The LHCb Upgrade and Prospects

Yiming Li 李一鸣
Institute of High Energy Physics, CAS

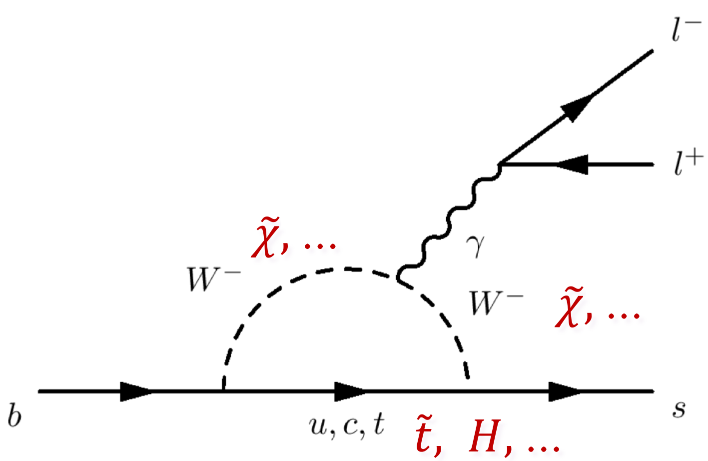
The 1st Workshop on Physics Frontiers at LHCb

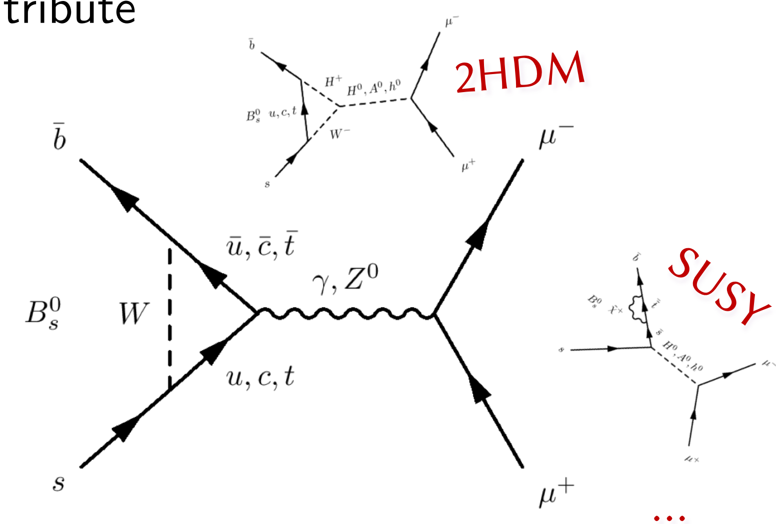
Content

- The current (past) LHCb detector
- Status of Upgrade I
- Plan for Upgrade Ib/II

Why flavour physics

- Flavour physics provides a tool of discovery in search of new physics
- Indirect search
  - Probing processes where loop diagrams are important
  - … where non-SM particles could contribute





Precise measurements of phenomena at low energy shed light on physics at higher energies!

LHC-B

CERN/LHCC 95-5
LHCC/ I 8
25 August 1995

Last update
28 March 1996

LETTER OF INTENT

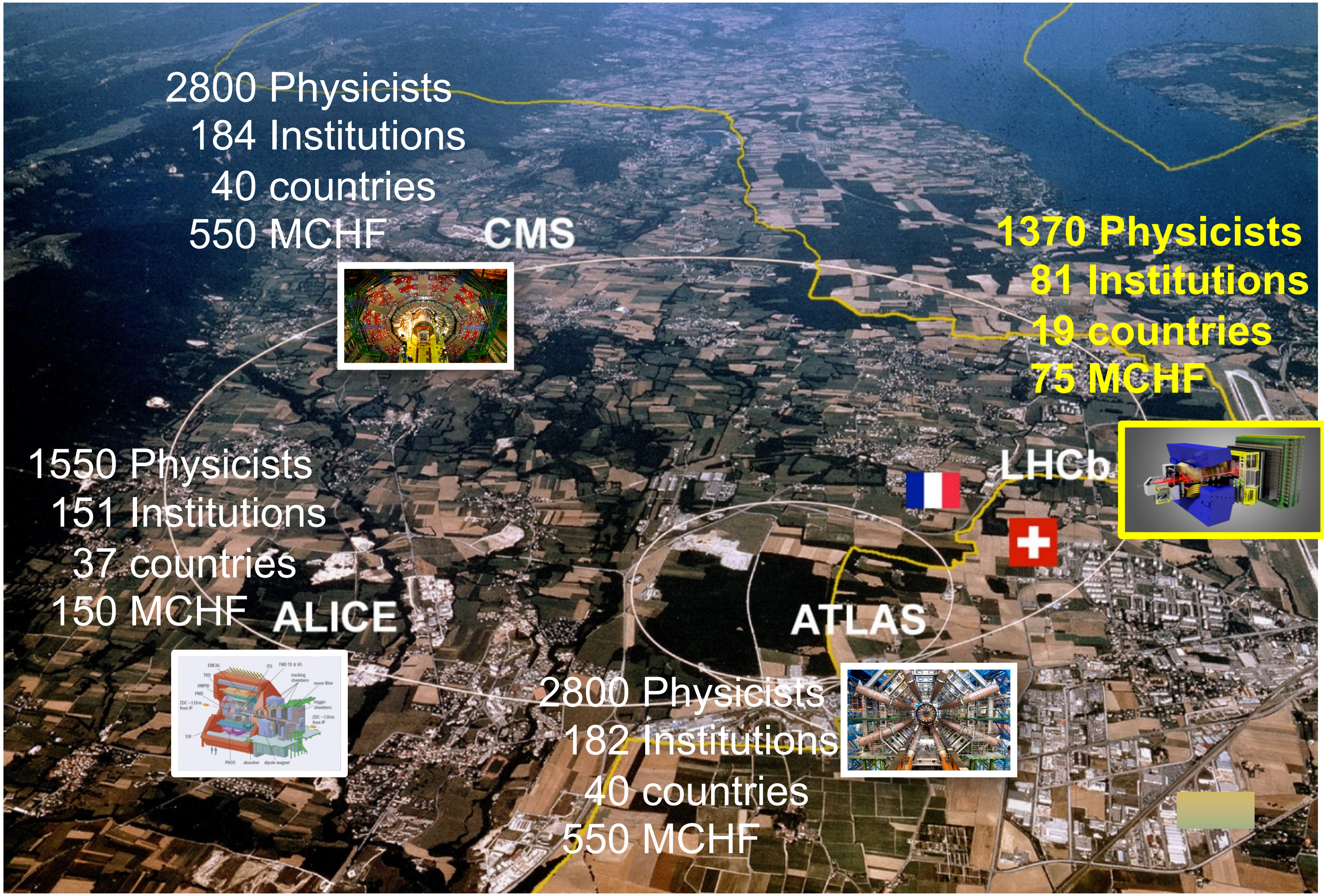
A Dedicated LHC Collider Beauty Experiment for Precision Measurements of CP-Violation

Abstract

The LHC-B Collaboration proposes to build a forward collider detector dedicated to the study of CP violation and other rare phenomena in the decays of Beauty particles. The forward geometry results in an average 80 GeV momentum of reconstructed B-mesons and, with multiple, efficient and redundant triggers, yields large event samples. B-hadron decay products are efficiently identified by Ring-Imaging Cerenkov Counters, rendering a wide range of multi-particle final states accessible and providing precise measurements of all angles, α, β and γ of the unitarity triangle. The LHC-B microvertex detector capabilities facilitate multi-vertex event reconstruction and proper-time measurements with an expected few-percent uncertainty, permitting measurements of B_s-mixing well beyond the largest conceivable values of x_s. LHC-B would be fully operational at the startup of LHC and requires only a modest luminosity to reveal its full performance potential.

... a forward collider detector dedicated to the study of CP violation and other rare phenomena in the decays of Beauty particles.

LHC experiments

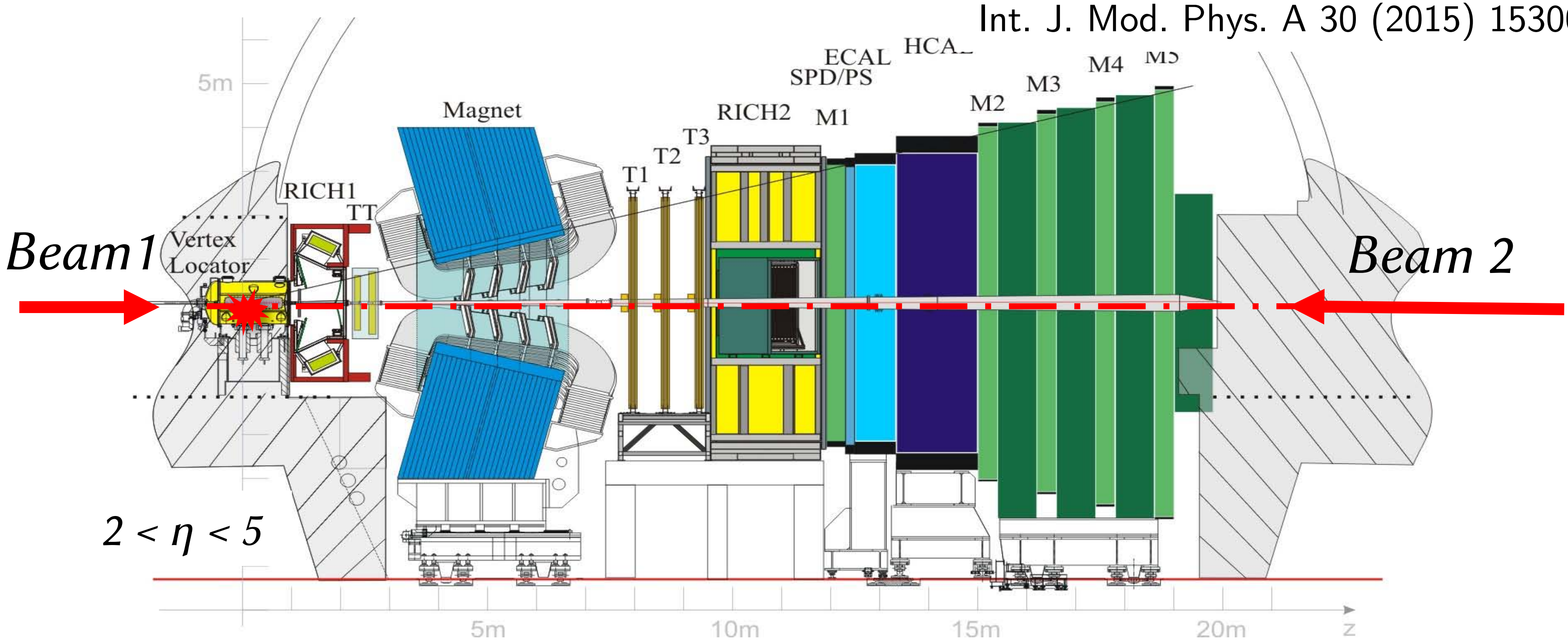


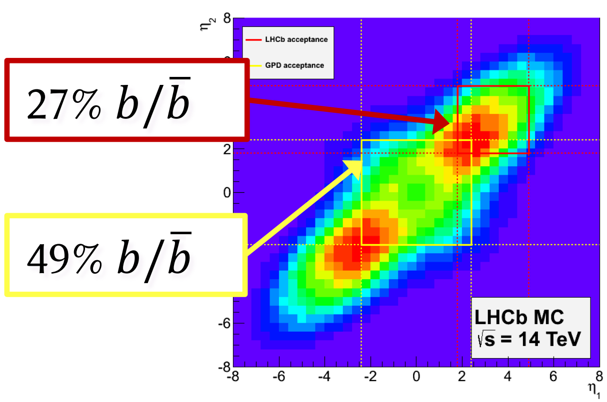
The Chinese members

- Starting with Tsinghua University
- Now 7 Chinese institutes
  - 97 members, 58 authors
- Leading many physics analyses with impact
  - *Observation of pentaquark states*
  - *Observation of doubly charmed baryon*
  - *... Benefiting from active interactions with theorists!*
- Contributing to tracking system upgrade and grid computing

The current detector

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

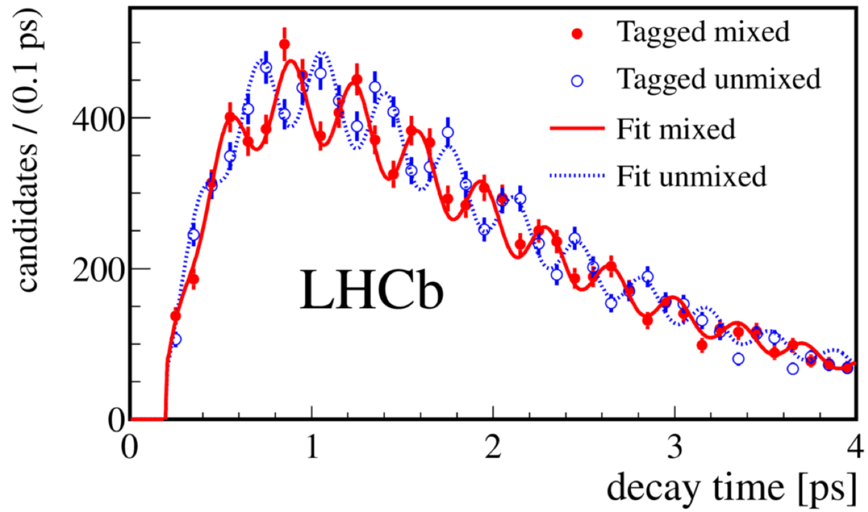


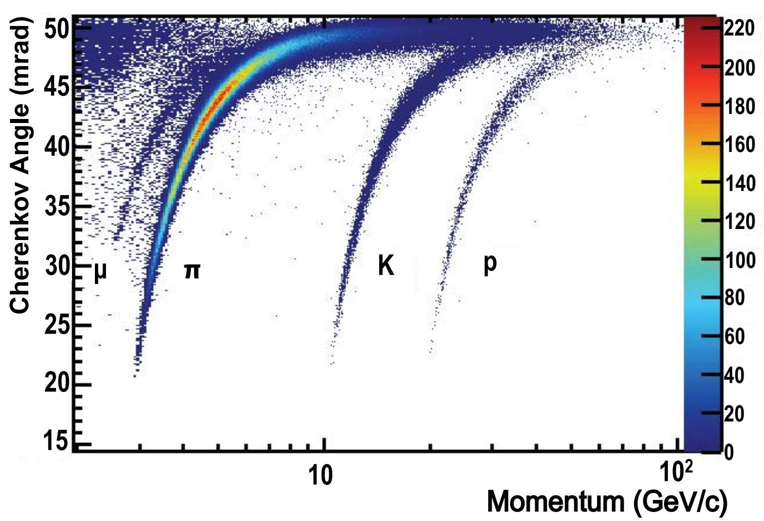


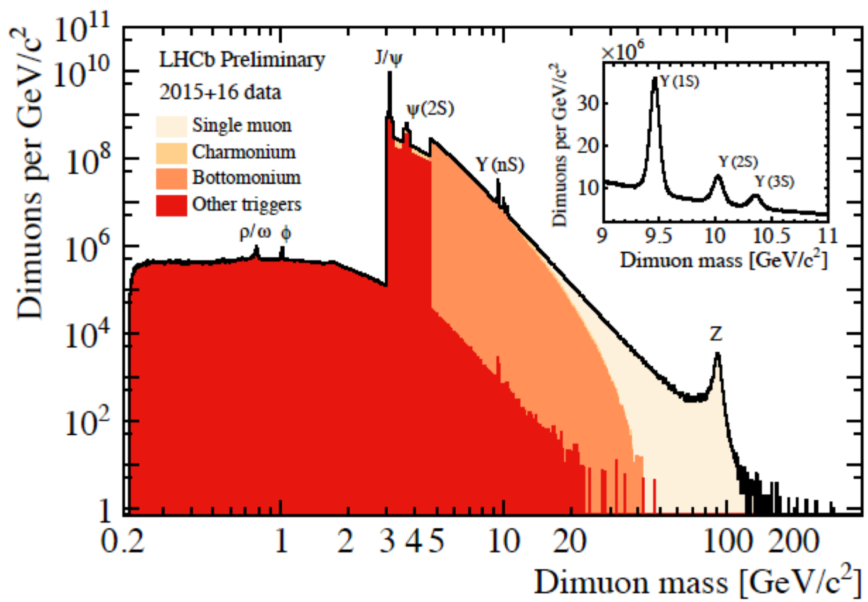
Vertex res.	$\sigma_{IP} = 20\ \mu m$
Time res.	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum res.	$\Delta p/p = 0.4 \sim 0.6\%$ (5 – 100 GeV/c)
Mass	$\sigma_m = 8$ MeV/c^2 for $B \to J/\psi X$
Hadron ID	$\varepsilon(K \to K) \sim 95\%$ mis-ID $\varepsilon(\pi \to K) \sim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

Detector performance

- Excellent vertexing , momentum resolution, and particle identification

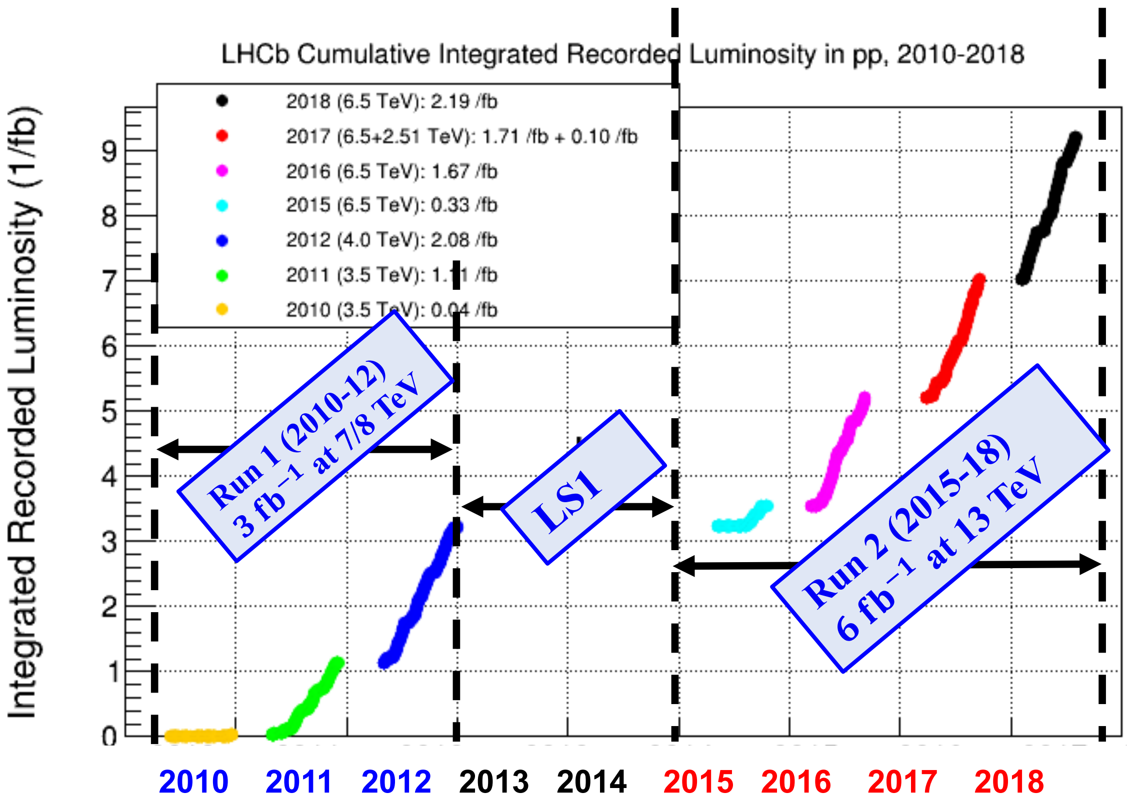


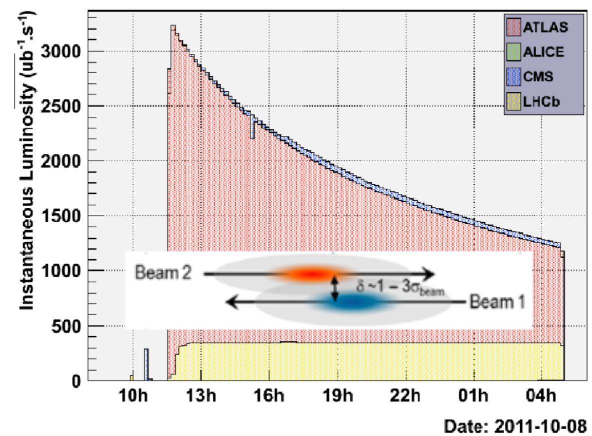




Operation

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



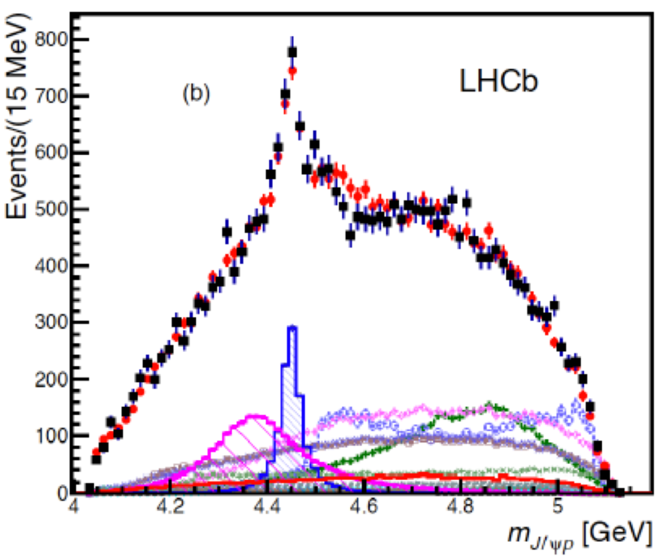


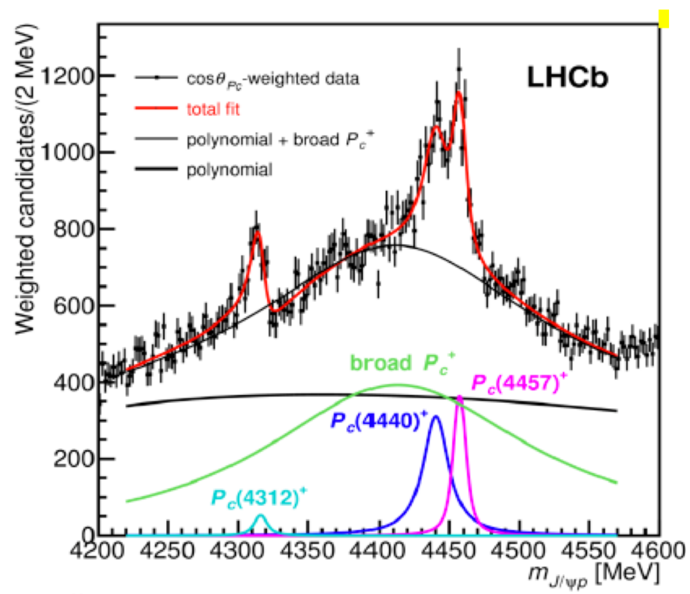
Luminosity levelling to maintain

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

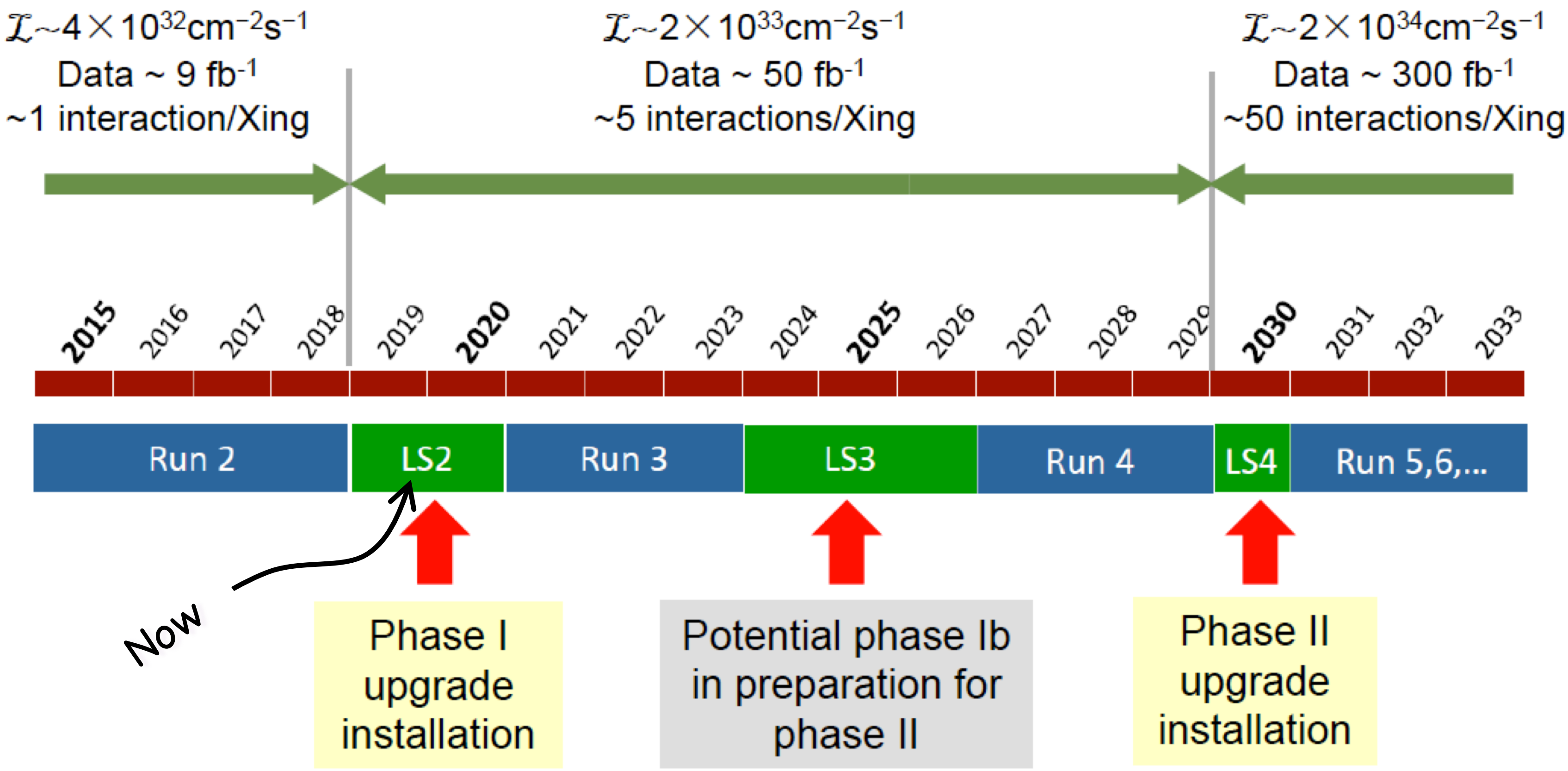
Pentaquark: example of Run 1+2 physics

- Observation of two pentaquark states Pc(4380)+ and Pc(4450)+ in $\Lambda_b \to J/\psi \Lambda K^-$ decay in 2015 [*PRL 115 (2015) 072001*]
- With more (Run 1+2) data, the yield is an order of magnitude higher ⇒ more structures revealed! [*PRL 122 (2019) 222001*]



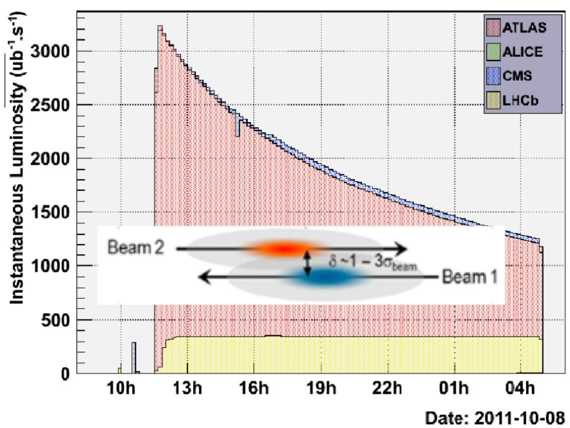


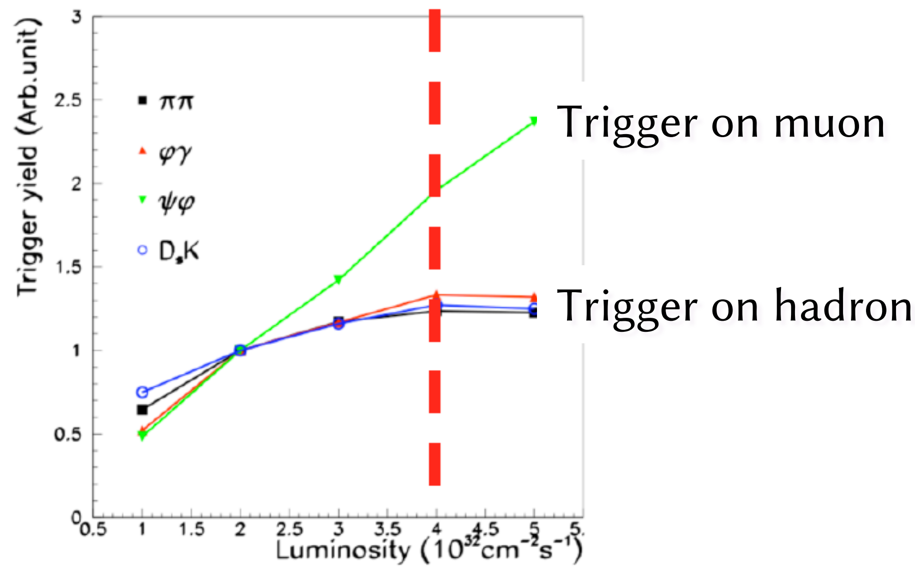
The way ahead – LHCb upgrade plans



Motivation of upgrade

- More data, higher discovery potential!
- Why cannot 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



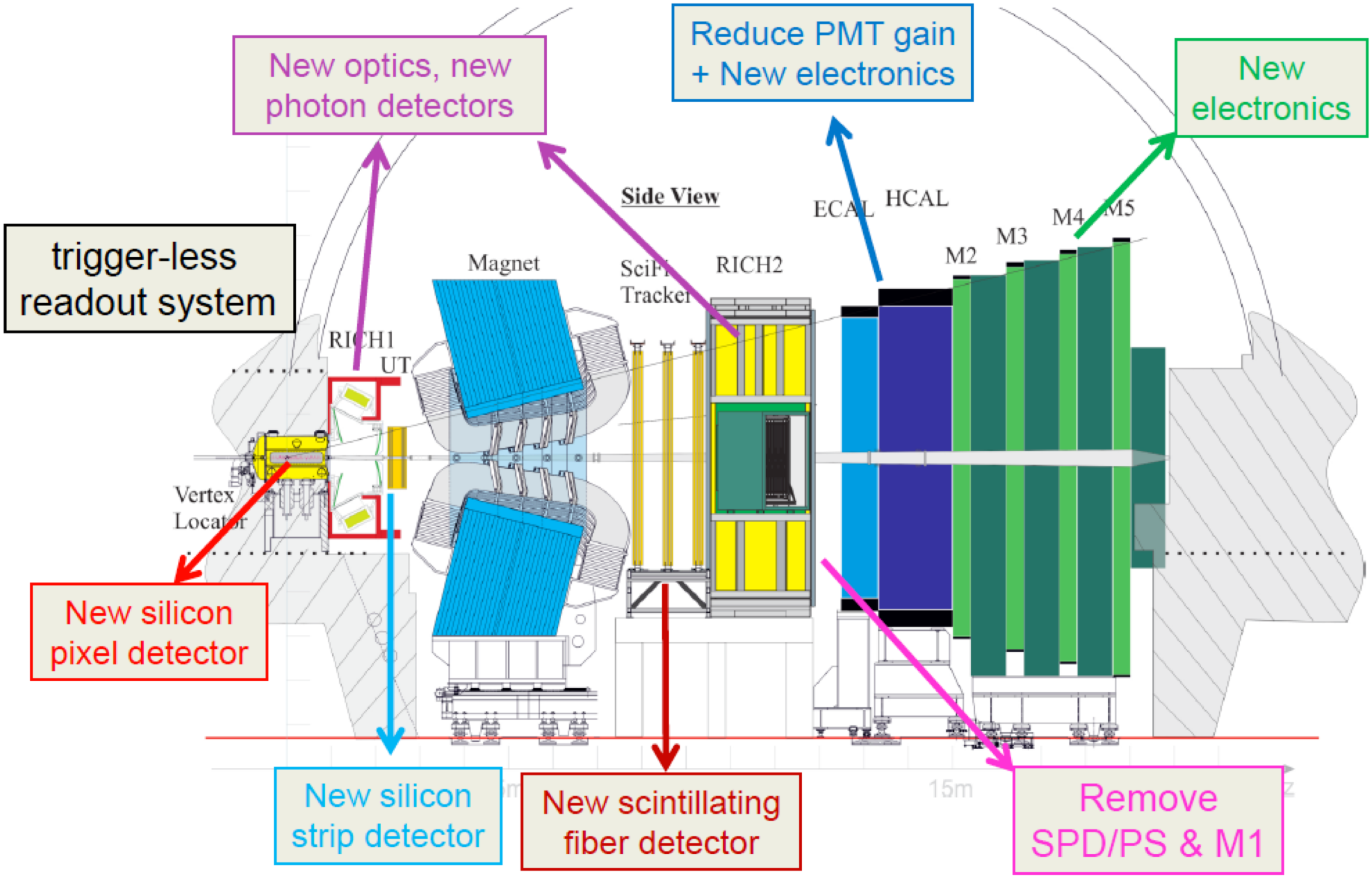


Goal of upgrade Phase I

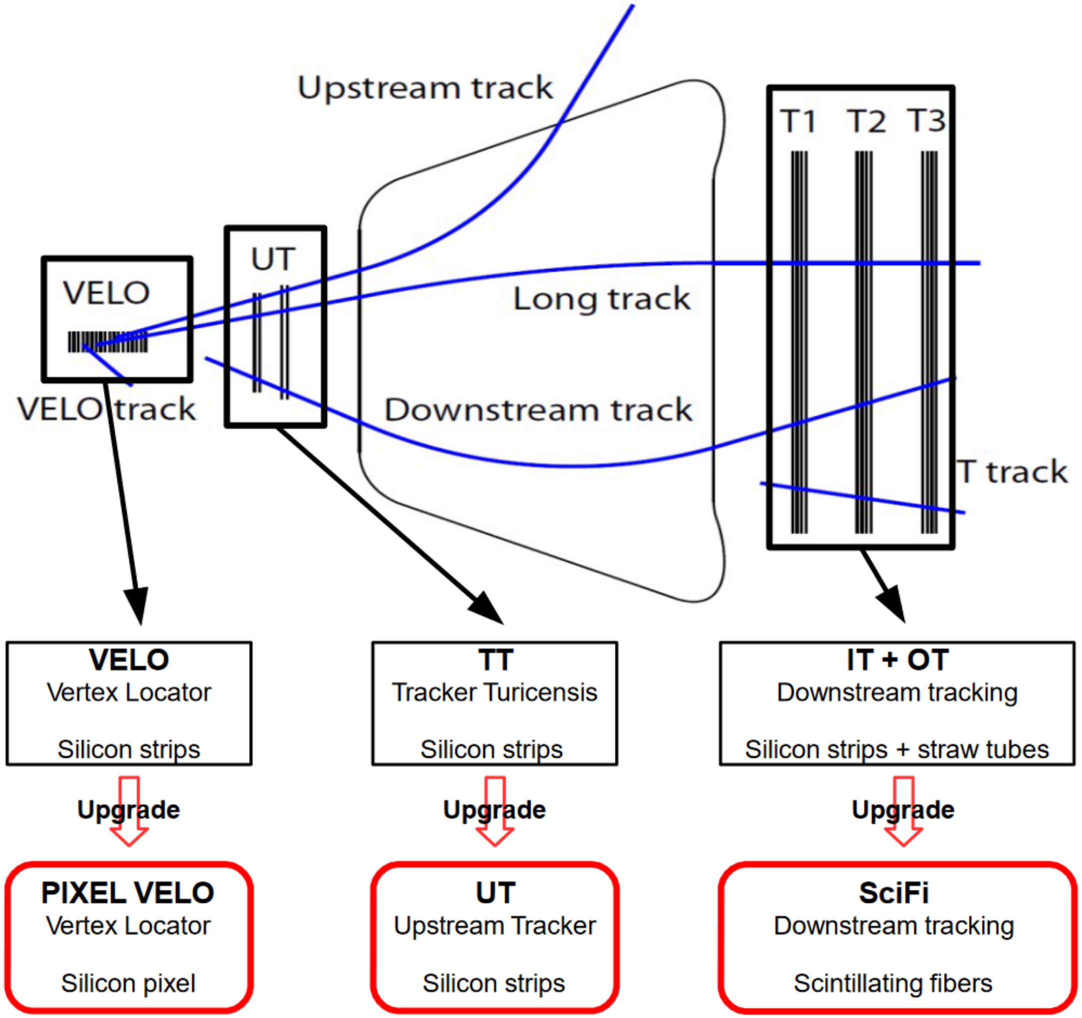
- More data, higher discovery potential!
- Why cannot fully exploit what LHC can offer?
  - Saturation of hadronic trigger at higher lumi due to 1MHz hardware trigger
  - Performance degradation with increase of detector occupancy
  - Limited radiation hardness of trackers

- Increase the instantaneous lumi to 2×10^{33} $cm^{-2}s^{-1}$ a factor of 5 increase
- 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

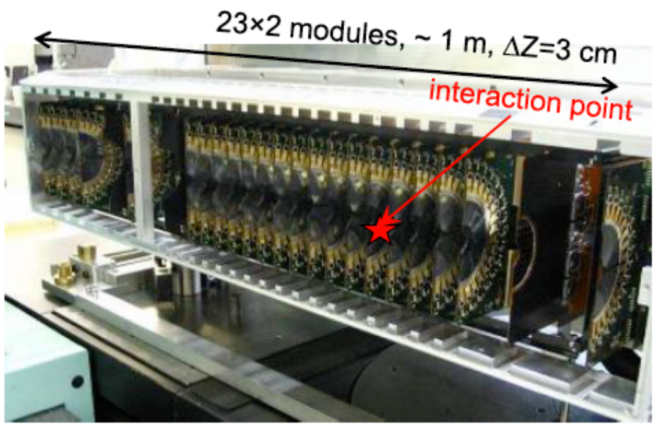
LHCb Upgrade Phase I



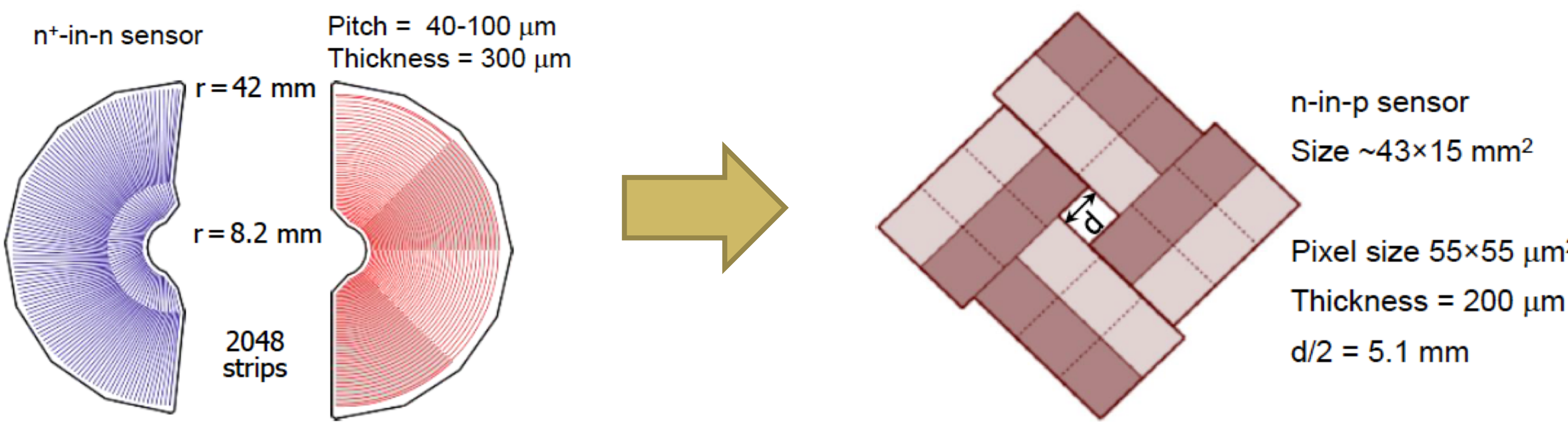
New tracking system



Vertex Locator (VELO)

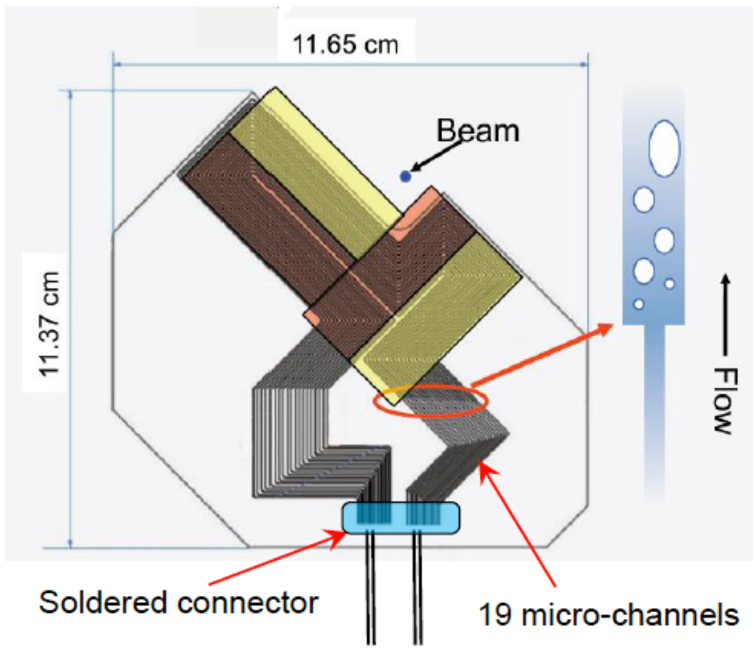


- Similar geometry as the old one
- Strip in r-ϕ → Hybrid pixel detector
- VeloPix ASIC, 256 × 256, readout@40MHz
- More radiation hard sensor:
  - $\Phi_{max} \sim 7\times10^{14} \rightarrow 8\times10^{15}\ n_{eq}\ \mathrm{cm}^{-2}$
- Closer approach to beampipe

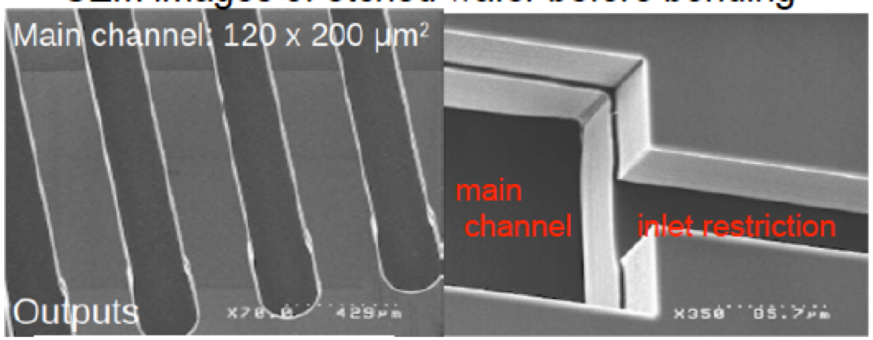


VELO cooling

- Due to harsh radiation environment VELO has to operate at -20 degree
- Cooling provided by evaporative CO_2 circulating in 200 × 120 um microchannels etched in 500 um thick silicon substrate
  - Thermal efficient, minimum material, rad hard… just very challenging!



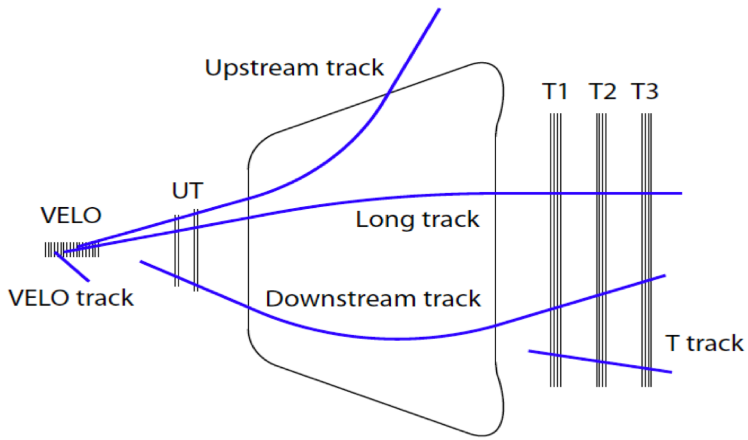
SEM images of etched wafer before bonding



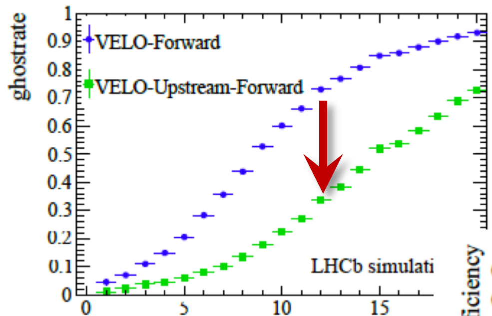
channels output directly to connector

Two step channel etching

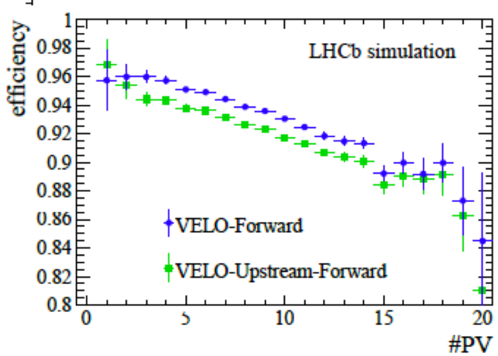
Upstream Tracker's (UT) role



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



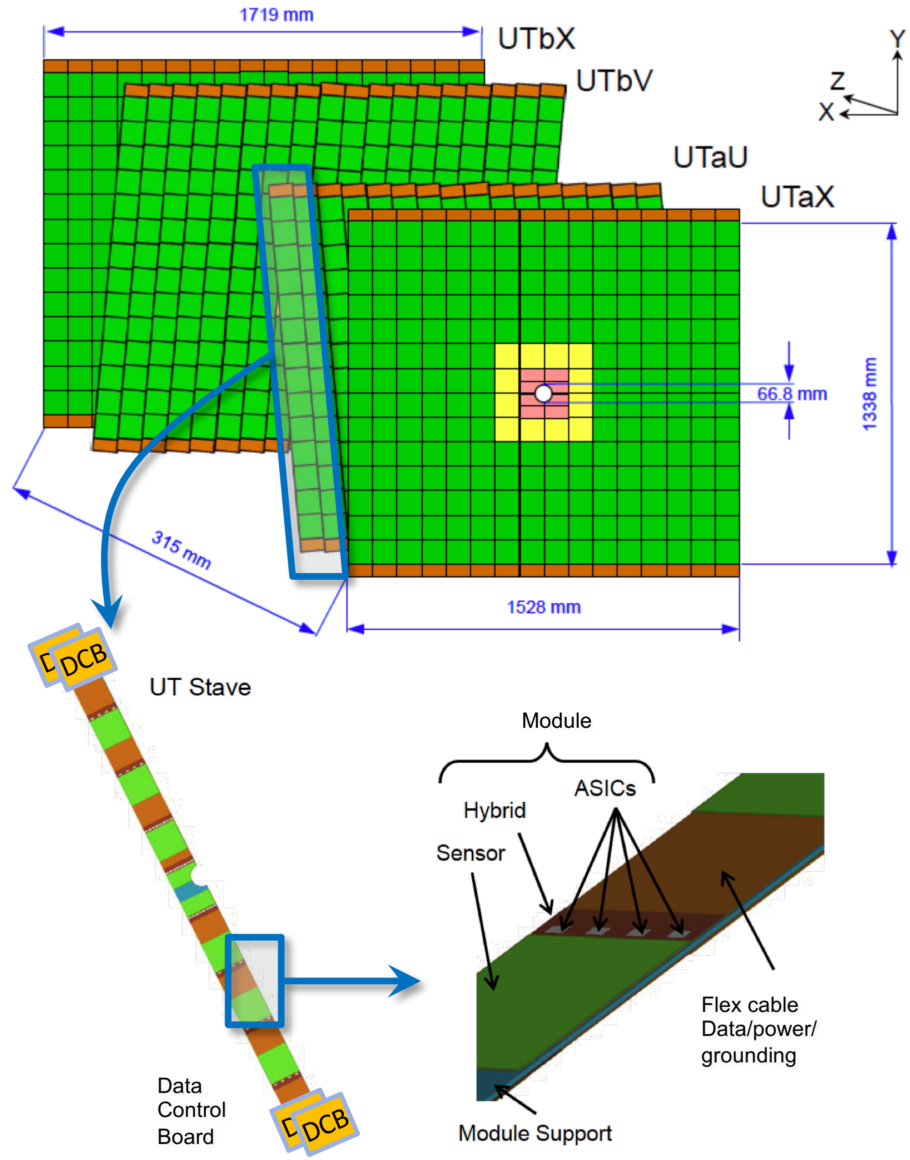
ghost rate reduced by requiring UT hits



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

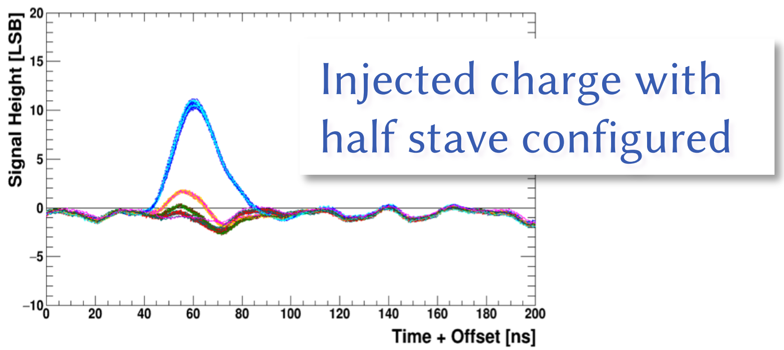
UT design

- Similar geometric configuration as TT
- Improved coverage and granularity
- Radiation hard sensor $\Phi_{max} \sim 5 \times 10^{14}\, n_{eq}\mathrm{cm}^{-2}$
- 40MHz FE readout near sensor
- More digital processing at end of detector

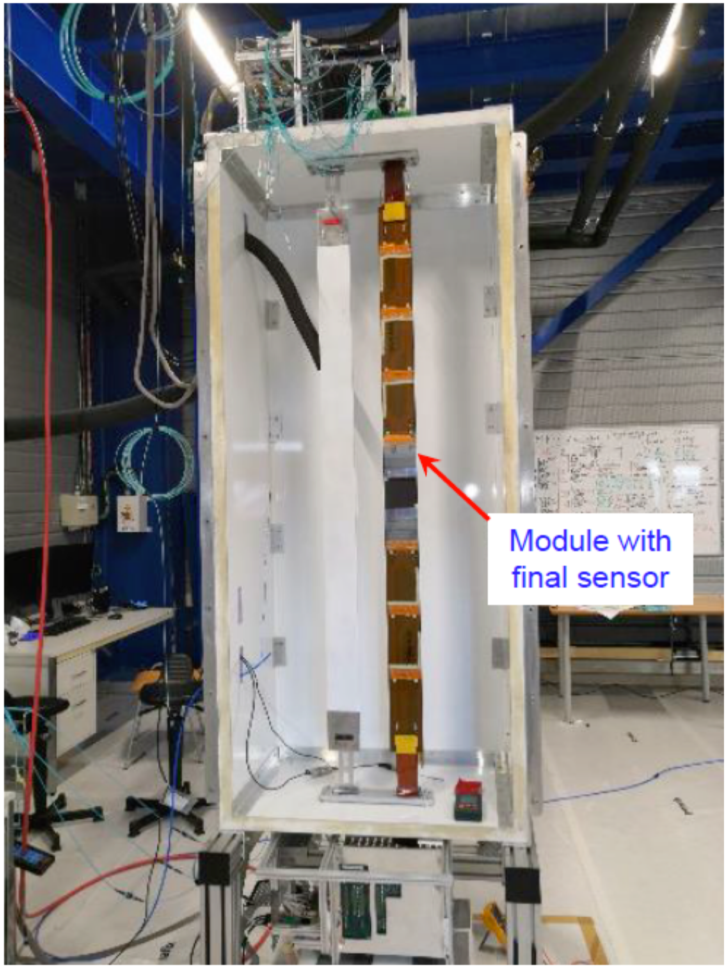


UT preparation for installation

- A slice system set up at CERN including a prototype stave, to enable the test of the full readout chain
- Performance of the module meets design goal
- The 1st stave being installed now

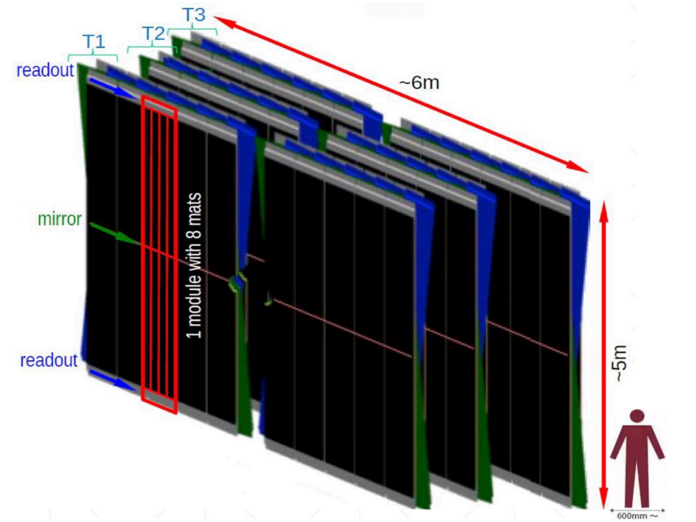


IHEP group is key player in the slice test, and will participate in the installation, commissioning and operation of UT

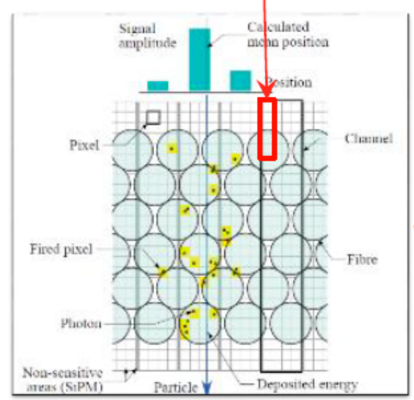


Scintillating Fiber Tracker (SciFi)

- 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%

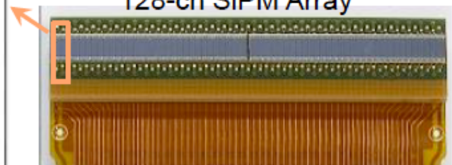


1 SiPM Channel



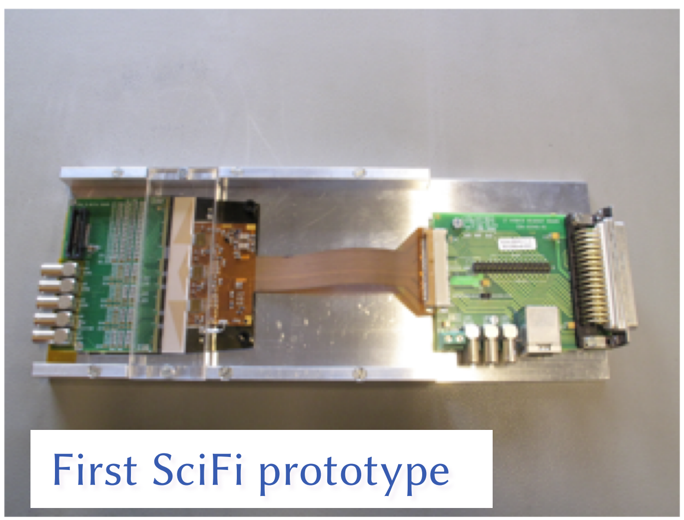
6 layers staggered
Ø250 µm fiber mats

128-ch SiPM Array

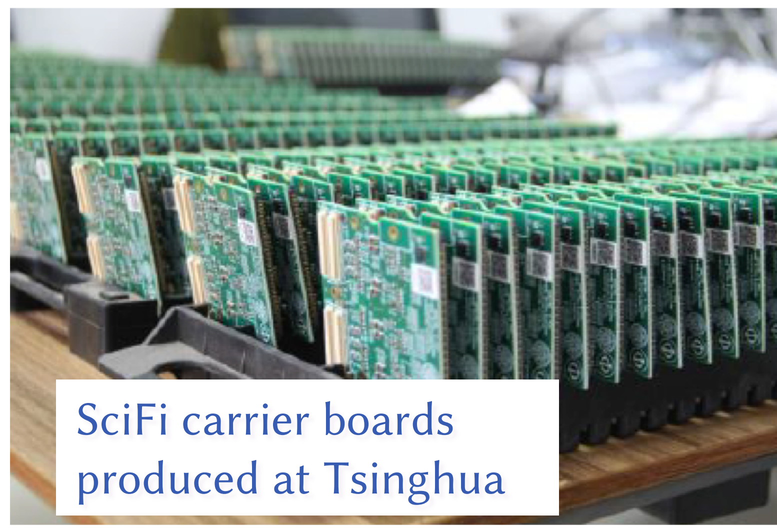


Tsinghua contribution to SciFi

- Tsinghua group designed the electronics readout for the first SciFi prototype in collaboration with EPFL 10 years ago
- Designed front-end electronics for SciFi since 2015 with MOST support
- Finished production of all PACIFIC board (2018-2019), with high quality. The boards are with CERN for installation



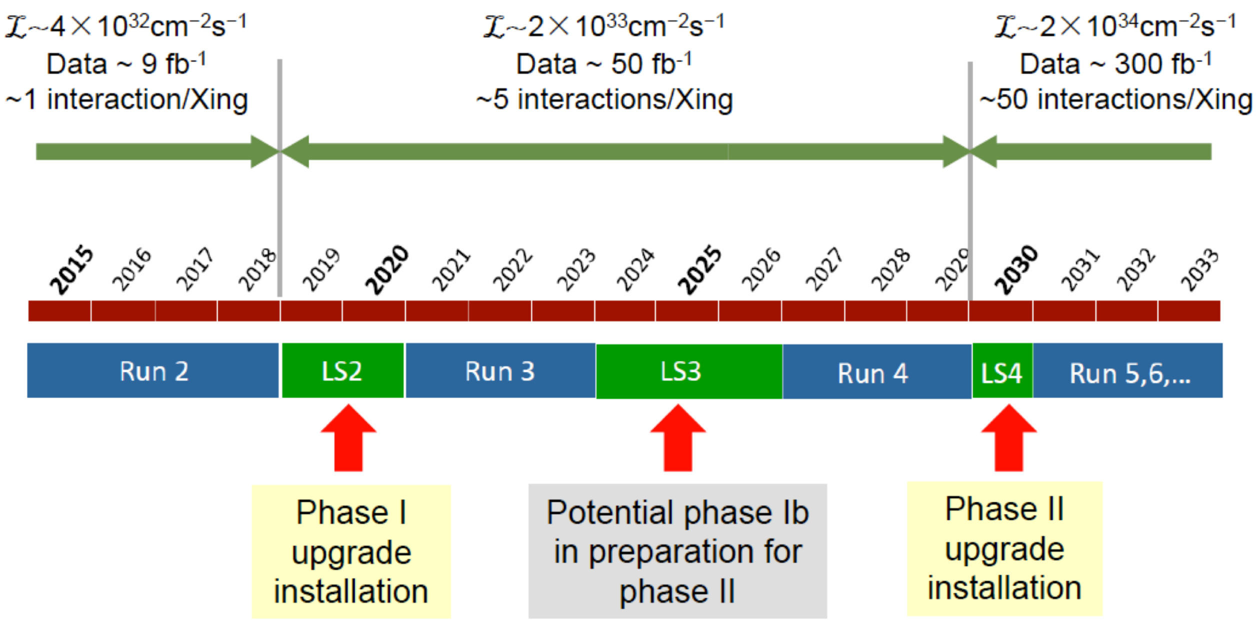
First SciFi prototype

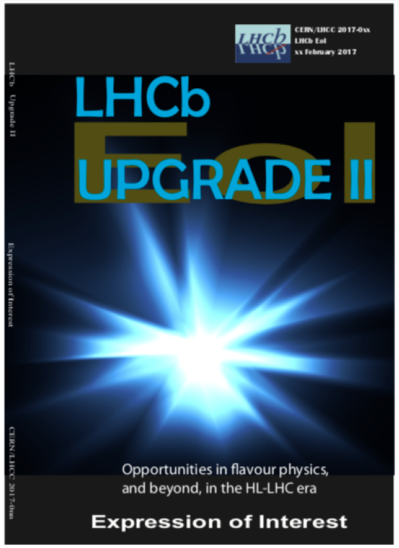


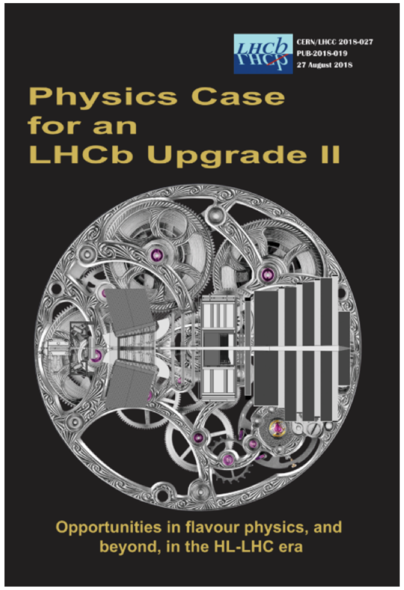
SciFi carrier boards produced at Tsinghua

Further ahead: Upgrade II

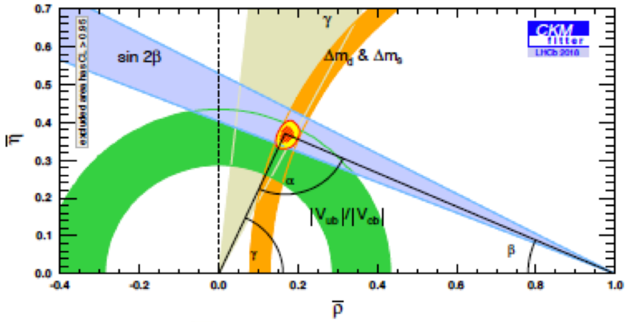
- Can we fully profit from the HL-LHC?
- What can we do with 300 fb^{-1} data?



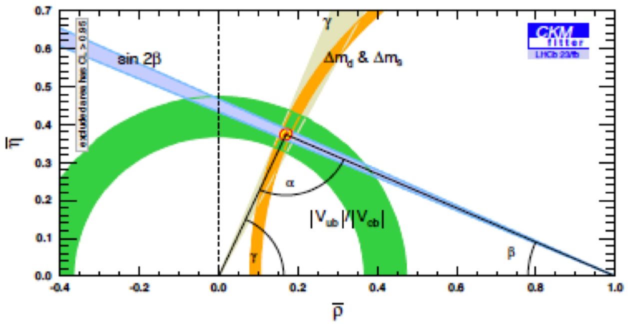




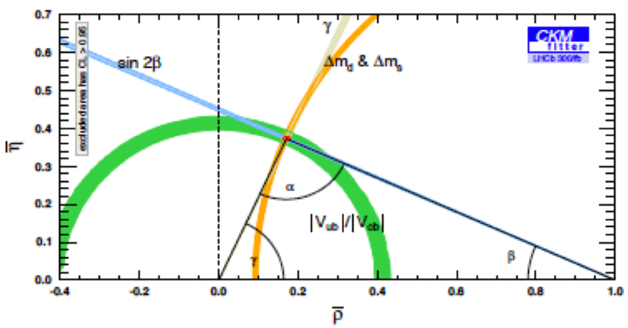
CKM matrix @ Upgrade II



Now



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

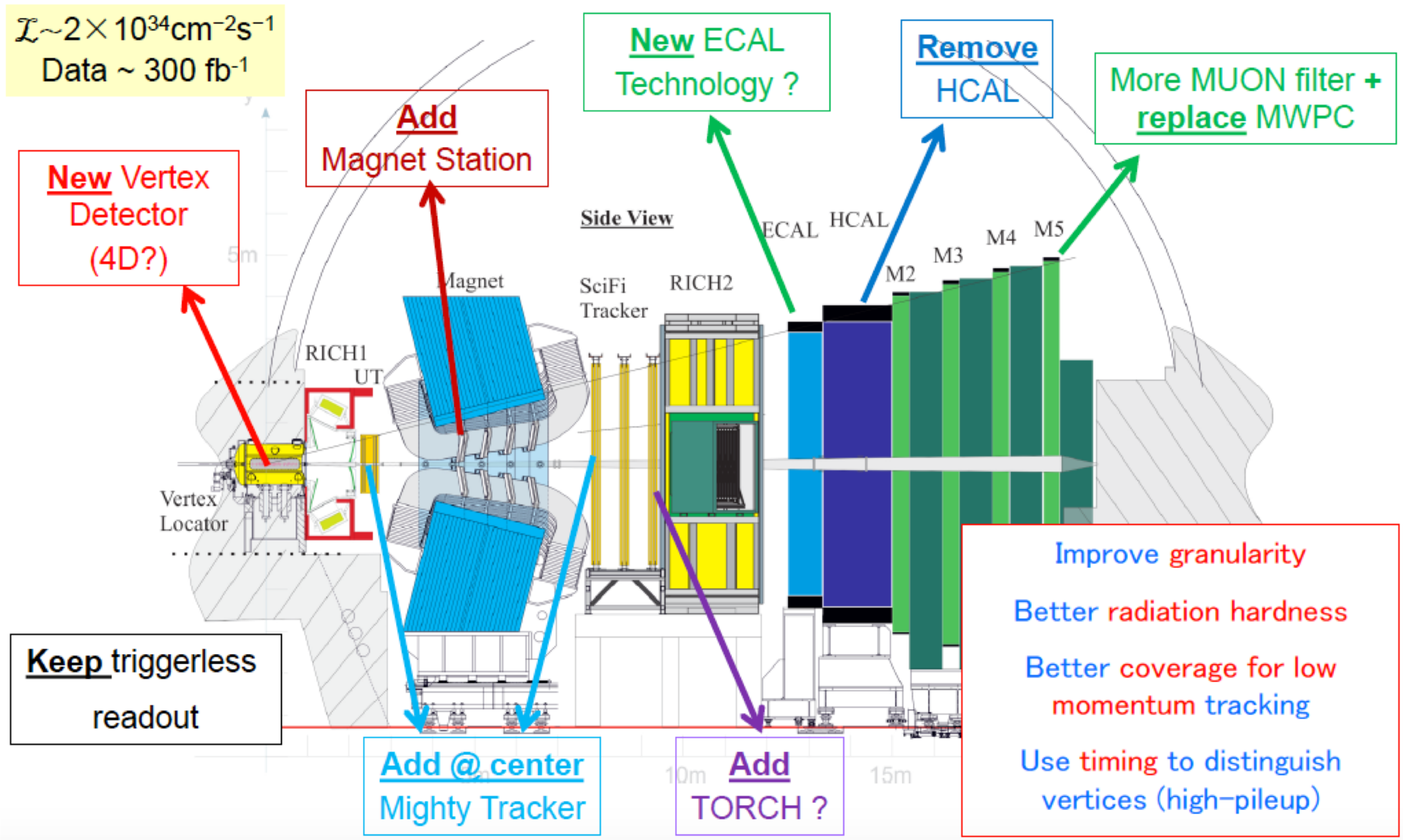


By 2035 (300 fb^{-1}, Upgrade II)

CKM matrix @ Upgrade II

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II
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
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}

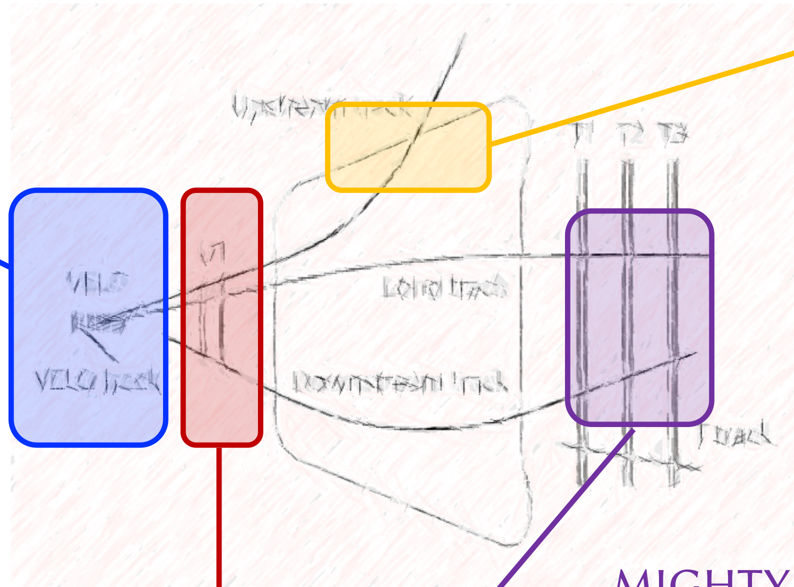
Possibilities in Upgrade Phase II



Upgrade II approved to proceed to Framework TDR by LHCC

Tracking

VELO
Finer granularity
Thinner RF foil,
Timing < 200ps

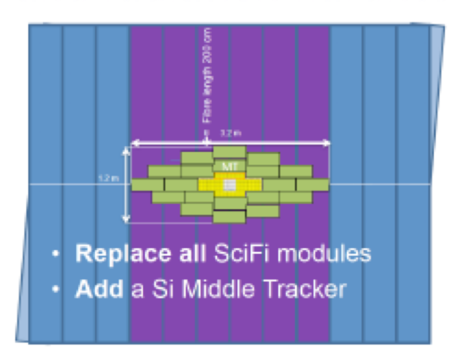


Magnet station
Within magnet
to improve
tracking at low
momentum

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

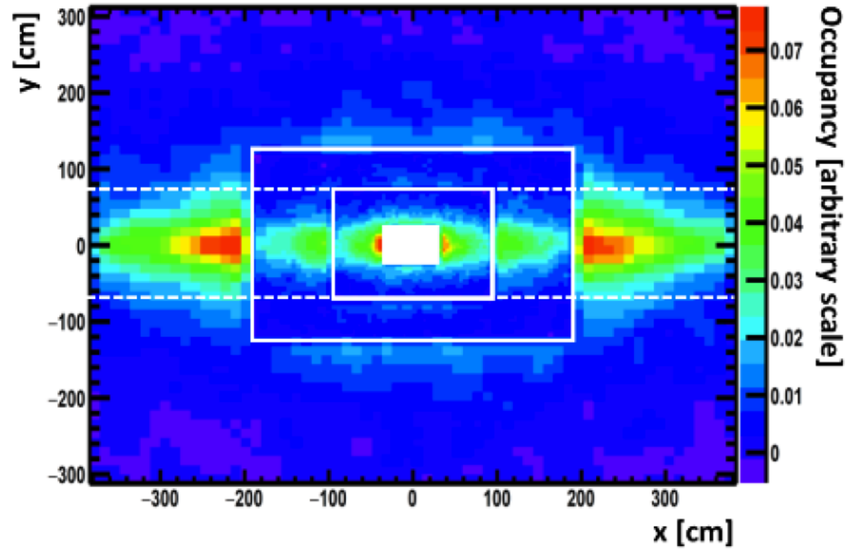


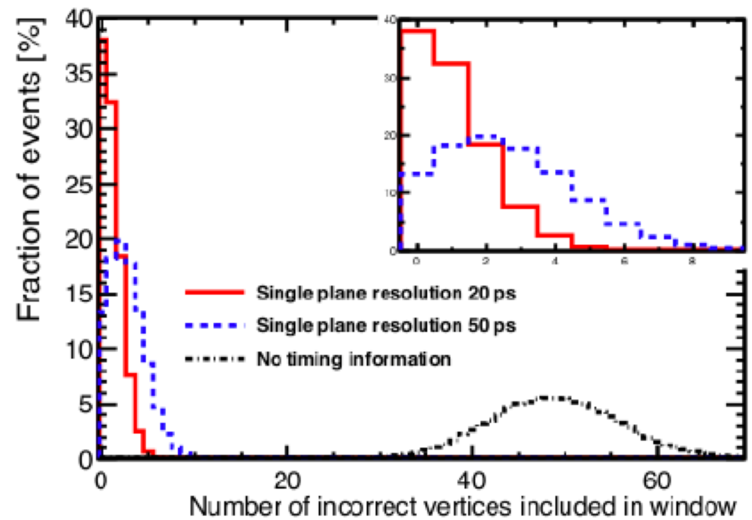
Interests from Chinese groups:

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

Calorimeter

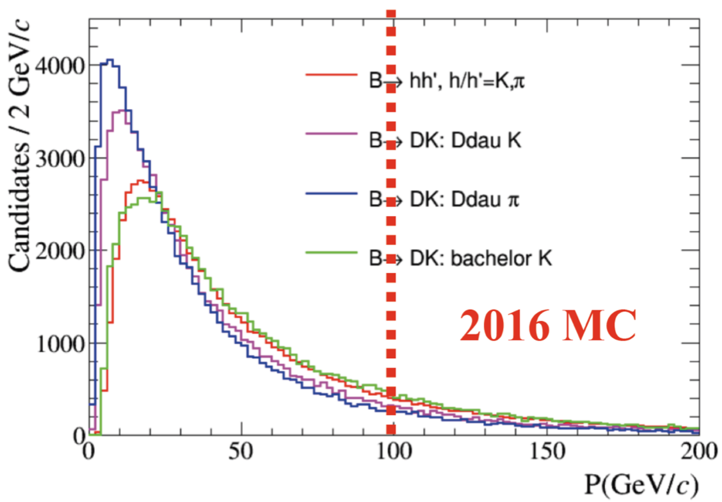
- Severe radiation
  - → Replacement with radiation technology for innermost or y=0
- Overlapping showers
  - → Smaller Molière radius, finer cells
- Huge # combinatorics from π^0
  - → Fast timing information desired
- Options being discussed
  - *Homogenous crystal with longitudinal segmentation*
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

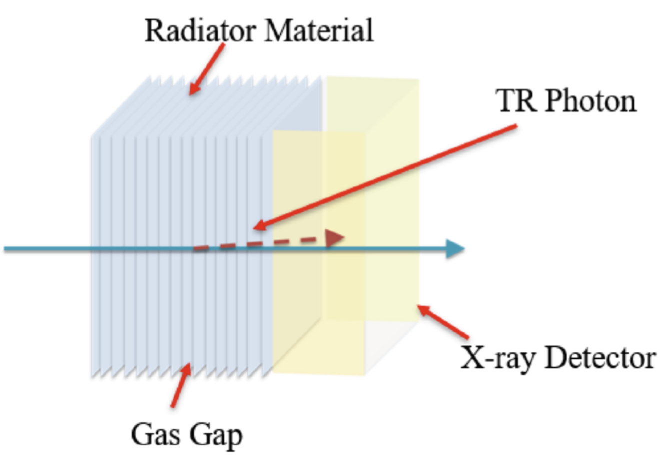




Transition Radiation Detector

- Goal: to improve charged particle ID > 100 GeV
- Could gain 30-40% more signals depending on channels
  - Very useful for electroweak channels!
- Possible structure: radiator + photon detector (MPGD?)
- *Chinese interests:*
  - *TRD prototype for astro project (HERD) tested by UCAS in beams*





Summary

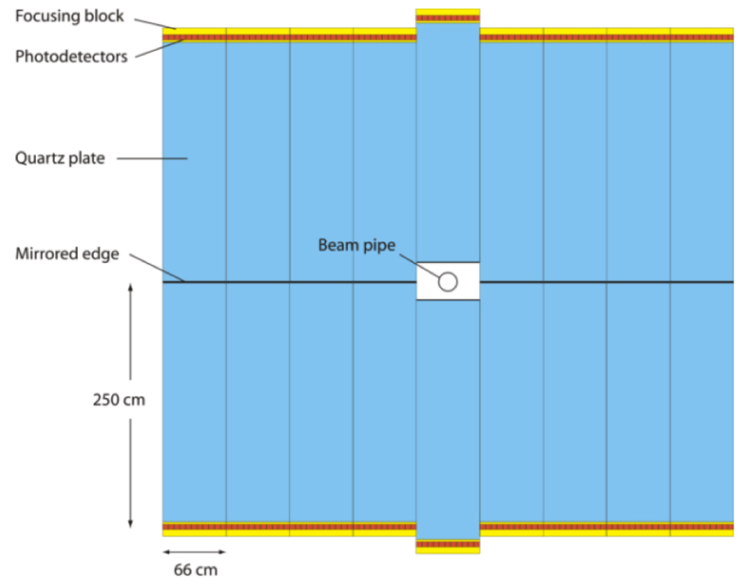
- LHCb has been successfully running until 2018
- Upgrade I is ongoing
  - with Chinese contributions!
- Planning for Upgrade II has started
- Ideas, proposals for the coming upgrade most welcome!

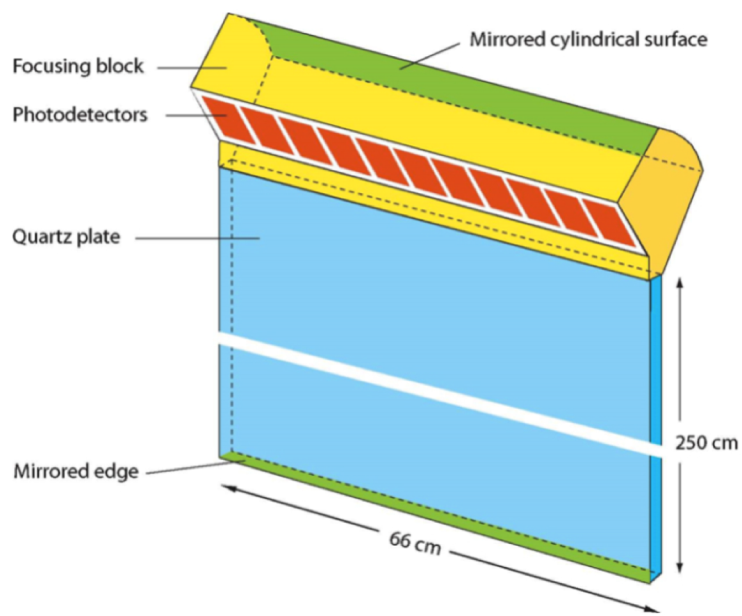
Thank you!

BACKUP

TORCH

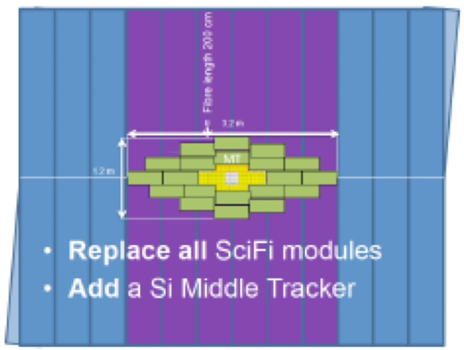
- Charged PID for low momentum p_T < 10 GeV with 10 ps timing
- 70 ps per photon for ~30 phots
- A first prototype built and tested in testbeam, using MCP-PMT

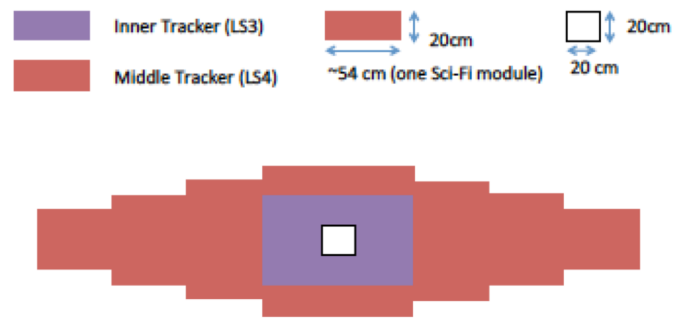




MIGHTY Tracker

Mighty Tracker Layout: x,y dimensions





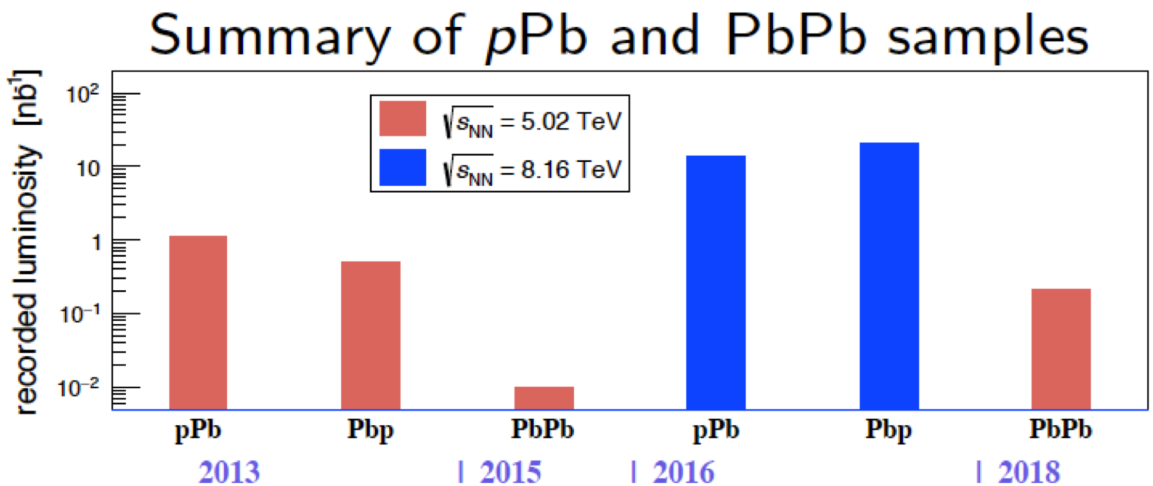
Drivers of size

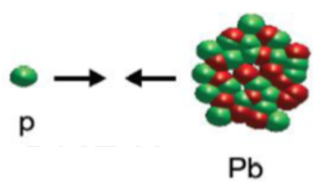
- Inner Tracker UIb
  - Tracking ghost rate
  - Limited modification of SciFi
- Middle Tracker UII
  - Radiation damage and occupancy in SciFi

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

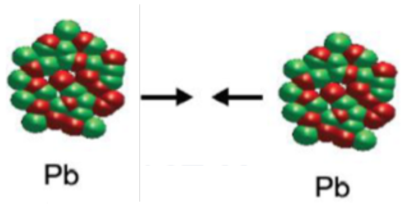
Chris Parkes, November 2019

Not only *pp*, also heavy ion



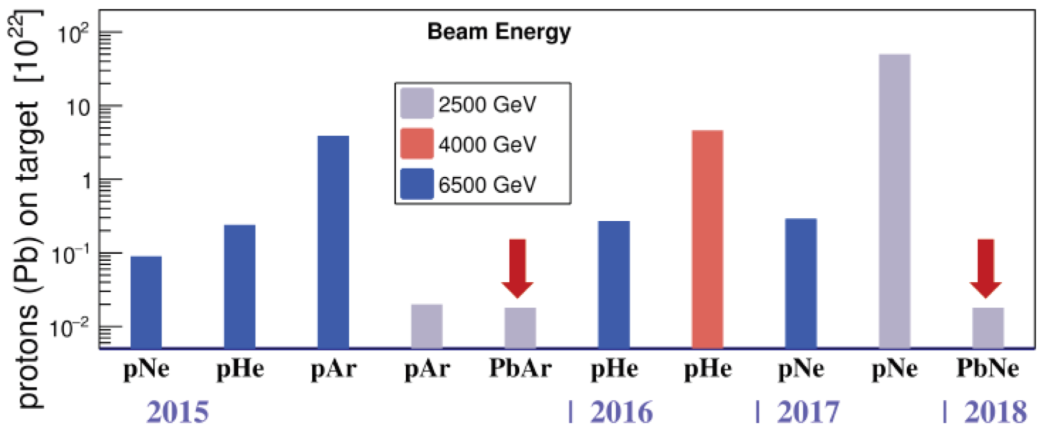


Cold nuclear matter

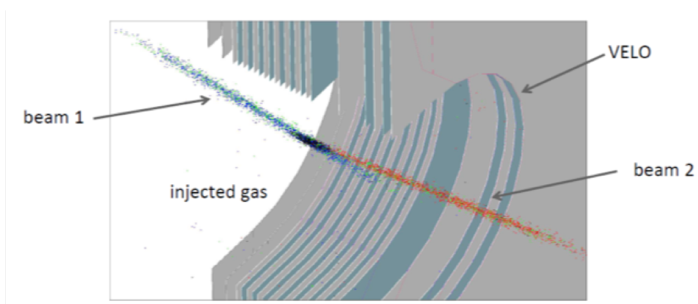


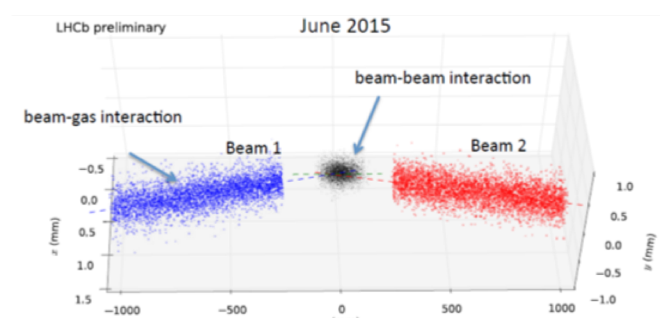
Quark Gluon Plasma ...

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

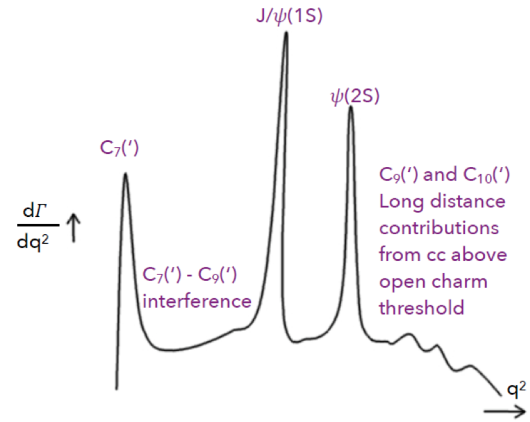


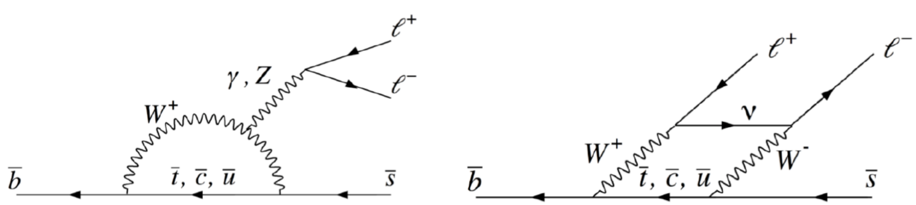


JINST 9 P12005

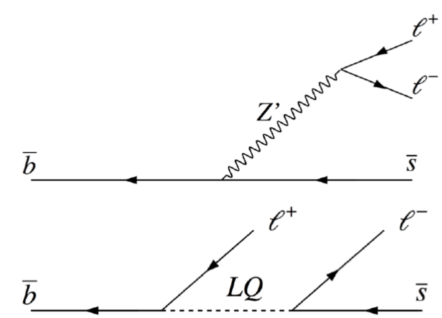
$B^0 \to K^*\mu^+\mu^-$ and friends

- The $b \to sll$ decays offer many observables probing NP and its helicity structure
- Different dimuon mass region sensitive to different Wilson Coefficient
- More observables can be constructed, eg. P_5'





SM



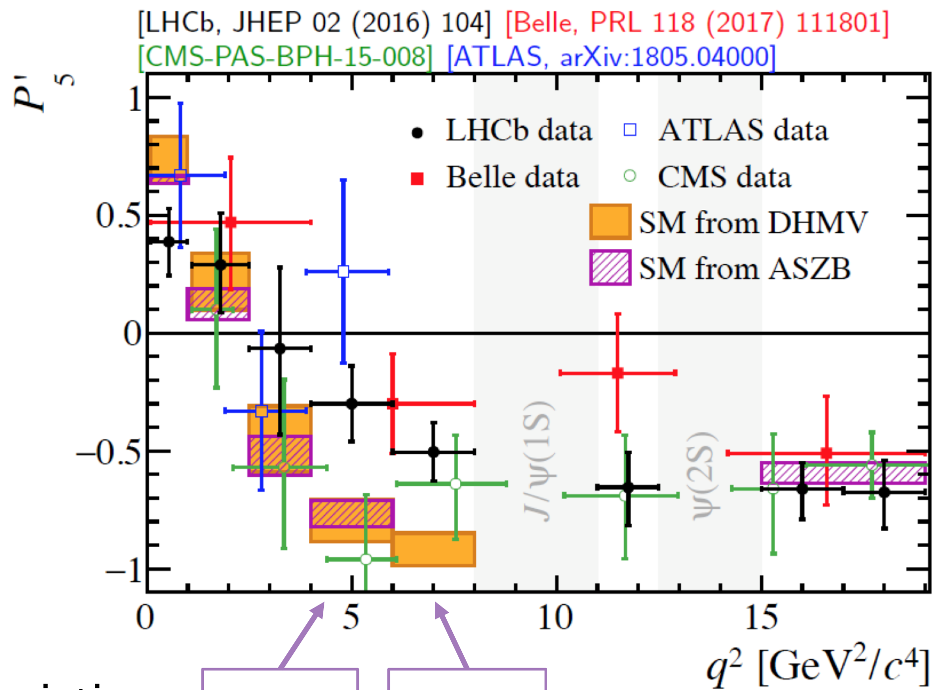
NP?

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

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

$B^0 \to K^*\mu^+\mu^-$: the P_5' conumdrum

- The P_5' is constructed from angular observables to be more robust against form-factor uncertainty
- Intesting deviation from (one) SM prediction at low q^2.

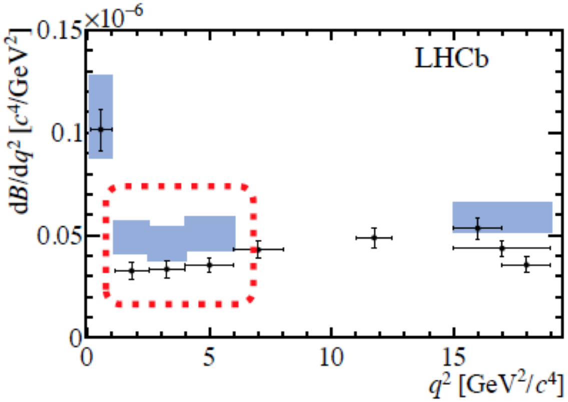


Local deviation: 2.8σ 3.0σ

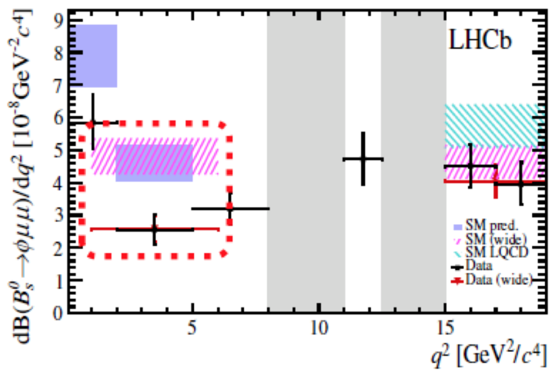
$B^0 \to K^*\mu^+\mu^-$ and friends: Branching ratios

- For multiple $b \to sll$ decays, BR in tension with SM at low q^2 consistently

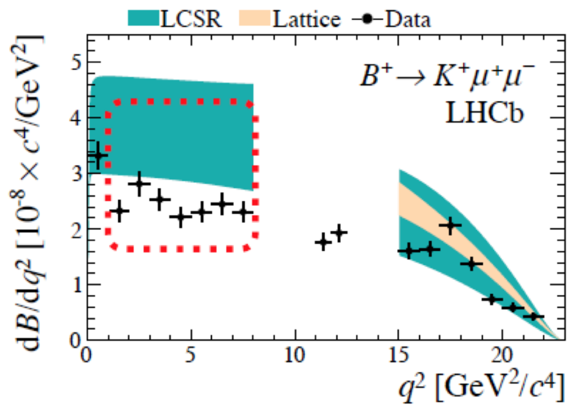
LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



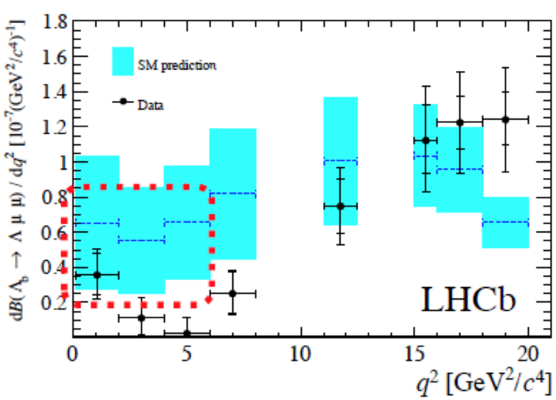
LHCb $B^0_s \to \phi\mu^+\mu^-$ [JHEP 09 (2015) 179]



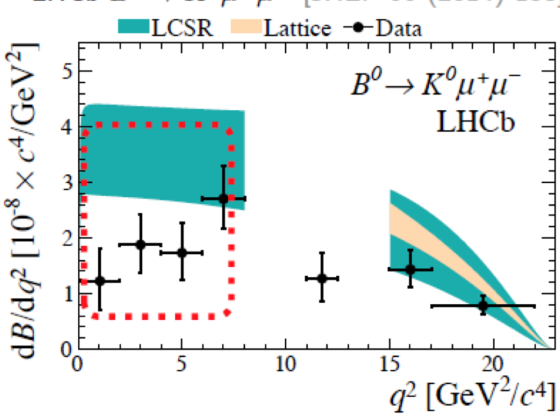
LHCb $B^+ \to K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]



$\Lambda^0_b \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



LHCb $B^0 \to K^0\mu^+\mu^-$ [JHEP 06 (2014) 133]



$B^+ \to K^{*+}\mu^+\mu^-$ [JHEP 06 (2014) 133]