The LHCb Upgrade

3 October 2014

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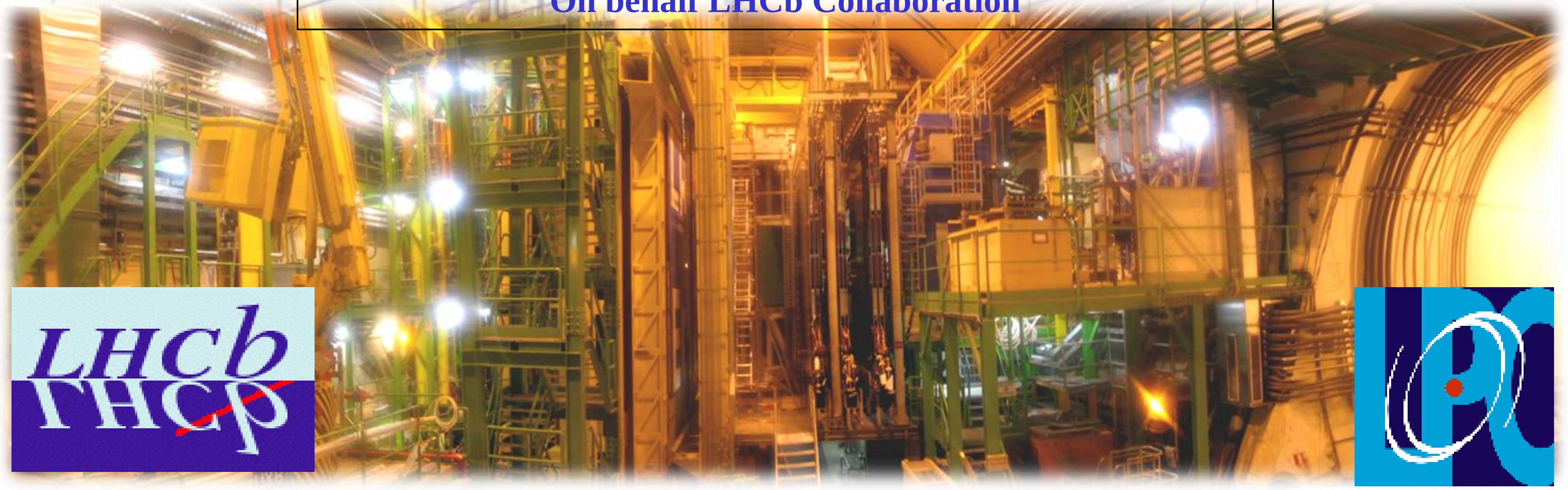
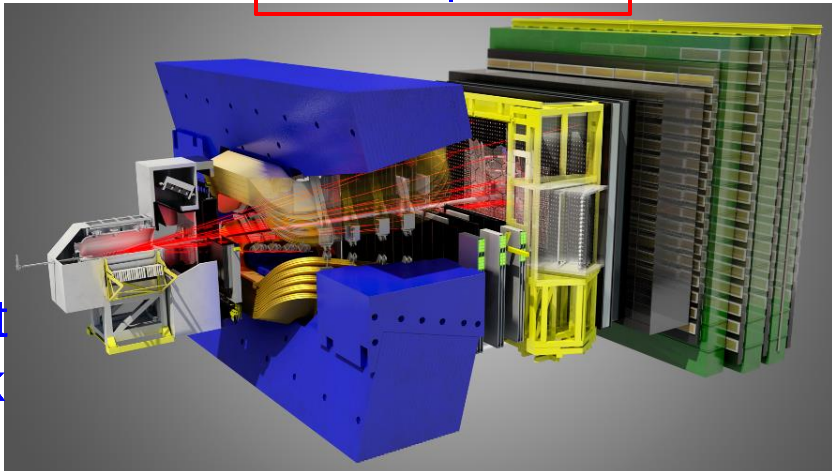
On behalf LHCb Collaboration



Introduction

- LHCb
  - A high precision experiment devoted to the search for New Physics (NP) beyond the Standard Model (SM) by
    - Studying CP violation and rare decays in the b and c-quark sectors
    - Searching for deviations from the SM due to virtual contributions of new heavy particles in loop diagrams
    - Being sensitive to new particles above the TeV scale not accessible to direct searches
  - A single-arm forward spectrometer
    - Exploiting the huge production of beauty-pairs at small angles
      - σ_{bb}:250 – 500 μb @$\sqrt{s}$=7–14TeV
      - σ_{cc} is 20 times larger!
    - Covers ~4% of the solid angle, but captures ~30% of the heavy quark production cross-section

LHCb region
$2 < \eta < 5$



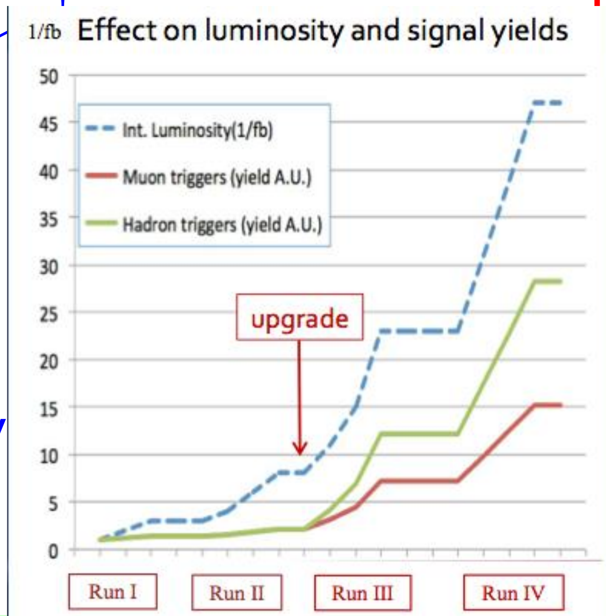
Motivation for the LHCb Upgrade

- Past and running experiments have shown that:
  - Flavour changing processes are consistent with the CKM mechanism
  - Large sources of flavour symmetry breaking are excluded at the TeV scale
  - The flavour structure of the NP, if it exists, would be very peculiar at the TeV scale (MFV)
- However:
  - Measurable deviations from the standard model are still expected, but should be small
  - Need to go to very high precision measurements to probe the most clean observables
- LHCb upgrade essential to increase statistical precision significantly!
- Reinforce LHCb as a general purpose forward detector

Expected luminosity evolution

Bunch spacing	50 ns	LS1	25 ns	LS2	25 ns	LS3
Start-up	2010 2011 2012 2013	2014	2015 2016 2017 2018	2019	2020…2023	…2025
$\sqrt{s}$ (TeV) = 0.9 - 7	- 8	-	13			
$\mathcal{L}$ ($cm^{-2}s^{-1}$) = 10^{32}	4×10^{32}		4×10^{32}		$>10^{33}$	
$\int \mathcal{L} dt$	$3\ fb^{-1}$		$\sim 5\ fb^{-1}$		$> 50\ fb^{-1}$	
	Run I		Run II		Run III	Run IV

- LHCb up to 2018:
  - $\sim 8\ fb^{-1}$
  - Find or rule-out large sources of flavour symmetry breaking at the TeV scale



- LHCb upgrade: $>50\ fb^{-1}$
  - Increase precision on quark flavour physics observables
  - Aim at experimental sensitivities comparable to theoretical uncertainties

- *Note that LHCb upgrade does not depend on LHC upgrade*
  - *A fraction of the available luminosity is used*

Motivation for the LHCb Upgrade

- LHCb statistical sensitivity to flavour observables
  - Expected statistical uncertainties on a few selected physics channels before and after the upgrade, compared to theory

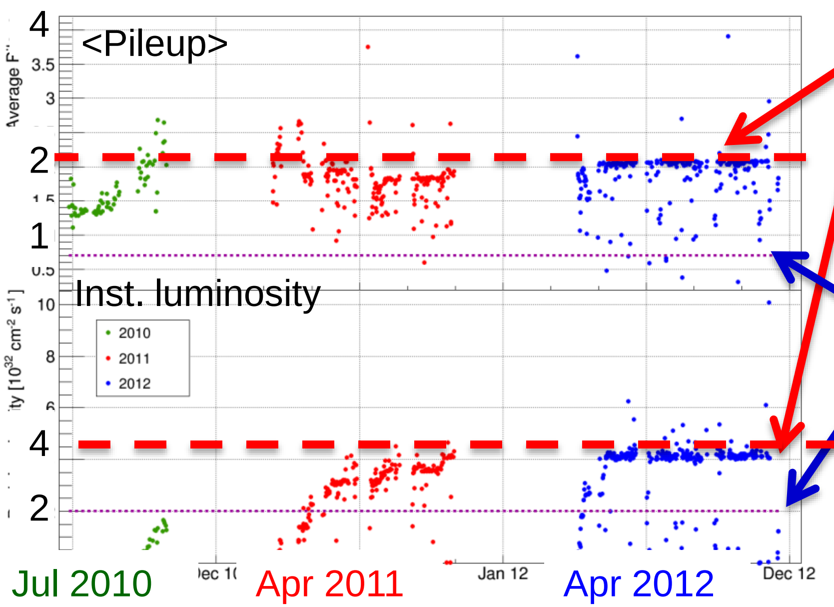
Few selected topics

	LHCb up to LS2		LHCb upgrade		Theory
	Run 1	Run 2	Run 3	Run 4	Theory uncertainty
Integrated lumi	3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	
$\frac{Br(B_d\to\mu\mu)}{Br(B_s\to\mu\mu)}$	-	110 %	60%	40%	5%
$q_0^2 A_{FB}(B_d \to K^{*0}\mu\mu)$	10%	5%	2.8%	1.9%	7%
$\phi_s(B_s \to J/\psi\phi, B_s \to J/\psi\pi\pi)$	0.05	0.025	0.013	0.009	0.003
$\phi_s(B_s \to \phi\phi)$	0.18	0.12	0.04	0.026	0.02
γ	7°	4°	1.7°	1.1°	negl.
$A_\Gamma(D^0 \to KK)$	3.4 10^{-4}	2.2 10^{-4}	0.9 10^{-4}	0.5 10^{-4}	-

From “Heavy Flavour Physics in the HL-LHC era” document prepared for the Aix-les-Bains ECFA Workshop – Oct 2013

LHCb operation

- Quite different conditions compared to LHCb design
  - 50 ns bunch spacing, 7/8 TeV < 1300 bunches
    - 25 ns bunch spacing, 2808 bunches, 14 TeV
  - Pileup up to μ=4 visible interactions /crossing
    - μ=0.7
  - L= $4x10^{32}cm^{-2}s^{-1}$
    - L= $2x10^{32}cm^{-2}s^{-1}$

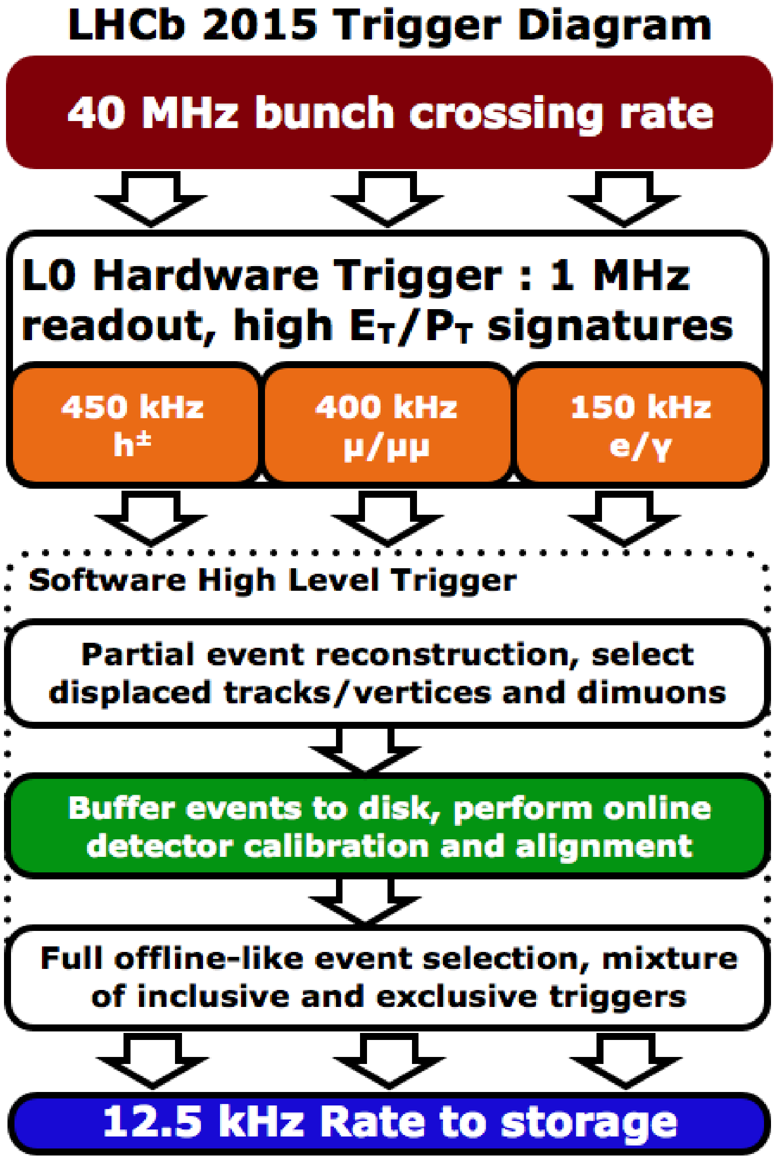


- 2012 working point:
  - μ=2.1
  - L = $4x10^{32}cm^{-2}s^{-1}$

Nominal design values

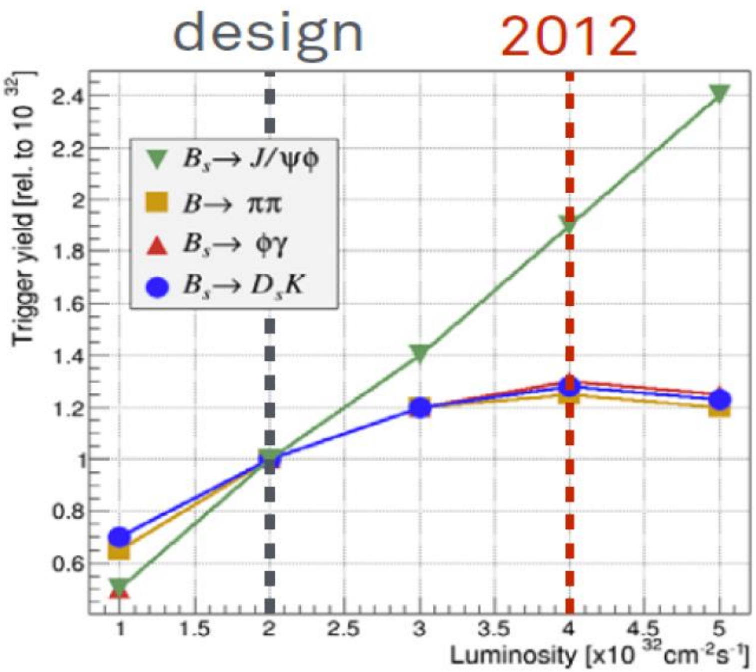
- *LHCb able to run smoothly at higher luminosity and μ*
  - *While performing good physics*

LHCb trigger … limitations



- Hardware Trigger (Level-0):
  - "Moderate" E_T/p_T threshold on *e/γ, h or μ*
  - Max output rate: 1Mz
- SoftwareTrigger (HLT):
- Storage rate: 2 - 5 - 12.5 kHz

LHCb trigger … limitations

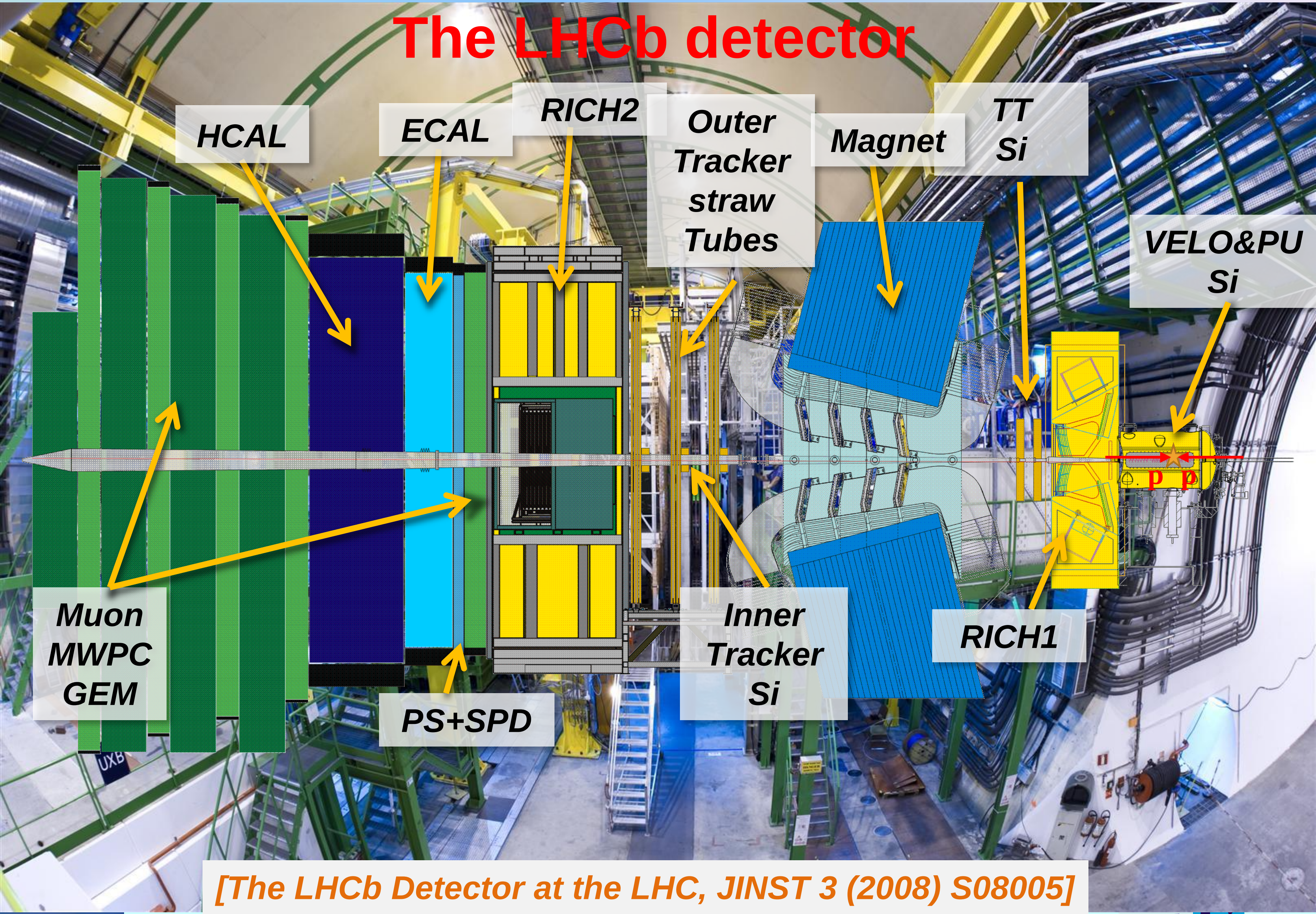


- At present conditions if we increase the luminosity:
  - We must raise E_T/p_T cut to stay within 1 MHz readout limit
    - Final states with muons
      - Linear gain
    - Hadronic final states
      - trigger yield saturates
  - To profit of a luminosity of $10^{33} cm^{-2} s^{-1}$, information has to be introduced that is more discriminating than E_T:
    - Impact parameter!

Upgrade strategy

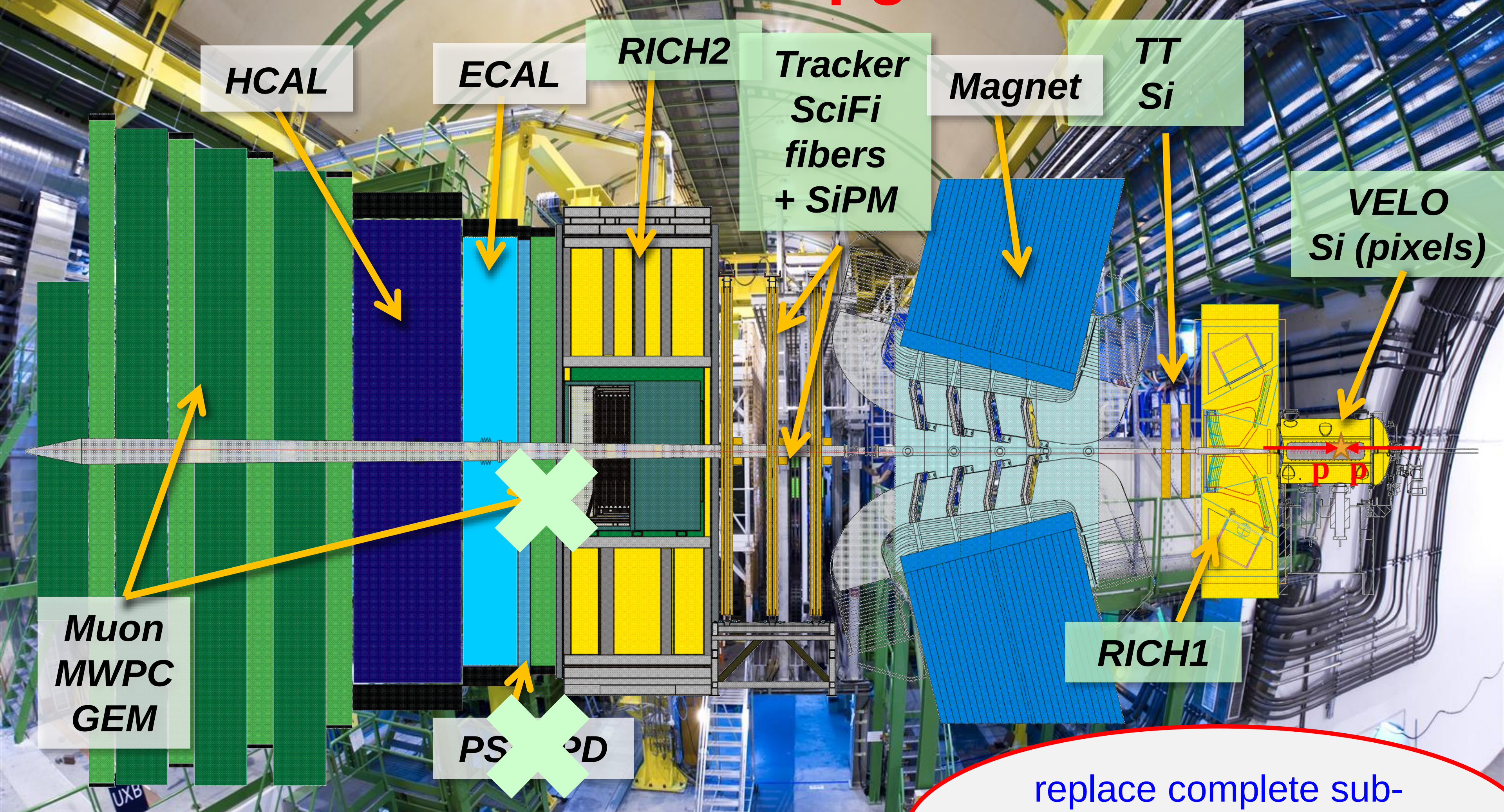
- Remove the level-0 hardware trigger
  - Readout an event every bunch crossing: 40MHz readout rate
  - New front-end electronics
    - on-chip zero suppression
  - New DAQ system
- Use an efficient fully software trigger accessing complete event information, running at the bunch crossing rate
- Adapt sub-systems to increased occupancies due to higher luminosity and to radiation damage
- Keep excellent performance of sub-systems

The LHCb detector



[The LHCb Detector at the LHC, JINST 3 (2008) S08005]

The LHCb Upgrade

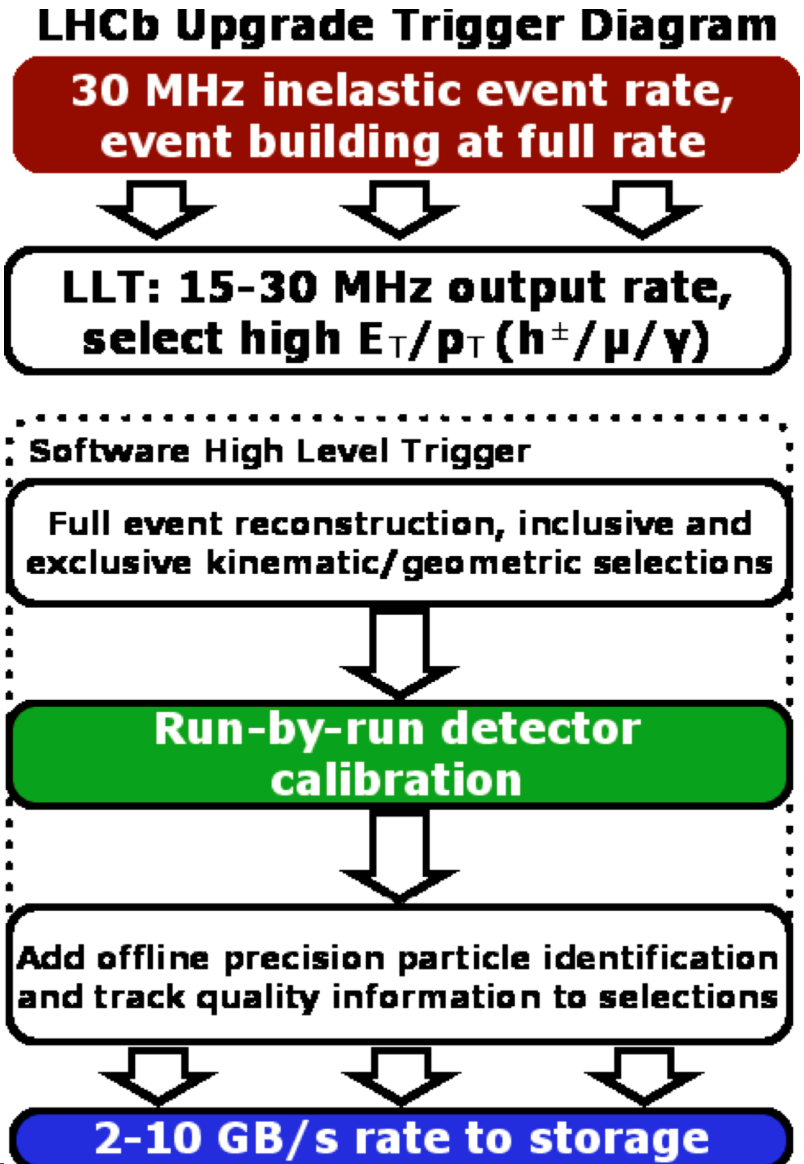


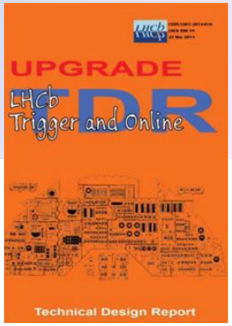
replace complete sub-systems with embedded FE electronics

- Fully software trigger + new DAQ + …

[LHCb Upgrade LoI: CERN-LHCC-2011-001]

Trigger and Online upgrade

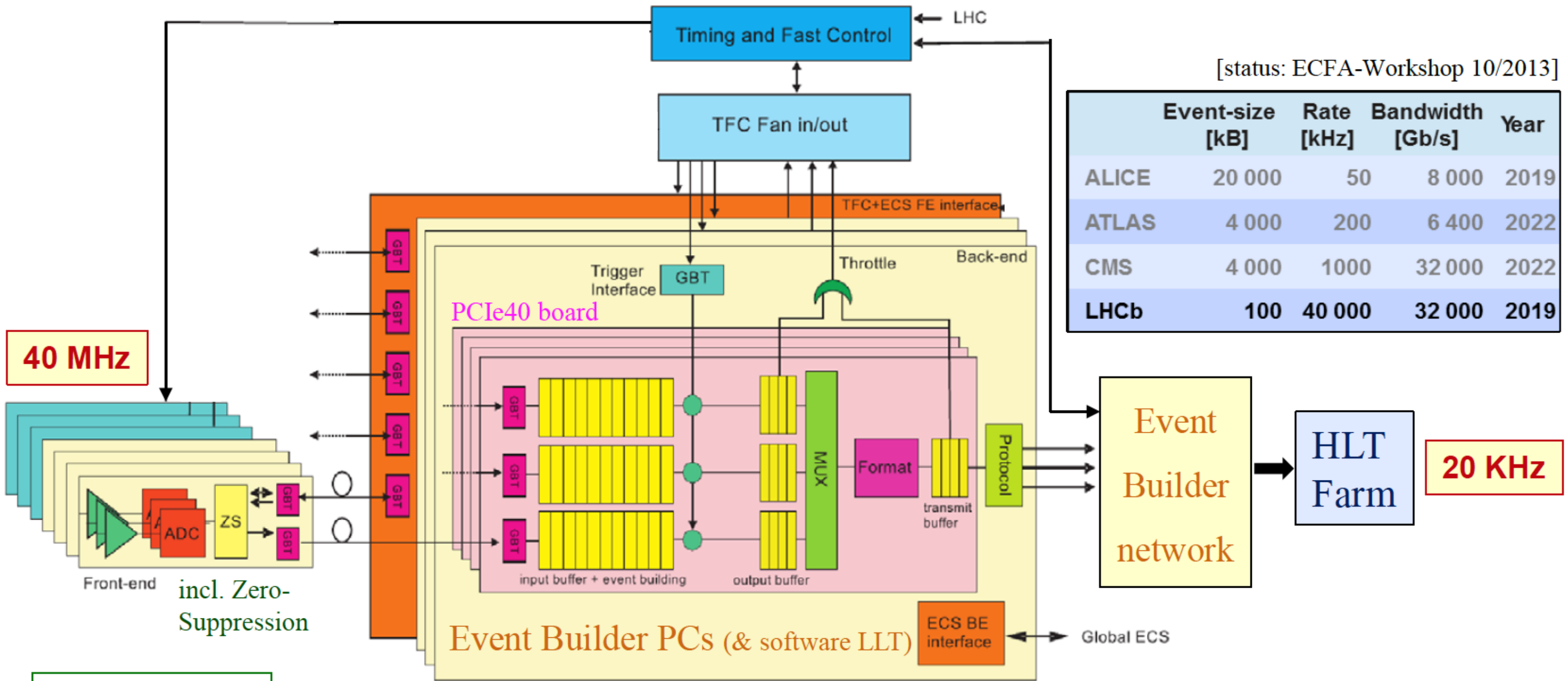




- Use complete event information, running at the bunch crossing rate
  - Low Level Trigger foreseen in early stage:
    - Partial information from calorimeter and muon detectors
    - LLT output rate increases as trigger farms grows
  - Online detector calibration
  - ~20-100 kHz storage rate

Trigger and Online upgrade

◆ The 40 MHz R/O Architecture



[status: ECFA-Workshop 10/2013]

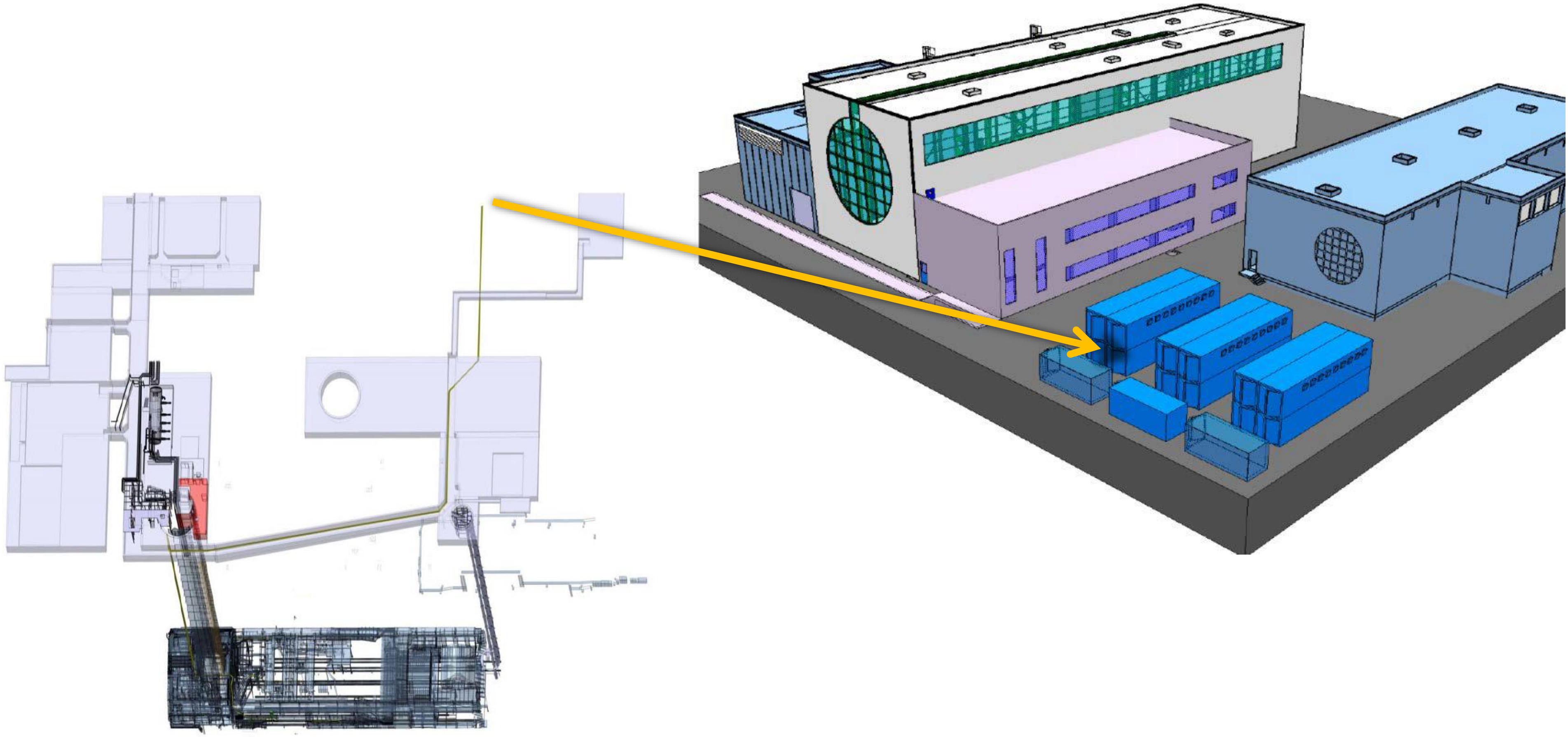
	Event-size [kB]	Rate [kHz]	Bandwidth [Gb/s]	Year
ALICE	20 000	50	8 000	2019
ATLAS	4 000	200	6 400	2022
CMS	4 000	1000	32 000	2022
LHCb	**100**	**40 000**	**32 000**	**2019**

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

Preparation for trigger upgrade

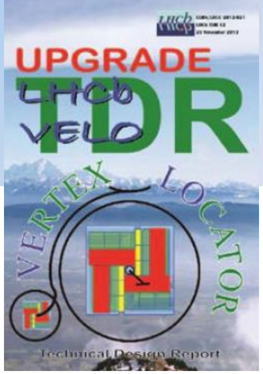
- Optical links
  - New PC farm at surface (prototype in 2015)
  - 17000x350m fibres from UX to SX



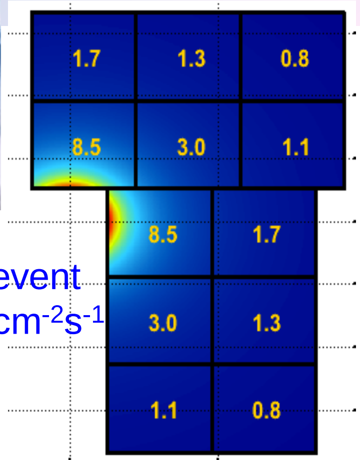
Preparation for trigger upgrade

- Civil engineering has started …

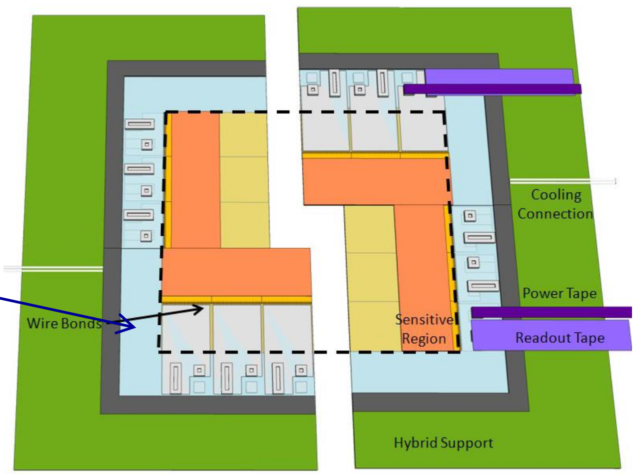
VELO upgrade

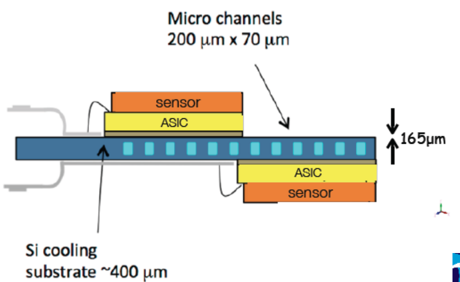


- Challenges:
  - Withstand increased radiation
    - Highly non-uniform radiation of up to $8 \cdot 10^{15}$ n_{eq}/cm^2 for 50 fb^{-1}
  - Handle high data volume (up to 20Gbit/s!)
  - Keep (improve) current performance
    - Lower materiel budget
    - Enlarge acceptance
- Technical choices:
  - 55x55 μm^2 Si pixel sensors (41×10^6)
    - 26 stations
    - Micro channel CO_2 cooling
    - 40 MHz VELOPIX
      - Evolution of TIMEPIX 3, Medipix, 8xfaster
      - 130 nm technology to sustain ~400 MRad in 10 years



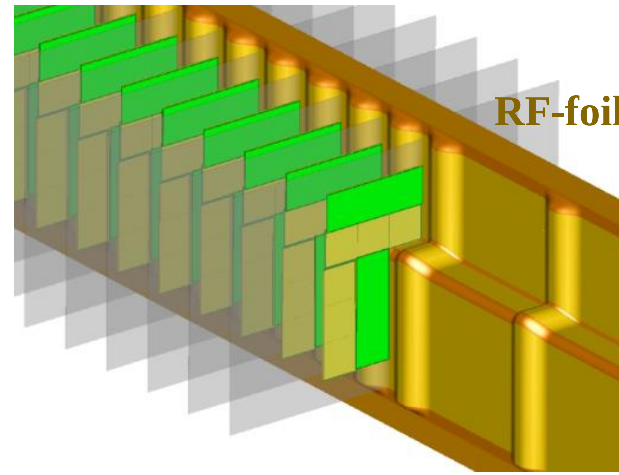
tracks/chip/event at $L = 2 \cdot 10^{33}$ $cm^{-2}s^{-1}$

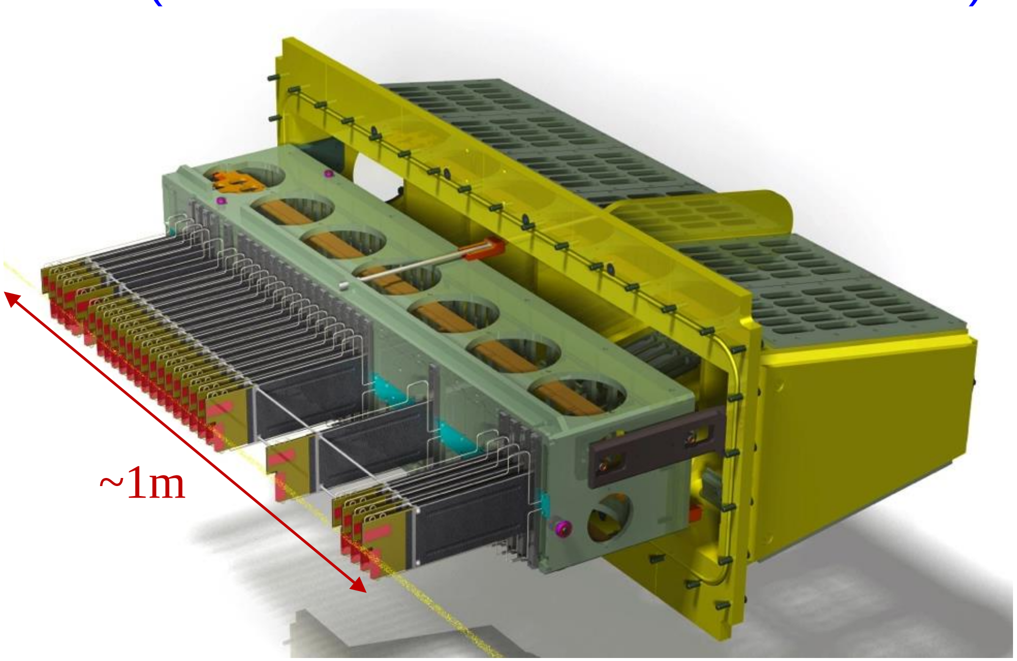


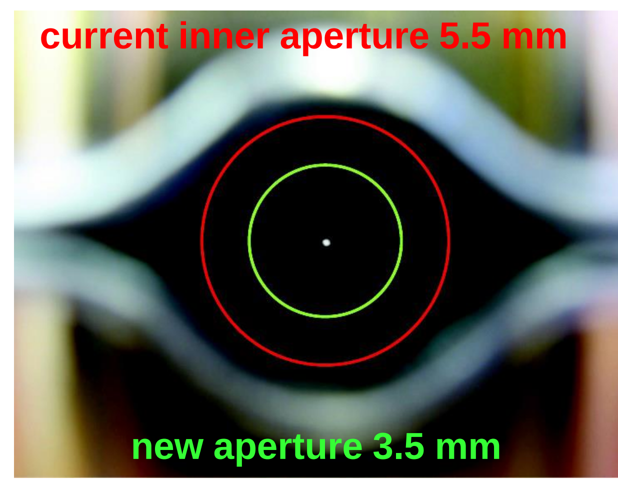


VELO upgrade

- Technical choices:
  - Replace RF-foil between detector and beam vacuum
    - Reduce thickness from 300 μm → ~150 μm
  - Move closer to the beam
    - Reduce inner aperture from 5.5 mm → 3.5 mm (first measurement 8.13mm → 5.1 mm)



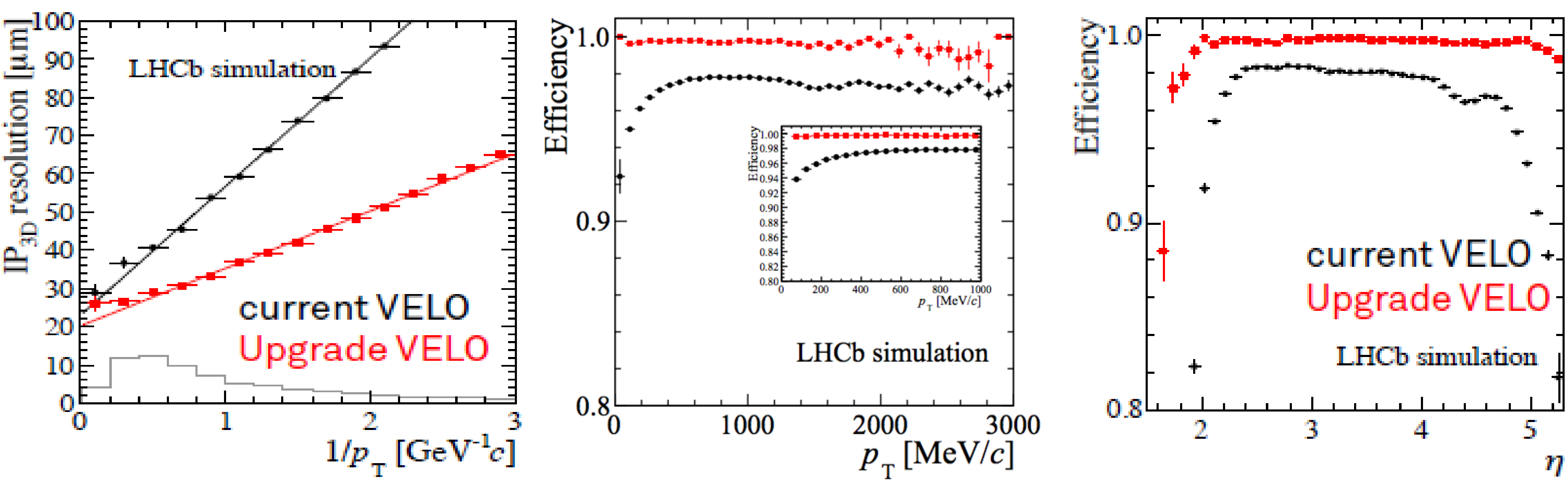




45 deg. rotated new VELO option under discussion

VELO upgrade performances

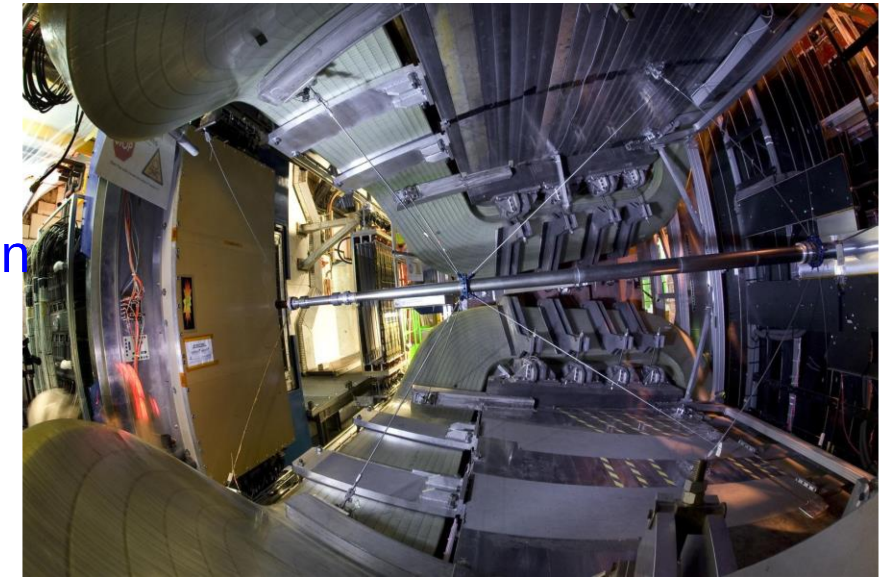
- Expected performances at ~$2\times10^{33}cm^{-2}s^{-1}$ are superior in essential every aspect with respect to the current VELO operating at high luminosity
  - Better impact parameter resolution due to reduced material budget
  - Reduced ghost rate due to pixels
  - Improved efficiency over full range in p_T, φ, η



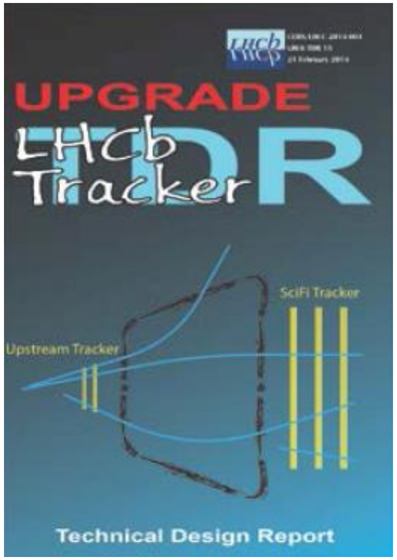
note: full GEANT Monte Carlo with standard LHCb simulation framework

Tracker upgrade

- Challenges:
  - Cope with increased particle density
    - Especially in downstream stations
  - Improve speed of track reconstruction
    - Crucial for trigger performance
  - Improve forward acceptance in upstream station
    - Approach closer to beam pipe

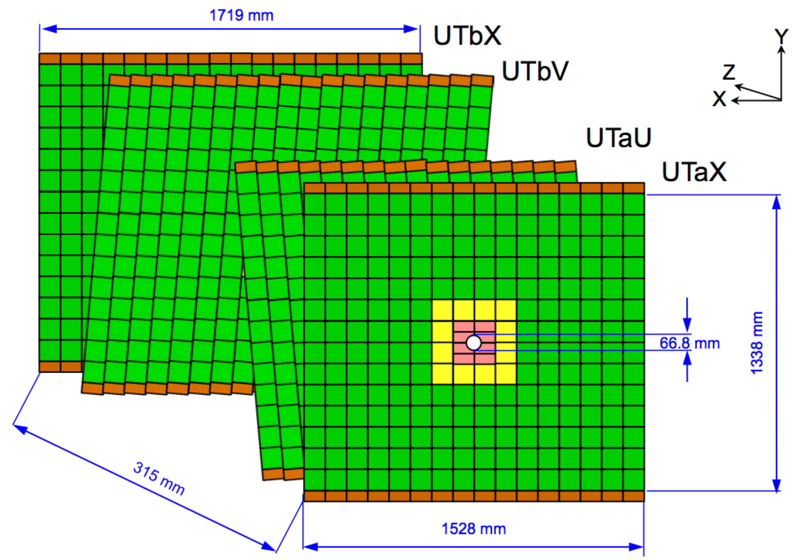


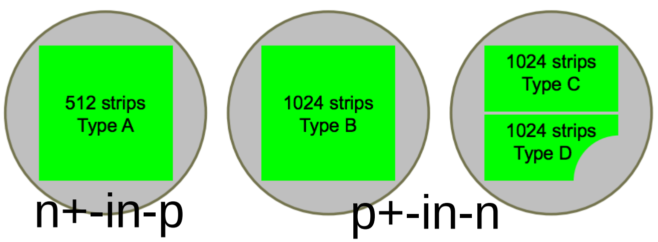
- Technical choices:
  - Keep current setup with 1+3 stations
  - Upstream: silicon strip detector with finer readout granularity
  - Downstream: scintillating fibres

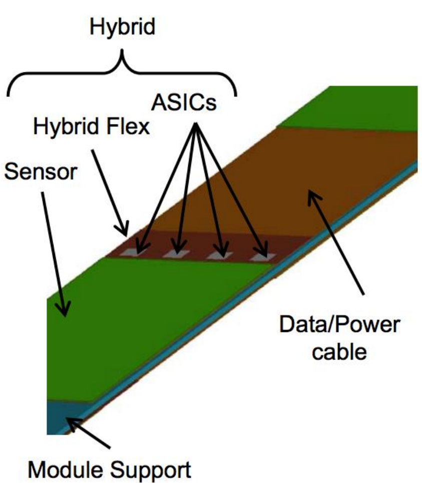


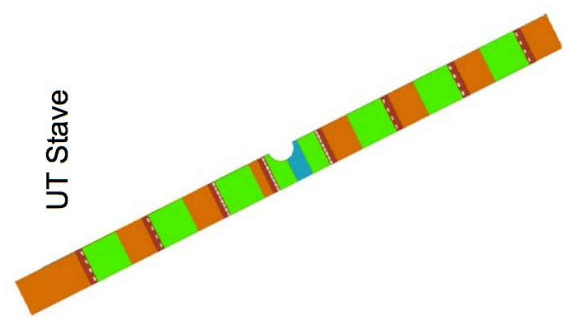
Upstream Tracker (UT)

- 4 detection planes, stereo
- Silicon strip detector
  - 250 µm thickness
- Segmentation and technology depends on expected dose and occupancy region
  - Three readout strip geometries
    - 49 (C,D) / 98 (B,A) mm long strips
    - 95 (B,C,D) / 190 (A) µm pitch
- 40 MHz R/O via SALT ASIC



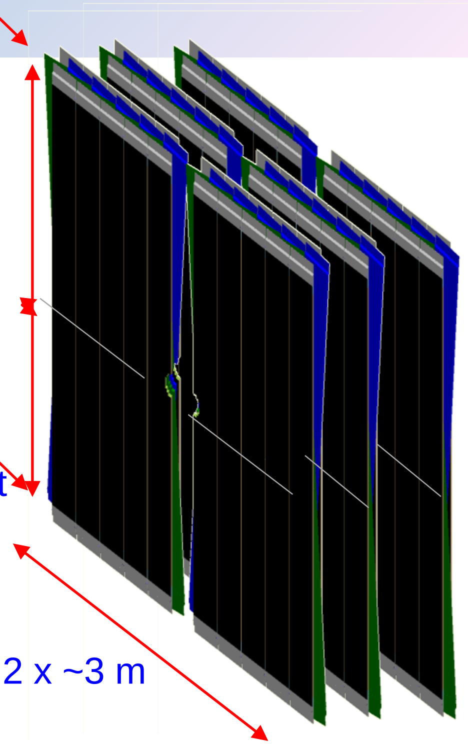


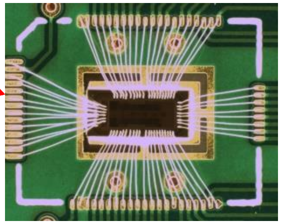


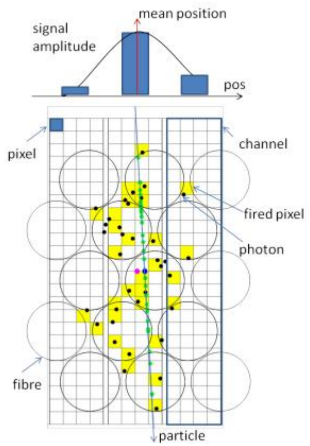


SciFi Tracker

- A single technology
  - Scintillating fibres read out with SiPMs
    - 3 stations of X-U-V-X (±5° stereo angle) planes: 12 layers
    - 2.5 m long, Ø=250 μm fibres
    - Excellent x-position resolution (50-75 μm)
    - Fast pattern recognition for HLT
  - 40 MHz R/O via PACIFIC ASIC
  - SiPM & R/O outside acceptance
- Challenges:
  - Radiation environment
    - Ionization damage to fibres: tested ok
    - Neutron damage to SiPM: operate at -40°C
  - Large size – high precision
    - O(10’000 km) of fibres
    - O(500’000) R/O channels



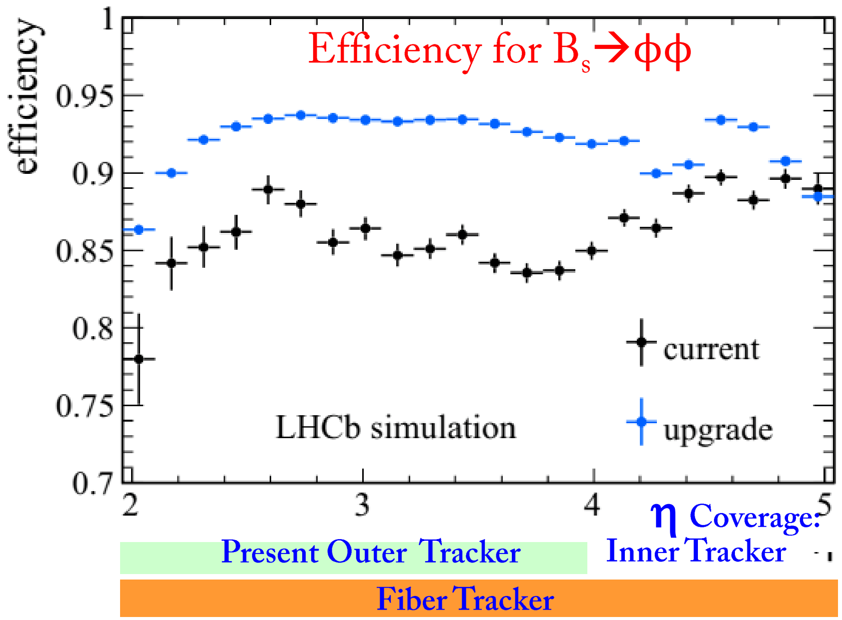


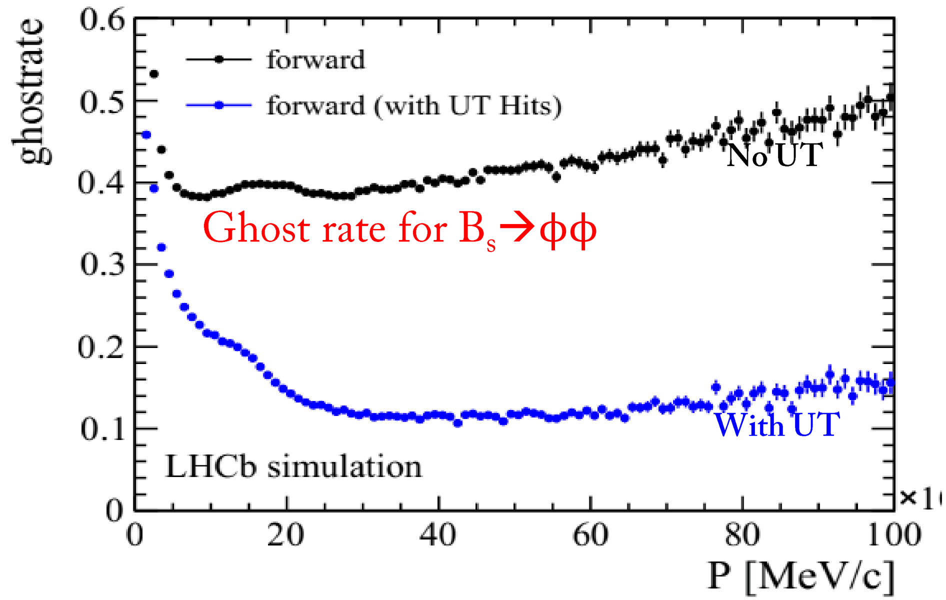


~15-20 p.e. for 5 layers of fibers

Upgraded Tracker performances

- Performance of the forward pattern recognition algorithm

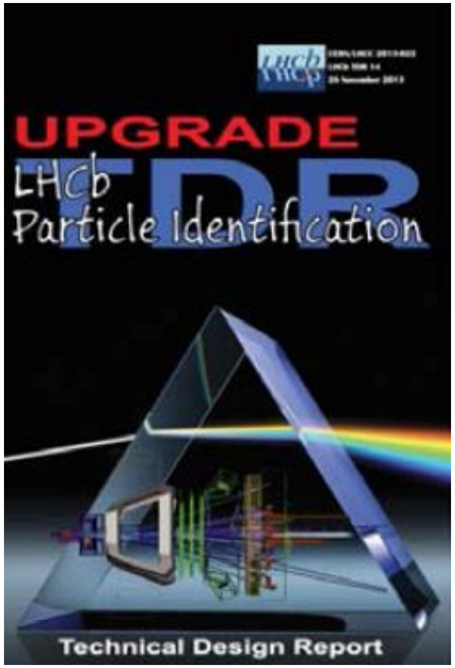




- Improved tracking efficiency with Fiber Tracker
- Improved background rejection with Upstream Tracker

Particule IDentification upgrade

- 3 systems:
  - RICHs
  - Calorimeters
  - Muon
- Challenges:
  - High occupancy and radiation rate
  - Keep excellent present performances!
- Technical choices:
  - Keep as much as possible current detectors
  - New electronics: R/O @40MHz

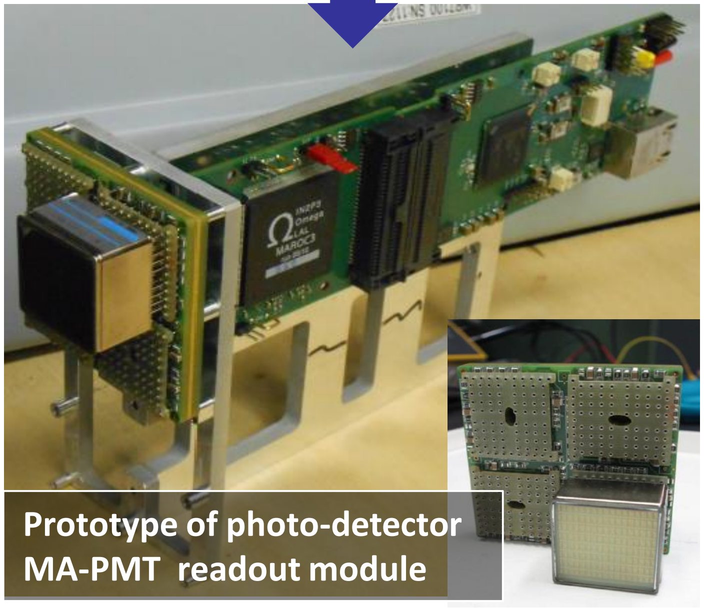


RICH upgrade

- New 40 MHz readout:
  - HPD photon detectors with embedded 1 MHz front-end readout electronics replaced by commercial Multi-Anode PMTs (64 ch.)
  - 40 MHz R/O via CLARO ASIC
- RICH1 re-optimization
  - Remove aerogel
  - Improve optics to spread out Cherenkov rings on the focal plane

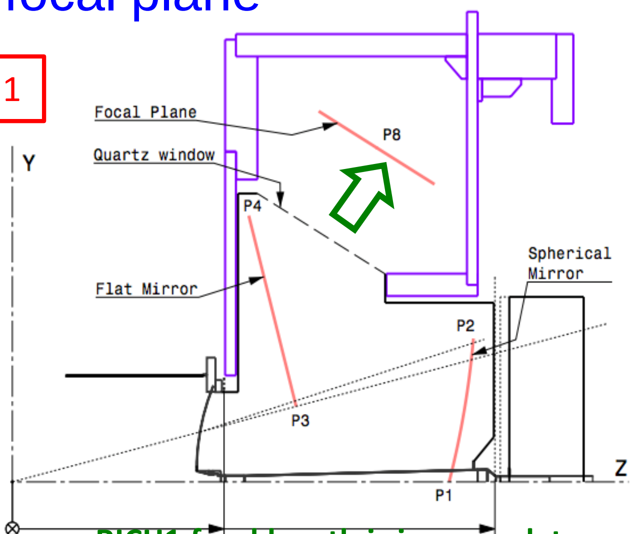
Hybrid Photon Detector

with embedded 1 MHz R/O chip



Prototype of photo-detector MA-PMT readout module

Upgraded RICH1

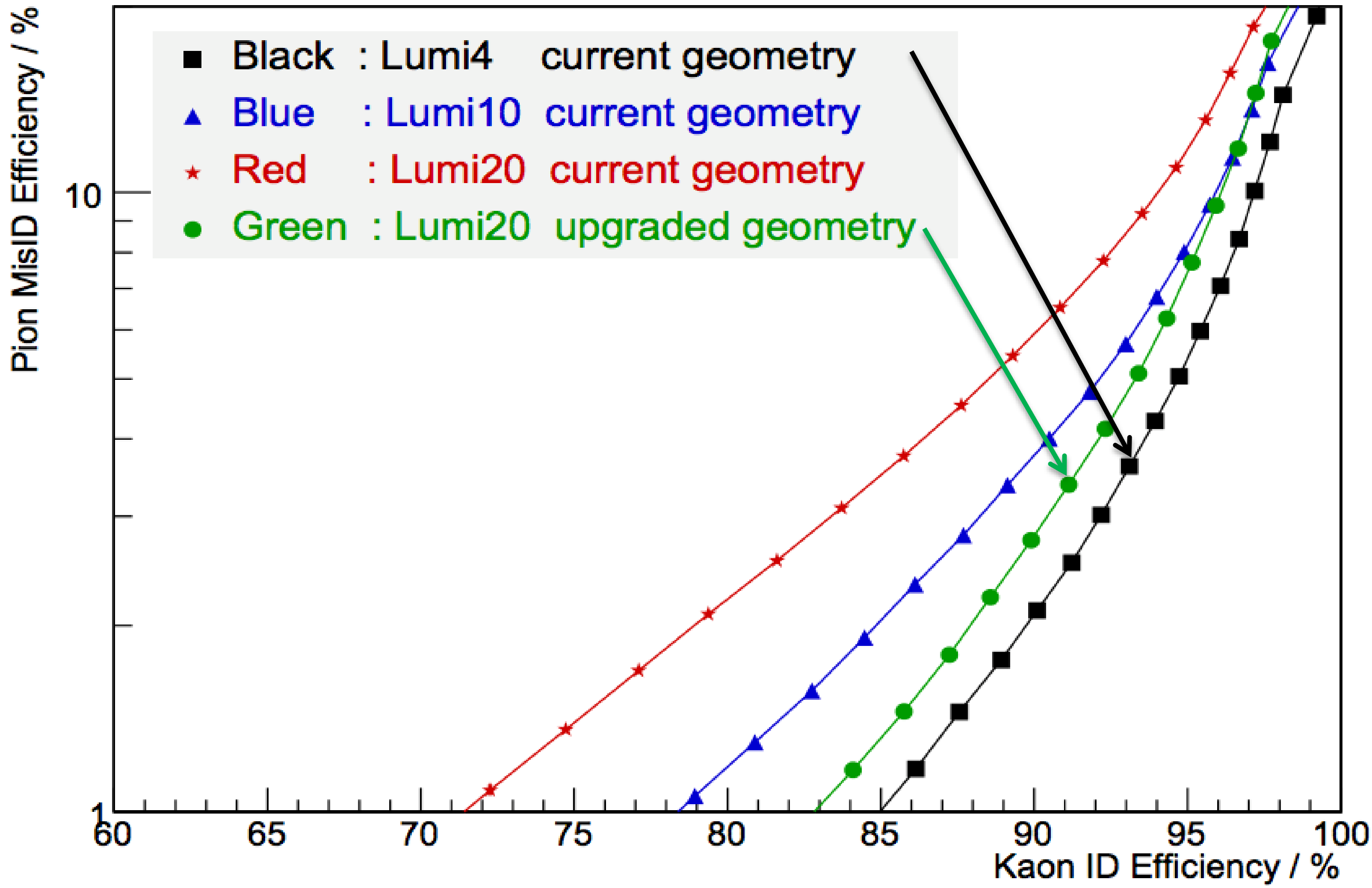


Optimise gas enclosure without modifying B-shield

RICH1 focal length is increased to reduce occupancy

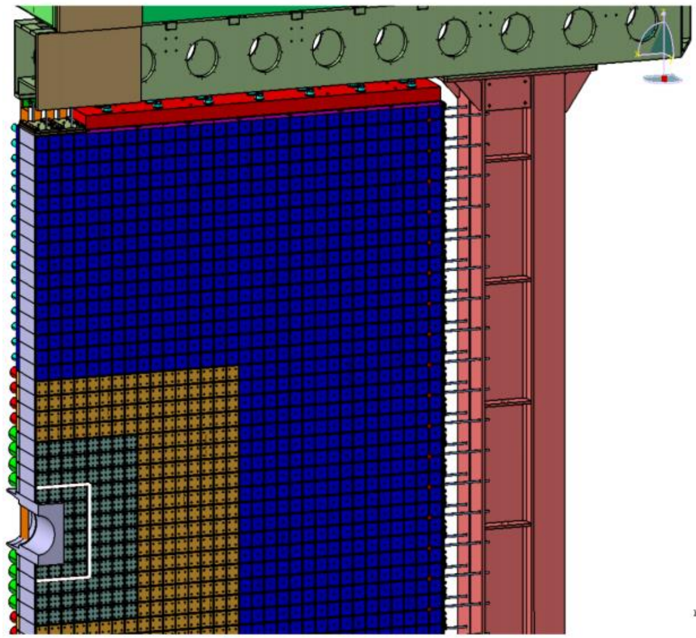
RICH upgrade performance

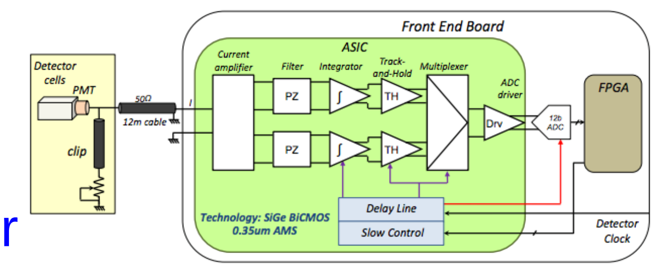
- Expected Performances at ~$2x10^{33} cm^{-2} s^{-1}$ close to current one
  - Expected K/π performance

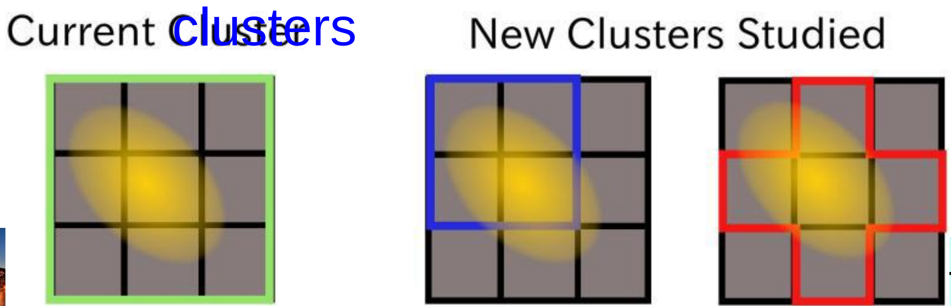


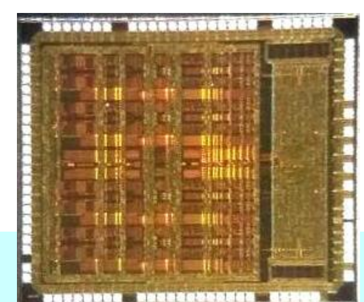
Calorimeter upgrade

- PS 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}
- Lowered PMT gains to guarantee extended operation at high luminosity
- New front-end electronics (5 times more gain)
  - 40 MHz R/O via ICECAL
- Impact of pile-up on the energy / position measurement:
  - Change the reconstruction and define smaller clusters



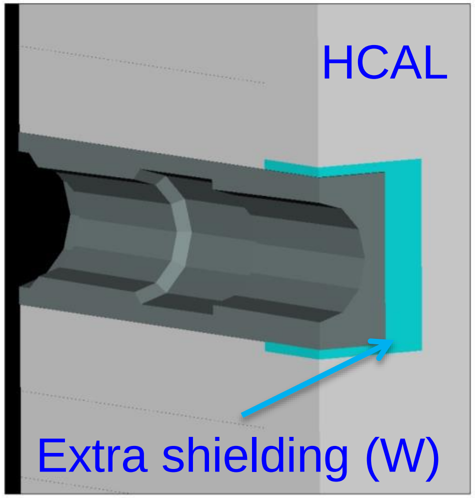


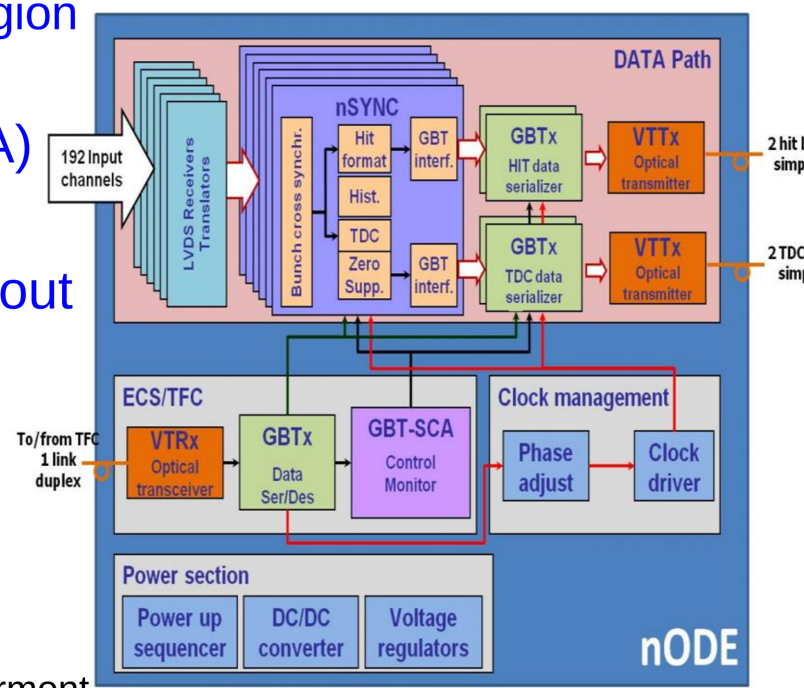




Muon system upgrade

- Main changes:
  - M1 will be removed
    - No more L0 muon trigger
    - Very high occupancies
  - Occupancy issues:
    - Additional shielding behind HCAL
      - To reduce the rate in the inner region of M2
    - Possible replacement of M2/M3 inner region detectors under study
  - Keep on-detector electronics (CARIOCA)
    - Already at 40 MHz readout !
  - New off-detector board for efficient readout via PCIe40 common R/O boards



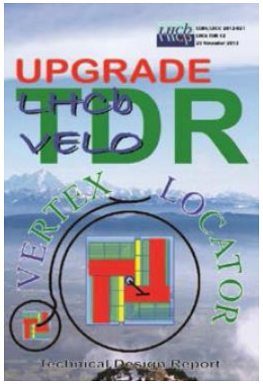


Summary & Conclusion

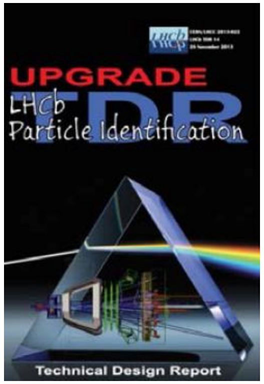
- **The LHCb upgrade is mandatory to reach experimental precision of the order of theoretical uncertainties**
  - Levelled luminosity of $2 \cdot 10^{33}$ cm^{-2}s^{-1} at 25 ns bunch spacing
  - The Upgraded LHCb trigger-less scheme with event processing at 40 MHz, will allow to collect 5 fb^{-1} per year
  - The upgrade will be performed during LS2 (2018-19)
    - New Si pixel VELO, UT, SciFi detectors
  - Data taking will start in 2020
- The LHCb upgrade is fully approved

CERN-LHCC-2011-001

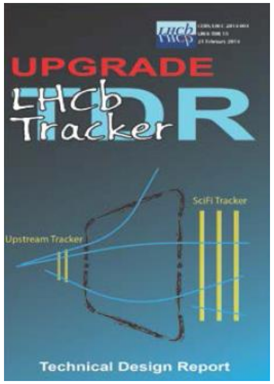
CERN-LHCC-2012-007



CERN-LHCC-2013-021



CERN-LHCC-2013-022



CERN-LHCC-2014-001

CERN-LHCC-2014-016

- Addendum to MoU for Common Projects submitted for signature to Funding Agencies, next one (detector) now submitted to RRB


LHC Days in Split
29 September - 4 October 2014
Diocletian´s Palace / Palazzo Milesi/
Split, Croatia

THANK YOU!

Physics reach after the upgrade

Type	Observable	Current precision	LHCb 2018	**Upgrade** (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s(B_s^0 \to J/\psi\phi)$	0.10 [139]	0.025	0.008	~0.003
	$2\beta_s(B_s^0 \to J/\psi f_0(980))$	0.17 [219]	0.045	0.014	~0.01
	a_{sl}^s	6.4×10^{-3} [44]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{eff}(B_s^0 \to K^{*0}\overline{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{eff}(B^0 \to \phi K_S^0)$	0.17 [44]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	<0.01
	$\tau^{eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [68]	0.025	0.008	0.02
	$s_0 A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [68]	6 %	2 %	7 %
	$A_I(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [77]	0.08	0.025	~0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [86]	8 %	2.5 %	~10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~100 %	~35 %	~5 %
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	~10–12° [252, 266]	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° [44]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [44]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

8 fb^{-1} up to 2018

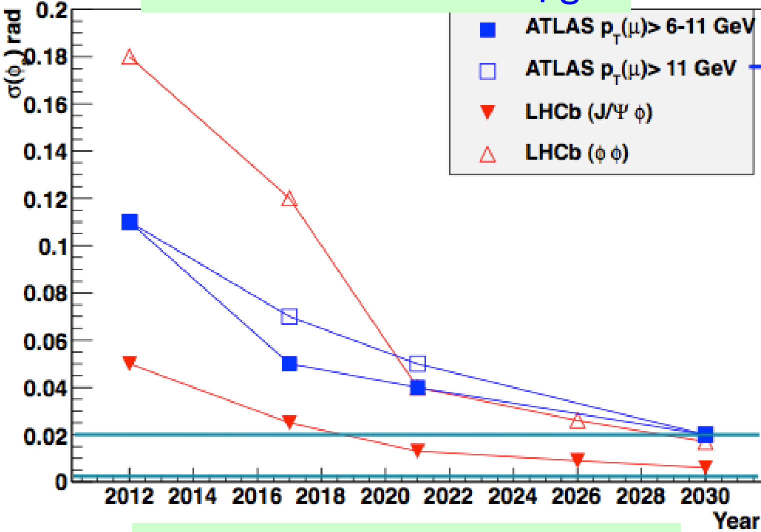
Eur. Phys. J. C (2013) 73:2373

Motivation for the LHCb Upgrade

- Expected precision: aim at experimental sensitivities cc oretical uncertainties

Few selected topics

Bs mixing phase ϕ_s

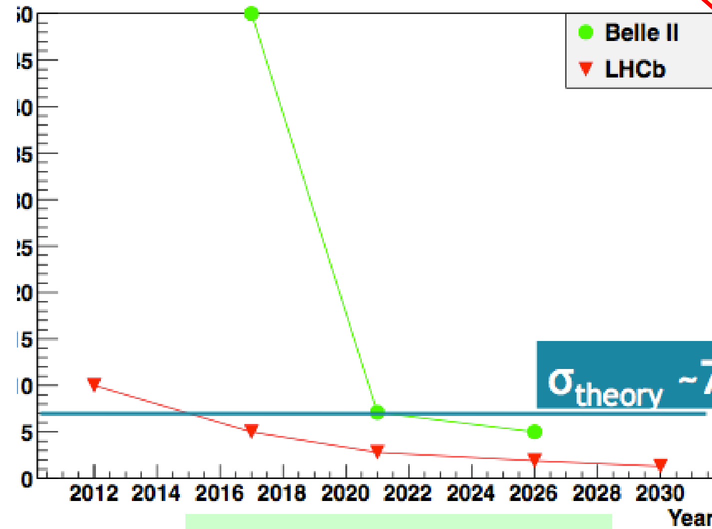


conservative

$\sigma^{\Phi\Phi}_{th}$ ~0.02

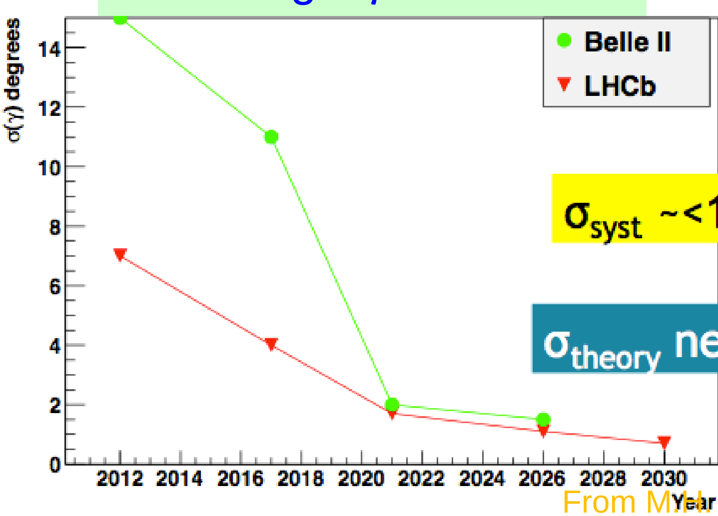
$\sigma^{J/\psi\Phi}_{th}$ ~0.003

q_0 from B→K*ll



σ_{theory} ~7 %

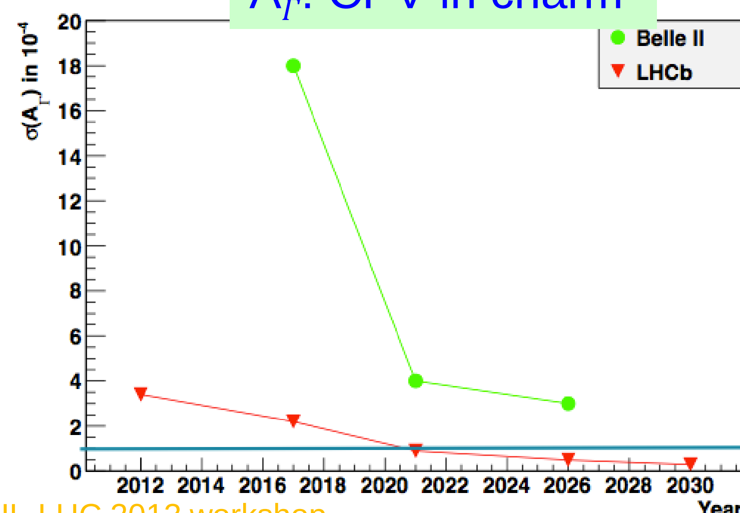
CKM angle γ from trees



σ_{syst} ~<1 °

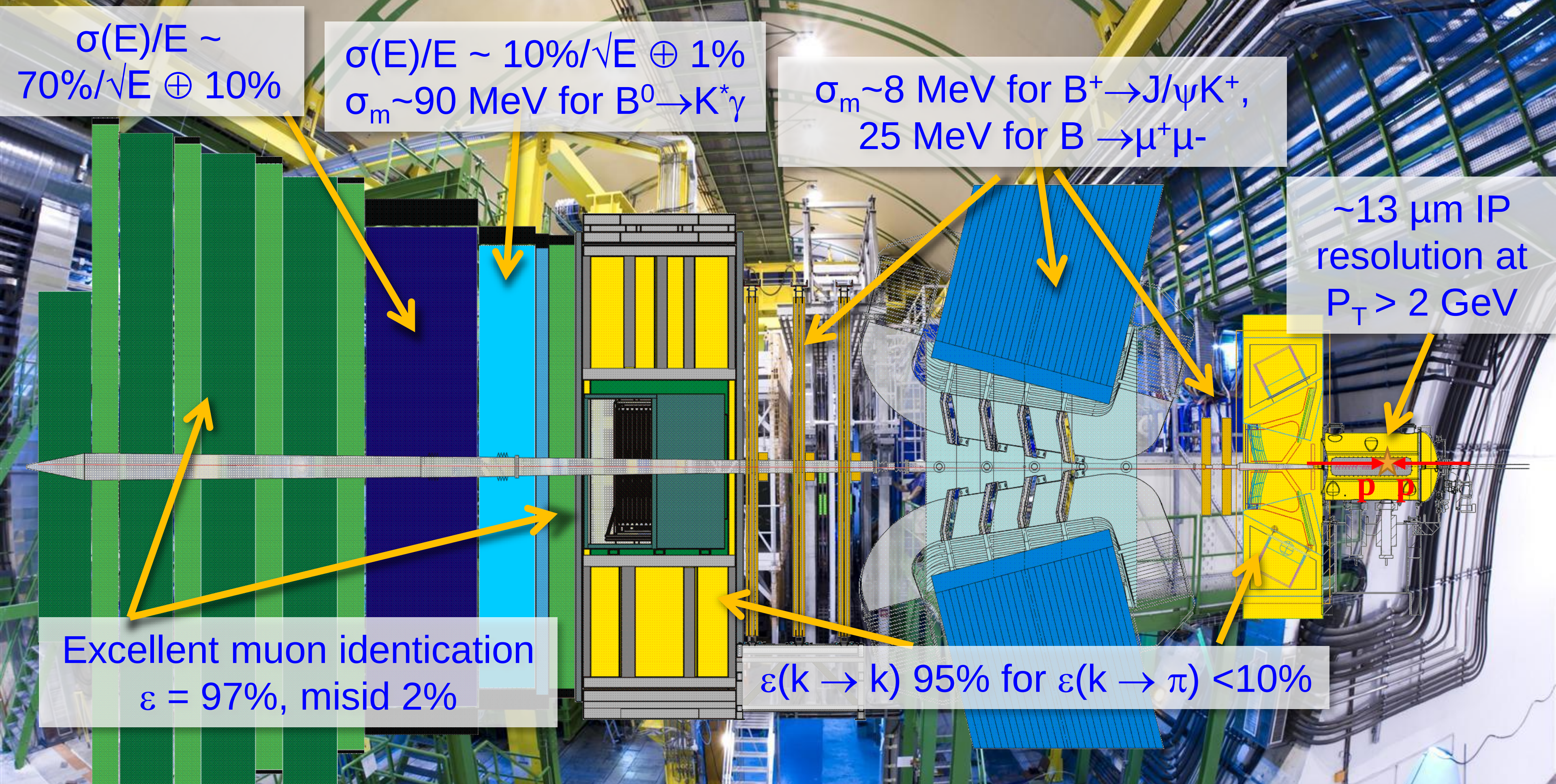
σ_{theory} negligible

A_Γ: CPV in charm



SM ~10^{-4}

The LHCb detector



- ❖ Great Vertex Resolution! Primary/secondary separation, proper time resolution.
- ❖ Excellent momentum and mass resolution.
- ❖ Outstanding PID (K-π) and μ reconstruction.
- ❖ Dedicated Trigger system for B and C!