The LHCb detector and physics results

Roger Forty (CERN)

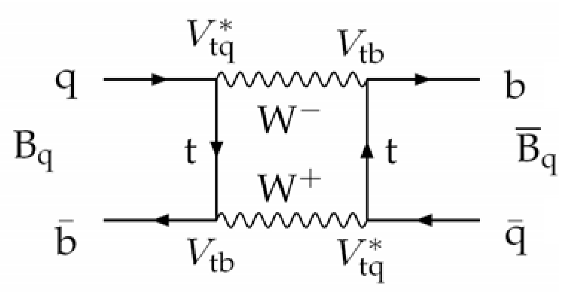
on behalf of the LHCb Collaboration

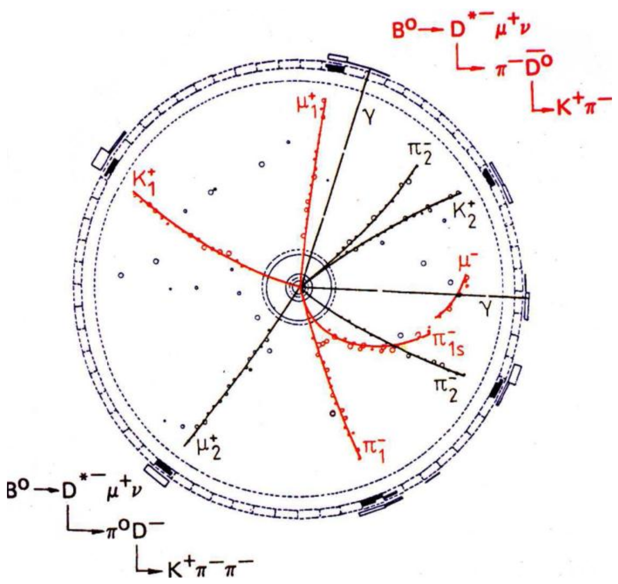
1. The LHCb experiment
2. Detector performance
3. Selected physics results

13th International Conference on Advanced Technology and Particle Physics
ICATPP, Como, 3–7 October 2011

1. The LHCb experiment

- LHCb is the dedicated **flavour physics** experiment at the LHC
- ATLAS and CMS search for the *direct* production of new states
  LHCb is designed to search for the *indirect* effect of such states on **charm** and **beauty** decays via virtual production in *loop* diagrams:





$e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB$

- Such an indirect approach can be very powerful:
  eg B^0–$\overline{B}^0$ mixing discovered at ARGUS (1987)

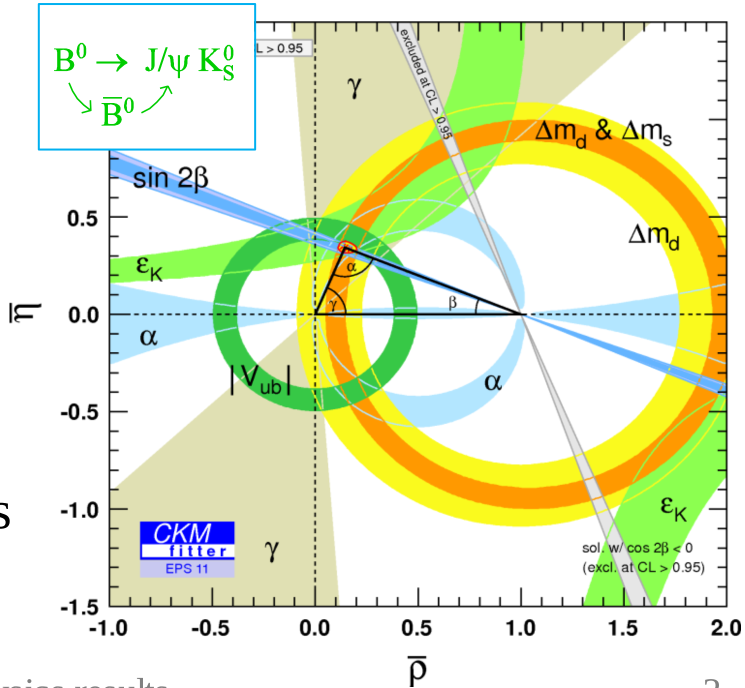
→ top quark unexpectedly heavy: $m(t) > 50$ GeV/c^2

Rare decays such as $B_s \rightarrow \mu^+\mu^-$ occur via similar diagrams: strongly suppressed in Standard Model, may be enhanced by SUSY or other new physics

CP violation

- CP violation arises in the Standard Model in the weak decays of hadrons from a *single* phase in the quark mixing (CKM) matrix
  → precise relationship between all observed CP asymmetries
- Necessary ingredient to generate **matter-antimatter asymmetry** but size in the Standard Model far too small to account for observed baryon/photon ratio → new physics is expected in CP sector
- Large CP effects seen in B decays: *eg*
  $\sin 2\beta = 0.69 \pm 0.02$ from B Factories
- **γ** poorly known: depends on b → u decays
  Much higher statistics available at LHC,
  $\mathbf{B_s}$ sector not yet explored in detail
- CP violation in **charm** not yet observed

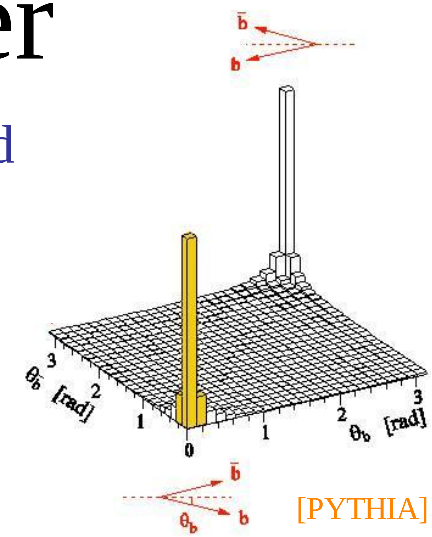
→ CP violation and rare decays of B hadrons and charm are the main focus of LHCb



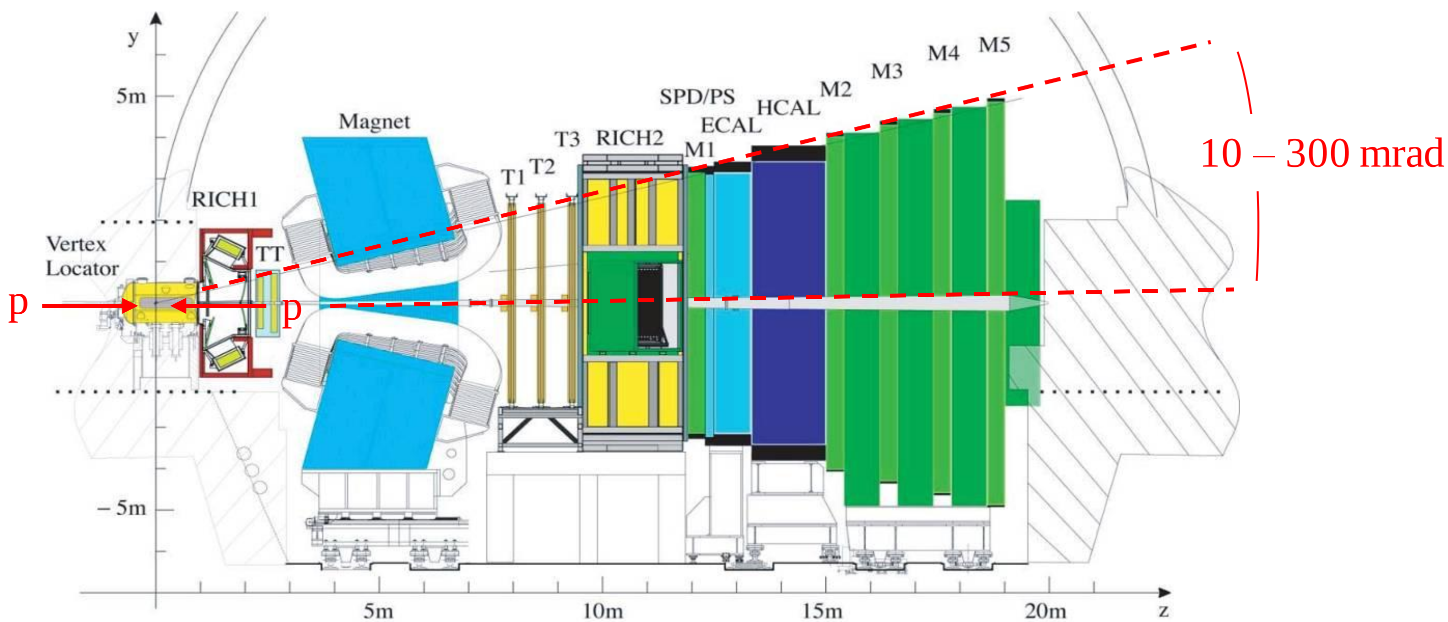
Forward spectrometer

- Forward-peaked production → LHCb designed as forward spectrometer (operating in collider mode)
- $b\bar{b}$ cross-section = 284 ± 53 μb at the LHC (pp collisions at $\sqrt{s}$ = 7 TeV) [PLB **694** 209]

→ ~ 100,000 $b\bar{b}$ pairs produced/second (10^4 × B factories)
Charm production factor 20 higher! [CONF-2010-013]

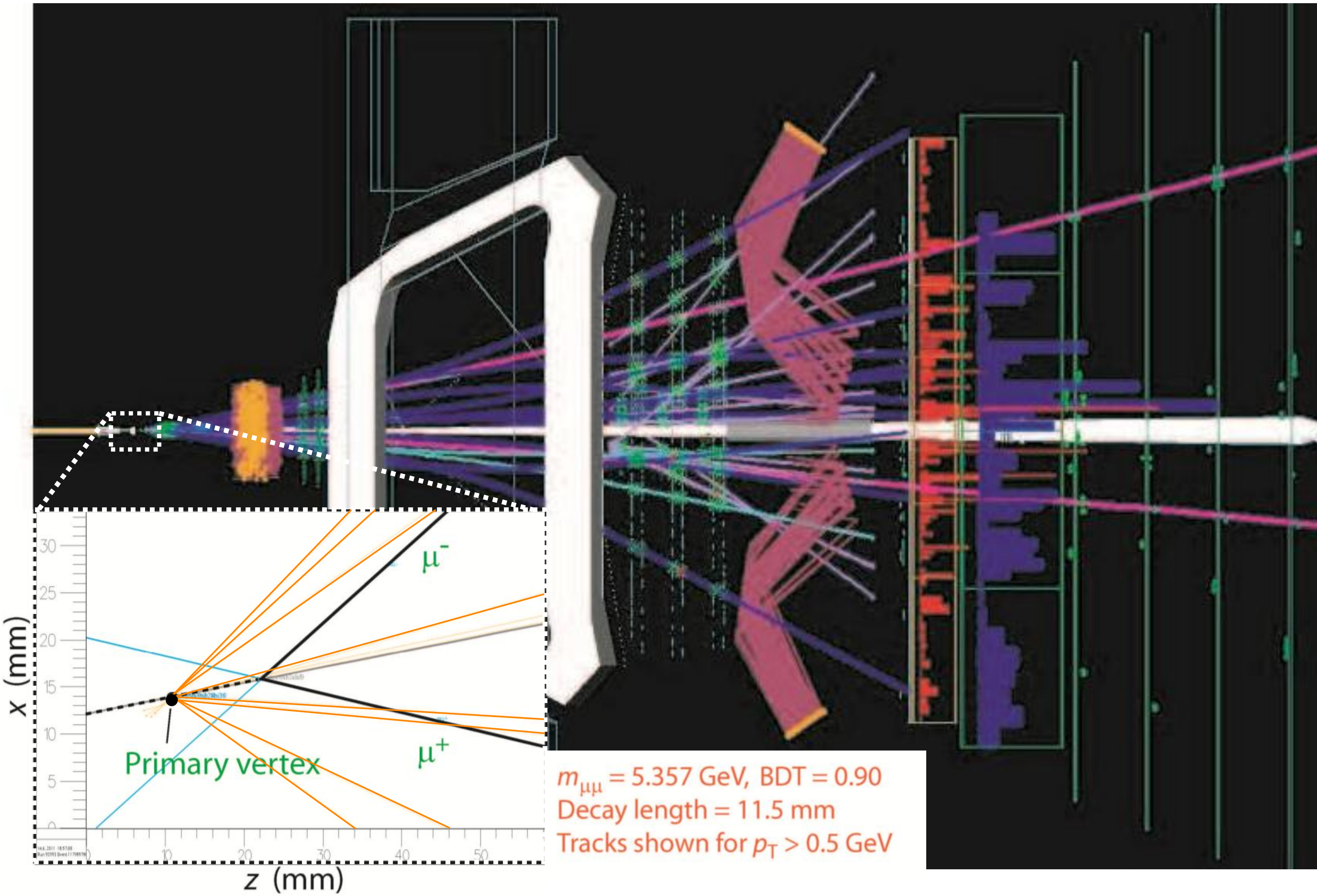


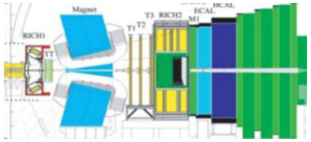
[PYTHIA]



Collaboration

An LHCb event

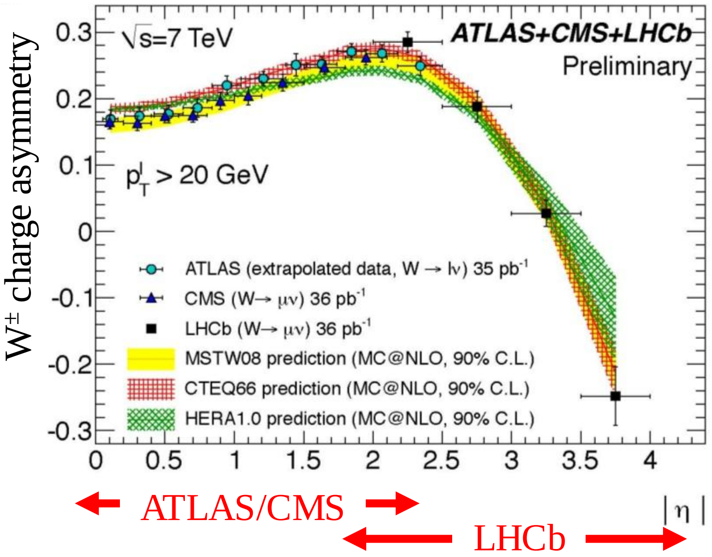




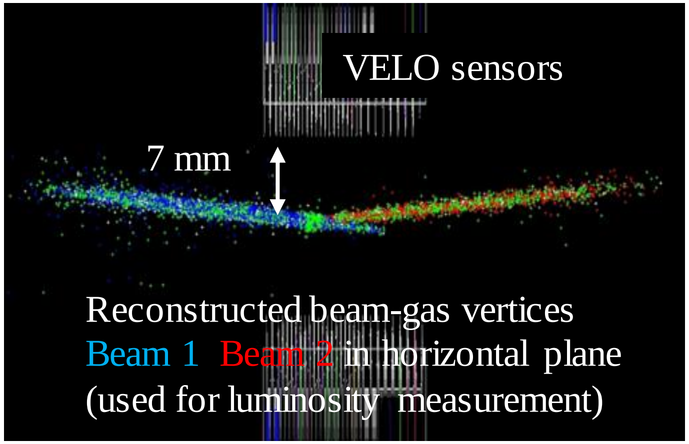
Advantages

- Forward spectrometer configuration gives > 2 × cross-section for b hadrons in LHCb acceptance (2 < η < 5) compared to general-purpose detectors
  Different acceptance interesting
  eg for electroweak and exotic physics
- Allows for planar detectors, easy access for maintenance
  Straightforward implementation of RICH detectors for hadronic PID
- Vertex detector can get very close to beam → very good resolution
- **Disadvantage:** high occupancy and radiation damage close to the beam

→ use high granularity, robust detectors



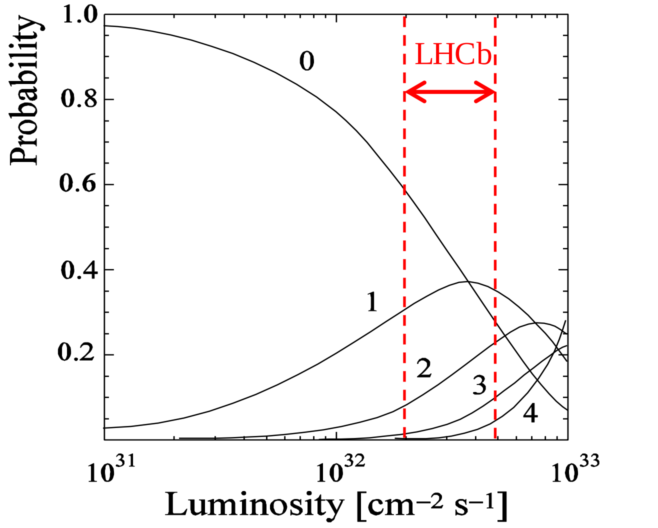
[LHCb-CONF-2011-039]

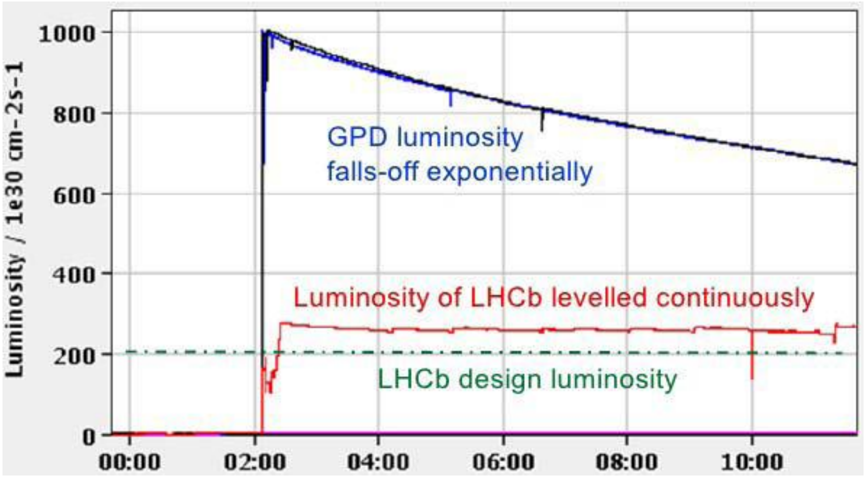


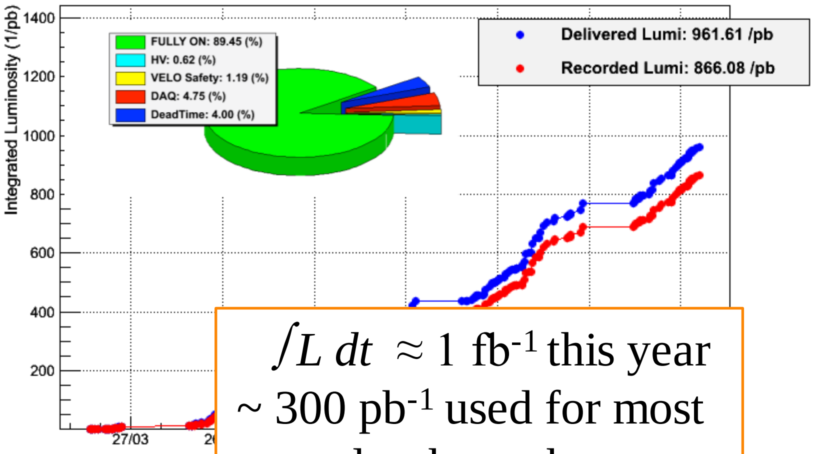
[PLB 693 69]

Data taking

- Nominal luminosity = 2×10^{32} cm^{-2} s^{-1}
  LHC started up in 2010 with few bunches,
  so have adapted to handle higher pileup ($\mu \sim 2$)
- Continuous (automatic) adjustment of offset of colliding beams allows luminosity to be levelled
- Data taken with high efficiency ~ 90%
  Offline data quality rejects < 1%
  Sub-detectors all with > 98% active channels



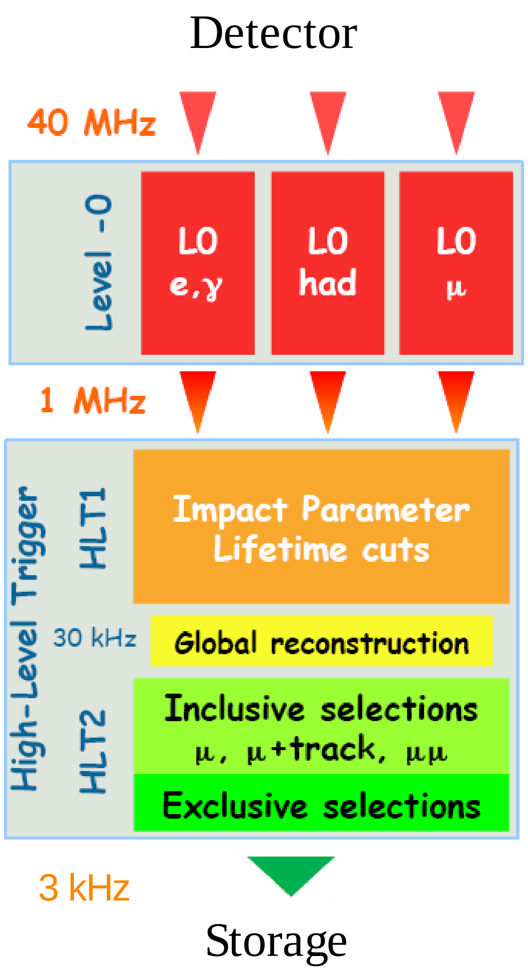




$\int L\,dt \approx 1$ fb^{-1} this year
~ 300 pb^{-1} used for most results shown here

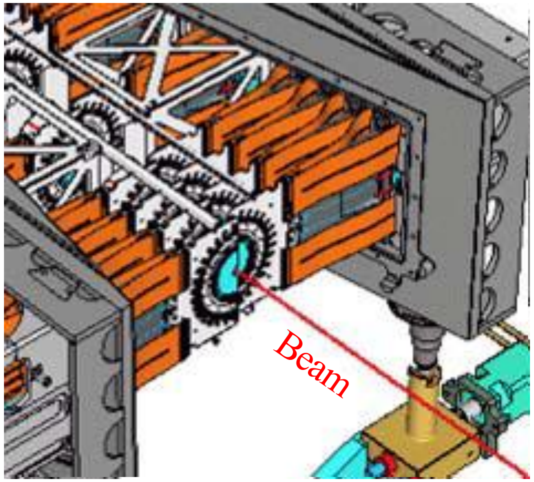
Data processing

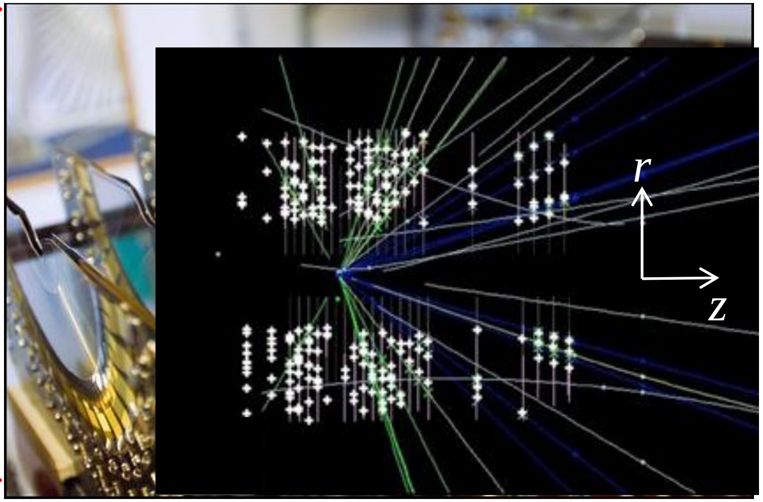
- Sophisticated **trigger** required to reduce data rate
  40 MHz bunch crossing → ~ 3 kHz to storage
  (events are relatively small ~ 35 kB)
- Trigger in two steps: **Level-0** in hardware
  on p_{T} of e, μ, *h* to reduce rate to 1 MHz (in 4 μs)
  Typical thresholds: 1–3 GeV
- Then read out all detectors into large CPU farm
  (1500 nodes) **High Level Trigger** in software
- HLT efficiencies high (> 80 %)
  Typical overall L0 × HLT efficiencies range from
  30 % (multibody hadronic) – 90% (dimuons)
- $O(10^{10})$ events recorded per year
  Requires centralized **stripping** selection to reduce
  to samples of < ~10^7 events for individual analysis
  ~ 600 selections!



2. Detector performance

- **Vertex Locator** (VELO):
  21 modules of back-to-back silicon sensor disks, *R*-ϕ strip geometry
- Must be retracted for safety during beam injection
- 300 µm-thick silicon (*n*-on-*n*)
  2048 strips/sensor, 40 µm inner pitch

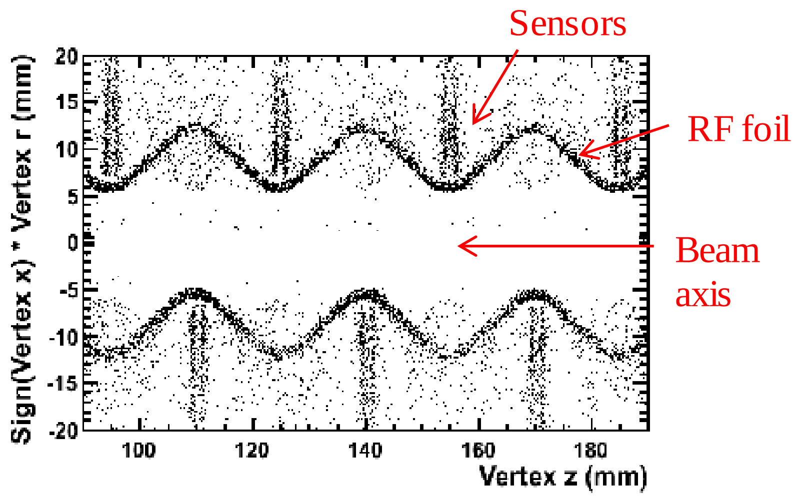




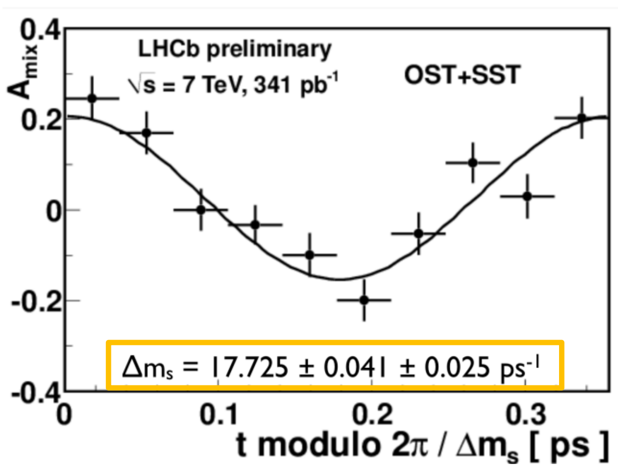
Vertex performance

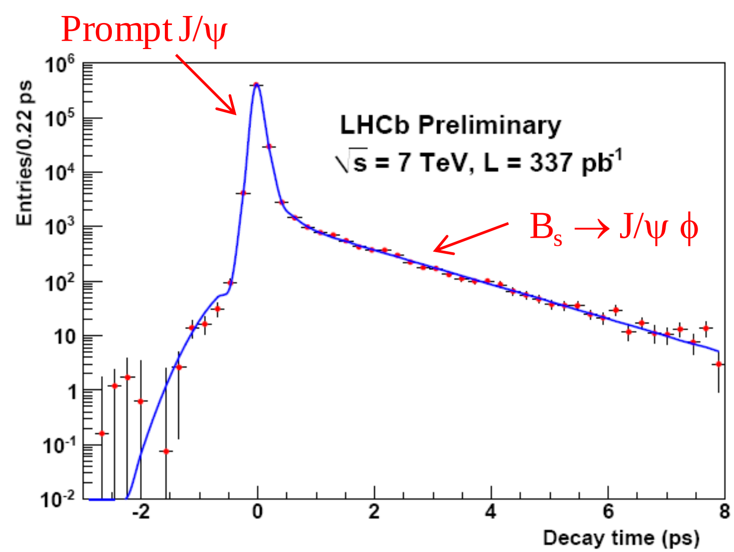
[Alexander Leflat, Justin Garofoli]

- Impact parameter resolution = 12 μm for high p_T tracks. For 25 track vertex: σ_x = 13 μm, σ_z = 70 μm
- Hadronic vertices used to study material, in good agreement with simulation
- Proper-time resolution: σ_t = 40 fs
  B_s–$\overline{B}_s$ oscillations measured:



[LHCb-CONF-2011-50]



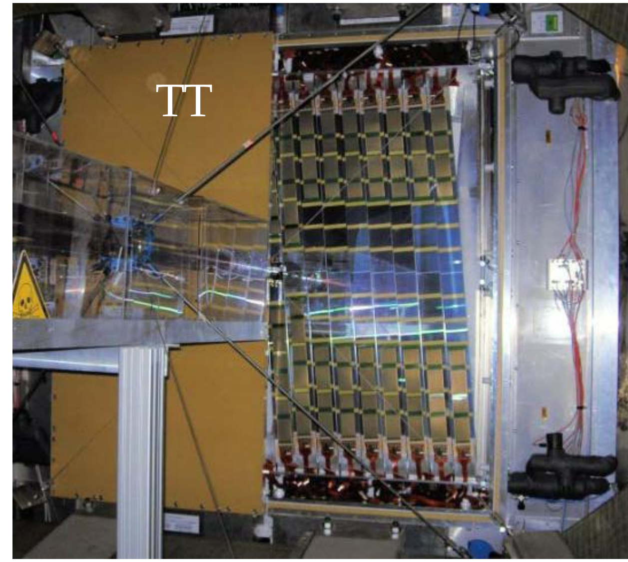


[LHCb-CONF-2011-049]

cf CDF: 17.77 ± 0.10 ± 0.07 ps^{-1} (σ_t = 87 fs) [PRL 97 242003]

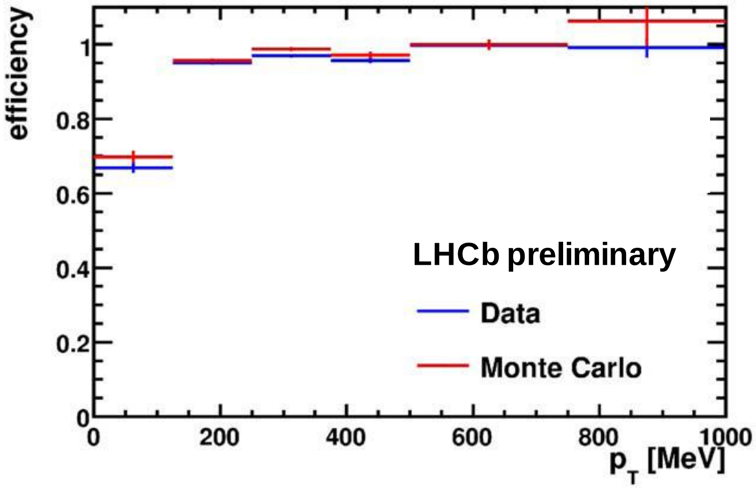
Tracking system

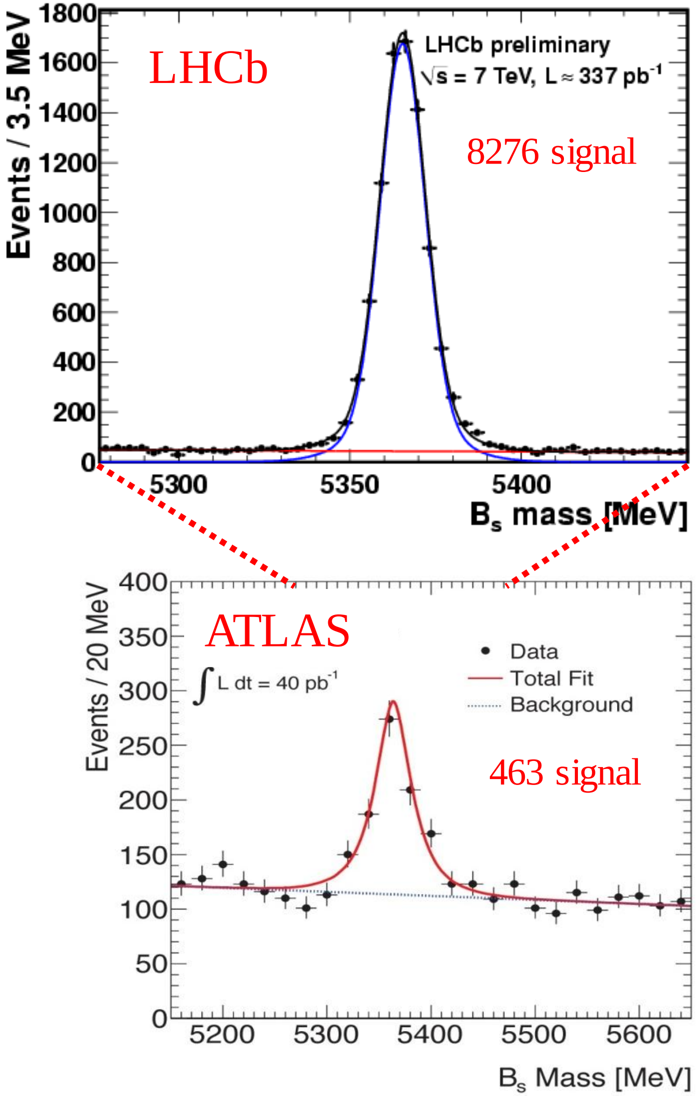
[Mark Tobin, Barbara Storaci, Andreas Jaeger, Raphael Märki]



- Fish-eye view inside dipole magnet: $\int B\, dl$ = 4 Tm, polarity regularly reversed
- Conical beryllium beam pipe
- **TT** and **Inner Tracker**: silicon microstrips ~ 200 μm pitch
  12 m^2 of silicon 4 layers with (0°, +5°,–5°, 0°) stereo angle
- **Outer Tracker**: drift chamber with 5 mm diameter straws
  gas $Ar/CO_2/O_2$ (70:28.5:1.5)

Tracking performance





[LHCb-CONF-2011-049]

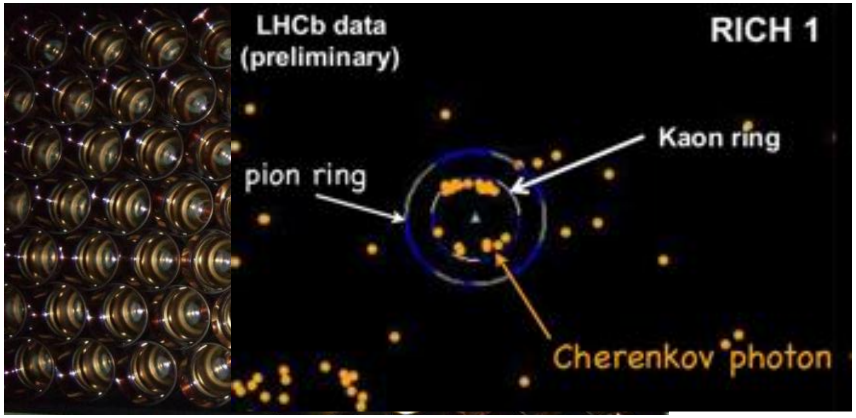
[ATLAS-CONF-2011-092]

- Tag-and-probe with $K_S \to \pi^+\pi^-$
- Momentum resolution: $\Delta p/p = 0.4$–$0.8\,\%$ (2–100 GeV/c)
- $B_s \to J/\psi\,\phi$ signal selection ($J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$)
  $\sigma(m_B) = 7$ MeV/c^2 (LHCb)
  cf ~ 20 MeV/c^2 (ATLAS/CMS)
  yields/pb^{-1} and S/B lower

Particle identification

[Ailsa Sparkes]

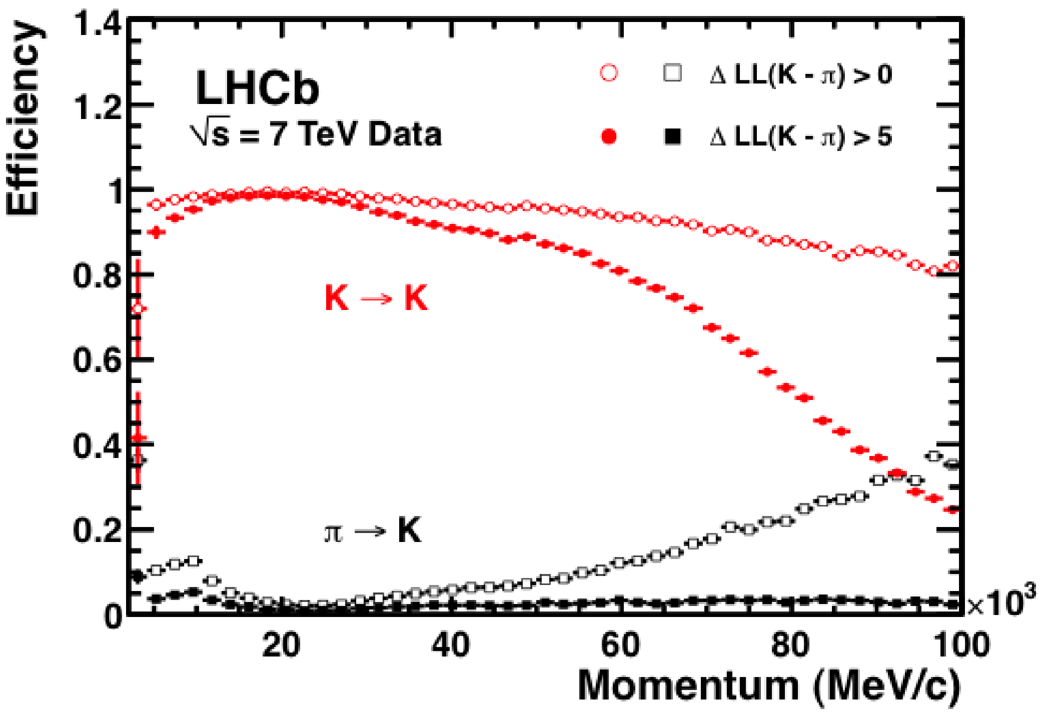
- Charged particles identified with two Ring-imaging Cherenkov detectors covering $2 < p < 100$ GeV/c
- Hybrid Photon Detectors (HPDs) used: 500 tubes each with 1024 pixels
High efficiency: QE = 30% at 270 nm
Low noise: < 1 noise hit/HPD/event
- Cherenkov angle resolution 0.66 mrad per photon achieved (in RICH 2)



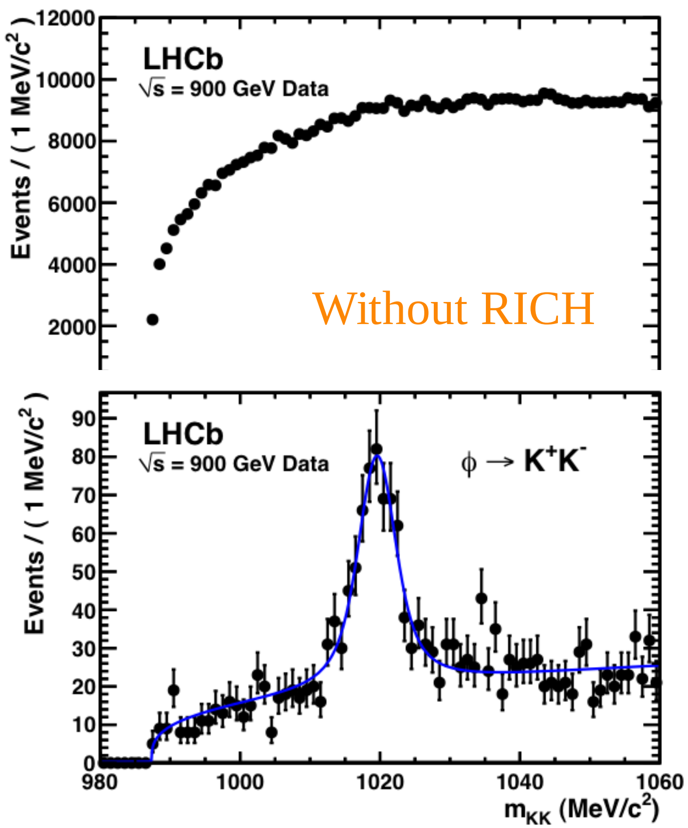
PID performance

- Kaon identification efficiency > 90% for pion misidentification < 5% over a large momentum range

Data

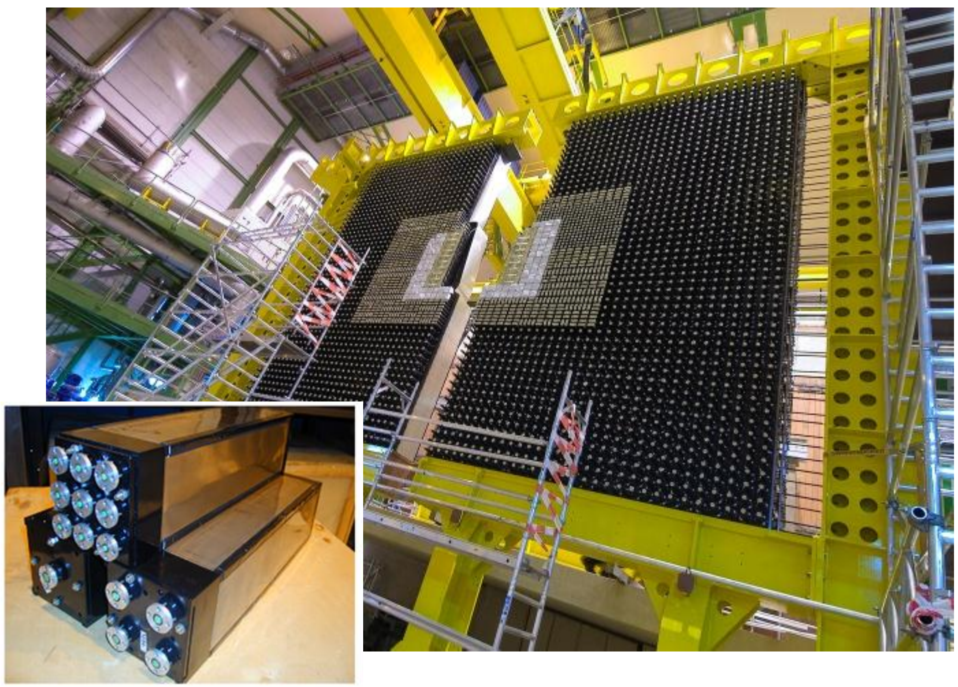


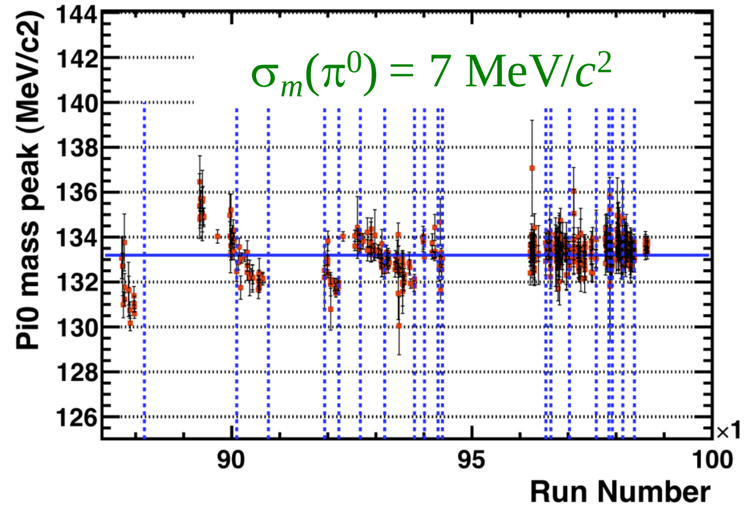
- Allows strong suppression of combinatorial background *eg* for $\phi \to K^+K^-$



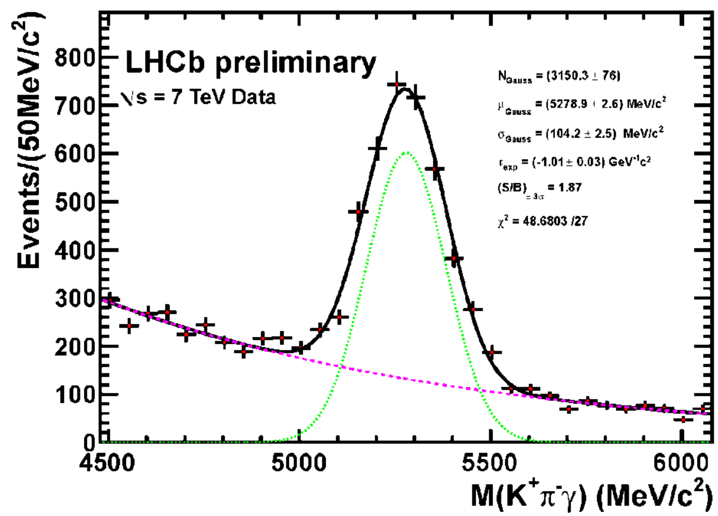
Neutrals

- ECAL: Shashlik Pb-scintillator
  $\sigma(E)/E = 10\% / \sqrt{E} \oplus 1\%$
- HCAL: Tile Fe-scintillator
  $\sigma(E)/E = 80\% / \sqrt{E} \oplus 10\%$
- Calibration to few % with E-flow and π^0



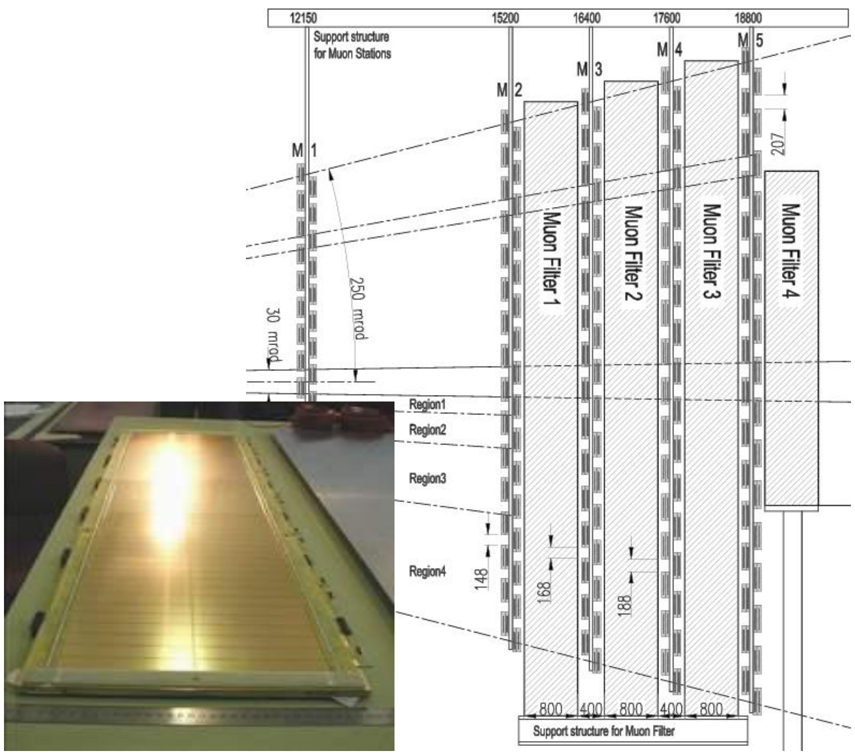


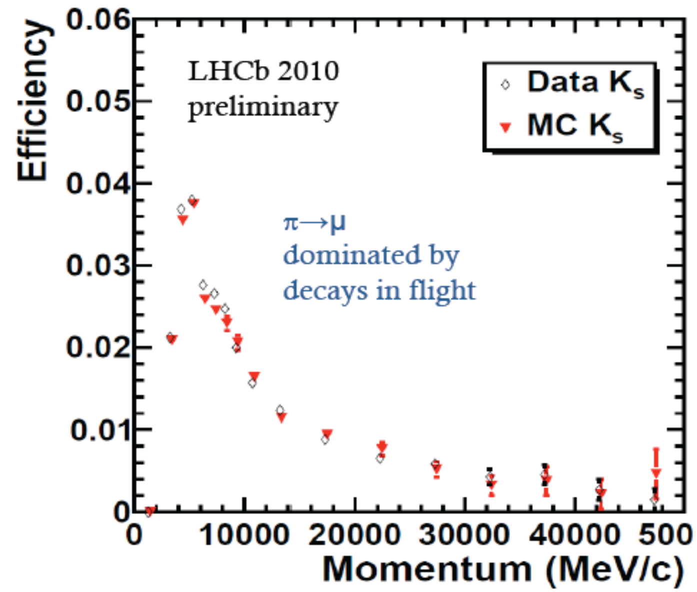
$B^0 \rightarrow K^* \gamma$ ($\sigma_m = 104$ MeV/c^2)

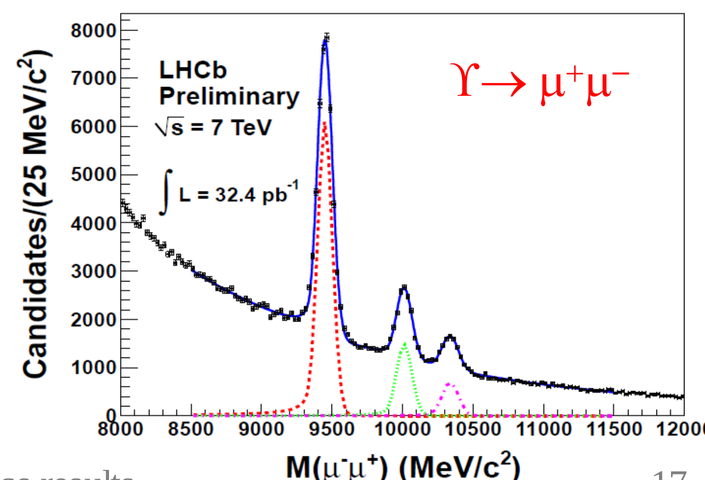


Muon ID

- Muon system: 5 layers of detectors (mostly MWPCs, 3-GEM for highest rate) interleaved with Fe walls
- μ ID eff. ~ 97% for $\pi \rightarrow \mu$ misID rate ~ 1%

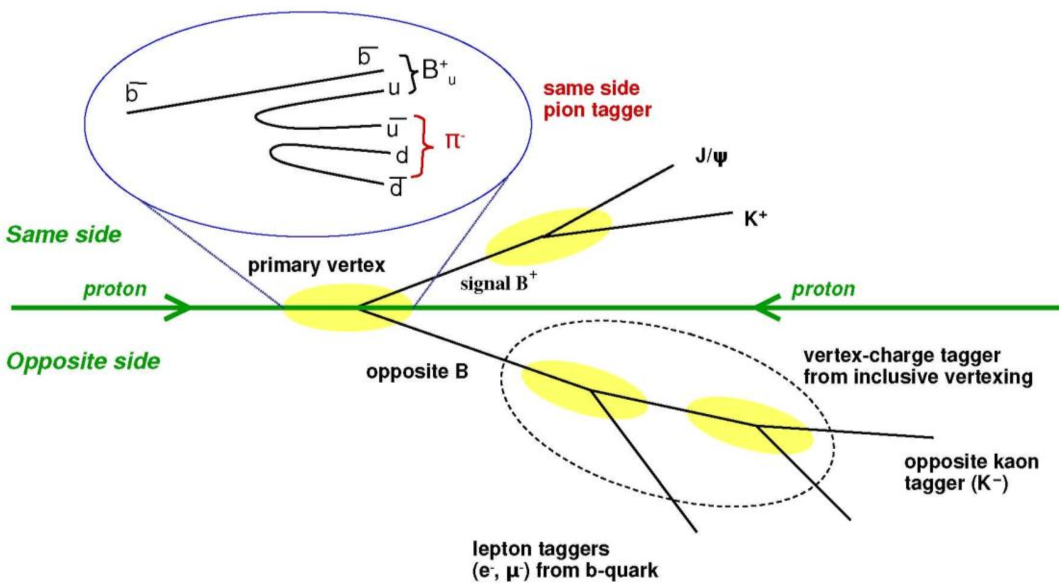


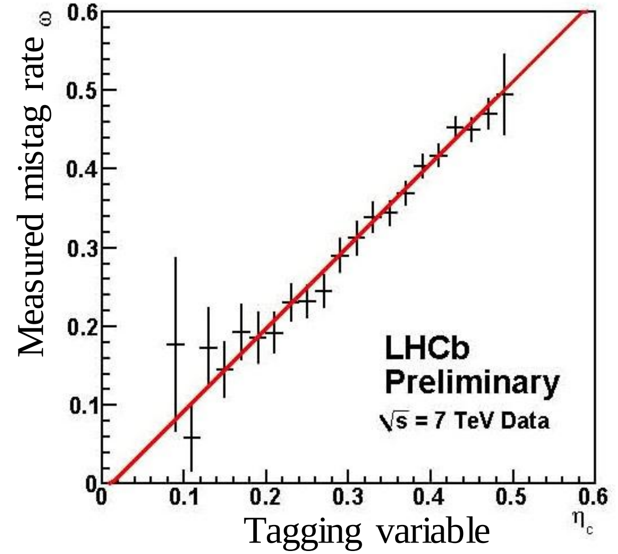


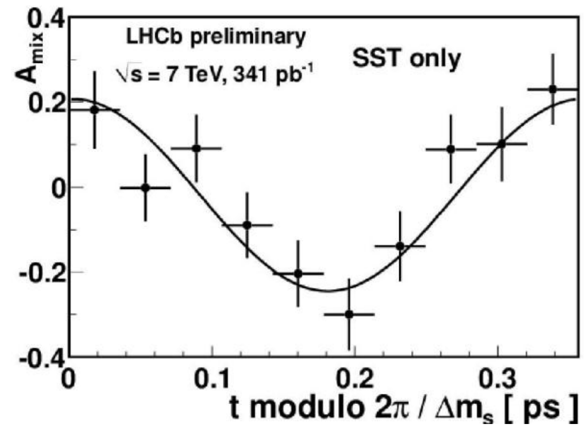


Flavour tagging

- Tagging of production flavour (B or $\overline{B}$) important for mixing and CP analyses
  Performance calibrated using control channels such as $B^+ \rightarrow J/\psi K^+$
- Tagging power: $\varepsilon(1-w)^2$ = (3.2 ± 0.8) % (OS) (1.3 ± 0.4) % (SS) determined with B_s mixing

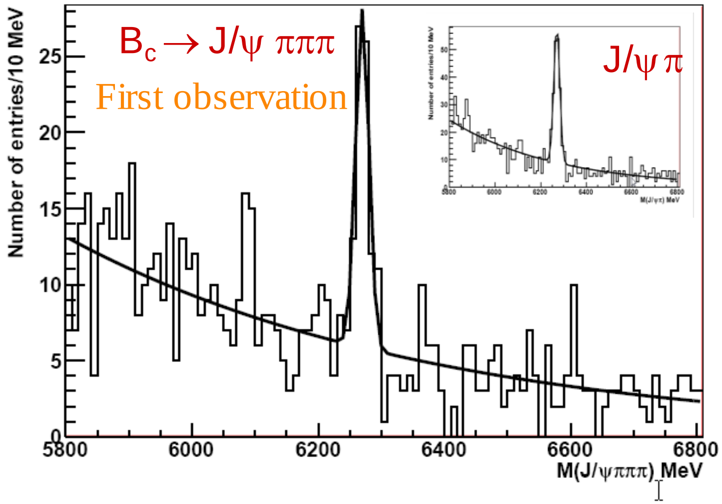


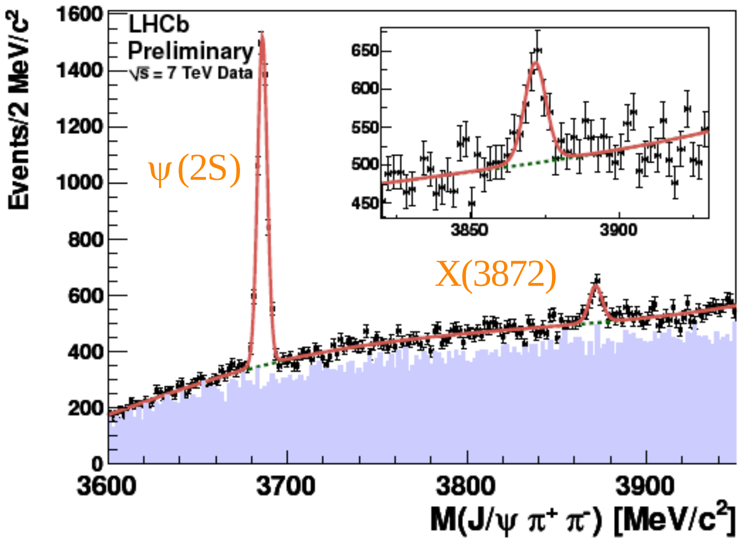




3. Physics results

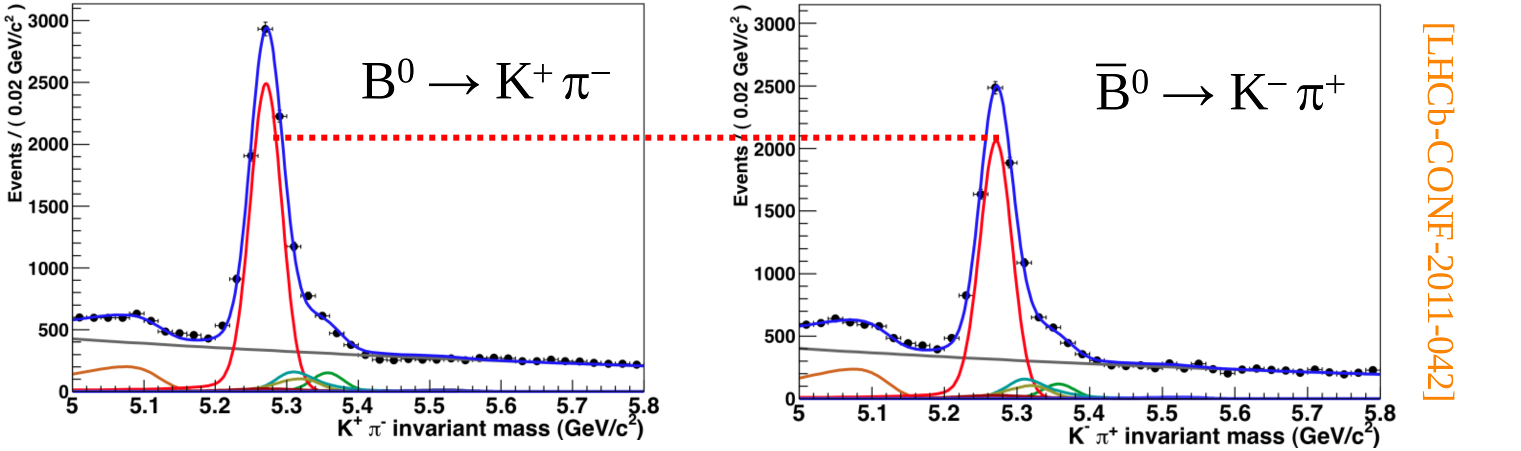
- 59 results from LHCb have been submitted as Conference Papers available at www.cern.ch/lhcb (most will soon be out as journal publications)
- Many results in spectroscopy *eg* B_c decays, exotics such as X(3872), branching ratios, lifetimes…
- Will focus on a few key measurements (for some of which there were previously hints of physics beyond the Standard Model)





Direct CP violation

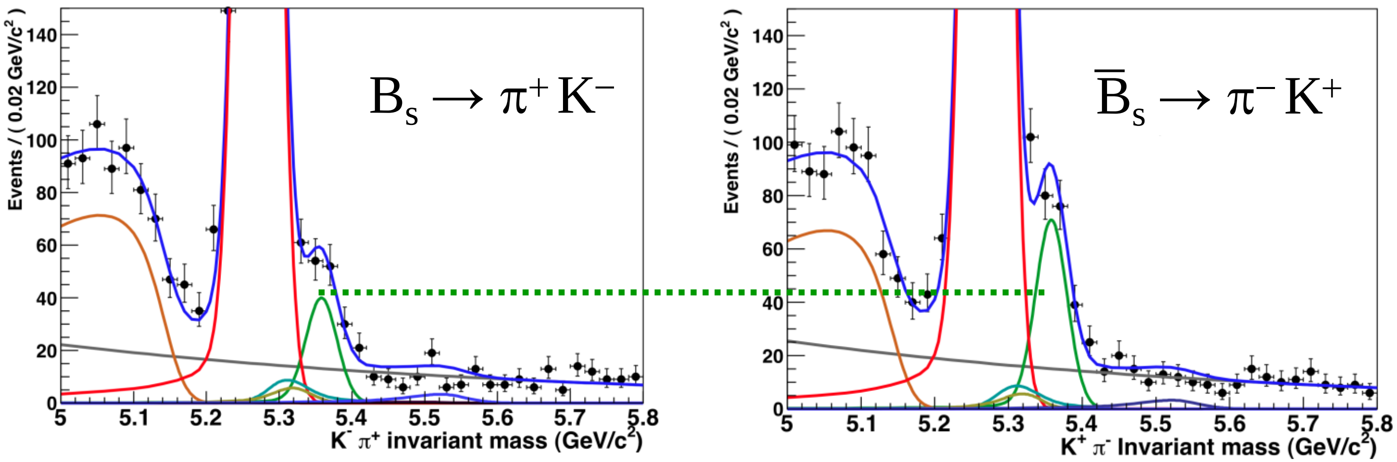
- Using the particle identification capability of LHCb, can isolate clean samples of the different decays contributing to 2-body $B \to h^+h^-$ ($h = \pi$, K, p)
- $B^0 \to K^+\pi^-$: *direct* CP violation (in decay) clearly visible in raw distributions



[LHCb-CONF-2011-042]

- Corrections required for detector and production asymmetries controlled using $D^0 \to K^-\pi^+$, $B^0 \to J/\psi\, K^{*0}$ samples: percent-level effects
- $A_{CP} = \Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)$ / sum = $-0.088 \pm 0.011 \pm 0.008$
  in good agreement with world average: $-0.098 \pm ^{0.012}_{0.011}$
  Most precise, and first 5σ observation of CP violation in hadronic machine

- Adjusting the selection, can enhance the $B_s \rightarrow \pi^+ K^-$ contribution
  $\rightarrow$ First 3σ evidence for CP asymmetry in B_s decays

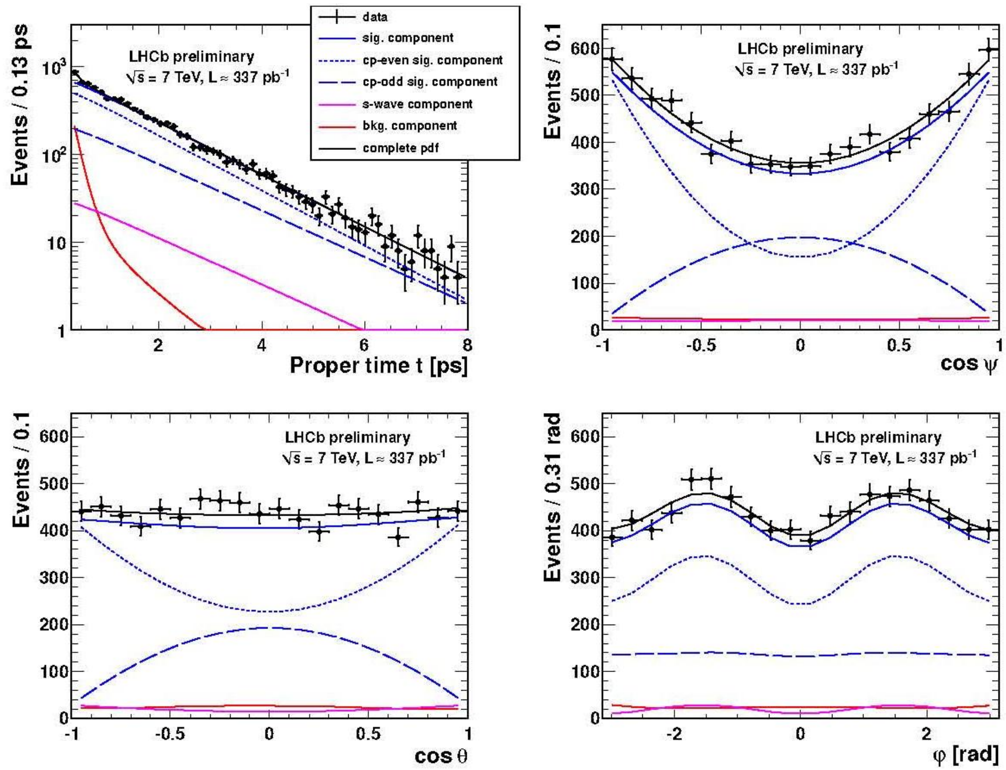


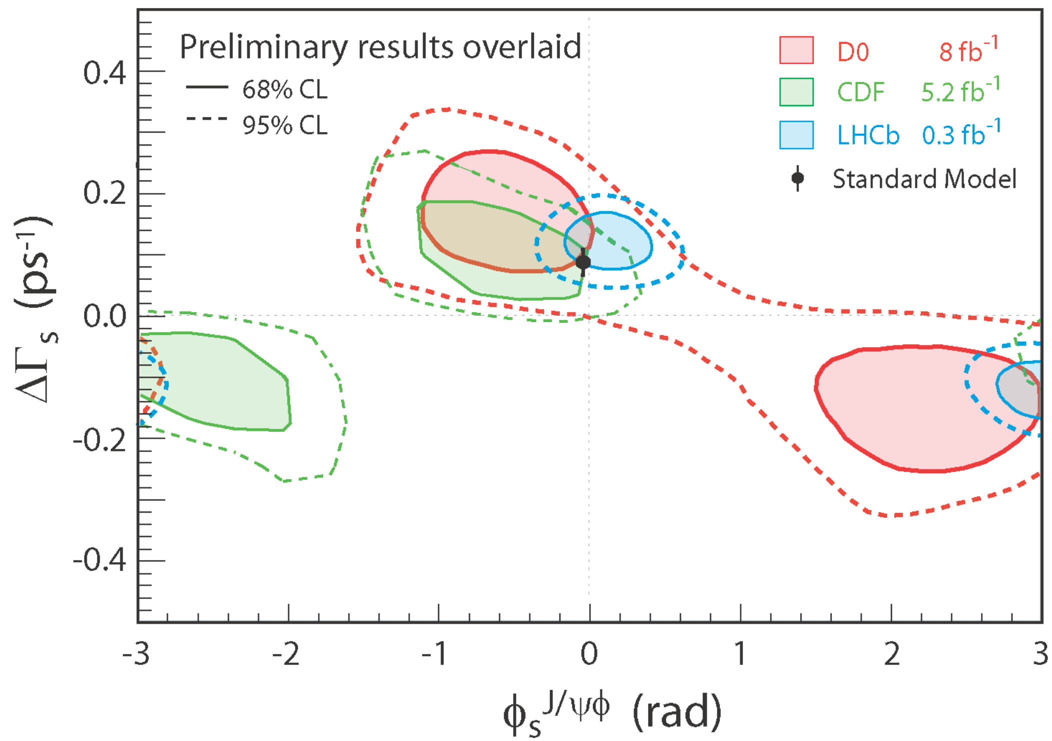
- $A_{CP}(B_s \rightarrow \pi^+ K^-) = 0.27 \pm 0.08 \pm 0.02$
- Eventual goal to measure time-dependent asymmetries *eg* $B_{(s)} \rightarrow \pi^+\pi^-, K^+K^-$
  $\rightarrow$ determine CKM angle γ from *loop* decays
- Compare to many other γ measurement from *tree* decays (*eg* $B_{(s)} \rightarrow D_{(s)}K$)
  $\rightarrow$ determine any contribution from new physics

CPV in B_s mixing

- Analogue of 2β (phase of B^0 mixing) in the B_s system is expected to be very small, and precisely predicted: $\phi_s = -0.036 \pm 0.002$
- First measurements from the Tevatron indicated large values for ϕ_s discrepancy with SM reaching almost 3σ at one point
- Golden mode for this study is $B_s \to J/\psi\,\phi$ (shown earlier)
- VV final state: mixture of CP-odd and CP-even components Separated using an angular analysis

[LHCb-CONF-2011-049]





Results correlated with $\Delta\Gamma_s$ = width difference of the B_s mass eigenstates
$\rightarrow$ plotted as contours in (ϕ_s *vs* $\Delta\Gamma_s$) plane
[reference plots in backup]

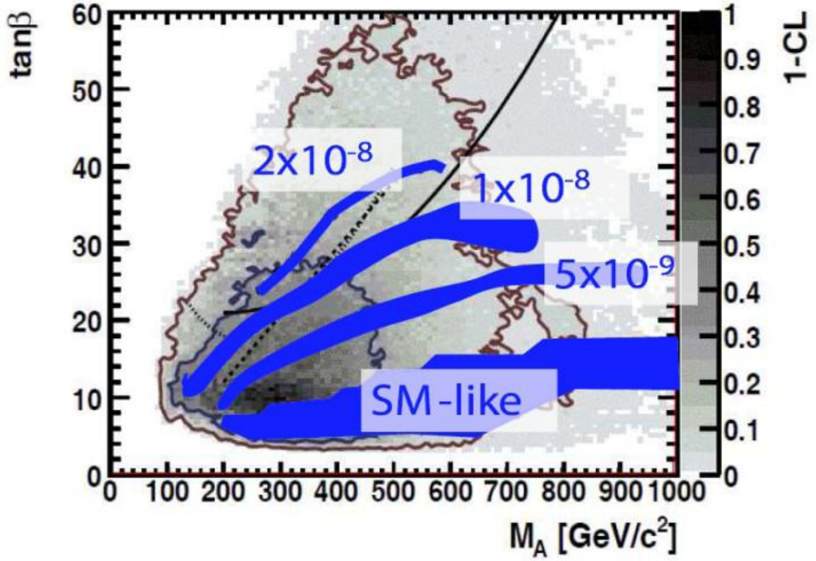
Ambiguous solution for
($\phi_s \rightarrow \pi - \phi_s$, $\Delta\Gamma_s \rightarrow -\Delta\Gamma_s$)

- LHCb result is consistent with Standard Model
  First significant direct measurement of $\Delta\Gamma_s = 0.123 \pm 0.029 \pm 0.008\ ps^{-1}$
- ϕ_s also measured in a second mode: $B_s \rightarrow J/\psi\, f_0$ (first observed in LHCb) with lower statistics but CP-odd final state, so no angular analysis required
- Combined result: $\phi_s = 0.03 \pm 0.16 \pm 0.07$
  Still room for new physics, will continue to improve precision

$B_s \to \mu^+\mu^-$

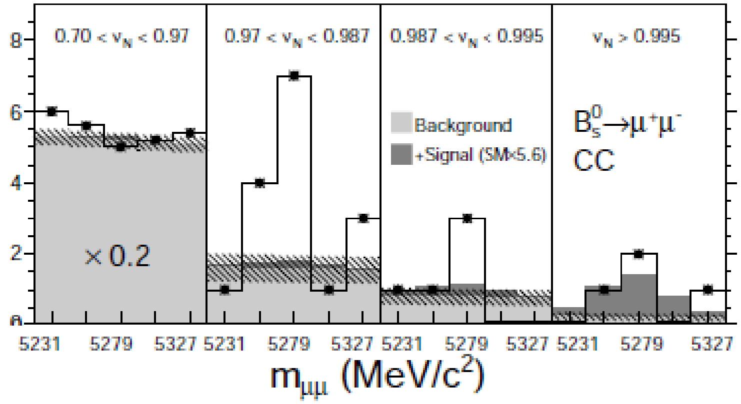
- Decay strongly suppressed in SM
  Predicted BR = $(3.2 \pm 0.2) \times 10^{-9}$
  very sensitive to new physics

SUSY fit [EPJ **C64** 391]

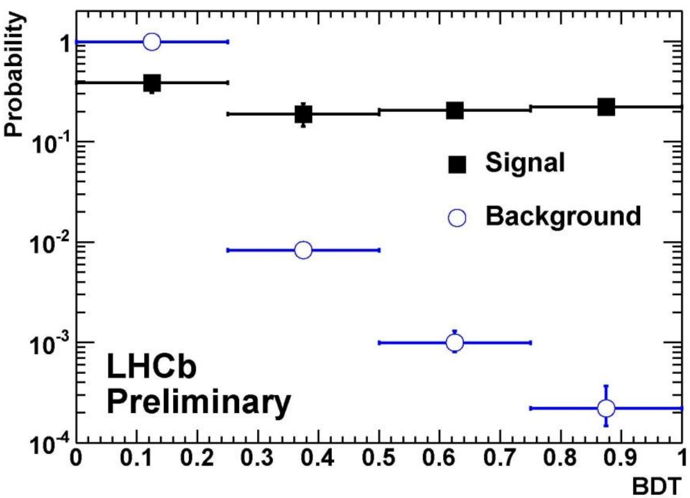


- Recent excitement from CDF showing an excess of a few events, giving
  BR = $(1.8 \pm ^{1.1}_{0.9}) \times 10^{-8}$ (= 5.6 × SM)

[arXiv:1107.2304]



- LHCb selection based on multivariate estimator (BDT) combining vertex and geometrical information



- Mass distribution calibrated using $B \to hh$ and dimuon resonances

  Studied in 4 bins of BDT, expect ~ 1 event in each bin from SM signal

- No significant excess observed
  BR < 1.5×10^{-8} (from 0.3 fb^{-1})
  (Limits quoted at 95% CL)

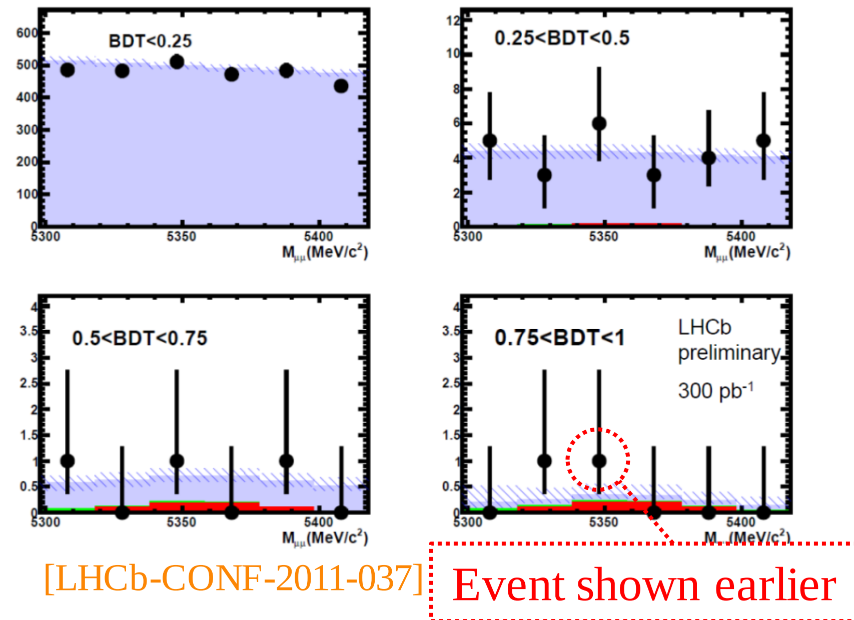
- CMS also set a limit this Summer
  BR < 1.9×10^{-8} (from 1.1 fb^{-1})

  LHCb + CMS analyses combined
  BR < 1.1×10^{-8} (3.4 × SM value)

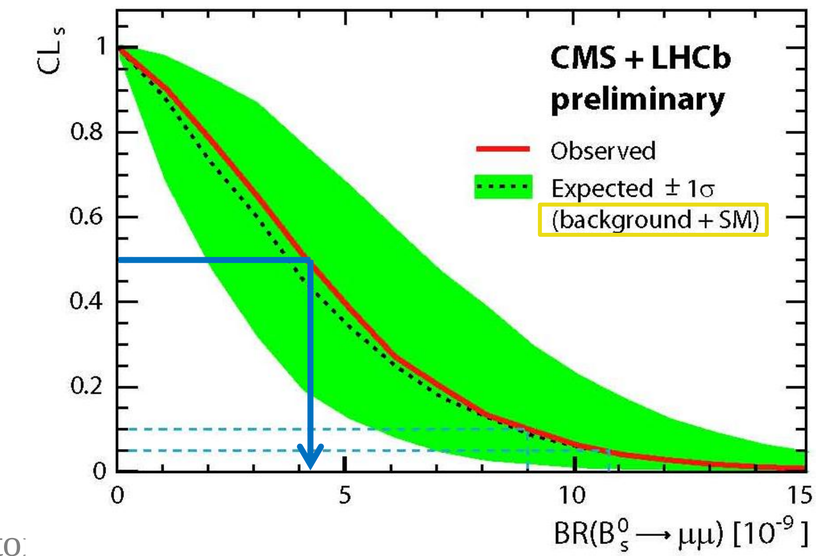
  [CMS-PAS-BPH-11-019, LHCb-CONF-2011-047]

- Most probable value ~ 4×10^{-9}
  Excess over SM not confirmed

$M_{\mu\mu}$ for signal region in 4 bins of BDT



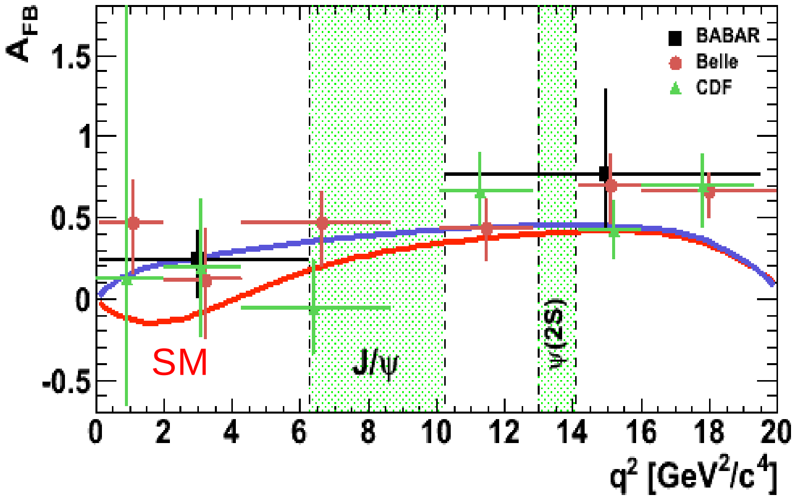
[LHCb-CONF-2011-037]



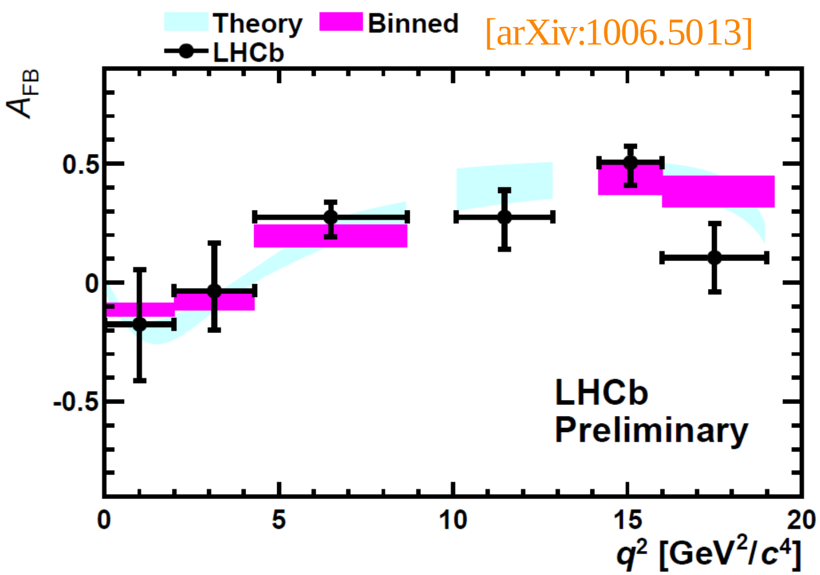
$B^0 \to K^*\mu^+\mu^-$

- Another rare decay (not so strongly suppressed) from related b→s diagram
- Forward-backward asymmetry sensitive to modification of the helicity structure
  Previous results hinted at discrepancy
- LHCb has largest sample in world, as clean as the B Factories!
  $A_{\rm FB}$ consistent with Standard Model

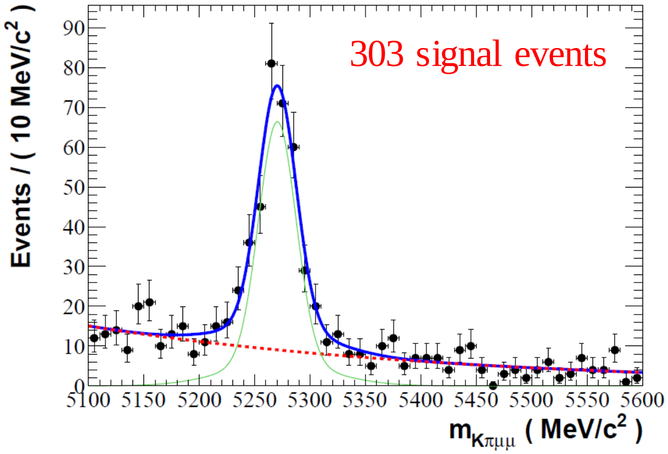
[arXiv:1101.0470]



[arXiv:1006.5013]



[LHCbCONF-2011-038]



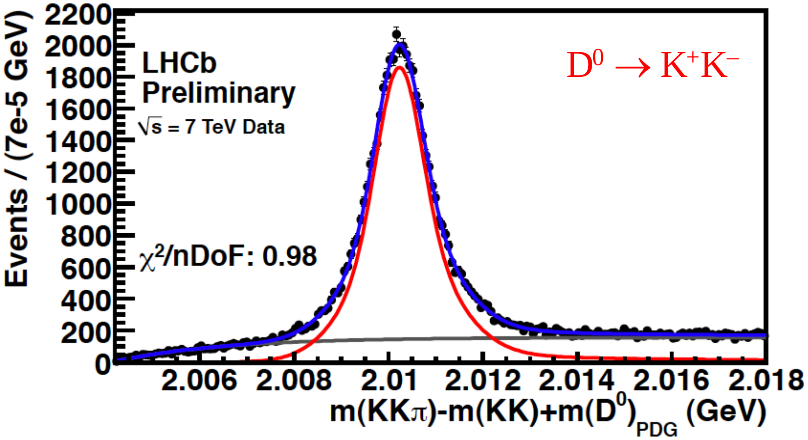
Charm

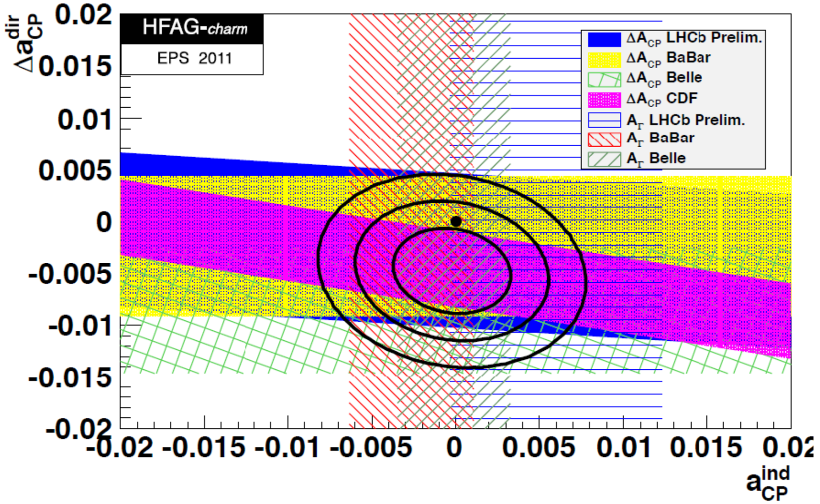
[LHCb-CONF-2011-023]

- D^0 mixing now established (%-level) but CP violation not yet seen in charm
  Expected to be small in the Standard Model (~ 10^{-3} or less)

- Enormous statistics available:
  $> 10^6$ $D^0 \to K^+K^-$ from $D^{*+} \to D^0 \pi^+$
  Charge of π from D^* determines production state of the D^0

- ΔA_{CP} = difference in CP asymmetry for $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$
  Very robust: possible detection and production asymmetries cancel
  First measurement with 30 pb^{-1}:
  $\Delta A_{CP} = (-0.28 \pm 0.70 \pm 0.25)\%$

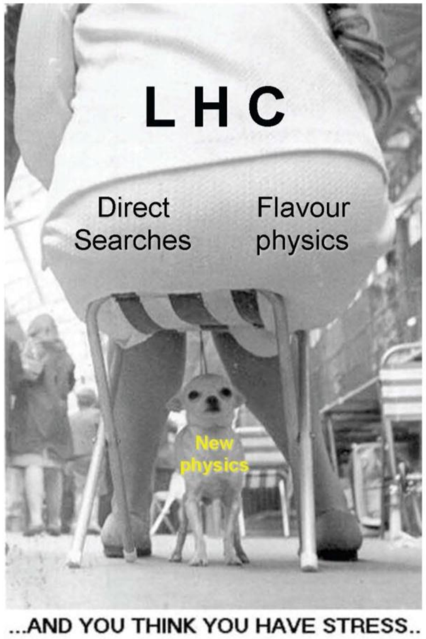




World average for direct CP component = $(-0.48 \pm 0.27)\%$ — update soon!

Conclusions

- LHCb is taking data at the LHC with high efficiency
  - Luminosity above design, 1 fb^{-1} recorded so far
- Detectors working according to specification
  - Excellent mass and time resolution, particle ID…
- World-best measurements of various physics parameters
  - Δm_s, $\Delta\Gamma_s$, ϕ_s, BR($B_s \to \mu^+\mu^-$), masses, lifetimes, etc
    First observations of decays (B_s, B_c, b-baryons)
- So far all in good agreement with the Standard Model
  $\rightarrow$ New physics constrained in the flavour sector
- Still room for new physics, higher precision required…

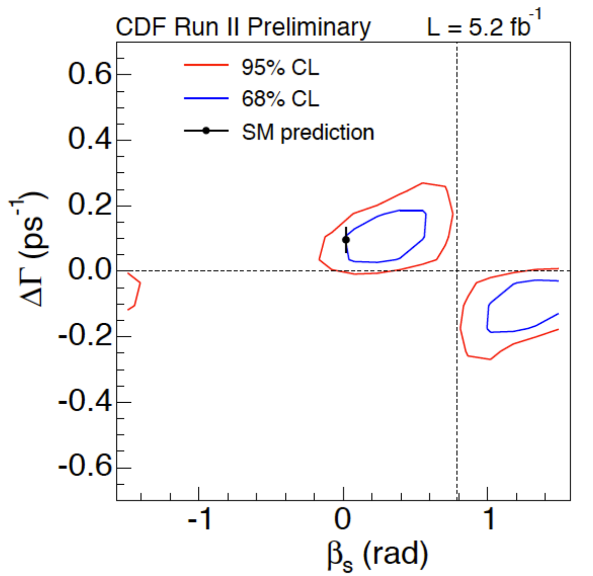


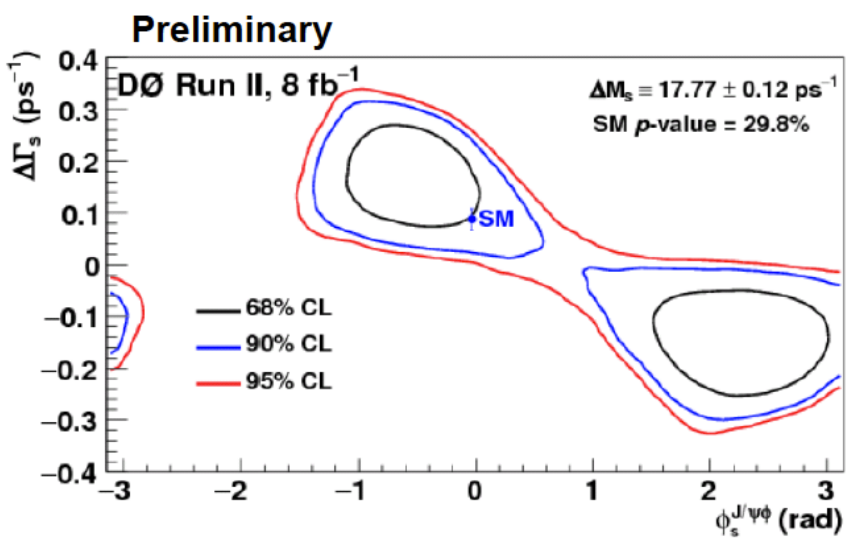
[Vincenzo Chiochia, workshop on Implications of LHC results, CERN, 1 Sep 2011]

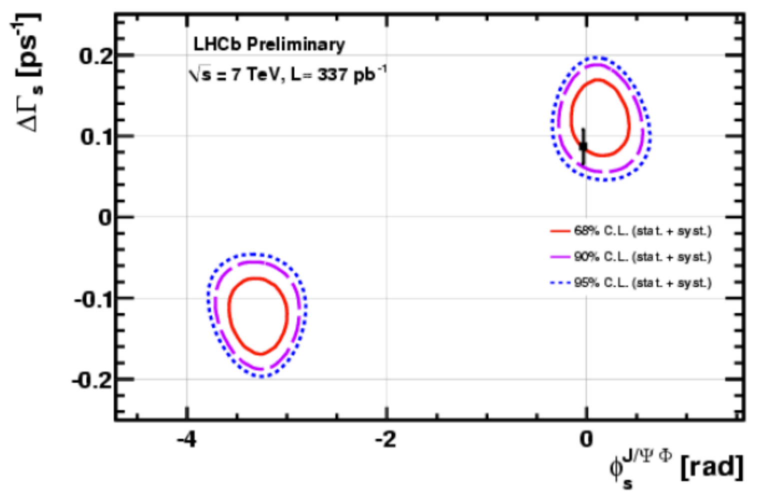
Outlook: LHC run continues in 2012, then 2014-17 at ~14 TeV $\rightarrow \sim 5\ fb^{-1}$
Upgrade of LHCb detector planned for 2018 to take 10× more data: 50 fb^{-1}
Much more to come!

Additional slides

- Original plots from the three experiments overlaid earlier, after converting to $\phi_s = -2\beta_s$ and wrapping $\phi_s < -\pi \rightarrow \phi_s + 2\pi$
  - D0: S.Burdin, EPS 2011 conference
  - CDF: Public Note 10206
  - LHCb-CONF-2011-049

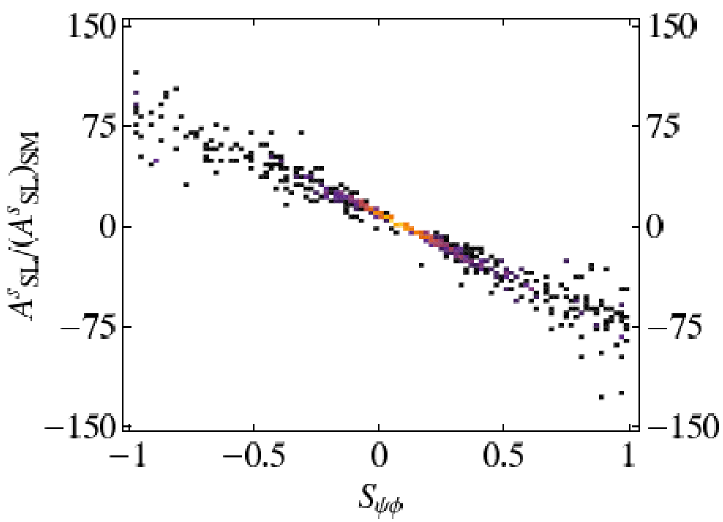




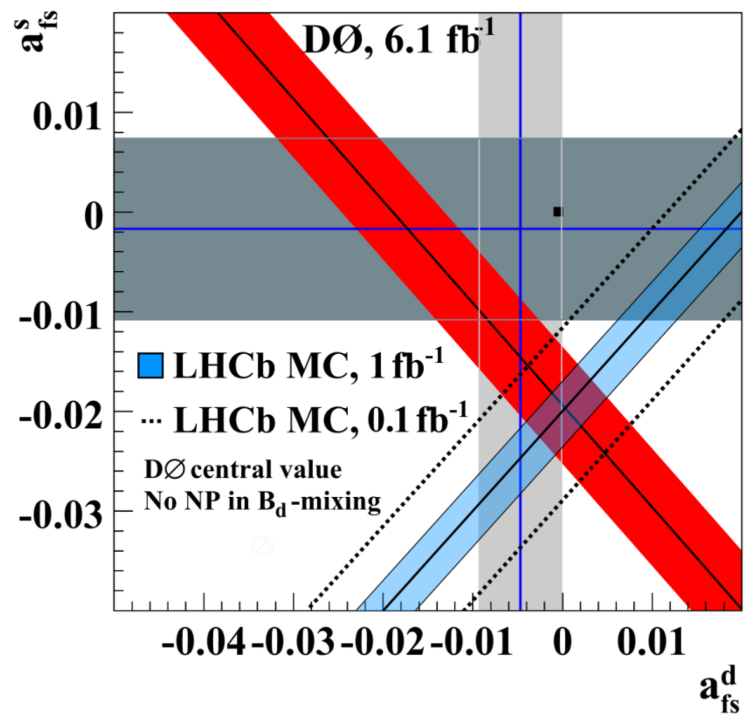


A_{SL}

- Strong interest in semileptonic (or flavour-specific) asymmetry due to D0 result for dimuon asymmetry (comparing # of $\mu^+\mu^+$ and $\mu^-\mu^-$ events)
  $A_{SL} = (-9.57 \pm 2.51 \pm 1.46) \times 10^{-3}$ [arXiv:1005.2757] (expect $< 10^{-3}$ in SM)
- Same approach difficult at pp machine due to production asymmetries
  Instead use semileptonic decays, $B_{(s)} \to D^+_{(s)} (K^+K^-\pi^+) \mu^- X$
  Result from LHCb expected soon
- **Note:** if A_{SL} *is* large, expected to see large ϕ_s in most models



[arXiv:0910.1032]



LHCb Upgrade

- Main limitation that prevents exploiting higher luminosity is the Level-0 (hardware) trigger
- To keep output rate < 1 MHz requires raising thresholds → hadronic yields reach plateau
- Proposed upgrade is to *remove* hardware trigger read out detector at 40 MHz (bunch crossing rate) Trigger fully in software in CPU farm
- Will allow to increase luminosity by factor ~ 10 to 1–2 × 10^{33} cm^{-2} s^{-1} (available from LHC)
- Requires replacing front-end electronics Planned for the long shutdown in 2018 Running for 10 years will then give ~ 50 fb^{-1}
- Letter of Intent recently submitted to the LHCC Physics case endorsed, detector R&D underway (*eg* scintillating-fibre tracking, TOF, …)