The LHCb Upgrade

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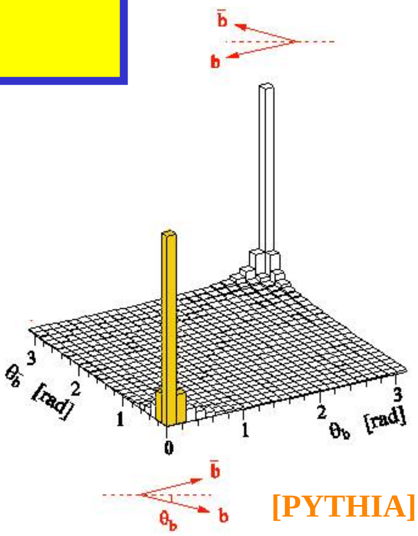
Outline

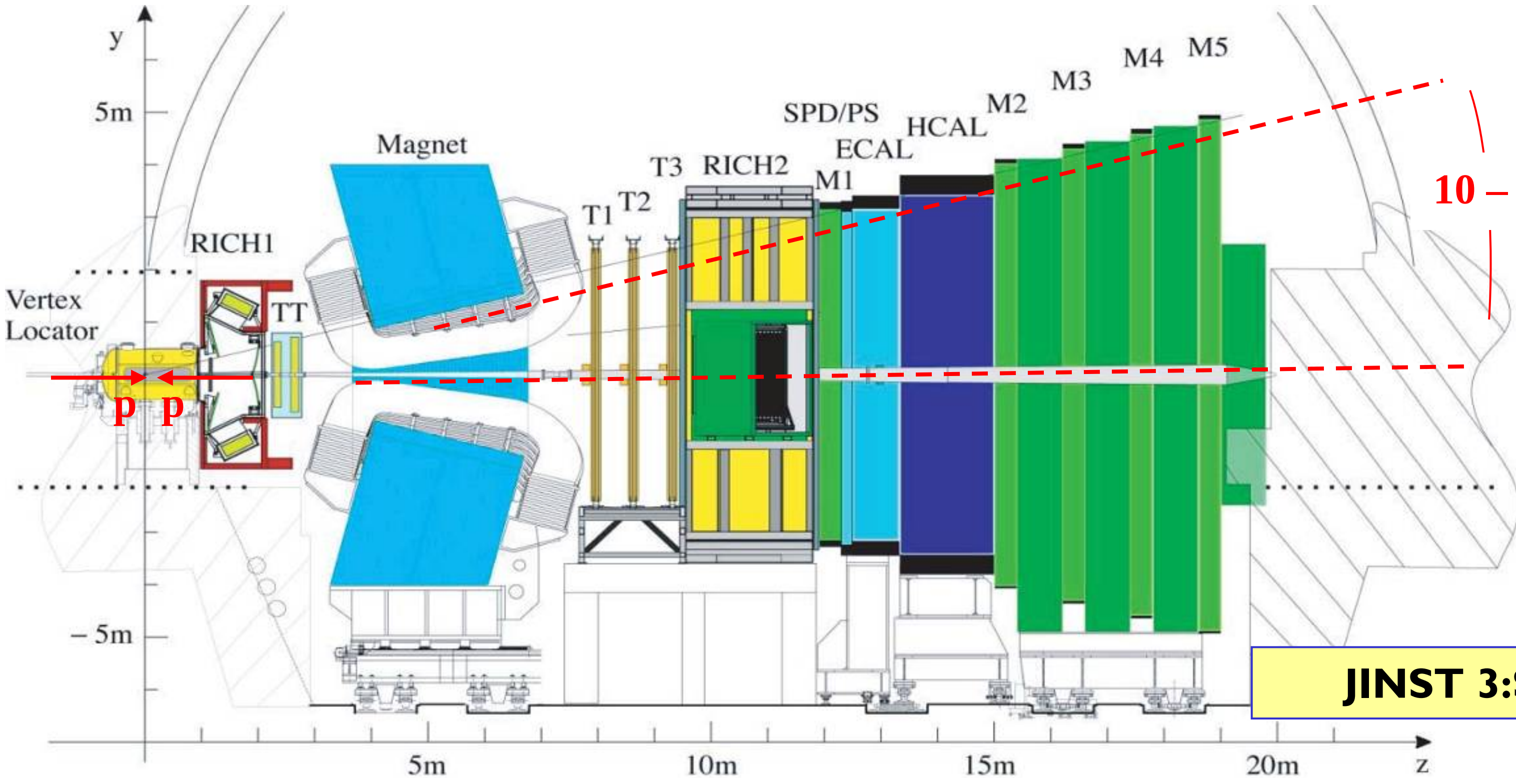
- Why upgrade LHCb?
- The physics case
- The LHCb detector upgrade
    - Trigger & DAQ
    - The detector components
- Summary

Reminder of LHCb

- Forward-peaked production → LHCb is a forward spectrometer (operating in LHC collider mode)
- $b\bar{b}$ cross-section = 284 ± 53 μb at $\sqrt{s}$ = 7 TeV and around a factor 2 greater at 14 TeV [PLB 694 209]

→ ~ 10^{12} $b\bar{b}$ pairs produced per LHC year

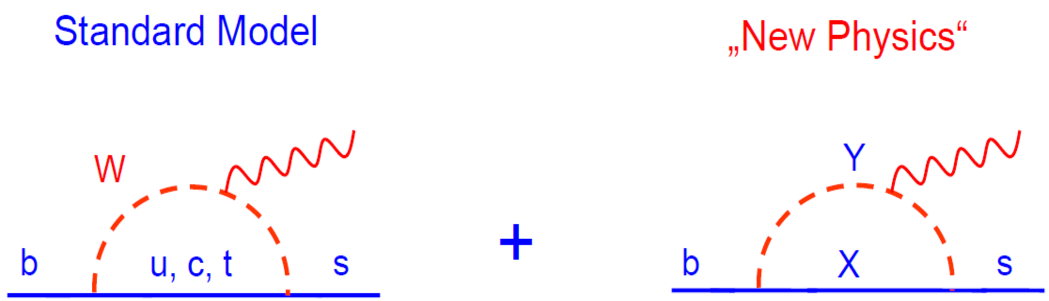




JINST 3:S08005 (2008)

Why upgrade ?

- Any New Physics model with new heavy particles or flavour breaking interactions must "hide" behind the SM interactions



$$\mathcal{A}_{SM} \quad + \quad \mathcal{A}_{NP}$$

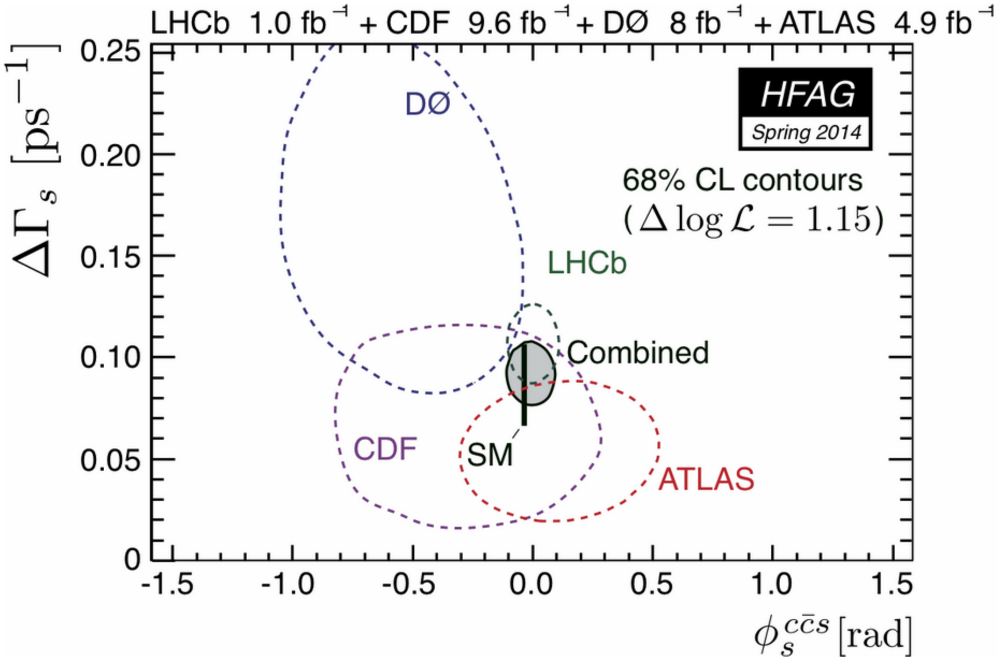
$$\mathcal{A}_{BSM} = \mathcal{A}_0 \left(\frac{c_{SM}}{m_W^2} + \boxed{\frac{c_{NP}}{\Lambda^2}} \right)$$

Probes physics at >>TeV-scale

- We know by now NP contributions are small.
- We have clean Standard Model predictions
- We have precise measurements (high statistics, incl. control channels)

Standard Model withstands challenges

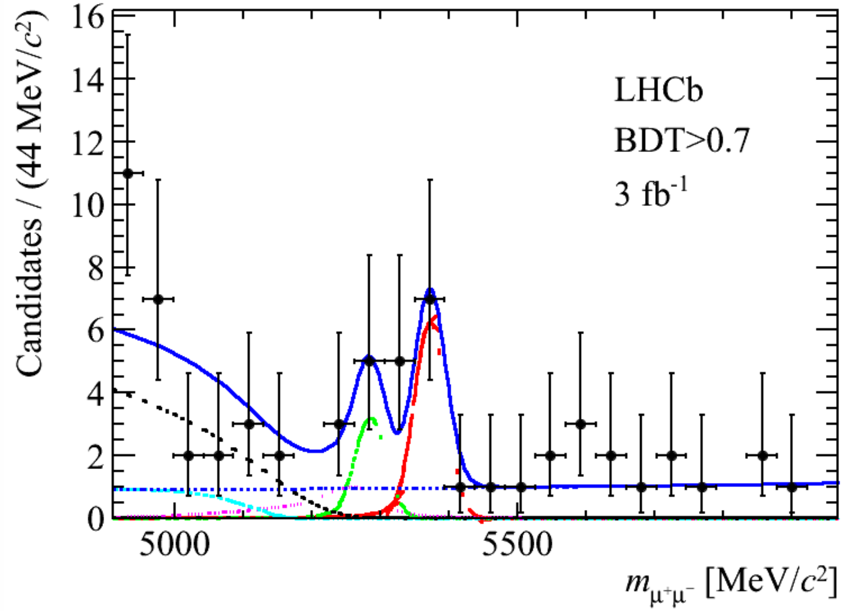
- B_s mixing phase φ_s



Theo. uncertainty: ±0.0016 rad

Exp. error (best): ±0.07 rad

- BR($B_s \to \mu^+ \mu^-$)



Theo. uncertainty: ±6%

Exp. error (best): ±24%

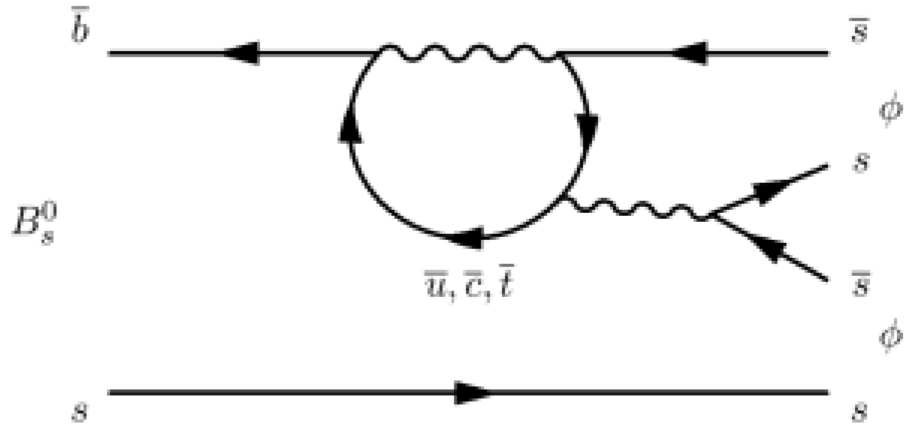
- Theoretical precision not reached → higher statistics required!

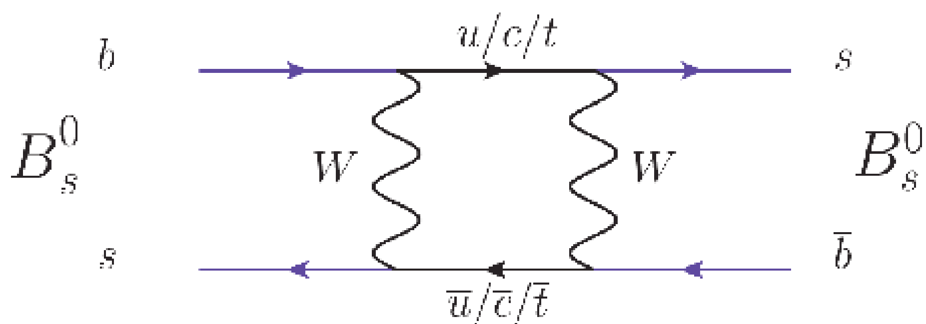
What can be tested ?

- Predictions with small SM theory uncertainty
  - "Null tests", no signals expected in SM
  - Precision tests of the unitarity of the CKM matrix
    - Only one CP violating phase, look for in consistency of angles
    - Measure sides via ratios of CKM matrix elements (needs theory I/P)
  - Precision measurements of BRs and aungular distributions of forbidden, or nearly forbidden decays
  - Lepton universality
- Type of decays (beauty and charm)
  - Fully leptonic decays
  - Ratios in semi-leptonic decays
  - CP violation in hadronic decays

Example of a null test: $B^0_s \to \varphi\varphi$

- Measure CP violation in $B^0_s \to \varphi\varphi$
- The $B^0_s \to \varphi\varphi$ decay is a unique place to look for NP in loop decays
- In SM the CP violation in the decay and the loop cancel
- This is a null-test of the SM that has high predictive power with small uncertainties

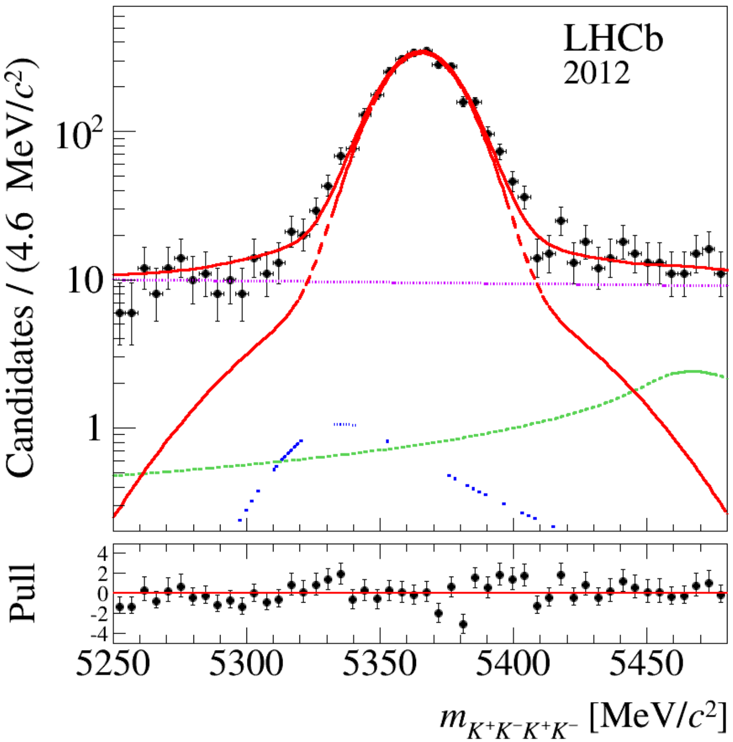




$B^0_s \to \phi\phi$ continued

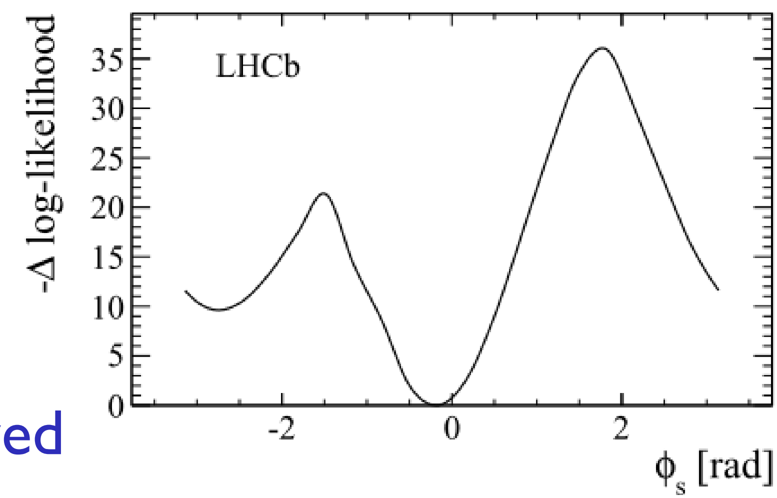
arXiv:1407.2222

- Current status of LHCb's $B^0_s \to \phi\phi$ measurement



- $B^0_s \to \phi\phi$
- Combinatorial
- $\Lambda^0_b \to \phi p K$
- $B^0 \to \phi K^*$

- N_{events} ~ 4000 of $B^0_s \to \phi(K^+K^-)\phi(K^+K^-)$
- A vector-vector decay; a mixture of CP even and CP odd distributions

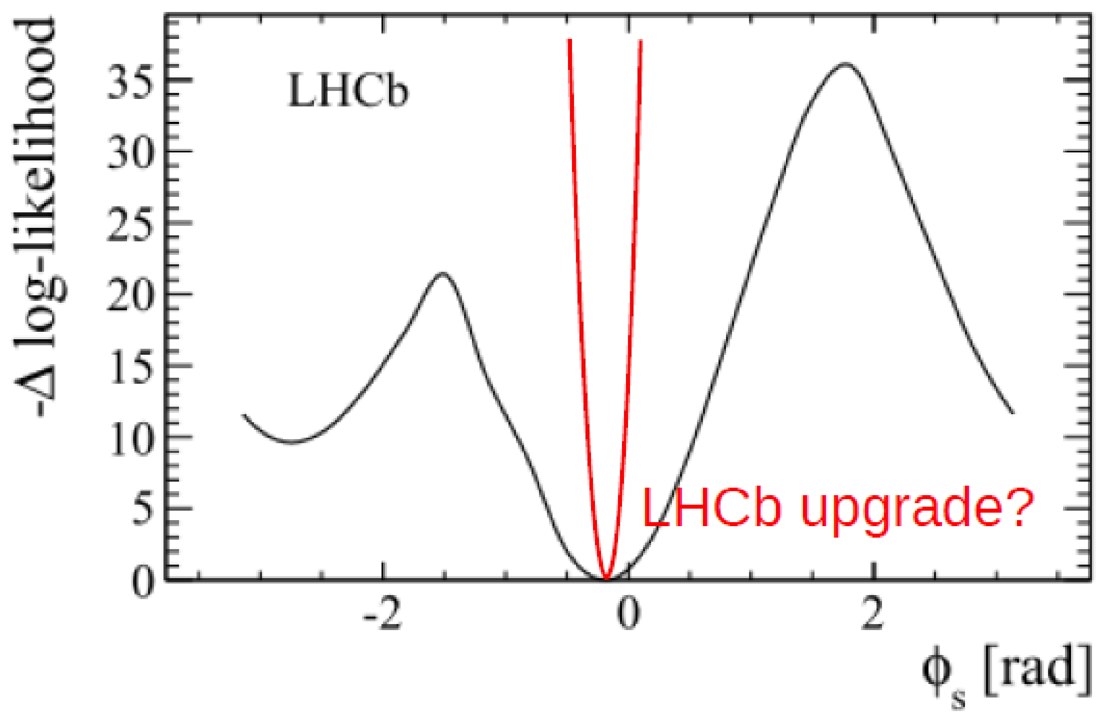


- No significant CP violation observed

$$\phi_s = -0.17 \pm 0.15\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})\ \ \mathrm{rad}$$

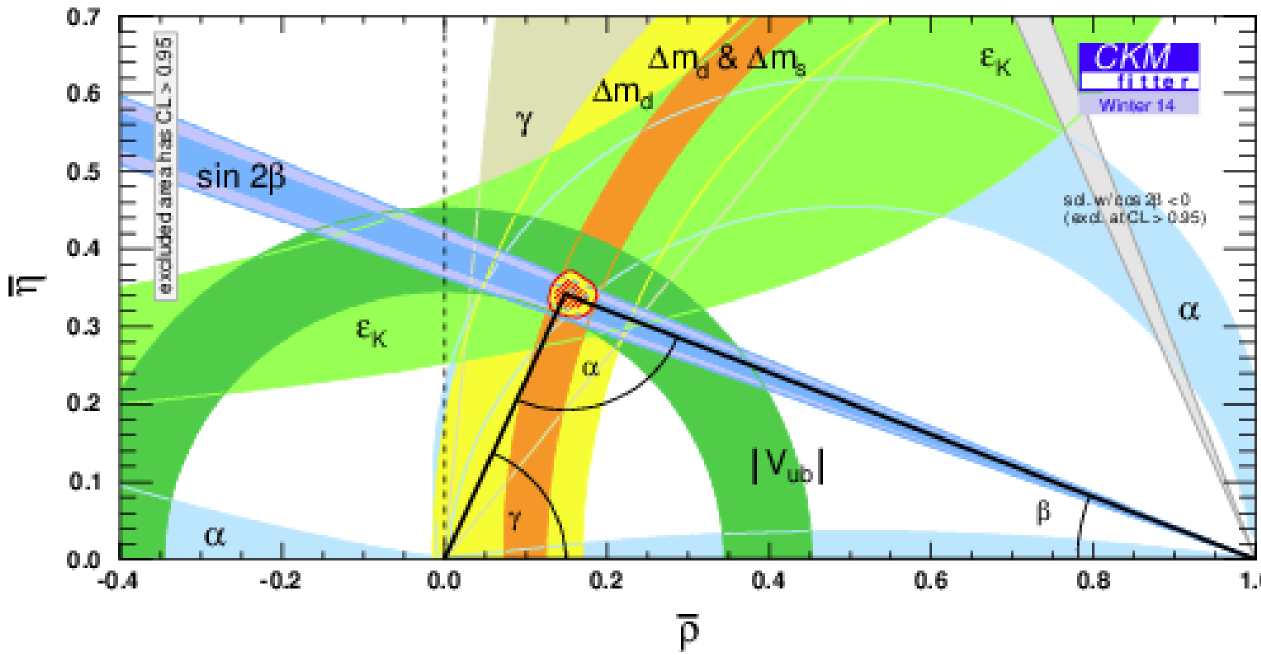
$B^0_s \to \varphi\varphi$ with the upgraded detector

- LHCb upgrade will bring precision on this down to 0.02
- To the same level as the current theoretical uncertainty



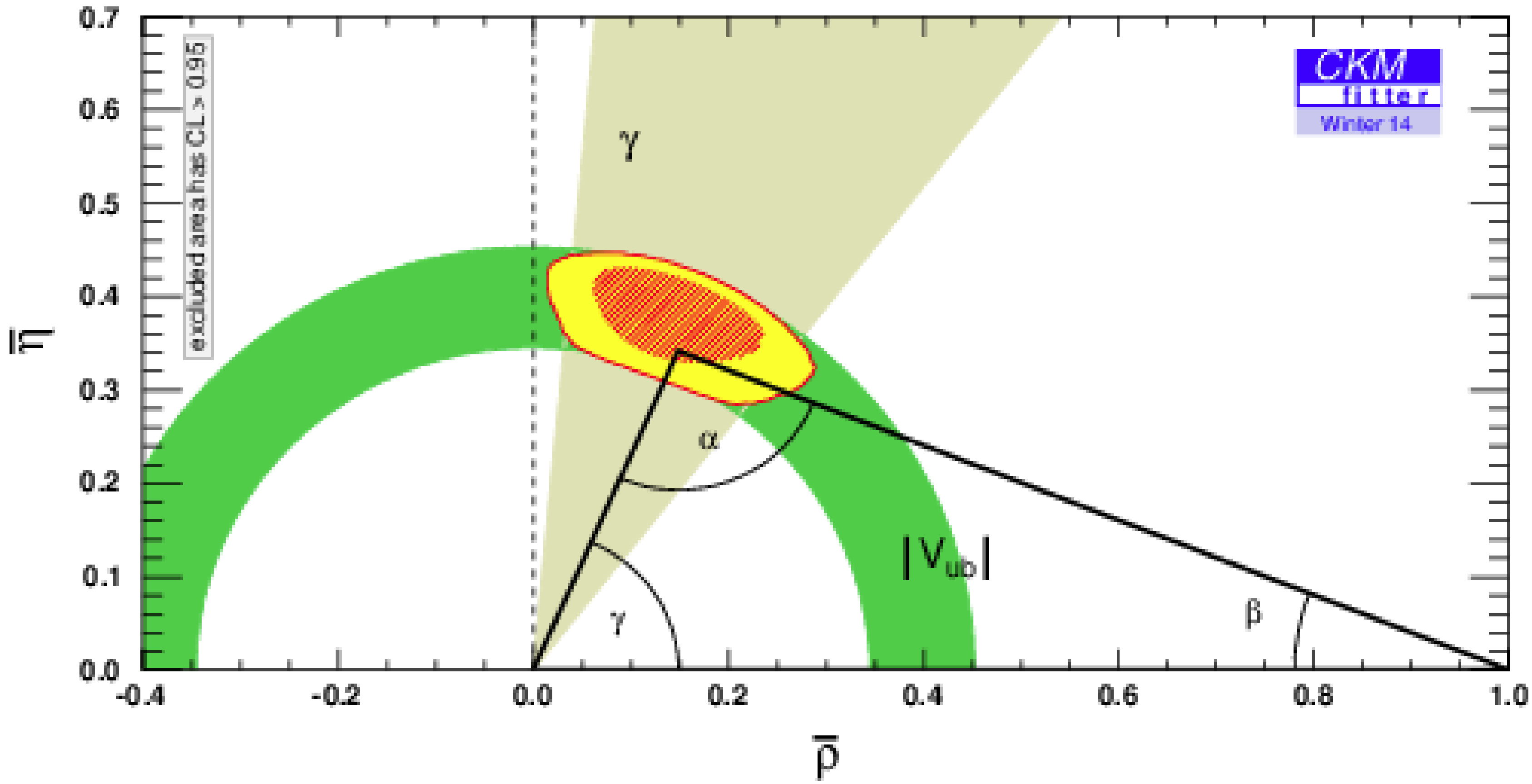
Unitarity of CKM matrix

- The SM requires that many different fits to the unitary triangle all result in the same apex
- If not, there will be additional amplitudes coming from NP
- Largest uncertainties are coming from left side ($|V_{ub}|/|V_{cb}|$) and the angle γ



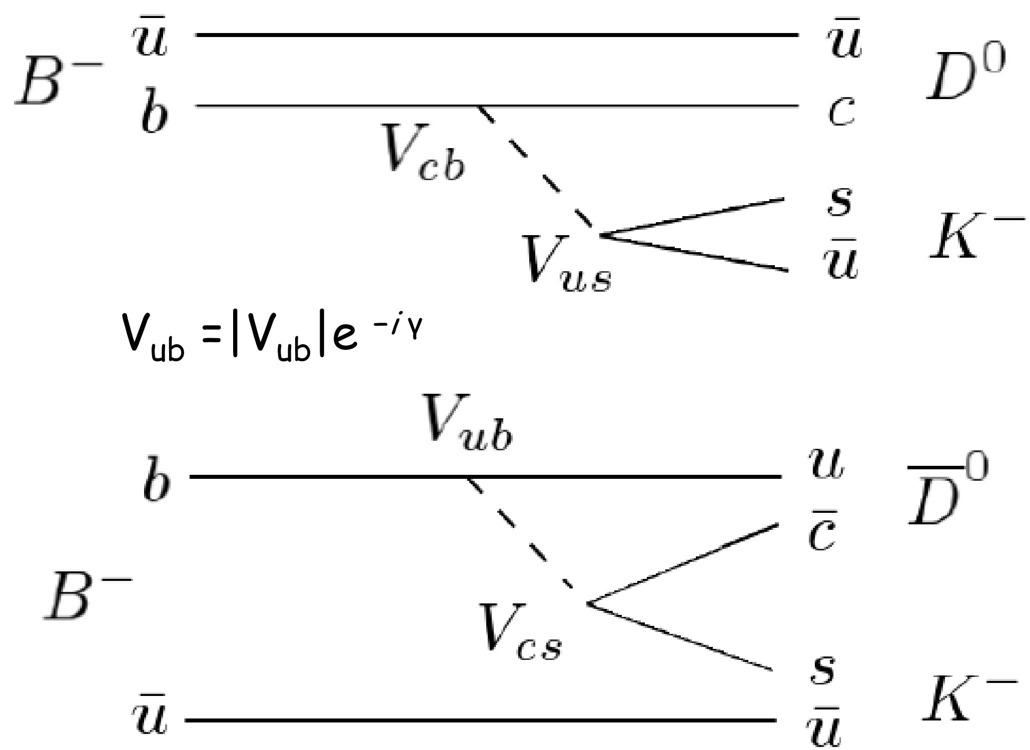
Unitarity of CKM matrix

- Current measurements are dominated by loop processes.
- These are still large uncertainties from measurements coming solely from tree processes

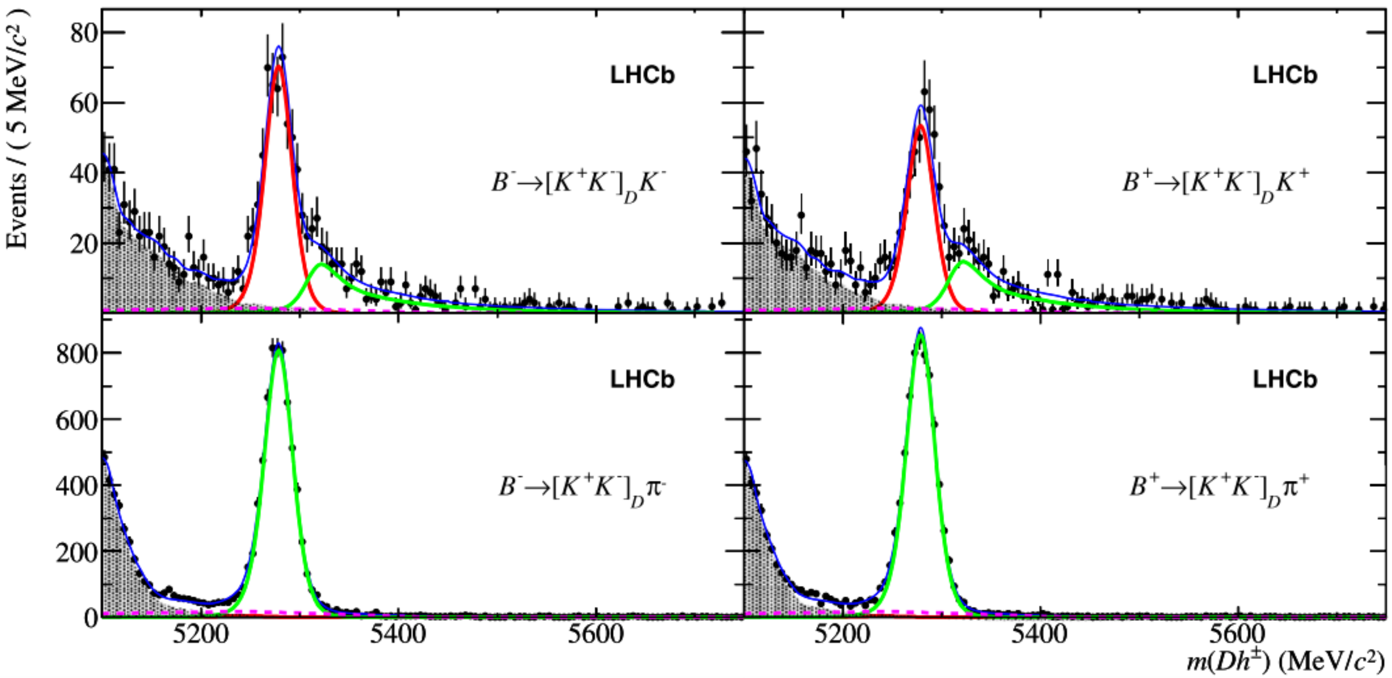


Determination of CP angle γ

- Best determined through interference between tree amplitudes
- D or $\overline{\mathrm{D}}$ produced followed by decay to a common final state: $K^+ \pi^-$, $K^+ \pi^- \pi^0$, $K^+ K^-$, ... etc
- Theoretical uncertainty on the method is extrmely small (JHEP 01 (2014) 05)



Determination of CP angle γ



PLB 712 (2012) 203

- Need large signal yield in the different final states (and to differentiate them cleanly)
- LHCb currently measure $(67 \pm 12)^\circ$ with mainly 2011 (1 fb^{-1}) data
- Statistical reach for LHCb upgrade will be 1° (for Belle-II it is ~2°)
- To keep systematic uncertainty below this requires to understand tracking for positive/negative particles exceptionally well

The need to resolve $|V_{ub}|$

- The measurement of $|V_{ub}|$ has an internal inconsistency between
  - Exclusive measurement: $B^0 \rightarrow \pi^- \mu^+ \nu$
  - Inclusive measurement : $B^0/B^+ \rightarrow X_u \mu^+ \nu$

$V_{ub}(\text{excl}) = (3.42 \pm 0.22)\ 10^{-3}$
$V_{ub}(\text{incl}) = (4.40 \pm 0.31)\ 10^{-3}$
$V_{ub} = (3.75 \pm 0.46)\ 10^{-3}$

~1.9 σ discrepancy

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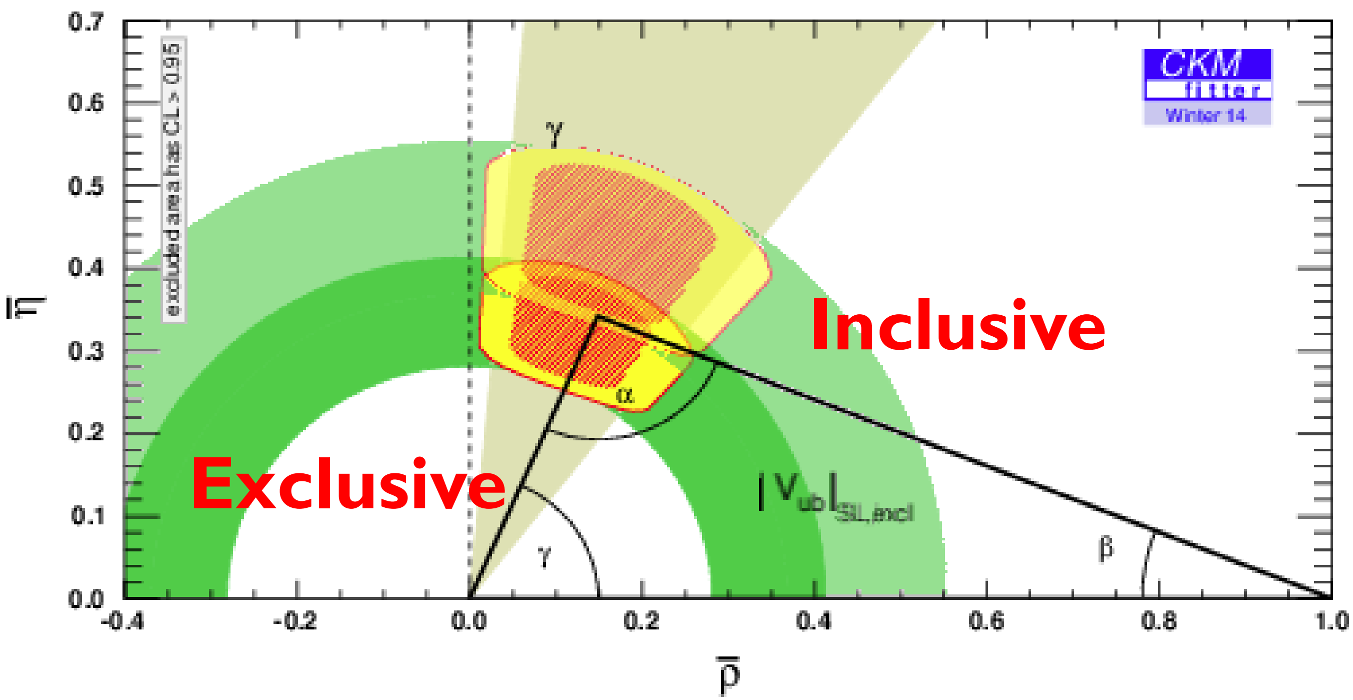
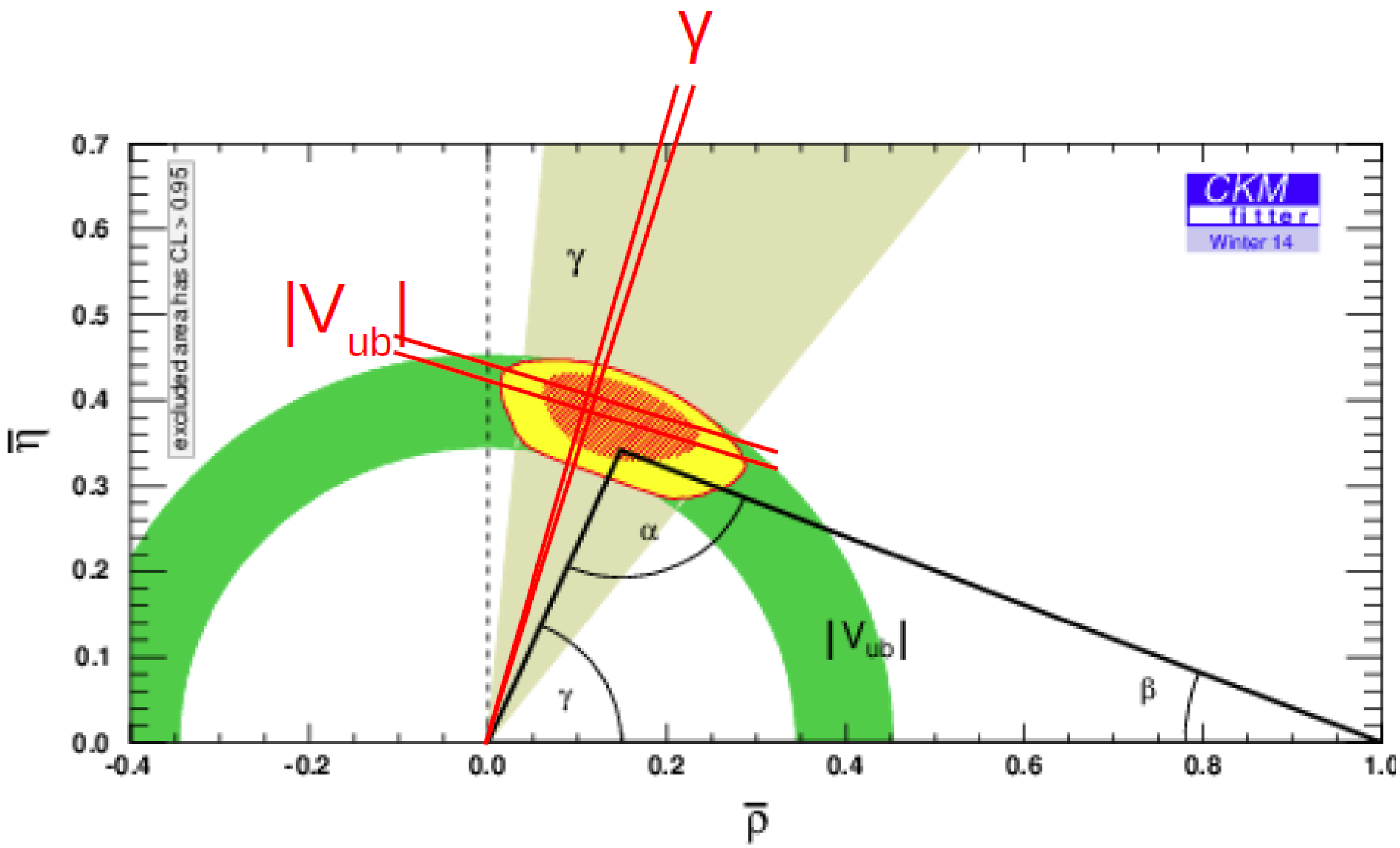


$|V_{ub}|$ continued …

- Is internal inconsistency a sign of NP ... maybe not, but need more measurements and theoretical improvements.
- More independent measurements required
  - $\Lambda_b \rightarrow p\, \mu^- \nu$ In progress with LHCb (which rely on new $\Lambda_b \rightarrow p$ form factors from the lattice)
- $B_c^+ \rightarrow D^0\, \mu^+ \nu$
  - Possible at LHCb or LHCb upgrade.
- Also inclusive measurements from Belle-II
- $|V_{ub}|$ at a few percent level will be possible

In 2025 with the LHCb upgrade …

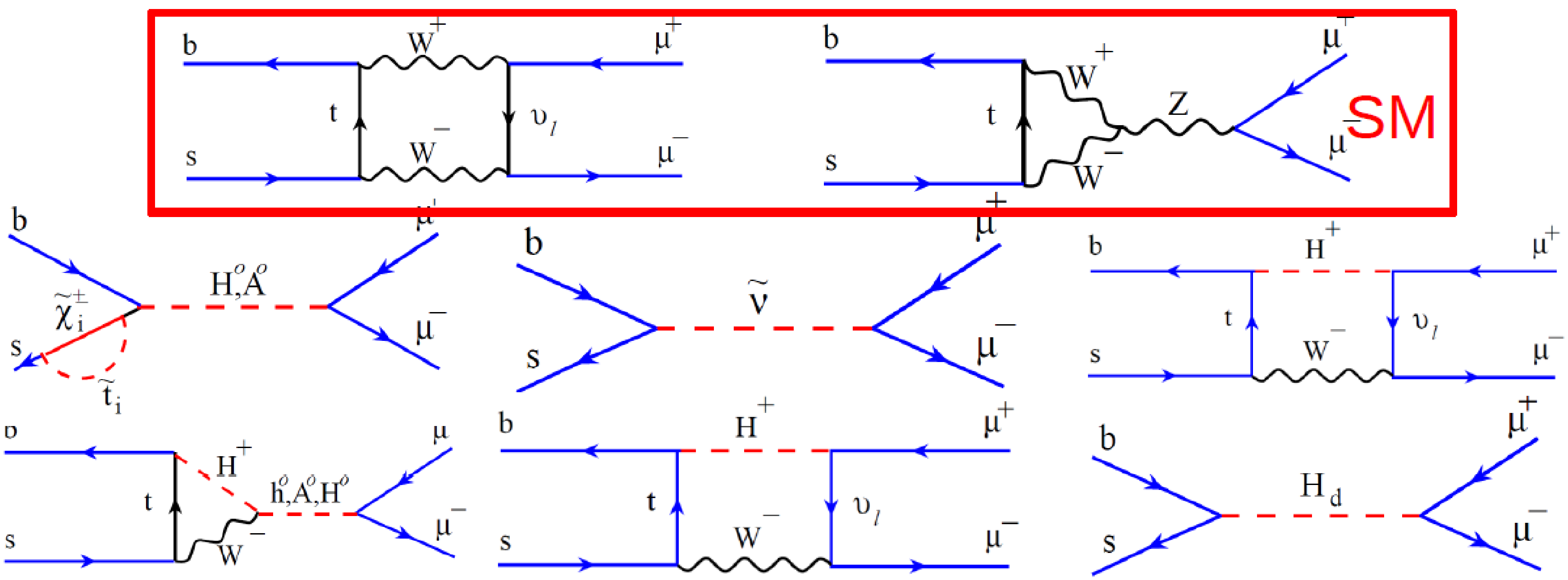
- Left side ($|V_{ub}|/|V_{cb}|$) and the angle γ will be precision measurements in the future



Nearly forbidden decays

The $B^0_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ decays

- The two very rare decays $B^0_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ have attracted much interest
- Predictions of SM branching fractions with good precision
  - $BF(B^0_s \rightarrow \mu^+\mu^-)$ SM = $3.56 \pm 0.18 \times 10^{-9}$
  - $BF(B^0 \rightarrow \mu^+\mu^-)$ SM = $0.10 \pm 0.01 \times 10^{-9}$
- Sensitive to the scalar sector of flavour couplings



Observing $B^0 \rightarrow \mu^+\mu^-$

PRL 111 (2013) 101805

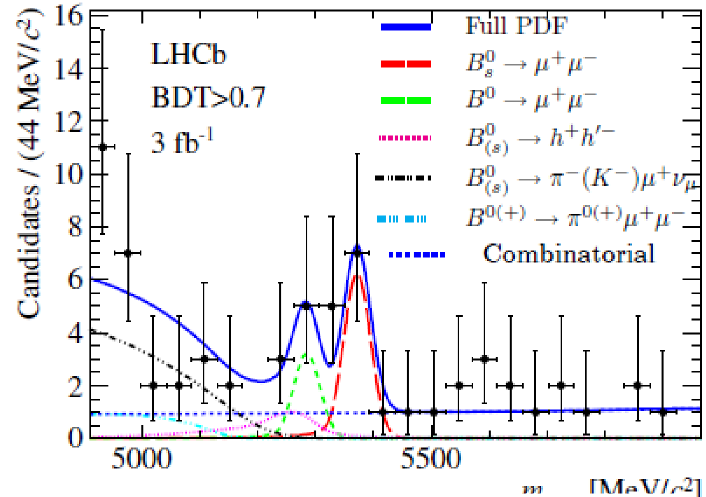
- LHCb and CMS combined result

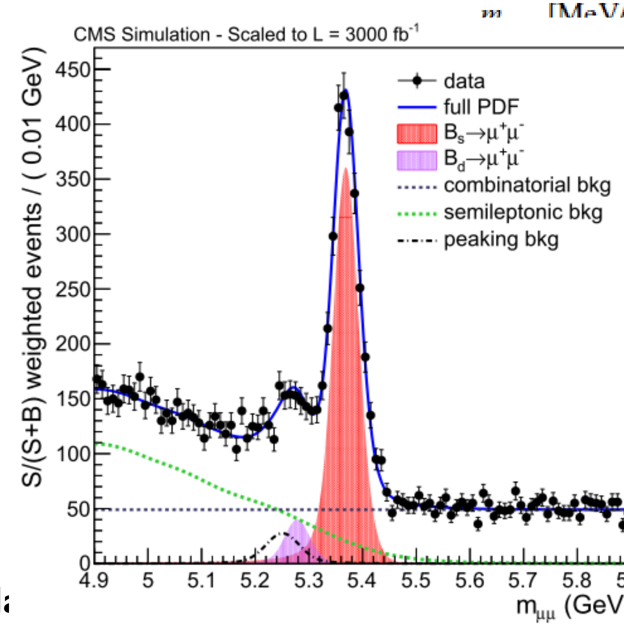
$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$ (> 5 sigma)

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (3.6\,^{+1.6}_{-1.4}) \times 10^{-10}$$

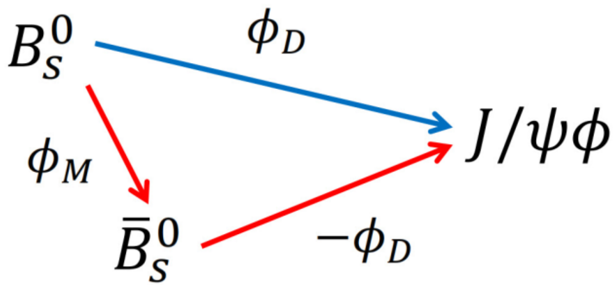
PRL 112 (2014) 101801

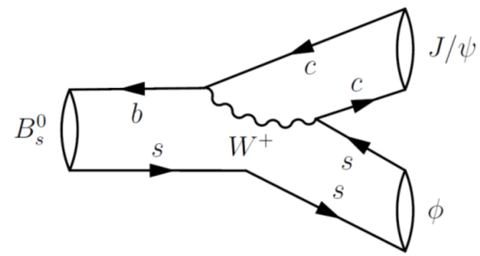
- Following $B^0_s \rightarrow \mu^+\mu^-$ observation, challenge now is to observe for $B^0 \rightarrow \mu^+\mu^-$
- In the SM suppressed by $|V_{ts}|^2/|V_{td}|^2 \sim 25$
- New physics may manifest itself as a higher $B^0 \rightarrow \mu^+\mu^-$ rate
- LHCb upgrade expects to measure the ratio to a 35% accuracy
- CMS upgrade at full 3 ab^{-1} expected to improve this to 21%

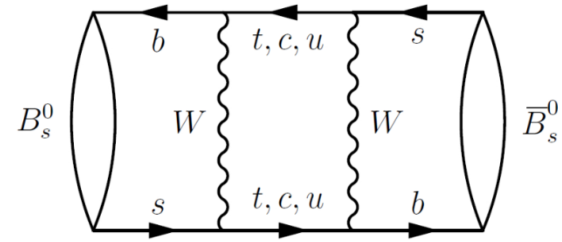




B_s weak mixing phase ϕ_s in $B_s \rightarrow J/\psi\ \phi$

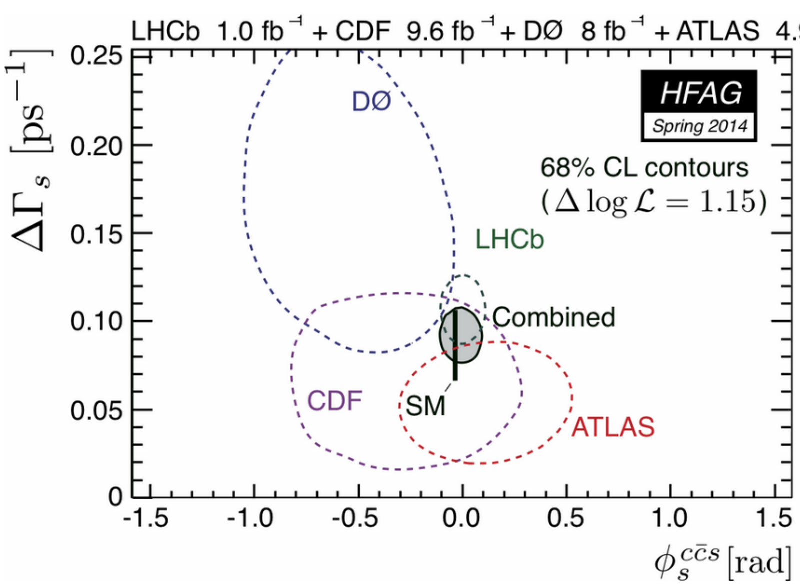


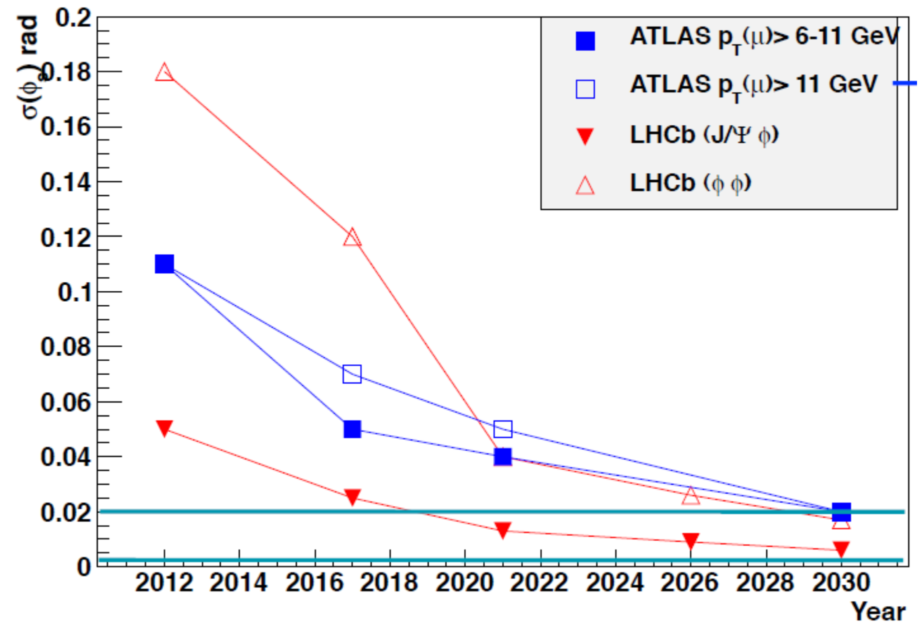




- Measurements by ATLAS, CMS and LHCb:

  LHCb (50 fb^{-1}): $\delta\varphi_s \approx \pm\ 0.009$ (SM -0.036 ±0.003) (current meas. ± 0.07)





Lepton universality test in $B^+ \to K^+ \ell^+ \ell^-$

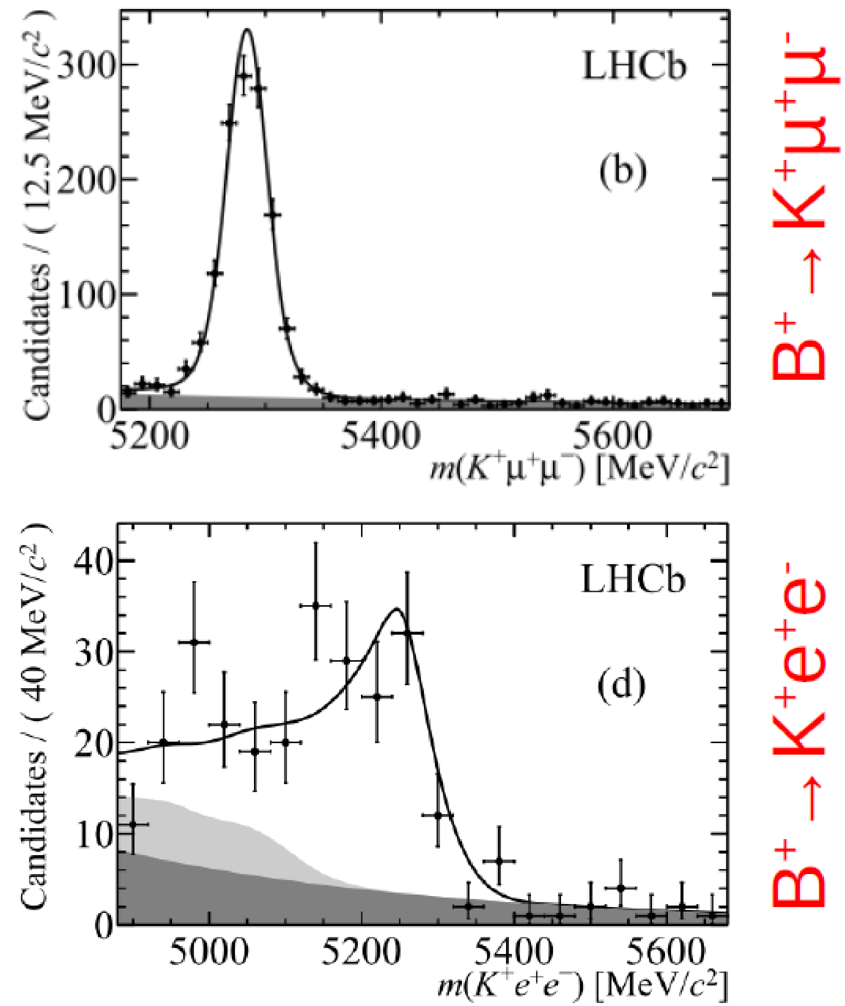
- Due to lepton universality, the $B^+ \to K^+ \mu^+ \mu^-$ and $B^+ \to K^+ e^+ e^-$ decays should have same BF to within a factor 10^{-3}
- The ratio

$$R_K = \frac{BF\left(B^+ \to K^+ \mu^+ \mu^-\right)}{BF\left(B^+ \to K^+ e^+ e^-\right)}$$

is sensitive to lepton flavour violating NP

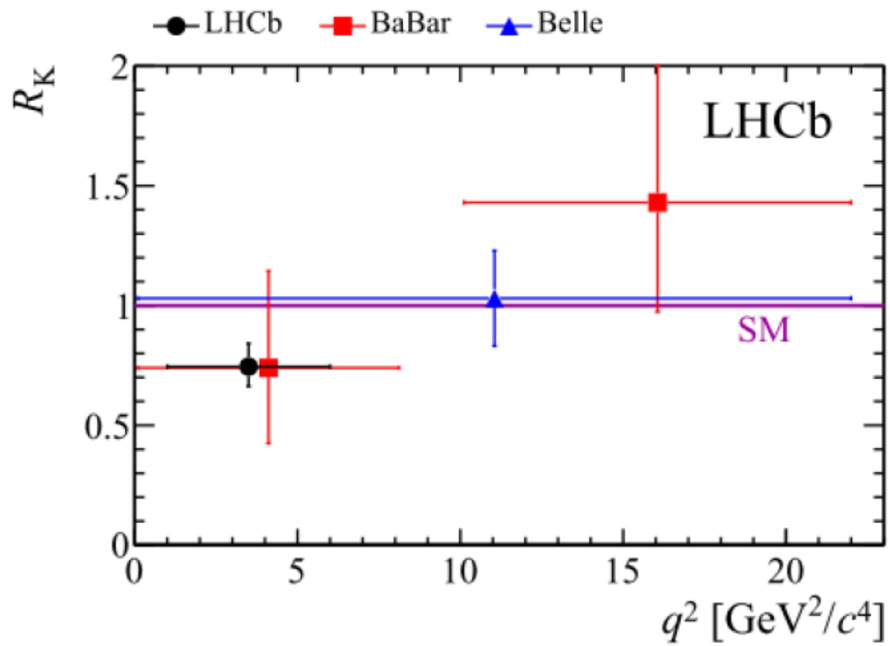
- The electron mode is a challenge for LHCb

LHCb : arXiv:1406.6482



Lepton universality test in $B^+ \to K^+ l^+ l^-$

- Current status of measurements as a function of dilepton mass: $R_K = 0.745^{+0.090}_{-0.074}\,(\mathrm{stat}) \pm 0.036\,(\mathrm{syst})$



- Expected precision from both LHCb upgrade (and also Belle-II) at the few % level
- Will resolve the issue with the 2.6 σ tension currently seen

Upgrade sensitivities 50 fb^{-1}

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

Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [24]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [26]	0.045	0.014	~ 0.01
	$A_{\rm fs}(B_s^0)$	6.4×10^{-3} [41]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [41]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [42]	0.025	0.008	0.02
	$s_0\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [42]	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [9]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [43]	8 %	2.5 %	$\sim 10\,\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [4]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim 100\,\%$	$\sim 35\,\%$	$\sim 5\,\%$
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [28, 29]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [41]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [41]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [8]	0.65×10^{-3}	0.12×10^{-3}	–

Complementarity with Belle-II

LHCb

ATLAS & CMS

- Rare decays: $B_{d,s} \to \mu\mu$
- B_s system
- b-baryons
- Spectroscopy
- CKM phases (β, γ)
- Gluonic penguins
- EW penguins
- Charm physics
- Semileptonics: Mixing, A_{SL}
- Semileptonics: V_{xb}
- $B \to \tau\nu$, $\boxed{D\tau\mu,}$
- $B \to K^*\nu\nu$
- τ-physics

Some only LHCb, some only Belle II

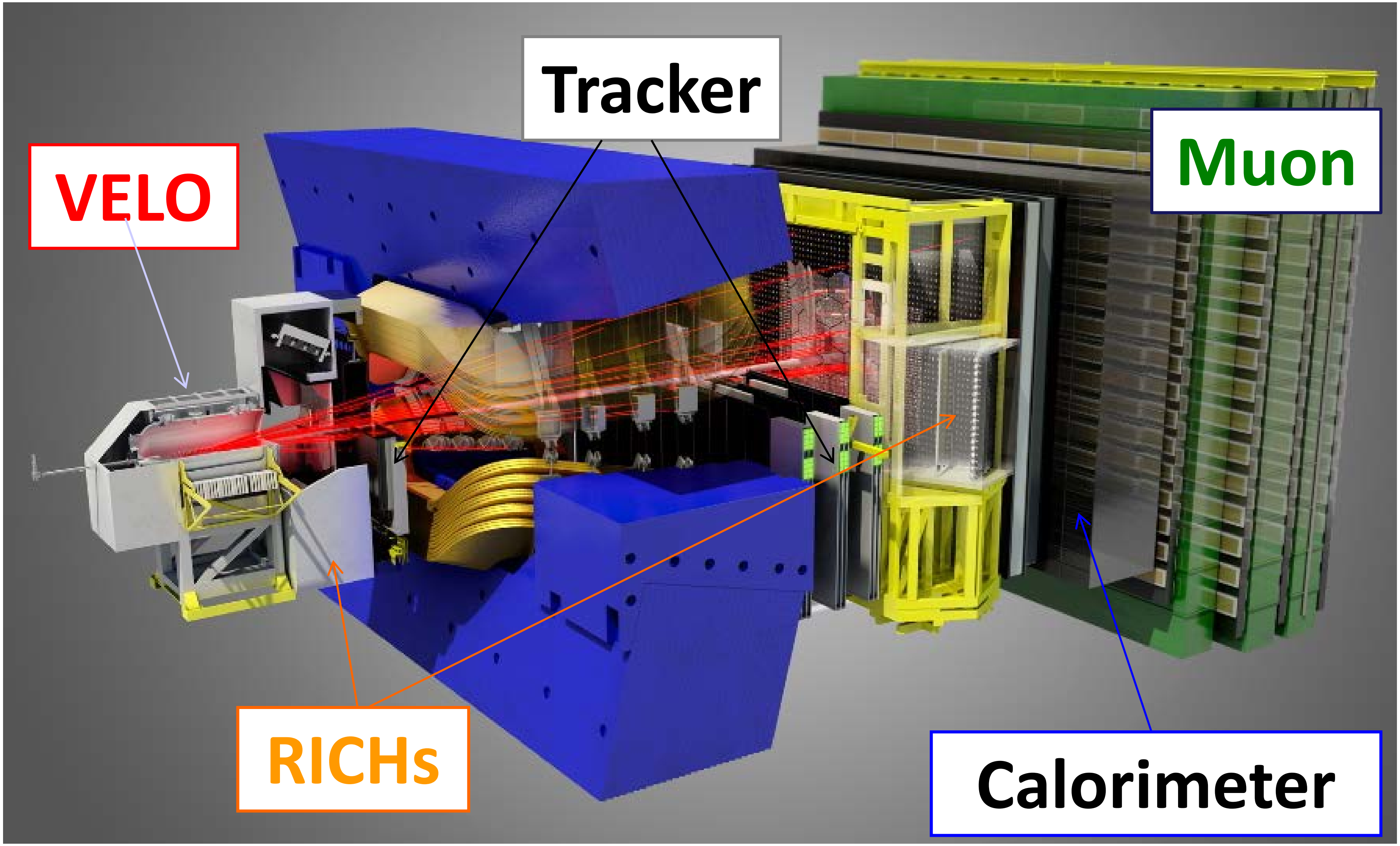
On-going

Belle II

The LHCb detector upgrade

- Detector overview
- The issue with the trigger
- The major hardware changes
  - The VELO
  - The tracking detectors
  - The RICH

LHCb subsystems overview



Why upgrade: current LHCb limitations

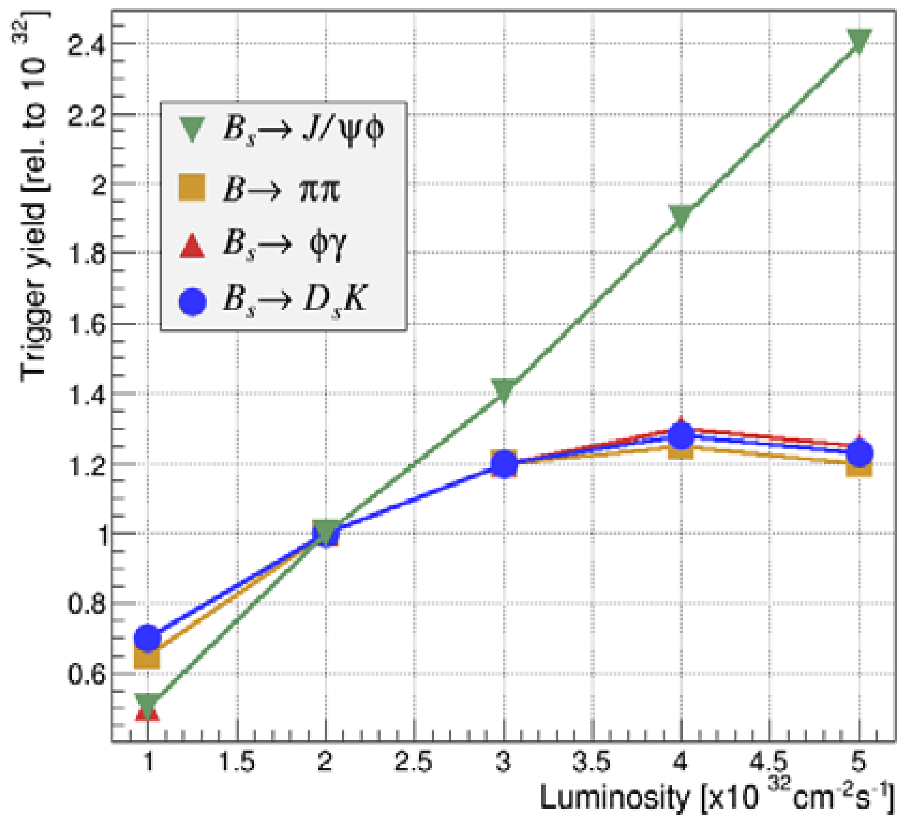
- No evidence for New Physics in LHC Run1
  - Need more (x10 or more) data, aiming at experimental sensitivities comparable to theoretical uncertainties

- Need to increase levelled luminosity from $0.4{\times}10^{33}$ up to $2{\times}10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (pile-up ~8)

- However the current 1 MHz level-0 trigger output is a severe limitation!

- If we increase the luminosity
  - Need harder cuts on P_t due to the 1 MHz bandwidth limit
  - The trigger yield of hadronic events saturates
  - there's no real gain in statistics

Need a radical change in the trigger strategy to get to 5pb^{-1} per year



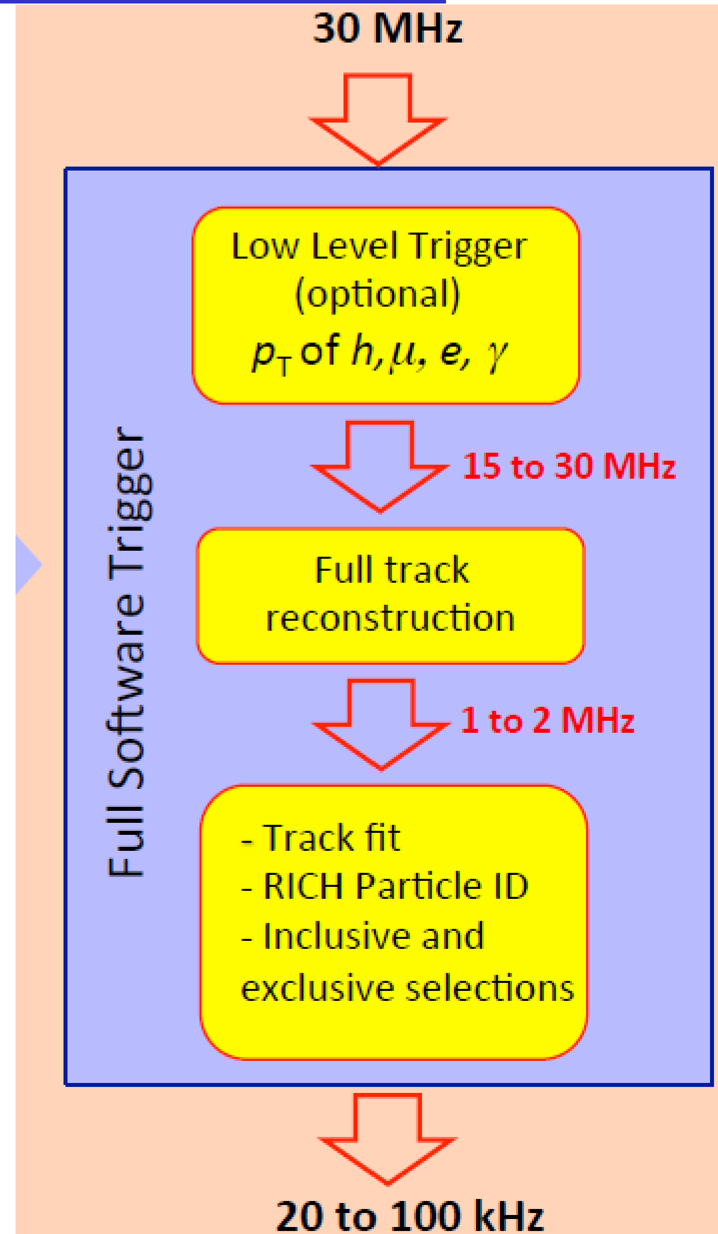
The trigger

- Remove the level-0 hardware trigger
  - Readout an event every bunch crossing (40 MHz)
  - New front-end electronics (on-chip zero suppression)
  - New DAQ system

- Use an efficient fully software trigger accessing complete event information, running at the bunch crossing rate

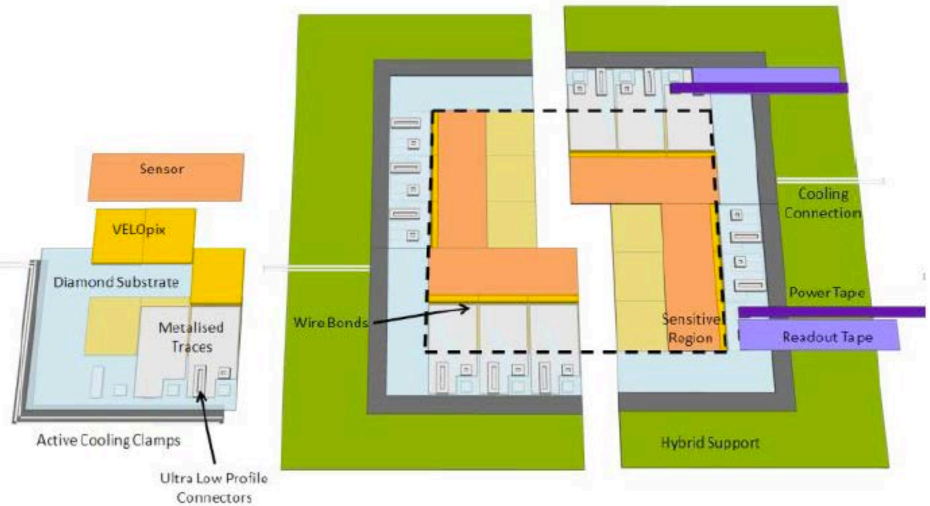
- The high instantaneous luminosity of $2\times10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ implies higher occupancies in all subsystems ➔ redesign several detectors to adapt them to new conditions

- Install by LS2 (Long-shutdown 2) in 2018-2019



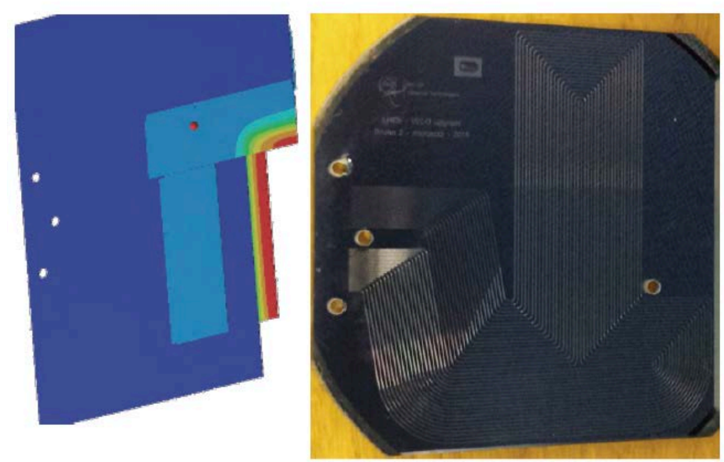
Upgraded VELO (vertex detector)

- Challenges
  - Very high particle rates
  - Highly non-uniform radiation damage (up to $8 \times 10^{15}\ n_{eq} cm^{-2}$ for 50 fb^{-1})

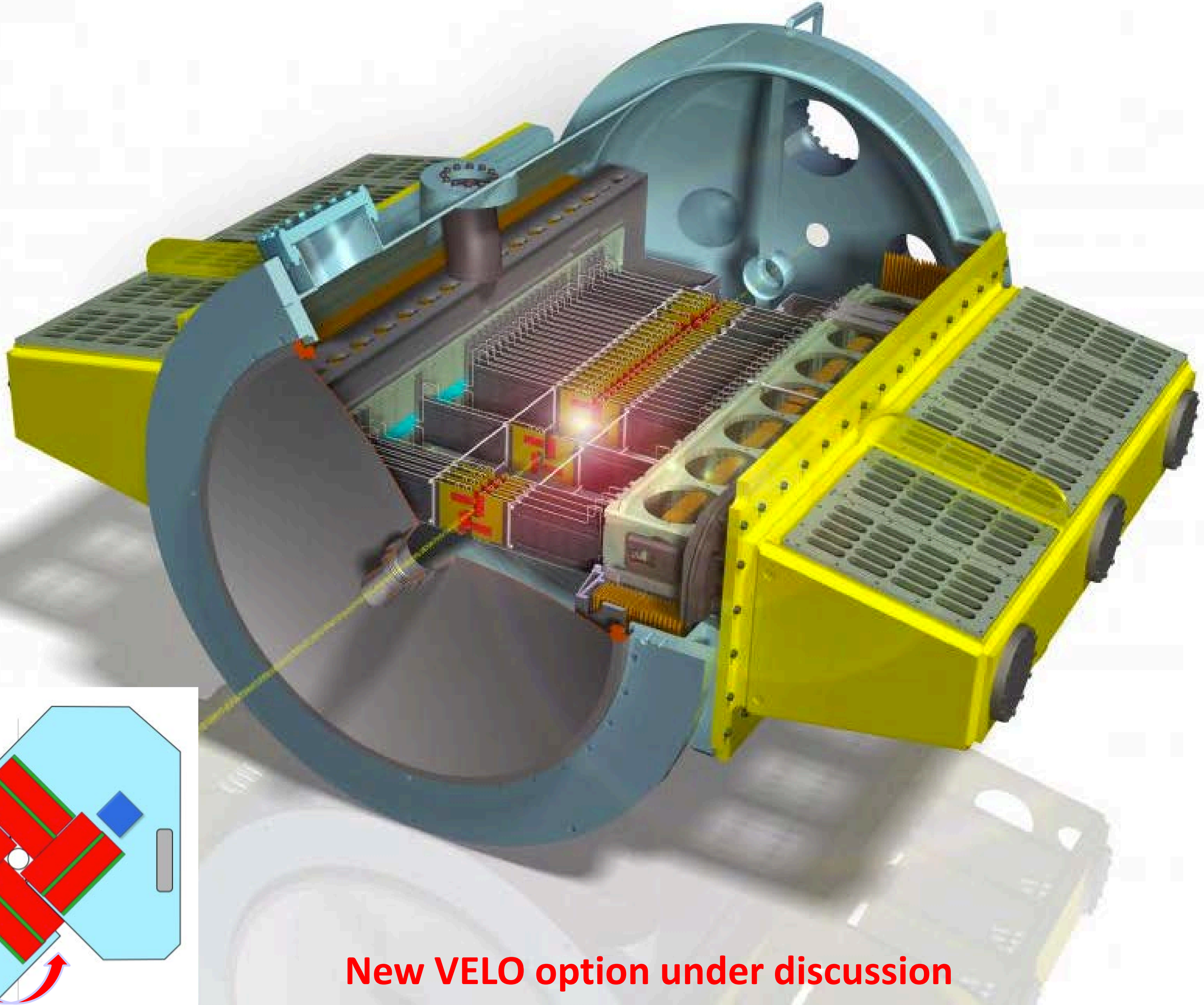


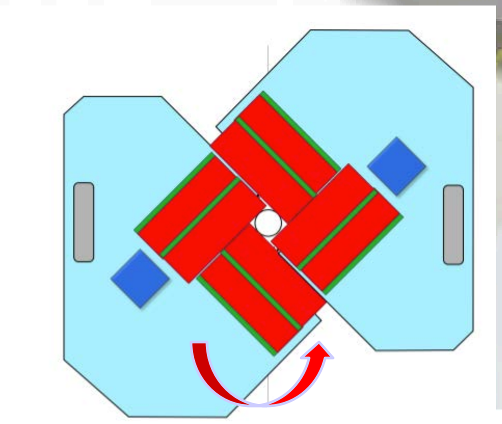
- Technical choices
  - Silicon strips replaced by pixels. 256 x 256 pixel matrices, with 55 x 55 μm^2 pixels
  - Micro-channel CO_2 cooling
  - New FE electronics : Velopix

Micro-channel



CO_2 passes through channels etched in a silicon plate

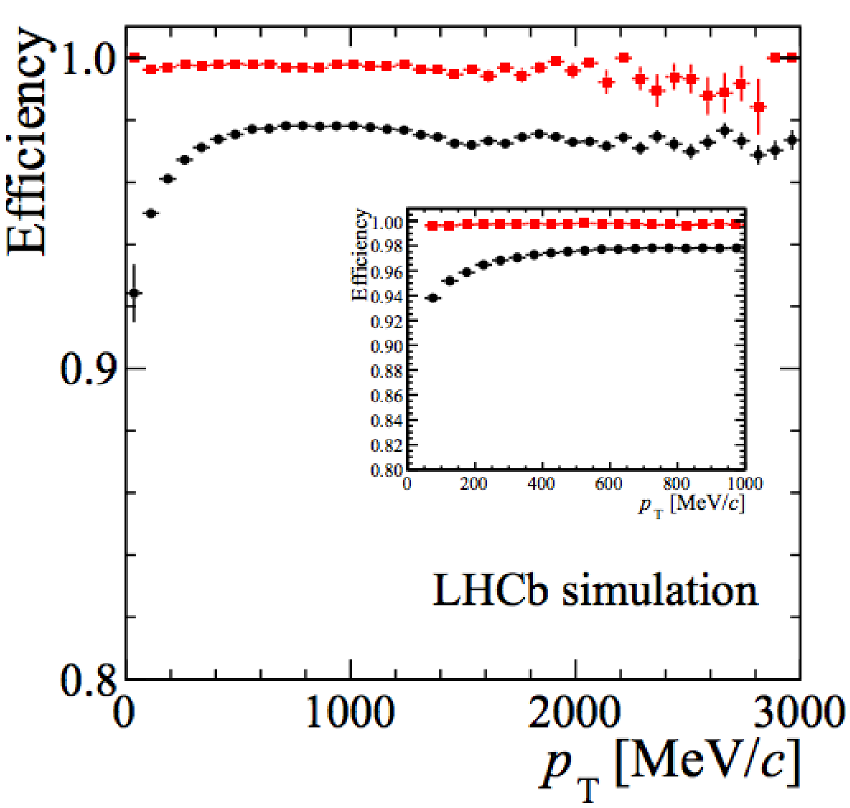


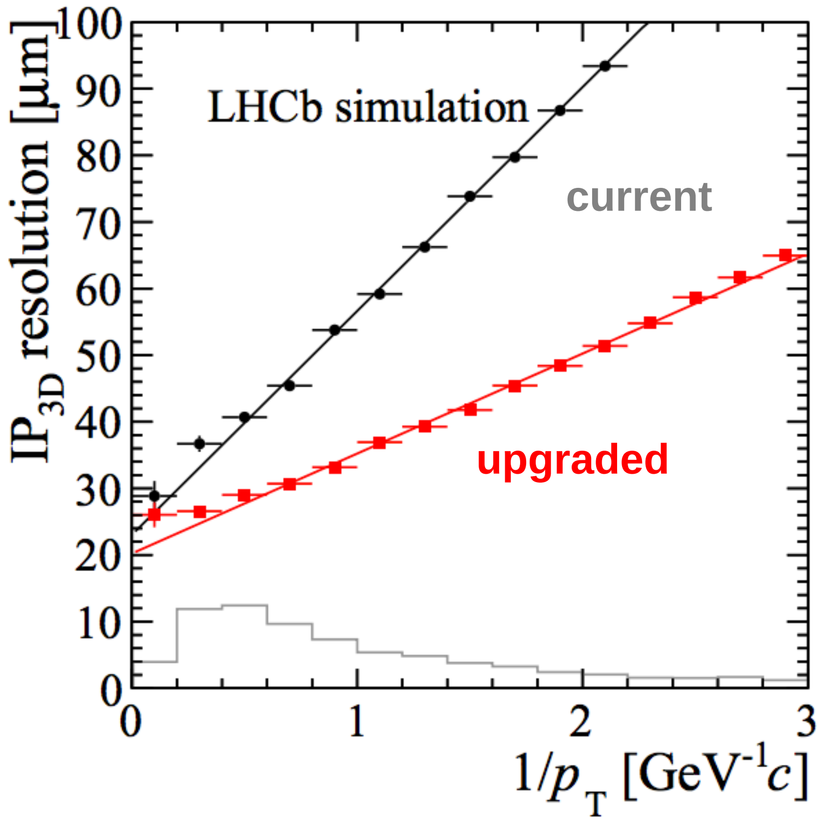


New VELO option under discussion

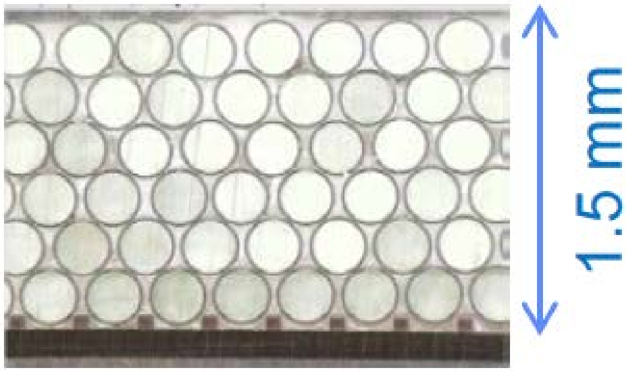
New VELO Performance

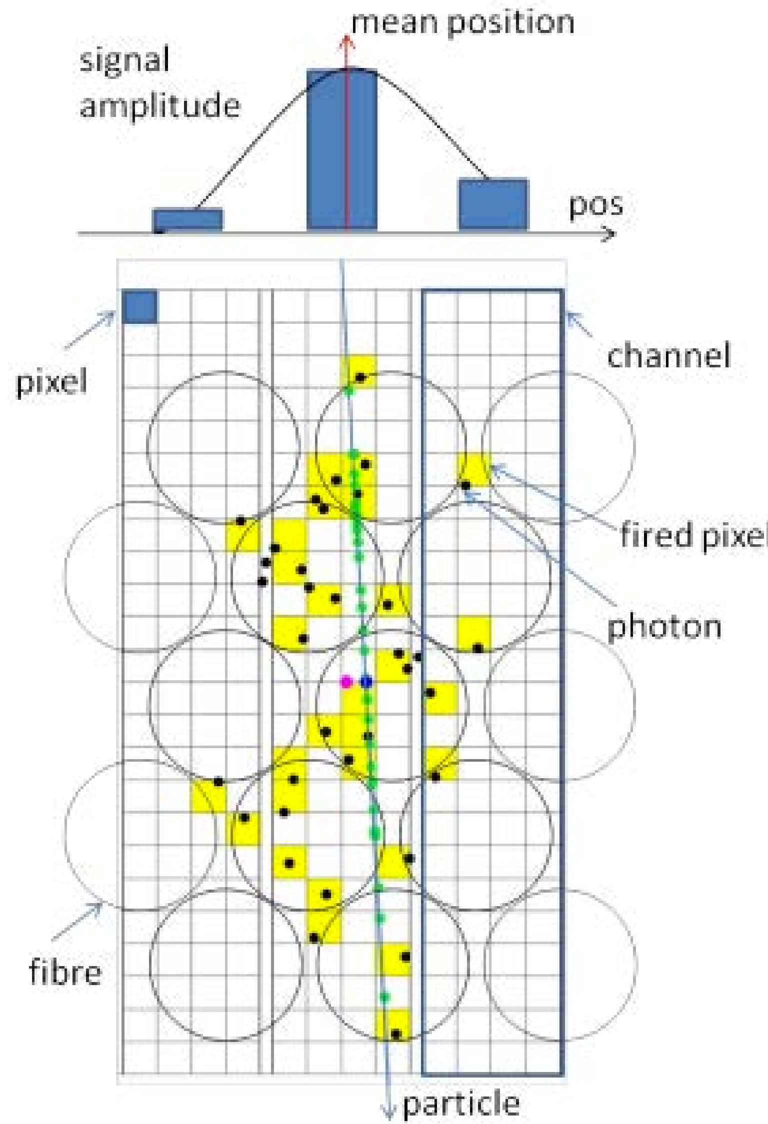
Predicted performance at $2 \times 10^{33}/\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is superior in almost every aspect with respect to the current VELO operating at high luminosity





Fiber Tracker (FT) technology

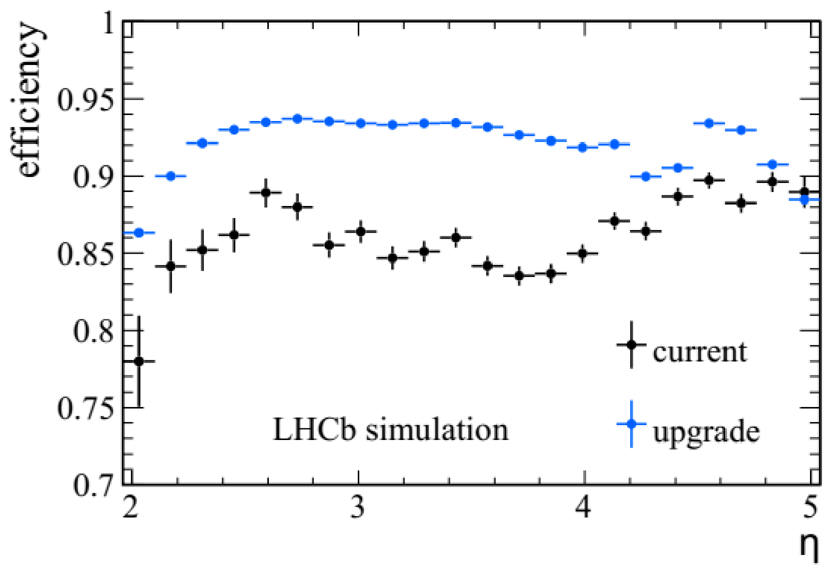




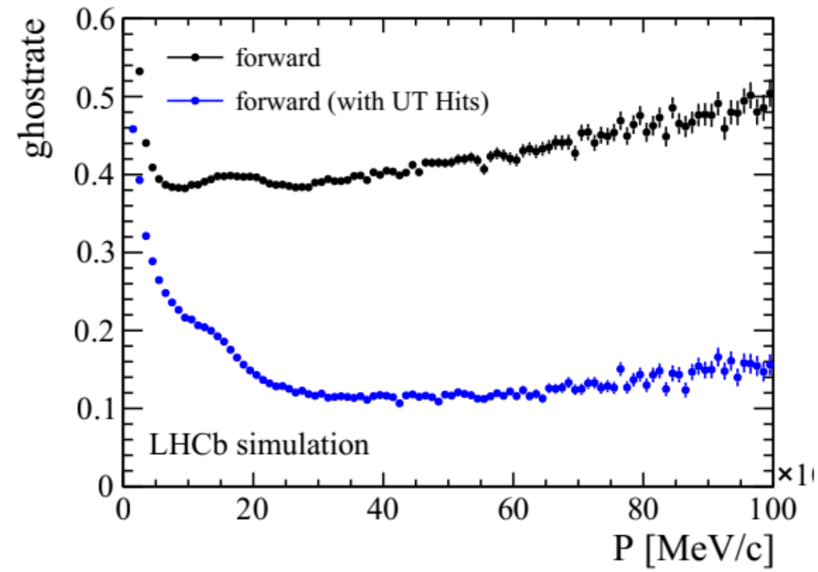
- Current tracker straw tubes will be replaced
- Upgrade will have scintillating fibre planes (5-6 fibres thick)
- 250 μm diameter scintillating fibres
- 12 detection layers in 3 stations
- Readout via 2x64 channel silicon photomultiplier (SiPM) arrays
- Electronics: dedicated 128 channels 40 MHz PACIFIC ASIC

Upgraded Tracker Performance

Efficiency for $B_s \rightarrow \phi\phi$



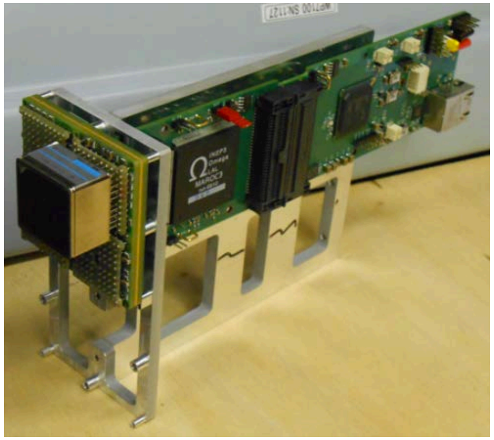
Ghost rate (long tracks) for $B_s \rightarrow \phi\phi$

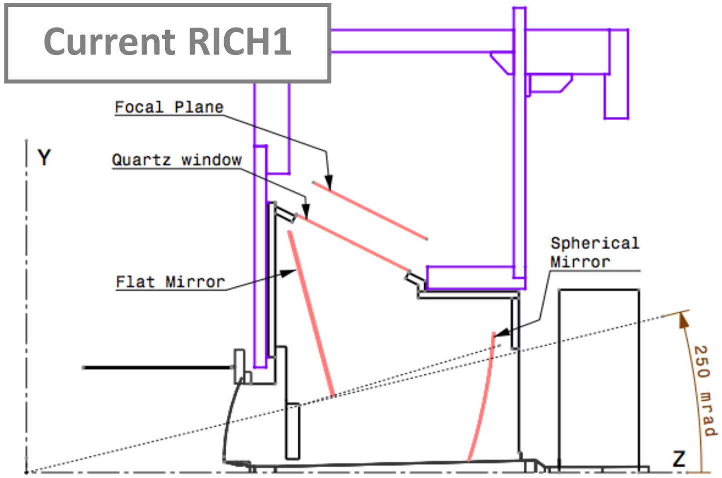


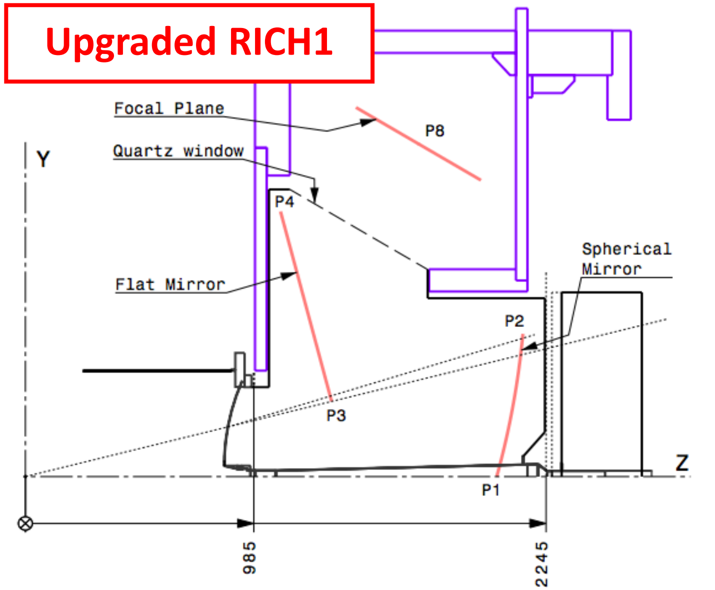
- FT : Improved tracking efficiency
- UT : Improved background rejection

RICH Upgrade

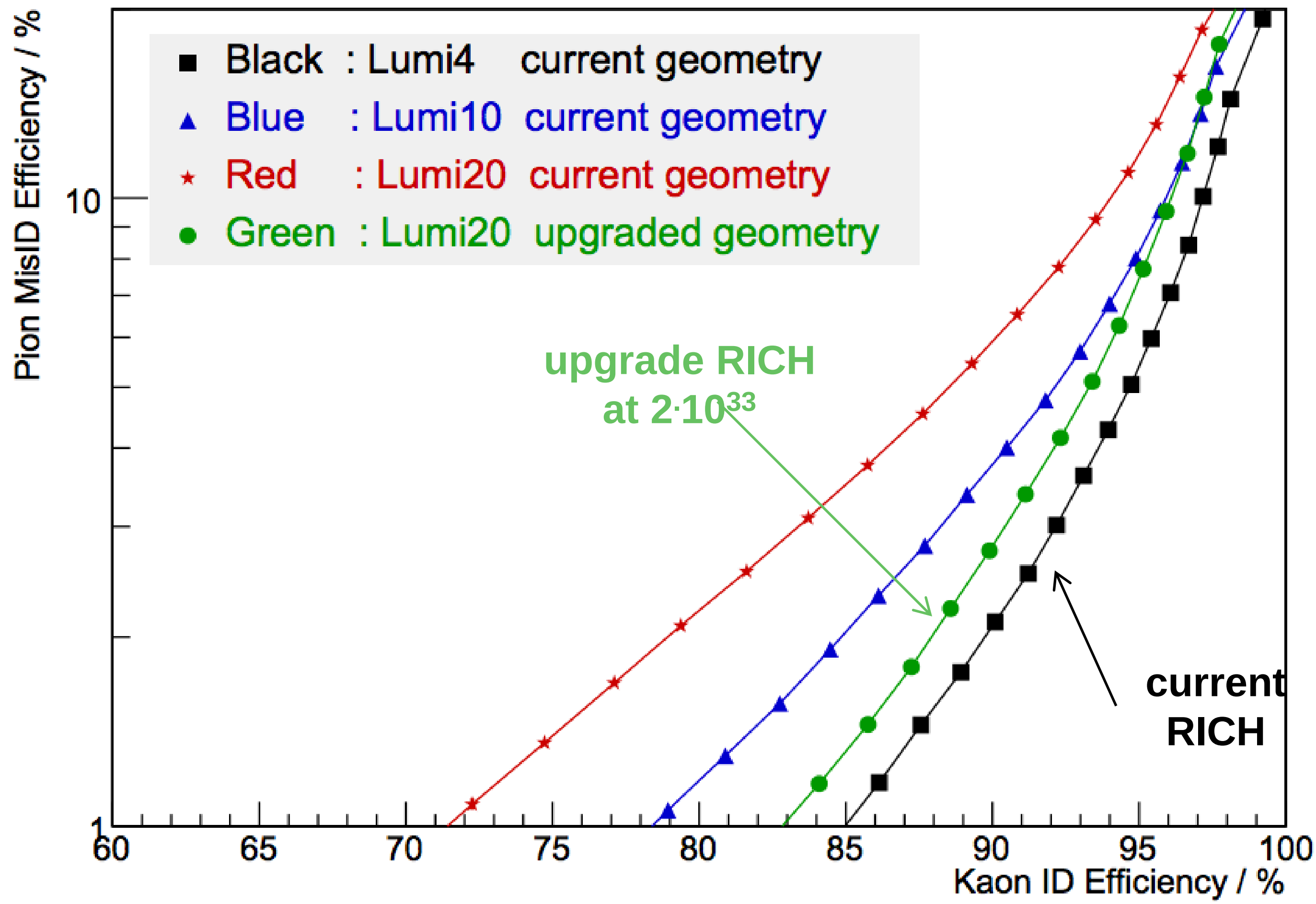
- New readout: 64 channel multi-anode PMTs
- 40 MHz CLARO front-end ASIC
- In addition, for RICH1:
  - Remove aerogel
  - improve optics to spread out Cherenkov rings on the focal plane





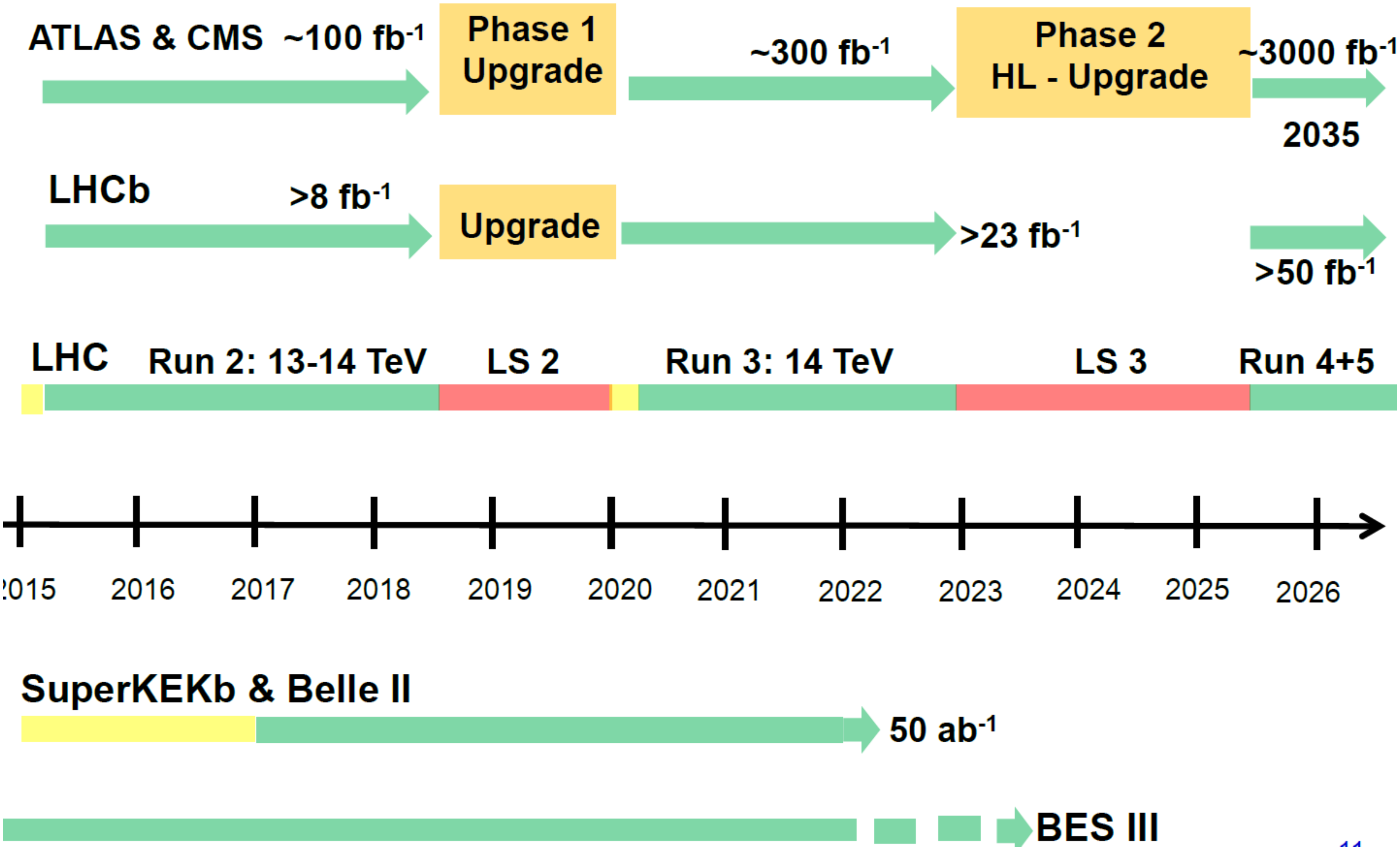


Upgraded RICH performance



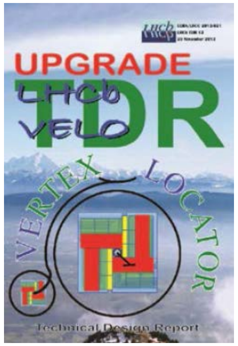
Upgraded RICH performance at $2{\times}10^{33}$ close to current one

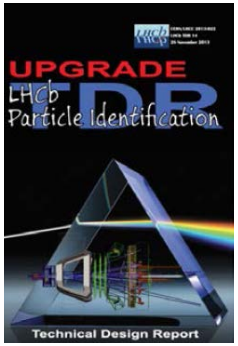
The timeline ...

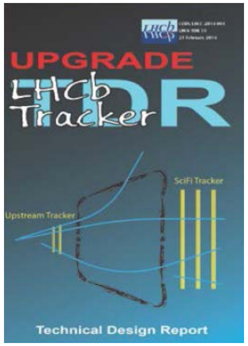


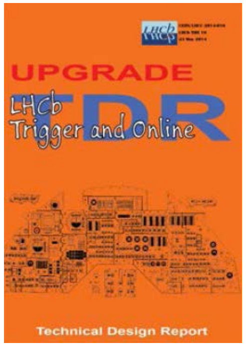
Summary

- LHCb is producing world best measurements in the beauty and charm sector and has a rich future ahead
- The Upgraded LHCb trigger scheme allows collection of 5 fb^{-1} of data per year
- The upgrade will be performed in 2018-19 during LS2; data taking will start in 2020
- All future facilities LHCb upgrade, Belle-II, CMS/ATLAS have their respective strengths and combined information will be a great handle to reveal New Physics









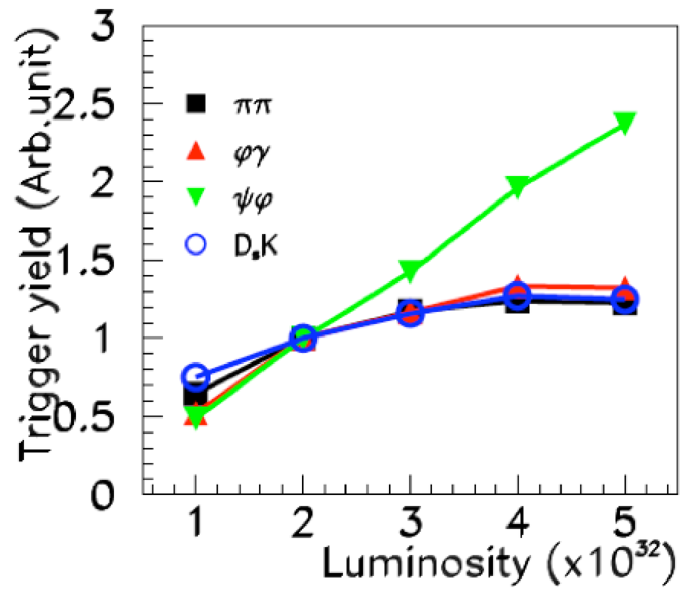
Spare slides from here on

B-physics at the intensity frontier

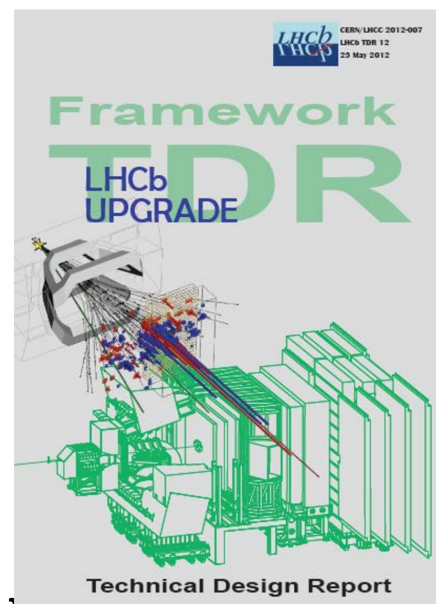
	LHC era		High-lumi LHC era		
	2010-2012	2015-2018	2020-2022	2025-2028	2030+
ATLAS & CMS	25 fb^{-1}	100 fb^{-1}	300 fb^{-1}	→	3000 fb^{-1}
LHCb	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}
Belle II		0.5 ab^{-1}	25 ab^{-1}	50 ab^{-1}	-

Outlook: LHCb Upgrade

- Main limitation that prevents exploiting higher luminosity is the Level-0 (hardware) trigger
- To keep output rate < 1 MHz requires raising thresholds → hadronic yields reach plateau
- Proposed upgrade is to *remove* hardware trigger: read out detector at 40 MHz (bunch crossing rate). Trigger fully in software in CPU farm. Requires replacing all front-end electronics
- Will allow to increase luminosity by factor ~ 10 to 1–2 × 10^{33} cm^{-2} s^{-1}
- Framework TDR submitted to the LHCC: Physics case enthusiastically endorsed, detector R&D underway



Upgrade of LHCb detector planned for 2019 to take at least 10× more data: 50 fb^{-1}



Upgrade scenario

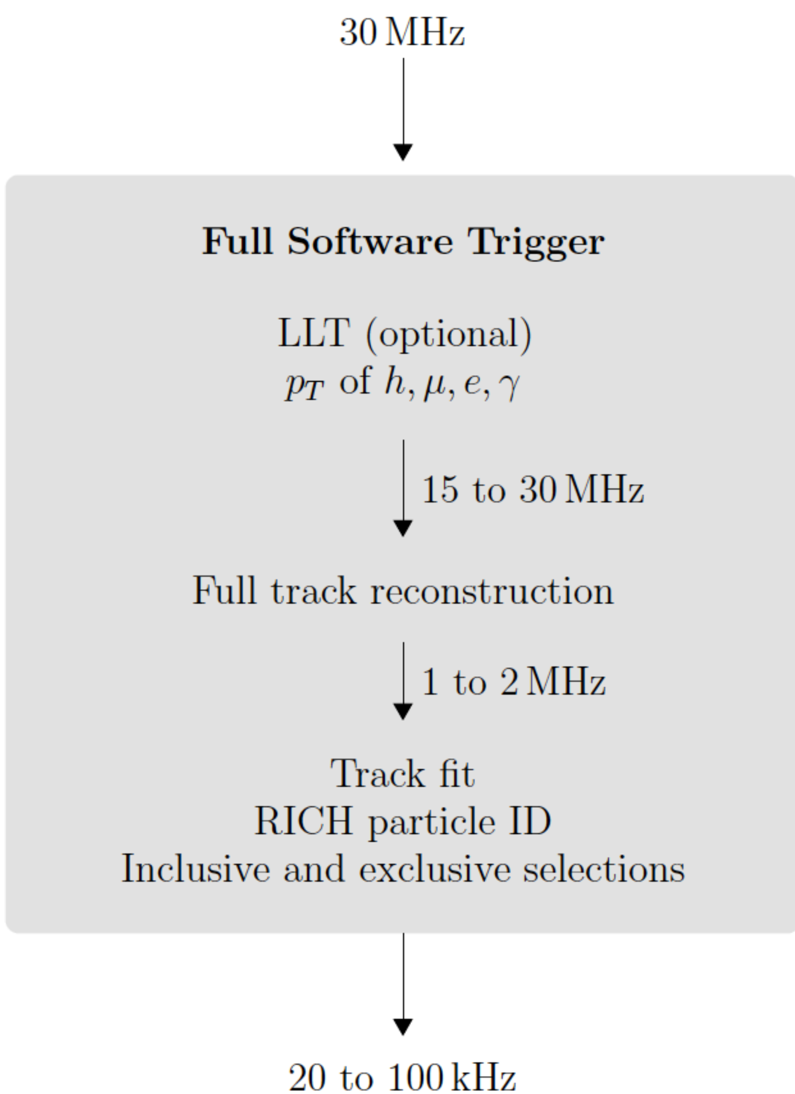
- Data taking conditions
  - Leveled instantaneous luminosity of $2 \cdot 10^{33}/cm^2/s$
  - 30 MHz collisions
  - 20-100 kHz to disk
  - $\sim 5\ fb^{-1}$ per year

- Challenges
  - High pile-up
  - Large occupancies
    - event reconstruction is more difficult
    - more difficult PID
  - Radiation damage

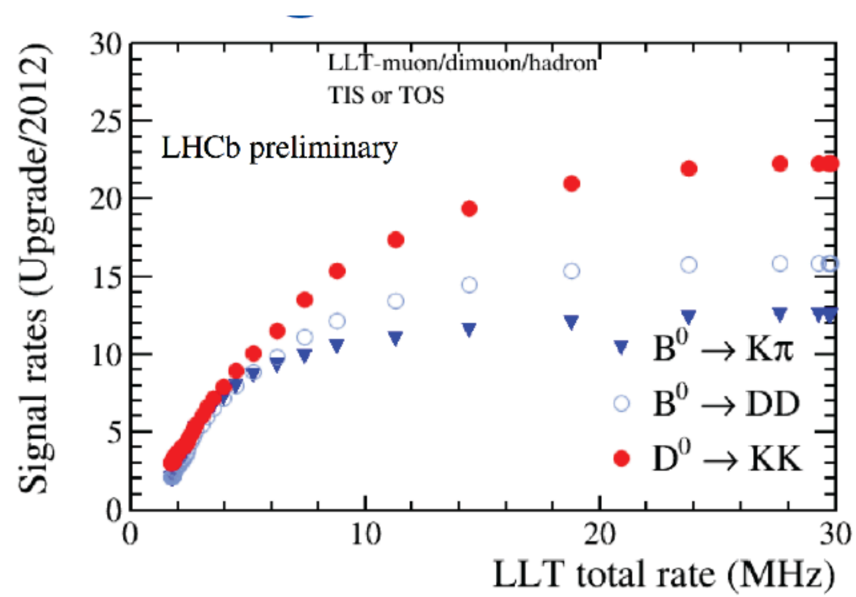
LHCb requirements

- Separate secondary decay vertices from primary production vertex → 20μm impact parameter resolution for high–p_t tracks
- Excellent momentum resolution: as low as 0.35% at 5 GeV/c (and still 0.55% at 100 GeV/c), which provides a mass resolution of 10 – 25 MeV/c^2
- Excellent particle identification capabilities, to unambiguously identify photons, electrons, muons, pions, kaons, protons in the b-meson decay chain, essential to select rare beauty and charm exclusive decays
- Efficient multi-stage trigger for leptonic and hadronic final states

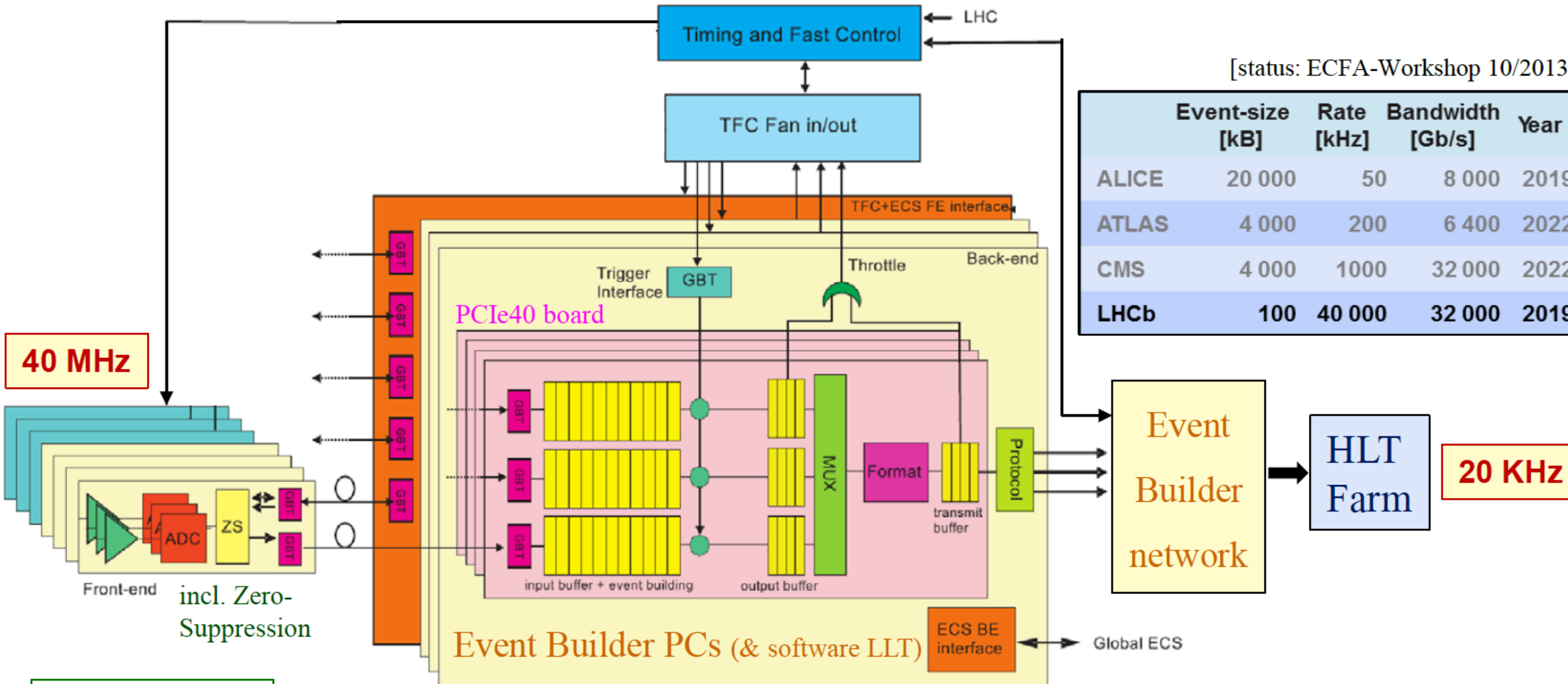
The software trigger



- **Trigger farm: 50k logical CPU cores**
- **Offline-like reconstruction tuned to available time constraints**
- **Mixture of exclusive and inclusive selection algorithms**
- **LLT output rate progressively increases as trigger farms grows**



The 40 MHz R/O architecture



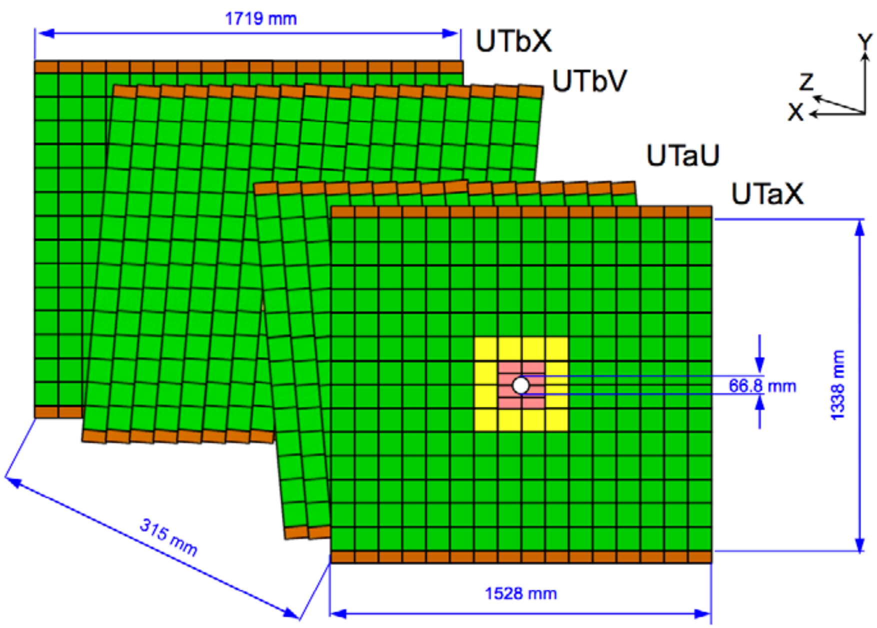
[status: ECFA-Workshop 10/2013]

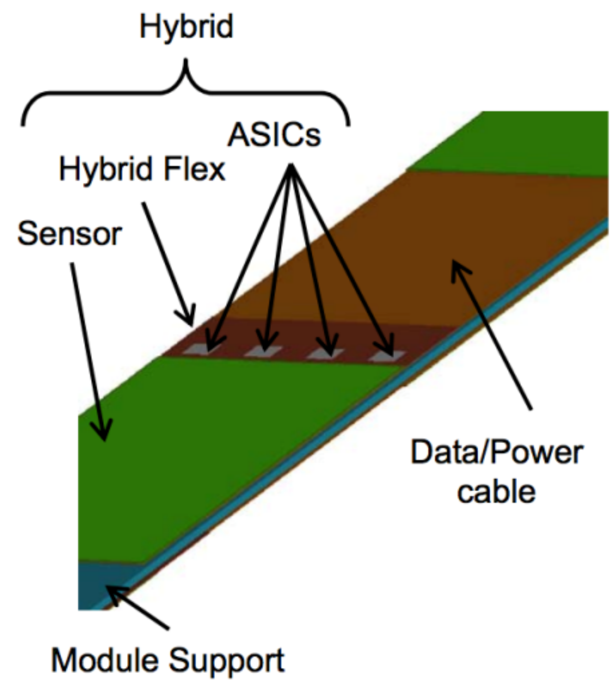
	Event-size [kB]	Rate [kHz]	Bandwidth [Gb/s]	Year
ALICE	20 000	50	8 000	2019
ATLAS	4 000	200	6 400	2022
CMS	4 000	1000	32 000	2022
LHCb	**100**	**40 000**	**32 000**	**2019**

individual sub-systems Front-End electronics → optical link via GBT → PC servers with PCIe40 R/O LLT and Event Building → pure software trigger

underground — ~300m — on surface

TT upgrade: Upstream Tracker (UT)

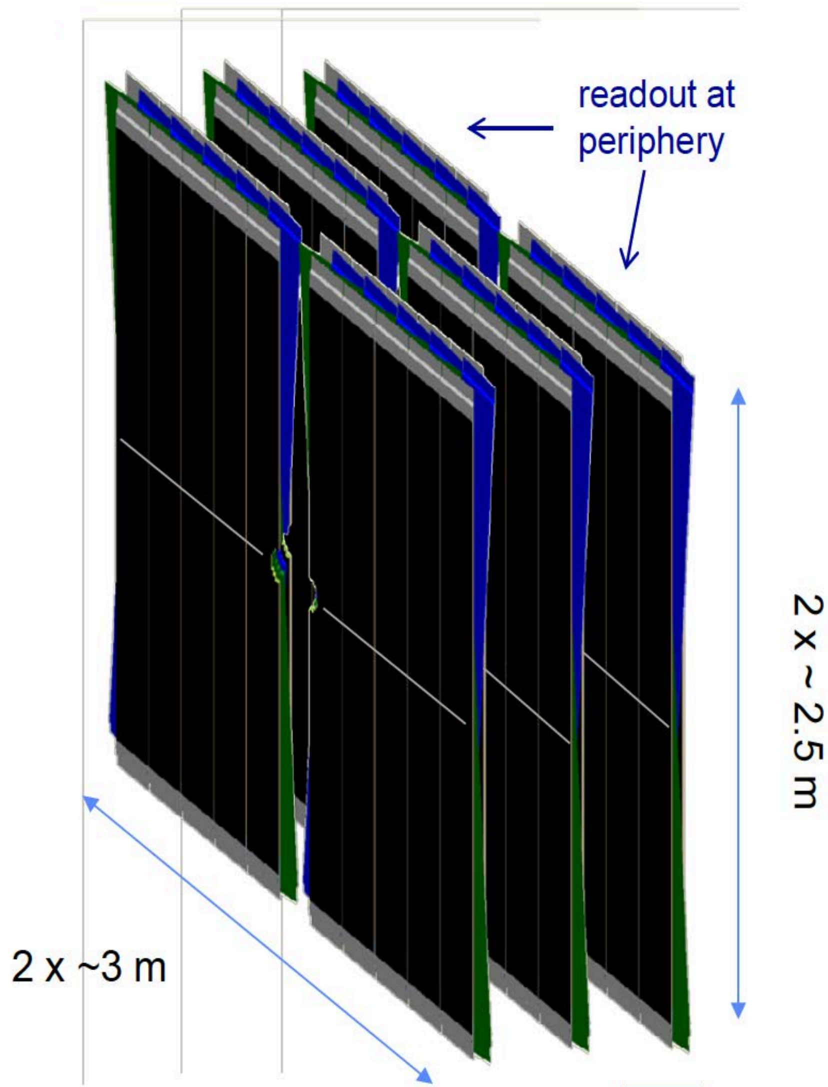




- Replace current inner silicon planes
- Upgrade: 4 detection planes, stereo
- Silicon strip detector, 250 μm thick
- Segmentation and technology depends on expected dose and occupancy
- 40 MHz R/O via SALT ASIC

FT Design

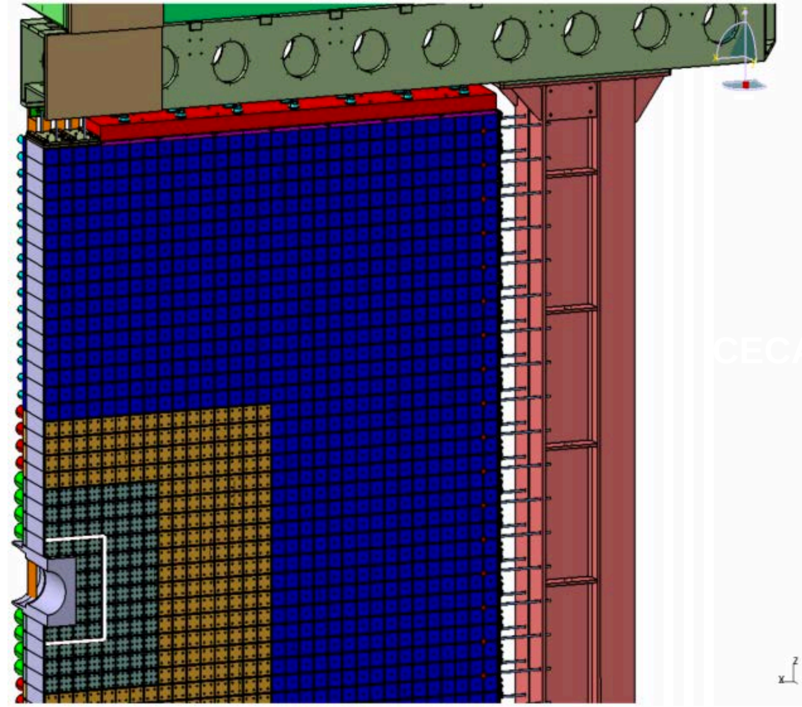
- 12 detection layers in 3 stations
- Each station has *XUVX* layers (*U,V*: ±5°)
- Advantages
  - Single technology easy to operate
  - High granularity (250 μm) gives excellent x-position resolution (50-75 μm)
  - Uniform material budget
  - SiPM & R/O outside acceptance
- Challenges
  - Radiation damage to fiber → tested, ok
  - SiPM rad. damage → operate @ -40° C

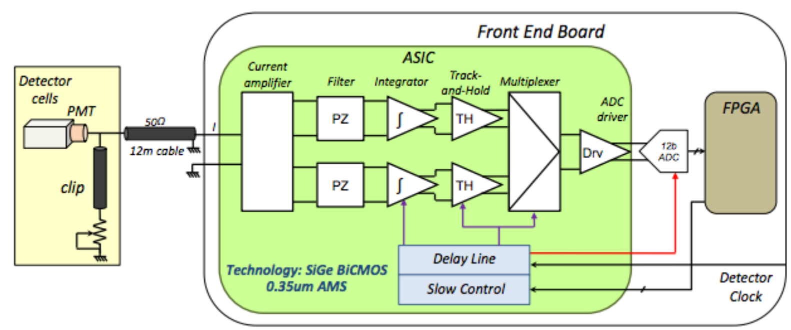


Calorimeter System Upgrade

Occupancy and radiation issues

- Pre-shower and SPD will be removed (no more L0 calorimeter trigger)
- ECAL expected to be fine up to 20fb^{-1}, inner ECAL cells could be replaced at LS3
- HCAL OK up to 50 fb^{-1}
- Lower PMT gains to guarantee extended operation at HL
- New front-end electronics: ICECAL
- New back-end electronics, calculating ECAL and HCAL 2x2 cell energy for LLT

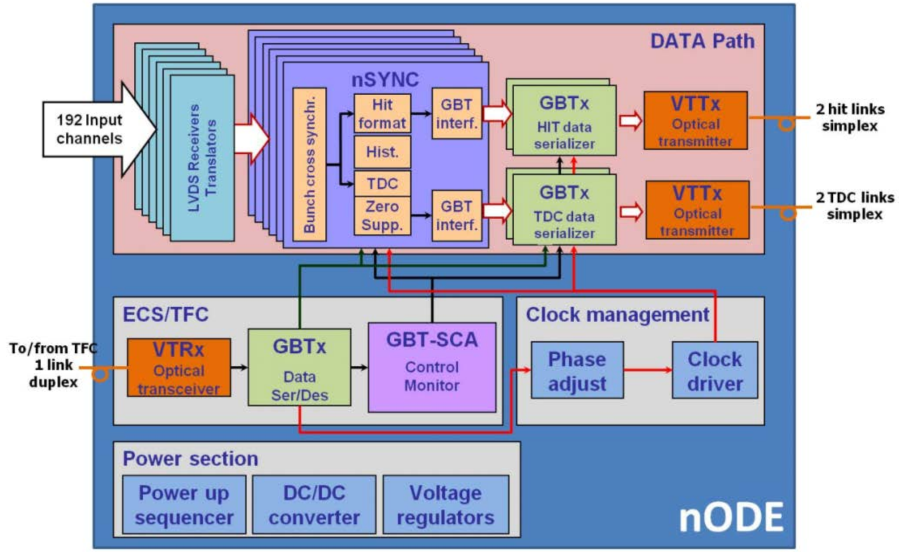


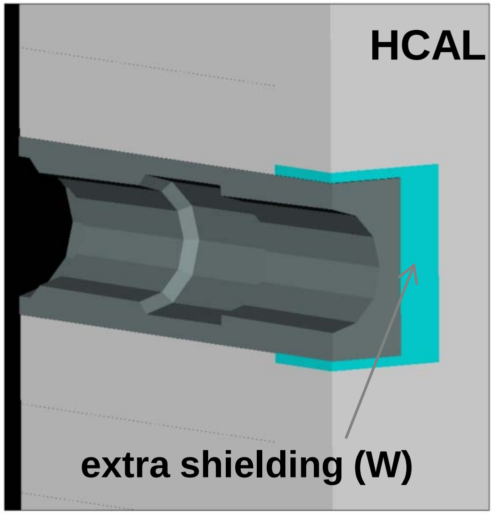


Muon system Upgrade

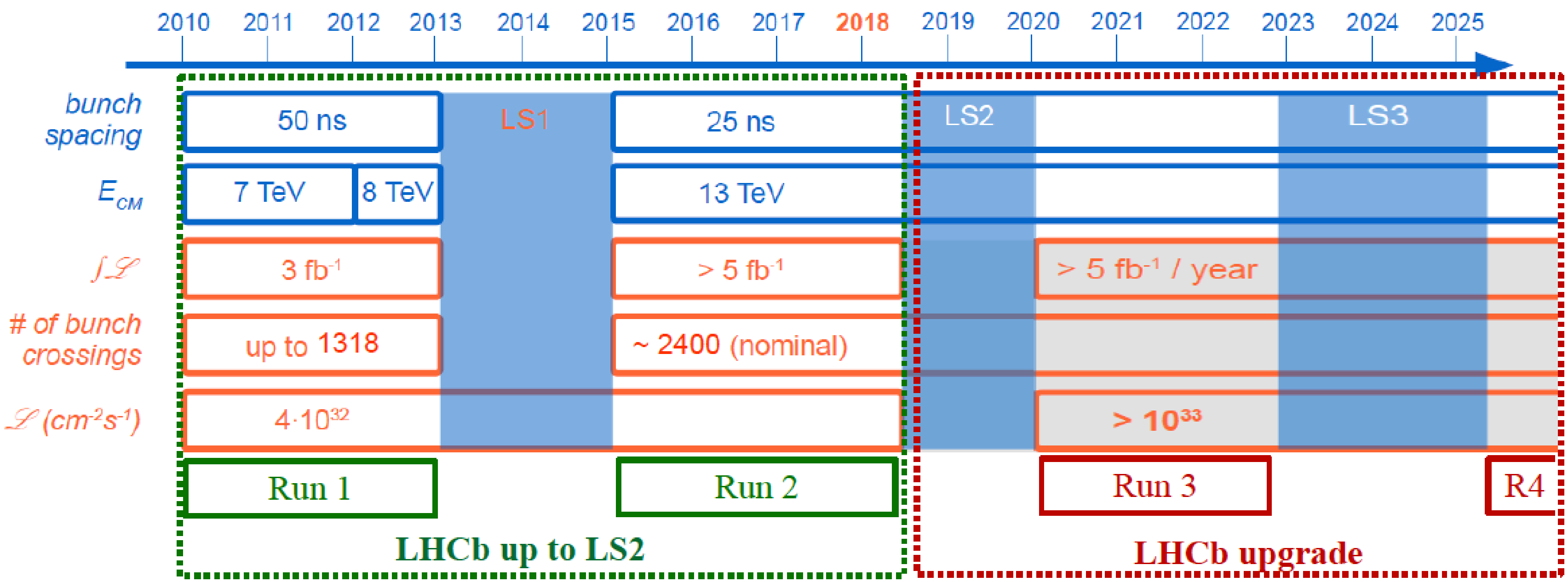
R/O and occupancy issues

- Muon detector front-end CARIOCA already operating at 40 MHz
- New off-detector board for efficient readout via PCIe40 common R/O boards
- Remove M1
  - no muon level-0 muon trigger
  - Very high occupancies
- Additional shielding behind HCAL to reduce rate in inner regions of M2
- Possible replacement of M2/M3 inner region detectors under study





The next years



- Run2 starts in 2015, the aim is to collect 5 fb^{-1}
- LS2: 18 months for full LHCb upgrade
- Then: collect ~5 fb^{-1}/year