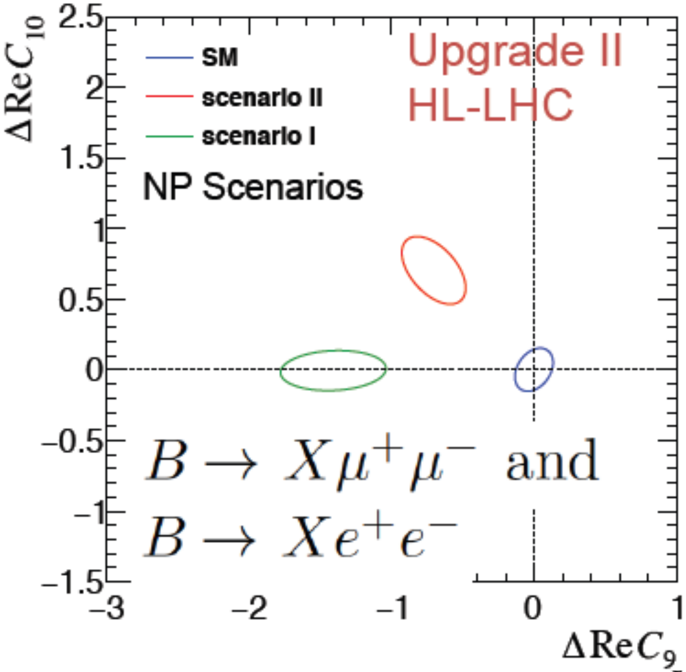
Physics Case: Rare decays

- Wide range of $b \rightarrow sl^+l^-/dl^+l^-$ observables
- 10 % precision on

$$R \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$$







[LHCB-PUB-2018-009] arXiV:1808.08865

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

- Flavour changing neutral current → loop

- Allows to test Lorentz-structure:

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_i [\ \underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu) O_i'(\mu)}_{\substack{\text{right-handed part} \\ \text{suppressed in SM}}}\ ]$$

$i = 1,2$	Tree
$i = 3-6,8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9,10$	Electroweak penguin
$i = S$	Higgs (scalar) penguin
$i = P$	Pseudoscalar penguin

- Angular analysis of $B^0 \rightarrow K^{*} \mu^{+}\mu^{-}$
  - $K^{*} \rightarrow K\pi$ self tagging → allows to probe helicity structure
  - Highly sensitive to $C_7^{(')}$, $C_9^{(')}$, $C_{10}^{(')}$

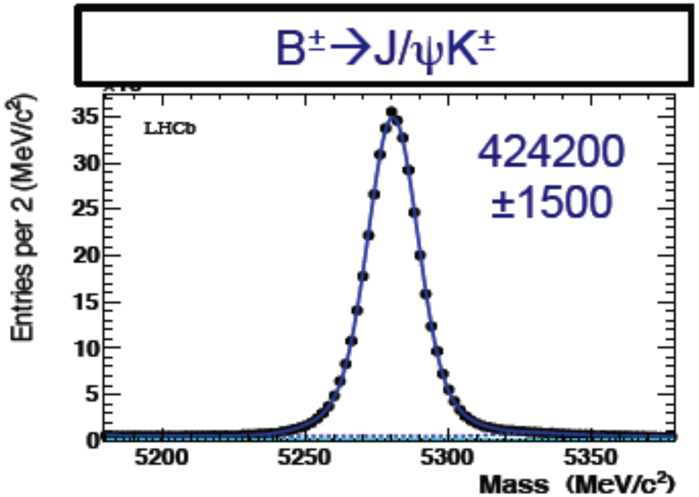
- Can measure a variety of angular observables which have small hadronic uncertainties
  - A_{FB}, the forward-backward asymmetry and its zero crossing point
  - F_L, the fraction of K^{*0} longitudinal polarization
  - $S_3 \sim A^2_T (1-F_L)$, the asymmetry in K^{*0} transverse polarization

$B^0/B_s \rightarrow \mu^+\mu^-$

- **Selection**
  - Soft selection to reduce size of dataset, similar to control channels unchanged to previous analyses
- **Normalization**
  - Convert number of observed events in branching fraction by normalizing to $B^\pm \rightarrow J/\psi K^\pm$ and $B \rightarrow K^+\pi^{'-}$

$$BR = BR_{cal} \cdot \frac{\varepsilon_{cal}^{Rec} \cdot \varepsilon_{cal}^{Sel}}{\varepsilon_{Bs}^{Rec} \cdot \varepsilon_{Bs}^{Sel}} \cdot \frac{\varepsilon_{cal}^{Trig}}{\varepsilon_{Bs}^{Trig}} \cdot \frac{f_{cal}}{f_{B_s}} \cdot \frac{N_{B\rightarrow\mu\mu}}{N_{cal}} = \alpha \cdot N_{B\rightarrow\mu\mu}$$

from MC data checked | from data | fraction $b \rightarrow B_s$ (updated, next slide)

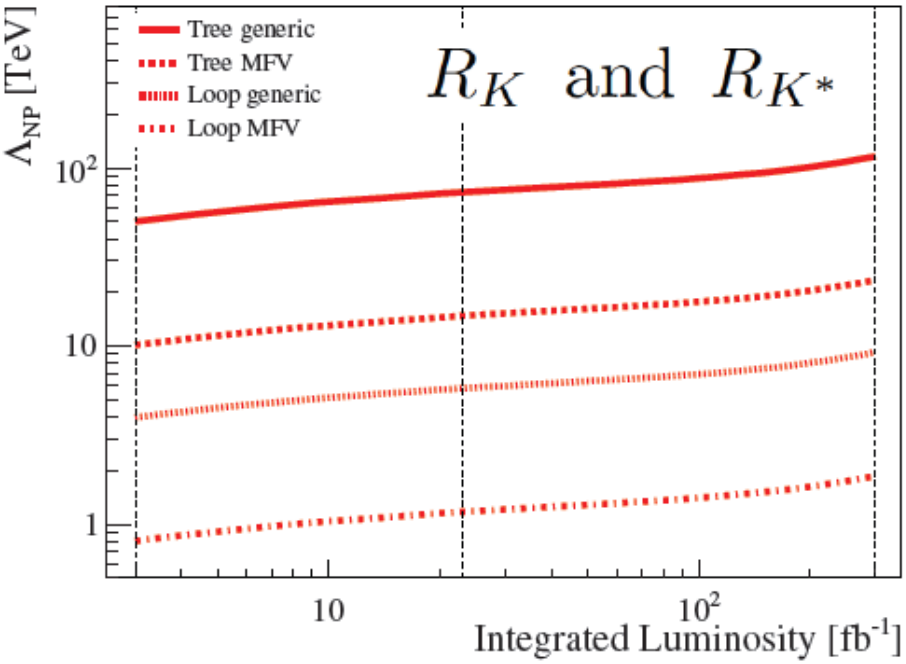


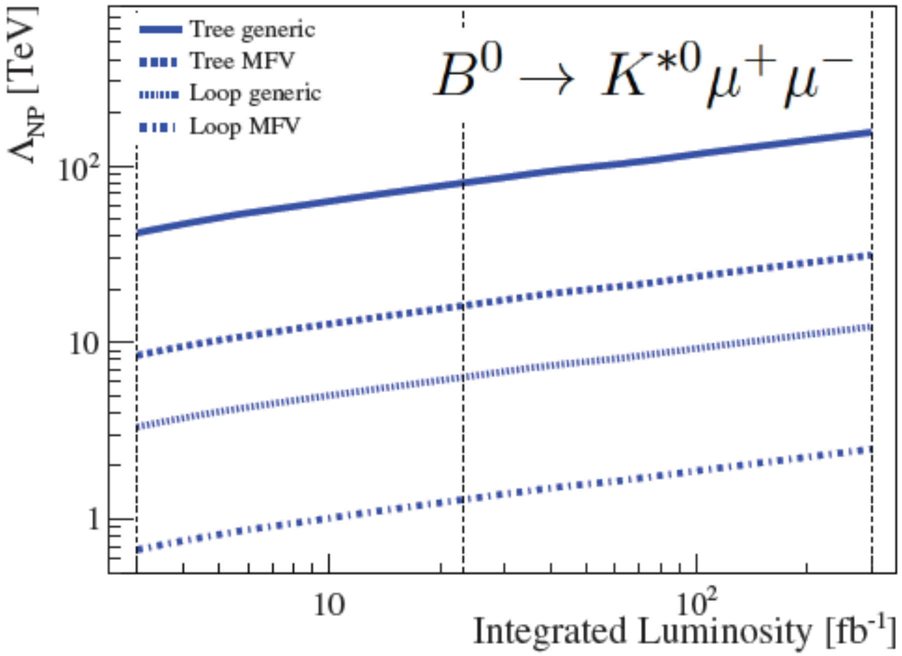
Normalization factors

$$\alpha(B_s \rightarrow \mu^+\mu^-) = (2.52 \pm 0.23) \times 10^{-10}$$
$$\alpha(B^0 \rightarrow \mu^+\mu^-) = (6.45 \pm 0.30) \times 10^{-11}$$

Slightly lower than in 2011 measurement due to higher $\mathcal{L}$ and x-section

Physics Case: Wilson Coeff. & NP scale





- Effective field theory approach
- Generic New Physics scale probed exceeds 100 TeV

Summary

$$R_K\ (1 < q^2 < 6\,\mathrm{GeV}^2c^4)$$

Current	0.1
LHCb 2025	0.025
Belle II	0.036
LHCb Upgrade II	0.007

EW Penguins

γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K^0_S$	0.04 [606]	0.011	0.005	0.003	–
$B^0_s, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [609]

Charm

Summary

ϕ_s, with $B^0_s \to J/\psi\phi$

Current	49 mrad
LHCb 2025	14 mrad
ATLAS,CMS HL-LHC	22 mrad
LHCb Upgrade II	4 mrad

EW Penguins					
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K^0_S$	0.04 [606]	0.011	0.005	0.003	–
$B^0_s, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [609]
Charm					

Summary

$B_s^0, B^0 \to \mu^+\mu^-$

Current 90%

LHCb 2025 34%

ATLAS,CMS HL-LHC 21%

LHCb Upgrade II 10%

$\sin 2\beta$, with $B^0 \to J/\psi K^0_S$	0.04 [606]	0.011	0.005	0.003	–
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [609]

Summary

$R(D^*)$

Current	0.026
LHCb 2025	0.007
Belle II	0.005
LHCb Upgrade II	0.002

EW Penguins

γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K^0_S$	0.04 [606]	0.011	0.005	0.003	–
$B^0_s, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [609]
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [610]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–

Summary

Charm CPV $x \sin \phi$

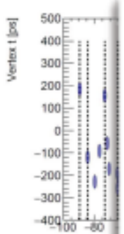
Current	2.8×10^{-4}
LHCb 2025	4.0×10^{-5}
Belle II	1.2×10^{-4}
LHCb Upgrade II	8.0×10^{-6}

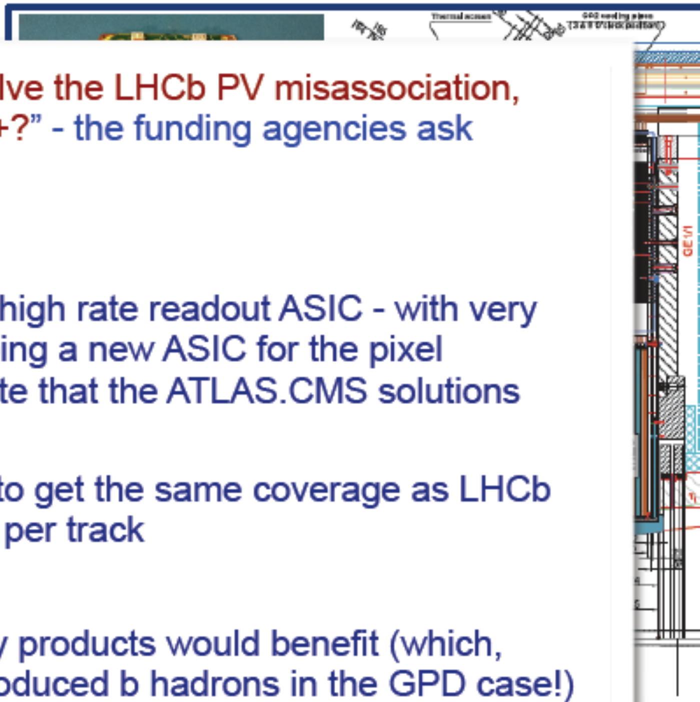
EW Penguins					
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K^0_s$	0.04 [606]	0.011	0.005	0.003	–
$B^0_s, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [609]
Charm					

Upgrade II Velo 4 D detector

ATLAS/CMS solution

Timing is used in the forward region, to reject Pileup vertices
(This is solving a subtly different problem to our PV association issue: b production in the central region does not necessarily need SV time tagging!)





"Could this style of track time tagging solve the LHCb PV misassociation, instead of putting timing in the VeloPix++?" - the funding agencies ask

Maybe! But:

- Development needed of yet another high rate readout ASIC - with very precise timing - in addition to developing a new ASIC for the pixel detector to handle the high rates. Note that the ATLAS.CMS solutions are not appropriate
- Need to equip a relatively large area to get the same coverage as LHCb and would not benefit from many hits per track
- No timing on VELO only tracks
- Even if PV misassociation for b decay products would benefit (which, note, is NOT the case for centrally produced b hadrons in the GPD case!) we would lose all other timing benefits (see next slides)

25

ATLAS:
~200 to
Solve with HGTD system

rs
ker
in a radiation field integrating up to 10^{16} n_{eq}/cm^2

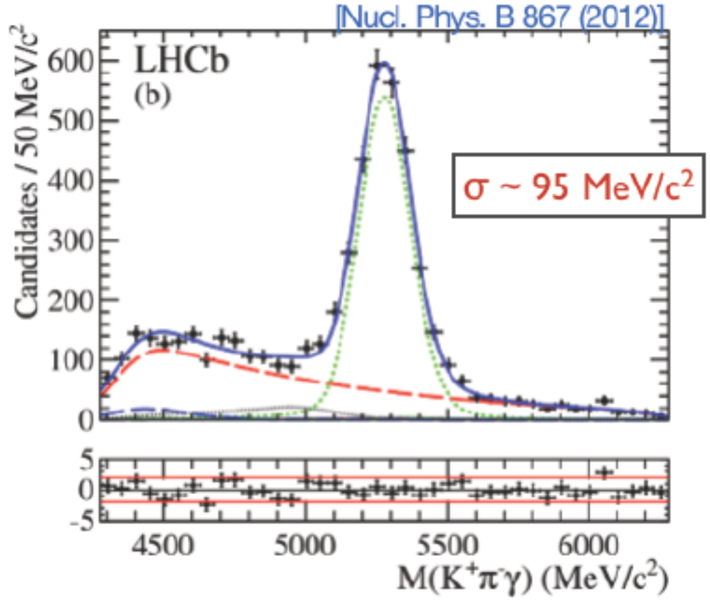
Upgrade II Velo 4 D detector

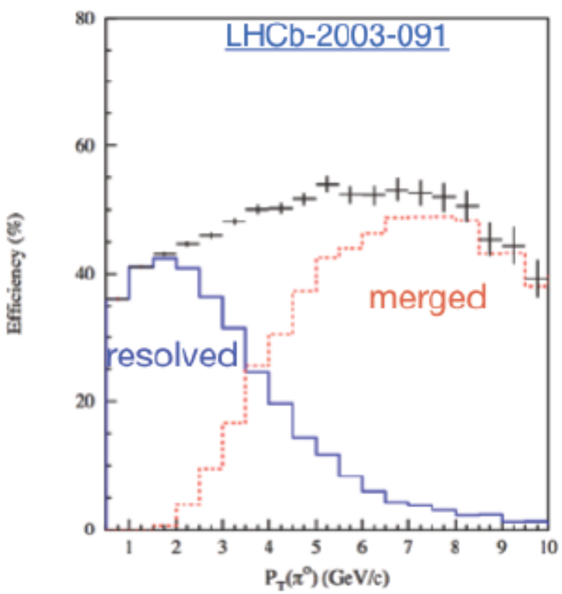
Do we need a 4D pixel tracker? We absolutely do!
Can we build a 4D pixel tracker? We absolutely can!

- Our need for timing is very different to the GPDs. In the GPD case; forward timing planes are used to time tag primary vertices and reject pileup. The centrally produced b hadrons have a z resolution which is much more competitive with the PV separation; in our case the forward flying b hadron needs time tagging on it's decay products with 100% efficiency. Time tagging only the tracks is not un-useful, but in addition to PV misassociation we need timing for many, many more reasons - and our timescale means that we should demand it.
- Studies on PR with timing are crucial; the more quantitative the better
- We need to optimise the VELO design with appropriate input from the reconstruction
- The ASIC design is conceptually mapped out; but much R&D ahead
- Idem for the sensors
- Idem for the mechanics
- System aspects are also critical: studies can start already with the Timepix4 on the benefit of time measurement combinations

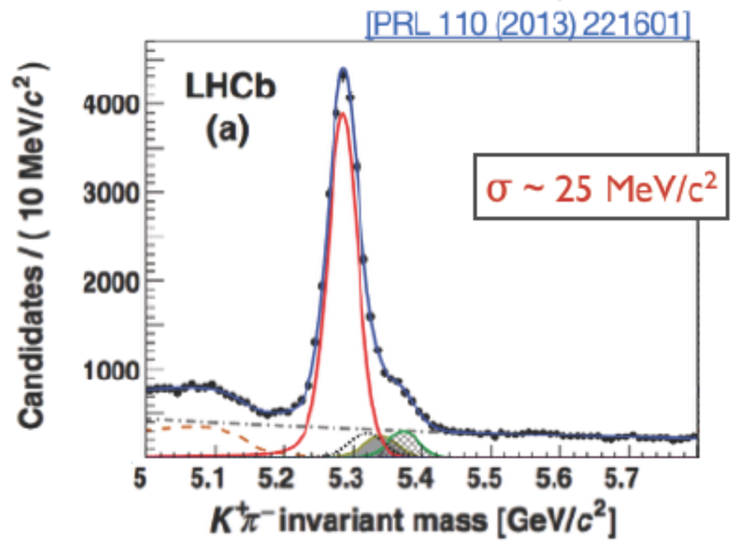
Upgrade II CALO experimental challenges

- Mass resolution dominated by photon reconstruction
  - **σ~95 MeV/c²** for B→K*γ decays, compared to ~25 MeV/c² for B→Kπ decays.
- Backgrounds:
  - Above transverse energies of 4 GeV, $\pi^0 \to \gamma\gamma$ reconstructed as a single cluster in the calorimeter
  - Combinatorial: $O(10)$ reconstructed photons per event





5



Upgrade II Calorimetry

[CERN-LHCC-2017-003]

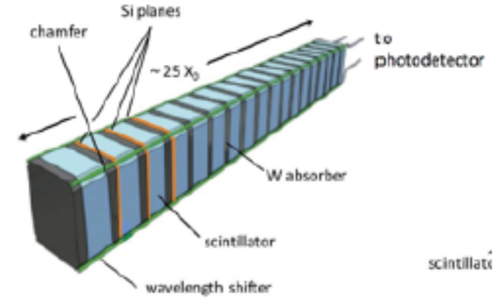
POSSIBLE SOLUTIONS:

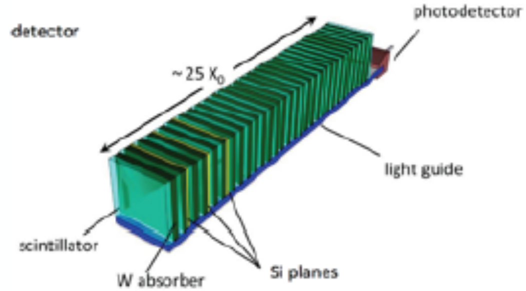
1) Sampling calorimeter:
   - Tungsten-based absorber
   - CMS-inspired designs:
     - WLS in chamfers along side of module (tested with CeF3 as a scintillator)
     - Cerium-doped LYSO, quartz - radiation-hard alternatives to WLS fibres
     - Compact LYSO/W shashlik
   - As an alternative, could use clear light-guides . Potentially better light yield and radiation hardness

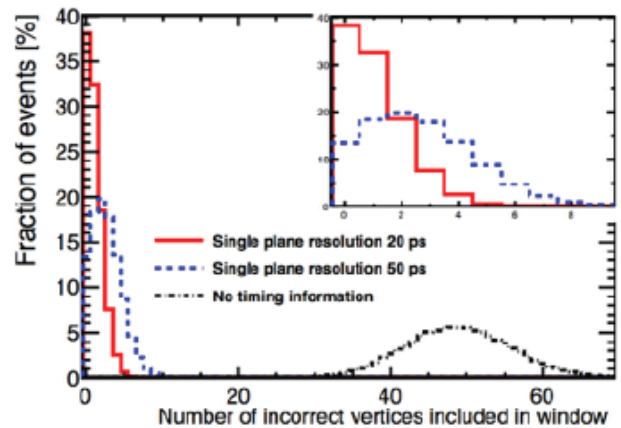
2) Homogeneous calorimeter made of heavy inorganic scintillator, e.g., LYSO, PWO, GAGG;

3) Homogeneous Cerenkov calorimeter based on KRS-6 (solid Thallium Bromo-Chloride) or NBW (NaBi(WO4)2) crystals (fast signal);

4) Sampling W-Si calorimeter
   - Time information impact seen in simulated environment with 50 int. per BX w/ three layers of Si planes with spatial resolutions of 20ps or 50ps.







**** Synergies with other CERN R&D projects UltraFast** (ASIC development for ultrafast RO electronics)