Physics Highlights from the LHCb Experiment

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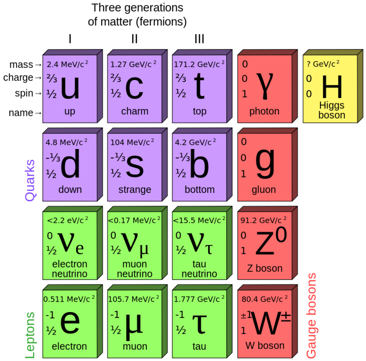
Outline

- Introduction
- LHCb Design and Performance
- Selected Results
- Upgrade Plans
- Summary and Outlook

➜ *an extremely successful theory: the Standard Model*



- 1 fundamental scalar
- 2 types of fermions
- 3 generations
- 4 fermions/generation
- 3 gauge interactions
- 4 gauge bosons

why?

➜ *some of today's big physics questions . . .*

What is the origin of mass?

➜ *how do fundamental particles acquire mass?*

- Standard Model: Higgs mechanism
  - ➜ space is filled with a Higgs background field
  - ➜ mass arises as resistance to movement through this field
  - ➜ if the model is correct, then a Higgs particle must exists
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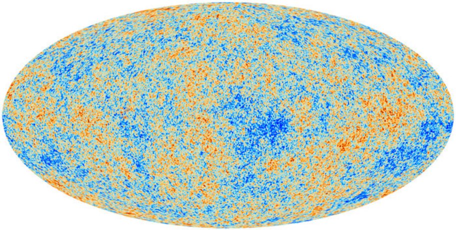
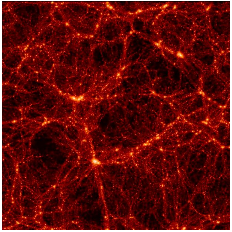
→ *what determines the mass values?*

- the Higgs mechanism does not predict mass values
- understanding mass hierarchy requires New Physics
  - → new (heavy) particles and fields
  - → rich new phenomenology

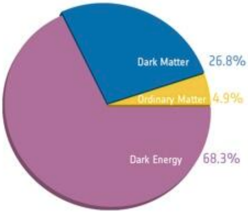
What is Dark Matter made of?

➜ *cosmic microwave background & structure formation:*





- the universe is "flat" (euclidean)
- its energy content is [Planck]
  - ➜ 68.3% dark energy
  - ➜ 4.9% ordinary matter
  - ➜ 26.8% dark matter (heavy particles?)



Where is the Antimatter?

➜ *the puzzle*

- antimatter (in small quantities) is observed in lab-experiments
- always same amounts of matter and antimatter created
- the same processes occured in the early universe, but
- no evidence for sizeable amounts of antimatter in the universe


(image: HST)

✔ no evidence for anti-matter annihilation radiation

✔ no evidence for anti-nuclei in cosmic rays

Looking for answers

➜ *Sakharov: a matter-dominated universe requires:*

1. baryon number non-conservation
2. C- and CP-violation (C=particle-antiparticle exchange, P=parity)
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- the SM-Higgs is to heavy to drive a 1st order phase transition
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❖ conclusions:

- instead of the Sakharov conditions on has CPT-violation
- alternatively there are new, additional sources of CP-violation
  - ➜ in the quark-sector (baryogenesis)
  - ➜ in the lepton-sector (transferred to the quark sector, leptogenesis)

→ *strong arguments for New Physics beyond the Standard Model*

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- new particles could mediate extra CP-violation

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  - ➜ new particles will have additional couplings
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  - ➜ phases in couplings will affect CP-violation
- flavour physics (weak interaction) is expected to play a key role
  - ➜ weak interaction couples to all known fields
  - ➜ already in the Standard Model there is C- and CP-violation
  - ➜ charged weak currents couple with complex phases
  - ➜ trivial for degenerate masses, i.e. depend on mass hierarchy

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CP violation can only occur in the interference between different complex amplitudes, and if an invariant phase ("strong phase") exists which is not complex-conjugated under particle-antiparticle exchange.

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- CP-violation in interference of mixing and decay
  - ➜ $\Gamma(B \to f) \neq \Gamma(\bar{B} \to f)$
  - ➜ decay into CP-eigenstate
  - ➜ mixing and decay mediated by only weak interactions
  - ➜ very clean since "strong phase" exactly known

CPV in the interference of mixing and decay

CP-Asymmetry A_{CP} for decays into a final state y:

$$A_{CP} = \frac{\Gamma(X \to y) - \Gamma(\overline{X} \to \bar{y})}{\Gamma(X \to y) + \Gamma(\overline{X} \to \bar{y})}$$

with partial widths $\Gamma(\cdot) = |a(\cdot)|^2$

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Consider mixing induced CP-violation in decays to a CP-eigenstate $y = y_{CP}$:

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with phase factors

- decay phase: ω
- mixing phase: ϕ

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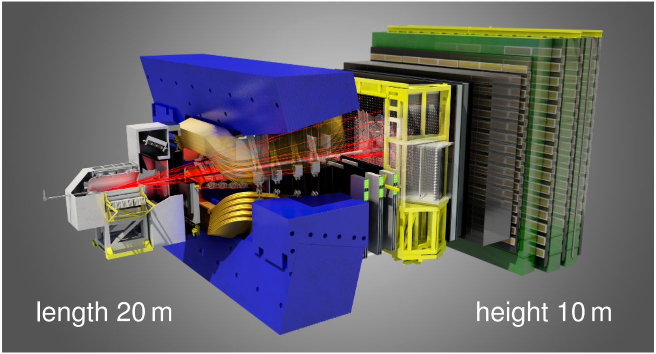
$\Rightarrow$ $$A_{CP} = -\sin(\Delta m t)\sin(\phi - 2\omega)$$

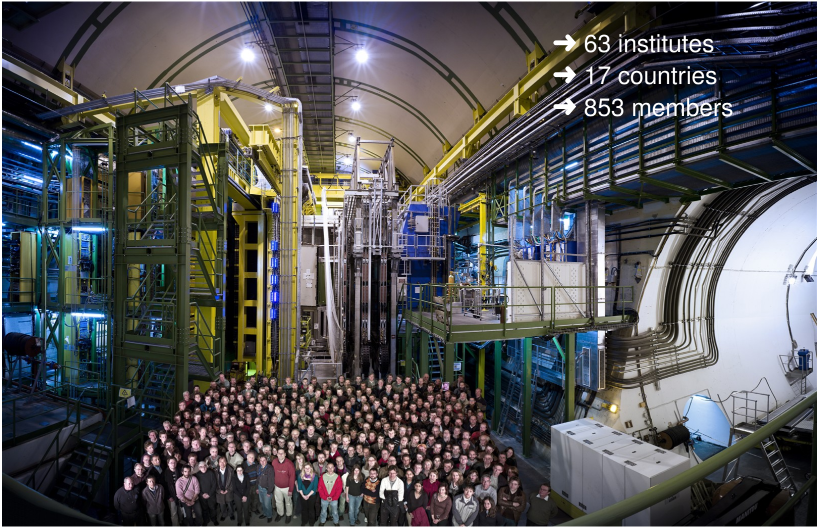
2. LHCb DESIGN AND PEFORMANCE

- forward spectrometer with $15 < \Theta < 300$ mrad and $\int Bdl = 4$ Tm



- VELO: silicon strip detector for precise secondary vertex reconstruction
- TT,T1,T2,T2: tracking stations, silicon strip and straws for charged particles
- RICH1, RICH2: ring imaging cherenkov detectors for $\pi/K/p$-separation
- ECAL, HCAL: electromagnetic & hadronic calorimeters for trigger and neutrals
- M1-M5: tracking stations for muon identification

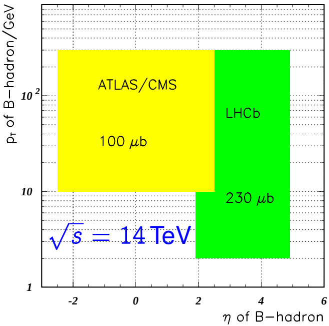
Installation in the cavern

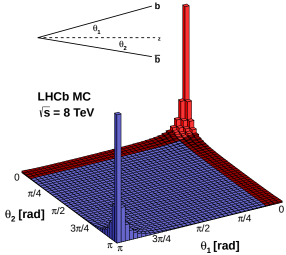


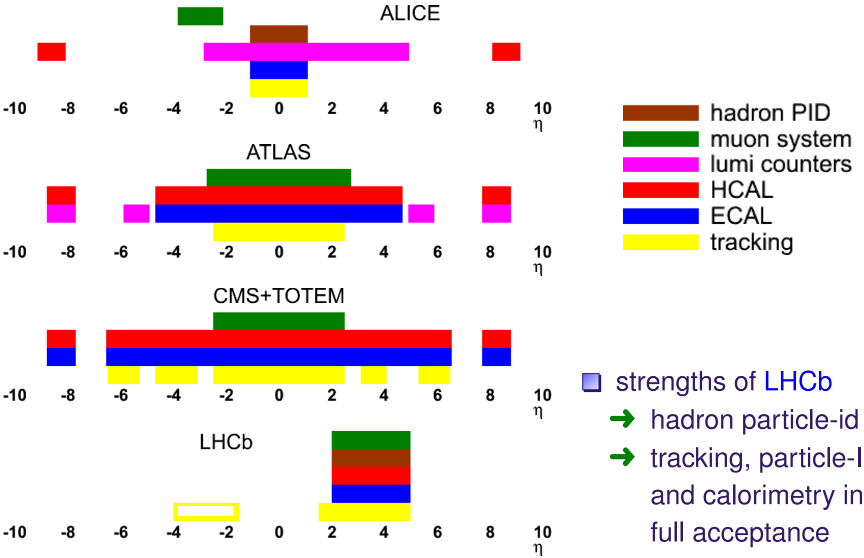
Inside the spectrometer magnet

➜ *optimization for B-Physics*

- forward angular coverage ➜ large boosts: B decay lengths O(1 cm)
- focus on vertex reconstruction and particle identification
- phase space coverage down to low p_T, small x_{Bj} and large η
- flexible and highly selective trigger







- strengths of LHCb
  - ➜ hadron particle-id
  - ➜ tracking, particle-ID and calorimetry in full acceptance

Key points

- huge production rate of heavy flavour hadrons
  - ➜ $\sigma(b\bar{b}) = 284 \pm 53\,\mu\text{b}$ ($\sqrt{s} = 7\,\text{TeV}$)
    - ❖ $O(100)$ kHz $b\bar{b}$-events
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  - ➜ $BR(B^+ \to \pi^+\mu^+\mu^-) = (2.4 \pm 0.6_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-8}$
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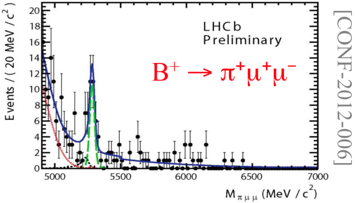

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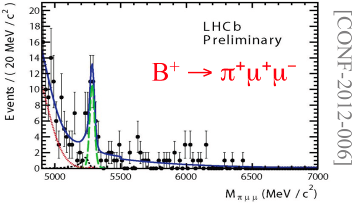

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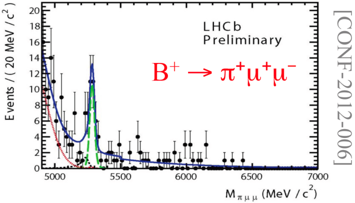

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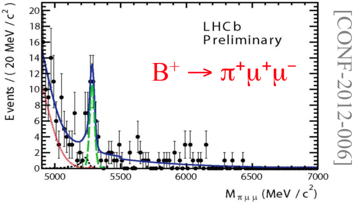

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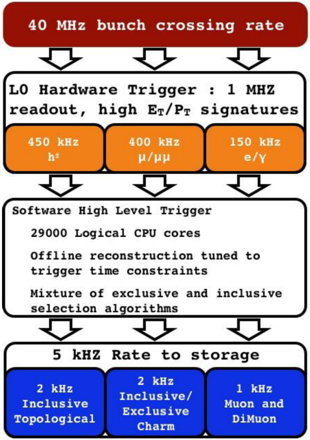
- complementary coverage for electroweak studies, QCD, exotics, . . .



ca. 50 kB/event

➜ *allow selection of rare processes*

- Level-0 Trigger: hardware
  - ➜ fully synchronous at 40 MHz
  - ➜ use calorimeters and muon system
  - ➜ selection of high-p_T particles
    - ✔ $p_T(\mu) > O(1)$ GeV/c
    - ✔ $p_T(h, e, \gamma) > O(3)$ GeV/c

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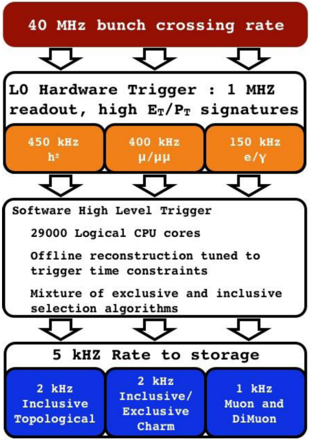

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  - ➜ HLT1: add VELO information
    - ✔ impact parameter- and lifetime cuts
  - ➜ HLT2: global event reconstruction
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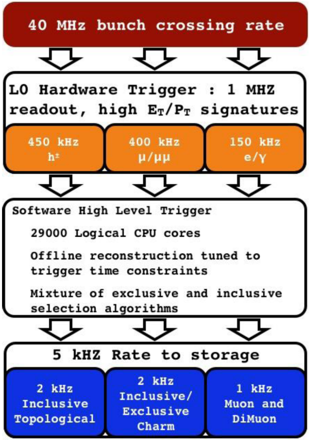

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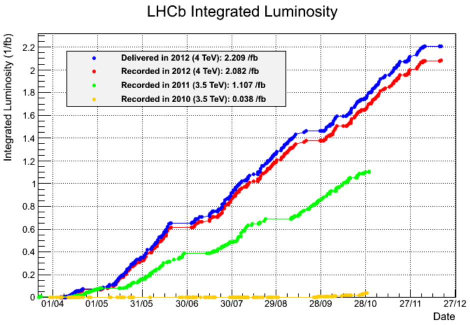
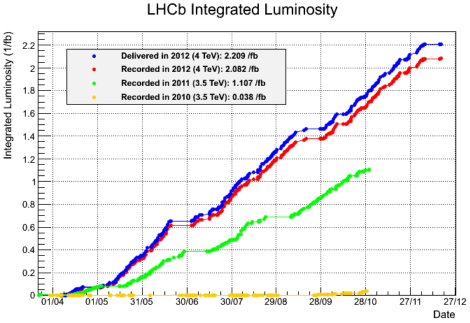


- DAQ efficiency $\approx$ 95%
- instantaneous luminosity up to $L = 4 \times 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - ➜ twice design value at double the nominal bunch spacing
  - ➜ luminosity leveling for LHCb by beam steering
- a total of 2×10^{14} pp-collisions scrutinized

Data taking history



year	luminosity	E[TeV]
2009	$6.8\,\mu b^{-1}$	0.9
2010	$0.3\,nb^{-1}$	0.9
2010	$0.37\,pb^{-1}$	7
2011	$0.1\,pb^{-1}$	2.76
2011	$1\,fb^{-1}$	7
2012	$2\,fb^{-1}$	8
2013	$1.3\,nb^{-1}$	5 (pA)
2013	$0.6\,nb^{-1}$	5 (Ap)

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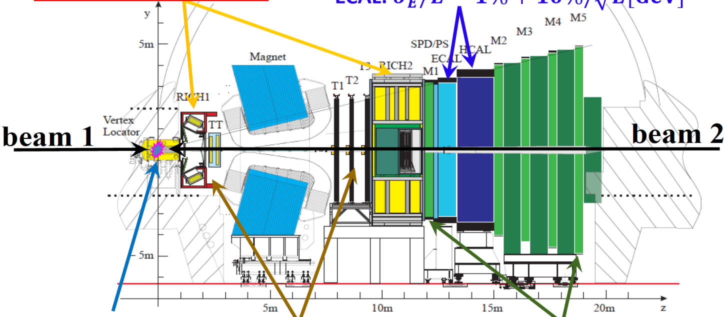
Pseudorapidity acceptance
$2 < \eta < 5$

RICH1 & RICH2
$\epsilon(K \to K) \sim 95\%$
$\pi \to K$ mis-id: $\sim 5\%$

Calorimeters
ECAL: $\sigma_E/E \sim 1\% + 10\%/\sqrt{E[\mathrm{GeV}]}$



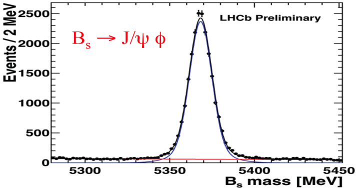
VELO
$\sigma_{IP} \sim 20\ \mu m$
for high-p_T tracks

Tracking System
$\Delta p/p = 0.4\%@5\ \mathrm{GeV}/c$
to $0.6\%@100\ \mathrm{GeV}/c$

Muon System
$\epsilon(\mu \to \mu) \sim 97\%$
$\pi \to \mu$ mis-id: $1 \sim 3\%$

Tracking and vertexing performance

- excellent mass resolution for complex decays



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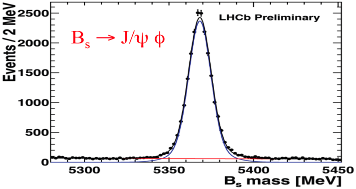

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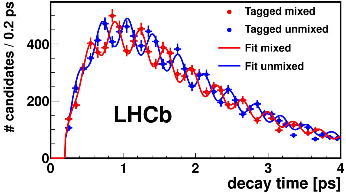
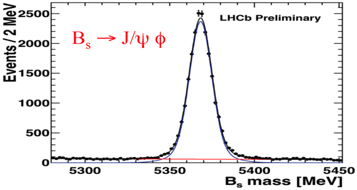
with J/ψ mass constraint

- excellent vertex- and proper-time resolution



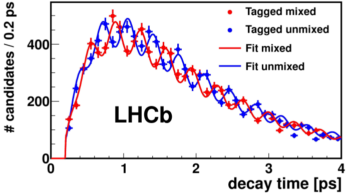
➜ proper time resolution:
$\sigma_t \sim 45\,\mathrm{fs}$
for B_s-mixing

- excellent mass resolution for complex decays



➜ B-mass resolution:
$\sigma(m_B) = 8\,\mathrm{MeV}/c^2$
for $B_s \to J/\psi X$
with J/ψ mass constraint

- excellent vertex- and proper-time resolution



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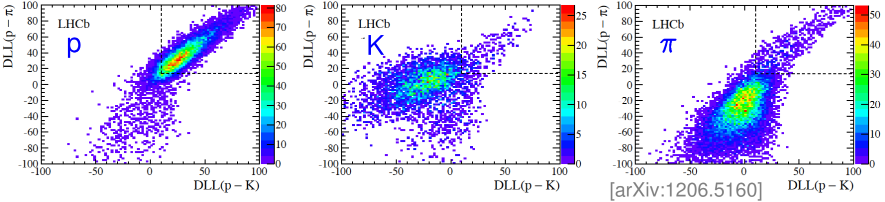
❖ polarity switching of dipol magnet allows to control systematics

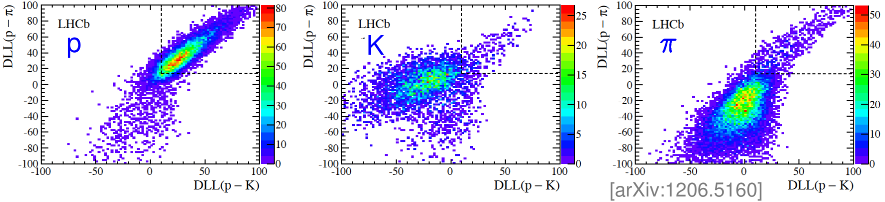
➜ RICH log-likelihood differences from calibration samples



[arXiv:1206.5160]

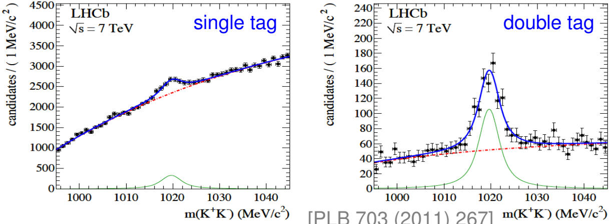
Particle identification performance

➜ RICH log-likelihood differences from calibration samples



[arXiv:1206.5160]

- check of K-identification with $\phi \to K^+K^-$-signal

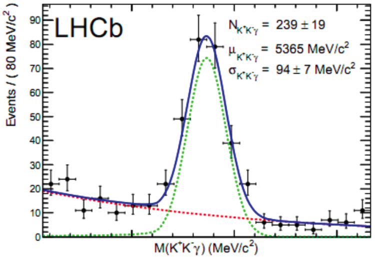


[PLB 703 (2011) 267]

➜ allows in-situ calibration of kaon identification

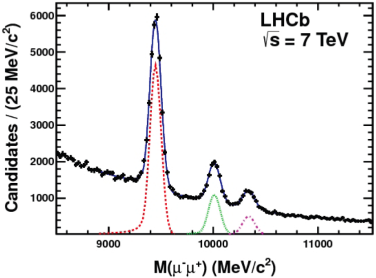
- ECAL: optimized to measure radiative B-decays
- HCAL: for triggering on hadronic final states
- Muon system for quarkonium and semi-leptonic decays

$B_s \rightarrow \phi\,\gamma$



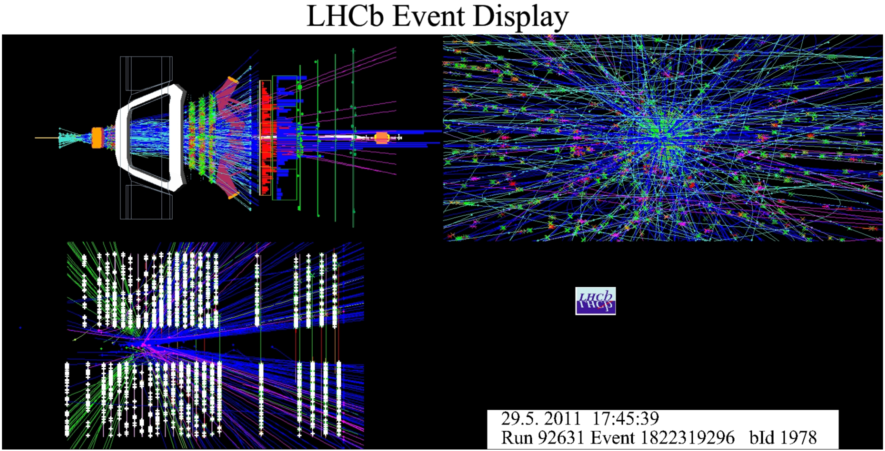
[arXiv:1202.6267]

$\Upsilon \rightarrow \mu^+\mu^-$



[arXiv: 1202.6579]

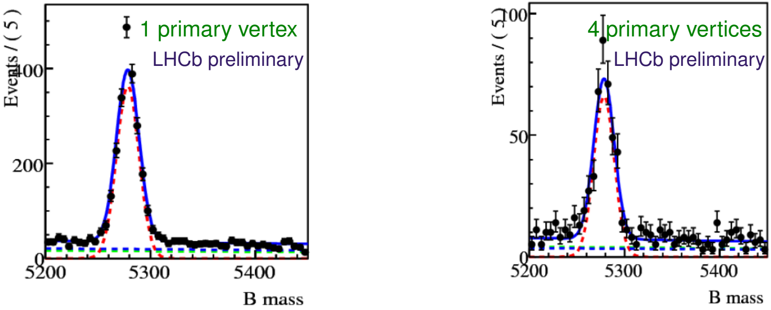
➜ pp high-pileup event in LHCb



➜ more quantitatively

→ *e.g. reconstruction of B-meson decays . . .*

for example: $B^{\pm} \to J/\psi K^{\pm}$



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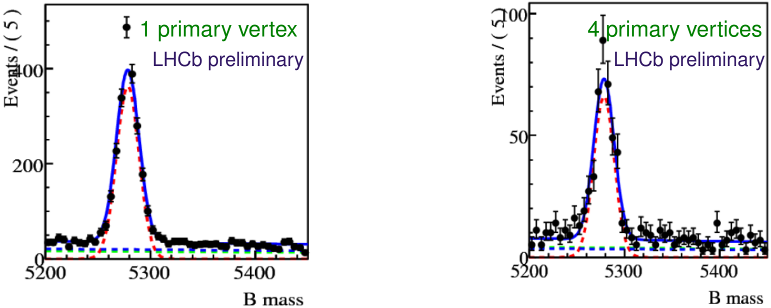

- ✔ clean signal for $N_{PV} = 1$ and $N_{PV} = 4$
- ✔ S/B basically unaffected by pileup
- ✔ particle-ID still operational at $N_{PV} = 4$

3. SELECTED RESULTS

➜ *wide range of physics topics covered by the experiment*

- QCD measurements and spectroscopy
  - ➜ particle production, particle ratios, forward energy flow
  - ➜ b- and c-hadron spectroscopy
  - ➜ charmonium, bottomonium
  - ➜ measurement of exotic states, search for lepton number violation
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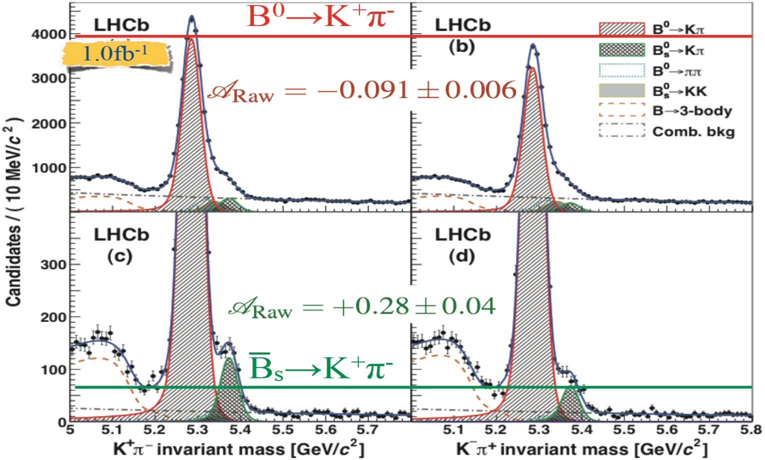
❖ explore the limits of the Standard Model!

Direct CP-violation in B-decays

→ study $B_d, \bar{B}_s \to K^+\pi^- + c.c.$ decays



[LHCB-PAPER-2013-018] in preparation

→ *corrections for detector and production asymmetries*

$$A_{CP} = A_{\rm raw} - (A_{\rm det} + A_{\rm prod})$$

- LHCb made of matter
- LHCb not perfectly symmetric for positive and negative tracks
- initial pp state is purely matter

Results based on 1 fb^{-1}

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➜ *first observation of CPV in B_s system*

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- dominant systematics from fit model

The B_s-mixing frequency

➜ *measure by means of flavour-specific B_s-decays*

- second-order weak process
- only small phase from CKM-couplings
- decay modes studied
  - ➜ $B_s^0(\bar{b}s) \to D_s^-(\bar{c}s)\pi^+$
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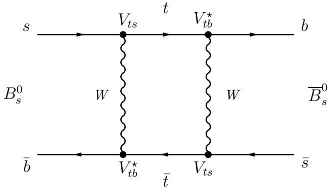

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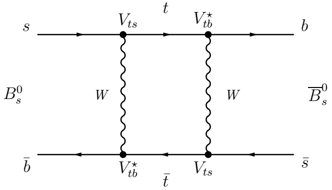

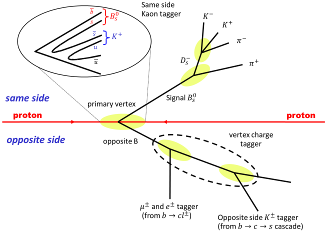

- flavour tagging of initial state
  - ➜ opposite side taggers:
    partial reconstruction of 2nd B-hadron
  - ➜ same side kaon tagger:
    self-tagging from hadronization
  - ➜ combined tagging power:
    $\varepsilon(1-2\omega)^2 = 3.5 \pm 0.5\,\%$

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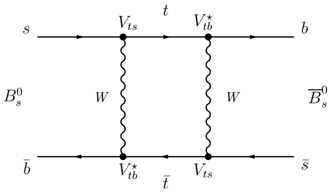

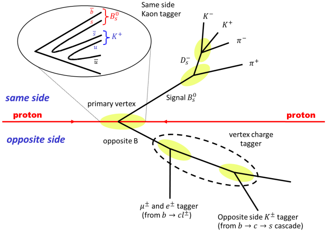

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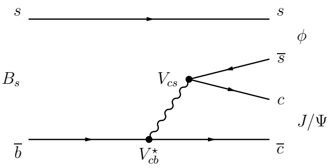
result: $\Delta m_s = 17.768 \pm 0.023 \pm 0.006\,\mathrm{ps}^{-1}$ Moriond 2013

➜ *CP-violation from interference between mixing and decay*



- "golden decay" in the B_s-system
- SM-dominated tree-level decay
- small SM phase between mixing & decay
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  - ➜ sensitive to New Physics in mixing

Search for CP violation

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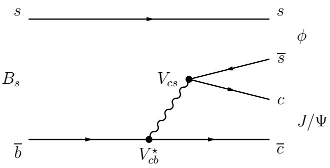

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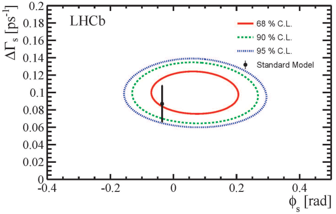
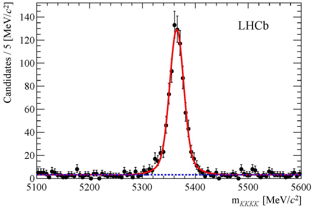
- measure mixing phase and lifetime-difference
- study flavour symmetric decay modes
  - ➜ $B_s \to J/\psi\phi$, $B_s \to J/\psi\pi^+\pi^-$
- angular analysis for vector-vector states
  - ➜ $\phi_s = 0.01 \pm 0.07 \pm 0.01\,\mathrm{rad}$
  - ➜ $\Delta\Gamma_s = 0.106 \pm 0.011 \pm 0.007\,\mathrm{ps}^{-1}$

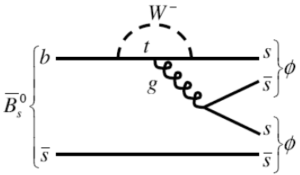
consistent with Standard Model



Moriond 2013

→ *first measurements of $B_s \to \phi\phi \to K^+K^-K^+K^-$* Moriond 2013

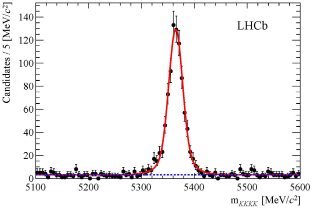


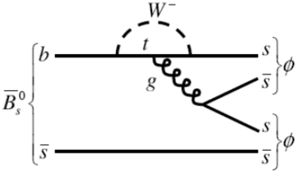


- penguin dominated decay process in vector-vector final state
  - → angular analysis of current data $\phi \in [-2.46, -0.76]$ @ 68 % CL

Outlook

➜ *first measurements of* $B_s \to \phi\phi \to K^+K^-K^+K^-$ Moriond 2013





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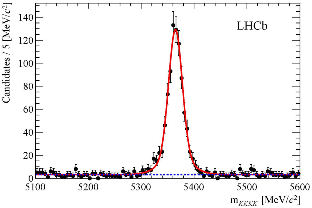

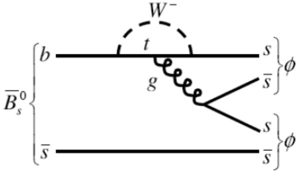

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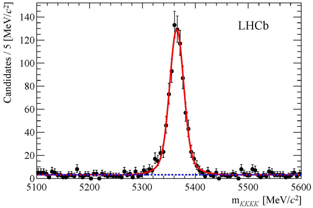

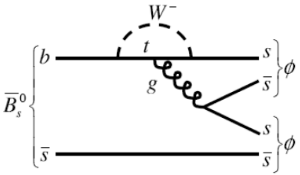

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- similar channel w/o complication of angular analysis: $B_s \to K_S^0 K_S^0$

- *very rare FCNC decays*
  - SM prediction [Eur.Phys.J. C72 (2012)2172]
    $BR(B_s \to \mu^+\mu^-) = (3.23 \pm 0.27) \cdot 10^{-9}$
    $BR(B_d \to \mu^+\mu^-) = (1.07 \pm 0.10) \cdot 10^{-10}$
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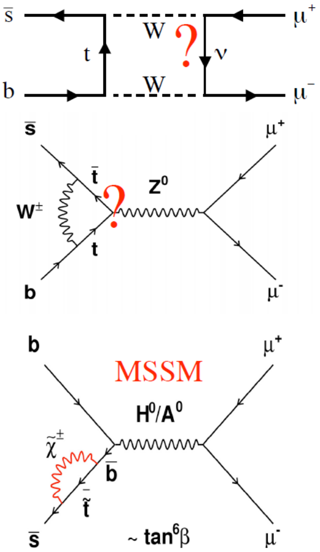
  - possibly strong enhancements in MSSM
    $BR(B \to \mu^+\mu^-) \propto \tan^6\beta$



The rare decays $B \to \mu^+\mu^-$

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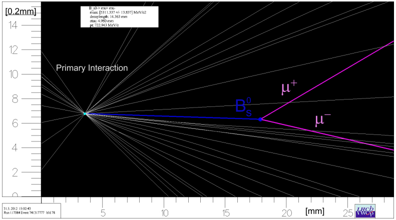

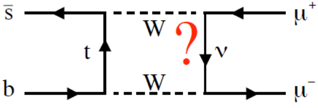

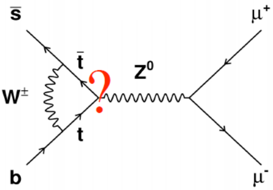

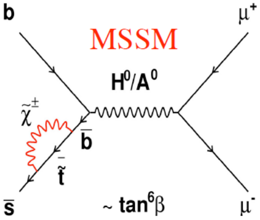

Experimental results

➜ *multivariate analysis* [arXiv:1211.2674]

- Boosted Decision Tree combining topological information
- $1.0\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7\,\mathrm{TeV}$ plus $1.1\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8\,\mathrm{TeV}$
- $3.5\,\sigma$ evidence $BR(B_s \to \mu^+\mu^-) = (3.2\,\pm^{1.4}_{1.2}\,\pm^{0.5}_{0.3}) \times 10^{-9}$
- 95% CL limit $BR(B_d \to \mu^+\mu^-) < 9.4 \times 10^{-10}$

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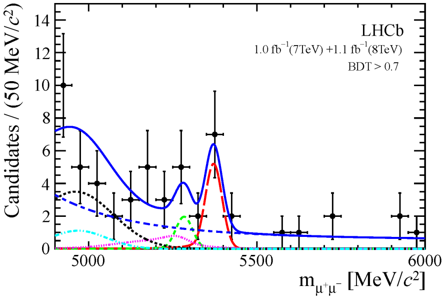

→ in signal region mainly combinatorial background

→ peaking contributions from $B \to h^+h^-$

→ low mass background from $B^0 \to \pi^-\mu^+\nu_\mu$ (dominant) and $B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$

Implications of LHCb results

- strong constraints on New Physics
- complementary approach to direct searches by GPDs

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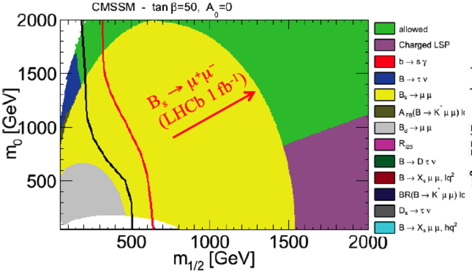
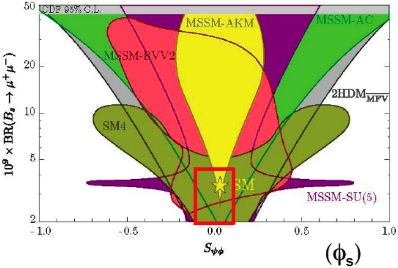
- two recent examples:
  - ➜ limits on MSSM mass-scales from $B_s \to \mu^+\mu^-$
  - ➜ accessible $\{\phi_s, BR(B_s \to \mu^+\mu^-)\}$ range for various models

[N. Mahmoudi, Moriond QCD]

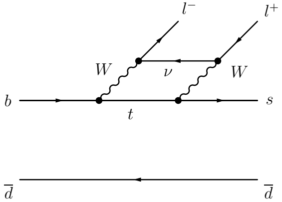


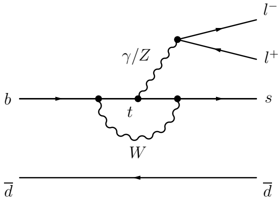
[D. Straub, arXiv:1107.0266]



limits based on summer 2012 data

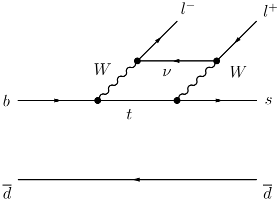
→ *sensitivity to New Physics from box and penguin contributions*

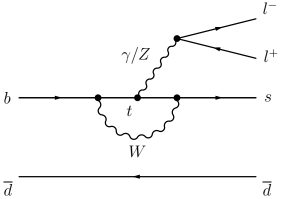




The decay $B_d \to K^* \mu^+ \mu^-$

➜ *sensitivity to New Physics from box and penguin contributions*



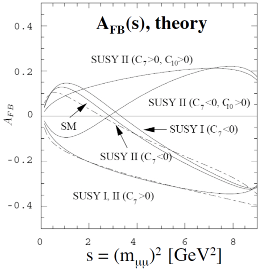


- branching ratio $BR \sim 1.2 \cdot 10^{-6}$
- measure angular variables, e.g.:
  - ➜ B_d-direction in the $\mu^+\mu^-$ rest system
  - ➜ forward-backward asymmetry vs $m^2_{\mu^+\mu^-}$

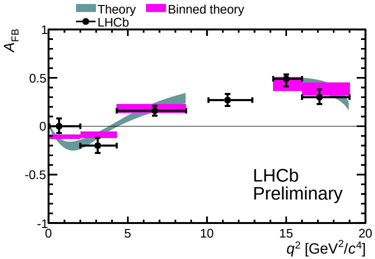
$$A_{FB} = (n_F - n_B)/(n_F + n_B)$$

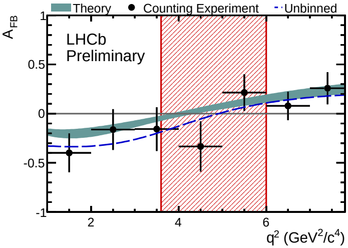
  - ➜ sensitive to Wilson-Coefficients C_7, C_9
  - ➜ constrain existence & type of New Physics

[PRD 61 (2000) 074024]



- data sample of 900 events, as clean as at the B factories
  - ➜ largest sample in the world [arXiv:1105.0376]
- prediction for zero-crossing: $q^2(A_{FB} = 0) = 4.0 - 4.3\,\mathrm{GeV}^2/c^4$
- current LHCb measurement: $q^2(A_{FB} = 0) = 4.9 \pm^{1.1}_{1.3}\,\mathrm{GeV}^2/c^4$ [LHCb-CONF-2012-008]
- earlier hints at discrepancies not confirmed
- improved results to be published soon





[LHCb-CONF-2012-008]

CP-violation in the charm sector

→ *status summer 2012*

- *"CP violation . . . at the percent level signals new physics"*

  [arXiv:hep-ph/0609178] Y. Grossman; (and many others)

- $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$
  - → large event sample from 0.6 fb^{-1}
  - → self-tagging by decay $D^{*+} \to D^0\pi^+$
  - → systematics cancel in the difference

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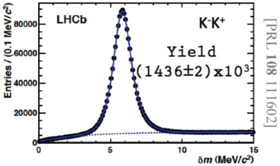
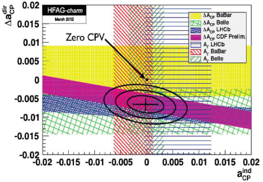
  - ➜ systematics cancel in the difference
- result $\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%$
- large value confirmed by others
- interpretation: large strong phases. . .

  "We have shown that it is plausible that the SM accounts for the measured value . . . Nevertheless, new physics could be at play"

  [arXiv:1111.5000] J.Brod et al.





Improved analysis with full 2011 statistics

- improved background suppression by factor 2.5
- two sources of D-mesons to probe systematics
  - ➜ self-tagging charm decays $D^{*+(-)} \to D^0(\bar{D}^0)\pi^{+(-)}$
  - ➜ semileptonic B-decays $B^{+(-)} \to \bar{D}^0(D^0)\mu^{+(-)}\nu$

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- new results [Moriond, 2013]

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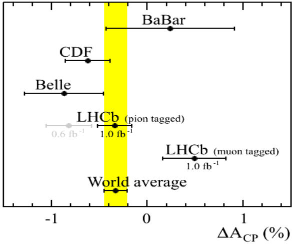

➜ *overall consistent picture*
- slight tension between measurements
- less spectacular CP-asymmetry
- more data on disk . . .

Study of exotic states

➜ *determination of the quantum numbers of the X(3872)*

- exotic state which does not fit into the standard scheme of hadrons
- first observed by Belle: $B^+ \to X(3872)K^+ \to (J/\psi\pi^+\pi^-)K^+$
- quantum numbers limited to $J^{PC} = 1^{++}$ or $J^{PC} = 2^{-+}$ by CDF

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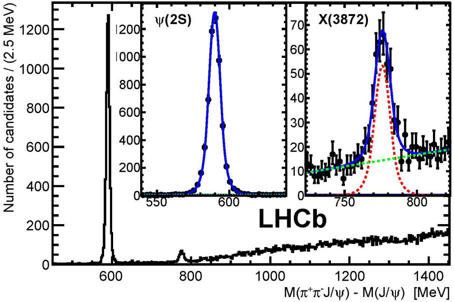
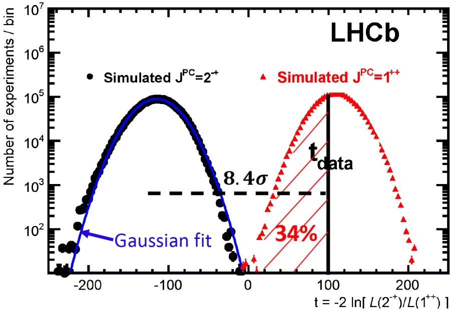


- ➜ clean signal seen by LHCb
- ➜ enough statistics to test quantum number assignments

➜ *likelihood-ratio test to decide between hypotheses*

- full 5-dim space of helicity angles
- test variable $t = -2\ln L(2^{-+})/L(1^{++})$



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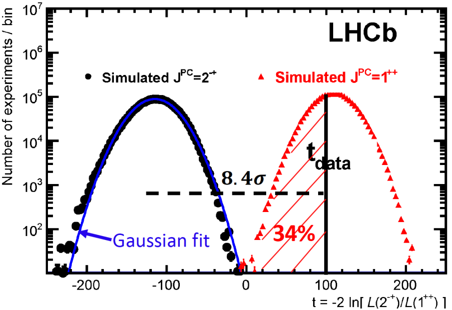
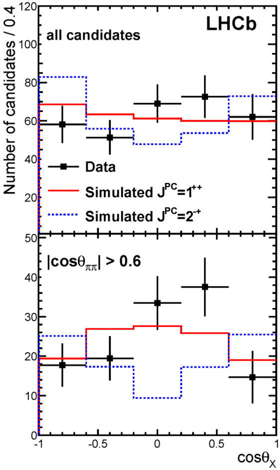


projections on $\cos\Theta_X$



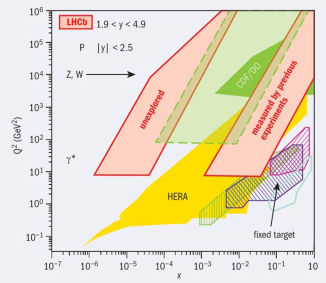
➜ 8-sigma exclusion of $J^{PC} = 2^{-+}$

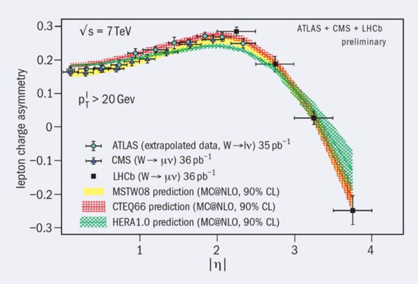
➜ p-value $p = 0.34$ for $J^{PC} = 1^{++}$

➜ study W and Z production

- forward electroweak gauge bosons from high-x – low-x collisions
- large center-of-mass energy allows to reach very low x
- probe parton densities e.g. by W-charge asymmetry

$$A_{\mathrm{ch}}(W) = \frac{\sigma(W^+) - \sigma(W^-)}{\sigma(W^+) + \sigma(W^-)} \sim \frac{\sigma(u\bar{d}) - \sigma(\bar{u}d)}{\sigma(u\bar{d}) + \sigma(\bar{u}d)}$$





➜ *increase integrated luminosity by 1 order of magnitude*

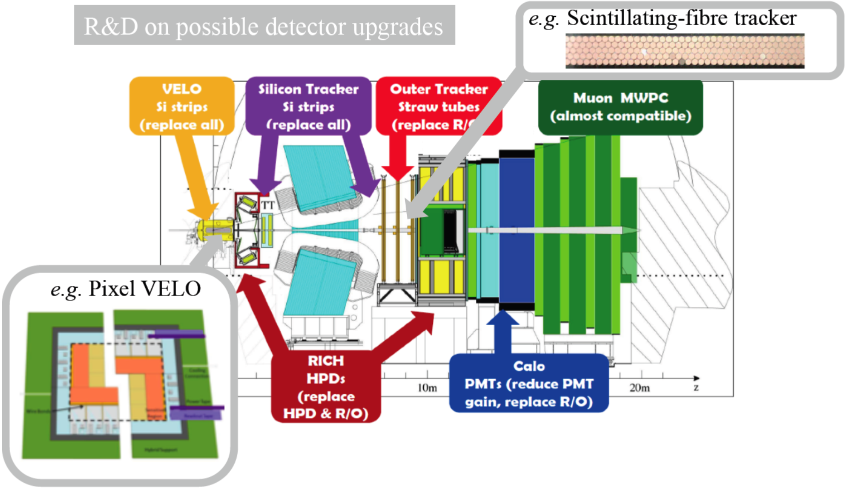
Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\rm fs}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.13 %	0.03 %	0.02 %
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
	$s_0\ A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	8 %	2.5 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	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	$\gamma\ (B \to D^{(*)}K^{(*)})$	$\sim 20^\circ$ [19]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_sK)$	–	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}	–

Framework TDR for the LHCb Upgrade [CERN/LHCC 2012-007]

Modifications to the detector

➜ *40 MHz readout at* $L = 2 \times 10^{33} cm^{-2} s^{-1}$

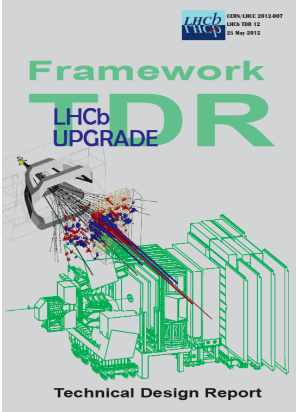
R&D on possible detector upgrades



Timeline

➜ *ambitious schedule*

- 2011 Letter of intent for the LHCb upgrade
- 2012 Framework TDR
  - ➜ CERN/LHCC 2012-007
  - ➜ submitted on May 25, 2012
- 2012-2013 R&D for technical options
- 2013 Subsystems TDRs
- 2014-2016 tendering and production
- 2017 acceptance testing
- 2018 installation during long shutdown LS2
- 2019 data taking with new detector
- 2020- new physics results. . .



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  - ➜ higher than design luminosity and pileup
  - ➜ integrated luminosity $3\,\mathrm{fb}^{-1}$ from Run 1
  - ➜ many ongoing analyses for LS1

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  - ➜ most stringent limits for rare decays
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