Determination of γ from $B^{\pm}\to DK^{\pm}$: LHCb and CLEOc

Jim Libby (University of Oxford)

Outline

- Motivation for the precise determination of γ
- LHCb
  - Overview
  - Status
- Measuring γ with $B^{\pm}\rightarrow DK^{\pm}$ at LHCb
- Complementary measurements of D decay at CLEO-c

Flavour physics

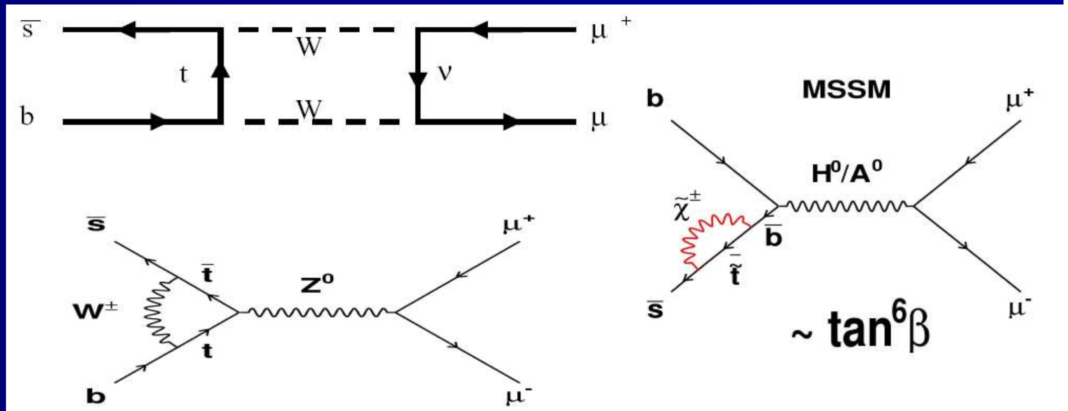
Flavour physics has been essential to formation of the Standard Model:

- **GIM mechanism → charm**
- **CP Violation → 3 generations**
- **B mixing → heavy top**

All surprises that predated 'direct' discovery!

We may assume same story will continue!
Precise measurements ⇒nature of new physics at multi-TeV scale

In B physics goal is to look for new sources of CP violation, or deviations from SM in very rare CP conserving processes, eg. BR($B_s \to \mu\mu$)



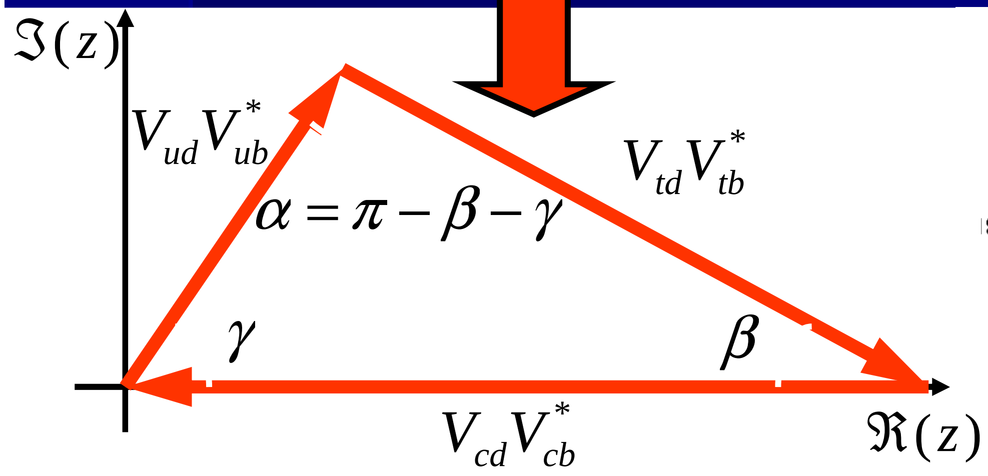
CP violation in weak decays of quarks

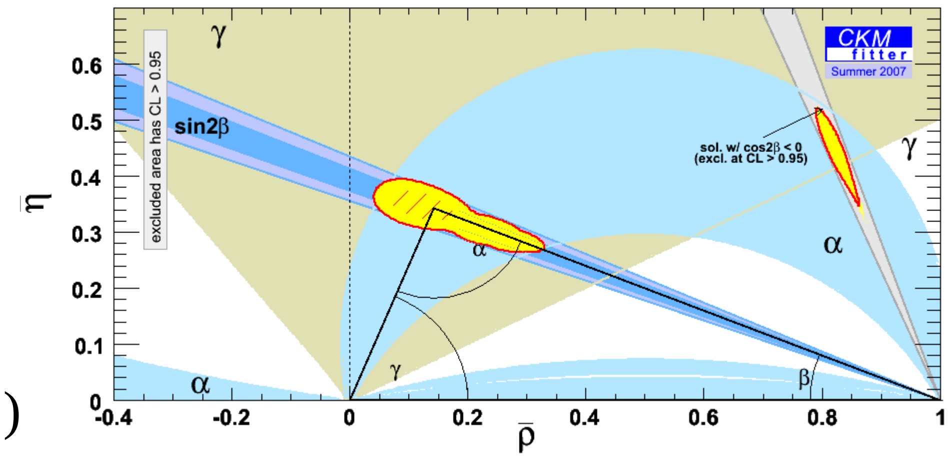
- *CP* violation implies differences between **matter** and **antimatter**
- In the Standard Model the weak and flavour eigenstates of the three generations of quarks are related by a unitary matrix
- A complex phase introduces CP violating effects
- Represented in terms of the **Unitarity Triangle**

$$\mathbf{V}_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \propto e^{i\gamma} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} \propto e^{i\beta} & V_{ts} & V_{tb} \end{pmatrix}$$

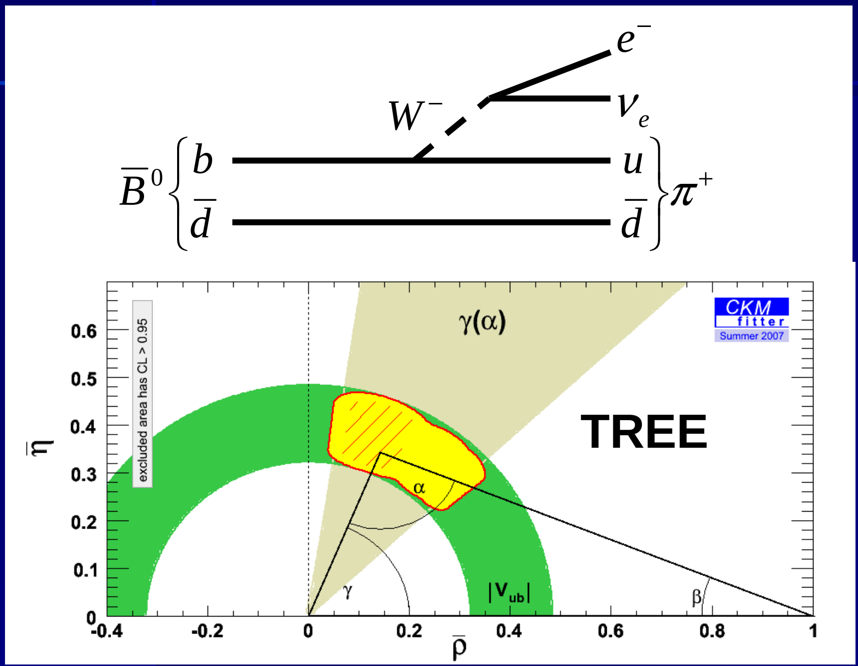
All sides and angles can be measured in *b*-hadron decay

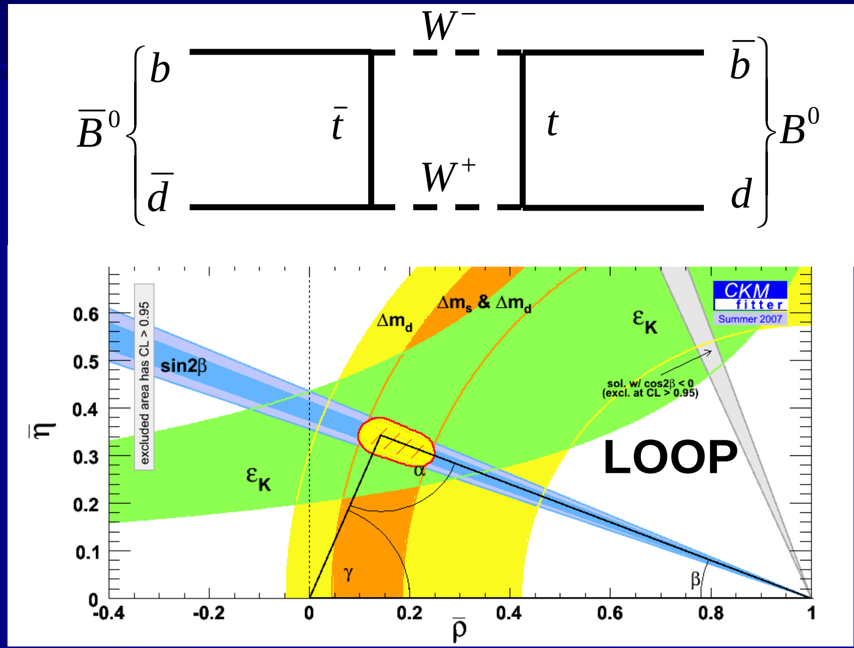
$$\mathbf{V}_{\mathbf{CKM}}\mathbf{V}_{\mathbf{CKM}}^{\dagger} = \mathbf{I} \Rightarrow V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$



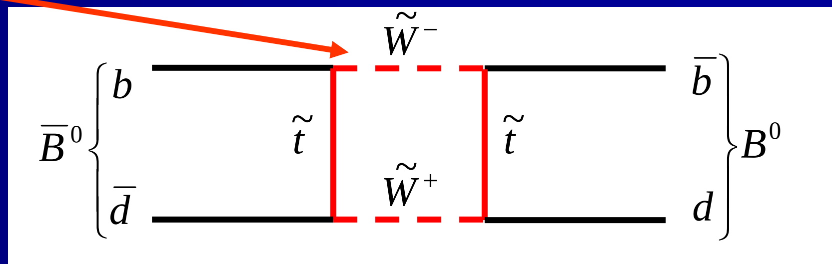


Searching for new physics

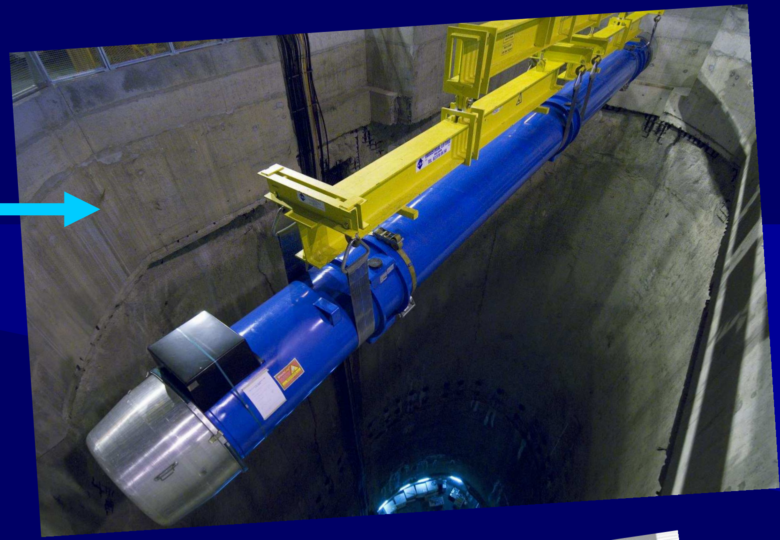




- Non Standard Model particles contribute within the virtual loops
- Differences between tree-level and loop-level triangles
  - **Signature of new physics**
- **Complements direct searches**



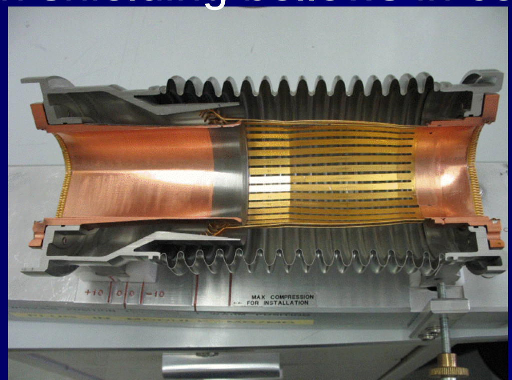
LHC Status



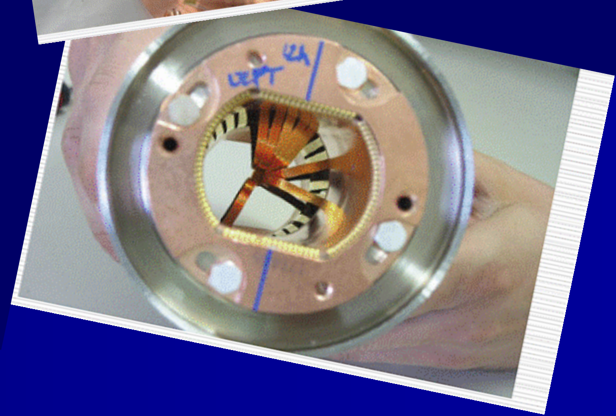
- Last dipole lowered April 26th this year! (First was in March 2005)
- Last interconnect – Nov 2007
- Quad triplet remediation – Sep 2007

Latest official schedule had beam commissioning beginning in May ’08, with then 2 months estimated before first 14 TeV collisions

Since then, there have been problems, eg. with shielding bellows in cold interconnects



Warm up of sector 7-8

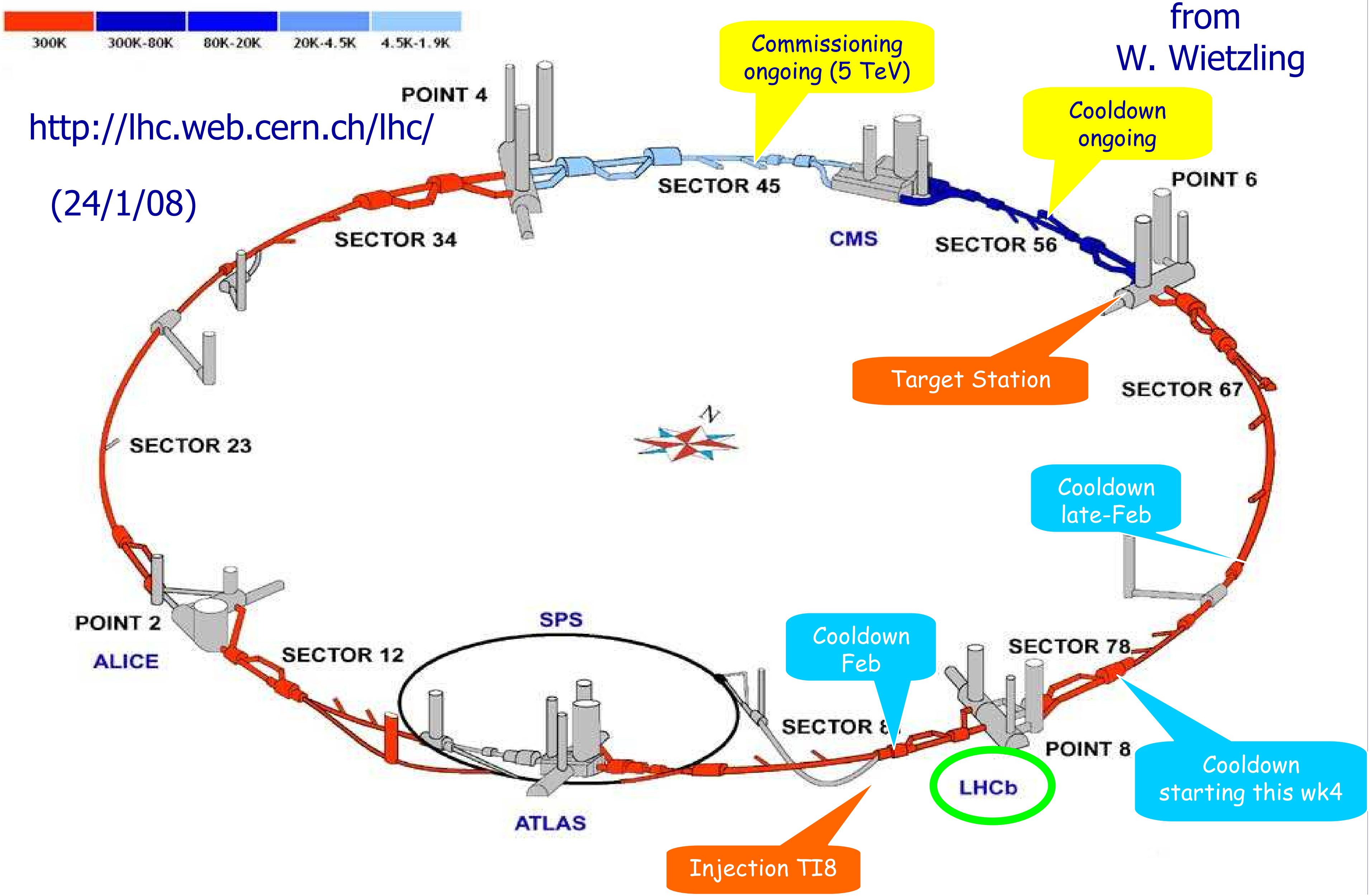


Status of the LHC Machine

from
W. Wietzling

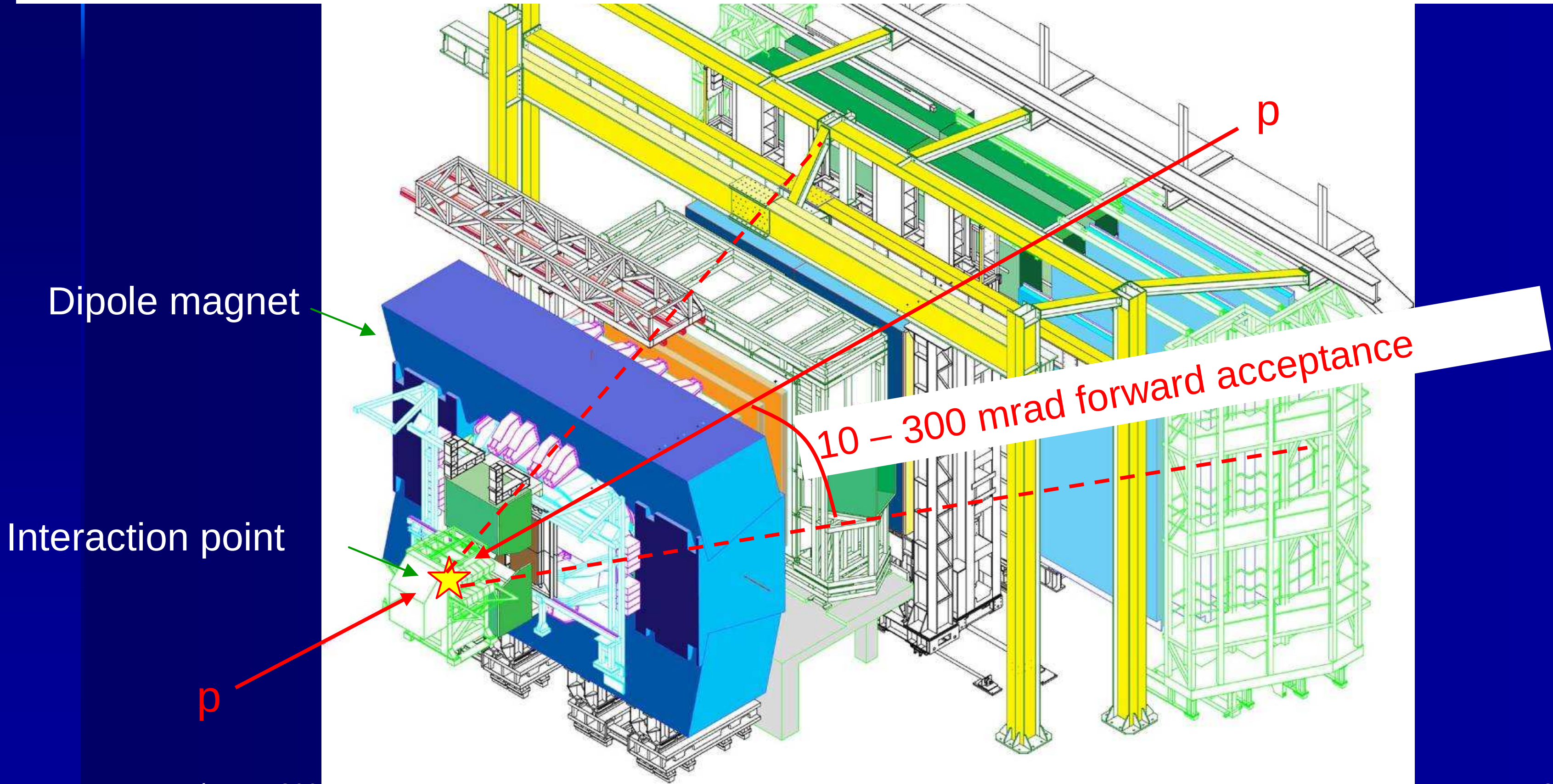
http://lhc.web.cern.ch/lhc/

(24/1/08)



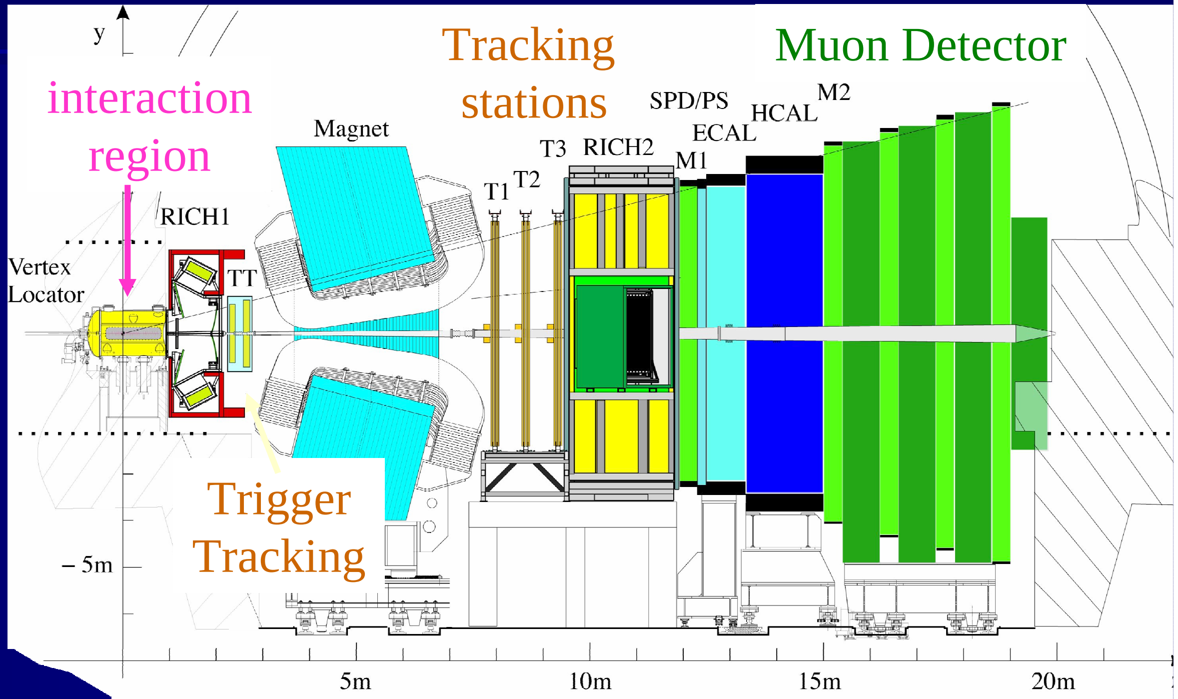
The LHCb Experiment

- Dedicated experiment for precision measurement of CP violation and rare decays of b-hadrons (and charm) at the LHC
- Collider-mode operation at same time as the general-purpose detectors, with less-focused beams → most events have a single pp interaction



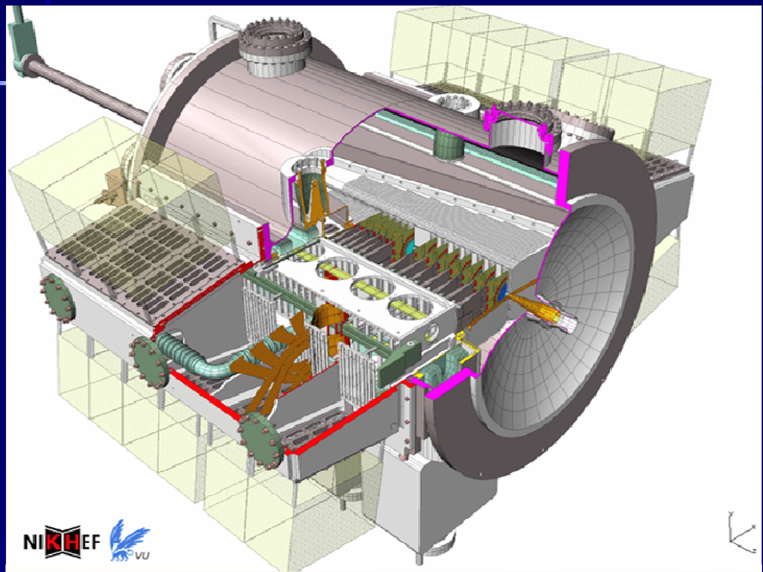
LHCb in a slide

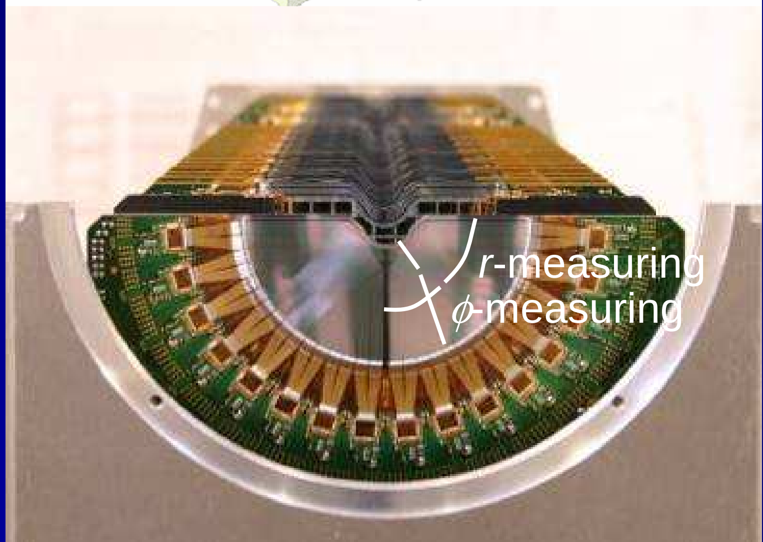
- *pp* collisions at a centre of mass energy of 14 TeV
  - 10^{12} $b\bar{b}$/year
- Ring Imaging Cherenkov detectors
  - hadron ID for momentum from 2 to 100 GeV/c



- First level hardware trigger rate from 10→1 MHz
  - 10 MHz the rate of bunch crossings with 1 or more interaction
  - Bunch crossing rate 30 MHz (offset interaction point)
- Software Higher Level Trigger (HLT):
  - inclusive and exclusive selections to reduce storage rate to 2 kHz

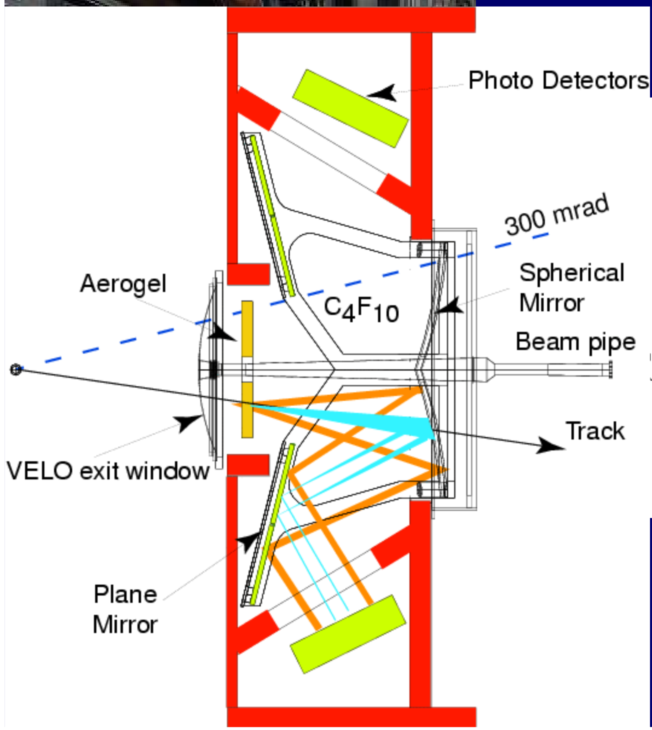
Si Vertex Locator (VELO)

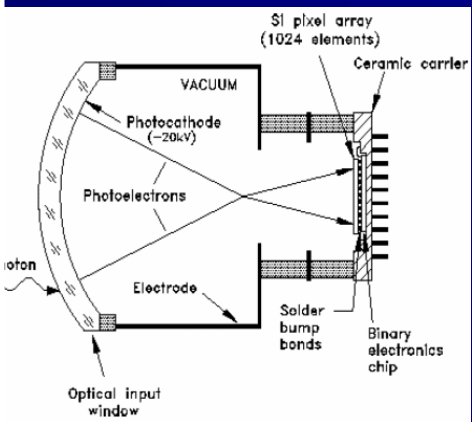




- 21 stations of Si wafer pairs with r and ϕ strip readout
- Split in two halves to allow retraction from beam line
  - When closed 8 mm from beam
- Both detector halves now installed in the pit

RICH



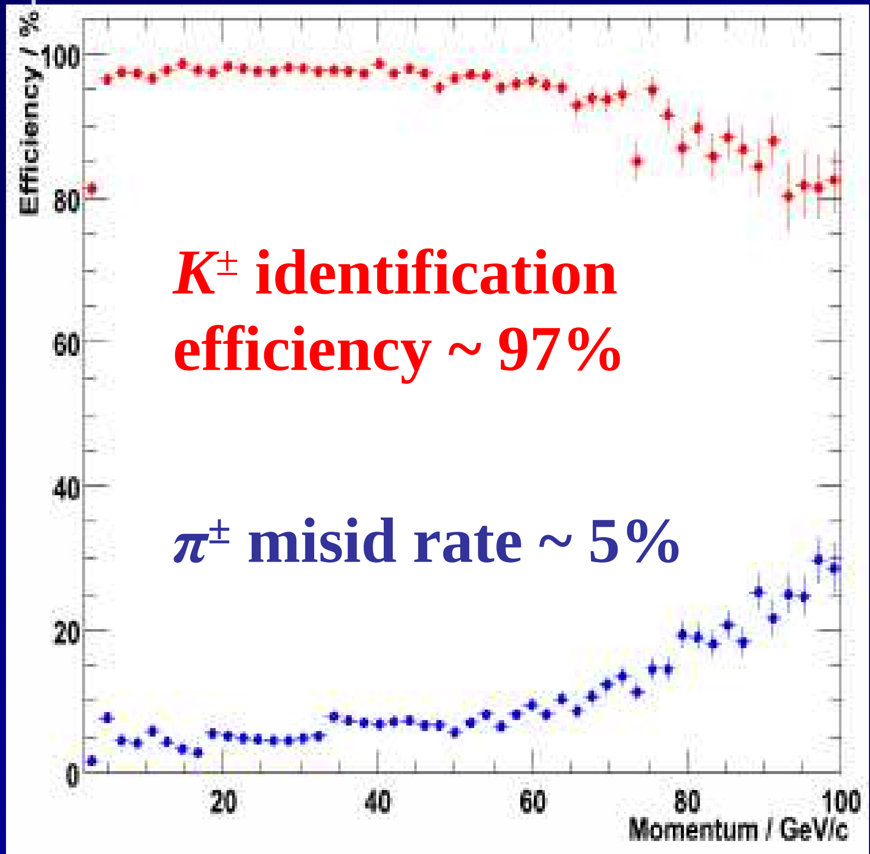


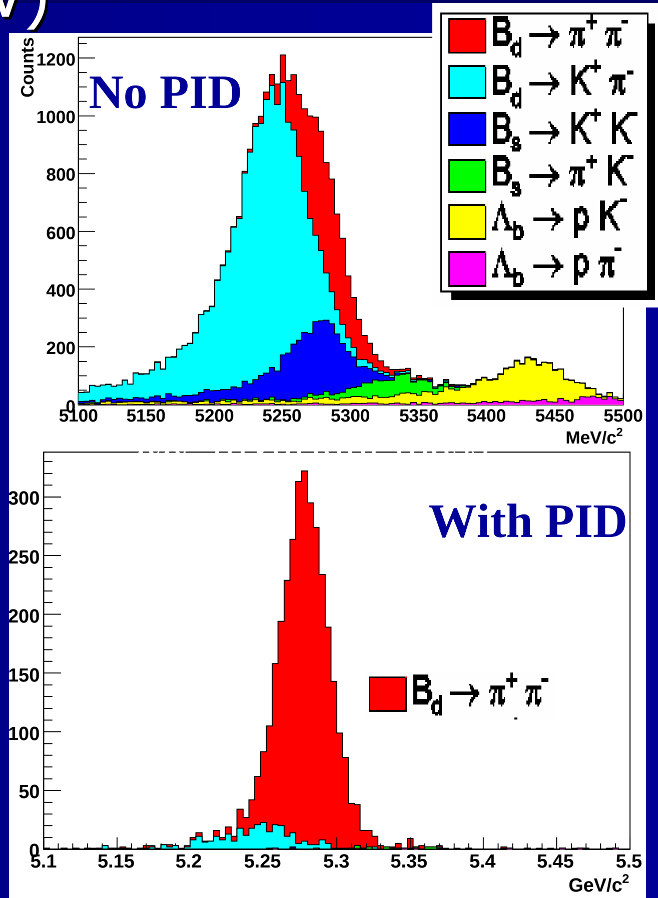
Readout: Hybrid PhotoDiodes HPD – 1024 pixels – LHCb development

RICH Detectors

3 radiators: RICH1 Aerogel (2-10 GeV), C_4F_{10} (10-60 GeV)

RICH2 CF_4 (16-100 GeV)





ππ invariant mass

Status: RICH2 ready: full DAQ exercised

RICH1: full commissioning early 2008

Trigger

Full bandwidth for flavour unlike GPDs

Hardware trigger (L0)

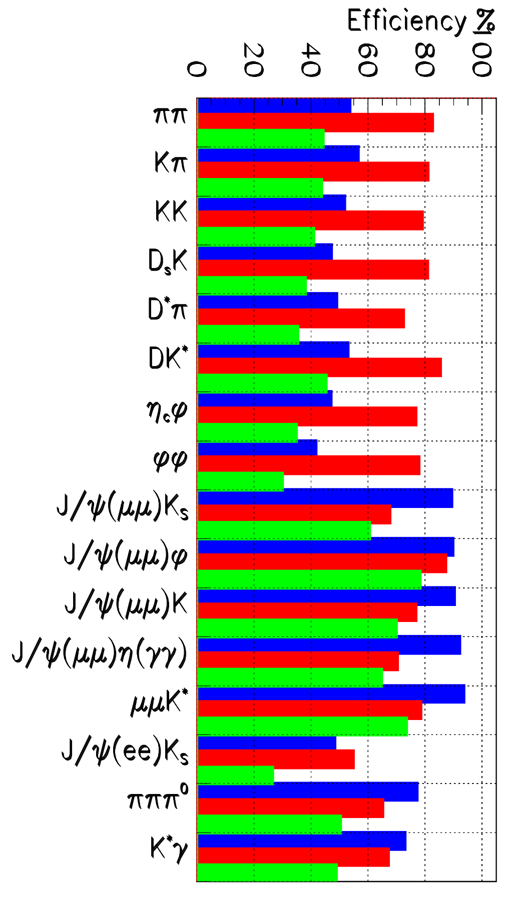
- Fully synchronized (40 MHz), 4 μs fixed latency
- High p_T particles: μ, μμ, e, γ and hadron
  - (typically p_T ~1-4 GeV/c)

1 MHz (readout of all detector components)

Software trigger (HLT)

- 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

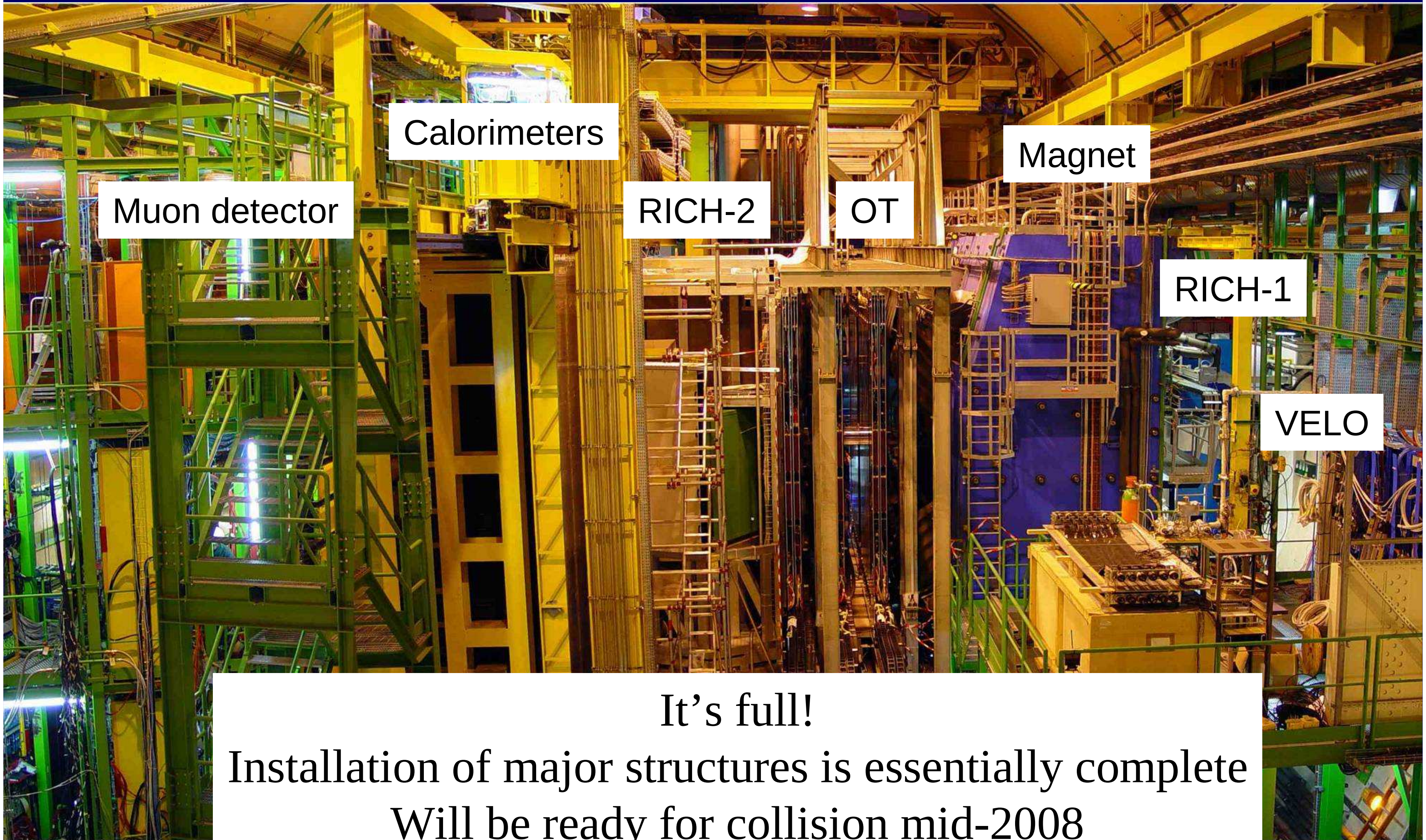
≤ 2 kHz (storage: event size ~35kB)



L0 HLT and L0×HLT efficiency

PC farm of ~1000 nodes (multicore)

View of the cavern



It's full!
Installation of major structures is essentially complete
Will be ready for collision mid-2008

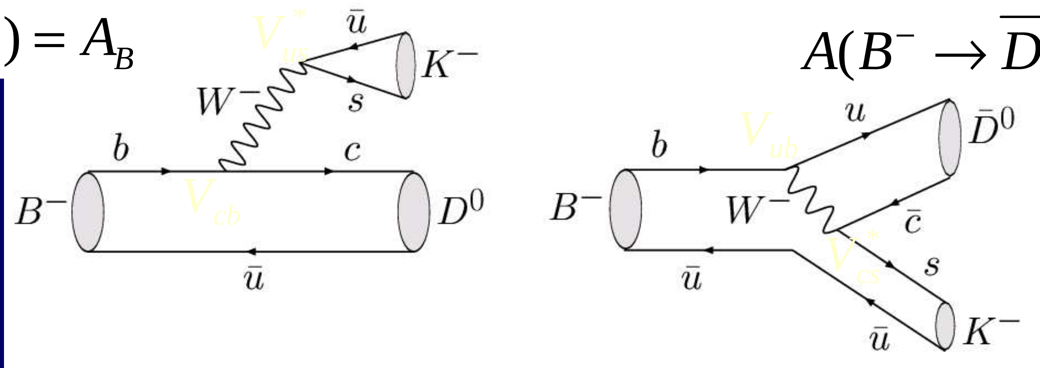
Introduction $B^{\pm}\rightarrow DK^{\pm}$

- $B\rightarrow DK$ decays involve b→c and b→u transitions

Strong phase difference

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

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



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 ⇒CKM standard candle
  - largest correction is sub-degree from D-mixing
- LHCb looking at a number of strategies to study such decays
  - B^+: Atwood-Dunietz-Soni ('ADS'), 3 and 4 body Dalitz Plot Anal.

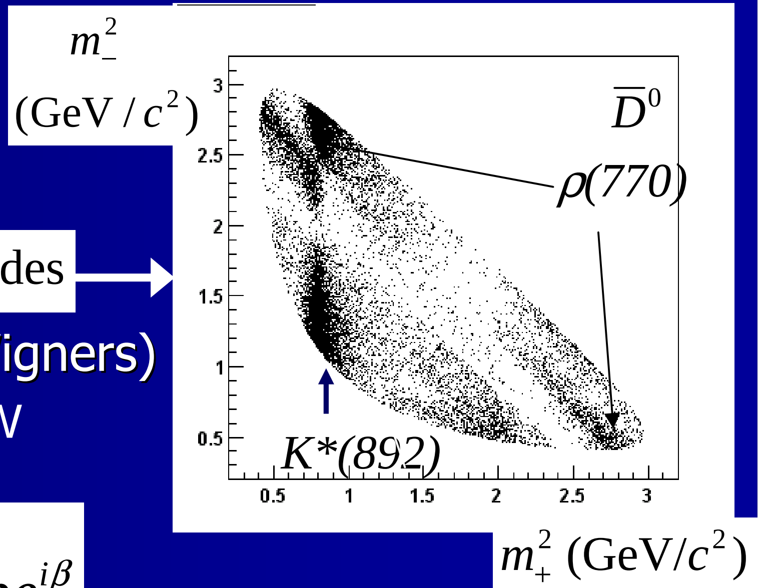
$B^{\pm}\to D(K^0{}_S\pi^+\pi^-)K^{\pm}$

- For $B^+\to D(K^0\pi^+\pi^-)K^+$

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

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

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



- Assume isobar model (sum of Breit-Wigners)

Number of resonances — Rel. BW

$$f(m_+^2, m_-^2) = \left[\sum_{j=1}^{N} a_j e^{i\alpha_j} A_j(m_+^2, m_-^2)\right] + be^{i\beta}$$

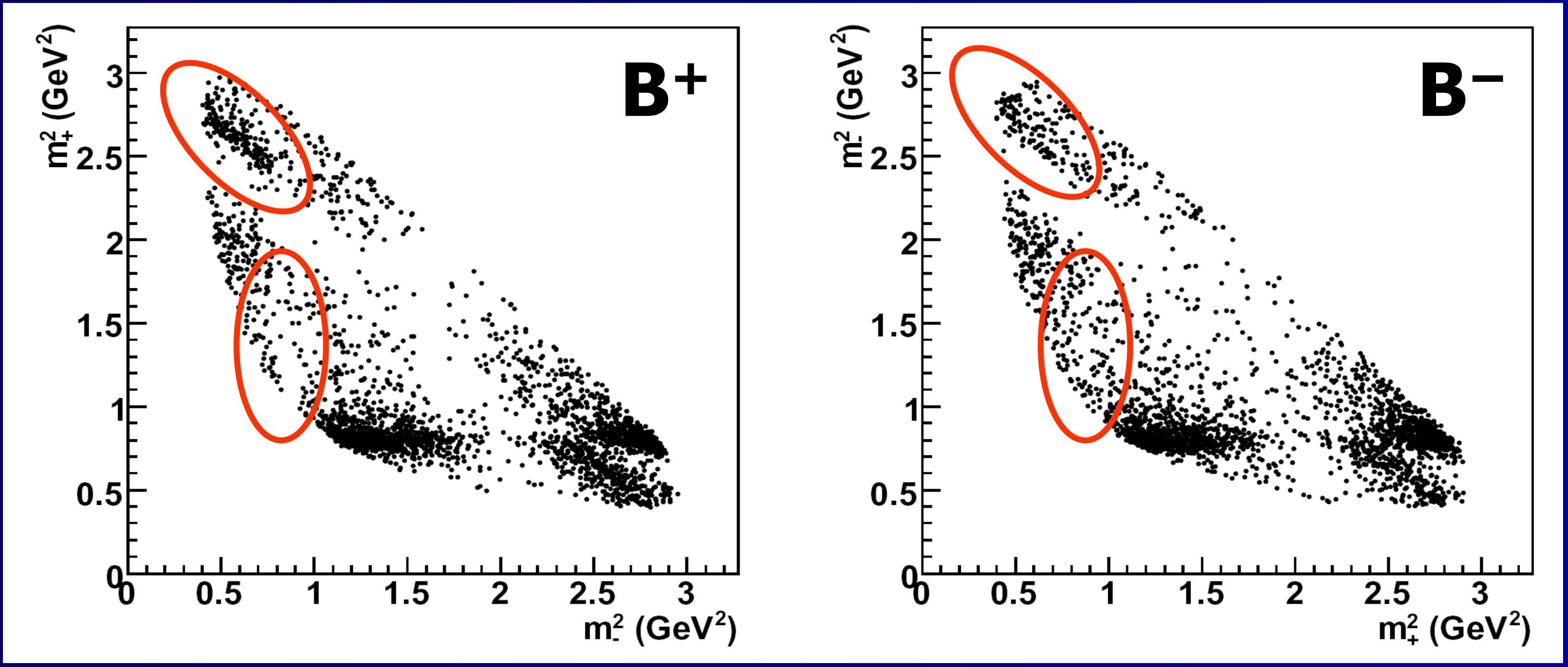
Amplitude and phase extracted from $D^{*+}\to D^0\pi^+$ sample at B-factories

Non-resonant

- Fit D-Dalitz plots from B-decay to extract γ, r_B and δ_B

$B^{\pm} \to D(K^0_S \pi^+ \pi^-) K^{\pm}$

Absence of CP violation: distributions would be identical



Simulated LHCb data

Current e^+e^- results

PRD 73, 112009 (2006)
hep-ex/0607104

- Current best direct constraints on γ:

$$\phi_3 = (53^{+15}_{-18}(\text{stat}) \pm 3(\text{syst}) \pm 9(\text{model}))^\circ \text{ [Belle]}$$

$$\gamma = (92 \pm 41(\text{stat}) \pm 11(\text{syst}) \pm 12(\text{model}))^\circ \text{ [BABAR]}$$

- Based on ~300 events each (~1/3 of final data set)
- **However, large error from isobar model assumptions**
- BABAR and Belle use large samples of flavour tagged $D^{*+} \to D^0\pi^+$ events to find parameters of the isobar model
  - Excellent knowledge of $|f|^2$ but phases less well known
- Model uncertainties from assumptions about the resonance structures in the model

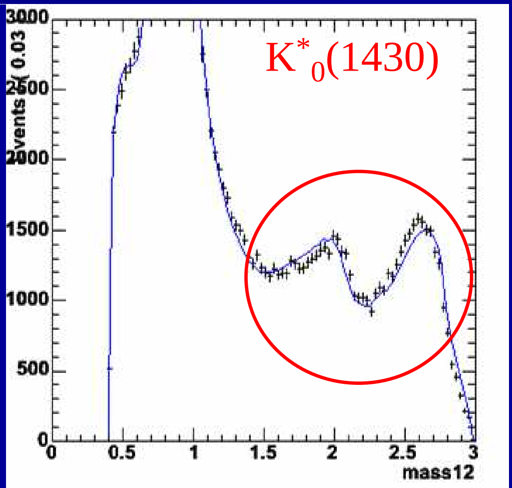
Isobar model uncertainty

BABAR (PRL 95 121802,2005)

Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.781 ± 0.018	131.0 ± 0.8	0.586
$K_0^*(1430)^-$	2.45 ± 0.08	-8.3 ± 2.5	0.083
$K_2^*(1430)^-$	1.05 ± 0.06	-54.3 ± 2.6	0.027
$K^*(1410)^-$	0.52 ± 0.09	154 ± 20	0.004
$K^*(1680)^-$	0.89 ± 0.30	-139 ± 14	0.003
$K^*(892)^+$	0.180 ± 0.008	-44.1 ± 2.5	0.006
$K_0^*(1430)^+$	0.37 ± 0.07	18 ± 9	0.002
$K_2^*(1430)^+$	0.075 ± 0.038	-104 ± 23	0.000
$\rho(770)$	1 (fixed)	0 (fixed)	0.224
$\omega(782)$	0.0391 ± 0.0016	115.3 ± 2.5	0.006
$f_0(980)$	0.482 ± 0.012	-141.8 ± 2.2	0.061
$f_0(1370)$	2.25 ± 0.30	113.2 ± 3.7	0.032
$f_2(1270)$	0.922 ± 0.041	-21.3 ± 3.1	0.030
$\rho(1450)$	0.52 ± 0.09	38 ± 13	0.002
σ	1.36 ± 0.05	-177.9 ± 2.7	0.093
σ'	0.340 ± 0.026	153.0 ± 3.8	0.013
Non Resonant	3.53 ± 0.44	128 ± 6	0.073

- Most challenging aspects of the model uncertainty come from $K\pi$ and $\pi\pi$ S-wave

Fit to flavour tag sample



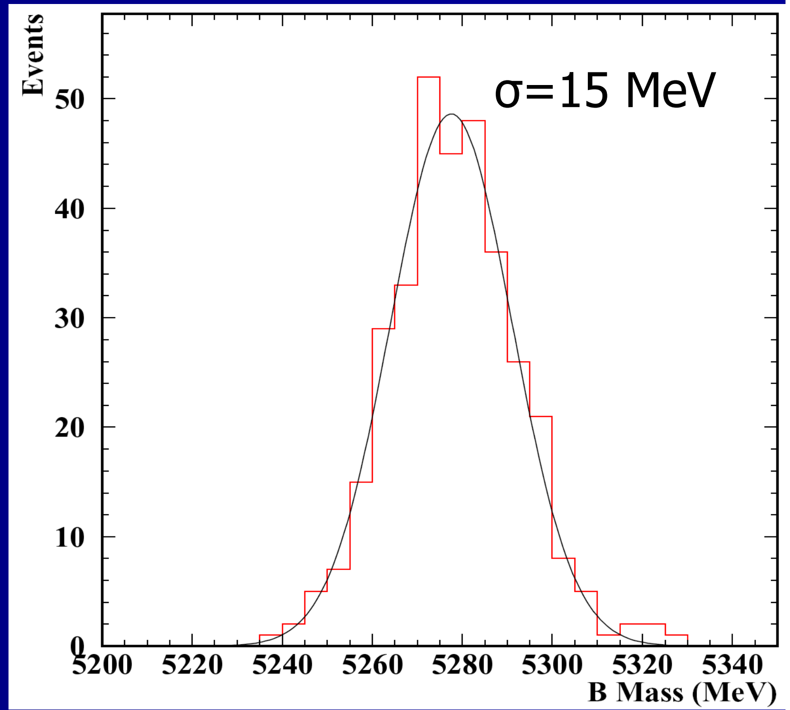
$B^{\pm} \rightarrow D(K^0_S \pi^+ \pi^-) K^{\pm}$ at LHCb

- Simulation studies performed to determine the expected yields and backgrounds at LHCb
  – One 'nominal' year of data-taking 2 fb^{-1}
  – Total luminosity goal 10 fb^{-1}
- Selection studies performed on PYTHIA/EVTGEN/GEANT4 simulated samples of signal and background events
- Limited statistics available for background estimates
  – 34 million b-inclusive events corresponds to ~15 minutes of data taking at nominal luminosity
- Trigger simulation is applied for Level-0 and large impact parameter with p_t HLT

$B^{\pm}\rightarrow D(K^0{}_S\pi^+\pi^-)K^{\pm}$ at LHCb

(LHCb-048-2007)

- Selection based on large impact parameter, RICH particle ID and good p resolution
- Efficiency = 0.7×10^{-3}
- Backgrounds:
  - $B^{\pm}\rightarrow D(K^0{}_S\pi^+\pi^-)\pi^{\pm}$ B/S=0.24
  - Combinatoric B/S<0.7 at 90% c.l.



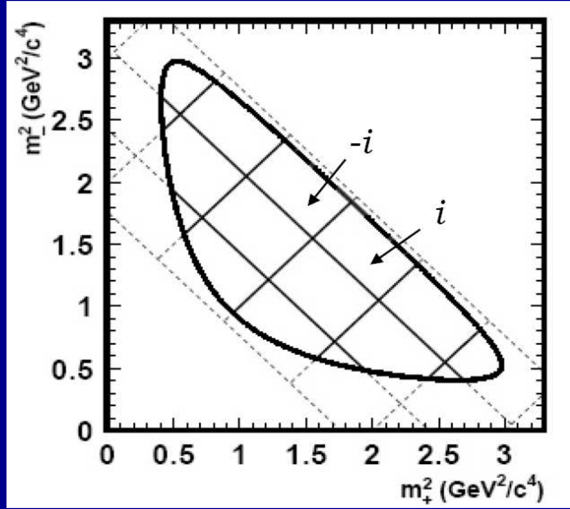
5000 events/2fb^{-1}

Model uncertainty impact on LHCb

- The model-dependent likelihood fit yields an uncertainty on γ between 7-12° for an r_B=0.1
  - Range represents differing assumptions about the background
- However, the current model uncertainty is 10-15° with an r_B=0.1
  - Uncertainties $\propto 1/r_B$
- **Without improvements LHCb sensitivity will be dominated by model assumptions within 1 year of data taking**
- Motivates a model-independent method that relies on a binned analysis of the Dalitz plot
  - Disadvantage is that information is lost via binning

Binned method

- Proposed in the original paper by Giri, Grossman, Soffer and Zupan and since been extended significantly by Bondar and Poluektov
  - GGSZ, PRD **68**, 054018 (2003)
  - BP, most recently arXiv:0711.1509v1 [hep-ph]
- Bin the Dalitz plot symmetrically about $m_-^2 = m_+^2$ then number of entries in B^- decay given by:



∝ # events in bin of flavour tagged D^0 decays

$$N_i^- \propto \int_{D_i} \left| f(m_-^2, m_+^2) \right|^2 dD + r_B^2 \int_{D_i} \left| f(m_+^2, m_-^2) \right|^2 dD$$

$$+ 2\sqrt{\int_{D_i} \left| f(m_-^2, m_+^2) \right|^2 dD \int_{D_i} \left| f(m_+^2, m_-^2) \right|^2 dD}\,(x_- c_i + y_- s_i)$$

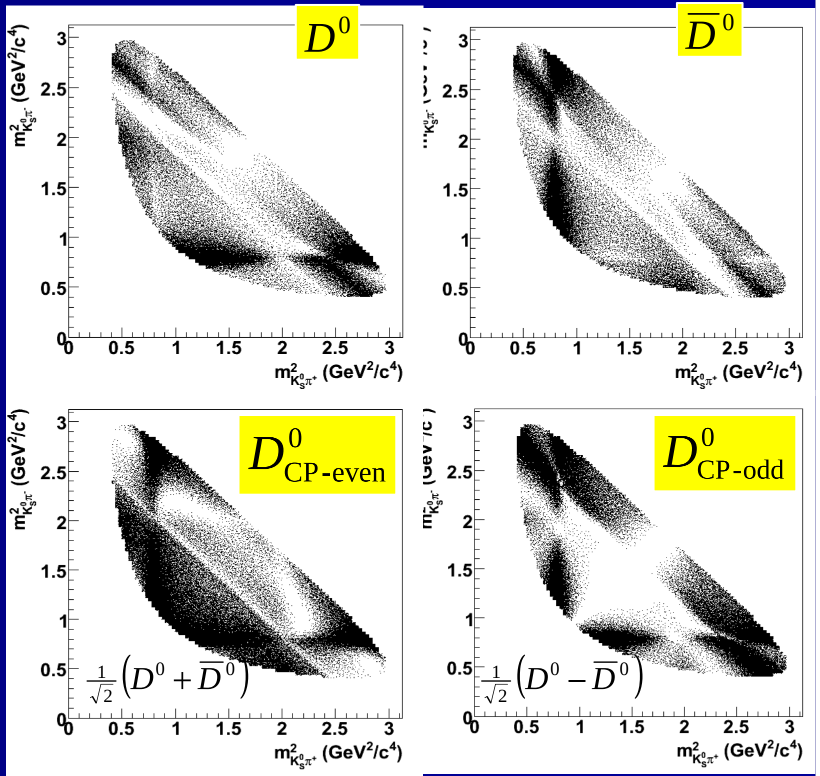
$$x_\pm = r_B \cos(\delta_B \pm \gamma) \qquad y_\pm = r_B \sin(\delta_B \pm \gamma)$$

'Cartesian coordinates'

Average cosine and sine of strong phase difference between D^0 and $\bar{D}^0$ decay amplitudes ($\Delta\delta_D$) in this bin

Binned method continued

- Can determine s_i and c_i at the same time as extracting γ, r_B and δ_B from B data
  - 3 + N_{bins} free parameters ($c_i = c_{-i}$ and $s_i = -s_{-i}$)
  - Huge loss in γ sensitivity not practical until you have O(10^6) events (2500/fb^{-1} @ LHCb)
- However, **CP-correlated** $e^+e^- \rightarrow \psi'' \rightarrow D^0\overline{D^0}$ data where one decay is to $K_S\pi\pi$ and the other decays to a CP eigenstate and $K_S\pi\pi$ allows c_i and s_i to be determined, respectively



Enter CLEO-c

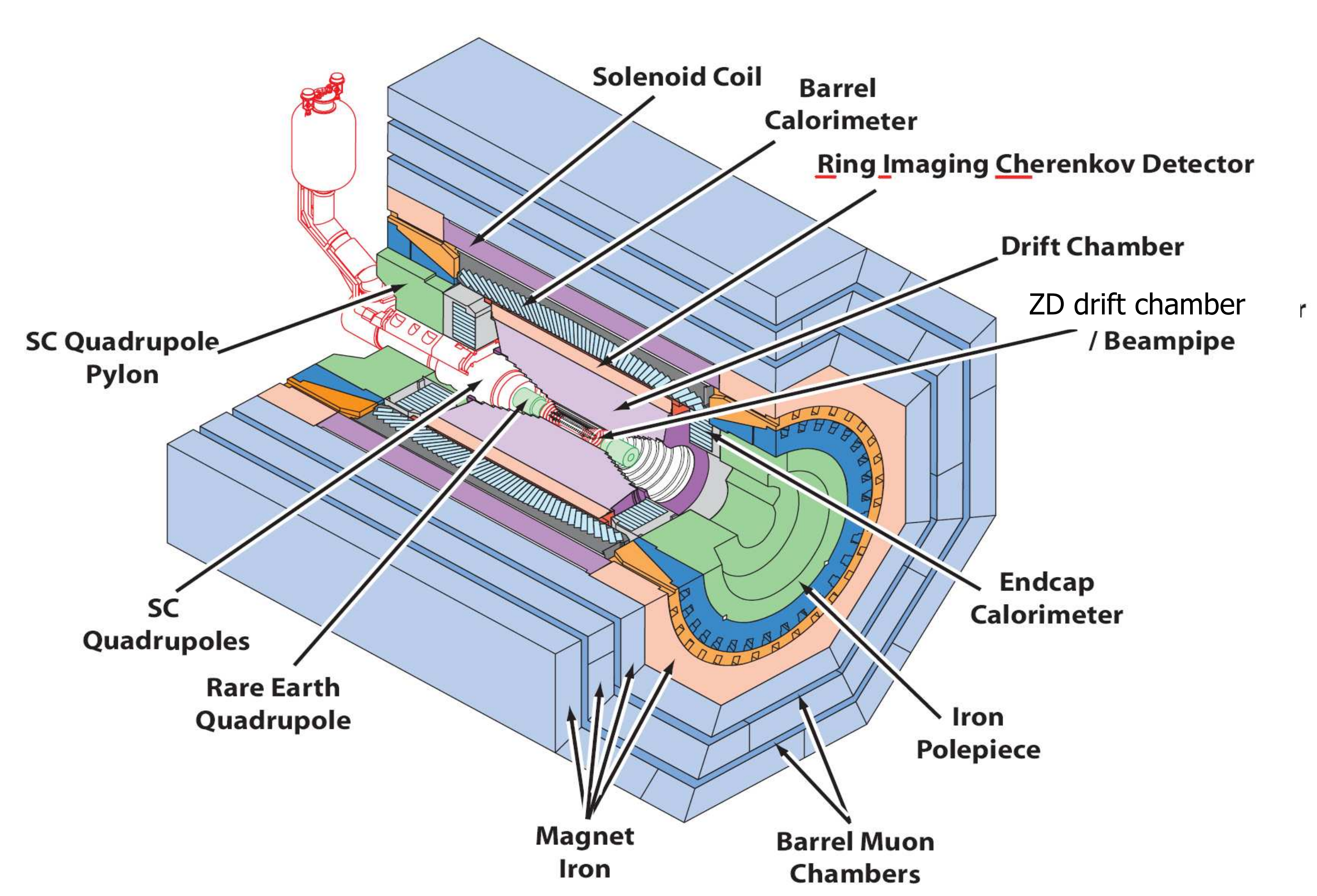
CLEO is the grand-daddy of flavour physics, with history of achievement dating back over 25 years

CLEO-c is latest incarnation. Dedicated programme of data-taking at and above the $c\bar{c}$ threshold
Important studies for LQCD and B physics

Oxford LHCb physicists (with Bristol) have joined CLEO-c in order to measure quantities essential for the γ studies

Cornell University, Ithaca NY, USA

CLEO-c detector



CLEO-c data samples

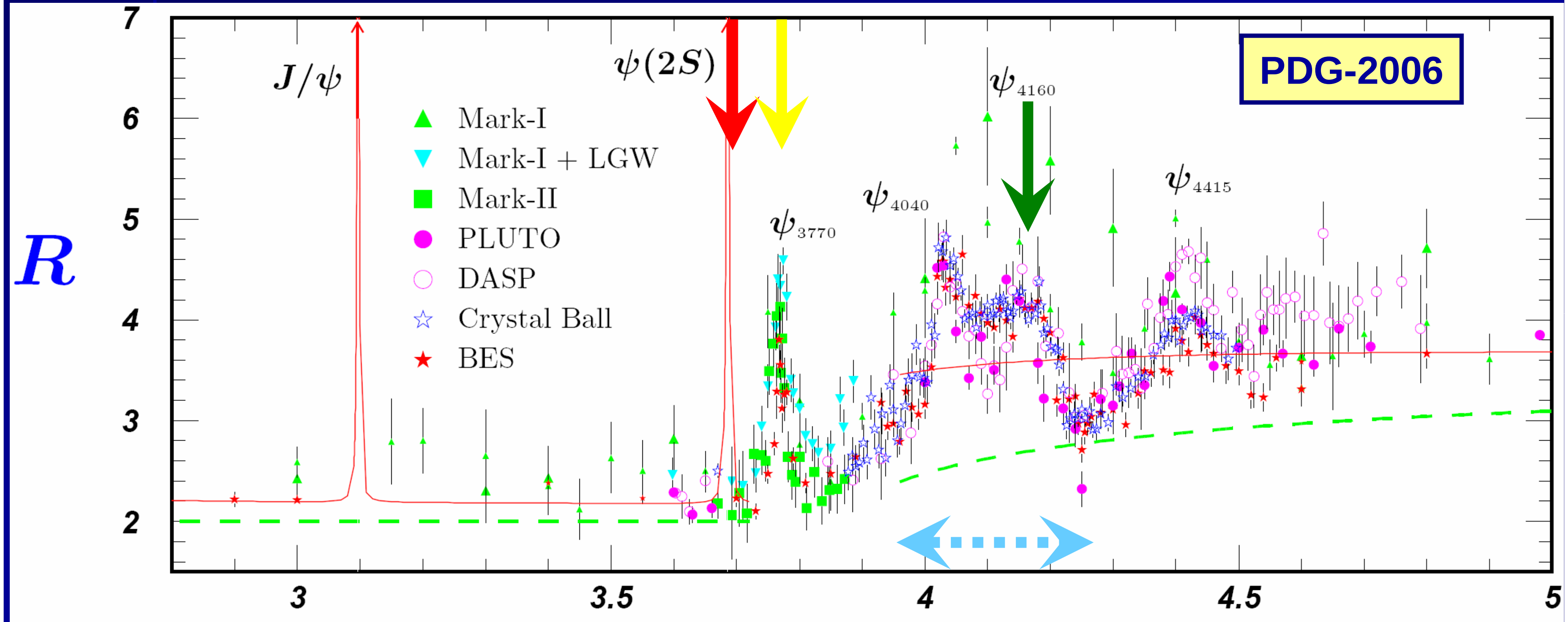
CLEO-c: Oct. 2003 – April Fool's Day 2008

3686MeV, 54 pb^{-1}, N(ψ(2S))≈27M **$e^+e^- \to \psi(2S) \to \pi\pi J/\psi, \gamma\chi_c$ etc.**

3773MeV, 800pb^{-1} delivered, ~3 milion $\psi(3770) \to D^0\overline{D^0}$

4170MeV, 195 pb^{-1} → ~ 300pb^{-1} →more→ ~720pb^{-1}, $D_{(s)}^{(*)}\overline{D}_{(s)}^{(*)}$

3970–4260MeV energy scan, 60pb^{-1} in 12 points

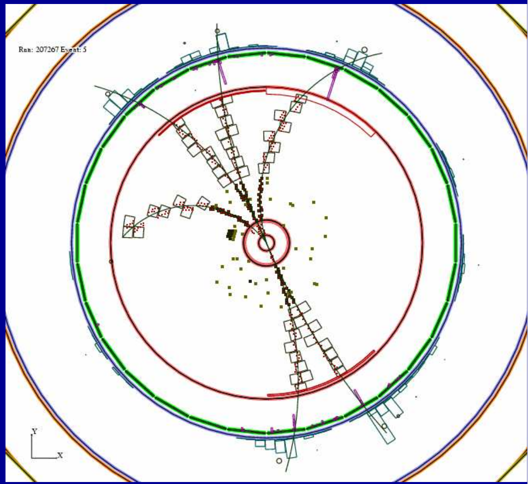


CLEO-c: double tagged ψ(3770) events

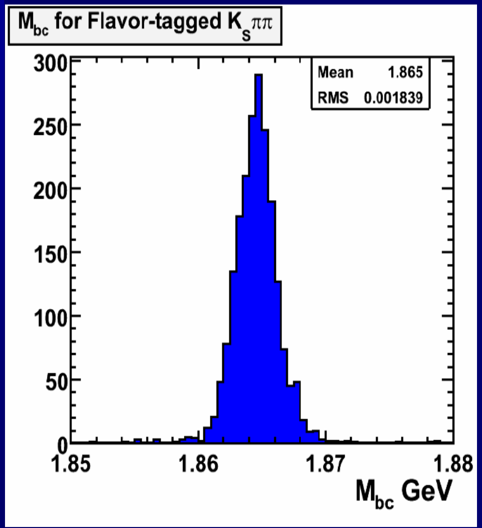
CLEO-c has collected ~ 800 fb^{-1} at the ψ (3770)

DDbar produced in quantum entangled state:

$$e^+e^- \to \psi'' \to \tfrac{1}{\sqrt{2}}\left[D^0\overline{D}^0 - \overline{D}^0 D^0\right]$$



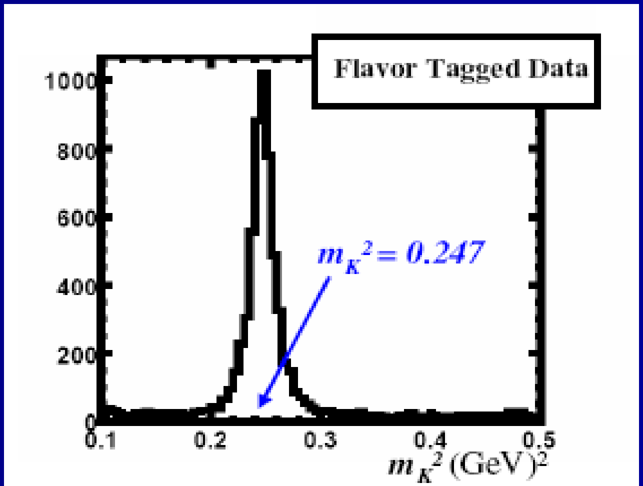
Reconstruct one D in decay of interest for γ analysis (eg. Kππ), & other in CP eigenstate (eg. KK, $K_s\pi^0$ …) then CP of other is fixed.



⇐Almost background free

Can use K_L⇒

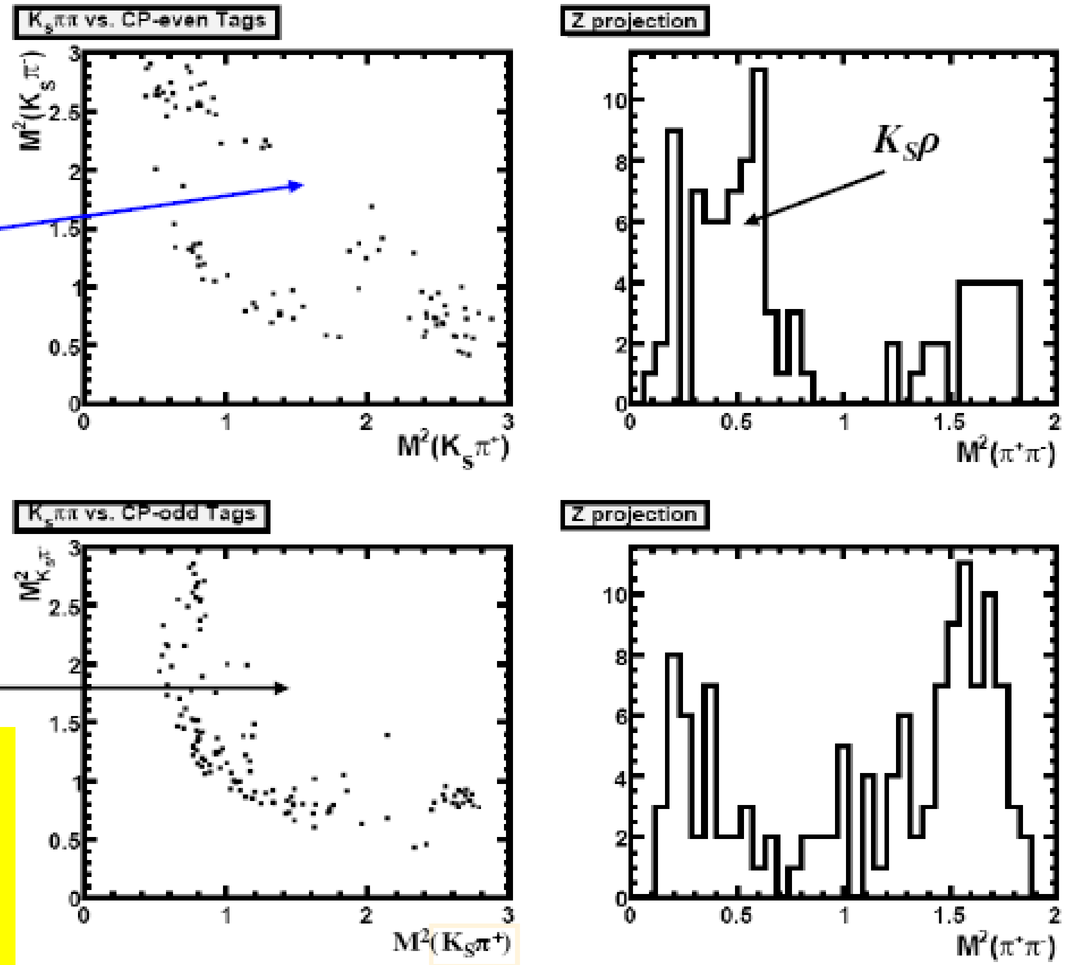
From talk by E. White at Charm 07



CP-tagged $K_S\pi^+\pi^-$ Dalitz Plots

1/3 of total data
(<1/2 the CP tags)

$K_S\rho^0$ resonance enhanced in CP-odd Dalitz plot



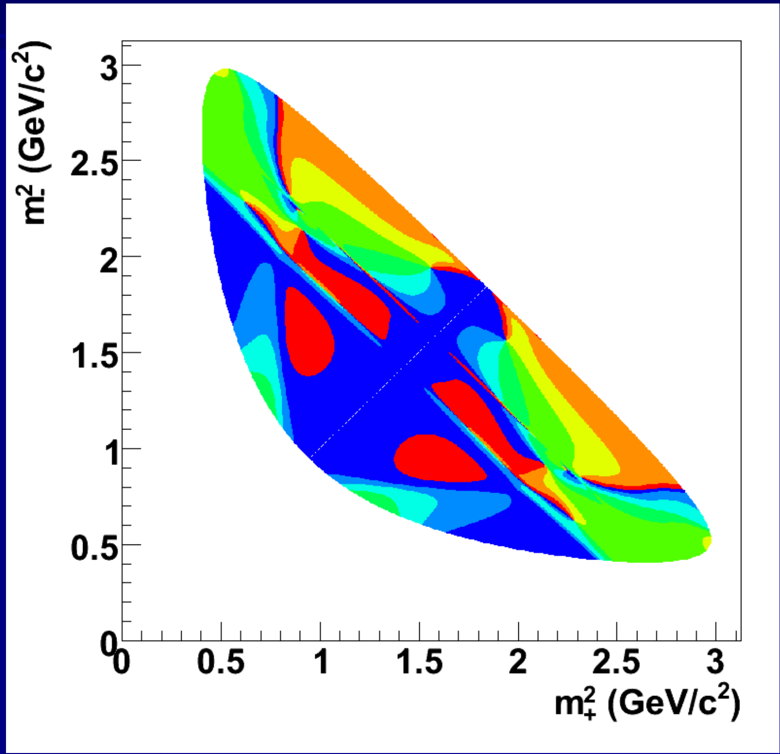
CP-odd $K_S\rho^0$ resonance absent in CP-even Dalitz plot

Studies not complete
but projected uncertainties
on c and s will lead to
3-5 degree uncertainty on γ

Inkblot test

Absolute value of strong phase diff.
(BABAR model used in LHCb-48-2007)

- Bondar and Poluektov show that the rectangular binning is far from optimal for both CLEOc and γ analyses
  - 16 uniform bins has only 60% of the B statistical sensitivity
  - c and s errors would be 3 times larger from the ψ''
- Best B-data sensitivity **when $\cos(\Delta\delta_D)$ and $\sin(\Delta\delta_D)$ are as uniform as possible** within a bin



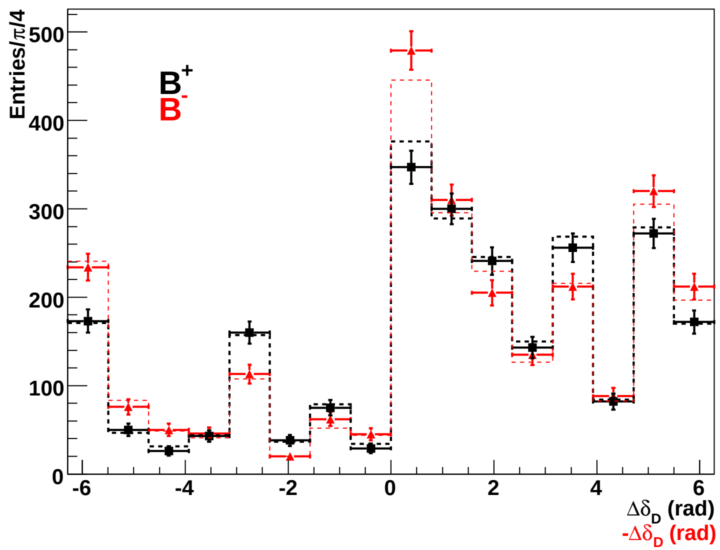
Good approximation and the binning that yields smallest s and c errors is equal $\Delta\delta_D$ bins-80% of the unbinned precision

$$2\pi(i-\tfrac{1}{2})/N < \Delta\delta_D(m_+^2, m_-^2) < 2\pi(i+\tfrac{1}{2})/N$$

Implementation at LHCb

(γ=60°, r_B=0.1 and δ_B=130°)

- Generate samples of $B^{\pm}\rightarrow D(K^0{}_S\pi\pi)K^{\pm}$ with a mean of 5000 events split between the charges
- Bin according to strong phase difference, $\Delta\delta_D \Rightarrow$
- Minimise χ^2



$$\chi^2 = \sum_{i=-8(i\neq 0)}^{8}\left[\frac{(n_i^+ - N_i^+(x_+,y_+,h))^2}{n_i^+} + \frac{(n_i^- - N_i^-(x_-,y_-,h))^2}{n_i^-}\right]$$

$$n_i^{\pm} = \text{number of } B^{\pm}\rightarrow D(K_S^0\pi^+\pi^-)K^{\pm} \text{ events in } i^{\text{th}} \text{ bin}$$

$$N_i^{\pm}(x_{\pm},y_{\pm},h) = h\left[K_{\pm i} + r_B^2 K_{\mp i} + 2\sqrt{K_i K_{-i}}\,(c_i x_{\pm} \pm s_i y_{\pm})\right]$$

$$h = \text{normalization factor}$$

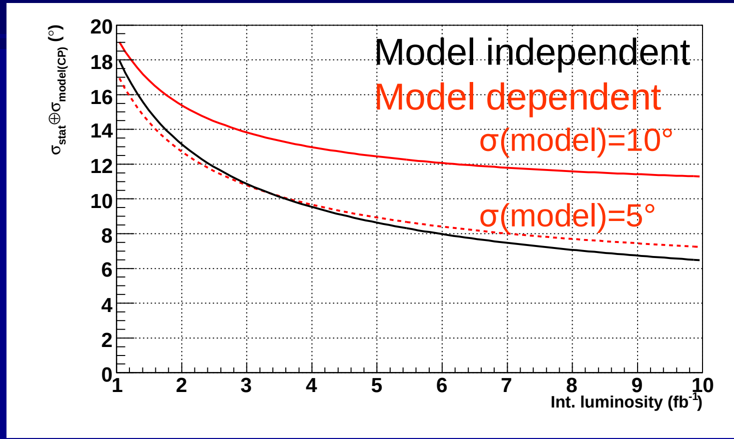
$$K_{\pm i} = \int_{D_i}\left|f(m_+^2,m_-^2)\right|^2 dD\,[\text{measured from flavour tag data}]$$

- K_i, c_i and s_i amplitudes calculated from model
- In reality from flavour tagged samples and CLEO-c

γ uncertainties with 5000 toy experiments

Scenario	2 fb^{-1} Mod. Indep.	10 fb^{-1} Mod. Indep.	2 fb^{-1} Mod. Dep. (LHCb-048-2007)
No background	**7.9°**	**3.5°**	5.9°
Acceptance	**8.1°**	**3.5°**	5.5°
$D\pi$ (B/S = 0.24) (Best case scenario)	**8.8°**	**4.0°**	**7.3°**
DK_{comb} (B/S=0.7) (Worst case scenario)	**12.8°**	**5.7°**	**11.7°**

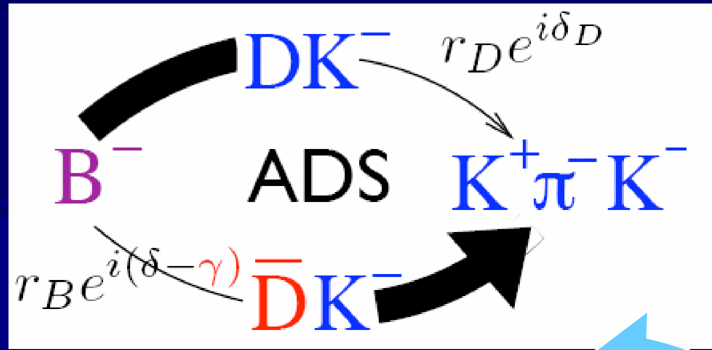
$B^{\pm}\rightarrow D(K^0_S\pi^+\pi^-)K^{\pm}$ at LHCb



- Model independent fit with binning that yields smallest error from exploiting CLEO-c data
  - **Binning depends on model - only consequence of incorrect model is non-optimal binning and a loss of sensitivity**
- Measurement has no troublesome and hard-to-quantify systematic and outperforms model-dependent approach with full LHCb dataset with currently assigned model error
  - **10 fb^{-1} statistical uncertainty 4-6° depending on background**
- **CLEO-c measurements essential to validation of assumptions in model dependent measurement**
- LHCb-2007-141 – Available via CERN document server

ADS

ADS method



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

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

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

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

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

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

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

h=π or K

- 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
- Important constraint from CLEOc $\sigma(\cos \delta_D^{K\pi})$=0.1–0.2
- **Overconstrained: 6 observables and 5 unknowns**

Expected yields

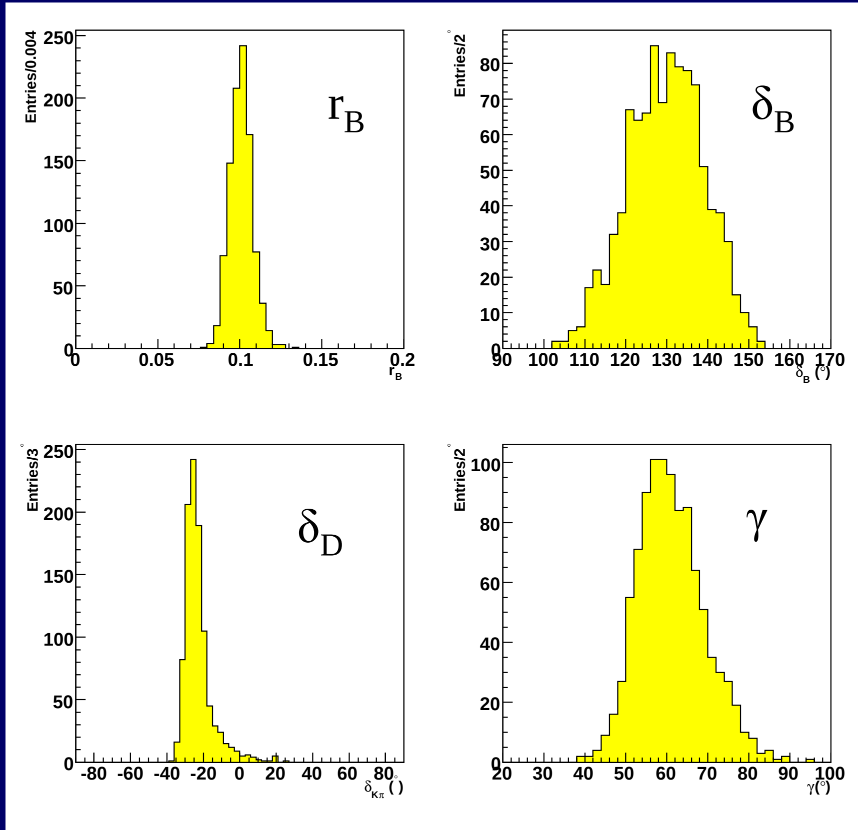
- ADS measurement is a counting experiment - but suppressed modes have ~10^{-7} BRs
  - Principal challenge background suppression
- Detailed selections studies as for Dalitz analysis
  - LHCb-2006-066

Channel	Signal yield/2 fb^{-1}	B/S	B-factory yields (~1/4 final data set)
$B^{\pm} \to (K^{\pm}\pi^{\mp})_D K^{\pm}$	**56,000**	**0.6**	**4000**
$B^{\pm} \to (h^{-}h^{+})_D K^{\pm}$	**8200**	**1.8**	**500**

- The suppressed modes have yields varying from 0 to 500 depending on the strong parameters
  - 780 background events predicted

Sensitivity from 2-body

δ_D= -25^o – fit results from 1000 toy 2 fb^{-1} experiments :



δ_D constraint leads to a 0.5-1.0° reduction in σ_γ

Also important for D mixing measurements

δ_D (°)	-25	-16.6	-8.3	0	8.3	16.6	25
σ_γ (°)	9.5	8.6	7.5	8.6	8.6	9.3	9.4

Four-body ADS

- $B \to D(K\,\pi\pi\pi)K$ can also be used for ADS style analysis
- Similar yields to 2-body – slightly worse B/S
  - LHCb-2007-004
- However, need to account for the resonant substructure in $D \to K\pi\pi\pi$
  - made up of $D \to K^*\rho$, $K^- a_1(1260)^+$,,,...
  - in principle each point in the phase space has a different strong phase associated with it - 3 and 4 body Dalitz plot analyses exploit this very fact to extract γ from amplitude fits
- Atwood and Soni (hep-ph/0304085) show how to modify the usual ADS equations for this case
  - Introduce **coherence parameter $R_{K3\pi}$** which dilutes interference term sensitive to γ

$$\Gamma(B^- \to (K^+\pi^-\pi^-\pi^+)_D K^-) \propto r_B^2 + (r_D^{K3\pi})^2 + 2 r_B r_D^{K3\pi} R_{K3\pi} \cos(\delta_B + \delta_D^{K3\pi} - \gamma)$$

- $R_{K3\pi}$ ranges from
  - 1=coherent (dominated by a single mode) to
  - 0=incoherent (several significant components)
- Can slice and dice phase space to find most coherent regions

Determining the coherence factor

- Measurements of the rate of K3π versus different tags at CLEO-c allows direct access to $R_{K3\pi}$ and $\delta_{K3\pi}$

1. Normalisation from CF $K^-\pi^+\pi^+\pi^-$ vs. $K^+\pi^-\pi^-\pi^+$ and $K^-\pi^+\pi^+\pi^-$ vs. $K^+\pi^-$
2. CP eigenstates: $\Gamma(K3\pi : CP\pm) = \Gamma^{CF}_{K3\pi}\Gamma_{CP}\left[1+\left(r_D^{K3\pi}\right)^2 \mp 2r_D^{K3\pi}R_{K3\pi}\cos\delta_D^{K3\pi}\right]$
3. $K^-\pi^+\pi^+\pi^-$ vs. $K^-\pi^+\pi^+\pi^-$: $\Gamma(K^-3\pi : K^-3\pi) = \Gamma^{CF}_{K3\pi}\Gamma^{DCS}_{K3\pi}\left[1-R^2_{K3\pi}\right]$
4. $K^-\pi^+\pi^+\pi^-$ vs. $K^-\pi^+$: $\Gamma(K^-3\pi : K^-\pi) \approx \Gamma^{CF}_{K3\pi}\Gamma^{DCS}_{K3\pi}\left[1+\left(\frac{r_D^{K3\pi}}{r_D^{K\pi}}\right)^2 + 2\frac{r_D^{K3\pi}}{r_D^{K\pi}}R_{K3\pi}\cos\delta_D^{K3\pi}\right]$

Assume $\delta_D^{K\pi} \sim \pi$

K3π tag side	800 pb⁻¹ yield
K3π CF	4000
Kπ CF	5200
K3π/Kπ DCS	0-40 per mode
$K^0_S\pi^0$	700
K^+K^-	500
$\pi^+\pi^-$	200

$\sigma_{stat} \sim 0.1$ **with 800 pb^{-1}**

Conclusion-LHCb

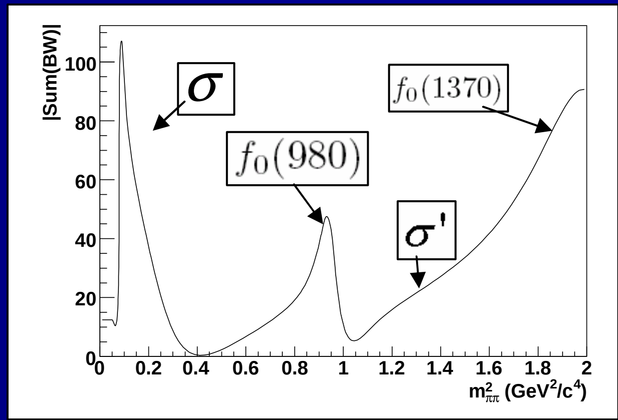
- LHCb has estimated 2 fb^{-1} sensitivity to γ in $B^{\pm}\rightarrow DK^{\pm}$ with
  - $D\rightarrow K^0{}_S\pi^+\pi^-$ - $\boldsymbol{\sigma_\gamma}$ **=7-12°**
  - $D\rightarrow K^-\pi^+$ and $D\rightarrow h^+h^-$ - $\boldsymbol{\sigma_\gamma}$ **=7.5-9.5°**
  - $D\rightarrow K^-\pi^+\pi^+\pi^-$ will add additional information
- Not the whole story with theoretically clean measurements:
  - $B^0\rightarrow DK^*$ $\boldsymbol{\sigma_\gamma}$ **~ 9°** [LHCb-2007-050]
  - $B_s\rightarrow D_sK$ $\boldsymbol{\sigma_{\gamma+\varphi s}}$ **~ 10°** [LHCb-2007-041]
- **CLEO-c measurements essential to fulfilling this goal**
- **Combined: a few degree precision on γ by the end of LHCb**
- Current world average: 77±31° (CKMfitter)

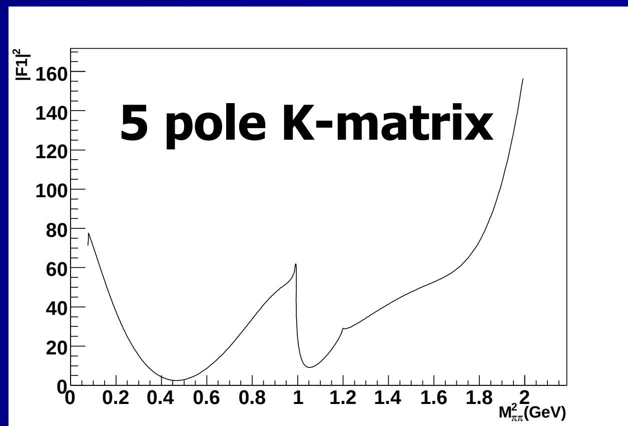
Additional slides

Aside: K-matrix

- Breit Wigner description of broad overlapping resonances violates unitarity and requires non-physical σ′
- K-matrix description preserves unitarity

- First studies (Lauren Martin/JL) of LHCb γ fit with one K-matrix parameterisation of the ππ S-wave
  - Difference between assuming K-matrix and BW model consistent with B-factory observations
  - Draft available from CPWG webpage
- Explore different physical K-matrix parameterisation to evaluate systematic rather than introduce σ′ **will reduce model uncertainty**

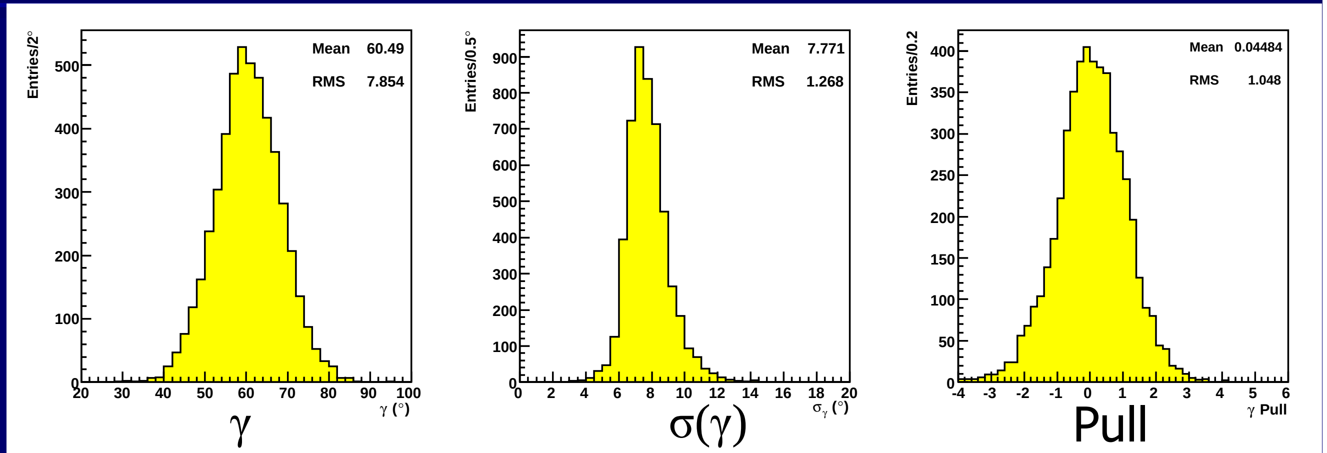


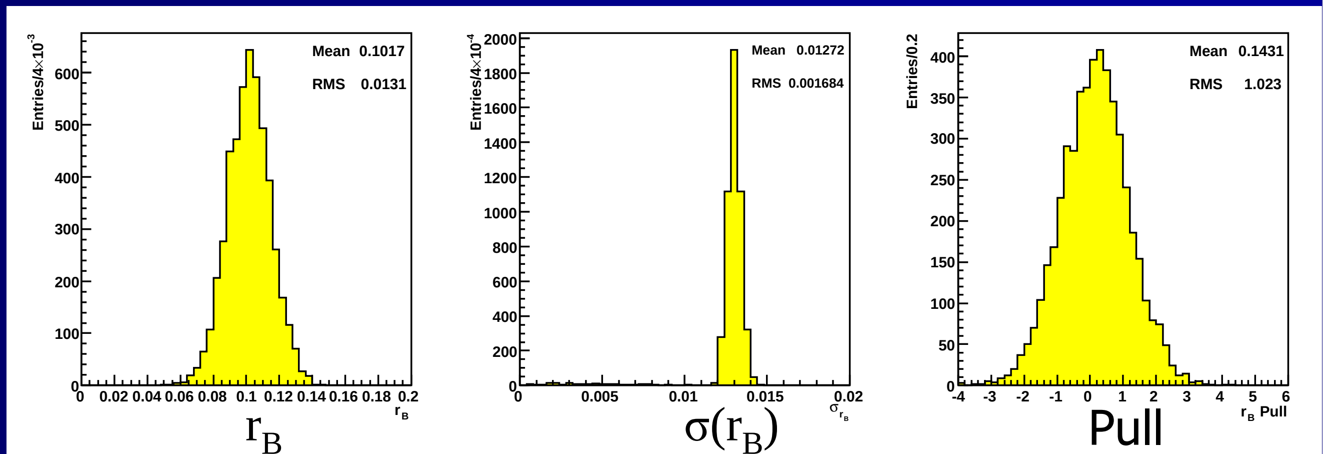


No background with predicted 2 fb^{-1} yield

5000 experiments

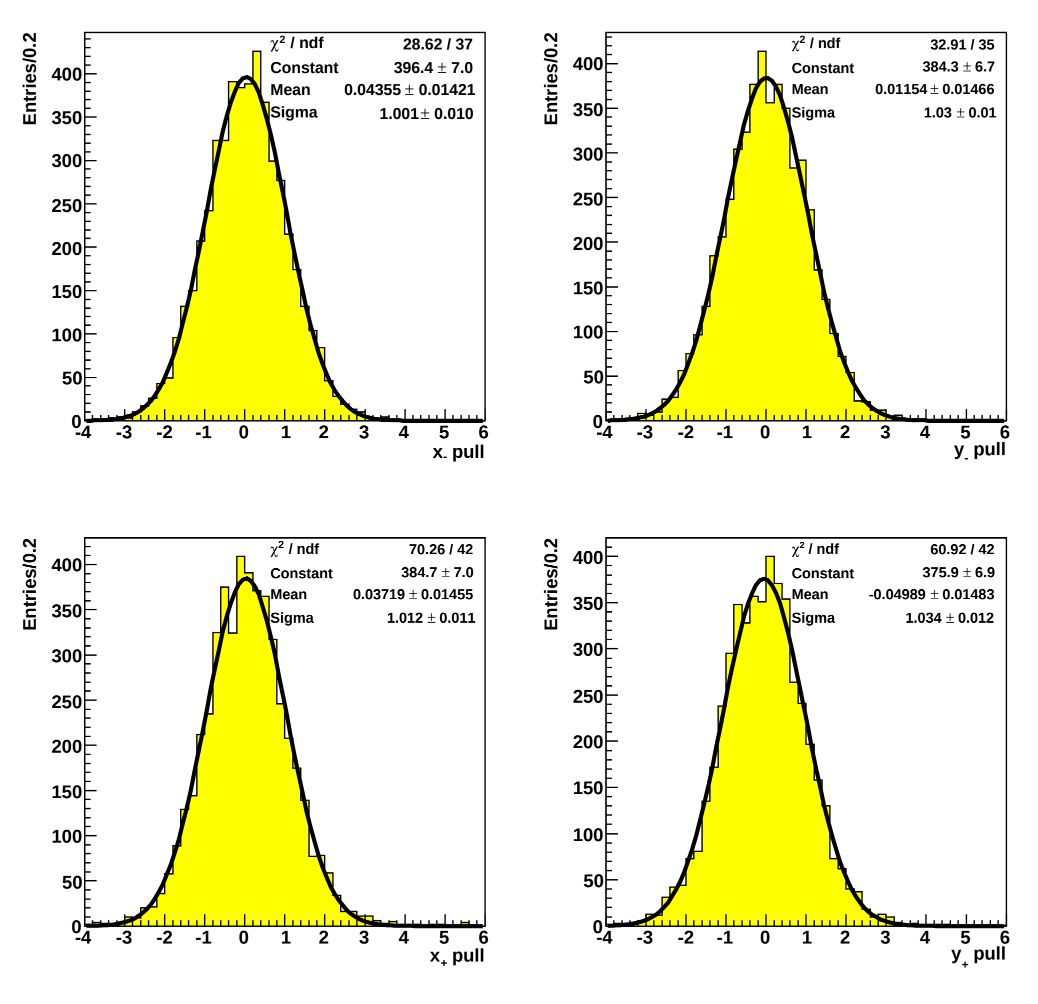
Input parameters
γ=60°, r_B=0.1 and
δ_B=130°





Model independent average uncertainty 7.9° (c.f. Mod el dependent 5.9°)

No background with predicted 2 fb^{-1} yield



5000 experiments

Input parameters
$\gamma=60°$, $r_B=0.1$ and $\delta_B=130°$

The four Cartesian coordinates and normalization are free parameters

All pulls are normal therefore calculate γ, r_B and δ_B with propagated Cartesian uncertainties

Toy experiment results: γ (2 fb^{-1})

Scenario	Mean	RMS	Mean σ	Mean pull	Pull RMS
No bck	60.5±0.1	7.9	7.8	0.045±0.015	1.05
Acc	60.7±0.1	8.1	7.8	0.075±0.015	1.07
Dπ	60.7±0.1	8.8	8.8	0.088±0.015	1.04
Dπ + DK (B/S=0.7)	60.7±0.2	12.8	12.2	0.049±0.016	1.11
Dπ + PS (B/S=0.7)	60.8±0.2	12.8	12.5	0.064±0.015	1.05
Dπ + DK+ PS (50:50) (B/S=0.7)	60.7±0.2	12.7	12.6	0.049±0.015	1.04

Toy experiment results: γ (10 fb^{-1})

Scenario	Mean	RMS	Mean σ	Mean pull	Pull RMS
No bck	60.17±0.05	3.5	3.4	0.050±0.015	1.03
Acc	60.13±0.05	3.5	3.4	0.036±0.015	1.01
Dπ	60.22±0.06	4.0	3.9	0.054±0.015	1.03
Dπ + DK (B/S=0.7)	60.18±0.08	5.7	5.7	0.030±0.015	1.01
Dπ + PS (B/S=0.7)	60.26±0.08	5.5	5.5	0.045±0.015	1.00
Dπ + DK+ PS (50:50) (B/S=0.7)	60.22±0.08	5.4	5.6	0.038±0.015	0.97

Toy experiment results: r_B (2 fb^{-1})

Scenario	Mean	RMS	Mean σ	Mean pull	Pull RMS
No bck	0.1017±0.0002	0.013	0.013	0.143±0.015	1.02
Acc	0.1017±0.0002	0.014	0.013	0.175±0.016	1.13
Dπ	0.1015±0.0002	0.014	0.014	0.123±0.015	1.02
Dπ + DK (B/S=0.7)	0.1031±0.0003	0.020	0.020	0.215±0.016	1.16
Dπ + PS (B/S=0.7)	0.1035±0.0003	0.020	0.019	0.175±0.015	0.99
Dπ + DK+ PS (50:50) (B/S=0.7)	0.1038±0.0003	0.020	0.020	0.186±0.015	0.98

Toy experiment results: r_B (10 fb^{-1})

Scenario	Mean	RMS	Mean σ	Mean pull	Pull RMS
No bck	0.1003±0.0001	0.006	0.006	0.056±0.015	1.00
Acc	0.1003±0.0001	0.006	0.006	0.051±0.015	1.01
Dπ	0.1003±0.0001	0.006	0.006	0.049±0.015	0.98
Dπ + DK (B/S=0.7)	0.1009±0.0001	0.009	0.009	0.101±0.015	0.97
Dπ + PS (B/S=0.7)	0.1008±0.0001	0.009	0.009	0.093±0.015	0.99
Dπ + DK+ PS (50:50) (B/S=0.7)	0.1007±0.0001	0.009	0.009	0.077±0.015	0.98

Acceptance

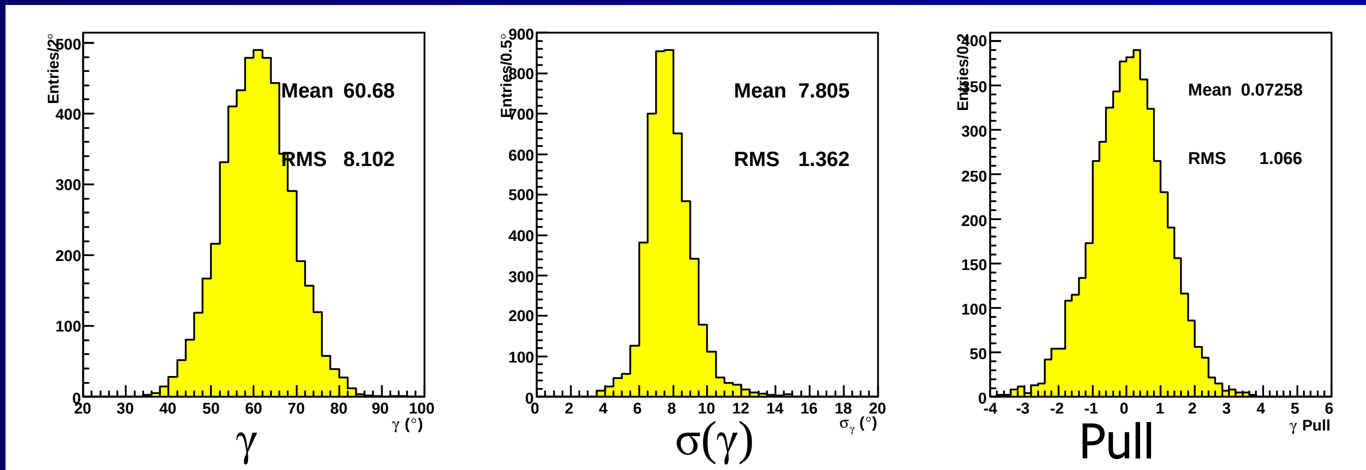
- Acceptance in each bin calculated as a weighted average of the acceptance function used for model dependent studies
  - 15% relative difference amongst bins
- Modifies the fit function:

$$N_i^{\pm}(x_\pm, y_\pm, h) = h\varepsilon_{\pm i}\left[K_{\pm i} + r_B^2 K_{\mp i} + 2\sqrt{K_i K_{-i}}\left(c_i x_\pm \pm s_i y_\pm\right)\right]$$

$$\varepsilon_i = \frac{\int_{D_i} \left| f(m_+^2, m_-^2)\right|^2 \varepsilon(m_+^2, m_-^2)\,dD}{K_i} \quad \text{where } \varepsilon(m_+^2, m_-^2) = 0.28\times 10^{-3}\left(1 - 0.08(m_+^2 + m_-^2)\right)$$

Can be calculated from Dπ

- Average γ uncertainty increases to 8.1°



Background

- 3 types of background to consider
  - $B \to D(K_S\pi\pi)\pi$ (B/S = 0.24)
    - $r_B(D\pi)$ $O(10^{-3})$ so Dalitz plots are like D^0 and $\overline{D^0}$ for B^- and B^+, respectively
  - Combinatoric (B/S<0.7)-mixtures of two types considered
    1. DK_{comb}: real $D \to D(K_S\pi\pi)$ combined with a bachelor K
       - Dalitz plot an even sum of D^0 and $\overline{D^0}$ decays
    2. PS_{comb}: combinatoric D with a bachelor K
       - Follows phase space
- Integrate background PDFs used in model-dependent analysis over each bin, then scaled to background level assumed:

$$N(D\pi)_i^{\pm} \propto \varepsilon_{\pm i} K_{\pm i}$$

$$N(DK_{comb})_i^{\pm} \propto \tfrac{1}{2}(\varepsilon_{\pm i} K_{\pm i} + \varepsilon_{\mp i} K_{\mp i})$$

$$N(PS_{comb})_i^{\pm} \propto P_i$$

P_i: fractional area of Dalitz space covered by bin

Systematic related to acceptance

- The acceptance varies over the Dalitz plane
- The relative acceptance in each bin can be measured using the $B \to D\pi$ control sample with DK selection applied without bachelor K PID

$$\varepsilon_i = \frac{\int_{D_i} \left| f(m_+^2, m_-^2) \right|^2 \varepsilon(m_+^2, m_-^2) dD}{K_i} \propto \frac{\mathrm{N}(\mathrm{B} \to \mathrm{D}(\mathrm{K}_\mathrm{S}^0 \pi\pi)\pi)_i}{K_i}$$

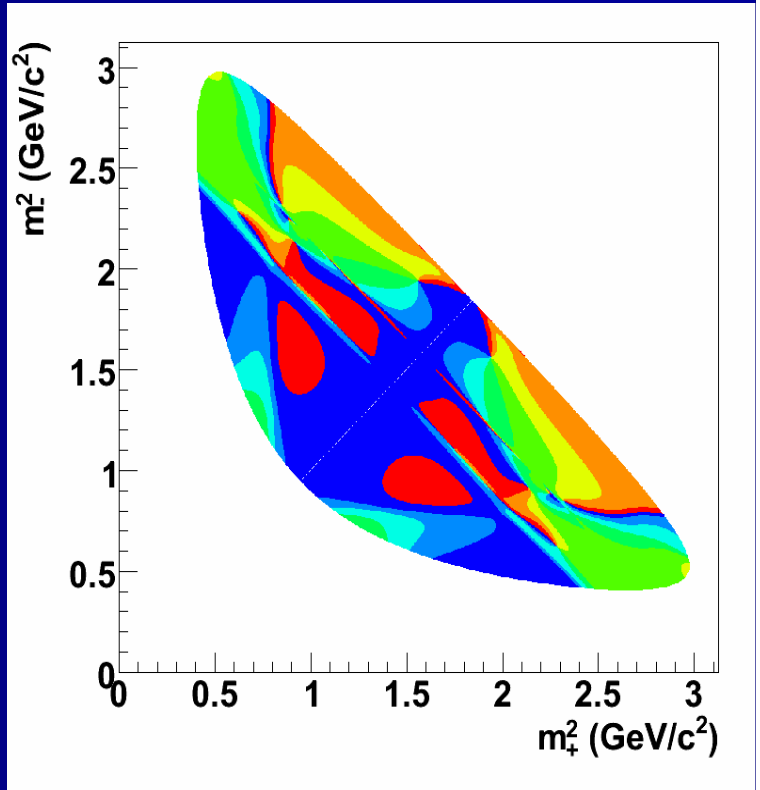
- With the DC04 selection expect 60k events/2 fb^{-1}
  - Relative relative-efficiency uncertainty 1-4%/$\Delta\delta_D$ bin with 2 fb^{-1}
  - Increased statistics reduces error
- Toy MC study smearing bin efficiencies in event generation by this amount leads to an additional 1° uncertainty without background and **3.2° uncertainty** with DK_{comb} B/S=0.7
  - **Small effect compared to statistical uncertainty**
- NB: the efficiency related to the PID of the bachelor π/K can be factored out and will be determined from the $D^* \to D(K\pi)\pi$ data to better than one percent-ignore at present

Asymmetry in efficiency in Dalitz space

- Considered charge asymmetries in the efficiency across the Dalitz plane
  - $\varepsilon(m^2_+, m^2_-) \neq \varepsilon(m^2_-, m^2_+)$
- Generated with the efficiency biased relative to one another depending on whether the event had $m^2_+ > m^2_-$ or $m^2_+ < m^2_-$
- **Maximum bias on γ induced was $<1°$ for 10% relative effect and full background**
- 10% effects would be evident in the $D\pi$ sample

Resolution

- $\Delta\delta_D$ binning has some narrow regions in Dalitz space
- Investigation of how resolution on the Dalitz variables might affected the extraction of γ
- 10 MeV^2/c^4 resolution (DC04) on Dalitz variables and generated toy experiments with this smearing
- Found that this led to a few bins with largest (red) and smallest (dark blue) phase difference having a 2-3% relative changes in expected yields due to resolution induced migration
- **Fit results on toy experiments where resolution included in generation but ignored in fit found no significant bias (<0.5°) on γ**



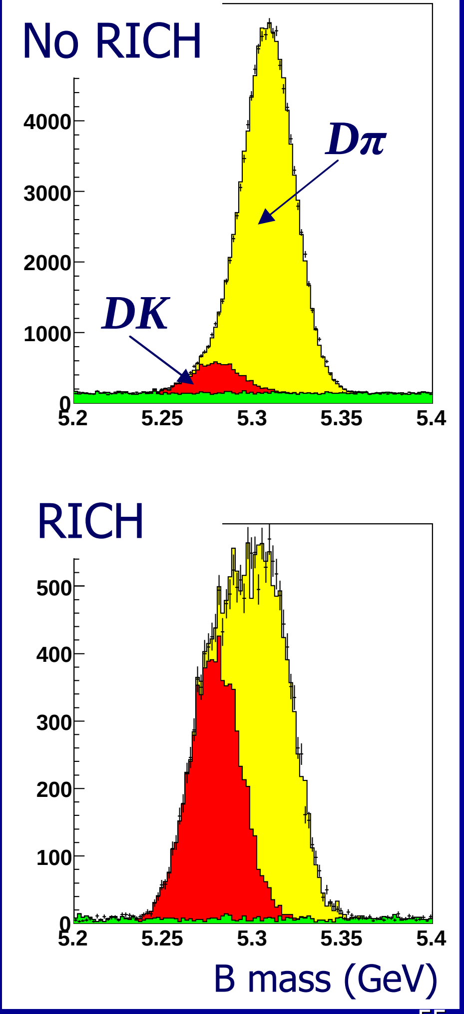
Background fractions

- Combinatoric background rate will be determined from B and D mass sidebands which will cover at least 2-3 times the area of the signal region
  - Use 10× in DC04 background studies but this will probably be unrealistic with data
- If background distributions relatively flat in masses one can estimate that this leads to B/S will be determined absolutely to around 0.01 or better
  - **Toy studies suggest that there is no impact on γ precision with this kind of uncertainty**
- Maybe complications depending on Dalitz space distribution of the PS background but can only speculate until we have the data in hand

Background composition

- For favoured mode background dominated by $B \to D\pi$
  - 14 × larger BF
  - Power of the RICH
- For suppressed combinatoric dominates (green)
- For $B \to D(hh)K$ more even mixture of comb. and $D\pi$
  - $B \to D(KK)K$ has significant non-resonant $B \to KKK$ component

0.5 fb^{-1}



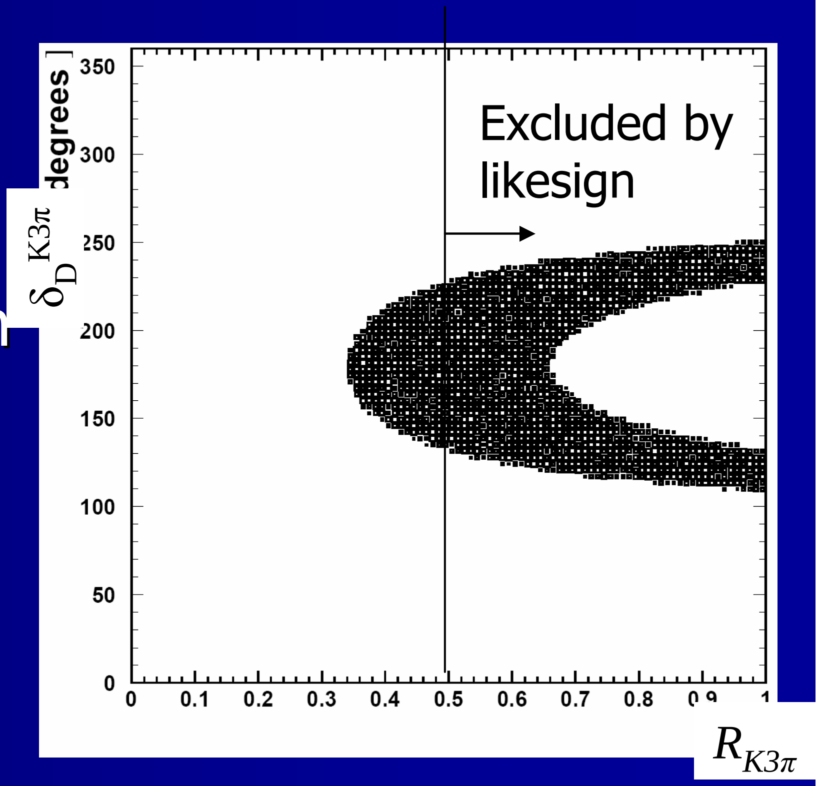
Determining the coherence factor

- Analysis underway 10% effects in CP modes so great care with
  - Background subtraction
  - Efficiency calculation

- Estimate of current sensitivity with the addition of $K^0_L\pi^0$ and further CP tags i.e. $K^0_S\eta$ to be added

- Further information in mixed CP SCS tags such as $K^0_S\pi^+\pi^-$

σ_{stat} ~ 0.1 with 800 pb^{-1}



Conclusion CLEOc

- **CLEO-c measurements essential to fulfilling this goal**
- **But there is much more that can be done**
- Full amplitude analysis of 4-body should yield ultimate precision
  - Need DCS model, which can be accessed via CP tags at CLEOc
  - Also will guide division of phase space for binned coherence factor analysis
- Other modes that can be used:
  - $D \to K^- \pi^+ \pi^0$ (Coherence analysis underway)
  - $D \to K^0_S K^+ K^-$ and $D \to K^0_S K^+ \pi^-$
  - $D \to K^- K^+ \pi^+ \pi^-$ and $D \to K^0_S \pi^- \pi^+ \pi^0$