MANCHESTER 1824
The University of Manchester

LHCb

Perspectives on Quark Flavour Physics after 2025

Emphasis on LHCb Longterm Plans

Chris Parkes

- Other dedicated Flavour physics experiments (not hadron collider)

- LHCb in HL-LHC era

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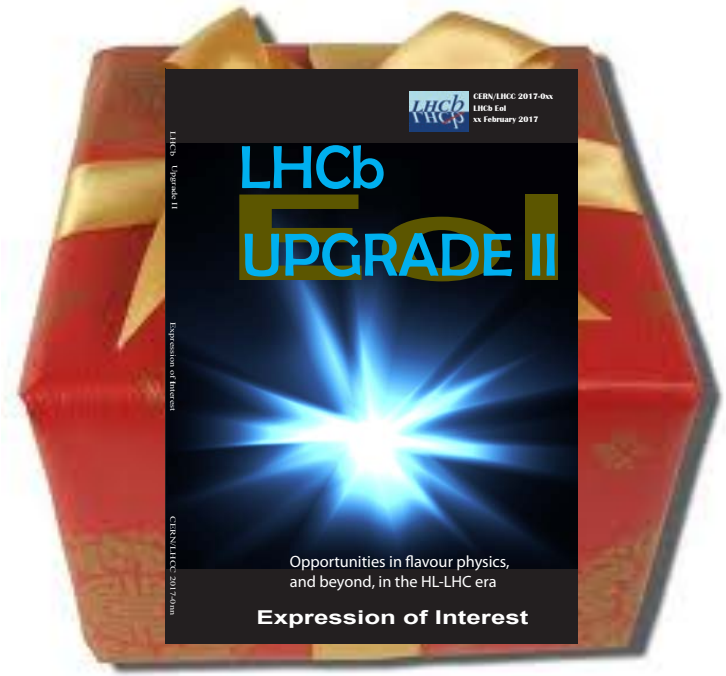


Has Santa Claus Brought New Physics ?

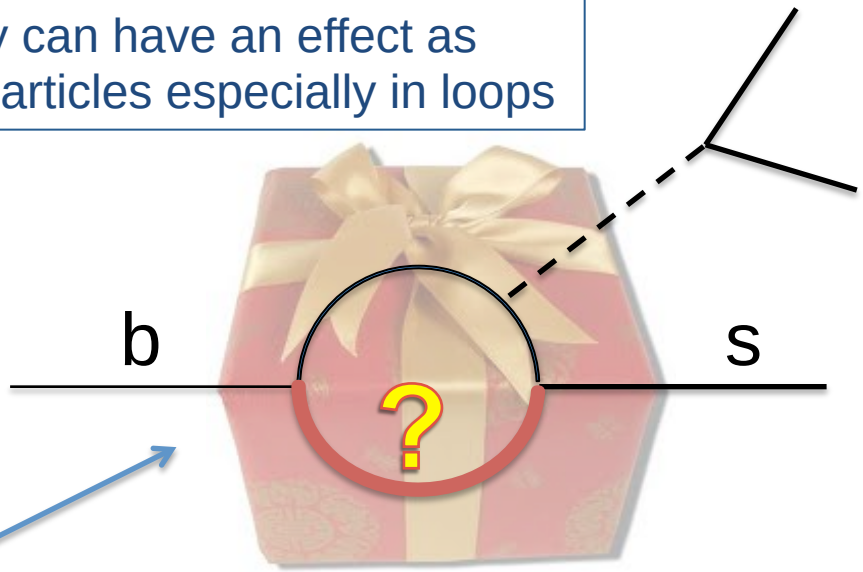
Two ways to find out

Direct Observation

Presents with $MC^2>E$ cannot be produced directly

Indirect Effects

But they can have an effect as virtual particles especially in loops



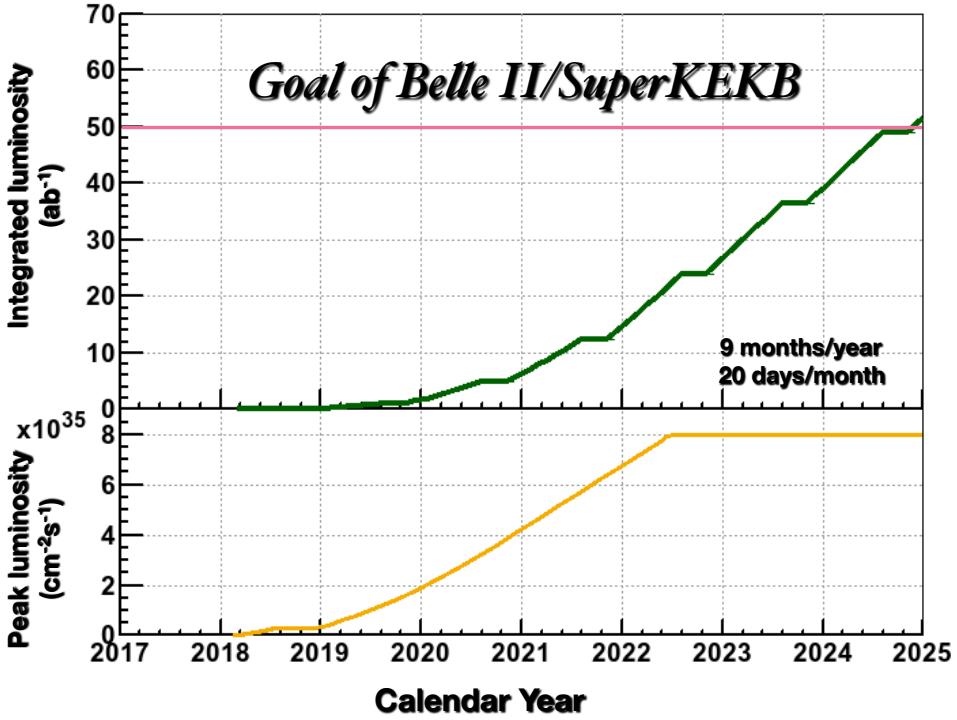
This kind of approach is sensitive to particles far heavier than produced directly at a collider. It is what **flavour physics** is about it lets you see beyond the energy frontier.

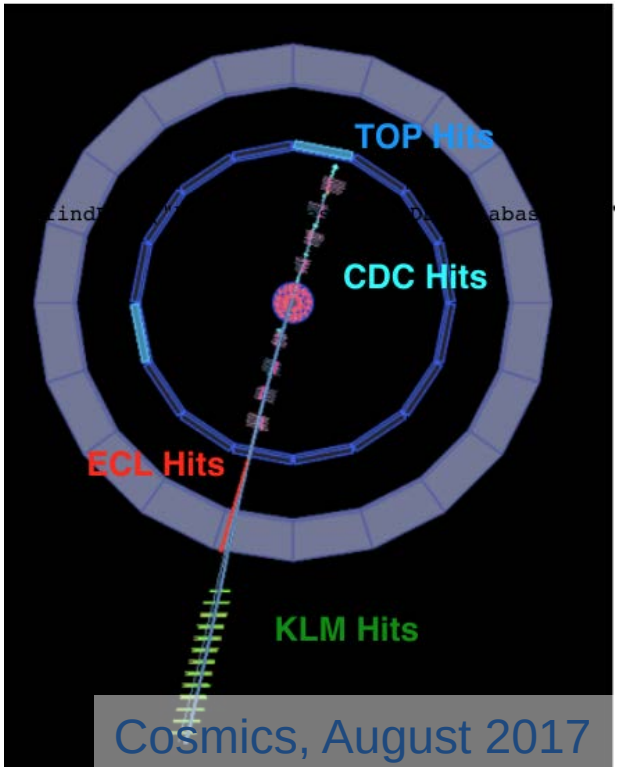
Belle II

P. Goldenzweig,
HL-LHC Meeting,
November 2017

- Currently commissioning
- Physics programme 2018-2025
- Aim to collect 50 times Belle lumi.

SuperKEKB luminosity projection

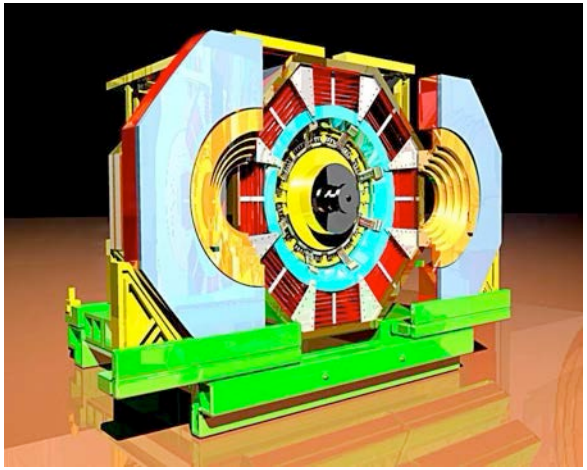


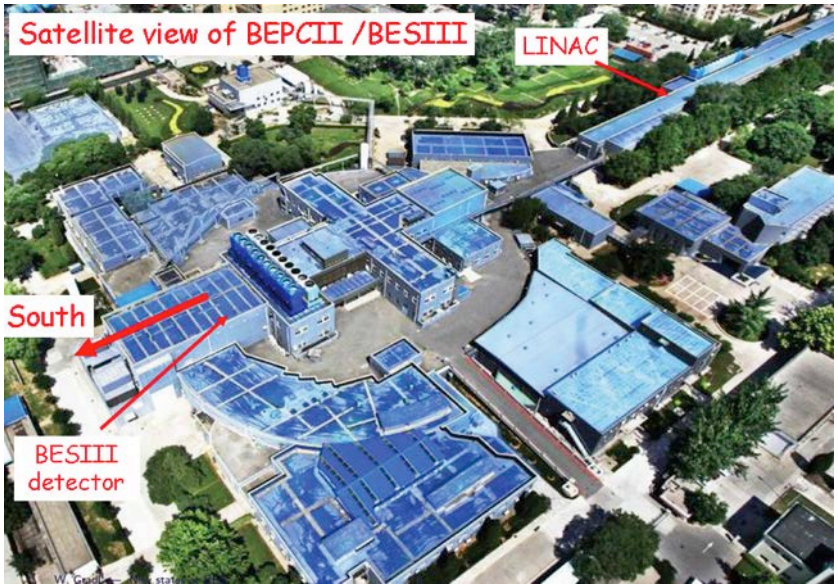


BES III

Xin Shi, DIS 2017
Xiaoyan SHEN, Charm 2016

- Beam Energy 1.0-2.3 GeV
- Physics Programme
  - Leptonic, hadronic
  & rare D decays
  - Hadronic spectroscopy (XYZ)
  - Unique Quantum Correlated D $\underline{D}$
- Operating since 2009
- Plans to run through early 2020s

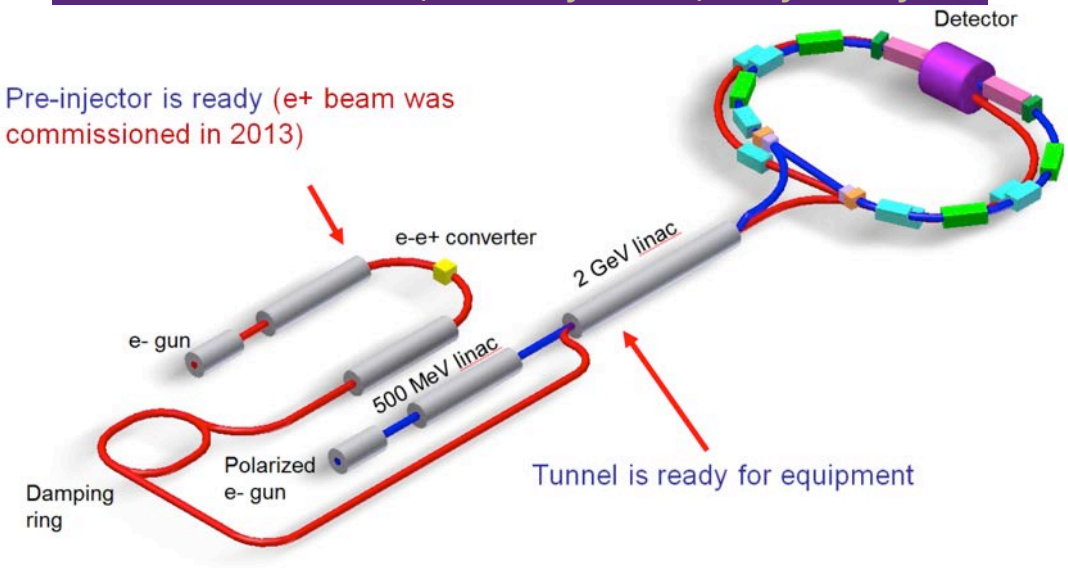




Super c-τ Factory at BINP (Novosibirsk)

Thanks to:Alex Bondar, Simon Eydelman, Vitaly Vorobyev

- Physics
  - Charm mixing
  - CP violation
  - Rare and forbidden charm decays
  - Spectroscopy
  - LFV $\tau \rightarrow \mu\gamma$



- Collider
  - L=5-10 x 10^{34} cm^{-2} s^{-1}
  - 2-5 GeV Collisions
  - Longitudinally polarised e^- beam
  - Crab waist collisions
  - 800m rings

- Status
  - CDR Issued (2011)
  - One of six Russian Federation mega-science projects
  - R&D in progress
  - Six year build plan
  - Workshop May 2018

Future Kaon Physics

Thanks: August Cecucci, Cristina Lazzeroni
Physics Beyond Colliders, November 2017

- New physics sensitive rare decay $K^+ \rightarrow \pi^+ \nu\underline{\nu}$
- Applying to continue running after LS2
- Finished by LS3 (2025)

- Two experiments for neutral analogue $K_L \rightarrow \pi^0 \nu\bar{\nu}$

- **KOTO**, JPARC expects to reach SM sensitivity by 2021.
  - Step 2 upgrade concept to reach O(100) events
  - Indicative timescale: data taking start 2025

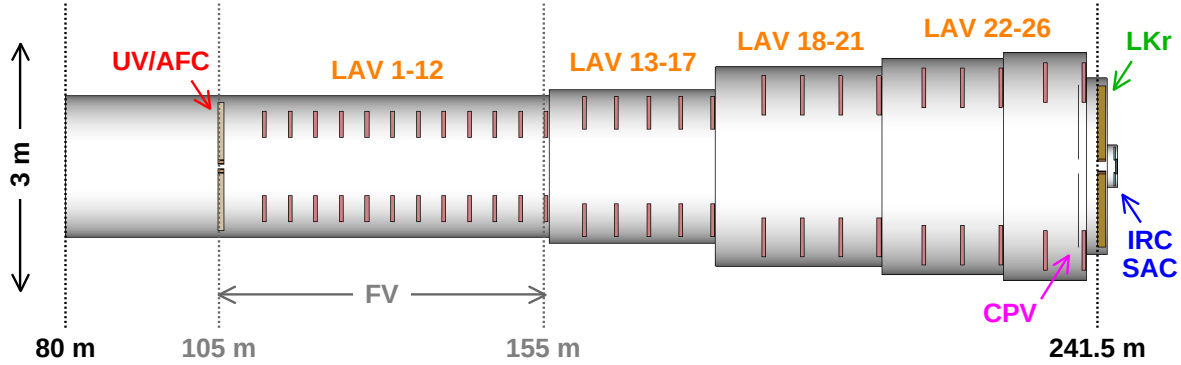
- **KLEVER**, Fixed-target at CERN SPS
  - New proposal, aim to reach ~60 events
  - Data taking from 2026 (Run 4 after LS3)

K_LEVER

Expression of Interest to SPSC

- **Actively seeking new collaborators**

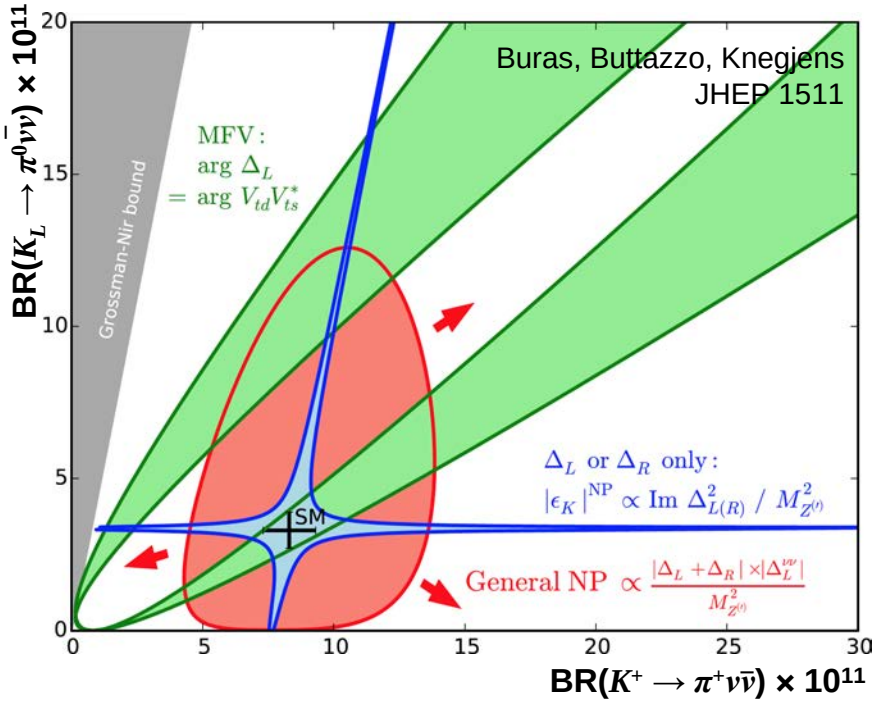
K_LEVER



Main detector/veto systems:

UV/AFC	Active final collimator/upstream veto
LAV1-26	Large-angle vetoes (26 stations)
LKr	NA48 liquid-krypton calorimeter
IRC/SAC	Small-angle vetoes
CPV	Charged-particle veto

10^{19} pot/yr × 5 years → 2 × 10^{13} ppp/16.8s = 6× increase relative to NA62



- New physics affects BRs differently K^+, K_L
  - Both allows to distinguish NP
    - Minimal Flavour Violation
    - LH/RH couplings dominate
    - Randall-Sundrum

ATLAS/CMS Flavour Physics @ HL-LHC

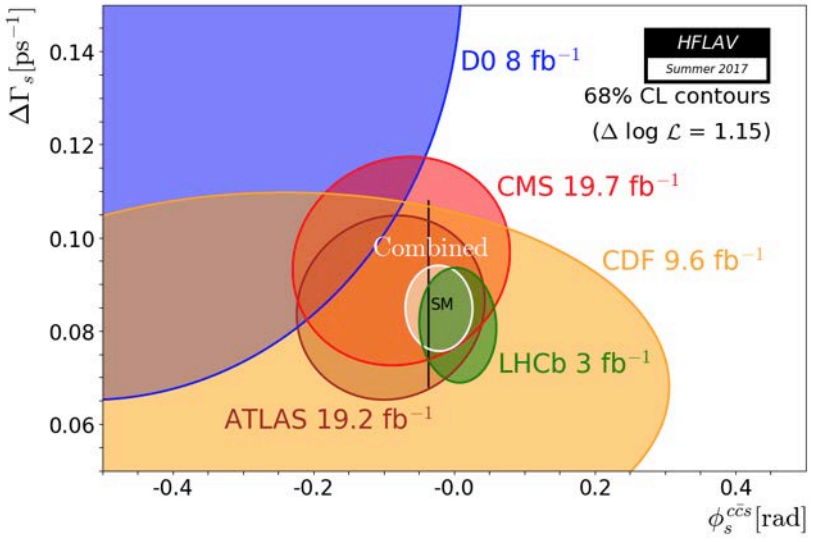
P. Reznicek, S. Sarkar, CERN HL-LHC Meeting, November 2017

- Continue current programmes
  - CPV and rare processes with muons in final state
    - $B_s \rightarrow J/\psi\phi$, $B_{(s)} \rightarrow \mu\mu$, $b \rightarrow s\mu\mu$…
    - CMS: $B_s \rightarrow \phi\phi \rightarrow KK$, showcases L1 tracking
  - Heavy Flavour production
- Trigger thresholds key to programmes
- "Pile-up tends to weaken b-physics potential"

ATLAS:
- Closer and smaller pixels help improve decay time resolution
- New small wheel muon with fast track trigger

CMS:
- Improvements in tracker
- Increased muon coverage
- Trigger – tracking at 40 MHz

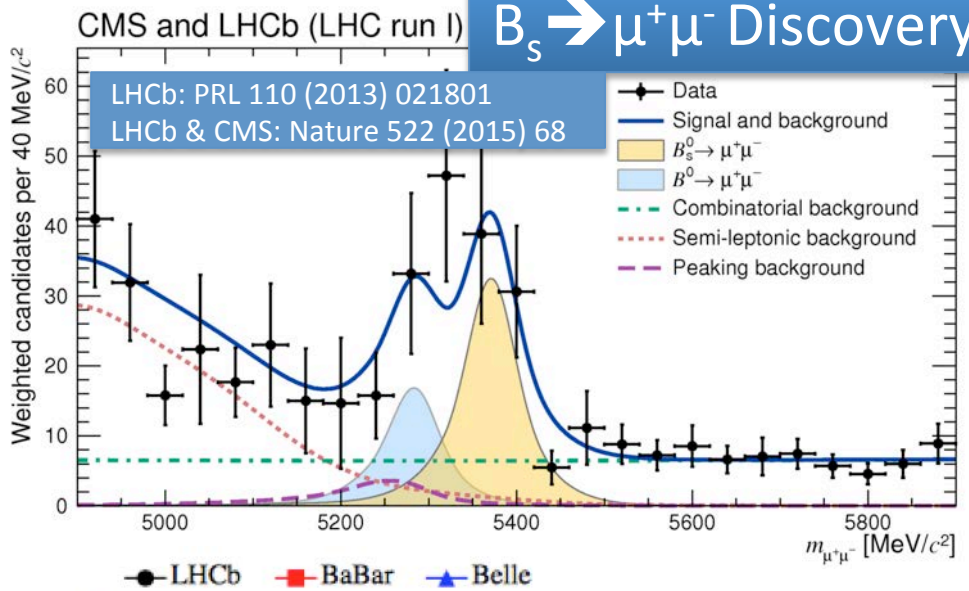
- Though ATLAS measurement in same LHC Runs not as precise as LHCb, still providing cross-check and improving visibly overall average



LHCb Highlights

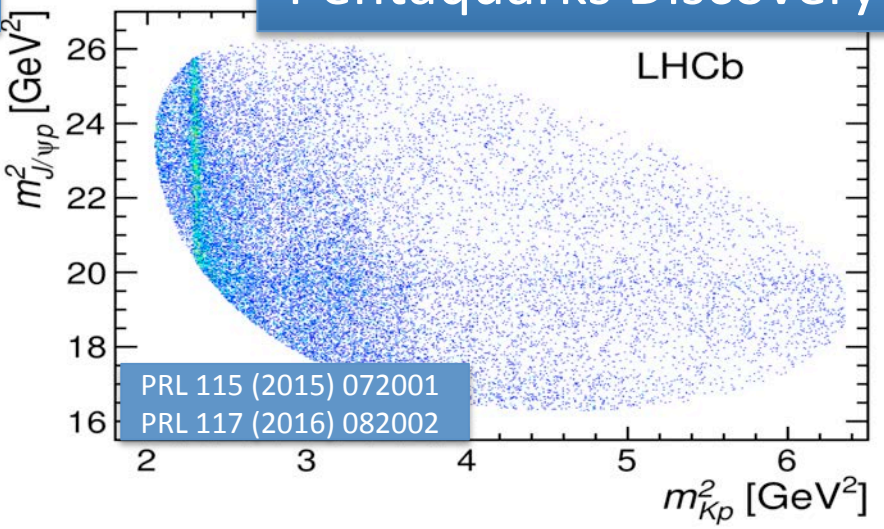
408 Physics Papers 798 Authors 74 Institutes

$B_s \rightarrow \mu^+\mu^-$ Discovery



LHCb: PRL 110 (2013) 021801
LHCb & CMS: Nature 522 (2015) 68

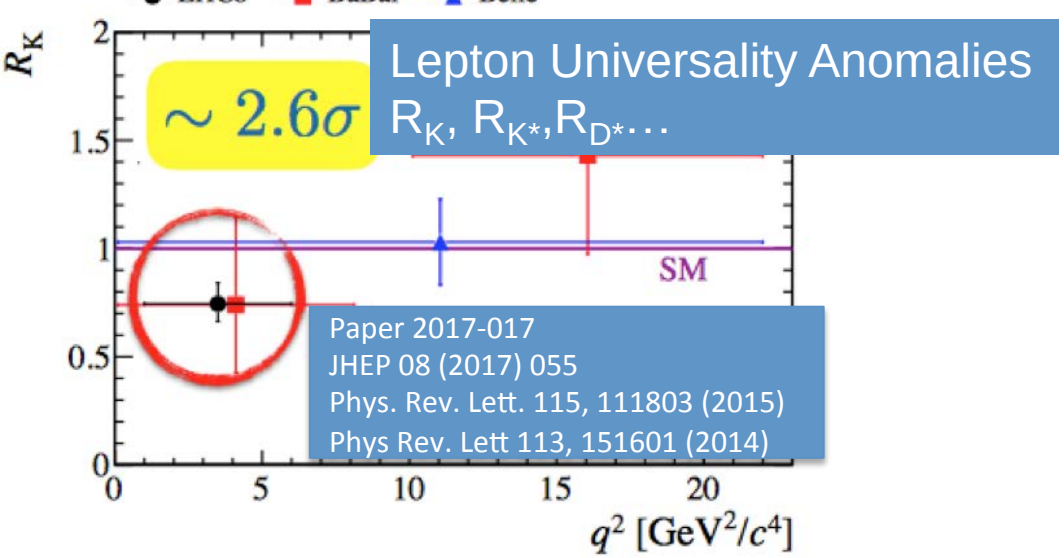
Pentaquarks Discovery



PRL 115 (2015) 072001
PRL 117 (2016) 082002

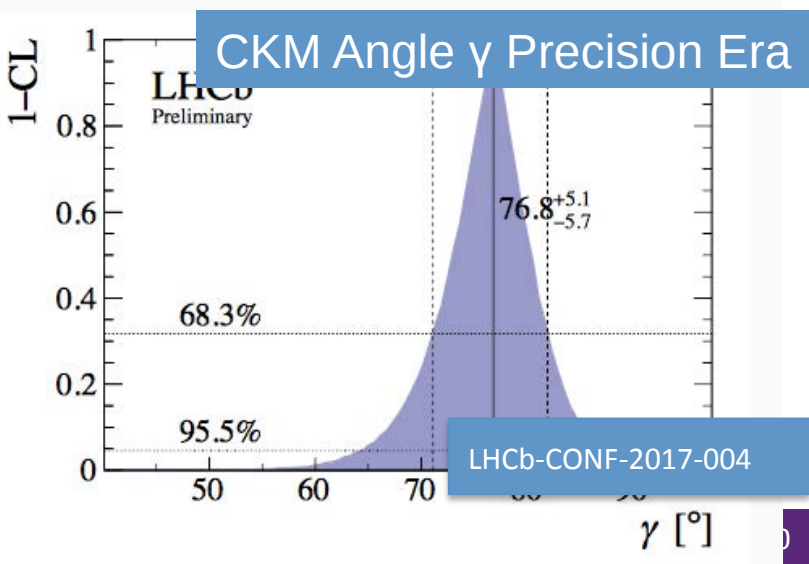
Lepton Universality Anomalies

R_K, R_{K^*}, R_{D^*}…



Paper 2017-017
JHEP 08 (2017) 055
Phys. Rev. Lett. 115, 111803 (2015)
Phys Rev. Lett 113, 151601 (2014)

CKM Angle γ Precision Era



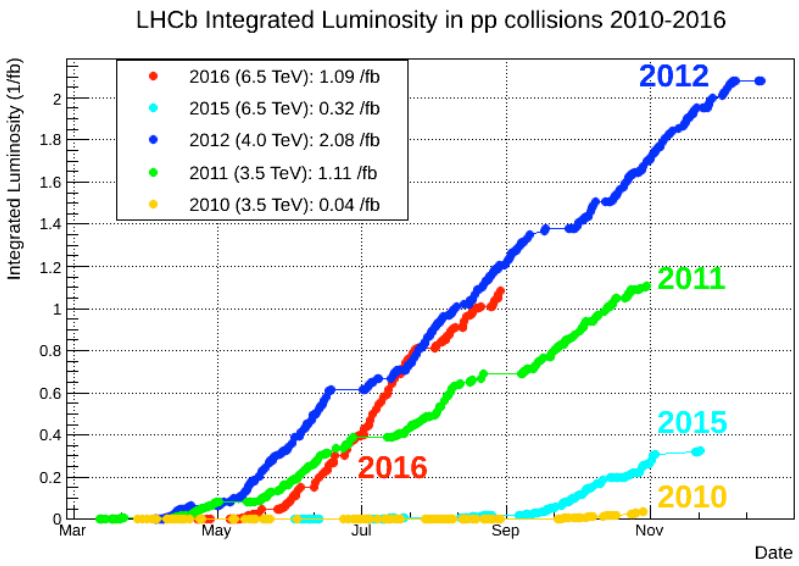
LHCb-CONF-2017-004

LHCb Timeline

- LHC Run-I (2010-2013)
- LHC Run-II (2015-2018)
  - Trigger computing increased.
- LHC Run-III, Run-IV (2021-2023, 2026-2029)
  - Major ‘New’ Experiment: **LHCb Upgrade [I(a), I(b)]**
- LHC Run-V (2031-)
  - Major ‘New’ Experiment

LHCb Upgrade II

– May be only general heavy flavour expt on this timescale



Physics Programme

Limited by Detector

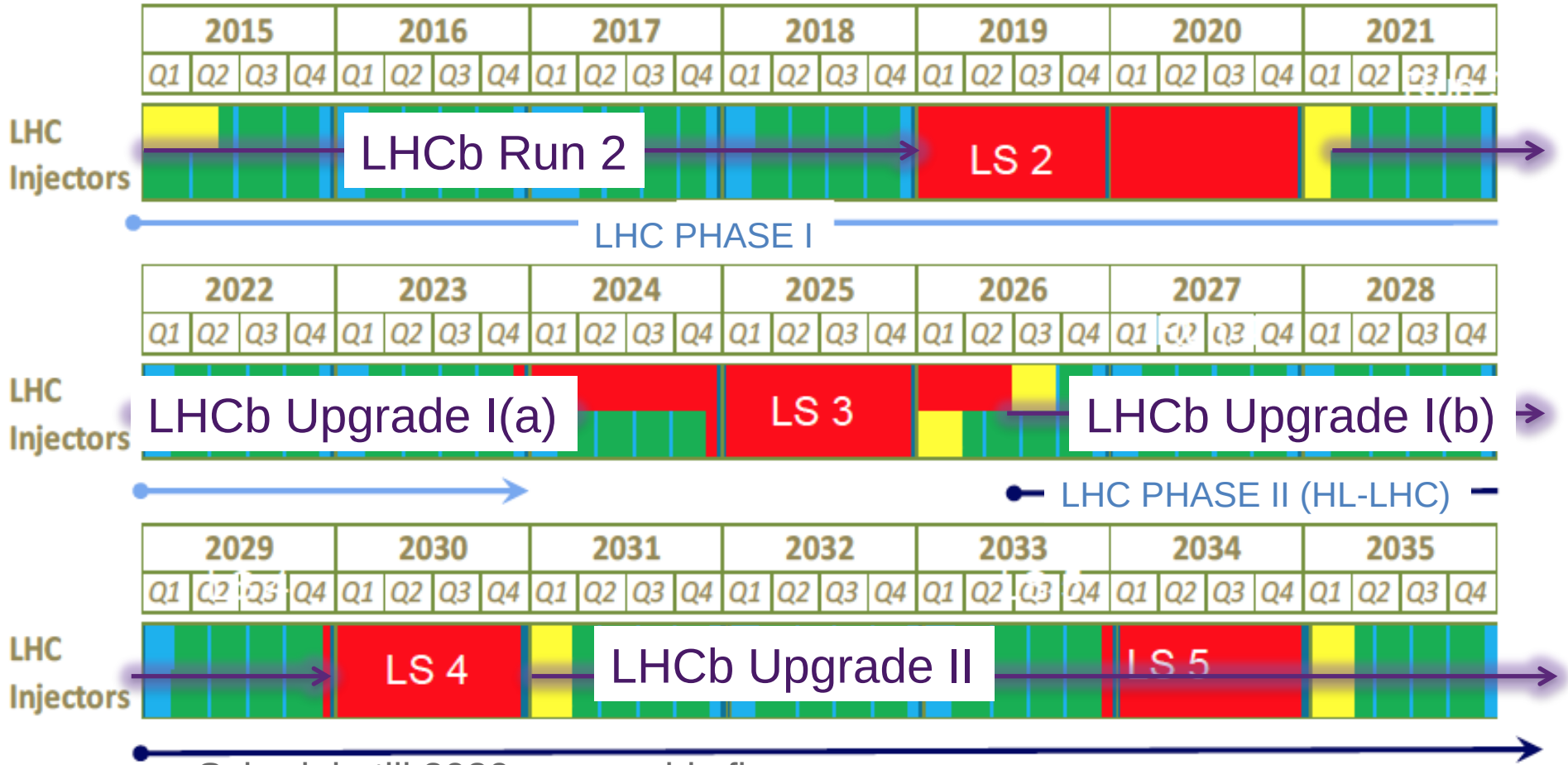
But **NOT** Limited by LHC

- 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 ~ $2x10^{33}$ cm^{-2} s^{-1}
- Upgrade II Collect > 300 fb^{-1} data
  - L ~ 1-$2x10^{34}$ cm^{-2} s^{-1}
- 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

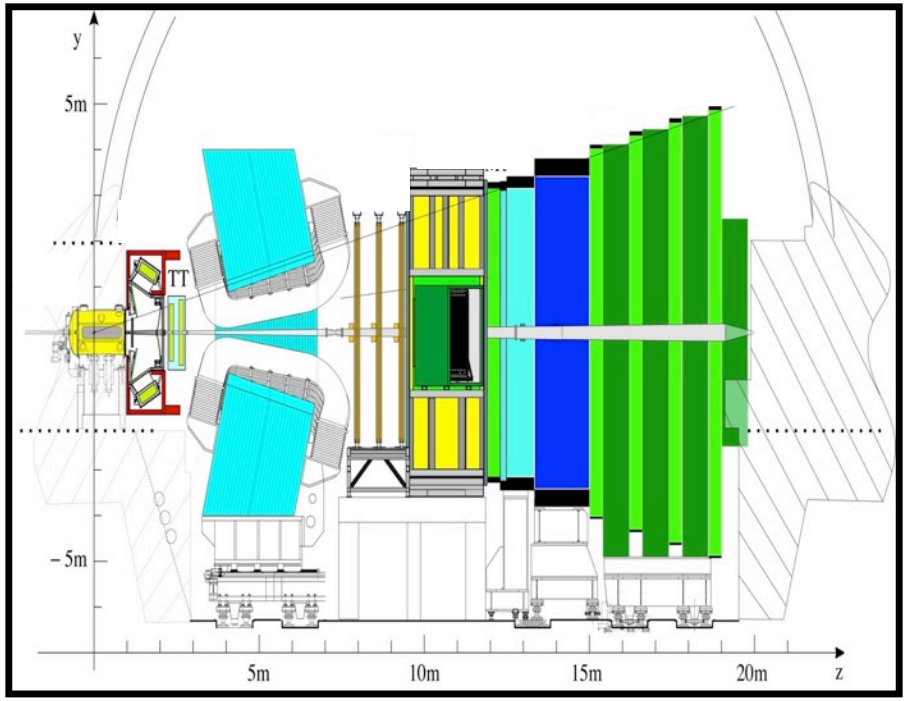
LHC Schedule & LHCb



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

Physics
Shutdown
Beam commissioning
Technical stop

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 elements keeping to schedule

Upgrade 1(b) – Consolidate & Enhance

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

Not many new gifts

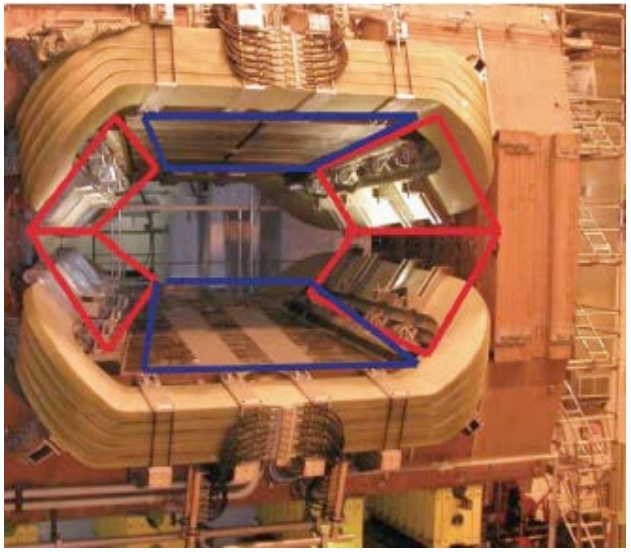
Same timescale:

ATLAS EXPERIMENT Upgrade Phase II

CMS Upgrade Phase II

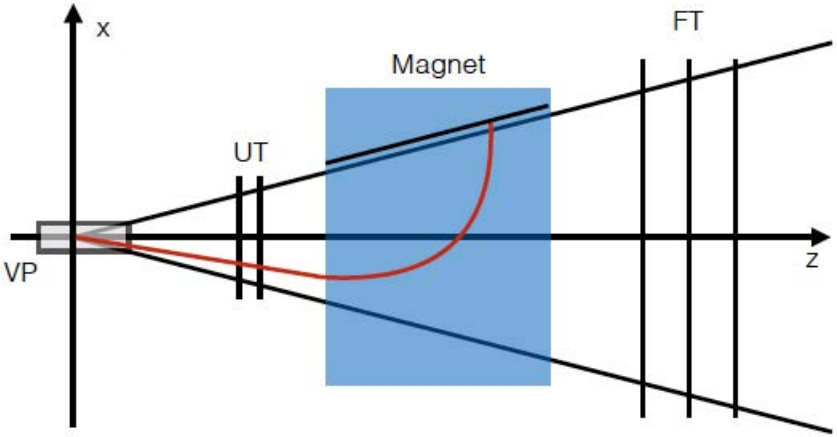
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

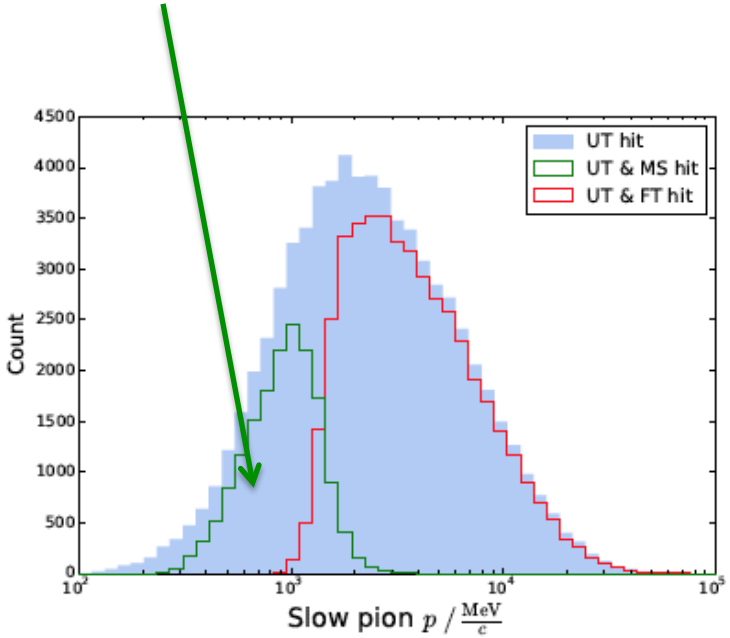
Upgrade 1(b) e.g. – Magnet Side Stations



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

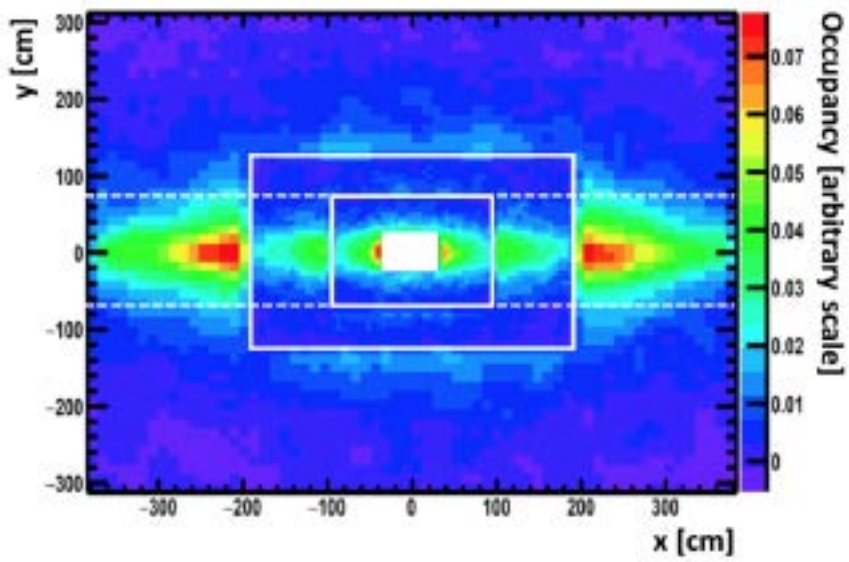
e.g. $D^{*+} \rightarrow D\ \pi_s^+$, 40% extra slow pions



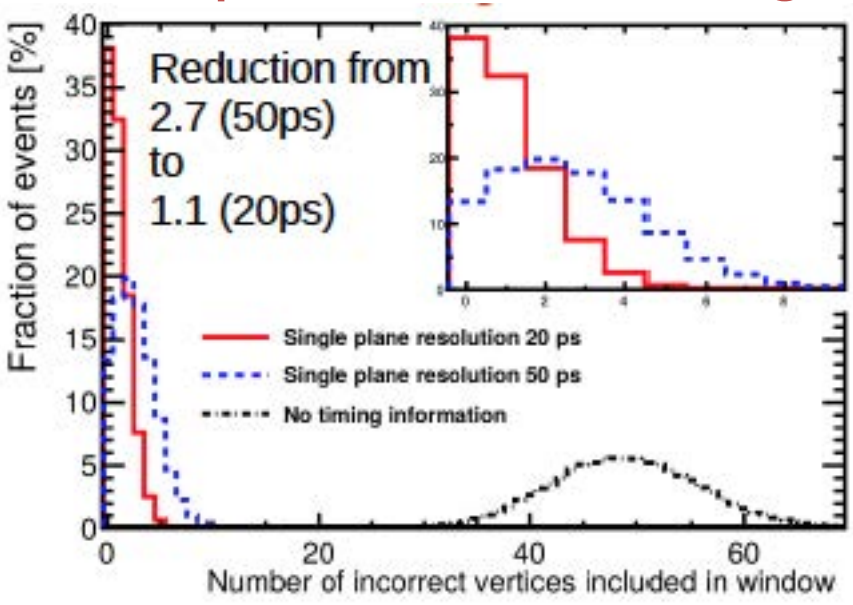


Upgrade 1(b) e.g. – E'magnetic Calorimeter

- 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



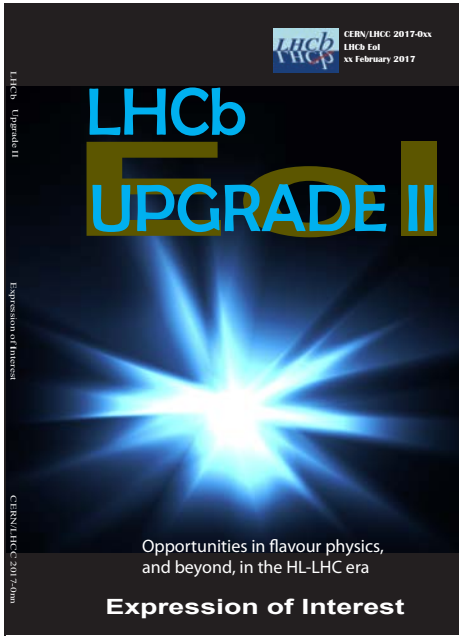
HL-LHC Flavour Physics: Upgrade II

"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

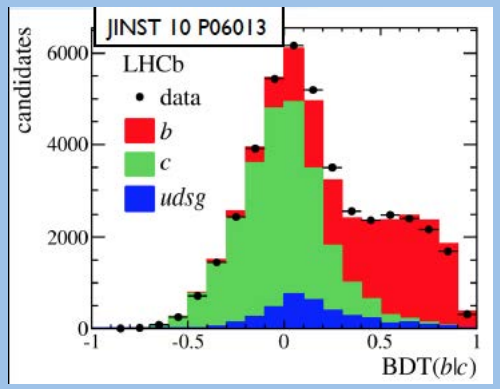
Physics Case - ask the analysts….

Phase-2 upgrade: benchmarking topics

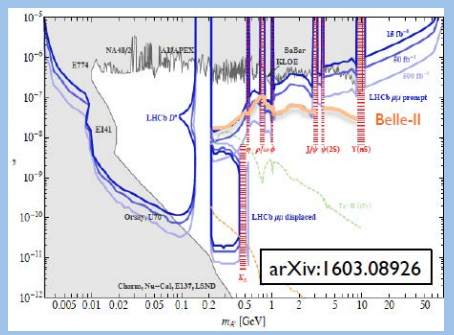
- CP
- CP
- CP
- De
- Se
- El
- Rare and radiative decays
- Lepton universality tests

Everything we currently do and a few more for good measure!

Qualitatively new Era: Challenge theory precision with measurements



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



Dark photon
A'→μμ

best sensitivity

Rare (and very rare) Decays

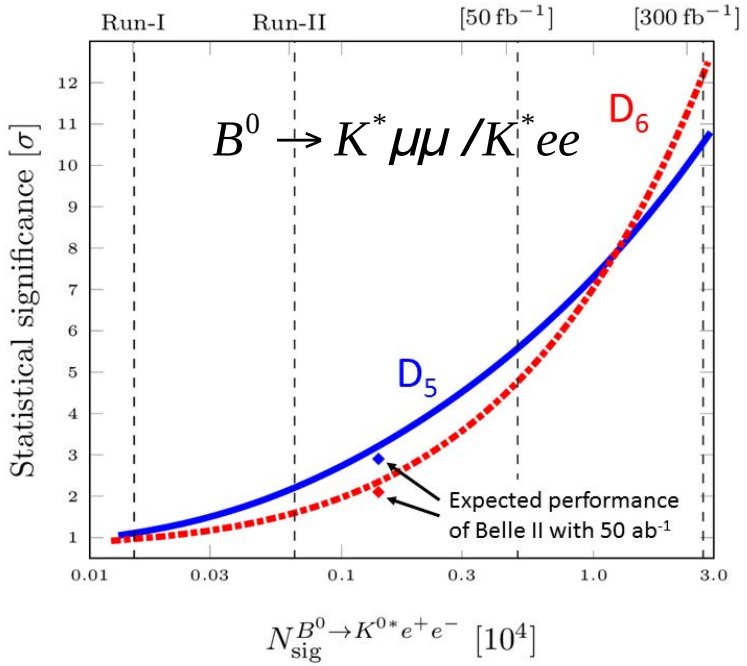
Complementarity of Observables for New Physics Discovery

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

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

LFU Prospects: distinguish New Physics scenarios

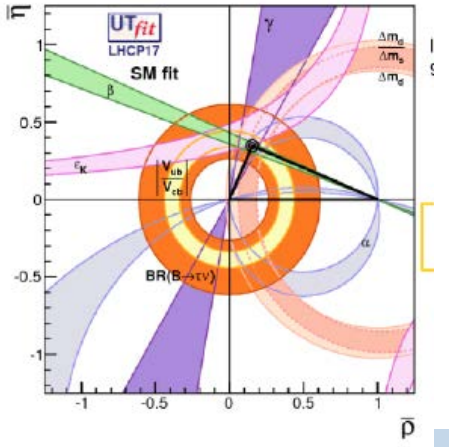
Also exciting prospects in:
$B_s \to \mu\mu$ lifetime to 2%
$B \to ee$, $B \to \tau\tau$….
rare charm, rare kaon…

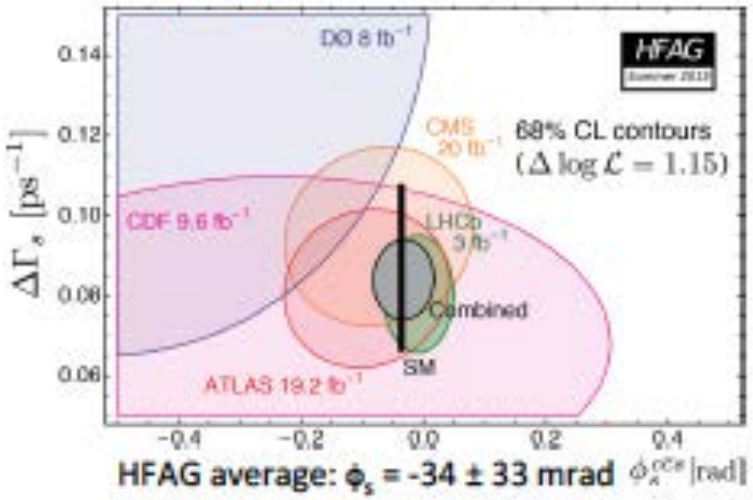


CPV Examples

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

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





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

Upgrade II Physics

- 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

- 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

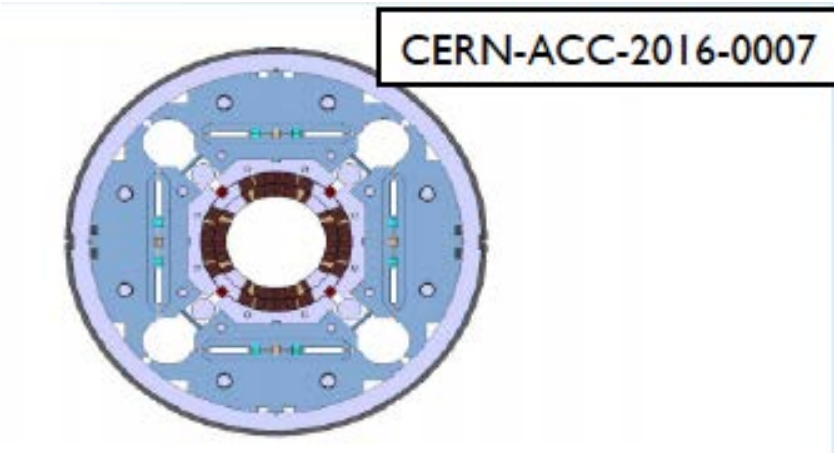
Accelerator: Can LHCb Phase II run ?

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



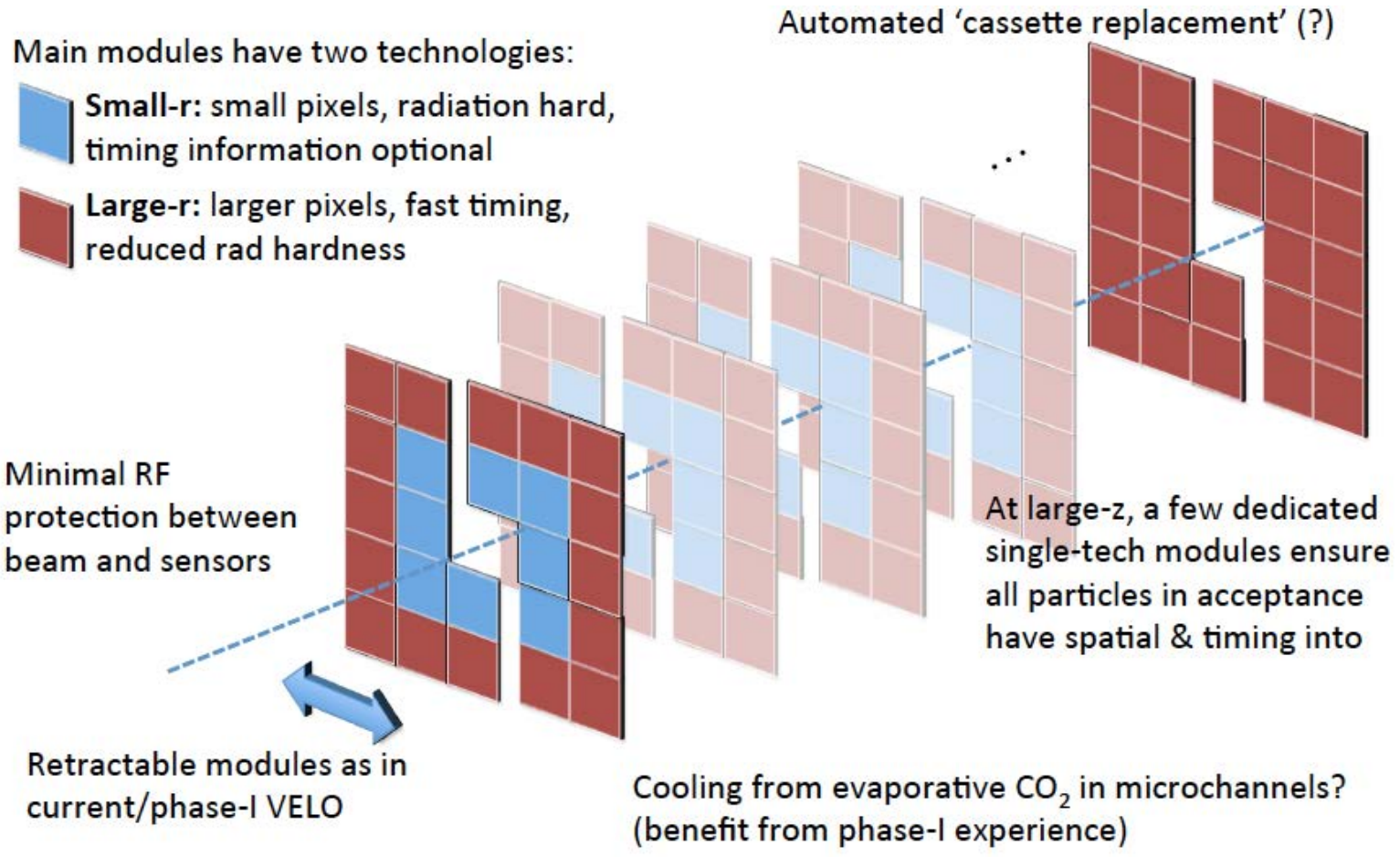
- LHCb IP not designed for HL-LHC experiment
- Inner Triplet quadropole need to be replaced at ~**300 fb^{-1}**
  - Probably prohibitively expensive
- LHC side impressive studies on
- additional requirements
  - **No showstoppers !**

VELO

Challenge A: 10x particle multiplicity — Small Pixels

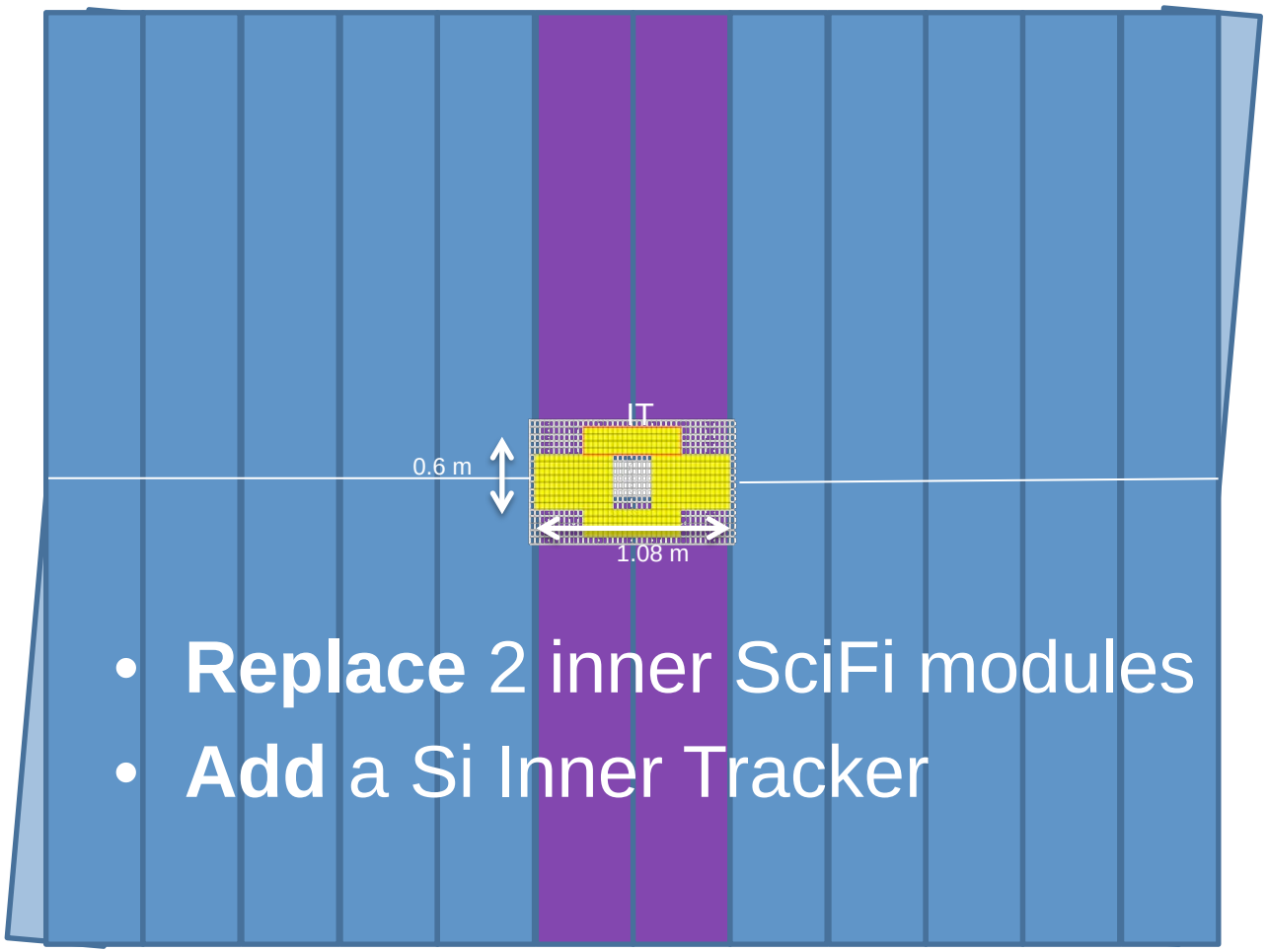
Challenge B: 10x vertex multiplicity — Timing

Challenge C: 10x radiation damage — Replacement



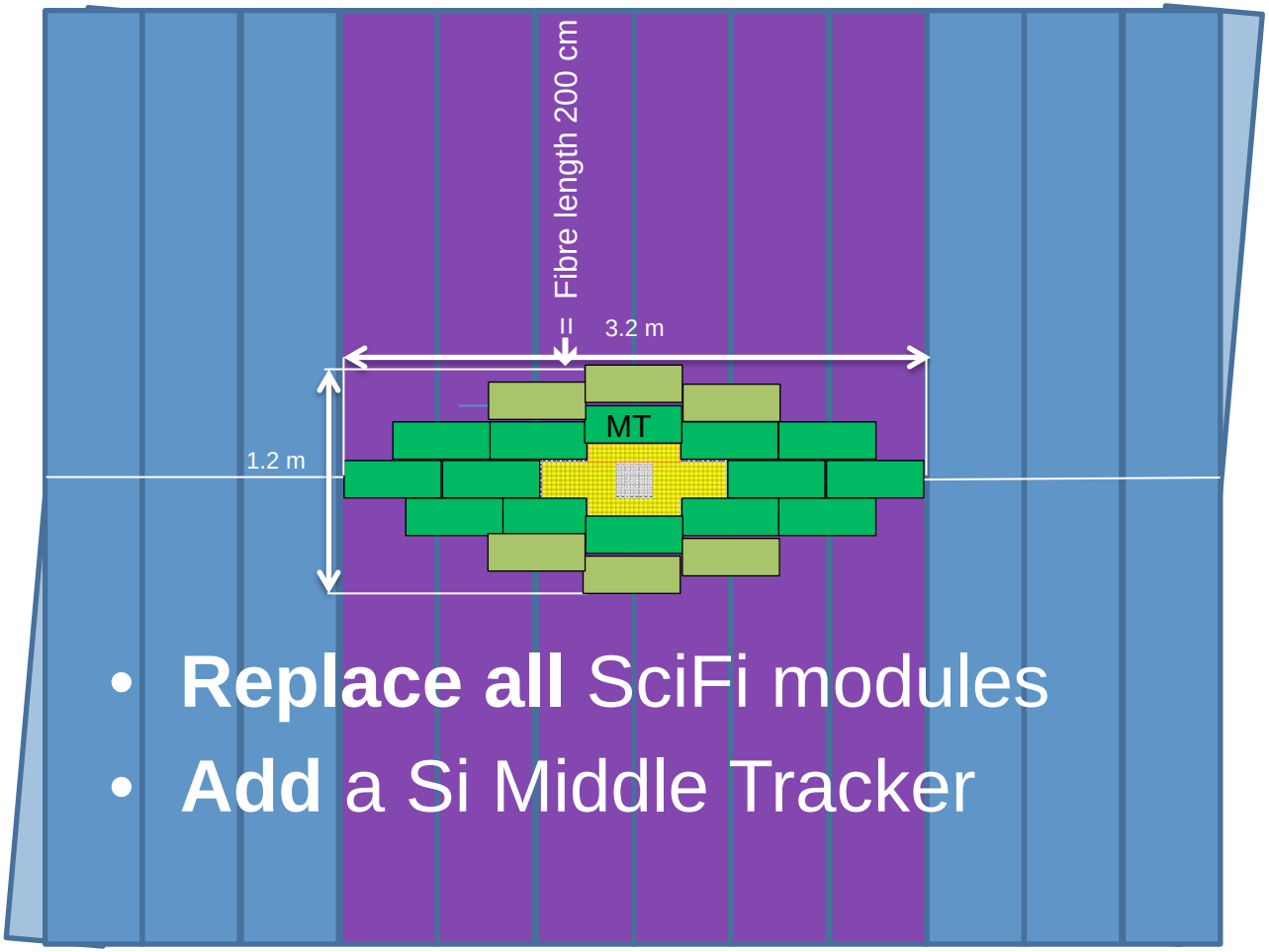
Phase 1b Tracker

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



Phase II Tracker

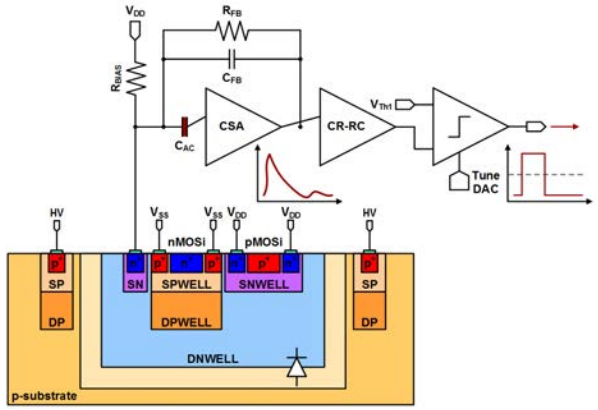
- Expand MT relative to EOI to assist Sci-Fi -*O*(20m^2)



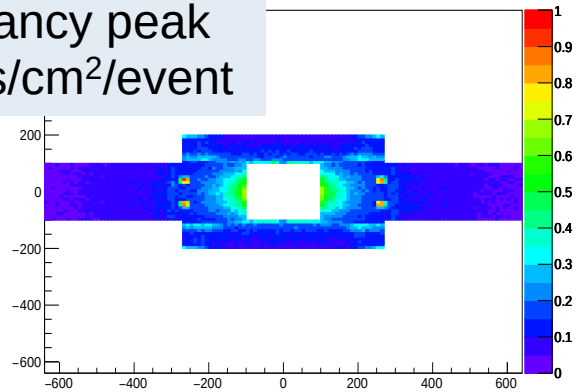
- SciFi for large area tracking

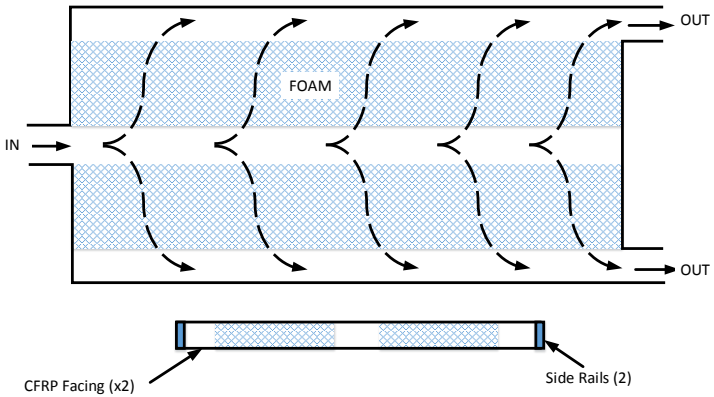
Inner Tracker – HVCMOS

- 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

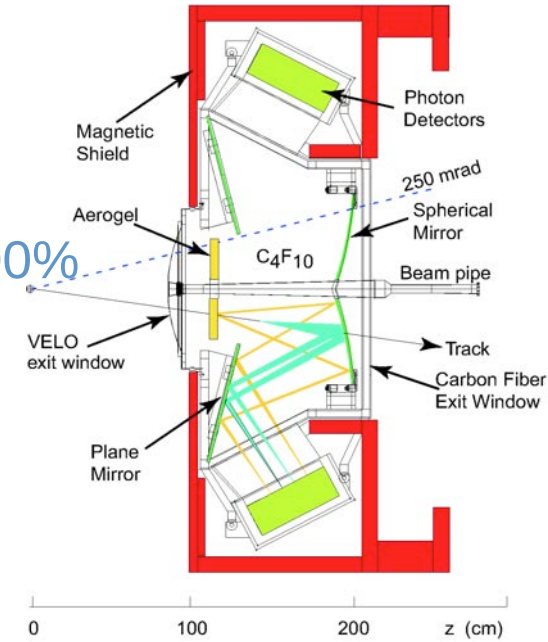
- Time resolution
  - Disentangle busy events

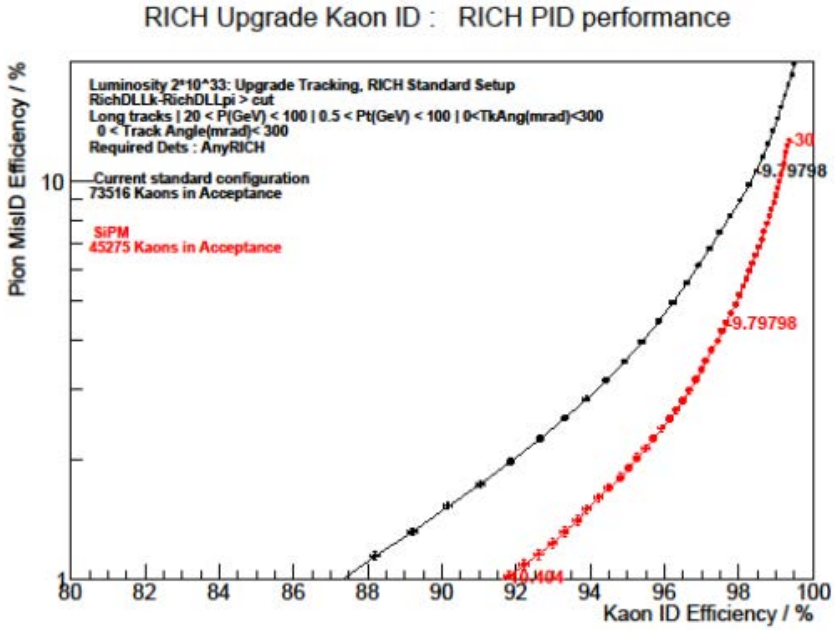
- Use B-field insensitive photodetectors
  - SiPM or MCP

- Concepts for improving
- Optical and chromatic uncertainty

- Equip central region

For **Upgrade 1(b)** ?



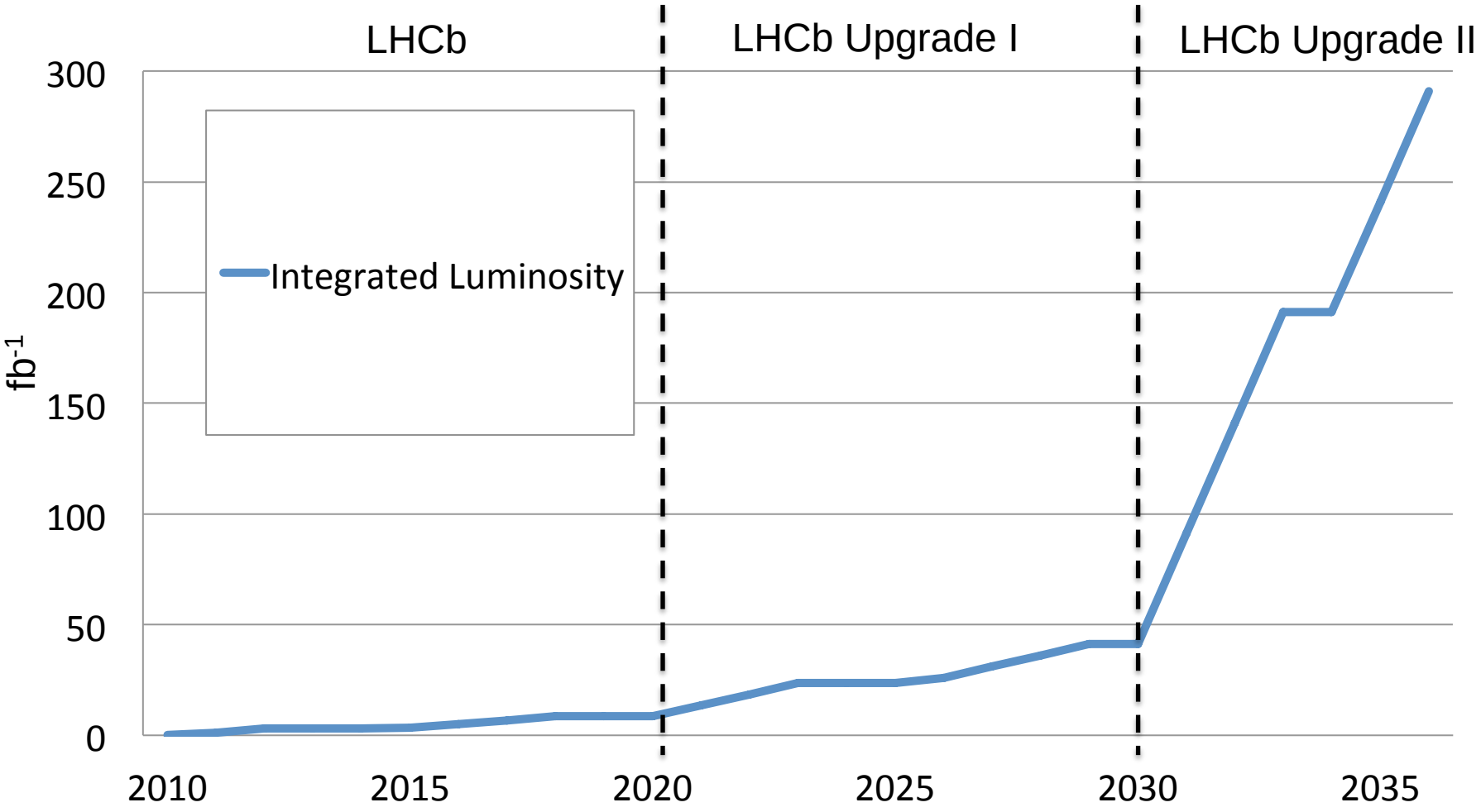


Technical Associates

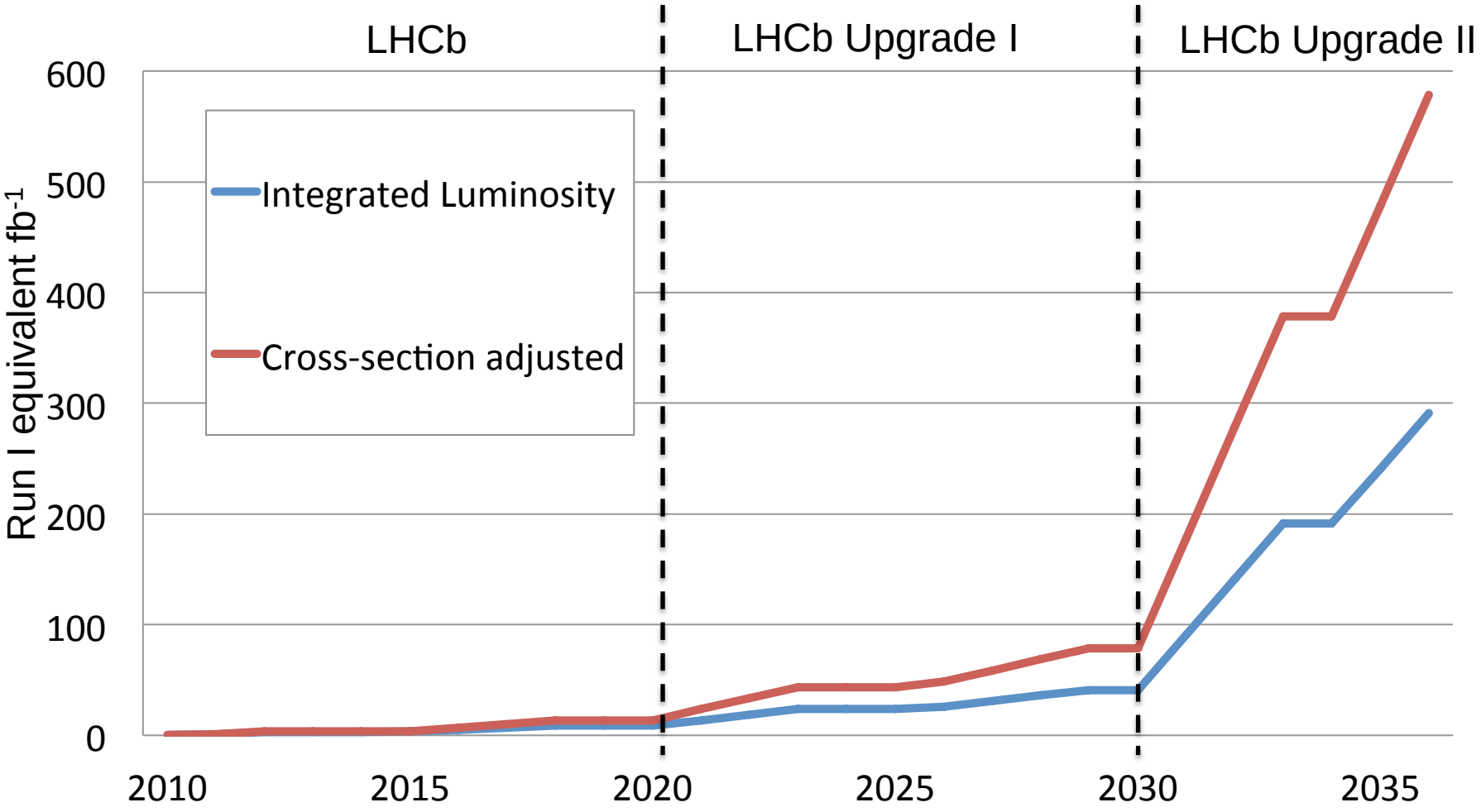
- Option for new groups to join to work on R&D
  - Join the detector R&D effort
  - Do not work on physics or sign papers
  - Approved at Collaboration Board September 2017

- 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

LHCb Statistics- Timeline

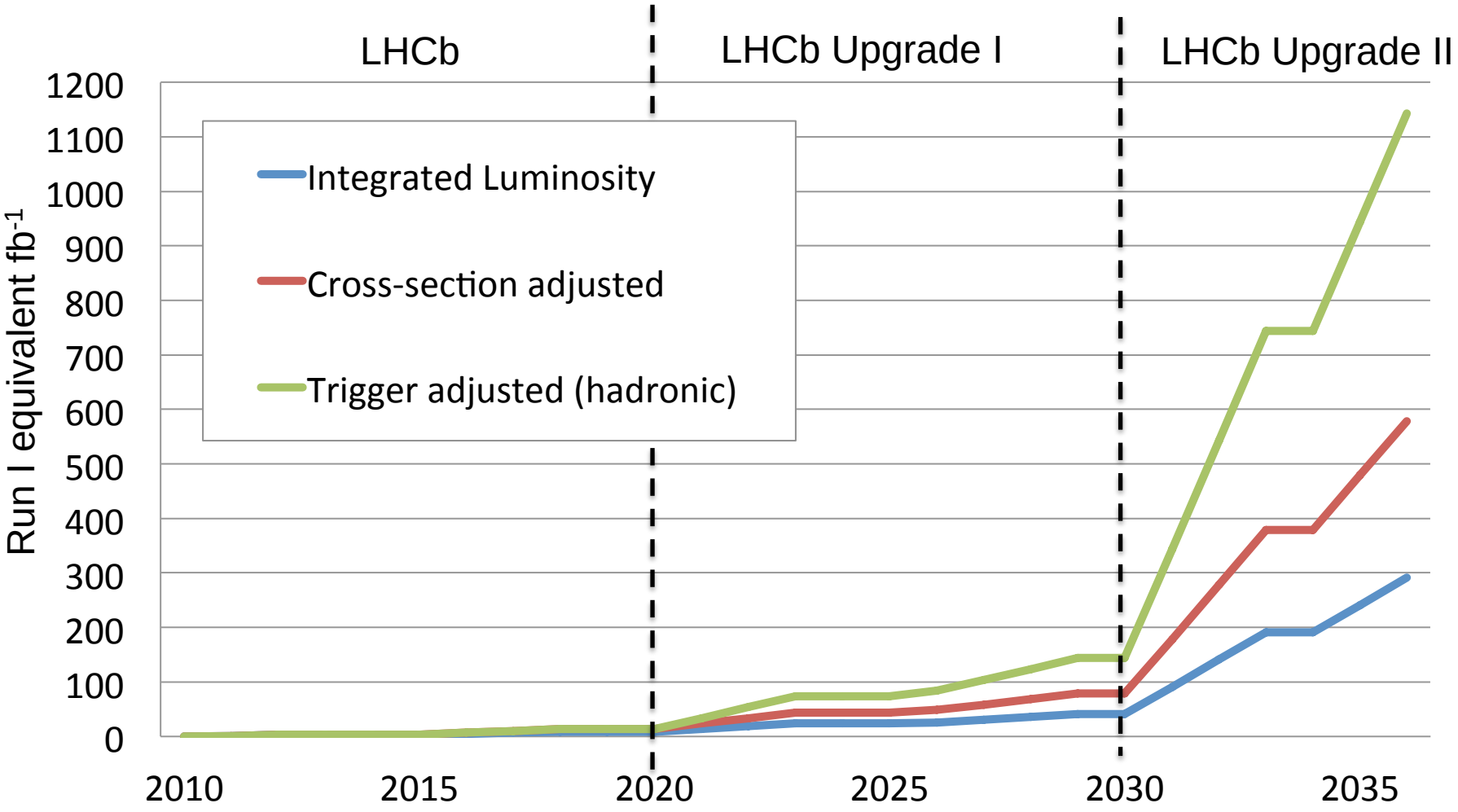


LHCb Statistics- Timeline



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

LHCb Statistics- Timeline



- Assumptions made on relative trigger efficiencies have significant uncertainty

3rd LHCb Workshop on Upgrade 1b/II

- 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

Summary – Flavour Post 2025

- Rare Kaon: Koto & K_LEVER, *O*(100) events $K_L \to \pi^0 \nu\bar{\nu}$
- Super c-τ factory: BINP Novosibirsk proposal
- ATLAS/CMS: continuation of programmes

- LHCb:
  - 2025: Upgrade 1b: consolidate & enhance
  - 2030: Upgrade II
  - Physics – leaps in performance in key channels
  - Detector – timing information may be key
  - *O*(10) * luminosity: LHC can provide

Opportunities for existing & new German groups in Upgrade II

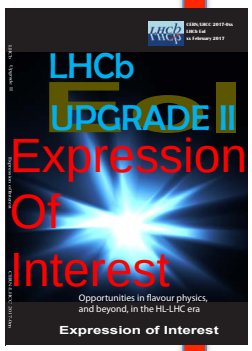
Backup

LHCb Upgrade II Timeline

Year 0 2 4 6 8 Run 4 10 12 14 Run 5

1 3 5 7 9 11 13

2017 2018 2020 2023 2026 2031



Physics Case

Upgrade II Technical Design Report

Upgrade 1b PID Technical Design Report

Upgrade 1b Tracking Technical Design Report

? ? ? ?

Upgrade II Detector TDRs

In addition:

HL-LHC Studies

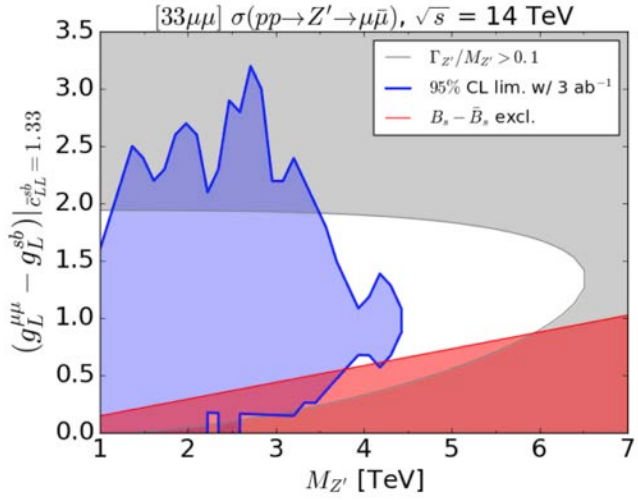
European Strategy Meeting

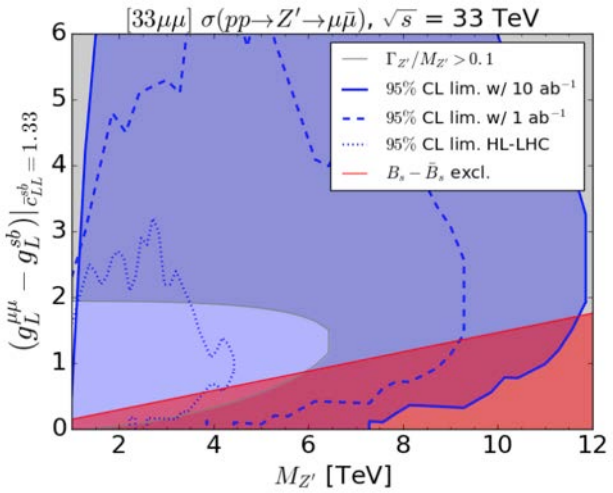
HE-LHC / FCC & Flavour

- No serious discussion on Flavour Physics Potential yet
  - Will be (peripherally) adressed in context of CERN HL-LHC/HE-LHC workshop series
- Some gain in cross-section from higher energy
- Physics becomes more forward

[arxiv:1710.06363]

- **Case for future hadron colliders from b→sμμ anomalies**
  - Complete coverage of Z' models at 100 TeV
    - Significant reach at 33 TeV
  - Contrived LQ models can survive at 100 TeV





Summary - Take Home Message

- 2021: LHCb Upgrade I construction on track

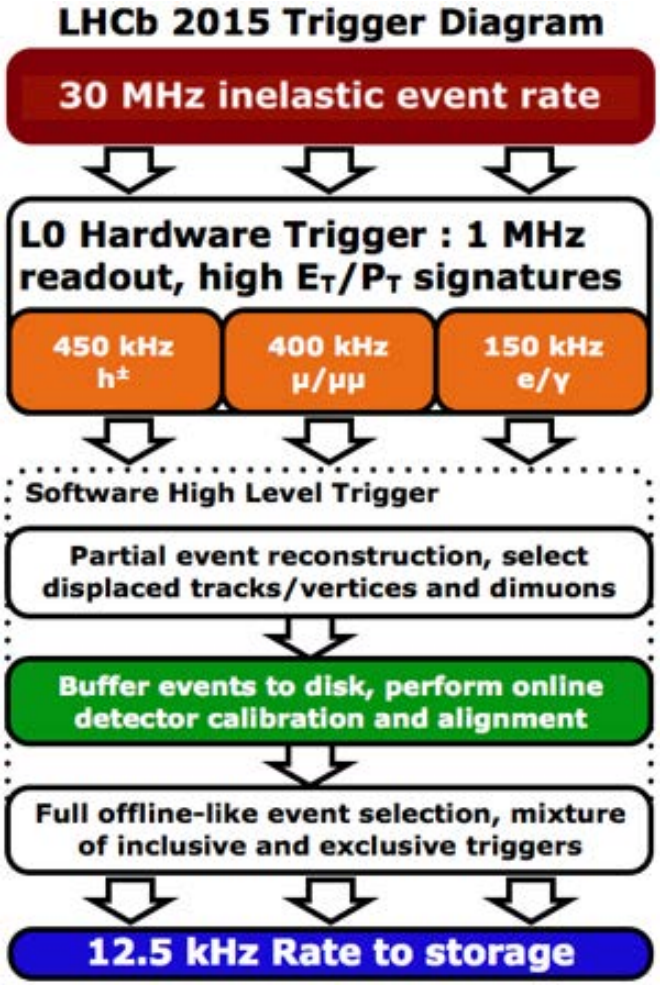
- 2025: Phase I(b) Upgrade: consolidate & enhance
  - Same luminosity as upgrade phase 1(a)

- 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

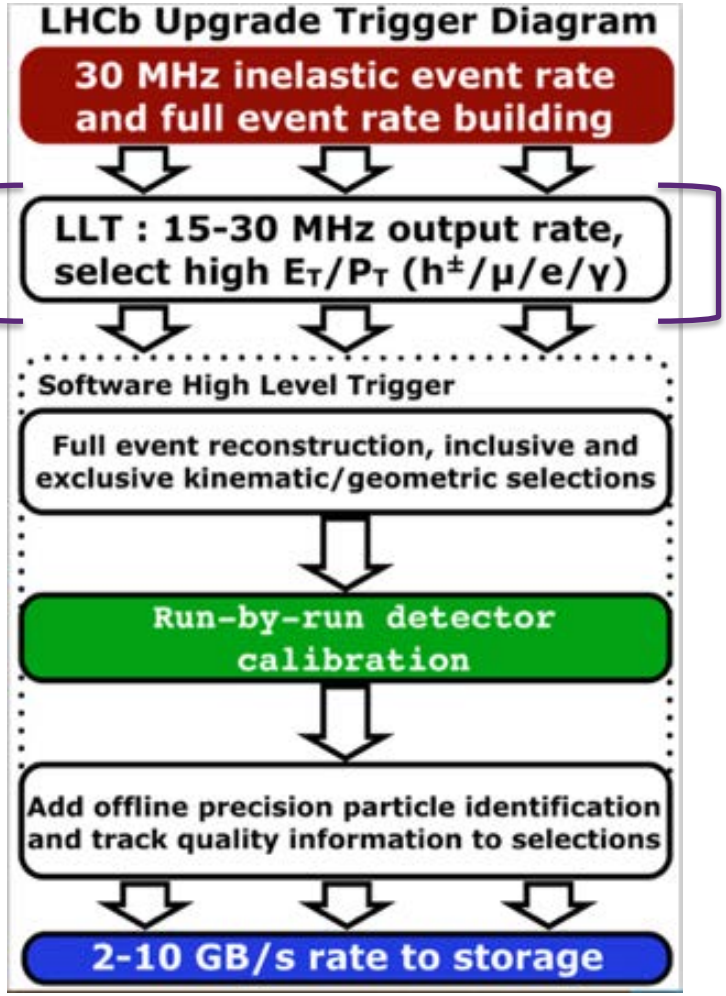
German groups crucial to achieving Phase II Upgrade objectives

Trigger Evolution – Upgrade I

Run II



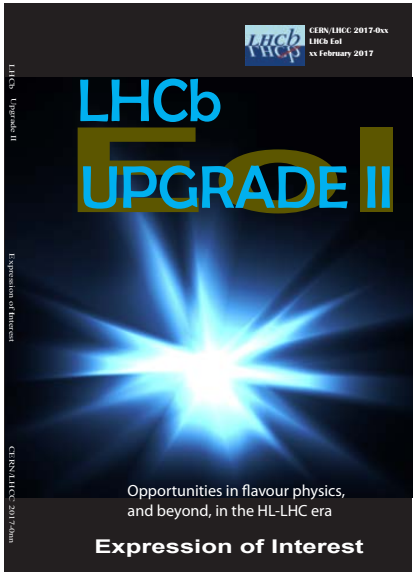
Upgrade I



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.



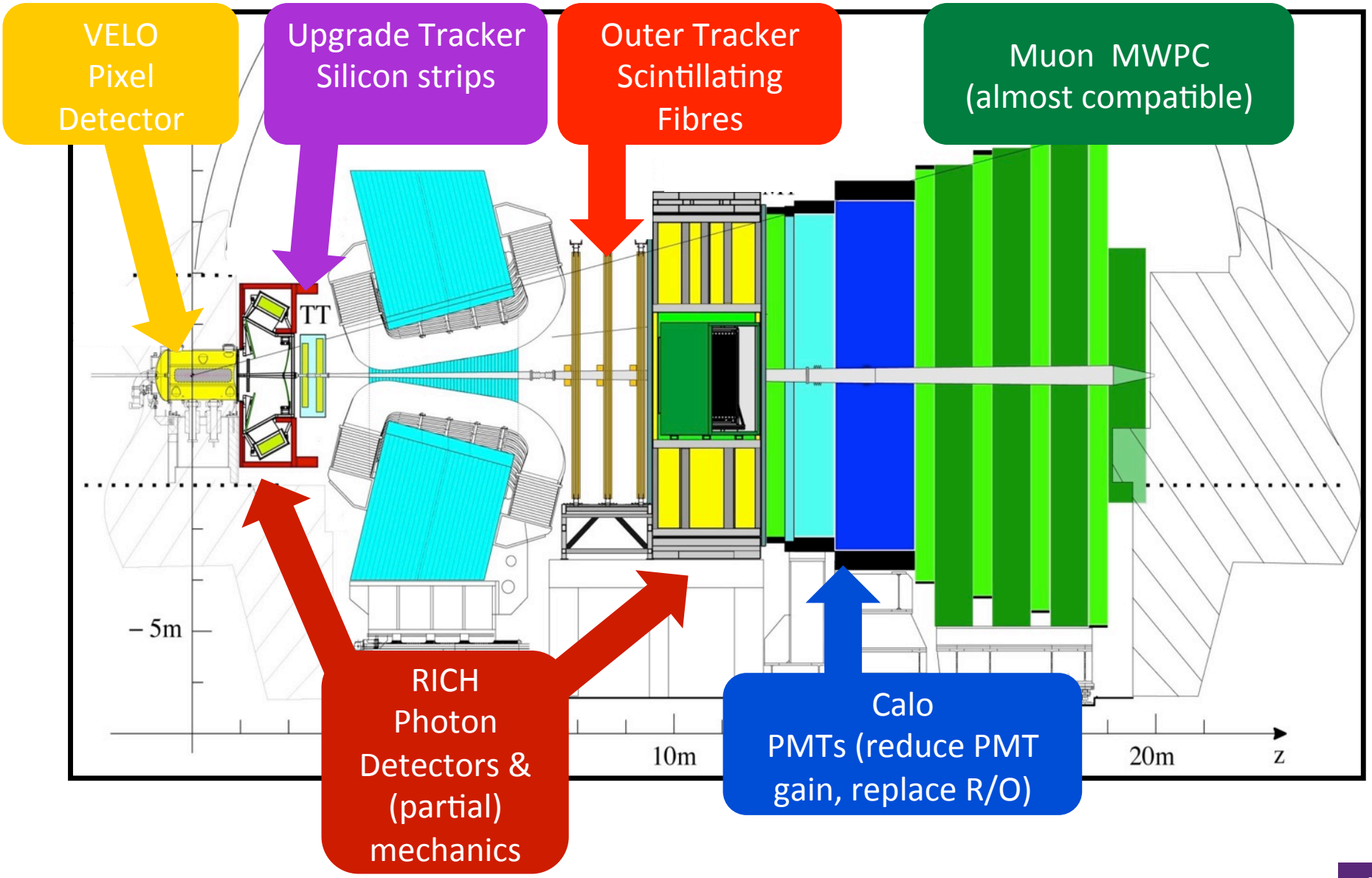
Interpret as:

- Physics case document required
- Increase interaction with

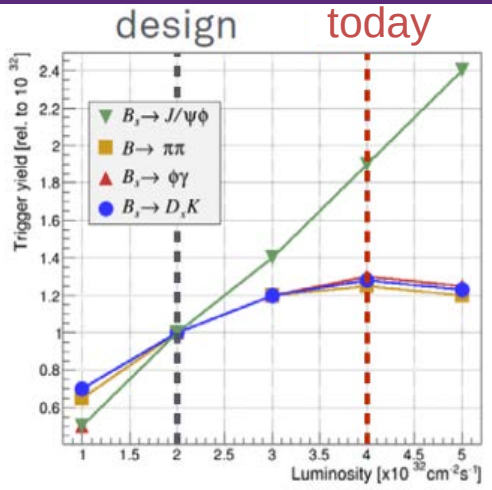
LHC accelerator experts

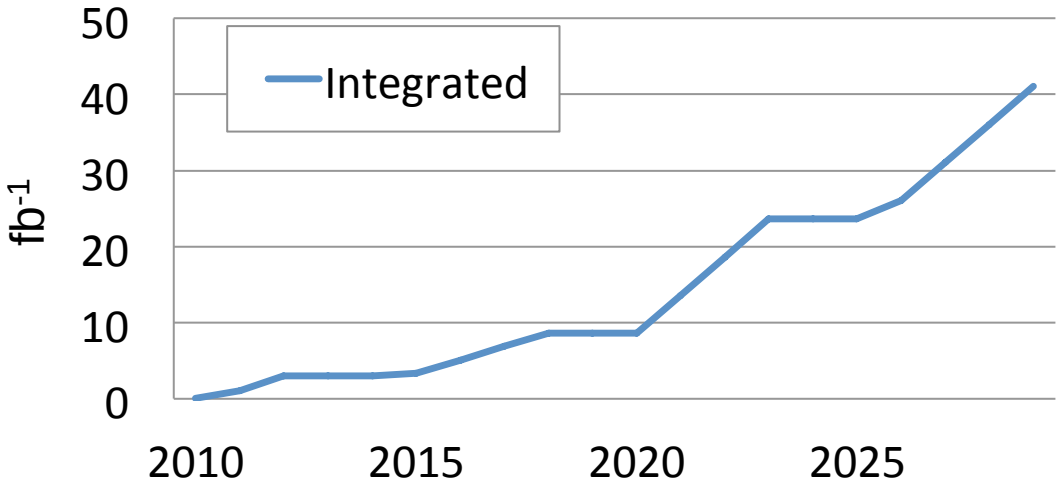
Presented timescale on next slides to LHCC referees last month

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

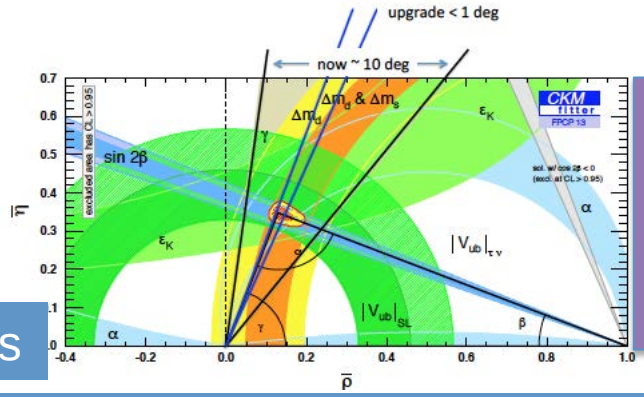
New Physics in Rare Decays

New Physics in CP Violation

New Physics in Charm

Electroweak & QCD Physics

Long Lived Stable Particle Searches, Dark Photon Searches

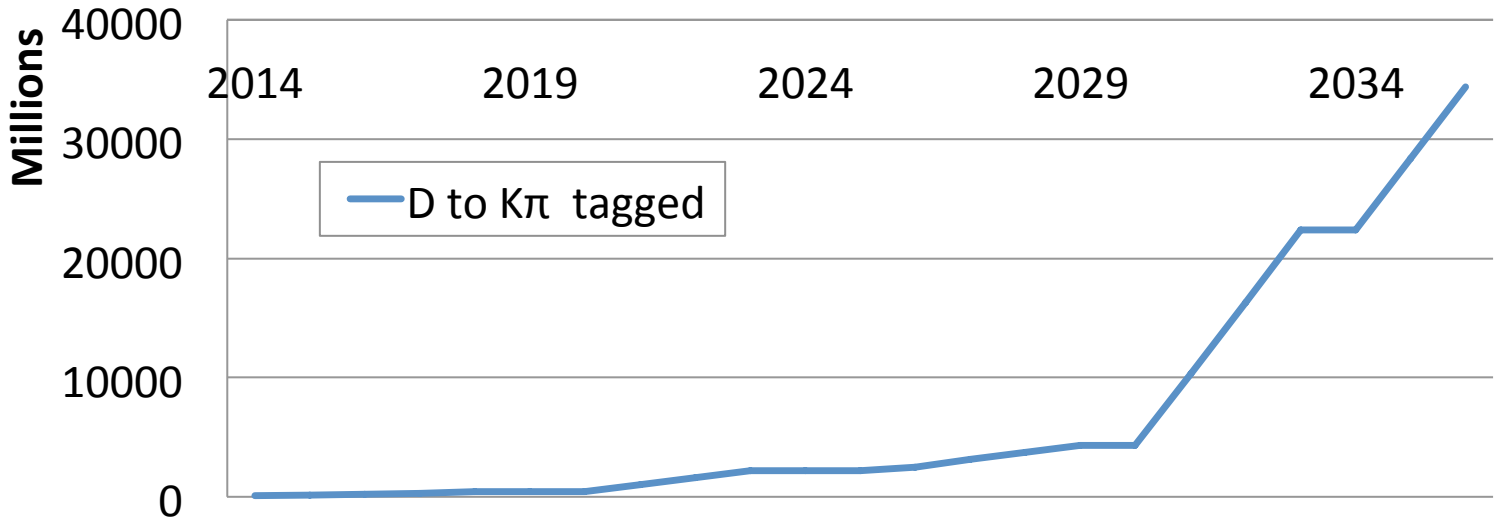


Probe **100 TeV** for tree-level couplings

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

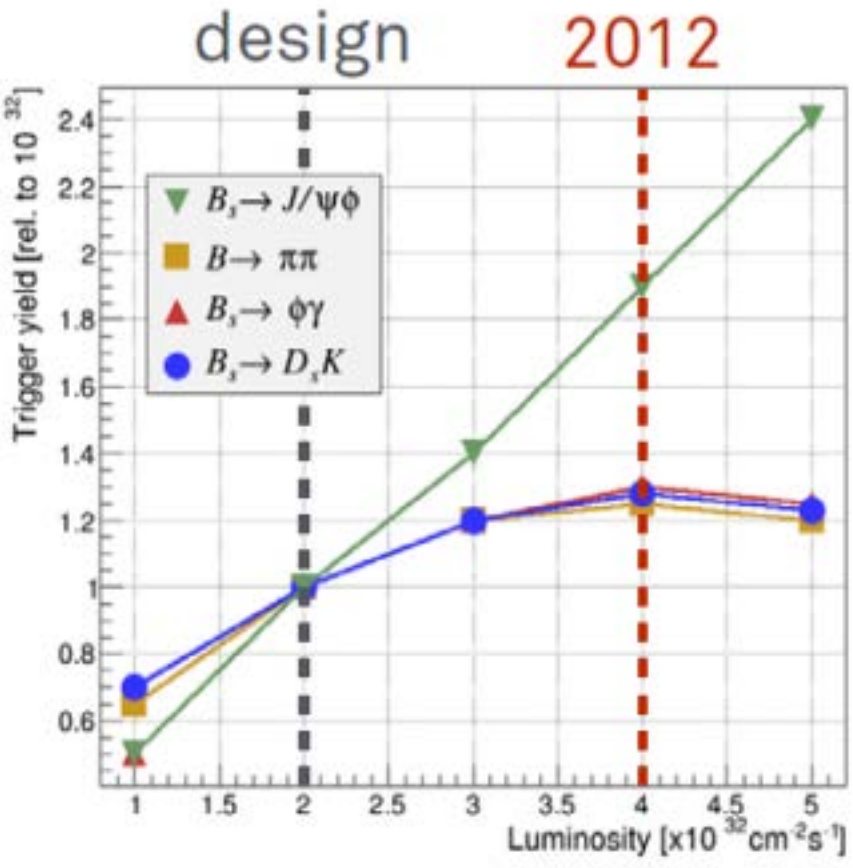


- ~30MHz of charm events produced in acceptance!

Observe SM level CPV at LHCb Upgrade II

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 $2x10^{33}$ cm^{-2} s^{-1}



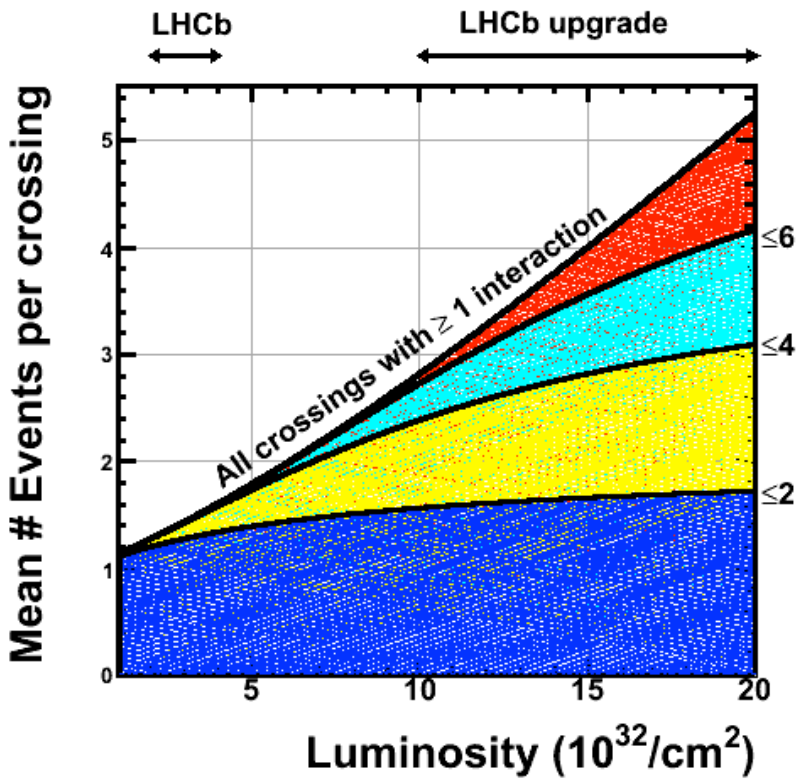
Current First Trigger Level:
Hardware Muon/ECAL/HCAL
1.1 MHz readout

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



Upgrade 1(b) 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 I
  - Removal of hardware trigger brings factor 2 efficiency boost for non-muon triggered events
  - 5fb^{-1} per year
- Upgrade 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

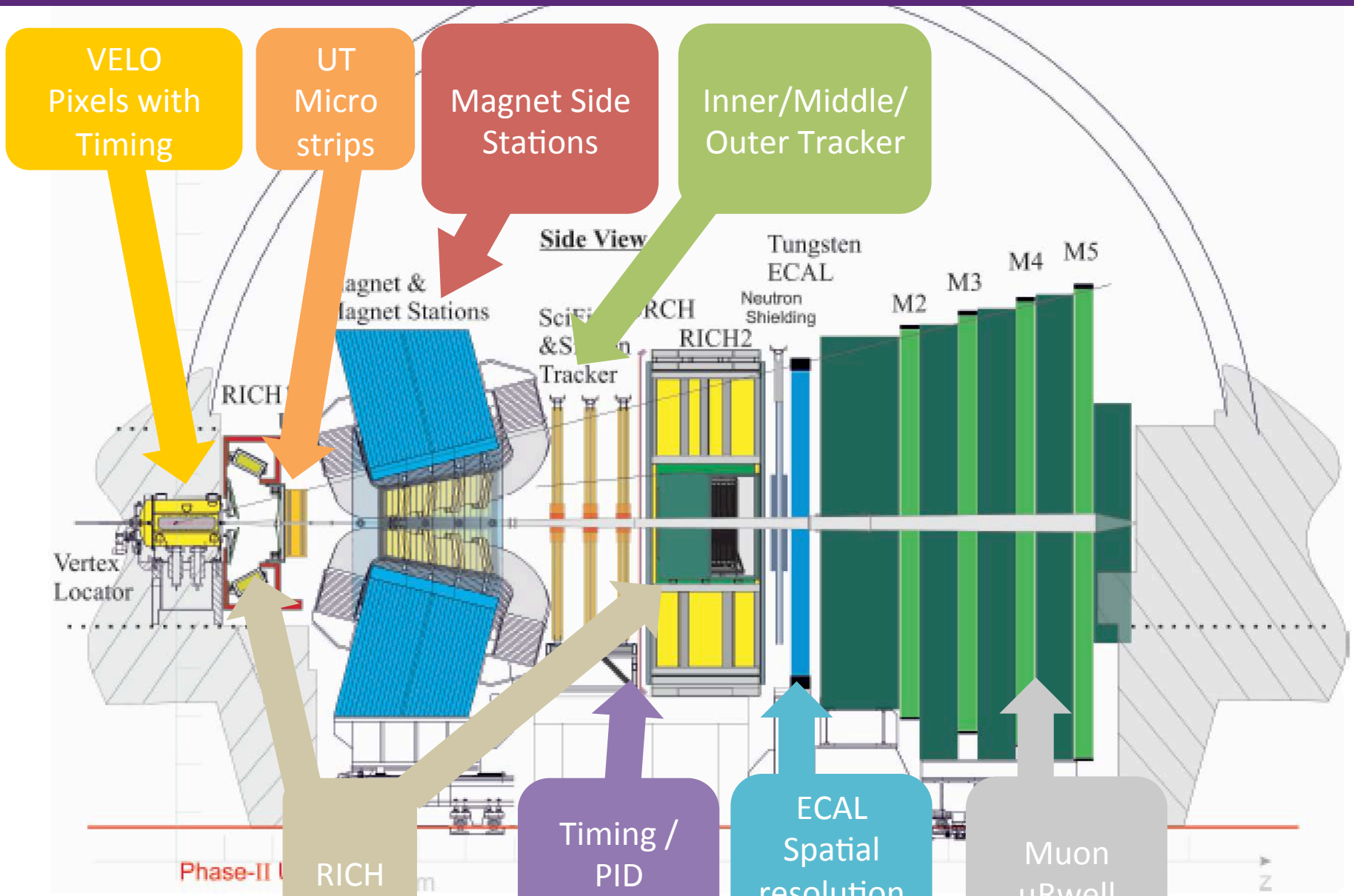
LS3: "Consolidation", Upgrade 1b Installation

- 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

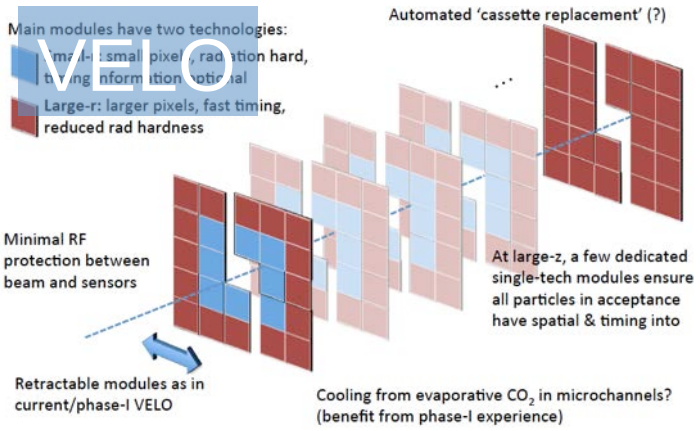
- Run 5/6 (2031-)
  - LHCb Upgrade II Total Int L ~ 300fb^{-1}
  - L=1-2x10^{34} cm^{-2} s^{-1}, ~50 fb^{-1}/yr

Upgrade II Detector

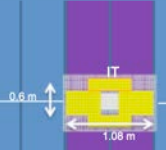


Detector Concepts

VELO

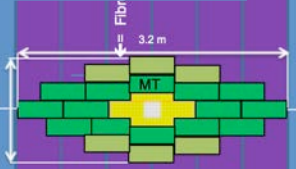


Tracker 1b



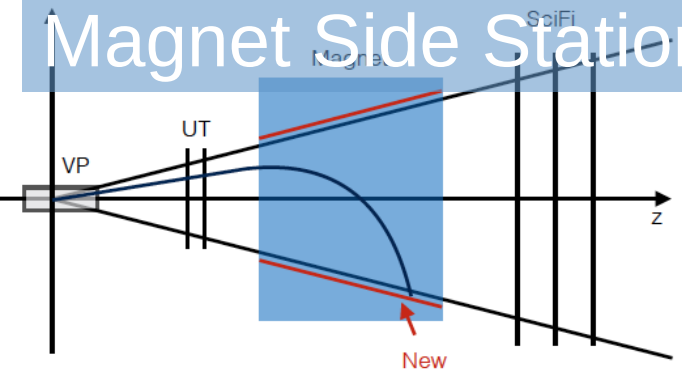
- **Replace** 2 inner SciFi modules
- **Add** a Si Inner Tracker

Tracker II

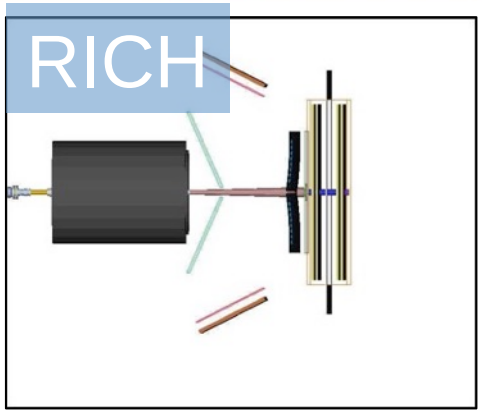


- **Replace all** SciFi modules
- **Add** a Si Middle Tracker

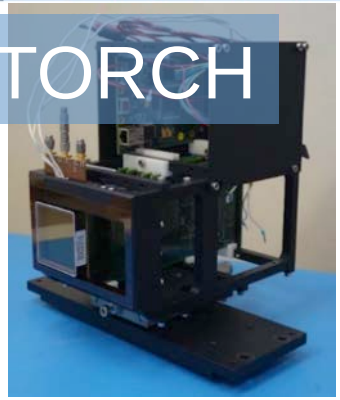
Magnet Side Stations



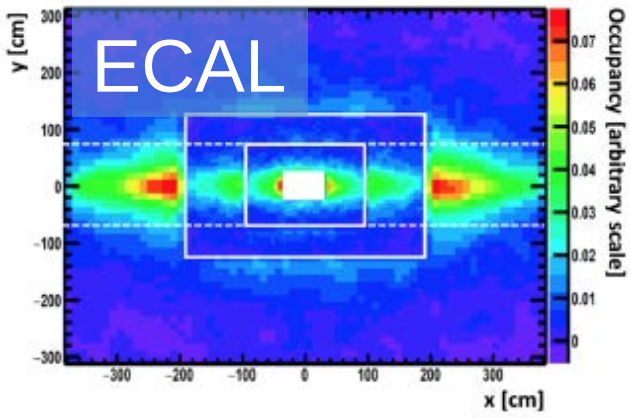
RICH



TORCH

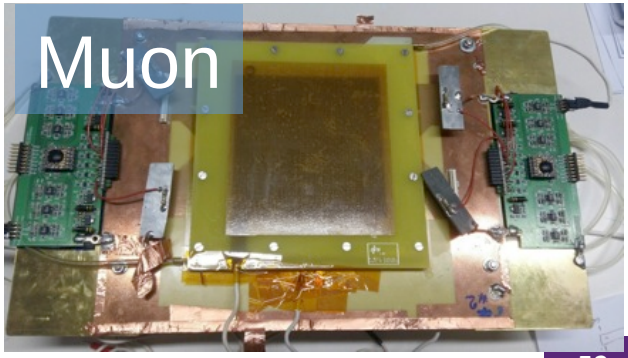


ECAL

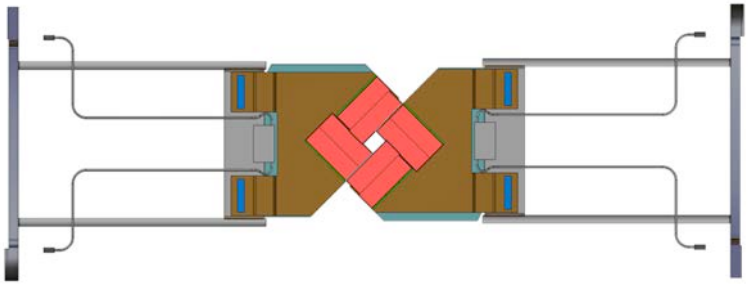


FPGA Tracking

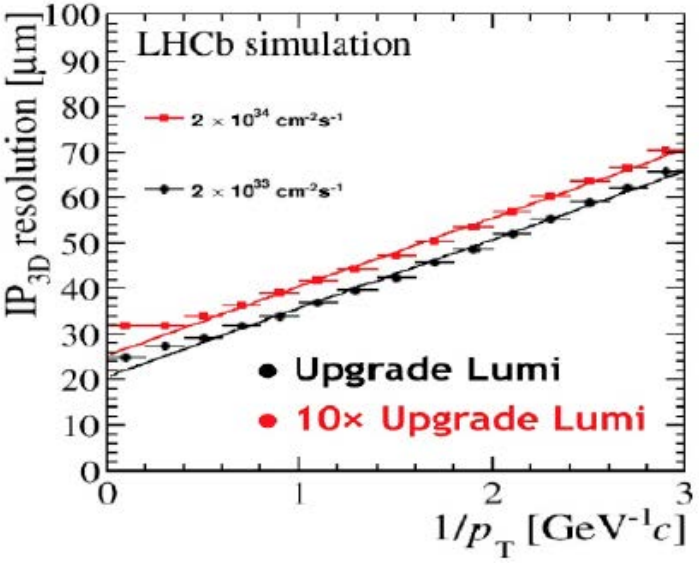
Muon

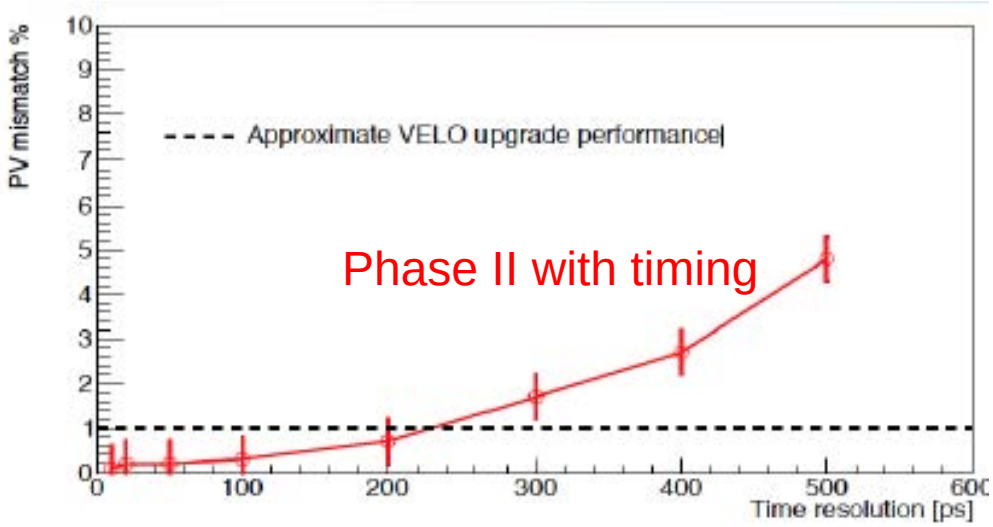


Vertex Detector: VELO



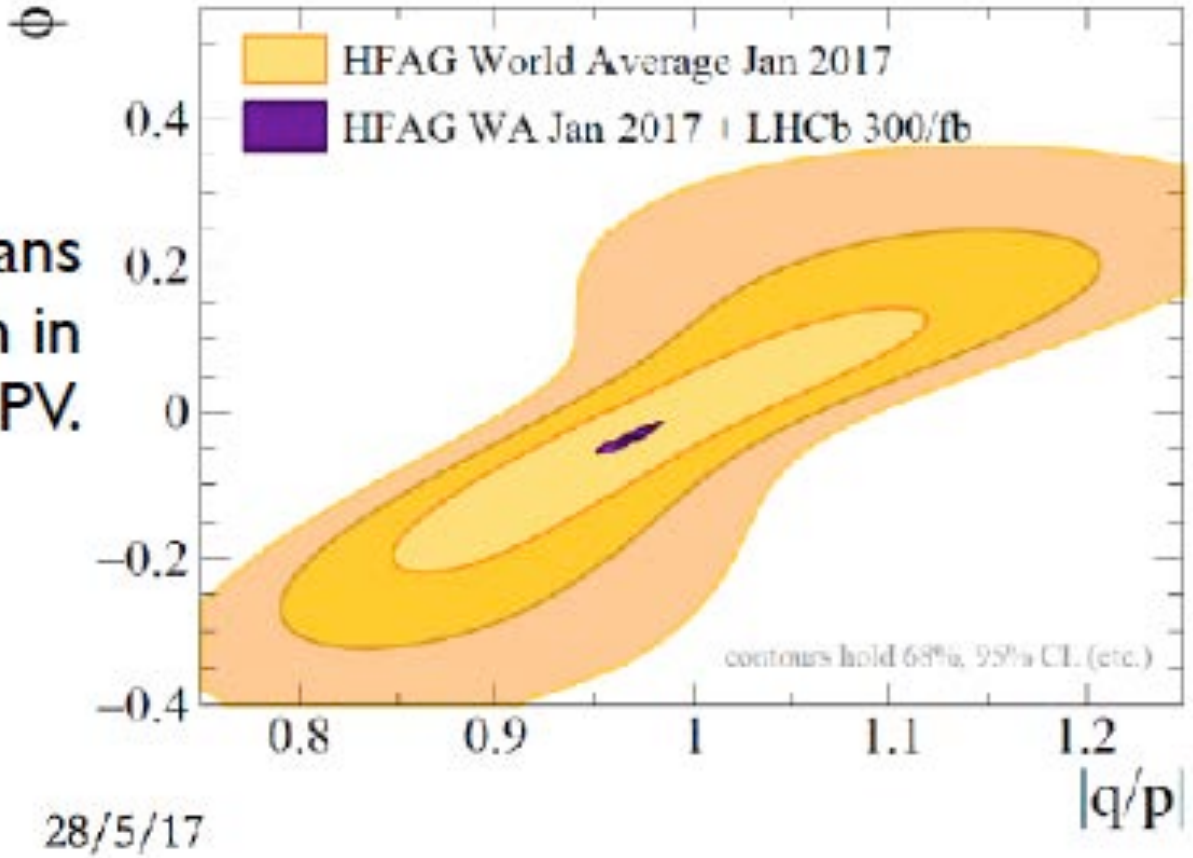
- Radiation Damage
  - Dose at 10^{17} 1 MeV n_{eq} / cm^2 level for full lifetime
  - Replace / increase inner radius
- Pile-up
  - Mismatch b/c decays to wrong PV
  - 4D: Timing at 200ps level required





Charm

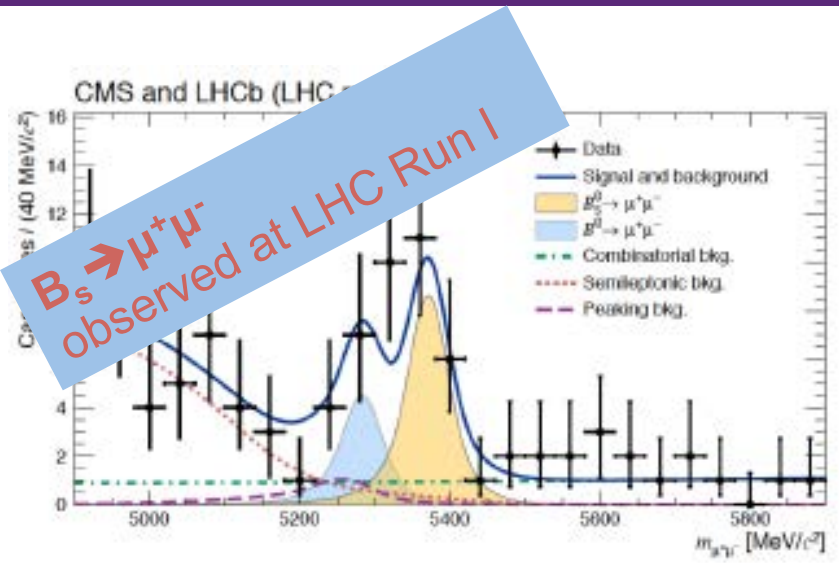
300/fb means tremendous reach in the clean indirect CPV.



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



$B_s \rightarrow \mu^+\mu^-$ observed at LHC Run I

Next Target:

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

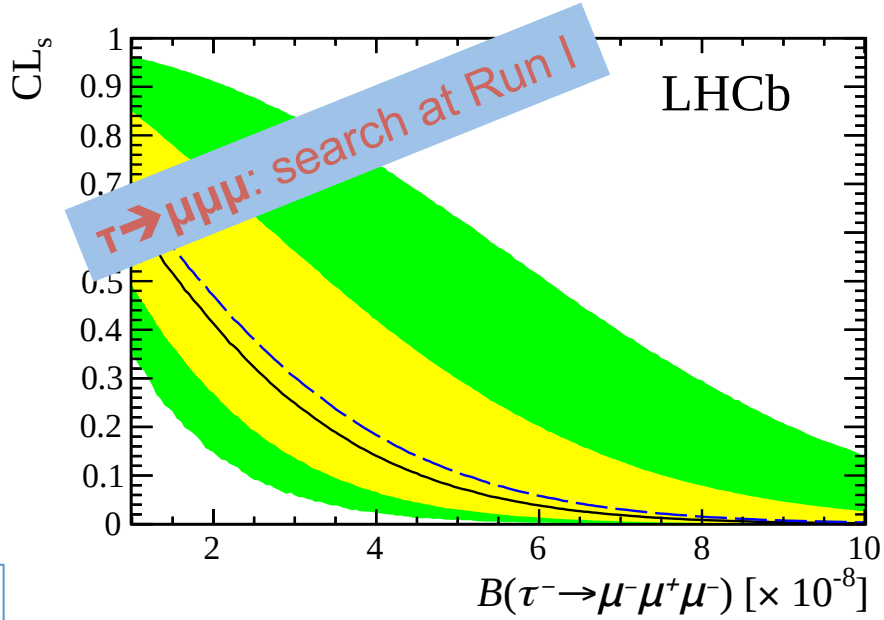
$\sigma(R)/R$ < 10% for Phase II

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 ?

- **$\tau \rightarrow \mu\mu\mu$: a classic e+e- B-factory mode**

- Phase II LHCb precision comparable with Belle II ~ $O(10^{-9})$



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