Studies of Hadronic B Decays with Early LHCb Data

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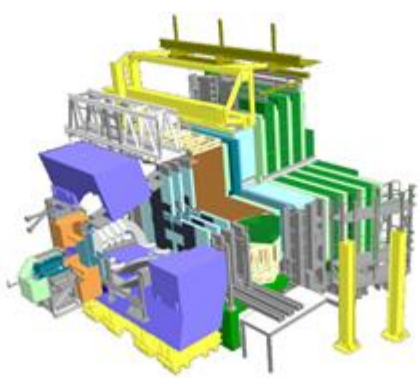
On behalf of the LHCb Collaboration

DISCRETE 2010, Rome, Italy, 9 December 2010



OUTLINE:

- *$B \rightarrow D\,X$ decays*
- *$H_b \rightarrow h\,h$ decays*
- *Prospects for the 2011 LHC(b) run*

Is the study of hadronic B decays worth it ?

= Discussed in talk

CP violation

Dynamics of heavy flavour decays

Quark mixing

Discovery channels

CKM γ angle

Hadronic B decays

Theory

Experiment

$H_b \to h\,h$

$B \to h\,h\,h$

Time-(in)dependent measurements

$B \to D\,X$

2-body baryonic

CP asymmetries

3-body baryonic

Lifetimes

Branching ratios

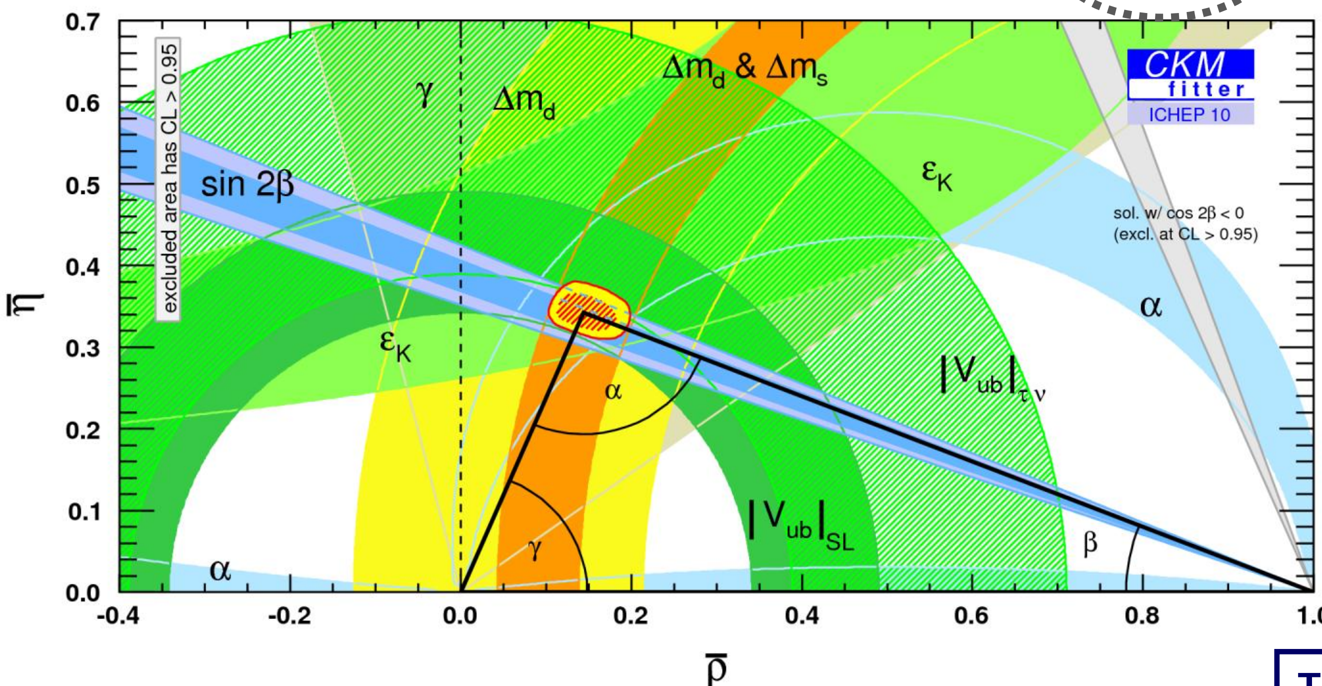
(Non-comprehensive listing)

Status of γ in CKM global fits

Tree-level decays ⇒ **Standard Model benchmark measurement of γ**

"Loop" decays ⇒ **Measurement of γ sensitive to New Physics**

Fit with all constraints: $\gamma = (67.2 \pm 3.9)°$



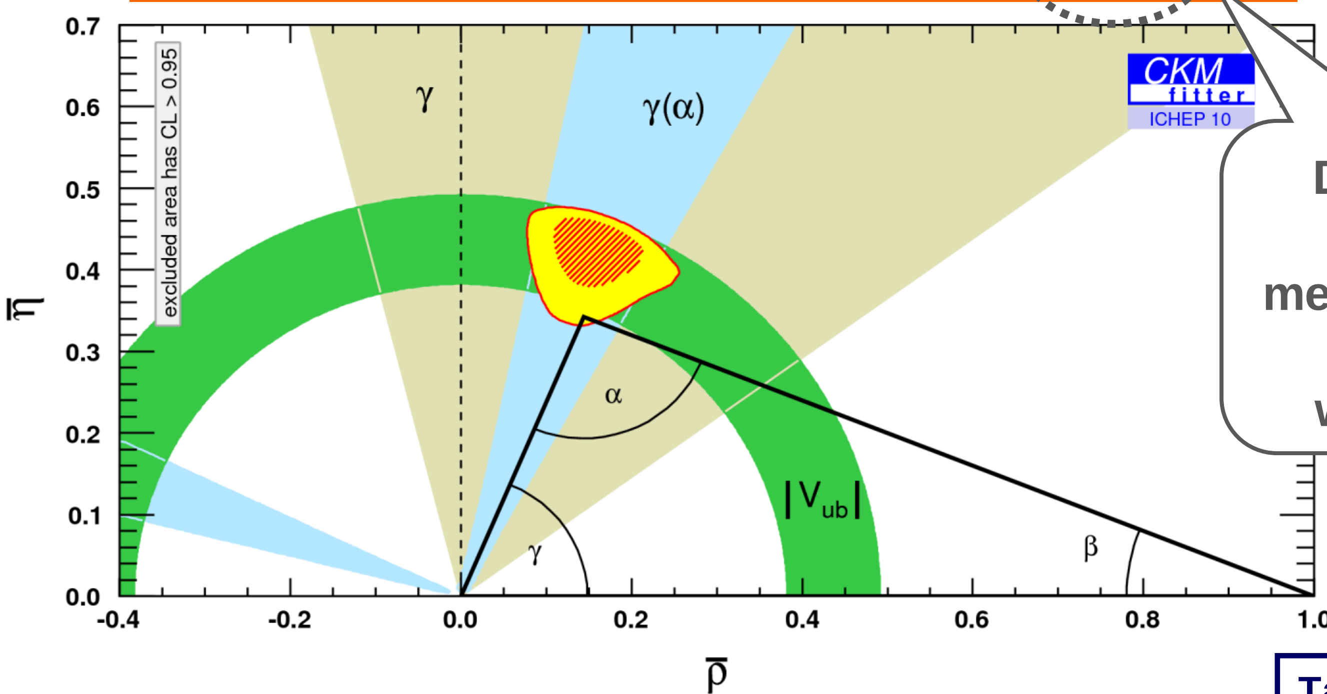
Taken from CKMfitter
http://ckmfitter.in2p3.fr

Status of γ in CKM global fits

Tree-level decays ⇒ **Standard Model benchmark measurement of γ**

"Loop" decays ⇒ **Measurement of γ sensitive to New Physics**

Fit with "trees" only : $\gamma = (71 \pm 23)°$



Direct and precise measurements are … welcome !

Taken from CKMfitter
http://ckmfitter.in2p3.fr

Direct measurements of γ

Tree-level decays ⇒ **Standard Model benchmark measurement of γ**

$B \to D X$ decays :

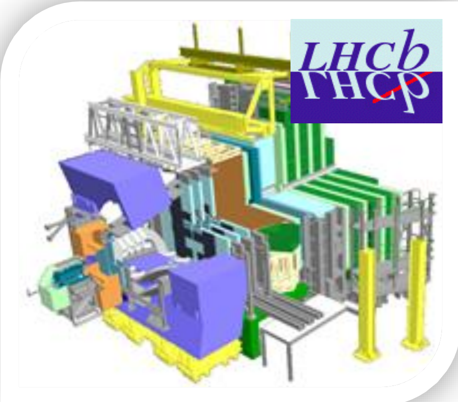
- Time-integrated measurements
- Time-dependent measurements

LHCb can do them all !

"Loop" decays ⇒ **Measurement of γ sensitive to New Physics**

$B \to h h (h)$ modes :

- Time-dependent measurements exploiting U-spin symmetry ($B \to hh$)
- Time-integrated Dalitz plot analysis ($B \to hhh$)



The LHCb experiment

The LHCb experiment @ the LHC

Forward spectrometer

Acceptance: ~10 – 300 mrad

Nominal lumi.: $2 \bullet 10^{32}$ cm^{-2} s^{-1}

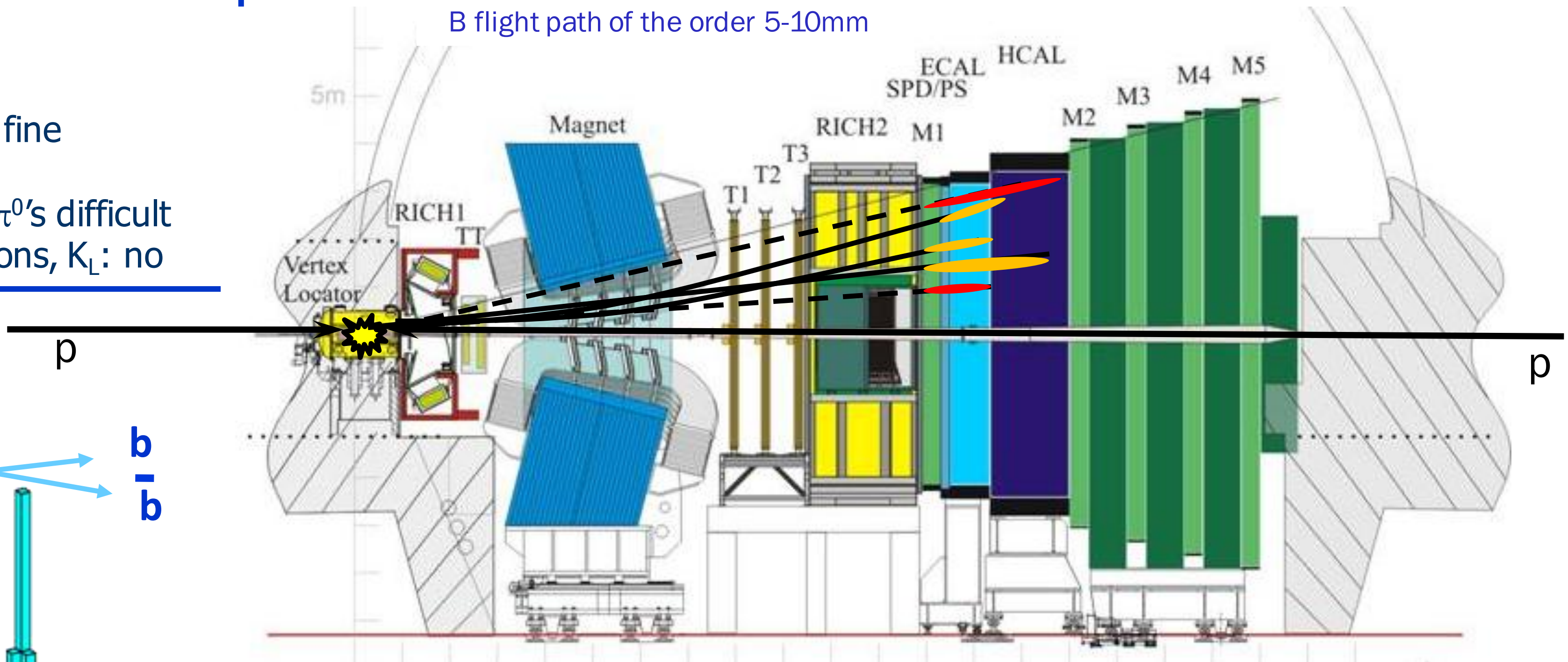
Nominal # B's / 2fb^{-1}: 10^{12}
(nominal year)

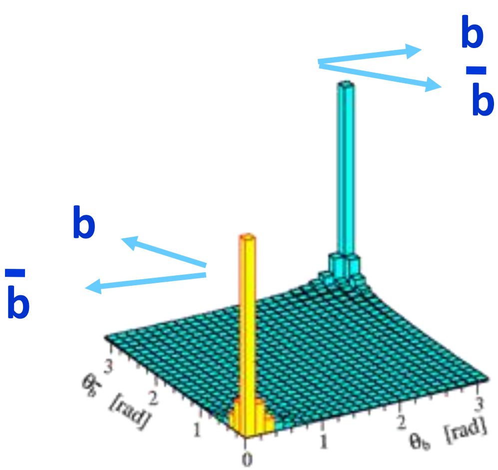
Reconstruction:
- muons: easy
- hadronic tracks: fine
- electrons: OK
- π^0's, K_S, Λ: OK; π^0's difficult
- neutrinos, neutrons, K_L: no

Mission statement

- **Search for new physics probing the flavour structure of the SM**
- **Study CP violation and rare decays with beauty & charm hadrons**

B flight path of the order 5-10mm





σ(inclusive) ~ 80 mb
σ(b bbar) ~ 0.5 mb

All b-hadron species produced

System requirements

(Hadronic) trigger

- Fast, flexible and efficient

Vertexing

- Precise reconstruction and separation of primary and secondary vertices
  - identification of long-lived heavy flavour decays

Tracking

- Precise determination of track parameters
  ⇒ excellent momentum resolution
  $\delta p/p$ = 0.35% to 0.55%
  ⇒ excellent impact parameter (IP) resolutions

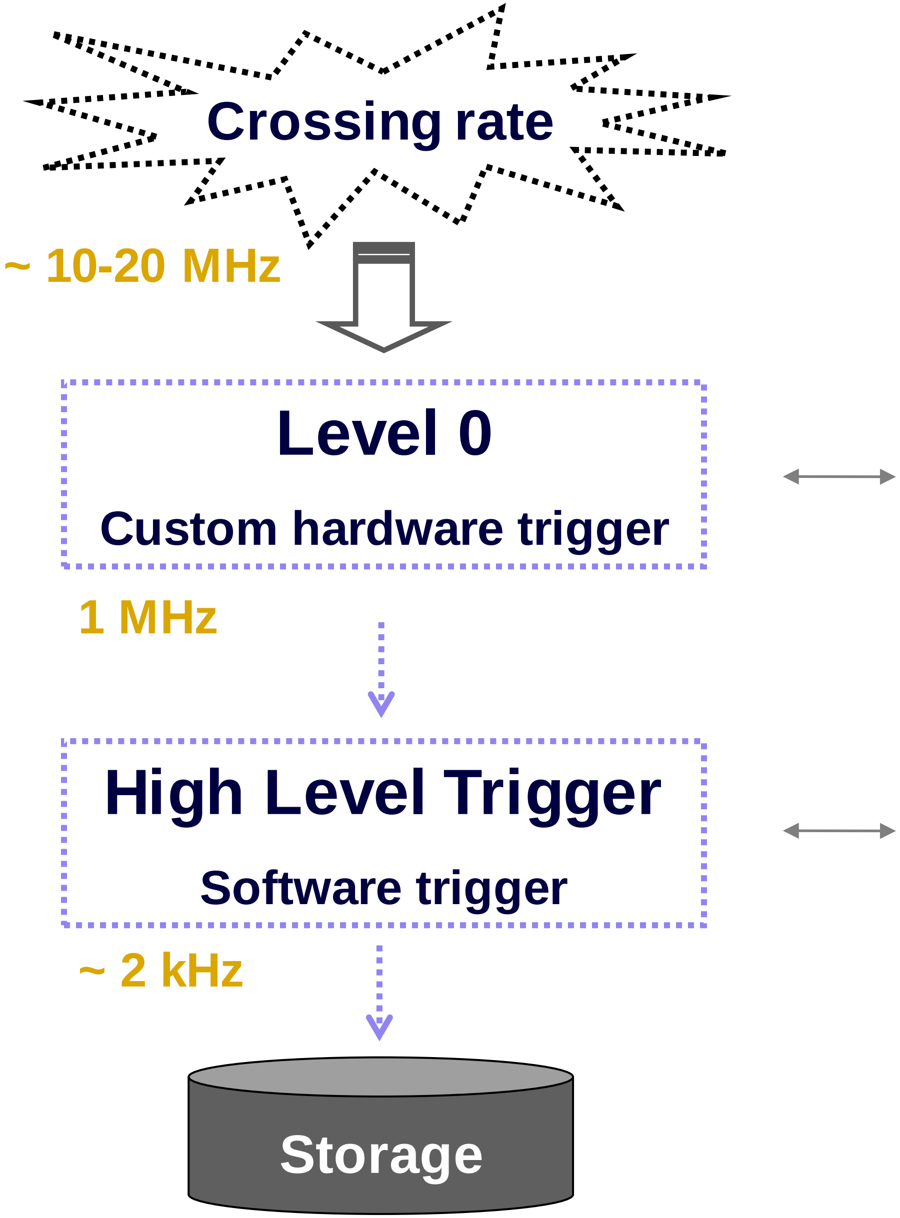
Particle identification

- Mass peaks often overlap
  -> need for excellent π/K/p separation over large momentum range to separate the topologically similar decay modes

Crucial to LHCb physics programme

Beauty & charm mesons
Excellent
- *mass resolutions* ~10-40 MeV
- *propertime resolution* ~50 fs

Trigger scheme



High E_T particles

- Partial detector information
- Fast decision

Search for physics signatures

- Software trigger run in event farm
- Full detector information
- Increasing level of complexity in event reconstruction and selection

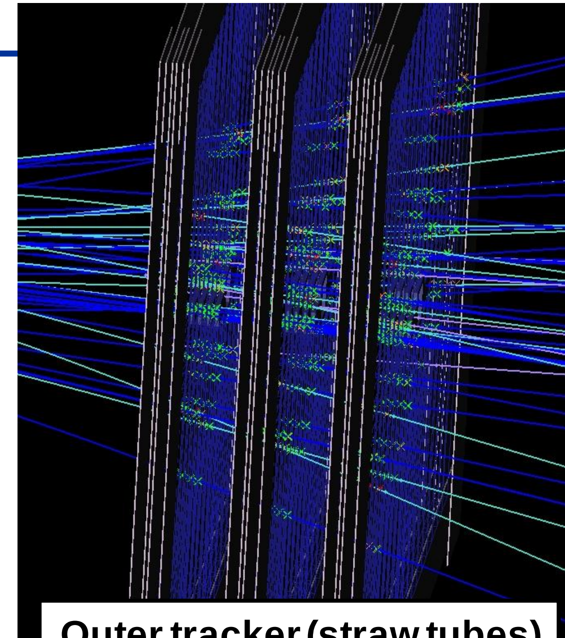
Tracking

- High momentum resolution needed to separate topologically similar decay modes

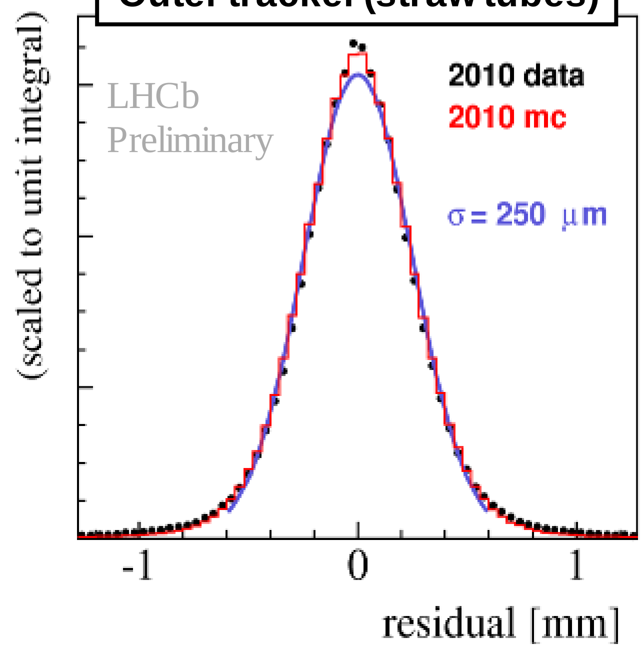
- Silicon strip and straw-tube detectors for tracking
  - long lever arm ~ 10 m
  - hit resolutions ~ 55 and 250 μm, respectively

- Together with precise determination of track slopes provides very good mass resolutions
  - Worse by 10-20% compared to MC.
    But still excellent.

- Provides with high vertex resolutions an excellent propertime resolution



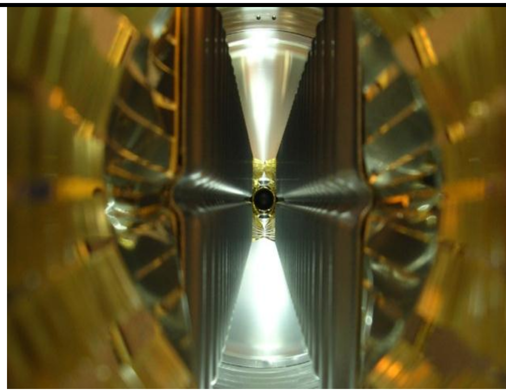
Outer tracker (straw tubes)

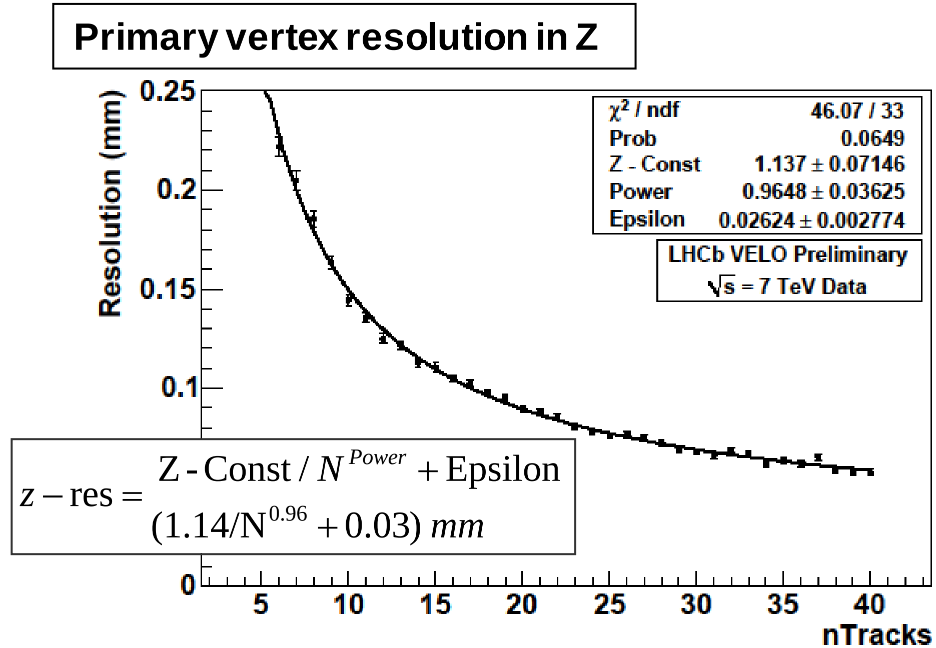


Vertexing

- ❑ **Best such resolutions at the LHC !**

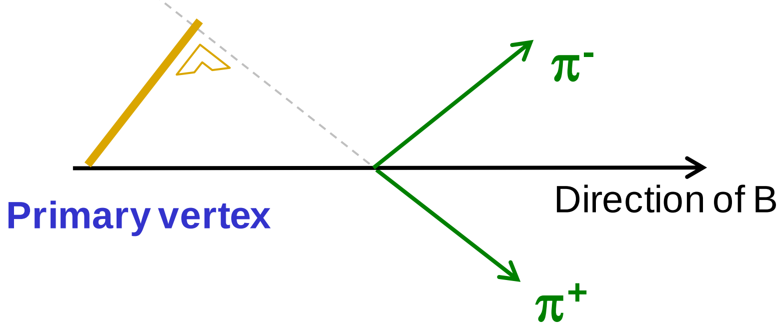
Vertex detector – 2 retractable halves

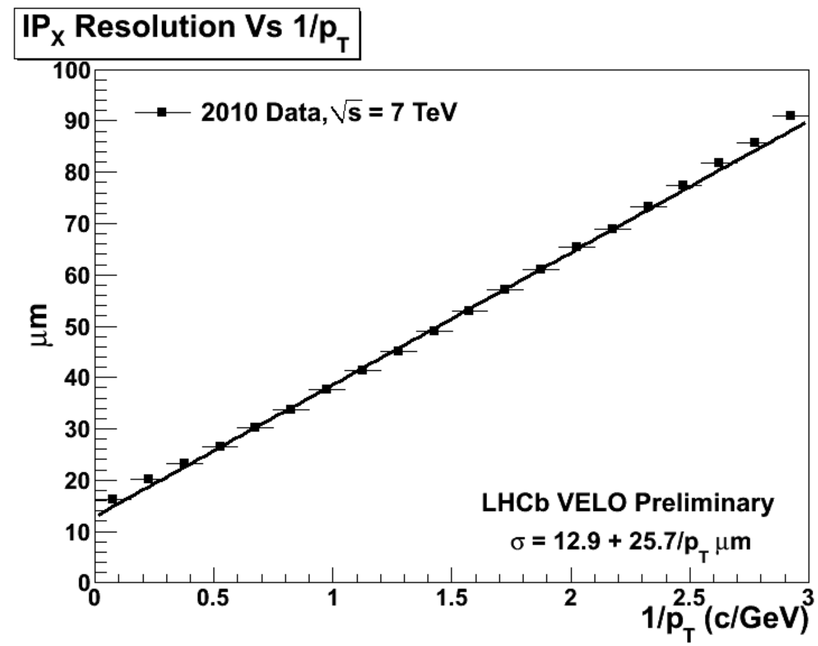




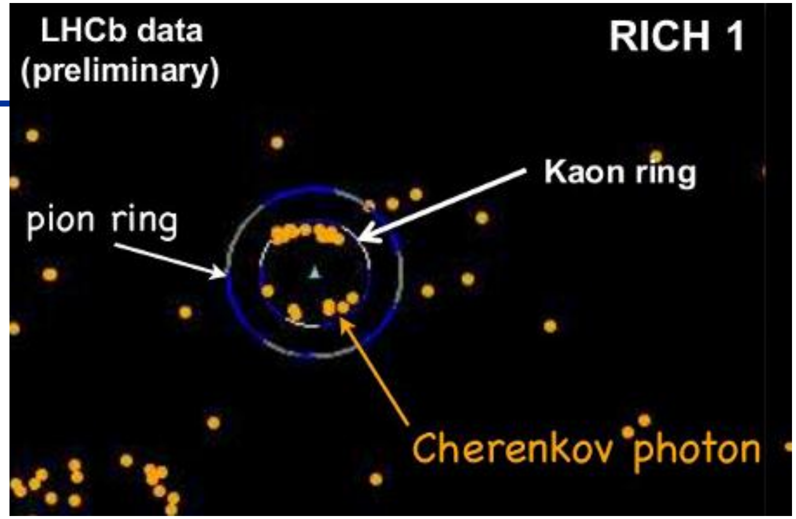
- ❑ **IP resolutions ~ 20% worse than in MC. But still excellent**

IP = Impact Parameter

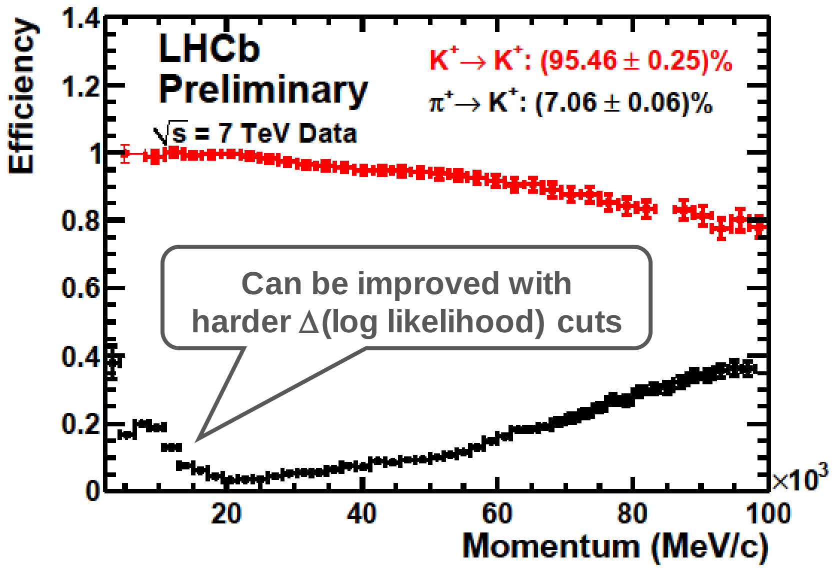


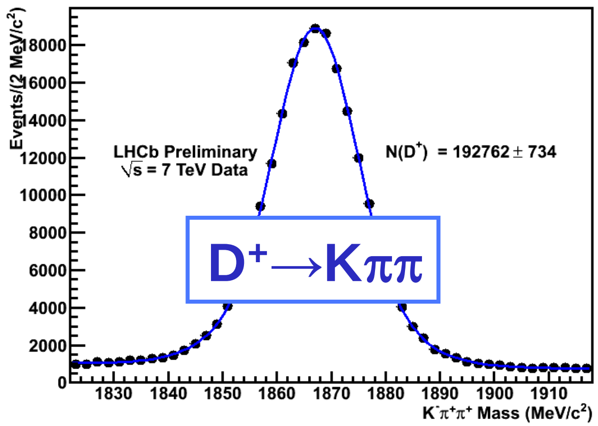


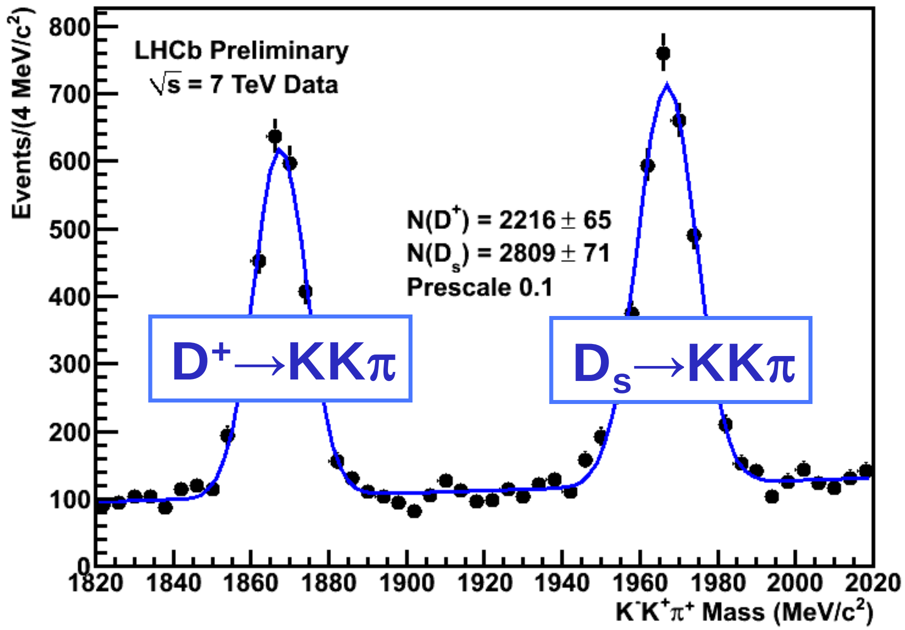
Particle identification



- LHCb has 2 RICH detectors
- Provide excellent π, K and p separation over the large spectrum $p \in [2, 100]$ GeV/c



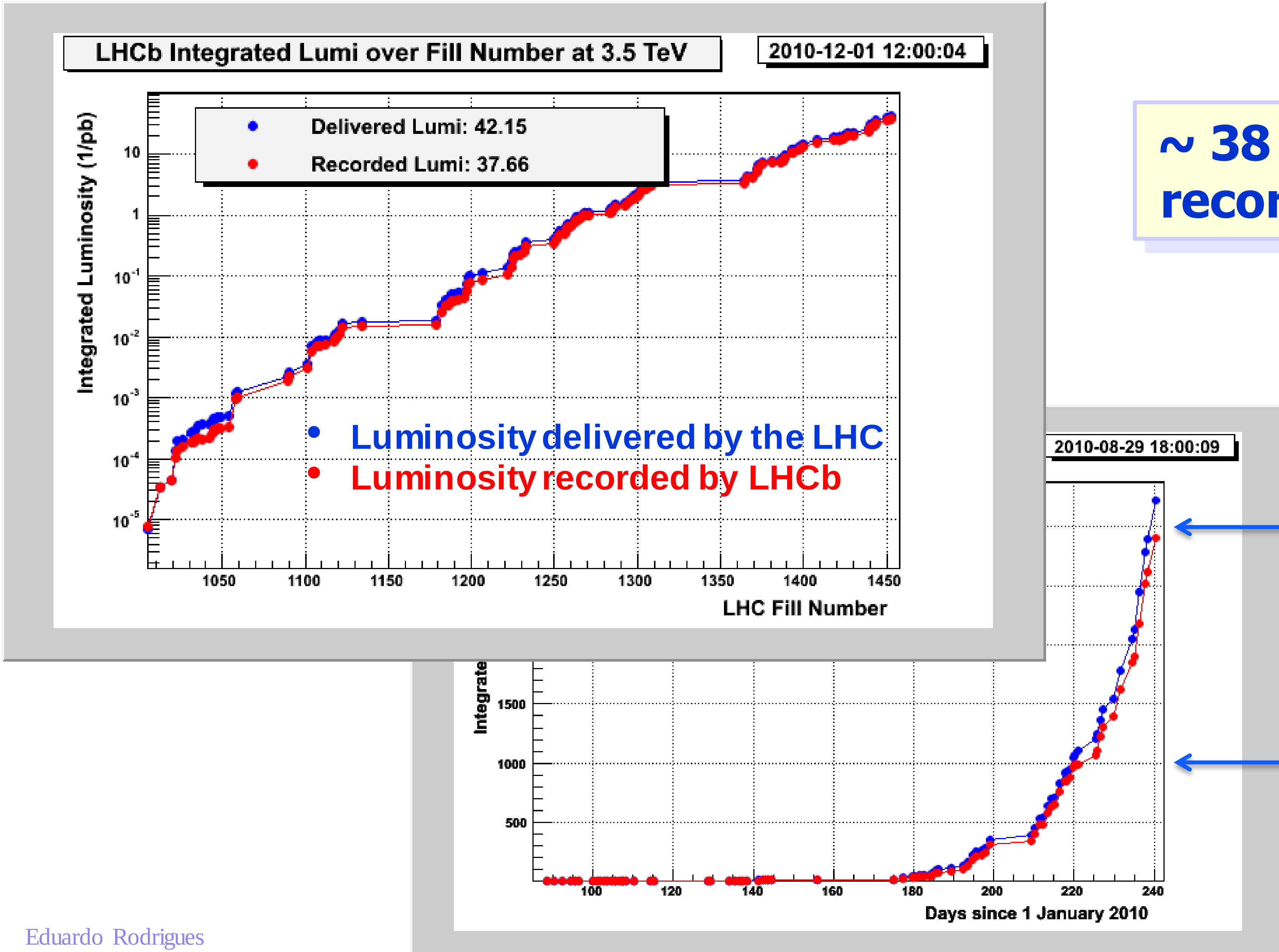




(Only 0.6 pb^{-1})

The 2010 LHC(b) run and prospects for 2011

2010 data taking – luminosity recorded



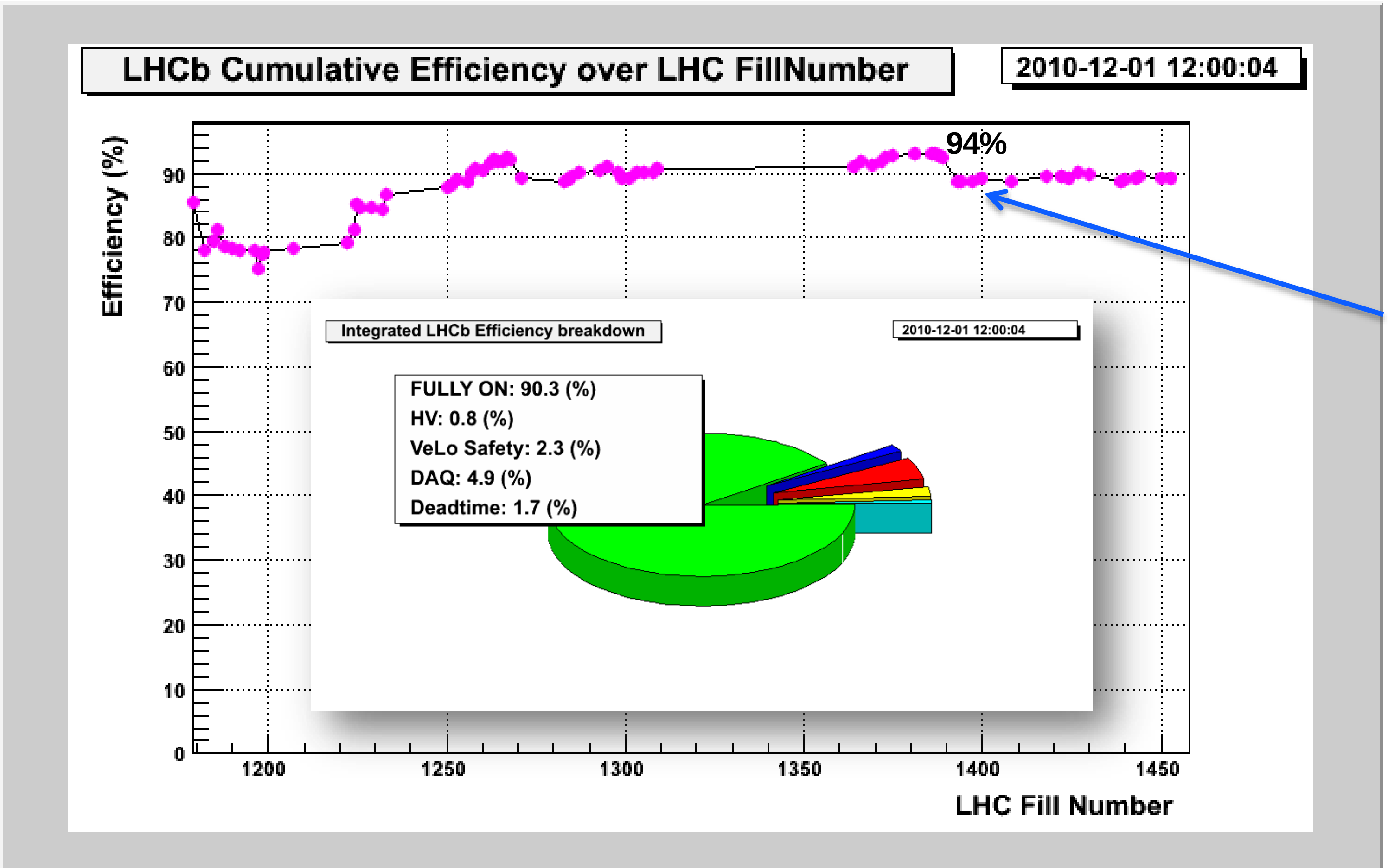
~ 38 pb^{-1} recorded

Over 3 pb^{-1} 20 days later!

1 pb^{-1} on 7th August

2010 data taking – efficiency

Excellent efficiency ~ 90%



Running with high average # of visible interactions per crossing

- ❑ Stable data taking
- ❑ High efficiency of all sub-detectors, increasing with time (experience)

2010 & 2011 running conditions

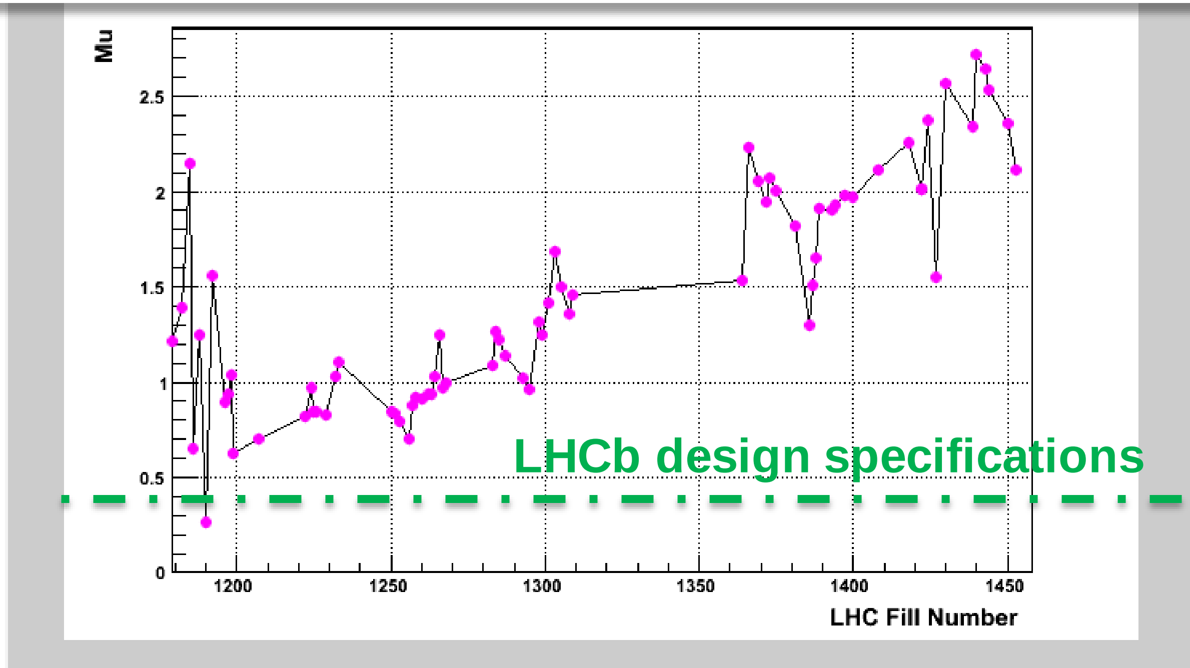
2010 running conditions :

- Collisions at 7 TeV
- ~ 38 pb^{-1} collected

Expectations for 2011 :

- Reach 1 fb^{-1} = 1000 pb^{-1} by end 2011
- Discussion ongoing for 8 TeV run

Average number of visible pp interactions per crossing



(80% of design luminosity reached with 344 colliding bunches instead of 2622)

Towards γ with $B \to D X$ decays

Standard Model benchmark measurement

The (large) B → D X family

Modes :

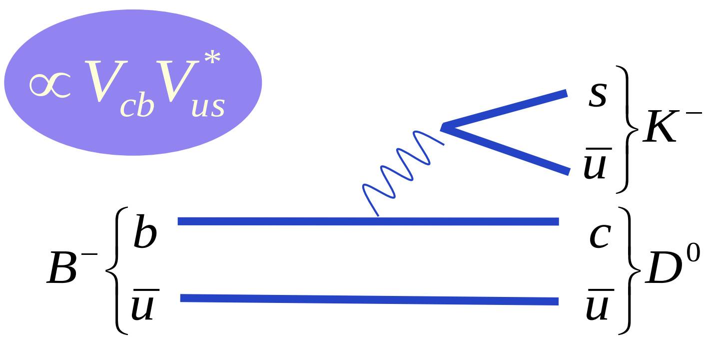
- ❑ $B^0 \to D\,\pi$, $D\,K^{(*)}$
- ❑ $B^- \to D\,\pi^-$, $D\,K^-$
- ❑ $B_s \to D_s\,\pi$, $D_s\,K$, $D\,K^*$, $D\,\phi$
- ❑ The above with D → 2-/3-/4-body

Physics :

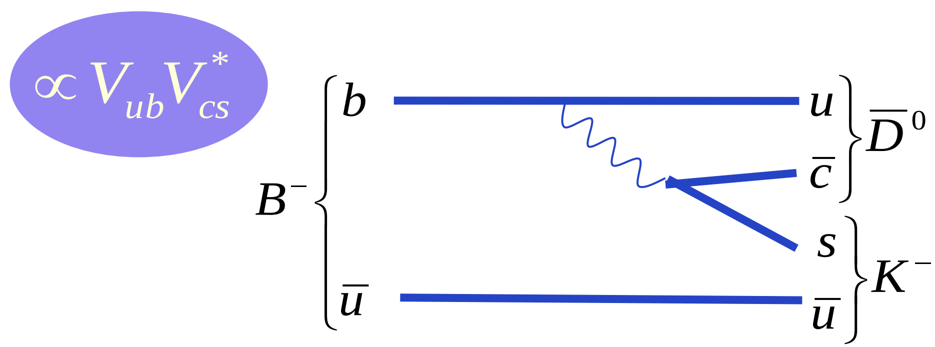
- ❑ Set of modes with rich scope for CP violation measurements, BR ratios
- ❑ Theoretically clean measurement of γ with $B \to$ DK modes
  (relative weak phase between the 2 diagrams = $-\gamma$)

✓ Sensitivity to γ from interference between the 2 diagrams

✓ Only requirement: D^0 and $\overline{D}^0$ decay to common final state



- final state contains D
- colour allowed

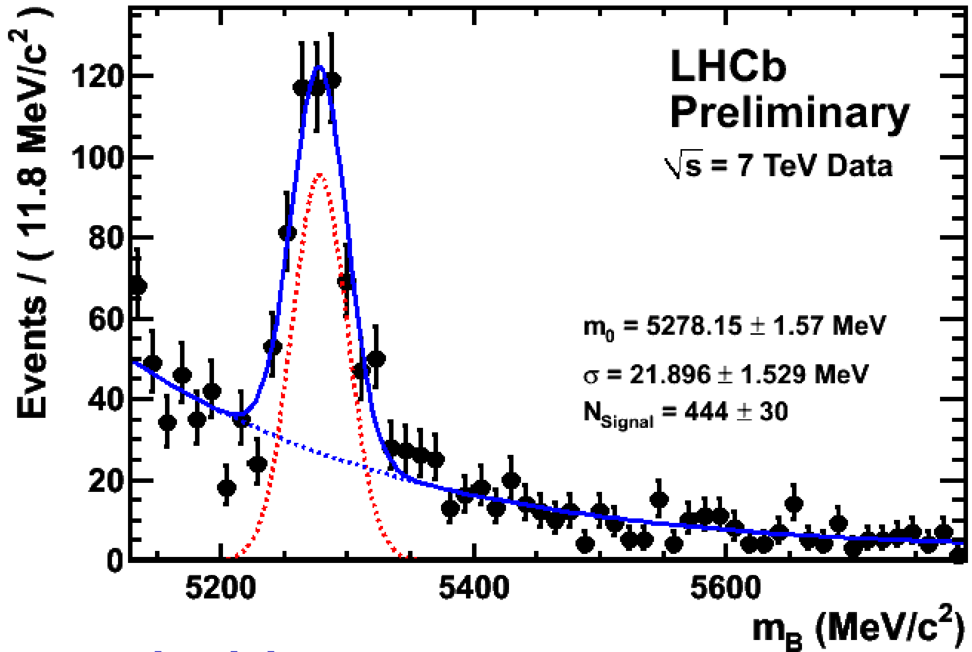


- final state contains D-bar
- colour suppressed

$B \to D\pi$ / K decays – 2-body $D \to h h$ decays

- Mass peak with **~ 34 pb^{-1}**

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



- Clean signals seen for
  - $B \to D\pi$ with $D \to K\pi$, KK, $\pi\pi$
  - $B \to DK$ with $D \to K\pi$

- $B \to DK$ / $B \to D\pi$ BR measurement
  (Currently measured as 6.8%±1.7%)

- Time-integrated analyses (ADS/GLW methods)
  $\Rightarrow$ expect (stat.) error $\sigma_\gamma \sim 17^o$ with 1 fb^{-1} (2010+11 data sample)

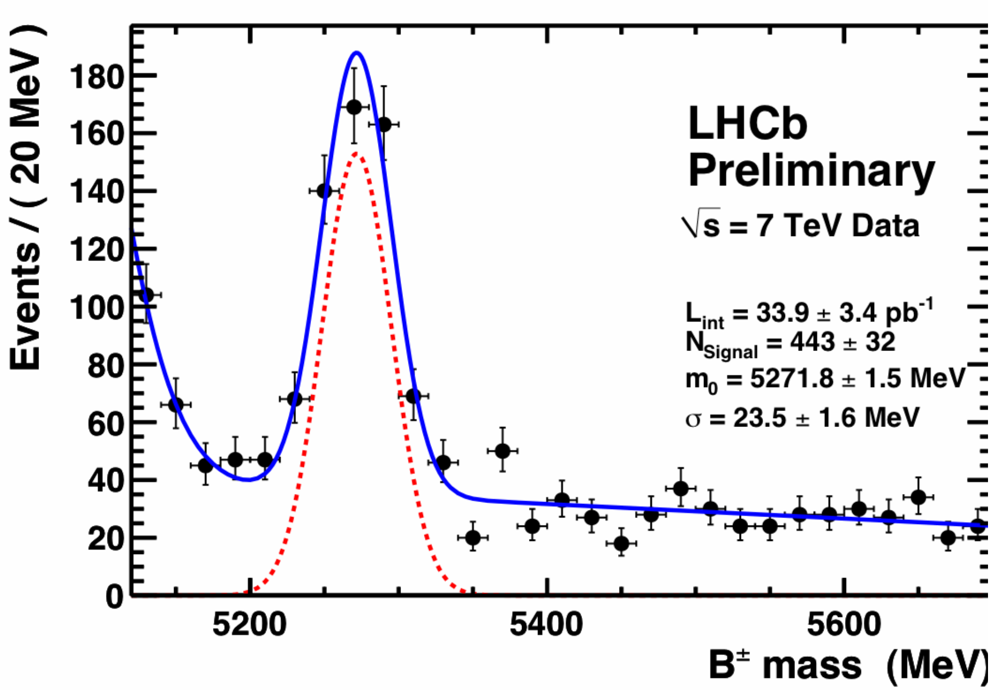
Monte Carlo: expected yields in 1 fb^{-1} @ 7 TeV (2011 running)

$B^+ + B^- \to D_{\rm fav} K^\pm$	$B^+ + B^- \to D_{\rm sup} K^\pm$	$B^+ + B^- \to D_{CP+} K^\pm$
~20000	~400	~2750

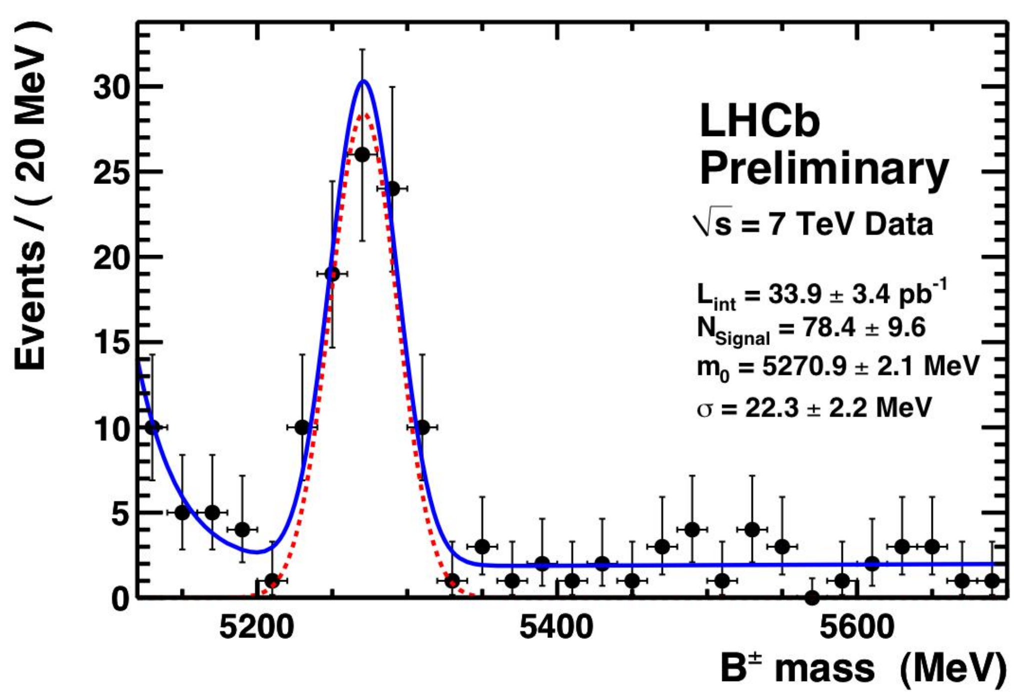
$B \to D\pi$ decays – Dalitz analyses

- Mass peaks with ~ 34 pb^{-1}, i.e. almost all the 2010 data sample

$B^+ \to D^0 (K_s\pi\pi)\,\pi$



$B^+ \to D^0 (K_sKK)\,\pi$

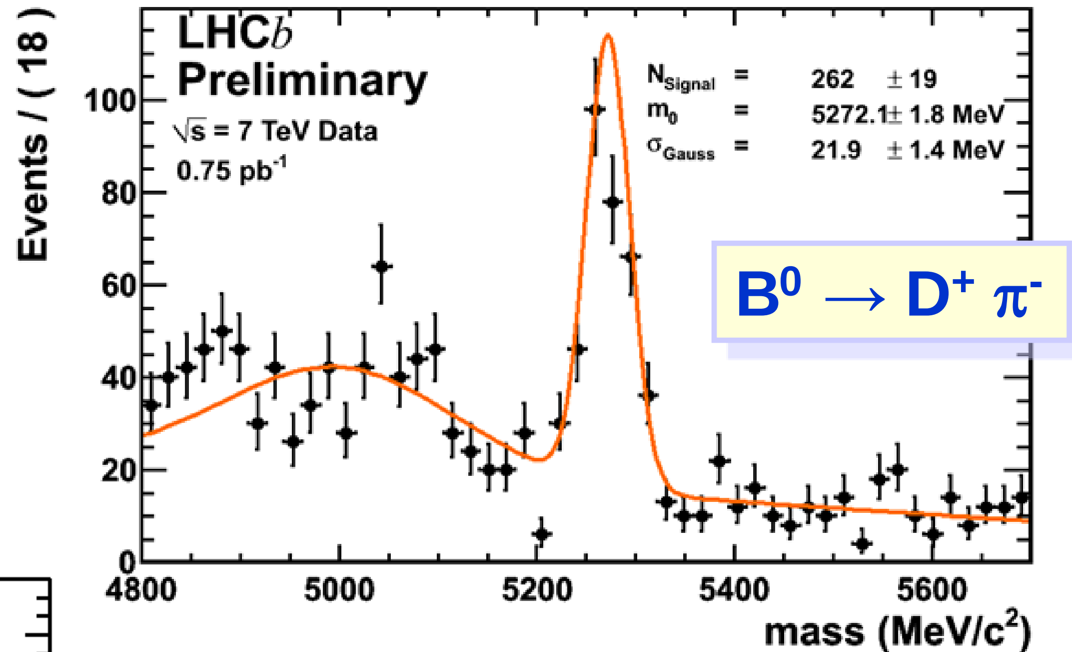


- Dalitz plot analysis of $B \to DK$ with $D \to K_s\pi\pi$

  $\Rightarrow$ expect (stat.) error $\sigma_\gamma \sim 18^o$ with 1 fb^{-1} (2010+11 data sample)

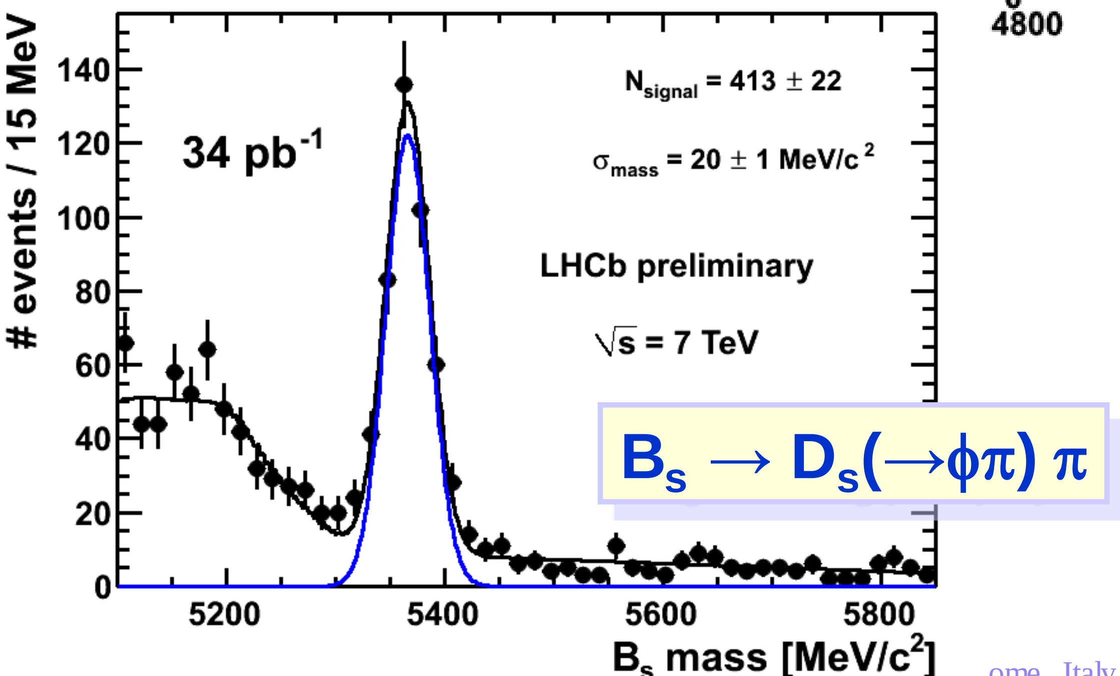
$B_{(s)} \to D_{(s)}$ h decays

❑ Mass peaks with ~ 34 pb^{-1}



Time-dependent CP studies:

❑ Eventually, measurement of γ from $B_s \to D_s$ h ($h = \pi$, K)



Mixing / other studies :

❑ $\Delta m_s / \Delta m_d$ measurements

❑ f_s / f_d measurement

$B \to D X$: physics *goals* with the 2010-11 data sample?

- Measurement of f_d/f_s ratio ($b \to d/s$ fragmentation)
- Measurement of the $D_sK/D_s\pi$ branching fractions ratio
- Measurements of relative rates and CP asymmetries
  - Focus first on 2-body non-suppressed D decays

} **2010**

- Combination of various γ measurements will provide world-best results
  - Sensitivity ~ 6-8º (statistical error) with 1 fb^{-1} according to MC studies

} **2010+11**

Towards γ with charmless B decays

New Physics sensitive measurement

The $H_b \to h\,h$ family

"Standard" modes (BRs ~ 10^{-5}–10^{-6}) **:**

- $B^0 \to \pi\pi$, $B_s \to KK$
- $B^0 \to K\pi$, $B_s \to \pi K$
- $\Lambda_b \to pK, p\pi$

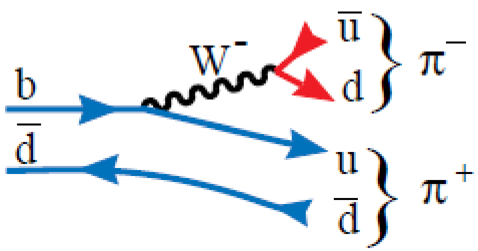
Rare modes :

- $B^0 \to KK$, $B_s \to \pi\pi$
  not yet found experimentally

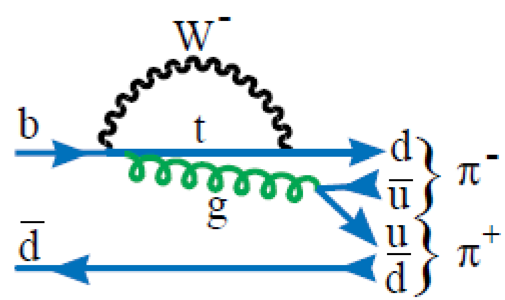
Physics :

- Set of modes with rich scope for
  CP violation measurements
  - Time-independent and dependent A_{CP}
- Access to γ with $B^0 \to \pi\pi$ and $B_s \to KK$

Tree-level diagram



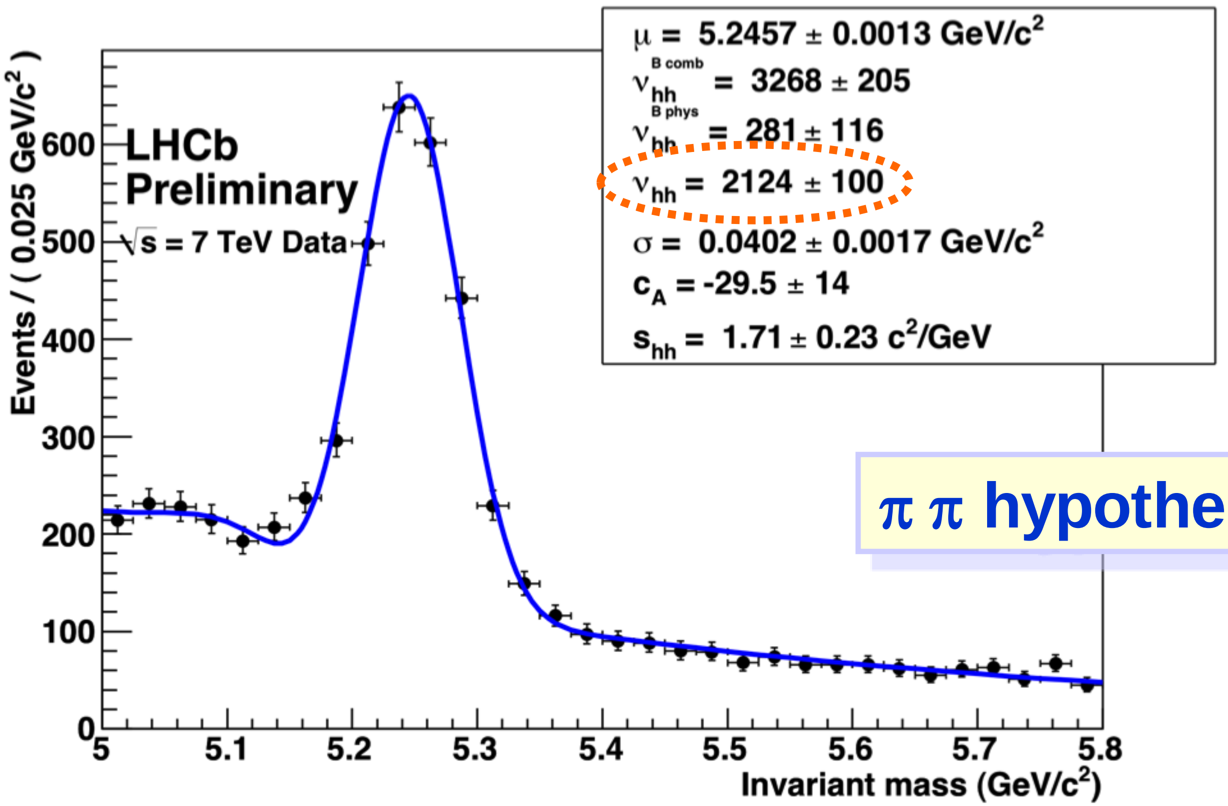
Penguin diagram



The $H_b \to h\, h$ family

- What's in the basket with **35 pb^{-1}**, i.e. almost all the 2010 data sample ?

~ 2100 signal events



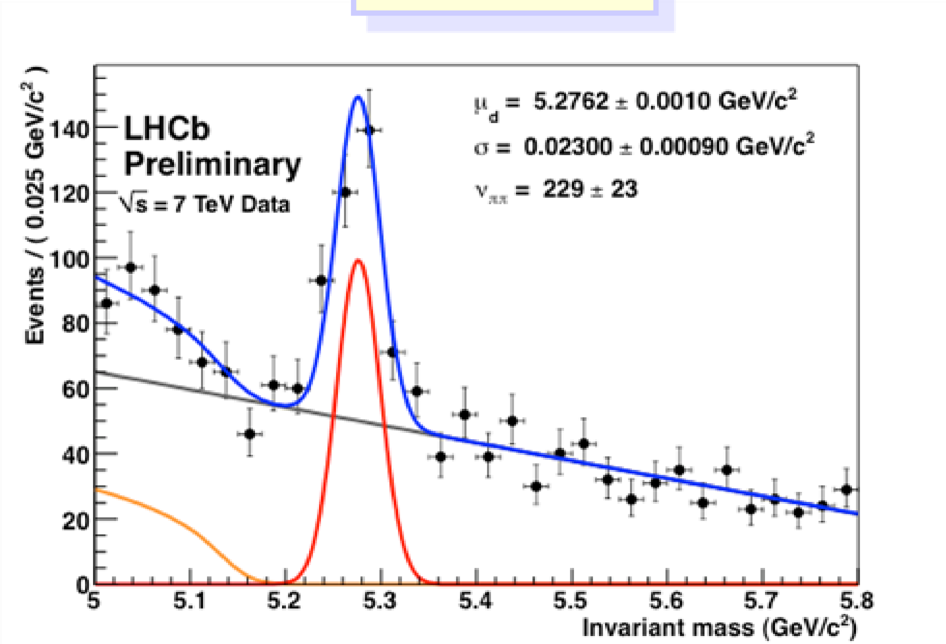
π π hypothesis

(No PID cuts)

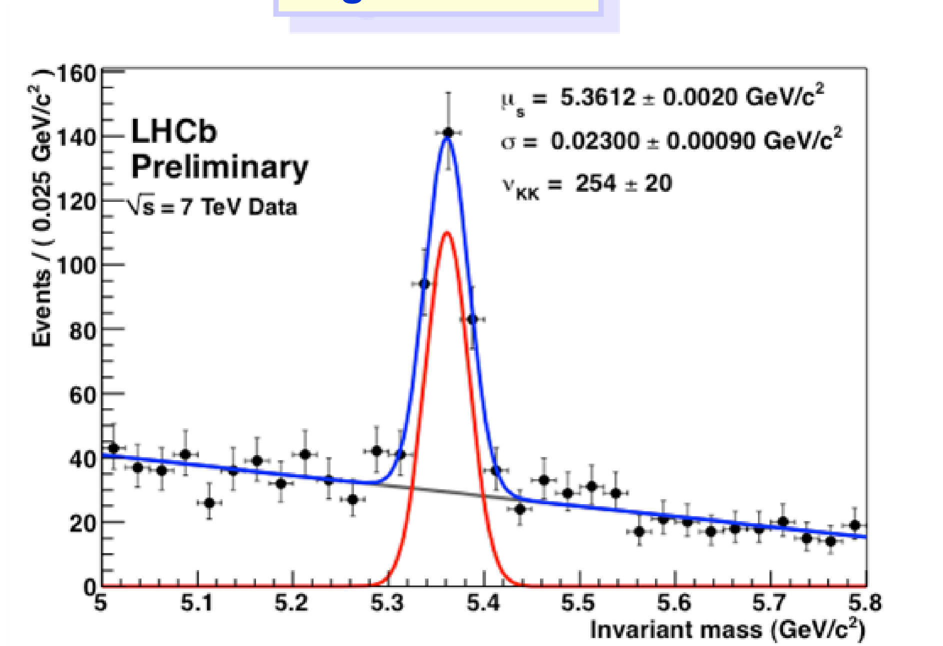
Loose selection – $B^0 \to \pi\pi$ and $B_s \to KK$

- Applying particle identification cuts …

$B^0 \to \pi\pi$

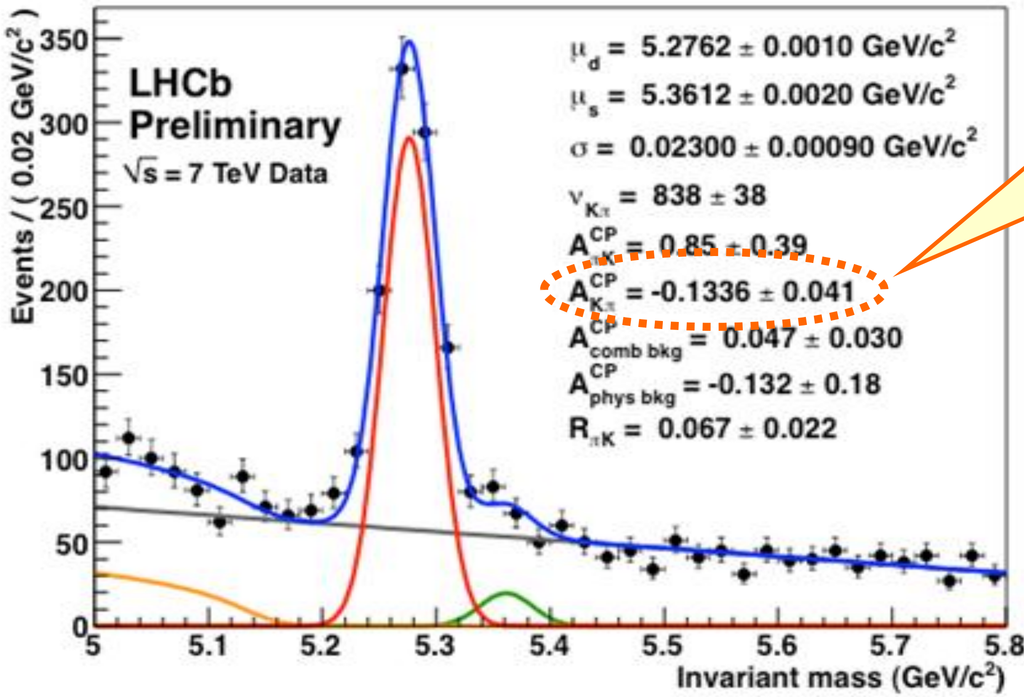


$B_s \to KK$



- Time-dependent CP asymmetries in view of γ measurement will take time ...
  (R. Fleischer method using U-spin symmetry – Phys. Lett. B 459 (1999), 306)

Loose selection – $B \to K\pi$



RAW $A_{CP}(B^0)$ = -0.134 ± 0.041 (stat.)

HFAG average : -0.098 ± 0.012

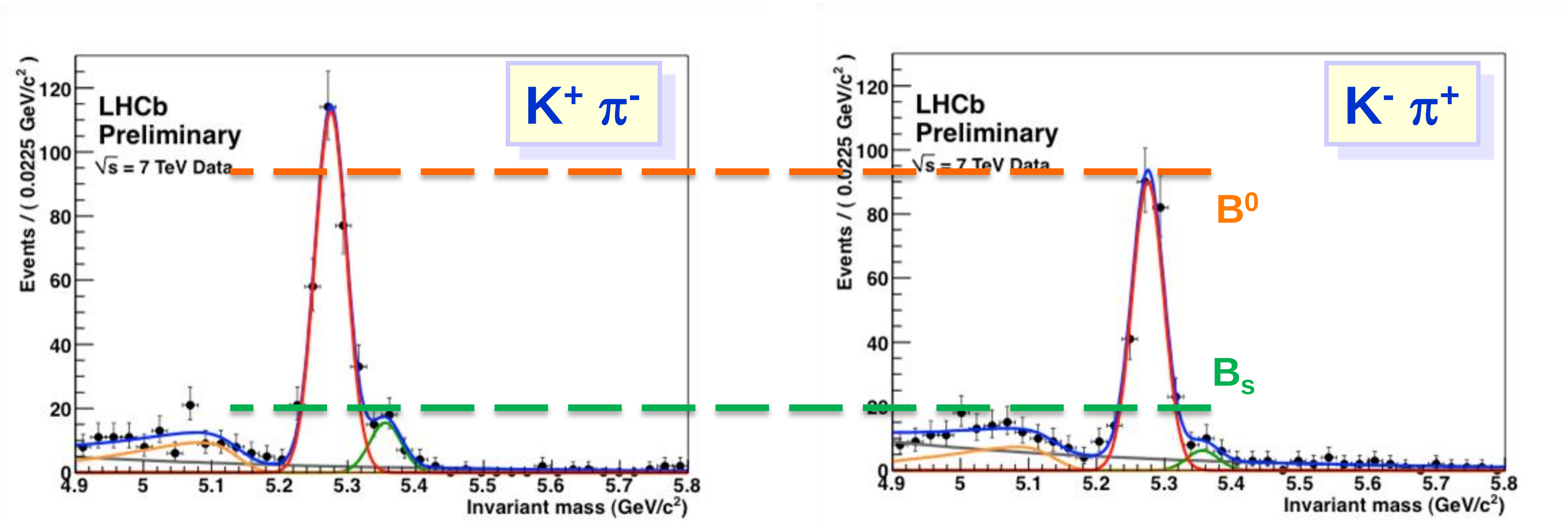
Yield: 838 ± 38

Note:

- **Raw numbers**
- **No corrections for production/detector asymmetries**
  (same comment goes for all subsequent A_{CP} results)

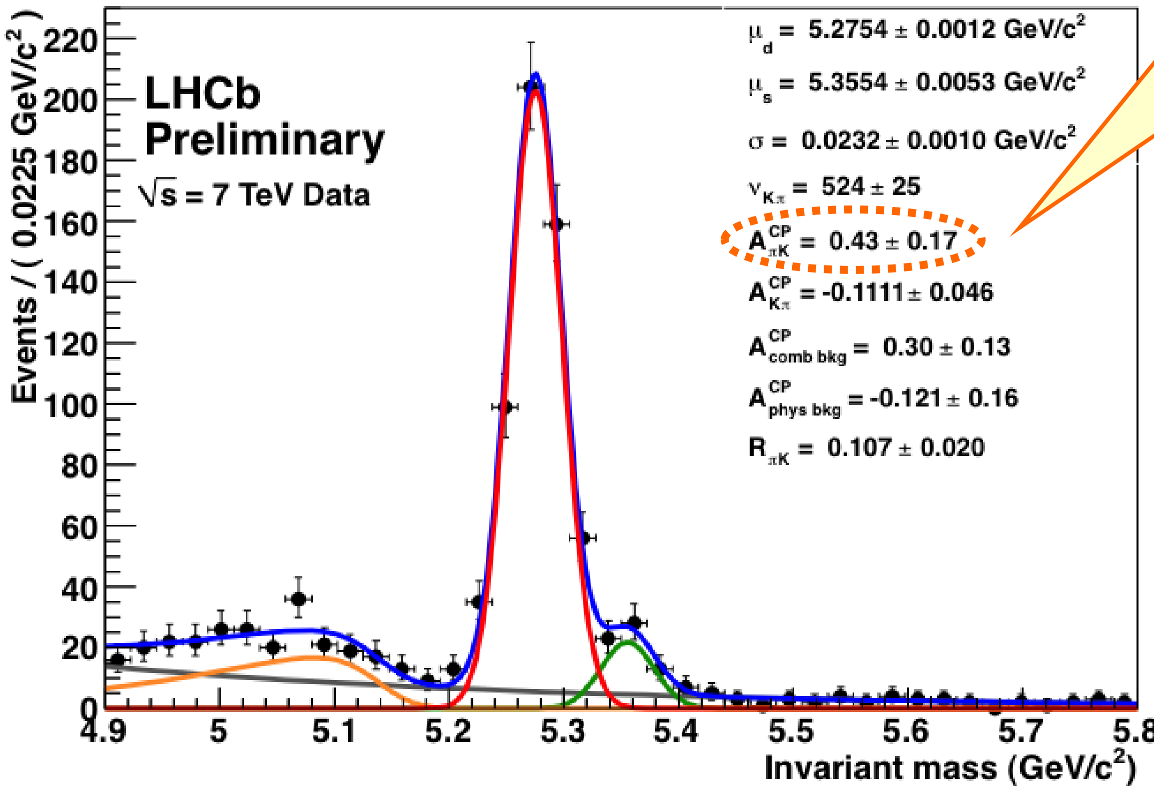
Charge asymmetry in $B^0/B_s \rightarrow K\,\pi$ (tight selection)

RAW asymmetry is visually obvious !



Note: No corrections for production/detector asymmetries

Tight selection optimised for $B_s \to \pi K$



Raw A_{CP} (B_s) = 0.43 ± 0.17 (stat.)

CDF, 1 fb^{-1} : 0.39 ± 0.15 (stat.)

± 0.08 (syst.)

⇓

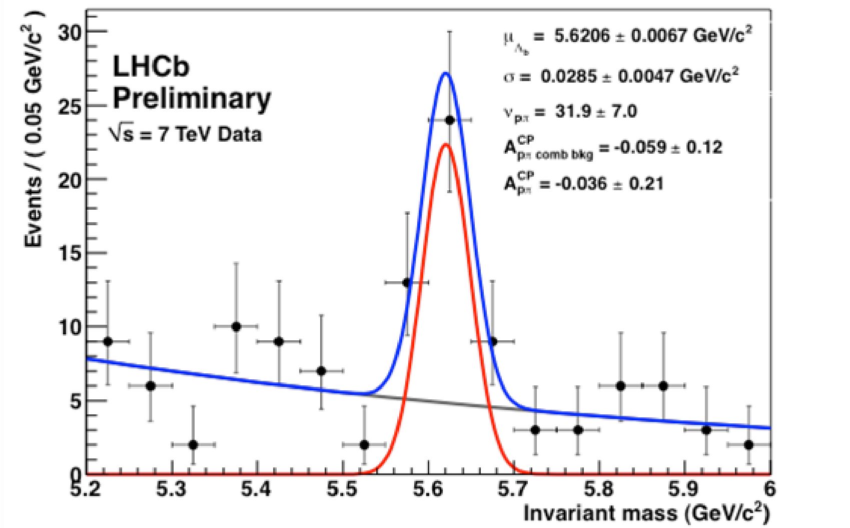
LHCb competitive with CDF with ~ 25 less luminosity !

- RAW B_s / B_d relative yield $R_{\pi K}$ = (10.7 ± 2.0) % (stat. error only)

$\Lambda_b \to$ p h decays

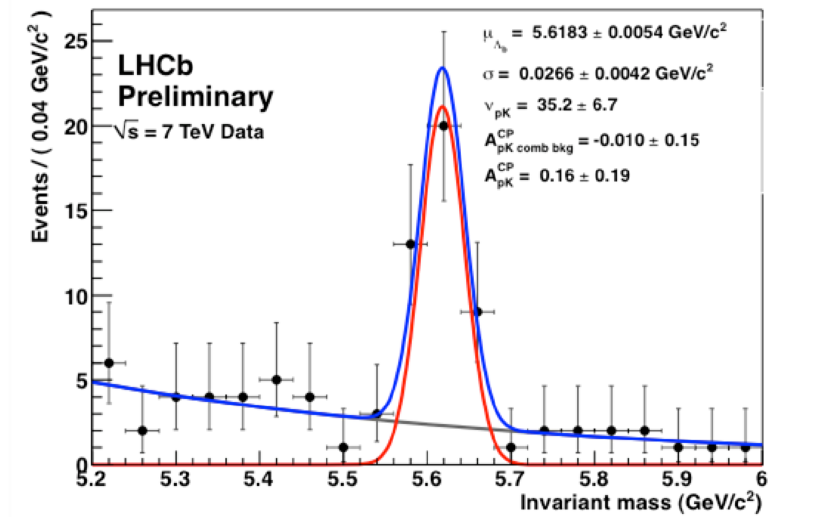
Both signals clearly seen

$\Lambda_b \to p\,\pi$



RAW yield: 31.9 ± 7.0 (stat.)

$\Lambda_b \to p\,K$



RAW yield: 35.2 ± 6.7 (stat.)

- ❑ **CP asymmetry measurements to follow shortly …**

$H_b \to h\,h$: physics *goals* with the 2010-11 data sample

- Expected yields by end 2011 (1 fb^{-1}) :

Mode	Yield (1 fb^{-1})
$B^0 \to K\,\pi$	~ 24 k
$B^0 \to \pi\,\pi$	~ 6.5 k
$B_s \to K\,K$	~ 7 k
$\Lambda_b \to p\,K/\pi$	~ 1 k

- CP asymmetry measurements in $B^0 \to K\,\pi$, $B_s \to \pi\,K$ and $\Lambda_b \to p\,h$
- Measurement of relative branching ratios (with respect to $B^0 \to K\,\pi$)

2010

- Relative $B_s \to KK$ / $B^0 \to \pi K$ lifetime measurement
- Absolute $B_s \to KK$ lifetime measurement

2010(+11?)

- Potential discovery of rare modes $B^0 \to KK$, $B_s \to \pi\pi$

2010+11

- New Physics sensitive measurement of γ
  - Sensitivity ~ 7° with 2 fb^{-1} according to MC studies

2011 and beyond

In short: LHCb already competitive with CDF given the 2010 data sample !

Summary

- **LHCb has already proven to be a heavy flavour experiment at a hadron machine**

- **Excellent and promising results are coming out**
  - This was just the beginning

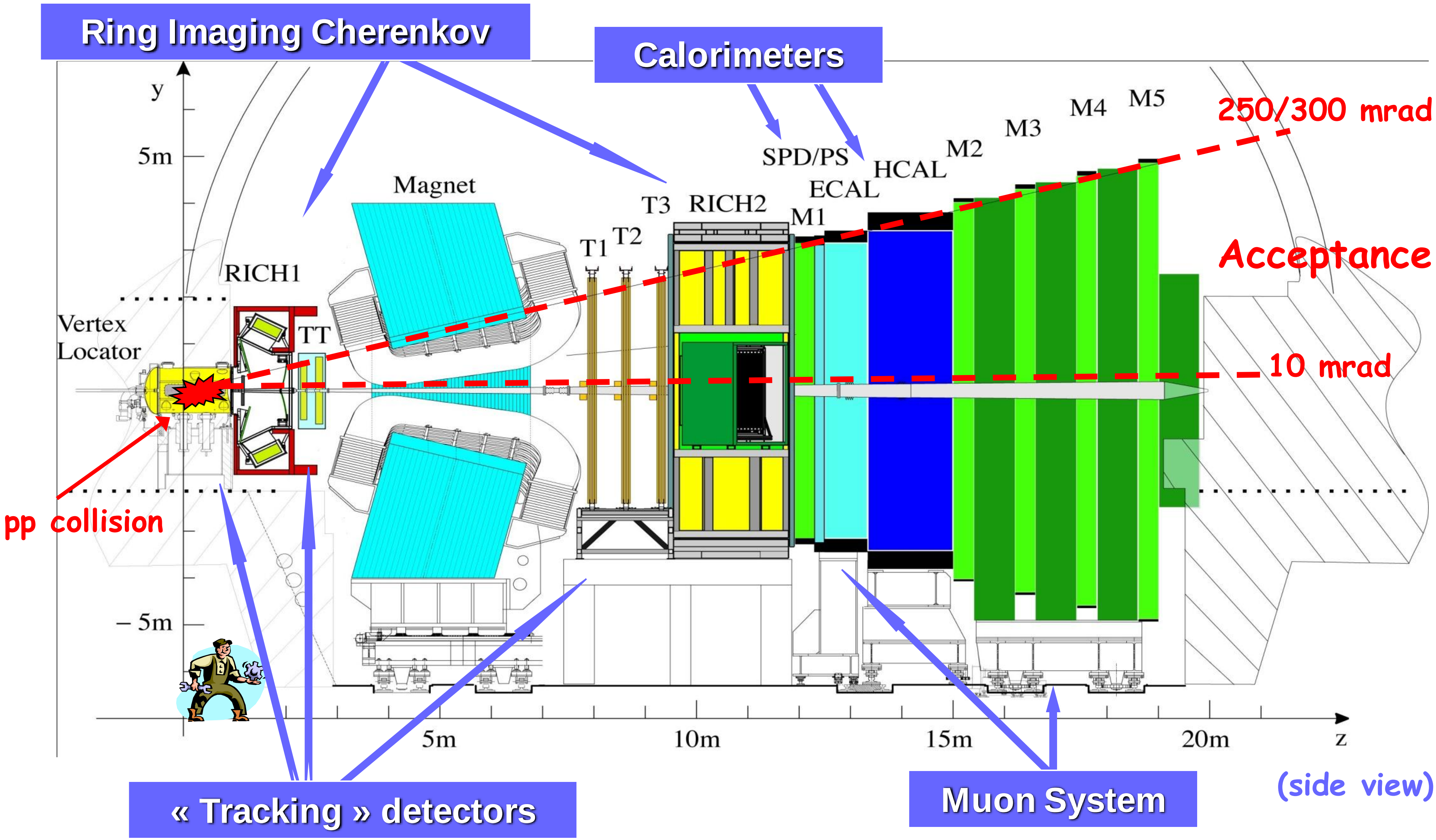
- **Many world-class measurements just around the … year**
  - And many competitive with the TeVatron results

- **Stay tuned …**

- **Thumbs up !**

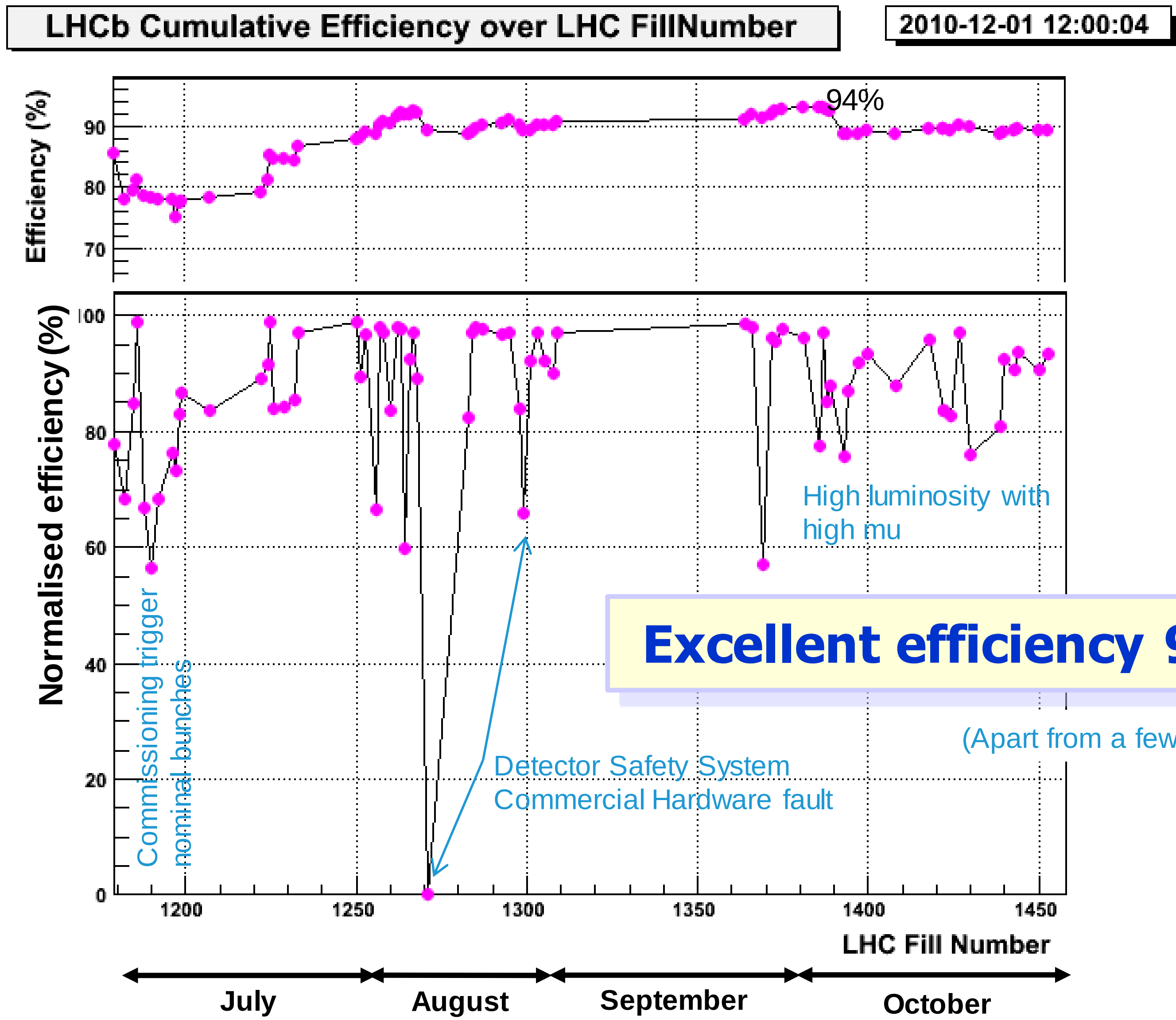
Back-up slides

The LHCb detector



2010 data taking – efficiency

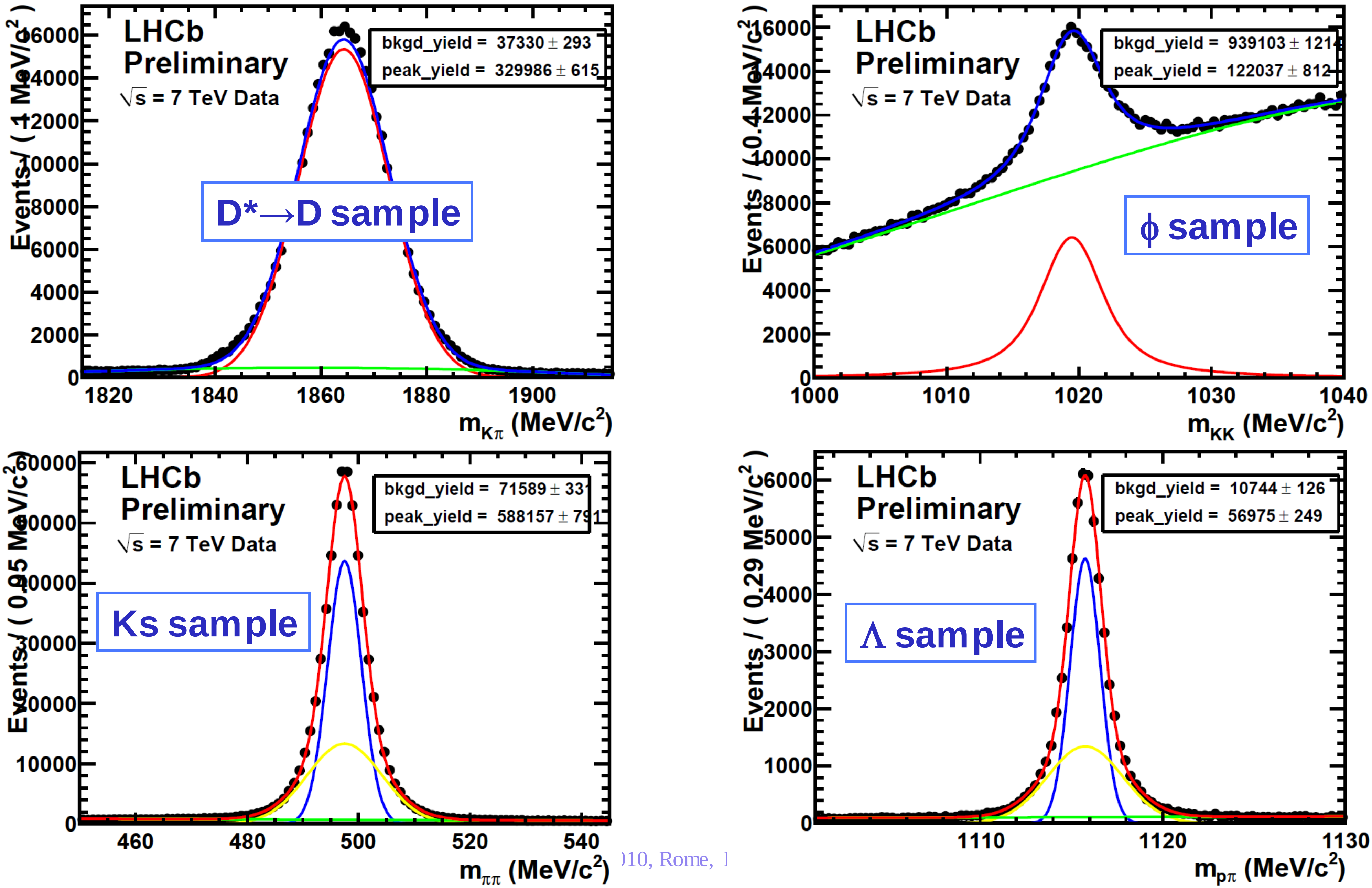
All fills normalised to 1 pb^{-1}



Excellent efficiency 93-98%

(Apart from a few one-off problems)

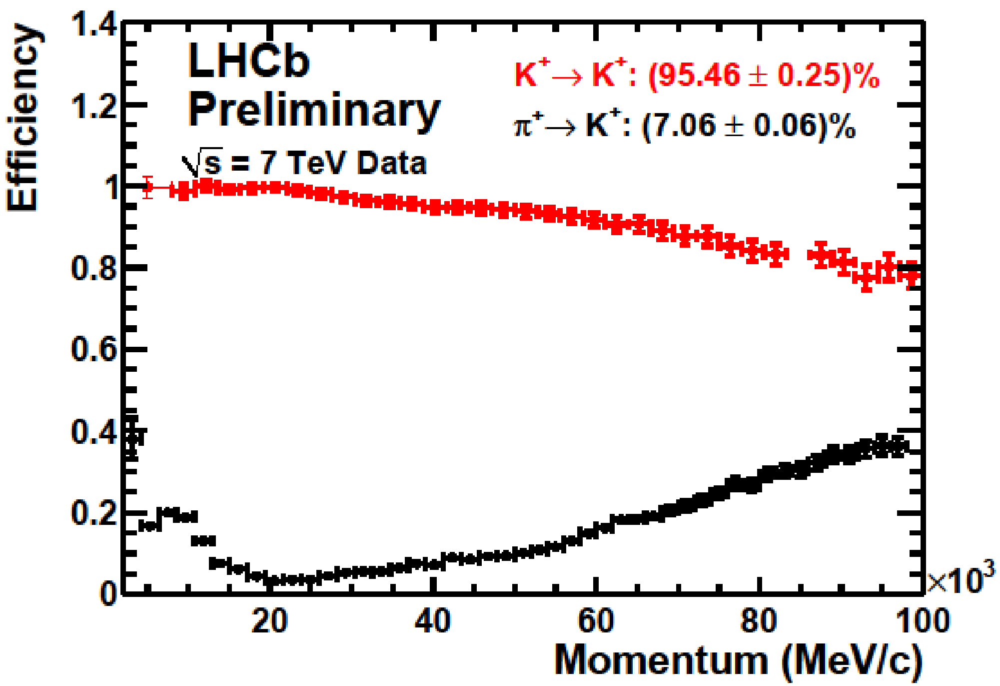
Particle identification – performance determined on data



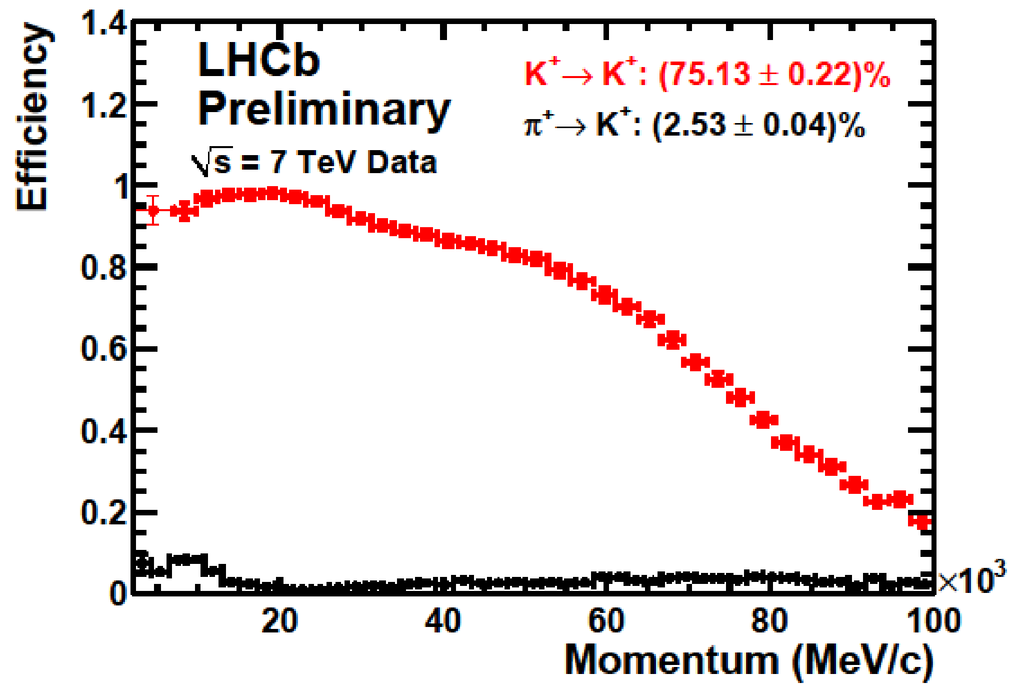
Particle identification – delta log likelihood tuning

Tuning matters

DLL(K-π) > 0

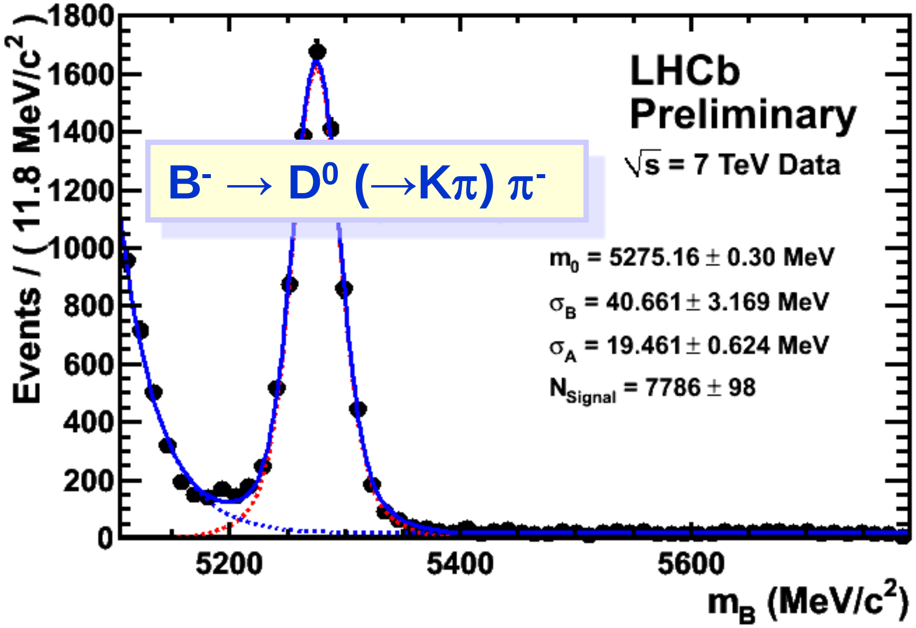


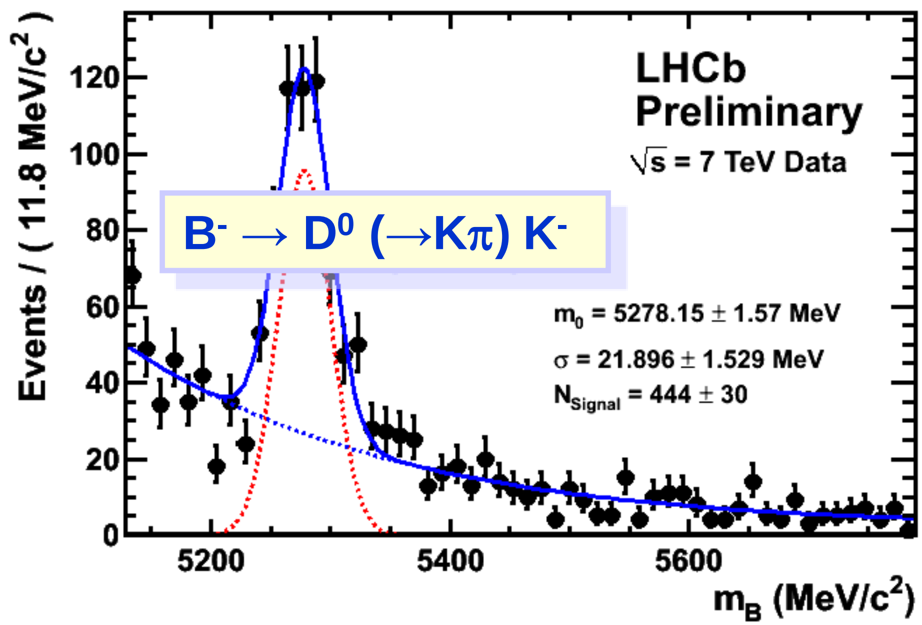
DLL(K-π) > 5

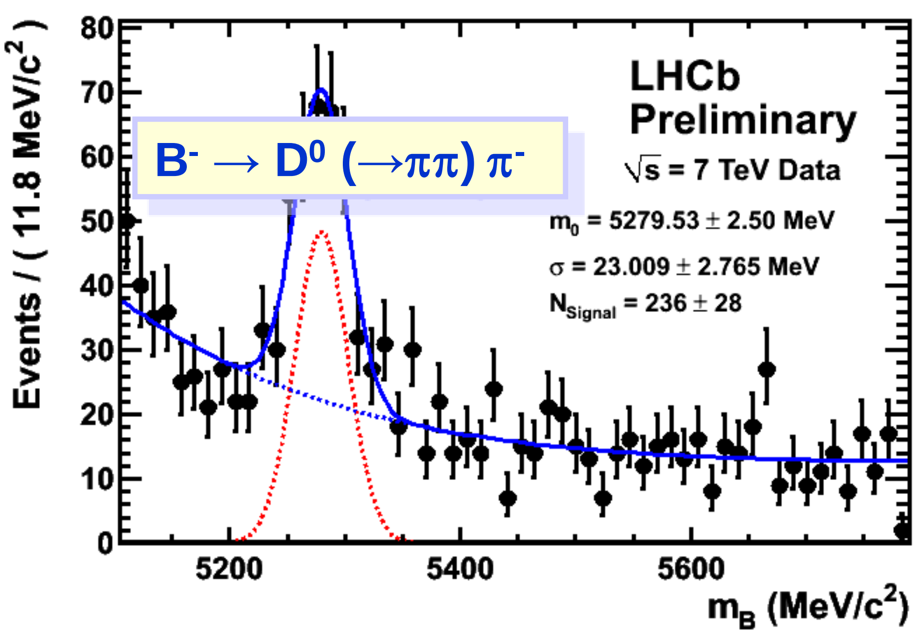


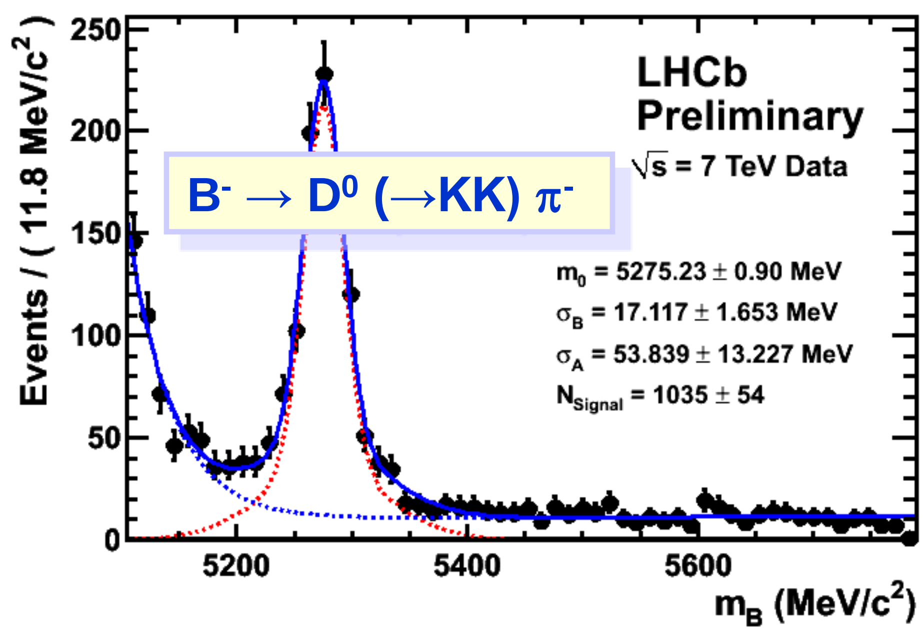
$B \to D(\to hh)\ \pi$ / K decays

Luminosity: ~ 34 pb^{-1}





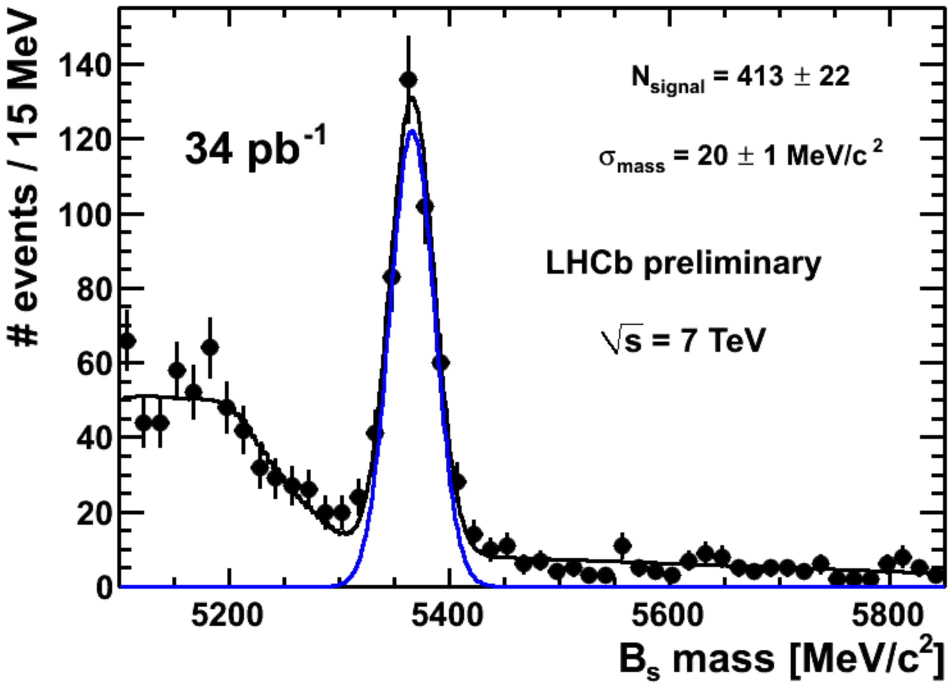




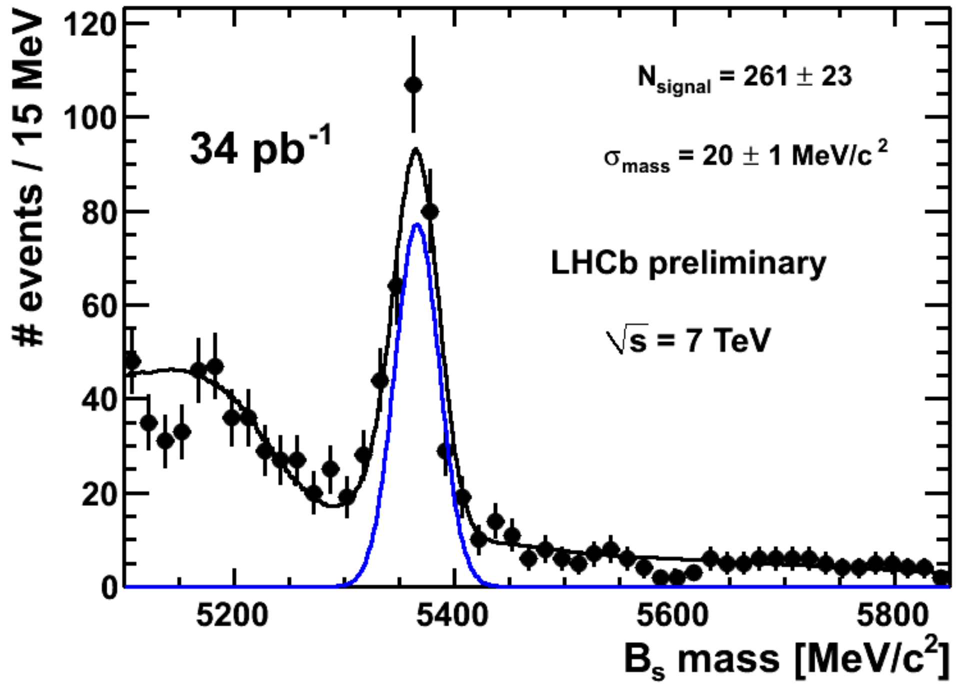
$B_s \to D_s\,\pi$ decays

Luminosity: ~ 34 pb^{-1}

$B_s \to D_s(\to\phi\pi)\,\pi$

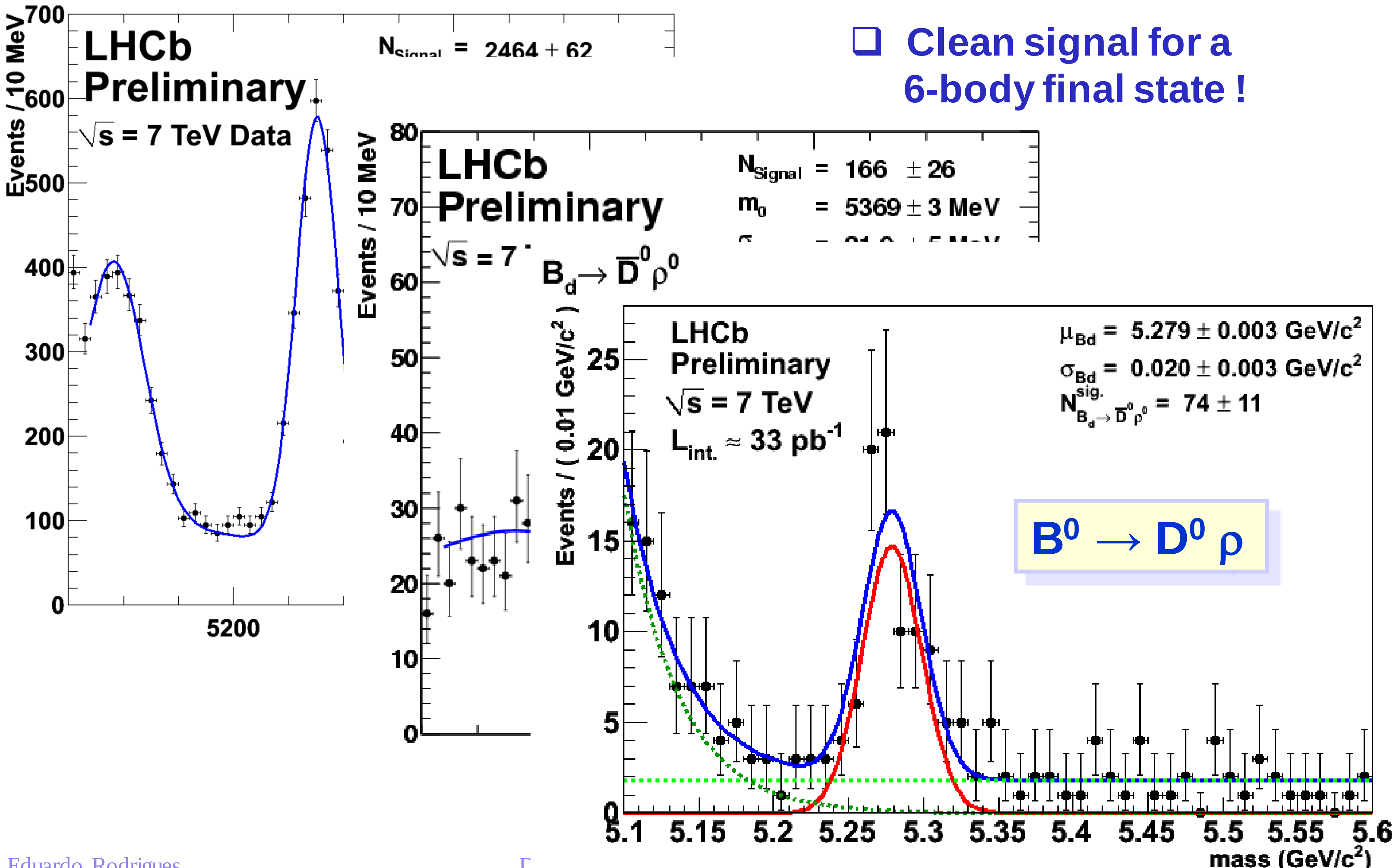


$B_s \to D_s(\to K^*K)\,\pi$



Is that all B → D X modes we see? Nope!

- Clean signal for a 6-body final state !



$H_b \to$ h h decays – a rich physics case

- $B^0 \to \pi\pi$: time-dependent asymmetry
  - so far inconsistency in direct CP contribution ($C_{\pi\pi}$) between BaBar and Belle
- $B^0 \to K^+\pi^-$: direct CP violation measurement
- $B_s \to \pi^+K^-$: direct CP violation, branching ratio (BR) measurement
- $B_s \to KK$: time-dependent asymmetry, BR measurement, lifetime measurement
- Gronau, Lipkin and Rosner relation

$$\left|A\left(B_s \to \pi^+ K^-\right)\right|^2 - \left|A\left(\overline{B}_s \to \pi^- K^+\right)\right|^2 = \left|A\left(\overline{B}^0 \to \pi^+ K^-\right)\right|^2 - \left|A\left(B^0 \to \pi^- K^+\right)\right|^2$$

- $B^0 \to K^+\pi^-$, $B^+ \to K^+\pi^0$: ≠ in CP asymmetry hard to understand theoretically
- $B^0 \to \pi\pi$, $B_s \to KK$: determination of the CP angle γ exploiting U-spin symmetry
- Rare $B \to h^+h'^-$: h = π, K … but also a baryon such as p, Λ
- $\Lambda_b \to pK$, $p\pi$: CP asymmetries, lifetime ratio measurements (wrt B^0)
- Etc. List non exhaustive

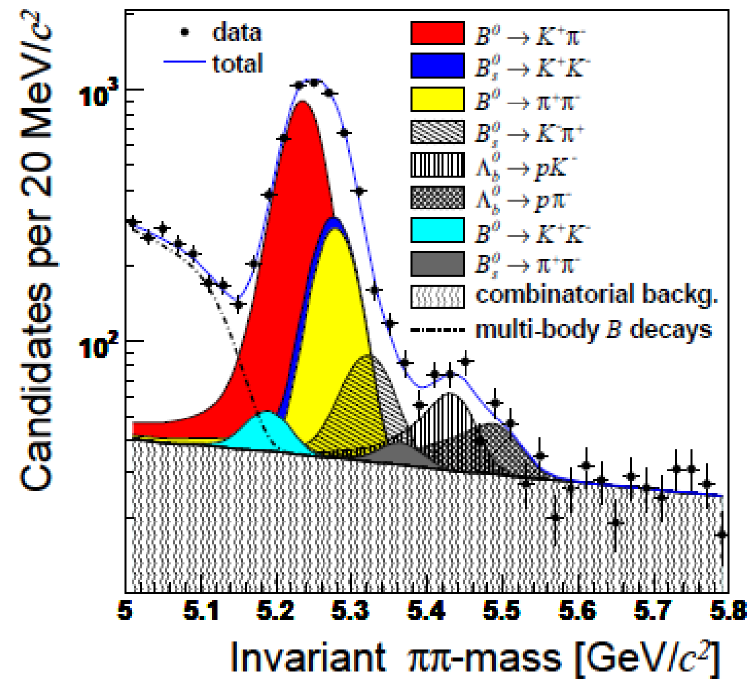
Some CDF results on $H_b \to$ hh decays

CDF Collaboration,
arXiv:0812.4271v1 [hep-ex]

1 fb^{-1}

TABLE I: Yields and significances of rare mode signals. The first quoted uncertainty is statistical, the second is systematic.

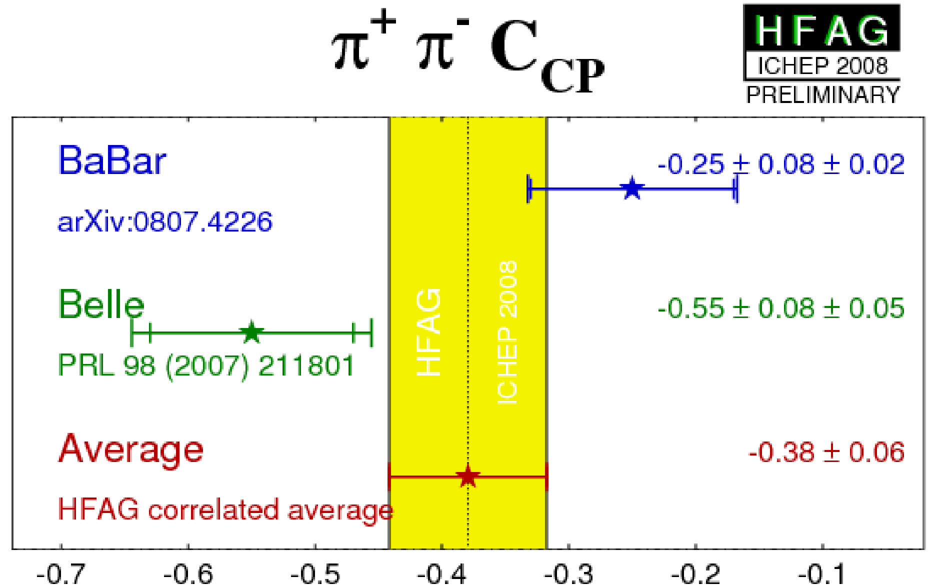
Mode	N_s	Significance
$B_s^0 \to K^-\pi^+$	$230 \pm 34 \pm 16$	8.2σ
$B_s^0 \to \pi^+\pi^-$	$26 \pm 16 \pm 14$	$< 3\sigma$
$B^0 \to K^+K^-$	$61 \pm 25 \pm 35$	$< 3\sigma$
$\Lambda_b^0 \to pK^-$	$156 \pm 20 \pm 11$	11.5σ
$\Lambda_b^0 \to p\pi^-$	$110 \pm 18 \pm 16$	6.0σ

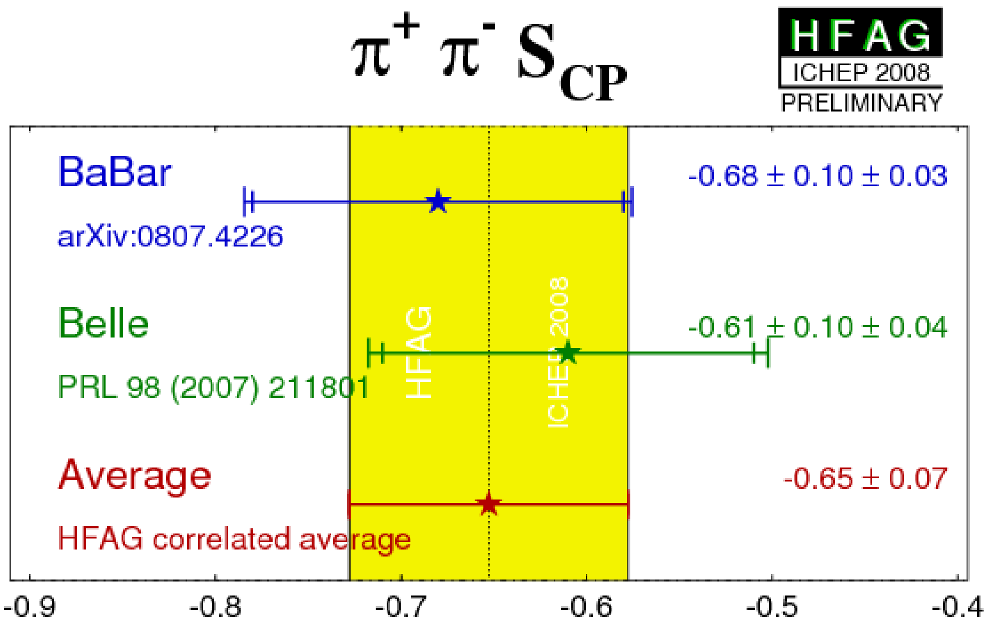


$B^0 \to \pi\pi$ direct and mixing-induced CP asymmetries (1/2)

Time-dependent measurements

BaBar and Belle still do NOT agree on direct CP asymmetry !

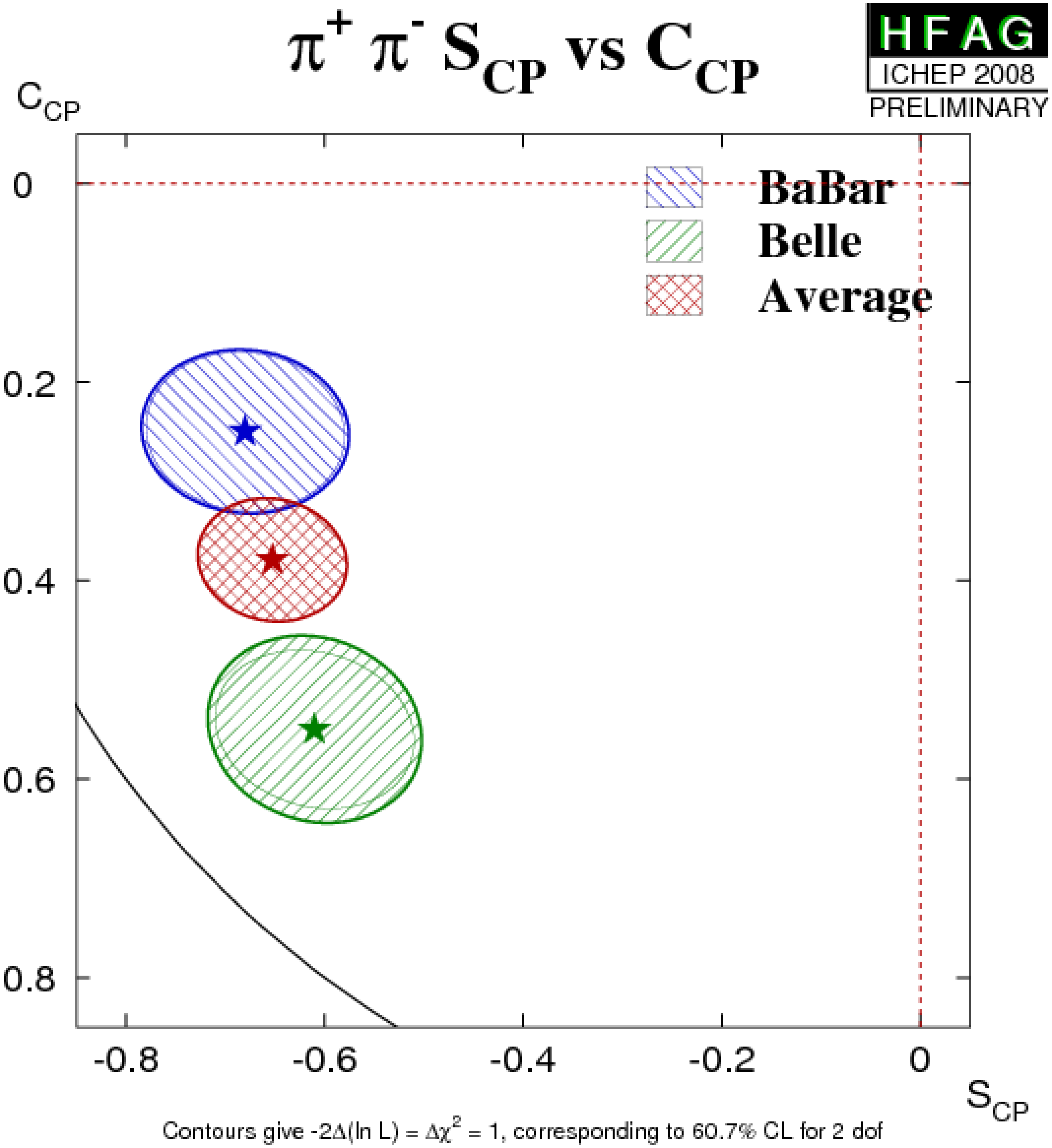




LHCb 0.5 fb^{-1} expectation:
$\sigma(C_{CP}) \sim 0.13$ (stat.)
$\sigma(S_{CP}) \sim 0.13$ (stat.)

(remember: signs of C and S depend on conventions and definitions)

$B^0 \to \pi\pi$ direct and mixing-induced CP asymmetries (2/2)



BaBar and Belle

still do NOT agree on

direct CP asymmetry !

LHCb 0.5 fb^{-1} expectation:
try and sort this out

$B^0 \to K\pi$ charge asymmetry

Summaries from HFAG
http://www.slac.stanford.edu/xorg/hfag/

Charge asymmetry

August 2010
Heavy Flavor Averaging Group

Compilation of CP Asymmetries for B^0 modes

In PDG2010 | New since PDG2010 (preliminary) | New since PDG2010 (published)

RPP#	Mode	PDG2010 Avg.	BABAR	Belle	CLEO	CDF	New Avg.
210	$K^+\pi^-$	-0.098 ± 0.013	$-0.107 \pm 0.016^{+0.006}_{-0.004}$	$-0.094 \pm 0.018 \pm 0.008$	$-0.04 \pm 0.16 \pm 0.02$	$-0.086 \pm 0.023 \pm 0.009$	$-0.098^{+0.012}_{-0.011}$
213	$\eta' K^{*0}$	$0.08 \pm 0.25 \pm 0.02$	$0.02 \pm 0.23 \pm 0.02$				0.02 ± 0.23
–	$\eta' K_0^*(1430)^0$	New	$-0.19 \pm 0.17 \pm 0.02$				-0.19 ± 0.17
–	$\eta' K_2^*(1430)^0$	New	$0.14 \pm 0.18 \pm 0.02$				0.14 ± 0.18
215	ηK^{*0}	0.19 ± 0.05	$0.21 \pm 0.06 \pm 0.02$	$0.17 \pm 0.08 \pm 0.01$			0.19 ± 0.05
216	$\eta K_0^*(1430)^0$	$0.06 \pm 0.13 \pm 0.02$	$0.06 \pm 0.13 \pm 0.02$				0.06 ± 0.13
217	$\eta K_2^*(1430)^0$	$-0.07 \pm 0.19 \pm 0.02$	$-0.07 \pm 0.19 \pm 0.02$				-0.07 ± 0.19
222	$b_1^- K^+$	$0.07 \pm 0.12 \pm 0.02$	$0.07 \pm 0.12 \pm 0.02$				0.07 ± 0.12
227	ωK^{*0}	0.45 ± 0.25	$0.45 \pm 0.25 \pm 0.02$				0.45 ± 0.25
229	$\omega K_0^*(1430)^0$	-0.07 ± 0.09	$-0.07 \pm 0.09 \pm 0.02$				-0.07 ± 0.09
230	$\omega K_2^*(1430)^0$	0.37 ± 0.17	$0.37 \pm 0.17 \pm 0.02$				0.37 ± 0.17
[illegible]	[illegible]	[illegible]	[illegible]	$0.07 \pm 0.11 \pm 0.01$			$0.000^{+0.059}_{-0.061}$
[illegible]	[illegible]	[illegible]	[illegible]	$0.22^{+0.22+0.06}_{-0.23-0.02}$			0.15 ± 0.06
[illegible]	[illegible]	[illegible]	[illegible]				0.07 ± 0.15
[illegible]	[illegible]	[illegible]	[illegible]				$-0.22^{+0.32}_{-0.31}$
[illegible]	[illegible]	[illegible]	[illegible]				-0.01 ± 0.05
[illegible]	[illegible]	[illegible]	[illegible]	$-0.21 \pm 0.11 \pm 0.07$			-0.18 ± 0.07
246	$K_0^*(1430)^+\pi^-$	0.10 ± 0.07	$0.07 \pm 0.05 \pm 0.01$				0.07 ± 0.05
252	$K^{*0}\pi^0$	$-0.09^{+0.23}_{-0.26}$	$-0.15 \pm 0.12 \pm 0.02$				-0.15 ± 0.12
259	$K^{*0}\pi^+\pi^-$	$0.07 \pm 0.04 \pm 0.03$	$0.07 \pm 0.04 \pm 0.03$				0.07 ± 0.05
260	$K^{*0}\rho^0$	$0.09 \pm 0.19 \pm 0.02$	$0.09 \pm 0.19 \pm 0.02$				0.09 ± 0.19
261	$f_0(980)K^{*0}$	-0.17 ± 0.28	$-0.17 \pm 0.28 \pm 0.02$				-0.17 ± 0.28
264	$a_1^- K^+$	$-0.16 \pm 0.12 \pm 0.01$	$-0.16 \pm 0.12 \pm 0.01$				-0.16 ± 0.12
279	$K^{*0}K^+K^-$	$0.01 \pm 0.05 \pm 0.02$	$0.01 \pm 0.05 \pm 0.02$				0.01 ± 0.05
280	ϕK^{*0}	0.01 ± 0.05	$0.01 \pm 0.06 \pm 0.03$	$0.02 \pm 0.09 \pm 0.02$			0.01 ± 0.05
281	$K^{*0}\pi^+K^-$	$0.22 \pm 0.33 \pm 0.20$	$0.22 \pm 0.33 \pm 0.20$				0.22 ± 0.39
289	$\phi K_0^*(1430)^0$	0.20 ± 0.15	$0.20 \pm 0.14 \pm 0.06$				0.20 ± 0.15
294	$\phi K_2^*(1430)^0$	-0.08 ± 0.13	$-0.08 \pm 0.12 \pm 0.05$				-0.08 ± 0.13
301	$K^{*0}\gamma$	-0.16 ± 0.23	$-0.16 \pm 0.22 \pm 0.07$				-0.16 ± 0.23
316	$\pi^0\pi^0$		$0.43 \pm 0.26 \pm 0.05$	$0.44^{+0.73+0.04}_{-0.62-0.06}$			$0.43^{+0.25}_{-0.24}$

LHCb 0.5 fb^{-1} expectation:
$\sigma(A_{K\pi}) \sim 0.008$ (stat.)

CDF is competitive!
It has a word to say.