Heavy flavour physics at LHCb :

Run I highlights and future prospects

2015

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Simon Akar

Centre de Physique des Particules de Marseille

IN2P3 Les deux infinis

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE

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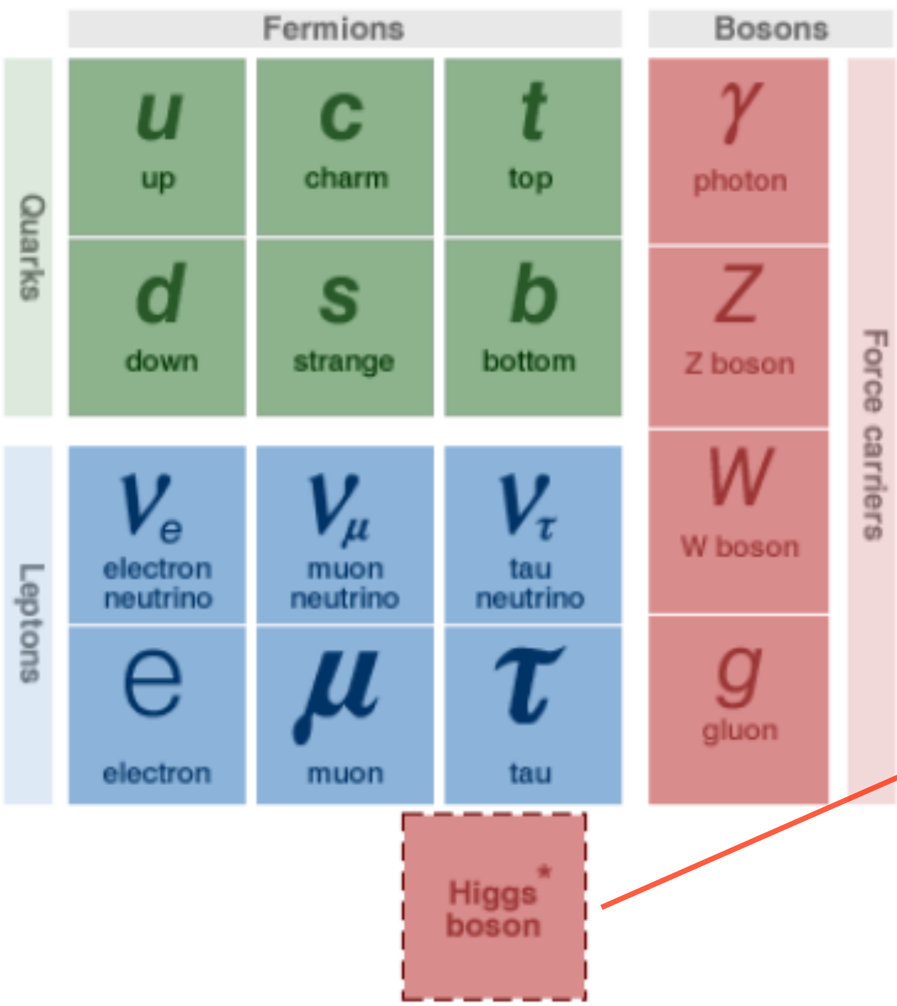
1

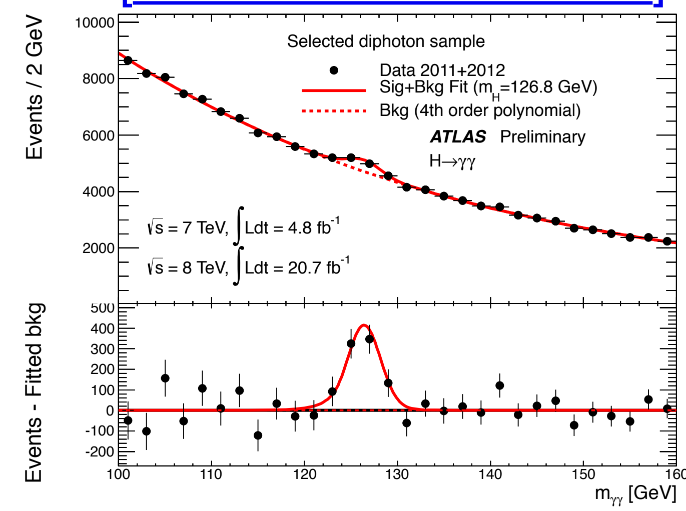
Introduction

The Standard Model
A remarkably successful theory!

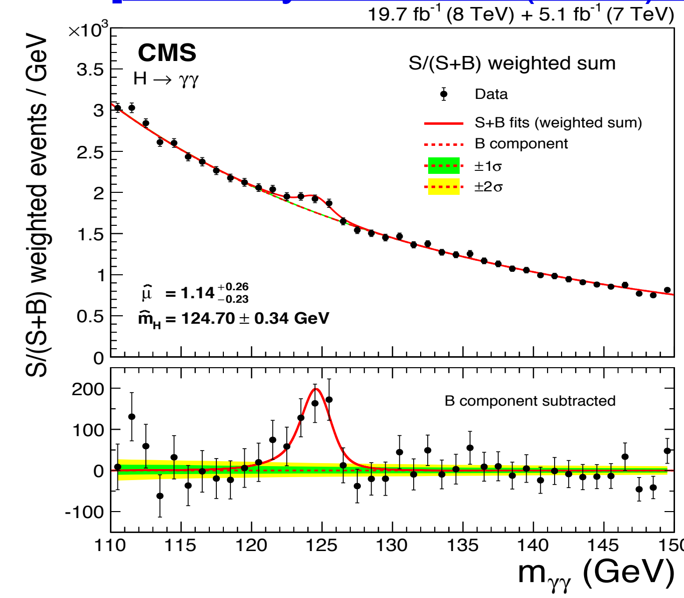
- **With the discovery of the Higgs boson, the Standard Model (SM) is now complete!**



[ATLAS-CONF-2013-012]



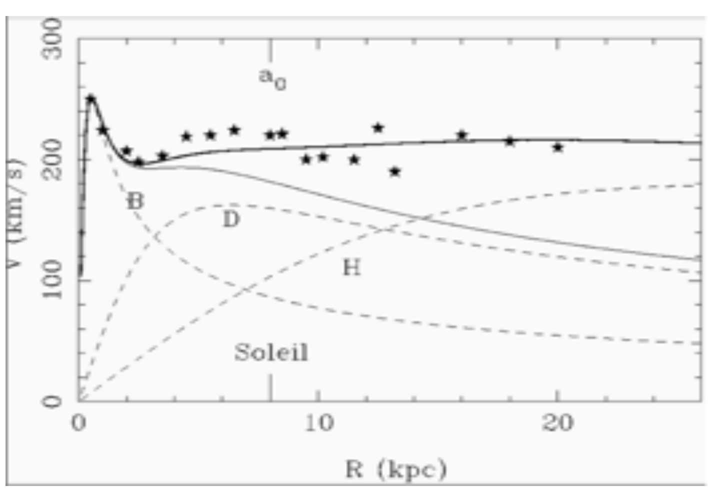
[Eur. Phys. J. C 74 (2014) 3076]

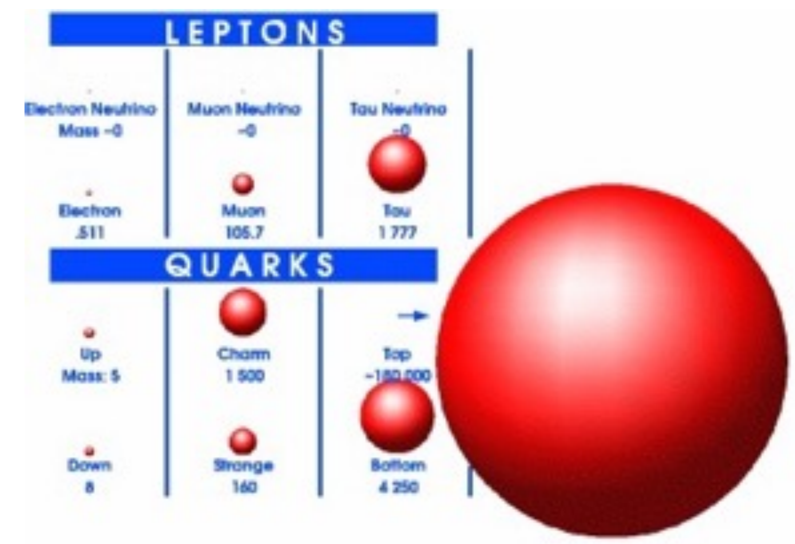


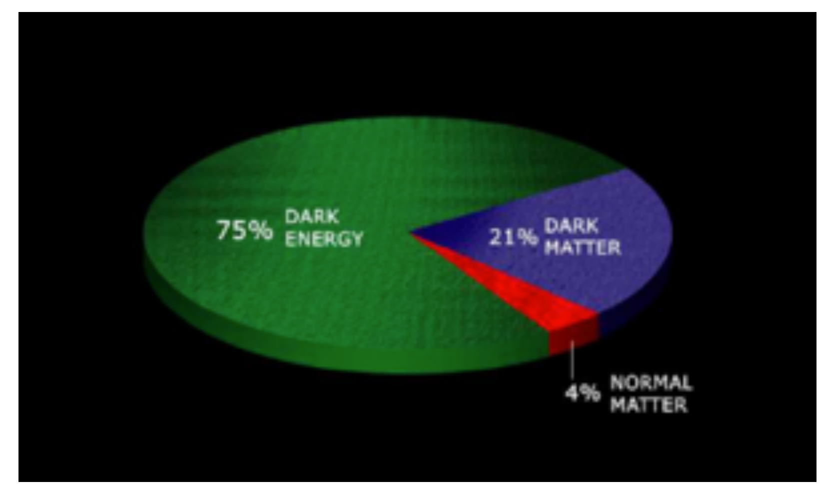
- **The SM withstood experimental tests for over 40 years...**

The Standard Model
A remarkably successful theory! But…

- **Many open questions with no answer in the Standard Model framework:**
  - Cosmological dark matter
  - Dark energy (Universe in accelerated expansion)
  - Baryon asymmetry of the Universe
  - Quarks and Letpons mass hierarchy
  - Non-zero neutrino masses
  - …







- **Compelling evidence for beyond the SM physics.**
  - But what and how do we search?

Physics beyond the Standard Model
What and how do we search?

- New Physics (NP) contribution can be expressed as a perturbation to the SM lagrangian:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{\rm d\geq 5} \frac{c_{\rm n}}{\Lambda^{d-4}} \mathcal{O}_{\rm n}^{(\rm d)}(\phi, A_{\rm a}, \psi_{\rm i})$$

Two major questions of particle physics today:

- Which is the energy scale of NP (or the value of Λ)
- Which is the symmetry structure of the new degrees of freedom (or the structure of the c_n)

⇔ High-energy experiments [high-energy frontier]

⇔ High-precision low-energy exp. [high-intensity frontier]

Physics beyond the Standard Model
What and how do we search?

Two complementary paths to search for NP:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{\text{d}\geq 5} \frac{c_{\text{n}}}{\Lambda^{d-4}} \mathcal{O}_{\text{n}}^{(\text{d})}(\phi, A_{\text{a}}, \psi_{\text{i}})$$

- Direct search (ATLAS & CMS)
  - production of new particles (real)
    - the heavier the new particles are, the more energy is needed to produce them
  - observation of their decay

Is there anything else beyond the SM at the TeV scale?

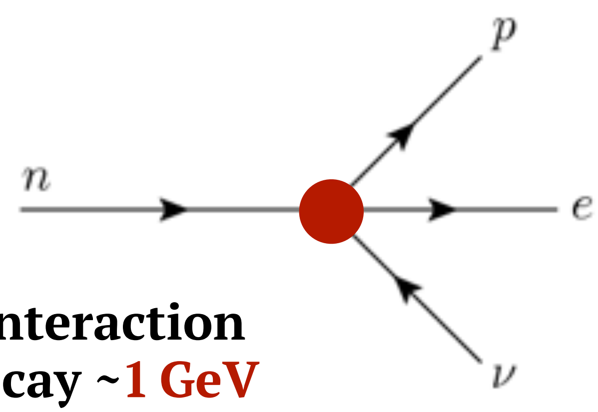
- Indirect search (LHCb)
  - virtual production of new particles
    - heavy particles can be produced virtually (off mass shell) with moderate energy in the center of mass of the collision
  - these virtual particles affect the decay processes
    - differences w.r.t. standard model prediction

What determines the observed pattern of masses and mixing angles of quarks and leptons ?

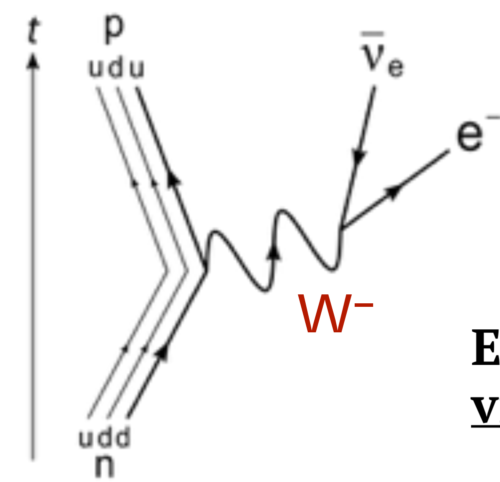
- Considering the present experimental constraints in flavour physics:
  - $c_n \sim 1 \Rightarrow \Lambda \sim [10^2 ; 10^5]$ TeV
  - $\Lambda \sim 1$ TeV $\Rightarrow c_n \sim [10^{-5} ; 10^{-11}]$

Physics beyond the Standard Model
What and how do we search?

- Historically, indirect observations of "new physics" has often been the portal to infer properties of heavy particles before experiments with sufficient energy to produce them.
  - Beta decay:

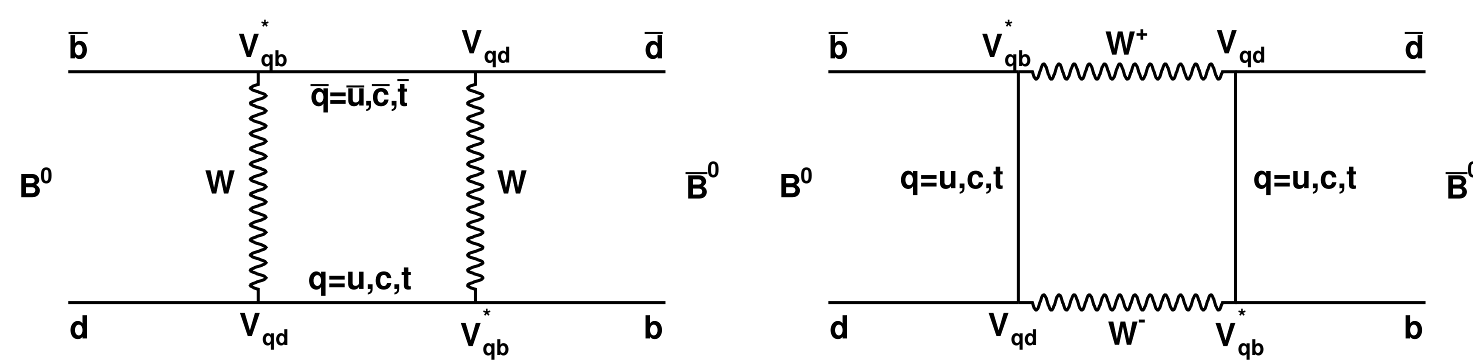


Fermi's 4-point interaction theory of beta decay ~1 GeV



Exchange of heavy virtual boson ~80 GeV

  - B meson mixing:



In 1987, the Argus experiment measured:

$$\Delta m_B \sim 0.00002 \times \left(\frac{m_t}{\mathrm{GeV}/c^2}\right)^2 \mathrm{ps}^{-1}$$

$$\sim 0.5\,\mathrm{ps}^{-1}$$

$$m_t \sim 250\,\mathrm{GeV}/c^2$$

First hint that the yet unseen top quark was much heavier than expected

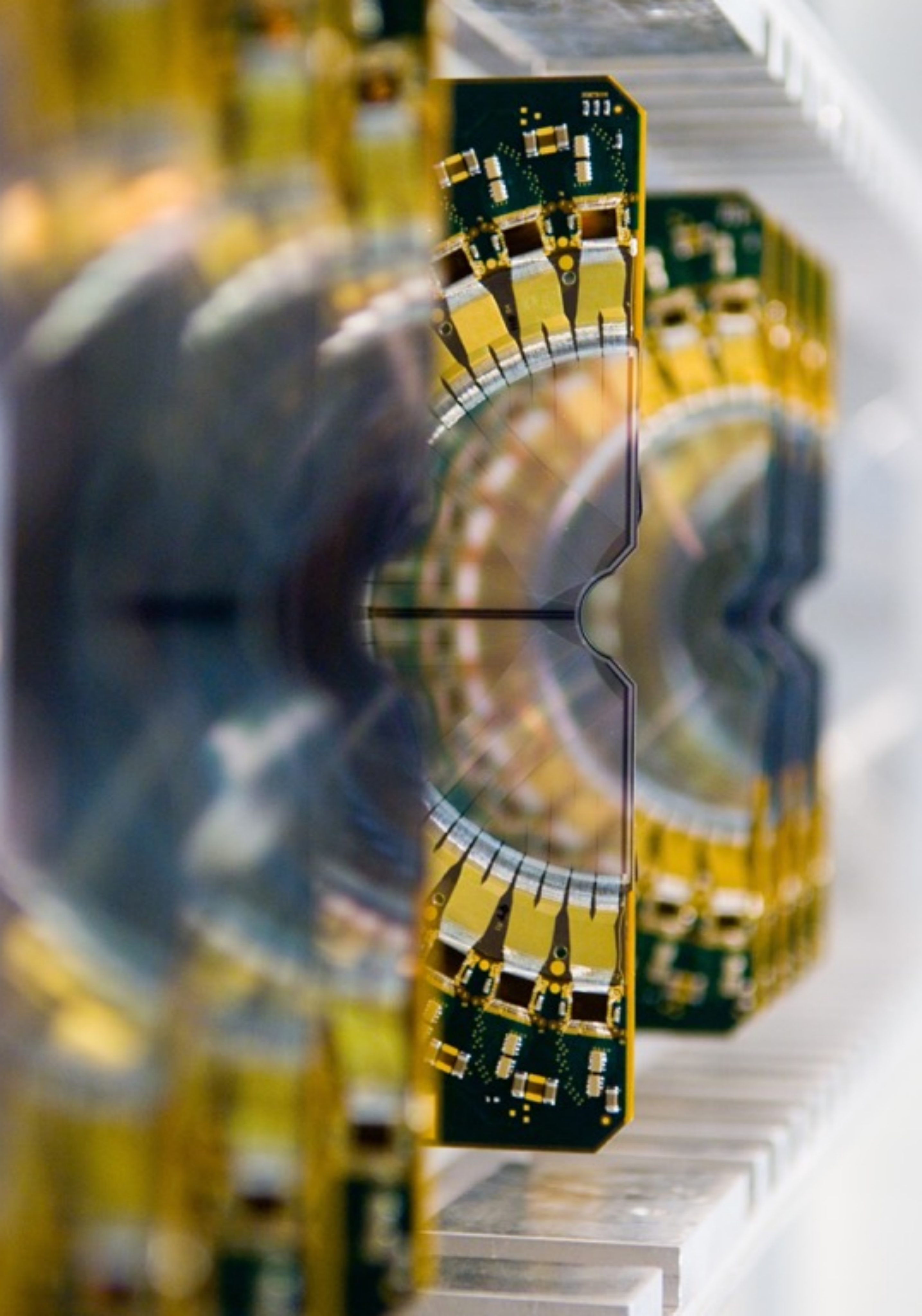
Discovered in 1995 at the Tevatron:

$$m_t = 173.21 \pm 0.51 \pm 0.71\,\mathrm{GeV}/c^2$$

Physics beyond the Standard Model
The LHCb physics program

- LHCb dedicated to precision measurements of heavy flavor:
  - Compare precision measurements and clean predictions to find evidence for NP
  - Flavor sector: very rich sector of the SM with precise theoretical predictions

- Different observables give different constraints on different NP models:
  - B decay to charmonium: B_s mixing, CP violation
  - Rare decays: leptonic, electroweak, radiative, Lepton Flavor Violation
  - Semileptonic B decays: Search for CPV in mixing, form factors, rare decay
  - Charm physics: Mixing and CPV, charm production and spectroscopy
  - B hadron and quarkonia: Production and spectroscopy
  - QCD, electroweak and exotica: EW boson production, long lived particles
  - …



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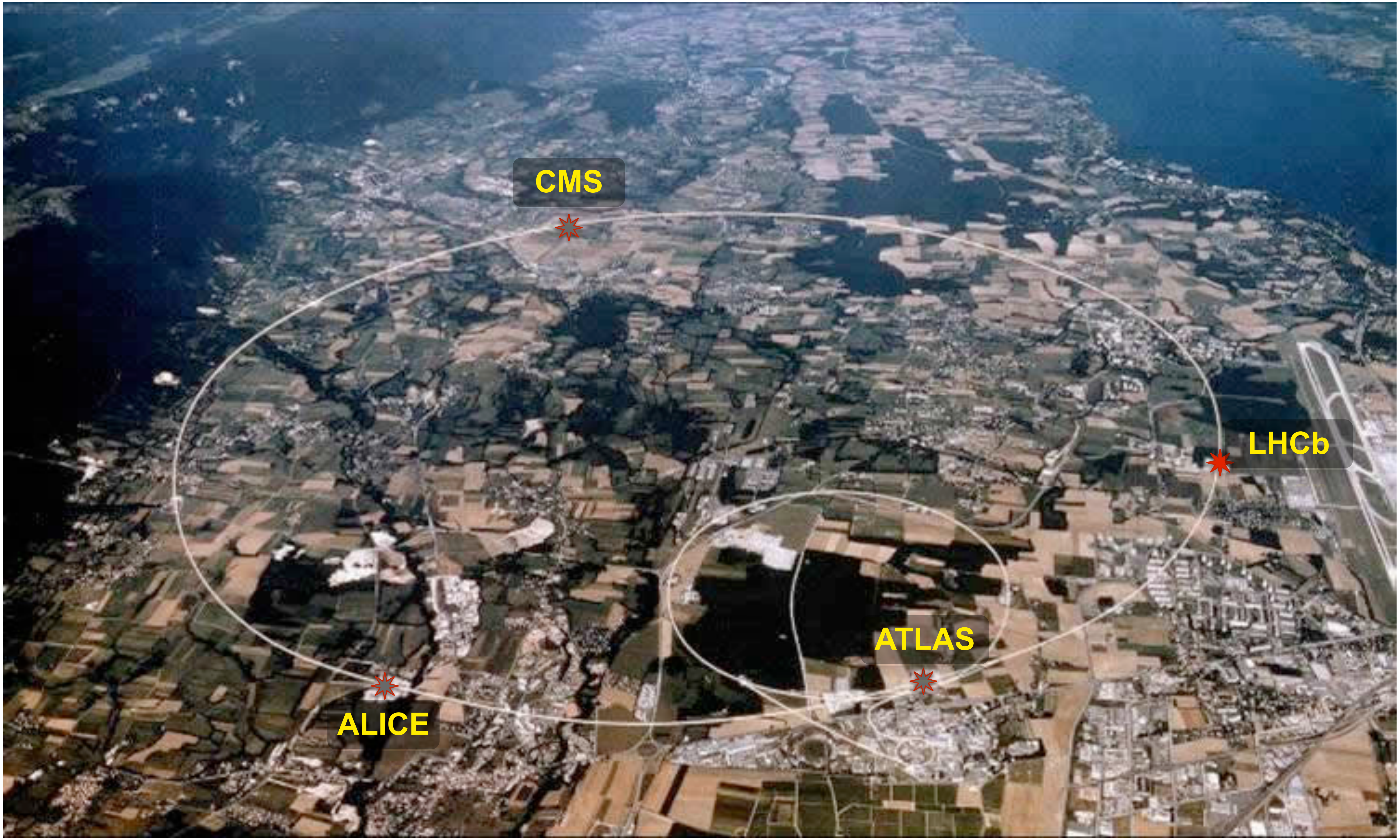
The LHCb experiment

The LHCb experiment
@ the LHC



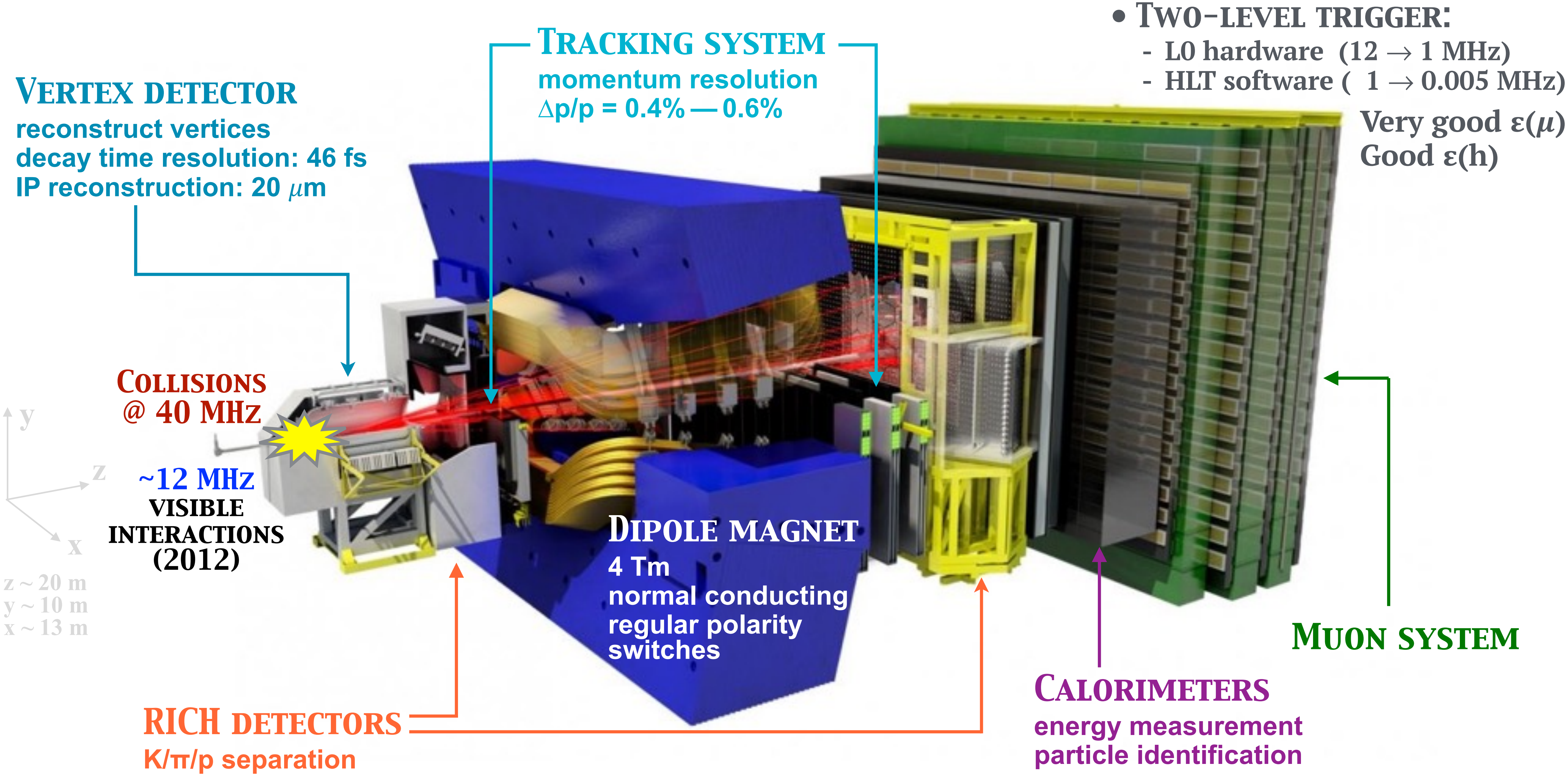
The LHCb experiment
Collaboration overview

The LHCb experiment
Detector overview

- Forward General-Purpose Detector at the LHC
- ~30 % of heavy quark production cross-section with just 4% of solid angle

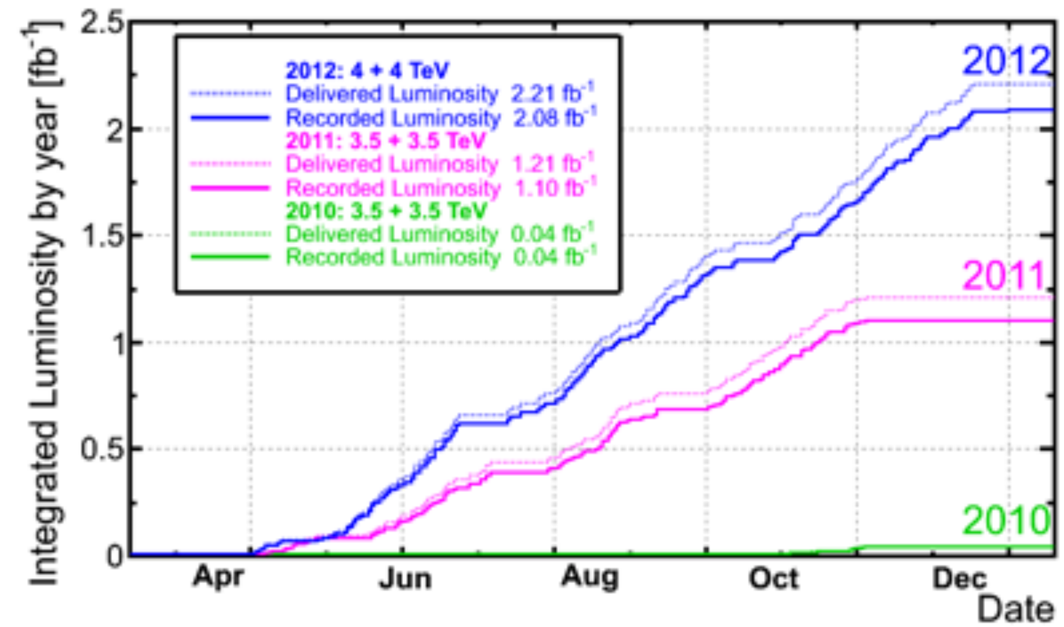
- **Two-level trigger:**
  - L0 hardware (12 → 1 MHz)
  - HLT software (1 → 0.005 MHz)

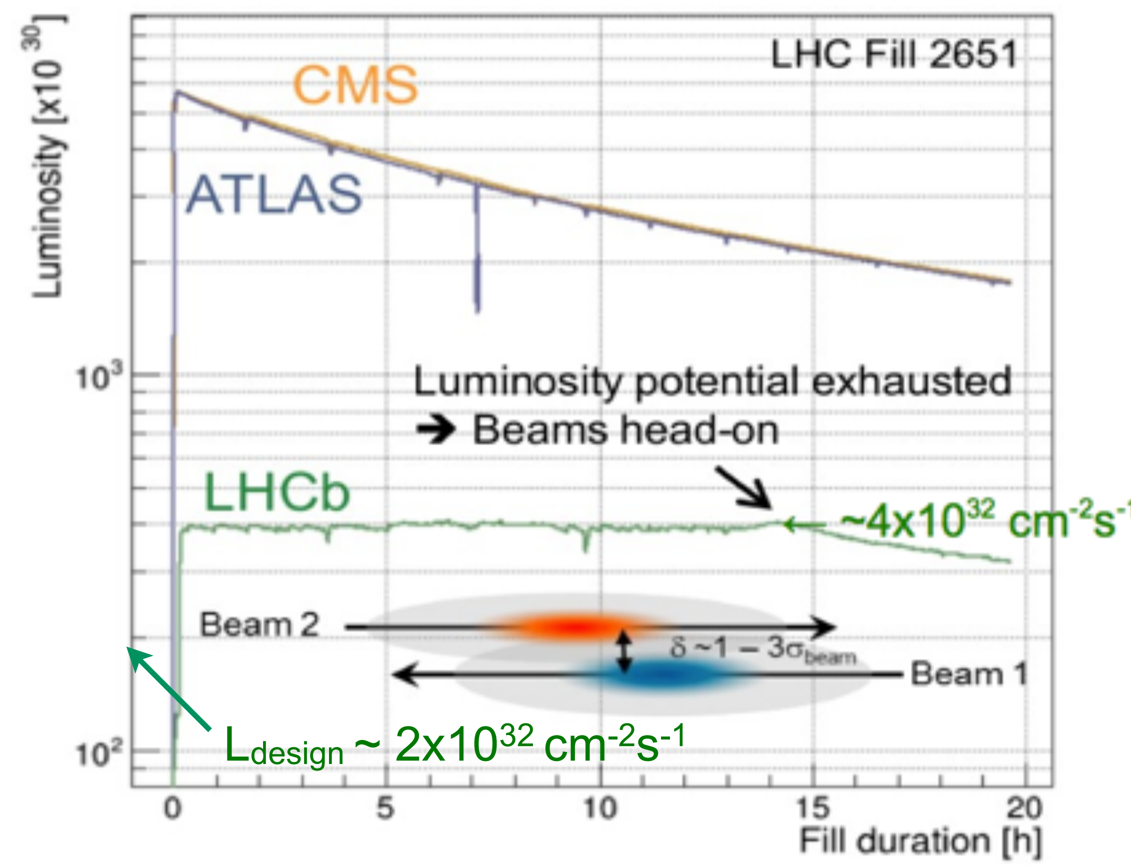
Very good ε(μ)
Good ε(h)



The LHCb experiment
Physics performances – Run I

- **Integrated luminosity**
  - 1 fb^{-1} @ 7 TeV (2011)
  - 2 fb^{-1} @ 8 TeV (2012)
- **Excellent LHCb performances**
  - > 99% detector channels working
  - > 99% collected data good for analysis
  - Stable operations with $L \sim 2 \times L_{design}$
- **luminosity leveling**
  - Displaced pp beams
  - Constant running conditions
  - Lower instantaneous luminosity
  - Lower pile-up
  - Better tracking and PID performances





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Highlights on some key results

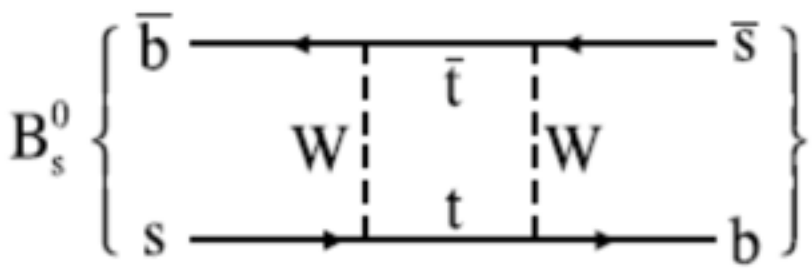
- **Weak phase ϕ_s:**
  - CPV in interference between mixing and decay
  - Small and precise SM prediction:

$$\phi_s^{\text{SM no Peng}} = -2\beta_s = -0.0365^{+0.0013}_{-0.0012}$$

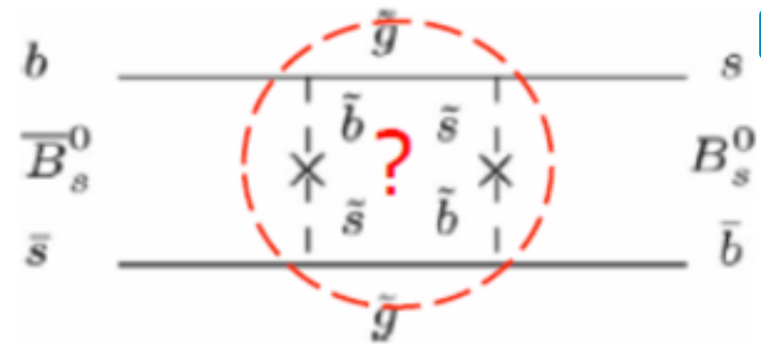
[CKMFitter]

$$\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

SM



NP



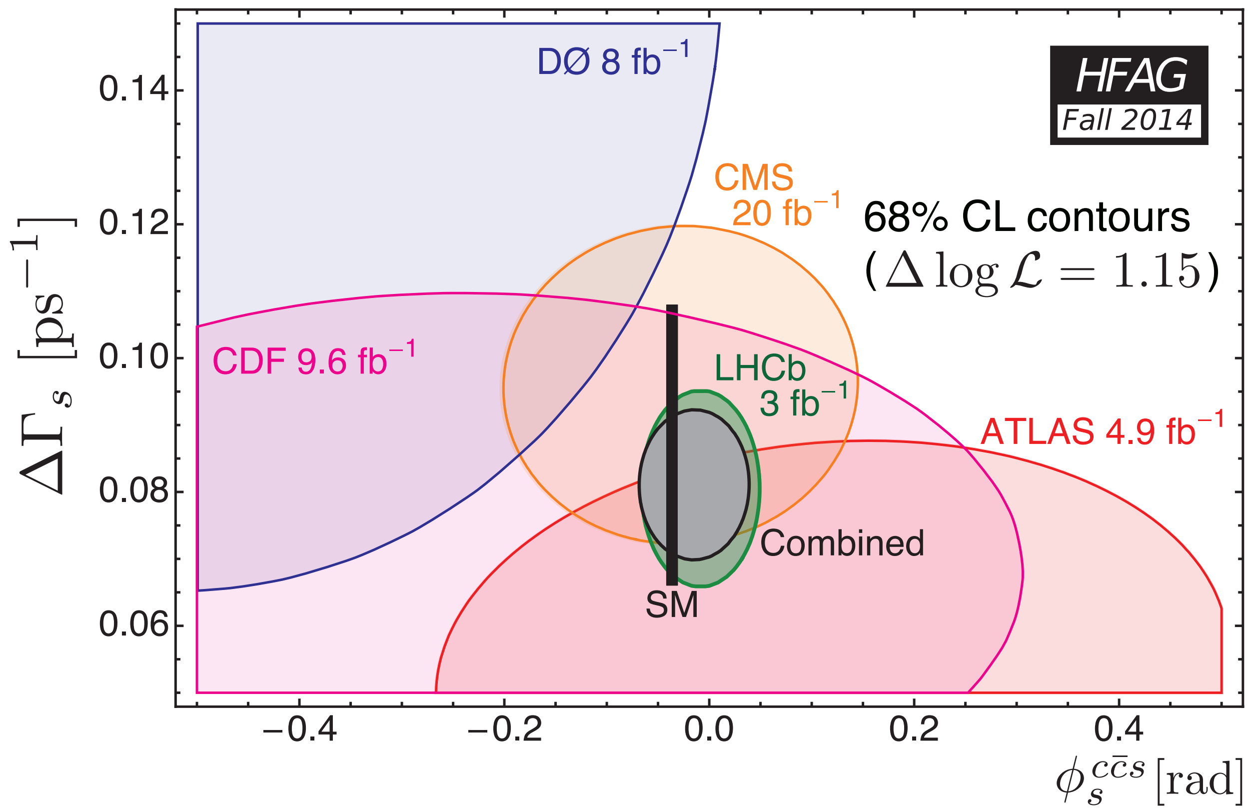
  - Golden mode: $B_s \to J/\psi K^+K^-$

$$\phi_s\ [\text{rad}] = -0.058 \pm 0.049 \pm 0.006$$

  - Other modes: $B_s \to J/\psi\, \pi^+\pi^-$, $B_s \to D_sD_s$
  - LHCb dominates world average:

$$\phi_s^{c\bar{c}s} = -0.015 \pm 0.035$$

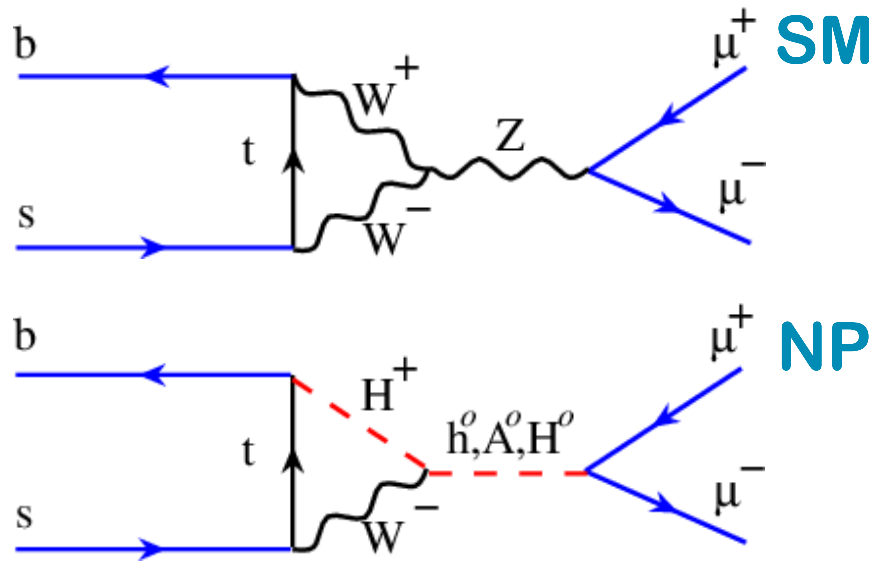
[HFAG]



LHCb highlights from Run I

$B_{s/d} \to \mu^+\mu^-$

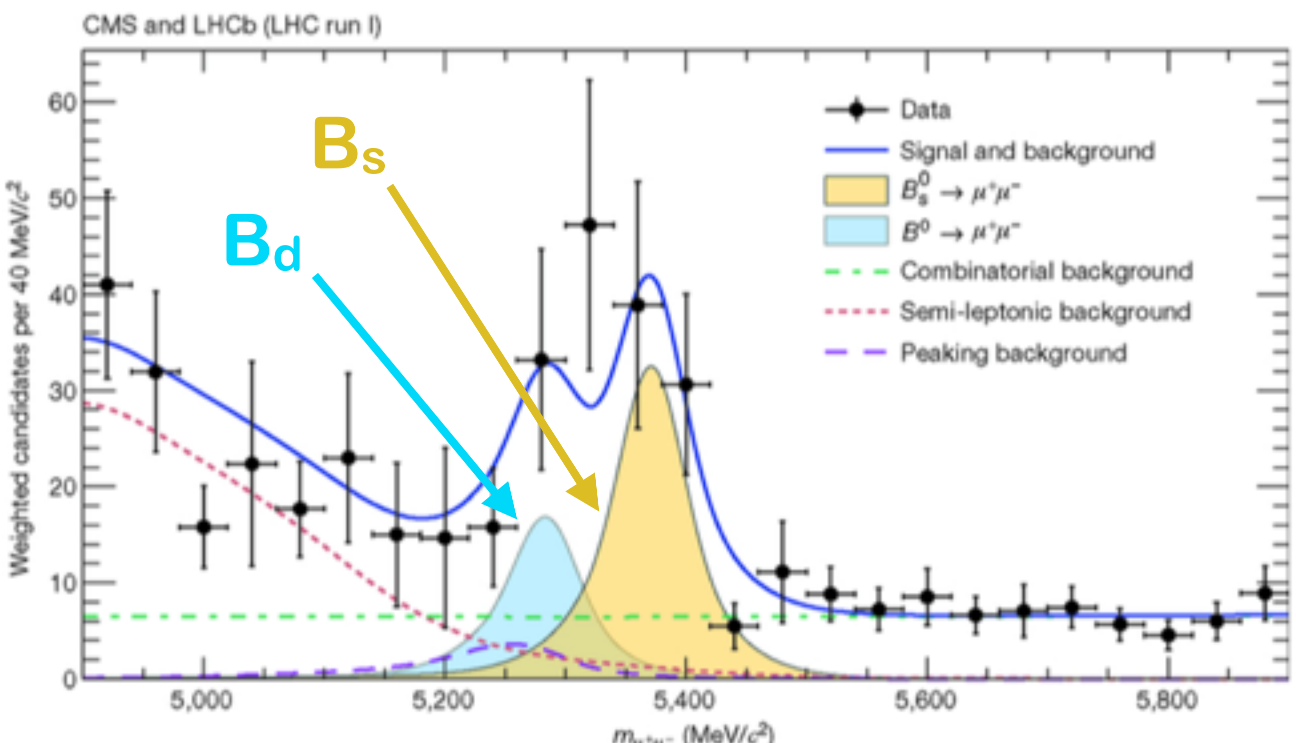
- **Very rare decays in the SM:**
  - FCNC and helicity suppressed
  - Precise SM prediction
  - Intensively searched since 30 years

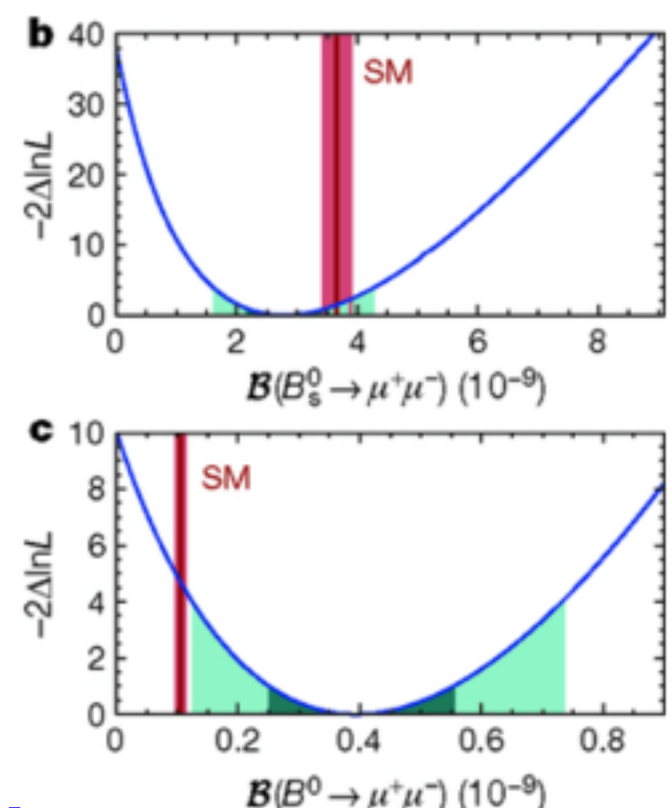


- **Combination with CMS data:**

$\mathcal{B}(B_d) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$, $3.2\ \sigma$

$\mathcal{B}(B_s) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$, $6.2\ \sigma$ first observation

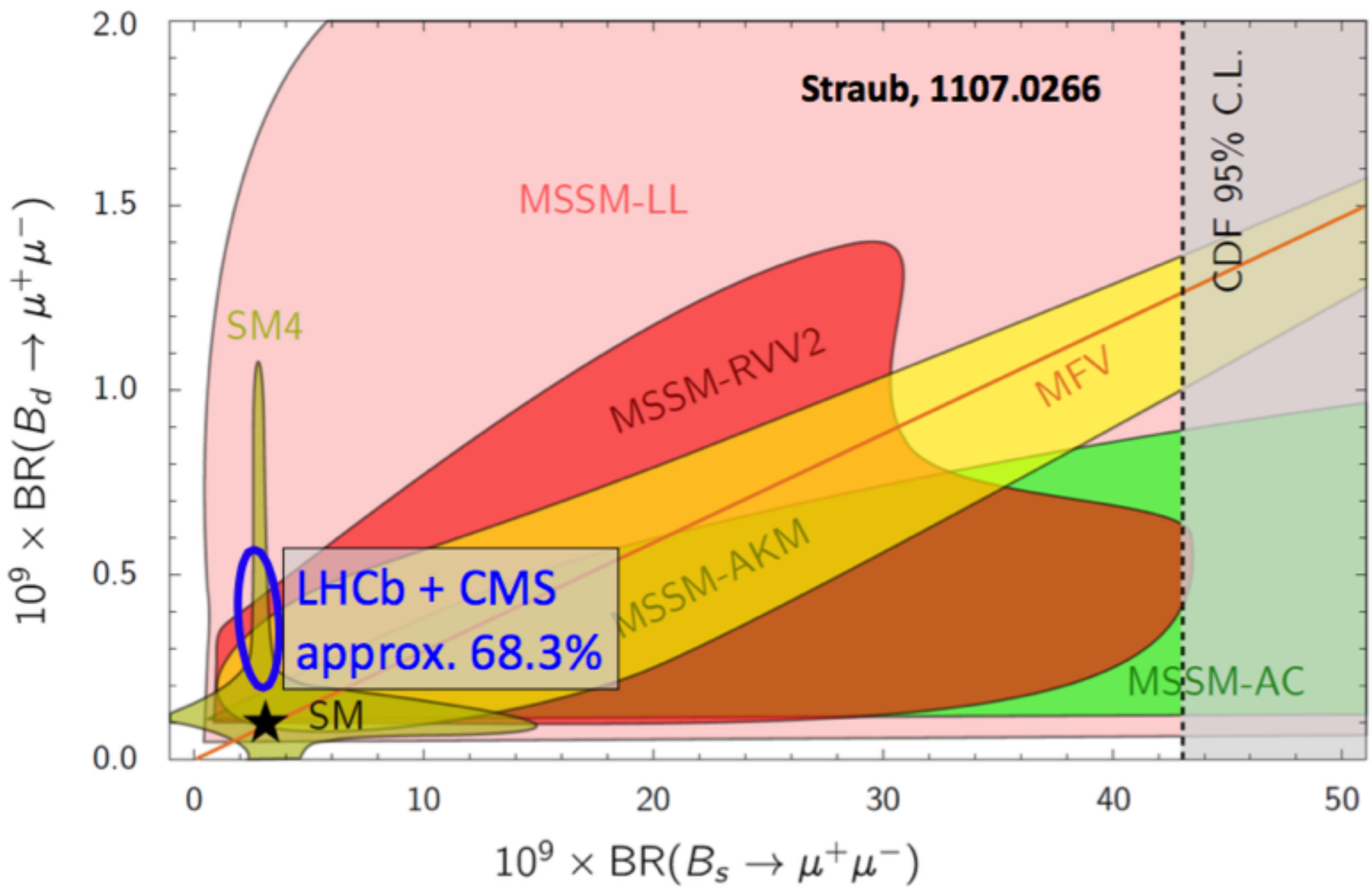




[Nature 522 (2015) 68]

$B_{s/d} \to \mu^+\mu^-$

- **Huge impact on NP models, such as SUSY:**

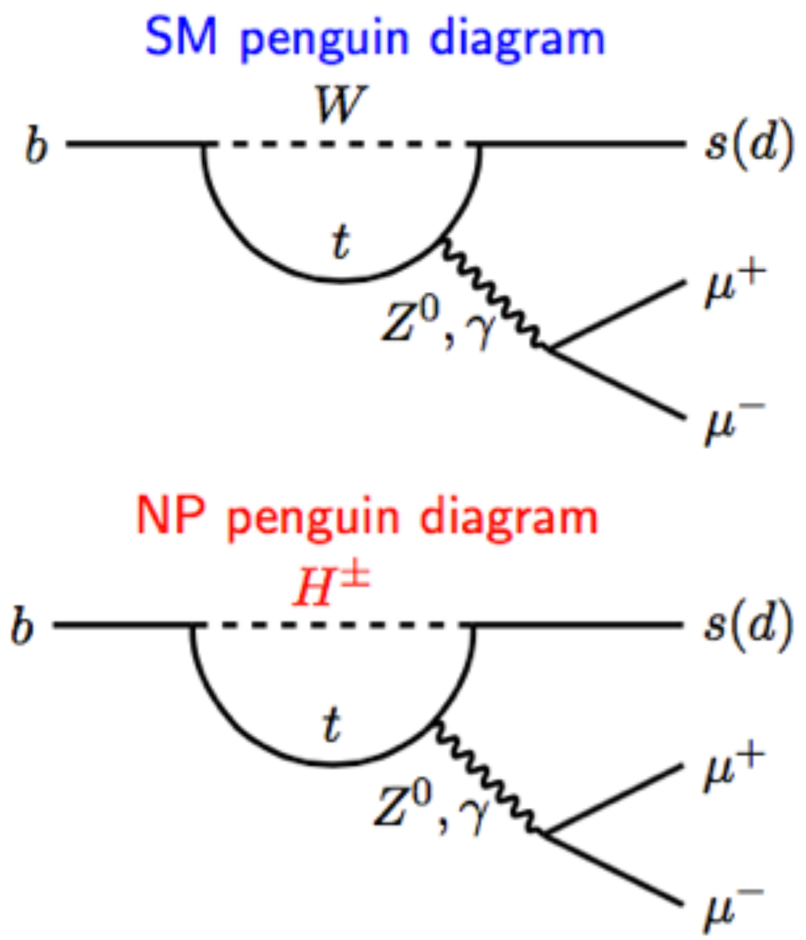


LHCb highlights from Run I
$b \to s \ell^+ \ell^-$

- **Rare FCNC process suppressed in the SM**
- **Model independent effective hamiltonian:**

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{\rm tb} V_{\rm tq}^* \sum_i \underbrace{\mathcal{C}_i \mathcal{O}_i}_{\text{Left handed}} + \underbrace{\mathcal{C}_i' \mathcal{O}_i'}_{\text{Right handed, } \frac{m_s}{m_b} \text{ suppressed}} + \sum \frac{c}{\Lambda_{\rm NP}^2} \mathcal{O}_{\rm NP}$$

$i = 1, 2$	Tree
$i = 3-6, 8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9, 10$	EW penguin
$i = S, P$	(Pseudo)scalar penguin



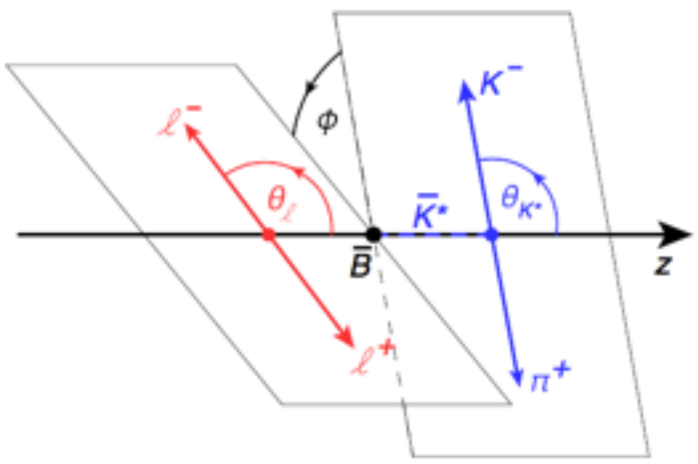
- **New heavy particles in NP models can appear in competing diagrams can affect branching fraction and angular distributions**
- **Experimentally clean signature**

LHCb highlights from Run I

$b \to s \ell^+ \ell^-$

- **Angular analysis of $B \to K^* \mu^+ \mu^-$:**

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^3(\Gamma+\bar{\Gamma})}{d\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + \tfrac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

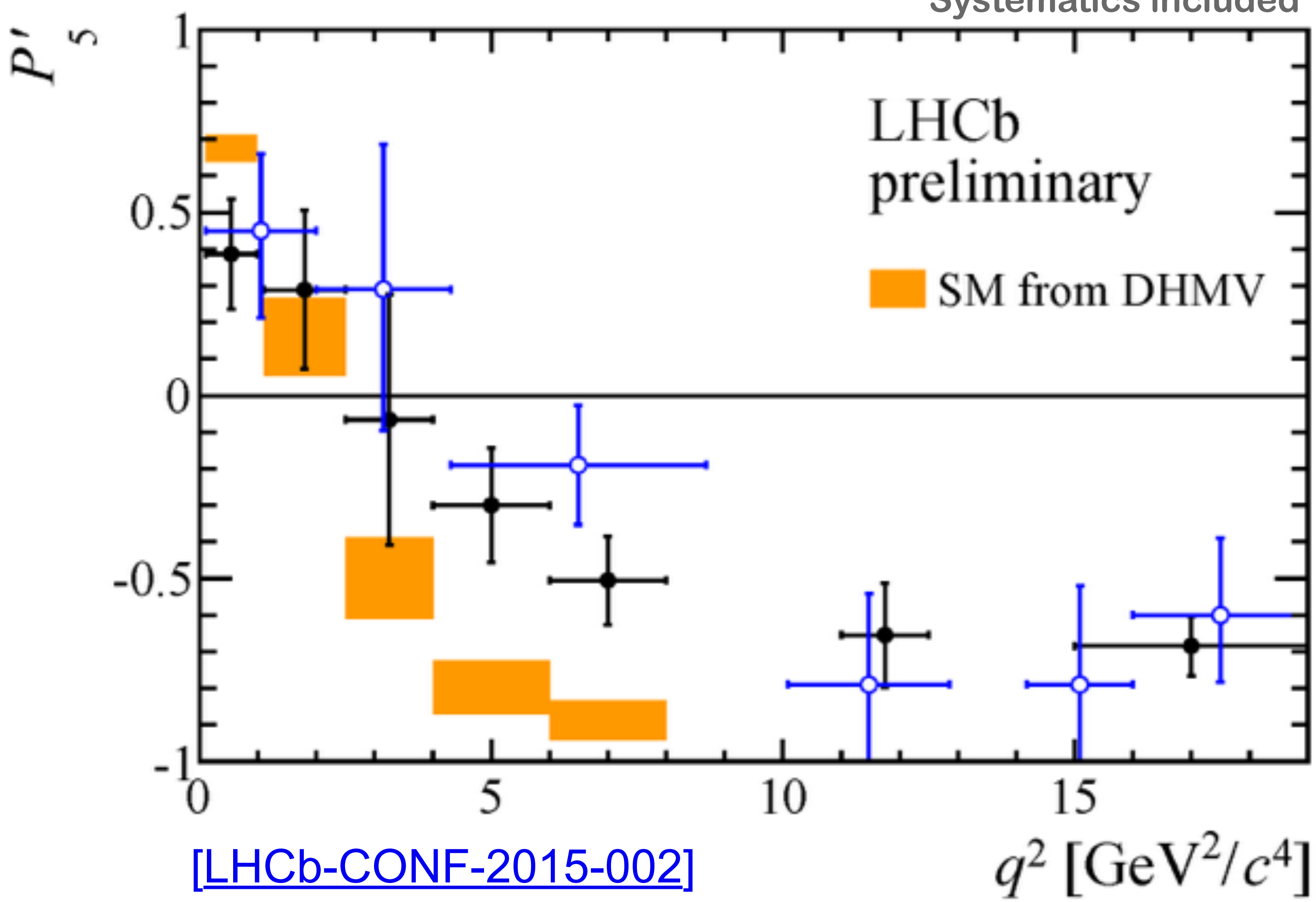


  - Angular observables, F_L, A_{FB}, S_i appearing in the full decay rate are related to Wilson coefficients C_7, C_9, C_{10}
  - Large part of theory uncertainty due to hadronic form-factors (FF)
  - Introduced the P_i' observables, less dependent on FF:

$$P'_{4,5} = S_{4,5}/\sqrt{F_L(1-F_L)}$$

- Angular analysis of $B \to K^* \mu^+ \mu^-$:
  - Local tension in P_5' of 3.7σ from SM

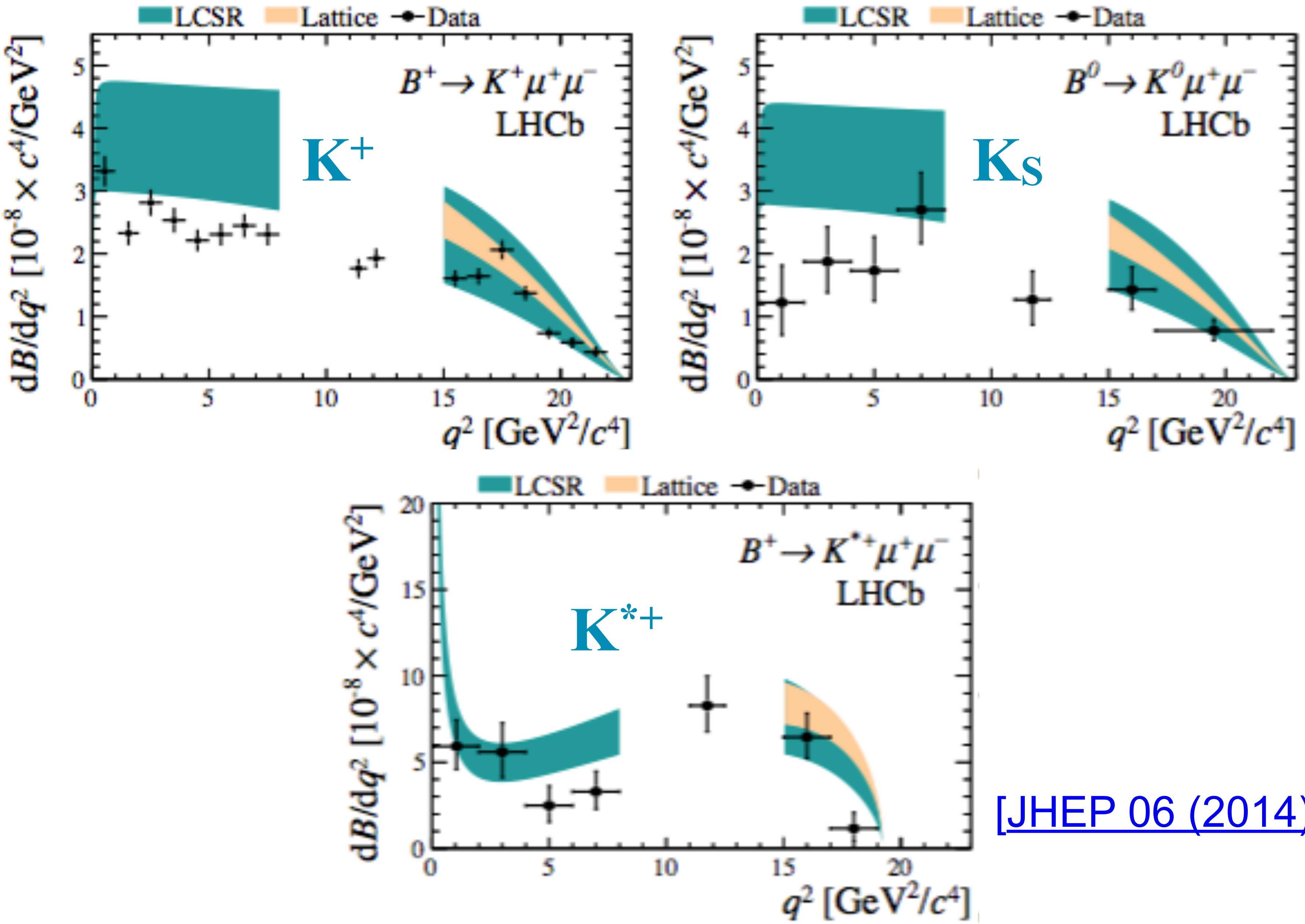
Systematics included



[LHCb-CONF-2015-002]

$b \rightarrow s\, \ell^+ \ell^-$

- **Branching fractions tends to lie below the SM** [PRL 112 212003] [arXiv:1411.3161]

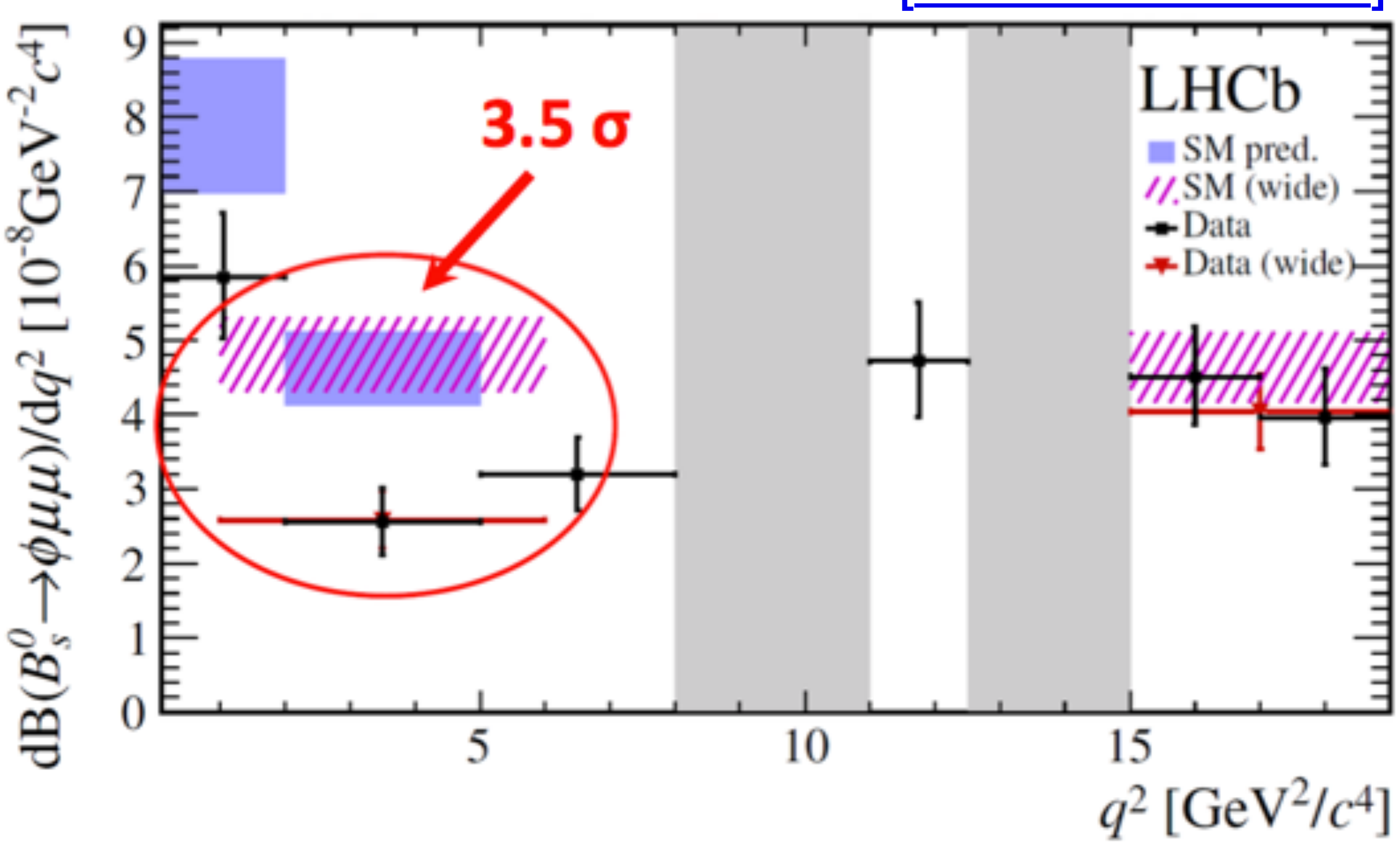


[JHEP 06 (2014) 133]

LHCb highlights from Run I
$b \to s \ell^+ \ell^-$

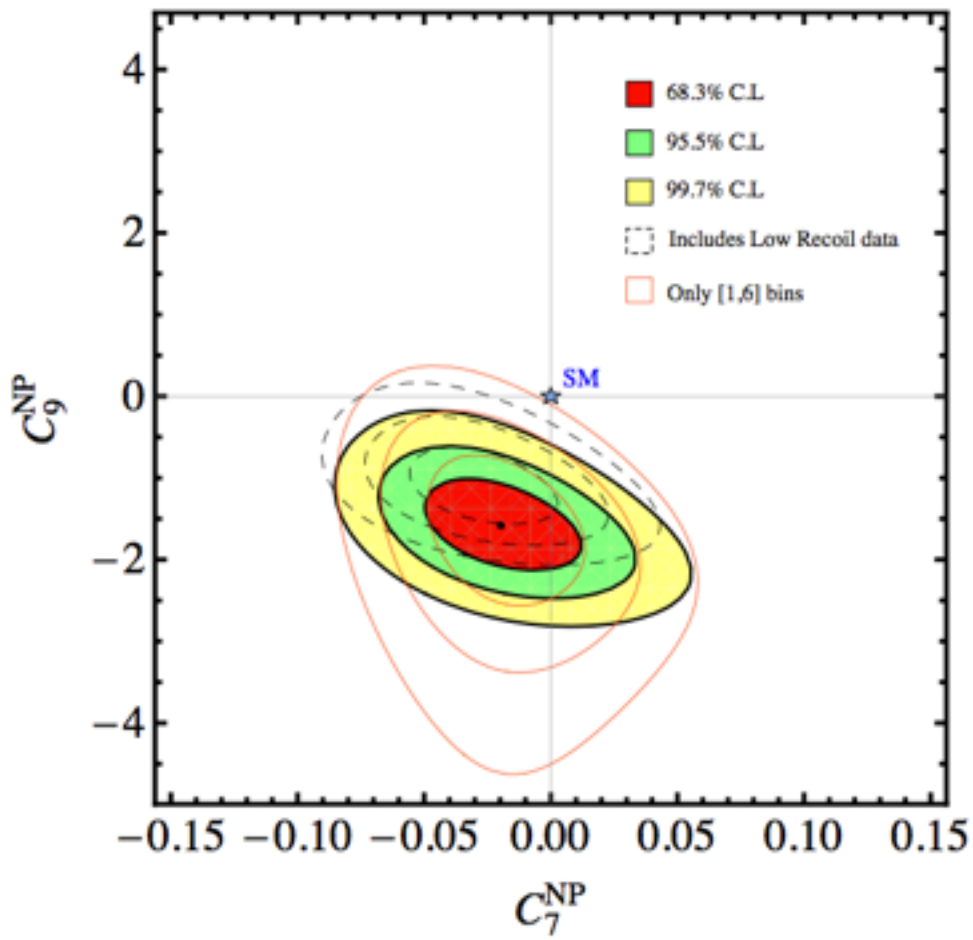
- **Angular analysis of $B \to \phi\mu^+\mu^-$:**
  - Full angular analysis performed
  - Angular observables consistent with the SM
  - **Branching fraction lower than SM prediction in** $(1 < q^2 < 6\ \mathrm{GeV}^2/c^4)$ [arXiv:1411.3161]

[arXiv:1506.08777]

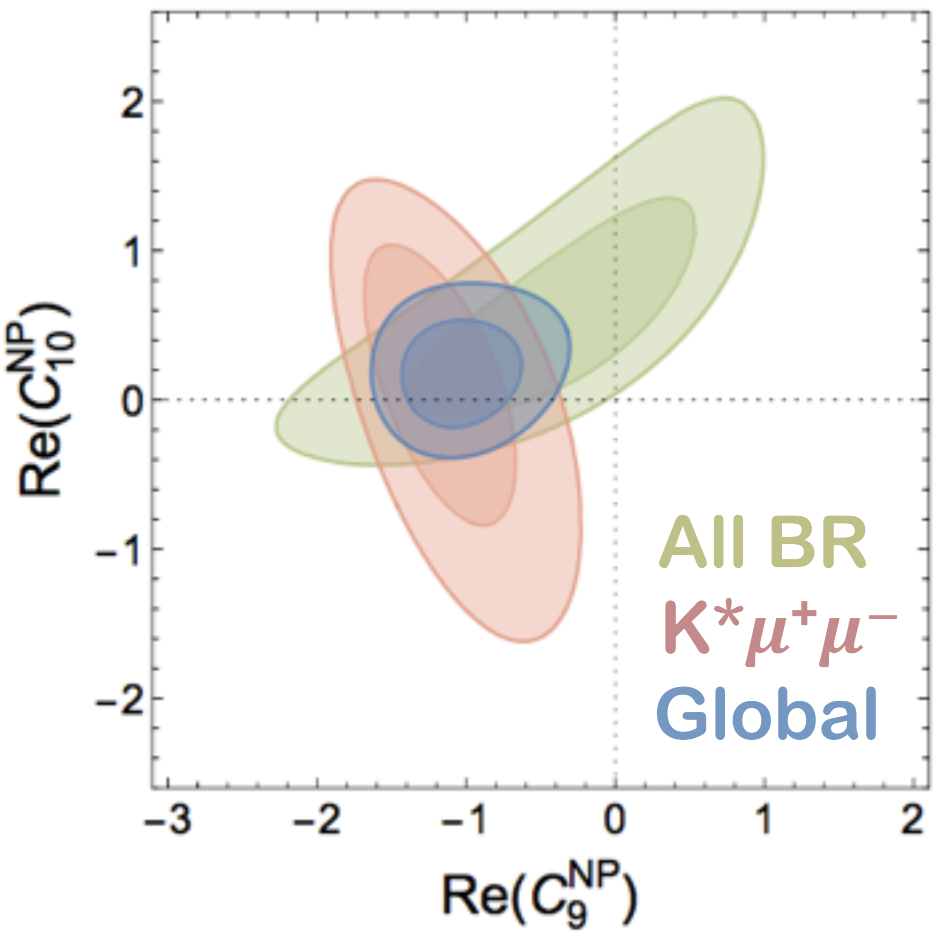


- **Global fit from $b \to s$ observables:**
  - Effects on the Wilson coefficients

[arXiv:1307.5683]



[Straub, Moriond'15]



- All theory groups find $C_9^{NP} < 0$
- Heavy Z′ boson (~TeV) with non-universal flavor couplings?

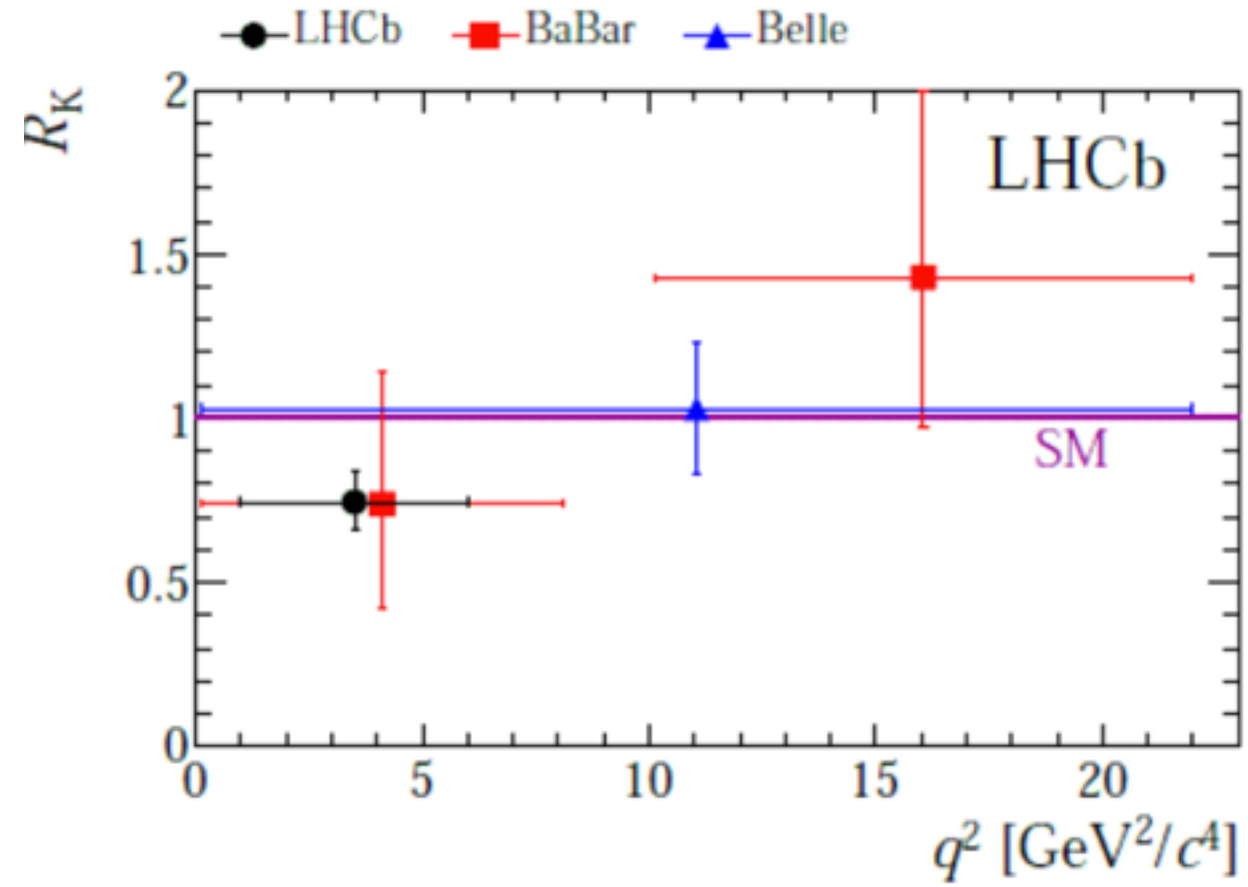
LHCb highlights from Run I
Lepton universality – R_K

- **Another unexpected development:**
  - Deficit of $B \to K\mu\mu$ compared to $B \to Kee$:

$$R_K \equiv \frac{\mathcal{B}(B \to K\mu\mu)}{\mathcal{B}(B \to Kee)} \overset{\text{SM}}{=} 1.0 \pm \mathcal{O}(10^{-4})$$

$$R_K^{\text{LHCb}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$(1 < q^2 < 6\ \text{GeV}^2/c^4)$

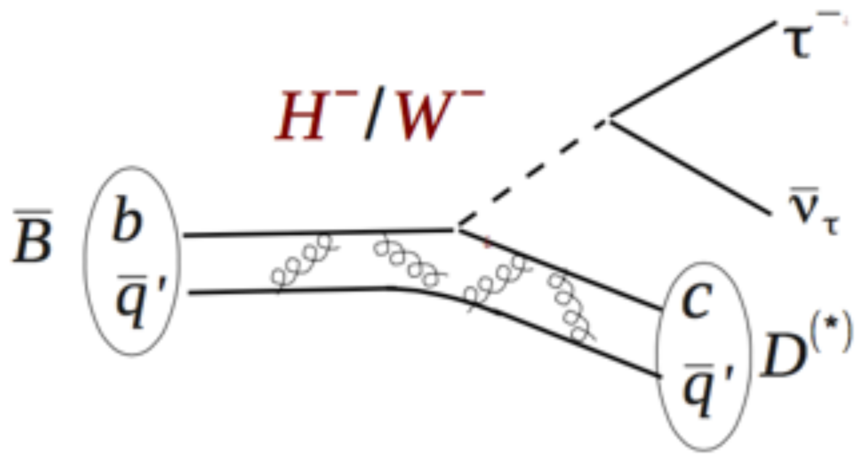


[PRL 113 (2014) 151601]

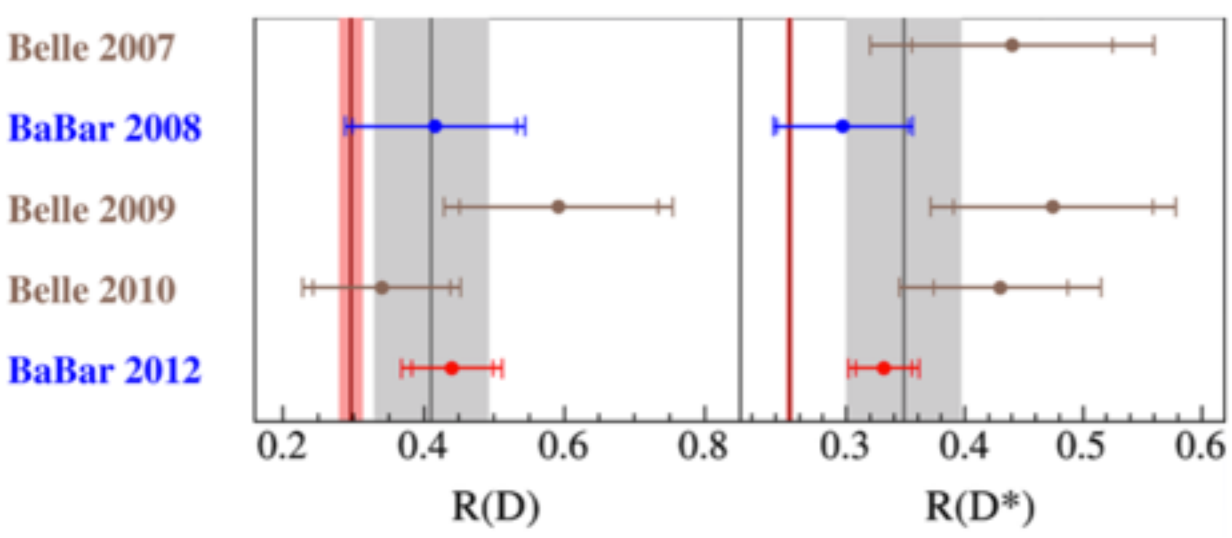
  - **<3σ tension**, but additional hint toward lepton universality violation

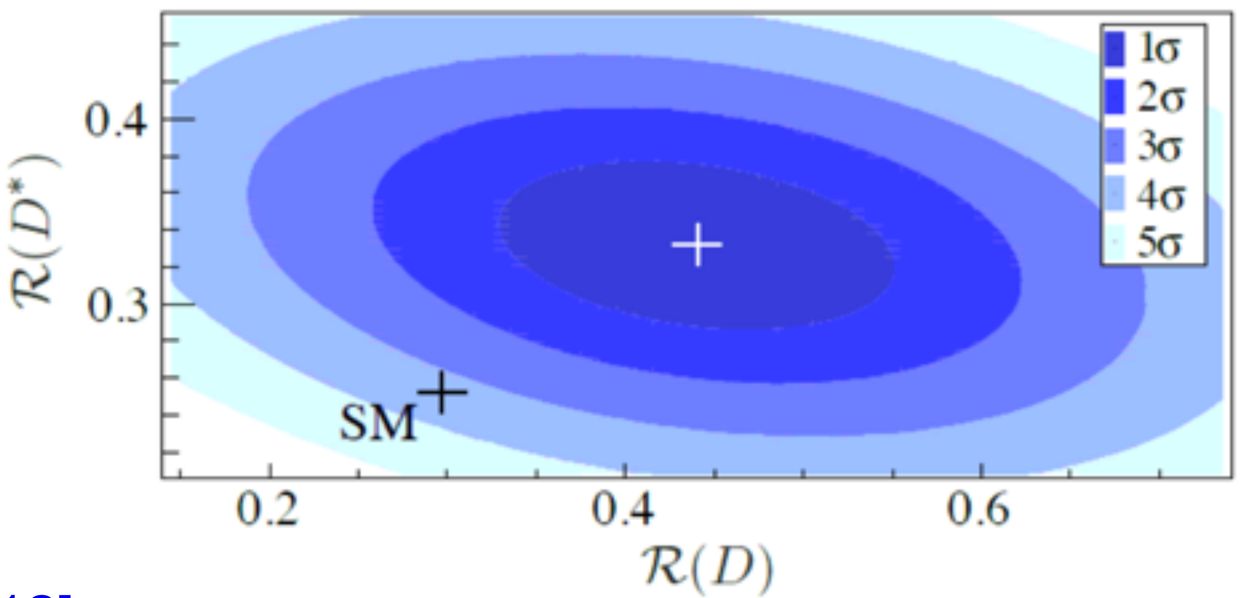
$B \to D^{*} \tau \nu$

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)}, \tau \to \ell\bar{\nu}_\ell\nu_\tau.$$



- **Powerful channel to test lepton universality:**
  - Charged Higgs can enter at tree level
- **Area of particular interest:**
  - **BaBar anomaly @ >3σ from SM**
  - Other hints of lepton universality violation (e.g. $H \to \tau\mu$, R_K)

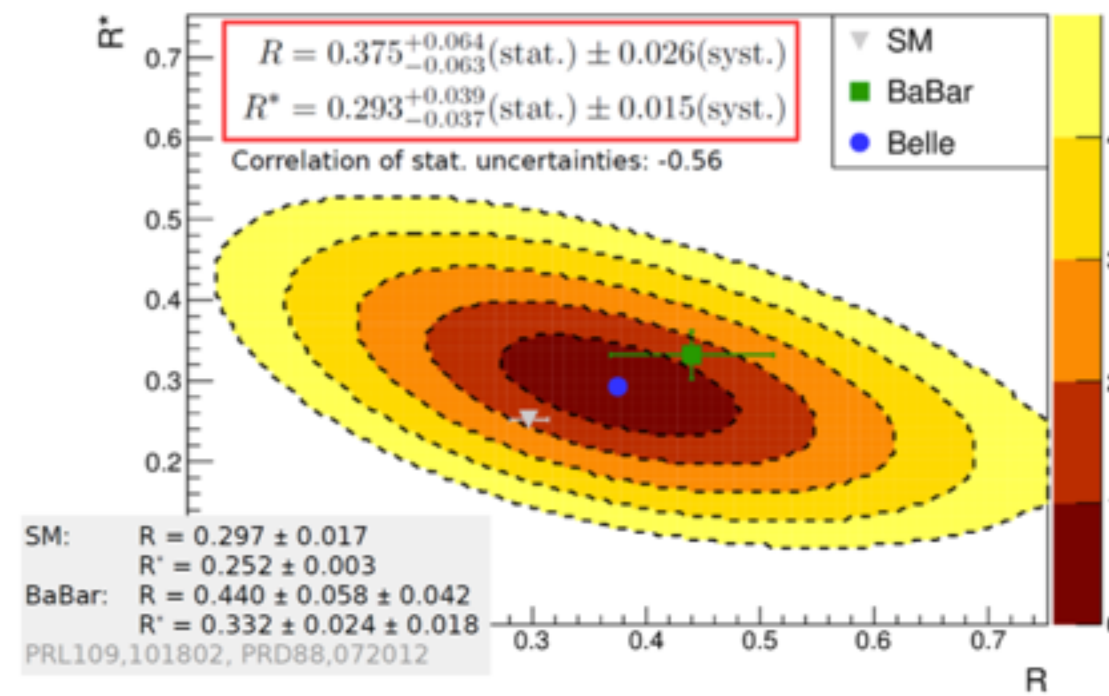


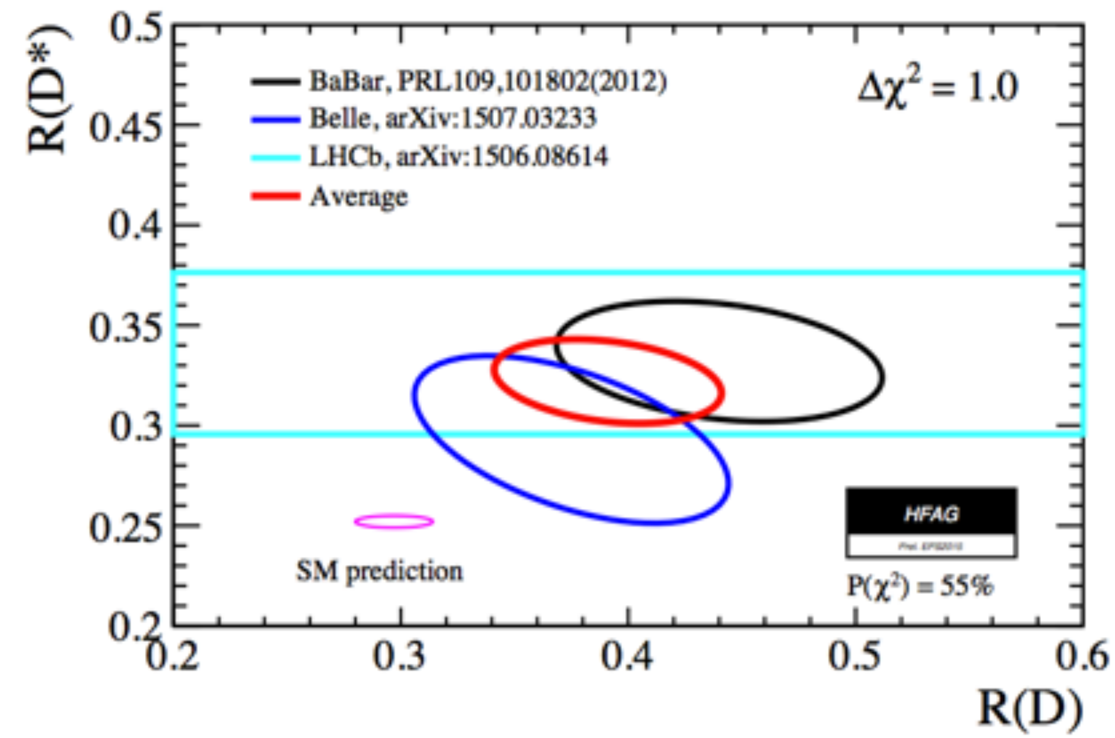


[PRL 109 (2012) 101802] [PRD 88 (2013) 072012]

LHCb highlights from Run I
$B \to D^* \tau\nu$

- **Belle update at FPCP'15:**
  - Full dataset + updated tagging algorithm [arxiv:1507.03233]
  - Consistant with previous Babar result
- **LHCb result at FPCP'15:**
  - Experimentally challenging due to the missing neutrinos
  - Consistant with previous Babar result [arxiv:1506.08614]
- **HFAG combination at EPS'15:**
  - Global effect @ 3.9σ from SM





SM: [PRD 85, 094025 (2012)]

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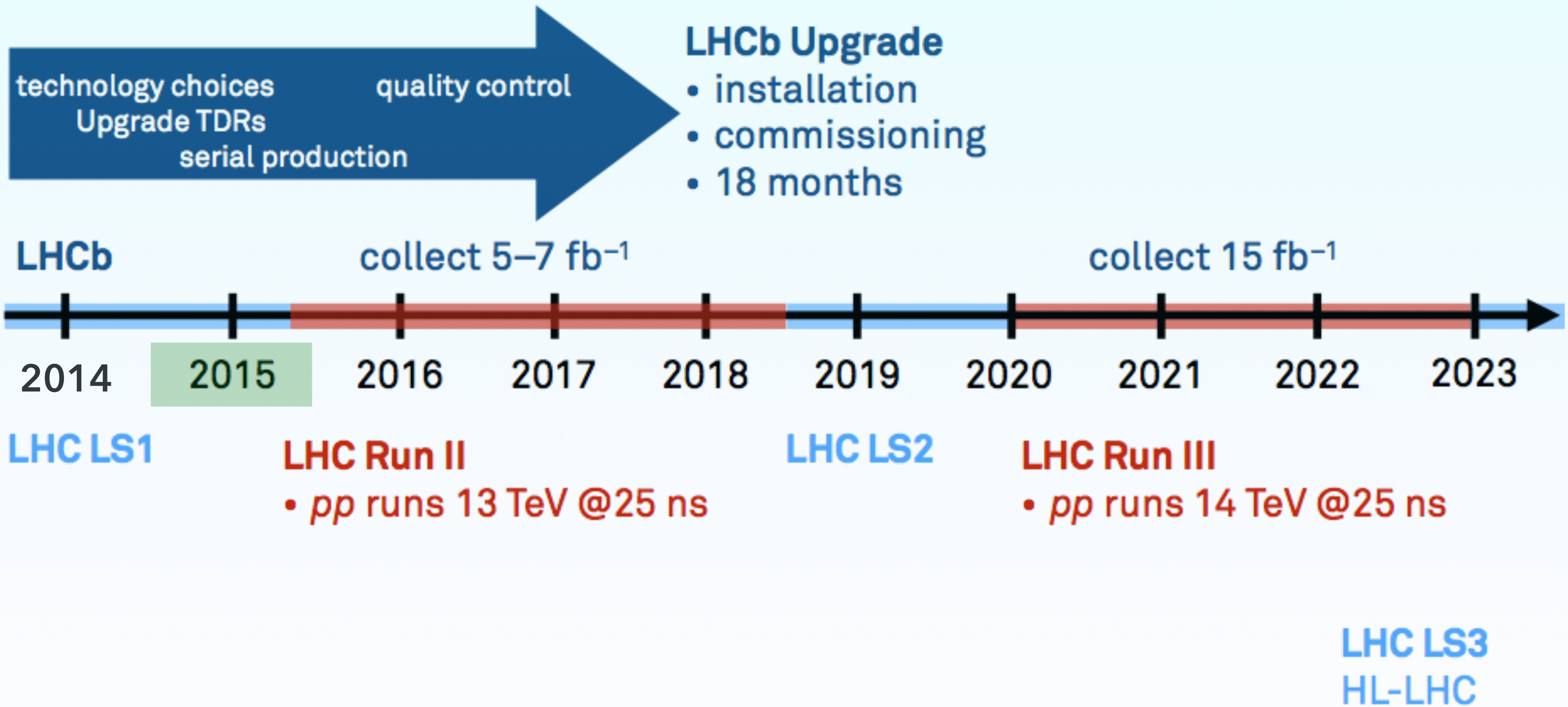
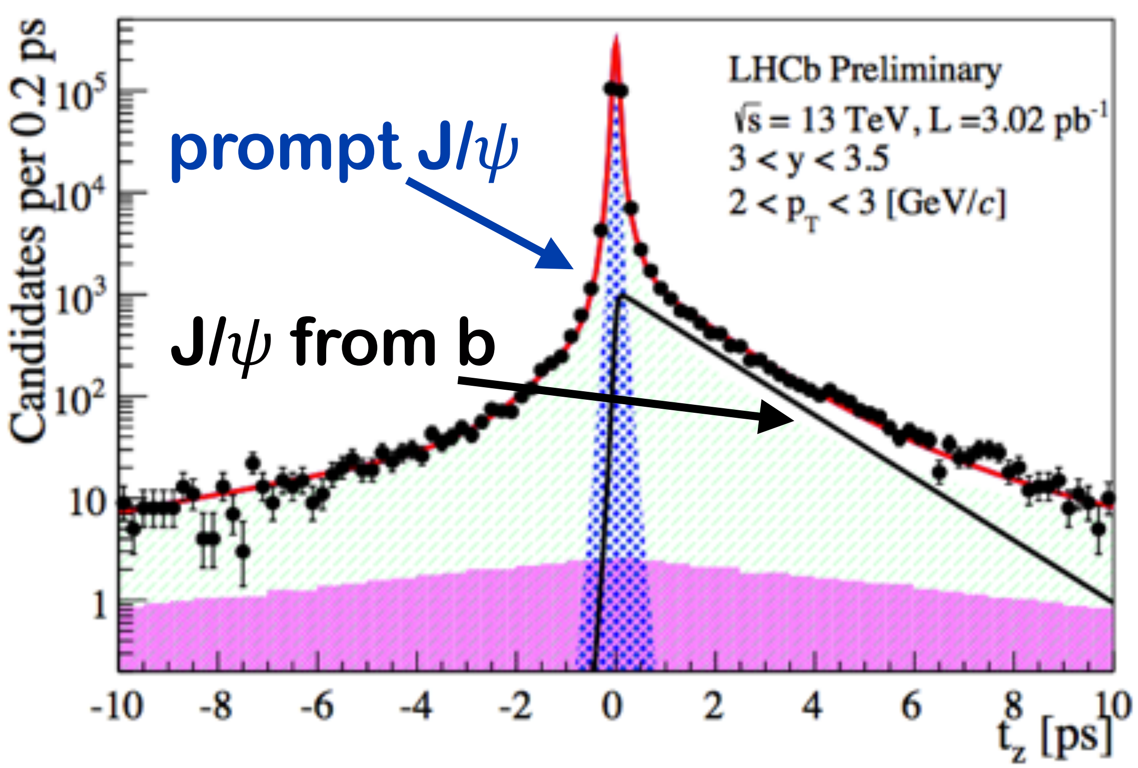
Prospects

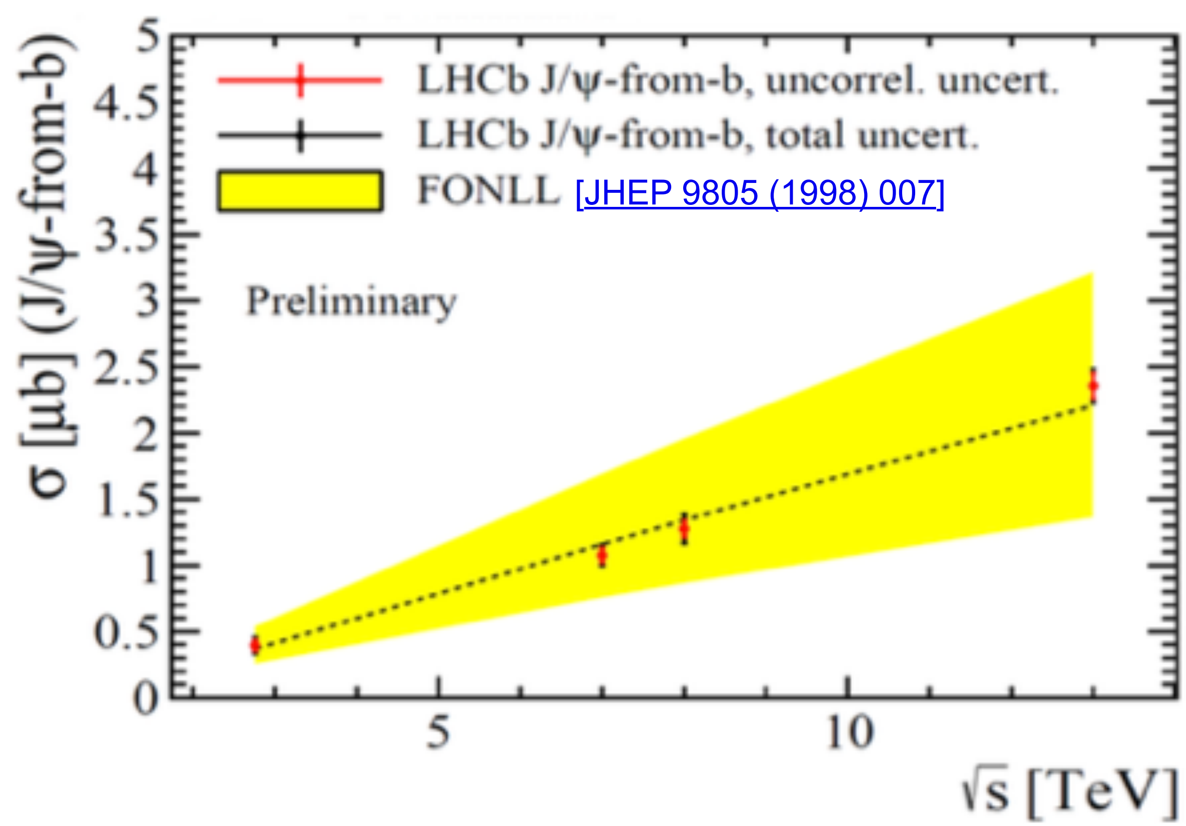
The LHCb experiment
Future prospects



The LHCb experiment
Run II

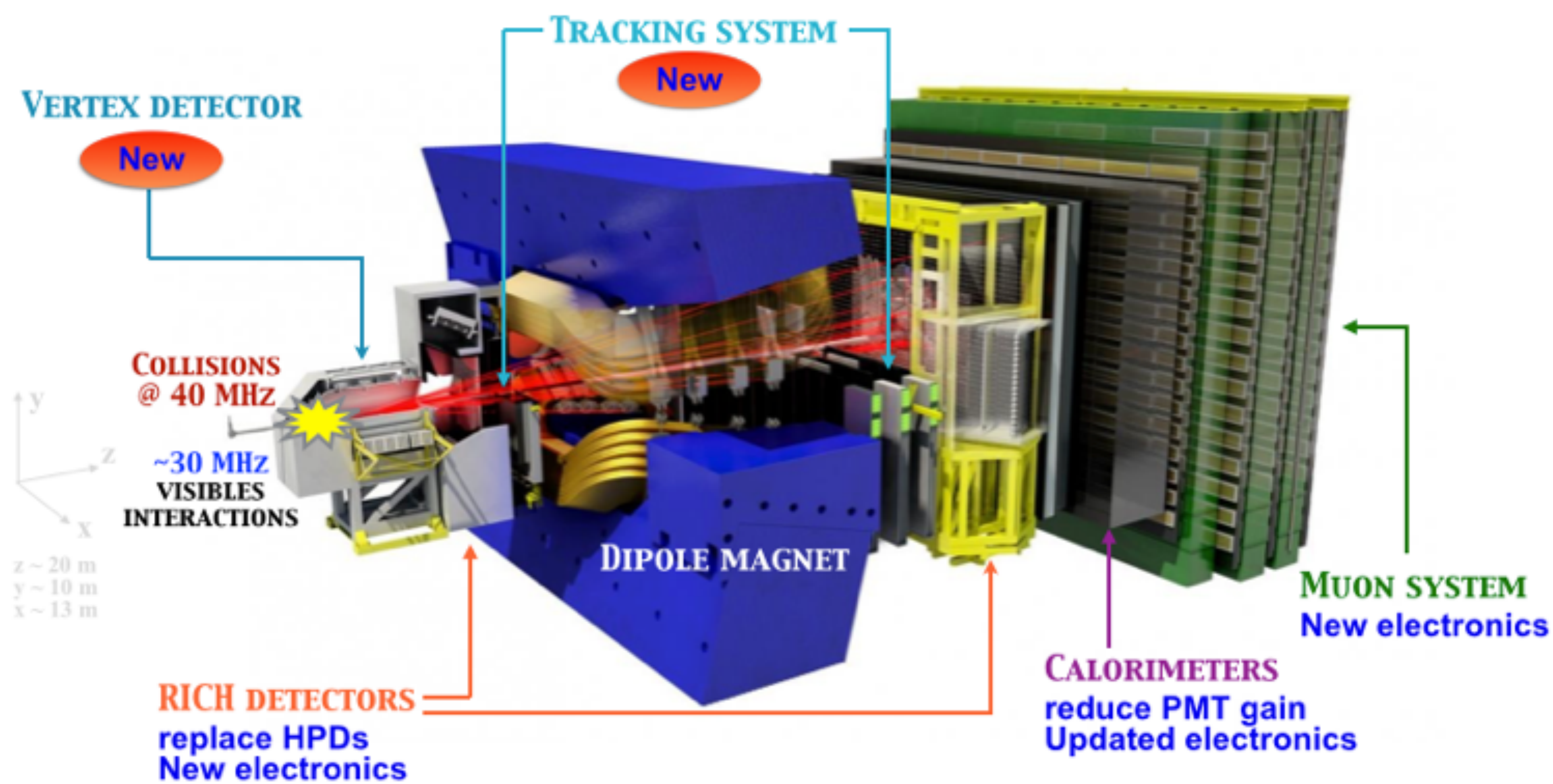
- No major hardware changes. Improved trigger (low pT), real-time tracking, calibration, alignment and PID goes into HLT:
  - LHCb is ready! Will gain from higher beam energies (increased production cross-section) and 25 ns bunch spacing (lower pile up)
  - Write to disk: 5 kHz (Run 1) ⇒ 12.5 kHz (Run 2)
- Already analyzing online reconstructed data: [EPS 2015 talk]





The LHCb Upgrade
Strategy overview

- Remove the main bottle-neck ⇒ L0 hardware trigger limited @ 1 MHz
- All detector readouts @ 40 MHz
- Operate @ L = $2x10^{33}$ $cm^{-2}s^{-1}$
- Full software trigger ⇒ efficiency gains



The LHCb Upgrade
Physics prospects

[CERN-LHCC-2012-007] LHCb Upgrade TDR

Statistical uncertainties

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 [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
	$A_{\text{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	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 [14]	0.025	0.008	0.02
	$s_0\, A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	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 %	$\sim 10\,\%$
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}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim 100\,\%$	$\sim 35\,\%$	$\sim 5\,\%$
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}	–

- **With ~8 fb^{-1} in 2018 → LHCb in high-precision era**
- **With ~50 fb^{-1} in 2028 → LHCb upgrade in very-high precision era**

  ↳ will be on the verge of reaching theoretical uncertainties!

5

Summary and Outlook

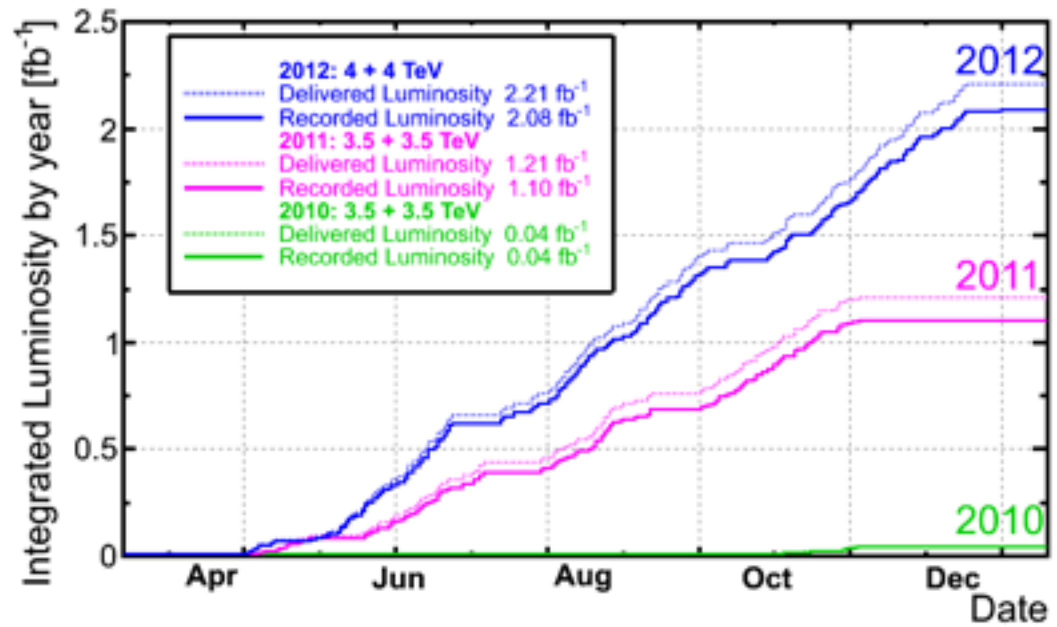
Summary & Outlook

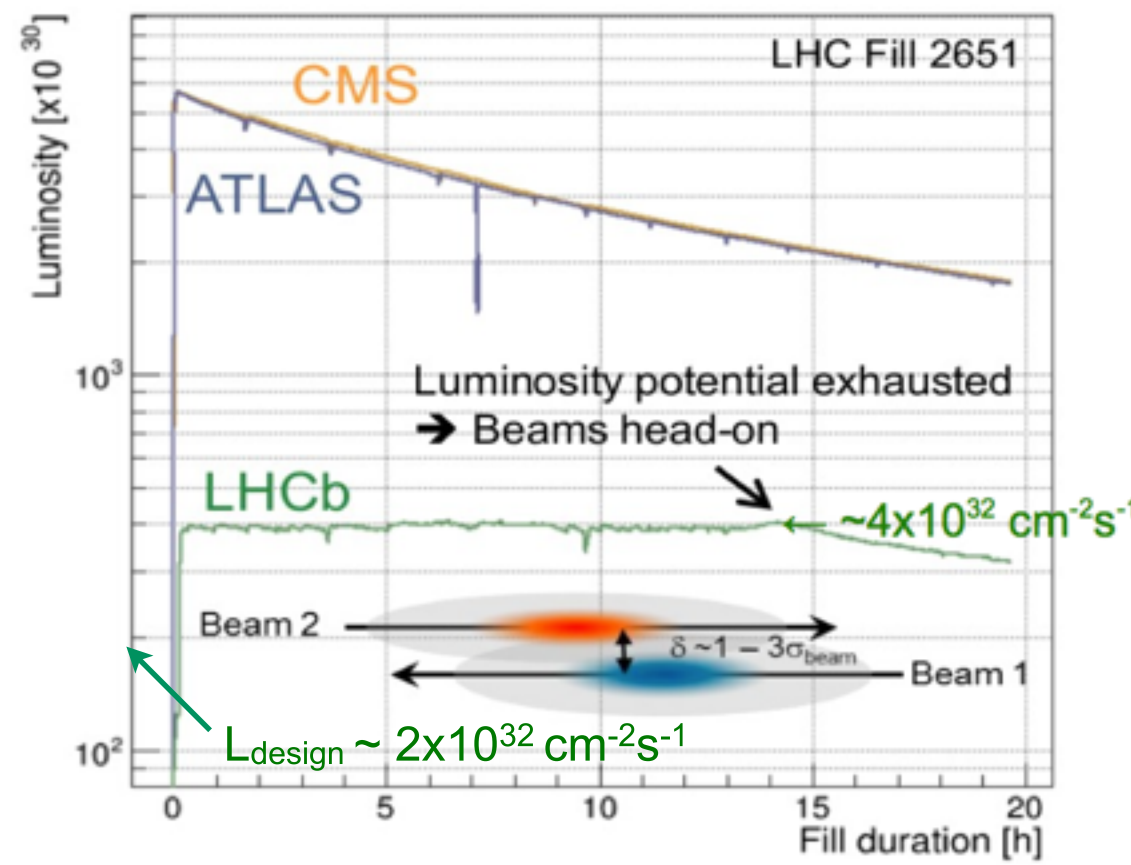
- **LHCb @ Run I**
  - Excellent performances of the LHCb detector
  - Several interesting tensions exist with the SM in the heavy quark flavor sector
- **LHCb @ Run II**
  - LHCb detector is ready and already shows good performances
  - Started analyzing the first data @ 13 TeV
- **LHCb Upgrade**
  - Mandatory to reach experimental precisions of the order of the theoretical uncertainties
  - The objective of 50 fb^{-1} collected in 10 years is made possible thanks to an efficient and selective software trigger

Spare slides

Physics performances — Run I

- **Integrated luminosity**
  - 1 fb^{-1} @ 7 TeV (2011)
  - 2 fb^{-1} @ 8 TeV (2012)
- **Excellent LHCb performances**
  - > 99% detector channels working
  - > 99% collected data good for analysis
  - Stable operations with $L \sim 2 \times L_{design}$
- **luminosity leveling**
  - Displaced pp beams
  - Constant running conditions
  - Lower instantaneous luminosity
  - Lower pile-up
  - Better tracking and PID performances

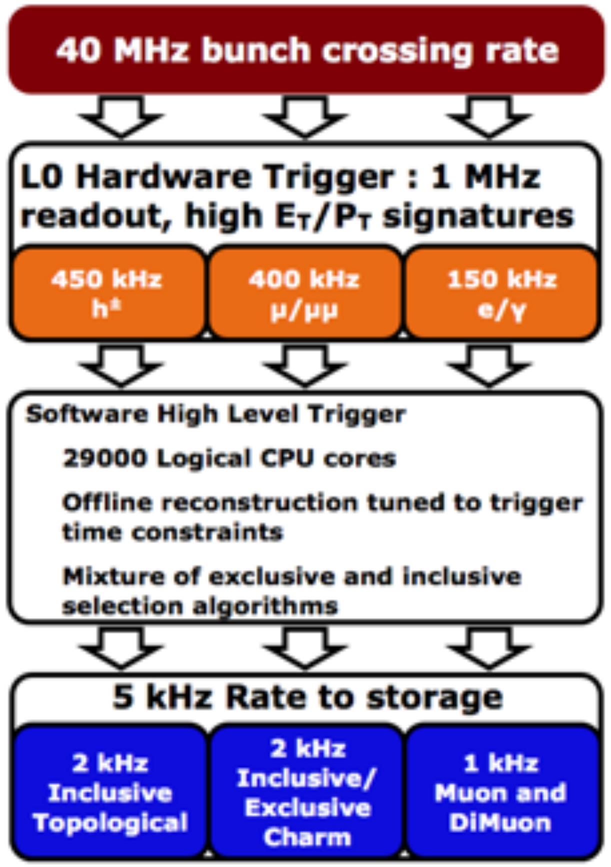


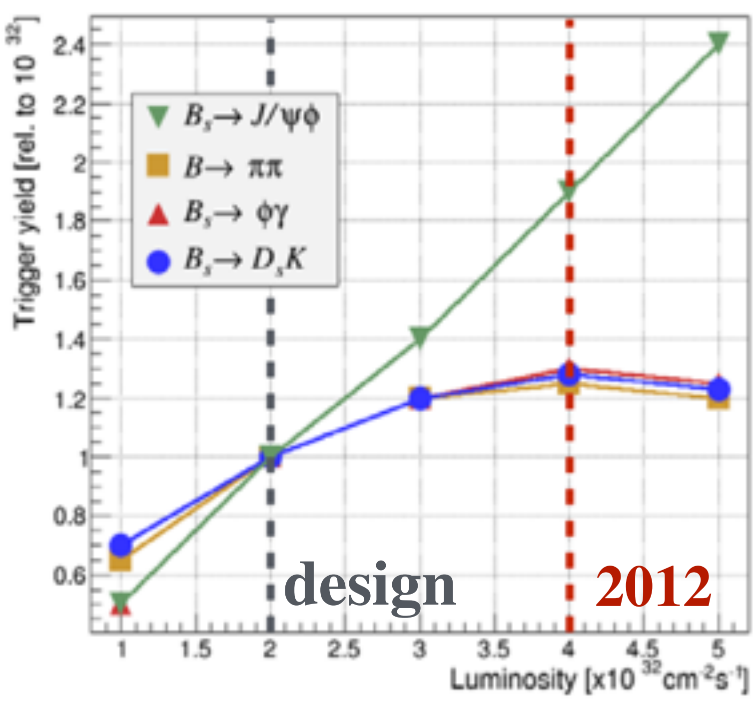


The LHCb experiment
Motivations for the Upgrade

- **Increase of LHC luminosity and energy**
  - 4×10^{32} cm^{-2}s^{-1} → 2×10^{33} cm^{-2}s^{-1}
  - 8 TeV → 14 TeV
  - Pile-up: ~1 → ~5
- **Main bottle-neck**
  - Hardware trigger (L0) and DAQ
  - Rate limited by bandwidth to 1 MHz
- **With high luminosities**
  - Events busier, reconstruction more difficult
  - Harsher cuts required on p_T and E_T
  - Higher radiation damage

In order to increase LHCb statistics significantly, the detector upgrade is essential to go beyond the current limitations

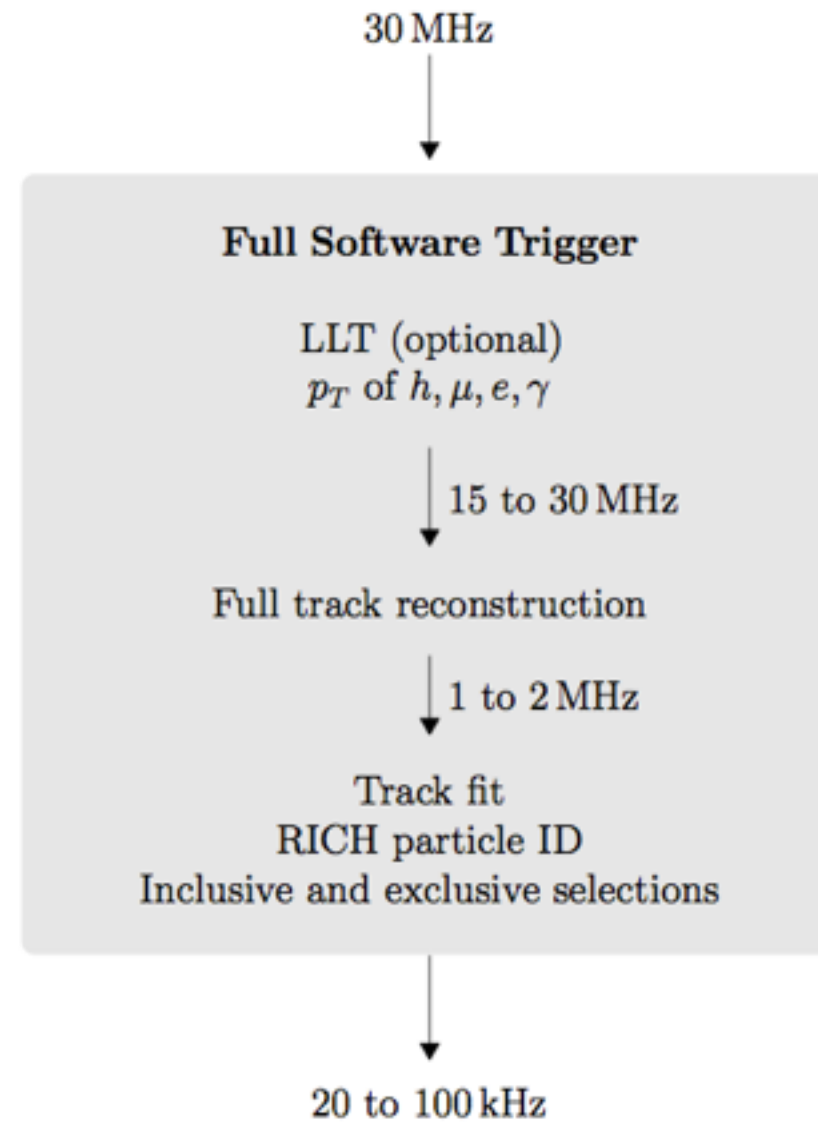




LHCb Upgrade
Strategy

- **Readout every LHC bunch crossing: 40 MHz**
  - Remove hardware trigger (L0)
  - Replace front-end electronics
  - Multi-Tb/s readout network
- **Full software trigger**
  - Very flexible and adaptable
  - Full event information can be used
  - Large gains for hadronic triggers
  - Keep performance of muon-triggers

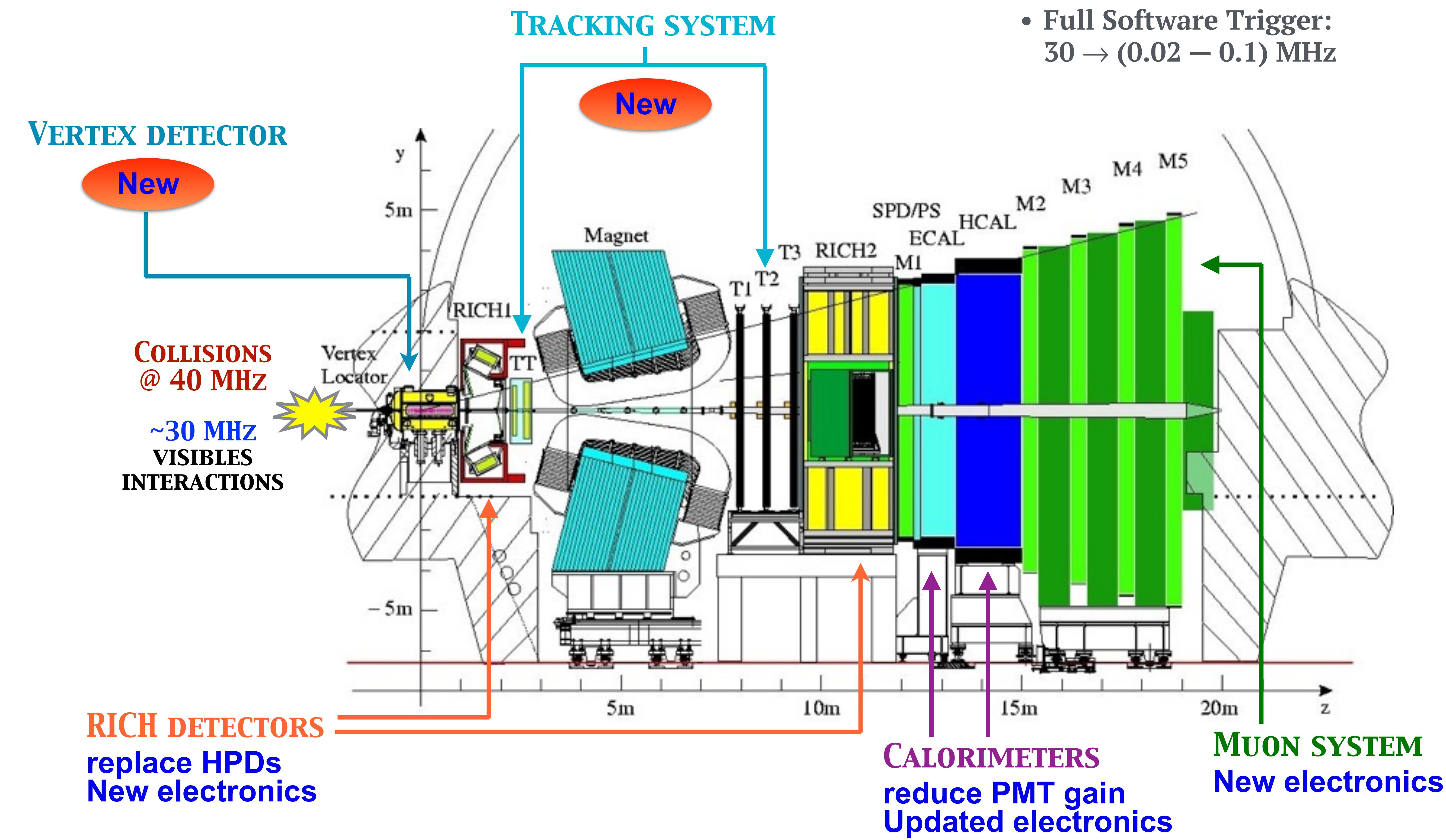
  [CERN-LHCC-2014-016] Trigger Upgrade TDR



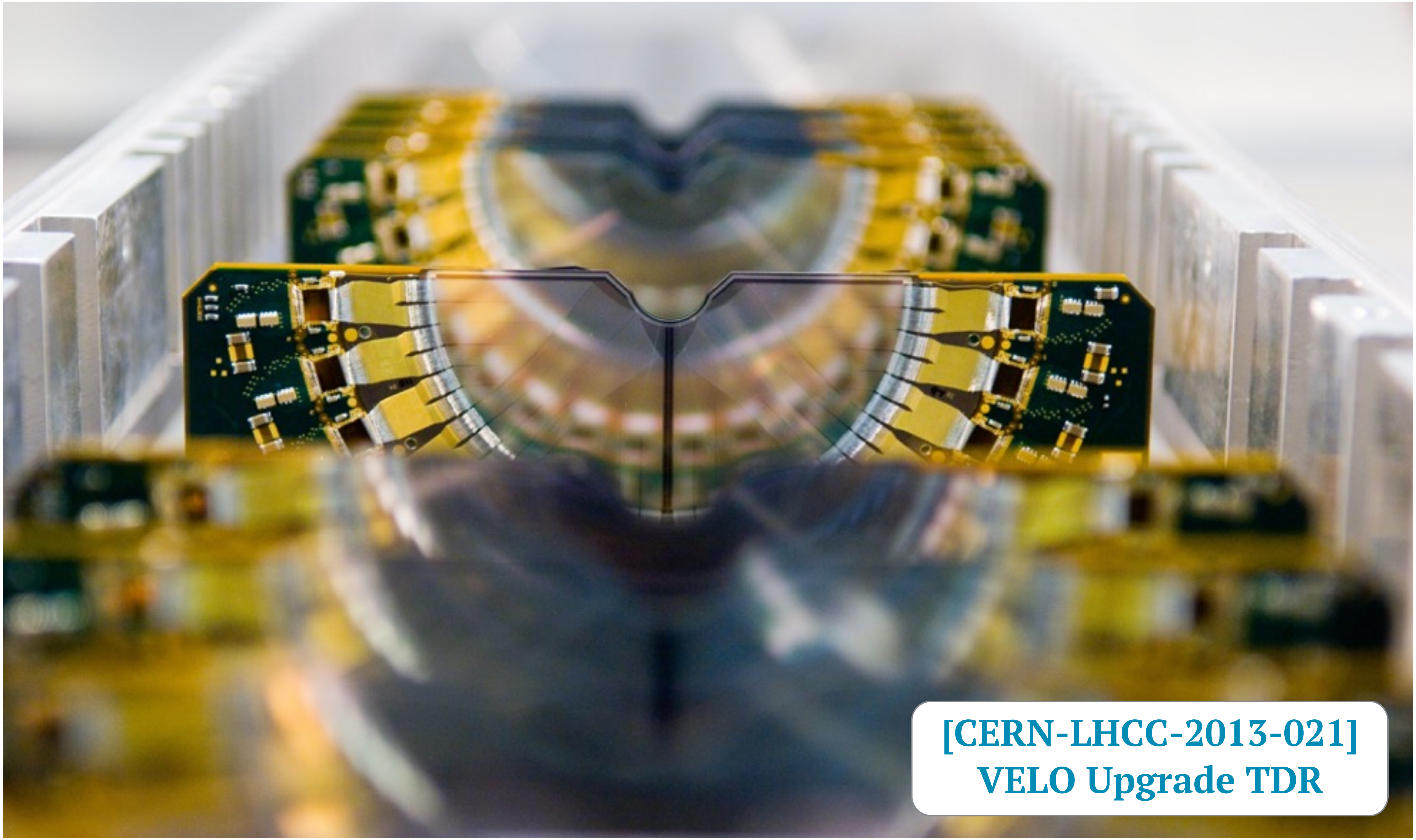
- **Upgraded sub-detectors**
  - Redesigned to cope with upgrade running conditions (high radiation, occupancy, …)
  - Redesign the readout architecture to increase bandwidth

LHCb Upgrade
Strategy

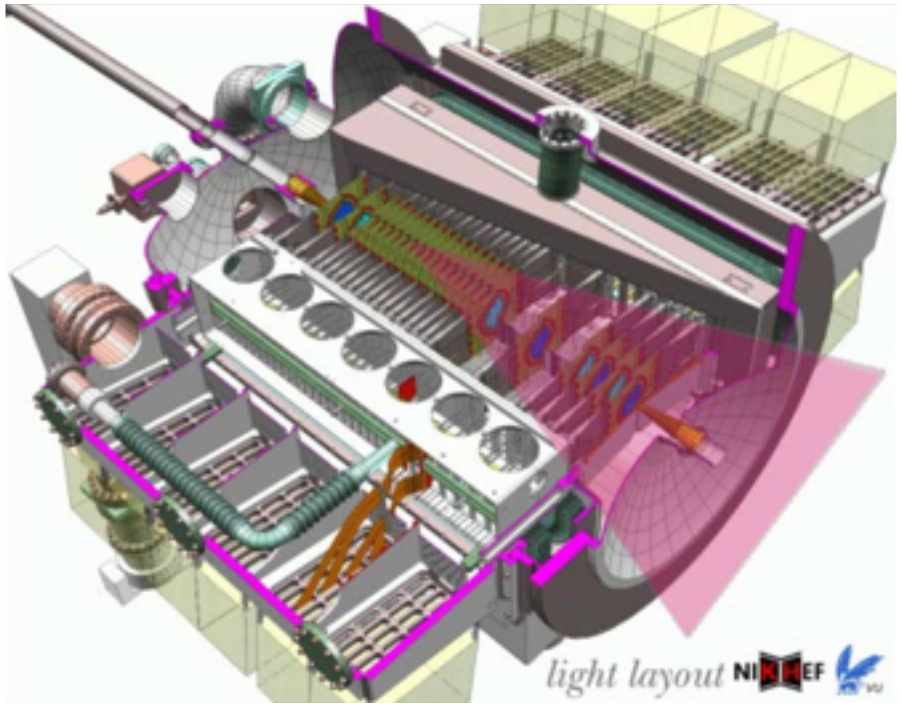
- Full Software Trigger: 30 → (0.02 — 0.1) MHz

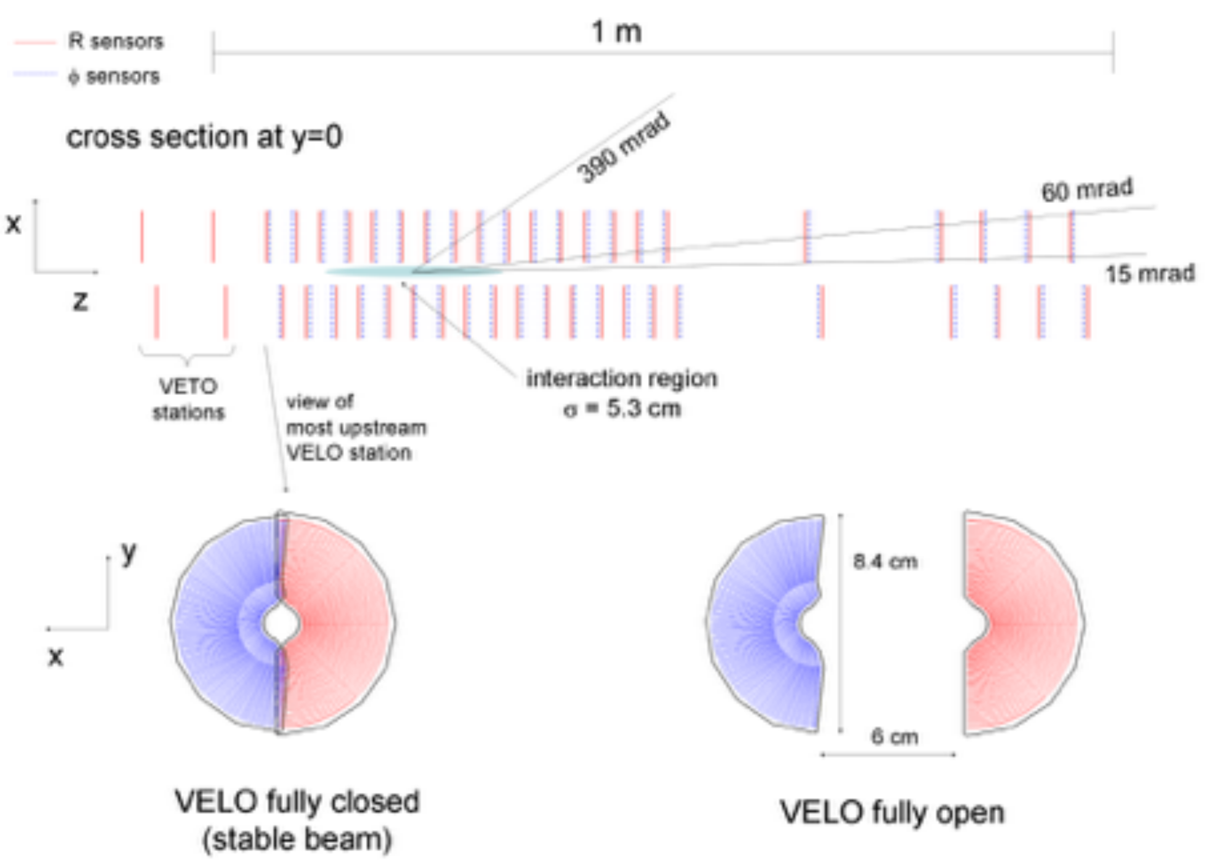


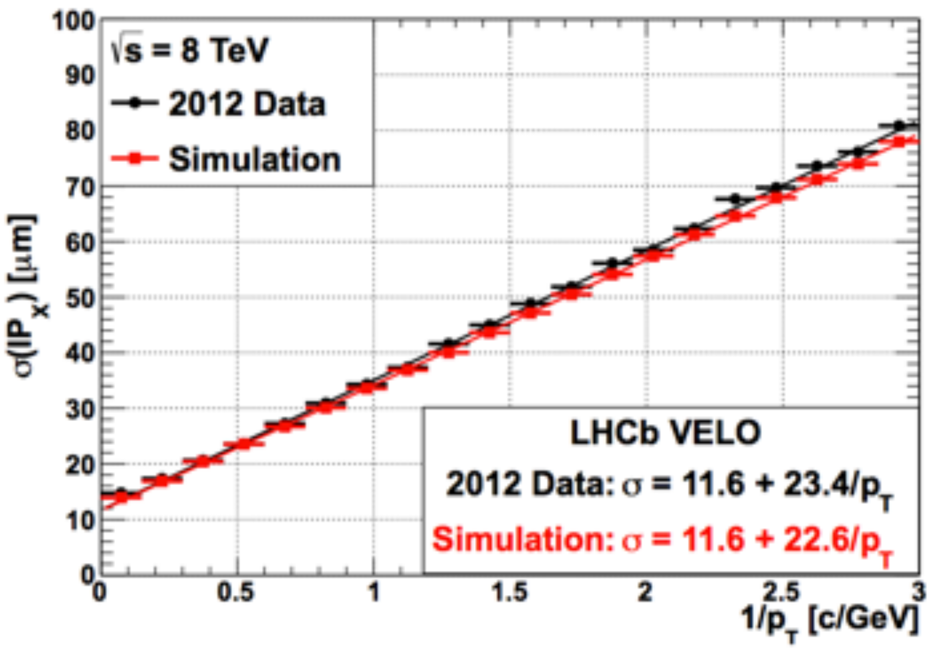
LHCb Upgrade
Vertex Detector



- **VErtex LOcator (VELO)**
  - Two movable halves:
    - 30 mm during injection
    - 5 mm when fully closed
    - 1st measurement @ 8.3 mm
  - R-ϕ sensors:
    - Silicon microstrips
    - 21 modules per half
  - Excellent performances:
    - hit resolution < 4 μm

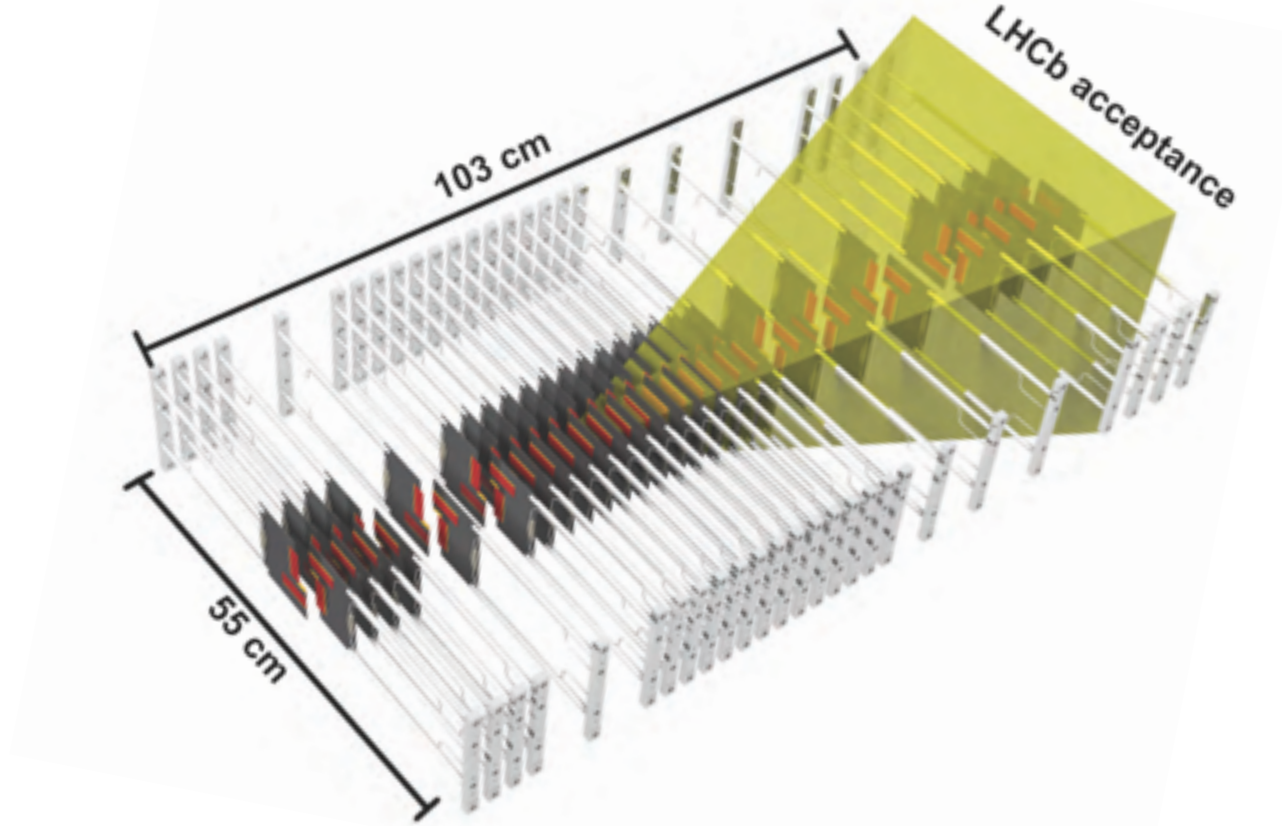




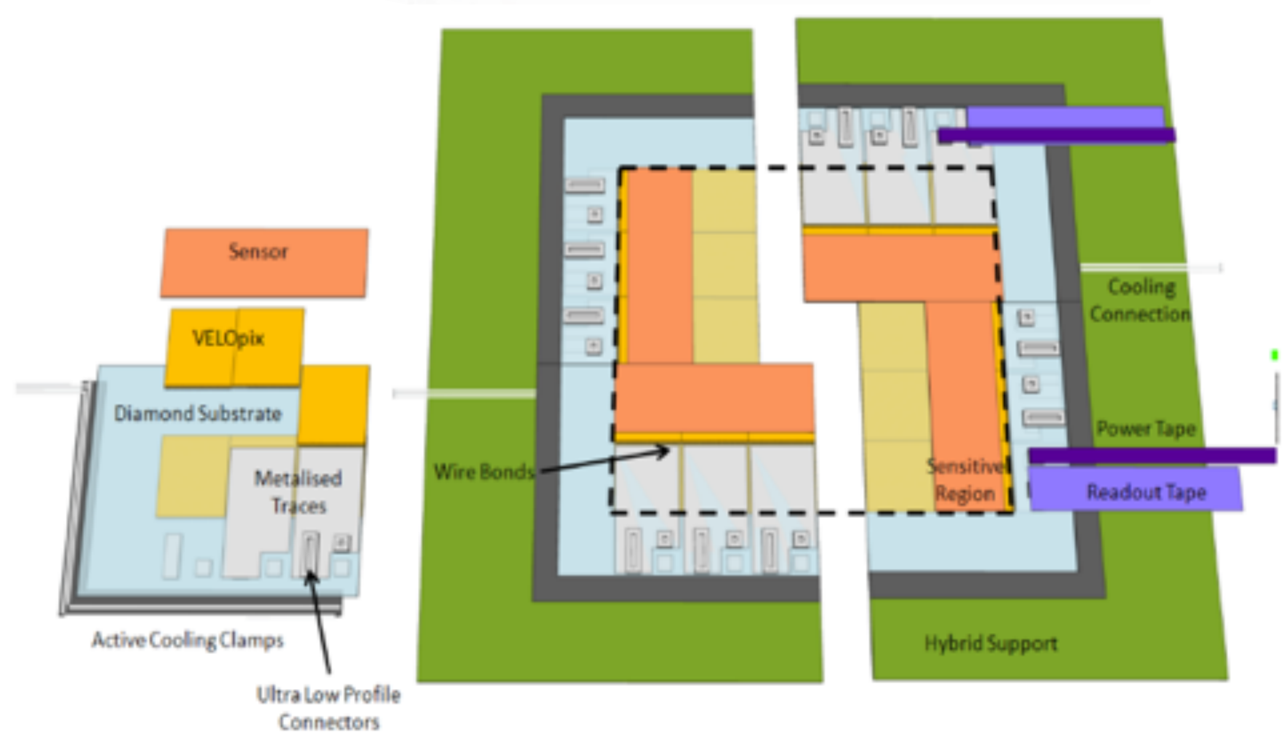


LHCb Upgrade
Vertex Detector: upgrade design

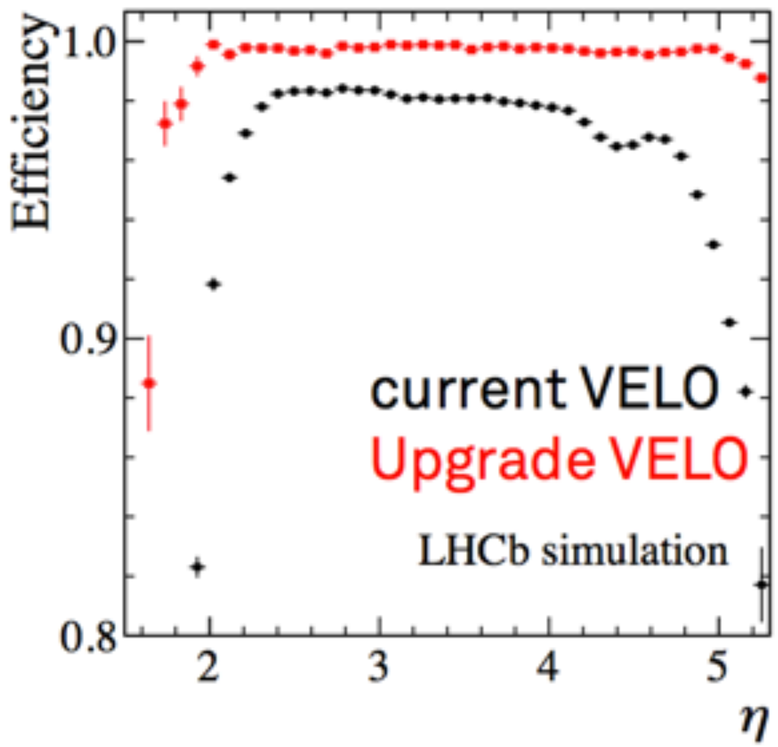
- **Upgrade challenge**
  - Harsher conditions:
    - resist to very high radiation
    - handle increased occupancies
  - Hold or improve performances:
    - lower material budget
    - handle high data volume
    - enlarge acceptance

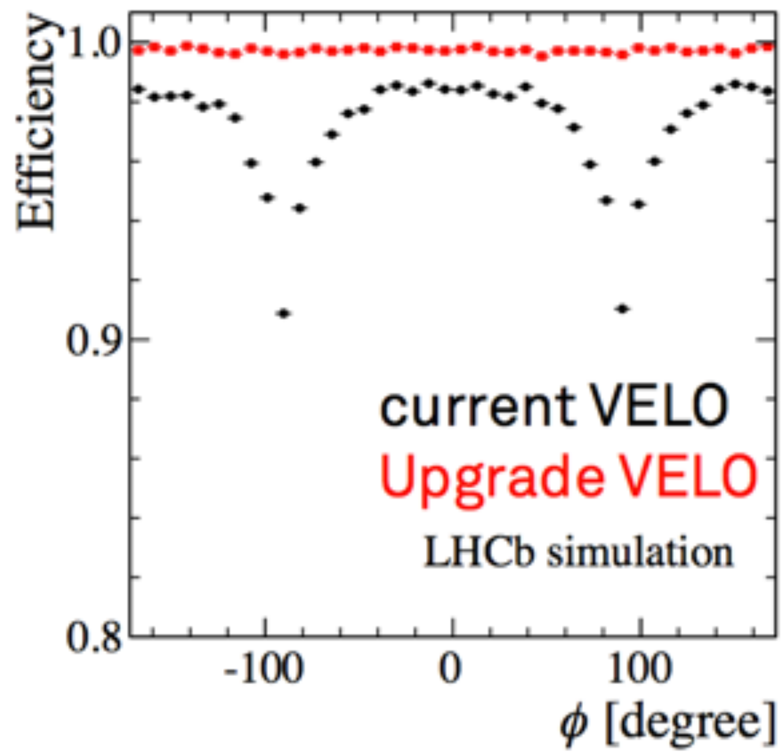


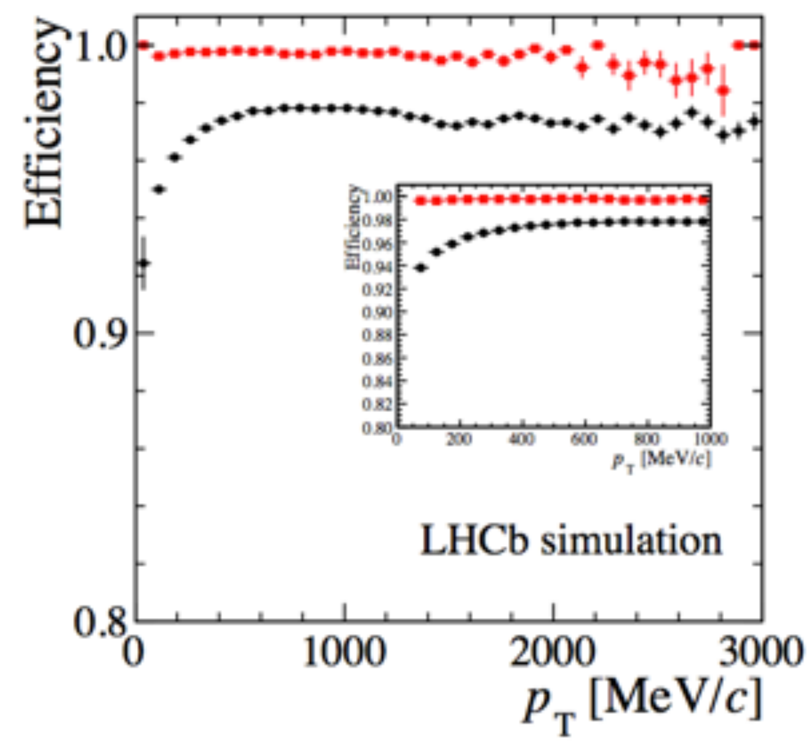
- **Technical choice**
  - Hybrid pixel detector:
    - $55\times55\ \mu m^2$ silicon pixel sensors
    - micro-channel cooling
  - Move closer to the beam:
    - $5 \rightarrow 3.5$ mm (closed)
    - 1st measurement: $8.3 \rightarrow 5.1$ mm



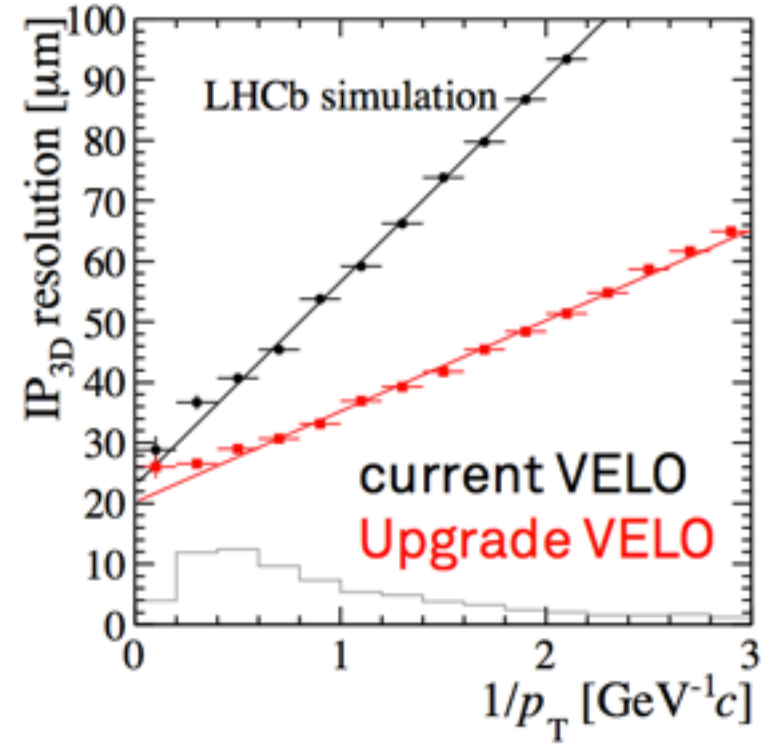
LHCb Upgrade
Vertex Detector: expected performances







- **With simulated events @ L = 2x10^{33} cm^{-2}s^{-1}:**
  - **Improvement of:**
    - ↳ impact parameter resolution
    - ↳ efficiency over p_T, ϕ and η



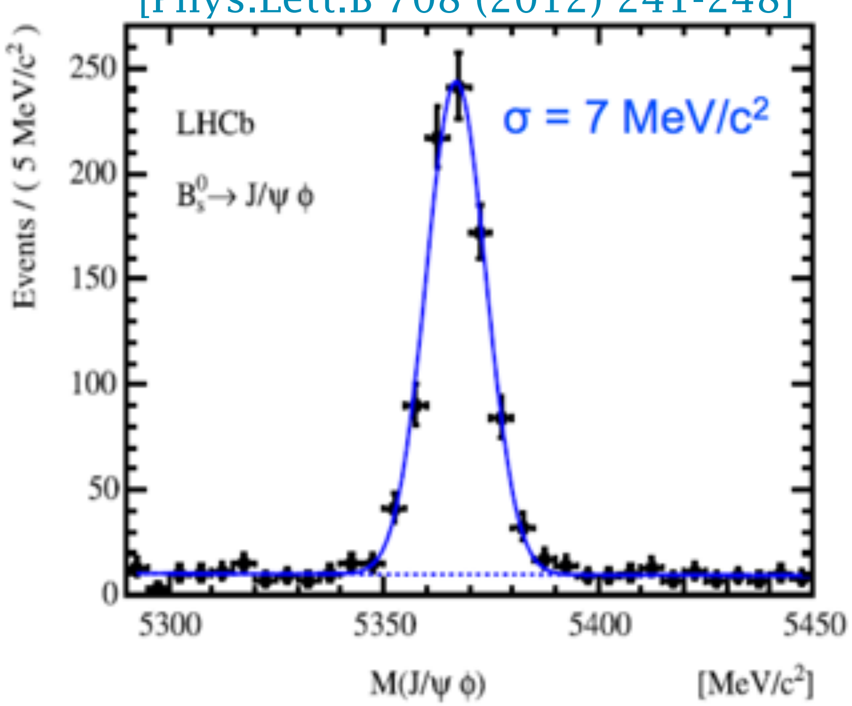
LHCb Upgrade
Tracking Stations

[CERN-LHCC-2014-001]
Tracker Upgrade TDR

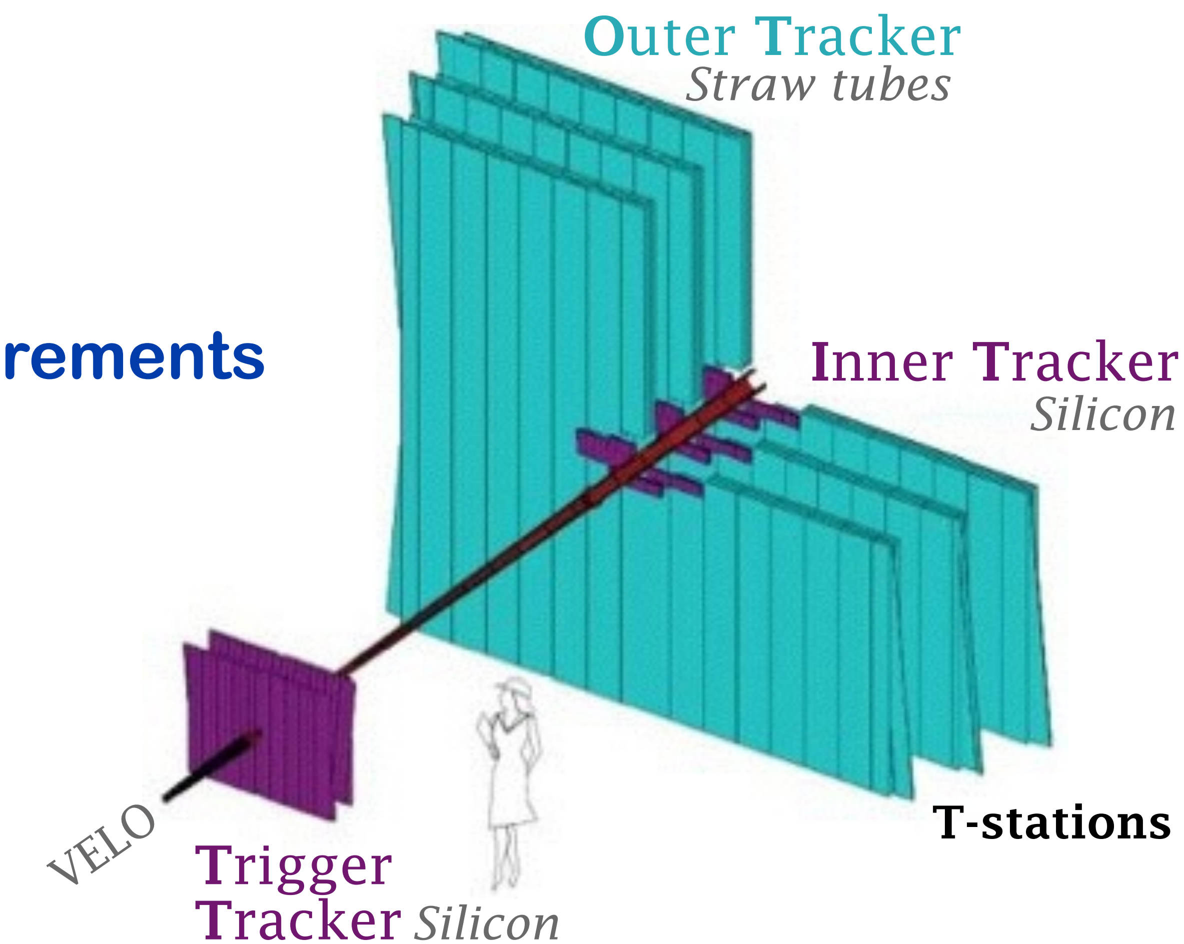
LHCb Upgrade
Tracking Stations: current system

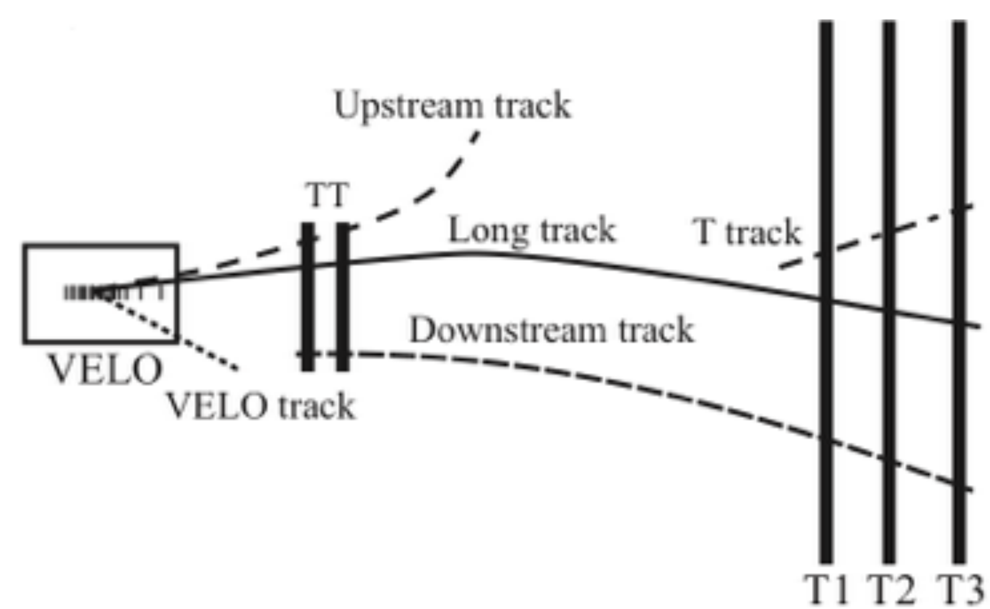
- **Current performances:**
  - Excellent mass resolution
  - Background level very low
  - b-hadron world's best mass measurements (including hits in the VELO)

[Phys.Lett.B 708 (2012) 241-248]



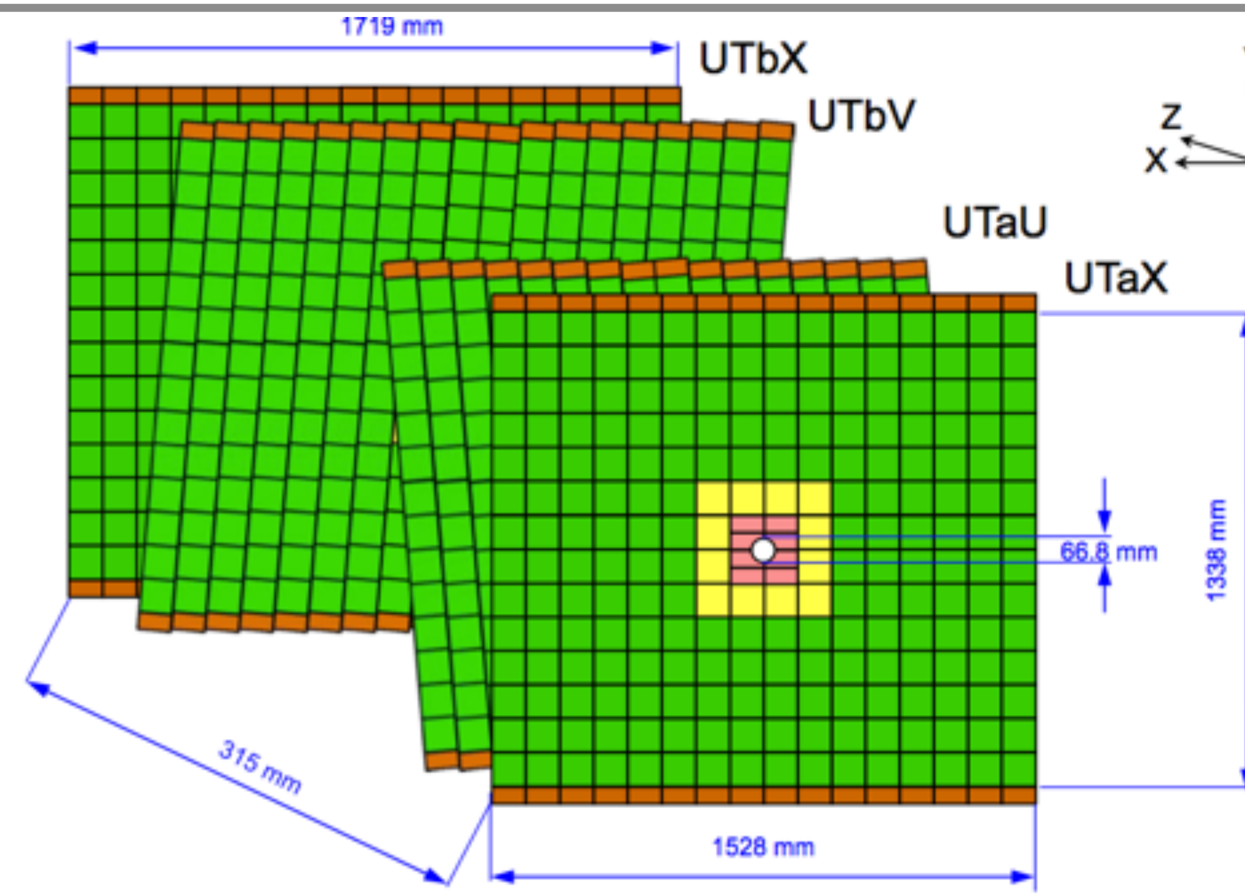
- **Main limitation:**
  - Cannot cope with expected occupancies of the upgrade running conditions

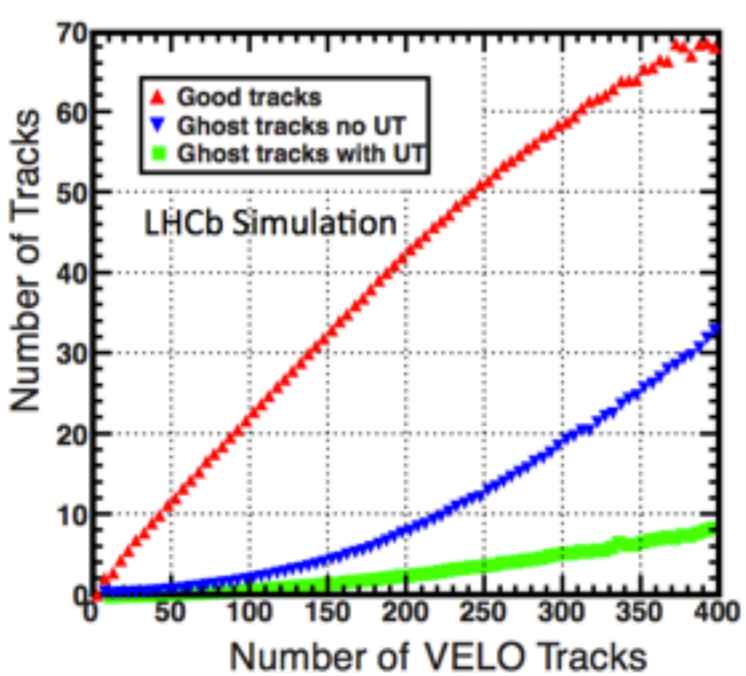


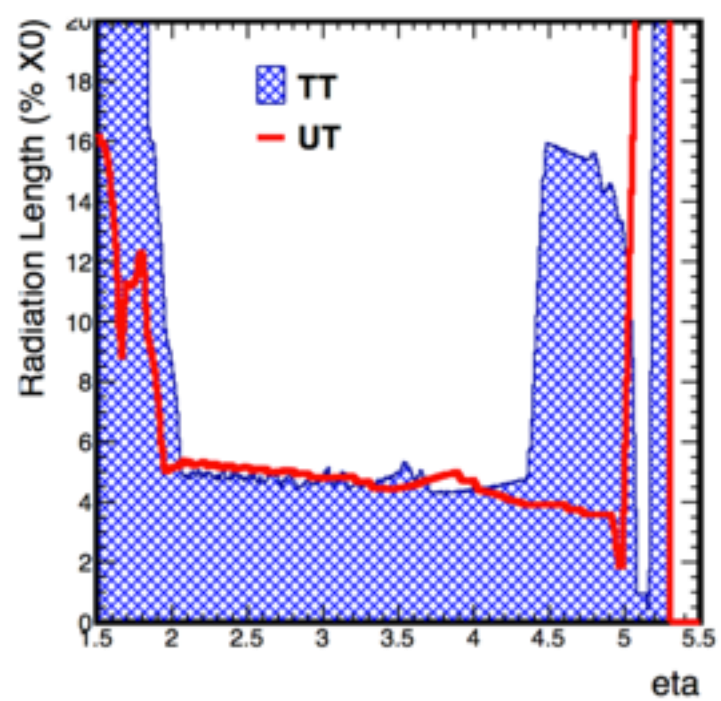


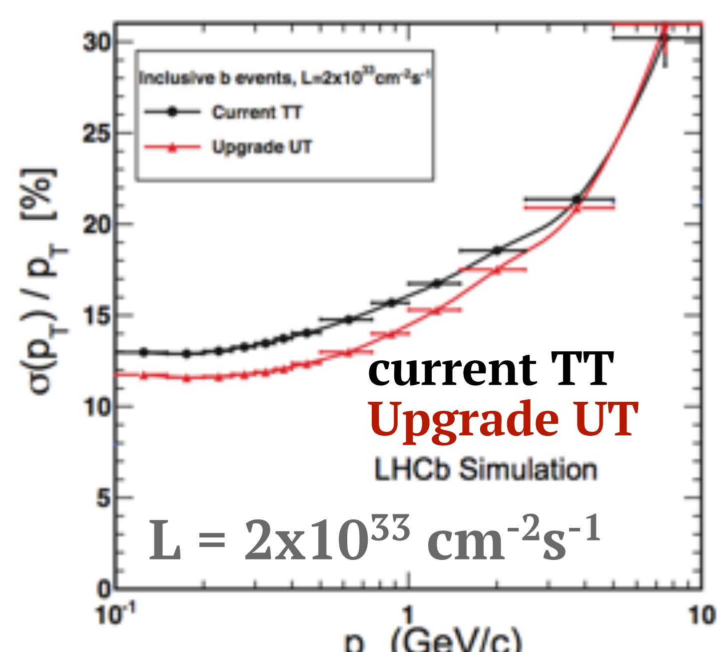
LHCb Upgrade
Upstream Tracker (UT)

- **TT → Upstream Tracker**
  - Keep same geometry:
    - four layers of Si-strips
  - Use finer granularity:
    - granularity varies according to the expected occupancies
    - reduce ghost rates
  - Lower material budget:
    - thinner sensors: 500 → 300 μm
  - Sensors closer to beam-pipe:
    - Increase acceptance @ large η



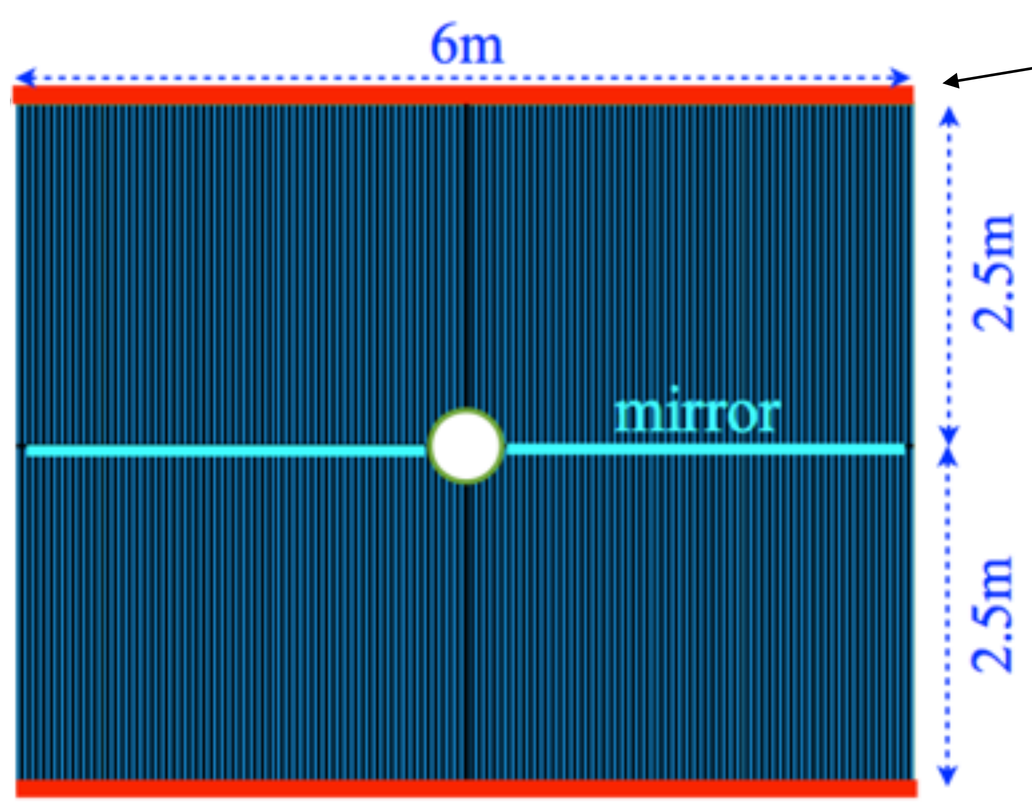




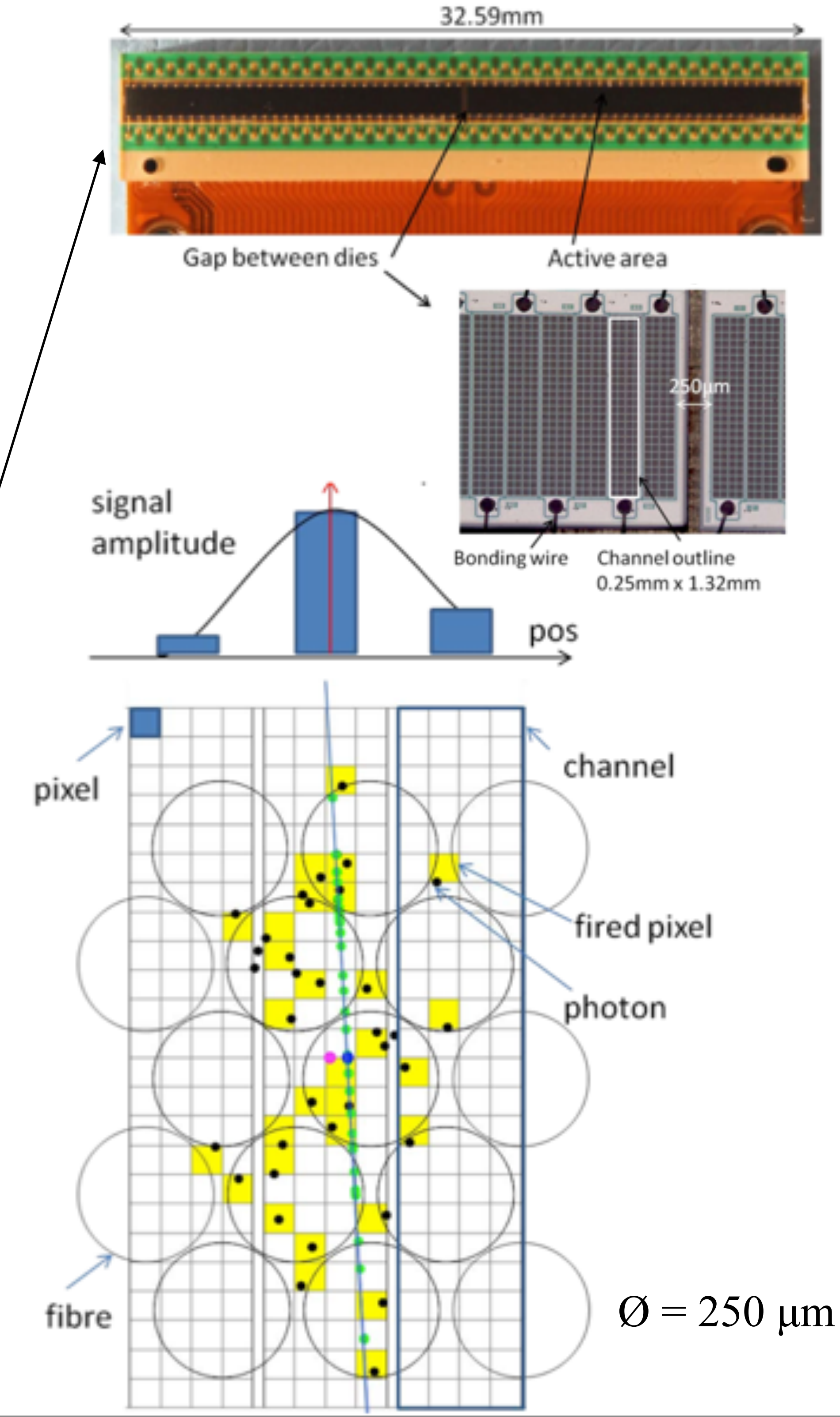


LHCb Upgrade
Sci-Fi Tracker: upgrade design

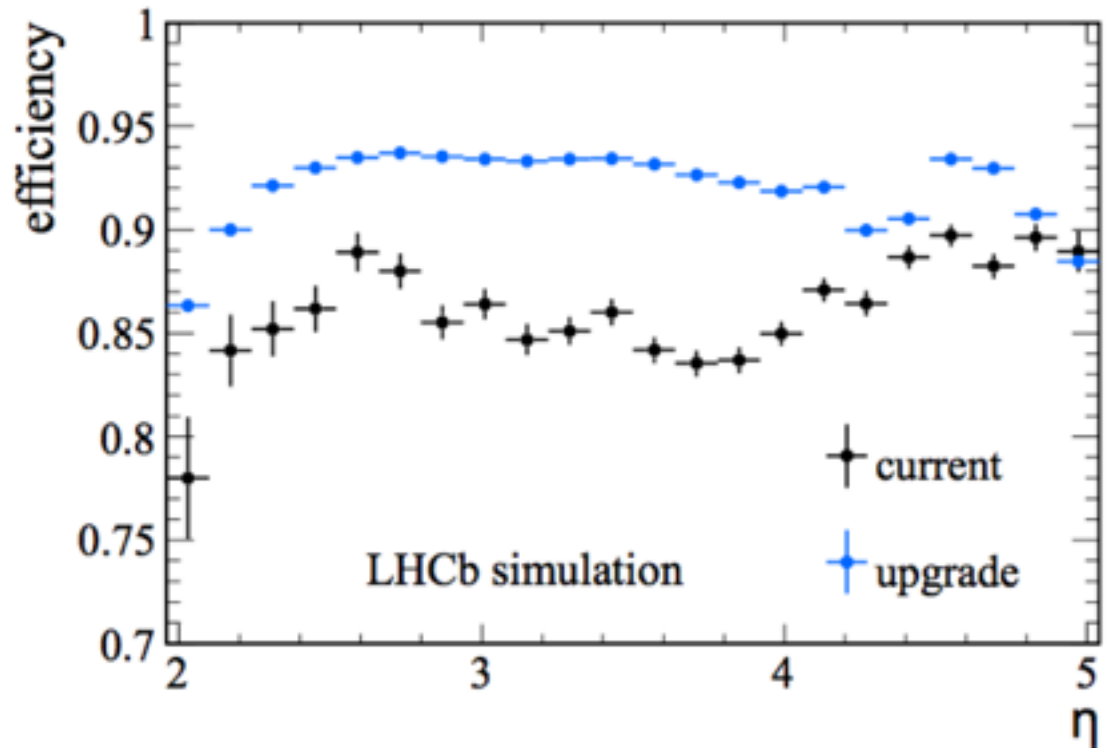
- **T-stations → Sci-Fi Tracker**
  - Scintillating fibres:
    - 2.5 m long & 250 μm diameter
    - arranged in 12 layers to cover the acceptance
  - Light detection:
    - SiPMs outside the acceptance
      ↳ minimize radiation damages
    - read-out with FE electronics @ 40 MHz
  - Radiation hardness of fibres → validated

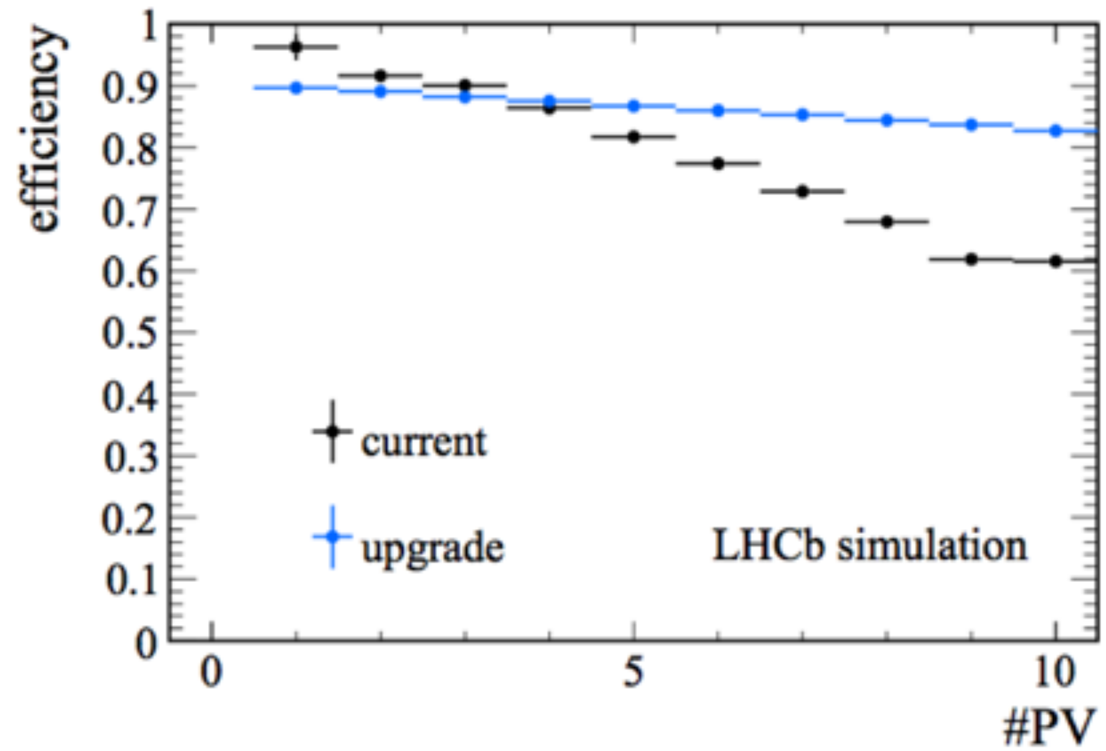


SiPMs

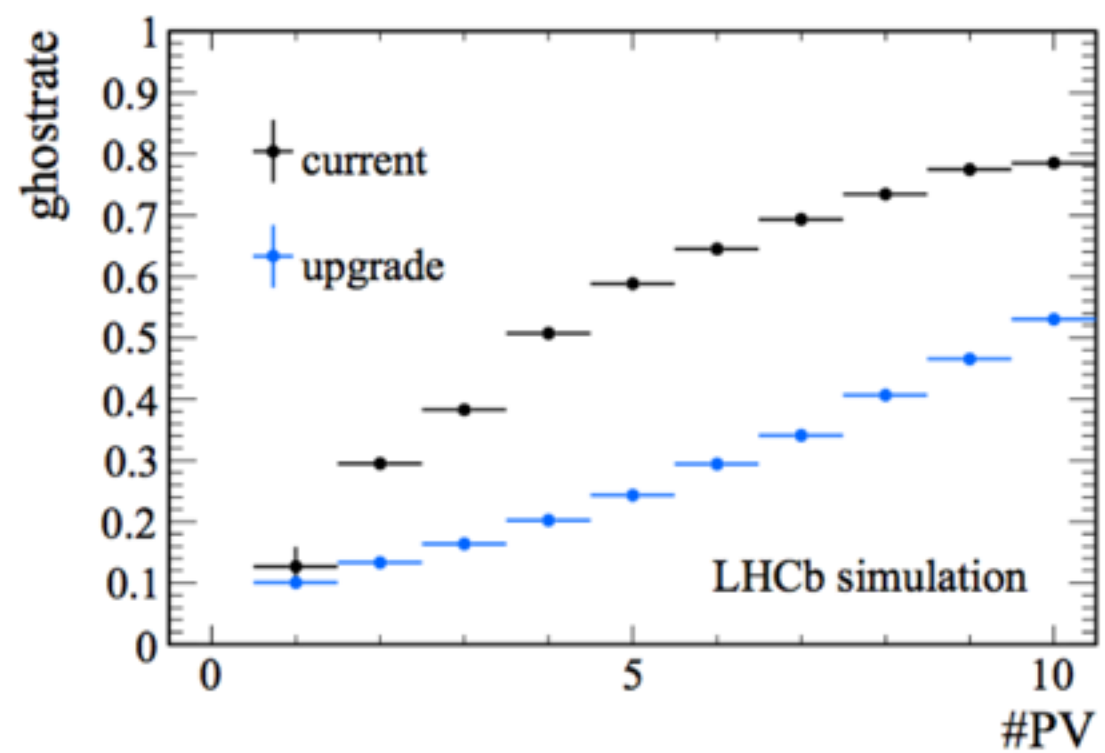


LHCb Upgrade
Sci-Fi Tracker: expected performances

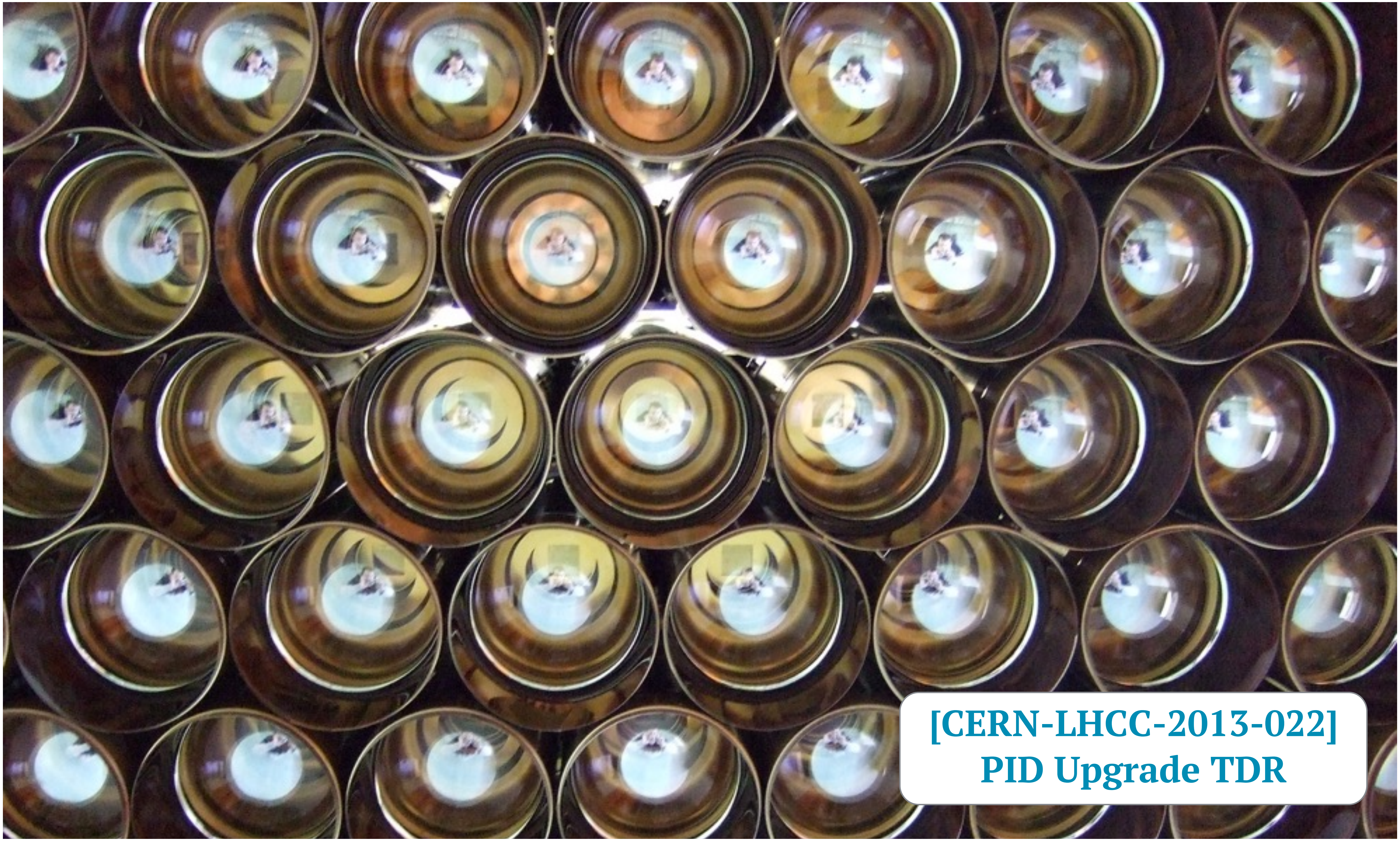




- **Benefits of the Sci-Fi concept:**
  - Improved tracking performance at upgrade luminosity
  - Fast pattern recognition for HLT
  - A single technology to operate
  - Uniform material budget



LHCb Upgrade
Particle Identification

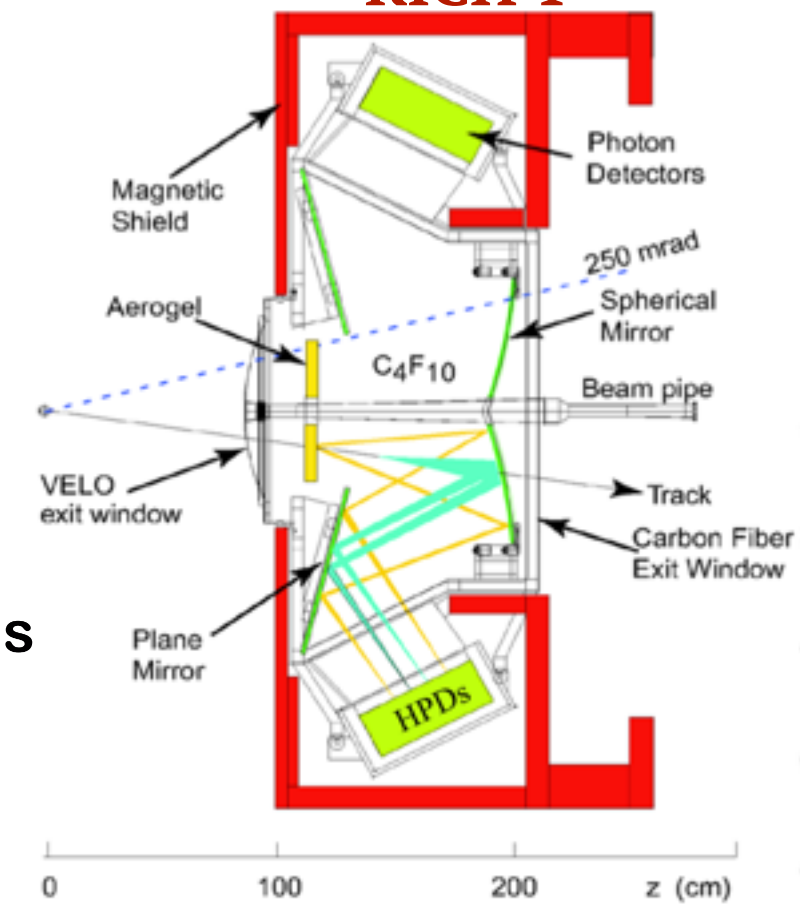


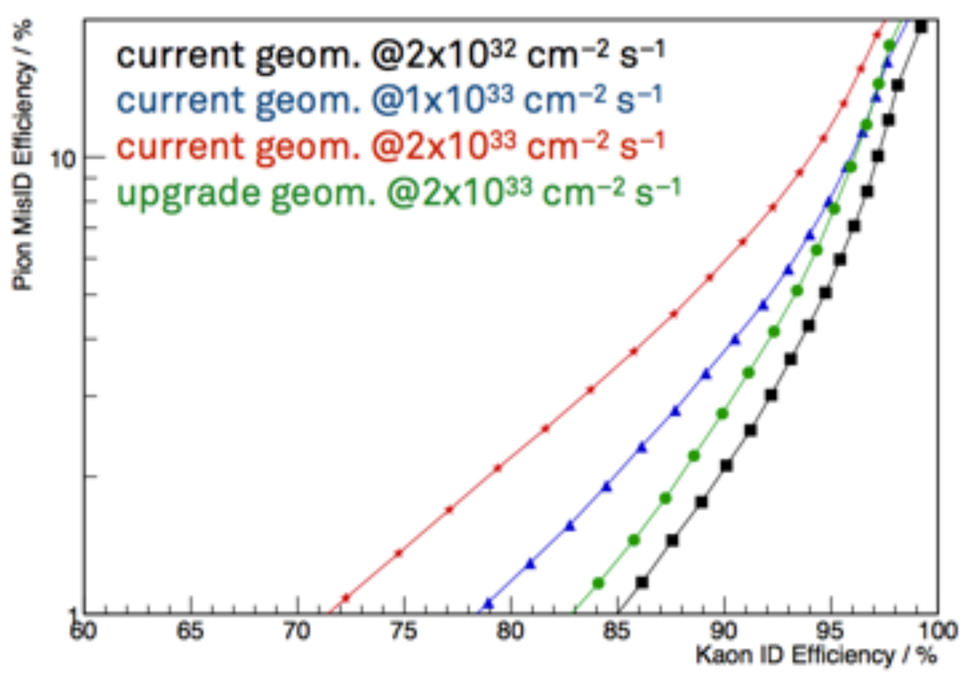
[CERN-LHCC-2013-022]
PID Upgrade TDR

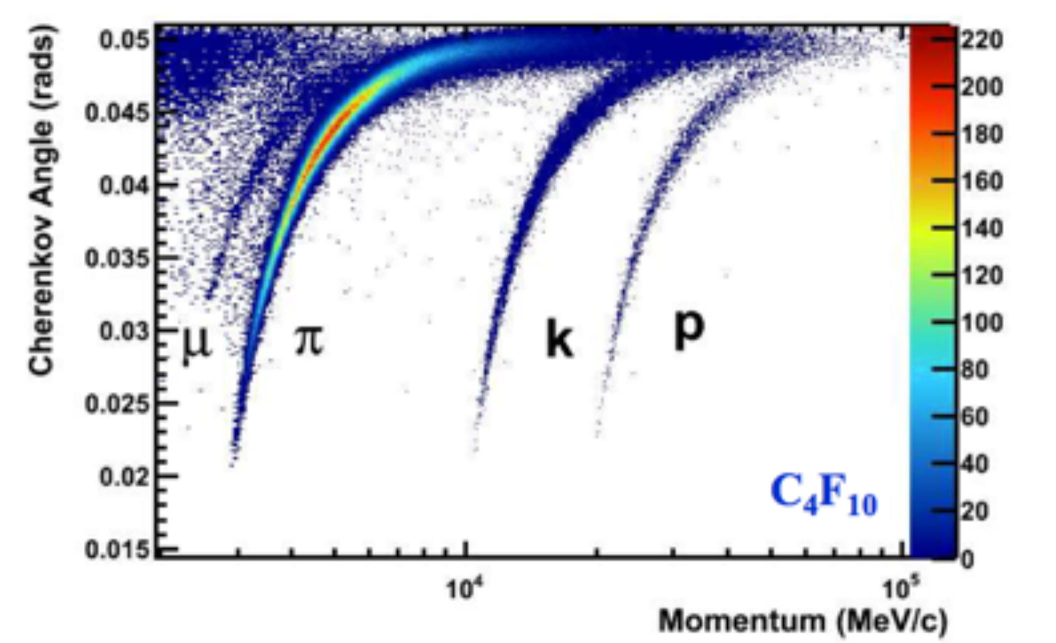
LHCb Upgrade
PID: RICH Detectors

- Two RICH detectors
  - Separates between K, π and p
  - Cherenkov light:
    - produced by particles traversing the radiator
    - collected by HPDs outside the acceptance
- Upgrade RICH detectors
  - Due to high occupancies:
    - remove aerogel radiator from RICH1
    - optimise optics in RICH1 to spread out Cherenkov rings
  - Readout @ 40 MHz:
    - replace HPDs (embedded FE @ 1MHz) by Multi-Anode-PMTs

RICH 1

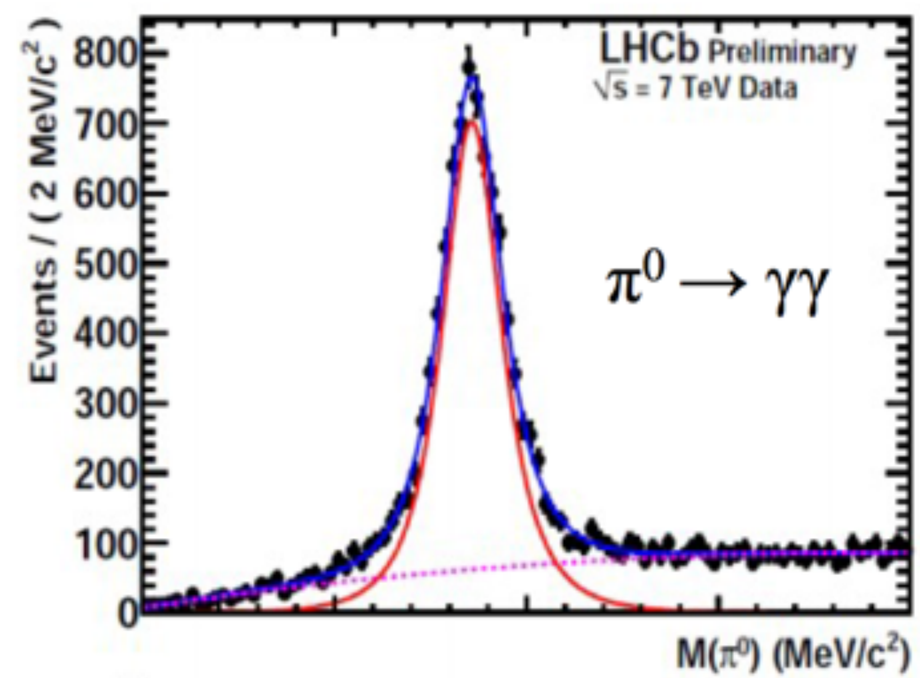






LHCb Upgrade
PID: Calorimeters & Muon system

- **Calorimeters (ECAL & HCAL)**
  - Current performance:
    - reconstruction of neutral hadrons
    - measured E_T used in L0
  - Upgrade:
    - remove PS and SPS (occupancy / no L0)
    - reduce PMT gain & adapt electronics for 40 MHz readout
    - replace inner-most part of ECAL due to radiation damage before ~20 fb^{-1}
    - HCAL ok up to ~50 fb^{-1}



- **Muon system**
  - Current performance:
    - high detection efficiency $\varepsilon(\mu) = (97.3 \pm 1.2)\%$
    - low misidentification rates
    - important in the L0 scheme
  - Upgrade:
    - remove 1st muon station (occupancy / no L0)
    - keep on-detector electronics (already @ 40 MHz)
    - new off-detector electronics