The LHCb Upgrade
and prospects on spectroscopy studies

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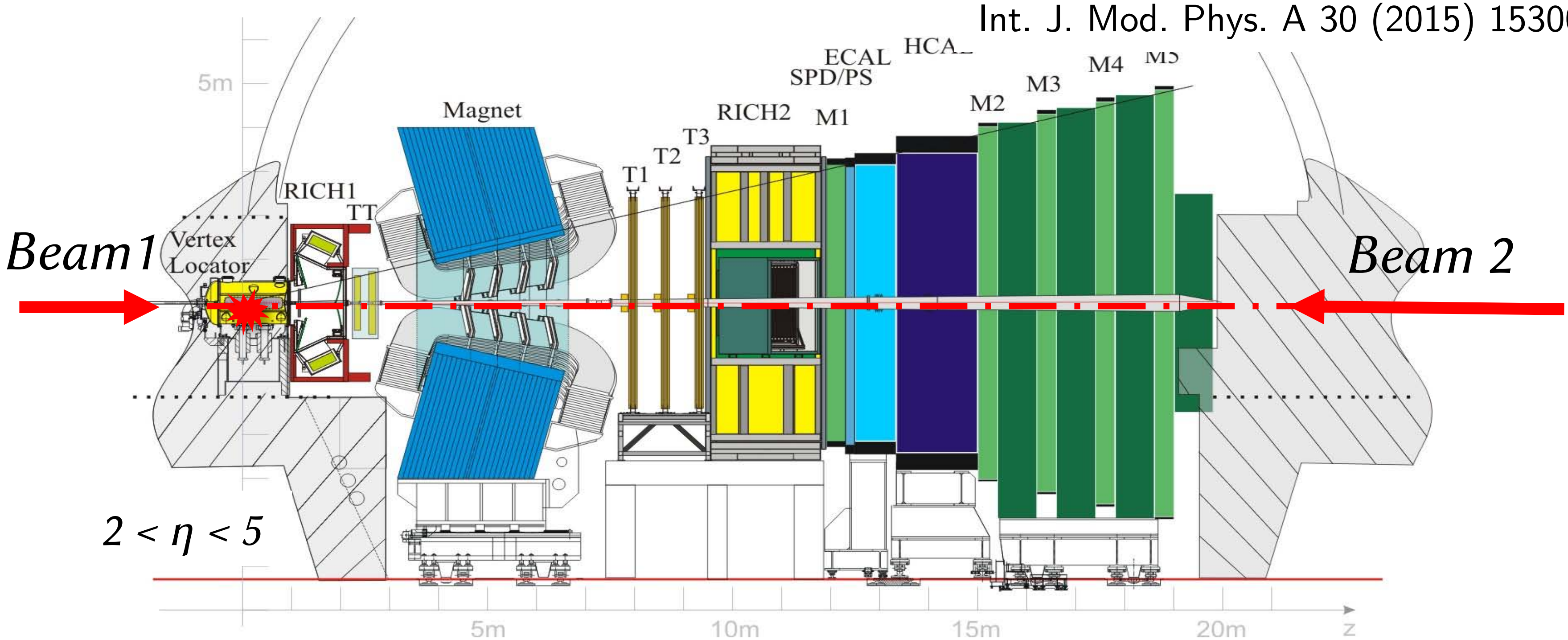
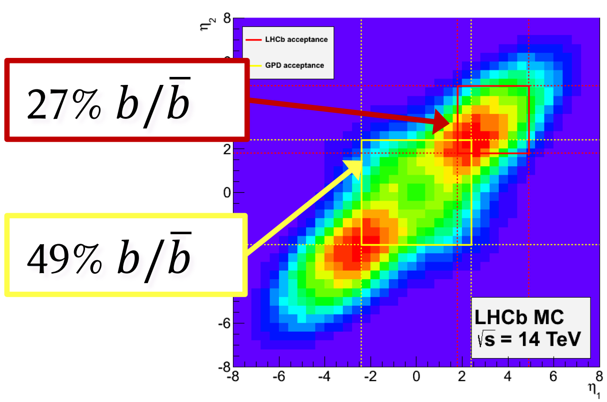
Content

- Why does LHCb need upgrade(s)?
- What is the plan?
- How does it affect spectroscopy studies?

The current (past) detector

JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30 (2015) 1530022

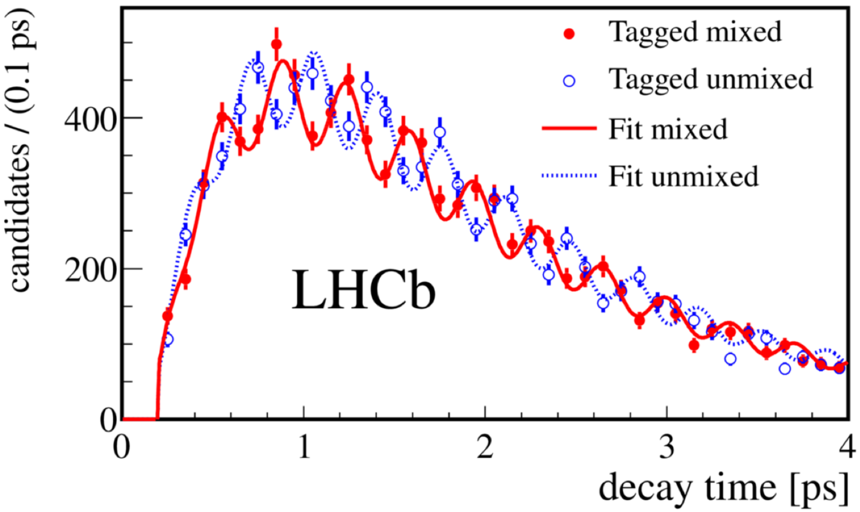


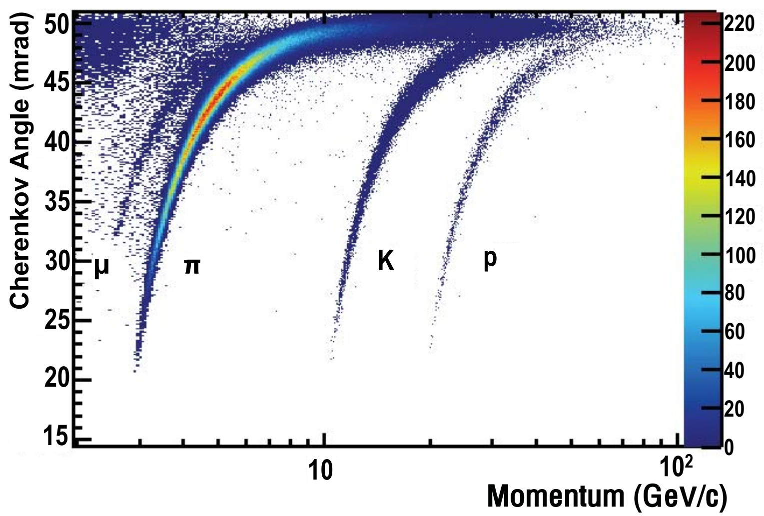


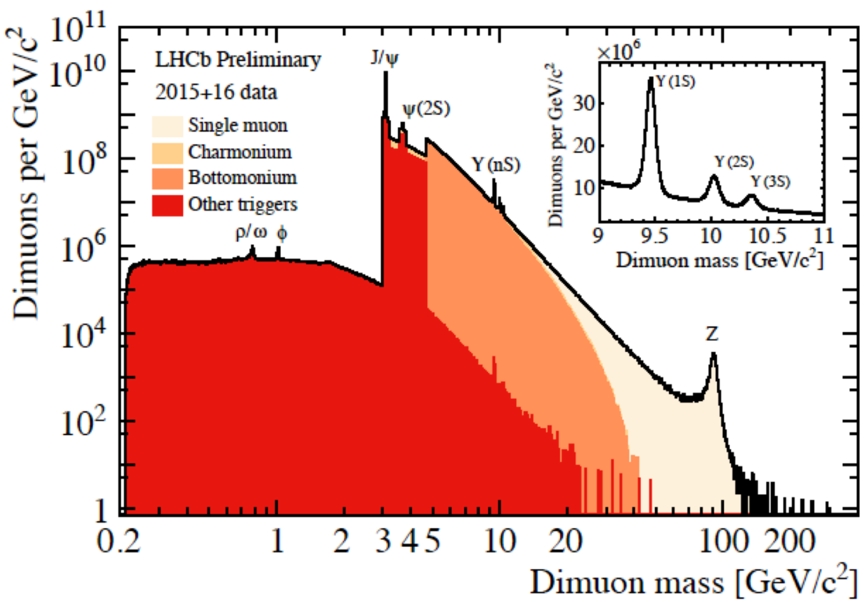
Vertex res.	$\sigma_{\rm IP} = 20\ \mu m$	
Time res.	$\sigma_\tau = 45$ fs	for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum res.	$\Delta p/p = 0.4 \sim 0.6\%\ (5 - 100\ {\rm GeV}/c)$	
Mass	$\sigma_m = 8\ {\rm MeV}/c^2$	for $B \to J/\psi X$
Hadron ID	$\varepsilon(K \to K) \sim 95\%$	mis-ID $\varepsilon(\pi \to K) \sim 5\%$
Muon ID	$\varepsilon(\mu \to \mu) \sim 97\%$	mis-ID $\varepsilon(\pi \to \mu) \sim 1 - 3\%$
ECAL res.	$\Delta E/E = 1\% \oplus 10\%/\sqrt{E\ ({\rm GeV})}$	

Detector performance

- Excellent vertexing , momentum resolution, and particle identification

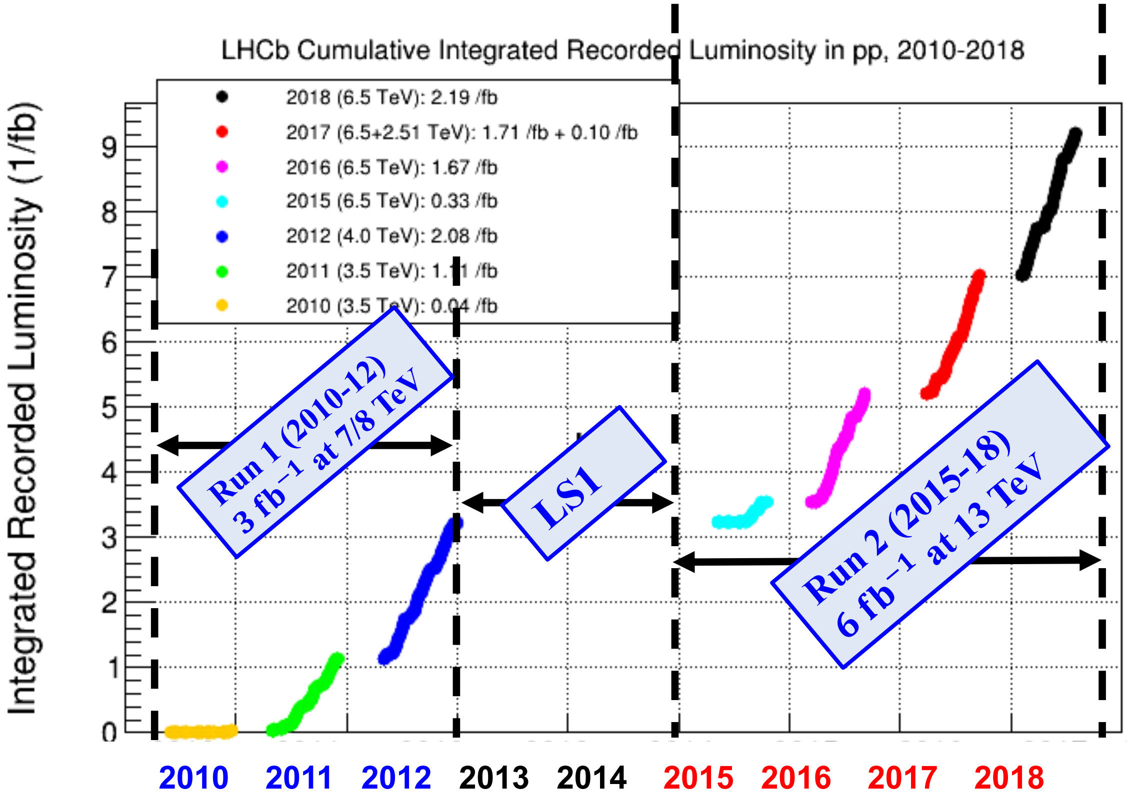


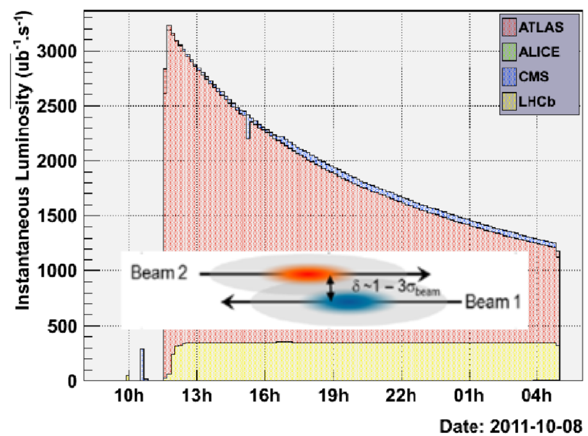




Operation

- Successful data-taking 2010 – 2018: integrated luminosity of **9 fb^{-1}**.





Luminosity levelling to maintain

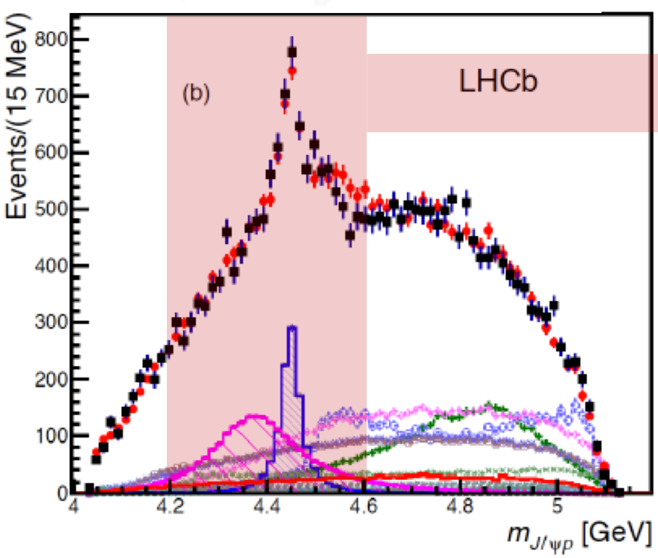
$\mathcal{L}_{inst} \sim 4 \times 10^{32}$ cm^{-2}s^{-1}.

Pentaquark: example of Run 1+2 physics

- Observation of two pentaquark states Pc(4380)+ and Pc(4450)+ in $\Lambda_b \to J/\psi\, pK^-$ decay in 2015

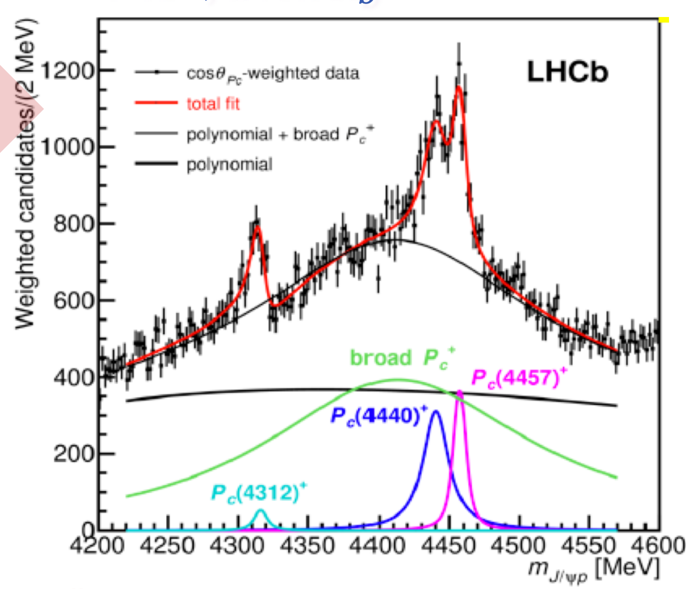
- With more (Run 1+2) data, the yield is an order of magnitude higher ⇒ more structures revealed!

3 fb^{-1}, 26k Λ_b



PRL 115 (2015) 072001

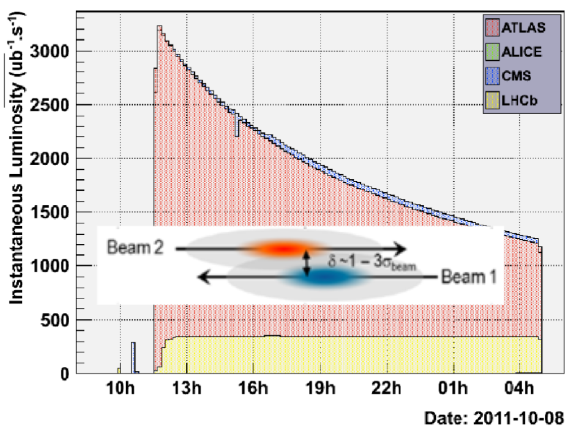
9 fb^{-1}, 246k Λ_b

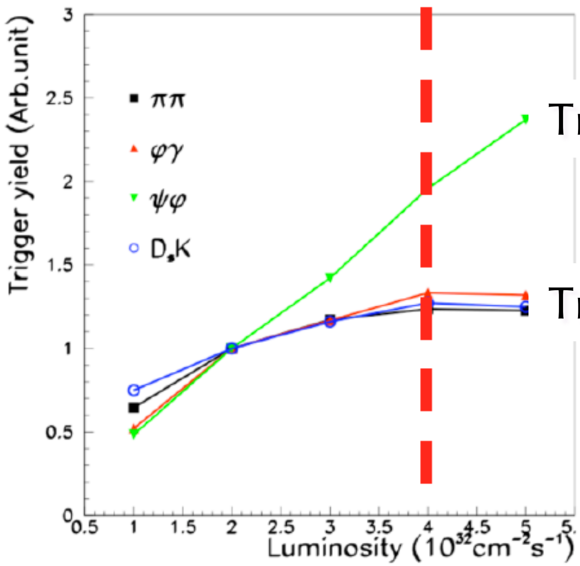


PRL 122 (2019) 222001

Motivation of upgrade

- More data, higher discovery potential!
- Why not fully exploit what LHC offers?
  - Saturation of hadronic trigger at higher lumi due to 1MHz hardware trigger
  - Performance degradation with increase of detector occupancy
  - Limited radiation hardness of trackers



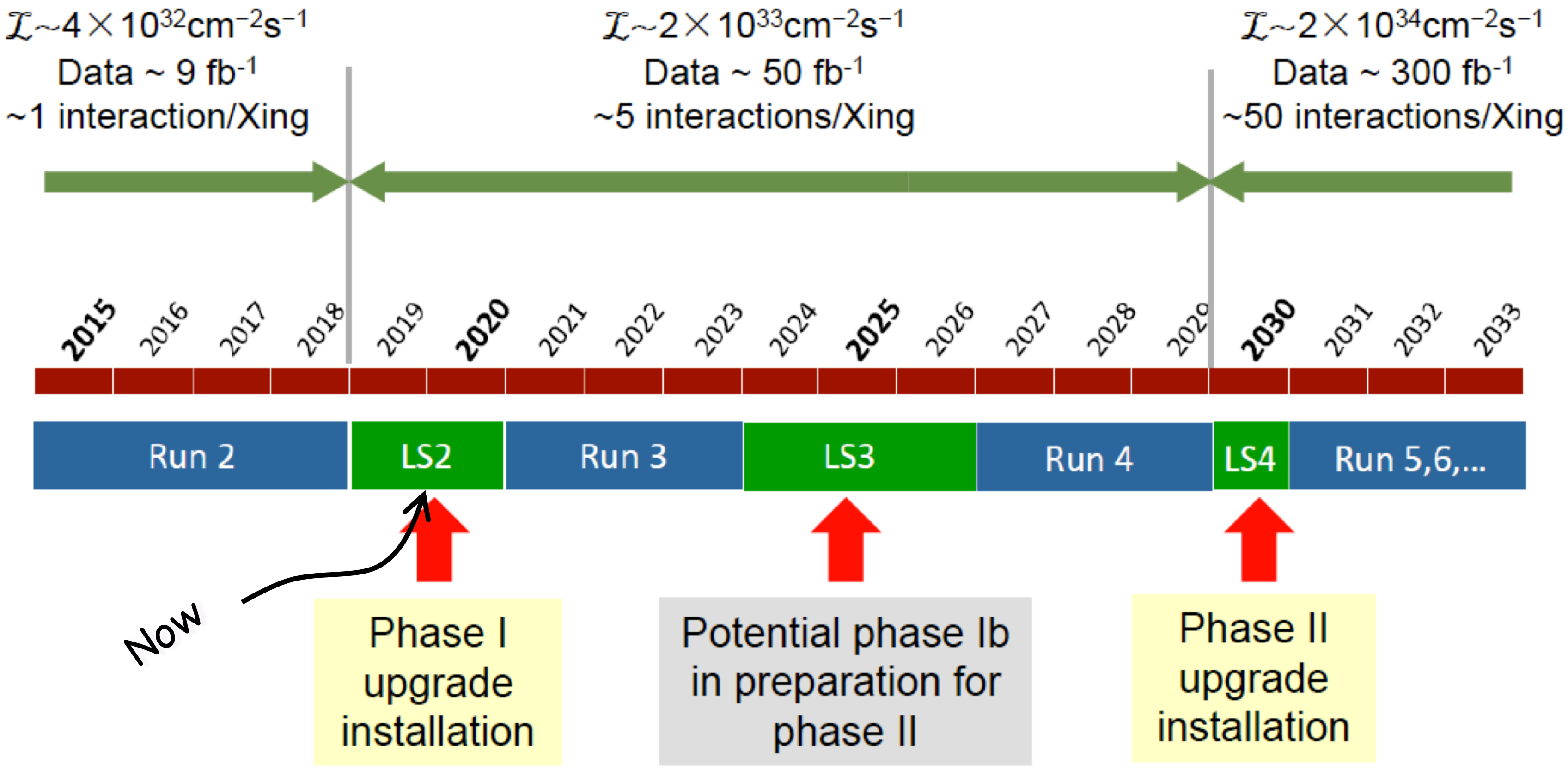


Goal of upgrade Phase I

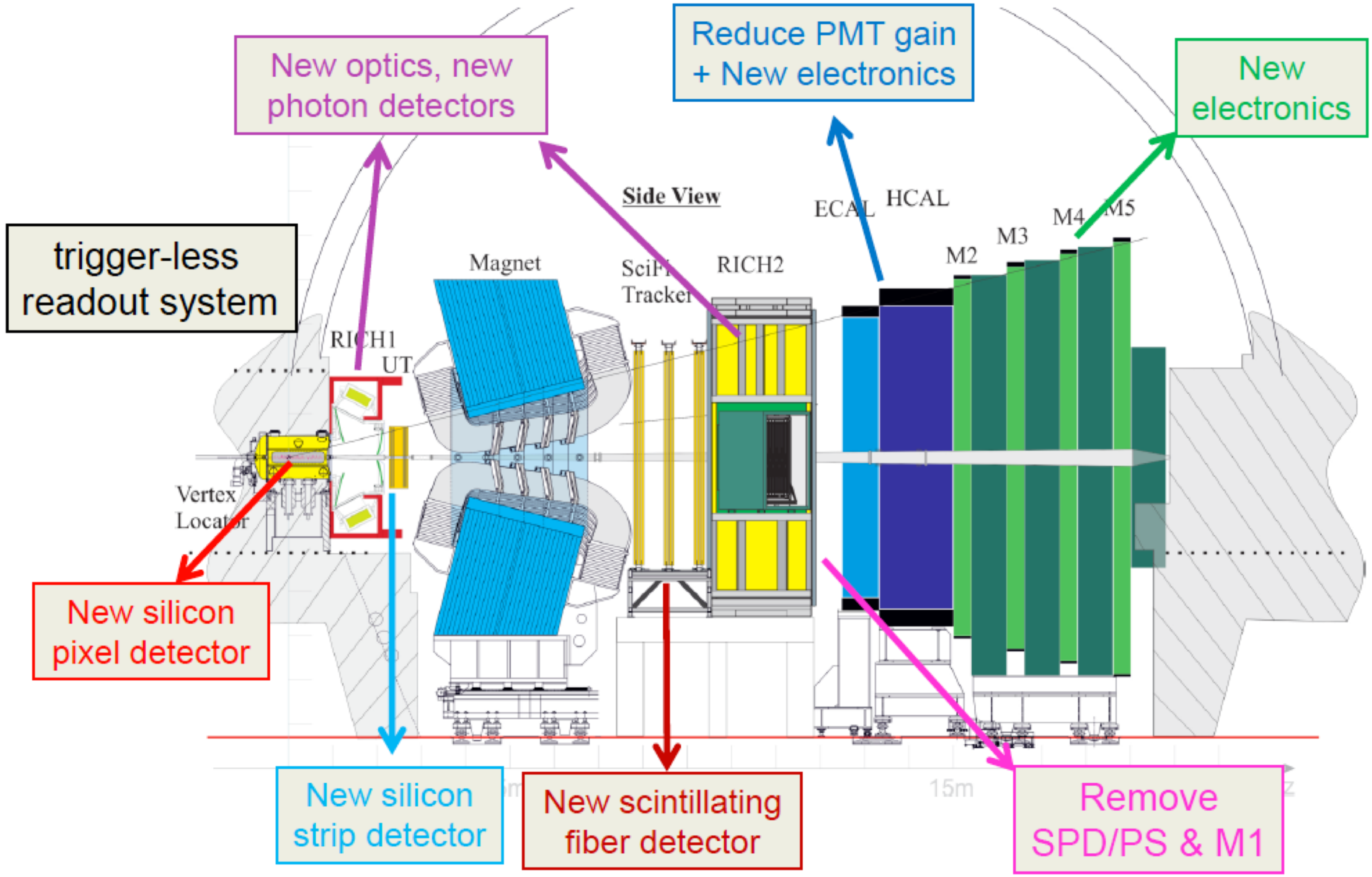
- More data, higher discovery potential!
- Why not fully exploit what LHC can offer?
  - Saturation of hadronic trigger at higher lumi due to 1MHz hardware trigger
  - Performance degradation with increase of detector occupancy
  - Limited radiation hardness of trackers

- Increase the instantaneous lumi to 2×10^{33} $cm^{-2}s^{-1}$ ($5 \times$ now)
- Remove the 1 MHz hardware trigger
  - All detectors read out @ 40MHz $\Rightarrow$ new FE electronics & readout network
  - Flexible software trigger entirely on a CPU farm
- Sub-detectors work at higher lumi
  - High granularity for higher occupancy
  - Radiation tolerance

The way ahead – LHCb upgrade plans

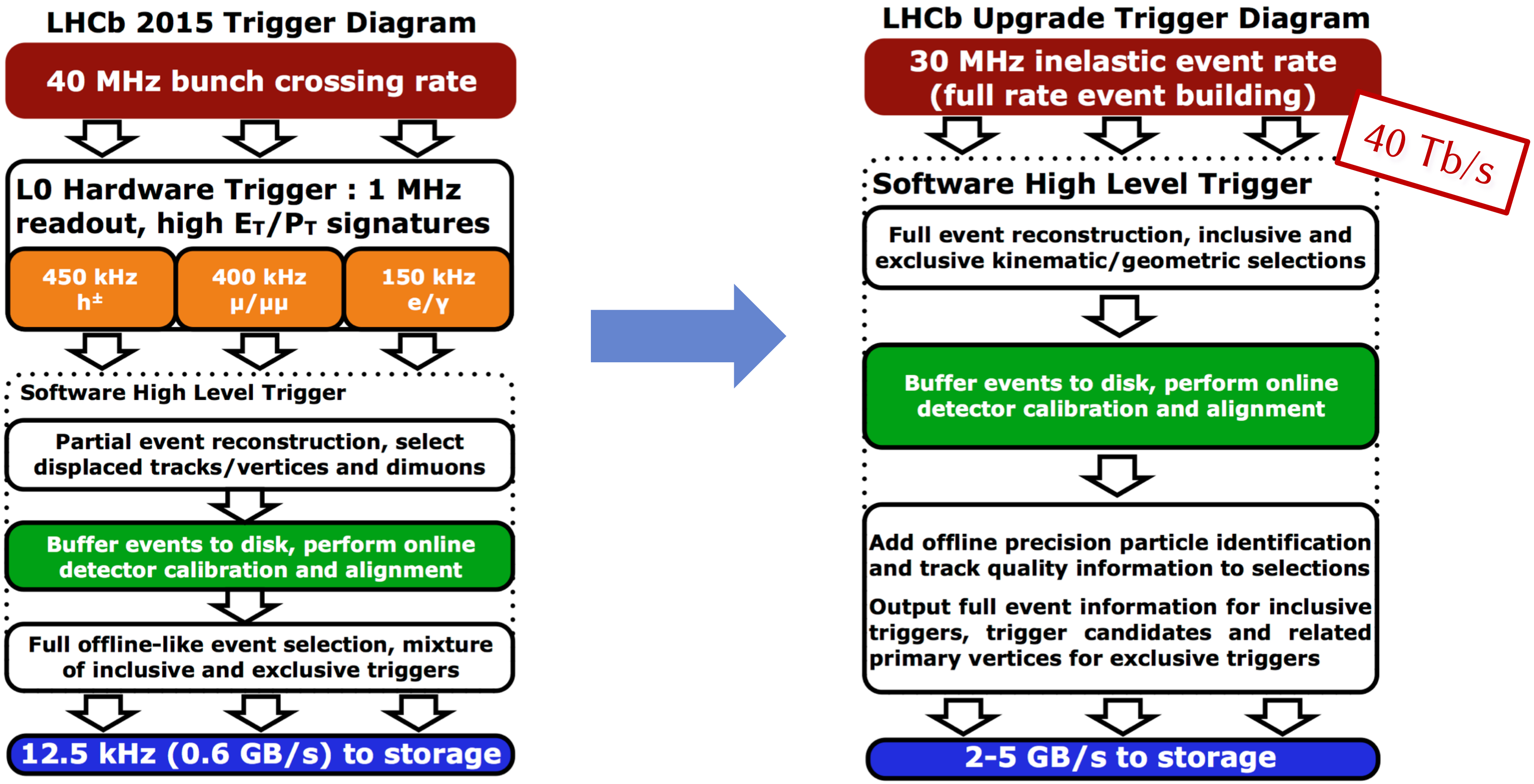


LHCb Upgrade Phase I

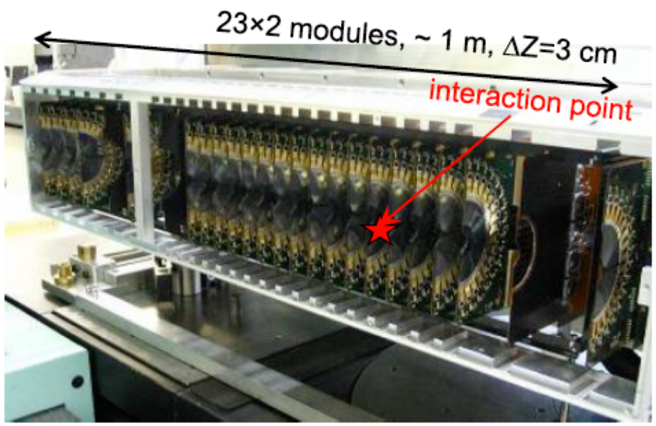


Trigger system

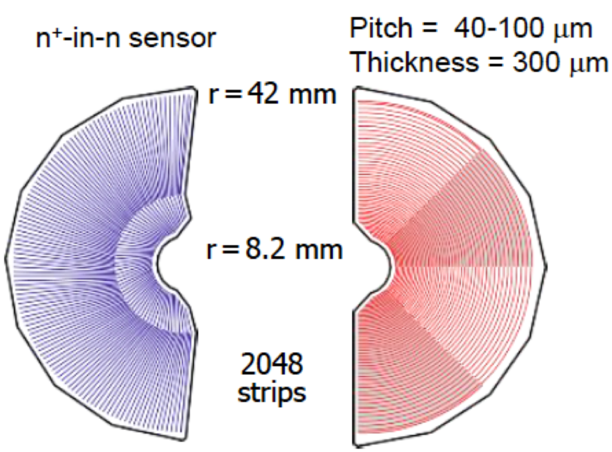
- Hardware trigger removed!

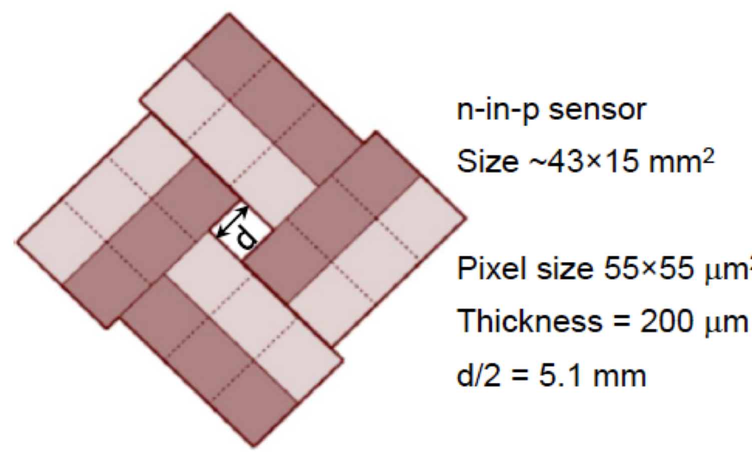


Vertex Locator (VELO)

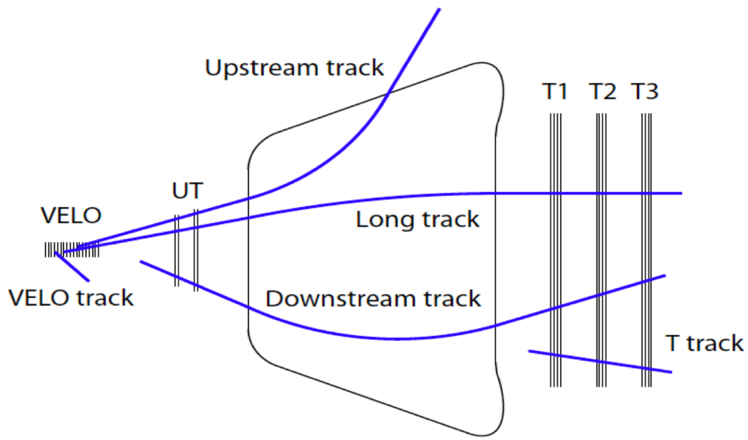


- Similar geometry as the old one
- Strip in r-ϕ → Hybrid pixel detector
- VeloPix ASIC, 256 × 256, readout@40MHz
- More radiation hard sensor:
  - $\Phi_{max} \sim 7\times10^{14} \rightarrow 8\times10^{15}\, n_{eq}\, \mathrm{cm}^{-2}$
- Closer approach to beampipe
- State-of-the-art microchannel cooling

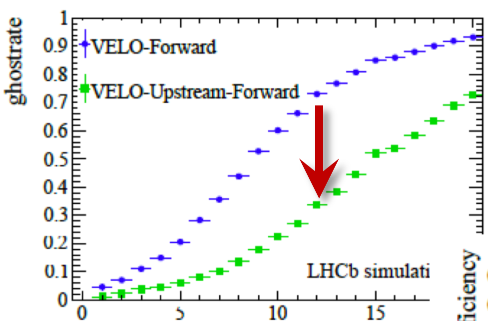




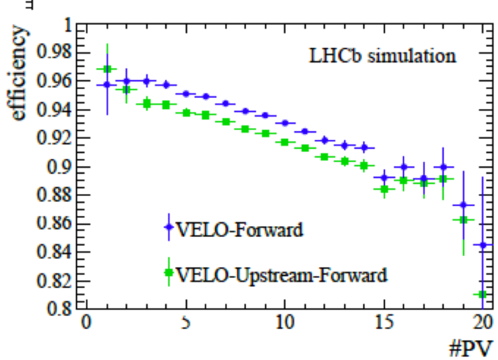
Upstream Tracker's (UT) role



- High tracking efficiency
  - Crucial for efficient reconstruction of particles decaying after VELO: K_S, Λ when combined with SciFi



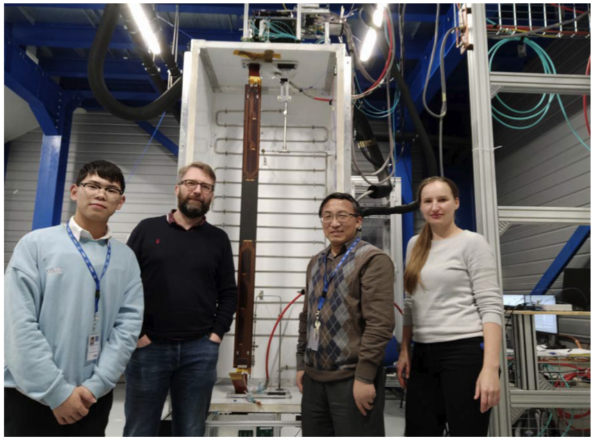
ghost rate reduced by requiring UT hits

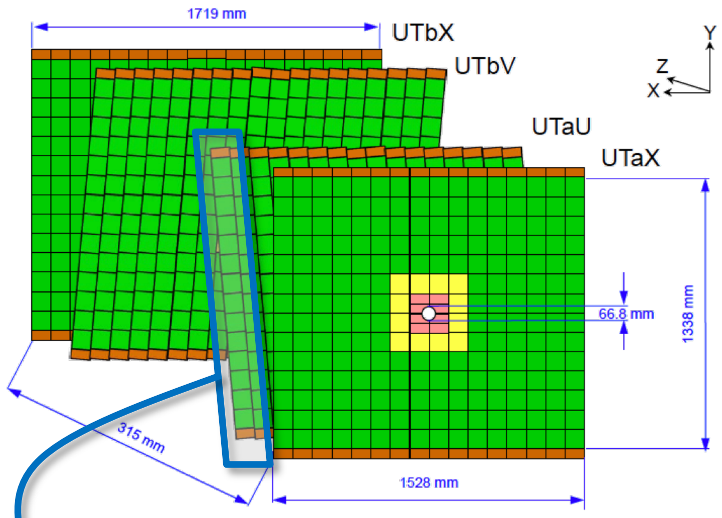


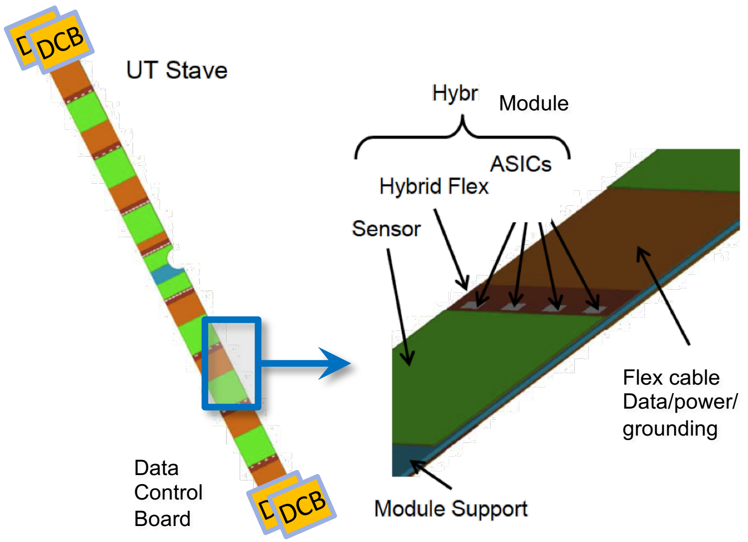
- Fast tracking algorithm
  - Reduction of 'ghost' tracks, speed up upstream & downstream matching, hence allowing a more performant tracking and triggering algorithms

UT design & installation

- Improved coverage and granularity wrt. TT
- Radiation hard sensor to tolerate $\Phi_{max} \sim 5 \times 10^{14}\, n_{eq}\mathrm{cm}^{-2}$
- 40MHz FE readout near sensor
- More digital processing at end of detector
- **IHEP group** is key player setting up the slice test, installing the first stave, and studying the radiation effect on the FE chip

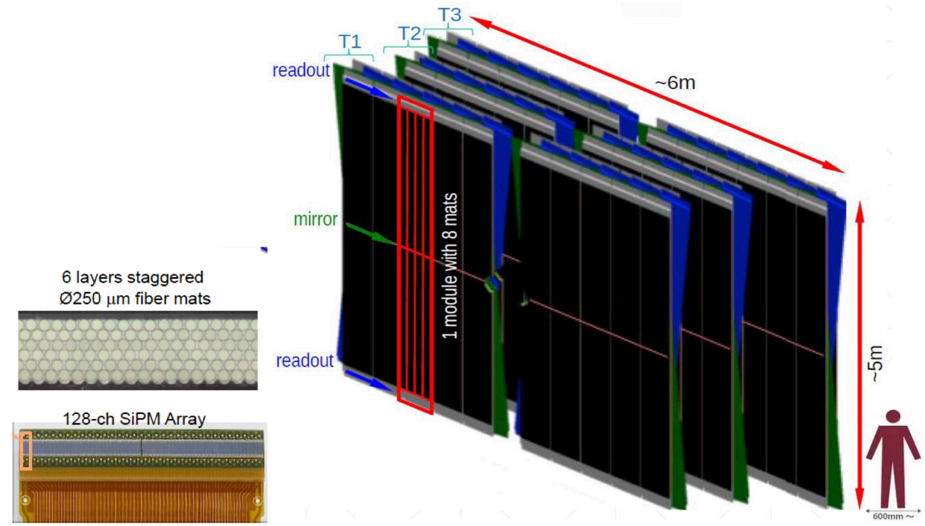




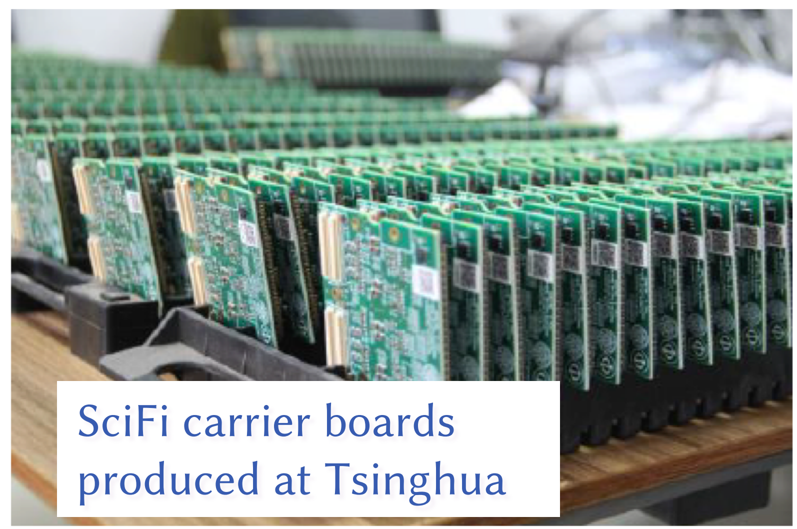


Scintillating Fiber Tracker (SciFi)

- Tracking stations replaced by 3-station scintillating fiber detector
- 340 m^2 sensitive area
- Readout with 4096 SiPMs + custom made PACIFIC ASIC. A total of ~ 0.5 M SiPM channels!
- Spatial resolution ~70 um in X
- Single hit efficiency ~99%

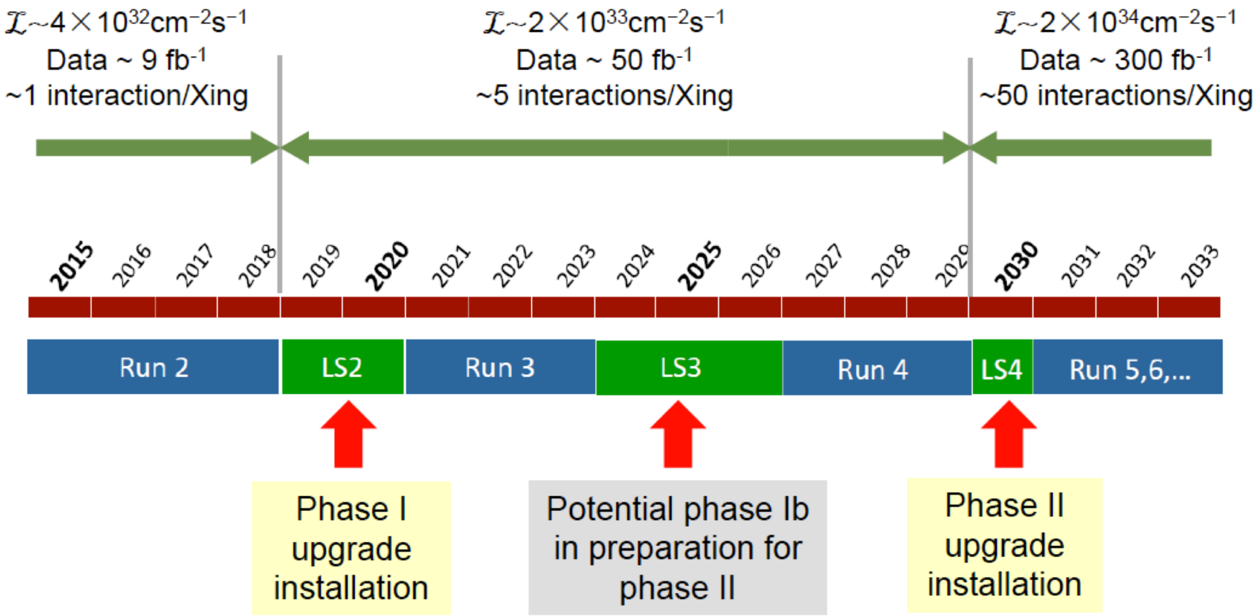


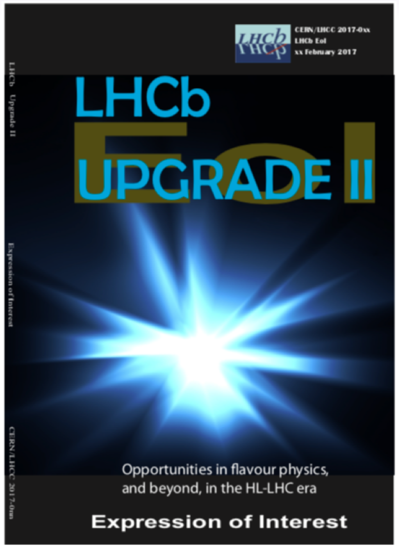
- Tsinghua University designed FE electronics PACIFIC for SciFi; Finished production of all PACIFIC boards with high quality (Now at CERN for installation)

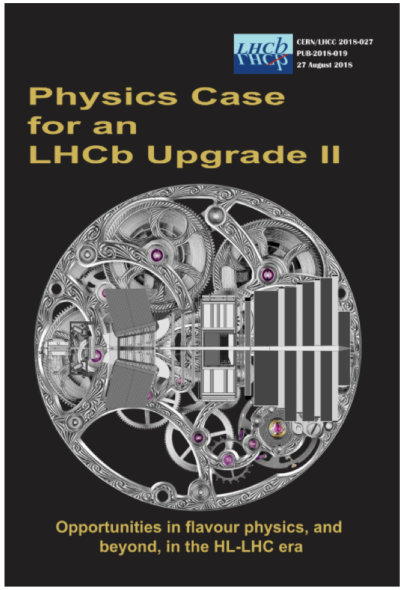

SciFi carrier boards produced at Tsinghua

Further ahead: Upgrade II

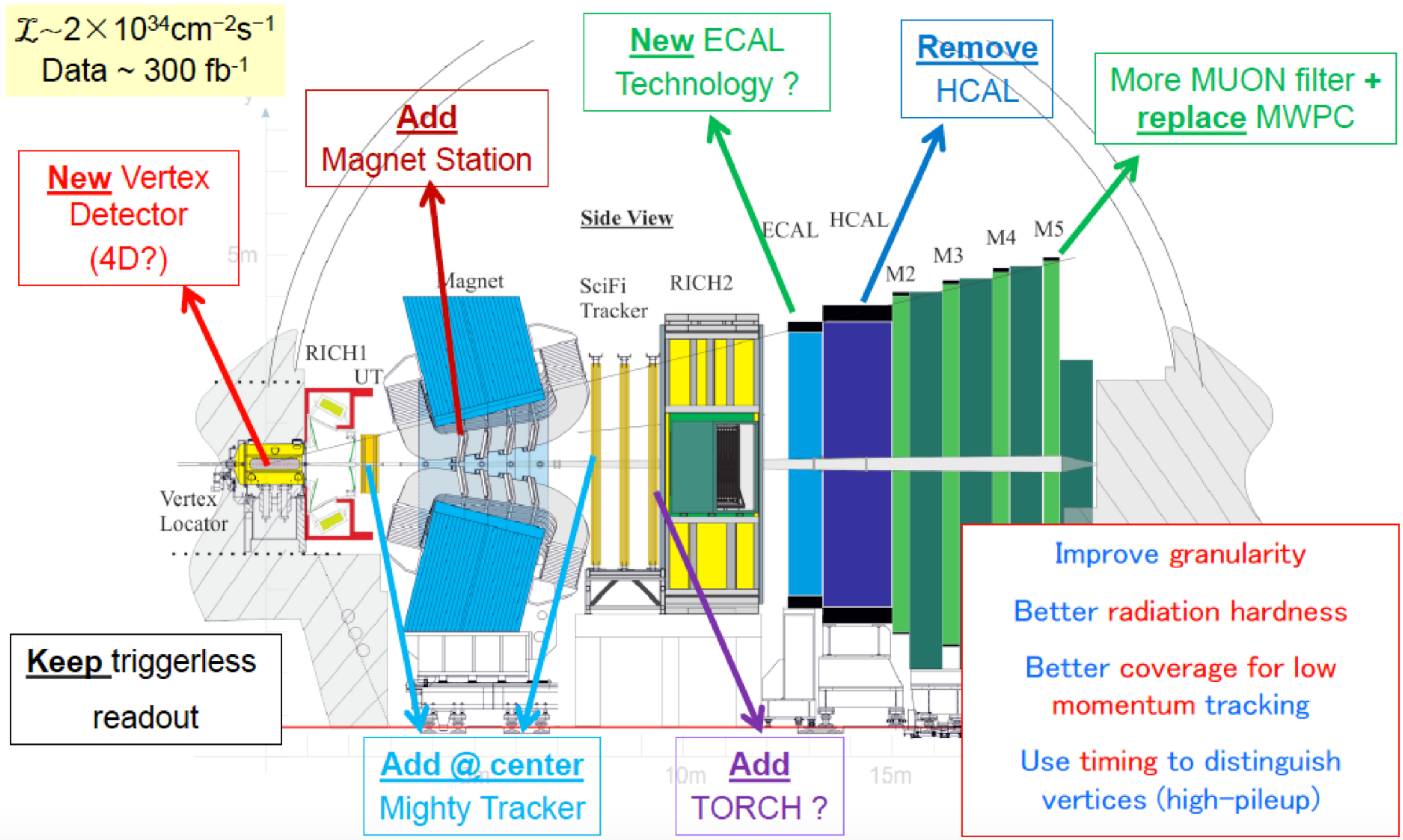
- Can we fully profit from the HL-LHC?
- What can we do with 300 fb^{-1} data?







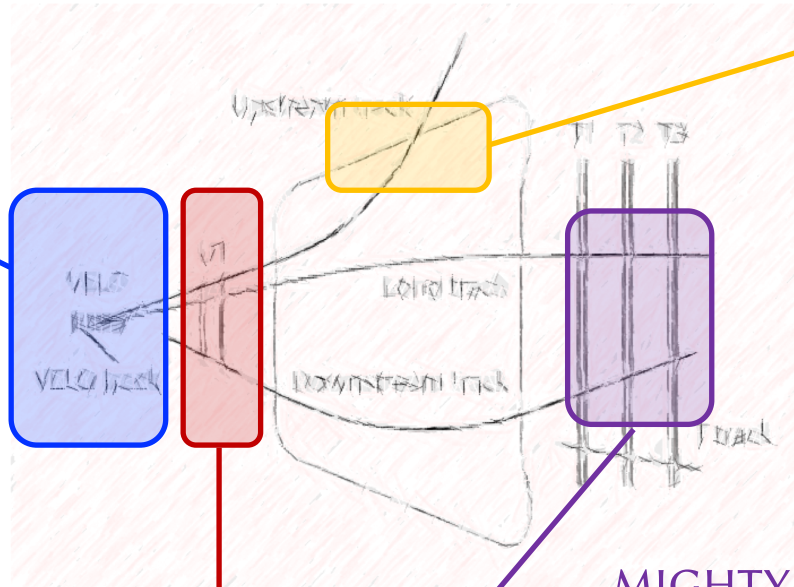
Possibilities in Upgrade Phase II



Upgrade II approved to proceed to Framework TDR by LHCC

Tracking

VELO
Finer granularity
Thinner RF foil,
Timing < 200ps

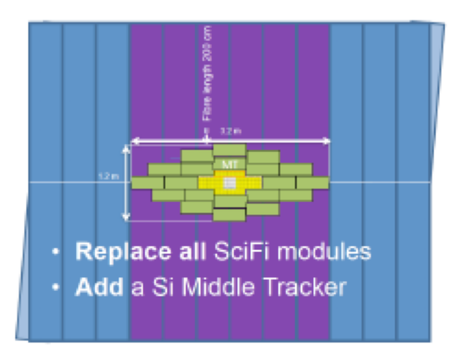


Magnet station
Within magnet
to improve
tracking at low
momentum

CMOS tracker for UT?
To improve the central
occupancy and
radiation hardness

CMOS Tracker

MIGHTY Tracker
Replacing central SciFi
with silicon stations
For better granularity
and radiation hardness

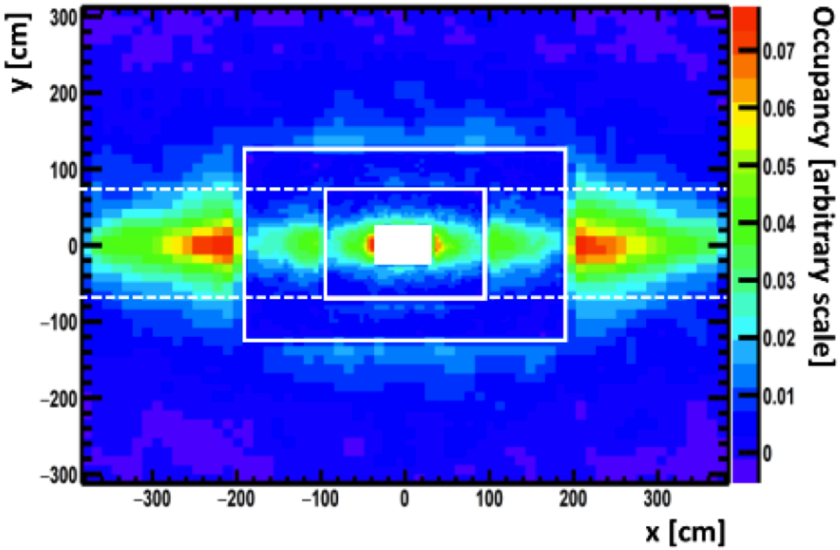


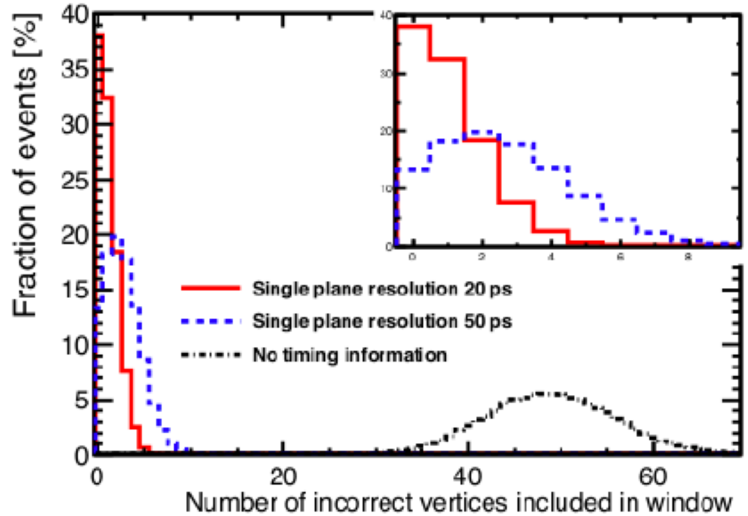
Interests from Chinese groups:

- *Natural continuation of UT*
- *Synergy with CEPC*

Calorimeter

- Severe radiation
  → Replacement with radiation technology for innermost or y=0
- Overlapping showers
  → Smaller Molière radius, finer cells
- Huge # combinatorics from π^0
  → Fast timing information desired
- Options being discussed
  - *Homogenous crystal with longitudinal segmentation*
  - *Shashilik or SpaCal with a crystal component for timing*
  - *Preshower layer of Si for timing*
  - ...
- *Interests from Chinese groups*





Prospects for Upgrade I

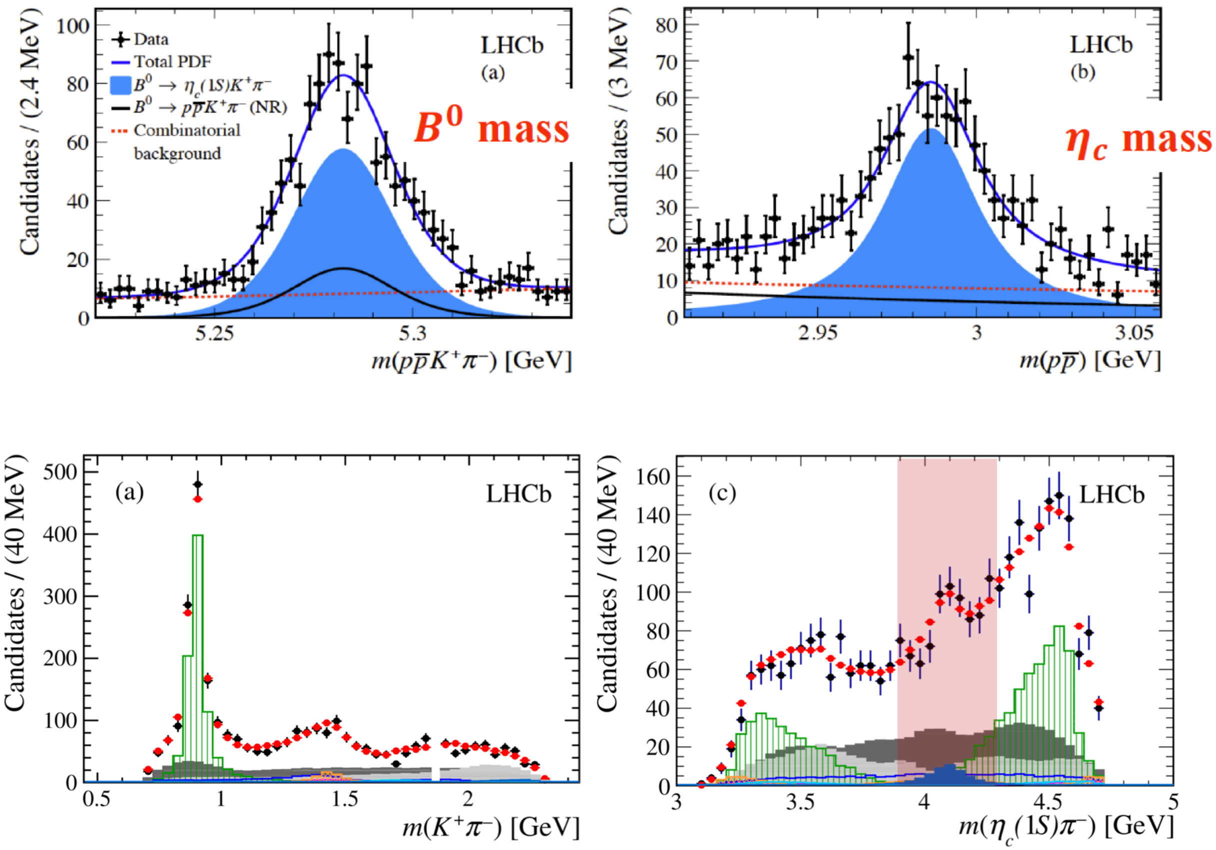
- Integrate luminosity increase:
  - 9 fb^{-1} (now) → 23 fb^{-1} (end of Run 3) / 50 fb^{-1} (end of Run 4)

- Opportunities for
  - Baryon spectroscopy
  - Charmonia(-like) states studies in decays
  - Pentaquark studies

- A few recent results from Run 1+2 to give an idea …

Evidence of Zc(4100)$^-$ in $B \to \eta_c(1S)K^+\pi^-$

EPJC 78 (2018) 1019



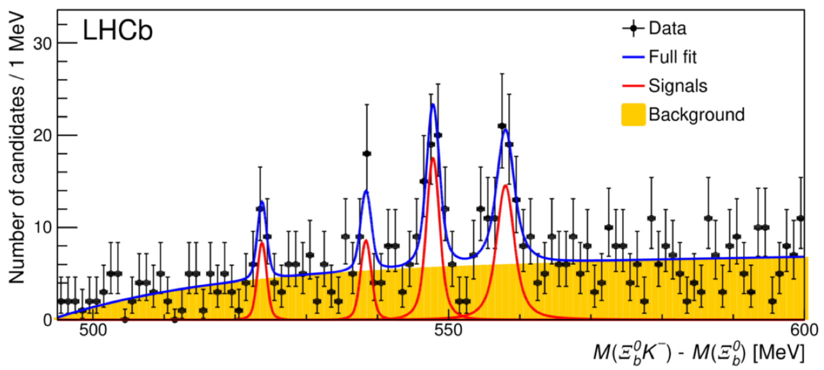
- 4.7 fb^{-1}, N_{sig} ~ 1900
- $Zc \to \eta_c\pi^-$
  - 4.8σ for $J^P = 1^-$
  - 0^+ also allowed
  - NB: all Zc observed so far in Y(4260), with $J^P = 1^+$

$$m_Z = 4096 \pm 20^{+18}_{-22}\ \text{MeV},$$
$$\Gamma_Z = 152 \pm 58^{+60}_{-35}\ \text{MeV}.$$

Newly observed b baryons

- Excited Ω_b (bss) in $\Xi_b^0 K^-$ final state

arXiv: 2001.00851

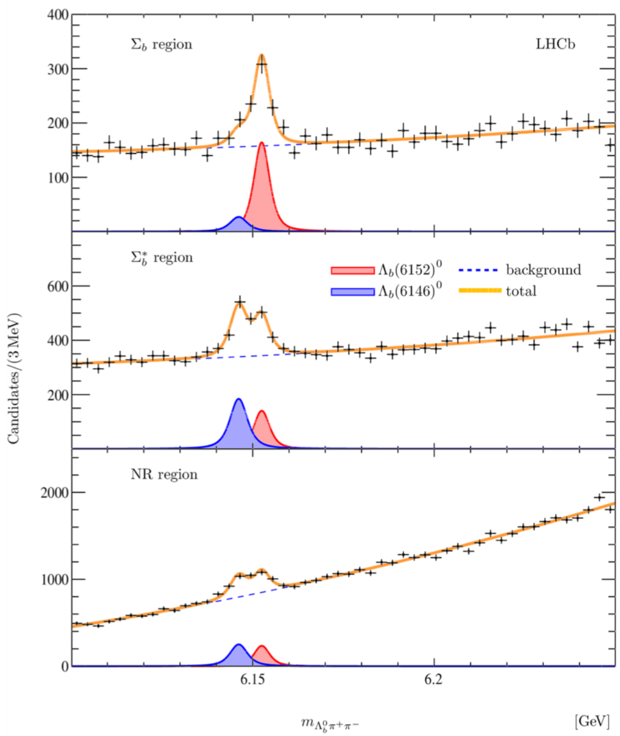


$$m(\Omega_b(6316)^-) = 6315.64 \pm 0.31 \pm 0.07 \pm 0.50\text{MeV},$$
$$m(\Omega_b(6330)^-) = 6330.30 \pm 0.28 \pm 0.07 \pm 0.50\text{MeV},$$
$$m(\Omega_b(6340)^-) = 6339.71 \pm 0.26 \pm 0.05 \pm 0.50\text{MeV},$$
$$m(\Omega_b(6350)^-) = 6349.88 \pm 0.35 \pm 0.05 \pm 0.50\text{MeV},$$

- New resonances in $\Lambda_b \pi^+ \pi^-$ final state
  - Possibly a doublet of $\Lambda_b(1D)$ states

$$m_{\Lambda_b(6146)^0} = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16\,\text{MeV},$$
$$m_{\Lambda_b(6152)^0} = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16\,\text{MeV},$$
$$\Gamma_{\Lambda_b(6146)^0} = 2.9 \pm 1.3 \pm 0.3\ \text{MeV},$$
$$\Gamma_{\Lambda_b(6152)^0} = 2.1 \pm 0.8 \pm 0.3\ \text{MeV},$$

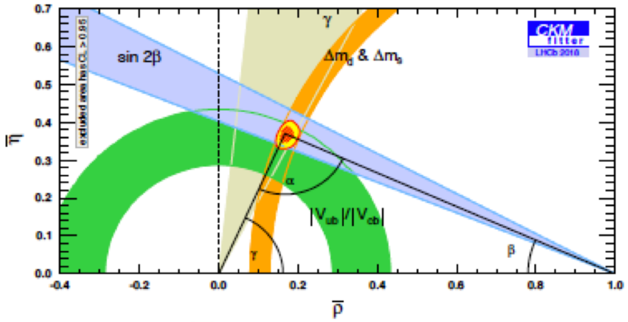
PRL 123 (2019) 152001



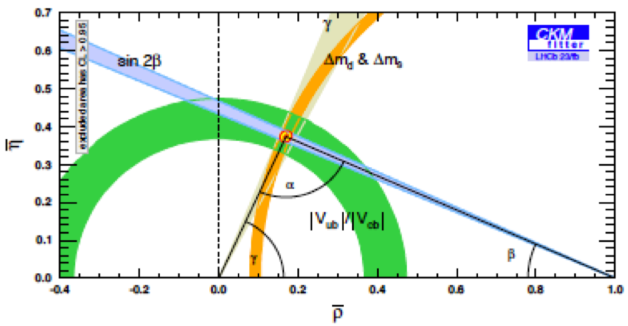
Key measurements @ Upgrade II

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
EW Penguins				
R_K $(1 < q^2 < 6\,\text{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007
R_{K^*} $(1 < q^2 < 6\,\text{GeV}^2c^4)$	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
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
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%
$\tau_{B_s^0 \to \mu^+\mu^-}$	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}

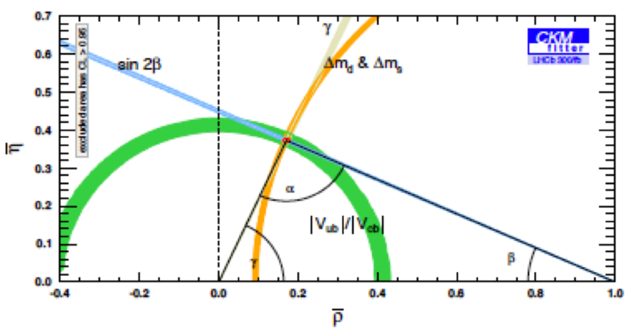
CKM matrix evolution



Now



By 2025 (23 fb^{-1}, Upgrade Ia)



By 2035 (300 fb^{-1}, Upgrade II)

Spectroscopy with 300 /fb

- Large data set will boost sensitivity in searches for heavy states
  - With small production sections
  - With suppressed decay rates

Decay mode	LHCb $23\,\mathrm{fb}^{-1}$	LHCb $50\,\mathrm{fb}^{-1}$	LHCb $300\,\mathrm{fb}^{-1}$	Belle II $50\,\mathrm{ab}^{-1}$
$B^+ \to X(3872)(\to J/\psi\,\pi^+\pi^-)K^+$	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	—

X(3872)

- X(3872):
  - $\chi_{c1}(2P)$? *Differential production xsec similar as* $\psi(2S)$; *Preference of* $\psi(2S)\gamma$ *over* $J/\psi\,\gamma$
  - Molecure? *Mass close to DD* threshold; Isospin-violating decay to* $J/\psi\rho$
  - Mixture?

- If a strong $\chi_{c1}(2P)$ component exists, X(3872) $\rightarrow \chi_c(1P)\pi^+\pi^-$ expected
  - $\chi_c(1P) \rightarrow J/\psi\,\gamma$ efficiency very low in current LHCb
  - A large sample from Upgrade II will help to establish such decay or to set UL

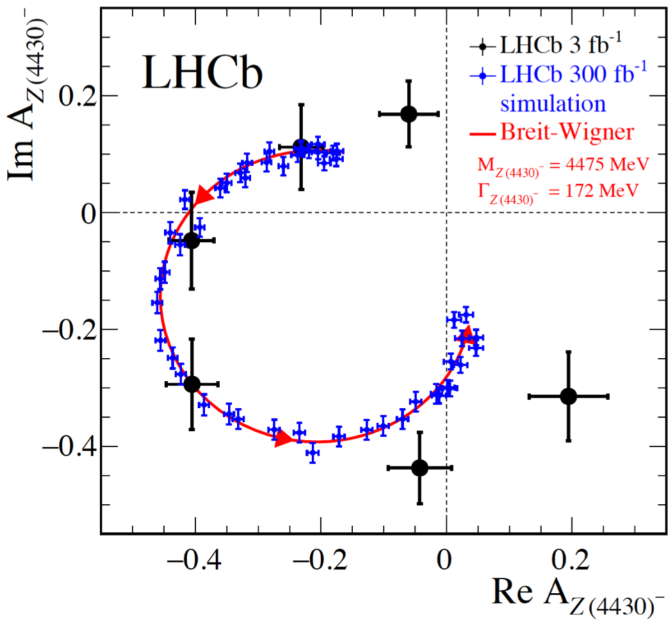
Amplitude analyses of exotic hadrons

- For resonances in b-decays, amplitude analyses help to determine the properties and to claim the existence

- Further test observed exotic states
  - Pc in $\Lambda_b \to J/\psi\, p\, K$
  - Z(4430) in $B \to \psi(2S) K\pi$

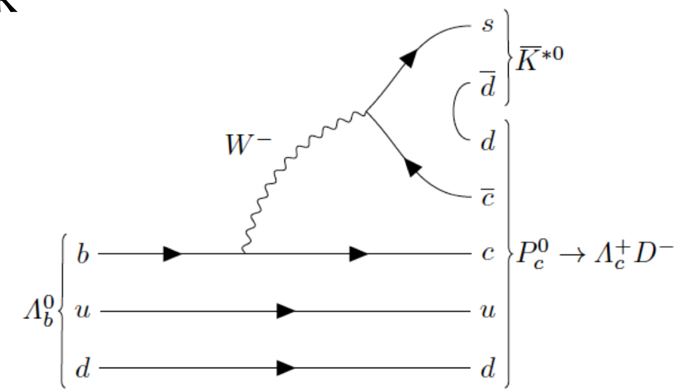
- With improved calorimetry:
  - Pc in $\Lambda_b \to \chi_{c1,2}\, p\, K$

- Pentaquark with strangeness
  - In $\Xi_b \to J/\psi \Lambda K$

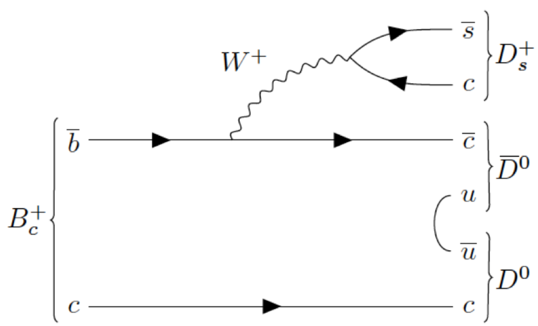


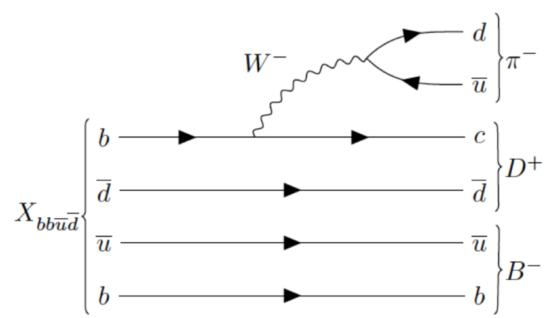
Other exotic searches

- Isospin multiplet of pentaquark
  - $c\bar{c}udd$ in $\Lambda_b \to \Lambda_c D\overline{K^*}$



- $QQq\bar{q}$ tetraquarks





- … and nice surprises when we study the heavy hadron decays

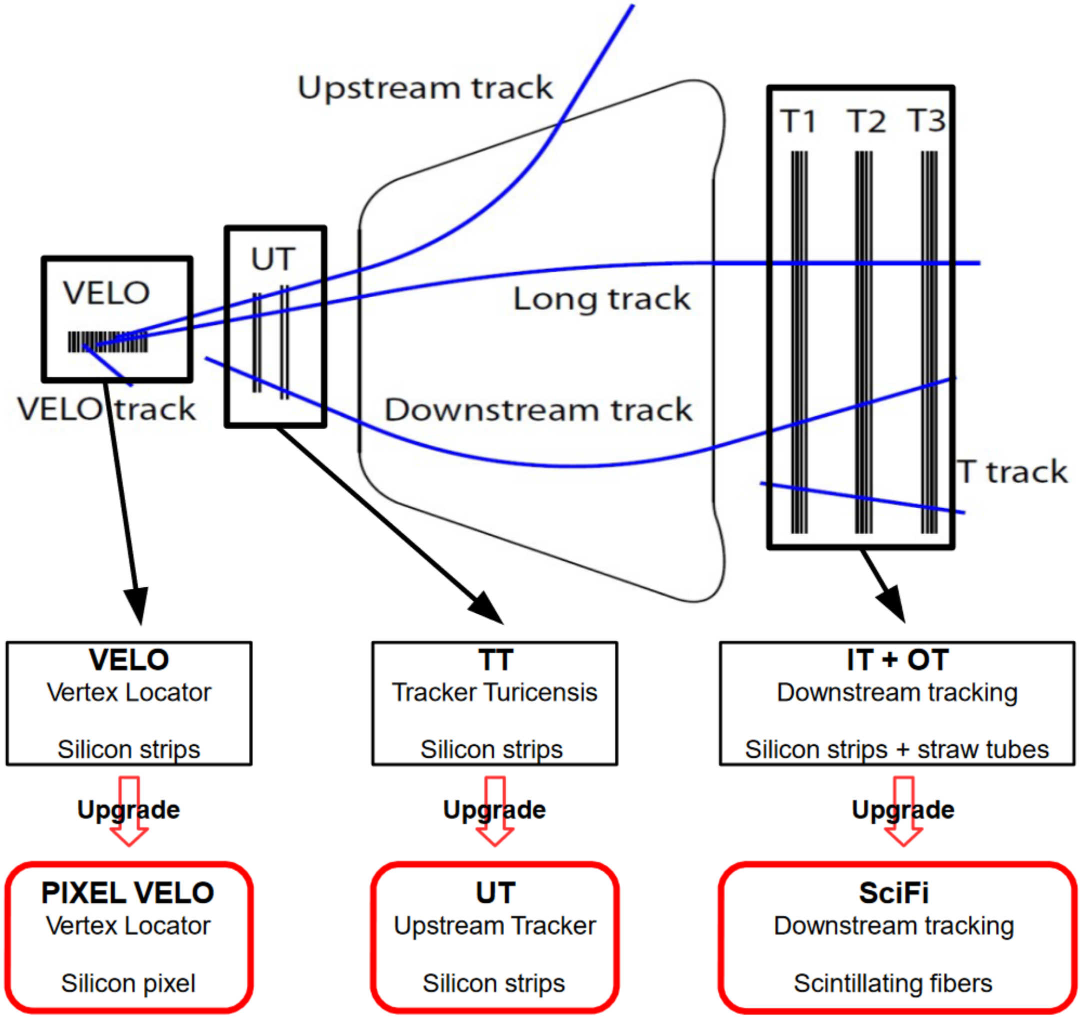
Summary

- LHCb has been successfully running until 2018
- Upgrade I is ongoing; Planning for Upgrade II has started
  - with Chinese contributions!
- Opportunities for spectroscopy studies
- Ideas, proposals for the coming upgrade most welcome!

Thank you!

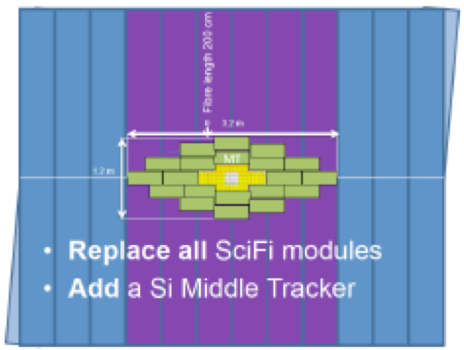
BACKUP

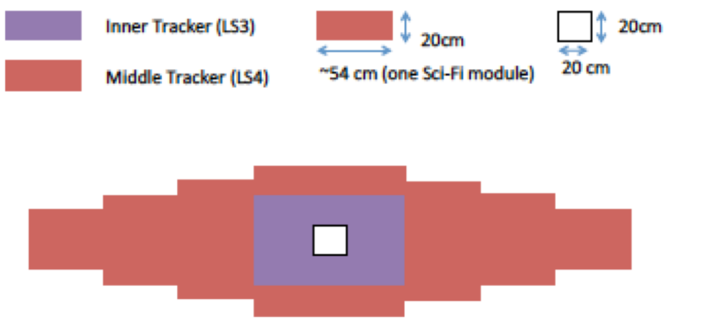
New tracking system



MIGHTY Tracker

Mighty Tracker Layout: x,y dimensions





Drivers of size

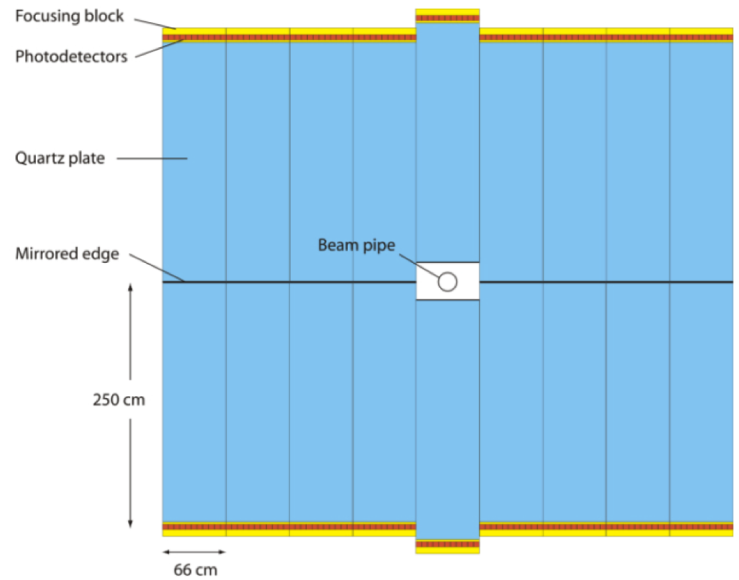
- Inner Tracker UIb
  - Tracking ghost rate
  - Limited modification of SciFi
- Middle Tracker UII
  - Radiation damage and occupancy in SciFi

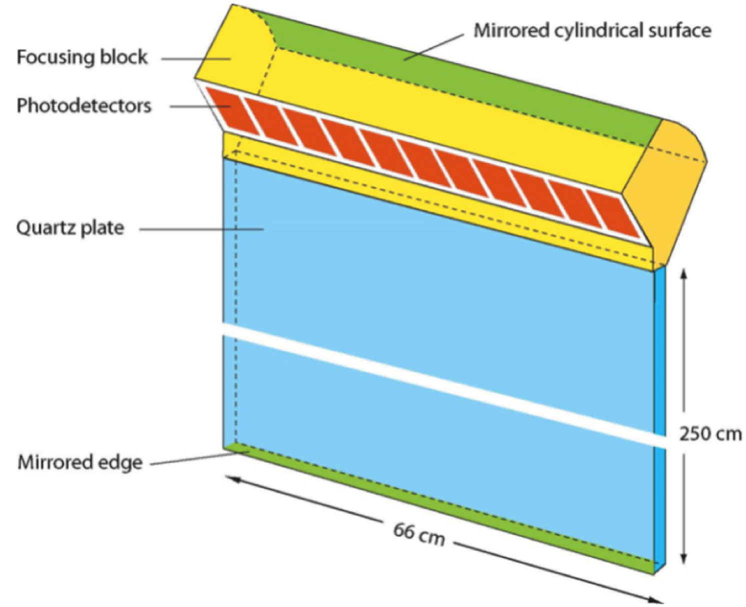
Baseline six layers, total
Upgrade Ib: ~5m^2
Upgrade II: ~20m^2

Chris Parkes, November 2019

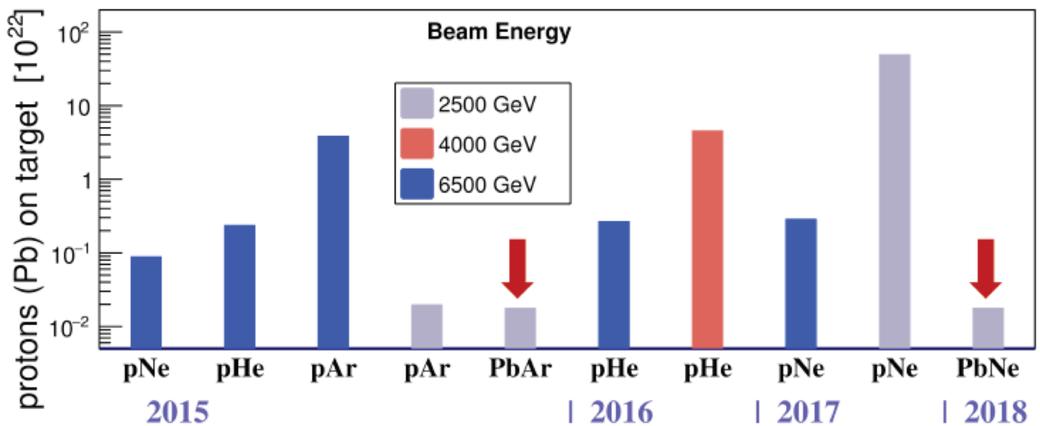
TORCH

- Charged PID for low momentum $p_T < 10$ GeV with 10 ps timing
- 70 ps per photon for ~30 phots
- A first prototype built and tested in testbeam, using MCP-PMT

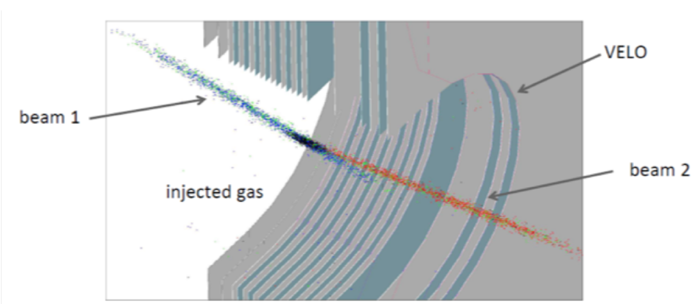


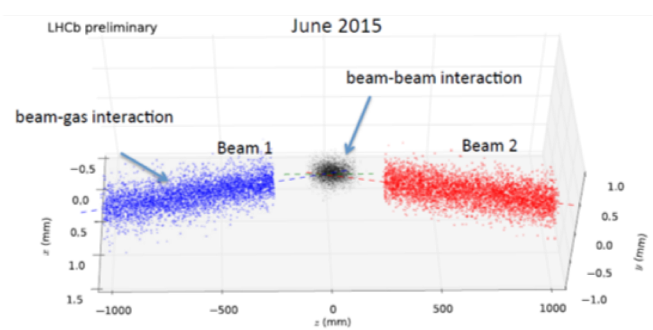


Not only *pp*, heavy ion, even fixed target



Unique sample enabled by noble gas injected to the beam pipe as target; inspired by the beam-gas imaging





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