CP violation measurements at LHCb

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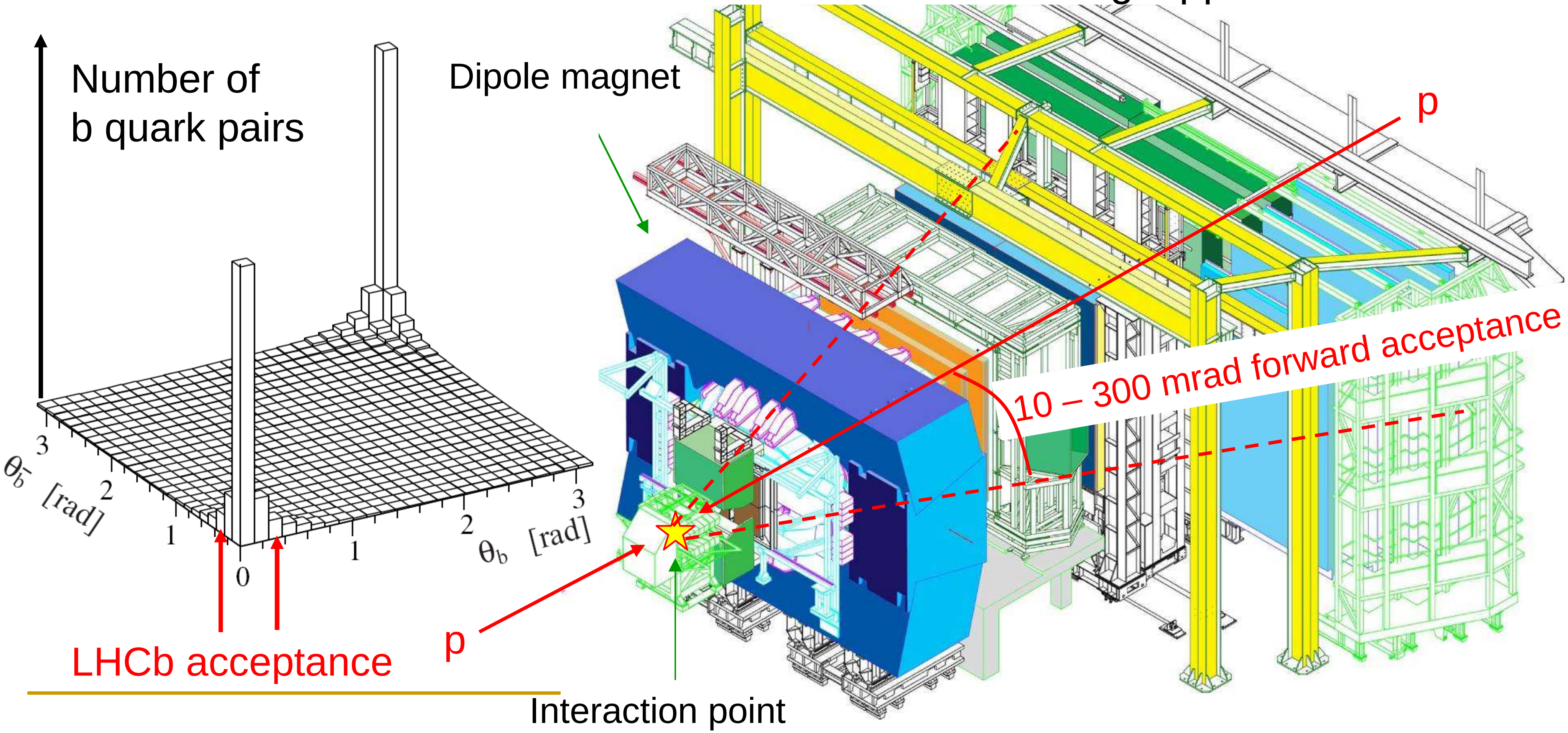
Outline

- Overview of LHCb
- CPV highlights:
  - β_s measured with $B_s \rightarrow J/\psi\phi$
  - γ measurements:
    - Purely tree level and loop influenced decays
  - CPV in charm decays
- Other CPV measurements
- Conclusion

LHCb overview

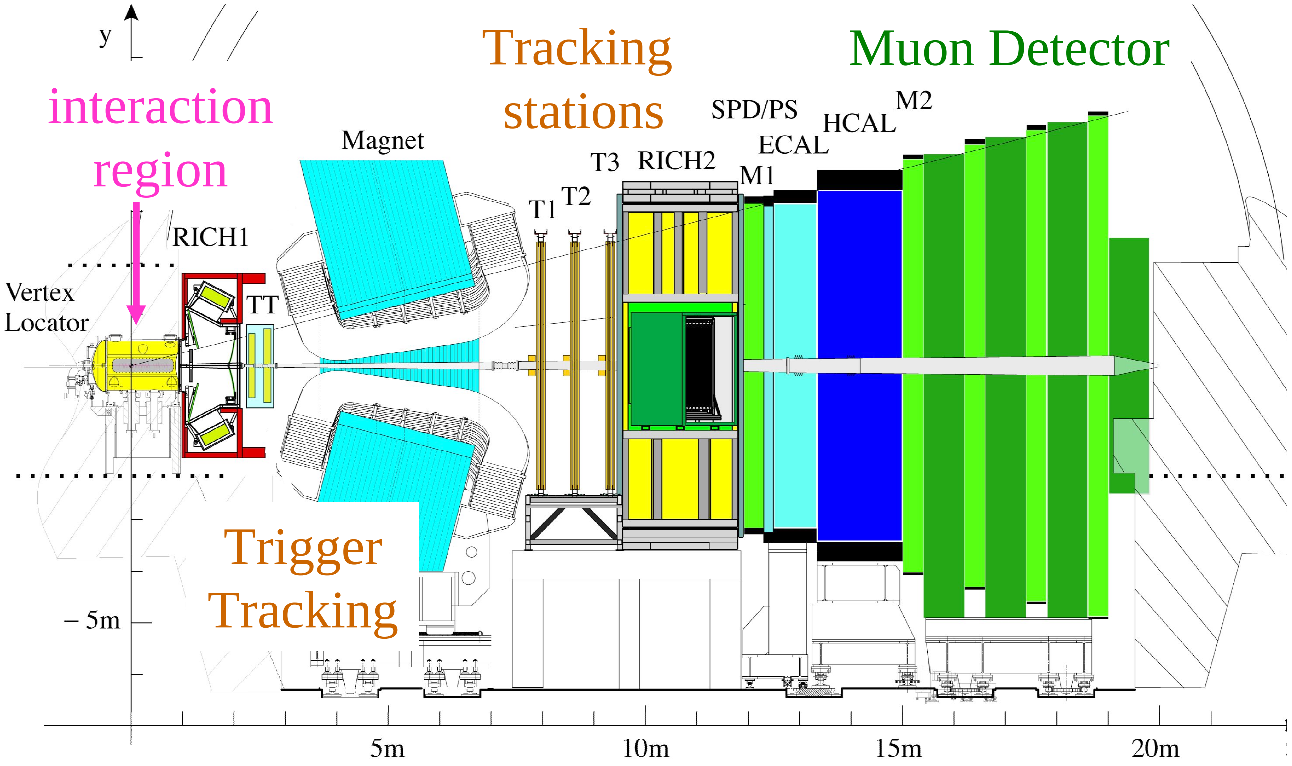
The LHCb Experiment

- Dedicated experiment for precision measurement of CP violation and rare decays of b-hadrons at the LHC
  - **Indirect searches for non-Standard Model physics**
- Collider-mode operation at same time as the general-purpose detectors, with less-focused beams → most events have a single pp interaction



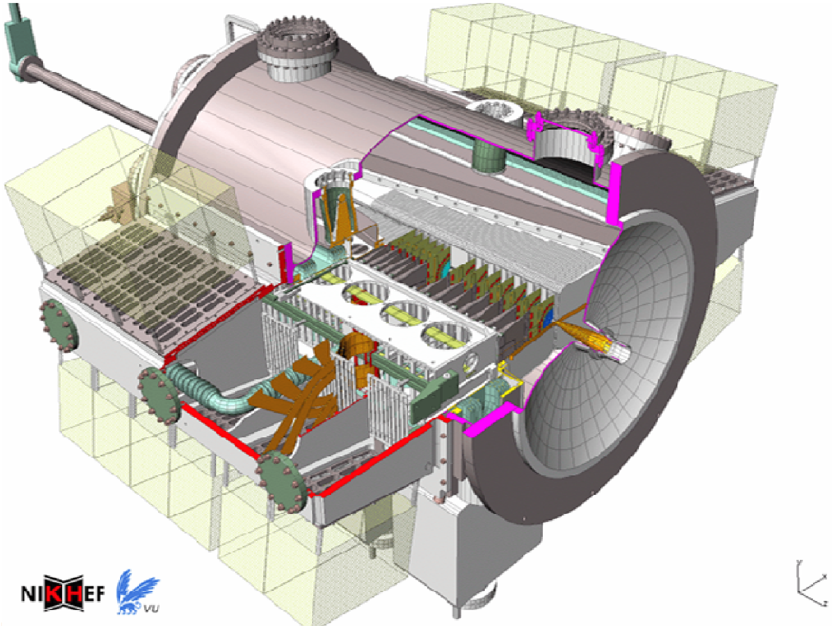
LHCb in a slide

- *pp* collisions at a centre of mass energy of 14 TeV
  - 10^{12} $b\bar{b}$/year
- Ring Imaging Cherenkov detectors
  - hadron ID for momentum from 2 to 100 GeV/c

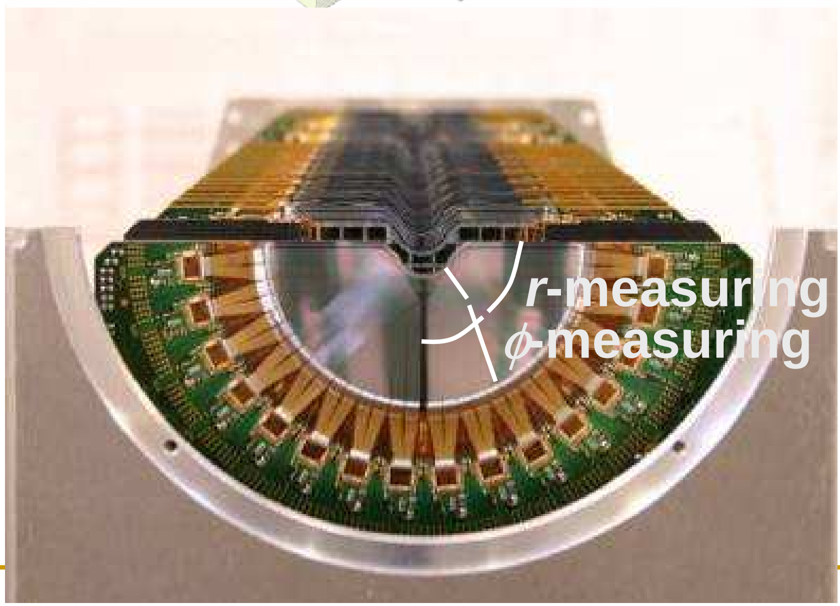


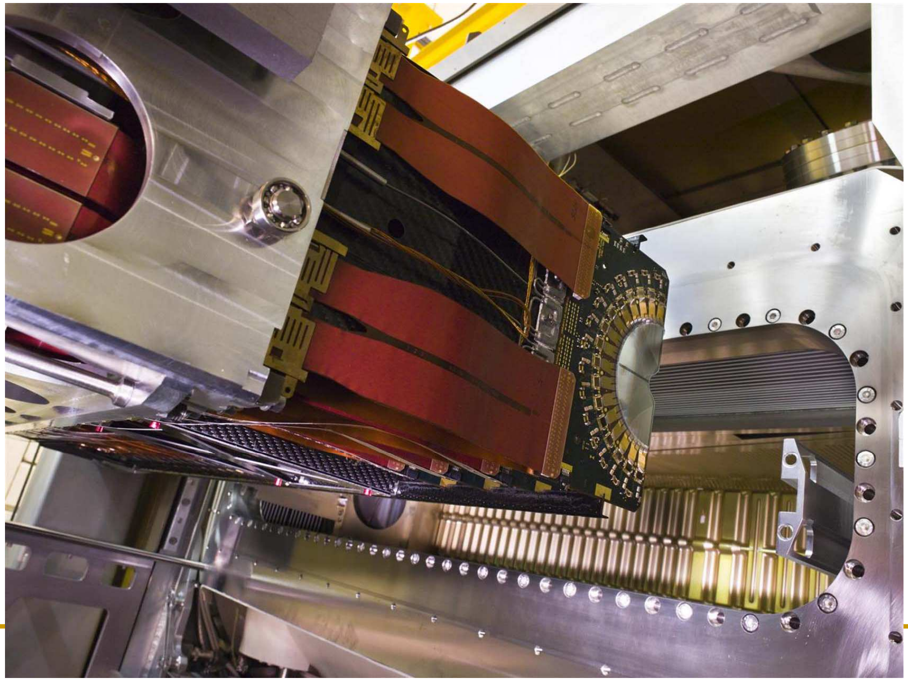
- First level hardware trigger rate from 40→1 MHz
- Software Higher Level Trigger (HLT):
  - inclusive and exclusive selections to reduce storage rate to 2 kHz

Si Vertex Locator (VELO) [Glasgow-Liverpool]

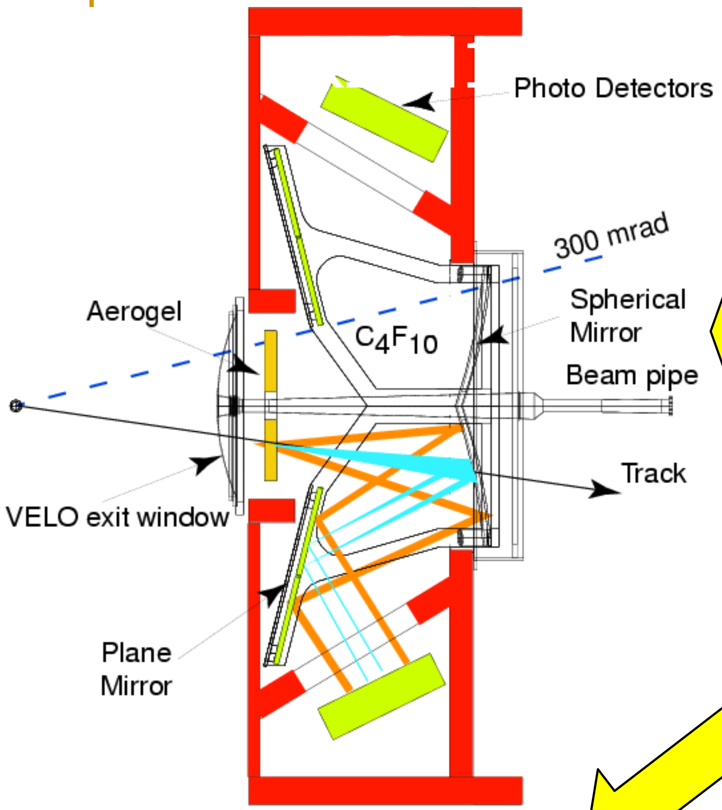


- 21 stations of Si wafer pairs with r and ϕ strip readout
- Most accurate detector at LHC
  - <10 μm precision
  - 40 fs proper time resolution
- Split in two halves to allow retraction from beam line
  - When closed 8 mm from beam

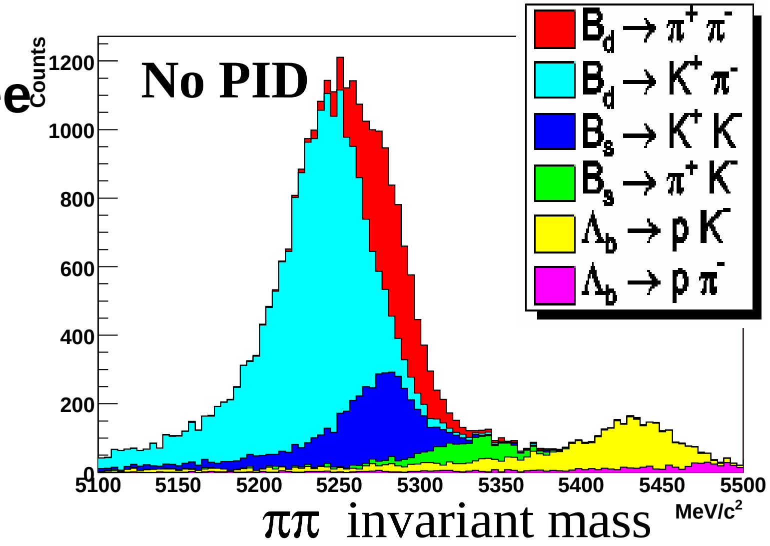




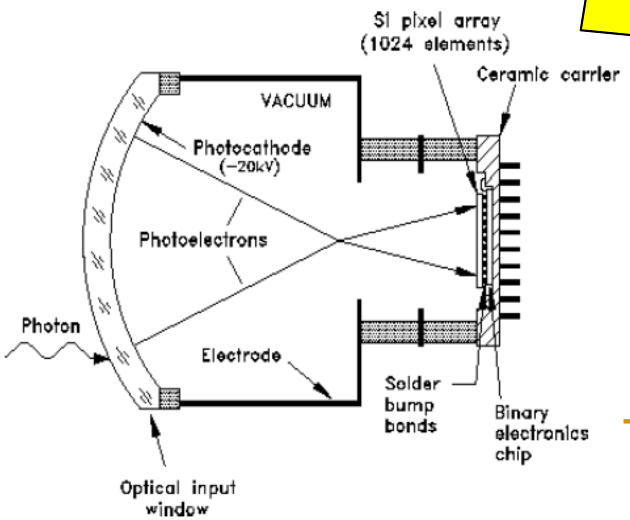
RICH [Bristol-Cambridge-Edinburgh-Glasgow-IC-Oxford-RAL]



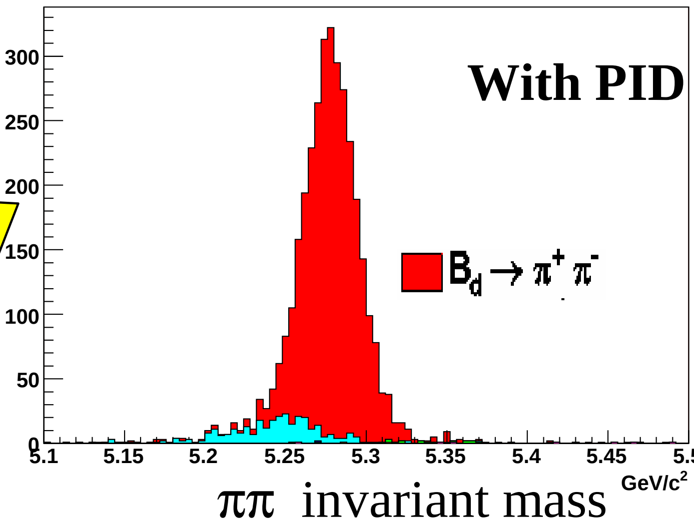
- **Two RICHs and three radiators:**
  - RICH1
    - Aerogel (2-10 GeV)
    - C_4F_{10} (10-60 GeV)
  - RICH2
    - CF_4 (16-100 GeV)



- **Readout**
  - Hybrid PhotoDiodes (HPD)
  - 1024 pixels/HPD
  - LHCb development



- **Performance:**
  - $K^{\pm}$ ID efficiency ~97%
  - $\pi \to K$ mis-ID ~4%



Trigger

Full bandwidth for flavour

Hardware trigger (L0)

- Fully synchronized (40 MHz), 4 µs fixed latency
- High p_T particles: μ, $\mu\mu$, e, γ and hadron
  - typically p_T thresholds 1 to 4 GeV/c

1 MHz readout of all detector components

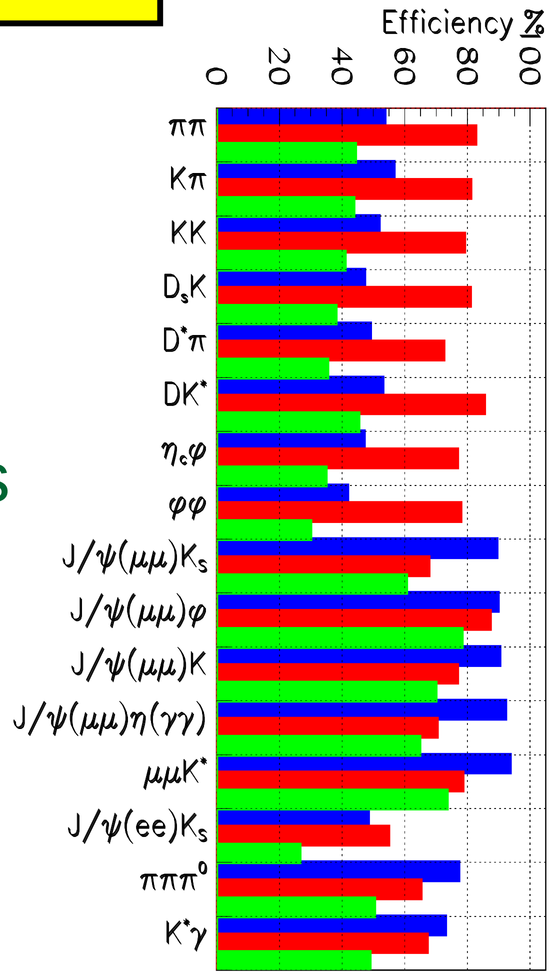
Software trigger on 1000 multicore-CPU farm

- Full detector info available, only limit is CPU time
- Use more tracking info to re-confirm L0+high IP
- Full event reconstruction: exclusive and inclusive streams tuned for specific final states

≤ 2 kHz storage

Storage

- Event size ~ 35 kB

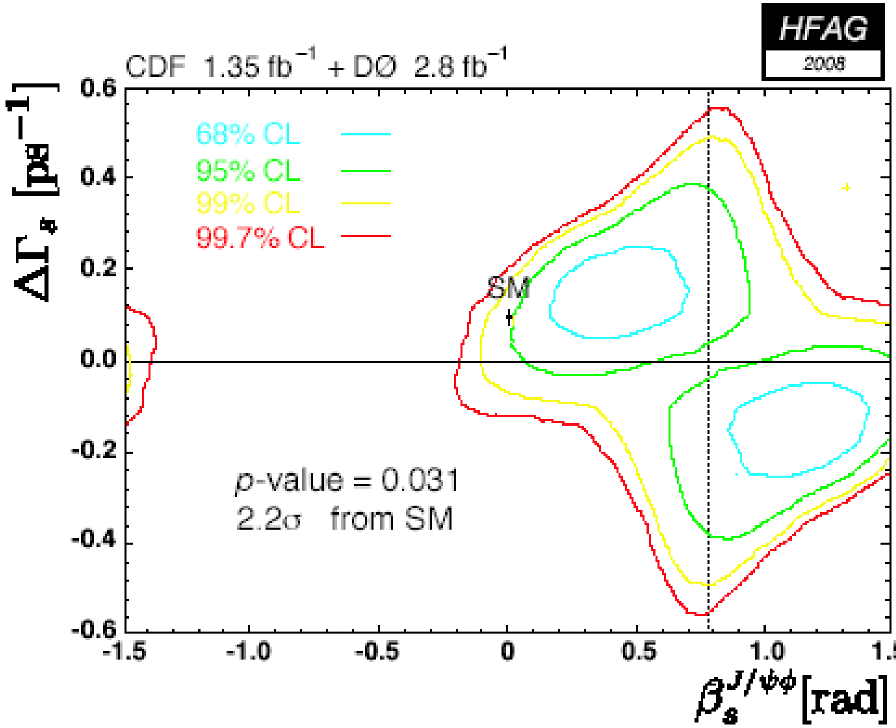


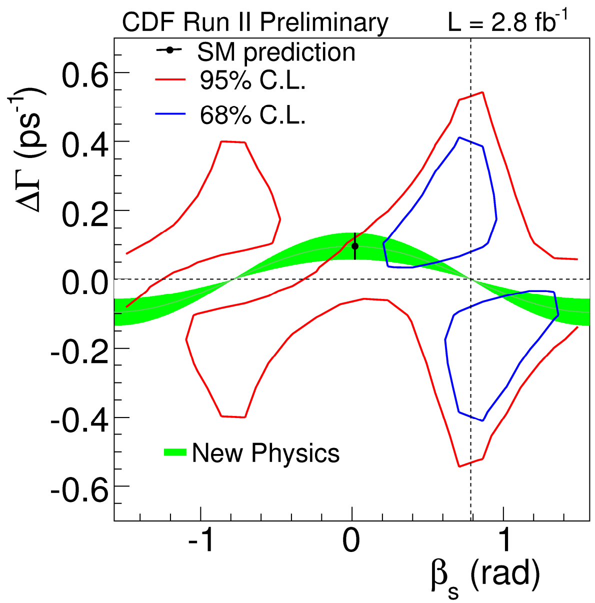
L0, HLT and L0×HLT efficiency

B_s mixing phase (for more information see G. Lanfranchi's talk at CKM2008: http://ckm2008.roma1.infn.it)

B_s mixing phase

- Predicted to be small in the SM
  - $-2\beta_s=(0.36\pm0.02)$ rad
    - CKMFitter Summer 2008
- However, indications that it is **significantly larger** from CDF and D0
- One of the principal goals of LHCb is a precise determination of this parameter



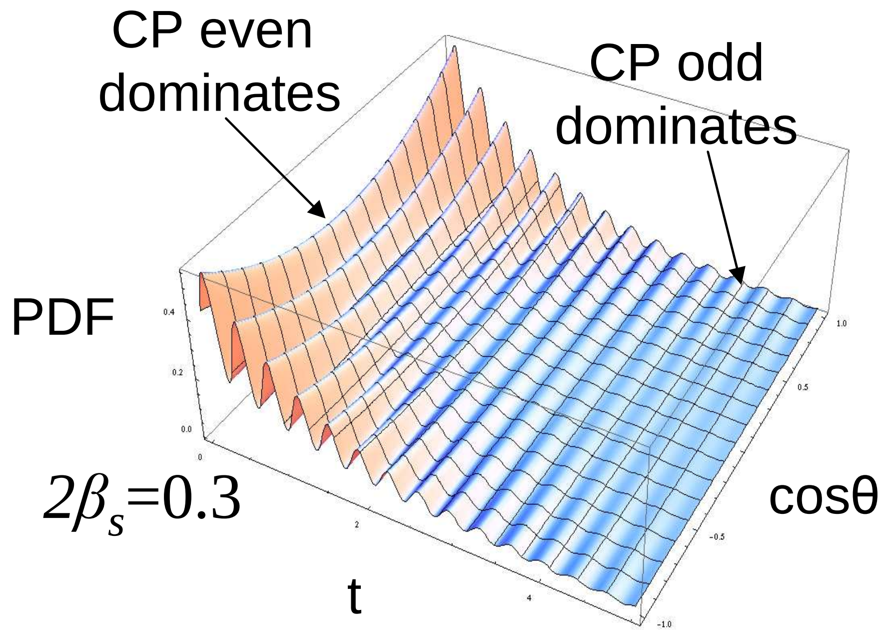


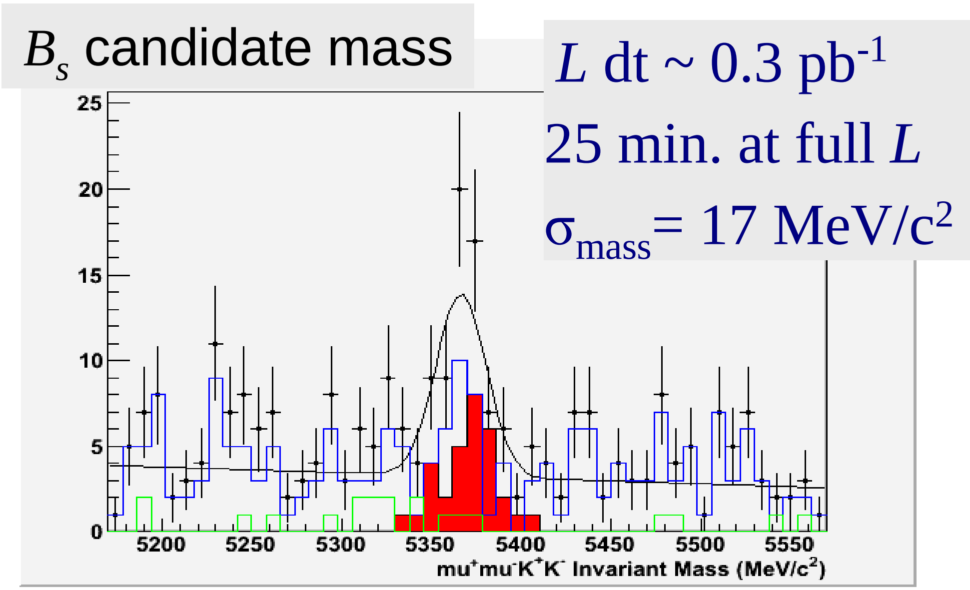
Updated CDF result even further from SM than that in HFAG average

Measuring β_s at LHCb

- $P \rightarrow VV$ decay $B_s \rightarrow J/\psi\phi$ is the golden mode for β_s
  - Time-dependent angular analysis required
  - Large signal yield in one nominal year (2 fb^{-1}) of 110k events with B/S ~ 2
  - Excellent proper-time and mass resolution
  - Tagging improved with RICH K PID

Tag	$Q=\varepsilon(1-2\omega)^2$
μ	0.75 ± 0.05
e	0.45 ± 0.04
K opp. side	**1.49 ± 0.07**
K same side	**2.13 ± 0.09**
Vertex charge	1.14 ± 0.07
Combined	**6.18 ± 0.14**





New physics sensitivity with β_s

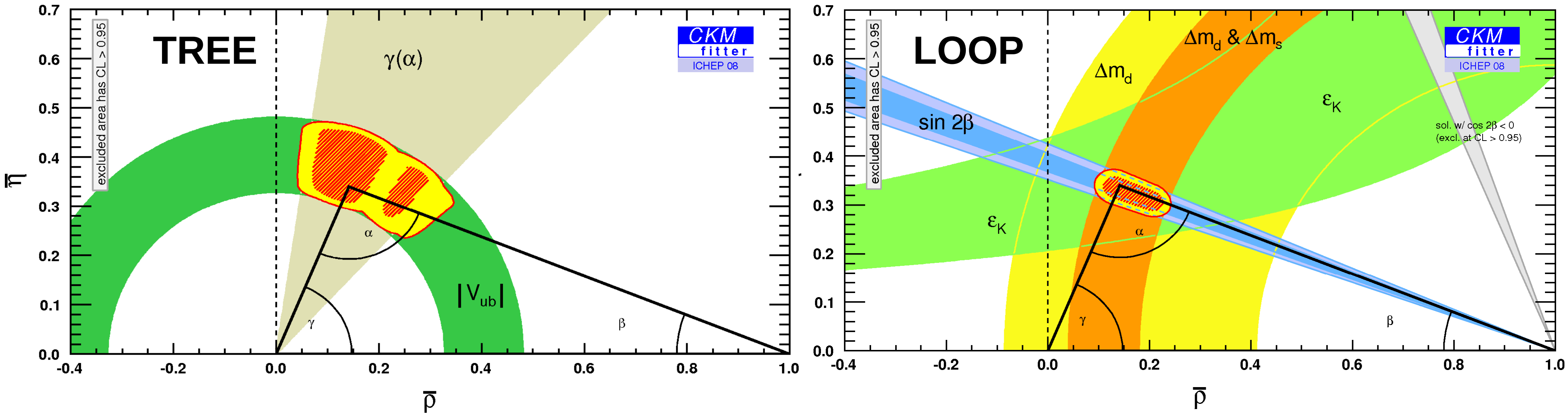
- Standalone simulations to estimate sensitivity based on results from GEANT4 simulation
  - 6 observables: proper time, 3 angles, tag and mass
  - 8 physics parameters: $2\beta_s$, $\Delta\Gamma_s$, Γ_s, two helicity amplitudes (R_0 and $R_\perp$) and two strong phases (δ_0 and $\delta_\perp$)
  - and experimental parameters (resolution, acceptance and tagging)
- 200 toy experiments corresponding to 1 year of data (2 fb^{-1})

Parameter	Input	Sensitivity
$\Delta\Gamma_s$	**0.084 ps^{-1}**	**0.008 ps^{-1}**
Γ_s	0.696 ps^{-1}	0.003 ps^{-1}
R_0	0.56	0.004
$R_\perp$	0.233	0.005
δ_0	-2.93 rad	0.07 rad
$\delta_\perp$	2.91 rad	0.10 rad
$2\beta_s$	**0.0368 rad**	**0.03 rad**

Potential to observe non-SM value within 1 year

Determination of γ (for more information see A. Carbone, A. Powell, G. Guerrer, E. Rodrigues and G. Wilkinson at CKM2008)

Motivation for precision tree level γ

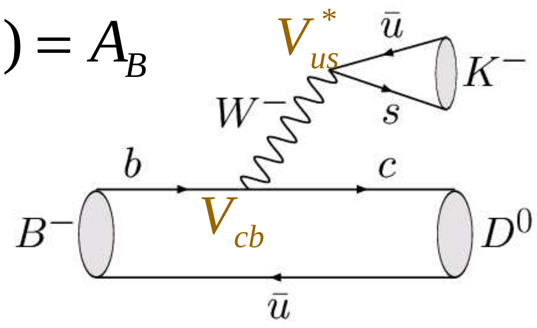


- A measurement of γ in tree level decays allows the construction of a pure SM unitarity triangle
  - Compare with loop determinations to search for new physics induced deviations
- Direct determination of γ average:
  - CKMFitter ICHEP 08: $\gamma = (68\pm30)°$
  - Compare to $\sigma(\beta)$~1°
- **Major goal of LHCb is degree level precision on γ**

Introduction $B^{\pm}\rightarrow DK^{\pm}$

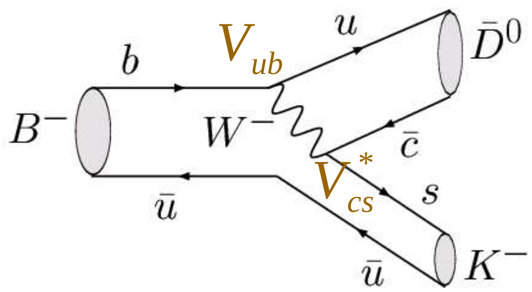
- Current B factory determinations use $B\rightarrow DK$ decays that involve both $b\rightarrow c$ and $b\rightarrow u$ transitions

$$A(B^- \rightarrow D^0 K^-) = A_B$$



Strong phase difference

$$A(B^- \rightarrow \overline{D}^0 K^-) = A_B r_B e^{i(\delta-\gamma)}$$



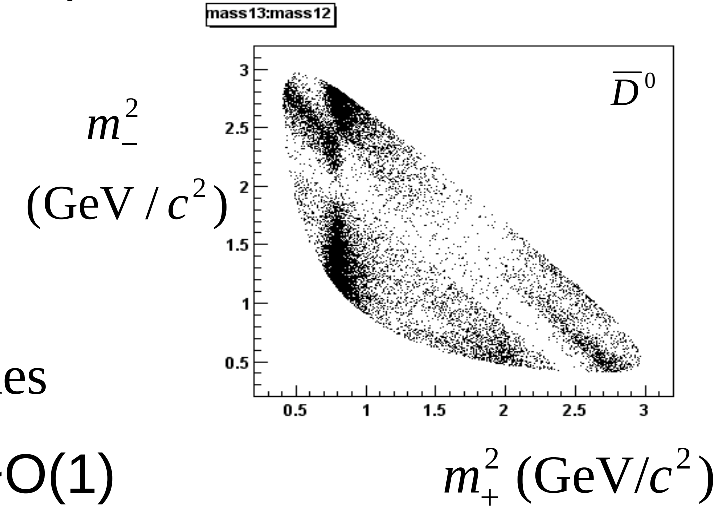
Ratio of absolute amplitudes of colour/CKM suppressed to favoured (~0.1)

- Access γ via interference if D^0 and $\overline{D}^0$ decay to the same final state
- These measurements are theoretically clean
  - no penguin $\Rightarrow$CKM standard candle
  - largest correction is sub-degree from D-mixing
- We have investigated several such decays

$B^+ \rightarrow D(K^0\pi\pi)K^+$

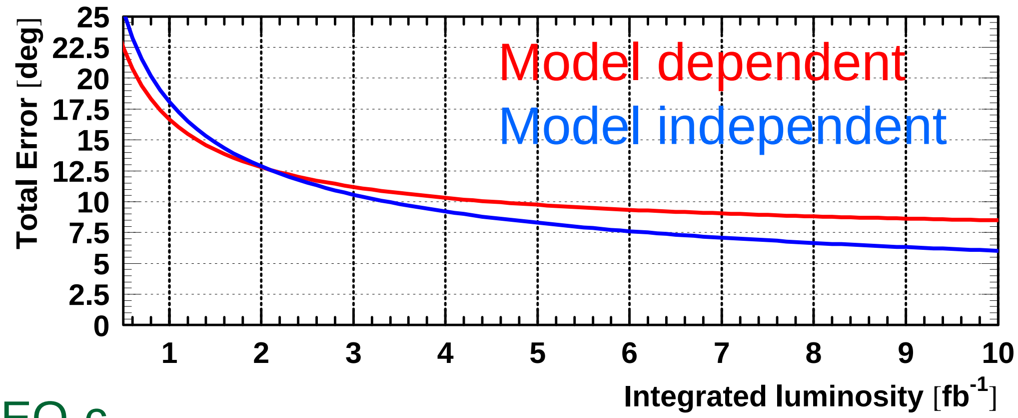
- Exploit differences between the $D \rightarrow K^0_S\pi^+\pi^-$ Dalitz plots from B^- and B^+

$$A^- = f(m_-^2, m_+^2) + r_B e^{i(-\gamma+\delta)} f(m_+^2, m_-^2)$$
$$A^+ = f(m_+^2, m_-^2) + r_B e^{i(\gamma+\delta)} f(m_-^2, m_+^2)$$

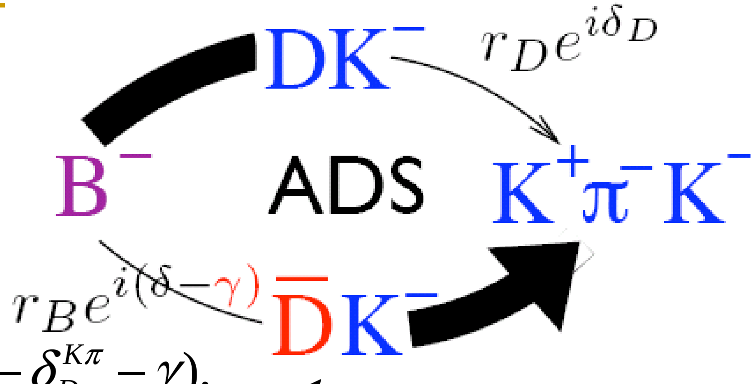


$m_{\pm} = K_S^0\pi^{\pm}$ invariant mass and $f(m_{\pm}^2, m_{\mp}^2)$ Dalitz amplitudes

- Reconstruct ~5k events/year at LHCb with B/S~O(1)
- Two methods:
  - Model dependent
    - unbinned analysis with resonance model
    - Pro: full statistical power
    - Con: model systematic uncertainty
  - Model independent
    - binned analysis information from CLEO-c
    - Pro: easier measurement including systematic studies
    - Con: loss of statistical power ~20%



$B \to D(hh)K^+$



- Look at DCS and CF decays of D to obtain rates that have enhanced interference terms

$$\Gamma(B^- \to (K^-\pi^+)_D K^-) \propto 1 + (r_B r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cos(\delta_B - \delta_D^{K\pi} - \gamma),$$

$$\Gamma(B^- \to (K^+\pi^-)_D K^-) \propto r_B^2 + (r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cos(\delta_B + \delta_D^{K\pi} - \gamma),$$

$$\Gamma(B^+ \to (K^+\pi^-)_D K^+) \propto 1 + (r_B r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cos(\delta_B - \delta_D^{K\pi} + \gamma),$$

$$\Gamma(B^+ \to (K^-\pi^+)_D K^+) \propto r_B^2 + (r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cos(\delta_B + \delta_D^{K\pi} + \gamma)$$

$$\Gamma(B^- \to (h^+h^-)_D K^-) \propto 1 + r_B^2 + 2 r_B \cos(\delta_B - \gamma)$$

$$\Gamma(B^+ \to (h^+h^-)_D K^+) \propto 1 + r_B^2 + 2 r_B \cos(\delta_B + \gamma)$$

h=π or K

GLW modes

- LHCb measure these rates
  - Unknowns : r_B~0.1, δ_B, $\delta_D^{K\pi}$, γ, $N_{K\pi}$, N_{hh} (r_D=0.06 well measured)
  - With knowledge of the relevant efficiencies and BRs, the normalisation constants ($N_{K\pi}$, N_{hh}) can be related to one another
  - **Overconstrained: 6 observables and 5 unknowns**
- Identical procedure with $B^0 \to D(hh)K^{*0}$ - smaller BF but r_{B0}~0.3
- **Can add multibody flavour specific states (i.e. K3π) exploiting CLEO-c data - UK involvement**

Combined results for tree-level γ

- Given common parameters amongst the modes a global fit has been implemented

δ_{B^0} (°)	0	45	90	135	180
σ_γ for 0.5 fb^{-1} (°)	8.1	10.1	9.3	9.5	7.8
σ_γ for 2 fb^{-1} (°)	4.1	5.1	4.8	5.1	3.9
σ_γ for 10 fb^{-1} (°)	2.0	2.7	2.4	2.6	1.9

Currently unknown – leads to largest variations in sensitivity

- CLEO-c inputs essential to these results
- Includes time-dependent measurements $B_s \to D_s K$ and $B \to D\pi$

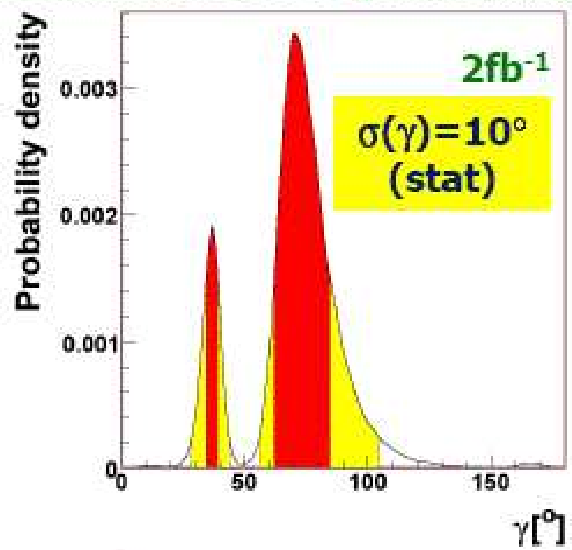
Analysis	$\delta_{B^0} = 0°$	$\delta_{B^0} = 45°$
$B^- \to D^0(hh)K^-$, $B^- \to D^0(K^\pm\pi^\mp\pi^+\pi^-)K^-$	25	38
$B^- \to D^0(K^0_S\pi^+\pi^-)K^-$	12	25
$B^0 \to D^0(hh)K^{*0}$	44	8
$B_s \to D_s^\mp K^\pm$	16	24
$B^0 \to D^\mp\pi^\pm$	3	5

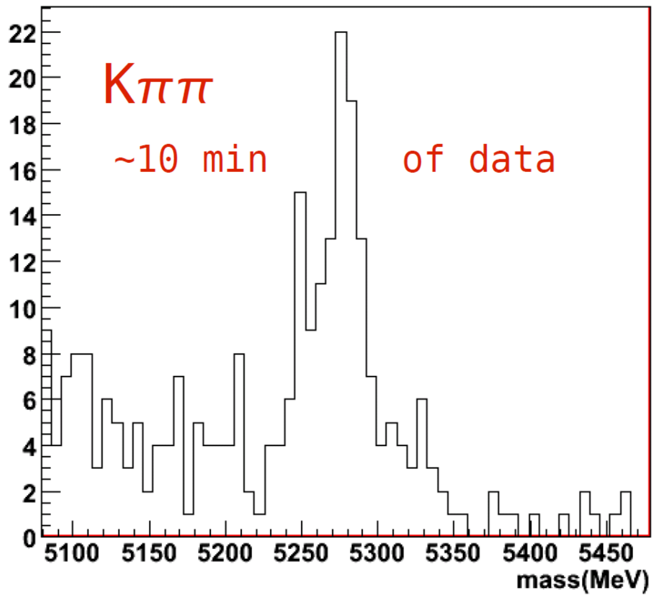
Weight of each mode

γ from loop influenced decays

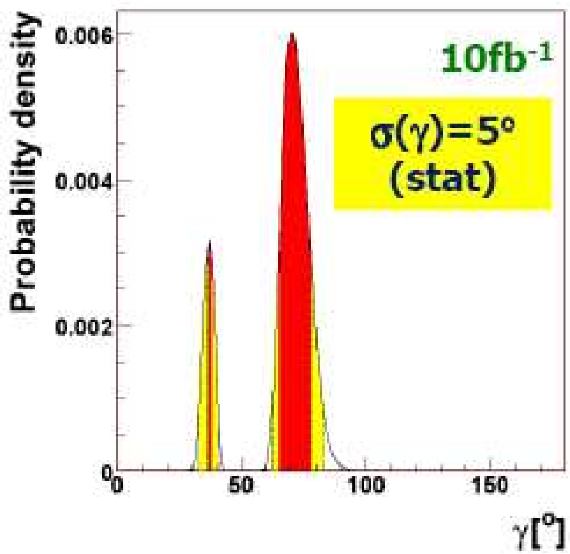
- Also studying loop influenced decays which measure γ
  - Both penguin and tree diagrams contribute
- U-spin ($d \leftrightarrow s$) combination of $B^0 \to \pi\pi$ and $B^0_s \to KK$ leads to 10 fb^{-1} sensitivity of ~5°
  - Allows for U-spin breaking at the 20% level

Fits allow for 20% U-spin breaking





- Also studying $B \to K\pi\pi$:
  - 500k/2 fb^{-1} with S/B~3
- Similar sensitivity to γ as $B \to hh$

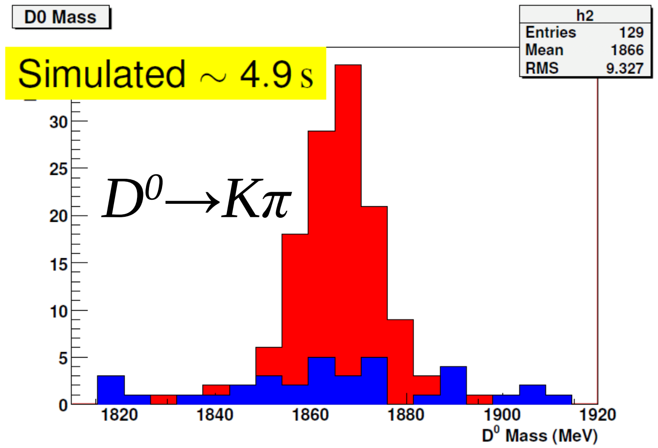


CPV in charm (for more information see P. Spradlin's talk at CKM 2008)

Charm physics at LHCb

- LHCb also excellent instrument for charm mixing and CP violation measurements
  - PID, vertexing and mass resolution
  - Up to 300 Hz of HLT output dedicated to $D^{*+} \rightarrow D^0(hh)\pi^+$
- For CP violation modes studies have been:
  - $D \rightarrow \pi\pi$ and $D \rightarrow KK$
  - Any deviations from zero (and between modes) signature of BSM physics

	Data set	$N(K^-K^+)$	$A_{CP}(K^-K^+)(\%)$
Belle	$540\ \mathrm{fb}^{-1}$	120×10^3	$-0.43 \pm 0.30 \pm 0.11$
BaBar	$386\ \mathrm{fb}^{-1}$	130×10^3	$0.00 \pm 0.34 \pm 0.13$
CDF	$123\ \mathrm{pb}^{-1}$	16×10^3	$2.0 \pm 1.2 \pm 0.6$
HFAG Avg			-0.16 ± 0.23
LHCb	$10\ \mathrm{fb}^{-1}$	8×10^6	$A_{CP} \pm 0.04\ (\mathrm{stat})^*$



- *only charm from B so far – prompt charm as well can significantly increase sample

Other potential charm measurements

- Relatively unexplored area on LHCb
- Many more CP violation measurements possible
  - Time-dependent CP violation in $D^0 \to K\pi$
  - Three-body decay amplitude analyses:
    - $D^0 \to K_S\pi\pi$, $D^0 \to K_S K\pi$ and $D^0 \to K_S KK$
    - $D^+ \to K\pi\pi$ and $D^+ \to KK\pi$
  - Four-body T-odd moments and amplitude analyses
    - $D^0 \to K\pi\pi\pi$
    - $D^0 \to KK\pi\pi$

More CPV B measurements

- Some other modes under study
  - sin2β
  - $B\rightarrow\rho\pi$ and $B\rightarrow\rho^0\rho^0$ to determine α
  - b→sg penguins: $B_s\rightarrow\phi\phi$, $B\rightarrow K^*K^*$ *and* $B\rightarrow\phi K^0{}_S$
    - see Y. Xie at CKM 2008
  - $B_s\rightarrow\phi\gamma$
    - see P. Koppenburg's talk at this meeting
  - Other $B\rightarrow DK$ modes:
    - $D\rightarrow K^0{}_S KK$, $D\rightarrow K\pi\pi^0$, $B\rightarrow D^*K$ and $B_s\rightarrow D\phi$
  - Time dependent measurements of γ
    - $B\rightarrow D^*\pi$, $B\rightarrow D^*\rho$ and $B_s\rightarrow D_sK\pi\pi$

Conclusions

- Opportunities at LHCb to observe new physics in:
  - B_s mixing phase
  - Comparison of tree level unitarity triangle to that determined from loop influenced measurements
- LHCb is also LHCc
  - Huge charm samples produced
  - Will be used to search for new physics induced CPV
- Many other CPV measurements will be made