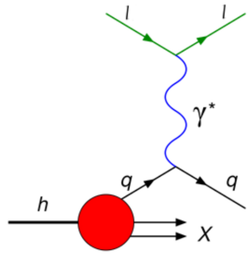


The LHCb Upgrade

Outline

- LHCb Detector
- Selected Physics Results
- Upgrade Plans
- Summary

On behalf of the LHCb Collaboration

Tomasz Szumlak AGH-UST

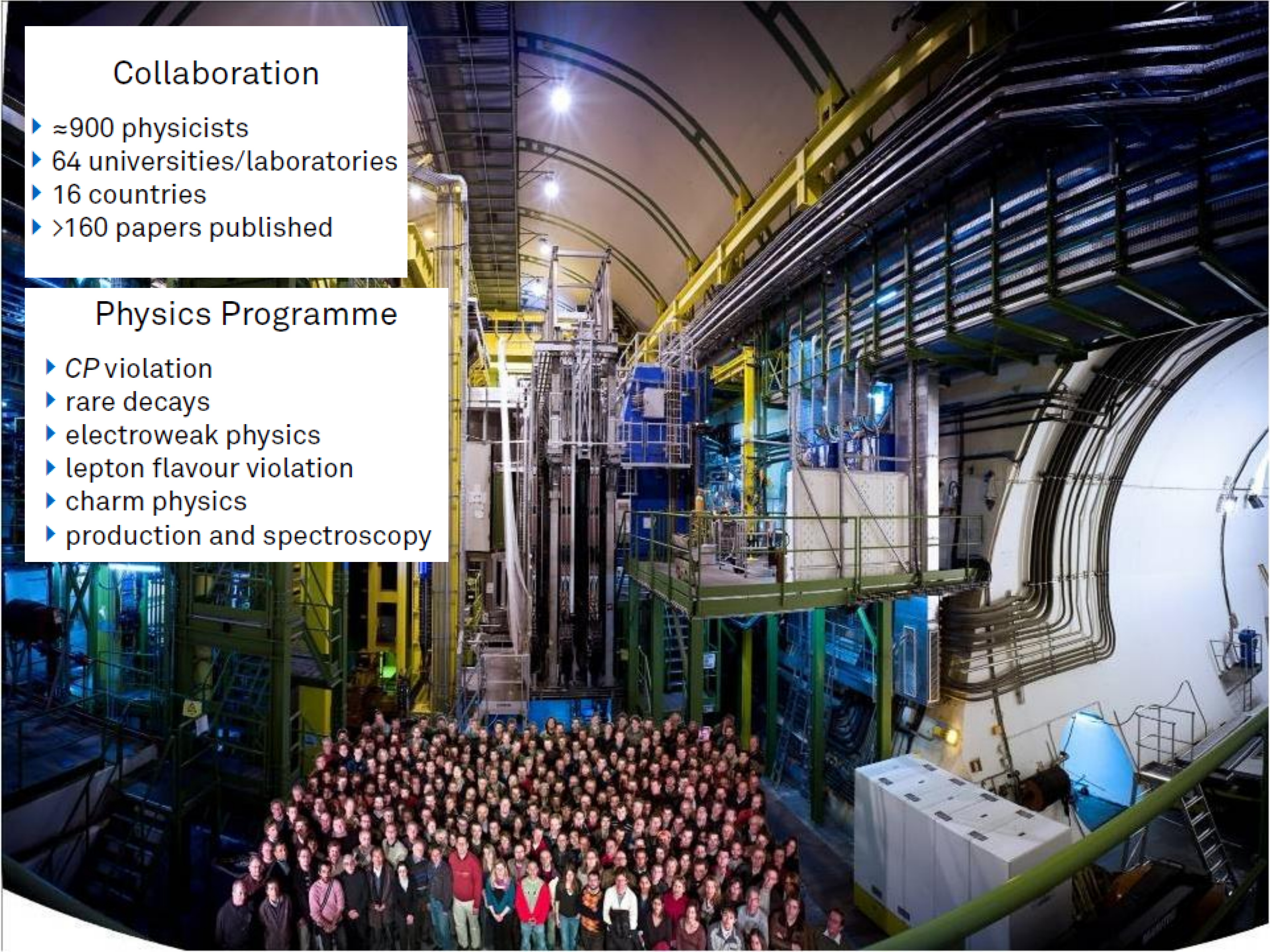
XXII International Workshop on Deep-Inelastic Scattering (DIS)
28/04 – 02/05/2014, Warsaw, POLAND

Collaboration

- ≈900 physicists
- 64 universities/laboratories
- 16 countries
- >160 papers published

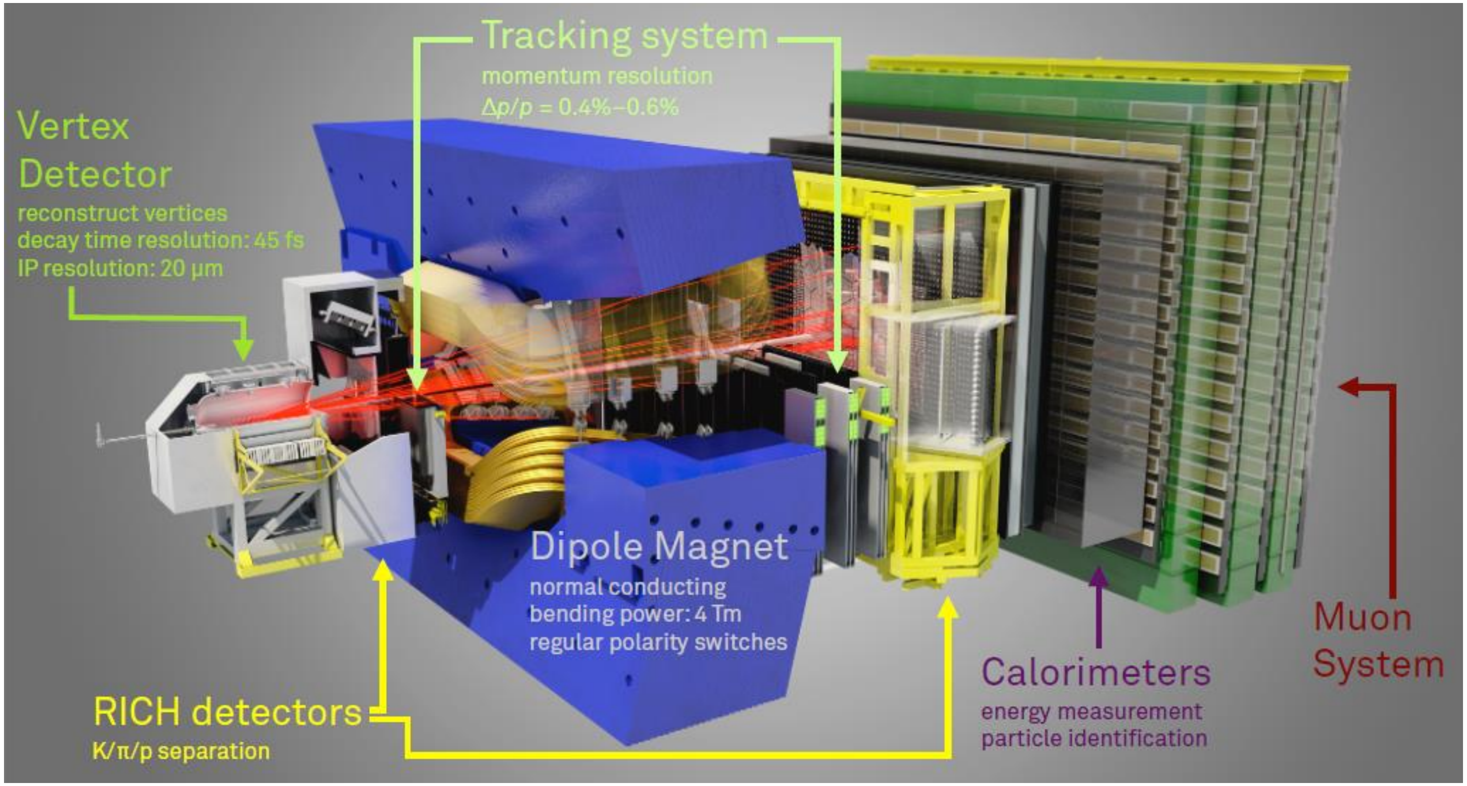
Physics Programme

- *CP* violation
- rare decays
- electroweak physics
- lepton flavour violation
- charm physics
- production and spectroscopy

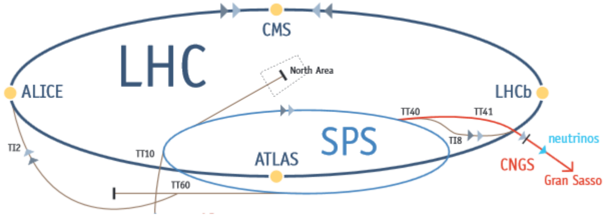


- LHCb is dedicated for studying heavy quark flavour physics
- It is a single arm forward spectrometer with pseudorapidity coverage $2 < \eta < 5$
- Precise tracking system (VELO, upstream and downstream tracking stations and 4 Tm magnet)
- Particle identification system (RICH detectors, calorimeters and muon stations)
- Partial information from calorimeters and muon system contribute to L0 trigger (hardware) that works at LHC clock – 40 MHz
- Full detector readout at 1 MHz

The LHCb detector at LHC (JINST **3** 2008 S08005)



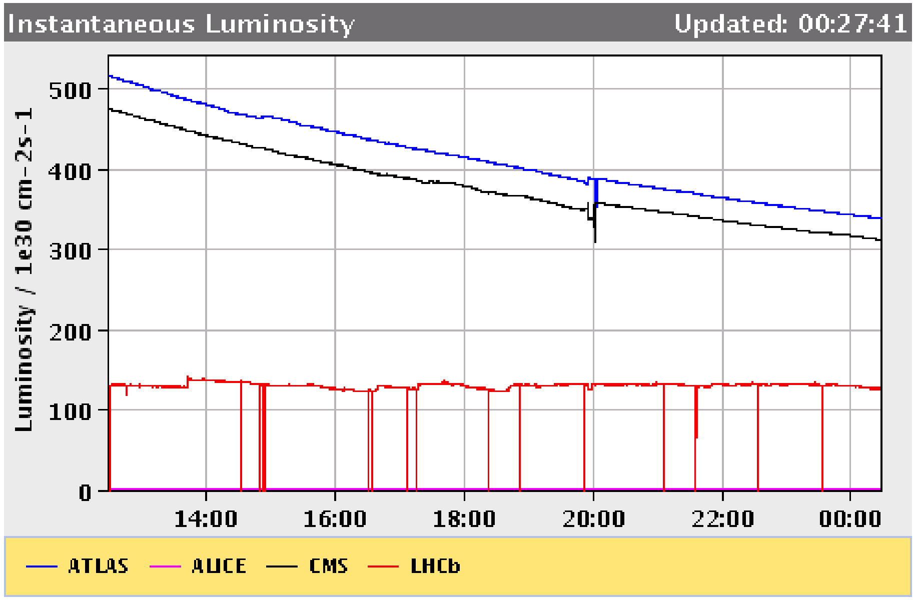
„Input” for the LHCb detector – LHC performance



	design	2011	2012
beam energy	7 TeV	3.5 TeV	4 TeV
bunches	2808	1380	1380
bunch spacing	25 ns	50 ns	50 ns
bunch intensity	1.15x10	1.45x10	1.7x10
peak luminosity	10	≈3.5x10	≈7.7x10

Operation conditions of the LHCb in 2011

- ❑ recorded luminosity L ≈ **1,2** [fb^{-1}] at beam energy 3.5 [TeV]
- ❑ LHCb stably operated at L_{inst} = **4.0 x 10^{32}** [$cm^{-2}s^{-1}$] (nominal **2.0 x 10^{32}**)
- ❑ Average number of visible interactions per x-ing μ = **1.4** (nominal **0.4**)
- ❑ Data taking efficiency ~**90 %** with **99 %** of operational channels
- ❑ HLT (High Level Trigger) input ~ **0.85 MHz**, output ~ **3 kHz**
- ❑ Ageing of the sub-detectors monitored – according to expectations

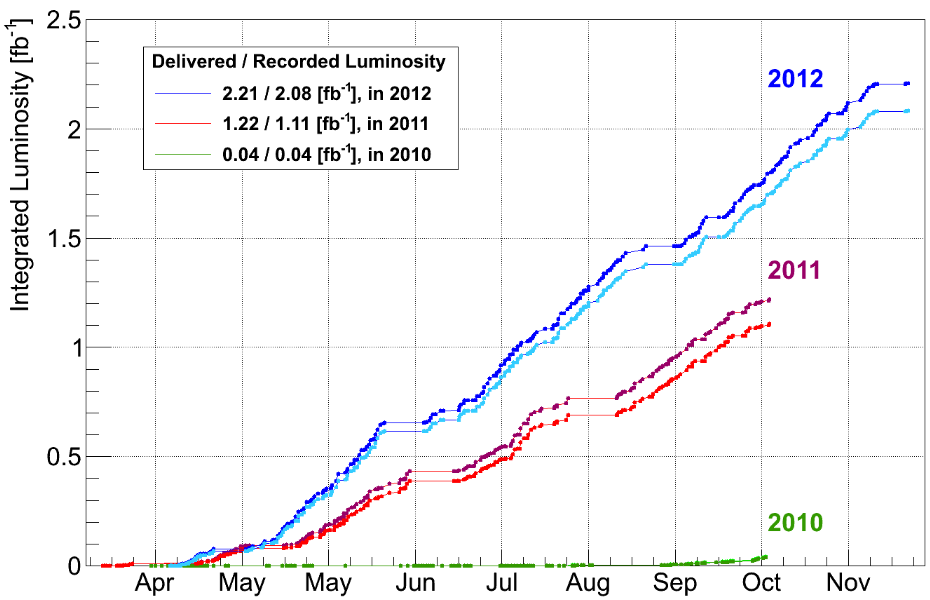


Luminosity leveling

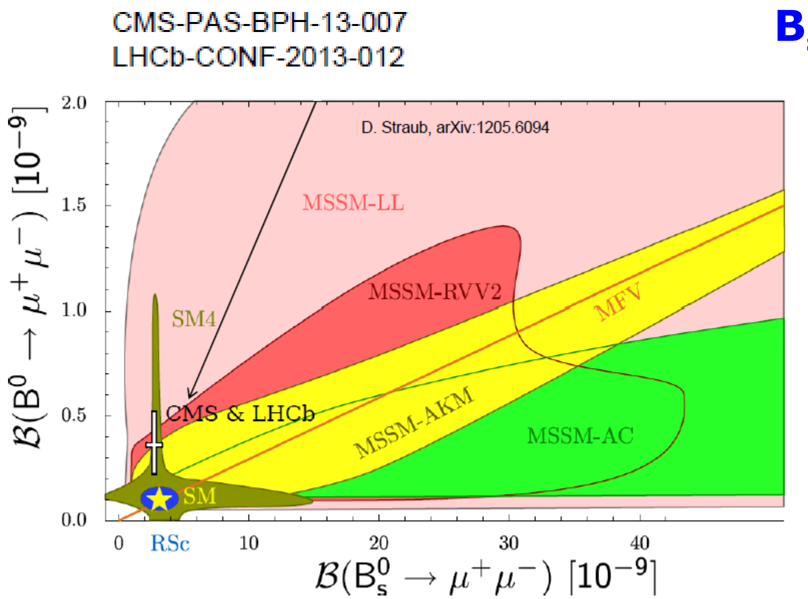
- ❑ Use displaced p-p beams
- ❑ Lower inst. Luminosity
- ❑ Stable conditions during the run
- ❑ Lower pile-up

Operation conditions of the LHCb in 2012

- ❑ Beam energy **4.0** [TeV] (15 % increase of the b-barb x-section)
- ❑ Keep the luminosity at L_{inst} = **4.0 x 10^{32}** [$cm^{-2}s^{-1}$] for this year
- ❑ Average number of visible interactions per x-ing slightly higher μ = **1.6**
- ❑ Keep high data taking efficiency and quality
- ❑ HLT (High Level Trigger) input ~ **1.0 MHz**, output ~ **5 kHz** (upgraded HLT farm and revisited code)
- ❑ Collected ~ **2.1 fb^{-1}** of collision data



Selected physics results (1)



$B_s \to \mu^+\mu^-$: constraining SUSY

- ❑ Strongly suppressed in the SM
- ❑ Theory - known with high precision
- ❑ Enhanced in MSSM
- ❑ **World's best measurement LHCb & CMS**

$$BR(B^0 \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$

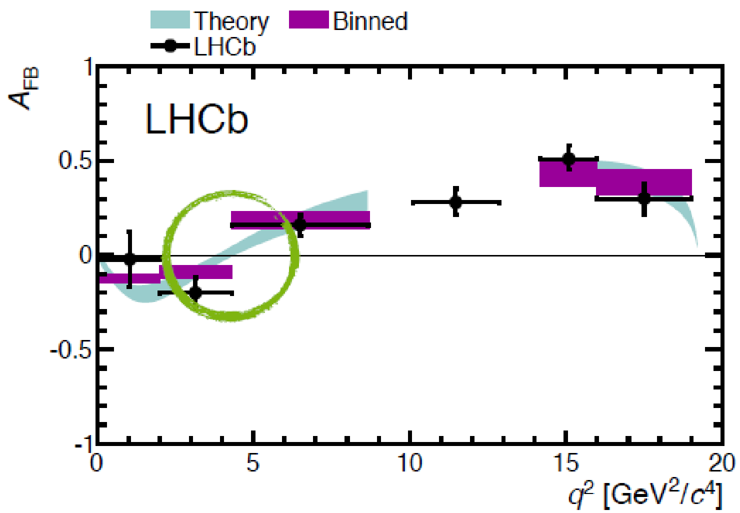
$$BR(B_S^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

$B^0 \to K^*\mu^+\mu^-$: NP in loops

- ❑ The largest sample collected
- ❑ Clear theoretical quantity
- ❑ Sensitive to Wilson coefficients
- ❑ **World's best measurement**

$$q_0^2 = 4.9 \pm 0.9\ \mathrm{GeV}/c^2$$

$$q_{0,SM}^2 \in [3.9, 4.4]\mathrm{GeV}/c^2$$

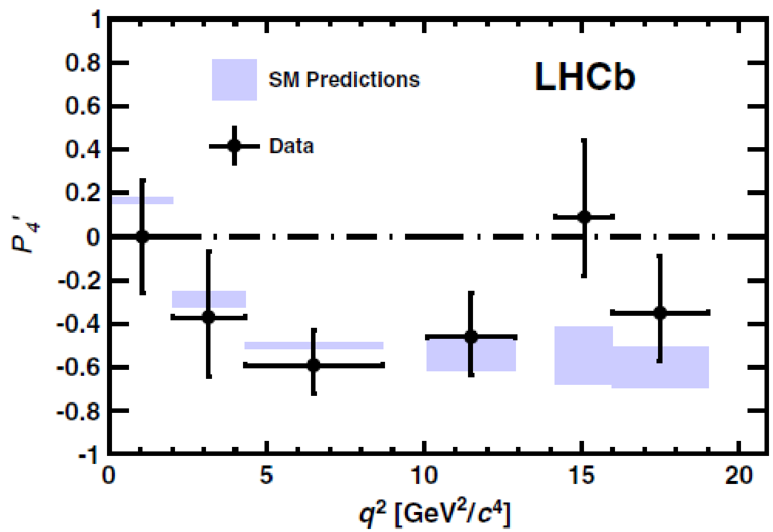


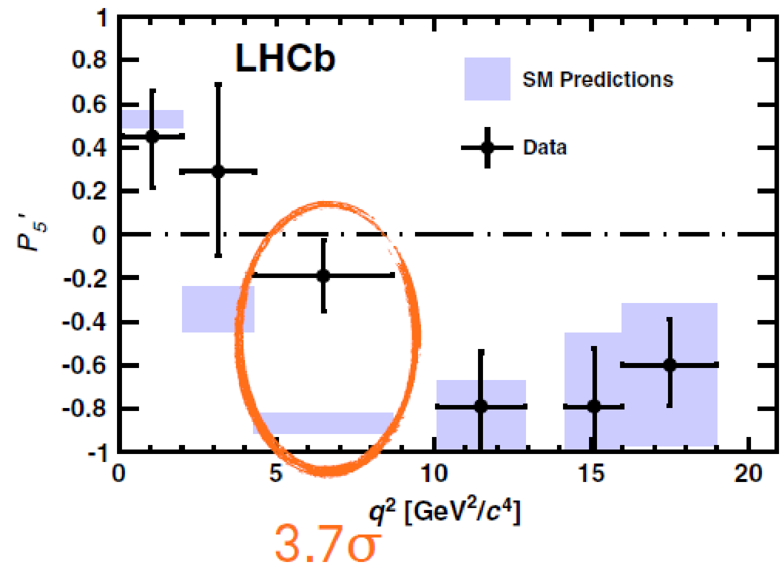
(JHEP 1308 (2013) 131)

Selected physics results (2)

$B^0 \to K^*\mu^+\mu^-$: NP in loops

- Observed forward-backward asymmetry very similar to that predicted by the SM
- Cannot clearly state any discrepancy – sample limitation
- New base of observables proposed
- Reduced dependency on hadronic form factors
- Observed discrepancy may be a hint of new heavy neutral Z′ particle





(PRL 111, 191801 (2013))

Overall summary of Run I

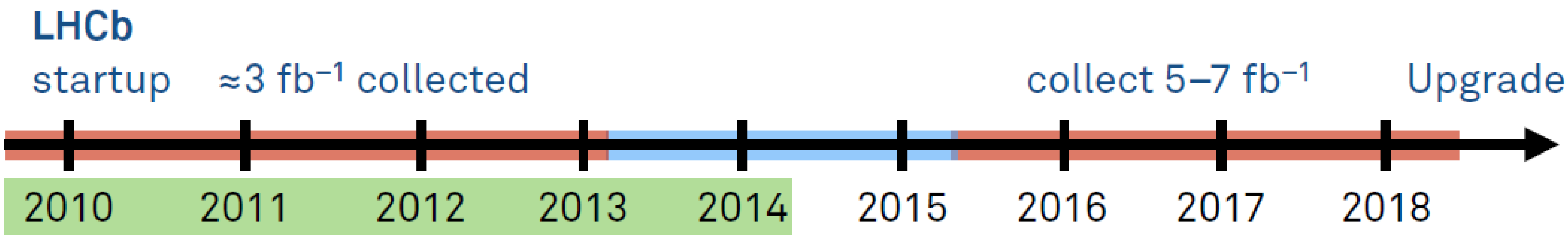
LHCb:

- Superb performance – greatly exceeded any expectations
- Stable operation at inst. luminosity **100%** higher than nominal
- **General purpose detector in forward direction**
- Many world leading results
- **Over 180 papers published**!

The pinch of salt:

- No conclusive BSM physics discovered
- There is still room for NP!
- Need push **precision** to the limits in order to challenge theoretical predictions
- **Need more data**

Data taking road map for LHCb before the upgrade



LHC Run I

- *pp* runs @50 ns
  - 7 TeV (2010,2011)
  - 8 TeV (2012)
- Pb Pb run @2.76 TeV
- *p* Pb run @5 TeV

LHC LS1

- repair splices
- consolidation

LHC Run II

- *pp* runs 13 TeV @25 ns
- L_{peak} 2x10^{34} cm^{-2} s^{-1}

Upgrade Plans

Why upgrade (i.e., what's wrong with the current design…?)

Superb performance – but **1 MHz** readout is a **sever limit**
- ❑ can collect **~ 2 fb^{-1}** per year, **~ 5 fb^{-1}** for the „phase 1" of the experiment
- ❑ this is not enough if we want to move from **precision** exp to **discover**y exp
- ❑ cannot gain with increased luminosity – trigger yield for **hadronic events saturates**

Upgrade plans for LHCb do not depend on the LHC machine
- ❑ we use fraction of the luminosity at the moment

Upgrade target
- ❑ full event read-out@40 MHz (flexible approach)
- ❑ completely new front-end electronics needed (on-chip zero-suppression)
- ❑ redesign DAQ system
- ❑ **HLT output@20 kHz, more than 50 fb^{-1} of data for the „phase 2"**
- ❑ increase the yield of events (up to 10x for hadronic channels)
- ❑ **experimental sensitivities close or better than the theoretical ones**
- ❑ expand physics scope to: lepton flavour sector, electroweak physics, exotic searches and QCD

Installation ~ 2018 - 2019

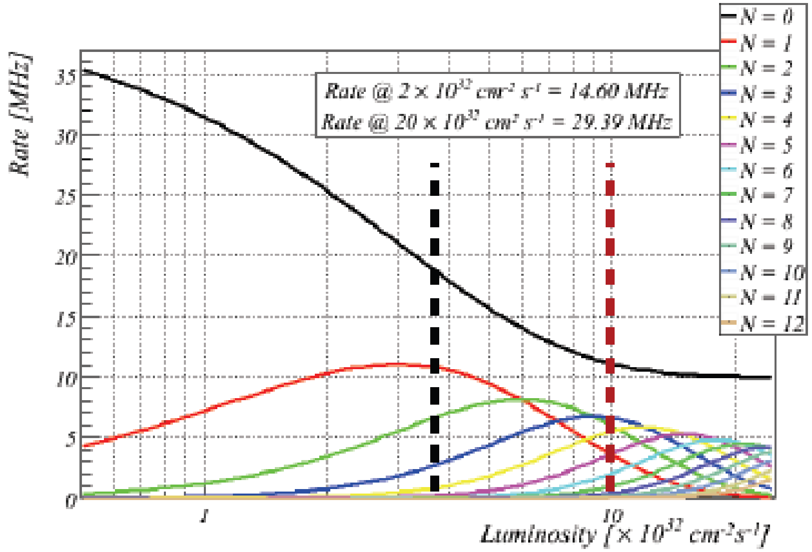
Sensitivities to key flavour observables

(for more see: **LHCb Upgrade: Technical Design Report**, **LHCb-TDR-12**)

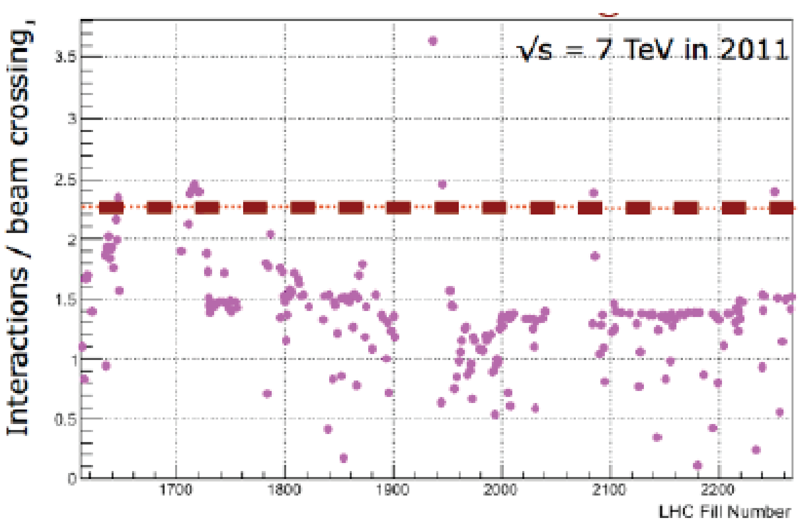
Type	Observable	Current precision	LHCb ($5\ \text{fb}^{-1}$)	Upgrade ($50\ \text{fb}^{-1}$)	Theory uncertainty
Gluonic penguin	$S(B_s \to \phi\phi)$	-	0.08	0.02	0.02
	$S(B_s \to K^{*0}\bar{K}^{*0})$	-	0.07	0.02	< 0.02
	$S(B^0 \to \phi K^0_S)$	0.17	0.15	0.03	0.02
B_s mixing	$2\beta_s\ (B_s \to J/\psi\phi)$	0.35	0.019	0.006	~ 0.003
Right-handed currents	$S(B_s \to \phi\gamma)$	-	0.07	0.02	< 0.01
	$\mathcal{A}^{\Delta\Gamma_s}(B_s \to \phi\gamma)$	-	0.14	0.03	0.02
E/W penguin	$A_T^{(2)}(B^0 \to K^{*0}\mu^+\mu^-)$	-	0.14	0.04	0.05
	$s_0\ A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	-	4%	1%	7%
Higgs penguin	$\mathcal{B}(B_s \to \mu^+\mu^-)$	-	30%	8%	$< 10\%$
	$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)}$	-	-	$\sim 35\%$	$\sim 5\%$
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	$\sim 20^\circ$	$\sim 4^\circ$	0.9°	negligible
	$\gamma\ (B_s \to D_s K)$	-	$\sim 7^\circ$	1.5°	negligible
	$\beta\ (B^0 \to J/\psi K^0)$	1°	0.5°	0.2°	negligible
Charm CPV	A_Γ	2.5×10^{-3}	2×10^{-4}	4×10^{-5}	-
	$A_{CP}^{dir}(KK) - A_{CP}^{dir}(\pi\pi)$	4.3×10^{-3}	4×10^{-4}	8×10^{-5}	-

Projected running conditions for the upgrade

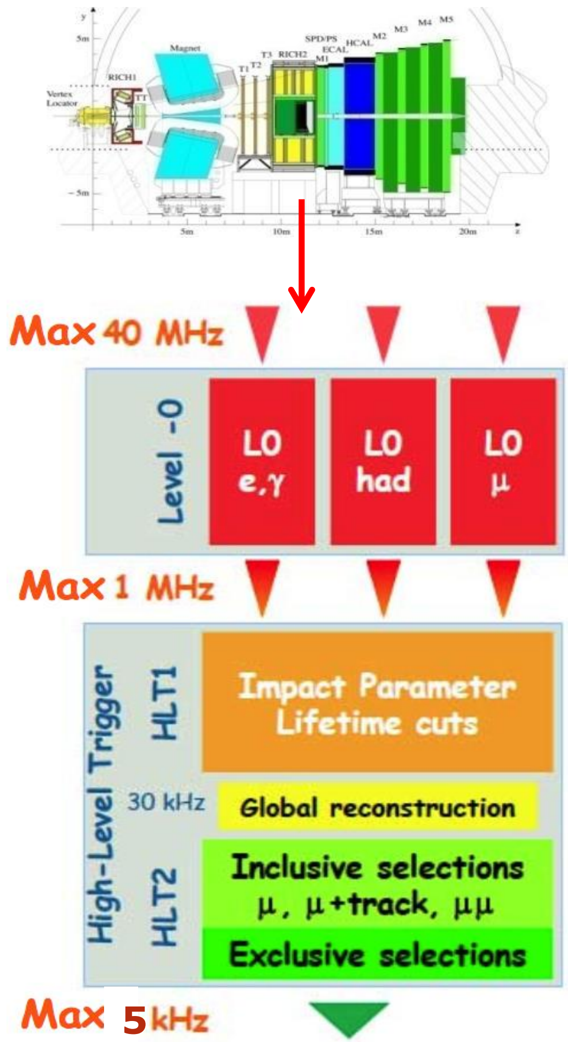
- Operational luminosity up to L_{inst} = **2 x 10^{33}** [$cm^{-2}s^{-1}$]
- 25 ns bunch time spacing
- Average number of visible interaction per x-ing μ ≈ 2.6
- Challenging environment for tracking and reconstruction
- Radiation damage

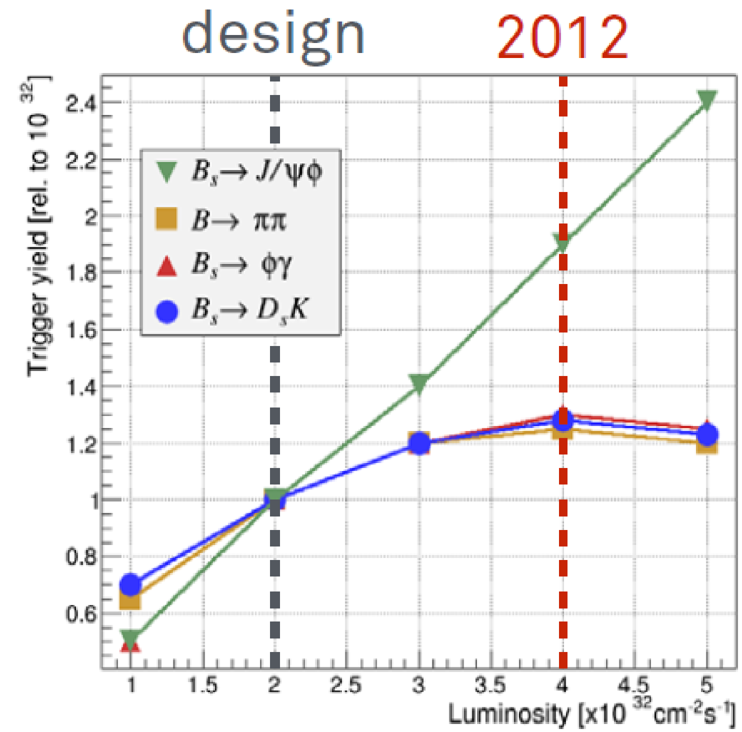


High μ already seen in LHCb!



Current trigger system

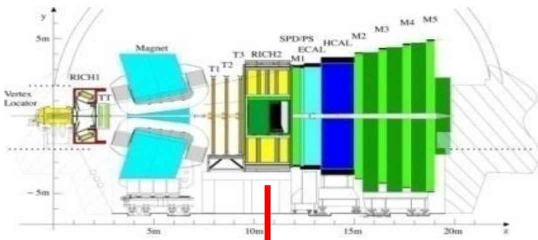




Problem for hadronic channels:

- ❑ saturation with increasing luminosity
- ❑ no gain in event yields

… and the upgraded one



40 MHz

Calorimeters
Muon

LLT

p_T of h, μ, e/γ

Custom electronics

1 – 40 MHz
All detectors information

HLT

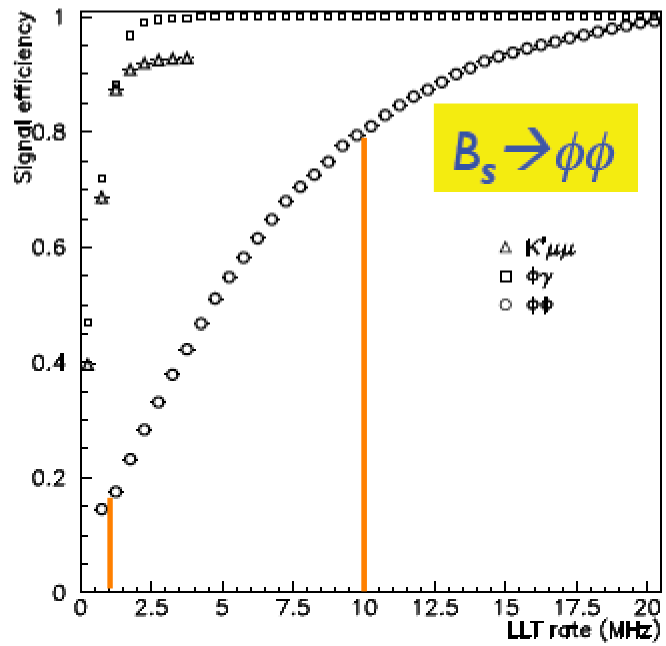
tracking and vertexing
p_T and impact parameter cuts
inclusive/exclusive selections

CPU farm

20 kHz

Staged approach:

- ❑ use Low Level Trigger (LLT) as a throttle
- ❑ enormous gain for hadronic final states such ΦΦ
- ❑ do as much as you can in HLT



Tracking is at heart of the current LHCb success

- Upgrade cannot compromise this performance
- This is not an easy task

At high luminosity we are expecting

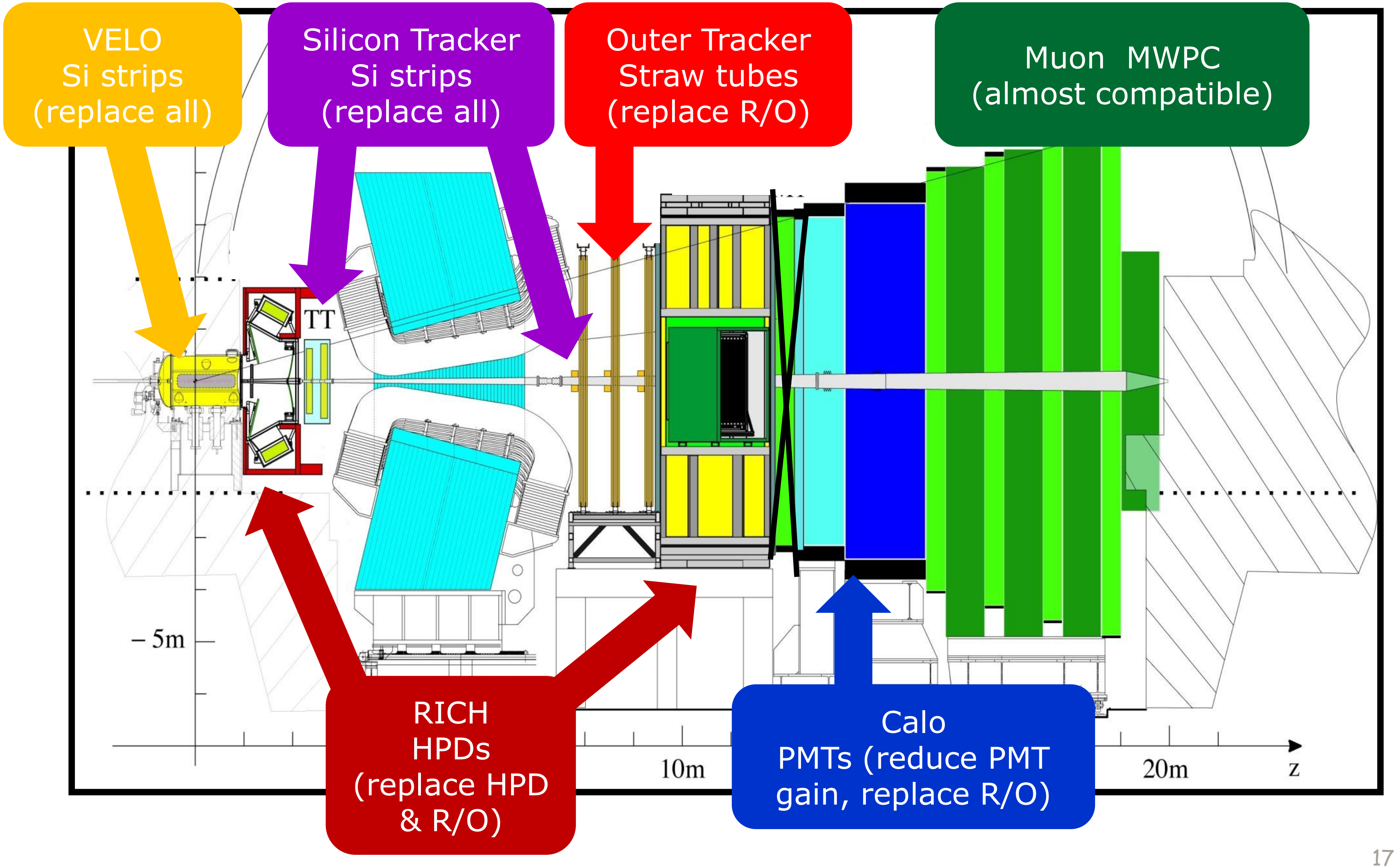
- More interactions per x-ing
- Higher track multiplicities, more vertices, higher detector occupancy
- More ghosts (scary and dangerous in many ways…)
- Spill-over

We need to maintain

- High tracking efficiency (~ 90% for $p > 5$ GeV)
- High relative momentum resolution (~ 3.5×10^{-3})
- Ghost rate as low as possible (less than ~ 10 %)
- Single event processing time in HLT as short as possible (~ 25 ms)
- And do not add to the material budget…

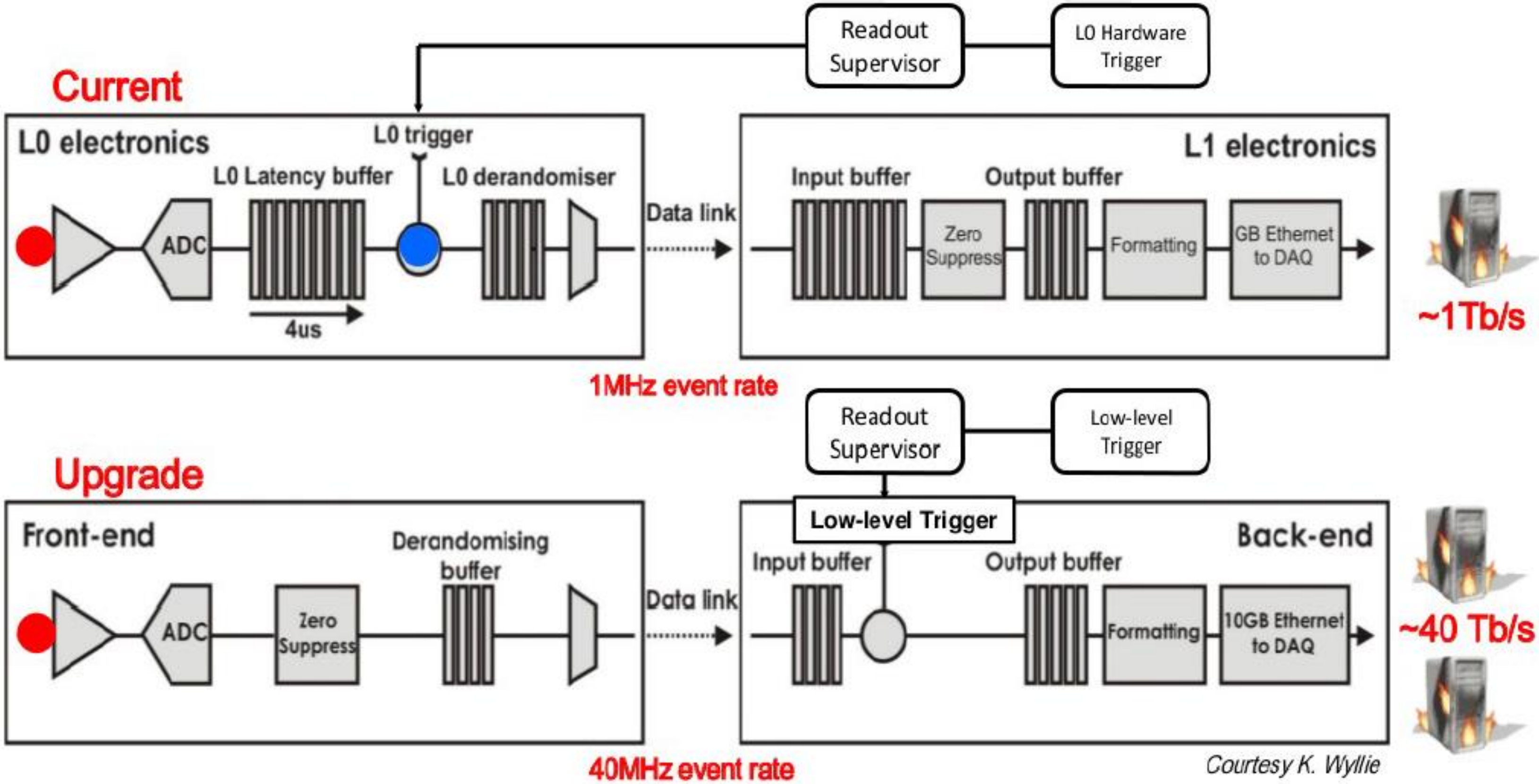
And in addition all of this using full detector information@40 MHz

What we must change to cope with the 40 MHz read-out



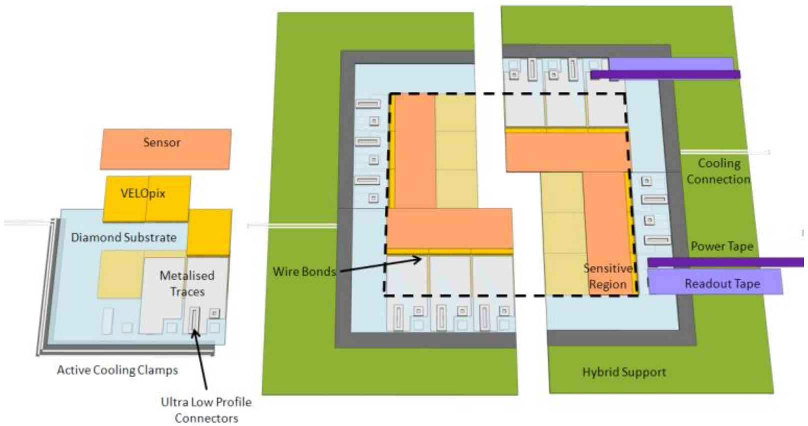
New front-end electronics

- ❑ Trigger-less
- ❑ Sends out data with the machine frequency
- ❑ On chip zero-suppression (SoC)



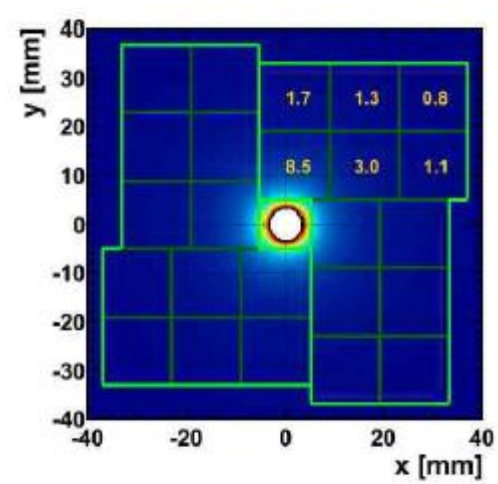
VErtex LOcator VELO2

- Current design: R-Φ geometry Si strip sensors with pitch between 38 – 100 μm
- To be replaced with pixel based device
  - ❑ low occupancy
  - ❑ much easier patter recognition
  - ❑ easier to control alignment
  - ❑ radiation hardness
  - ❑ extremely high data rate ~ 12 Gbit/s
  - ❑ un-uniform data rates/radiation damage
  - ❑ micro-channel CO_2 cooling



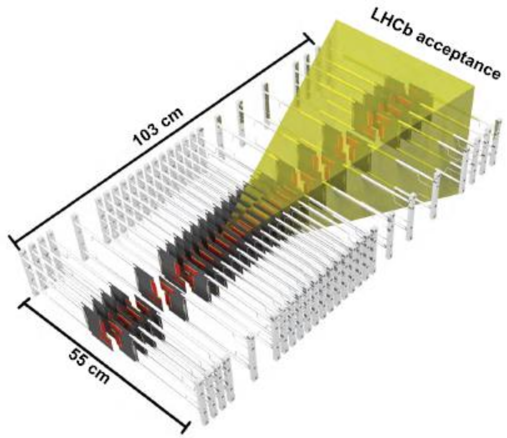
Read-out ASIC, VeloPix, based on TimePix/Medipix chip

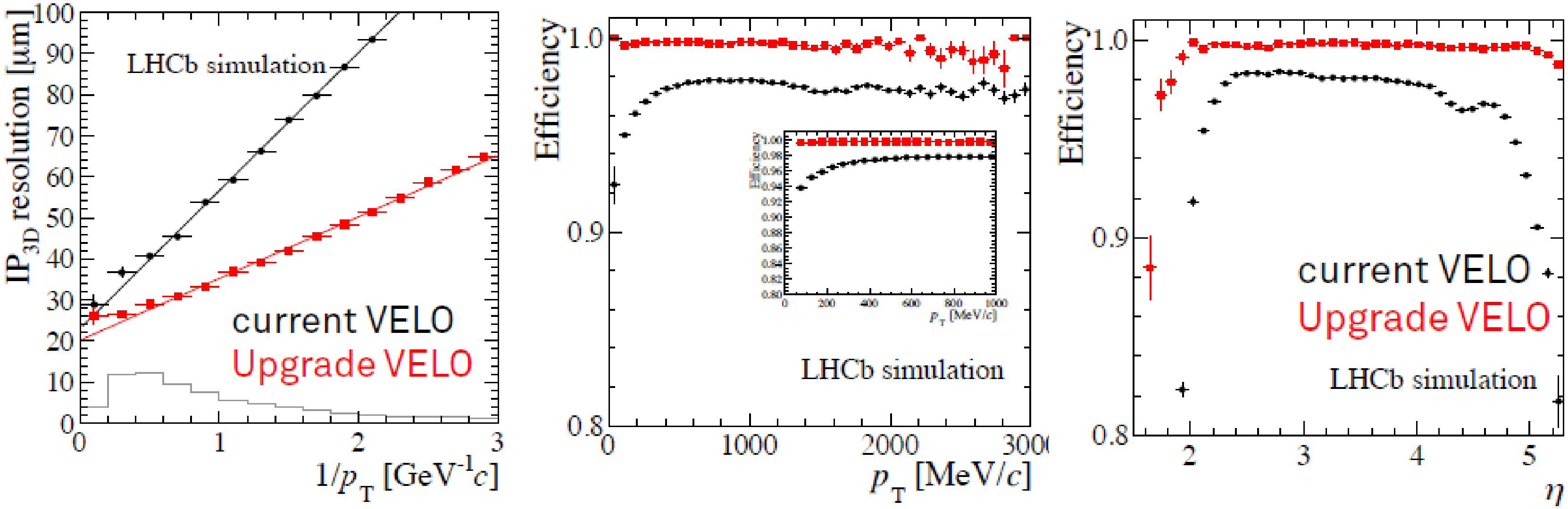
- ❑ 256x256 pixel matrix
- ❑ equal spatial resolution in both directions
- ❑ IBM 130 nm CMOS process
- ❑ great radiation hardness potential ~ 500 Mrad



VErtex LOcator VELO2

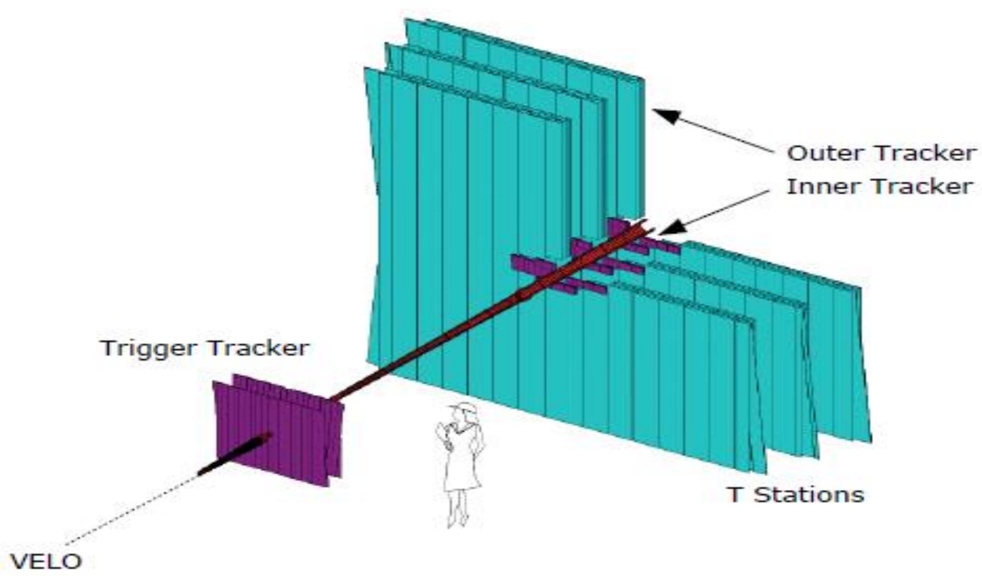
- ❑ Predicted performance superior in almost any aspect w.r.t the current VELO
- ❑ **This is essential for physics performance of the upgraded spectrometer**
- ❑ TDR document is out!

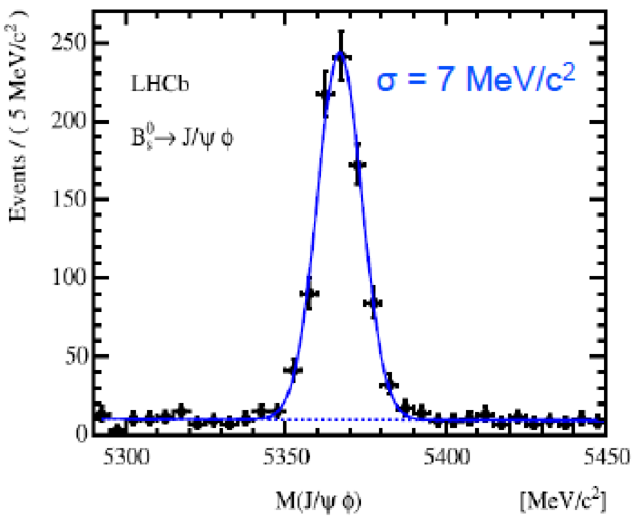




(VELO Upgrade: Technical Design Report, **LHCb-TDR-13**)

TT and T (IT + OT) trackers



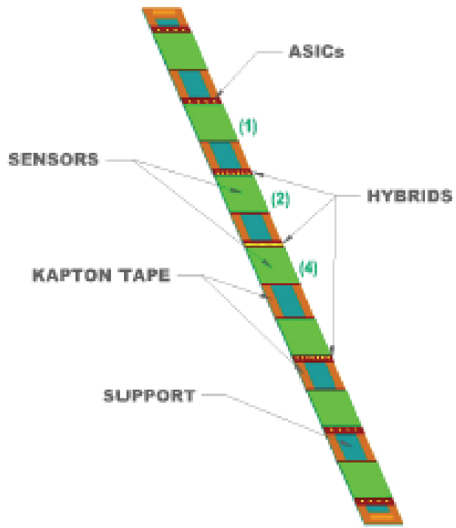


- TT and IT part of the T stations are Si strips based detectors
  - ❑ pitch 200 μm
  - ❑ long strips 11, 22 and 33 cm

- OT is a gaseous detector
  - ❑ very long (2.4 – 5 m)
  - ❑ and thin straws (5 mm)
  - ❑ occupancy limited to ~ 10 – 25 %

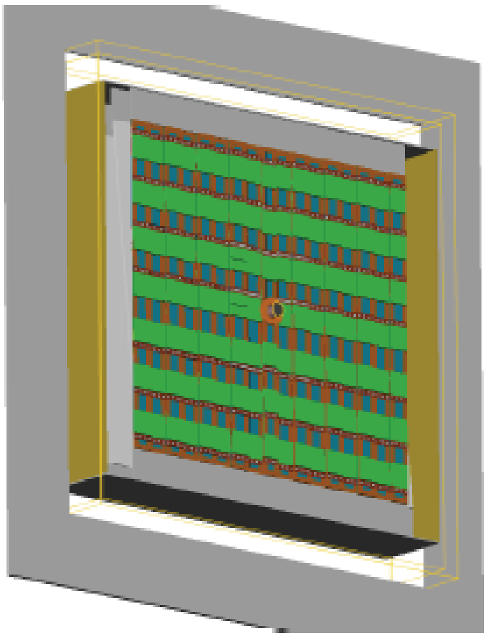
World's best b hadrons mass measurement!

TT tracker upgrade



Features after the upgrade

- ❑ high momentum track on-line selection (part of the trigger)
- ❑ reconstruct long lived particles decaying outside the VELO
- ❑ momentum estimate for slow particles
- ❑ improved matching with VELO segments

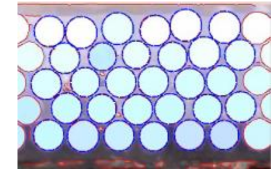


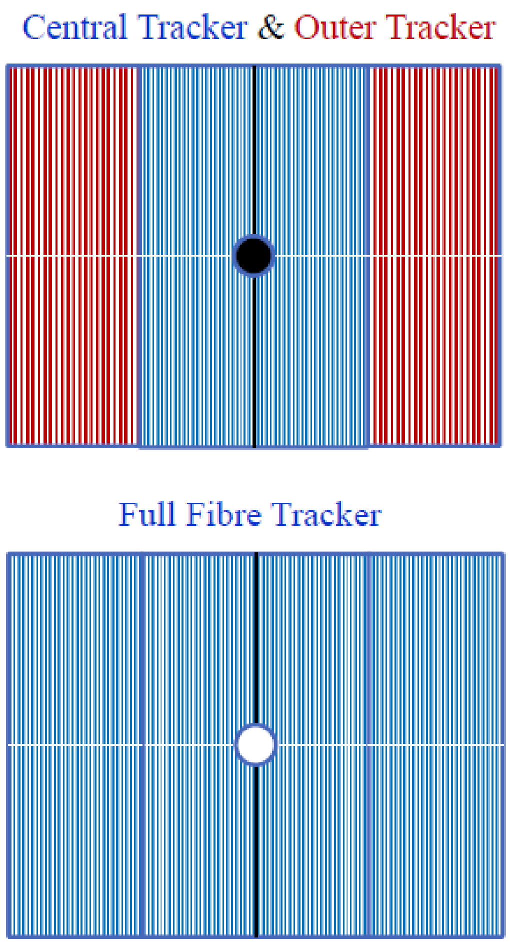
Upgrade technology

- ❑ 4 – 6 detector planes of Si strip detectors
- ❑ reduced silicon thickness 500 → 300 μm
- ❑ strip length 2.5 – 10 cm
- ❑ increase acceptance at low η
- ❑ new read-out electronics with on-chip zero-suppression SALT chip

(**Tracking Upgrade: Technical Design Report**, **LHCb-TDR-15**)

T stations upgrade

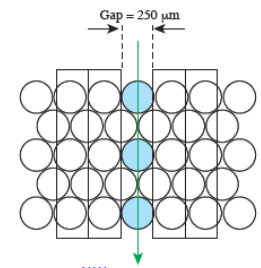




IT must be completely removed

- ❑ integrated 1 MHz electronics

Decrease the occupancy



- First option (Central Tracker)
  - ❑ central part: scintillating fibers with SiPM readout (128 readout channels)
  - ❑build with 5 layers of 250 μm scintillating fibers
  - ❑outer part is kept as is (straws)

- Second option (Full Fiber Tracker)
  - ❑ OT removed completely with 1 mm scintillating fibers

(**Tracking Upgrade: Technical Design Report**, **LHCb-TDR-15**)

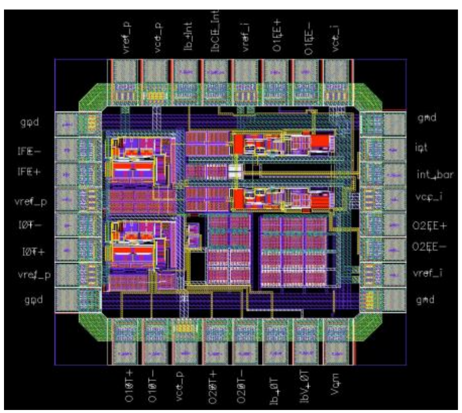
Particle ID and Calorimeters

MaPMTs by Hamamatsu

Both RICH1 and RICH2 remains

- ❑ new photo detectors (MaPMTs)
- ❑ square design to increase coverage
- ❑ 40 MHz read-out ASIC
- ❑ remove aerogel (cannot operate at expected luminosities)

ASIC prototype



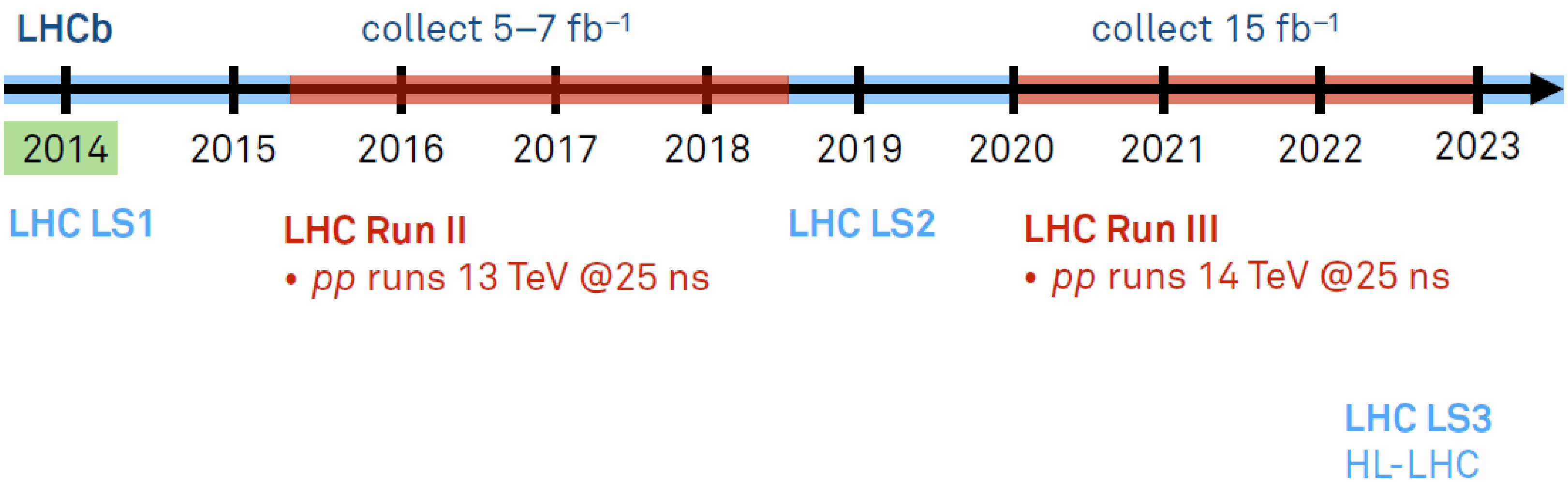
Calorimeters (ECAL and HCAL) are maintained

- ❑ PS/SPD removed (no L0!), e/γ separation provided by tracker (worked out in HLT)
- ❑ inner modules of the ECAL may be replaced due to radiation damage (LS3)
- ❑ front-end electronics adapted to 40 MHz read-out
- ❑ first prototype ready – under study
- ❑ lower gain

(**PID Upgrade: Technical Design Report**, **LHCb-TDR-14**)

Summary

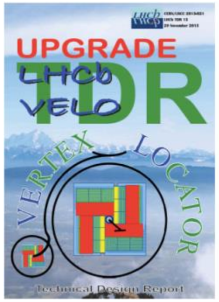
Run II and the upgrade road map

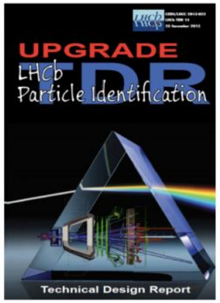


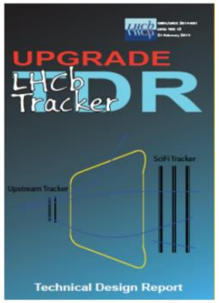
- **Superb performance of the LHCb experiment during Run I**
- Large number of world's best physics results
- **More than 180 papers published**

- We did not make any considerable dents on the Standard Model
- Upgrade of the present detector essential for discovery potential of the LHCb – **origin of the CP violation and NP**
- Can collect ~ **50 fb^{-1}** of data between 2019 and 2028
- Base-line technologies of the upgrade have been chosen
- Respective TDRs have been/are being submitted to the LHCC

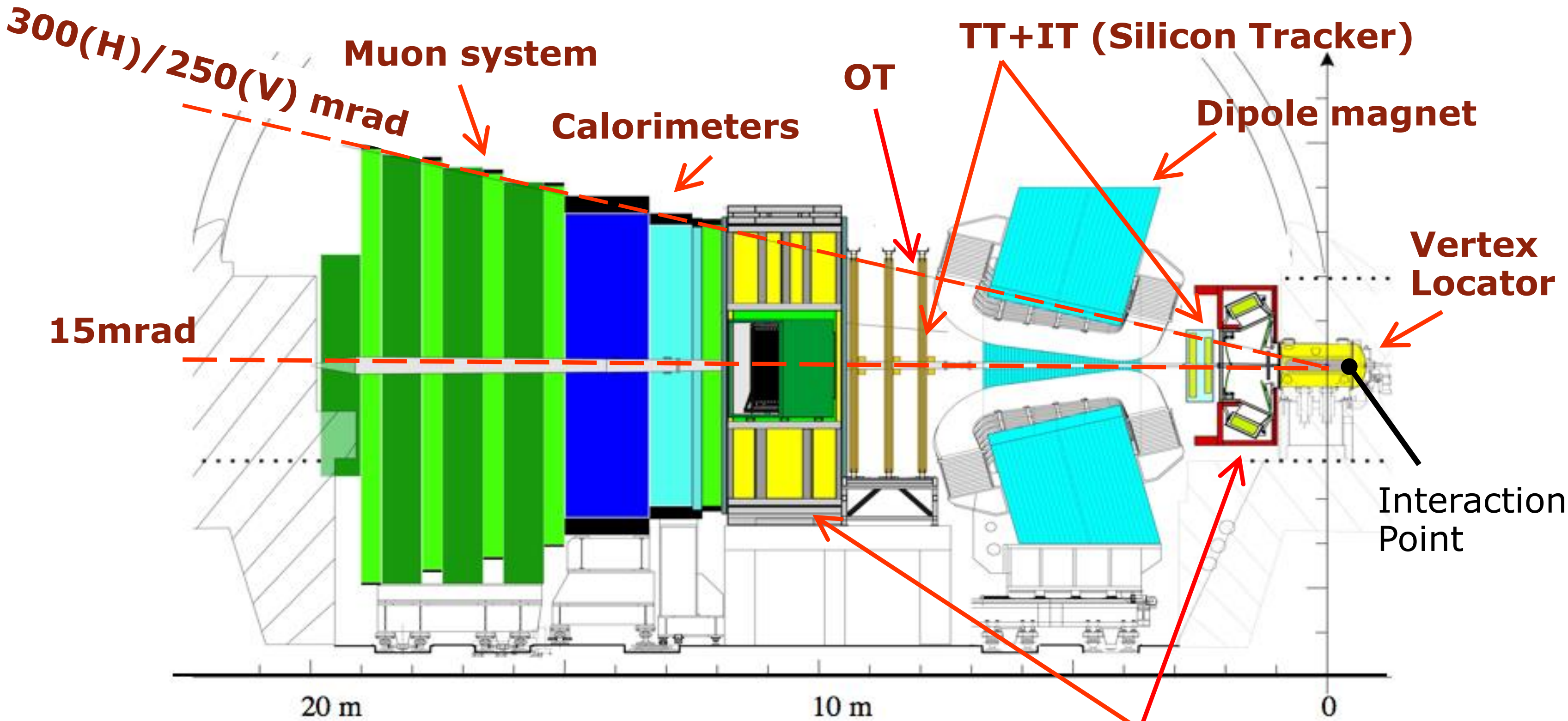
- **Stay tuned! A lot of exciting time is ahead!**







Back-up



OT – Outer Tracker
IT – Inner Tracker
TT – Trigger Tracker

- **Single arm spectrometer geometry**
- **Fully instrumented in rapidity range 2 < η <5**
- **Capable of reconstructing backward tracks (-4 < η < -1.5)**