The University of Manchester

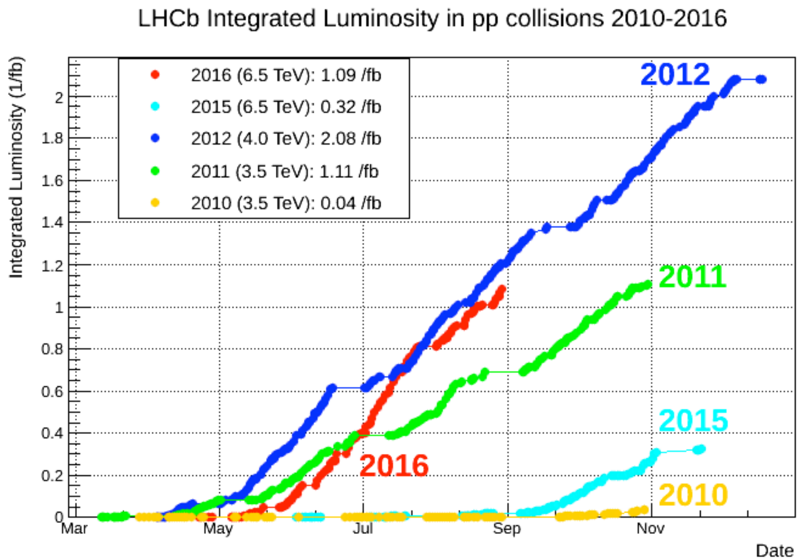
LHCb: Cathedral of Science

LHCb Longterm Plans

Chris Parkes
on behalf of the
LHCb Collaboration

LHCb Timeline

- LHC Run-I (2010-2013)
  - The results you know and love
- LHC Run-II (2015-2018)
  - Trigger computing increased. First results…
- LHC Run-III, Run-IV (2021-2023, 2026-2029)
  - Major ‘New’ Experiment: **LHCb Upgrade [Phase I(a), I(b)]**
- LHC Run-V (2031-)
  - Major ‘New’ Experiment **LHCb Upgrade Phase II**
  – May be only general heavy flavour expt on this timescale



Physics Programme

Limited by Detector

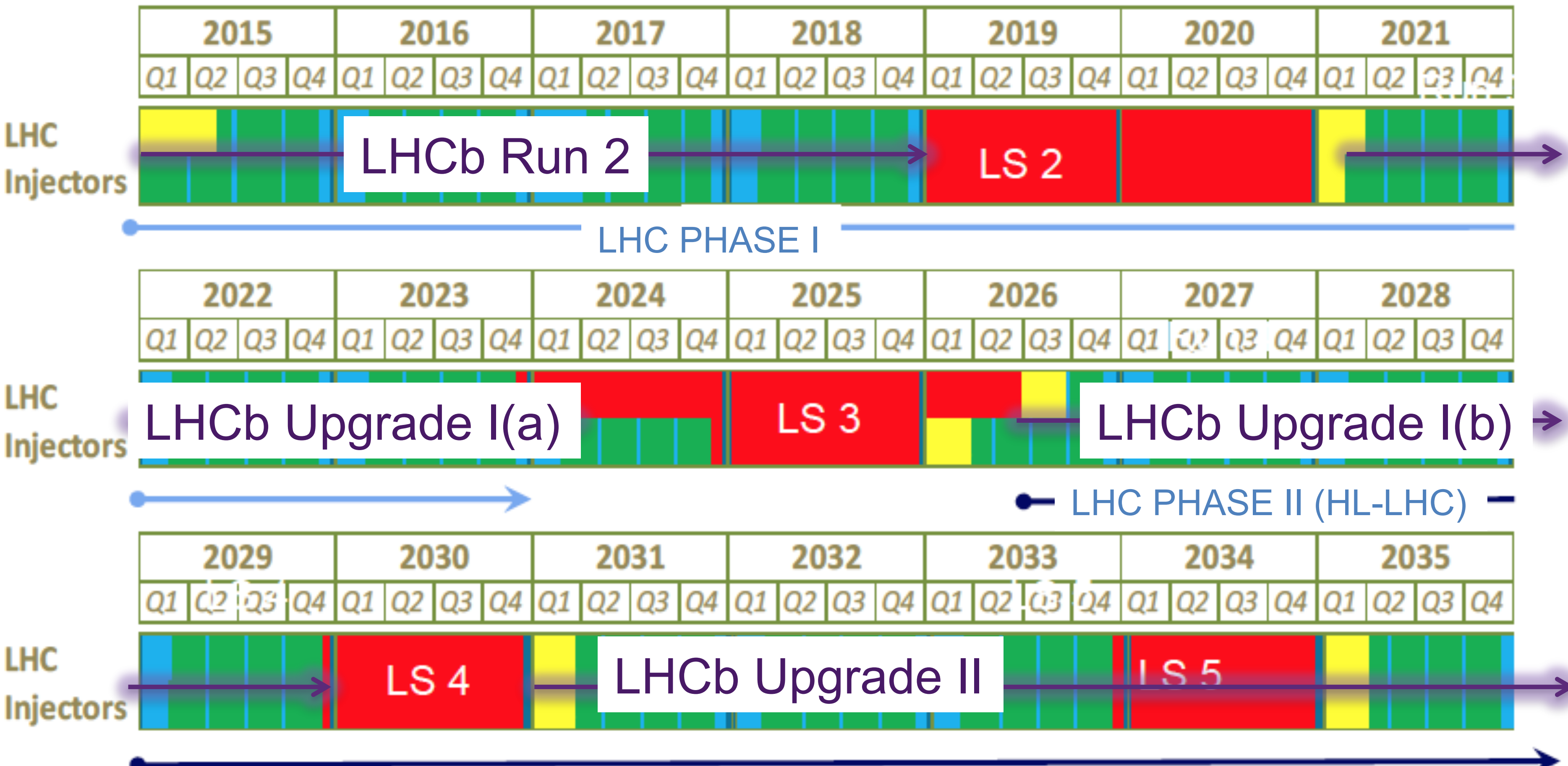
But **NOT** Limited by LHC

- Upgrade to extend Physics reach
  - Exploit advances in detector technology
    - Fully Software Trigger, **40MHz readout**
  - Better utilise LHC capabilities
- Upgrade I(a/b) Collect >50 fb^{-1} data
  - $L \sim 2 \times 10^{33}\ cm^{-2}\ s^{-1}$
- Upgrade II Collect > 300 fb^{-1} data
- Modest cost compared with existing accelerator infrastructure

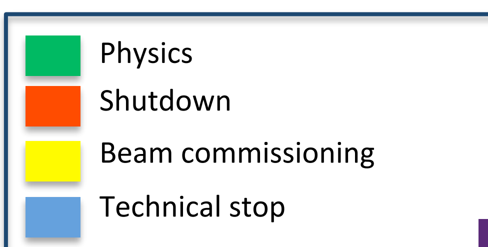
Upgrade I
- HL-LHC not needed
- But compatible With HL-LHC phase

Upgrade II
- Utilise HL-LHC phase luminosities

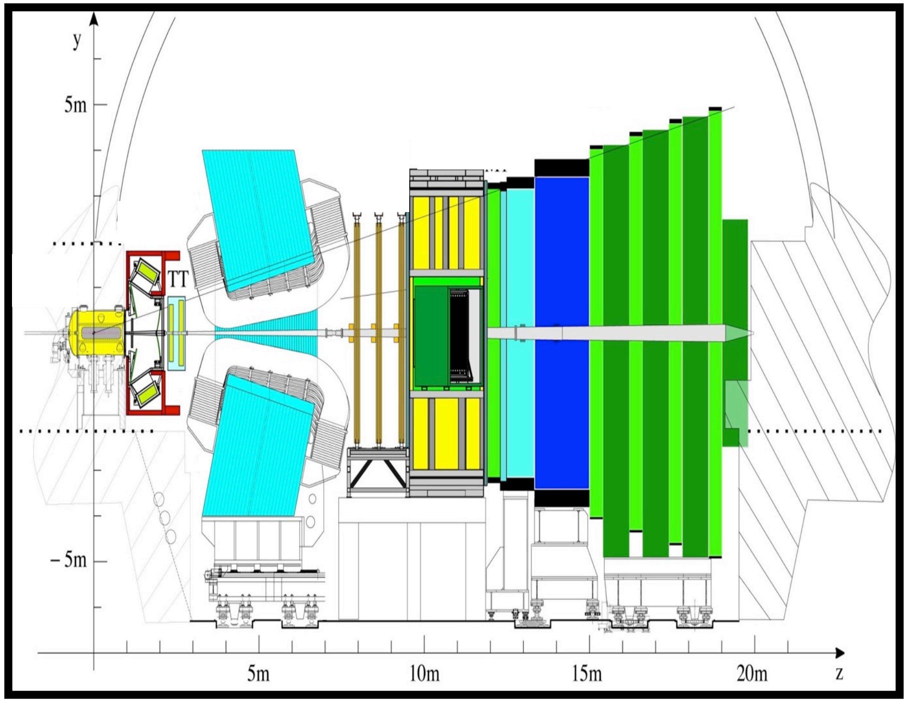
LHC Schedule & LHCb



- Schedule till 2020 reasonably firm
- GPD main upgrades (phase II) scheduled for LS3
- HL-LHC upgrade in LS3
- **Belle II finishes ~ 2025**



LHCb Upgrade I(a)
25ns readout, software only triggering



VELO
Pixel
Detector

Upgrade Tracker
Silicon strips

Outer Tracker
Scintillating Fibres

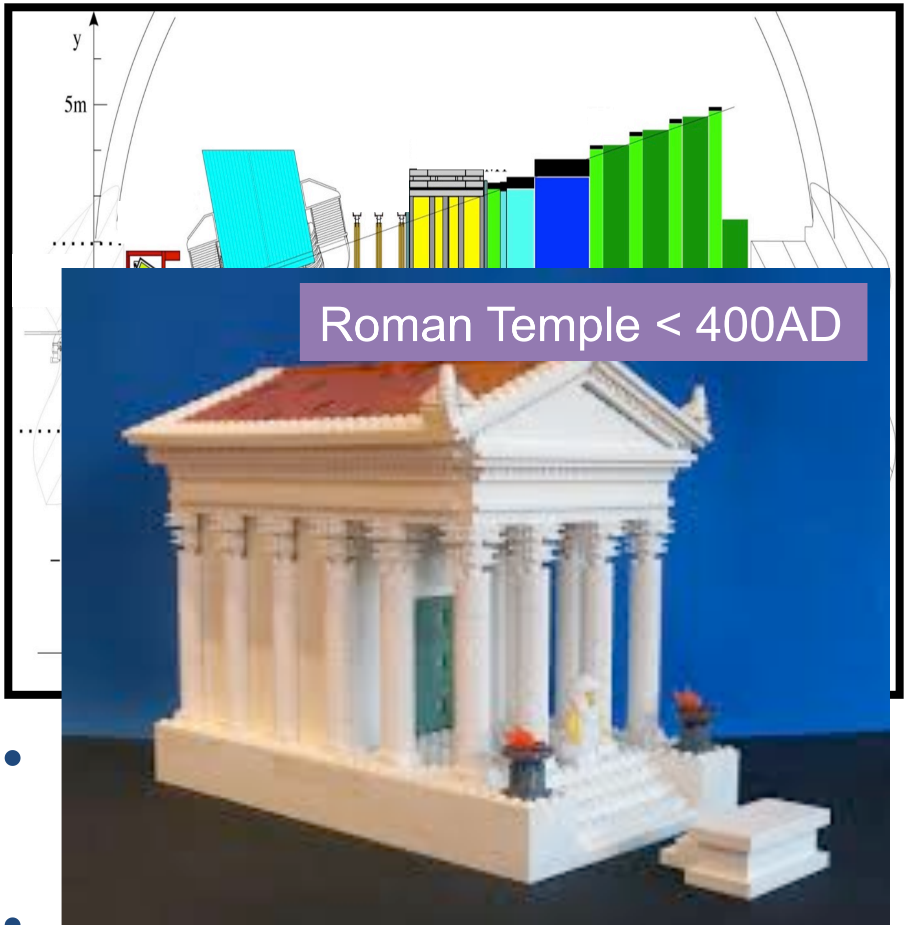
RICH
Photon Detectors &
(partial) mechanics

Calo
PMTs (reduce PMT
gain, replace R/O)

Muon MWPC
(almost compatible)

- Construction significantly advanced
- Most major industrial orders placed
- Most elements keeping to schedule

LHCb Upgrade I(a)
25ns readout, software only triggering



VELO
Pixel
Detector

Upgrade Tracker
Silicon strips

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PC
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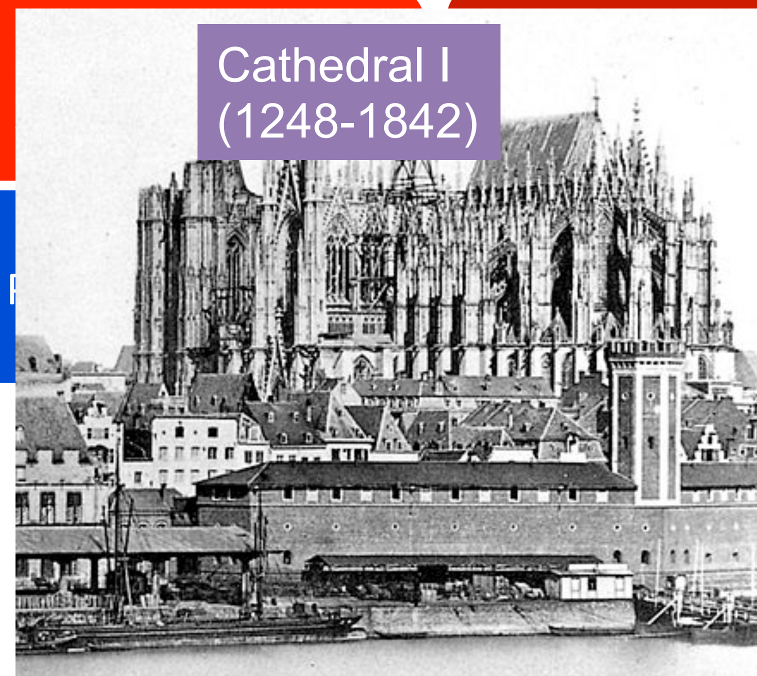
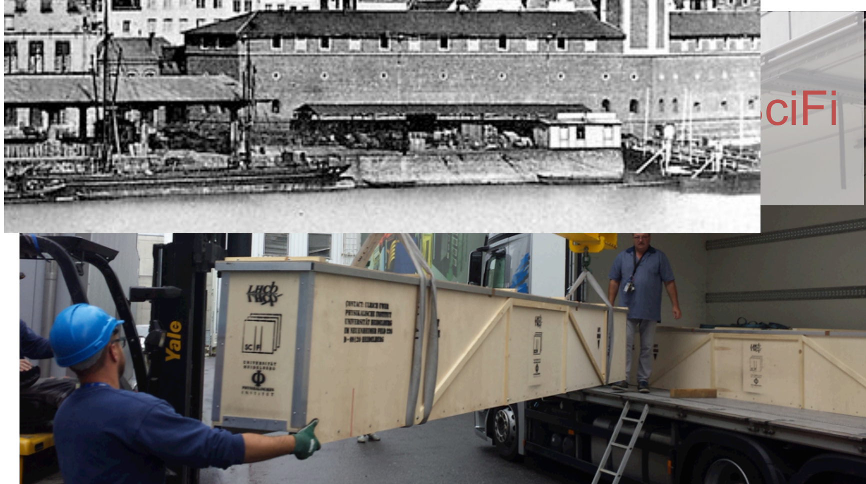




- Most major industrial orders placed
- Most elements keeping to schedule

Phase 1(b) – Consolidate & Enhance

- LS3: 2½ year shutdown in the middle of LHCb Upgrade I operations
  - Utilise this to consolidate upgrade experiment
    - Phase I(b), same luminosity
  - Enhance physics programme
    - Pathways to Phase II
  - Financial/ personnel resources limited

Not many new gargoyles

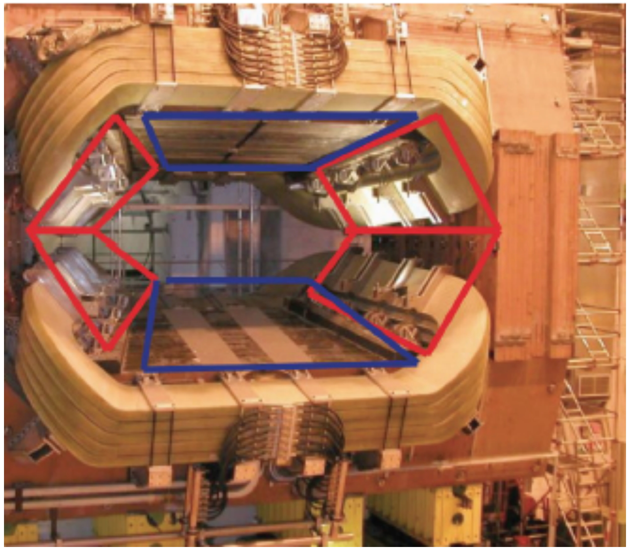
Same timescale:

ATLAS EXPERIMENT
Upgrade Phase II

CMS
Upgrade Phase II

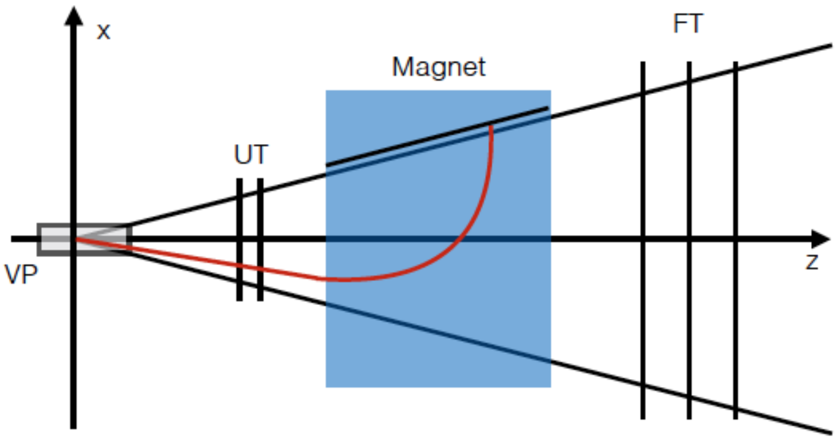
DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

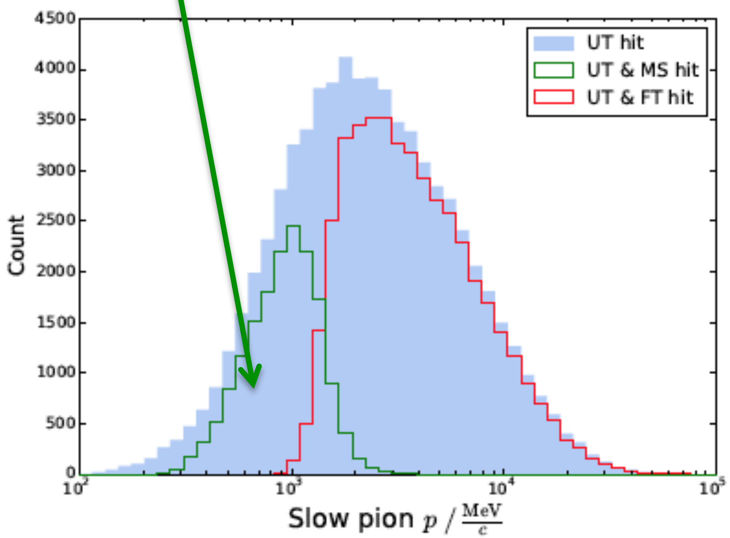
Phase 1(b) e.g. – Magnet Side Stations



- Improve tracking acceptance for low momentum particles
  - Install tracking stations on the dipole magnet internal sides

e.g. $D^{*+} \rightarrow D\ \pi_s^+$, 40% extra slow pions

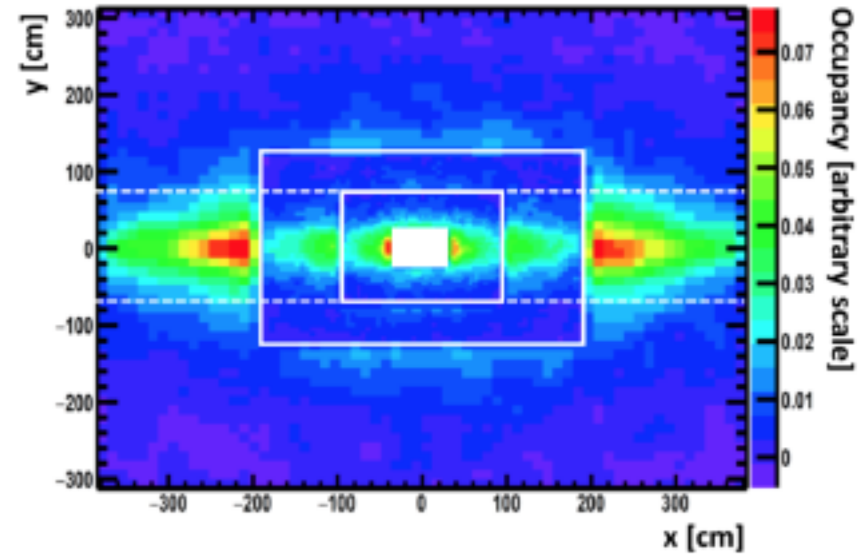




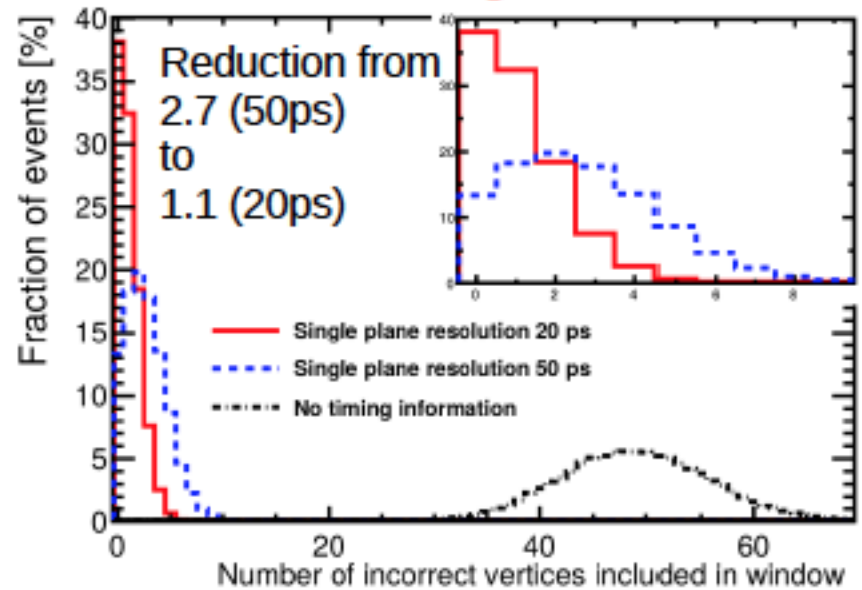
Strong involvement from Aachen group in design studies

Phase 1(b) e.g. – E'magnetic Calorimeter

- Inner ECAL replacement required due to radiation damage
  - Partial replacement only
- Strong Physics Interest: γ,π^0,e^-
- Improve performance with new technologies
- Improve energy/position resolution
  - Reduced Moliere radius, cell granularity



Importance of timing



Phase II – Major new Upgrade

"Formal approval of High luminosity LHC…secures CERN's future until 2035" CERN DG, June 2016

Secure Flavour Physics future

Target Luminosity: > 300 fb^{-1}, 1-2x10^{34} cm^{-2} s^{-1}
HL-LHC experiment: ~50 events/interaction pile-up

1. Physics case
2. LHC capabilities
3. Detector feasibility

Physics Case - ask the analysts….

Phase-2 upgrade: benchmarking topics

- *CP* violation in the interference between B_s mixing and decay
- *CP* violation in B_c and *b*-baryon decays
- *CP* violation in charm mixing and decay
- Determination of the angle γ
- Semileptonic asymmetries
- Electroweak penguin decays
- Rare and radiative decays
- Lepton universality tests
- Lepton flavour violation
- Search for Majorana neutrinos
- Forward Higgs production
- Dark photon searches
- Spectroscopy and exotic states

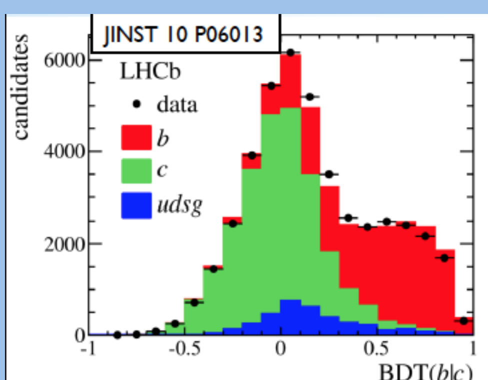
Vincenzo Vagnoni, Theatre of Dreams, April 2016

Physics Case - ask the analysts….

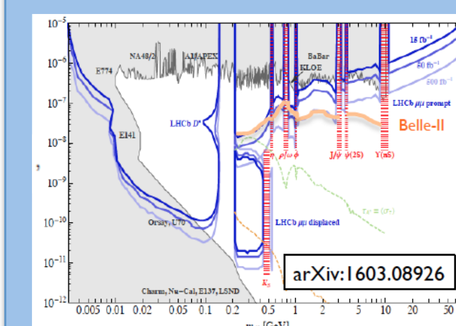
Phase-2 upgrade: benchmarking topics

- *CP* violation i… …ixing and decay
- *CP* violation i…
- *CP* violation i…
- Determinatio…
- Semileptonic…
- Electroweak …
- Rare and radi…
- Lepton universality tests

Everything we currently do and a few more for good measure



Phase II constrain **H➔$c\bar{c}$ coupling? 2-3xSM**



Dark photon A'➔μμ

best sensitivity

Rare (and very rare) Decays

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\frac{e^2}{16\pi^2}V_{tb}V_{ts}^*\sum_i C_iO_i + \text{h.c.}$$

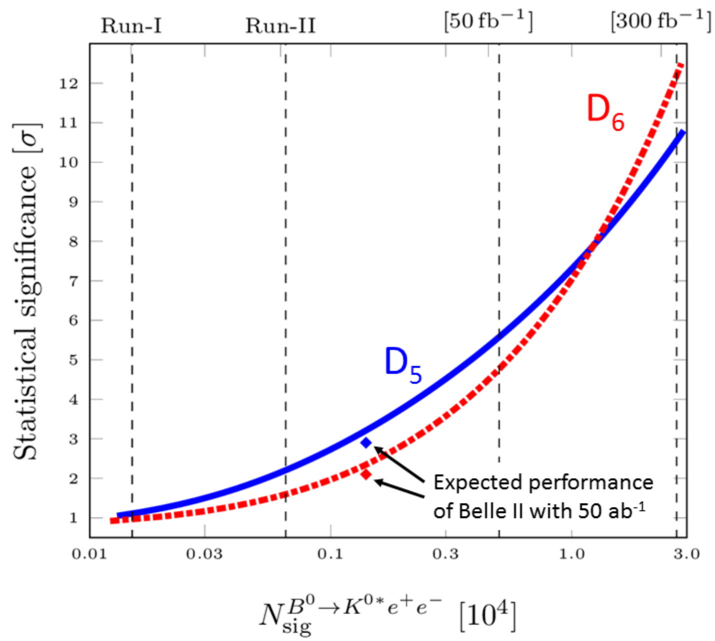
Decay	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$B \to X_s\gamma$	X			
$B \to K^*\gamma$	X			
$B \to X_s\ell^+\ell^-$	X	X	X	
$B \to K^{(*)}\ell^+\ell^-$	X	X	X	
$B_s \to \mu^+\mu^-$			X	X

Complementarity of Observables

At 300/fb achieve ~20% on $B_d\to\mu\mu/B_s\to\mu\mu$ $B_s\to\mu\mu$ effective lifetime to 2%

consider competition from CMS.

LFU Prospects: distinguish new Physics scenarios in $B^0 \to K^*\mu\mu / K^*ee$

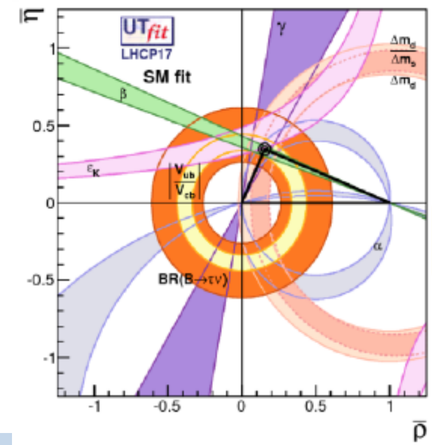


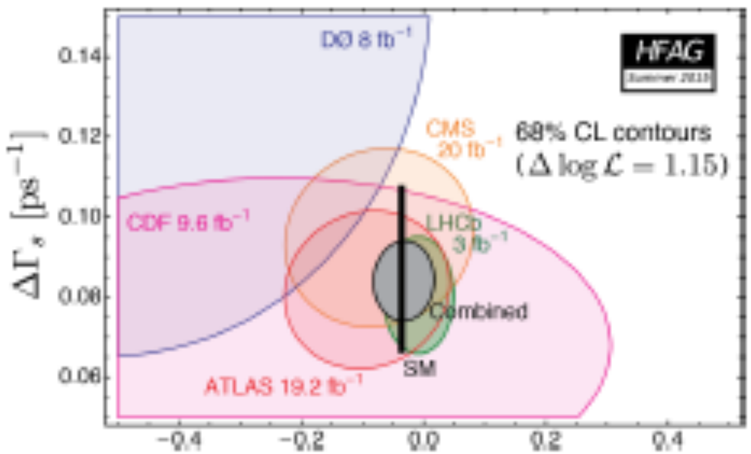
Also exciting prospects in:
B➔ee, B➔ττ,
rare charm, rare kaon

CPV Examples

- Time dependent measurements
  – more difficult in high pile-up environment

- Tree level determination of γ
- Phase II: <0.4° uncertainty in reach !





HFAG average: ϕ_s = -34 ± 33 mrad $\phi_s^{c\bar{c}s}$ [rad]

- ϕ_s in b→c$\underline{c}$s (B_s→J/ψ X…)
- Phase II: 3 mrad
  - **Indirect tree-level precision !**
- ϕ_s in b→s$\underline{s}$s (B_s→φφ)
- Phase II: 7 mrad

- Charm: y,A_Γ,ΔA_{CP} no limiting systematics known
- Constrain SM level CPV

Physics Case

- Sui Generis:
  - Unique attributes:
    - Low pT triggering, configurable fully software trigger
    - Acceptance, proper time resolution, PID
  - Potentially only general purpose flavour physics facility in the world on this timescale
  - And general purpose experiment in the forward direction
  - Given the scale and cost of the LHC we have a responsibility to exploit its full physics potential
    - LHC operational cost to CERN budget ~1bn €/year.
    - LHCb core construction cost ~0.06 bn € total

Poster boys for upgrade phase II

- Case shows objectively clear leaps in performance
- LFU: If hints are confirmed then many new physics models require Phase II upgrade to observe clear effects (see EoI)
- CKM tests: e.g. ϕ_s at ~ 3mrad, match precision from indirect determination from tree-level
- Charm CPV: for both direct and indirect the power to measure SM levels of CP and characterise NP contributions in the 'up' sector
- Beyond Flavour: best limits on Higgs to charm coupling, unique reach in dark sector searches

Poster boys for upgrade phase II

- Case … ce
- LFU … cs mod … r effec
- CKM … om indir
- Cha … er to mea cont
- Bey coup

Or

B-physics anomalies: theory outlook (30+5)

Speaker: Admir Greljo (University of Zurich)

Hadron physics (30+5)

Speaker: Greig Cowan (University of Edinburgh (GB))

Dark matter in flavour (30+5, Vidyo)

Speaker: Yotam Soreq (Massachusetts Institute of Technology)

Choose your own favourites…..

Accelerator: Can LHCb Phase II run ?

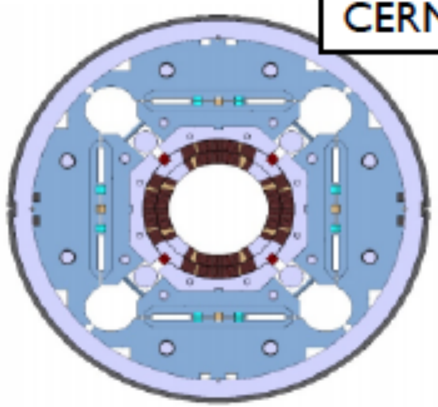
Riccardo de Maria @ Theatre of Dreams (April 2016)

Preliminary

Levelled luminosity LHCb [10^{34} $cm^{-2}s^{-1}$]	Opt fill length (IP1/5) [h]	Integrated luminosity ATLAS/ CMS [fb^{-1}/y]	Integrated luminosity LHCb [fb^{-1}/y]	β* IP8 [m]	Levelling time IP8 [h]
0.2 (nom.)	9.3	261	10.4	3	9
2	8.5	253	70	1	2

- LHCb collect ~ 50 fb^{-1} per year **without** affecting ATLAS/CMS

CERN-ACC-2016-0007



- LHCb IP not designed for HL-LHC experiment
- Inner Triplet quadropole need to be replaced at ~**300 fb^{-1}**
  - Probably prohibitively expensive
- LHC side impressive studies on
- additional requirements
  - **No showstoppers !**

Likely a luminosity difference between two magnet polarities

VELO

Challenge A: 10x particle multiplicity — Small Pixels

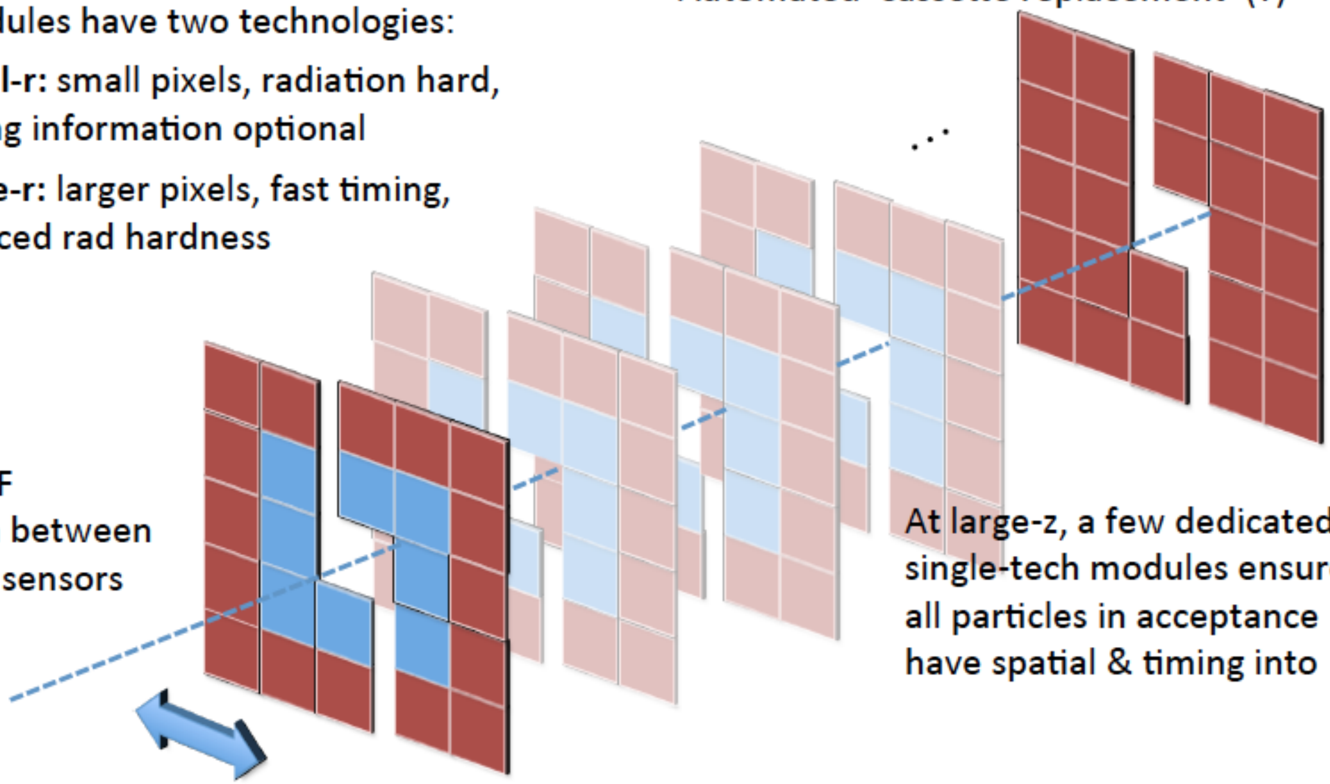
Challenge B: 10x vertex multiplicity — Timing

Challenge C: 10x radiation damage — Replacement

Main modules have two technologies:

- **Small-r:** small pixels, radiation hard, timing information optional
- **Large-r:** larger pixels, fast timing, reduced rad hardness

Automated 'cassette replacement' (?)



Minimal RF protection between beam and sensors

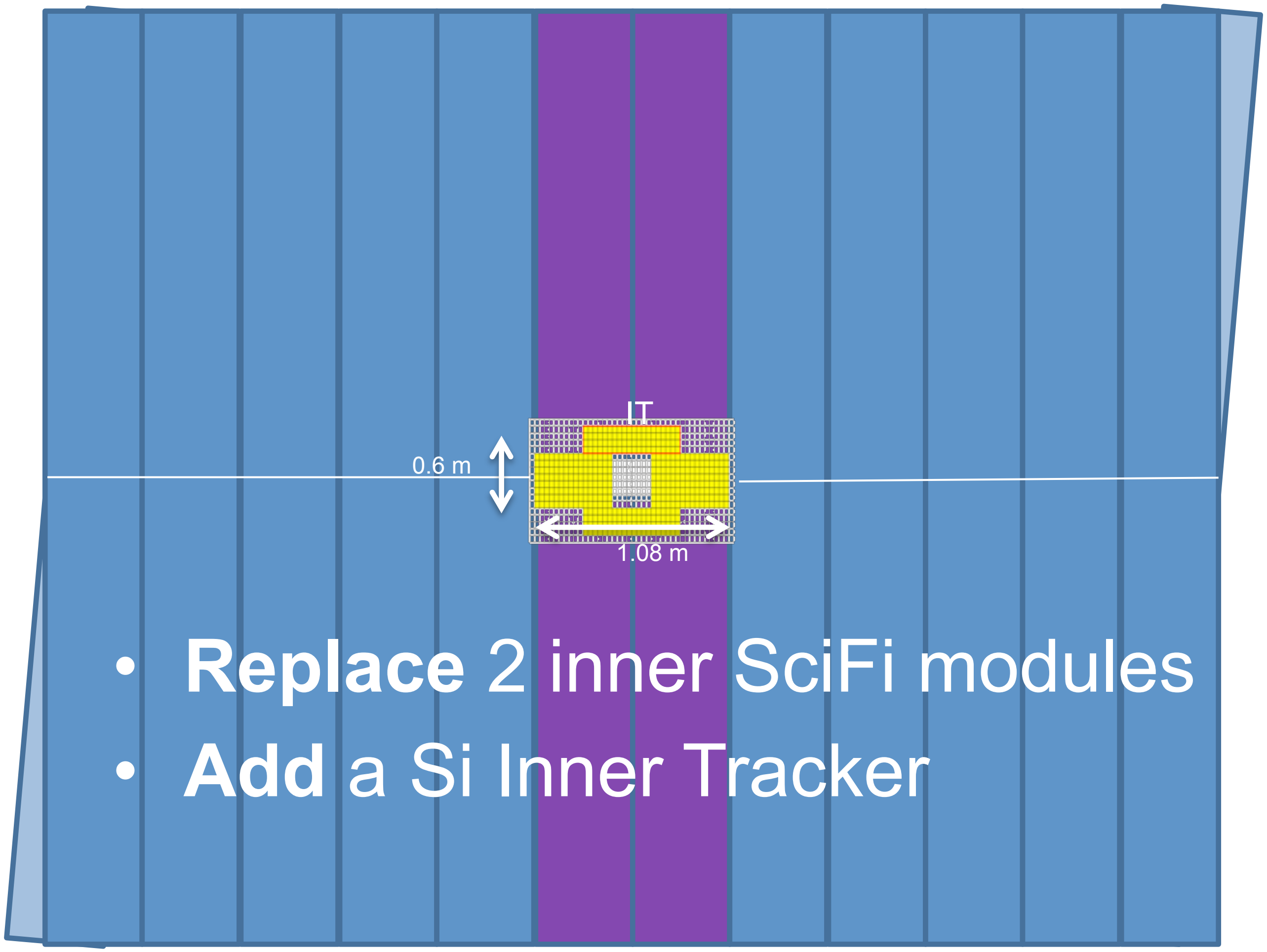
At large-z, a few dedicated single-tech modules ensure all particles in acceptance have spatial & timing into

Retractable modules as in current/phase-I VELO

Cooling from evaporative CO_2 in microchannels? (benefit from phase-I experience)

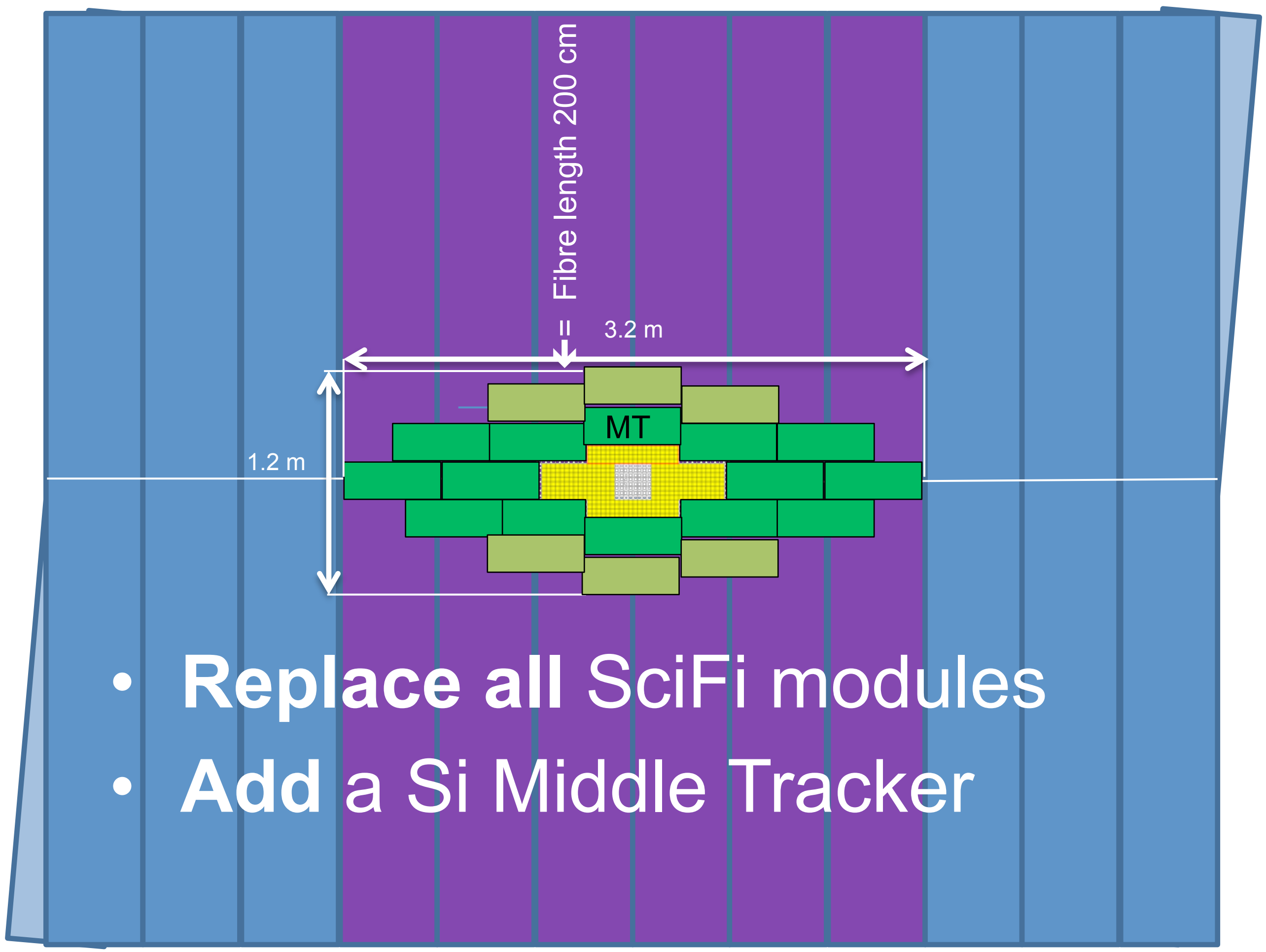
Phase 1b Tracker

- Expand IT relative to EOI to assist Sci-Fi – $O(5)\,m^2$



Phase II Tracker

- Expand MT relative to EOI to assist Sci-Fi -$O(20m^2)$

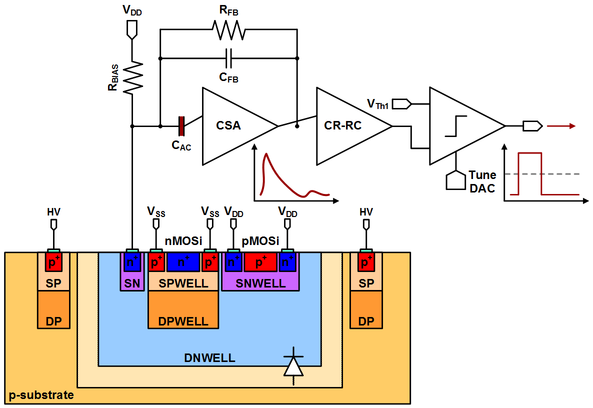


- **Replace all** SciFi modules
- **Add** a Si Middle Tracker

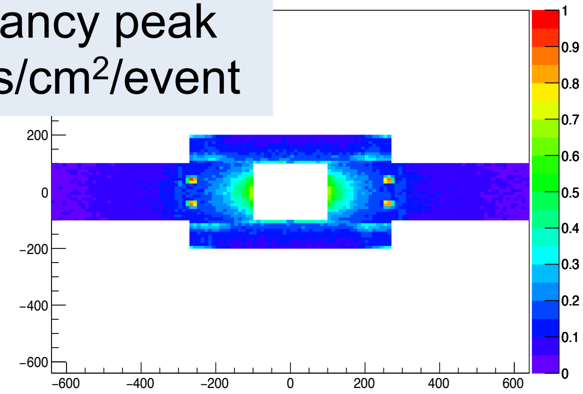
- SciFi Neutron "torture": may just survive 300 fb^{-1}

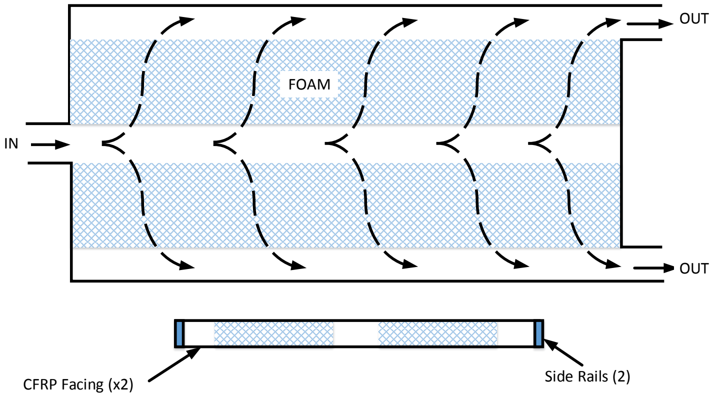
Inner Tracker - HVCMOS

- Sensor & Electronics on same chip
- Commercial Foundries
- Low cost (few CHF/cm^2)
- High granularity
- High signal/noise
- Low material (50µm)
- Radiation tolerant (>10^{14} 1 MeV n$_{eq}$/cm^2)



Occupancy peak
0.7 hits/cm^2/event

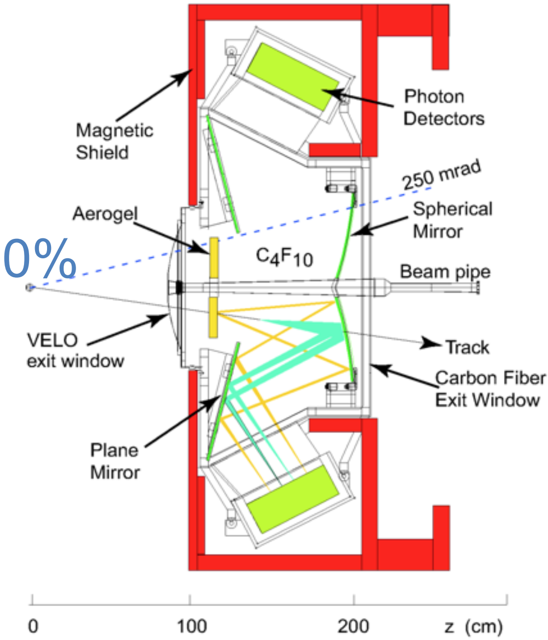




Support/Cooling Prototype

Particle Identification: RICH

- Granularity
- Phase II RICH I peak occupancies would exceed 100%
  - Increase pixel granularity 7mm^2 ➔ 1mm^2

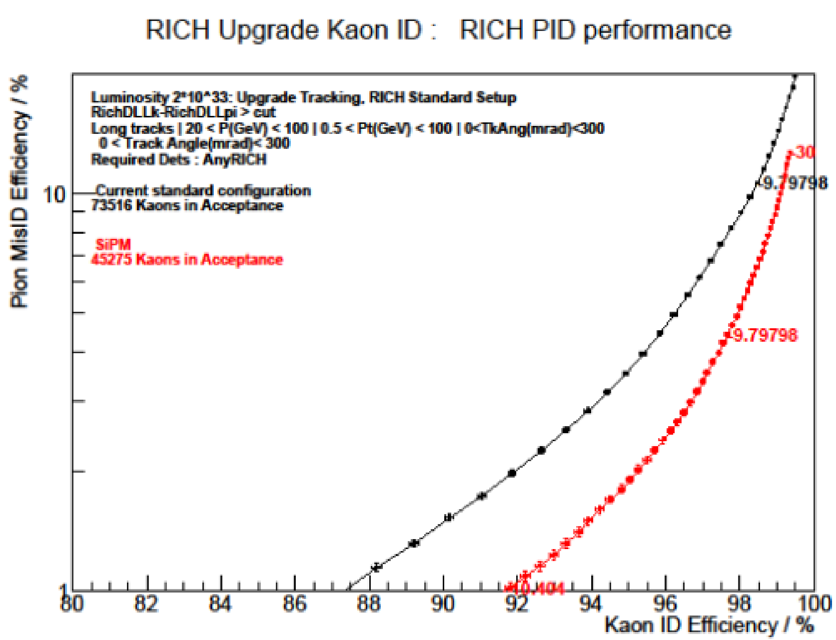


- Time resolution
  - Disentangle busy events

- Use B-field insensitive photodetectors
  - SiPM or MCP

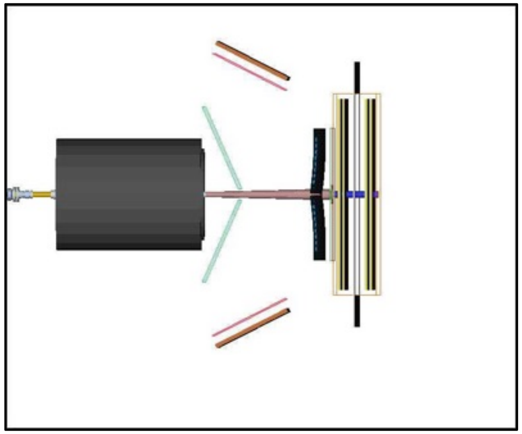
- Concepts for improving
- Optical and chromatic uncertainty

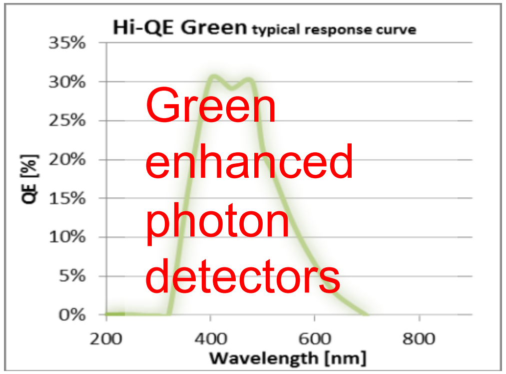
- Equip central region for **Phase 1(b)** ?

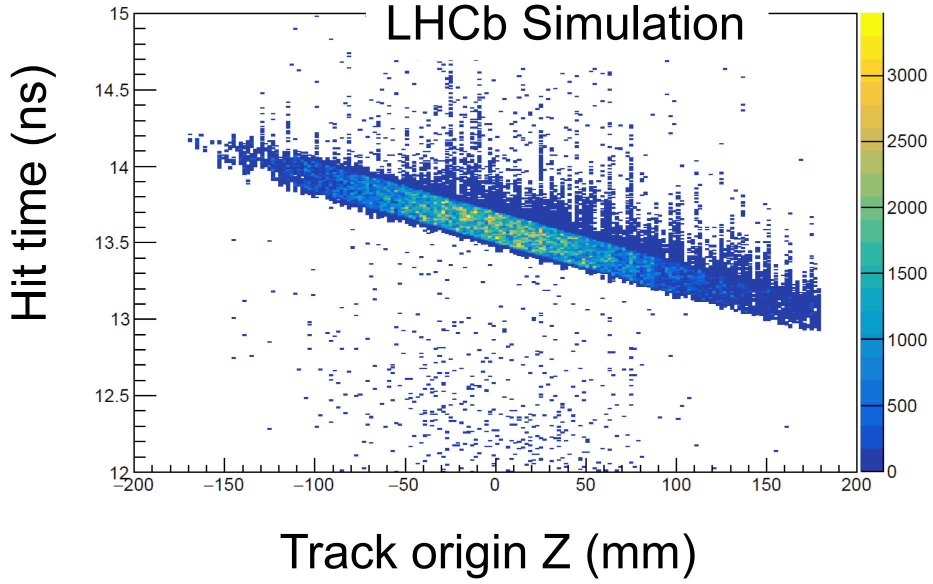


Particle Identification: RICH

Increase granularity ($7mm^2 \rightarrow 1mm^2$ in some regions)
Improve optical error,
Further reduce chromatic error
Provide the system with time resolution
Work on new and specific pattern recognition algorithms
Perhaps get rid of the magnetic shielding by using
B-insensitive photodetectors (SiPM or MCP)







Opportunities for German groups include

Scintillating Fibres
(development from Phase I)

- Phase 1b Sci-Fi
- Phase II Sci-Fi
- Phase 1b Magnet stations

Silicon and HV-CMOS
(development from Mu3e)

- Phase 1b Silicon Tracker
- Phase II Silicon Tracker

Technical Associates

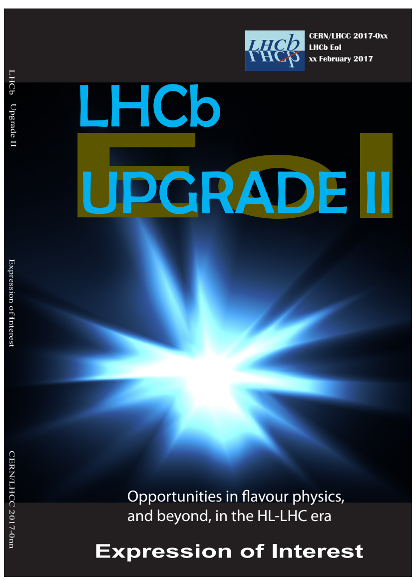
- Option for new groups to join to work on R&D
  - Do not work on physics or sign papers
  - Approved at Collaboration Board September 2017

- Potentially a useful mechanism to attract new groups for Phase 1b/II
  - e.g. could be of interest to some Belle II groups that are finishing their construction work and may be interested in LHCb after Belle II ?
- Can apply for full /associate membership subsequently
- Encouraged to consider opportunities in Germany
  - Strong Belle II groups with significant hardware/software involvement

LHCC response to EOI

From LHCC minutes: May 2017

- The **LHCC notes** the submission of the EoI for LHCb upgrades beyond Phase-I, and **encourages** LHCb to pursue the physics studies and collaboration with the LHC experts to motivate these upgrades with a solid physics case, taking into account the expected results from LHCb Phase-I and Belle II, and establish feasible running conditions that do not interfere with other LHC experiments. The **LHCC urges** the LHCb management to ensure that these activities have no impact on the on-going Phase-I upgrades, which must take priority.



Interpret as:
- Physics case document required
- Increase interaction with LHC accelerator experts

Presented timescale on next slides to LHCC referees last month

15 TeV ?

CERN | Memorandum

Date : 22 September 2017

To : F. Gianotti, Director-General

From : F. Bordry

Subject : Ultimate energy exploitation of the LHC

"CERN is evaluating the possibility of increasing the LHC beam energy towards the 'ultimate' value of 7.5 TeV, corresponding to a maximum dipole field of 9 T."

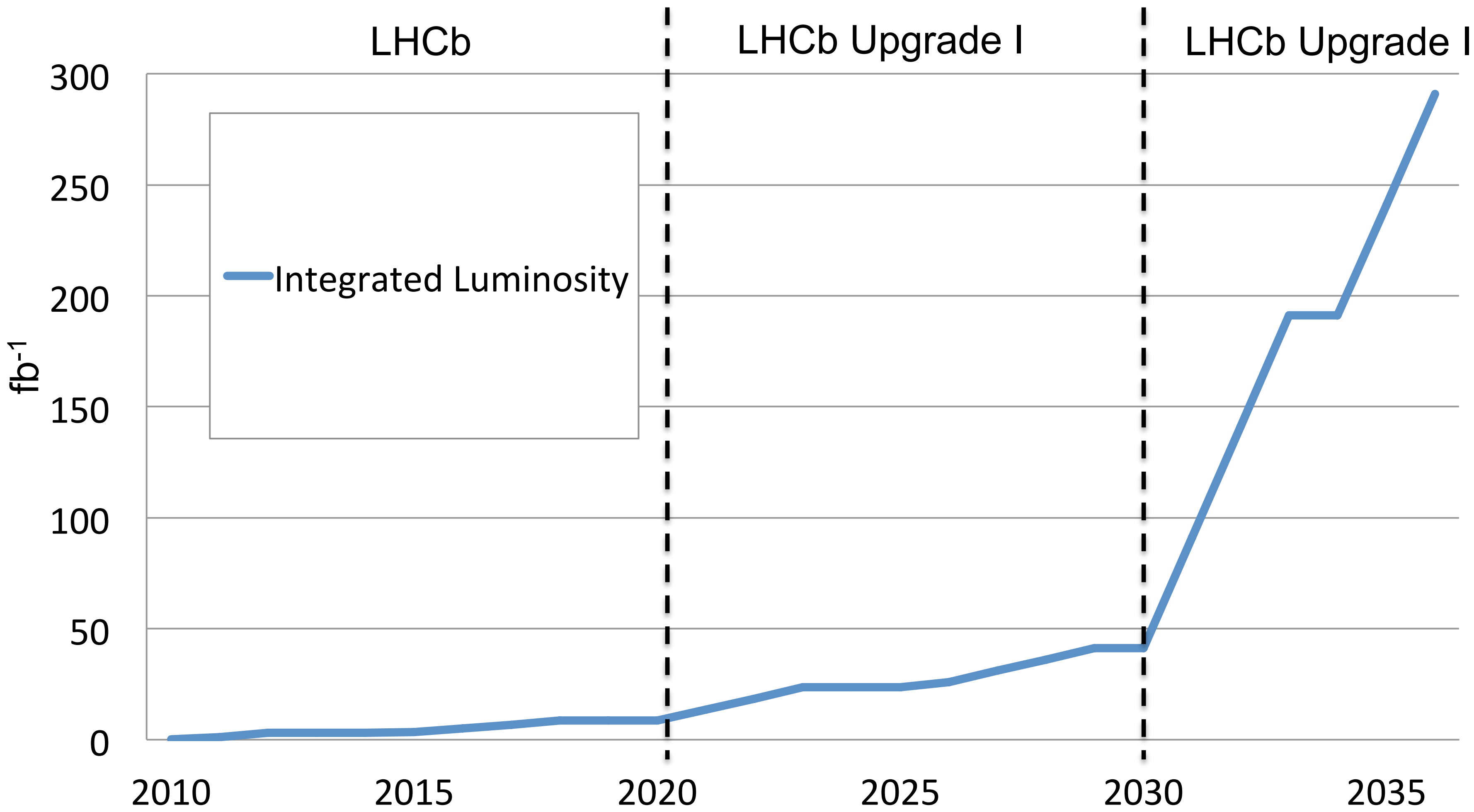
"implies an operation with reduced margins…
operation at ultimate energy might therefore imply a reduced machine efficiency"

"this would happen at the earliest at the end of LHC Run4"

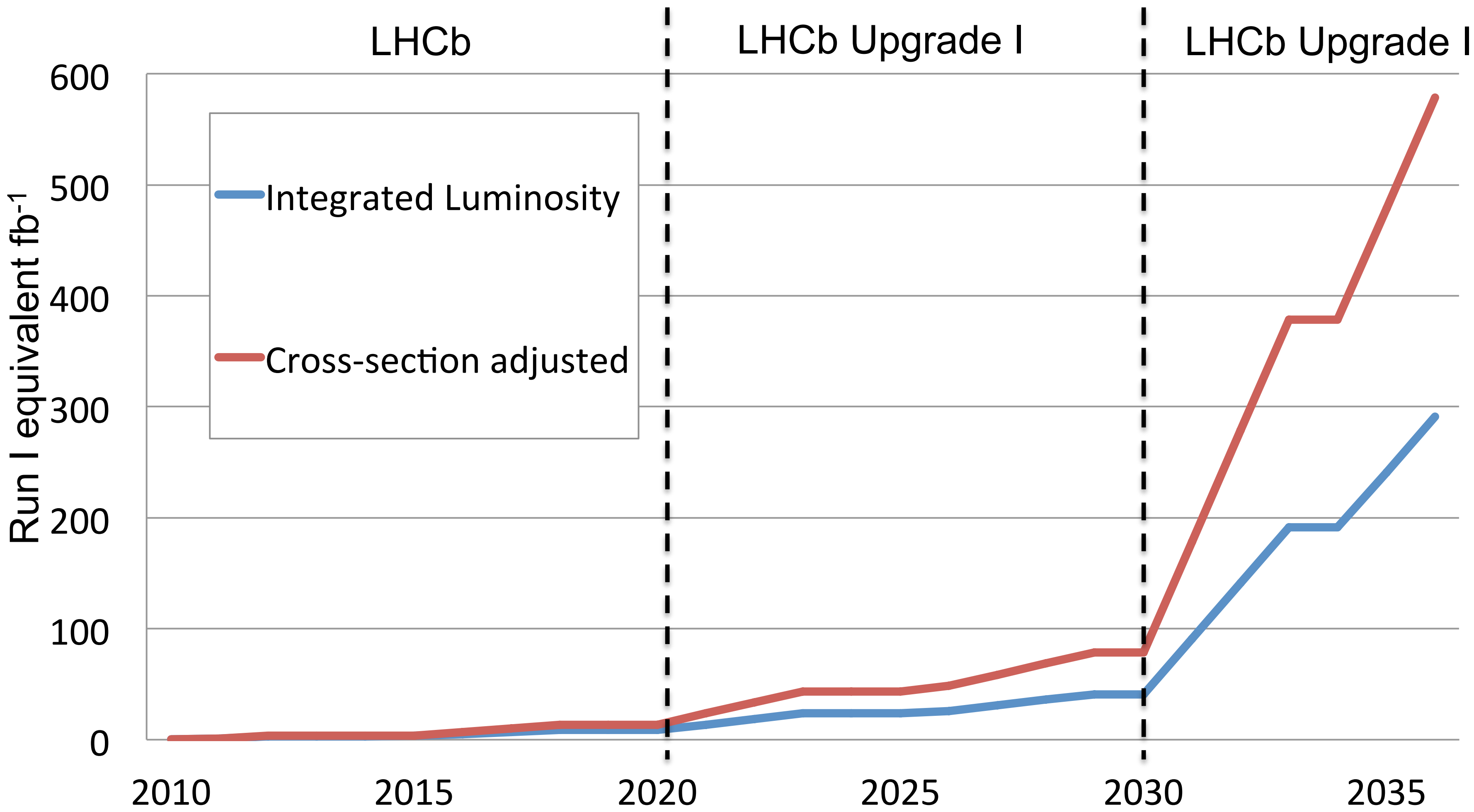
"encourage all hardware groups to keep this operation goal in mind when designing and implementing system upgrades"

Reduced efficiency would be a concern for Phase II upgrade.
On positive side:
Top production in LHCb acceptance increases by 20-30% between 14 and 15TeV

LHCb Statistics- Timeline

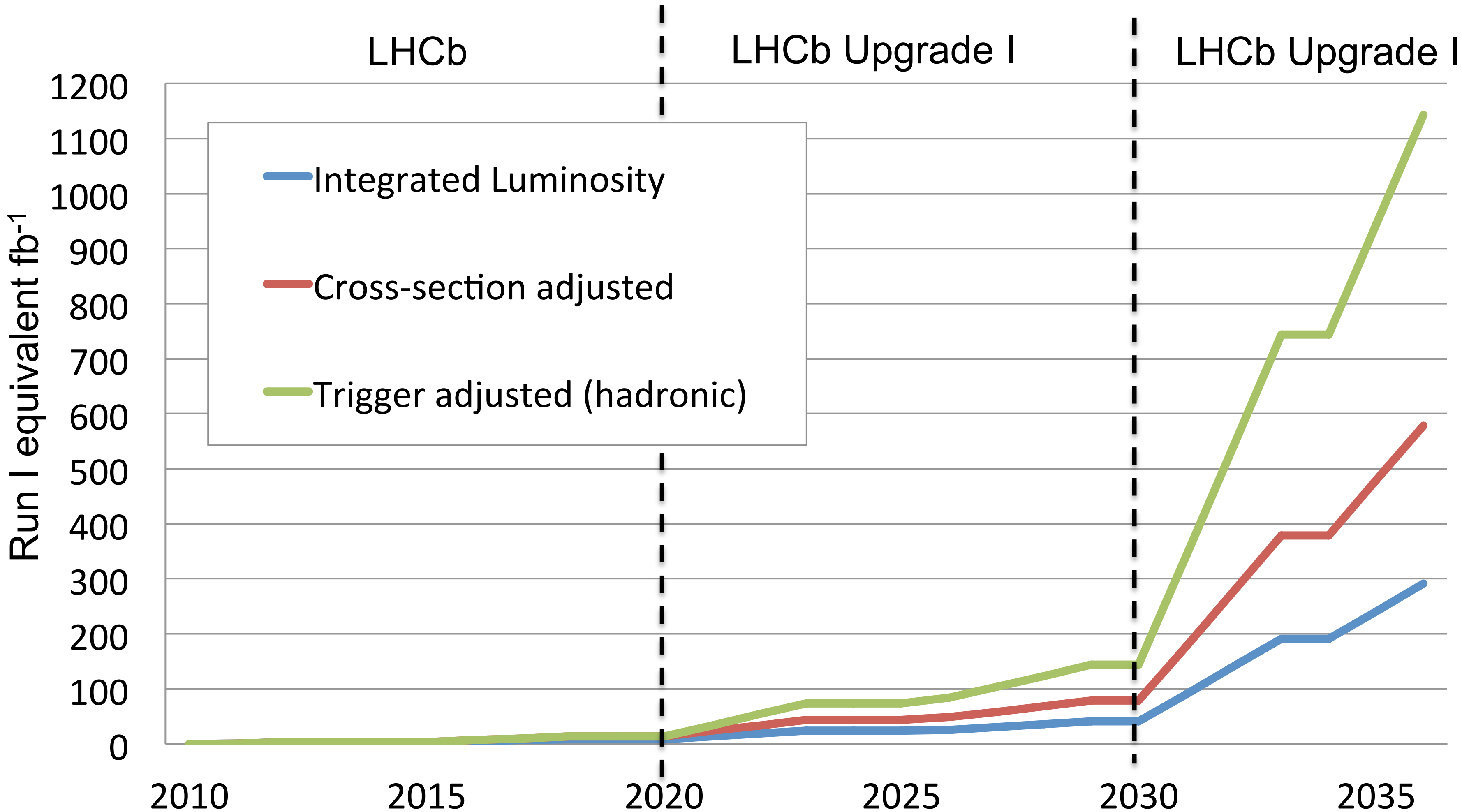


LHCb Statistics- Timeline



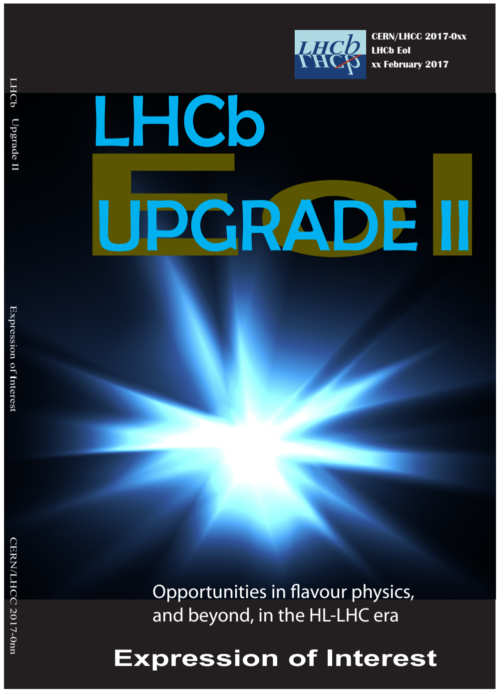
- Adjustment for 7/813/14 TeV cross-sections

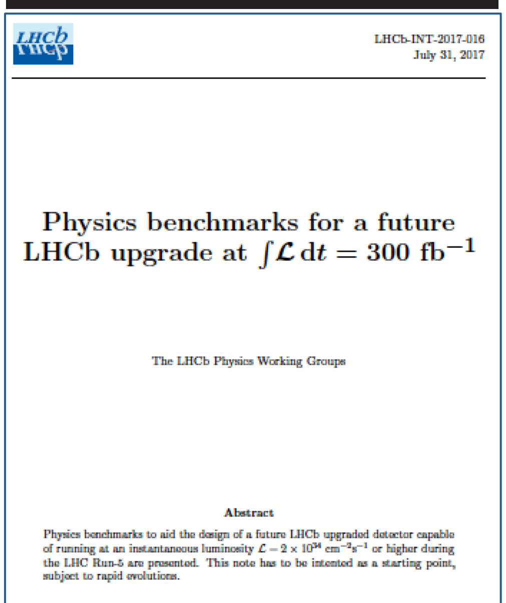
LHCb Statistics- Timeline



- Assumptions made on relative trigger efficiencies have significant uncertainty

Phase 1b/II Upgrade Status





LHCb-INT-2017-016
July 31, 2017

Physics benchmarks for a future LHCb upgrade at $\int \mathcal{L}\,dt = 300\ \mathrm{fb}^{-1}$

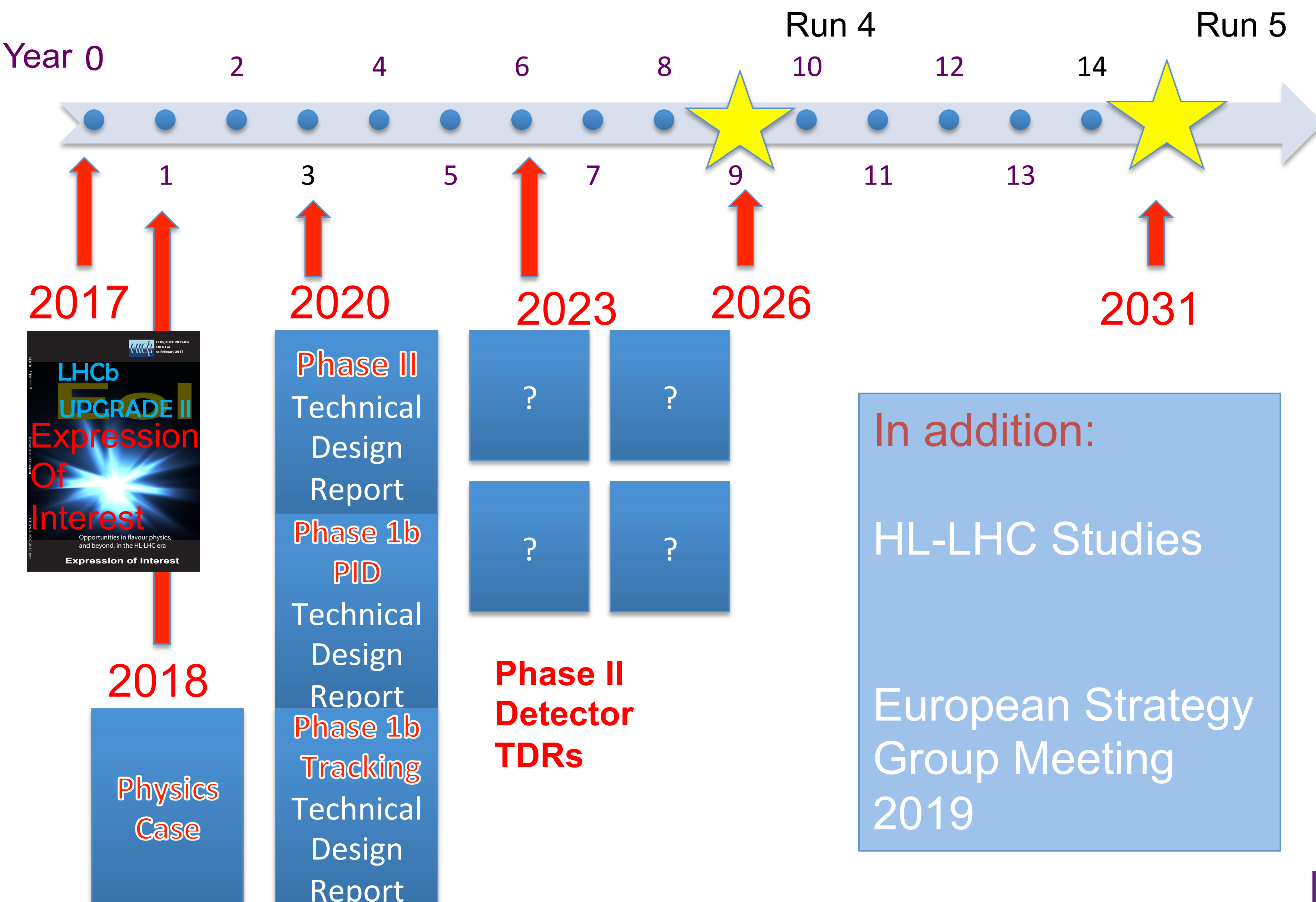
The LHCb Physics Working Groups

Abstract

Physics benchmarks to aid the design of a future LHCb upgraded detector capable of running at an instantaneous luminosity $\mathcal{L} = 2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ or higher during the LHC Run-5 are presented. This note has to be intented as a starting point, subject to rapid evolutions.

- EoI documents the “brainstorming” period
- Transitioning toward R&D Phase
  - Prototyping underway for some elements
  - In last month two countries have secured funds for R&D projects
  - Management putting more formal organisational structure in place
    - Structures already exist for some elements
    - Meetings with LHC machine starting
- Careful balance needed - this is the 3rd priority activity in LHCb
  - Current detector operations & exploitations
  - Upgrade Phase I Construction

LHCb Phase II Upgrade Timeline



3rd LHCb Workshop on Phase1b/II Upgrade

- Annecy have kindly agreed to host
- Dates: 21st -23rd March 2018
  - Again open to theorists and potential new collaborators
- Timed to provide input to LHCC May 2018 Physics document

2016


2017

Summary - Take Home Message

- 2021: LHCb Upgrade I construction on track

- 2025: Phase I(b) Upgrade: consolidate & enhance
  - Same luminosity as upgrade phase 1(a)

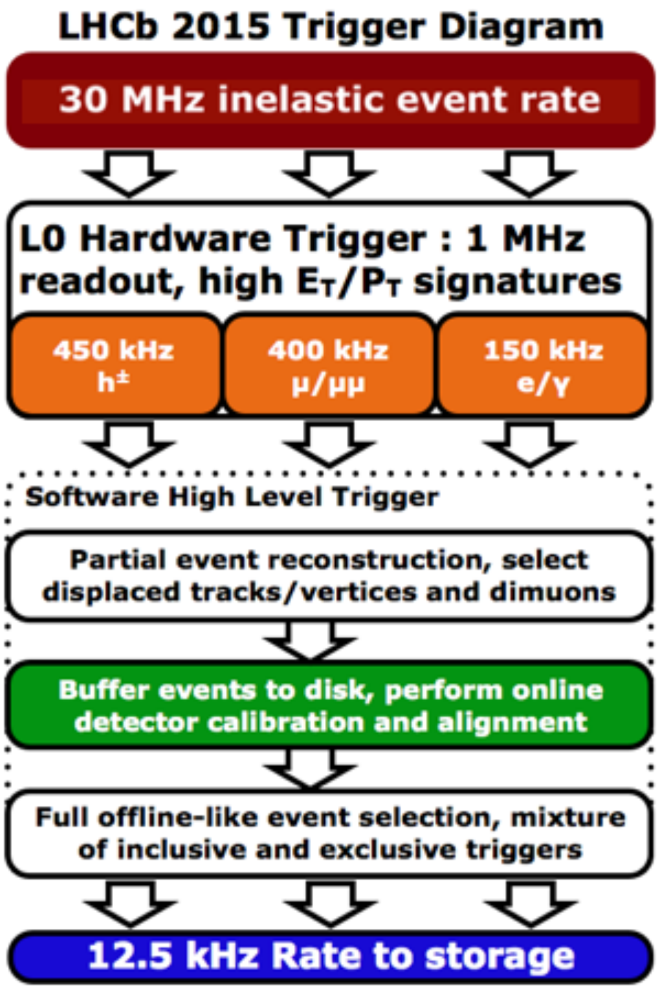
- 2030: Phase II Upgrade
  - Challenging project
  - Physics – leaps in performance in key channels
  - Detector – timing information may be key to coping with pile-up
  - Factor ten increase in luminosity
    - LHC can provide

German groups crucial to achieving Phase II Upgrade objectives

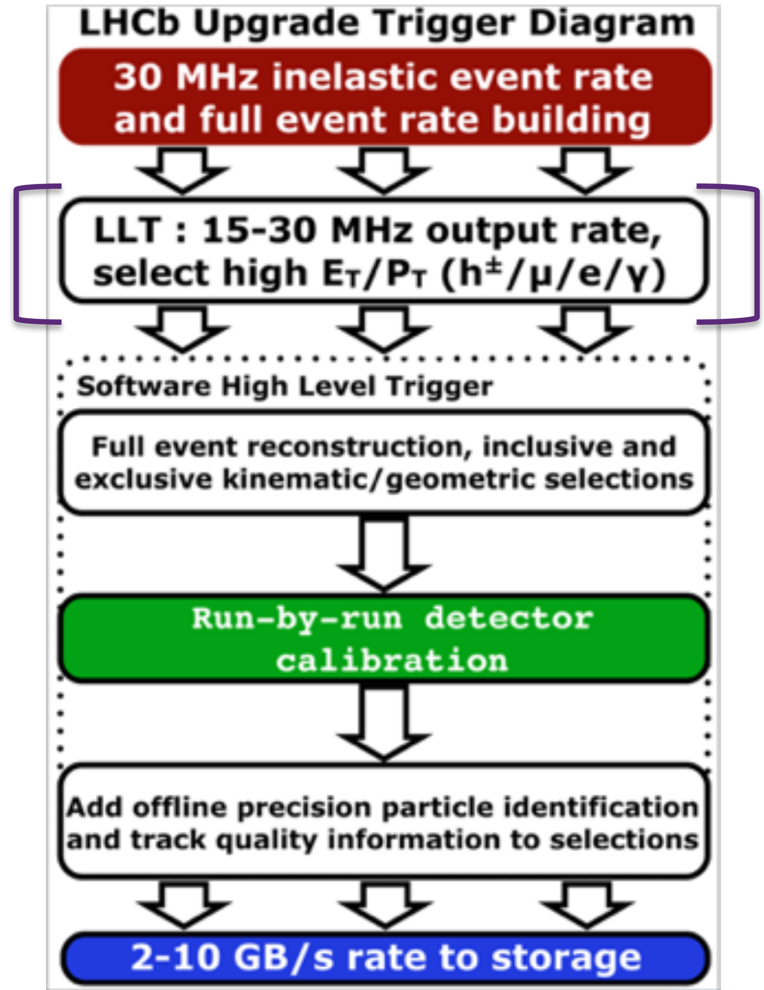
Backup

Trigger Evolution – Upgrade I

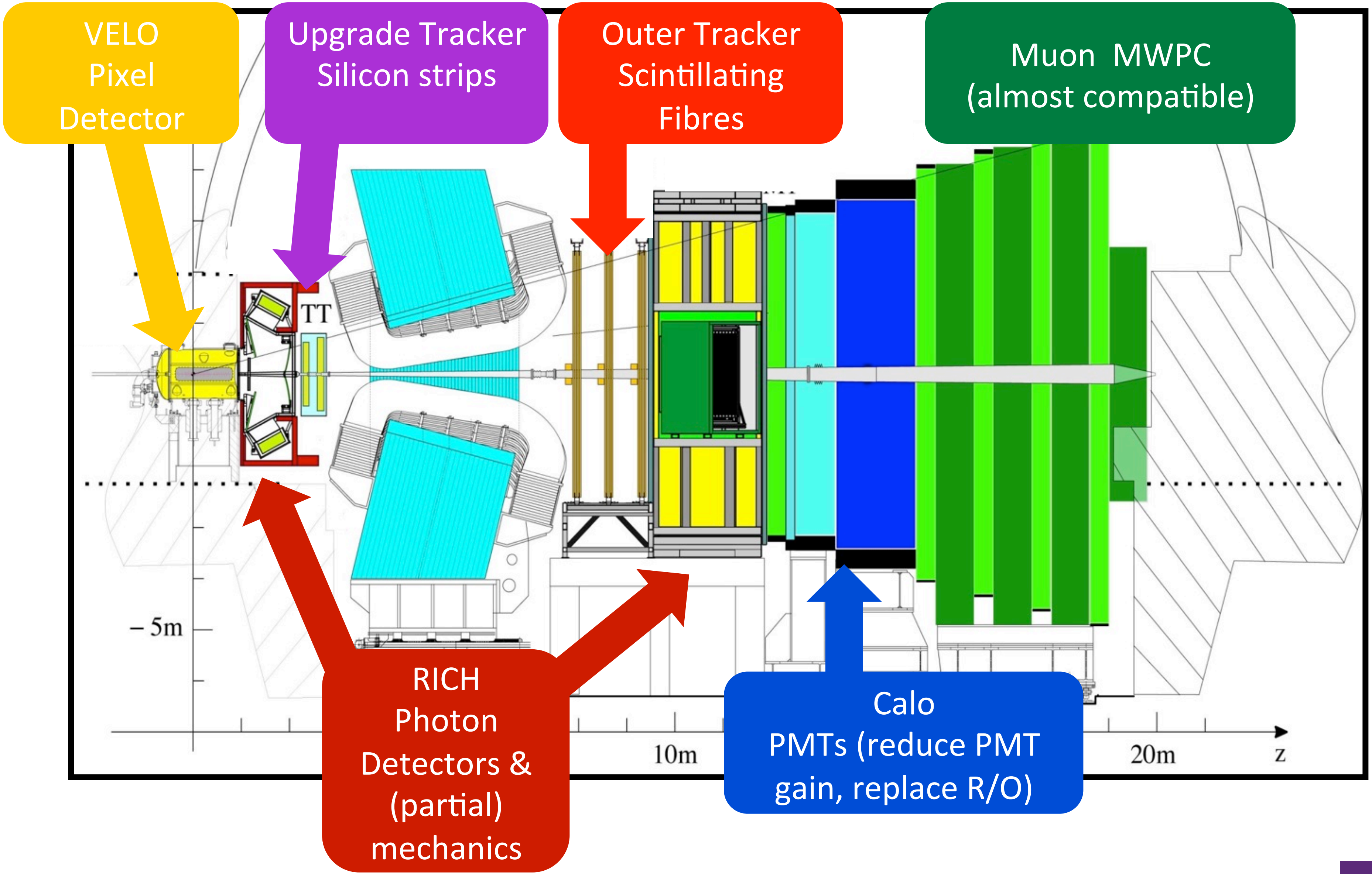
Run II



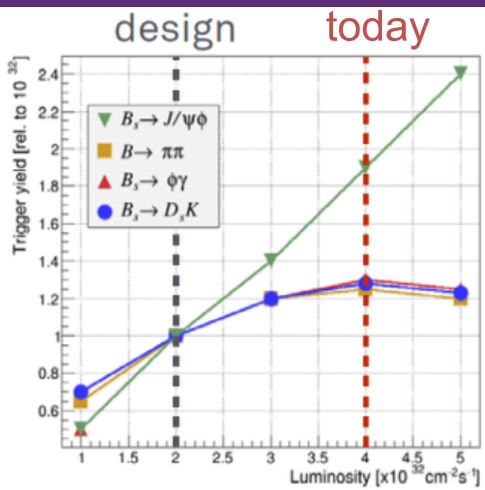
Upgrade I

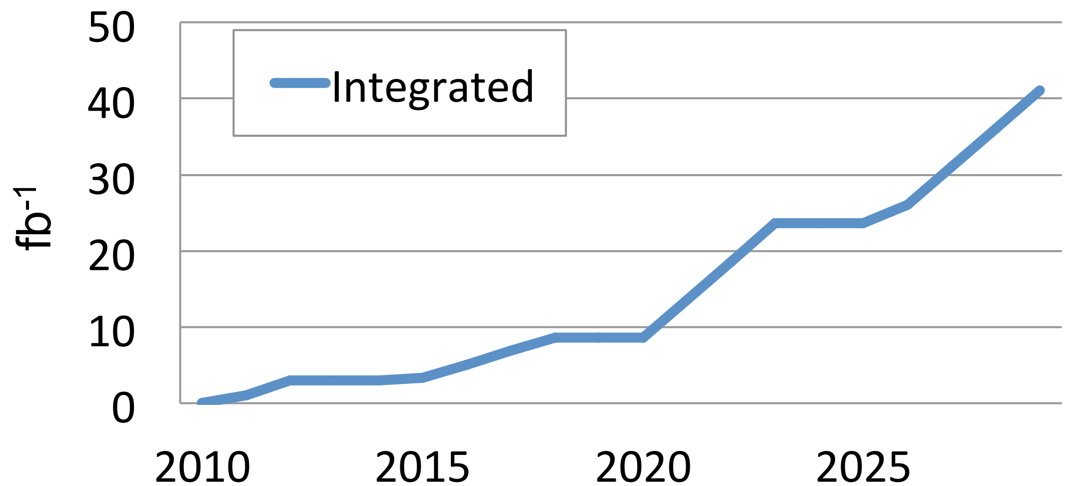


LHCb Upgrade I
25ns readout, software only triggering



Upgrade I – Beyond the Energy Frontier





- Hardware 1st Level Trigger ➔ Fully Software Trigger
- Increase Lumi to 2×10^{33} cm^{-2}s^{-1} to collect 50 fb^{-1}
- General purpose detector in forward region

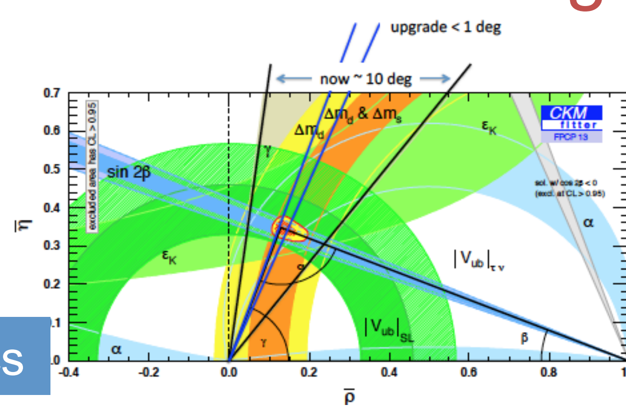
New Physics in Rare Decays

New Physics in CP Violation

New Physics in Charm

Electroweak & QCD Physics

Long Lived Stable Particle Searches, Dark Photon Searches

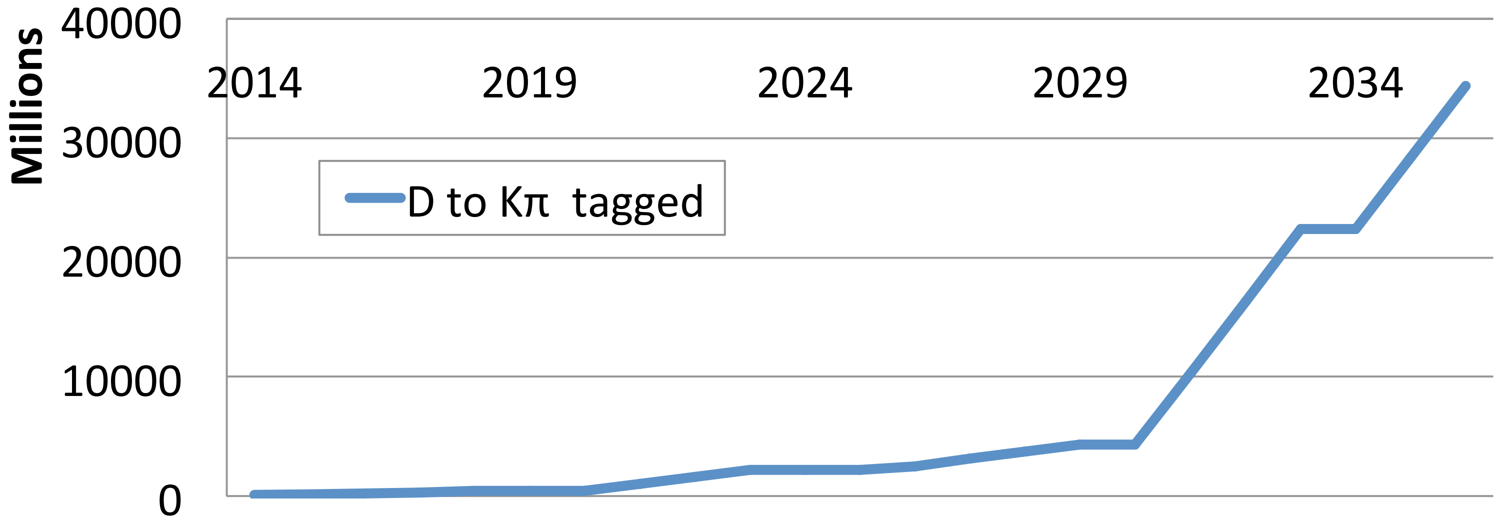


Probe 100 TeV for tree-level couplings

Eur. Phys. J. C (2013) 73:2373

Physics: Charm mixing & CPV

- Negatives:
- Lower momentum, shorter lifetime than B-sector
- Positives:
- $y, A_\Gamma, \Delta A_{CP}$ – no limiting systematics yet known

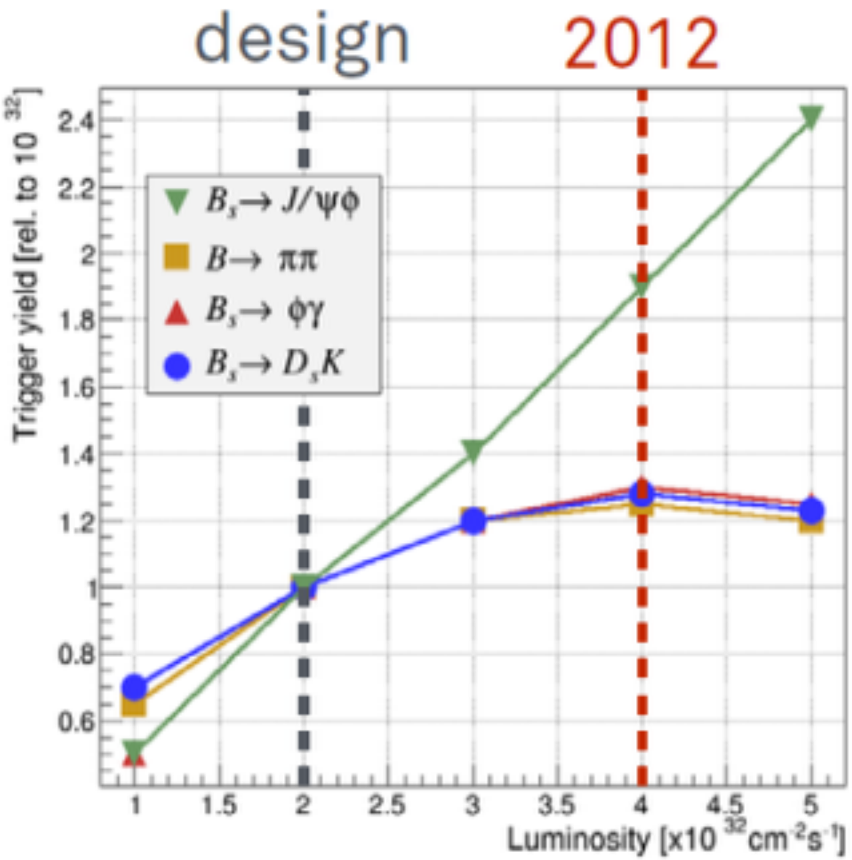


- ~30MHz of charm events produced in acceptance!

Observe SM level CPV at LHCb Phase II Upgrade

LHCb Trigger: the key to higher Lumi

- Aim: Increase integrated luminosity from 2 fb^{-1} to 5 fb^{-1} per year
  Increase instantaneous luminosity to 2×10^{33} cm^{-2} s^{-1}



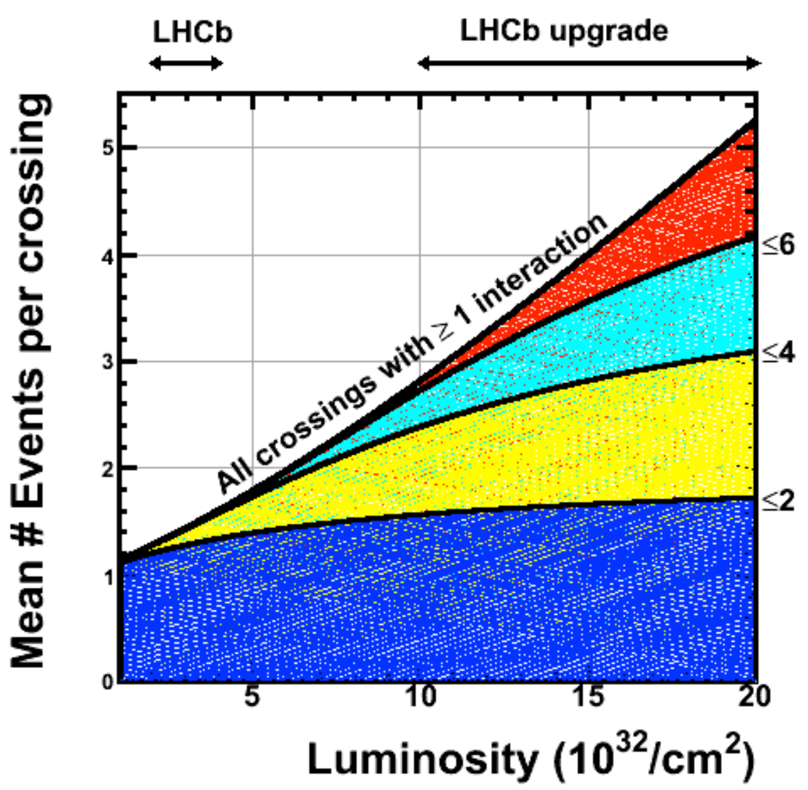
Current First Trigger Level:
Hardware Muon/ECAL/HCAL
1.1 MHz readout

Performance:
Muon channels scale
Hadronic channels saturate bandwidth

- No gain in hadronic channels with current trigger

Solution: Upgrade to 40MHz readout

- Read out full detector at 40MHz
  - Major detector changes
  - Front-end electronics must change
- Use fully software trigger
  - Increased flexibility
- Maintain (improve) current detector performance
  - At increased multiple Interactions
    – Occupancies
    – Radiation damage



Phase 1(b) Upgrade Ideas

- Improving the muon shielding by replacing HCAL with iron
- Building new, high rate, muon chambers for busy regions
- Replacing central region of RICH1 photodetector plane with new high granularity SiPMs
- Replacing inner SciFi modules with SciFi/ silicon
- Adding side chambers in magnet
- TORCH for fast-timing and PID purposes
- Replacing some of ECAL with high performant technology

Physics Performance Assumptions

- Run-2
  - Cross-section increases linearly with $\sqrt{s}$
  - Non-muon trigger efficiency suffers from tighter thresholds, but benefits from increased trigger eff.
  - 1.75 fb^{-1} per full year, ~5fb^{-1} in total for run II
- Upgrade Phase I
  - Removal of hardware trigger brings factor 2 efficiency boost for non-muon triggered events
  - 5fb^{-1} per year
- Upgrade Phase II
  - Same trigger eff. as upgrade (an upper limit?)
  - 50 fb^{-1} per year

Phase 1b/II

LS2: Major changes, Upgrade I Installation

- Run 3 (2021-2023)
  - LHCb Upgrade I
  - L=2x10^{33} cm^{-2} s^{-1}, ~5 fb^{-1}/yr

LS3: "Consolidation", Upgrade 1b Installation

- Run 4 (2026-2029)
  - LHCb Upgrade Ib
  - L=2x10^{33} cm^{-2} s^{-1}, ~5 fb^{-1}/yr

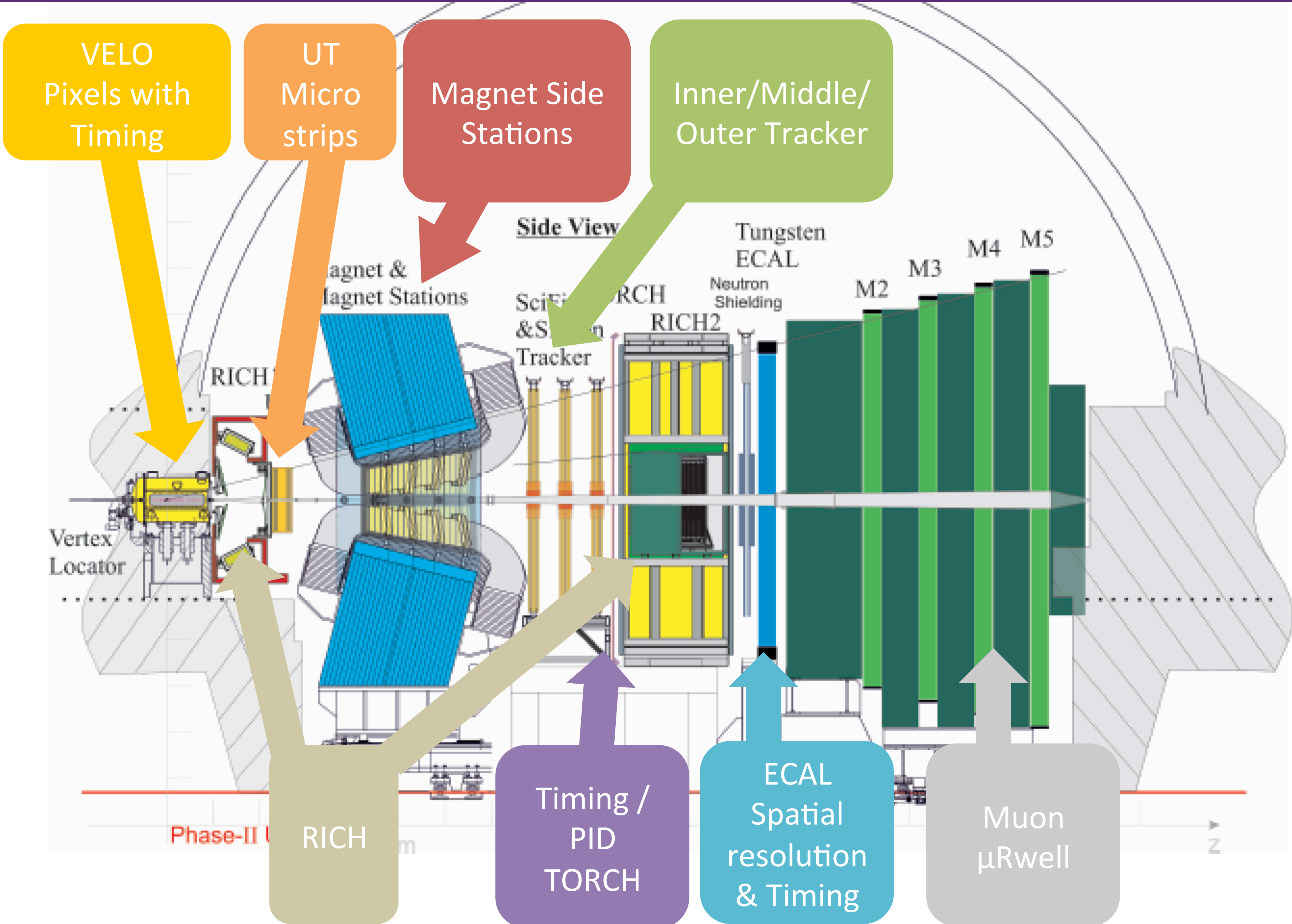
Total Int. L ~ 50fb^{-1}

LS4: Major Changes, Upgrade II Installation

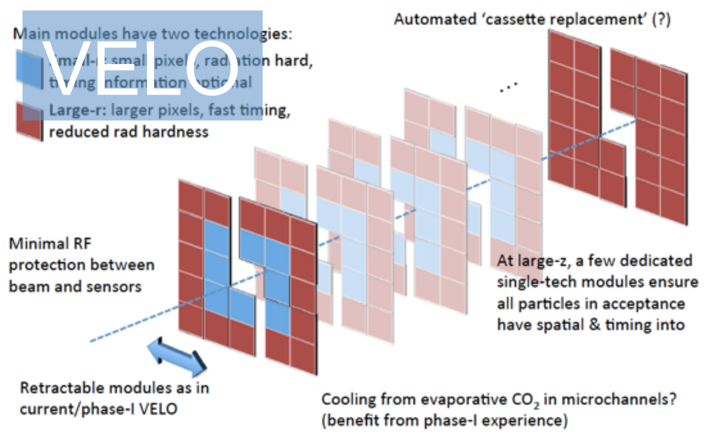
- Run 5/6 (2031-)
  - LHCb Upgrade II
  - L=1-2x10^{34} cm^{-2} s^{-1}, ~50 fb^{-1}/yr

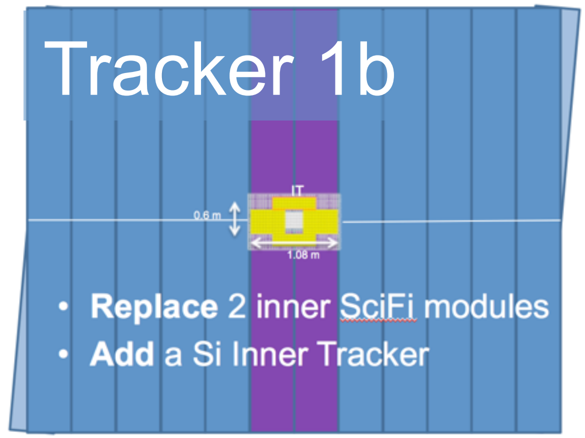
Total Int L ~ 300fb^{-1}

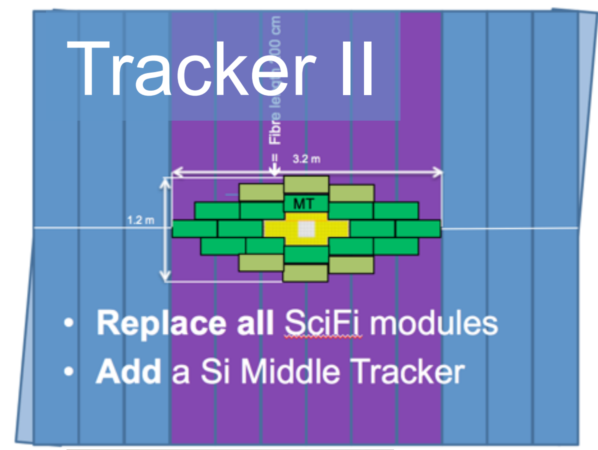
Phase-II Detector

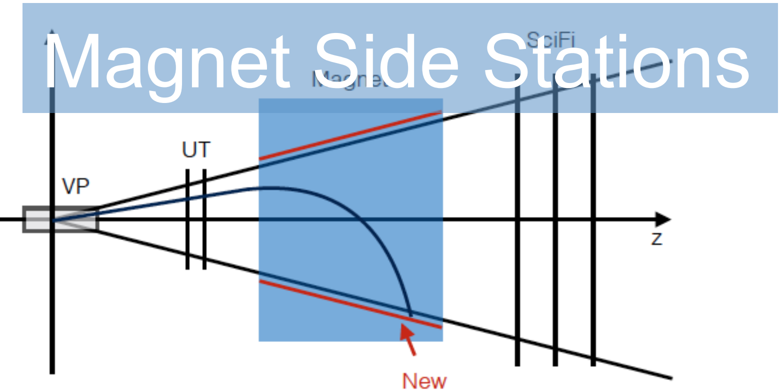


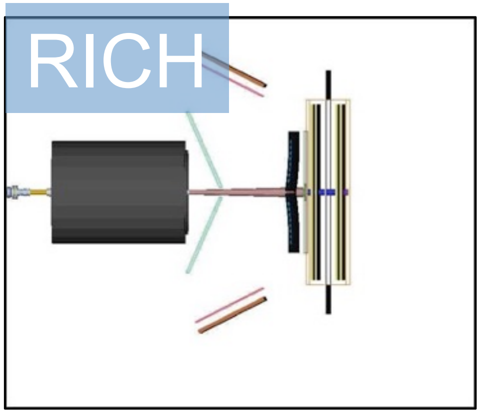
Detector Concepts

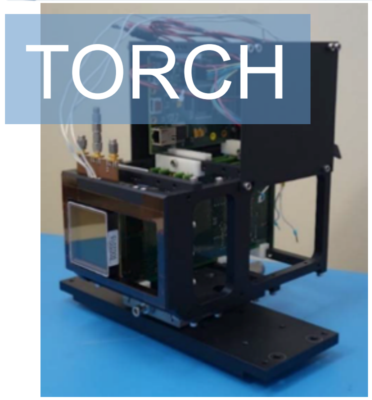


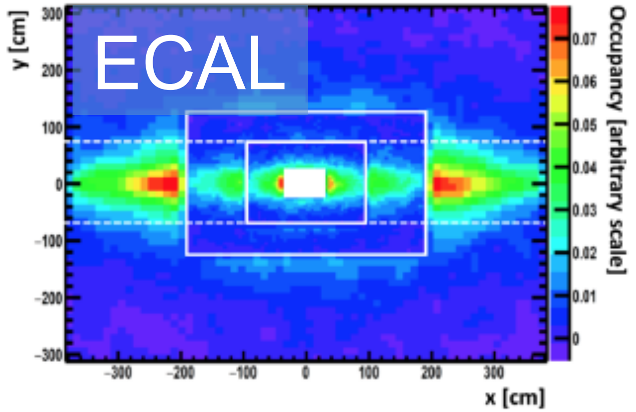


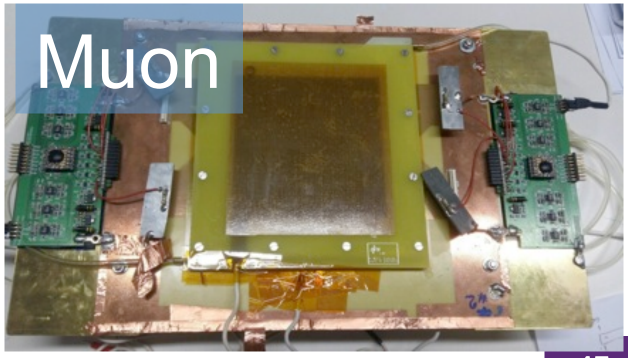












Phase 1b "Consolidation" Proposal Summary

Detector	Technology	Description
VELO R&D	Si hybrid pixels with timing	R&D, planes in backward direction ?
Inner Tracker	HV-CMOS	Silicon strips (current IT-like size)
Sci-Fi	Sci-Fi	2 modules per layer
Magnet Side	Scintillating fibre/ bar	Equip sides
'Retina' downstream track	FPGA	Hardware Track Reconstruction
RICH	e.g. SiPM, MCP...	In high occupancy RICH1 region
TORCH	MCP-PMT, Quartz	Low p PID, Charged particle timing
ECAL	W-Shaslik with si? Crystals ?	Replace Inner Cells (2x2 cm^2)
Muon	Iron	Additional Shielding
Muon	μ-RWELL MWPC	M2R1, M3R1, M2R2 M3R2

Phase 1b Comments

- General agreement that modifications to ECAL are highest priority item for this "consolidation" phase.
  - Long stated that ECAL needs modification due to radiation damage
  - Benefit to improve physics performance

- It is *highly unlikely* we will be able to afford all items on previous

- Consider as first stage towards Phase II

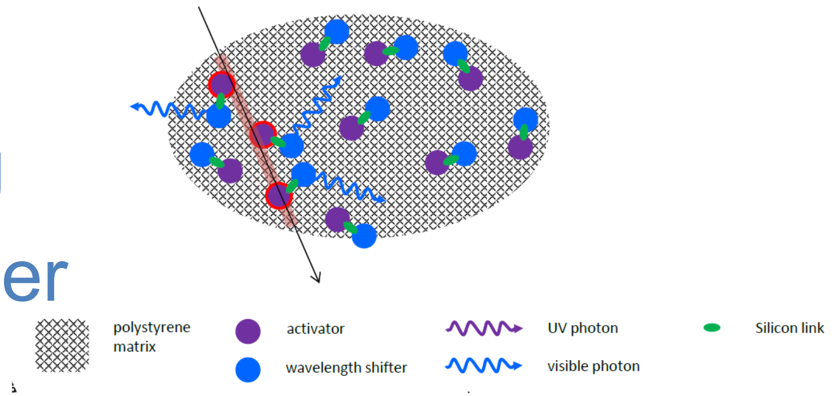
Phase II Proposal Summary (in addition to Phase 1b)

Detector	Technology	Description
VELO	Si hybrid pixels with timing	Rad. hard may need replacement
UT	Si strips	Increased granularity
Middle Tracker	HV-CMOS or conventional	Silicon strips ~20 m^2
Sci-Fi	Sci-Fi	Replace full system
RICH	e.g. cooled SiPM, MCP.., light flat mirror	Granularity /2-bit, angle resolution, timing
TORCH	Replace photon detectors? SiPM	Pile-up suppression
ECAL	W-Shaslik with Si? Crystals ?	Expand area of new technology
Muon	MWPC	M3-5 assess if replacements due to aging needed

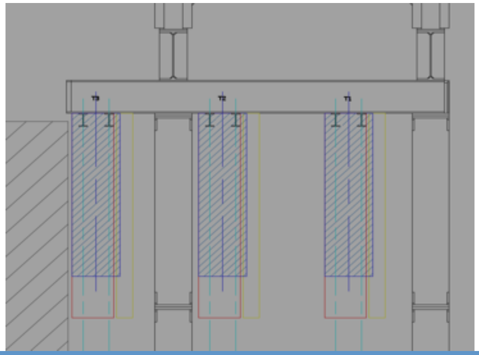
Sci-Fi

Christian Joram

- Neutron "torture"
  - Huge dark current rate
  - Temperature, shielding
  - SiPM E Field, FE shaper
- NOL Fibres

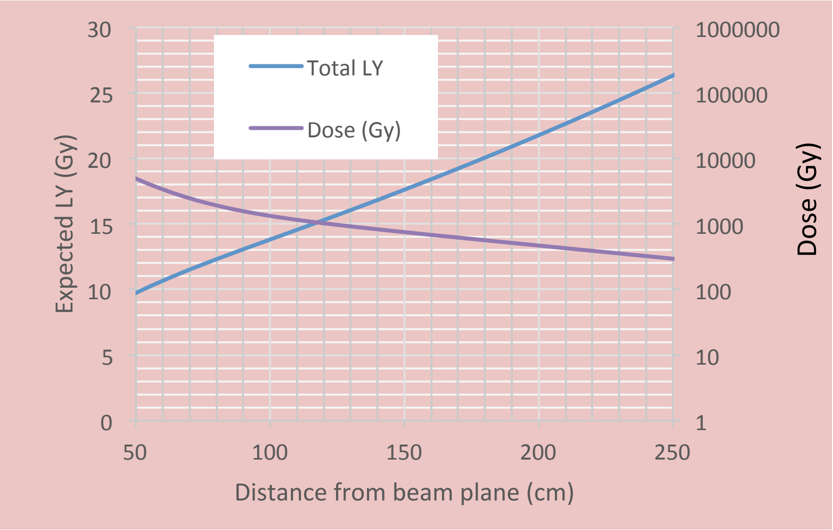


- Services constraint



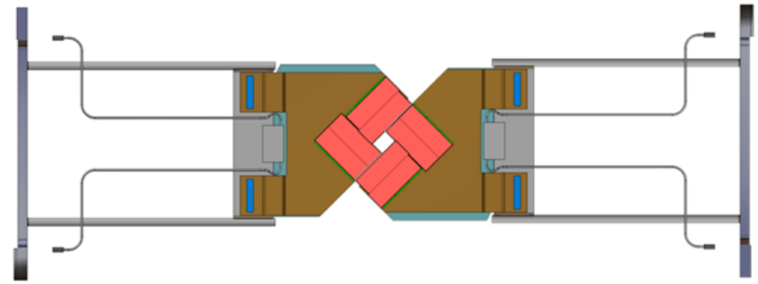
Limited z-space
For IT
Shared mechanics?

Alternative?
Micro Pattern Gas Detectors
attractive features but
higher non-uniform material budget

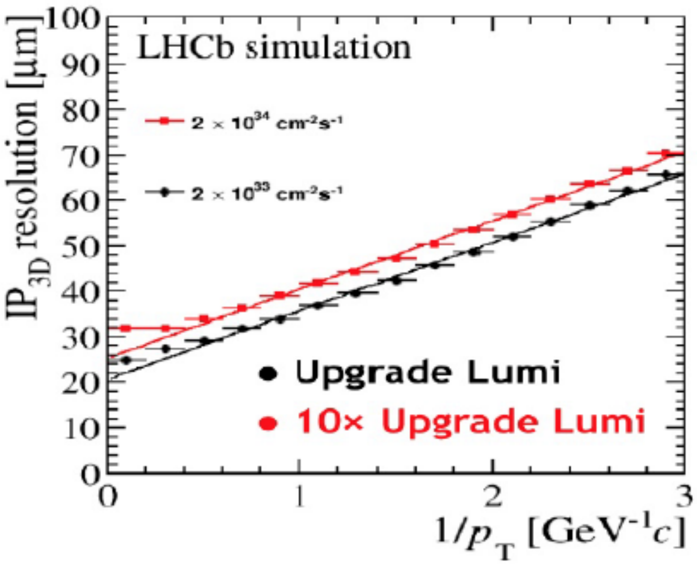


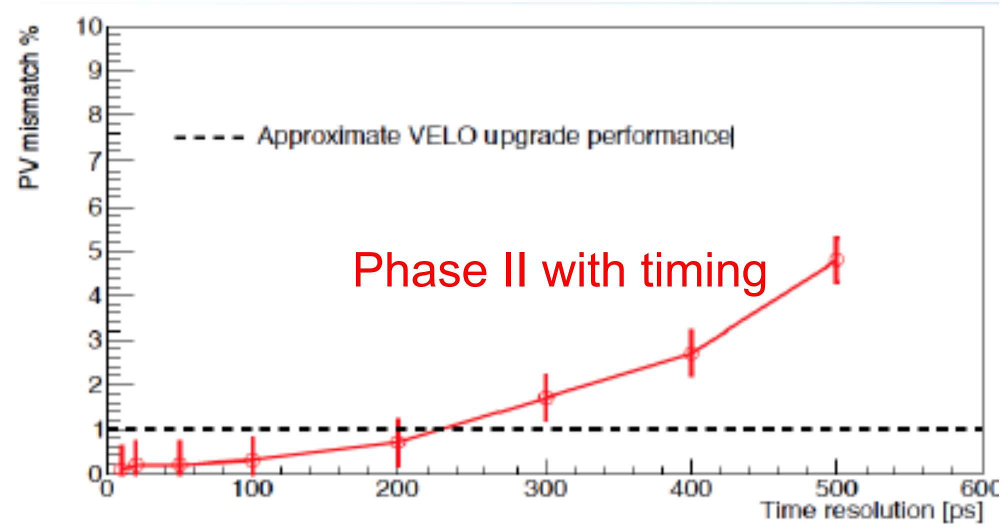
Fibres may just survive 300 /fb!

Vertex Detector: VELO

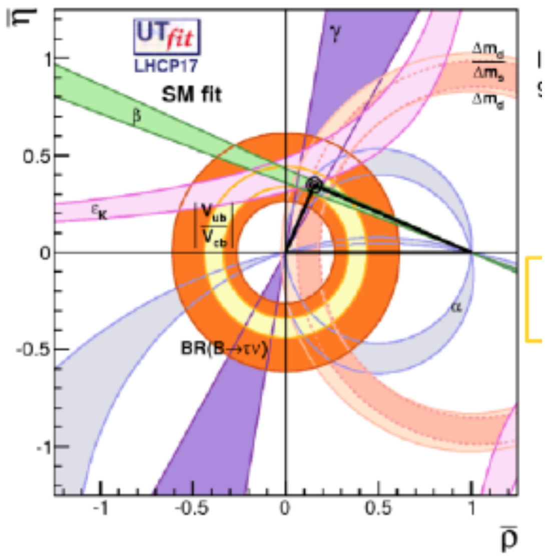


- Radiation Damage
  - Dose at 10^{17} 1 MeV n_{eq} / cm^2 level for full lifetime
  - Replace / increase inner radius
- Pile-up
  - Mismatch b/c decays to wrong PV
  - 4D: Timing at 200ps level required





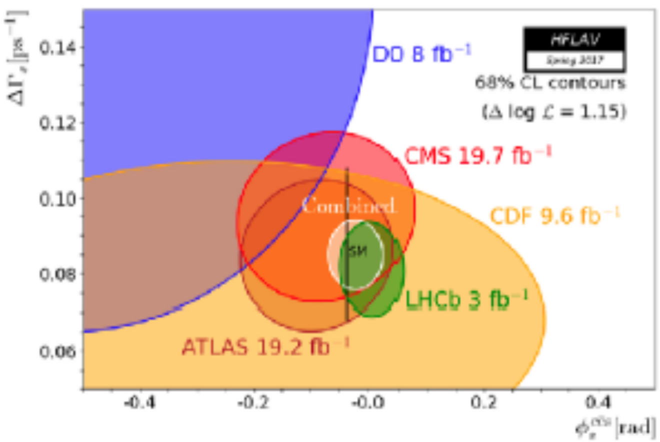
CPV & CKM unitarity



LHCb upgrade with 300/fb will allow to improve constraints on NP from the UT analysis without hitting the theoretical uncertainties wall

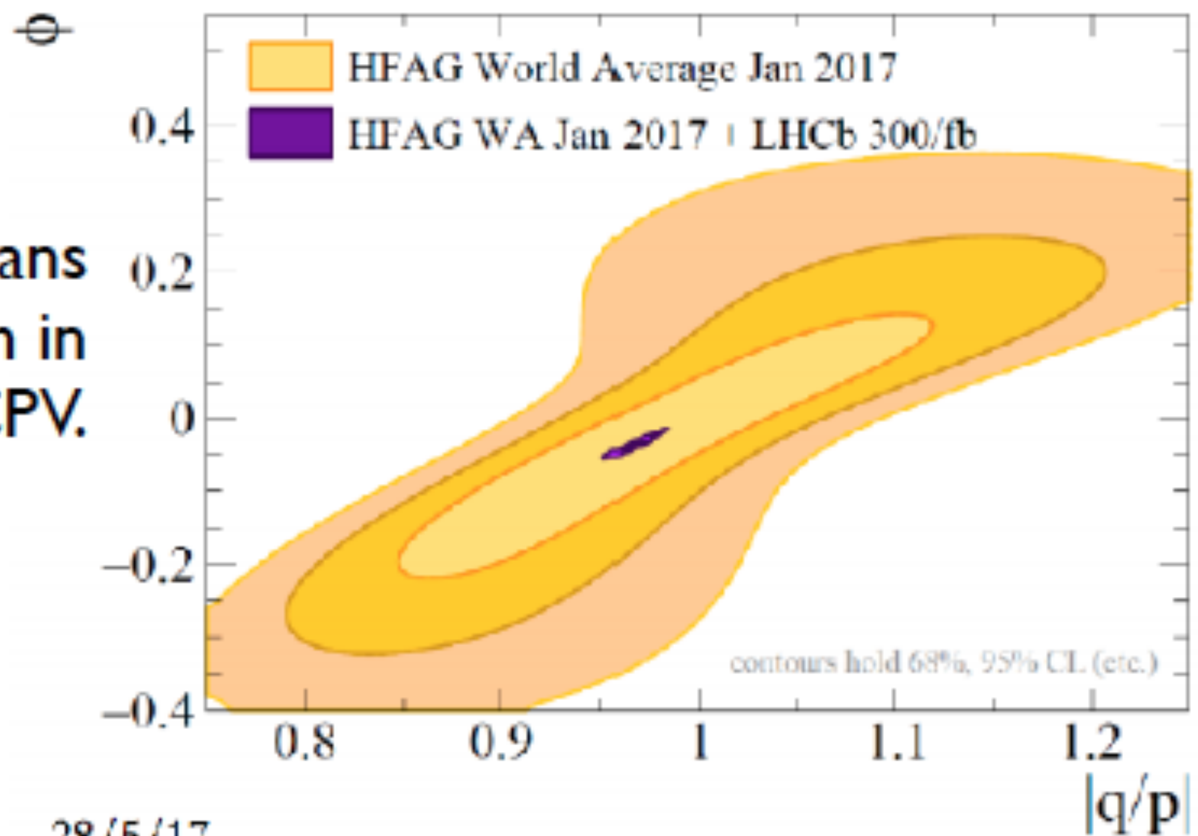
γ determination down to ~degree precision on individual modes. Start to probe tree-level NP.

Expect statistical scaling of Φ_s to continue to 300+/fb.



Charm

300/fb means tremendous reach in the clean indirect CPV.

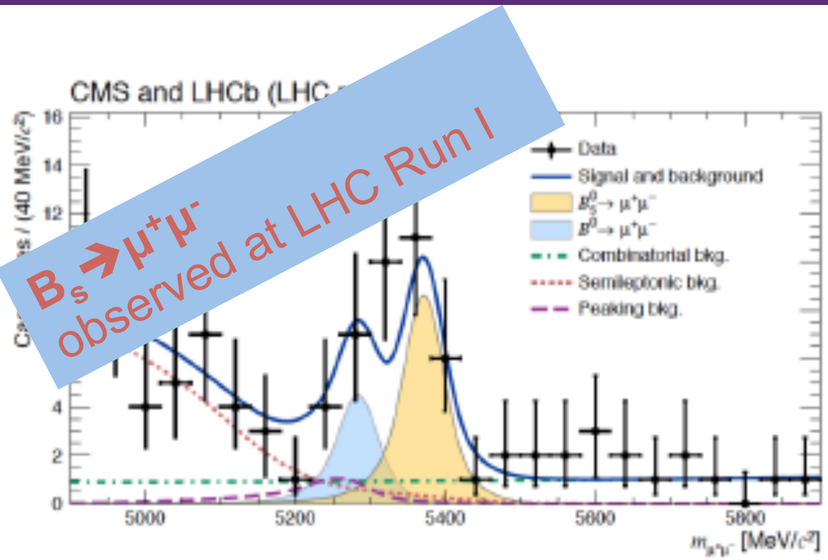


28/5/17

Compromise between magnet up / down luminosities to maximise int. luminosity

Expect to reach unprecedented precision on direct CPV, but requires theory breakthrough to be NP sensitive — let's be optimistic though.

Physics: Very Rare Decays Examples

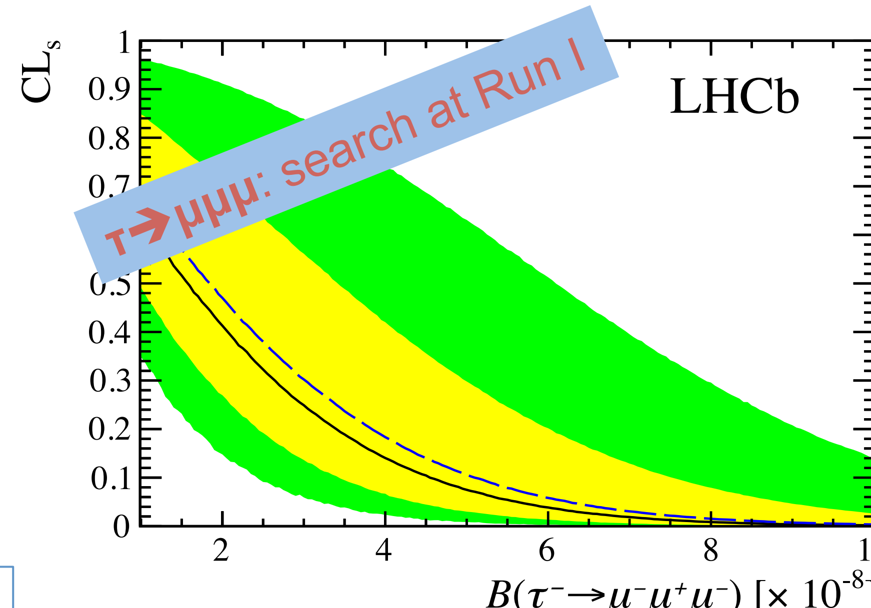


Next Target:

$$R = BR(B_d \to \mu^+\mu^-)/BR(B_s \to \mu^+\mu^-)$$

$\sigma(R)/R$ < 10% for Phase II

300 fb^{-1} 2400 B_s and 240 B^0
Effective lifetime ~ 2%
Test for CPV



- CLFV decays – strong interest: Neutrino mass linked to SM Higgs ?
- **τ→μμμ: a classic e+e- B-factory mode**
- Phase II LHCb precision comparable with Belle II ~ O(10^{-9})

- Future Charm Rare Decays
- e.g. $D^0 \to l^+l^-$, $D_{(s)}^+ \to h^+l^+l^-$, $D^0 \to h^+h^-l^+l^-$ with $l^+ = \mu^+$ and e^+