LHCb Upgrade(s)

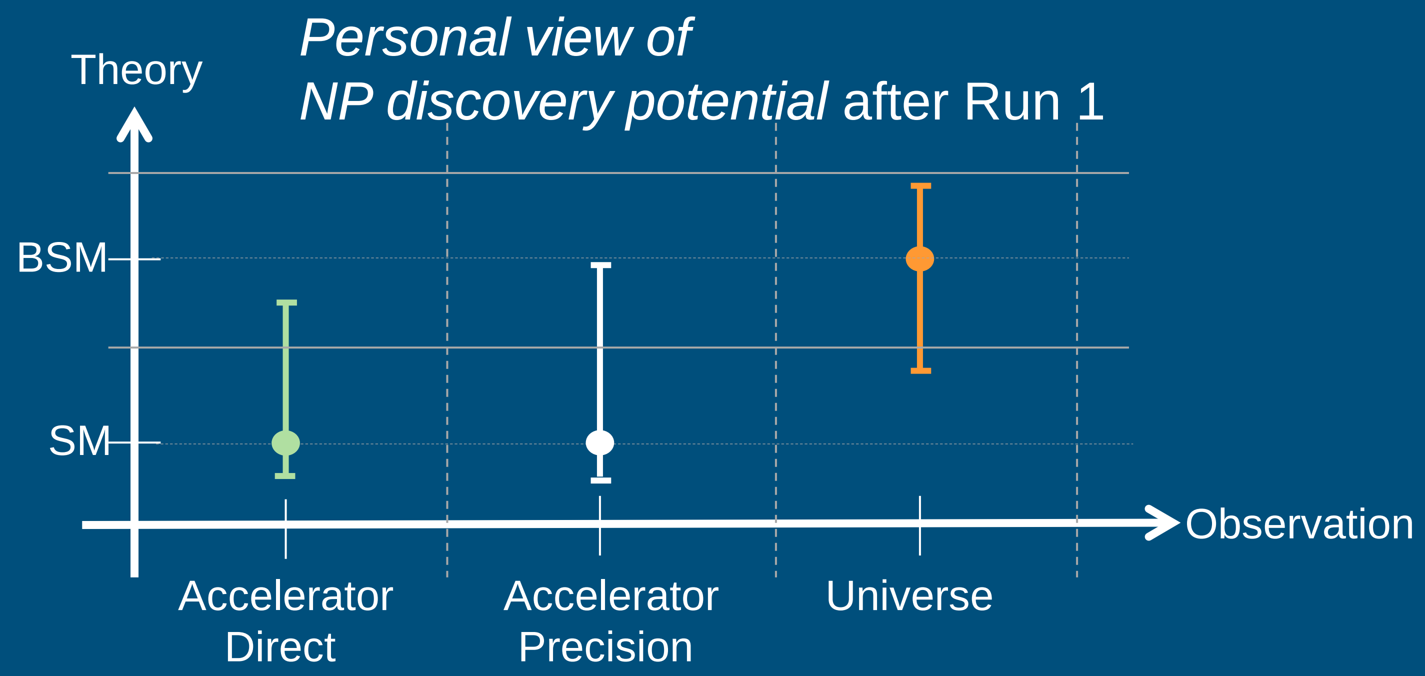
- up to 2028 -

R. Jacobsson

on behalf of the LHCb Collaboration

Outline
- Introduction
- LHCb objectives and observables
- Current status and foundation for the upgrade
- Current limitations and solutions
- LHCb upgrade plans, prospects and schedule
- Conclusions

Opening Scenario for 2015 and Beyond



- Precision measurements likely to have the largest discovery potential for new physics
  - Higgs (EW) precision physics (mainly ATLAS and CMS)
  - Flavour precision physics (mainly LHCb, and soon joined by Belle II)
  - Continued direct searches for on-shell production of new particles (mainly ATLAS and CMS)

➔ if observed directly, precision measurements allow characterizing the role of the new physics

,…or, …

- if not, virtual effects may be the only way to set the scale of BSM physics

In Praise of Precision Measurements

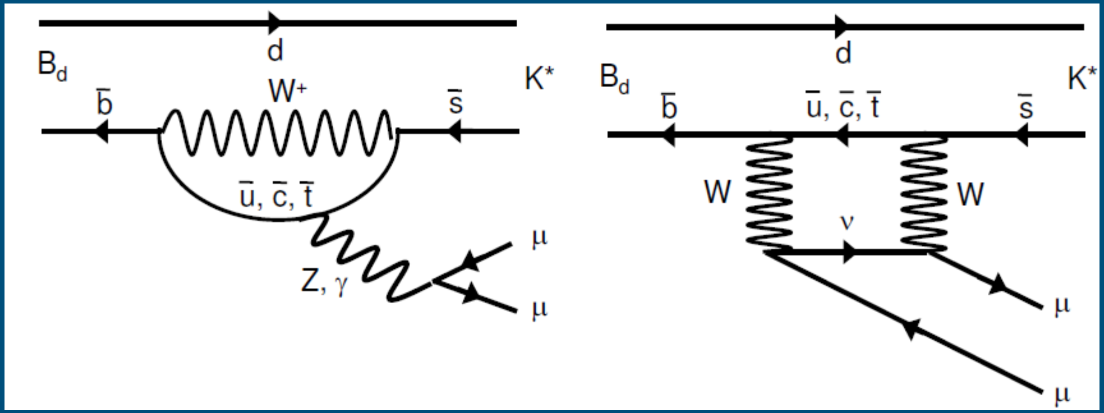
- With the success of virtual corrections in SM, difficult to imagine that new particles which have “sizeable” couplings to SM particles would not be seen in precision measurements…

➔ LHCb focus on measuring *indirect* effects of New Physics in CP violation and rare decays using FCNC processes mediated by box and penguin diagrams

- Strongly suppressed processes allow distinguishing NP sources
- Virtual effects allow probing energies much higher than the E_{cms} of the LHC

➔ Complementary to the direct searches by Atlas and CMS

- New Physics may enter differently in boxes and in penguin contributions
  - ➔ Aim for access to “all” modes and with sufficient precision to distinguish the different contributions



LHCb Objective and Observables

- Beauty and charm flavour sector contains a very large repertoire of decays and topologies
  - Aim at exploring all possible observables sensitive to New Physics
  - ➔ Phases: CP violating asymmetries
  - ➔ Amplitudes (masses and couplings): Branching ratios and oscillation frequencies
  - ➔ Helicity structure: Angular distributions
  - As compared to direct searches, these observables are relatively inclusive and less model dependent

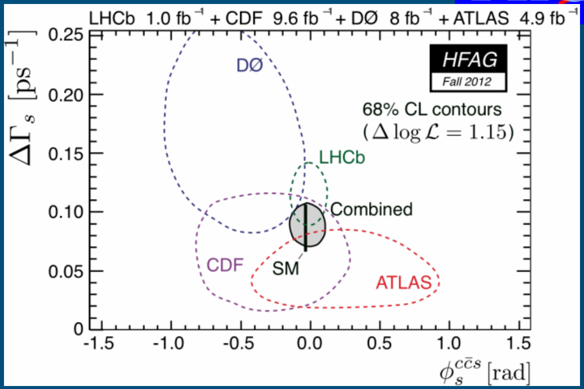
- Aim to reach experimental sensitivities which are comparable or better than theoretical uncertainties
  - Precision of many measurements not expected to be limited by systematics
  - Need 10-fold our statistics
    - In particular we need to improve the access to the hadronic modes
    - ➔Increase efficiency of hadronic channels by factor >2
    - ➔ Increase luminosity
    - ➔ Also improve output bandwidth and lower p_T to increase sensitivity for charm
  - ➔ Gives access to new modes and observables as well

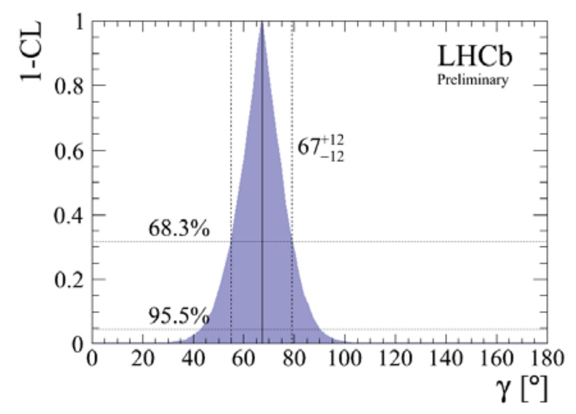
- Large benefit from flexible trigger in extending physics program in Run 1
  - ➔ Most important aspect of the upgrade lies in the flexibility to explore detector operation and physics goals beyond design

LHCb Objectives and Observables

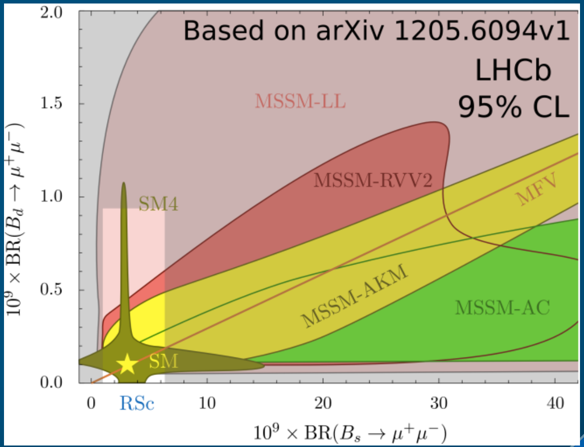
Examples of target channels in the upgrade

- CP violation B
  - B_s mixing phase ϕ_s from $B_s \to J/\psi\ \phi$, $B_s \to J/\psi\ f^0$, box diagram
  - $B_s \to \phi\phi$, gluonic penguin
    - CP violation and amplitude
    - $b \to s\bar{s}s$ in SM has cancellation of weak phases in mixing and decay yields $\phi_s^{sss} = 0$
  - $B_d \to \phi K_S$, $B_d \to \eta' K_S$, gluonic penguin
  - γ from trees ($B_d \to D^{(*)}K^{(*)}$, $B_s \to D_sK$)
  - γ from loops (penguins) ($B \to h^+h^-$, $B^+ \to K^+\pi^+\pi^-$)
- Rare decays
  - FCNC in penguins and boxes of $B_{s,d} \to \mu\mu$ decay and ratio
    - Sensitive to SUSY with additional scalars
  - Helicity structure in $B_d \to K^*\mu\mu$, $B_s \to \phi\mu\mu$ with angular analysis
    - Sufficient precision in additional observables with upgrade
    - Sensitive to SUSY at small tan β
  - Helicity structure $B_s \to \phi\gamma$
    - Sensitive to chirality flips in the loop
  - $B^+ \to \pi^+\mu^-\mu^+$, $b \to d$ electroweak penguin
    - Ratio to $B^+ \to K^+\mu^-\mu^+$ ($\Delta m_d/\Delta m_s$), and $m_{\mu\mu}$ spectrum
- Charm physics
  - CP asymmetries and mixing in charm decays
- Other e.g.
  - $\sin^2\theta_{eff}^{lept}$ from measuring A_{FB} of leptons in Z^0-decays
  - cLFV $\tau^- \to \mu^-\mu^+\mu^-$
    - BR($\tau^- \to \mu^-\mu^+\mu^-$) < 8.0×10^{-8} (90% CL) (LHCb 2013-062)





LHCb-CONF-2013-006, prel.



Physics Prospects *up to* LHCb Upgrade

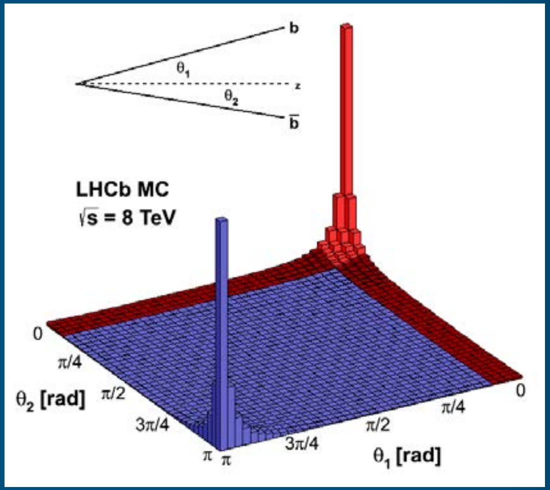
- Currently 3.2 fb^{-1} of integrated luminosity
- Expect ~4-5 fb^{-1} in 2015 – 2018 (Run 2)
  - ➔ Expected precision in 2018 for representative physics modes:

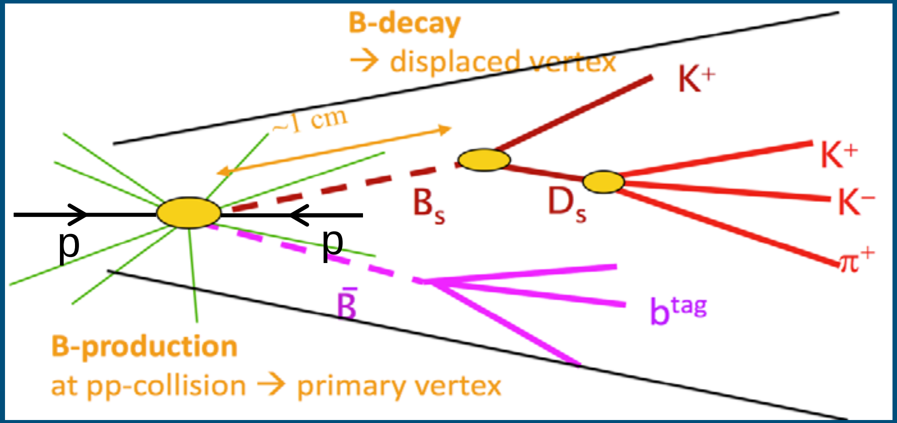
Type	Observable	Current precision	LHCb 2018	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	~ 0.01
	$A_{\rm fs}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.08 [14]	0.025	0.02
	$s_0\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.25 [15]	0.08	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [19, 20]	4°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [18]	0.6°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	–

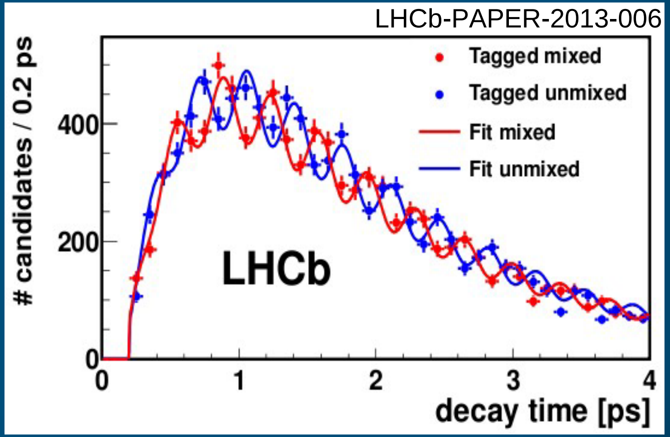
CERN/LHCC 2012-007

Key Features of LHCb

- Large signal cross-sections
  - >100 000 → 1 000 000 $b\bar{b}$ pairs per second at LHCb interaction point
  - Access to all quasi-stable b-flavored hadrons B_u (~40%), B_d *(~40%)*, B_s (~10%), and B_c, and *B*-baryons Λ_b *(~10%)* , … (arXiv:1111.2357v2, arXiv:1301.5286)
  - $c\bar{c}$ production 20x more
- The initial state partons have different longitudinal momentum fraction
- The final state $b\bar{b}$ / $c\bar{c}$ pair are boosted
  - → The B / D hadrons appear in the same hemisphere
  - → Very good proper time resolution
- → Flavor tagging
  - Same side, uses π or *K* emitted together with signal *B / D* hadron
  - Opposite side, detects flavor of partner *B / D* hadron from decay



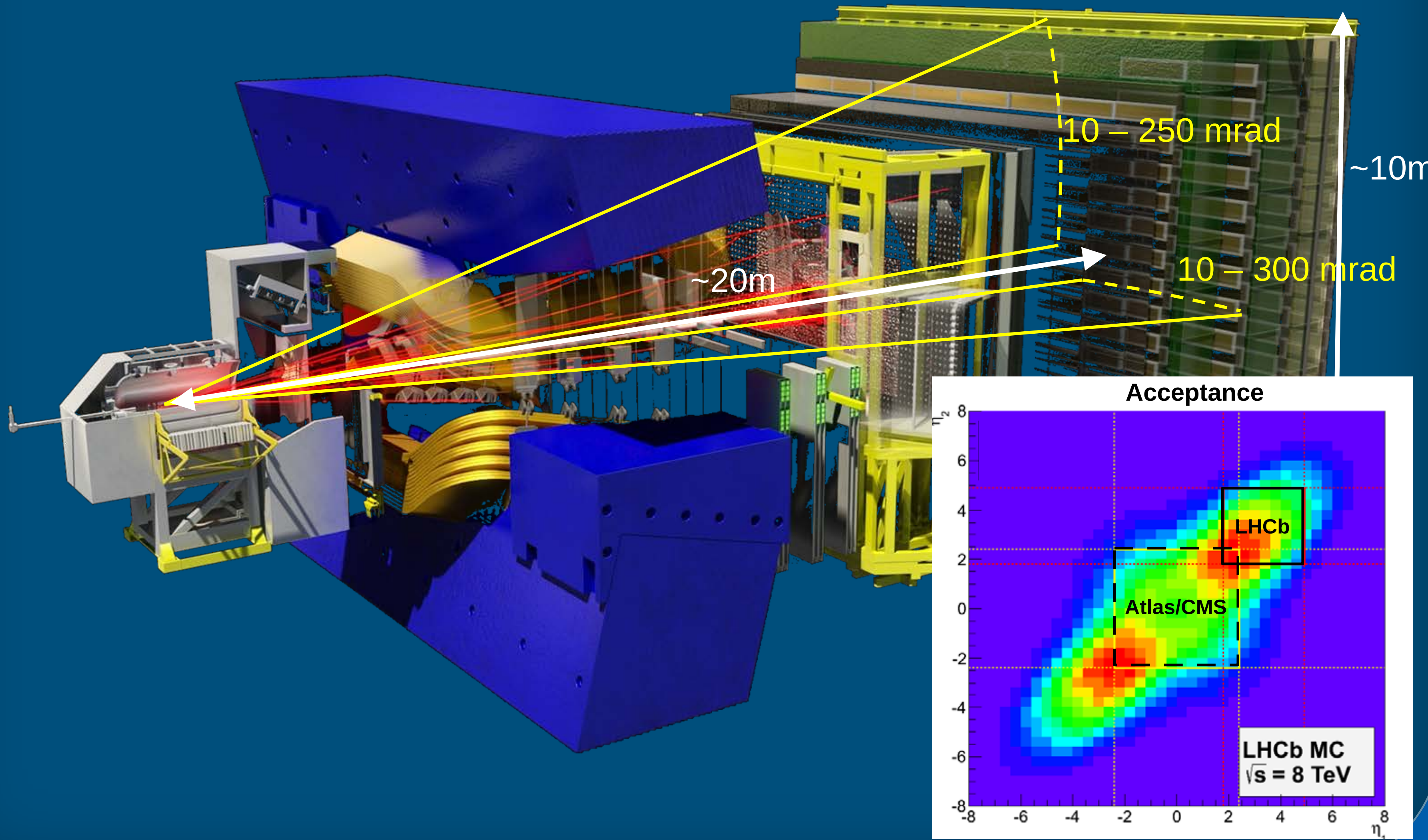




LHCb Detector

Covers ~4% of the solid angle, but captures ~40% of the heavy quark production cross-section

- Acceptance $2 < \eta < 5$ with entire detector



Operational Novelties in Run 1

Operational developments to maximize LHCb physics yield

1. Luminosity control
   - Stable luminosity (pileup) through-out fills / months
     - Same trigger configuration
     - Stable detector performance and radiation effects

     ➔Reduced systematics

     ➔95% of the total integrated luminosity was recorded within 3% of the optimal luminosity 2011-2012

2. Deferred triggering in High-Level Trigger Farm
   - Fraction of events written (~200 kHz) on local farm node disks and processed during inter-fill time

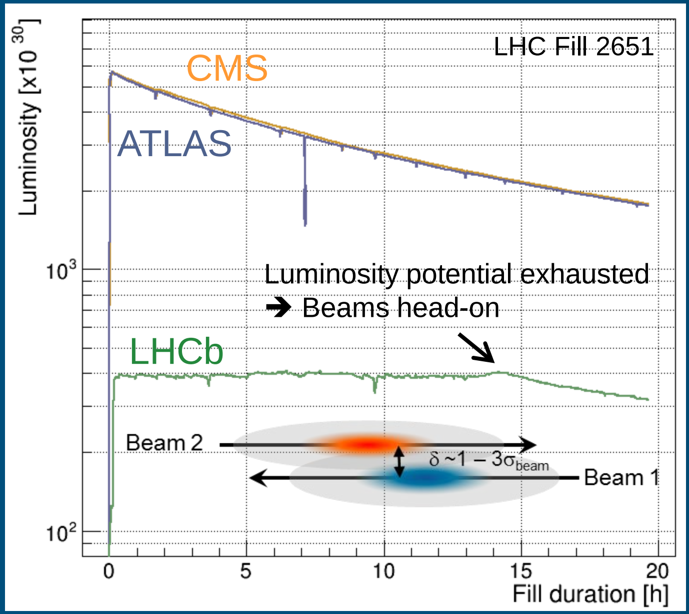
   ➔ 20 – 25% increase in effective CPU capacity

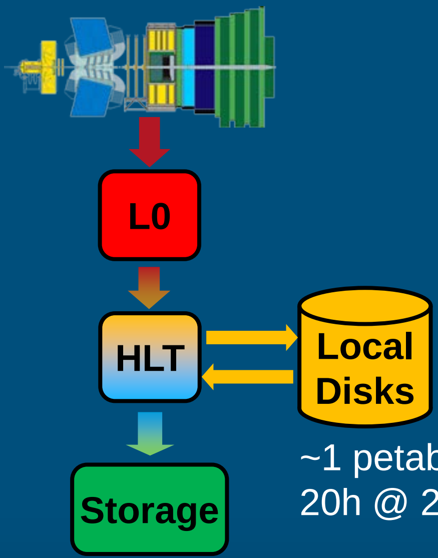
   ➔ Further developments in this area to improve further for Run 2

3. LHCb dipole polarity switches

   ➔Systematics from residual detector asymmetries averaged out by flipping dipole polarity every 1-2 weeks

➔ All of which will continue to be crucial in the future



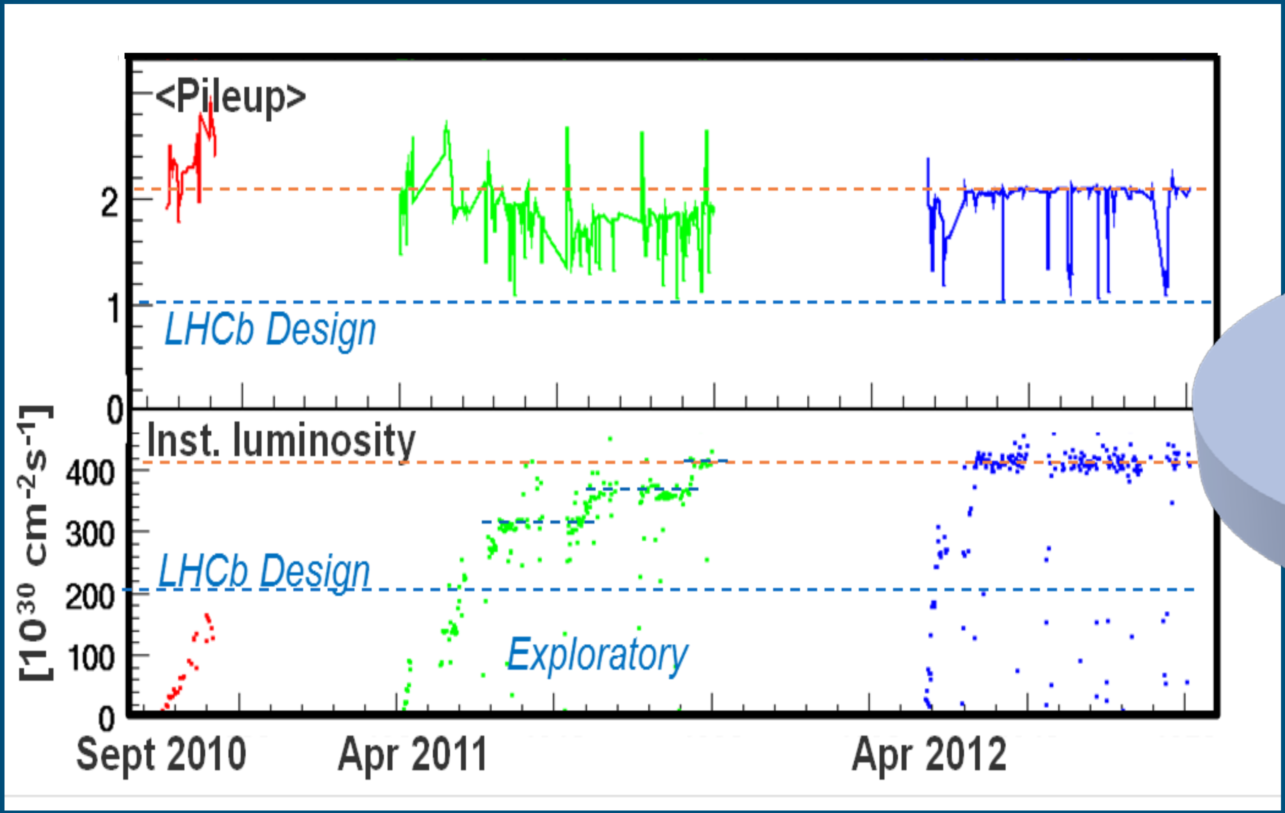


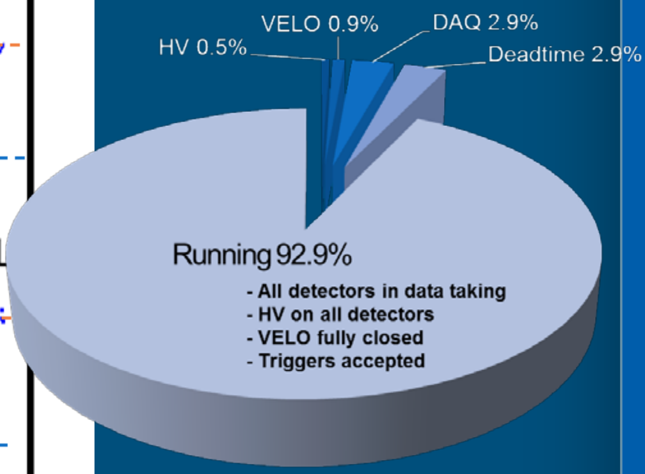
~1 petabyte
20h @ 200 kHz

R. Jacobsson, "LHCb Operation 2010-2012", Proc. IEEE NPSS-MIC 2012

Running Conditions and Strategy 2010 - 2012

R. Jacobsson, "LHCb Operation 2010-2012", Proc. IEEE NPSS-MIC 2012

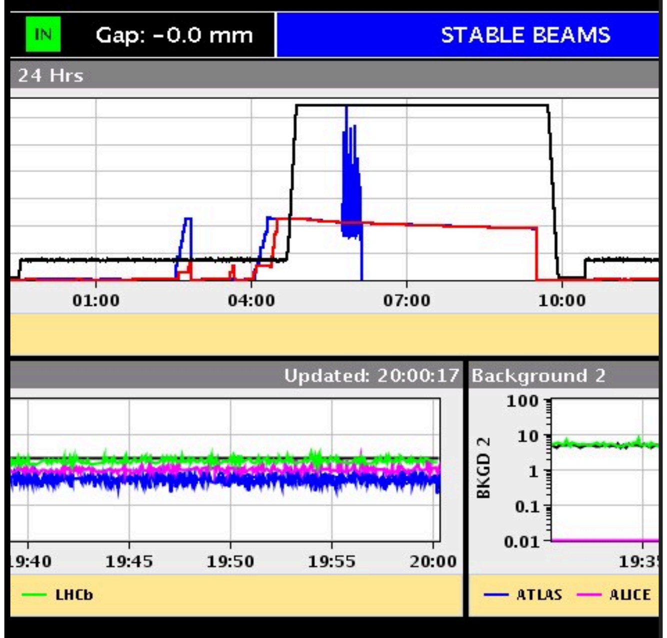




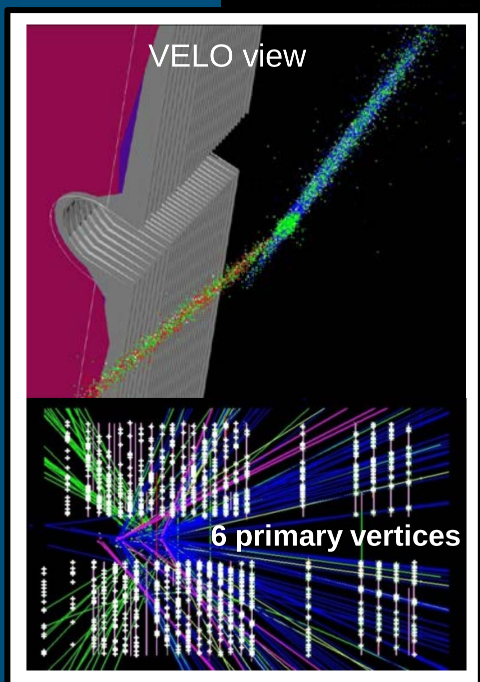
- Current detector and trigger operated efficiently at 4 times the design pileup conditions (and higher!)
- Physics output rate stepped up from 2 kHz in 2010 to 5 kHz in 2012 (initial design output was 200 Hz…)

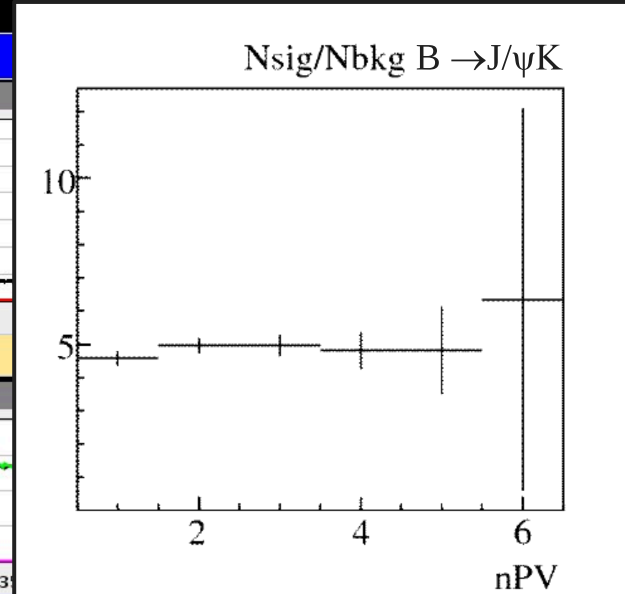
Upgrade "Deja-vu"

LHC web-based experiment overview display



04-Dec-2012 20:00:17	Fill #: 3374	Energy: 4000 GeV	I(B1): 2.03e+14	I(B2): 2.01e+14
	ATLAS	ALICE	CMS	LHCb
Experiment Status	PHYSICS	PHYSICS	PHYSICS	Upgrade!
Instantaneous Lumi [(ub.s)^-1]	5460.0	6.595	5604.2	999.1
BRAN Luminosity [(ub.s)^-1]	5494.5	4.272	5521.6	1123.1
Fill Luminosity (nb)^-1	27394.6	30.5	28708.4	2805.3
BKGD 1	0.723	0.982	2.195	1.615
BKGD 2	102.929	0.000	4.883	5.478
	1.792	7.130		

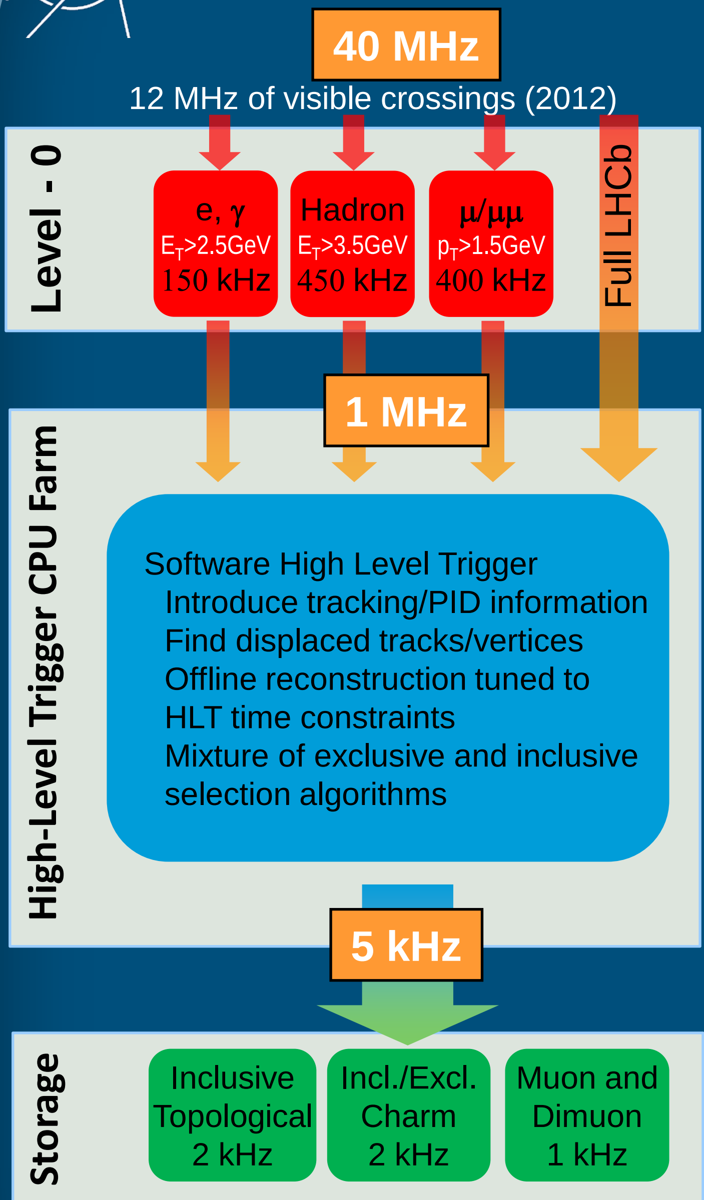




B S/N almost independent of pileup
D S/N shows some degradation vs pileup.

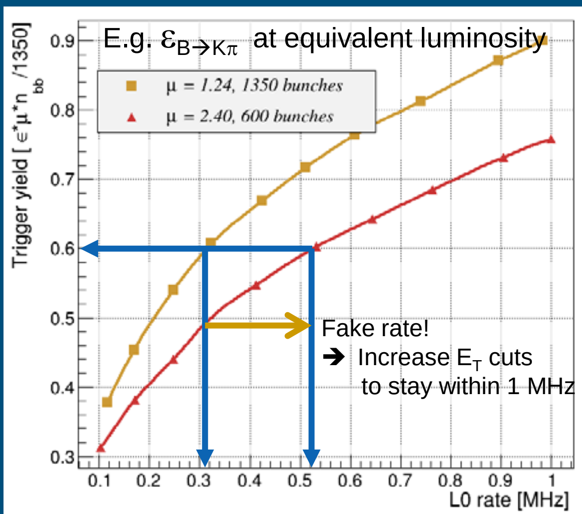
- ➔ Demonstrated *forward* high precision tracking and particle ID even with pileup
- ➔ Further demonstration of the concepts for the LHCb upgrade

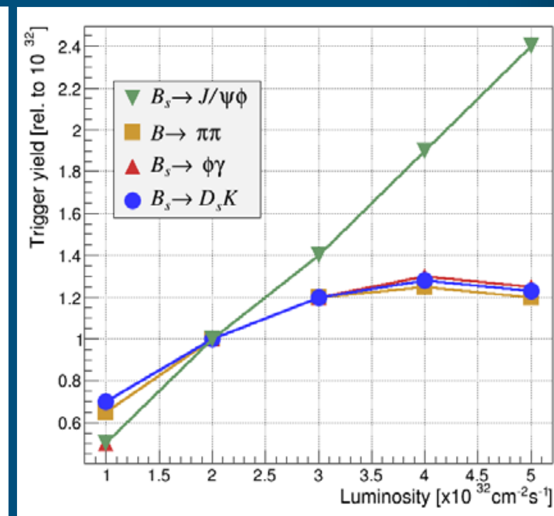
Current Trigger Architecture



- Performances at 8 TeV in 2012 (L0 x HLT)
  - B decays with μμ: ε ~ 90 %
  - B decays with hadrons: ε ~ 30 %
  - Charm decays: ε ~ 10 %
  - ➔ About half the interesting B decays are lost
- Limitation: FE readout time=900ns ➔ max 1.1 MHz
  - Increase luminosity (=increase pileup)?

CERN/LHCC 2011-001





➔ Efficient selection requires IP and p_T of tracks

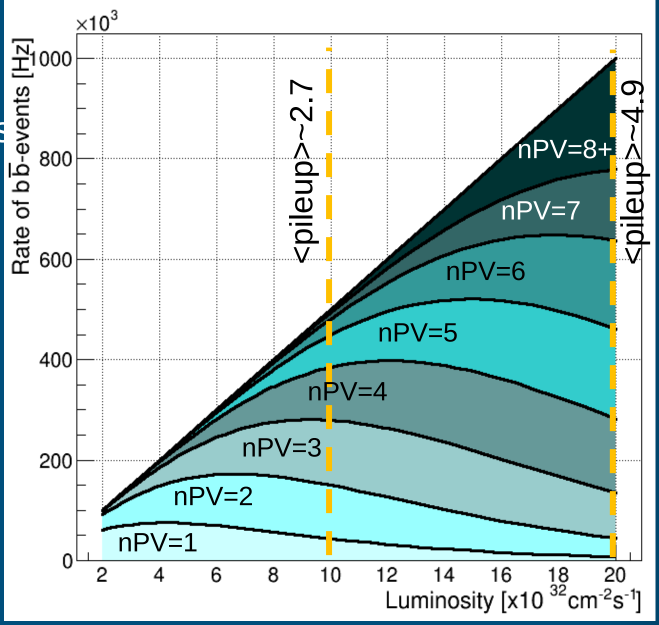
➔ Remove L0 bottle neck

➔ Readout detector at 40 MHz

Global LHCb Upgrade Strategy

Baseline

1. Full detector readout at 40 MHz up to CPU farm
2. Implement a fast high-level software trigger to select events based on their full topology
3. Improve sub-detectors
   - Geometry and granularity to allow fast full reconstruction
   - Allow increase instantaneous luminosity up to 2 x 10^{33} cm^{-2}s
   - Replacement due to radiation longevity (up to 100 fb^{-1})
4. Final output bandwidth at ~20 kHz



➔ Improve significantly trigger efficiencies for hadronic channels

➔ Increase statistics for all channels

Consequences:

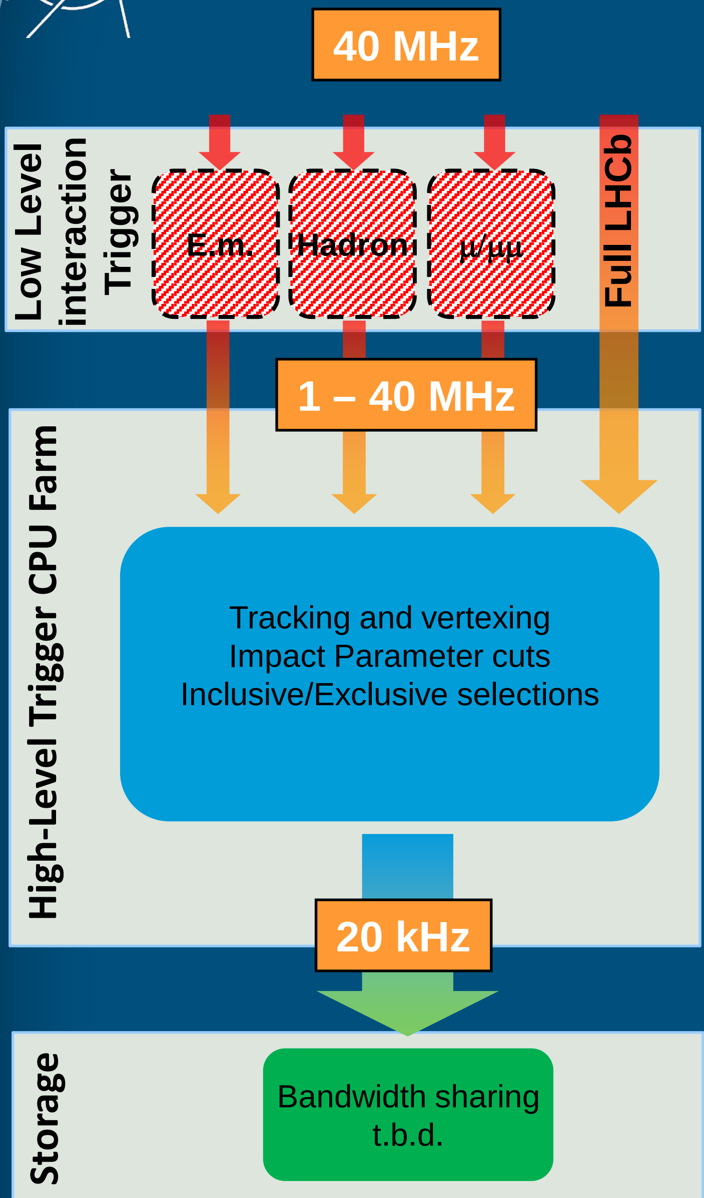
➔ 40 MHz readout requires replacing all FE and BE electronics

➔ Detector and readout upgrade must be done in one Technical Shutdown to be of benefit

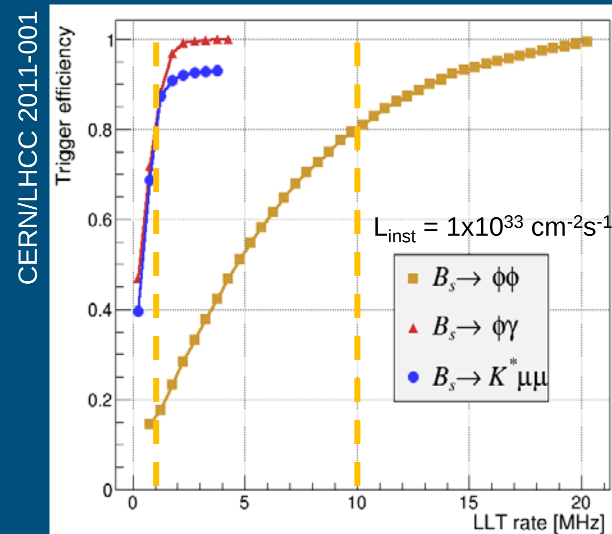
➔ Variable first level activity trigger (1-40 MHz) allows staging the capacity of the high-level trigger farm

- Starting point: 5 - 10 MHz event processing in farm at 1 x 10^{33} cm^{-2}s^{-1}

Upgrade Trigger Architecture



- Variable Low Level interaction Trigger: 1 – 40 MHz
  - Lower E_T/p_T cuts of e, γ, hadron, μ



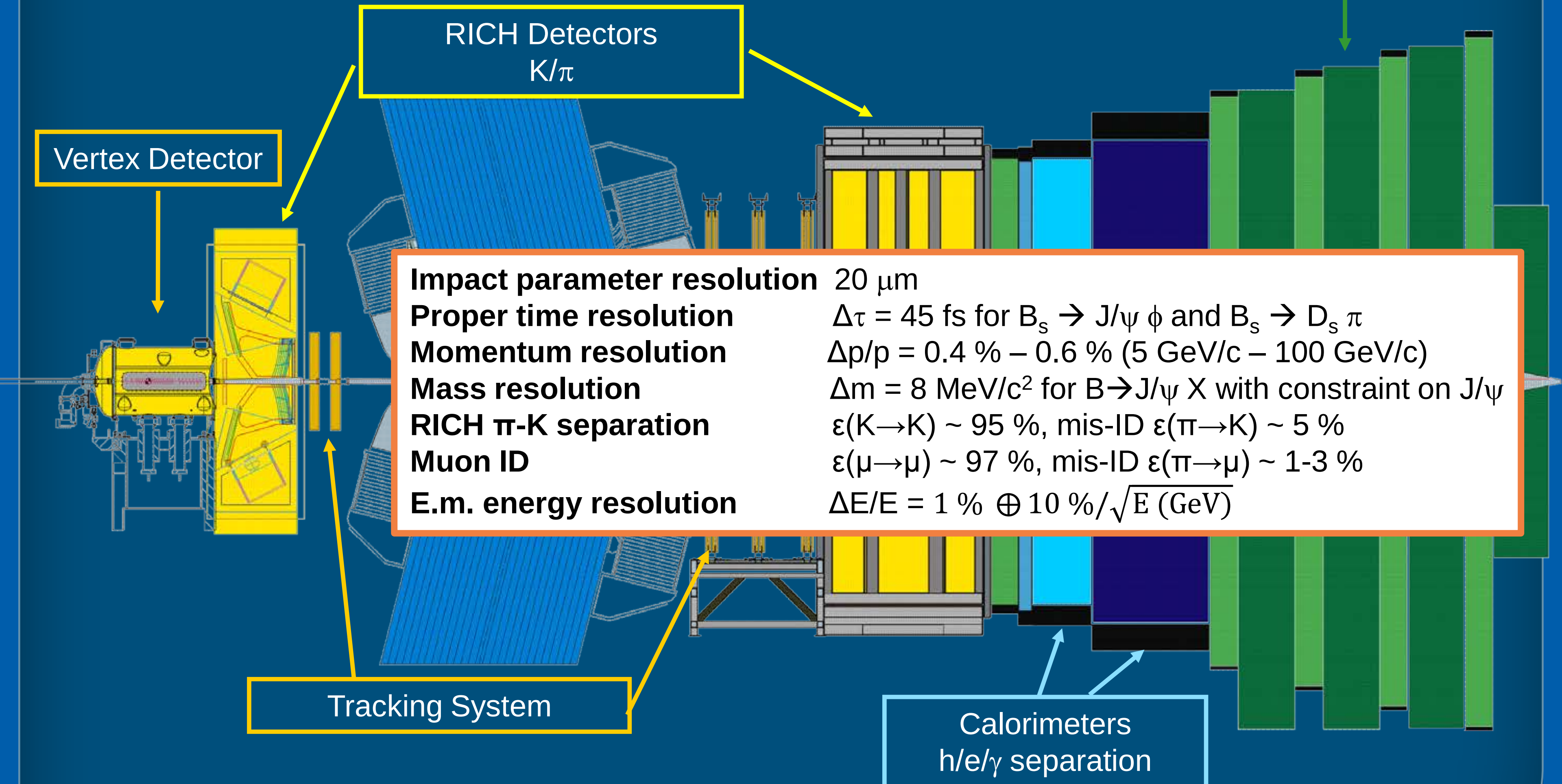
  - Yield of hadronic B's gains up to ~13x compared to 2012
  - Large gain for charm physics as well due to lower p_T
- Performance as function of HLT Farm CPU capacity
  - ➔ Non-optimized upgrade example:

HLT farm	3 x 2012	6 x 2012
LLT rate [MHz]	5.1	10.5
HLT1 rate [kHz]	270	570
HLT2 rate [kHz]	16	26
L0 x HLT efficiencies at 10^{33} cm^{-2} s^{-1}		
$B_s \to \phi\phi$	0.29	0.5
$B_d \to K^*\mu\mu$	0.75	0.85
$B_s \to \phi\gamma$	0.43	0.53

CERN/LHCC 2011-001

Current LHCb Detector Performance

- *Extremely good performance in the pileup environment*
- *Regular ageing scans with beam and calibrations vital*
- *Detector ageing under control*

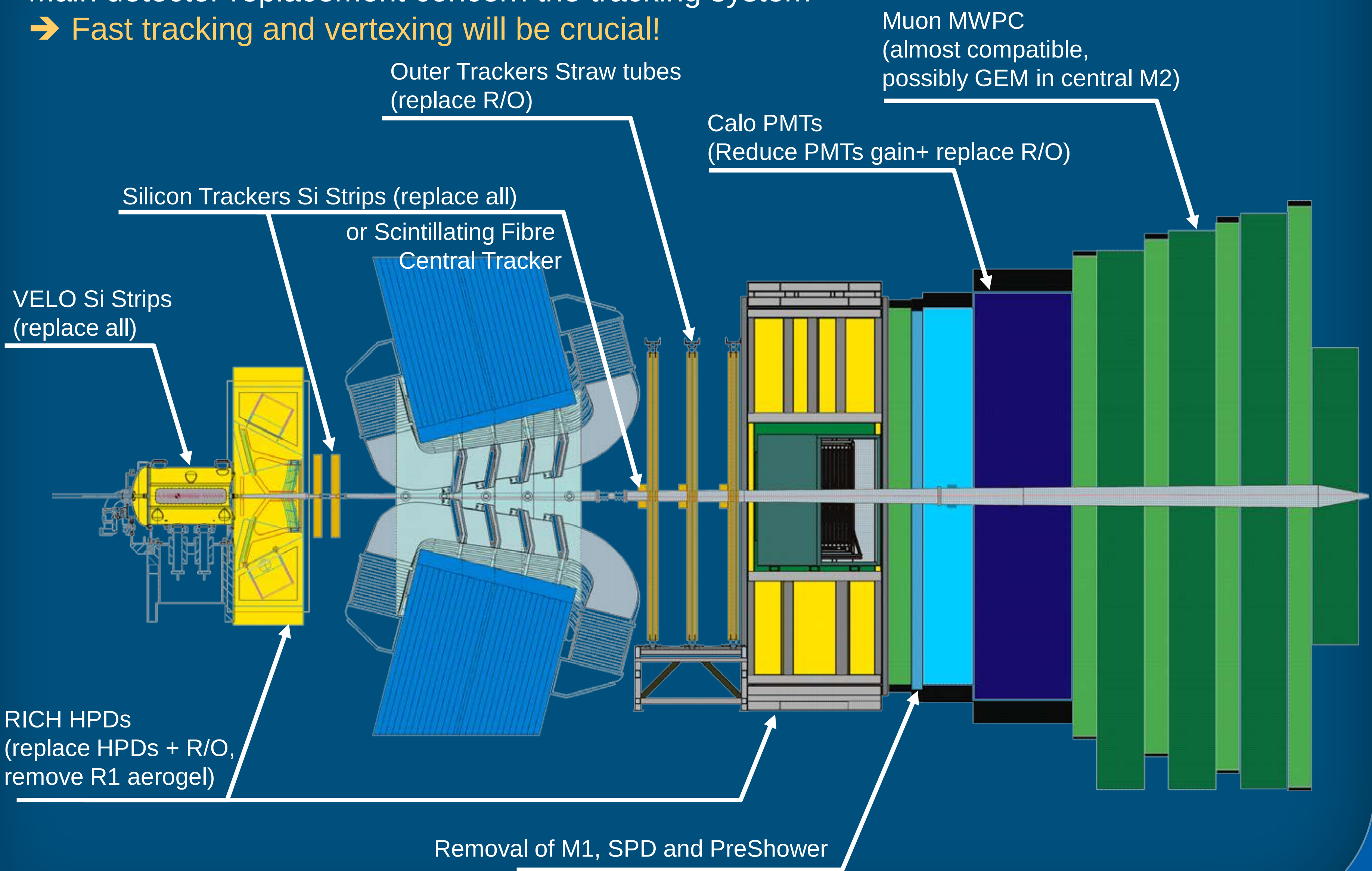


Impact parameter resolution	20 μm
Proper time resolution	$\Delta\tau$ = 45 fs for $B_s \rightarrow J/\psi\ \phi$ and $B_s \rightarrow D_s\ \pi$
Momentum resolution	$\Delta p/p$ = 0.4 % – 0.6 % (5 GeV/c – 100 GeV/c)
Mass resolution	Δm = 8 MeV/c^2 for $B \rightarrow J/\psi$ X with constraint on J/ψ
RICH π-K separation	ε(K→K) ~ 95 %, mis-ID ε(π→K) ~ 5 %
Muon ID	ε(μ→μ) ~ 97 %, mis-ID ε(π→μ) ~ 1-3 %
E.m. energy resolution	$\Delta E/E = 1\ \% \oplus 10\ \%/\sqrt{E\ (\mathrm{GeV})}$

- *Achieve at least same performance with upgraded detector at significantly higher pileup/occupancy*

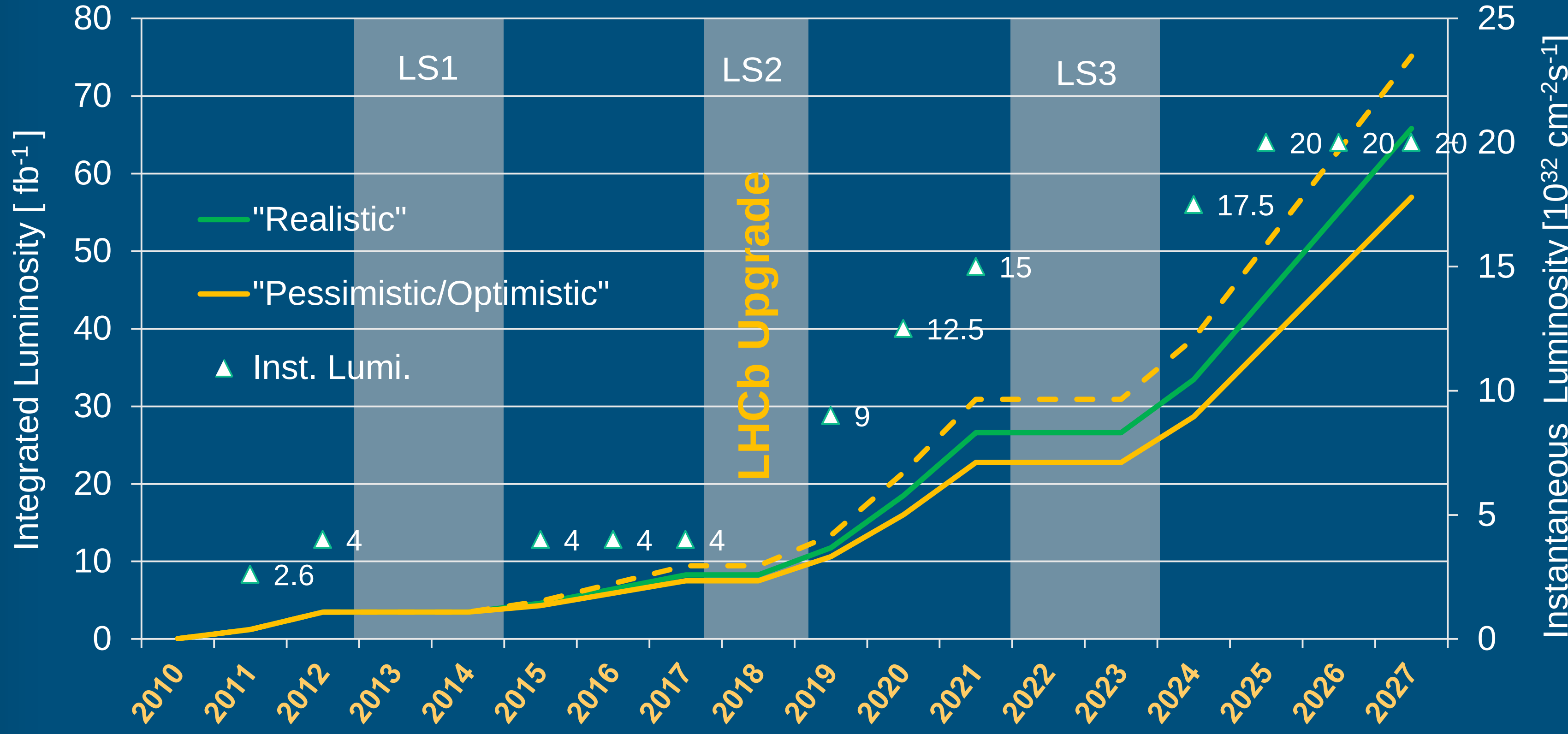
Sub-detector Upgrades – Baseline

Main detector replacement concern the tracking system
➔ Fast tracking and vertexing will be crucial!



Luminosity Projection

- Luminosity projection based on experience in Run 1 and updated schedules:



- Clearly, again with the experience of 2010 – 2012, it's very likely the luminosity trend will look different

Upgrade Physics Prospects

- Expected precision based on statistics uncertainties
- Precision not expected to be limited by systematics in many analyses

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 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	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° [19, 20]	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° [18]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

CERN/LHCC 2012-007

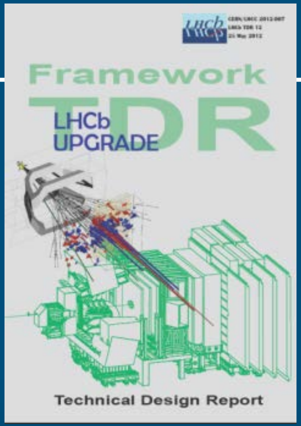
➔ But strength is the full software trigger to tune to any signature that may be popular in 2020!

Upgrade Schedule

Overall generic milestones:

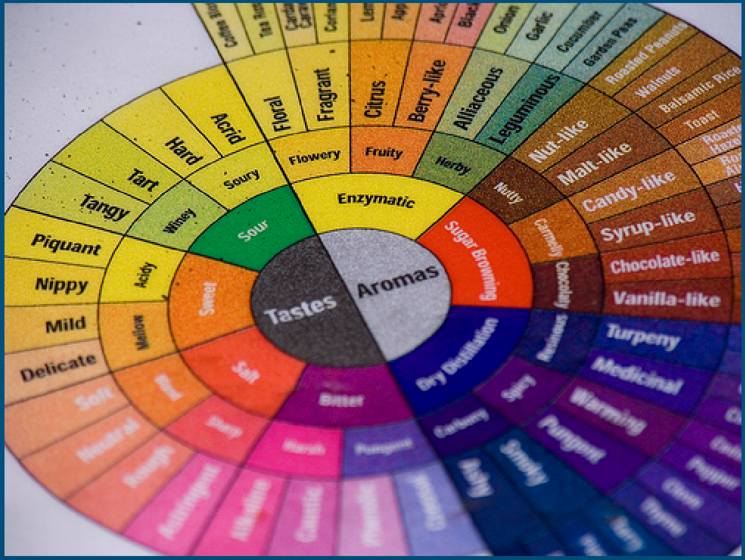
- in 2018/19: installation (18 months according to planning!)
- 2016-17: quality control & acceptance tests
- 2014-16: tendering & serial production
- Q3/Q4 2013: TDRs & prototype validation
- Q1/Q2 2013: technical reviews & choice of technologies
- ✓ 2012/2013: continue R&D towards technical choices
- ✓ 2012: “Framework TDR” submitted & endorsed
- ✓ June 2011: LoI submitted & encouraged to proceed to TDRs

timeline

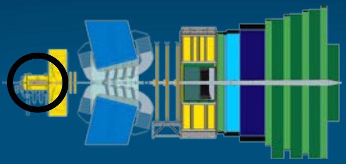


Conclusions

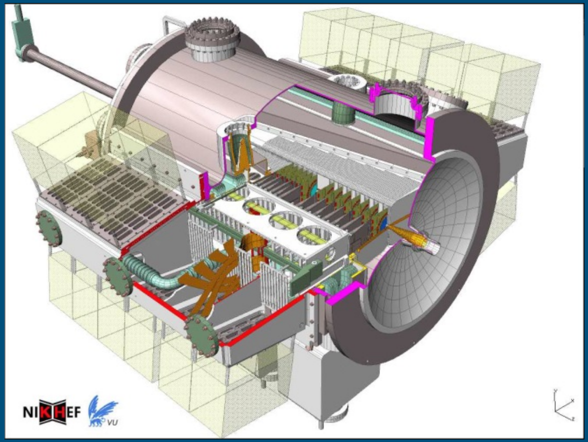
- LHCb has fought hard to earn the title of forward GPD
  - LHCb has demonstrated forward tracking and particle ID
  - A very rich physics program
  - Continuing on this the LHCb upgrade is largely a trigger upgrade with the ultimate flexibility!
- Folding in efficiencies and luminosity, upgrade get up to 20 times more hadronic events per second !
  - Challenging, but realistic
  - High pile-up data taken in 2010 and in 2012 very encouraging in view of a luminosity upgrade
  - Upgrade allows reaching theoretical uncertainties and opens the door to new observables
- The LHCb Upgrade has been fully approved by CERN
- In continuous search for new flavors!



EXTRA SLIDES



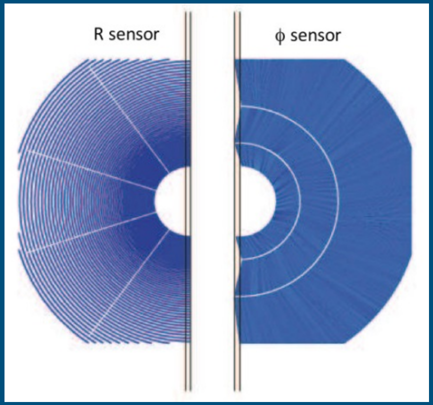
* VELO Upgrade

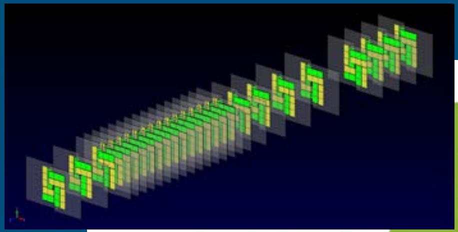


Two options still considered:

1. Microstrip sensors:
   - Similar to the existing VELO R and ϕ layout.
   - Finer pitch and segmentation to reduce occupancy, reduced thickness and inner radius.
2. Pixel sensors:
   - High granularity eases pattern recognition.
   - R&D is focusing on planar silicon sensors 55 μm ×55 μm (256×256 pixels).

➔ Project review for decision scheduled this month





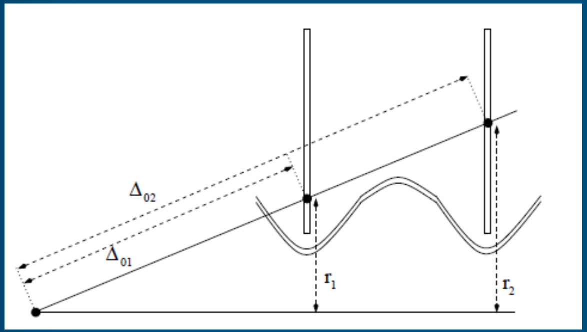
* VELO Upgrade

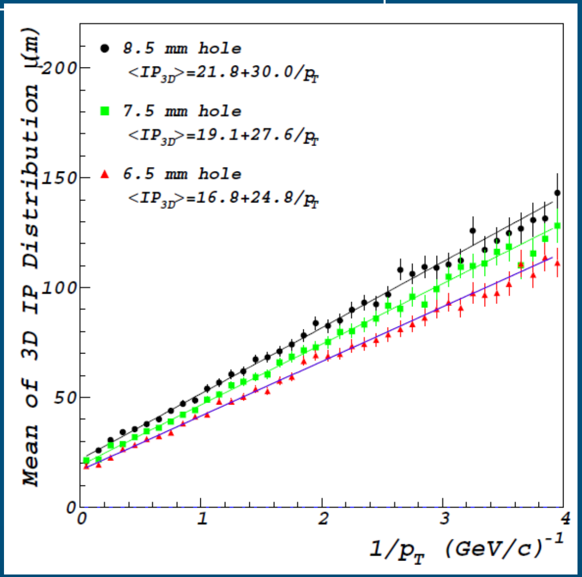
- Reduced sensor distance to beam and thinner RF foil
  - Inner radius of RF foil will be reduced from 5.5 mm to 3.5 mm to improve IP-resolution

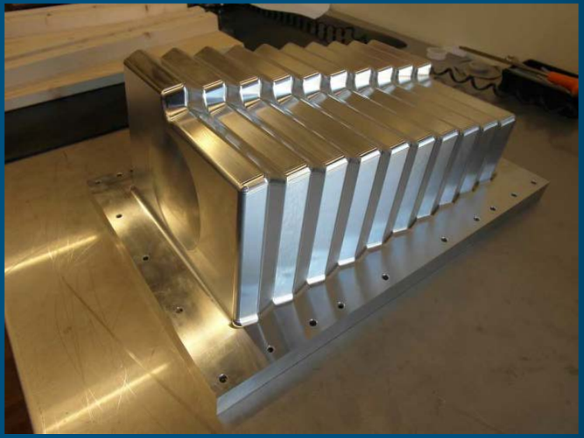
  - The RF foil currently contributes with 80% of the material budget before r1 and r2 points
  - ➔ Thinner foil from current 300μm to200 μm by milling

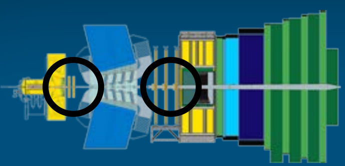
- Cooling challenge
  - Close to beam: ~ $5 \times 10^{15}\ n_{eq}cm^{-2}$
  - Must cool to -10oC to -15oC to prevent thermal runaway

$$\sigma_{IP}^{2} = \frac{r_1^{2}}{\sqrt{2}p_T^{2}}[13.6\frac{MeV}{c}\sqrt{\frac{x}{X_0}}(1+0.038\ ln\frac{x}{X_0})]^2 + \frac{\Delta_{02}^{2}\sigma_1^{2}+\Delta_{01}^{2}\sigma_2^{2}}{\Delta_{12}^{2}}$$

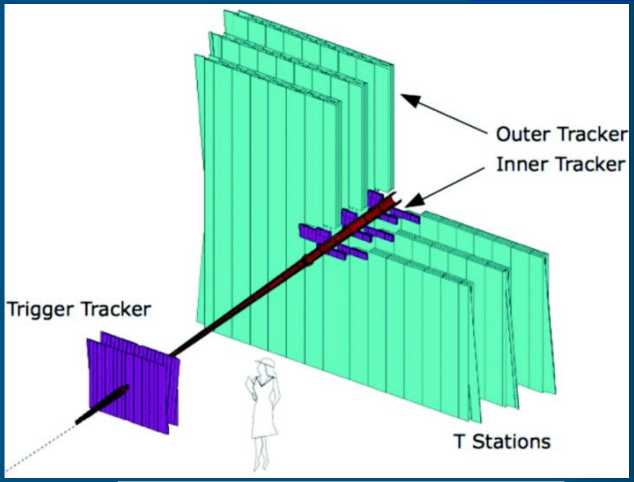








* Tracker Upgrades



- TT
  - Redone with same Si-strip technology but improved geometry:
    - Better coverage by overlapping sensors
    - Better vertical segmentation
    - Closer to beam pipe improve small-angle acceptance
    - Less material with thinner sensors (0.5 mm → 0.2−0.3 mm)
  - ➔ Aim at fast VELO-TT momentum measurement
  - ➔ Reduce fake VELO-IT/OT tracks

- IT/OT – two options considered for the "T-stations"
  1. Silicon IT
     - New silicon strip detector with larger coverage reducing geometry of OT in central region
     - "η" coverage: IT/(IT+OT): 33% → 54%
     - Si-IT size driven by OT performance – cut whole in central OT to reduce effect of two high occupancy
  2. Fibre Tracker
     - Central tracker based on Scintillating Fibres with Silicon Photo-Multiplier (SiPM)
     - Five layers of 2.5 m long scintillating fibres with 250 μm diameter.
     - Need to keep the fibres straight to ~50 μm and flat to ~200 μm over 2.5m
     - Expected performance: 60 – 100 μm spatial resolution.