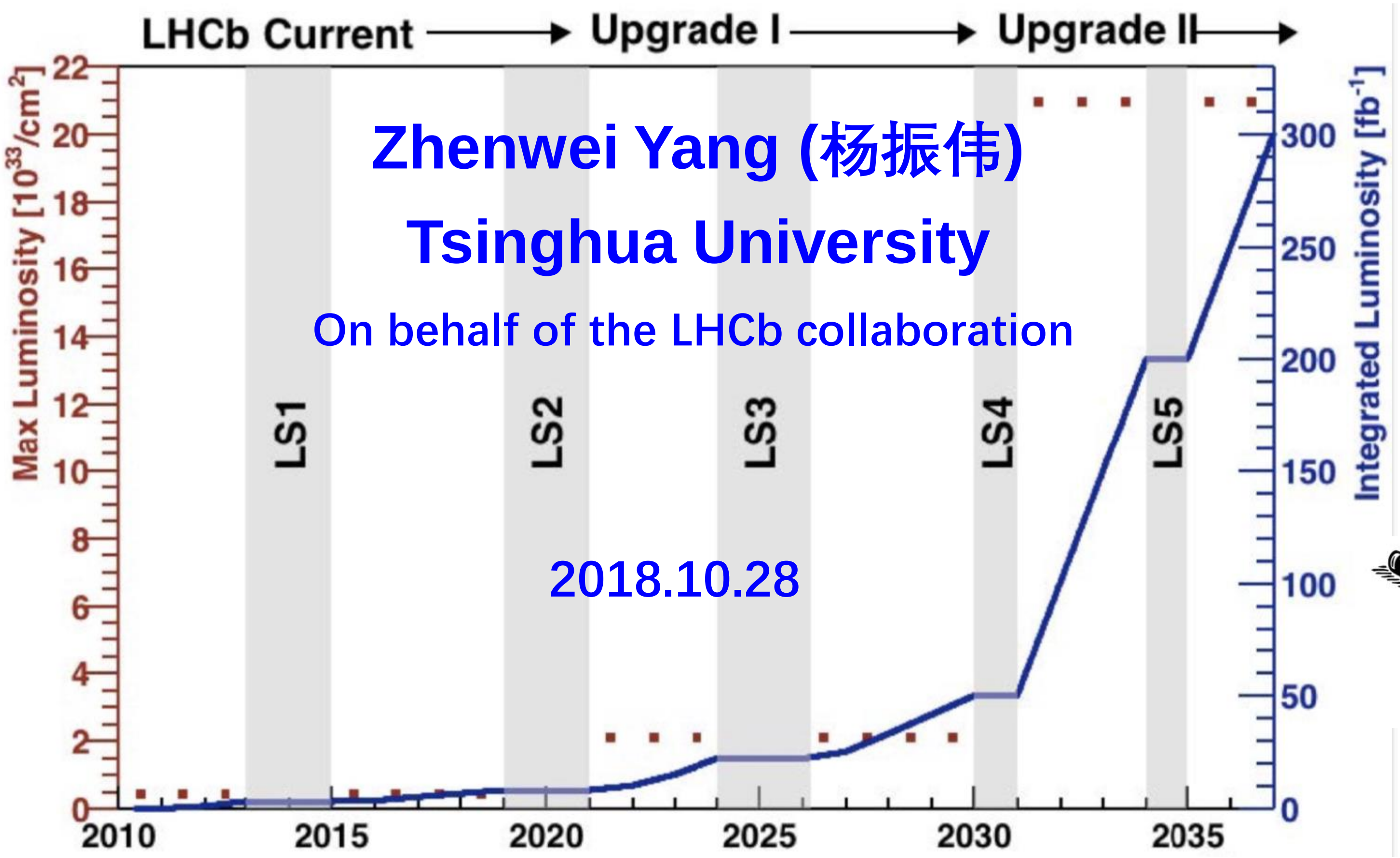
全国第十六届重味物理和CP破坏研讨会(HFCPV-2018)
2018.10.25-29，河南工业大学

LHCb upgrade and prospects

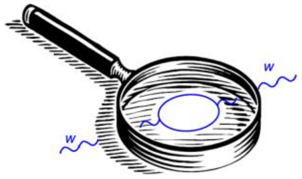


Zhenwei Yang (杨振伟)

Tsinghua University

On behalf of the LHCb collaboration

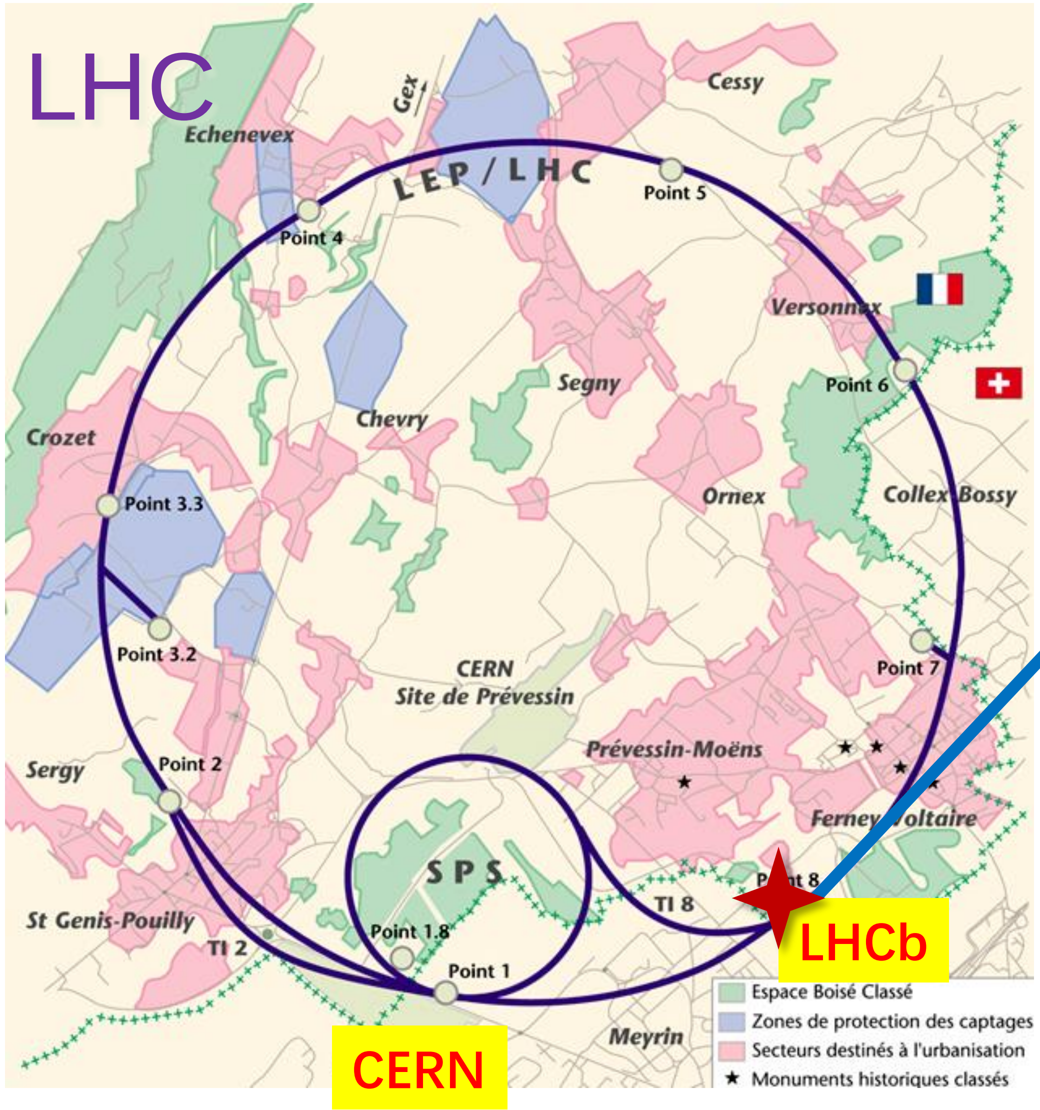
2018.10.28



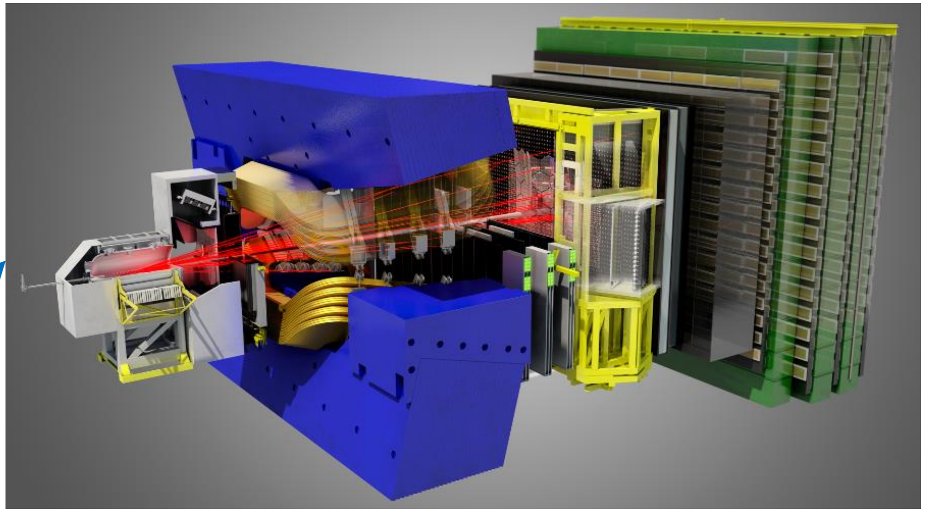
Outline

- Introduction
- The LHCb upgrade
- Selected physics cases
- Summary

The LHCb experiment

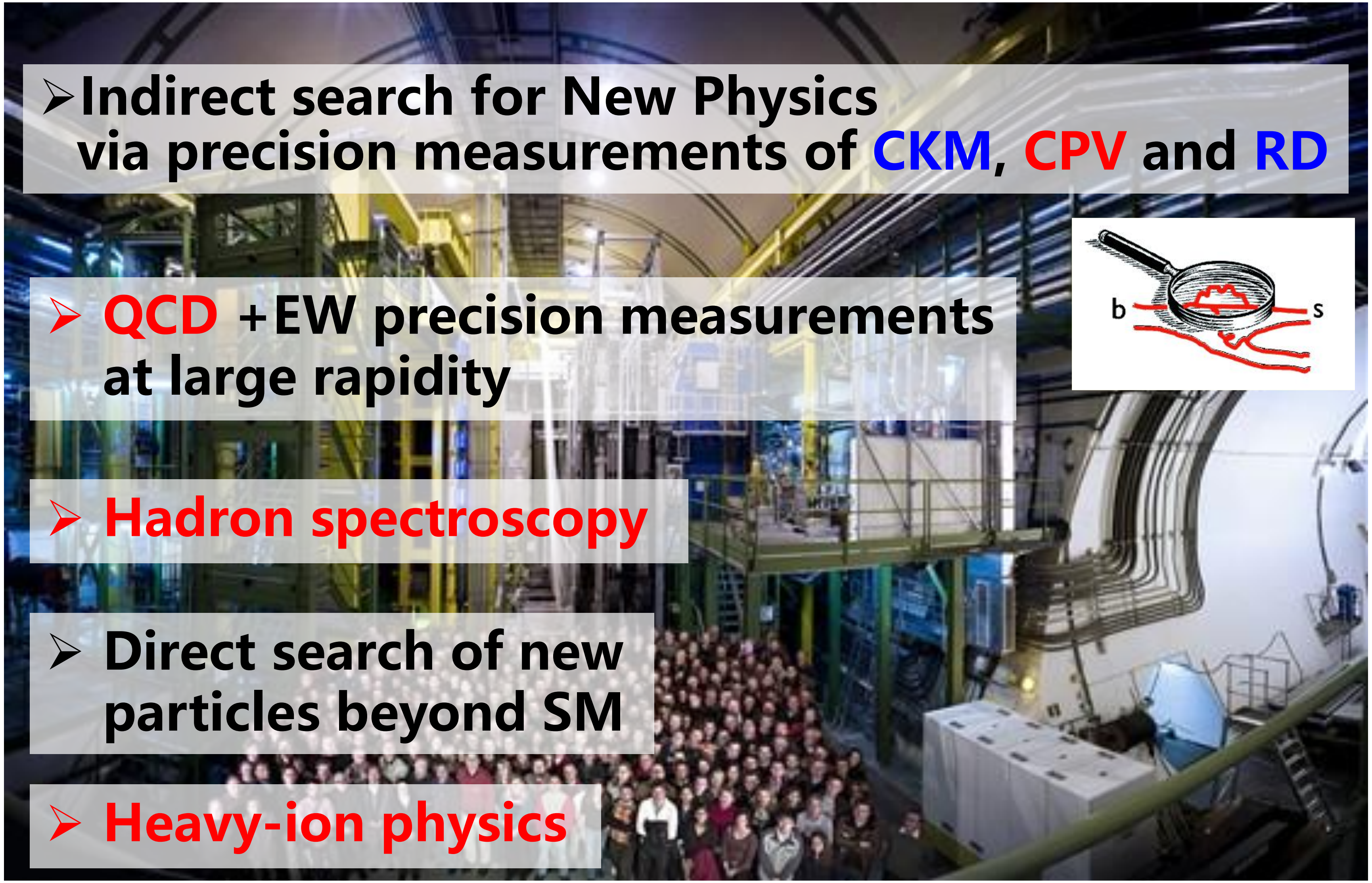


- A forward spectrometry at the LHC designed to the study of heavy flavour physics



- The LHCb collaboration
  - 1250 Members, from 79 institutes in 18 countries (by 17 September 2018)

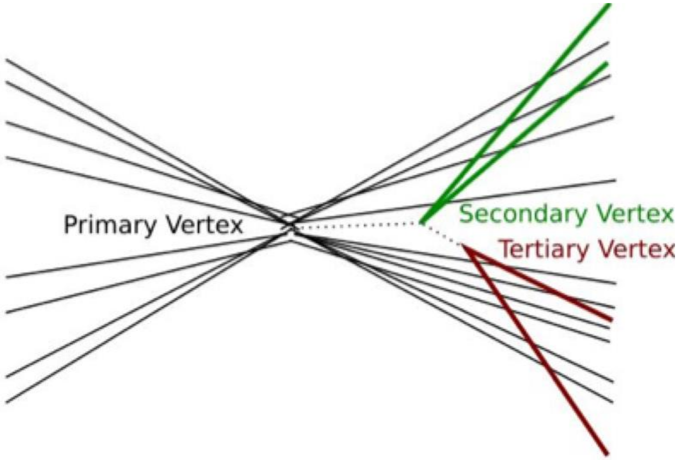
The Physics of LHCb



- ➢Indirect search for New Physics via precision measurements of **CKM**, **CPV** and **RD**

- ➢ **QCD** +EW precision measurements at large rapidity
- ➢ **Hadron spectroscopy**
- ➢ Direct search of new particles beyond SM
- ➢ **Heavy-ion physics**

Decay of b-hadrons

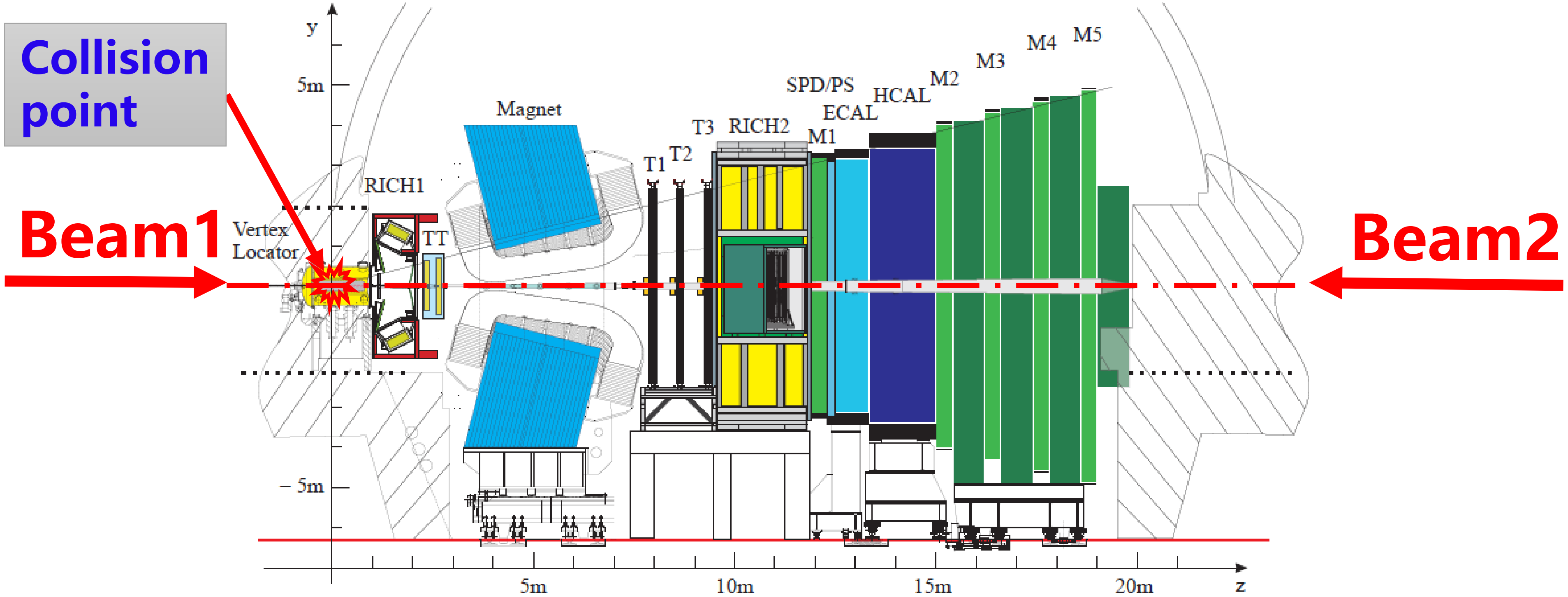


Requirements of HF

- ➢ Vertex resolution
- ➢ Time resolution
- ➢ Momentum resolution
- ➢ PID
- ➢ Efficient trigger

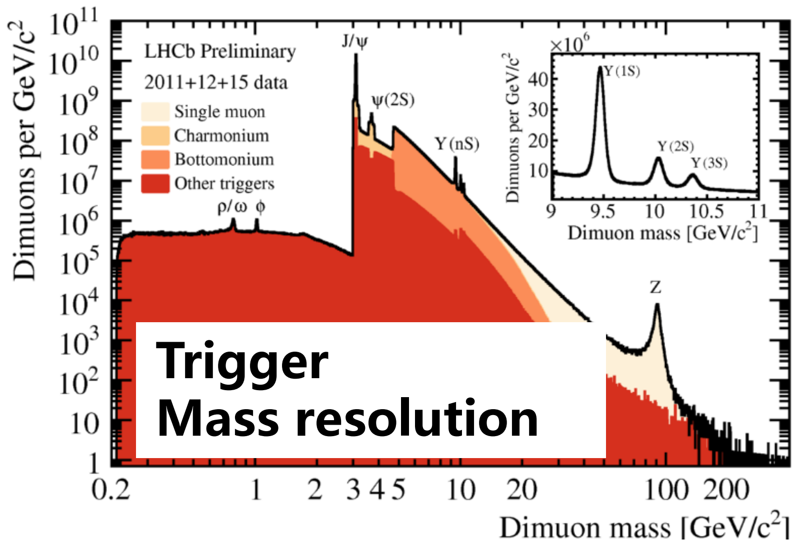
The LHCb detector

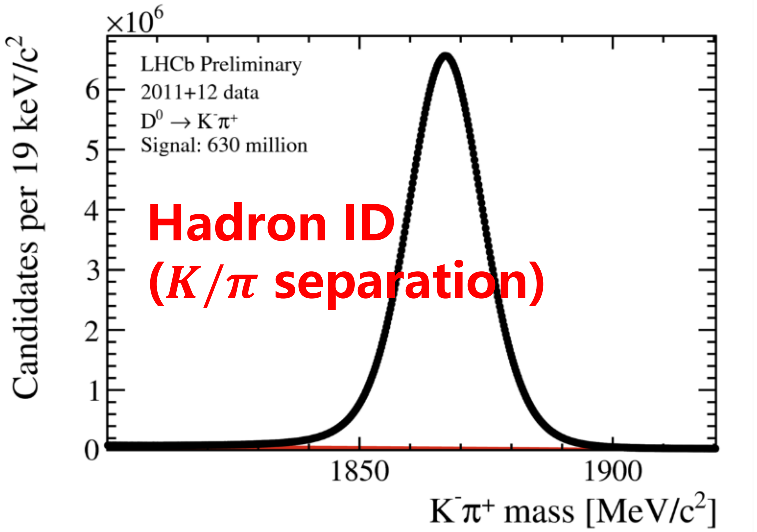
Int. J. Mod. Phys. A 30 (2015) 1530022

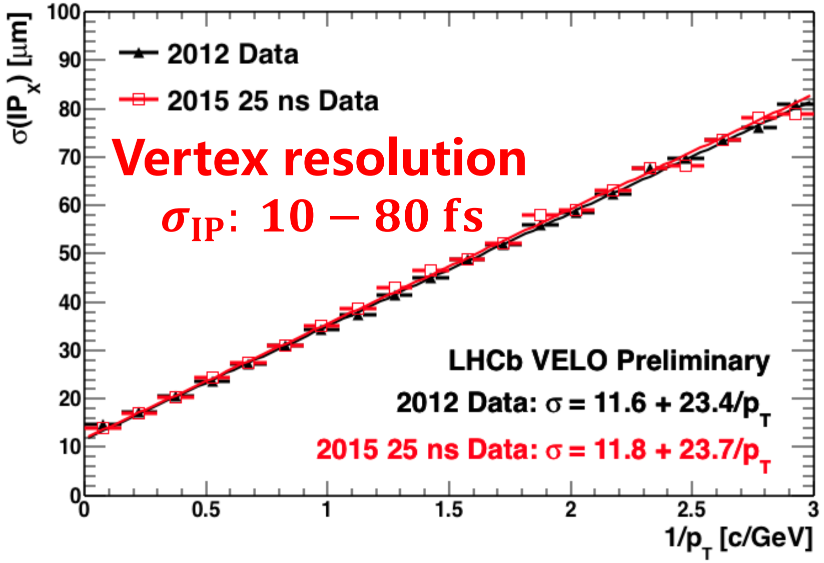


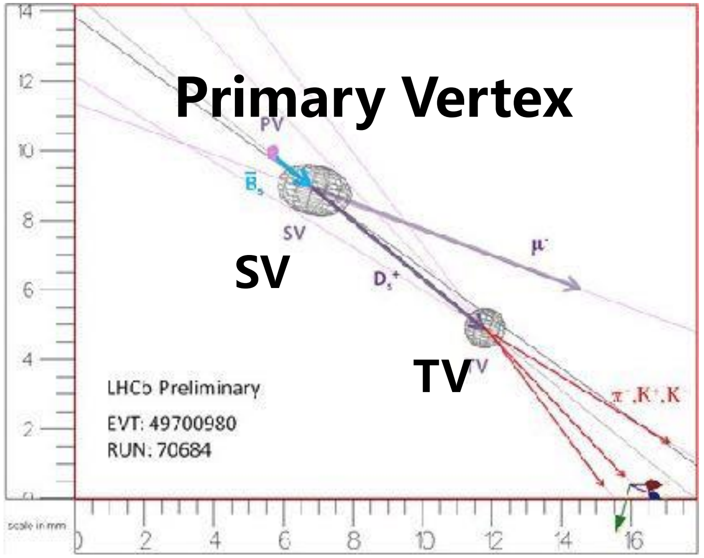
顶点精度:	$\sigma_{IP} = 20\ \mu\mathrm{m}$
时间分辨率:	$\sigma_\tau = 45\ \mathrm{fs}$ for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
动量分辨率:	$\Delta p/p = 0.4 \sim 0.6\%$ $(5 - 100\ \mathrm{GeV}/c)$
质量分辨率：	$\sigma_m = 8\ \mathrm{MeV}/c^2$ for $B \to J/\psi X$ (constrained $m_{J/\psi}$)
强子鉴别:	$\varepsilon(K \to K) \sim 95\%$ mis-ID $\varepsilon(\pi \to K) \sim 5\%$
缪子鉴别:	$\varepsilon(\mu \to \mu) \sim 97\%$ mis-ID $\varepsilon(\pi \to \mu) \sim 1 - 3\%$
电磁量能器:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E\ (\mathrm{GeV})}$

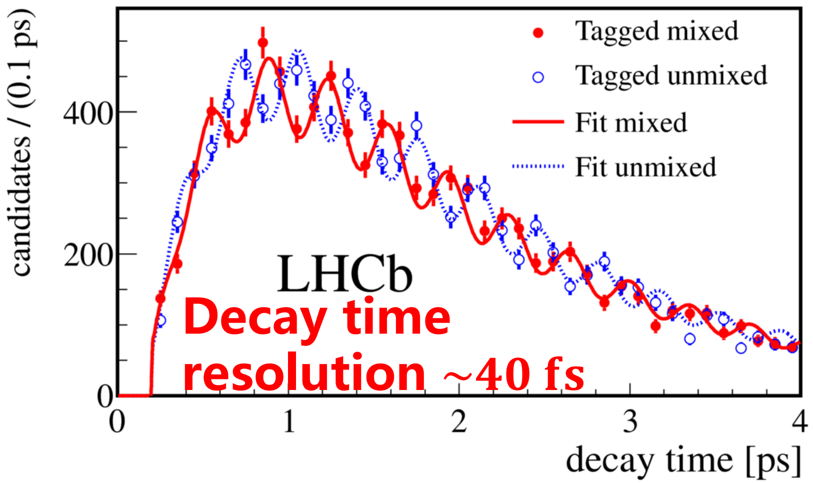
Performance of the LHCb detector



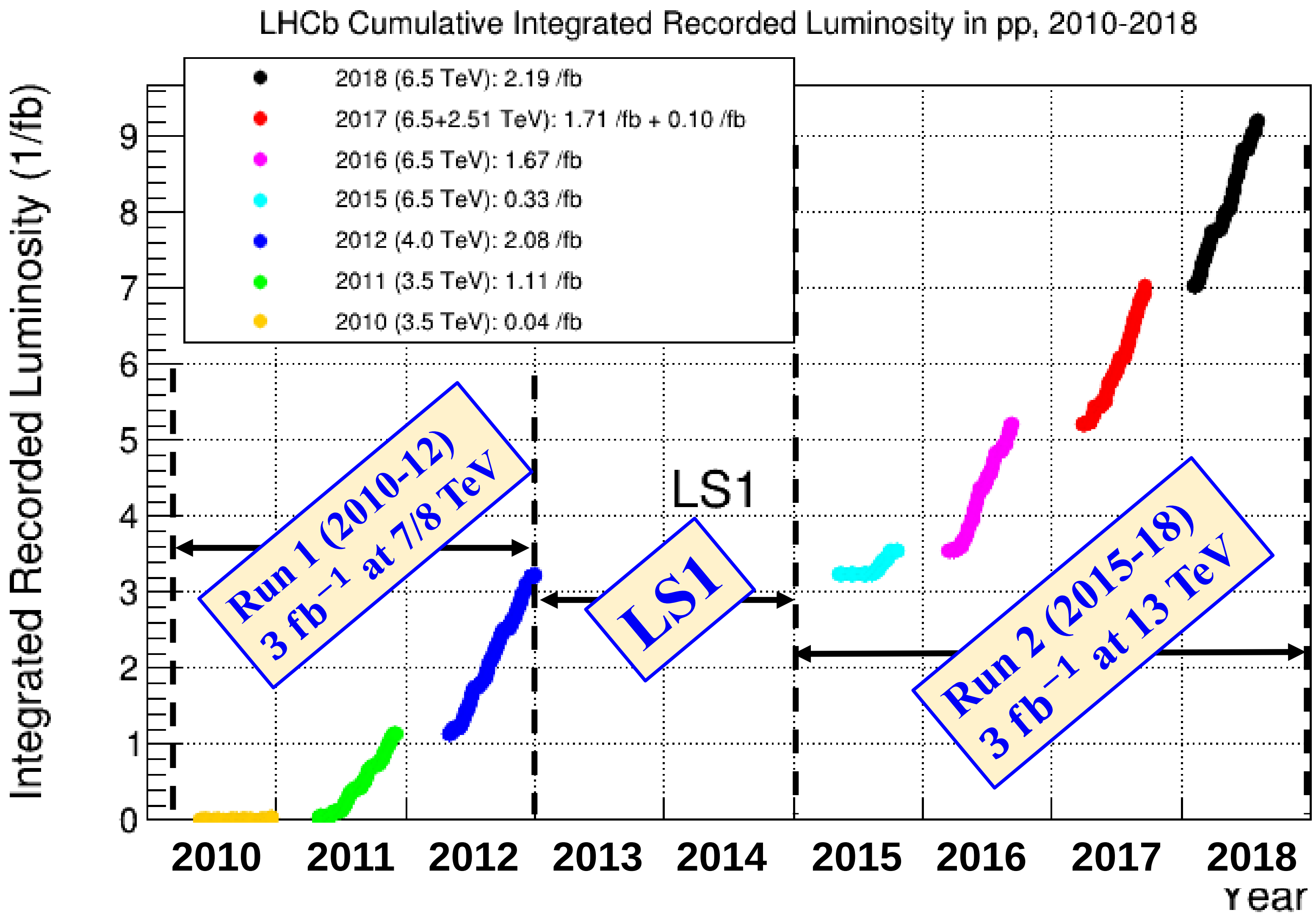








Data taking (run1+run2)



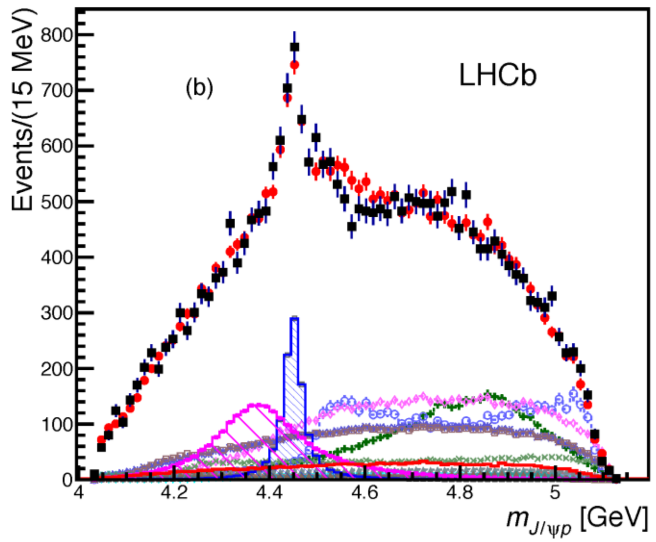
- A huge amount of $b\bar{b}$ and $c\bar{c}$ have been produced
  - $\sim 10^{12}\ b\bar{b}$
  - $\sim 10^{13}\ c\bar{c}$
- Many impressive results have been achieved
  - Mostly based on the Run1 data (3 fb^{-1})
  - Some analyses used 5 fb^{-1} data

More than 9 fb^{-1} accumulated in Run1+Run2

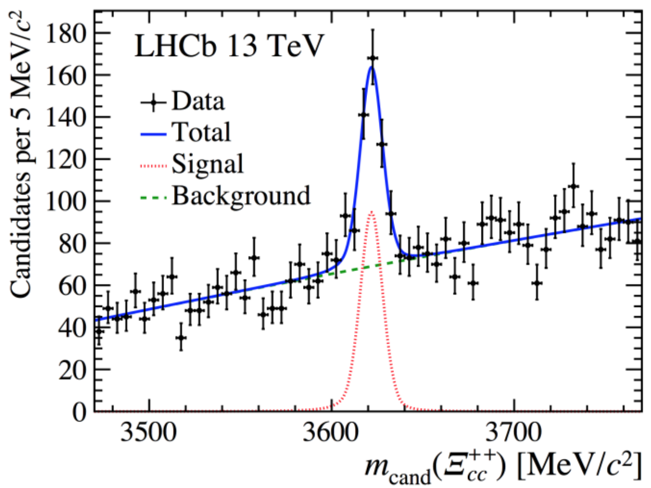
Spectroscopy: observation of P_c^+ and Ξ_{cc}^{++}

- Observation of two pentaquarks in the $J/\psi p$ spectrum of $\Lambda_b^0 \to J/\psi p K^-$ decays (2015)
  - Full amplitude analysis performed
- Observation of the doubly charmed baryon $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ (2017)
  - Mass and lifetime measured
  - Confirmed in the $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ decay

- The LHCb China groups have been playing a leading role in these observations
- Essential inputs from Chinese theorists



PhysRevLett.115.072001

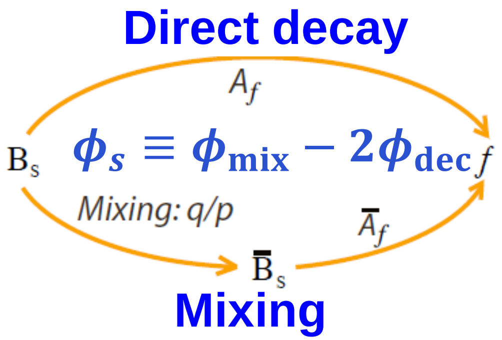


PhysRevLett.119.112001

CPV: ϕ_s measurement

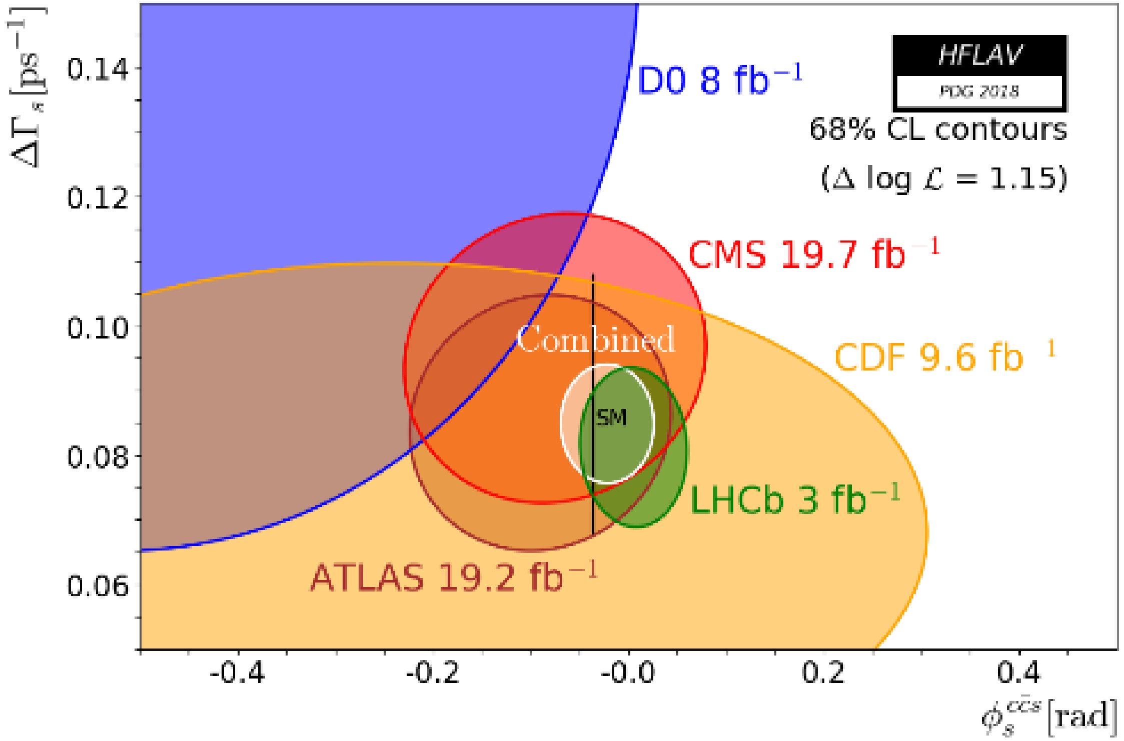
PRL 114 (2015) 041801

JHEP 08 (2017) 037



➢ The phase angle ϕ_s of $B_s^0 - \bar{B}_s^0$ mixing is a benchmark measurement of LHCb

- SM prediction: $\phi_s^{SM} = -0.038 \pm 0.001$ rad
- New Physics could introduce large ϕ_s



➢LHCb combination with the Run1 data

$$\phi_s = +0.001 \pm 0.037 \text{ rad}$$

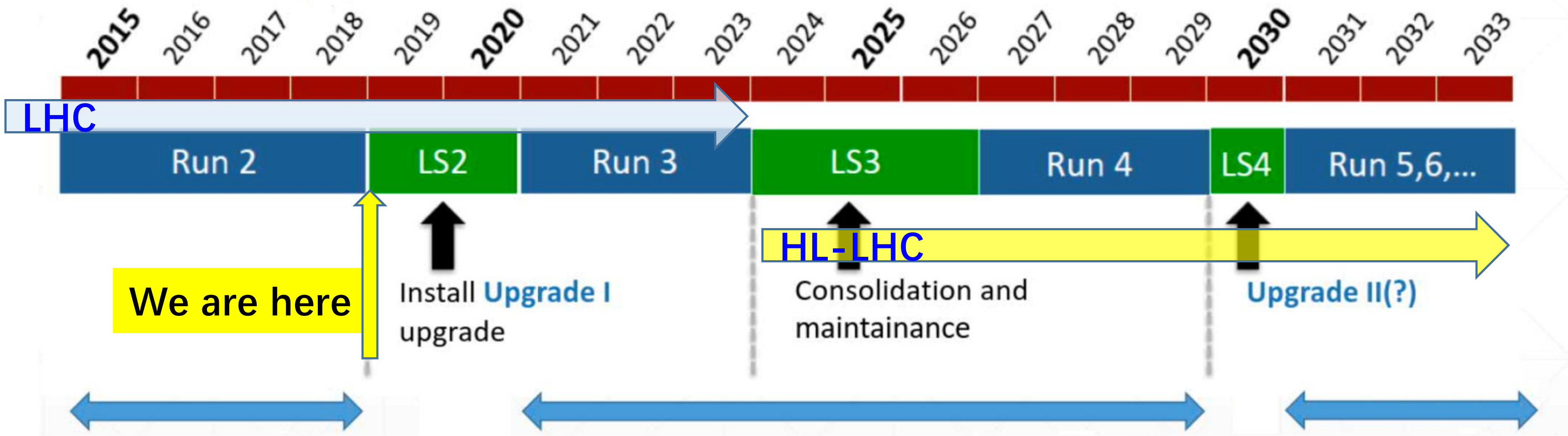
➢World average

$$\phi_s = -0.021 \pm 0.031 \text{ rad}$$

- The world average dominated by the LHCb result
- The LHCb China groups have been playing a leading role

Upgrade to deepen our understanding of HF ...

Plan of the LHC(b) upgrade



$\mathcal{L}^{\max} = 4 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
1.1 visible interactions per bunch crossing

$\mathcal{L}^{\max} \to 5\mathcal{L}^{\max}$

$\mathcal{L}^{\max} = 2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
5.5 visible interactions per bunch crossing

$\mathcal{L}^{\max} \to 10\mathcal{L}^{\max}$

$\mathcal{L} = 2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
55 visible interactions per bunch crossing

LHCb up to 2018→ $9\ \mathrm{fb}^{-1}$

- ✓ Demonstrated feasibility of high precision flavour physics at hadron colliders
- ➢ Find/rule out large sources of NP at the TeV scale

LHCb Upgrade I → $\geq 50\ \mathrm{fb}^{-1}$

- ✓ Increase trigger efficiency
- ➢ Aim at experimental sensitivities comparable to theoretical uncertainties

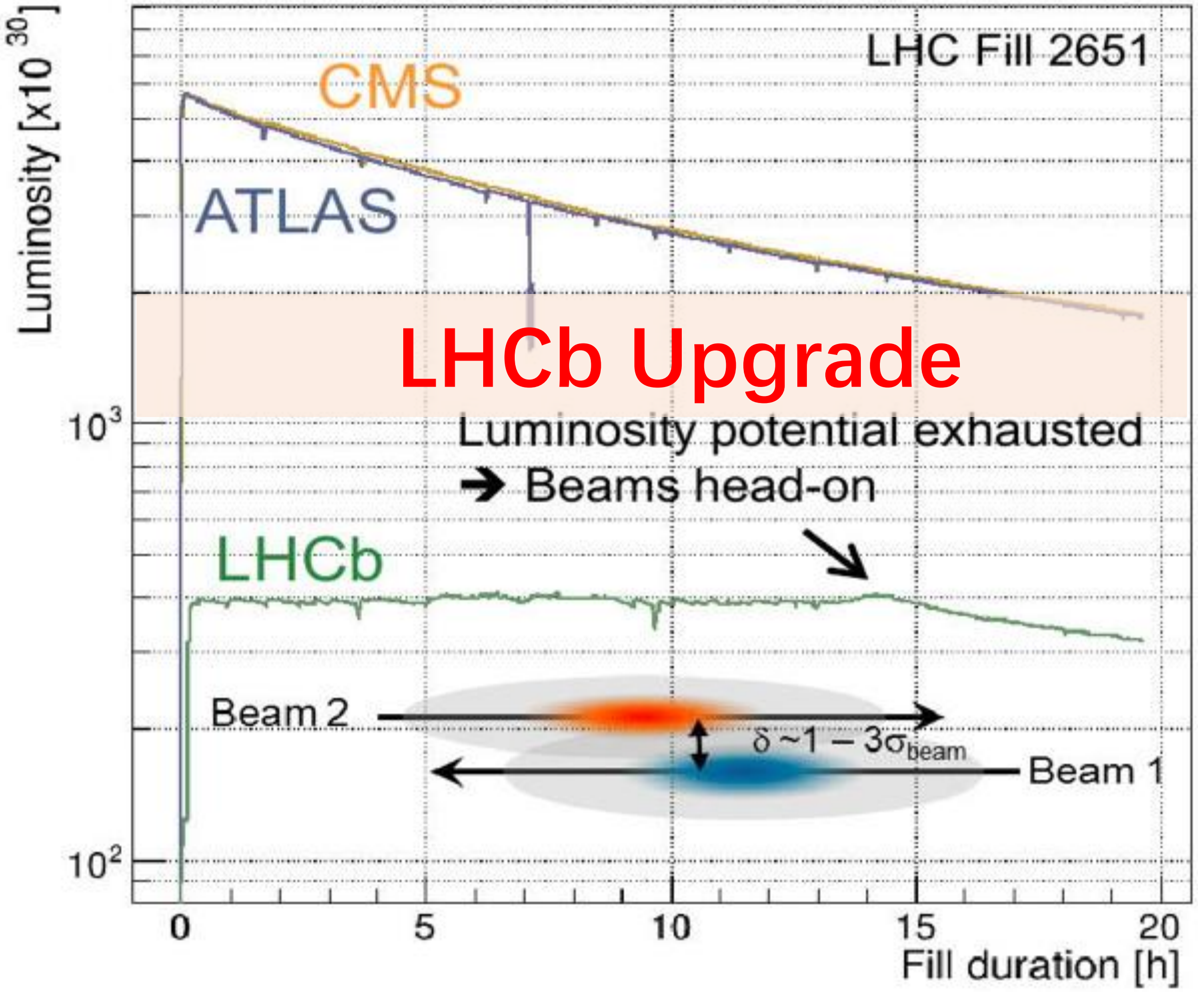
LHCb Upgrade II → $\geq 300\ \mathrm{fb}^{-1}$

- ✓ Take full profit of HL-LHC
- ➢ Physics document has been submitted to LHCC arXiv:1808.08865

LHCb Upgrade I

- Installation in 2019 and 2020
- Aiming at $\mathbf{50\ fb^{-1}}$ by 2029

How to increase the LHCb statistics significantly?

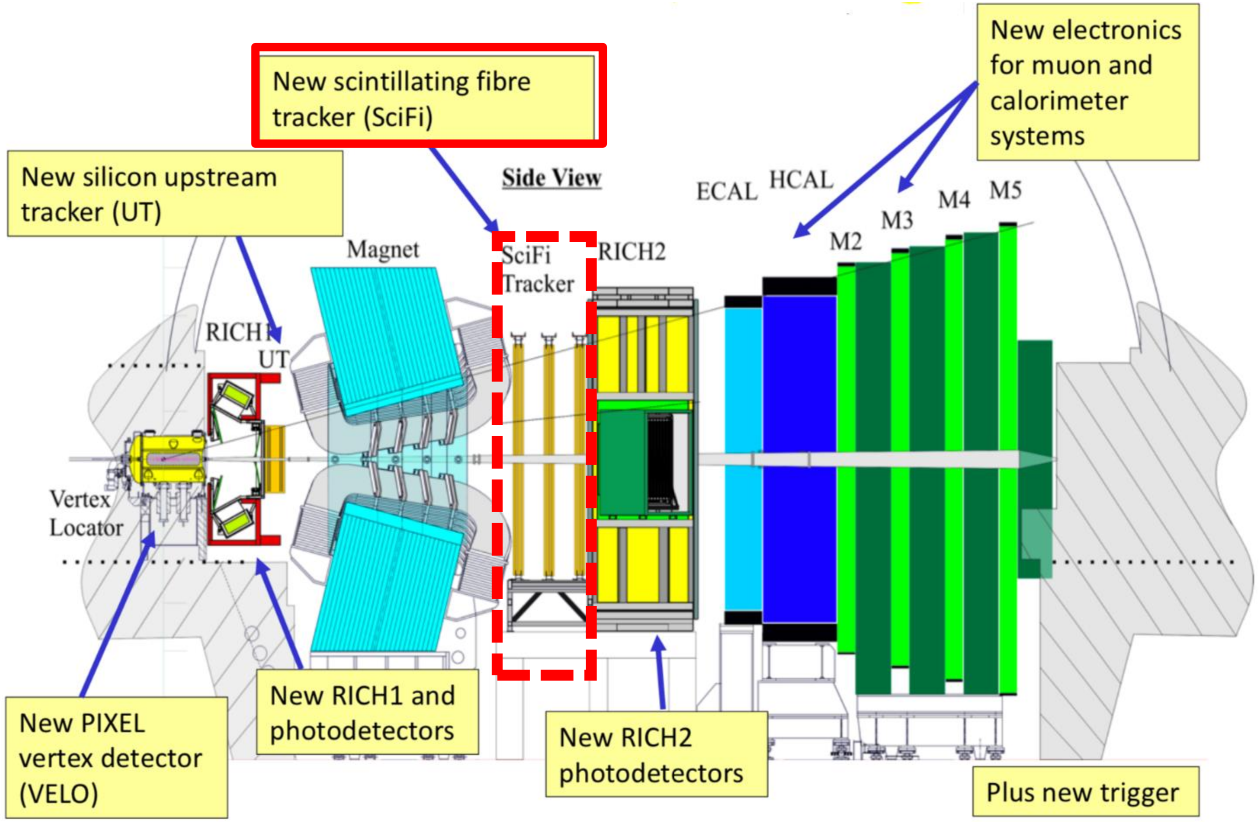


- **LHCb up to LS2 (2018)**
  - Running at levelled luminosity of $\sim 4 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, pile-up~1
  - First level hardware trigger running at event rate ~1 MHz
  - Record ~12 kHz (0.6 GB/s)
- **LHCb Upgrade I (2021-)**
  - Increase luminosity to a levelled $1 - 2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, pile-up~5
  - Run fully flexible and efficient software trigger up to 40 MHz
  - Record with 2-5 GB/s

The most severe bottlenecks:
- Hardware trigger limited to ~ 1 MHz
- Tracking reconstruction

The LHCb Upgrade I detector

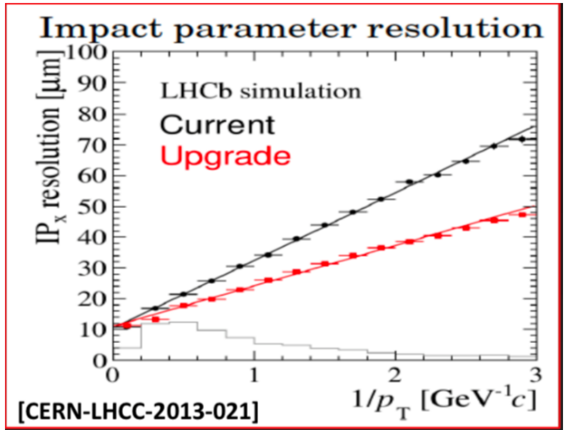
- A complete new detector
  - All sub-detectors read out at 40 MHz for a fully software trigger

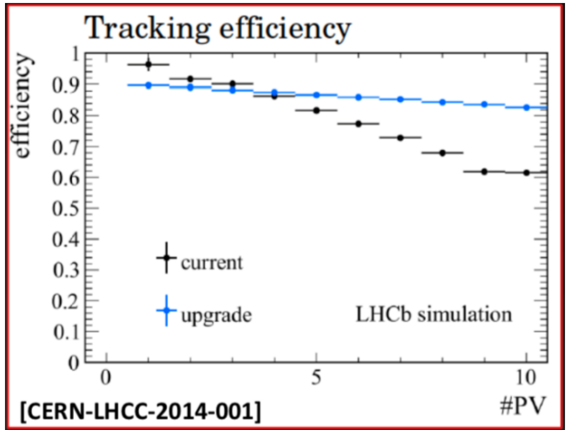


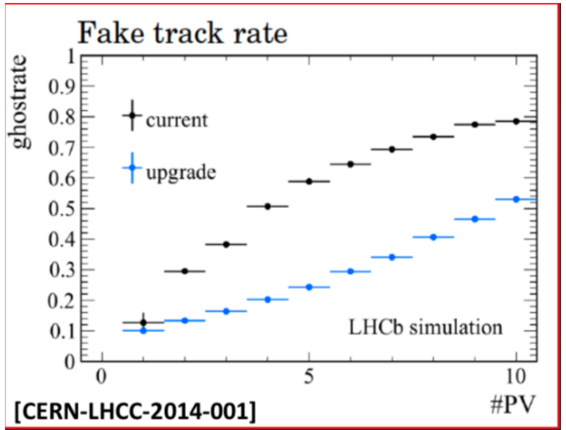
- **Tracking system**
  - VELO: Silicon strip → $55 \times 55\ \mu m^2$ PIXEL
  - TT→ UT: Silicon strip → Silicon microstrip
  - T1-T3→SciFi: Straw + silicon microstrip
    → Scintillating Fibre Tracker
- PID system
  - RICH: HPD → MaPMT
    improved optics + mechanics
  - ECAL/HCAL: remains the same
    ECAL inner modules replaced in LS3
  - Muon: increased granularity

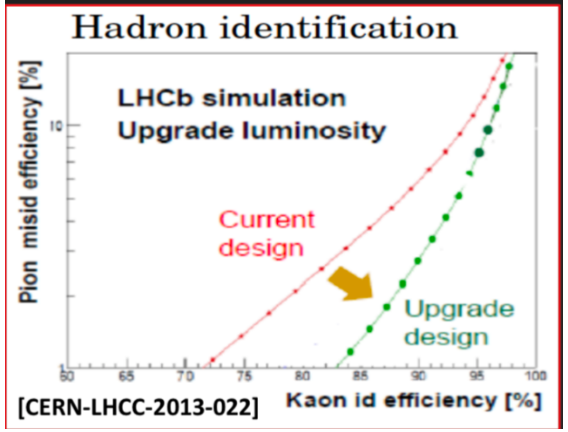
Expected detector performance

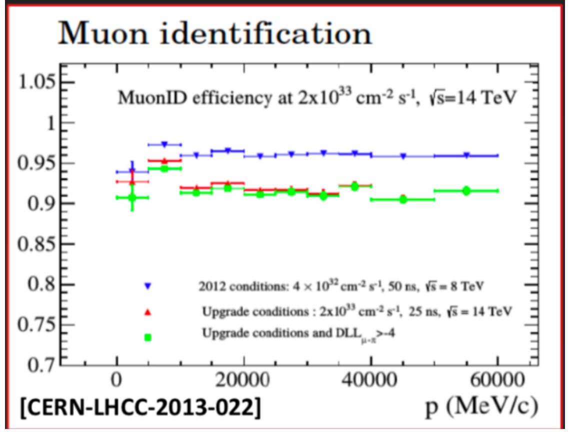
- Compare upgraded LHCb with current LHCb in upgrade condition
  - Resolution improved, efficiency increased, fake rate decreased

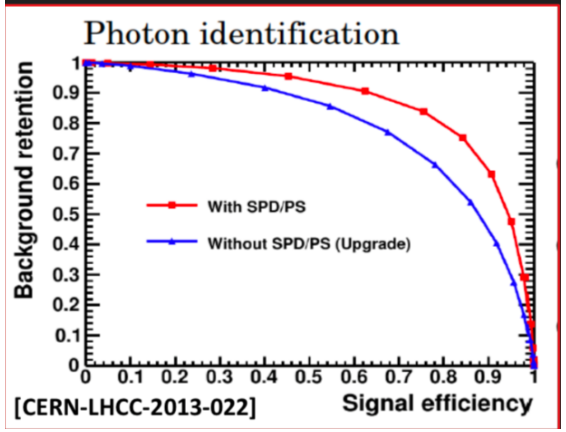




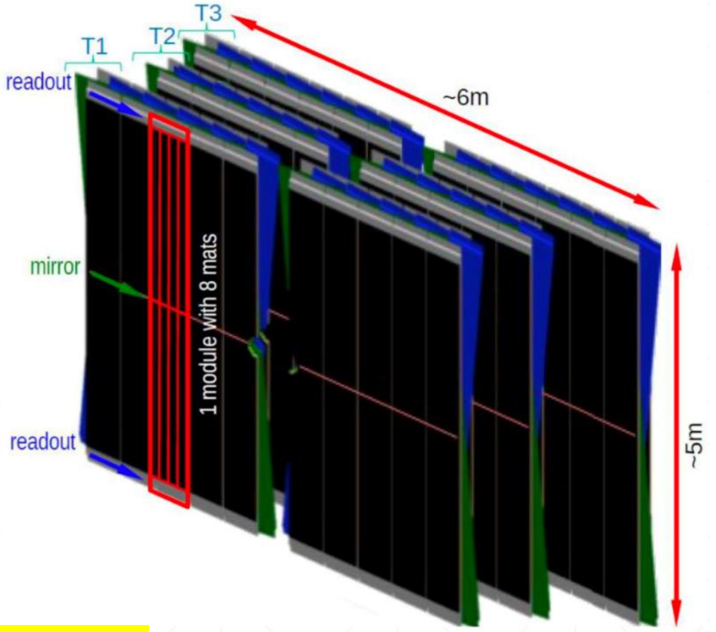








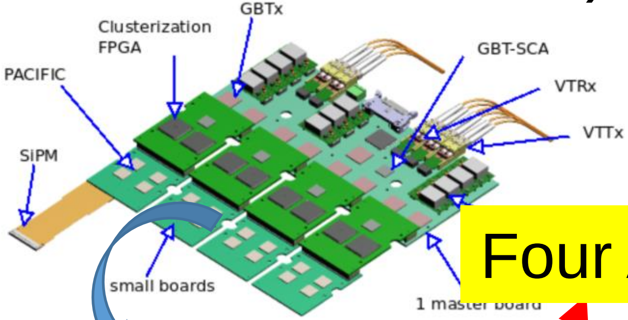
Scintillating Fibre (SciFi) tracker

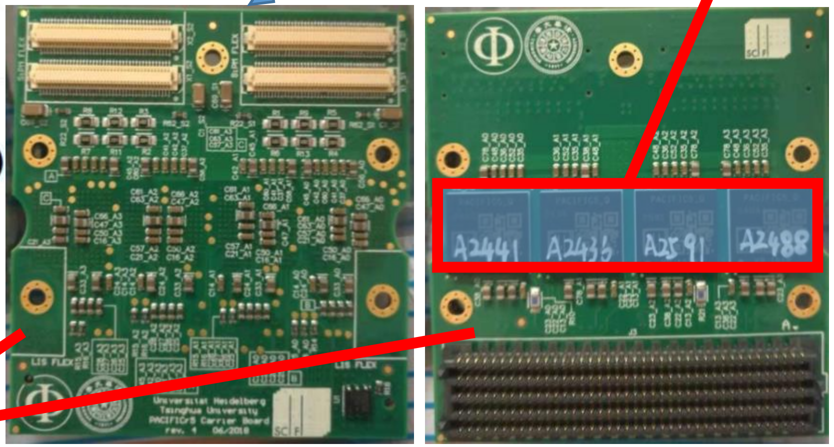


- 11,000 km of Ø250 μm fibres
- 524k SiPM channels
  - cooled down to −40 ℃
- 3 planes of modules

✓ fast, high efficiency (~99%)
✓ high granularity (250μm)
✓ high resolution (<100μm)
✓ low mass (<1% X_0 /layer)
✓ radiation hardness (up to 35 kGy)

Readout electronics)





Four ASICs

- **PASIFIC ASICs carrier board designed by Tsinghua & Heidelberg**
- **ASIC QA and carrier board QA system developed by Tsinghua**

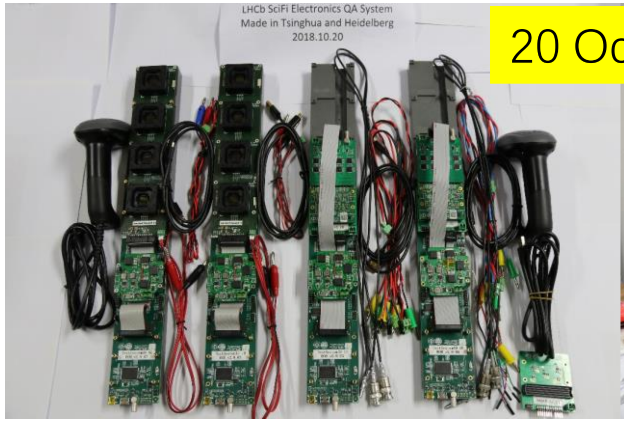
12000 ASICS, 2500 carrier boards

PACIFIC ASICs Carrier Board

SciFi electronics QA system

- The first bunches of ASICs tested by Tsinghua in May
- The first 22+228 carrier boards produced, tested and sent to CERN for testbeam in July and October
- A team sent to Barcelona and Valencia in 20 October to set up the QA systems (returned this morning)

21 Sept. at Tsinghua



20 Oct. at Tsinghua

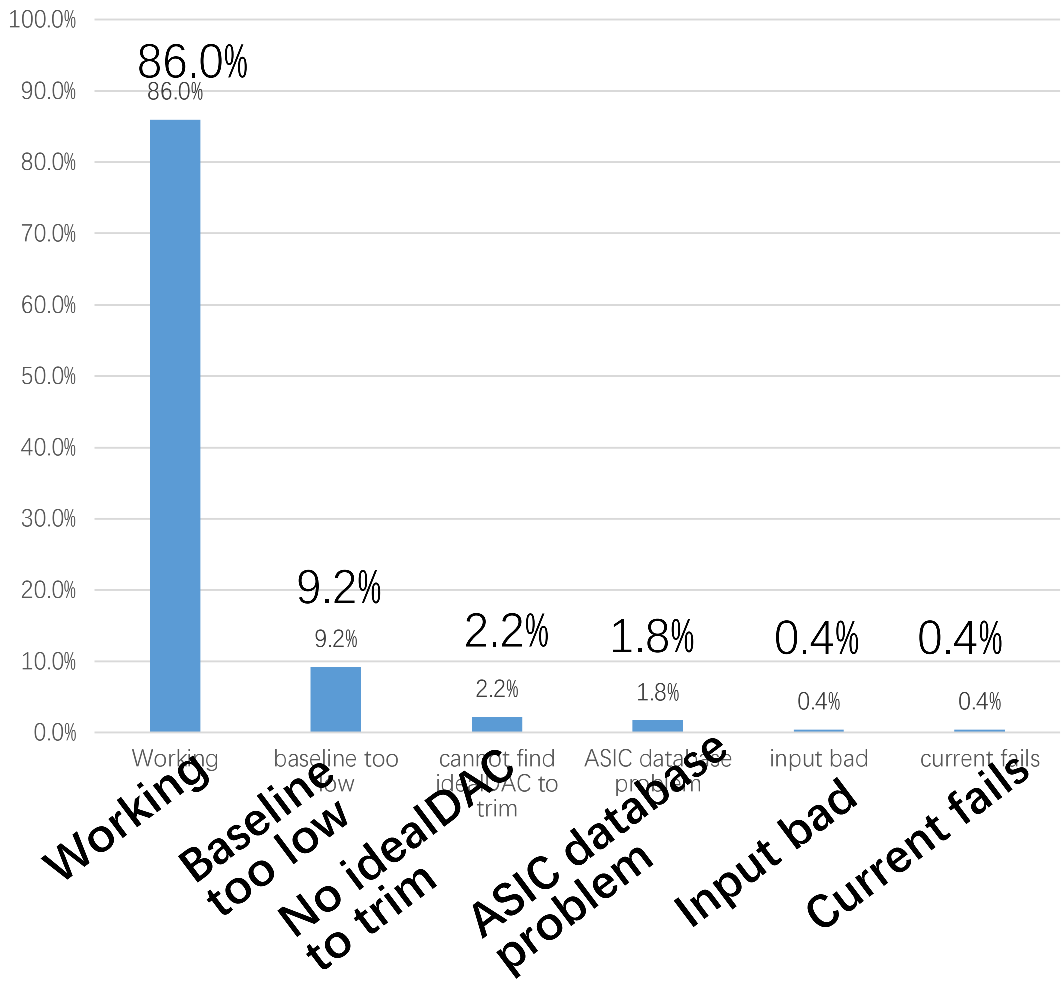
22 Oct. at Barcelona

24 Oct. at Valencia

28 Oct. at Tsinghua

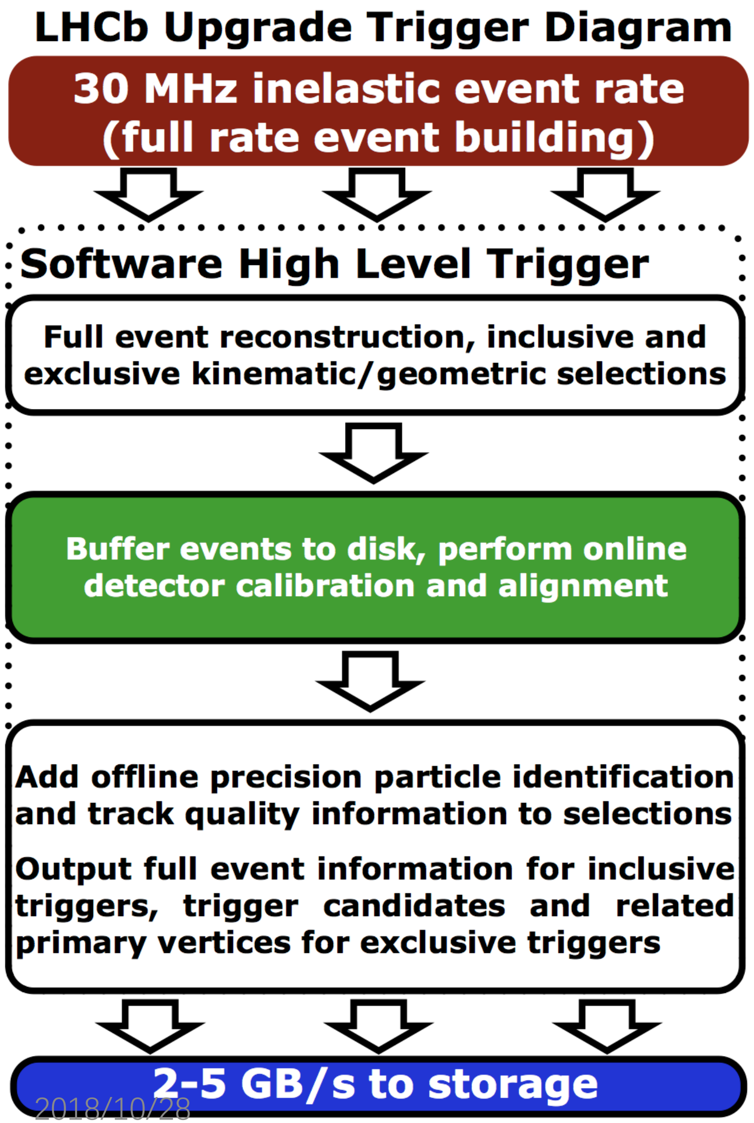
Carrier Board QA results

- 228 Carrier Boards tested
  - 196 Boards are working
  - 32 Boards are failed



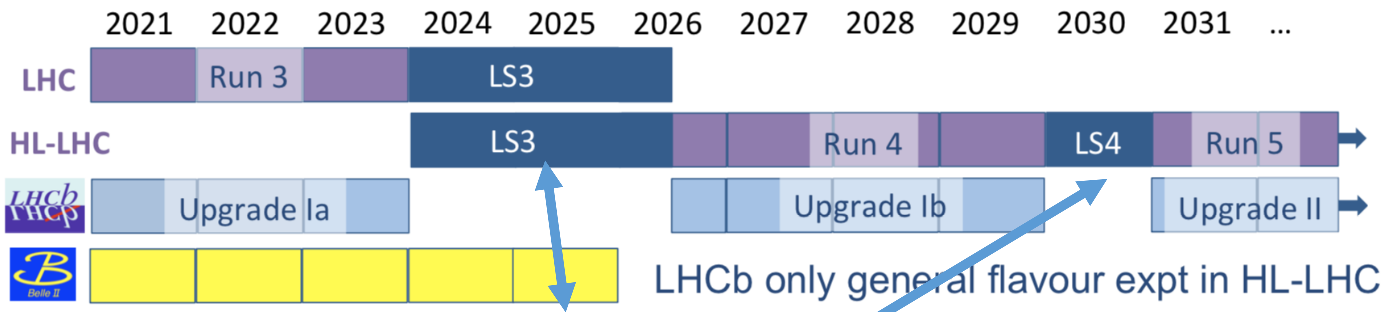
The ASIC test criteria tuned according to the result of the first bunch of Carrier Boards

LHCb Upgrade trigger



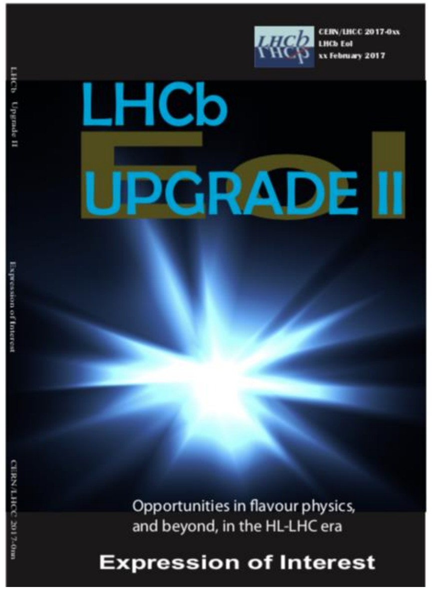
- Hardware triggerless
  - 30 MHz inelastic event rate
  - Online calibration and alignment
- Full reconstruction and physics analysis in real time
  - Save output in the "Turbo" scheme: only part of the event, e.g. primary vertex (PV) + secondary vertex (SV) + daughter tracks of triggered signals
    - Already used in Run2
  - Save to disk at 2-5 GB/s

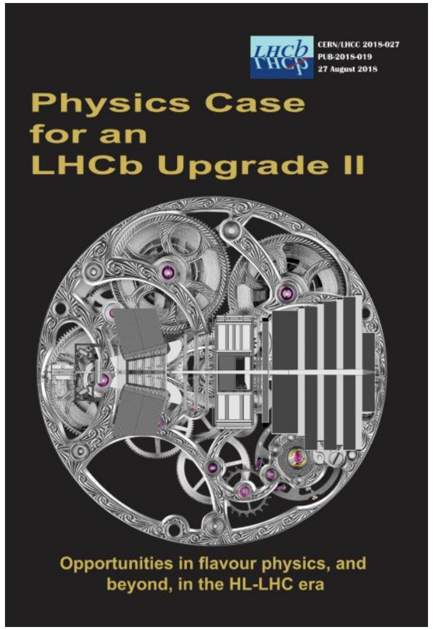
LHCb Upgrade II(+Ib)



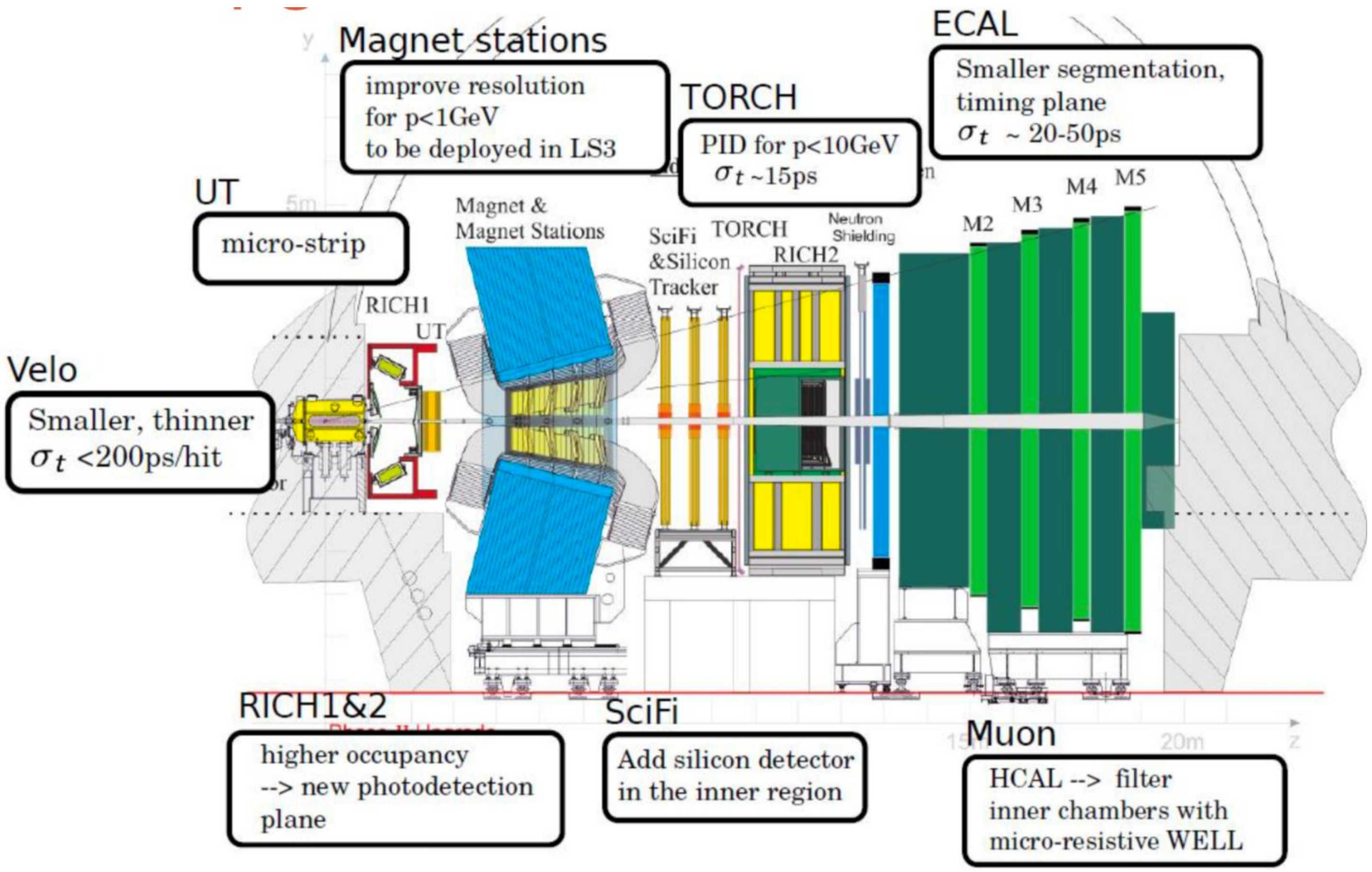
LHCb only general flavour expt in HL-LHC era

- ➢ Consolidate in LS3
- ➢ Major upgrade in LS4
- ➢ EOI submitted in 2017 (CERN-LHCC-2017-003)
- ➢ Physics document submitted in 2018 (arXiv:1808.08865)
- ➢ Aiming at $300\ \mathrm{fb}^{-1}$ after 2030





LHCb Upgrade II detector

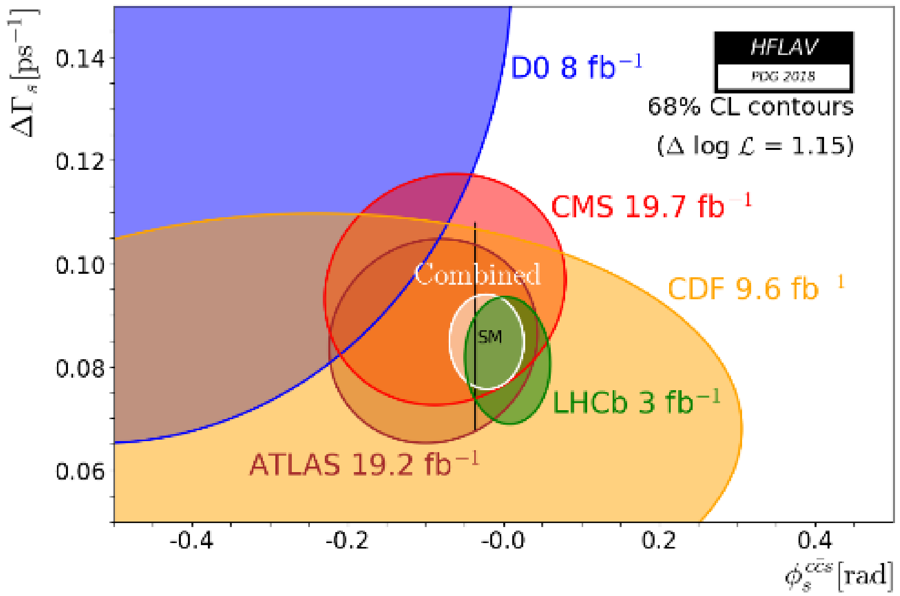


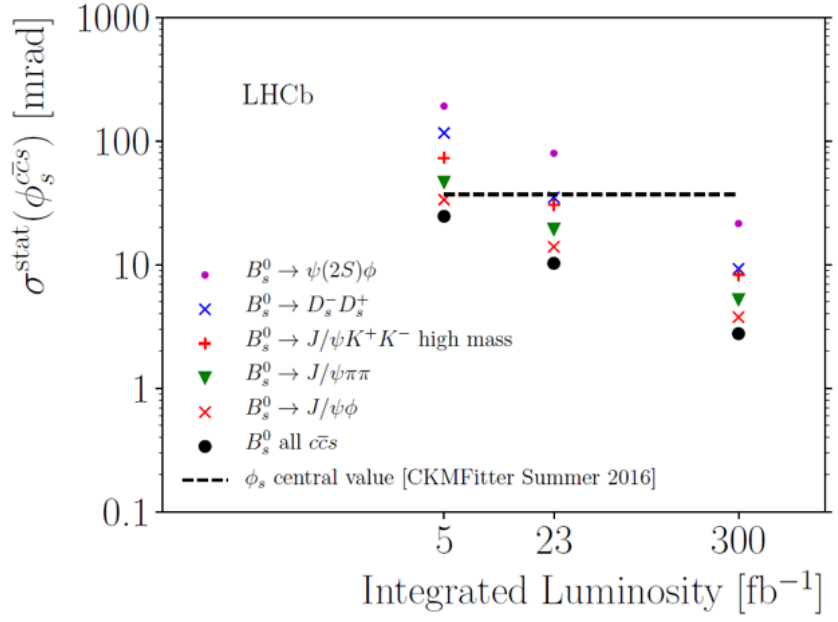
- Great challenge in detector R&D to cope with pile-up ~ 50
- Timing information essential to some subdetectors
- Feasibility studies started
- Tsinghua started the simulation study of ECAL in the beginning of 2018
  - Fast sim + full sim
  - 5D ECAL: (E, x, y, z, t)

PRL 114 (2015) 041801

JHEP 08 (2017) 037

Physics case: ϕ_s





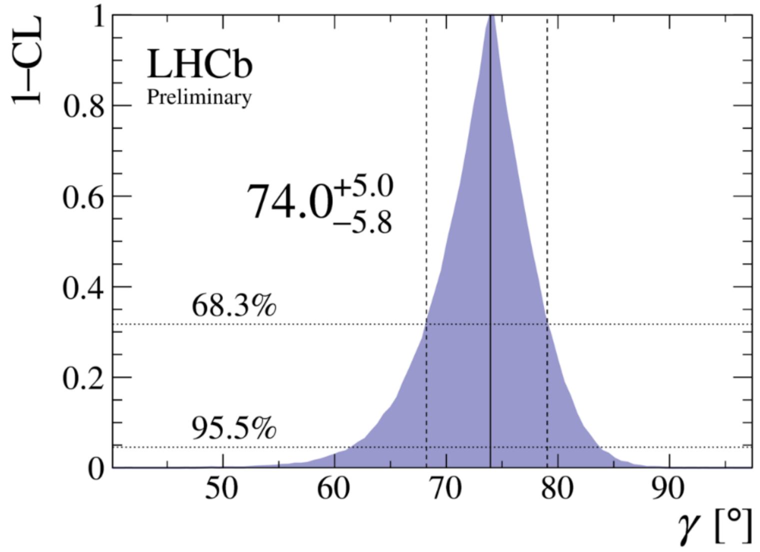
- Dominated by LHCb, with competition from other experiments
- Current precision with $B_s^0 \to J/\psi\phi$ is 49 mrad
  - 20-30 mrad with full Run1+Run2
  - ~10 mrad with $50\ \mathrm{fb}^{-1}$
  - ~ 4 mrad with $300\ \mathrm{fb}^{-1}$

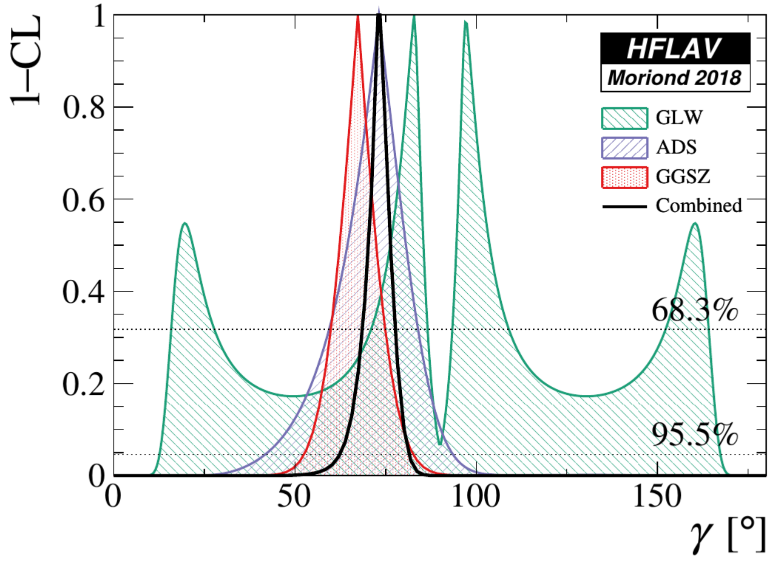
$$\phi_s^{\rm SM} = -38 \pm 1\ \mathrm{mrad}$$

Physics case: γ

- LHCb average $\gamma = (74.0^{+5.0}_{-5.8})^{\circ}$
  - Run1+Run2: $3-5\ \mathrm{fb}^{-1}$
  - World average $\gamma = (73.5^{+4.2}_{-5.1})^{\circ}$
  - Indirect determination: $\gamma = (65.3^{+1.0}_{-2.5})^{\circ}$
- Expected uncertainties
  - $< 4^{\circ}$ with full Run1+Run2
  - $\sim 0.9^{\circ}$ with 50 fb^{-1}
  - $< 0.35^{\circ}$ with 300 fb^{-1}

LHCb-CONF-2018-002

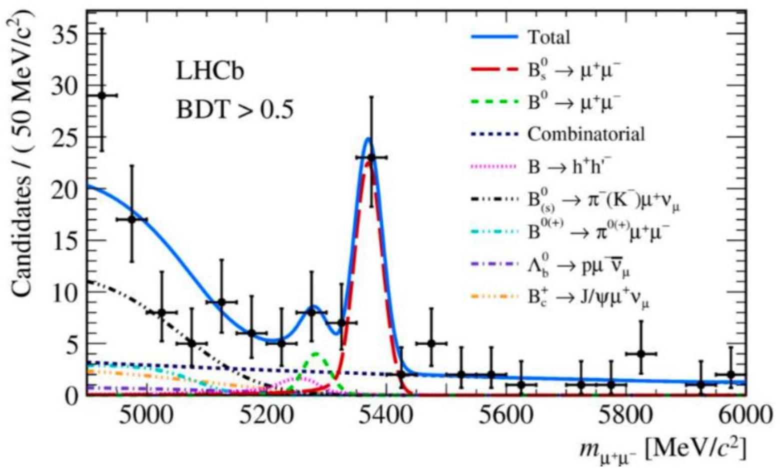


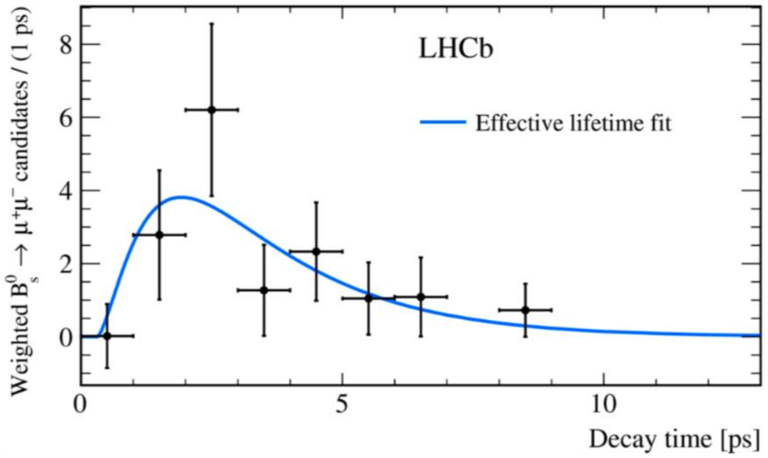


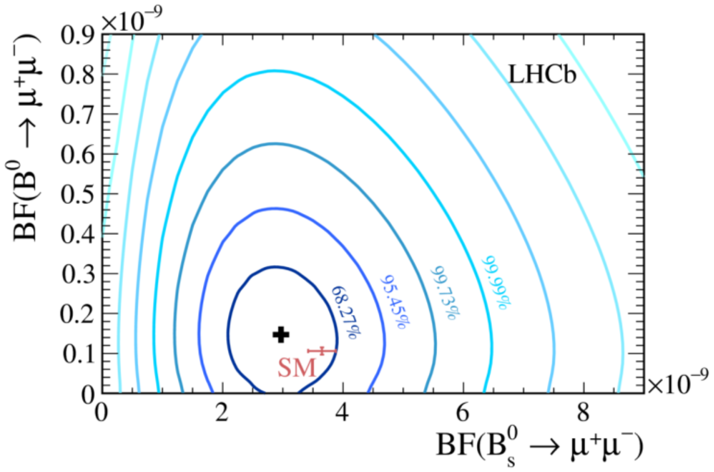
Physics case: $B^0_{(s)} \to \mu^+\mu^-$

PRL 119 (2017) 191801

- $\mathcal{B}(B^0_s \to \mu^+\mu^-)/\mathcal{B}(B^0 \to \mu^+\mu^-)$ expected to be measured with 10% uncertainty with $300\ \mathrm{fb}^{-1}$
- Effective lifetime with an uncertainty of ~ 2%
  - Good discrimination between NP models
- Worthwhile measurement (~20%) of CP asymmetry – impossible at Upgrade I





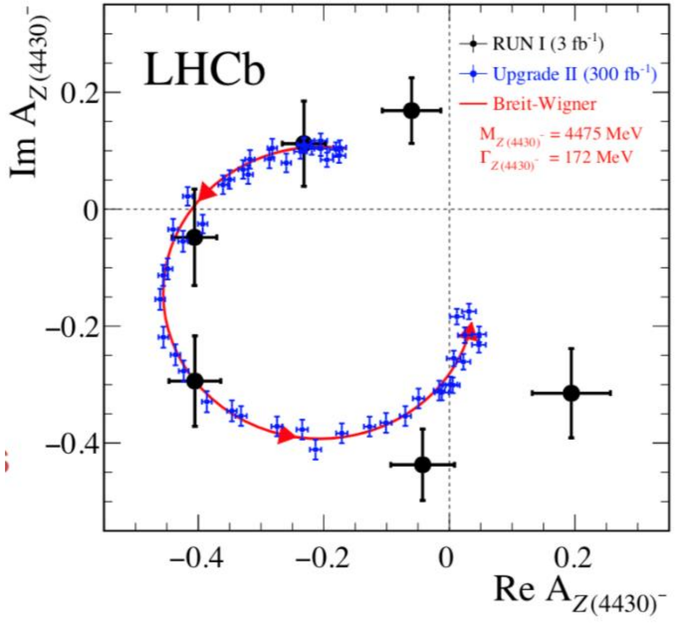


Physics case: hadron spectroscopy

arXiv:1808.08865

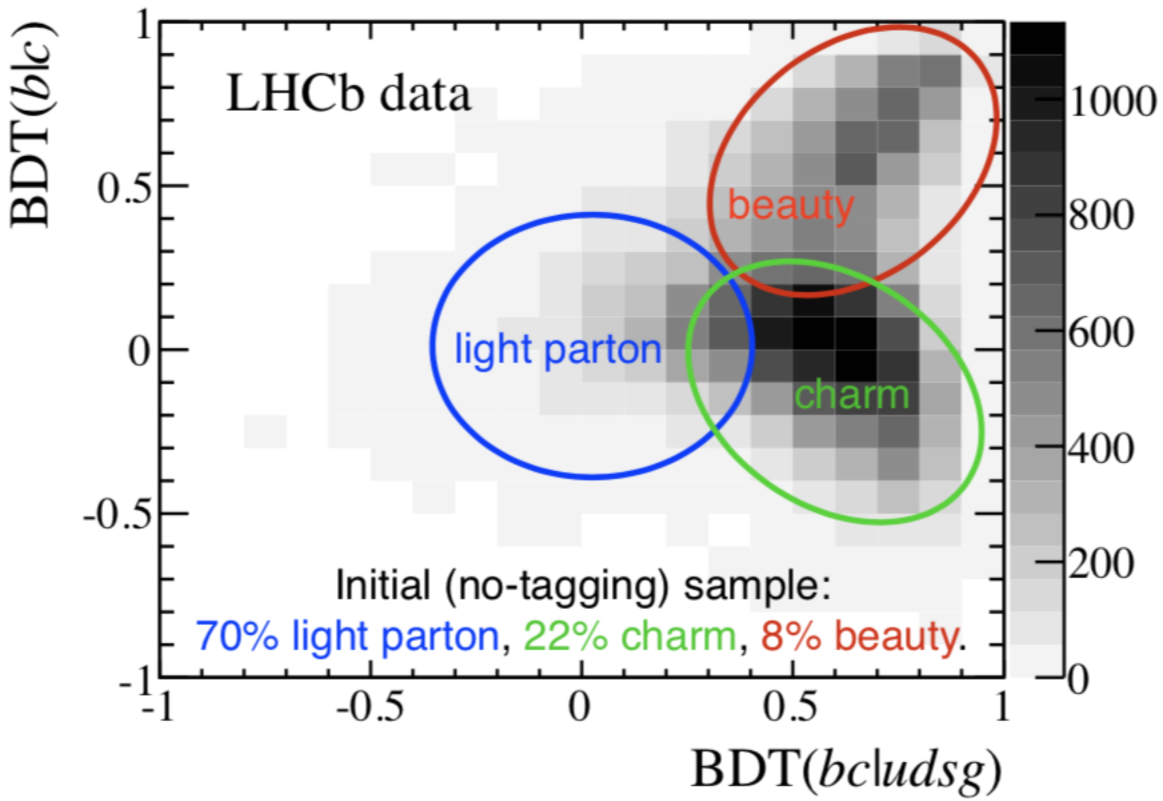
- Much more b- and c-hadrons would be produced with the Upgrade
- A gold mine of hadron spectroscopy studies
  - Observation of new states
  - Precision determination of the characteristics of observed hadrons
  - Understand the nature of these states and strong interactions

Decay mode	LHCb 23 fb^{-1}	LHCb 50 fb^{-1}	LHCb 300 fb^{-1}	Belle II 50 ab^{-1}
$B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$	14k	30k	180k	11k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k	4k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M	140k
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100	—
$\Lambda_b^0 \to J/\psi\, pK^-$	340k	700k	4M	—
$\Xi_b^- \to J/\psi\, \Lambda K^-$	4k	10k	55k	—
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$	7k	15k	90k	<6k
$\Xi_{bc}^+ \to J/\psi\, \Xi_c^+$	50	100	600	—



Physics case: Higgs

arXiv:1808.08865



- ➢ Potential for best Higgs to charm limits at the LHC
- ➢ Unique sensitivity for BSM long-lived and dark sector particles

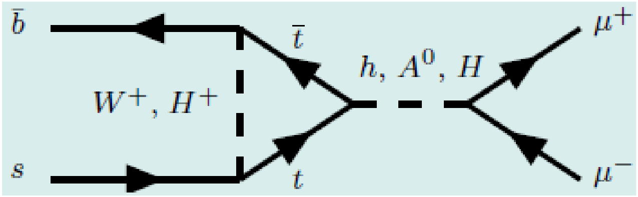
Summary

- LHCb has emphatically demonstrated its ability to make discoveries and perform unique measurements in topics beyond flavour physics
- LHCb Upgrade I detector will be installed during LS3
  - Hardware trigger at event rate ~30 MHz
  - Real time event construction
  - Expect 23 fb^{-1} by 2025 and $\mathbf{50\ fb^{-1}}$ by 2029
- LHCb Upgrade II aiming at $300\ \mathrm{fb}^{-1}$ with fully new detector to deepen our understanding of heavy flavour physics
- Your inputs are essentially welcome

Thank you

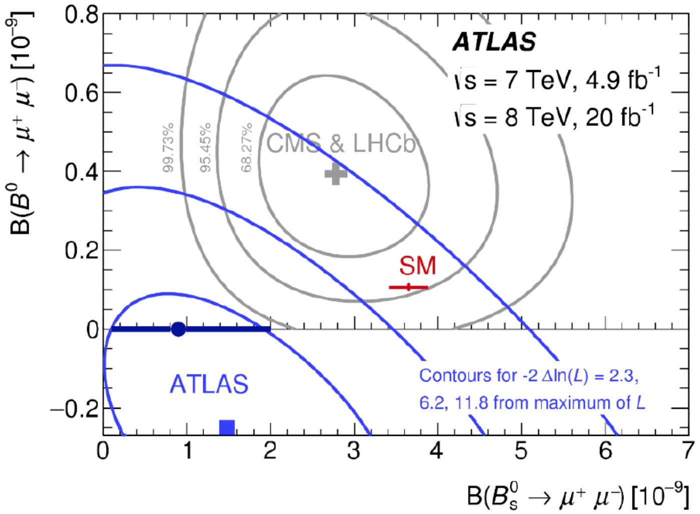
Backup slides

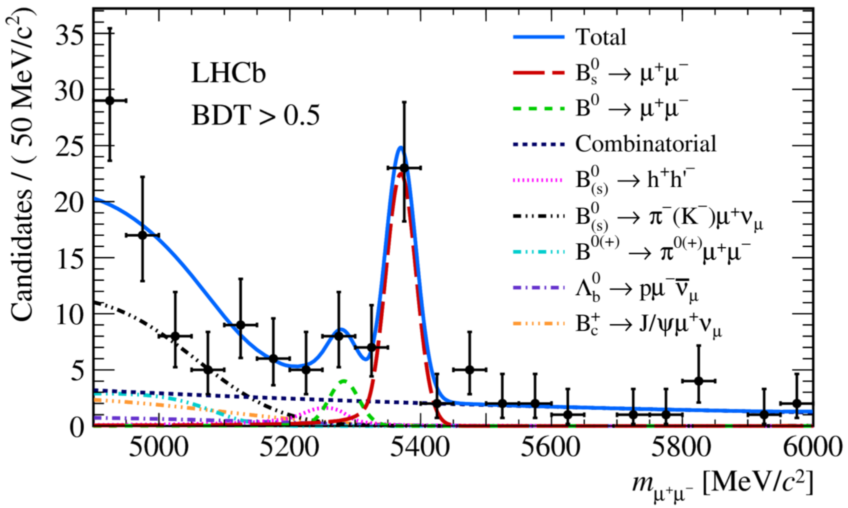
Rare decays: $B^0_{(s)} \to \mu^+\mu^-$

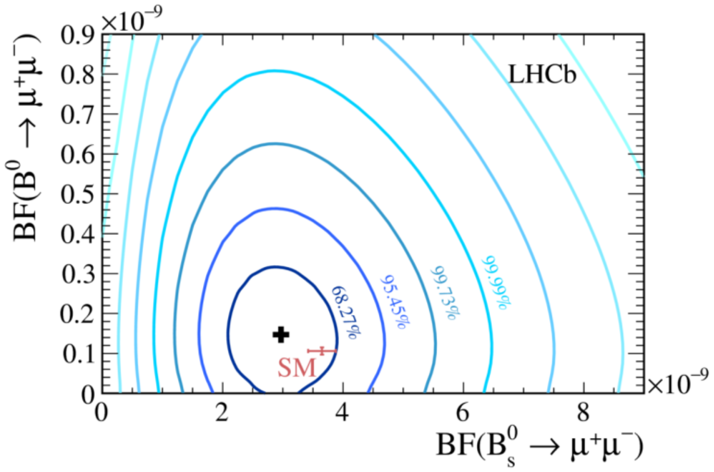


- Very suppressed in Standard Model, sensitive to NP
- Observation of $B^0_s \to \mu^+\mu^-$ by combined LHCb&CMS data in 2015
- Observation of $B^0_s \to \mu^+\mu^-$ by a single experiment (LHCb) in 2017

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

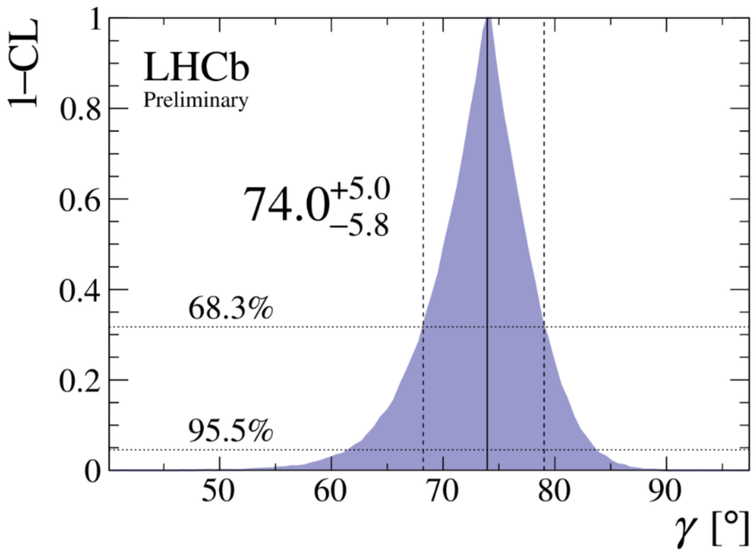


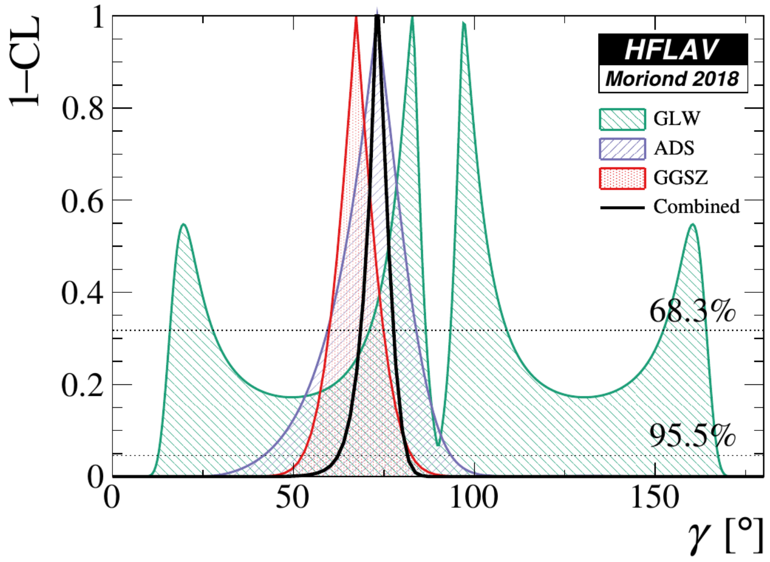




CKM: γ measurement

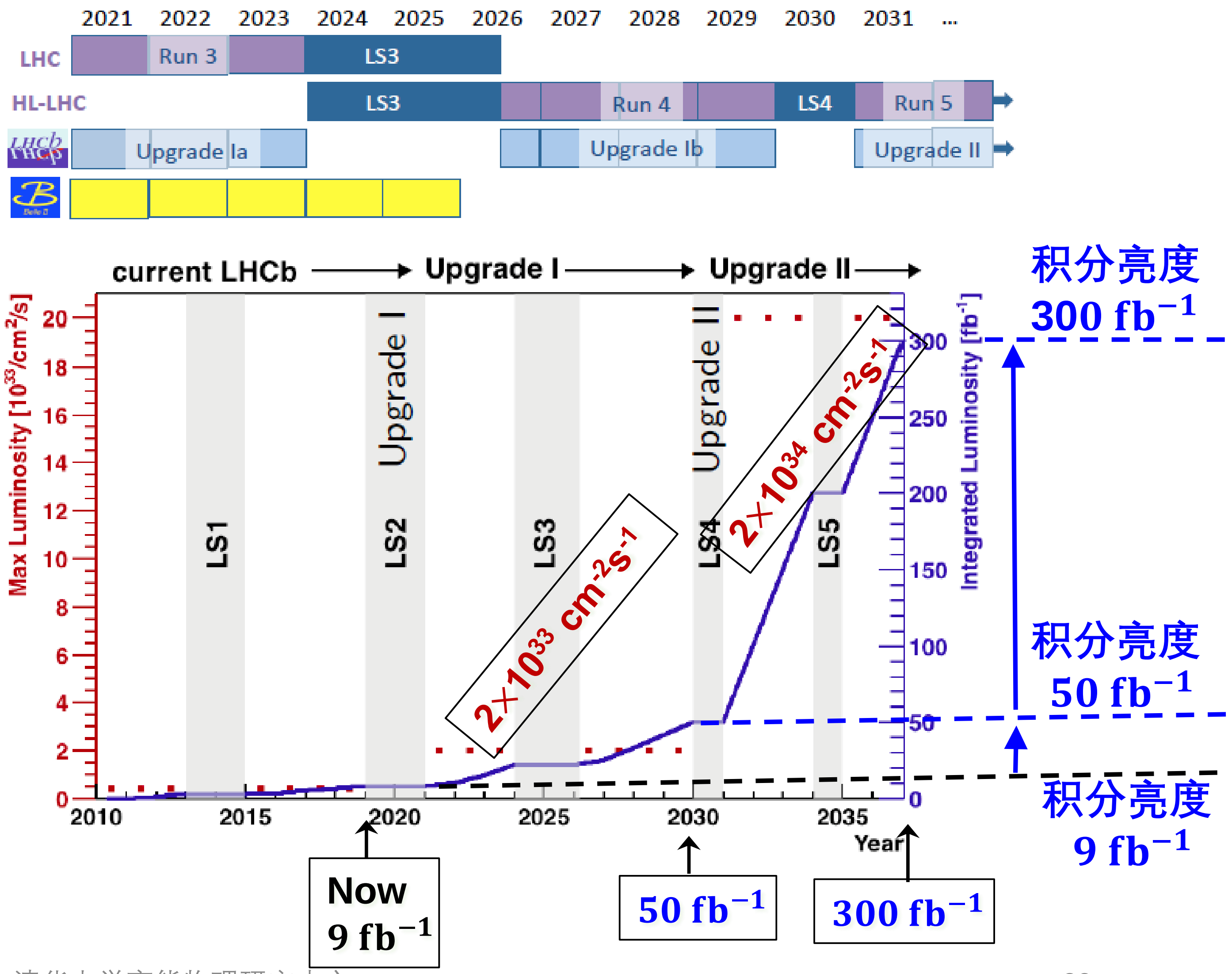
- LHCb average $\boldsymbol{\gamma = \left(74.0^{+5.0}_{-5.8}\right)^{\circ}}$
  - World average $\boldsymbol{\gamma = \left(73.5^{+4.2}_{-5.1}\right)^{\circ}}$
  - Indirect determination: $\gamma = \left(65.3^{+1.0}_{-2.5}\right)^{\circ}$



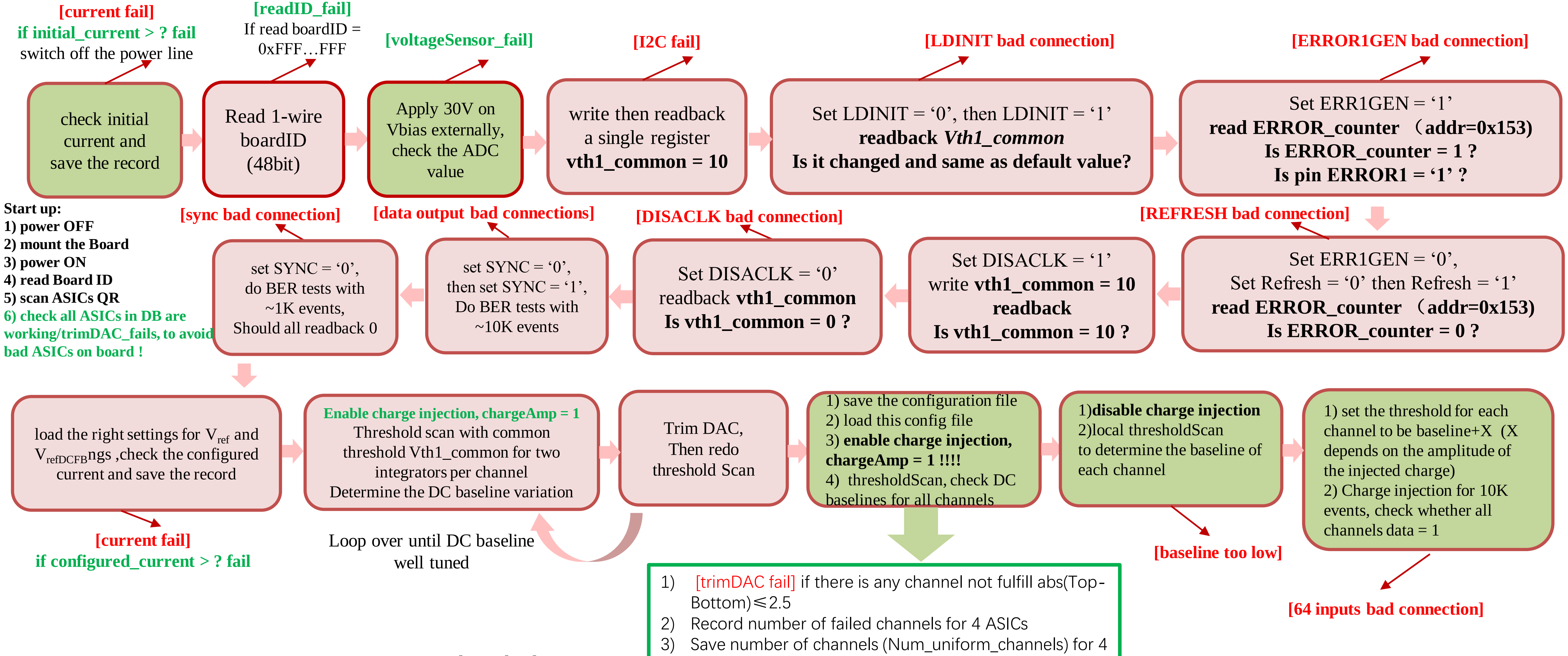


The LHCb Upgrade: status and plan

- The LHCb Upgrade (1a) during LS2 (2019-2020) was planned in 2011
  - $\mathcal{L}^{max}$: 4×10^{32} cm^{-2} s^{-1} ➔ 2×10^{33} cm^{-2} s^{-1}
  - Aiming at 50 fb^{-1} by 2029
- The Upgrade (1b)+(2) during LS3 (2024-2026) and LS4 (2030) is being planned
  - $\mathcal{L}^{max}$: 2×10^{33} cm^{-2} s^{-1} ➔ 2×10^{34} cm^{-2} s^{-1}
  - Aiming at 300 fb^{-1} by 2036



PACIFIC Carrier Board QA Test Routine



Save results to database:

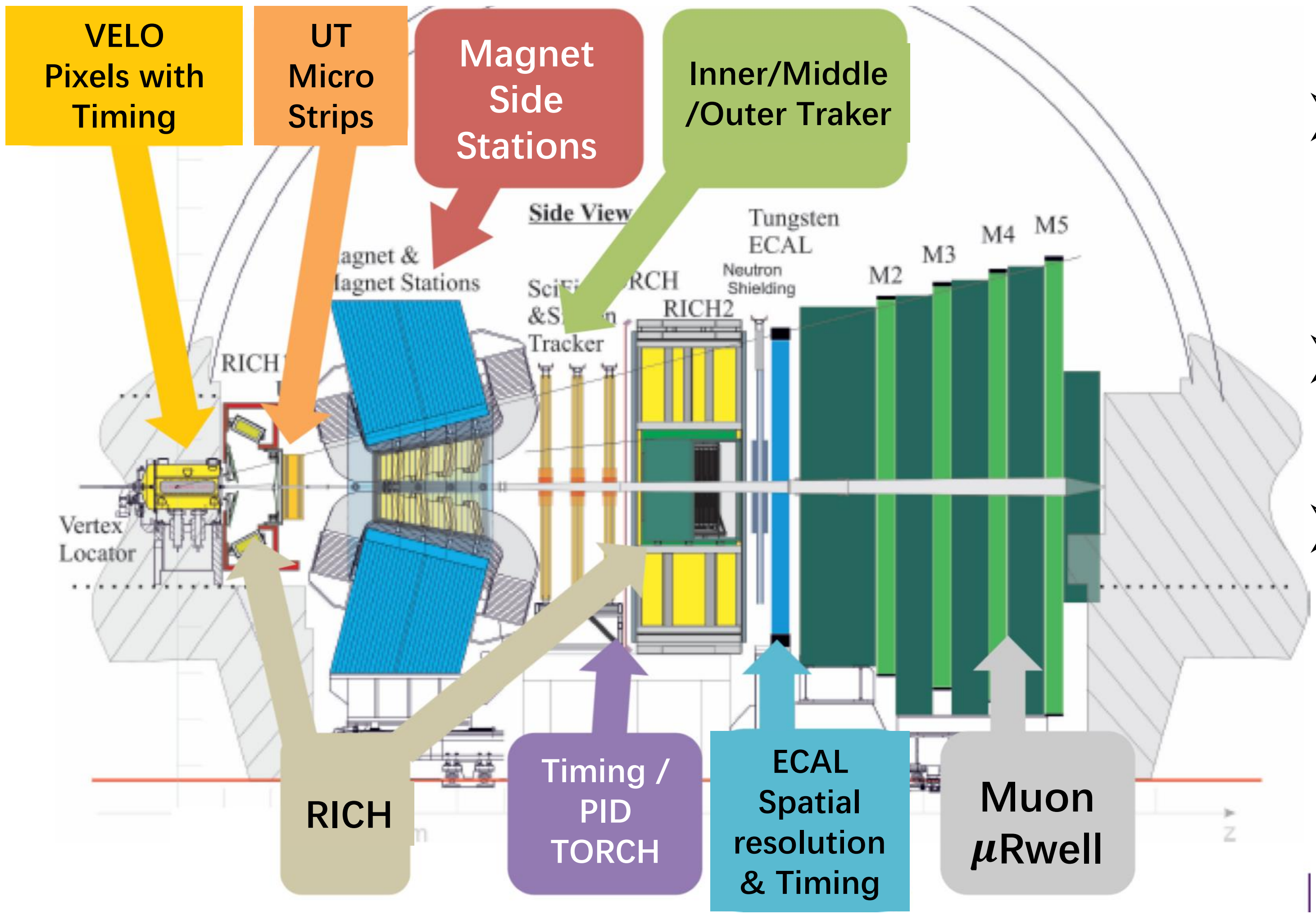
1) test log

2) all parameters into a configuration file: PB_XX.conf, which can be read later by SciFi readout system.

3) after trimming DC-baseline distribution

- ✓ **1-D histogram of 0.5ratio-transition-DAC value for all channels (both Top and Bottom DAC) for each ASIC**
- ✓ **1-D histogram of difference of Top and Bottom DAC within the same channel for each ASIC**

LHCb Upgrade II detector



- Great challenge in detector R&D to cope with pile-up ~ 50
- Timing information essential to some subdetectors
- Simulation studies ECAL by Tsinghua has started in the beginning of 2018
  - Fast sim + full sim
  - 5D ECAL: (E, x, y, z, t)

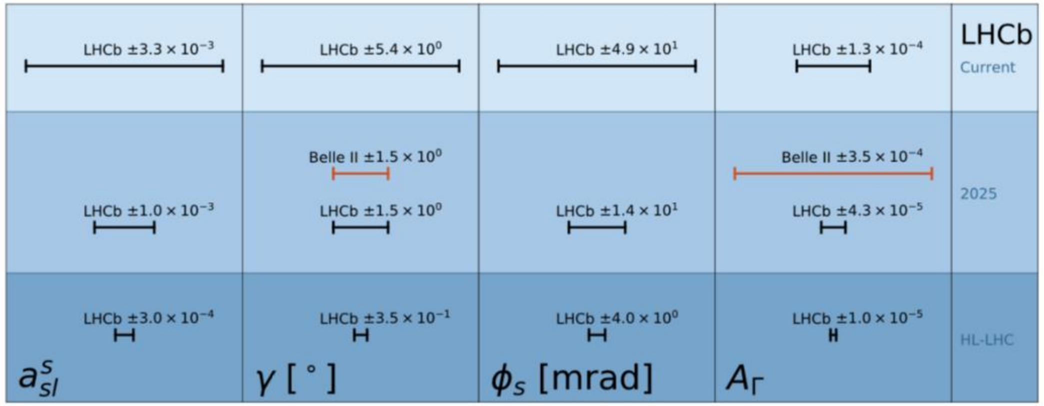
Machine challenges

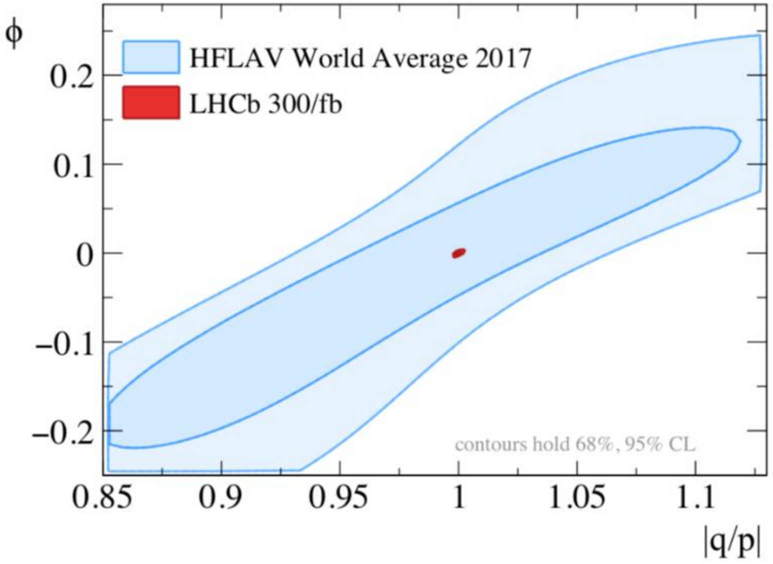
Parameter	Unit	Lumi Scenario					
Target Levelled Lumi	$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	**1.0**			**2.0**		
β^*	m	1.5					
Crossing Plane		H		V	H		V
Magnet Polarity		$-$	$+$	$\pm$	$-$	$+$	$\pm$
External x-ing angle	μrad	400	300	320	400	300	320
Full x-ing angle at IP	μrad	130	570	419	130	570	419
Virtual (Peak) Luminosity	$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	2.16	1.57	1.79	2.16	1.57	1.79
Levelled pile-up	1	28	28	28	56	44.2	50.3
RMS luminous region (start)	mm	52.7	39.5	44.7	52.7	39.5	44.7
Peak line Pile-up density (start)	mm^{-1}	0.20	0.28	0.25	0.41	0.44	0.44
Eff. line Pile-up density (start)	mm^{-1}	0.13	0.17	0.15	0.20	0.20	0.20
Fill duration	h	8.0	8.0	8.0	7.7	8.0	7.9
Leveling time	h	4.7	3.1	3.6	0.6	0	0
Integ. lumi. at LHCb	$\mathrm{fb}^{-1}/\mathrm{y}$	**46.3**	**40.9**	**42.5**	**61.7**	**46.2**	**51.0**
Integ. lumi. at ATLAS/CMS	$\mathrm{fb}^{-1}/\mathrm{y}$	257.1	257.7	257.5	255.1	257.0	256.4

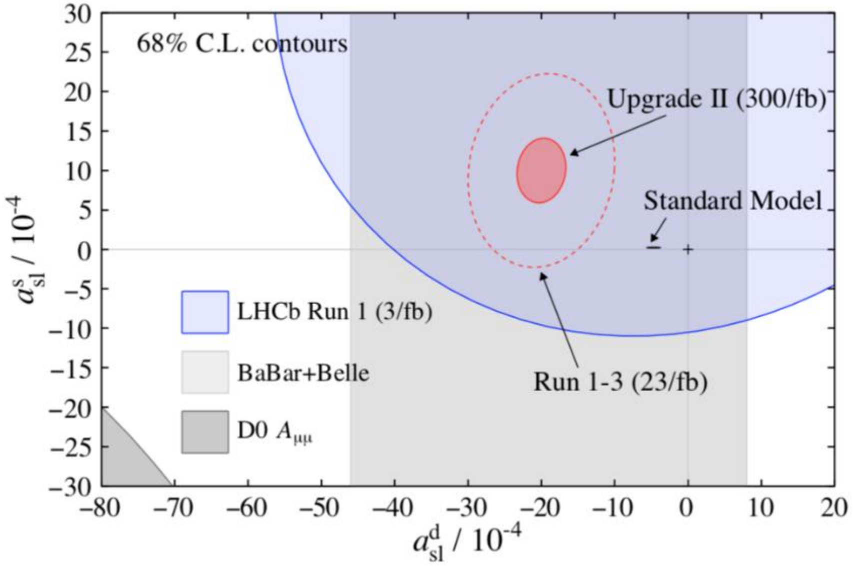
CERN-ACC-NOTE-2018-0038: "a range of potential solutions for operating LHCb Upgrade II as a luminosity of up to 2 x 1034 cm-2 s-1 and permitting the collection of 300 fb-1 or more at IP8 during the envisaged lifetime of the LHC."

Physics cases of Upgrade II: CPV

- γ: 0.4°
- ϕ_s: 3 mrad
- Charm CPV: $O(10^{-5})$

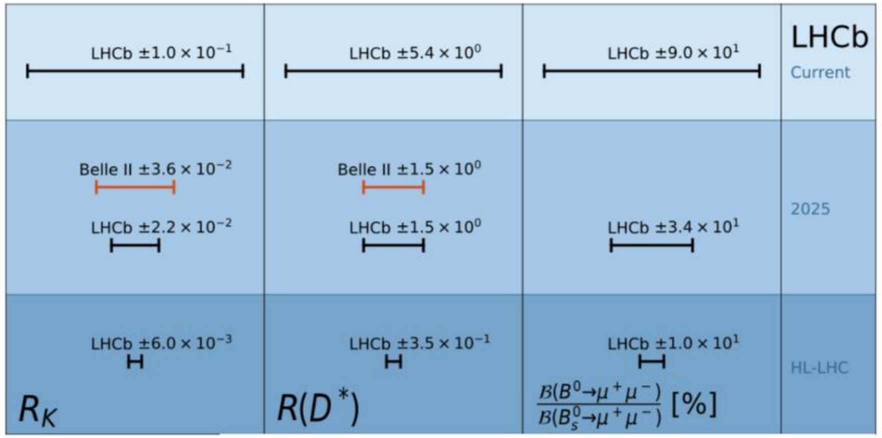


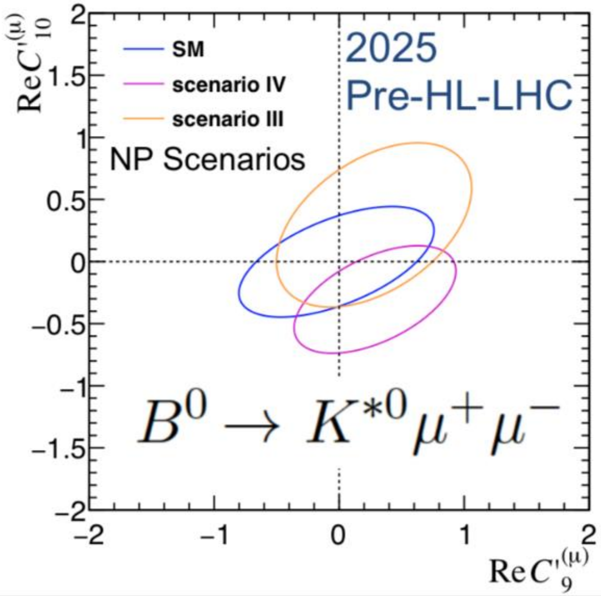


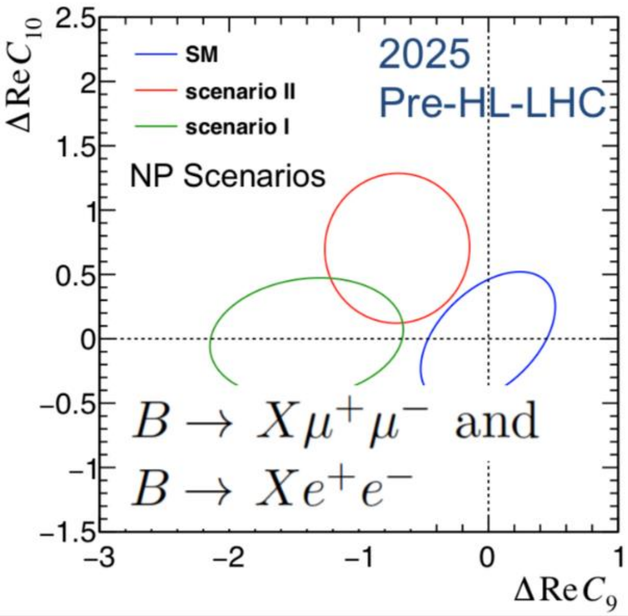


Physics cases of Upgrade Ib: rare decays

- Wide range of b➔sl⁺l⁻/dl⁺l⁻ observables
- 10 % precision on $R \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$







Physics cases of Upgrade II: rare decays

- Wide range of b➔sl⁺l⁻/dl⁺l⁻ observables
- 10 % precision on $R \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$