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LHCb Physics, Performance, Prospects

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on behalf of the LHCb collaboration

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- Short physics motivation
- **Brief introduction to the LHCb experiment**
- Some words on operational experience
- **A few selected results from 2010 data taking**
- Outlook for 2011 and beyond

CKM Matrix and Unitarity Triangle

- quark mixing in charged-current interactions

$$L_{cc} = \frac{g}{2\sqrt{2}} \cdot \bar{u}_i \cdot \gamma_\mu (1-\gamma_5) \cdot V_{ij} \cdot d_j \cdot W^\mu$$

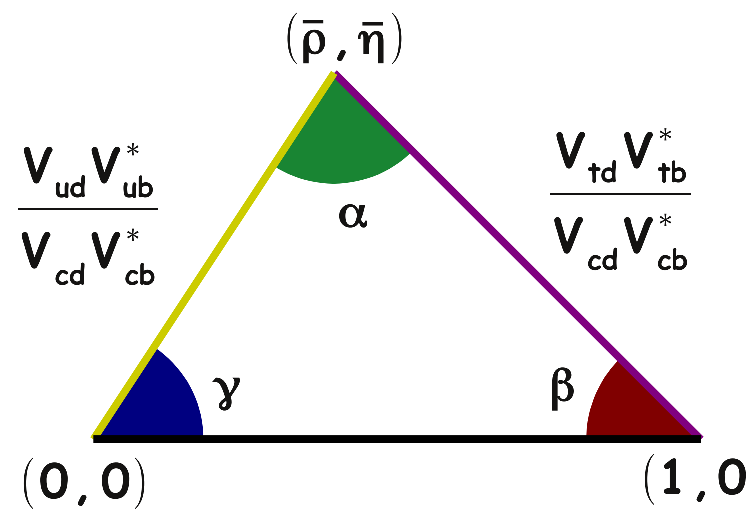
$$V_{ij} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- 3 quark families → 4 independent parameters

  3 rotation angles + 1 complex phase

- source of all CP violation in Standard Model
- unitarity implies 6 orthogonality conditions
  - 6 "unitarity triangles" in complex plane
- THE Unitarity Triangle from 1st and 3rd row:

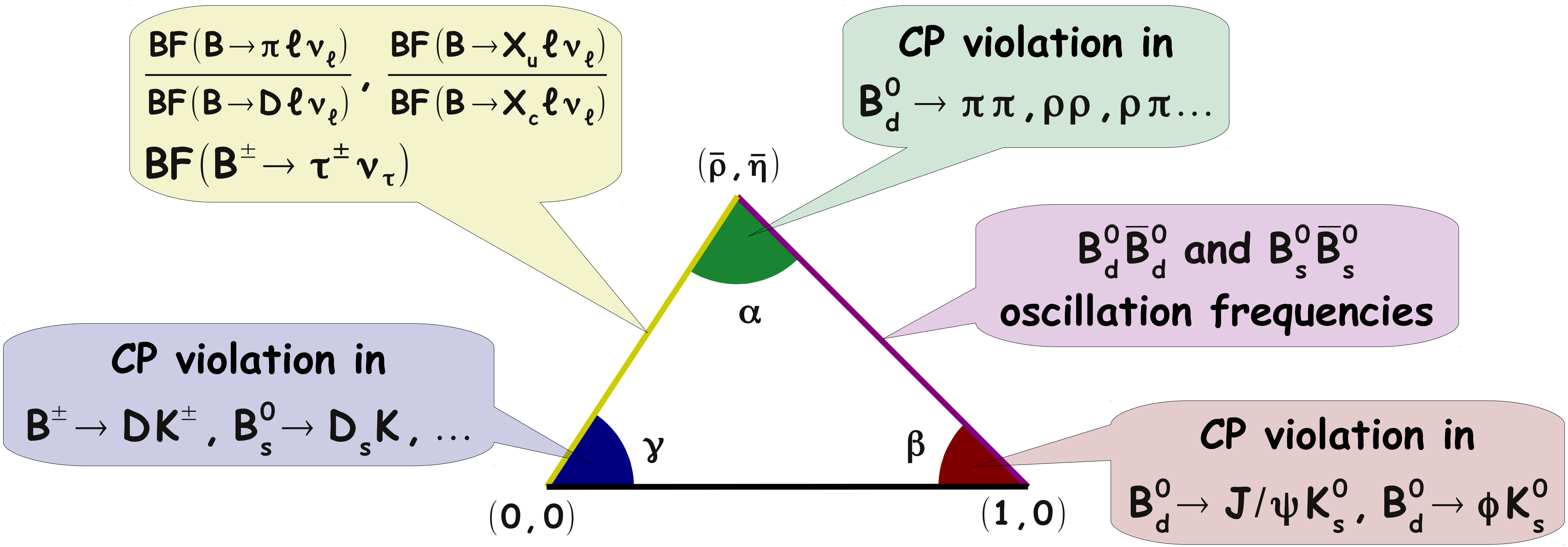
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



- sides and angles of Unitarity Triangle can be precisely determined from various observables in B meson systems: $B^+ = (u\bar{b})$, $B^0_{(d)} = (d\bar{b})$, $B^0_s = (s\bar{b})$ + cc.

Unitarity Triangle from B decays

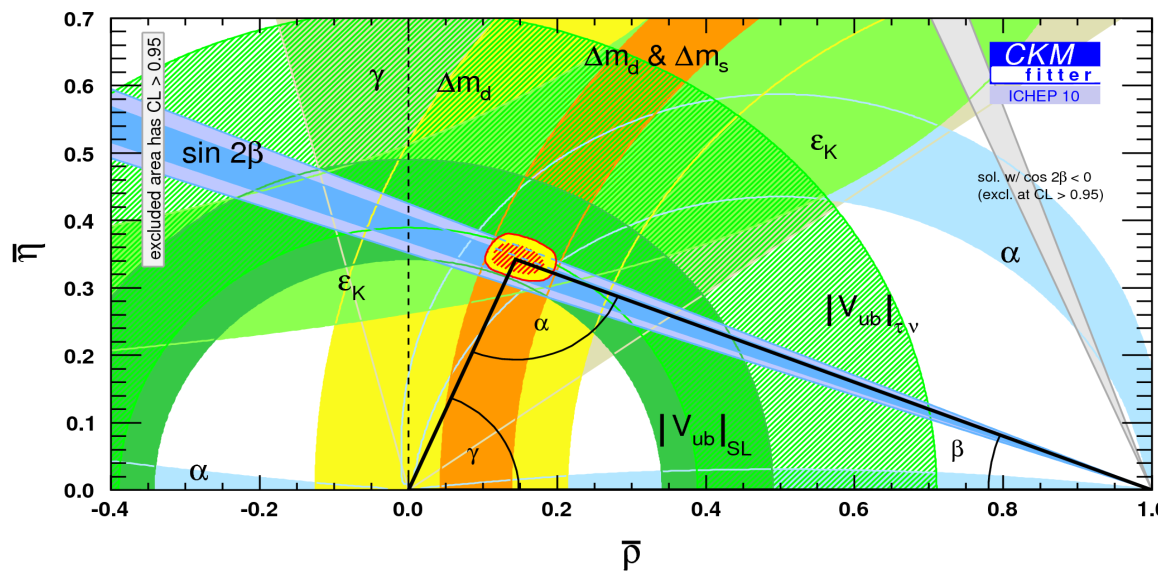
- many observables (just showing some of the more interesting ones):



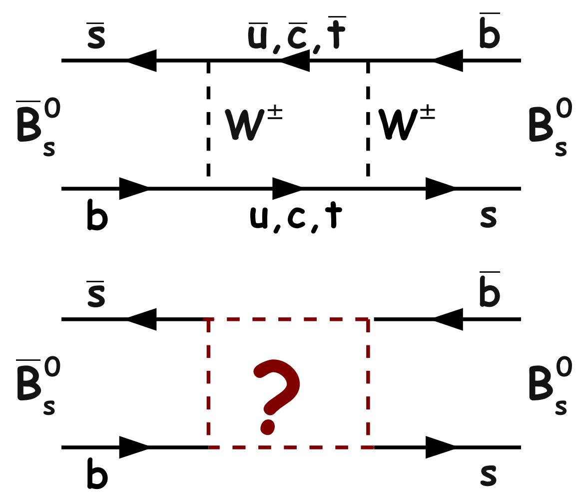
- over-constrained determination of Unitarity Triangle
- inconsistencies would be sign for New Physics beyond the Standard Model
- pattern of deviations can hint at underlying dynamics of the New Physics

Status 2010

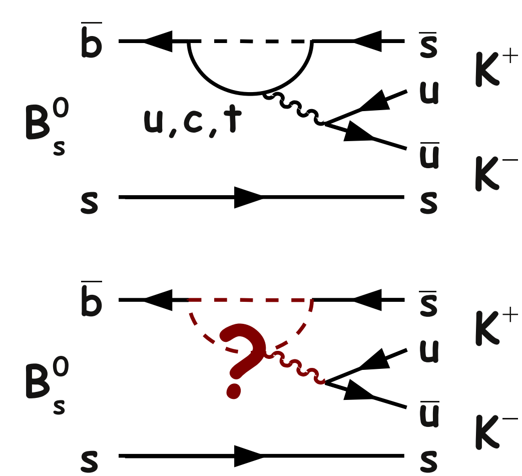
- many beautiful measurements at B factories (BaBar, Belle) and Tevatron (CDF, D0)
- all results consistent with Standard Model predictions → CKM dominant source of CP violation in quark sector
- measurement precision permits New Physics at ~10% level
- loop-mediated processes: new heavy particles can change amplitudes and phases
- potential for indirect discovery of new particles to masses far in excess of LHC energy



Box Diagrams



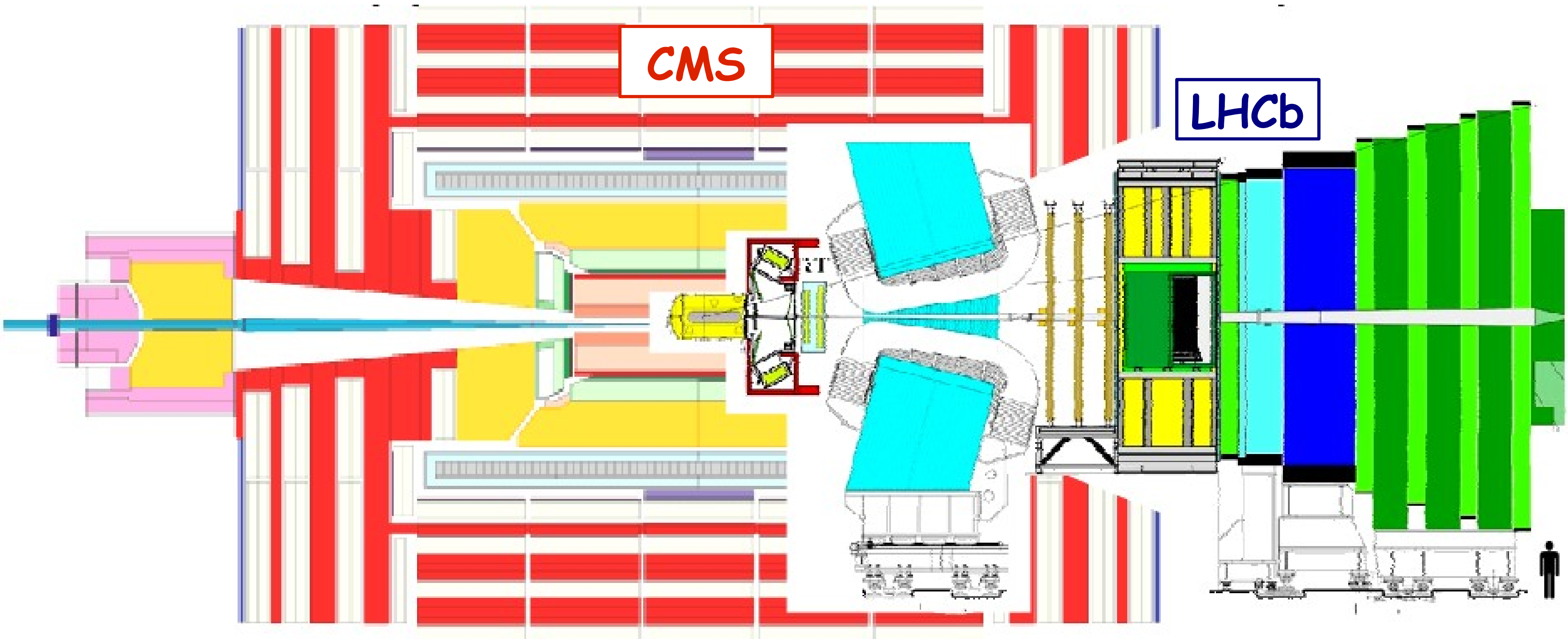
Penguins



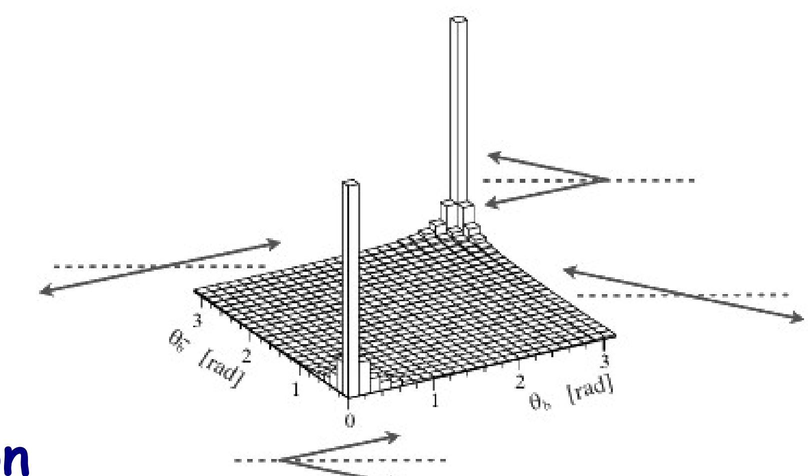
LHCb Physics Programme

- main goal: perform precision measurements of CP violating phases and rare heavy-quark decays
- special emphasis on observables with large sensitivity to New Physics
  - improve consistency tests of Unitarity Triangle
    - precision on CKM angle γ
  - compare processes with different sensitivity to New Physics
    - γ from Penguins & γ from Trees
  - observables that are predicted to be small in the Standard Model
    - $B_s^0 \overline{B}_s^0$ mixing phase, rare B decays
- exploit the large $\overline{b}b$ production cross section at the LHC
  - 290 µb at 7 TeV vs. 100 µb at Tevatron vs. 1 nb at B factories
- dedicated setup, fully optimized for its physics programme

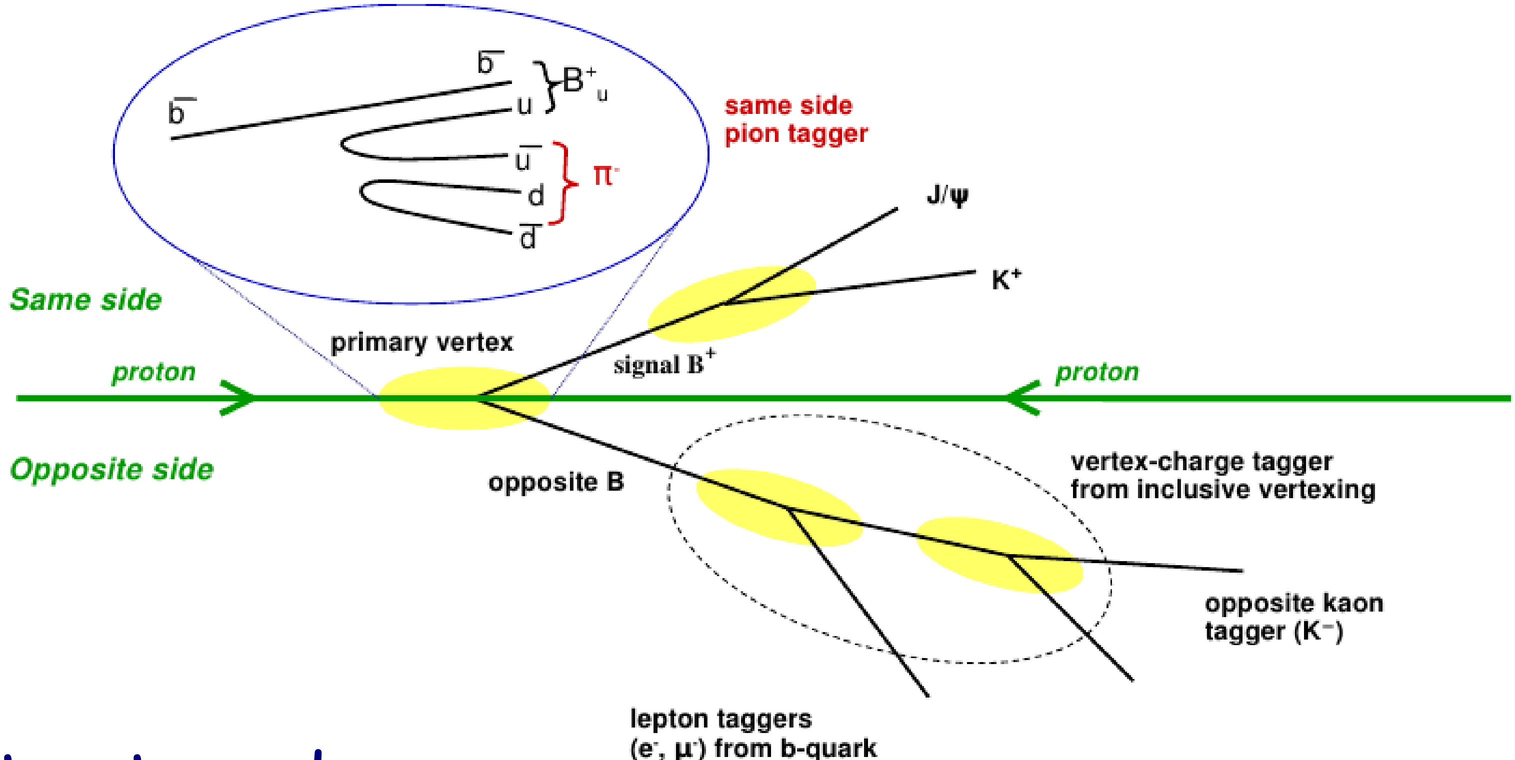
Forward Spectrometer



- covers forward region (1.9 < η < 4.9)
- optimized for the strongly forward peaked heavy quark production at the LHC
- covers only ~4% of solid angle but captures ~40% of heavy-quark production cross section

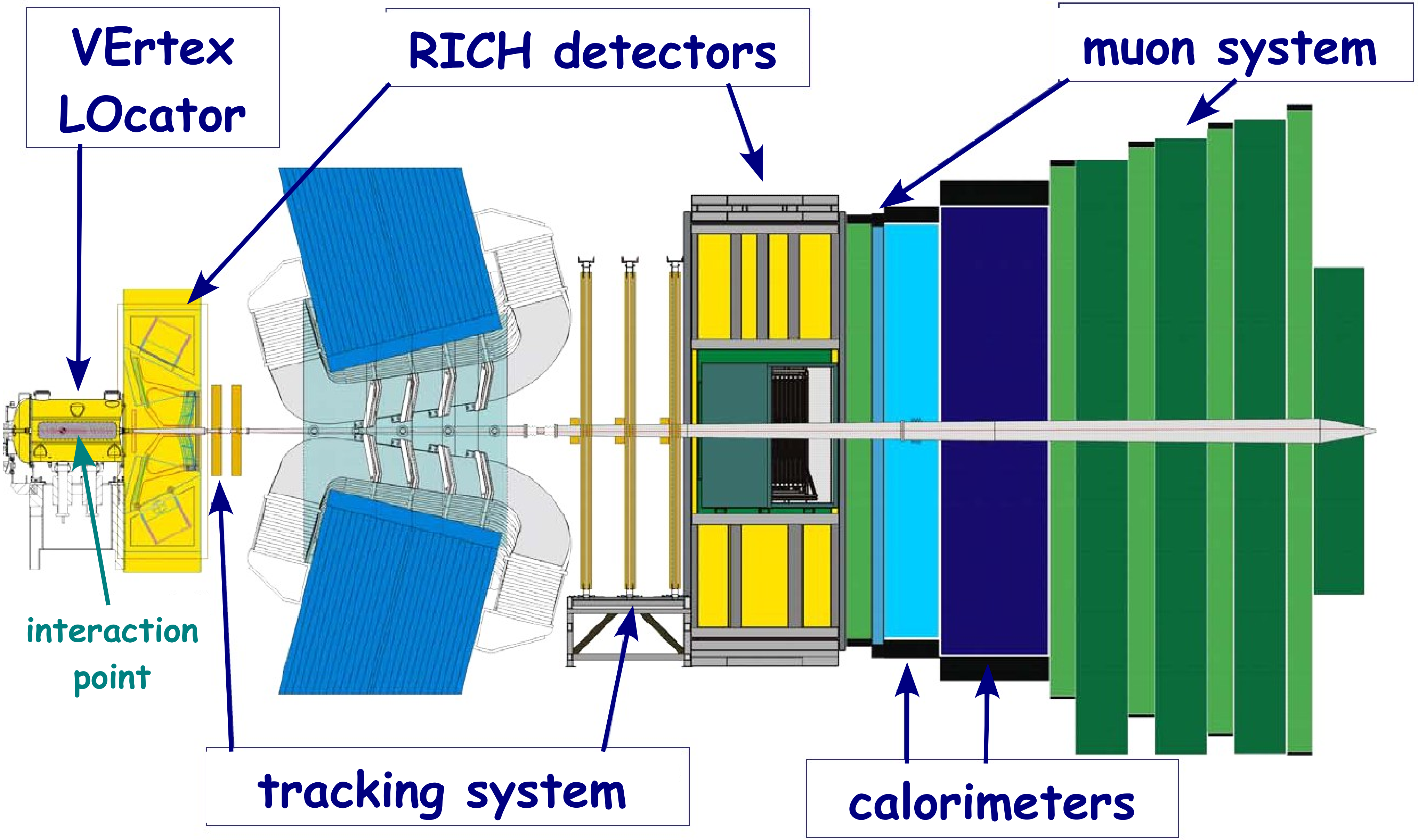


Key Features



- excellent vertex and <u>proper-time resolution</u>
  - secondary B decay vertex
  - rapid $B_s^0\overline{B}_s^0$ oscillations
- excellent momentum and <u>invariant mass resolution</u>
  - background rejection
- excellent <u>kaon/pion separation</u>
  - final states with kaons/pions
  - flavour tagging
- efficient trigger on <u>hadrons</u> as well as muons and electrons
  - purely hadronic final states

LHCb Detector



Optimized Trigger

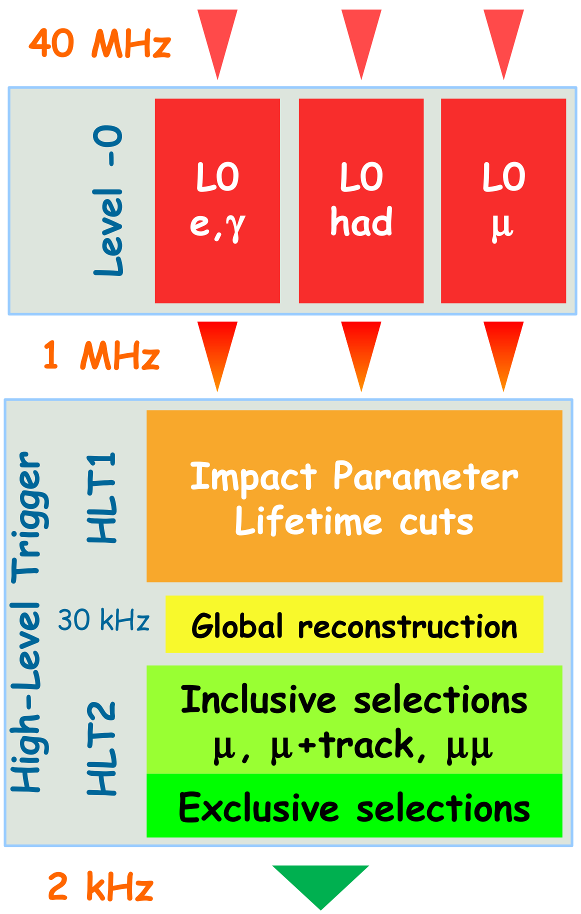
- overcome large inelastic cross section: >100 x $b\bar{b}$ cross section
- select interesting B decay channels: typical branching fractions of 10^{-5}
- exploit generic B decay signature: decay products with large p_T (few GeV) and high impact-parameter, well separated B decay vertex

Hardware level (L0):

- high-pT μ track segments in muon system
- high-ET clusters (e,h,γ) in calorimeters

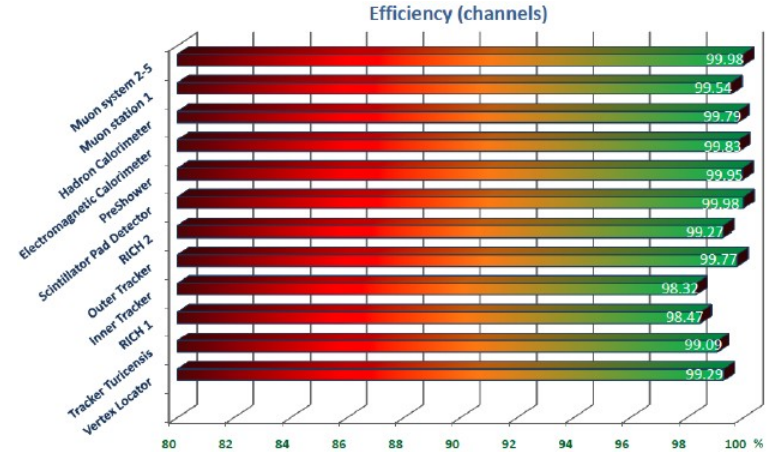
Software level (HLT):

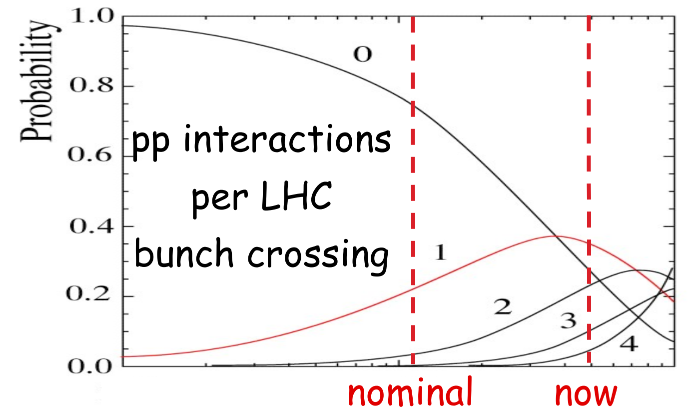
- multi-processor farm (14k cores)
- access to full detector data
- HLT1: cuts on impact parameter and lifetime
- HLT2: global event reconstruction
  + selections for specific channels

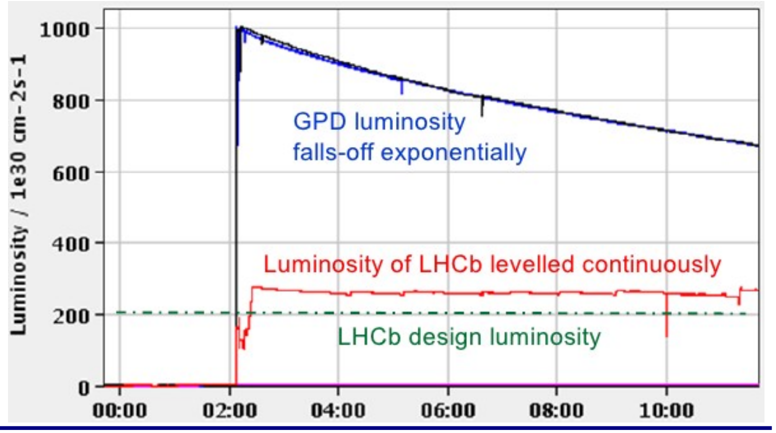


Data Taking

- **LHCb fully operational from first day of LHC collisions in March 2010**
  - **> 90% of detector channels operational**
  - **data taking efficiency > 90%**
- **cap instantaneous luminosity to keep fraction of events with multiple pp interactions small**
  - **track multiplicity in busy forward region**
  - **assignment of B decay to primary vertex**
- **luminosity levelling by steering of LHC beams**
- **operating successfully at significantly higher collision multiplicities than foreseen in design**
- **(preliminary) results shown here based on ~ 35 pb^{-1} of data collected in 2010**
- **already collected ~ 300 pb^{-1} in 2011**
- **expect 1 fb^{-1} by the end of the year**

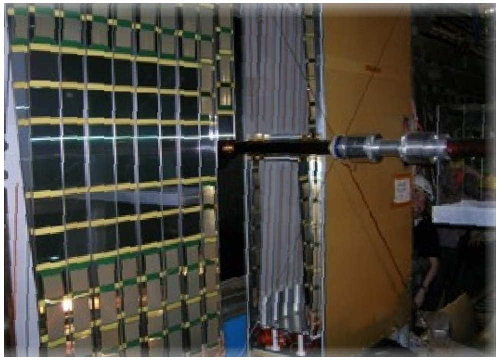


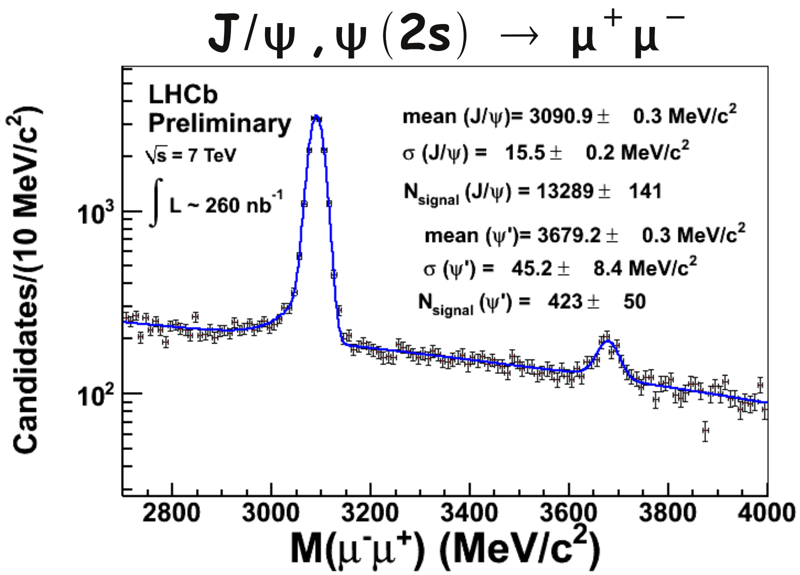


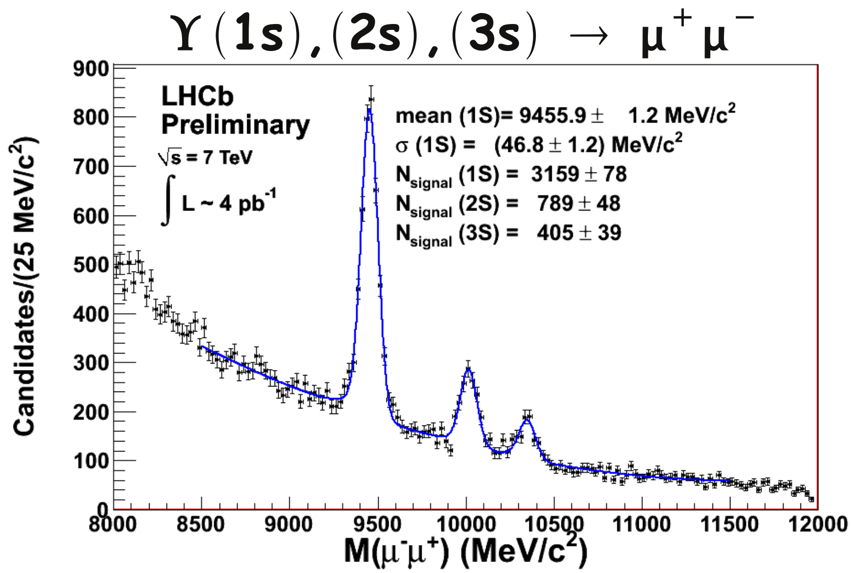


Charged Particle Tracking

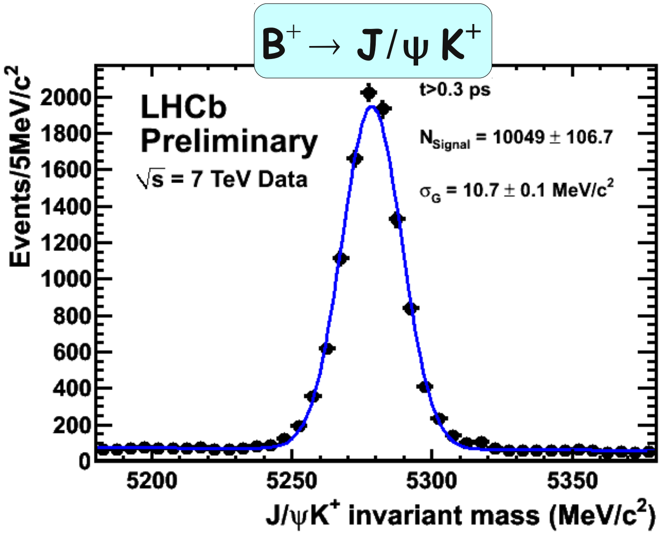
- silicon micro-strips upstream of magnet
- straws + silicon micro-strips downstream
- biggest challenge is spatial alignment
  - no detectors inside magnet
  - no acceptance for cosmics
- measured resolutions very close to simulation

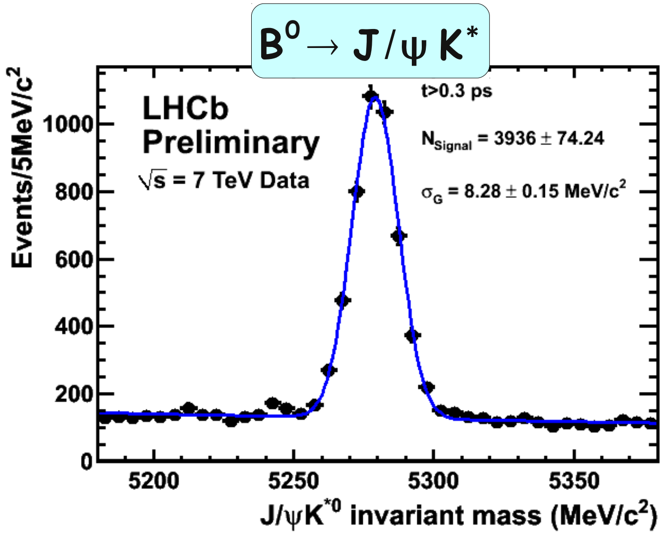


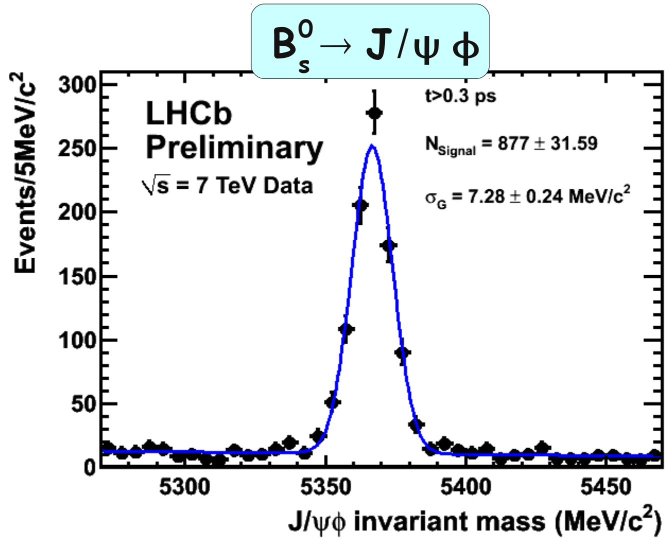


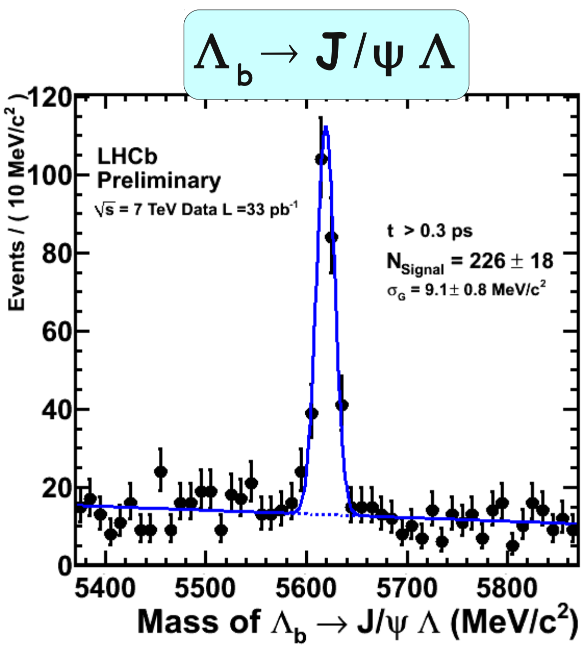


b → J/ψ X Signals









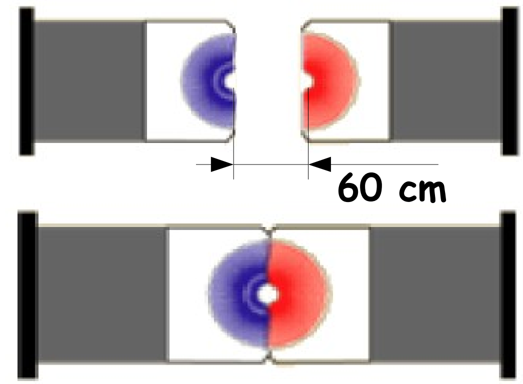
- clean signals, excellent mass resolutions
  - c.f. CMS: ~ 16 MeV, ATLAS: ~ 26 MeV
- world's best mass measurements

Channel		LHCb mass [MeV/c^2]	PDG [MeV/c^2]
$M(B^+ \to J/\psi K^+)$	=	5279.27 ± 0.11 (stat) ± 0.20 (syst)	5279.17 ± 0.29
$M(B^0 \to J/\psi K^{*0})$	=	5279.54 ± 0.15 (stat) ± 0.16 (syst)	5279.50 ± 0.30
$M(B^0 \to J/\psi K^0_S)$	=	5279.61 ± 0.29 (stat) ± 0.20 (syst)	5279.50 ± 0.30
$M(B^0_s \to J/\psi \phi)$	=	5366.60 ± 0.28 (stat) ± 0.21 (syst)	5366.30 ± 0.60
$M(\Lambda_b \to J/\psi \Lambda)$	=	5619.49 ± 0.70 (stat) ± 0.19 (syst)	5620.2 ± 1.6
$M(B^+_c \to J/\psi \pi^+)$	=	6268.0 ± 4.0 (stat) ± 0.6 (syst)	6277 ± 6

[LHCb-CONF-2011-027] preliminary

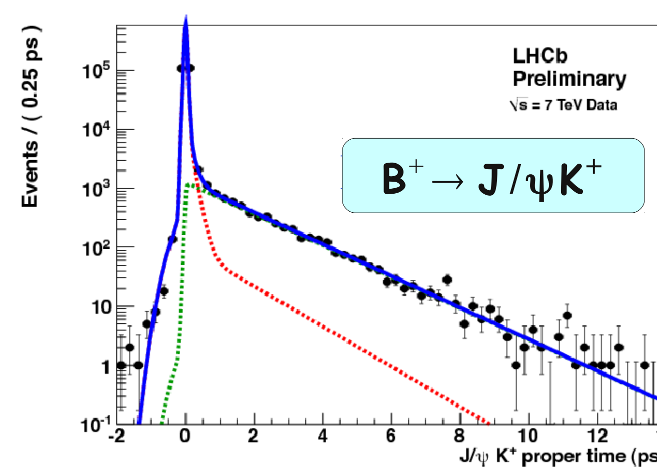
Vertex Reconstruction

- silicon strip detectors inside LHC vacuum pipe
- only 8mm from LHC beams during data taking
- retracted by ±3 cm in between fills
  - internal alignment better than 5 μm
- proper-time resolution $\sigma_t \approx 50$ fs
  - compare to B lifetimes: $\tau_B \approx 1500$ fs
- measured lifetimes compatible with PDG values



Channel	LHCb prelim. (ps)	Yield	PDG lifetime (ps)
$B^+ \to J/\psi K^+$	$1.689 \pm 0.022_{stat.} \pm 0.047_{syst.}$	6741 ± 85	1.638 ± 0.011
$B^0 \to J/\psi K^{*0}$	$1.512 \pm 0.032_{stat.} \pm 0.042_{syst.}$	2668 ± 58	1.525 ± 0.009
$B^0 \to J/\psi K^0_S$	$1.558 \pm 0.056_{stat.} \pm 0.022_{syst.}$	838 ± 31	1.525 ± 0.009
$B^0_s \to J/\psi \phi$	$1.447 \pm 0.064_{stat.} \pm 0.056_{syst.}$	570 ± 24	1.477 ± 0.046
$\Lambda_b \to J/\psi \Lambda$	$1.353 \pm 0.108_{stat.} \pm 0.035_{syst.}$	187 ± 16	$1.391^{+0.038}_{-0.037}$

[LHCb-CONF-2011-001] preliminary

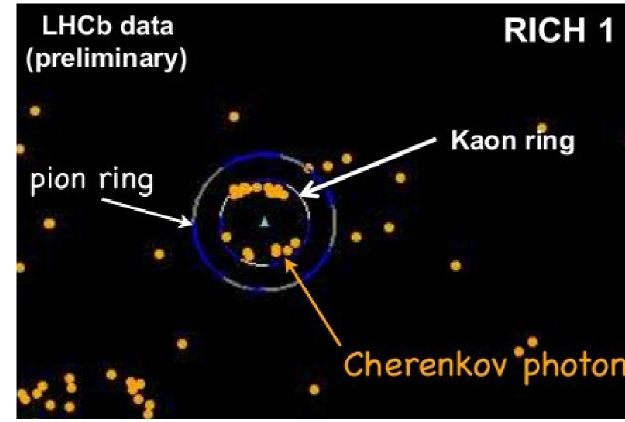


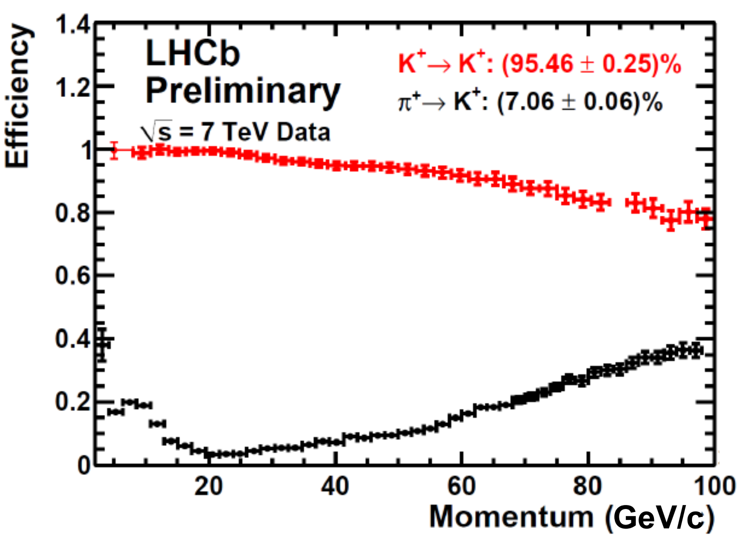
K/π Identification

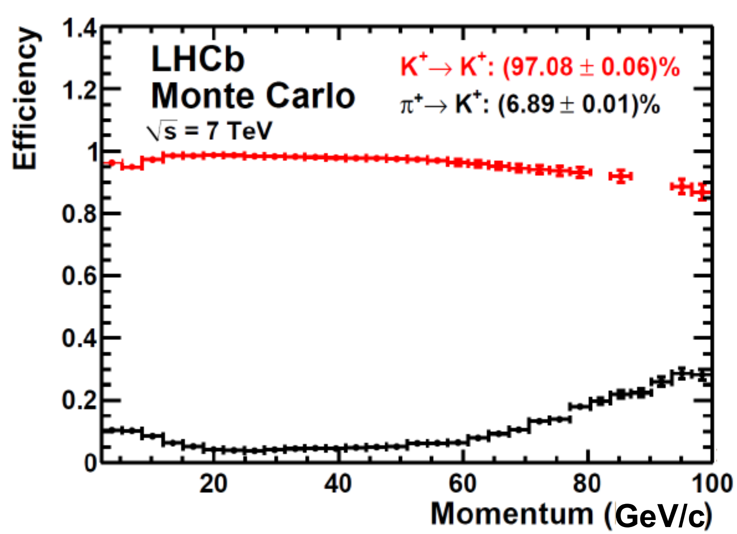
- B flavour tagging → down to few GeV
- two-body B decays → up to 100 GeV

$$B_d^0 \to \pi^\pm \pi^\mp \leftrightarrow B_{(d,s)}^0 \to K^\pm \pi^\mp \leftrightarrow B_s^0 \to K^\pm K^\mp$$

- two RICH detectors with three radiators
- photon-detection in pixel-HPDs
- performance close to simulation for all momenta



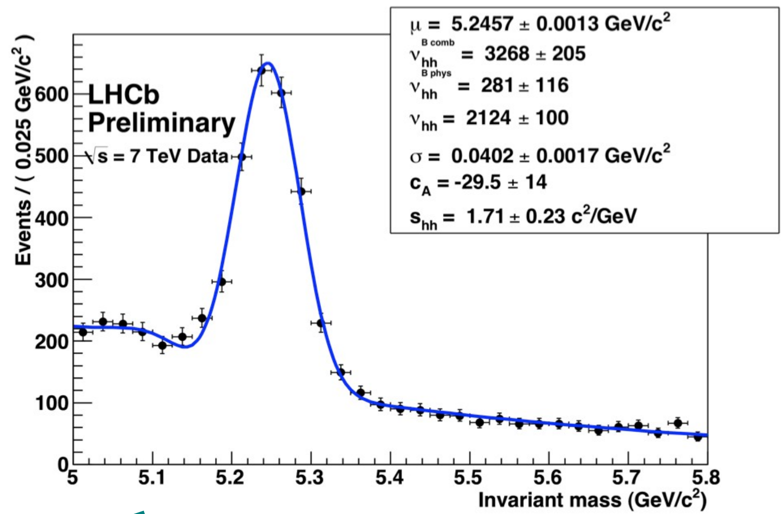




$B \to h^+h'^-$ Signals

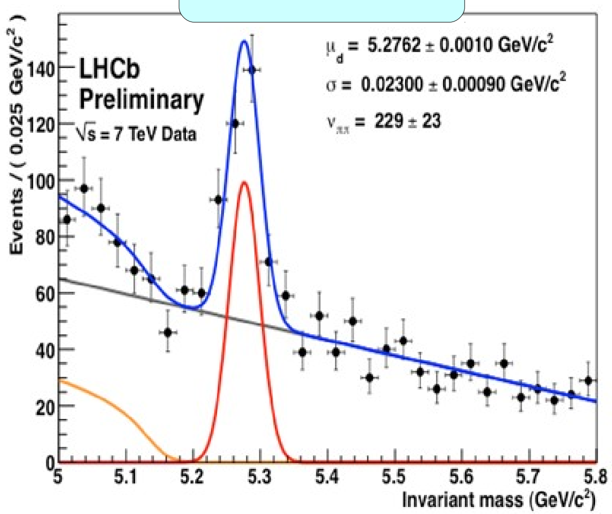
$B \to h^+h'^-$

2-body decays, no PID, π mass assumed for both decay particles

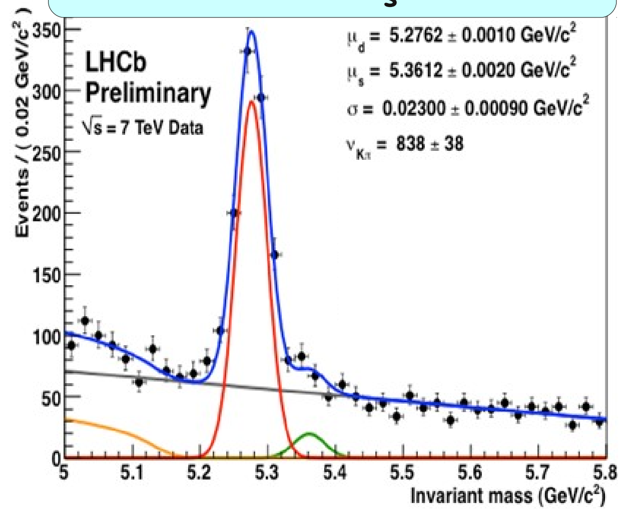


apply PID cuts

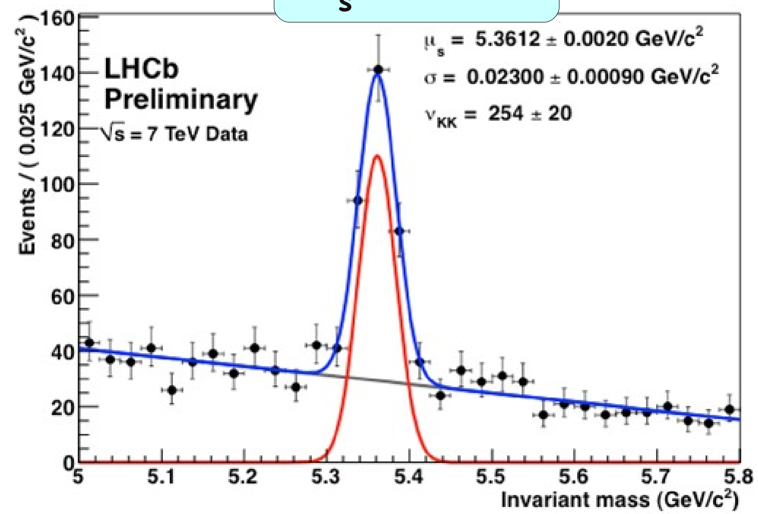
$B^0 \to \pi^+\pi^-$



$B^0 \to K^\pm\pi^\mp$, $B_s^0 \to K^\pm\pi^\mp$

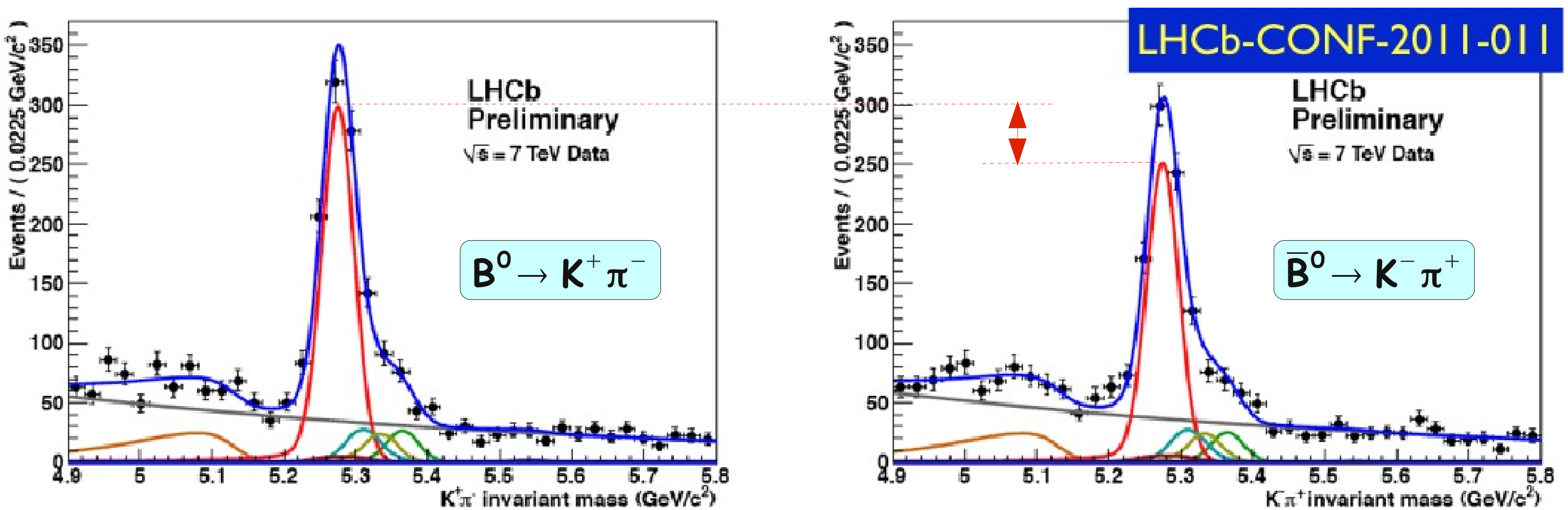


$B_s^0 \to K^+K^-$



CP Violation in $B^0 \rightarrow K^{\pm}\pi^{\mp}$

- further separate $B^0 \rightarrow K^{\pm}\pi^{\mp}$ sample into $B^0 \rightarrow K^{+}\pi^{-}$ and $\overline{B}^0 \rightarrow K^{-}\pi^{+}$
- asymmetry in signal yields shows CP Violation



- after correction for (small) production and detection asymmetries:

$$A_{CP}\left(B^0 \rightarrow K^{+}\pi^{-}\right) = -0.074 \pm 0.033 \pm 0.008$$

[LHCb-CONF-2011-011]
preliminary

- in good agreement with world average:

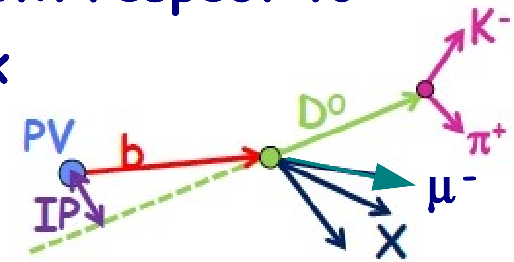
$$A_{CP}\left(B^0 \rightarrow K^{+}\pi^{-}\right) = -0.098^{+0.012}_{-0.011}$$

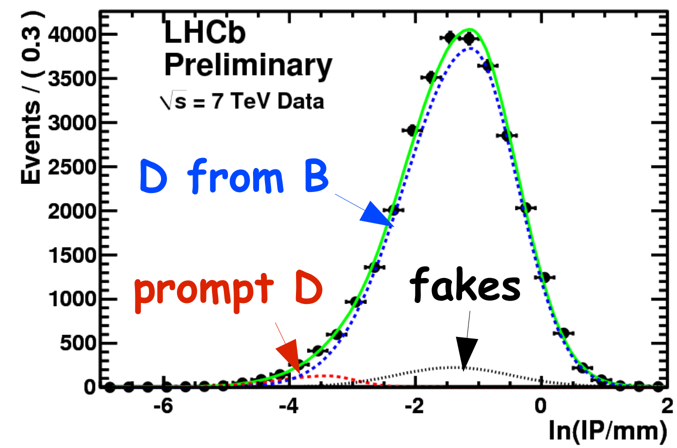
[HFAG 2010]

- charmless two-body B-decay modes central to LHCb physics programme
- significant contribution of Penguin diagrams → window to New Physics !

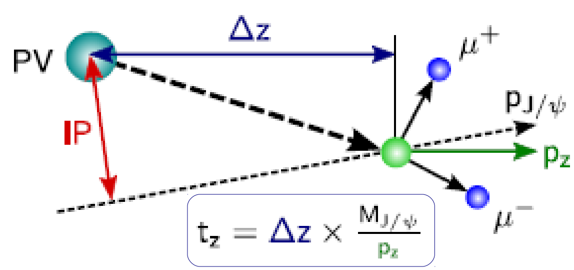
$\bar{b}b$ Production Cross Section

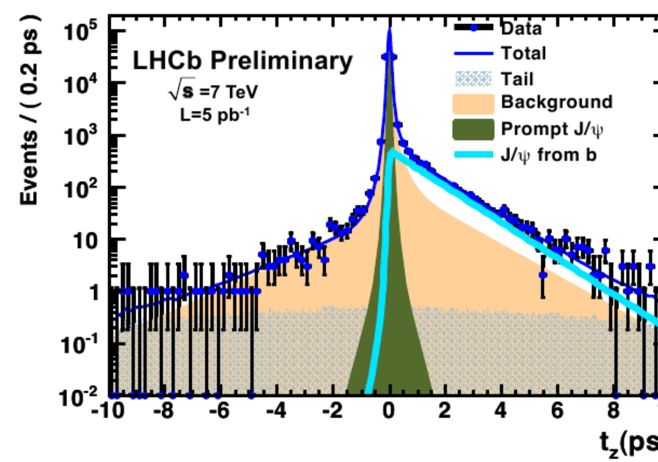
- from $B^0 \rightarrow D^0(K^-\pi^+)\,\mu^- X^+$: identify "D from B" by large impact parameter with respect to reconstructed primary vertex
- use wrong-sign $D^0\,\mu^+$ pairs to estimate backgrounds





- from $B \rightarrow J/\psi\ X$: use distribution of "pseudo proper time" t_z to identify J/ψ from b





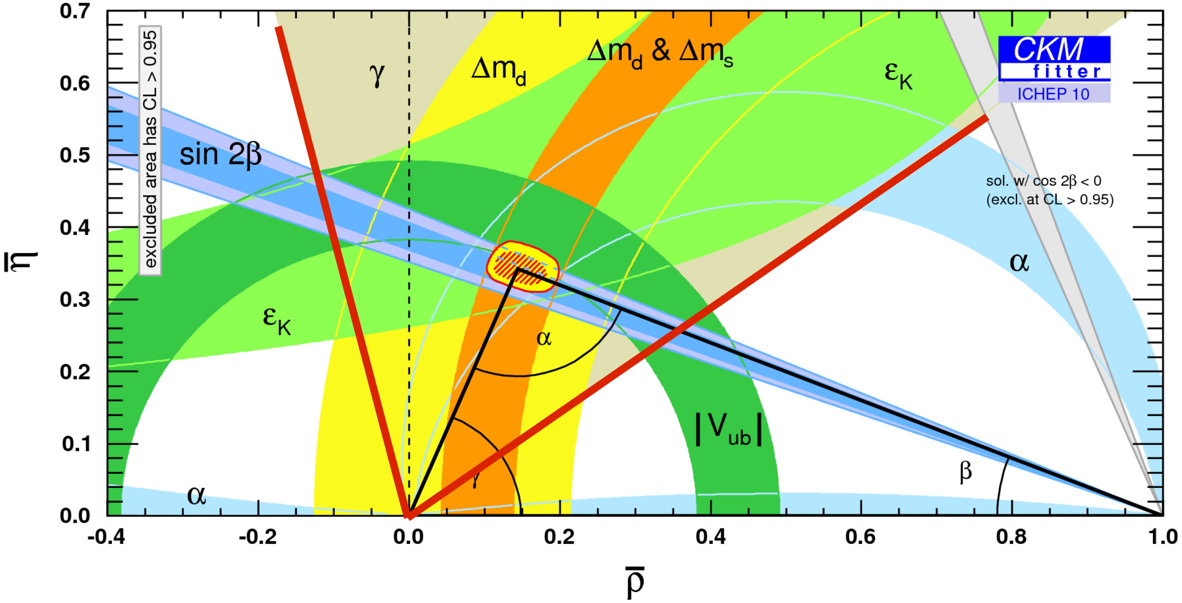
- extrapolate from LHCb acceptance to full phase space: Pythia Monte-Carlo

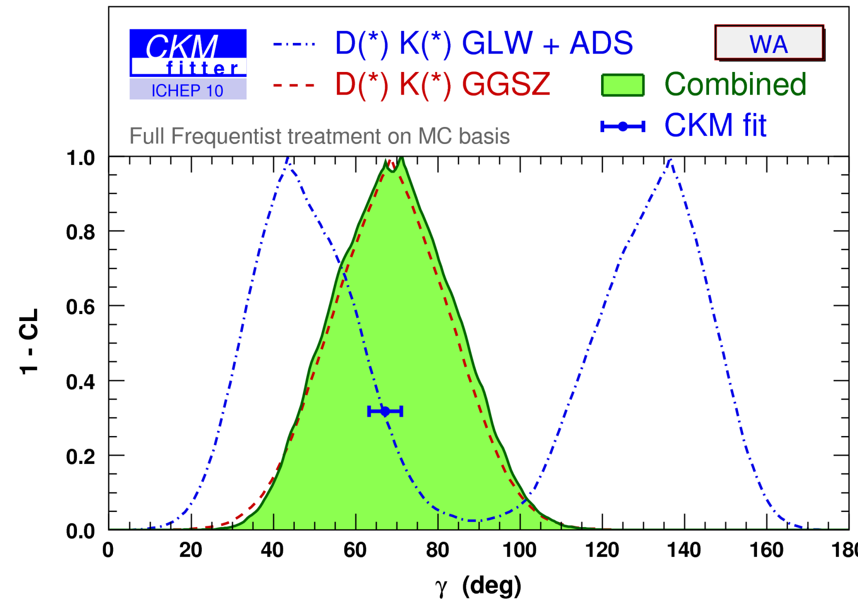
$$\sigma(pp \rightarrow b\bar{b}X) = (284 \pm 20 \pm 49)\ \mu b$$ [Phys Lett B 694 (2010) 209]

$$\sigma(pp \rightarrow b\bar{b}X) = (288 \pm 4 \pm 48)\ \mu b$$ [Eur Phys J C71 (2011) 1645]

- good news: LHCb performance simulations had assumed 250 μb at 7 TeV

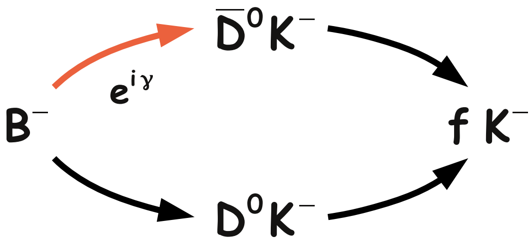
CKM angle γ

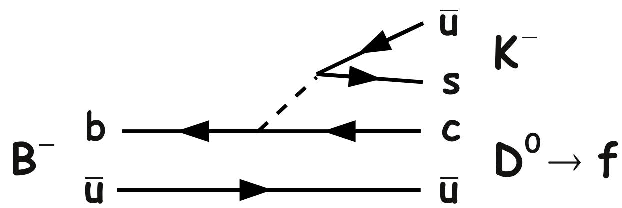


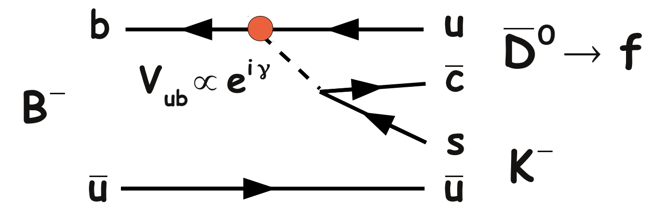


- **most poorly measured angle of the Unitarity Triangle**
  - **improving measurement precision tests consistency of Unitarity Triangle**
- **γ can be determined from pure Tree processes and from Penguin processes**
  - **comparison of results probes possible New Physics contribution in Penguins**
- **LHCb: for both approaches expect σ(γ) ~ 5° with 2011/12 data**

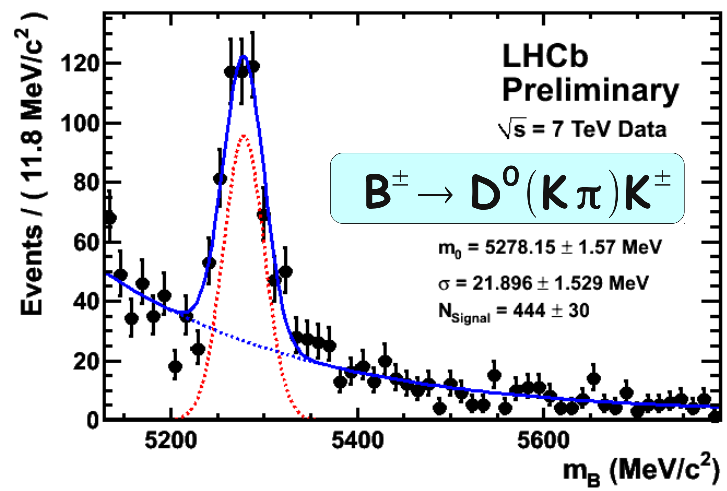
γ from Trees





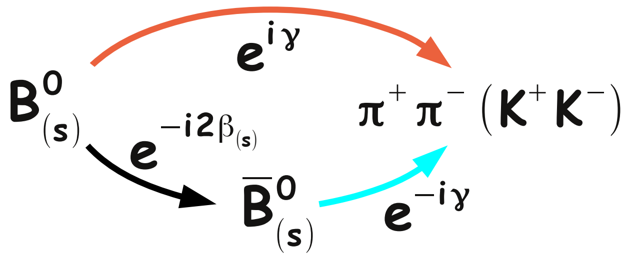


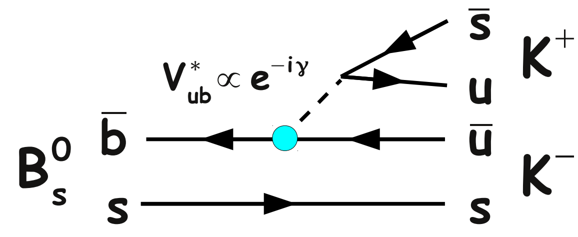
- final state f common to D^0 and $\overline{D}^0$ → interference of tree amplitudes with different weak phase leads to different decay rates for B^+ and B^- decays
  - $f = KK,\ \pi\pi\ ;\ f = K^+\pi^-\ ;\ f = K_s\pi\pi$
- various decay rate ratios and asymmetries → enough observables to extract γ, strong phase, ratio of magnitudes between the two diagrams
- but: interference small, branching ratios small
- statistics from Tevatron/B factories insufficient
- advantage LHCb: large B production rate, efficient trigger for hadronic final states, excellent K/π identification

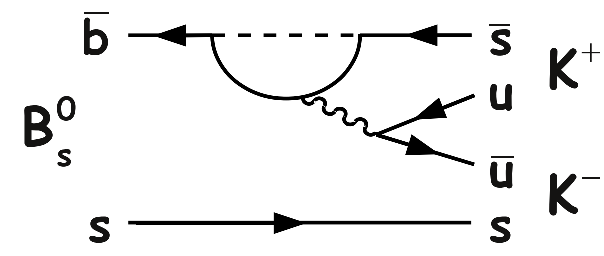


example $B^\pm \rightarrow D^0(K\pi)K^\pm$
LHCb: ~440 events from 0.035 fb^{-1}
CDF: ~1500 events from 5 fb^{-1}

γ from Penguins



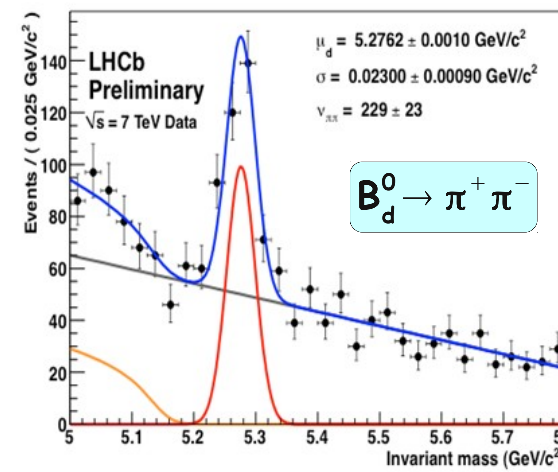


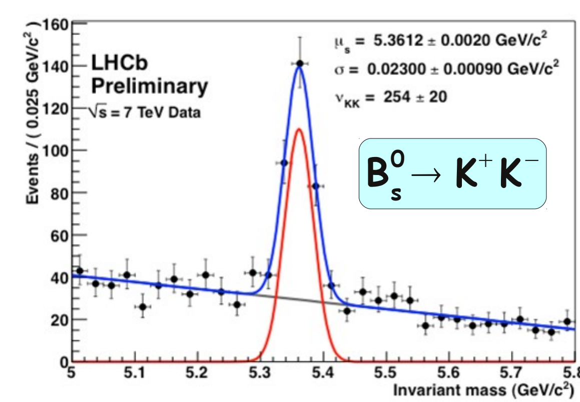


- CP violation from interference of mixing and decay
  - Penguin significant → New Physics sensitivity !
- measure two time-dependent CP asymmetries

$$A_{CP}(t) = A_{mix} \cdot \sin(\Delta m_{(d,s)} t) + A_{dir} \cdot \cos(\Delta m_{(d,s)} t)$$

- assume U-spin symmetry (exchange of s↔d quark)
  → Penguin/Tree ratio the same for both channels
- take mixing phases $\beta_{(s)}$ from $B^0_d \to J/\psi K^0_s$, $B^0_s \to J/\psi \phi$
- extract γ together with Penguin/Tree ratio (phase and magnitude) from the four amplitudes
- LHCb advantage: as before + excellent proper time resolution to resolve fast $B^0_s \overline{B}^0_s$ oscillations



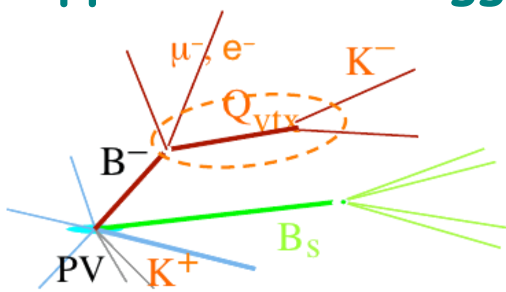


$B_s^0 \overline{B}_s^0$ Oscillation Frequency

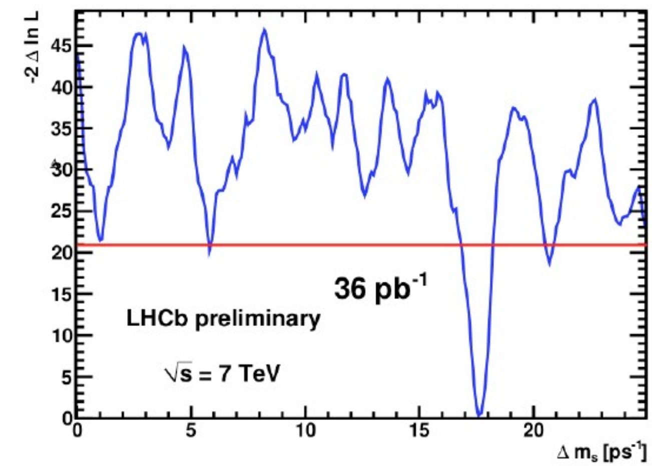
- measured using flavour-specific decays

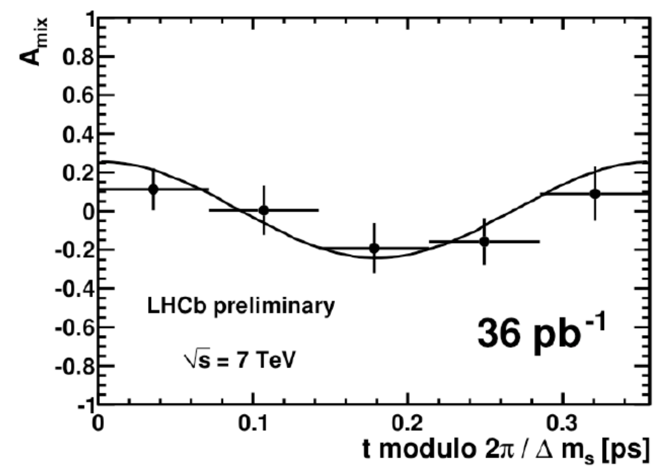
$$B_s^0 \to D_s^-(3)\pi^+ \text{ with } D_s^- \to K^+K^-\pi^-$$

- total of ~ 1300 signal events from 35 pb^{-1}
- flavour at production (B_s^0 or $\overline{B}_s^0$) implied from combination of opposite-side taggers
  - lepton charge
  - kaon charge
  - vertex charge



- calibrated on $B^+ \to J/\psi K^+$ and $B_d^0 \to D^-\pi^+$
- result competitive with previous world-best measurement from CDF (using 1000 pb^{-1})





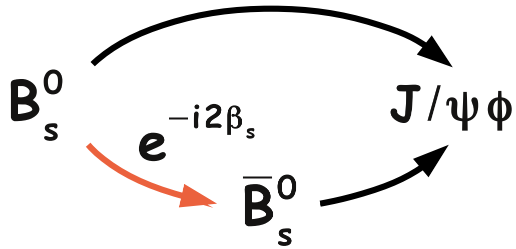
$$\Delta m_s = (17.63 \pm 0.11(\text{stat}) \pm 0.04(\text{syst}))\ ps^{-1}$$

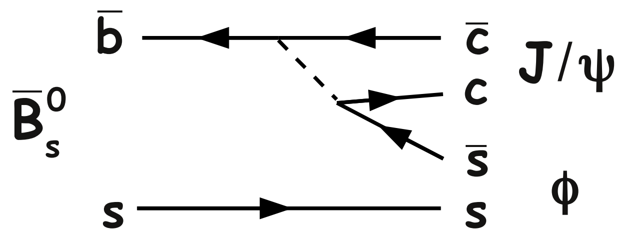
[LHCb-CONF-2011-005] preliminary

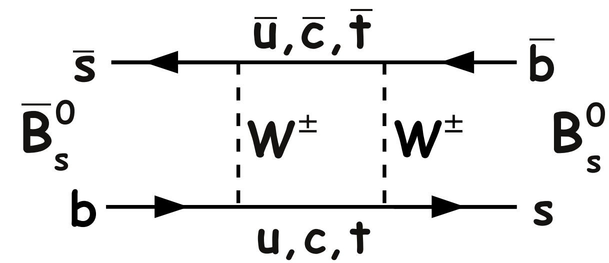
$$\Delta m_s = (17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst}))\ ps^{-1}$$

[PRL 97, 242003 2006]

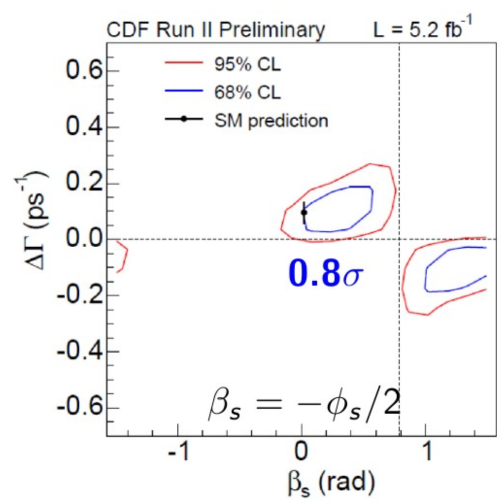
$B_s^0\overline{B}_s^0$ Mixing Phase $\phi_s = -2\beta_s$

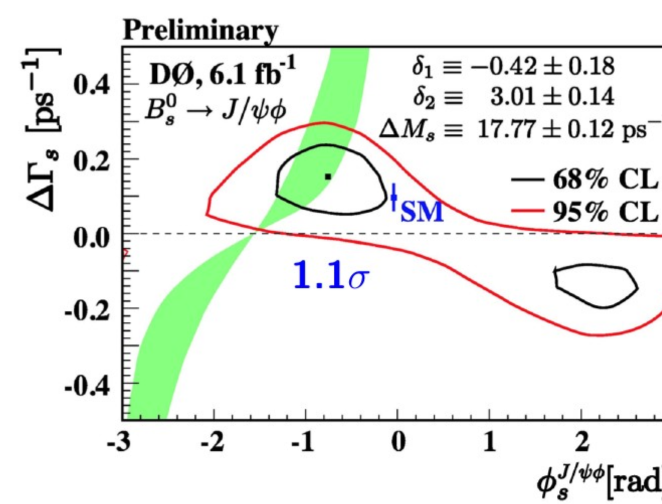




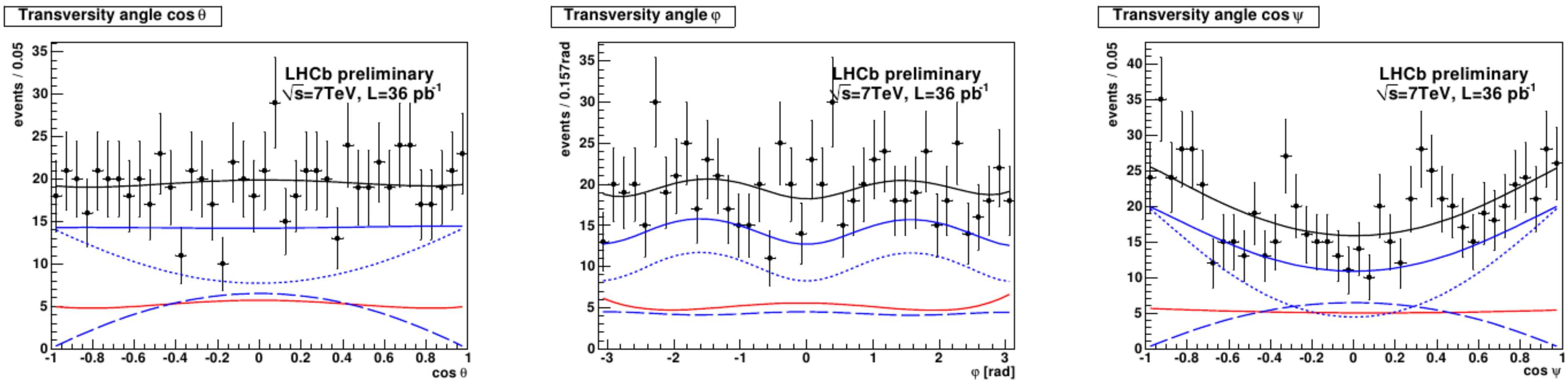


- ϕ_s predicted to be very small in Standard Model → New Physics sensitivity
- "golden channel": time-dependent CP asymmetry in $B_s^0 \to J/\psi\,\phi$
- complication 1: lifetime difference $\Delta\Gamma_s$ between the two CP-Eigenstates of the $B_s^0/\overline{B}_s^0$ system not well known → has to be determined simultaneously
- complication 2: $J/\psi\,\phi$ not produced in a CP Eigenstate → need time-dependent angular analysis to separate CP even/odd components
- best constraints so far:
  - CDF (5.2 fb^{-1})
    [CDF Note 10206]
  - D0 (6.1 fb^{-1})
    [D0 6098-CONF]





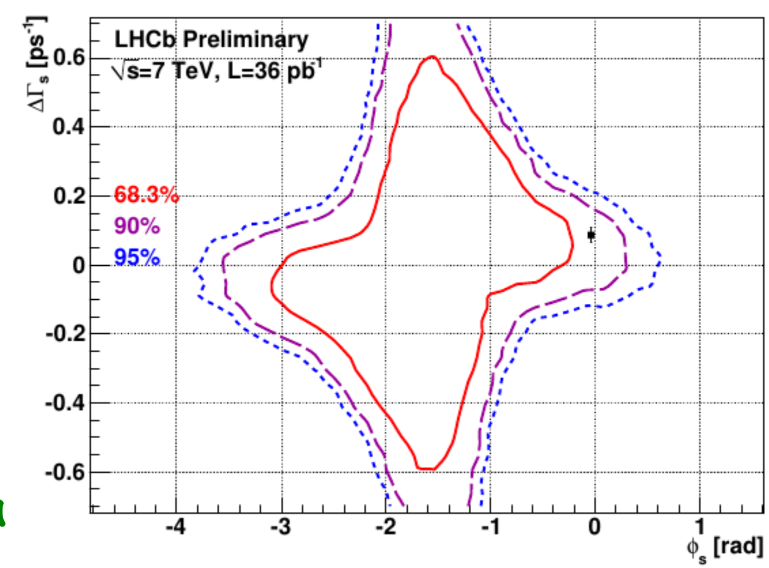
$B_s^0\overline{B}_s^0$ Mixing Phase $\phi_s = -2\beta_s$



- LHCb: statistics from 2010 data set too small for competitive measurement
  - used the data successfully to validate all aspects of analysis procedure
- obtained first constraints in $\phi_s/\Delta\Gamma_s$ plane

$$\phi_s^{SM} \in [-2.7, -0.5]\ \text{rad} \ \ @\ 68\ CL$$

[LHCb-CONF-2011-006] preliminary

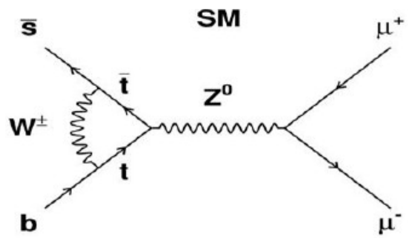


- good news: systematics very small → expect world best measurement of ϕ_s from 2011 data

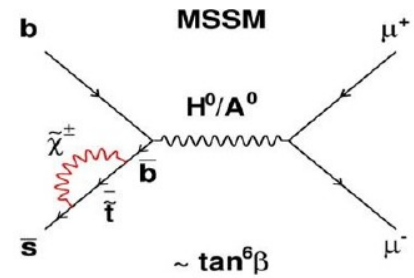
Rare Decays: $B_s^0 \to \mu^+\mu^-$

- very rare in Standard Model:

  $BR(B_s^0 \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$ [Buras, arXiv:1012.1447]

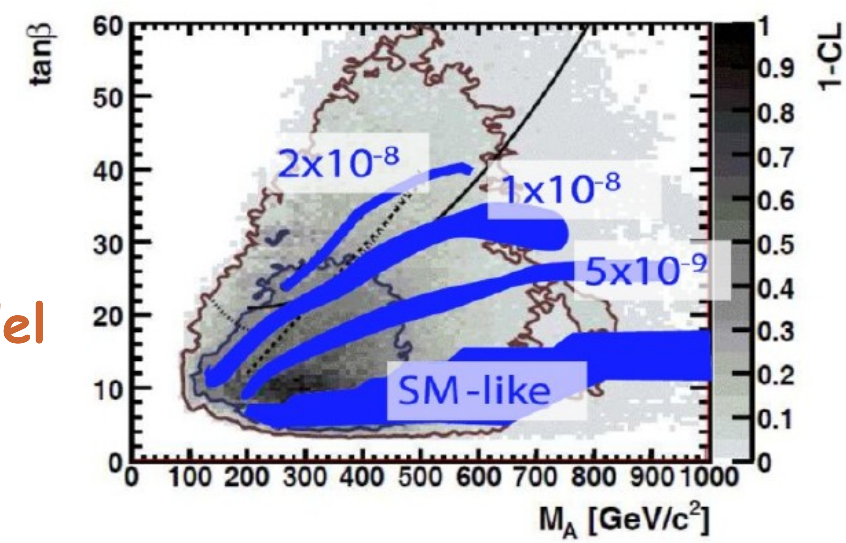


- but can be significantly enhanced by New Physics



- not yet observed, best upper limits so far from Tevatron
  - CDF (3.7 fb^{-1}): $BR < 3.6 \times 10^{-8}$ @ 90 CL [CDF note 9892]
  - DØ (6.1 fb^{-1}): $BR < 4.2 \times 10^{-8}$ @ 90 CL [PLB 693 (2010) 539]
- measuring branching fraction above Standard Model prediction would be clear sign for new physics
- improving on the upper limit constrains parameter space for New Physics models
- e.g. Minimal Supersymmetric Standard Model

$$BR(B_s^0 \to \mu^+\mu^-) \propto \frac{\tan^6\beta}{m_A^4}$$

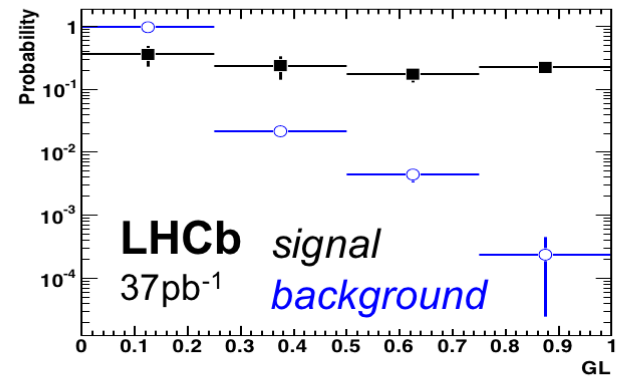


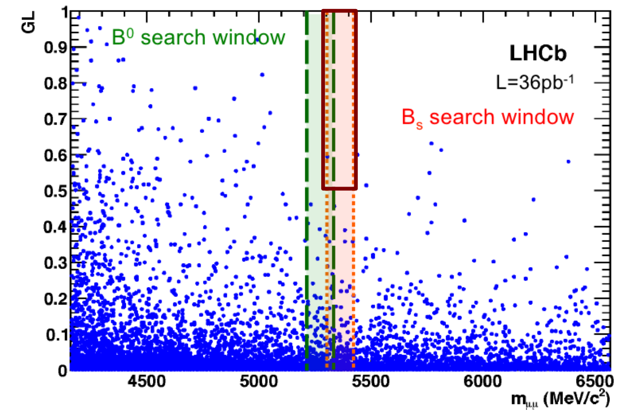
Rare Decays: $B_s^0 \to \mu^+\mu^-$

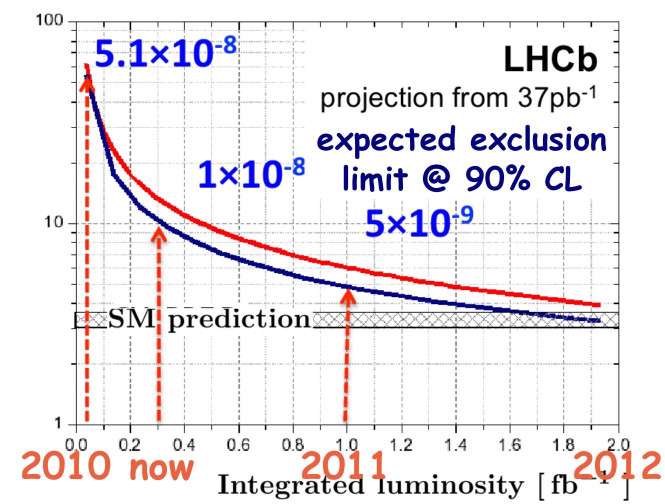
- advantage LHCb: large B production rate, excellent mass resolution
- classify events according to $\mu^+\mu^-$ invariant mass and GL: multi-variate classifier exploiting characteristics of the two-body event topology
  - distance of closest approach of the two μ's, their isolation and impact parameter wrt primary vertex
  - impact parameter, pT and lifetime of B candidate
- calibrate GL on $B^0 \to h^+h'^-$ events
- estimate invariant mass resolution from $B^0 \to h^+h'^-$ and from $J/\psi, \psi(2s) \to \mu^+\mu^-$, $\Upsilon(1s),(2s),(3s) \to \mu^+\mu^-$
- observed numbers of events in bins of invariant mass and GL compatible with expected background

$$BR(B_s^0 \to \mu^+\mu^-) < 4.3 \times 10^{-8} \text{ @ } 90\%\ CL$$

[Phys.Lett.B 699 (2011) 330]







Long-Term Outlook

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

Conclusions

- LHCb has a unique potential for the

INDIRECT DISCOVERY OF NEW PHYSICS

- both the LHC and the experiment are performing very well
- in some analyses already competitive results from the 2010 data set
- already 10x more data on disk, taken under much more stable conditions
- expect to collect 1 fb^{-1} by the end of this year
  - expect many world-best measurements from 2011 data
- stay tuned...

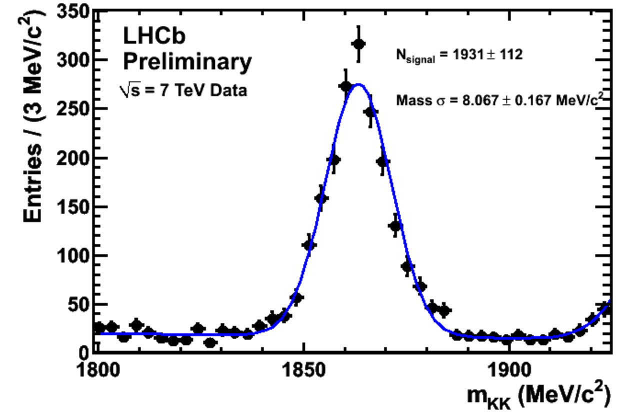
[ps. could only sketch a tiny fraction of the many analyses under way]
[in particular, did not say anything about Charm]

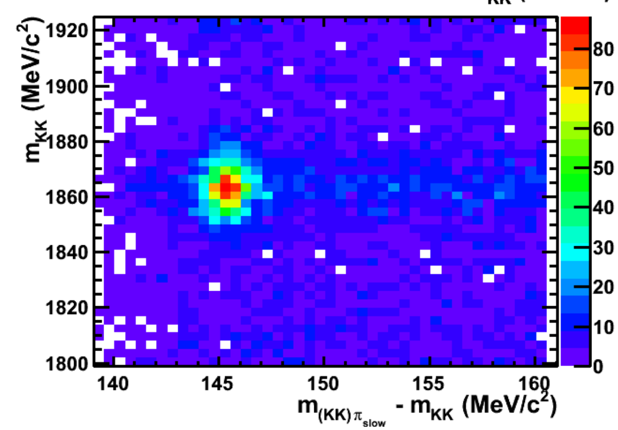
CP Violation in the Charm Sector

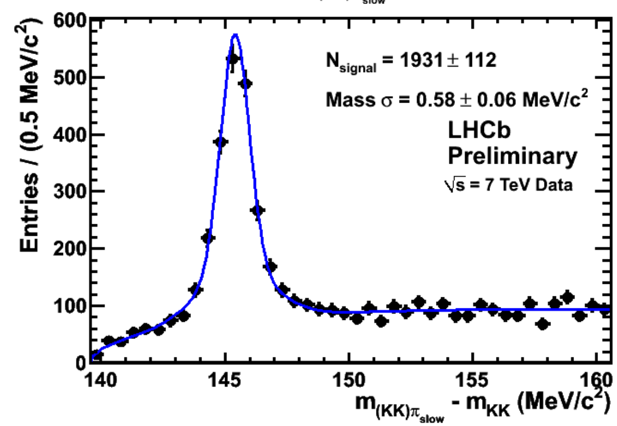
- CP violation in $D^0\overline{D}^0$ mixing predicted to be very small in Standard Model
- strong potential for New Physics enhancement
- experimentally unexplored field
- LHCb ideally suited for charm: already surpass B-factory yields with 2010 data
- most promising observables for early CP measurement: lifetime asymmetries, e.g.

$$A_\Gamma = \frac{\tau(\overline{D}^0 \to K^+K^-) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^+K^-) + \tau(D^0 \to K^+K^-)}$$

- use slow pion from $D^{*+} \to D^0\pi^+$ to tag D^0 flavour
- expect competitive measurements of A_Γ and other lifetime asymmetries from 2010 data
- several other CP violating observables in mixing and decay under investigation as well

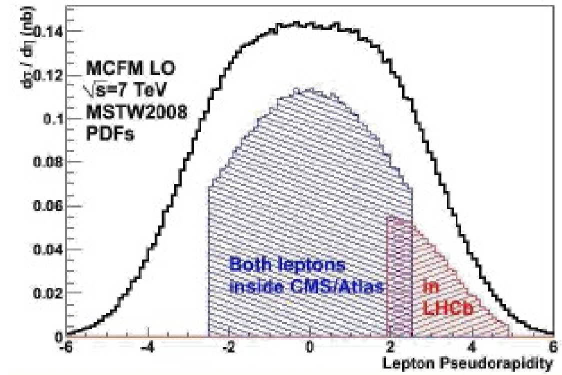


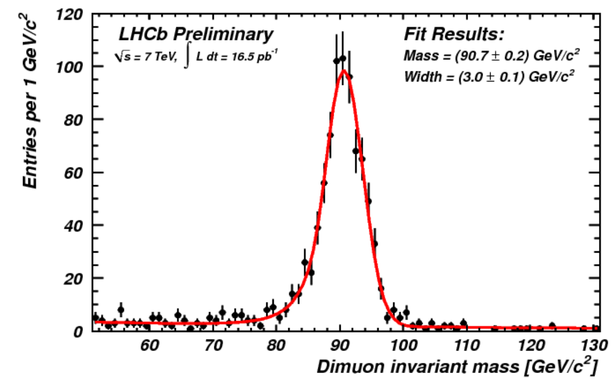


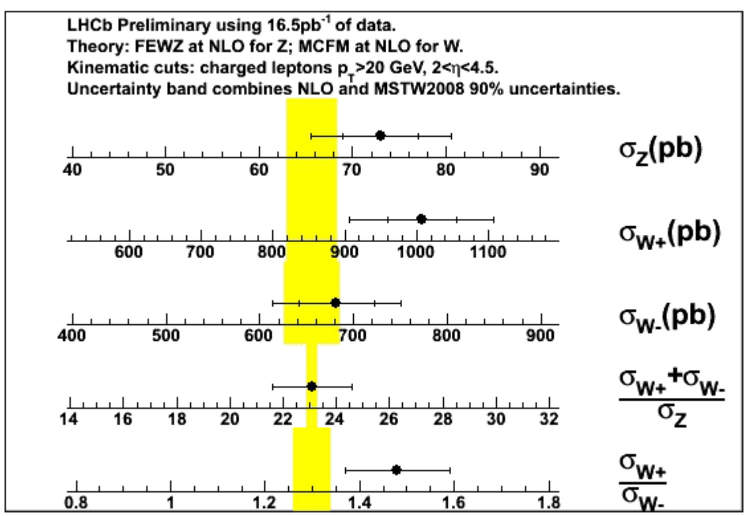


Electroweak Physics

- LHCb offers unique opportunity to study W and Z production in forward region
- clean event signatures, very clean Z^0 peak
- trigger and tracking efficiencies determined from data using tag-and-probe methods
- NEW Kruger2010, preliminary from 16.5 pb^{-1}: Z^0, W^+, W^- production cross sections, W/Z ratio, W^+/W^- production asymmetry for $2 < \eta$ (charged leptons) < 4.5
- all results in good agreement with theory
- provide new constraints on proton parton density functions at low x and high q^2
- Drell-Yan production studies ongoing to extend these measurements to lower q^2







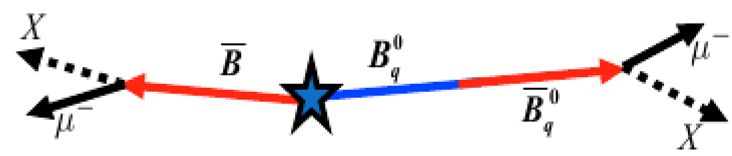
Semileptonic Asymmetry

- semileptonic charge asymmetry

$$a_{sl}^q = \frac{\Gamma(\bar{B}_q^0 \to \mu^+ X) - \Gamma(B_q^0 \to \mu^- X)}{\Gamma(\bar{B}_q^0 \to \mu^+ X) + \Gamma(B_q^0 \to \mu^- X)} \quad \text{with} \quad q = d, s$$

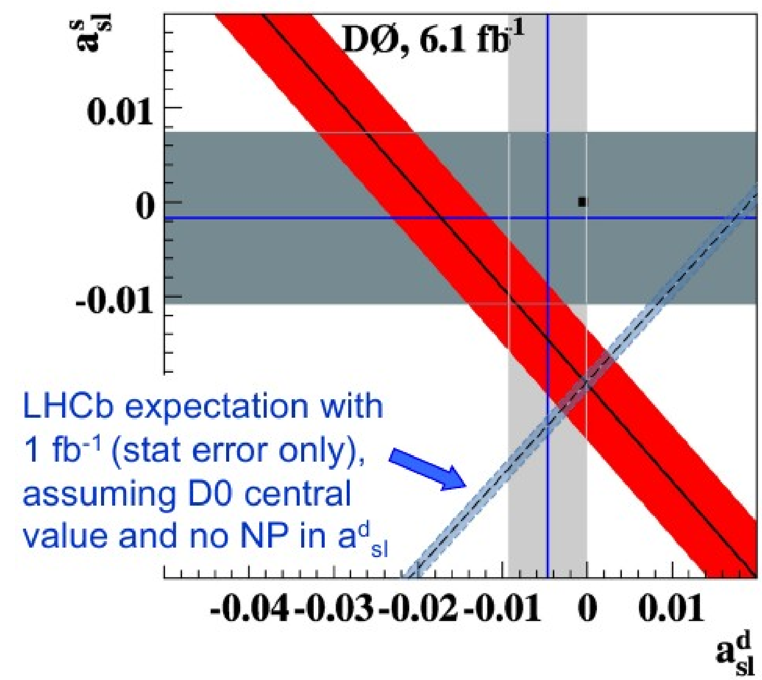
- Dzero measured di-lepton charge asymmetry

$$A_{sl}^b = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} \approx 0.5 \cdot a_{sl}^s + 0.5 \cdot a_{sl}^d$$



and found ~3.2 σ deviation from Standard Model prediction

- LHC is a pp collider → intrinsic charge asymmetry → measurement of A_{sl}^b difficult
- LHCb proposes to measure a_{sl}^s - a_{sl}^d by comparing the charge asymmetries in $B_s \to D_s^+(KK\pi)\mu^-\nu_\mu$ and $B^0 \to D^+(KK\pi)\mu^-\nu_\mu$
- this measurement gives a constraint orthogonal to the Dzero measurement



Luminosity Determination

- calculate instantaneous luminosity as a function of time from beam profiles and beam currents
- obtain beam currents from pick-up monitors
- obtain LHC beam profiles from
  - van-der-Meer scans:
    - move beams horizontally and vertically
    - measure minimum bias trigger rates
    - fully automated with LHC machine
  - measured vertex distributions in LHCb vertex detector (VELO)
- uncertainty on luminosity determination currently around 10 %, dominated by uncertainty on beam currents
- expect to go down to 5 % for 2011