Flavour Physics in the LHC Era

Lecture 2 of 2

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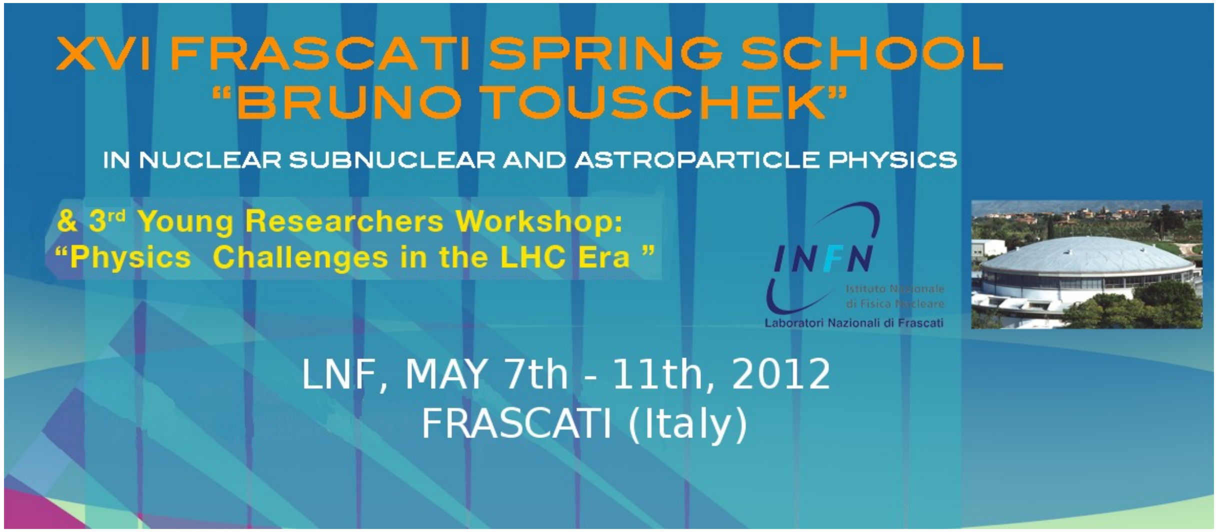
University of Warwick & CERN

LNFSS 2012

11th May 2012



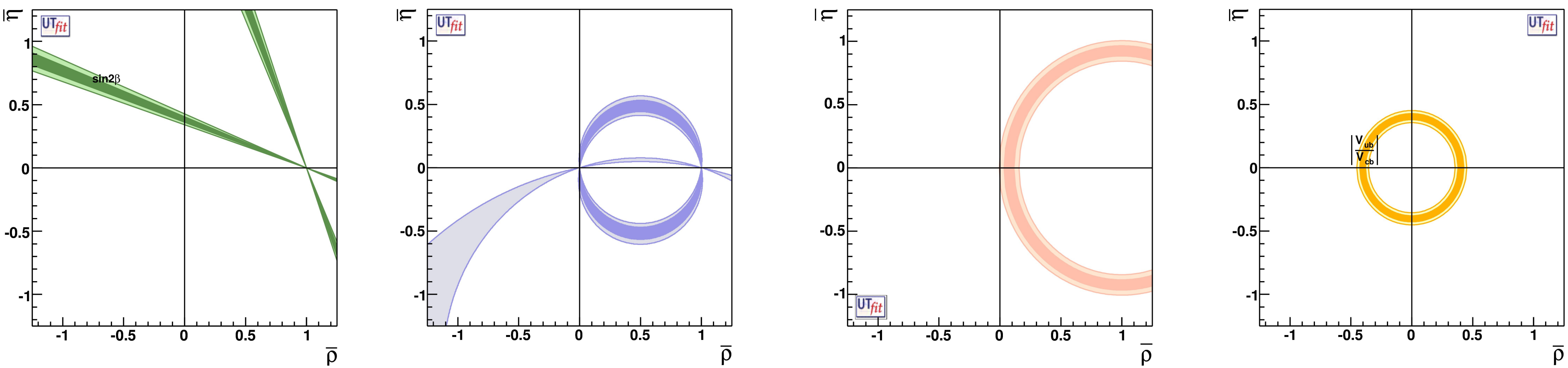
Contents

- Yesterday
  - Definitions of “flavour physics” and “the LHC era”
  - Why is flavour physics interesting?
  - What do we know about it as of today?

- Today
  - What do we hope to learn from current and future heavy flavour experiments?

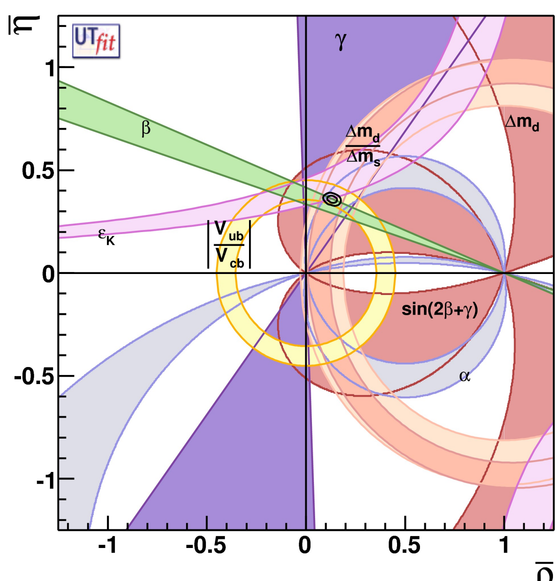
Summary from yesterday

$\sin(2\beta)$ α $|\Delta m_d / \Delta m_s|$ $|V_{ub}/V_{cb}|$



Adding a few other constraints we find

$$\bar{\rho} = 0.132 \pm 0.020$$
$$\bar{\eta} = 0.358 \pm 0.012$$



Consistent with Standard Model fit

- some "tensions"

Still plenty of room for new physics

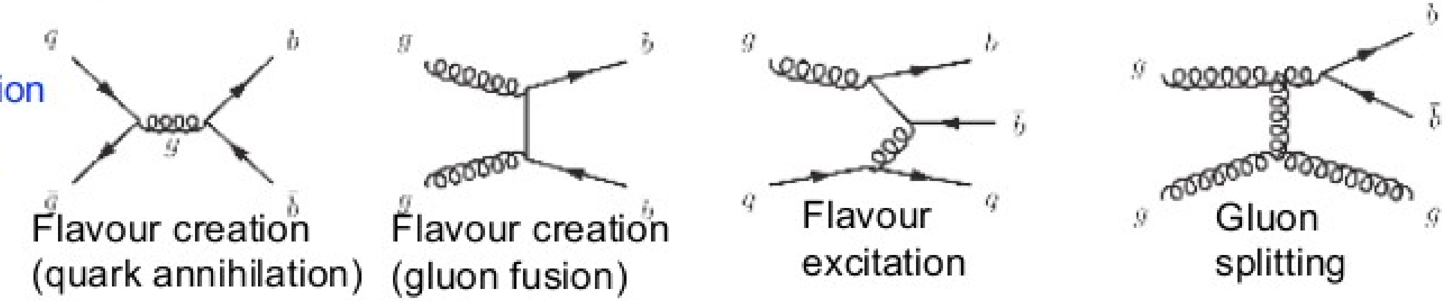
Topics to cover today

- Flavour physics at hadron colliders (mainly LHCb)
- More on CP violation
  - The third Unitarity Triangle angle: γ
  - Tree-dominated decays vs. loop-dominated decays
  - CP violating phase in B_s^0 oscillations
  - CP violating phase in D^0 oscillations
- Rare decays
  - $B_s^0 \to \mu\mu$, $B \to K^*\mu\mu$, $B_s^0 \to \phi\gamma$, $K \to \pi\nu\nu$
- Future experiments

Flavour physics at hadron colliders

	$e^+e^- \to \Upsilon(4s) \to B\bar{B}$ **PEP-II, KEK-B**	$p\bar{p} \to b\bar{b}X$ $(\sqrt{s} = 2\ \text{TeV})$ **TeVatron**	$pp \to b\bar{b}X$ $(\sqrt{s} = 14\ \text{TeV})$ **LHC**
prod	1 nb	~100 μb	~500 μb
typ. $b\bar{b}$ rate	10 Hz	~100 kHz	~500 kHz
purity	~1/4	$\sigma_{b\bar{b}}/\sigma_{inel} \approx 0.2\%$	$\sigma_{b\bar{b}}/\sigma_{inel} \approx 0.6\%$
pile-up	0	1.7	0.5-20
B content	$B^+B^-(50\%), B^0\bar{B}^0(50\%)$	$B^+(40\%), B^0(40\%), B_s(10\%), B_c(<1\%)$, b – baryons(10%)	
B boost	small, βγ~0.56	large, decay vertices are displaced	
event structure	BB pair alone	many particles non-associated to $b\bar{b}$	
prod. vertex	Not reconstructed	reconstructed with many tracks	
$B^0\bar{B}^0$ mixing	coherent	incoherent→ flavour tagging dilution	

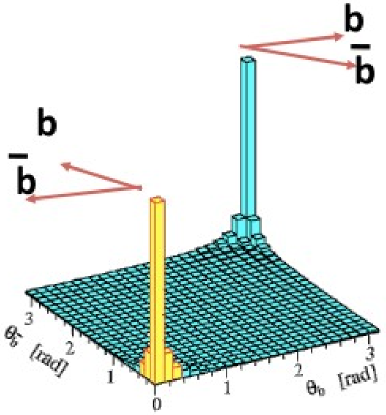
bb production at hadron colliders



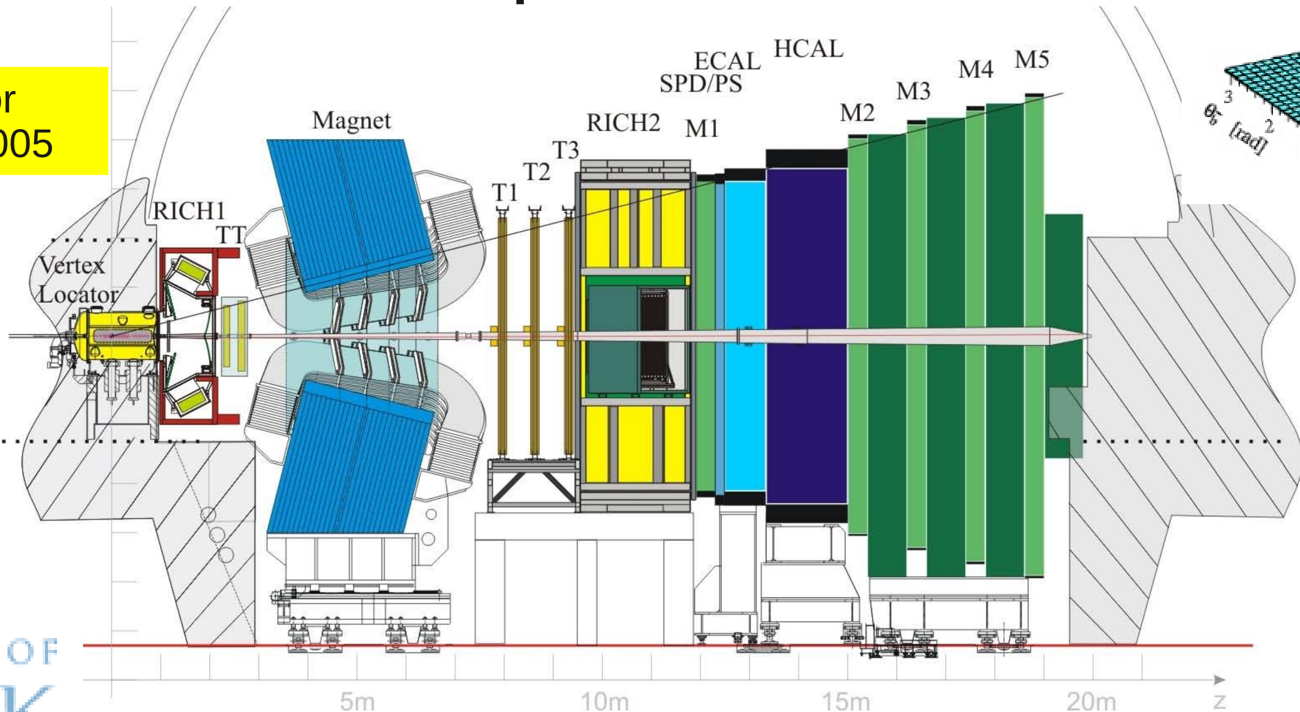
from Val Gibson HCPSS 2009

Geometry

- In high energy collisions, $b\bar{b}$ pairs produced predominantly in forward or backward directions
- LHCb is a forward spectrometer

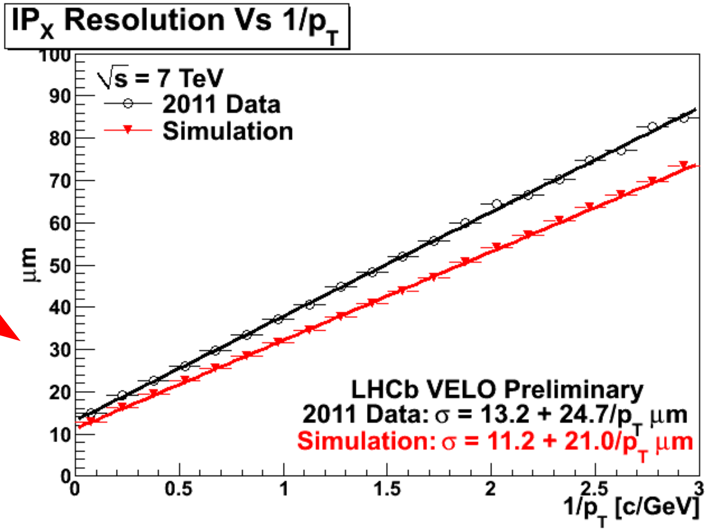


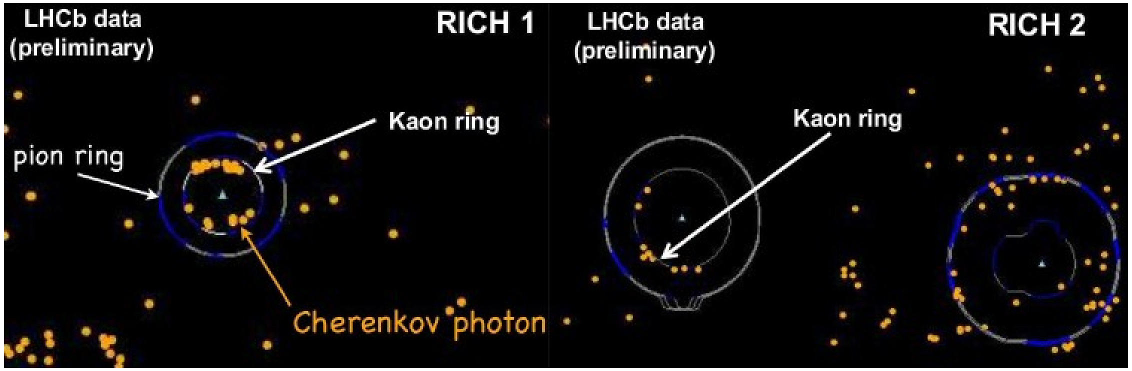
The LHCb Detector
JINST 3 (2008) S08005



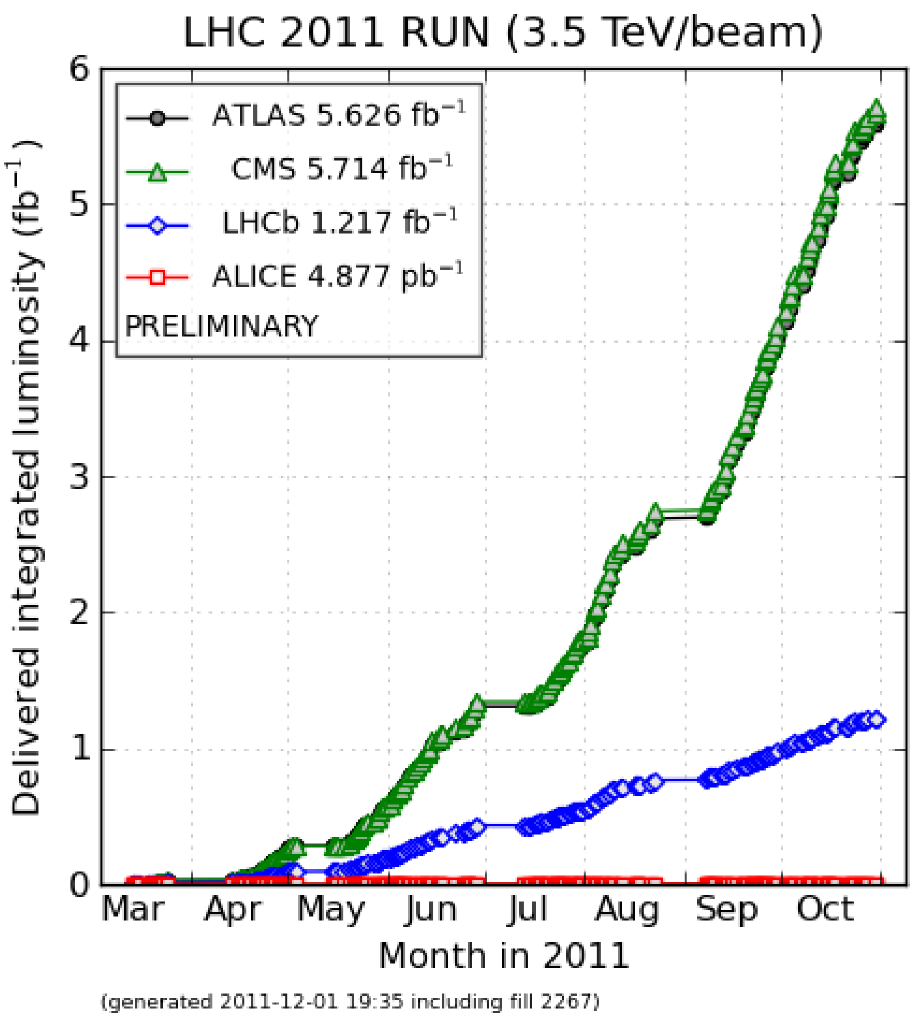
LHCb detector features

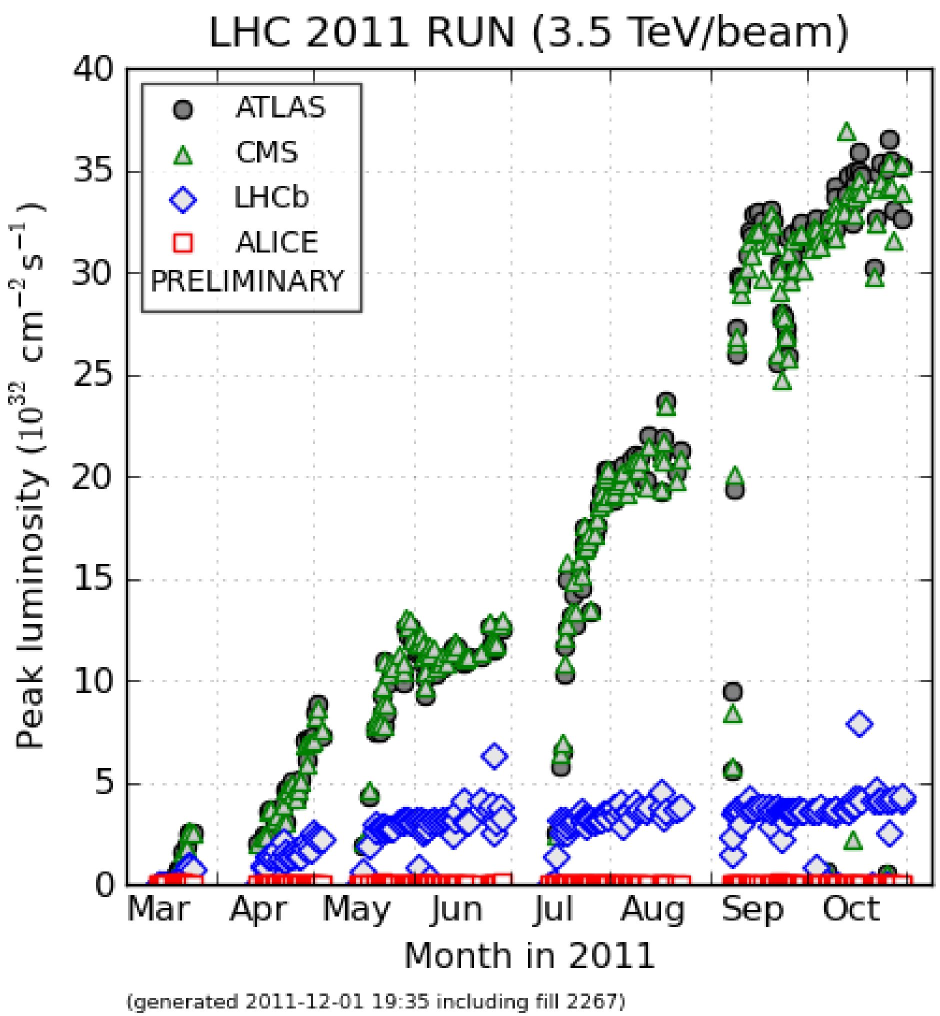
- Tracking and calorimetry
  - basic essentials of any collider experiment!
  - muon chambers
- VELO
  - reconstruct displaced vertices
- RICH
  - particle ID (K/π separation)
- Trigger
  - fast and efficient



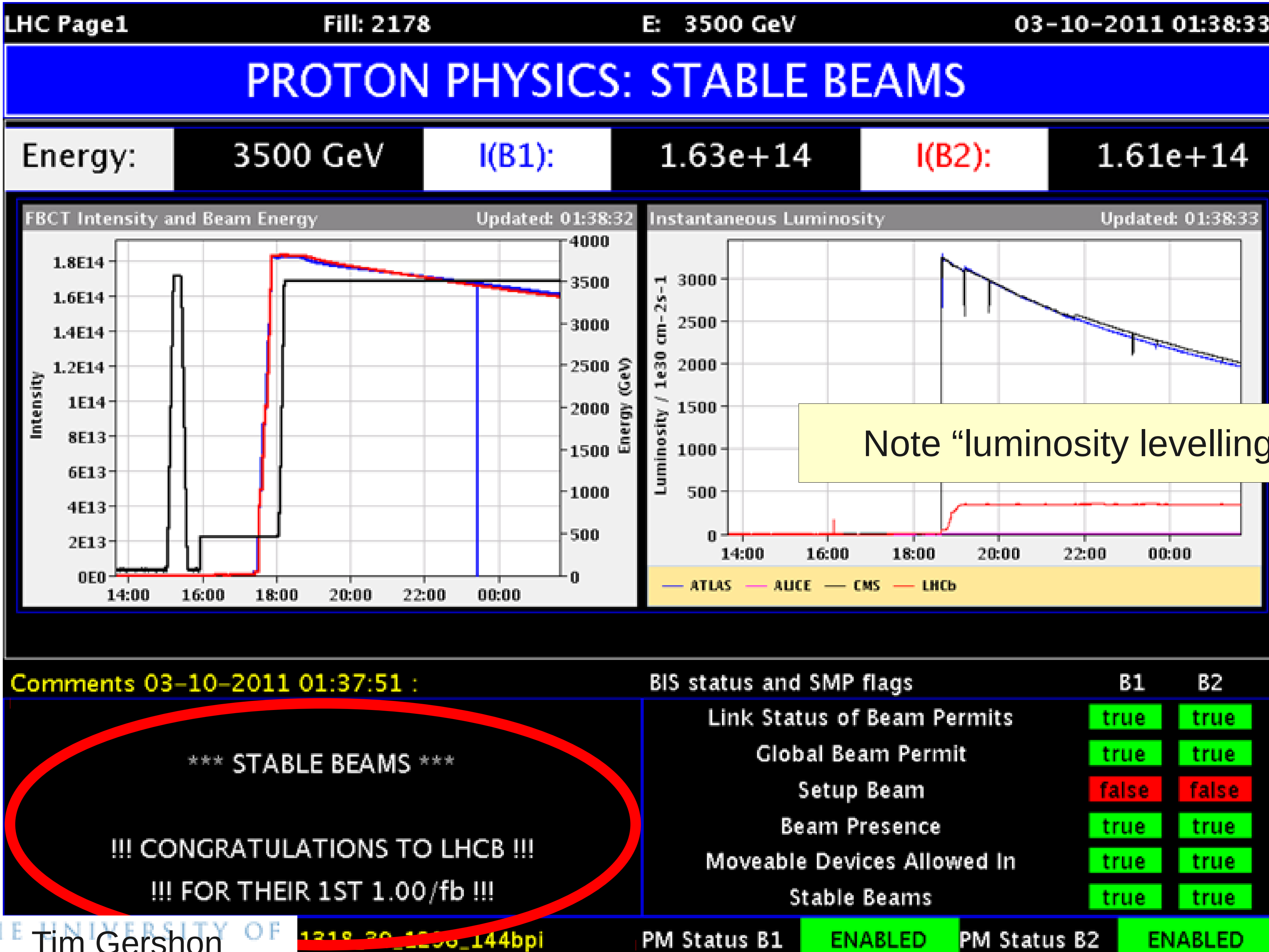


LHC performance 2011



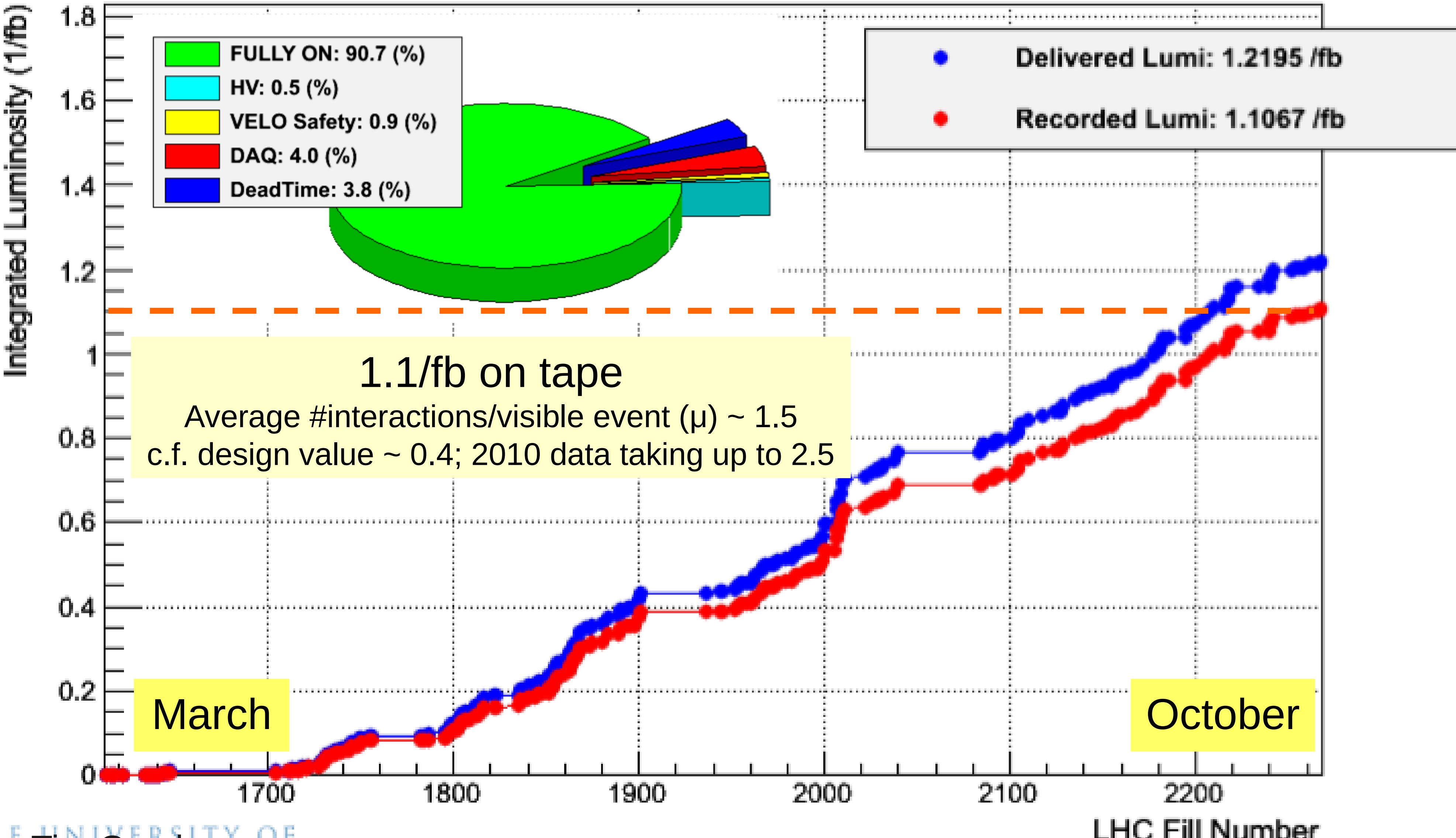


LHCb design luminosity: 2 10^{32}/cm^2/s



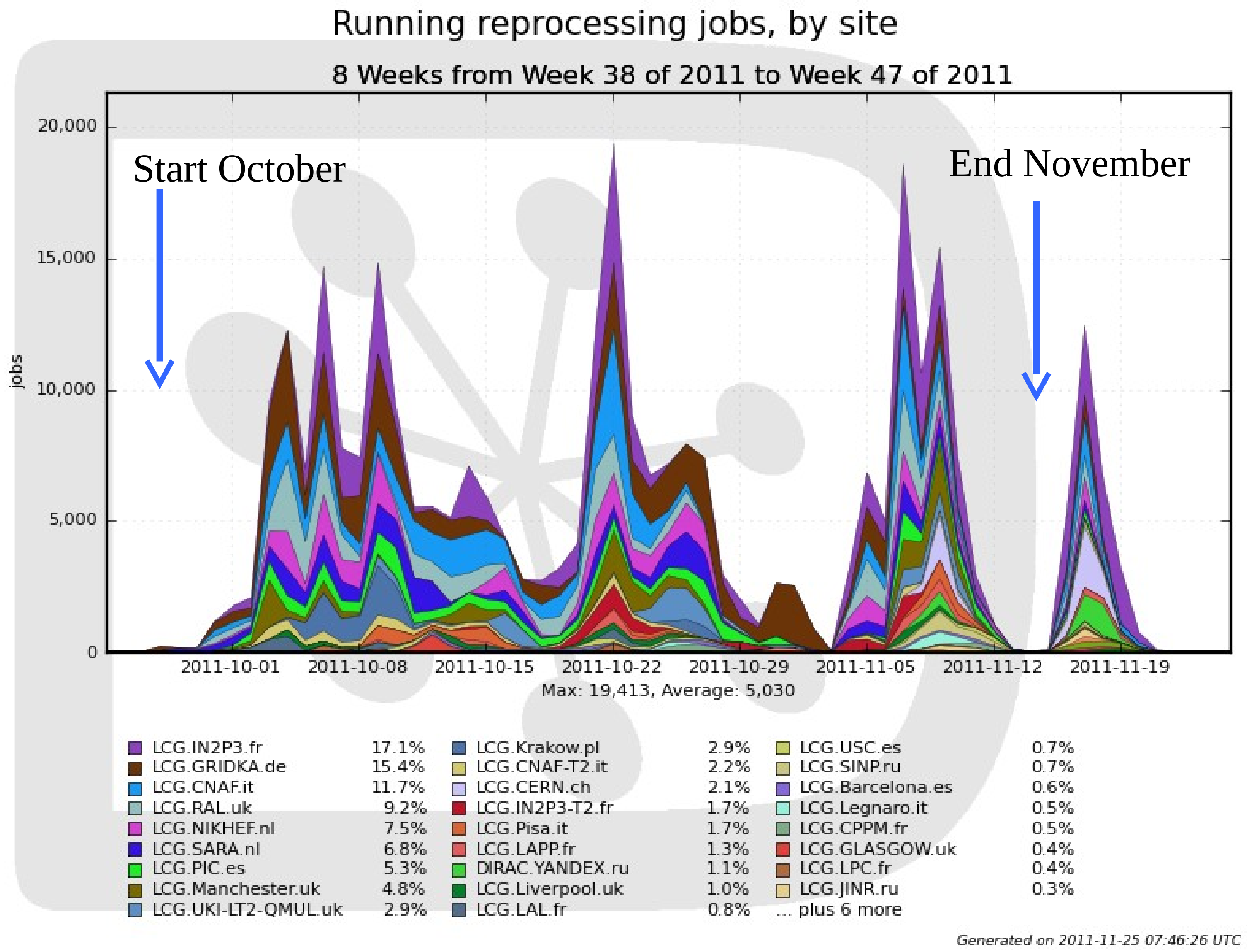
Note "luminosity levelling"

2011 data taking



Data taking efficiency close to 91 %

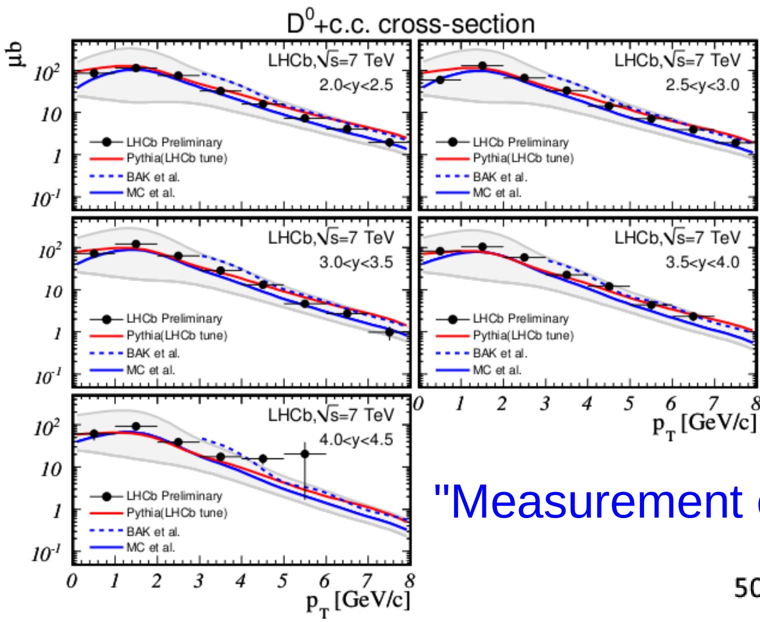
2011 data reprocessing



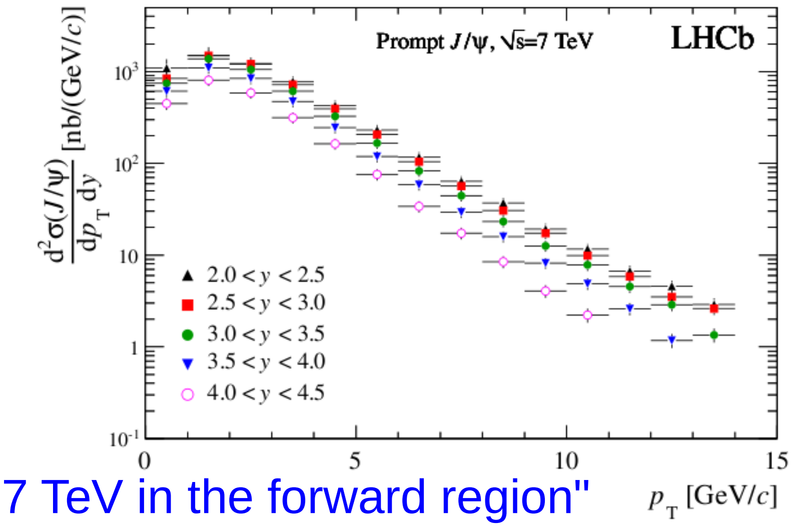
2011 data reprocessing completed in 8 weeks

Heavy flavour production @ LHCb

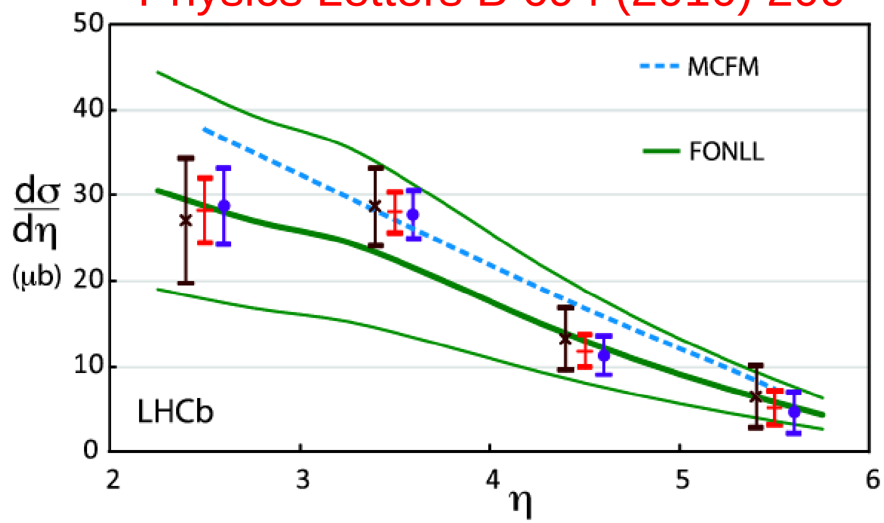
“Prompt charm production in pp collisions at √s = 7 TeV”
LHCb-CONF-2010-013



“Measurement of J/ψ production in pp collisions at √s = 7 TeV”
Eur. Phys. J. C 71 (2011) 1645



"Measurement of $\sigma(pp \to b\bar{b}X)$ at √s = 7 TeV in the forward region"
Physics Letters B 694 (2010) 209



What does $\int \mathcal{L} dt$ = 1/fb mean?

- Measured cross-section, in LHCb acceptance

$$\sigma(pp \to b\bar{b}X) = (75.3 \pm 5.4 \pm 13.0)\ \mu b$$

PLB 694 (2010) 209

- So, number of $b\bar{b}$ pairs produced

$$10^{15} \times 75.3\ 10^{-6} \sim 10^{11}$$

- Compare to combined data sample of e^+e^- "B factories" BaBar and Belle of ~ 10^9 $B\bar{B}$ pairs

for any channel where the (trigger, reconstruction, stripping, offline) efficiency is not too small, LHCb has world's largest data sample

- p.s.: for charm, $\sigma(pp \to c\bar{c}X) = (6.10 \pm 0.93)$ mb

LHCb-CONF-2010-013

The all important trigger

Challenge is

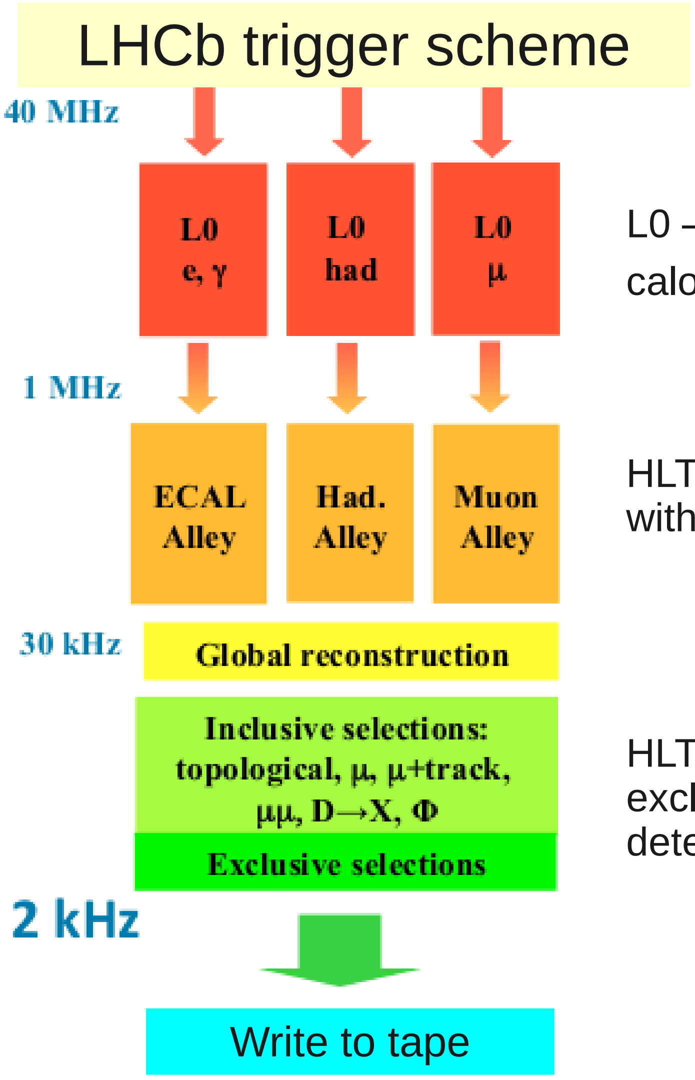
- to efficiently select most interesting B decays
- while maintaining manageable data rates

Main backgrounds

- “minimum bias” inelastic pp scattering
- other charm and beauty decays

Handles

- high p_T signals (muons)
- displaced vertices



L0 – high p_T signals in calorimeters & muon chambers

HLT1 – associate L0 signals with tracks & displaced vertices

HLT2 – inclusive signatures + exclusive selections using full detector information

Spectroscopy

- I've talked about the headline items of flavour physics
  - CP violation, searches for new physics
  - what we tell the funding agencies, and the press
- But, much of the physics performed by flavour experiments is the study of properties of hadronic states
  - lifetimes, masses, decay channels, quantum numbers
  - and the discoveries of new ones

1) **Observation of a narrow meson decaying to D+(s) pi0 at a mass of 2.32-GeV/c**2.**
By BABAR Collaboration (Bernard Aubert *et al.*). SLAC-PUB-9711, BABAR-PUB-03-011, Apr 2003. 7pp.
Press Release from SLAC.
Published in **Phys.Rev.Lett.90:242001,2003**.
e-Print: **hep-ex/0304021**

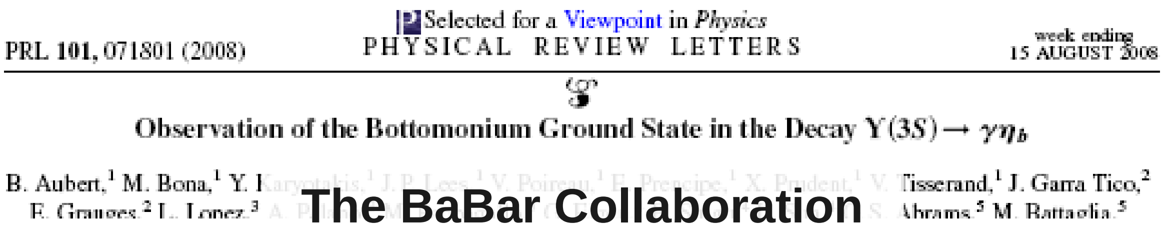
TOPCITE = 500+
References | LaTeX(US) | LaTeX(EU) | Harvmac | BibTeX | Keywords | Cited 521 times
Abstract and Postscript and PDF from arXiv.org (mirrors: au br cn de es fr il in it jp kr ru tw uk za aps lanl)
Journal Server [doi:10.1103/PhysRevLett.90.242001]
BaBar Publications Database
BaBar Password Protected Publications Database
CERN Library Record
pdgLive (measurements quoted by PDG)
Press Release about this paper
SLAC Document Server
EXP SLAC-PEP2-BABAR
Bookmarkable link to this information

Observation of a narrow charmonium - like state in exclusive B+- ---> K+- pi+ pi- J / psi decays.
By Belle Collaboration (S.K. Choi *et al.*). Sep 2003. 10pp.
Press release.
Published in **Phys.Rev.Lett.91:262001,2003**.
e-Print: **hep-ex/0309032**

TOPCITE = 500+
References | LaTeX(US) | LaTeX(EU) | Harvmac | BibTeX | Keywords | Cited 514 times
Abstract and Postscript and PDF from arXiv.org (mirrors: au br cn de es fr il in it jp kr ru tw uk za aps lanl)
Journal Server [doi:10.1103/PhysRevLett.91.262001]
pdgLive (measurements quoted by PDG)
Press Release about this paper
EXP KEK-BF-BELLE
Bookmarkable link to this information

Most highly cited papers from BaBar and Belle

Discovery of the lightest $b\bar{b}$ state – 2008


Selected for a Viewpoint in *Physics*
PRL 101, 071801 (2008) PHYSICAL REVIEW LETTERS week ending 15 AUGUST 2008

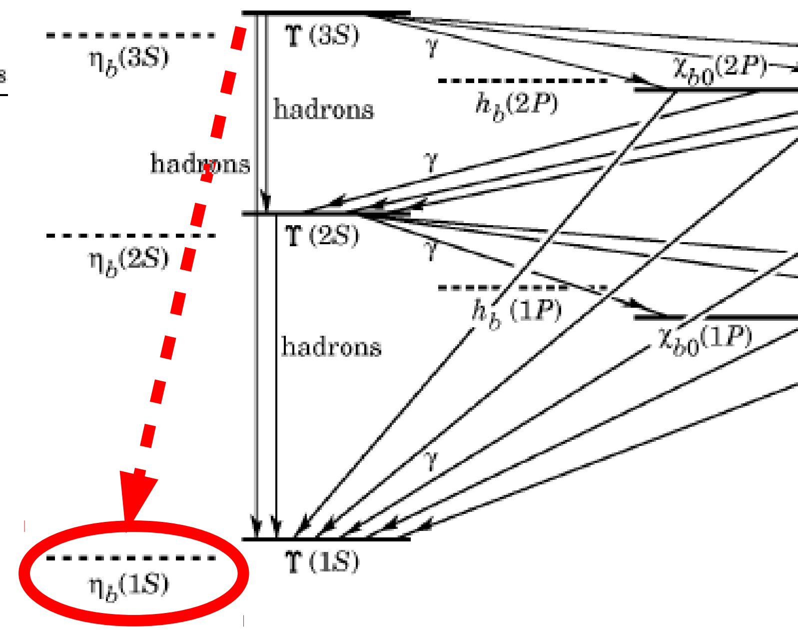
Observation of the Bottomonium Ground State in the Decay $\Upsilon(3S) \to \gamma\eta_b$

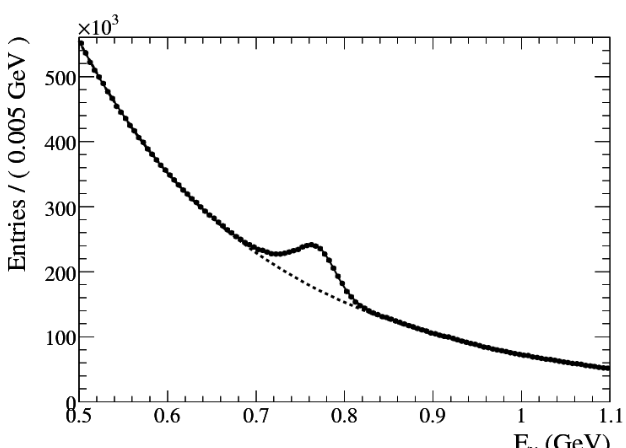
B. Aubert,[1] M. Bona,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] E. Prencipe,[1] X. Prudent,[1] V. Tisserand,[1] J. Garra Tico,[2]
E. Grauges,[2] L. Lopez,[3] ... S. Abrams,[5] M. Battaglia,[5]

The BaBar Collaboration

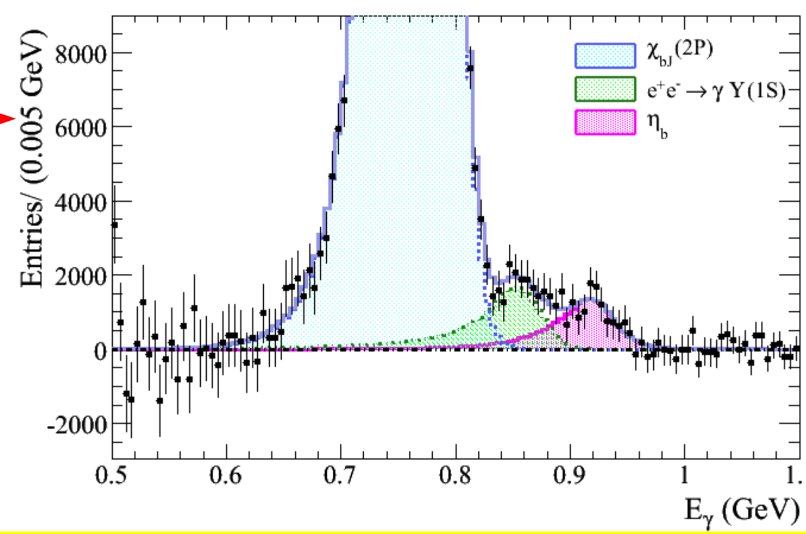
- Only recoil γ is reconstructed

$$m(\eta_b(1S)) = (9388.9\,^{+3.1}_{-2.3} \pm 2.7)\,\mathrm{MeV}/c^2$$
$$m(\Upsilon(1S)) - m(\eta_b(1S)) = (71.4\,^{+2.3}_{-3.1} \pm 2.7)\,\mathrm{MeV}/c^2$$
$$B(\Upsilon(3S) \to \gamma\,\eta_b(1S)) = (4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$$





subtract smoothly varying background



Signal confirmed in ϒ(2S) transitions by BaBar, and by CLEO

Why wasn't the η_b discovered at a hadronic experiment?

- Remember: Υ(1S) discovered at FNAL in 1977
  - fixed target experiment: p on Be

PRL 39 (1977) 252

- η_b is lighter
- Hadron collisions produce all types of b hadrons
- So why couldn't the η_b be discovered, e.g., at the Tevatron?

Why wasn't the η_b discovered at a hadronic experiment?

- Remember: Υ(1S) discovered at FNAL in 1977
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PRL 39 (1977) 252

- η_b is lighter
- Hadron collisions produce all types of b hadrons
- So why couldn't the η_b be discovered, e.g., at the Tevatron?
- It's all about the trigger!
  - need clean signature for trigger and reconstruction
  - CDF search used $\eta_b \rightarrow J/\psi J/\psi$ decay, with predicted BF ~ 0!

CDF note 8448

Digression on a digression: The “Oops Leon”

Observation of High-Mass Dilepton Pairs in Hadron Collisions at 400 GeV

D. C. Hom, L. M. Lederman, H. P. Paar, H. D. Snyder, J. M. Weiss, and J. K. Yoh
*Columbia University, New York, New York 10027**

and

J. A. Appel, B. C. Brown, C. N. Brown, W. R. Innes, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510†

and

D. M. Kaplan
*State University of New York at Stony Brook, Stony Brook, New York 11794**
(Received 28 January 1976)

We report preliminary results on the production of electron-positron pairs in the mass range 2.5 to 20 GeV in 400-GeV p-Be interactions. 27 high-mass events are observed in the mass range 5.5–10.0 GeV corresponding to $\sigma=(1.2\pm0.5)\times10^{-35}$ cm^2 per nucleon. Clustering of 12 of these events between 5.8 and 6.2 GeV suggests that the data contain a new resonance at 6 GeV.

PRL 36 (1976) 1236

Homework exercise:
1. Read this paper
2. Do you find the “discovery” convincing?
3. Explain what's wrong

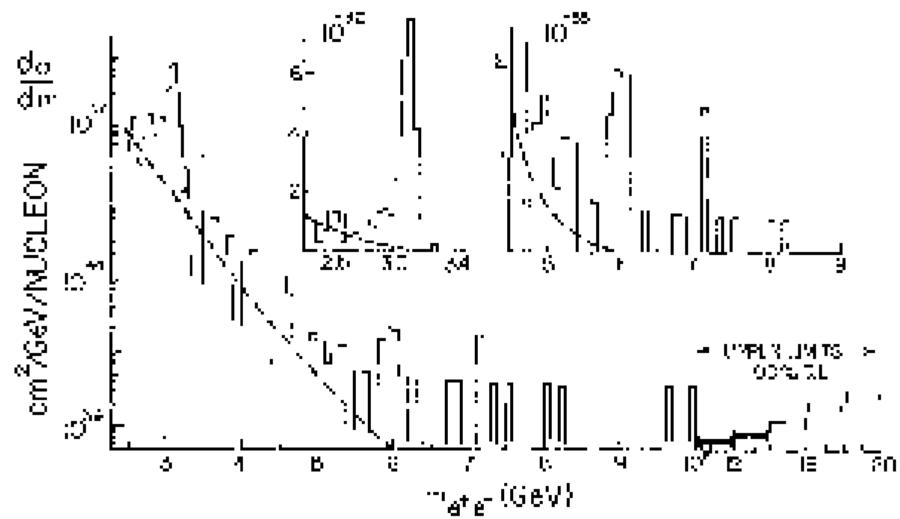
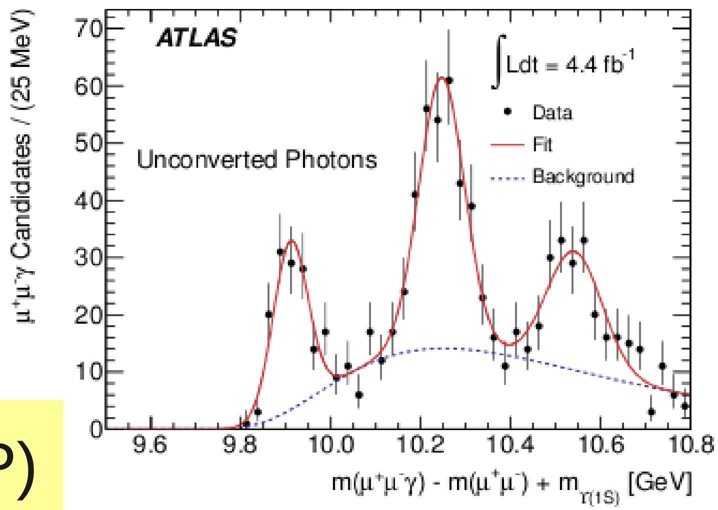


FIG. 2. Electron-positron mass spectrum: $d\sigma/dm$ per nucleon versus the effective mass. A linear A dependence is assumed. Note bin-width changes.

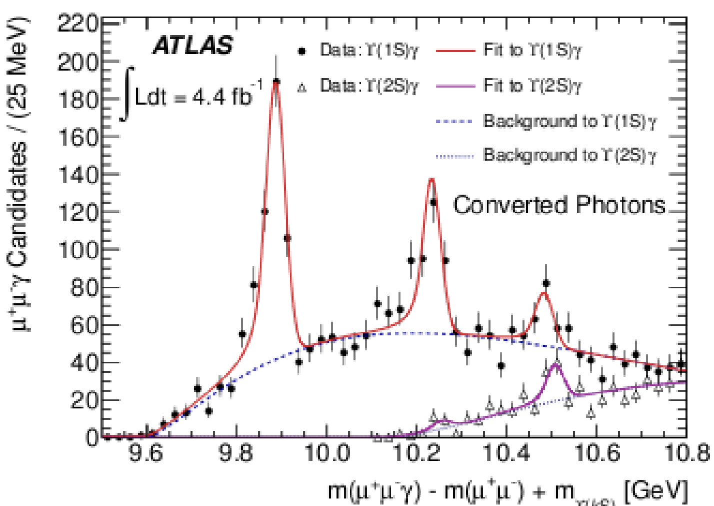
More new particles

ATLAS arXiv:1112.5154

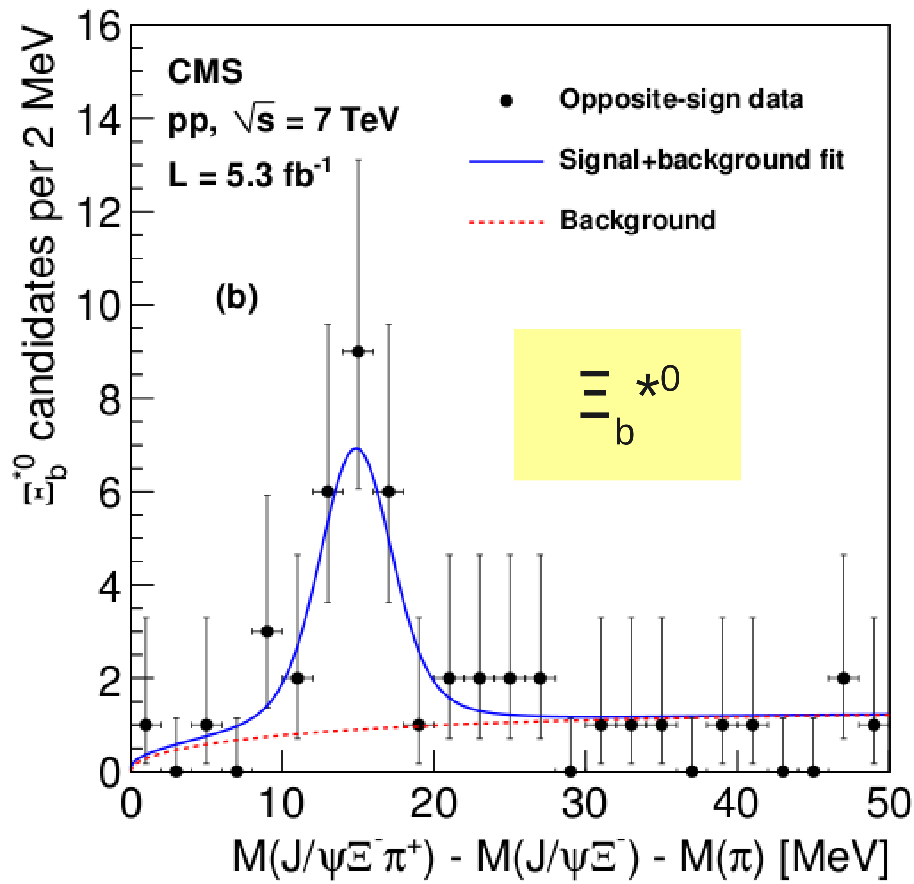
$\chi_b(3P)$



(a)



CMS arXiv:1204.5955

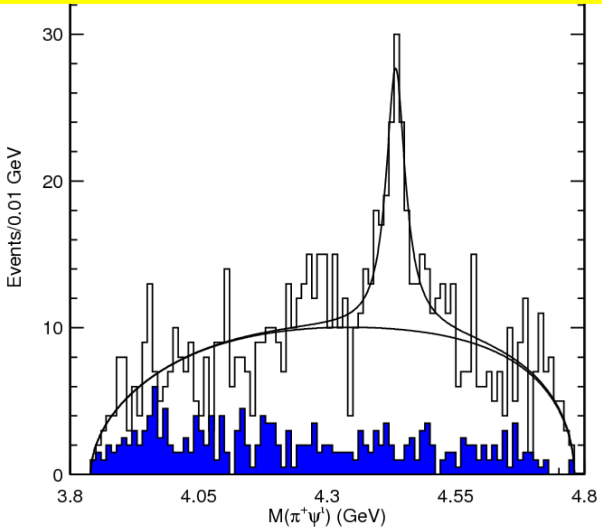


Ξ_b^{*0}

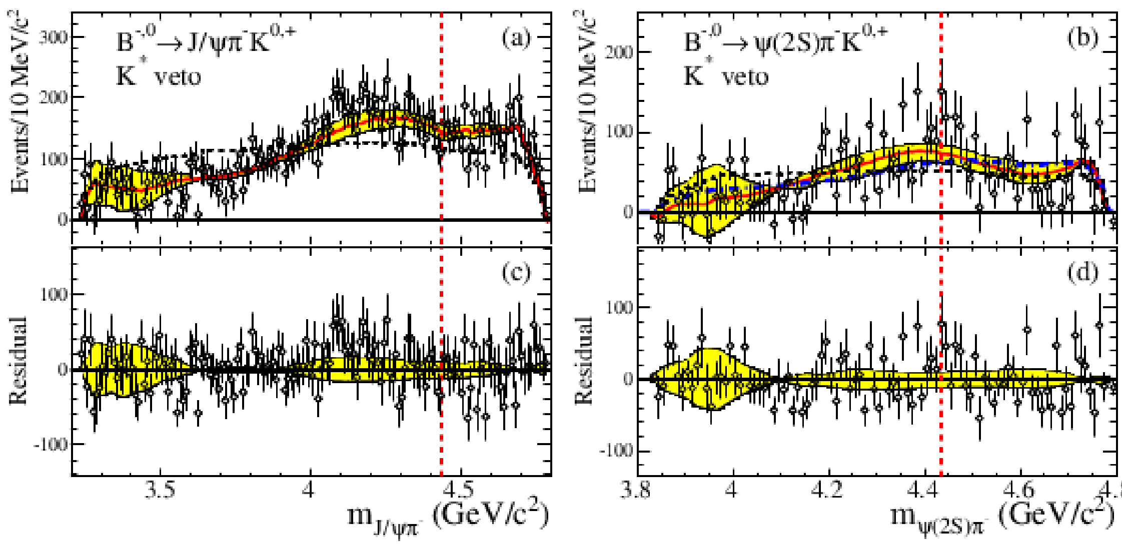
The smoking gun exotic hadron: A charged charmonium-like state

$B^0 \to Z(4430)^- K^+$, $Z(4430)^- \to \psi' \pi^-$

Belle PRL 100 (2008) 142001



BABAR PRD 79 (2009) 112001



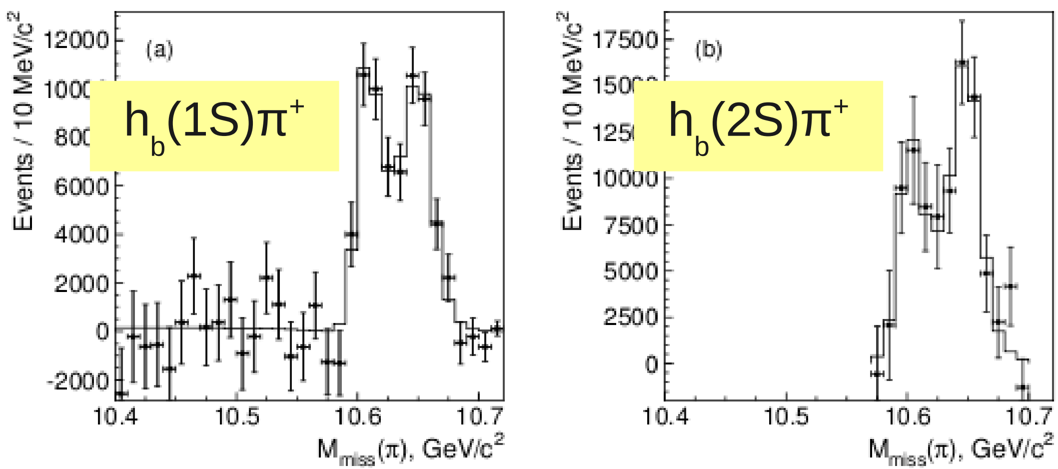
Clear peak
Still there in more detailed analysis
PRD 80 (2009) 031104

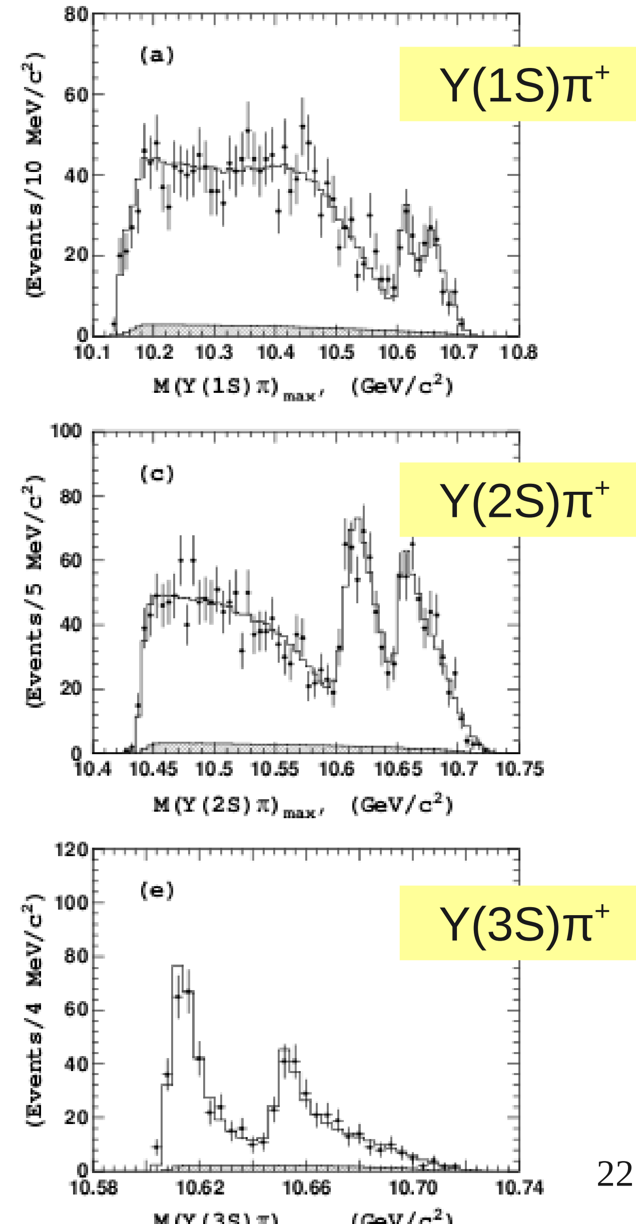
Data consistent with Kπ reflections
Slight peak but no evidence for new state
But also consistent with Belle

Need more experimental input
(CDF, D0, ATLAS, CMS or LHCb)

Charged bottomonium-like states

Belle
PRL 108 (2012) 122001





Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M[Z_b(10610)]$, MeV/c^2	$10611 \pm 4 \pm 3$	$10609 \pm 2 \pm 3$	$10608 \pm 2 \pm 3$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma[Z_b(10610)]$, MeV	$22.3 \pm 7.7^{+3.0}_{-4.0}$	$24.2 \pm 3.1^{+2.0}_{-3.0}$	$17.6 \pm 3.0 \pm 3.0$	$11.4\,^{+4.5+2.1}_{-3.9-1.2}$	$13\,^{+10+9}_{-8-7}$
$M[Z_b(10650)]$, MeV/c^2	$10657 \pm 6 \pm 3$	$10651 \pm 2 \pm 3$	$10652 \pm 1 \pm 2$	$10654 \pm 3\,^{+1}_{-2}$	10651^{+2+3}_{-3-2}
$\Gamma[Z_b(10650)]$, MeV	$16.3 \pm 9.8^{+6.0}_{-2.0}$	$13.3 \pm 3.3^{+4.0}_{-3.0}$	$8.4 \pm 2.0 \pm 2.0$	$20.9\,^{+5.4+2.1}_{-4.7-5.7}$	$19 \pm 7\,^{+11}_{-7}$
Rel. normalization	$0.57 \pm 0.21^{+0.19}_{-0.04}$	$0.86 \pm 0.11^{+0.04}_{-0.10}$	$0.96 \pm 0.14^{+0.08}_{-0.05}$	$1.39 \pm 0.37^{+0.05}_{-0.15}$	$1.6^{+0.6+0.4}_{-0.4-0.6}$
Rel. phase, degrees	$58 \pm 43^{+4}_{-9}$	$-13 \pm 13^{+17}_{-8}$	$-9 \pm 19^{+11}_{-26}$	187^{+44+3}_{-57-12}	$181^{+65+74}_{-105-109}$

OK, back to weak physics

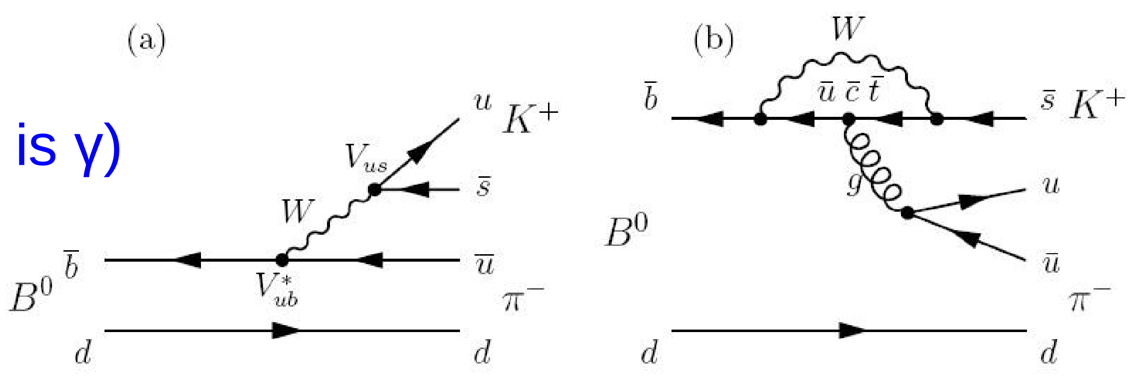
Direct CP violation

- Condition for DCPV: $|\bar{A}/A| \neq 1$
- Need $\bar{A}$ and A to consist of (at least) two parts
  - with different weak (φ) and strong (δ) phases
- Often realised by "tree" and "penguin" diagrams

$$A = |T| e^{i(\delta_T - \phi_T)} + |P| e^{i(\delta_P - \phi_P)} \qquad \bar{A} = |T| e^{i(\delta_T + \phi_T)} + |P| e^{i(\delta_P + \phi_P)}$$

$$A_{CP} = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} = \frac{2\,|T||P| \sin(\delta_T - \delta_P) \sin(\phi_T - \phi_P)}{|T|^2 + |P|^2 + 2\,|T||P| \cos(\delta_T - \delta_P) \cos(\phi_T - \phi_P)}$$

Example: B→Kπ
(weak phase difference is γ)



Feynman tree (a) and penguin (b) diagrams for the $B_d^0 \to K^+\pi^-$ decay

The famous penguin story

Penguin diagram

From Wikipedia, the free encyclopedia

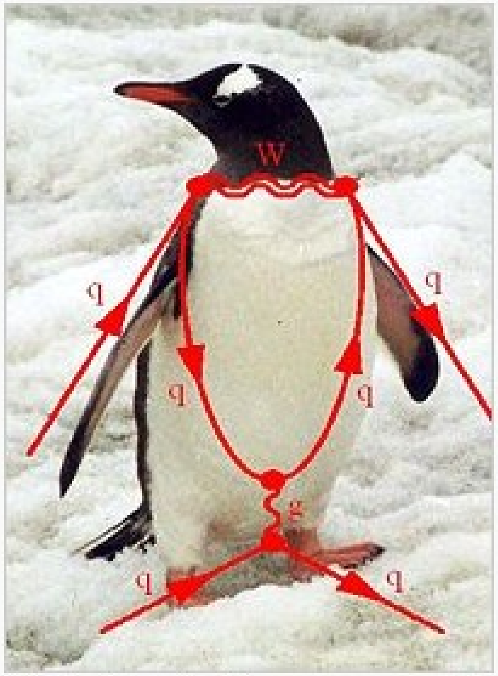
In quantum field theory, **penguin diagrams** are a class of Feynman diagrams which are important for understanding CP violating processes in the standard model. They were first isolated and studied by Mikhail Shifman, Arkady Vainshtein, and Valentin Zakharov.[1] The processes which they describe were first directly observed in 1991 and 1994 by the CLEO collaboration.

Origin of the name

[edit]

John Ellis was the first to refer to a certain class of Feynman diagrams as **penguin diagrams**, due in part to their shape, and in part to a legendary bar-room bet with Melissa Franklin. According to John Ellis:[2]

> Mary K. [Gaillard], Dimitri [Nanopoulos] and I first got interested in what are now called penguin diagrams while we were studying CP violation in the Standard Model in 1976... The penguin name came in 1977, as follows.
>
> In the spring of 1977, Mike Chanowitz, Mary K and I wrote a paper on GUTs predicting the b quark mass before it was found. When it was found a few weeks later, Mary K, Dimitri, Serge Rudaz and I immediately started working on its phenomenology. That summer, there was a student at CERN, Melissa Franklin who is now an experimentalist at Harvard. One evening, she, I, and Serge went to a pub, and she and I started a game of darts. We made a bet that if I lost I had to put the word penguin into my next paper. She actually left the darts game before the end, and was replaced by Serge, who beat me. Nevertheless, I felt obligated to carry out the conditions of the bet.
>
> For some time, it was not clear to me how to get the word into this b quark paper that we were writing at the time. Then, one evening, after working at CERN, I stopped on my way back to my apartment to visit some friends living in Meyrin where I smoked some illegal substance. Later, when I got back to my apartment and continued working on our paper, I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history.



Example of a penguin diagram

The famous penguin story

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From Wikipedia, the free encyclopedia

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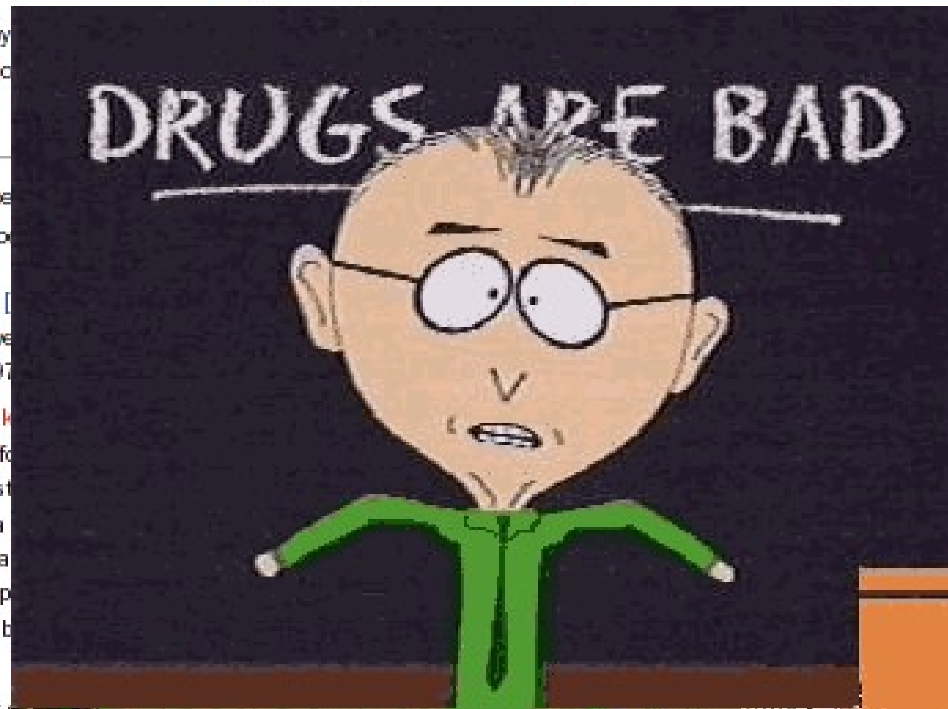

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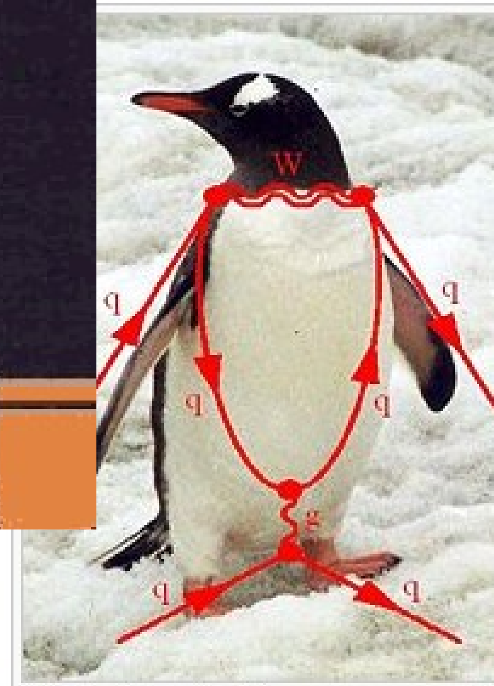
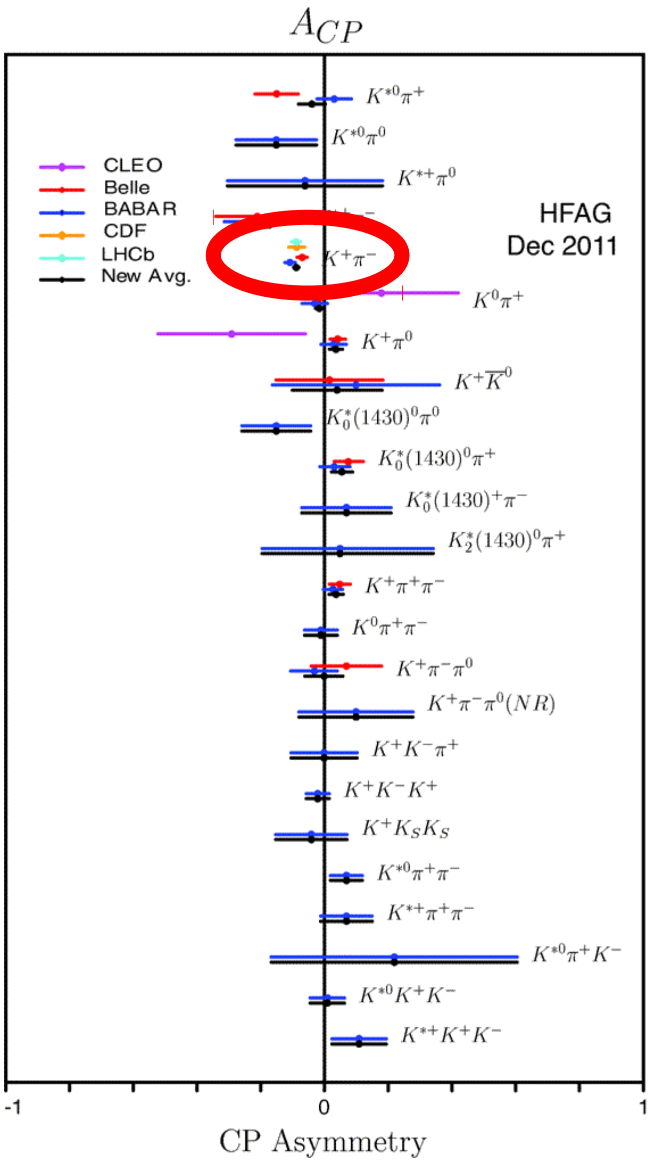
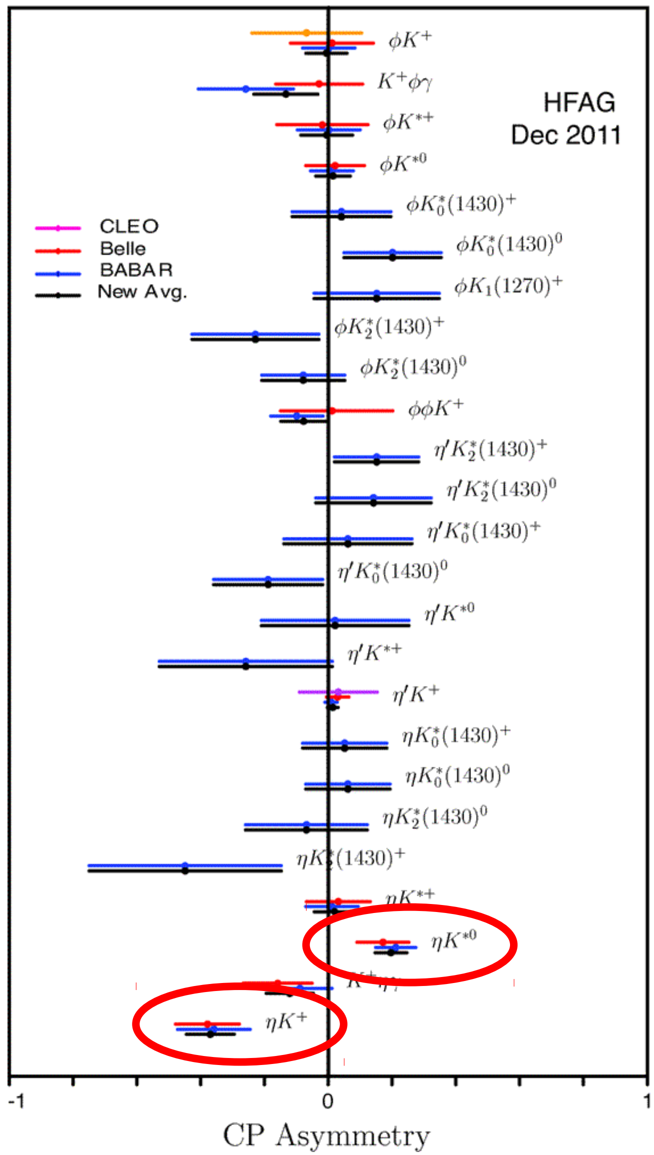
> Mary K. [Gaillard], Dimitri [
> penguin diagrams while we
> penguin name came in 197
>
> In the spring of 1977, Mik
> quark mass before it was fo
> Rudaz and I immediately st
> student at CERN, Melissa
> she, I, and Serge went to a
> lost I had to put the word p
> the end, and was replaced b
> conditions of the bet.
>
> For some time, it was not
> writing at the time. Then, one evening, after working at CERN, I stopped on my way back to my apartment to visit some friends living in Meyrin where I smoked some illegal substance. Later, when I got back to my apartment and continued working on our paper, I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history.

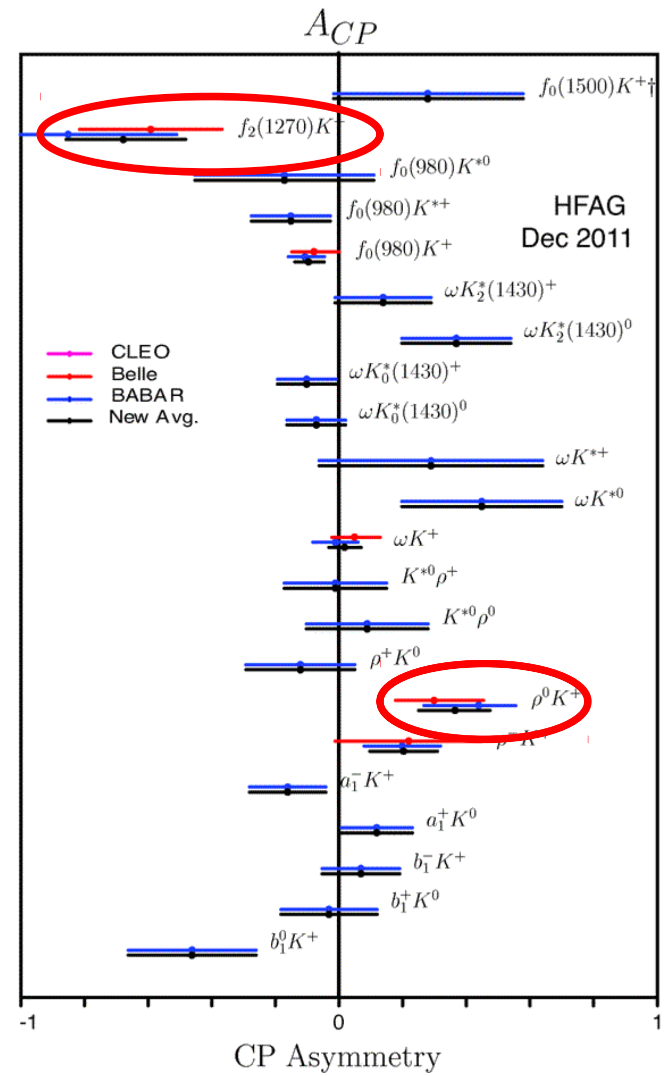


Example of a penguin diagram

Direct CP asymmetries in charmless hadronic B decays







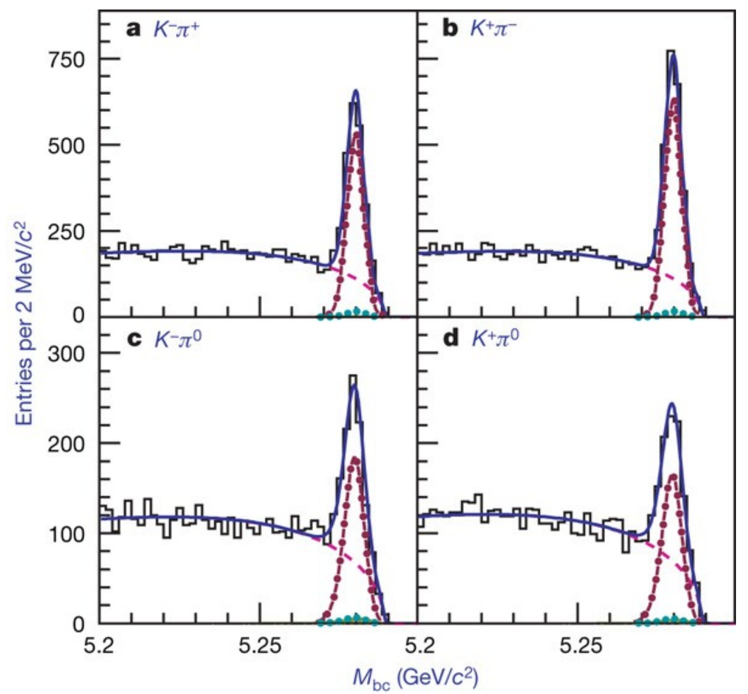
Direct CP violation in B → Kπ

- Direct CP violation in B → Kπ sensitive to γ

  too many hadronic parameters ⇒ need theory input

NB. interesting deviation from naïve expectation

Belle Nature 452 (2008) 332



"Kπ puzzle"

$A_{CP}(K^-\pi^+) = -0.087 \pm 0.008$

$A_{CP}(K^-\pi^0) = +0.037 \pm 0.021$

HFAG averages

Could be a sign of new physics …

… first need to rule out possibility of larger than expected QCD corrections

Clean observables in $B \to K\pi$ (etc.)

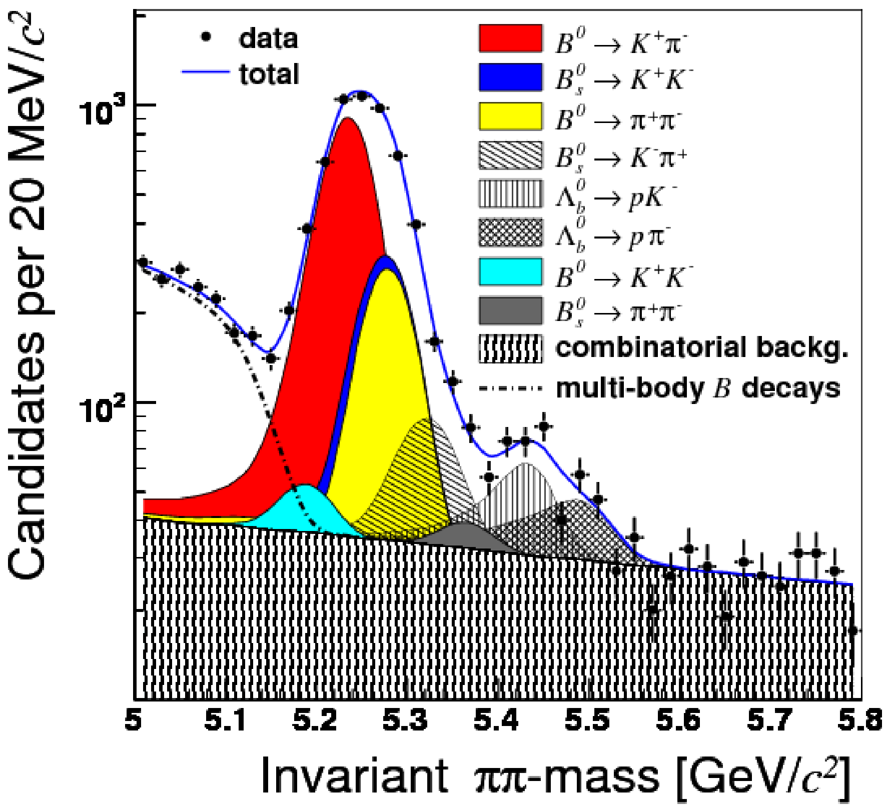
- Measure more $B_{u,d} \to K\pi$ decays & relate by isospin
- Perform similar analysis on $B \to K^*\pi$ &/or $B \to K\rho$
  - Dalitz plot analyses of $K\pi\pi$ final states extract both amplitudes and relative phases → more observables
- Measure $B_s \to KK$ decays & relate by U-spin
  - e.g. relation between time-dependent CP violation observables in $B_s \to K^+K^-$ and $B^0 \to \pi^+\pi^-$
- Dalitz plot analyses of $B_s \to KK\pi$

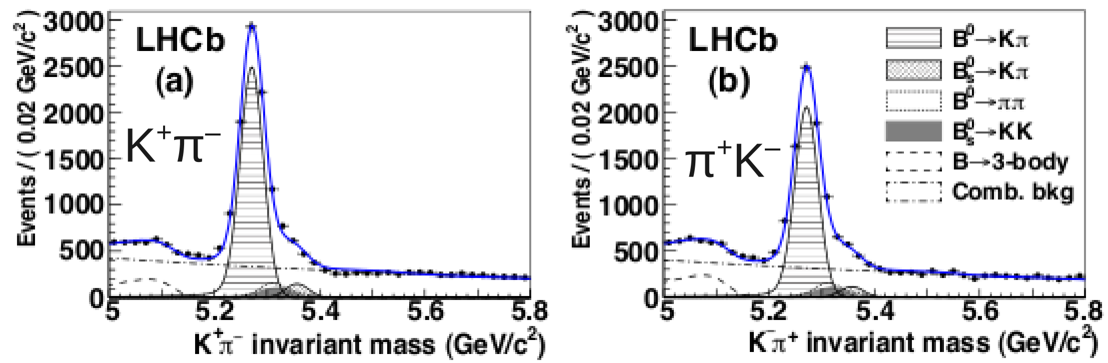
Note: flavour symmetries very useful
But, still get theory error from symmetry breaking (difficult to evaluate)
… data driven methods will win in the end (unless miracle breakthrough)

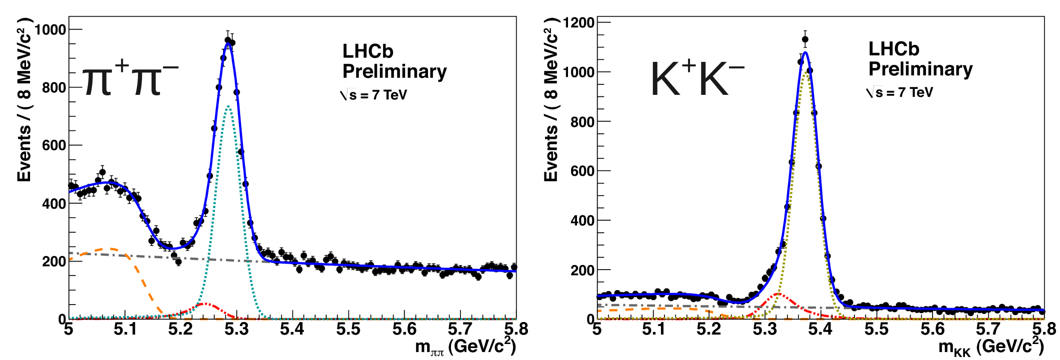
$B \to h^+h'^-$ at hadron colliders

- Excellent channel to profit from displaced vertex trigger
- Particle ID extremely important

LHCb arXiv:1202.6251







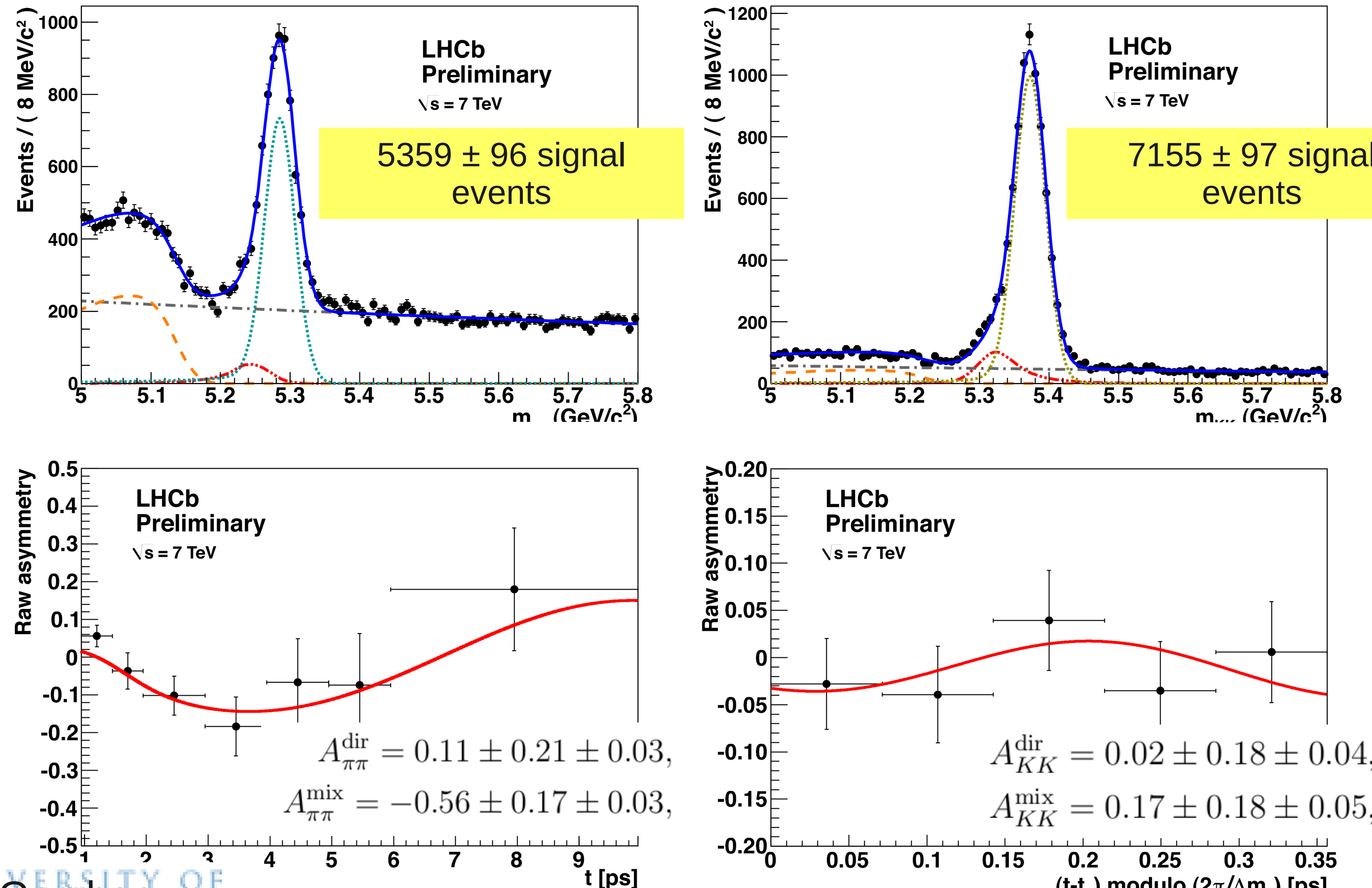
LHCb-CONF-2012-007

CDF PRL 103 (2009) 031801

$B^0 \to \pi^+\pi^-$ & $B_s^0 \to K^+K^-$

First CP violation measurements in these channels at a hadron collider ($B^0 \to \pi^+\pi^-$) / ever ($B_s^0 \to K^+K^-$)

LHCb-CONF-2012-007



$$A^{\rm dir}_{\pi\pi} = 0.11 \pm 0.21 \pm 0.03,$$
$$A^{\rm mix}_{\pi\pi} = -0.56 \pm 0.17 \pm 0.03,$$

$$A^{\rm dir}_{KK} = 0.02 \pm 0.18 \pm 0.04,$$
$$A^{\rm mix}_{KK} = 0.17 \pm 0.18 \pm 0.05,$$

Importance of γ from B→DK

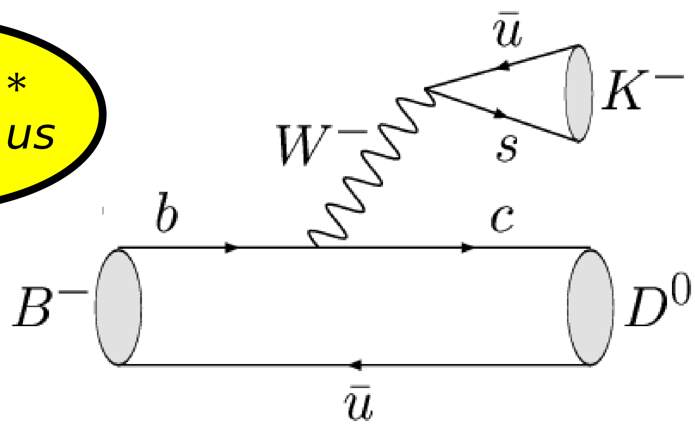
- γ plays a unique role in flavour physics

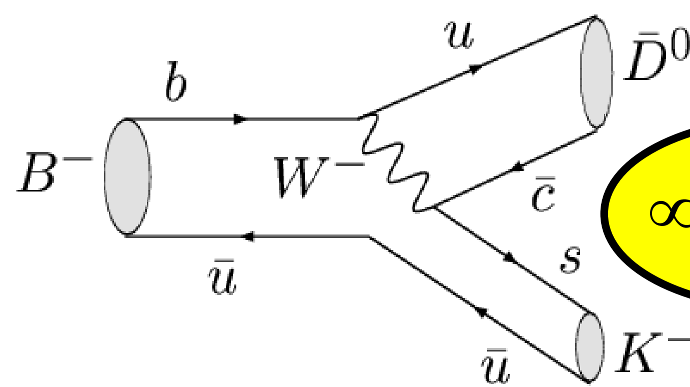
the only CP violating parameter that can be measured through tree decays (*)

(*) more-or-less

- A benchmark Standard Model reference point
  - doubly important after New Physics is observed

$\propto V_{cb} V^*_{us}$



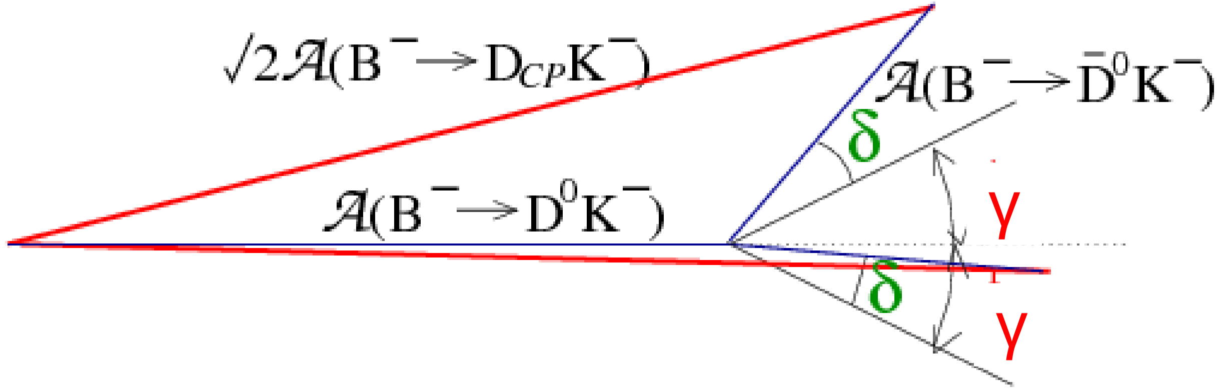


$\propto V_{ub} V^*_{cs}$

Variants use different B or D decays
require a final state common to both D^0 and $\bar{D}^0$

Why is B→DK so nice?

- For theorists:
  - theoretically clean: no penguins; factorisation works
  - all parameters can be determined from data
- For experimentalists:
  - many different observables (different final states)
  - all parameters can be determined from data
  - γ & δ_B (weak & strong phase differences), r_B (ratio of amplitudes)



$B \to DK$ methods

- Different D decay final states
  - CP eigenstates, e.g. K^+K^- (GLW)
  - doubly-Cabibbo-suppressed decays, e.g. $K^+\pi^-$ (ADS)
  - singly-Cabibbo-suppressed decays, e.g., $K^{*+}K^-$ (GLS)
  - self-conjugate multibody decays, e.g., $K_S\pi^+\pi^-$ (GGSZ)
- Different B decays

never studied before (or not much)

  - $B^- \to DK^-$, D^*K^- , DK^{*-}
  - $B^0 \to DK^{*0}$ (or $B \to DK\pi$ Dalitz plot analysis)
  - $B^0 \to DK_S$, $B_s^0 \to D\varphi$ (with or without time-dependence)
  - $B_s^0 \to D_sK$, $B^0 \to D^{(*)}\pi$ (time-dependent)

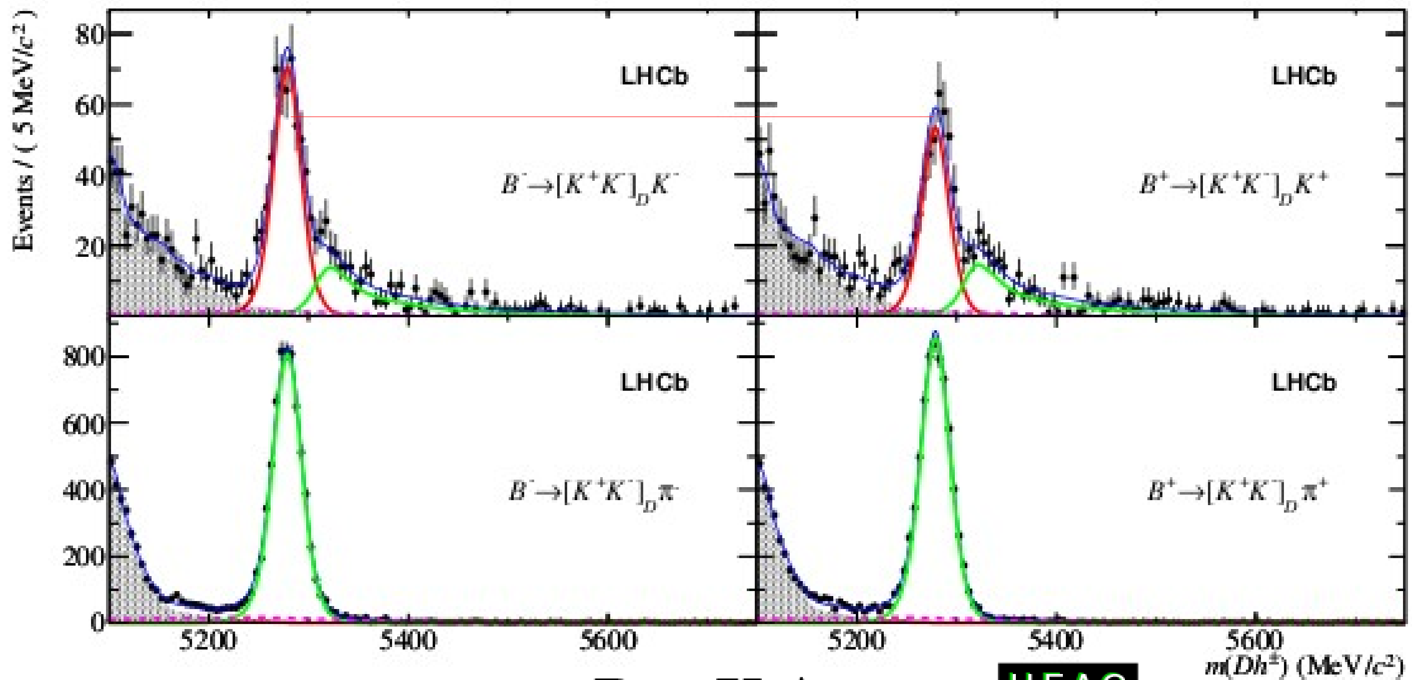
Search for direct CP violation caused by $\gamma \neq 0$

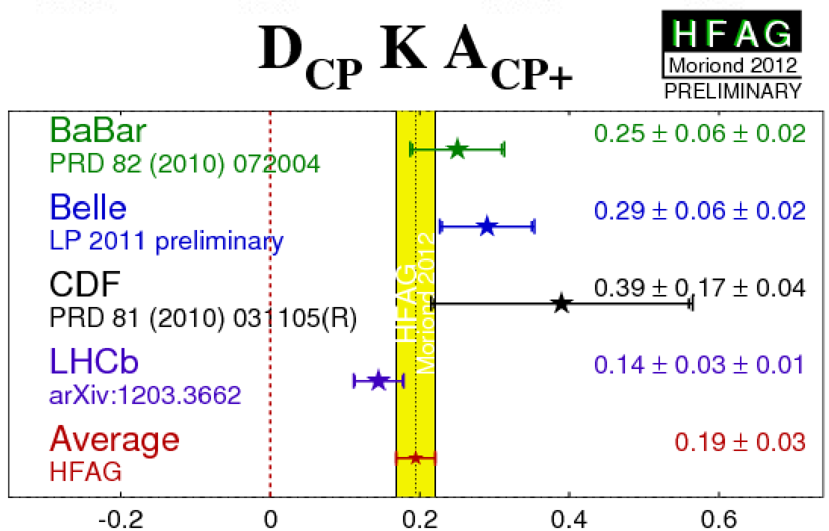
All parameters from data – no theory input needed

Latest results on B → DK : GLW

LHCb arXiv:1203.3662

Evidence for direct CP violation (γ≠0)





The other Unitarity Triangles

- High statistics available at LHCb will allow sensitivity to smaller CP violating effects
  - CP violating phase in B_s oscillations ($O(\lambda^4)$)
    - B_s oscillations (Δm_s) measured 2006 (CDF)
  - CP violating phase in D^0 oscillations ($O(\lambda^5)$)
    - D^0 oscillations ($x_D = \Delta m_D/\Gamma_D$ & $y_D = 2\Delta\Gamma_D/\Gamma_D$) measured 2007 (Babar, Belle, later CDF)

- Observations of CP violation in both K^0 and B^0 systems won Nobel prizes!

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1 + |\lambda_f|^2}{2} \, e^{-\Gamma t}$$
$$\times \left[\cosh \frac{\Delta\Gamma \, t}{2} + \mathcal{A}_{\rm CP}^{\rm dir} \, \cos(\Delta m \, t) + \mathcal{A}_{\Delta\Gamma} \, \sinh \frac{\Delta\Gamma \, t}{2} + \mathcal{A}_{\rm CP}^{\rm mix} \, \sin\left(\Delta m \, t\right) \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1 + |\lambda_f|^2}{2} \, (1 + a) \, e^{-\Gamma t}$$
$$\times \left[\cosh \frac{\Delta\Gamma \, t}{2} - \mathcal{A}_{\rm CP}^{\rm dir} \, \cos(\Delta m \, t) + \mathcal{A}_{\Delta\Gamma} \, \sinh \frac{\Delta\Gamma \, t}{2} - \mathcal{A}_{\rm CP}^{\rm mix} \, \sin(\Delta m \, t) \right] .$$

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, e^{-\Gamma t}$$
$$\times \left[\cosh\frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\rm CP}^{\rm dir}\, \cos(\Delta m\, t) + \mathcal{A}_{\Delta\Gamma}\, \sinh\frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\rm CP}^{\rm mix}\, \sin(\Delta m\, t)\right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, (1-a)\, e^{-\Gamma t}$$
$$\times \left[\cosh\frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\rm CP}^{\rm dir}\, \cos(\Delta m\, t) + \mathcal{A}_{\Delta\Gamma}\, \sinh\frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\rm CP}^{\rm mix}\, \sin(\Delta m\, t)\right].$$

CP violating asymmetries

CP conserving parameter

$$A_{CP}^{dir} = C_{CP} = \frac{1-|\lambda_{CP}|^2}{1+|\lambda_{CP}|^2} \qquad A_{\Delta\Gamma} = \frac{2\,\Re(\lambda_{CP})}{1+|\lambda_{CP}|^2} \qquad A_{CP}^{mix} = S_{CP} = \frac{2\,\Im(\lambda_{CP})}{1+|\lambda_{CP}|^2}$$

$$(A_{CP}^{dir})^2 + (A_{\Delta\Gamma})^2 + (A_{CP}^{mix})^2 = 1$$

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t} \times \left[\cosh \frac{\Delta\Gamma \, t}{2} \quad + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma \, t}{2} \quad \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1+a) \, e^{-\Gamma t} \times \left[\cosh \frac{\Delta\Gamma \, t}{2} \quad + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma \, t}{2} \quad \right] .$$

- Untagged analyses still sensitive to some interesting physics

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t}$$
$$\times \left[\cosh\frac{\Delta\Gamma\, t}{2} + 0 + \mathcal{A}_{\Delta\Gamma} \sinh\frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\rm CP}^{\rm mix} \sin\left(\Delta m\, t\right) \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1 + 0) \, e^{-\Gamma t}$$
$$\times \left[\cosh\frac{\Delta\Gamma\, t}{2} - 0 + \mathcal{A}_{\Delta\Gamma} \sinh\frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta m\, t) \right].$$

- In some channels, expect no direct CP violation
- and/or no CP violation in mixing

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t}$$
$$\times \left[1 + \mathcal{A}^{\rm dir}_{\rm CP} \cos(\Delta m \, t) + 0 + \mathcal{A}^{\rm mix}_{\rm CP} \sin(\Delta m \, t) \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1+a) \, e^{-\Gamma t}$$
$$\times \left[1 - \mathcal{A}^{\rm dir}_{\rm CP} \cos(\Delta m \, t) + 0 - \mathcal{A}^{\rm mix}_{\rm CP} \sin(\Delta m \, t) \right].$$

- In some channels, expect no direct CP violation
- B_d case: ΔΓ negligible

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

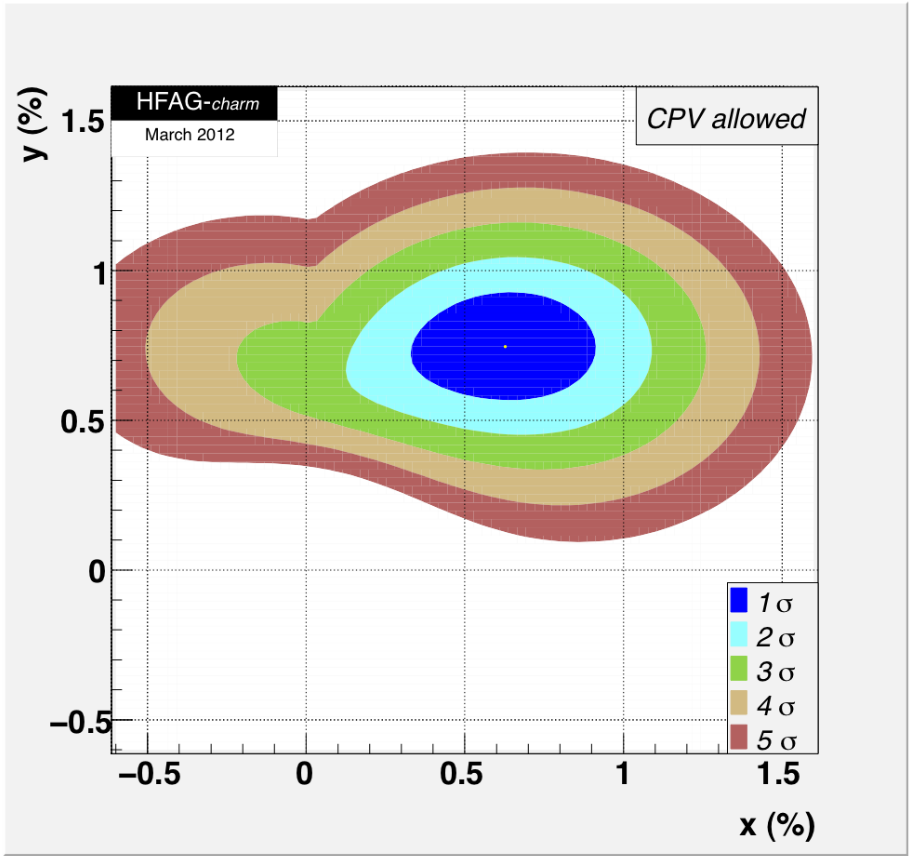
$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t}$$
$$\times \left[1 + \mathcal{A}_{CP}^{dir} \; 1 + \mathcal{A}_{\Delta\Gamma} \; y\Gamma t + \mathcal{A}_{CP}^{mix} \; x\Gamma t \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1+a) \, e^{-\Gamma t}$$
$$\times \left[1 - \mathcal{A}_{CP}^{dir} \; 1 + \mathcal{A}_{\Delta\Gamma} \; y\Gamma t - \mathcal{A}_{CP}^{mix} \; x\Gamma t \right] .$$

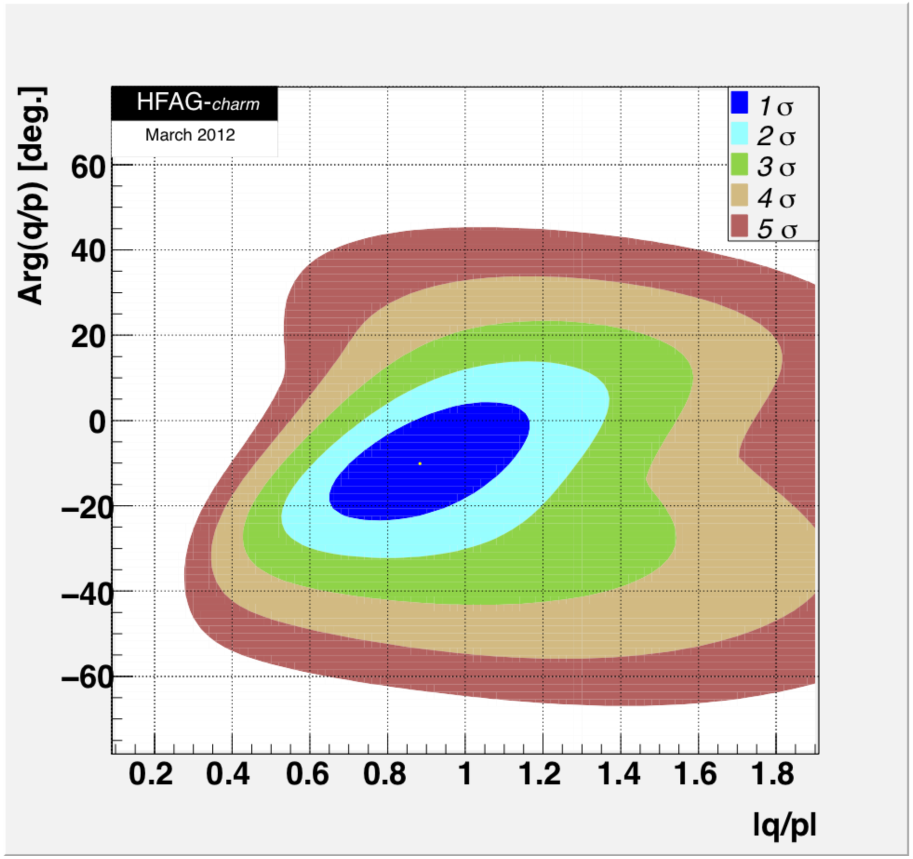
- In some channels, expect no direct CP violation
- B_d case: $\Delta\Gamma$ negligible
- D^0 case: both $x = \Delta m/\Gamma$ and $y = \Delta\Gamma/2\Gamma$ small

Charm mixing and CP violation

HFAG world average Including results from BABAR, Belle, CDF, CLEO(c), FOCUS



Inconsistent with no mixing point (0,0)



Consistent with no CP violation point (1,0)

At LHCb can use $D \to K^+K^-$ to measure

- $A_{\Delta\Gamma}$ y_D (untagged or tagged); A_{CP}^{mix} x_D (tagged)

Many other possible channels

Evidence for CP violation in D → h⁺h⁻ decays

LHCb PRL 108 (2012) 111602

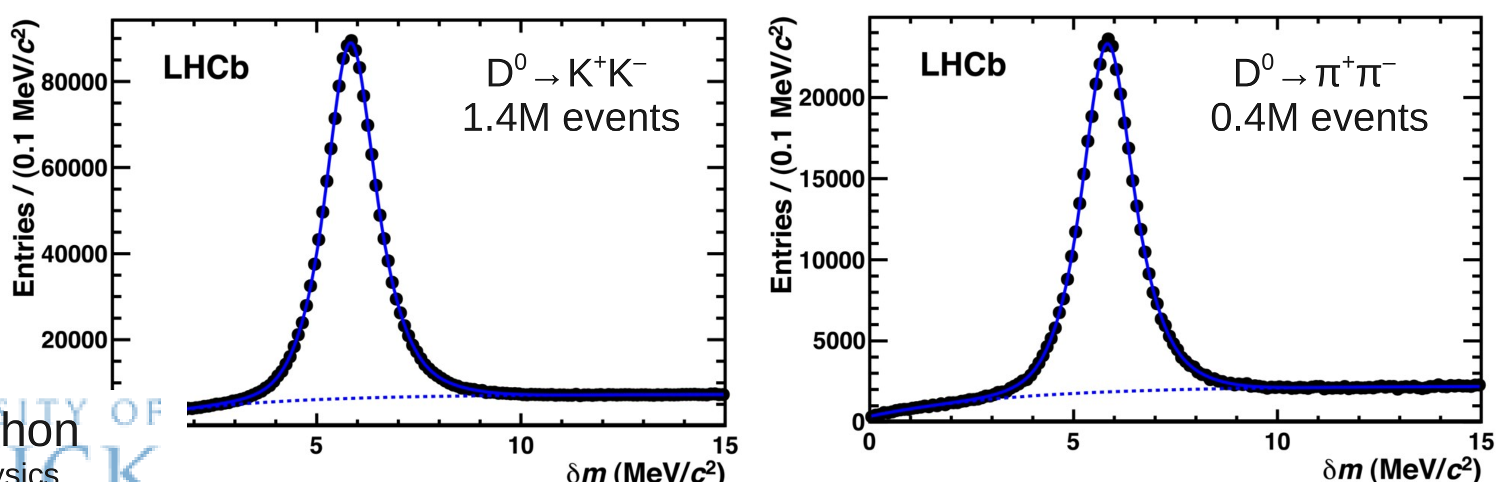
Measurement of CP asymmetry at pp collider requires knowledge of production and detection asymmetries; e.g. for $D^0 \to f$, where D meson flavour is tagged by $D^{*+} \to D^0\pi^+$ decay

$$A_{\rm raw}(f) = A_{CP}(f) + A_{\rm D}(f) + A_{\rm D}(\pi_s^+) + A_{\rm P}(D^{*+}).$$

final state detection asymmetry vanishes for CP eigenstate

Cancel asymmetries by taking difference of raw asymmetries in two different final states (Since A_D and A_P depend on kinematics, must bin or reweight to ensure cancellation)

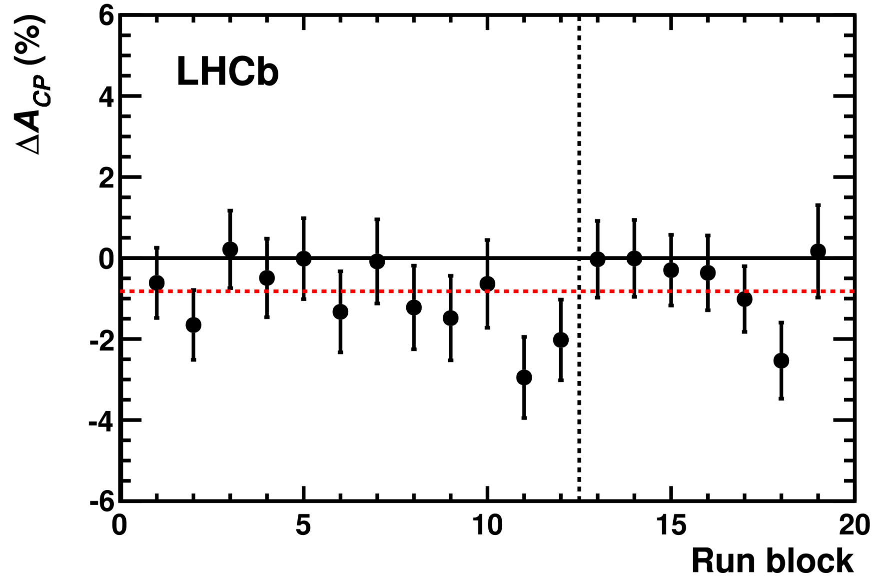
$$\Delta A_{CP} = A_{\rm raw}(K^-K^+) - A_{\rm raw}(\pi^-\pi^+).$$



Evidence for CP violation in D → h^+h^- decays

LHCb PRL 108 (2012) 111602

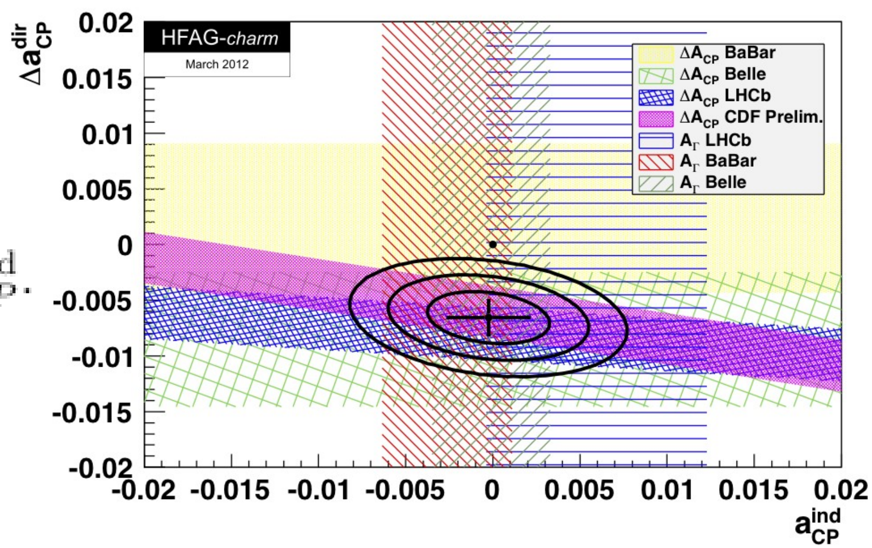
Result, based on 0.62/fb of 2011 data
ΔA_{CP} = [−0.82 ± 0.21(stat.) ± 0.11(syst.)]%



ΔA_{CP} related mainly to direct CP violation

(contribution from indirect CPV suppressed by difference in mean decay time)

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$
$$= \left[a_{CP}^{\rm dir}(K^-K^+) - a_{CP}^{\rm dir}(\pi^-\pi^+)\right] + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{\rm ind}.$$

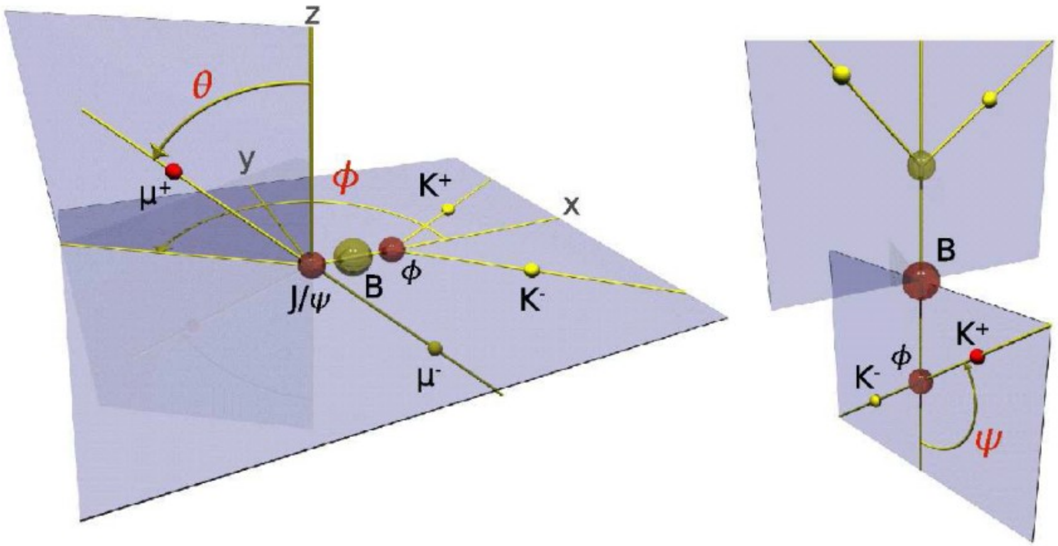


Evidence for CP violation in $D \to h^+h^-$ decays

- Naive SM expectation is for decays to be tree-dominated
  - Penguin contributions are possible for singly-Cabibbo-suppressed decays but CKM suppression is severe
  - So CP violation effects should be $O(10^{-4})$ … or should they?
    - Implications of the LHCb Evidence for Charm CP Violation arXiv:1111.4987
    - Direct CP violation in two-body hadronic charmed meson decays arXiv:1201.0785
    - CP asymmetries in singly-Cabibbo-suppressed D decays to two pseudoscalar mesons arXiv:1201.2351
    - Direct CP violation in charm and flavor mixing beyond the SM arXiv:1201.6204
    - New Physics Models of Direct CP Violation in Charm Decays arXiv:1202.2866
    - Repercussions of Flavour Symmetry Breaking on CP Violation in D-Meson Decays arXiv:1202.3795
    - On the Universality of CP Violation in Delta F = 1 Processes arXiv:1202.5038
    - The Standard Model confronts CP violation in $D0 \to \pi+\pi-$ and $D0 \to K+K-$ arXiv:1203.3131
    - A consistent picture for large penguins in $D \to$ pi+pi-, K+K- arXiv:1203.6659

… and many others! Further experimental input needed to clarify whether CPV is SM or NP

$\Phi_s = -2\beta_s$ ($B_s \to J/\psi\varphi$)



- VV final state

  three helicity amplitudes

  → mixture of CP-even and CP-odd

  disentangled using angular & time-dependent distributions

  → additional sensitivity

  many correlated variables

  → complicated analysis

- LHCb also uses $B_s \to J/\psi f_0$ ($f_0 \to \pi^+\pi^-$)
  - CP eigenstate; simpler analysis
  - fewer events; requires input from $J/\psi\varphi$ analysis (Γ_s, $\Delta\Gamma_s$)

$B_s \to J/\psi\phi$ formalism

Differential decay rate:

$$\frac{d^4\Gamma(B_s^0 \to J/\psi\phi)}{dt\, d\cos\theta\, d\varphi\, d\cos\psi} \equiv \frac{d^4\Gamma}{dt\, d\Omega} \propto \sum_{k=1}^{6} h_k(t) f_k(\Omega)$$

Bs | $\overline{\mathrm{Bs}}$

k	$h_k(t)$	$h_k(t)$	$f_k(\theta,\psi,\varphi)$
1	$\lvert A_0(t)\rvert^2$	$\lvert \bar{A}_0(t)\rvert^2$	$2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)$
2	$\lvert A_\parallel(t)\rvert^2$	$\lvert \bar{A}_\parallel(t)\rvert^2$	$\sin^2\psi(1-\sin^2\theta\sin^2\varphi)$
3	$\lvert A_\perp(t)\rvert^2$	$\lvert \bar{A}_\perp(t)\rvert^2$	$\sin^2\psi\sin^2\theta$
4	$\Im\{A_\parallel^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_\parallel^*(t)\bar{A}_\perp(t)\}$	$-\sin^2\psi\sin 2\theta\sin\varphi$
5	$\Re\{A_0^*(t)A_\parallel(t)\}$	$\Re\{\bar{A}_0^*(t)\bar{A}_\parallel(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\varphi$
6	$\Im\{A_0^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_0^*(t)\bar{A}_\perp(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\varphi$

$A_0(0) \to$ CP even
$A_\parallel(0) \to$ CP even
$A_\perp(0) \to$ CP odd

± signs differ for B_s and $\bar{B}_s$

$$|\bar{A}_0(t)|^2 = |\bar{A}_0(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\Phi\sin(\Delta m_s t)\right],$$

$$|\bar{A}_\parallel(t)|^2 = |\bar{A}_\parallel(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\Phi\sin(\Delta m_s t)\right],$$

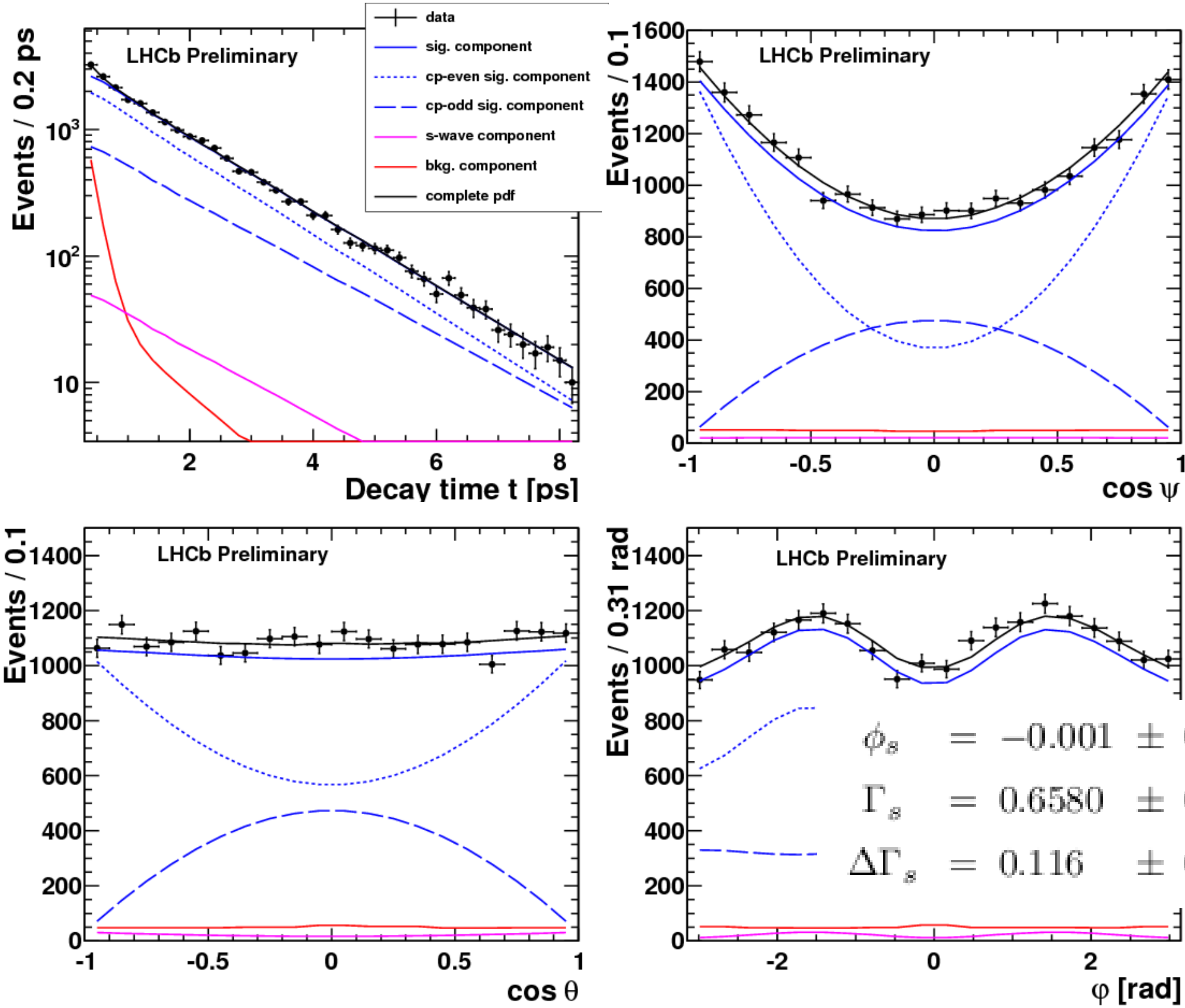
$$|\bar{A}_\perp(t)|^2 = |\bar{A}_\perp(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\Phi\sin(\Delta m_s t)\right],$$

$$\Im\{\bar{A}_\parallel^*(t)\bar{A}_\perp(t)\} = |\bar{A}_\parallel(0)||\bar{A}_\perp(0)|e^{-\Gamma_s t}\left[-\cos(\delta_\perp-\delta_\parallel)\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin(\delta_\perp-\delta_\parallel)\cos(\Delta m_s t) + \cos(\delta_\perp-\delta_\parallel)\cos\Phi\sin(\Delta m_s t)\right],$$

$$\Re\{\bar{A}_0^*(t)\bar{A}_\parallel(t)\} = |\bar{A}_0(0)||\bar{A}_\parallel(0)|e^{-\Gamma_s t}\cos\delta_\parallel\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\Phi\sin(\Delta m_s t)\right] \text{ and}$$

$$\Im\{\bar{A}_0^*(t)\bar{A}_\perp(t)\} = |\bar{A}_0(0)||\bar{A}_\perp(0)|e^{-\Gamma_s t}\left[-\cos\delta_\perp\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\delta_\perp\cos(\Delta m_s t) + \cos\delta_\perp\cos\Phi\sin(\Delta m_s t)\right].$$

CP violation in $B_s \to J/\psi\phi$ & $J/\psi\pi\pi$



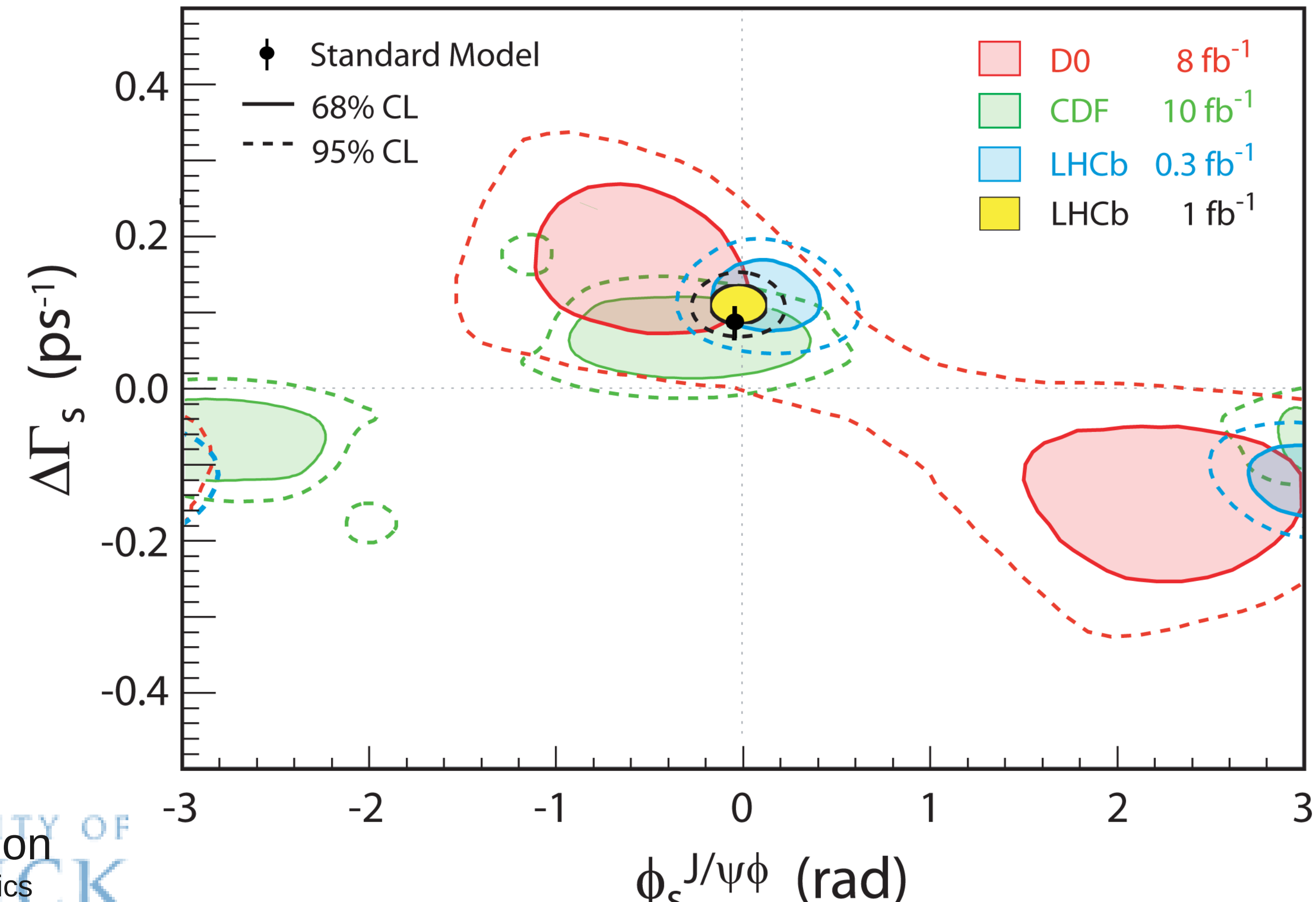
LHCb-PAPER-2011-028
0.37/fb
LHCb-CONF-2012-002
LHCb-PAPER-2012-005
LHCb-PAPER-2012-006
All 1/fb

LHCb-CONF-2012-002

$$\phi_s = -0.001 \pm 0.101 \;(\text{stat}) \pm 0.027 \;(\text{syst})\ \text{rad},$$
$$\Gamma_s = 0.6580 \pm 0.0054 \;(\text{stat}) \pm 0.0066 \;(\text{syst})\ \text{ps}^{-1},$$
$$\Delta\Gamma_s = 0.116 \pm 0.018 \;(\text{stat}) \pm 0.006 \;(\text{syst})\ \text{ps}^{-1}.$$

CP violation in $B_s \to J/\psi\phi$ & $J/\psi\pi\pi$

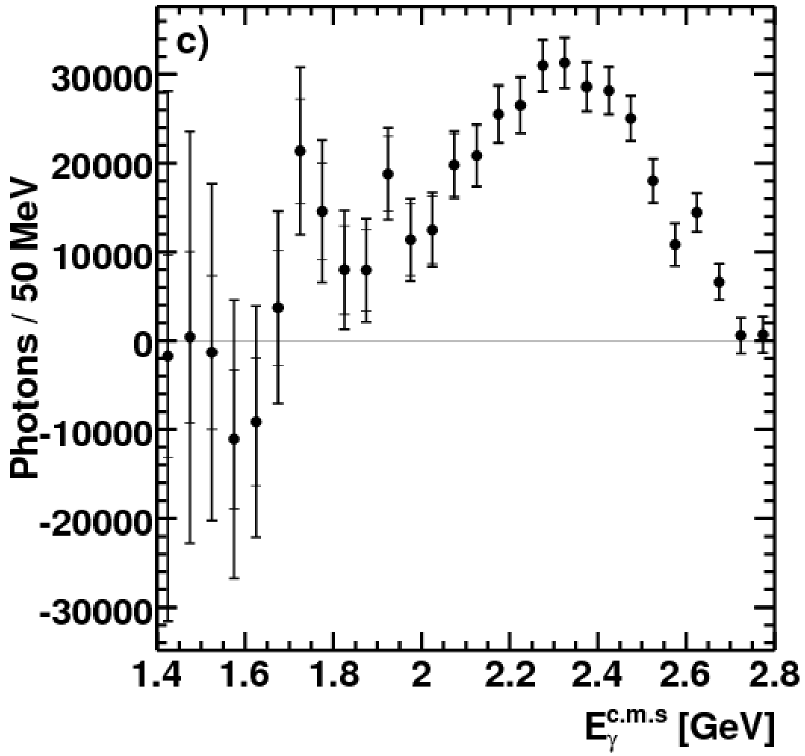
- Ambiguity resolution ↔ LHCb-PAPER-2011-028
- Tagged time-dependent angular analysis of $J/\psi\phi$ with 1/fb ↔ LHCb-CONF-2012-002
- Amplitude analysis to determine CP content of $J/\psi\pi\pi$ ↔ LHCb-PAPER-2012-005
- Tagged time-dependent analysis of $J/\psi\pi\pi$ ↔ LHCb-PAPER-2012-006



Rare Decays

$b \to s\gamma$ rate and photon energy spectrum

Archetypal FCNC probe for new physics



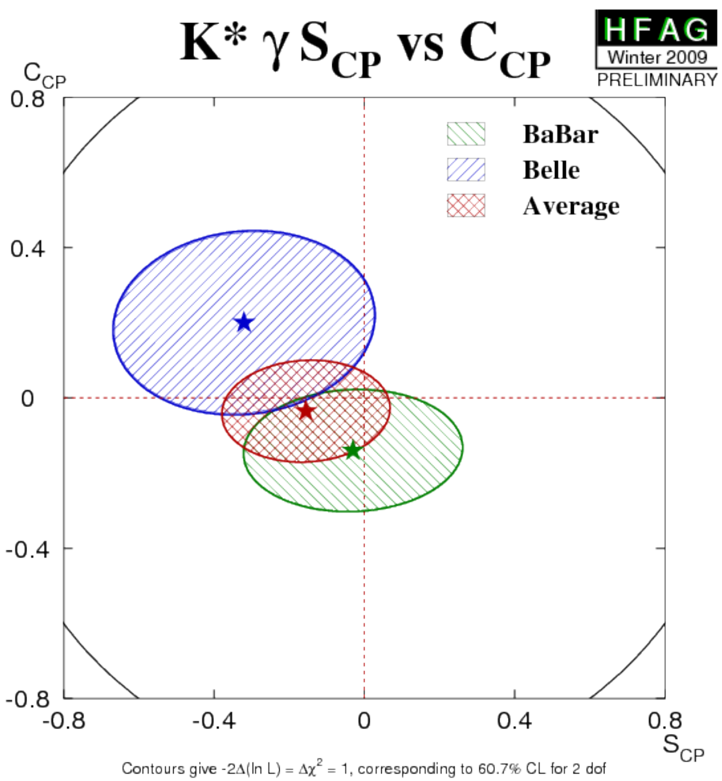
Belle PRL 103 (2009) 241801

$$B(B \to X_s \gamma)_{E_\gamma > 1.7\ GeV} = (3.45 \pm 0.15 \pm 0.40) \times 10^{-4}$$

consistent with the SM prediction

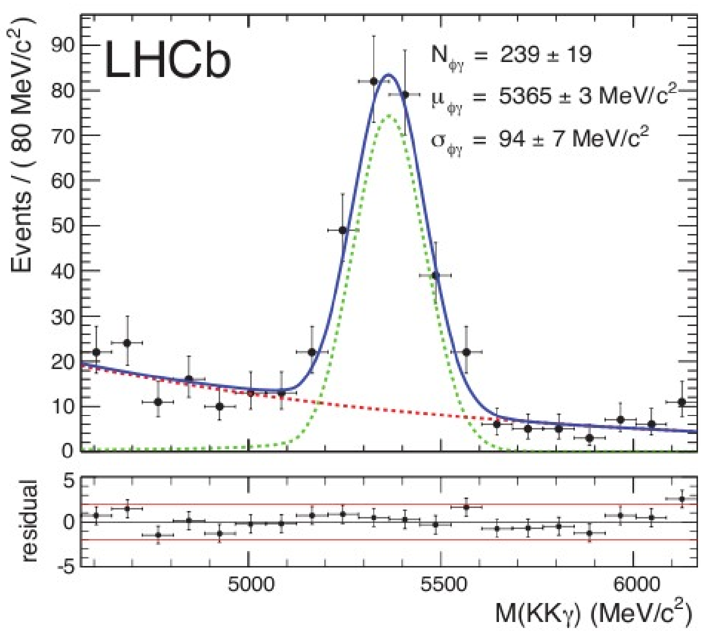
b→sγ photon polarisation measurement

- Search for time-dependent asymmetry
- Observable effect requires NP: left-handed current & new CP phase



Excellent prospects for LHCb with $B_s \to \phi\gamma$

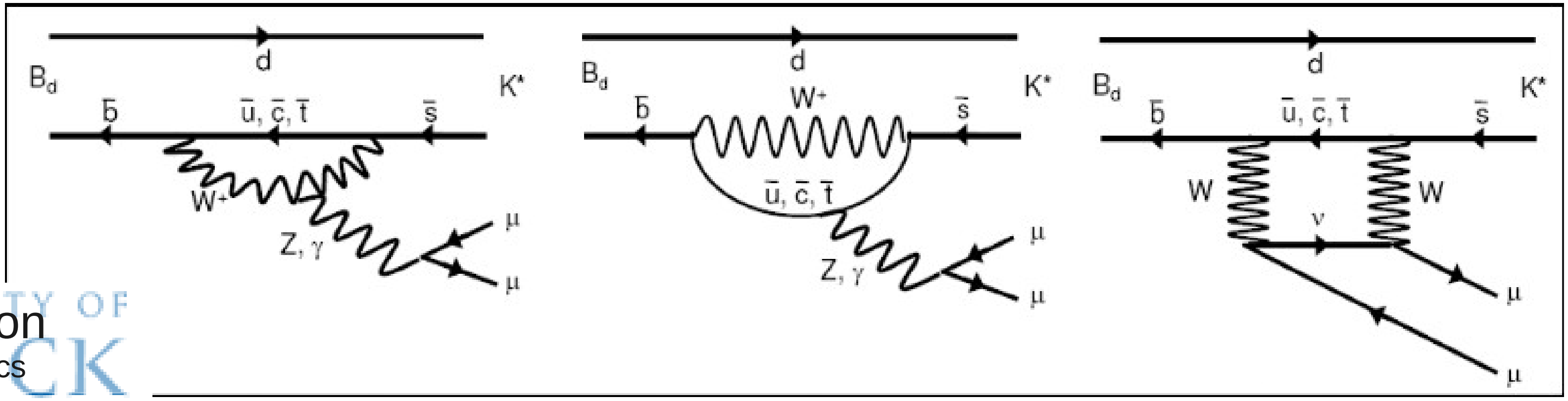
LHCb arXiv:1202.6267



Can also use, eg., $B \to K^* e^+ e^-$ (low q^2)

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

- $b \to s l^+ l^-$ processes also governed by FCNCs
  - rates and asymmetries of many exclusive processes sensitive to NP
- Queen among them is $B_d \to K^{*0} \mu^+ \mu^-$
  - superb laboratory for NP tests
  - experimentally clean signature
  - many kinematic variables …
  - … with clean theoretical predictions (at least at low q^2)



Operator Product Expansion

Build an effective theory for b physics

- take the weak part of the SM
- integrate out the heavy fields (W,Z,t)
- (like a modern version of Fermi theory for weak interactions)

$$\mathcal{L}_{(\text{full EW}\times\text{QCD})} \longrightarrow \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QED}\times\text{QCD}}\left(\begin{smallmatrix}\text{quarks} \neq t \\ \text{\& leptons}\end{smallmatrix}\right) + \sum_n C_n(\mu)\, Q_n$$

Q_n – local interaction terms (operators), C_n – coupling constants (Wilson coefficients)

Wilson coefficients

- encode information on the weak scale
- are calculable and known in the SM (at least to leading order)
- are affected by new physics

For K*μμ we care about C_7 (also affects $b\to s\gamma$), C_9 and C_{10}

Effective operators

$$\mathcal{H}_W^{\Delta B=1,\Delta C=0,\Delta S=-1} = 4\frac{G_F}{\sqrt{2}}\Big(\lambda_c^s\big(C_1(\mu)Q_1^c(\mu)+C_2(\mu)Q_2^c(\mu)\big)$$
$$+\lambda_u^s\big(C_1(\mu)Q_1^u(\mu)+C_2(\mu)Q_2^u(\mu)\big) - \lambda_t^s\sum_{i=3}^{10}C_i(\mu)Q_i(\mu)\Big)$$

where the $\lambda_q^s = V_{qb}^* V_{qs}$ and the operator basis is given by

$$Q_1^q = \bar{b}_L^\alpha\gamma^\mu q_L^\alpha\,\bar{q}_L^\beta\gamma_\mu s_L^\beta \qquad Q_2^q = \bar{b}_L^\alpha\gamma^\mu q_L^\beta\,\bar{q}_L^\beta\gamma_\mu s_L^\alpha$$
$$Q_3 = \bar{b}_L^\alpha\gamma^\mu s_L^\alpha\sum_q\bar{q}_L^\beta\gamma_\mu q_L^\beta \qquad Q_4 = \bar{b}_L^\alpha\gamma^\mu s_L^\beta\sum_q\bar{q}_L^\beta\gamma_\mu q_L^\alpha$$
$$Q_5 = \bar{b}_L^\alpha\gamma^\mu s_L^\alpha\sum_q\bar{q}_R^\beta\gamma_\mu q_R^\beta \qquad Q_6 = \bar{b}_L^\alpha\gamma^\mu s_L^\beta\sum_q\bar{q}_R^\beta\gamma_\mu q_R^\alpha$$
$$Q_7 = \frac{3}{2}\bar{b}_L^\alpha\gamma^\mu s_L^\alpha\sum_q e_q\bar{q}_R^\beta\gamma_\mu q_R^\beta \qquad Q_8 = \frac{3}{2}\bar{b}_L^\alpha\gamma^\mu s_L^\beta\sum_q e_q\bar{q}_R^\beta\gamma_\mu q_R^\alpha$$
$$Q_9 = \frac{3}{2}\bar{b}_L^\alpha\gamma^\mu s_L^\alpha\sum_q e_q\bar{q}_L^\beta\gamma_\mu q_L^\beta \qquad Q_{10} = \frac{3}{2}\bar{b}_L^\alpha\gamma^\mu s_L^\beta\sum_q e_q\bar{q}_L^\beta\gamma_\mu q_L^\alpha$$

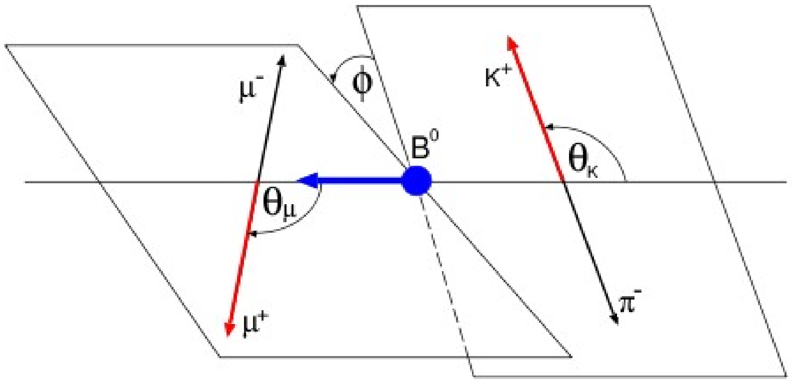
$$Q_{7\gamma} = \frac{e}{16\pi^2}m_b\bar{b}_L^\alpha\sigma^{\mu\nu}F_{\mu\nu}s_L^\alpha$$
$$Q_{8g} = \frac{g_s}{16\pi^2}m_b\bar{b}_L^\alpha\sigma^{\mu\nu}G_{\mu\nu}^A T^A s_L^\alpha$$
$$Q_{9V} = \frac{1}{2}\bar{b}_L^\alpha\gamma^\mu s_L^\alpha\,\bar{l}\gamma_\mu l$$
$$Q_{10A} = \frac{1}{2}\bar{b}_L^\alpha\gamma^\mu s_L^\alpha\,\bar{l}\gamma_\mu\gamma_5 l$$

Four-fermion operators (except $Q_{7\gamma}$ & Q_{8g}) – dimension 6

Theory of B → K*μ⁺μ⁻

- Given for inclusive $b \to s\mu^+\mu^-$ for simplicity
  - physics of exclusive modes ≈ same but equations are more complicated (involving form factors, etc.)
- Differential decay distribution

$$\frac{d^2\Gamma}{dq^2\, d\cos\theta_l} = \frac{3}{8}\left[(1+\cos^2\theta_l)\, H_T(q^2) + 2\,\cos\theta_l\, H_A(q^2) + 2\,(1-\cos^2\theta_l)\, H_L(q^2)\right]$$



$$H_T(q^2) \propto 2q^2\left[\left(C_9 + 2C_7\frac{m_b^2}{q^2}\right)^2 + C_{10}^2\right],$$

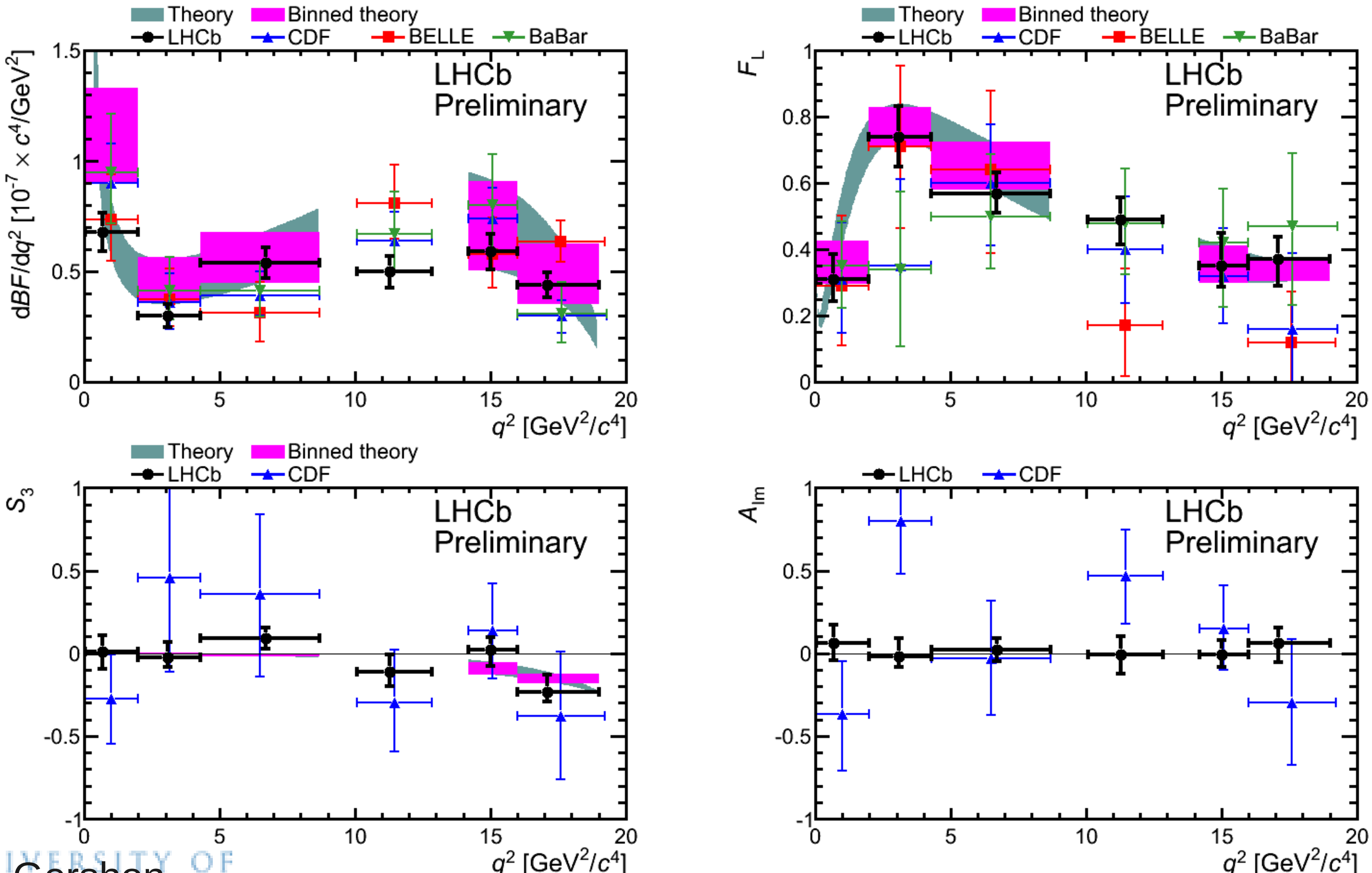
$$H_A(q^2) \propto -4q^2 C_{10}\left(C_9 + 2C_7\frac{m_b^2}{q^2}\right),$$

$$H_L(q^2) \propto \left[(C_9 + 2C_7)^2 + C_{10}^2\right].$$

This term gives a forward-backward asymmetry

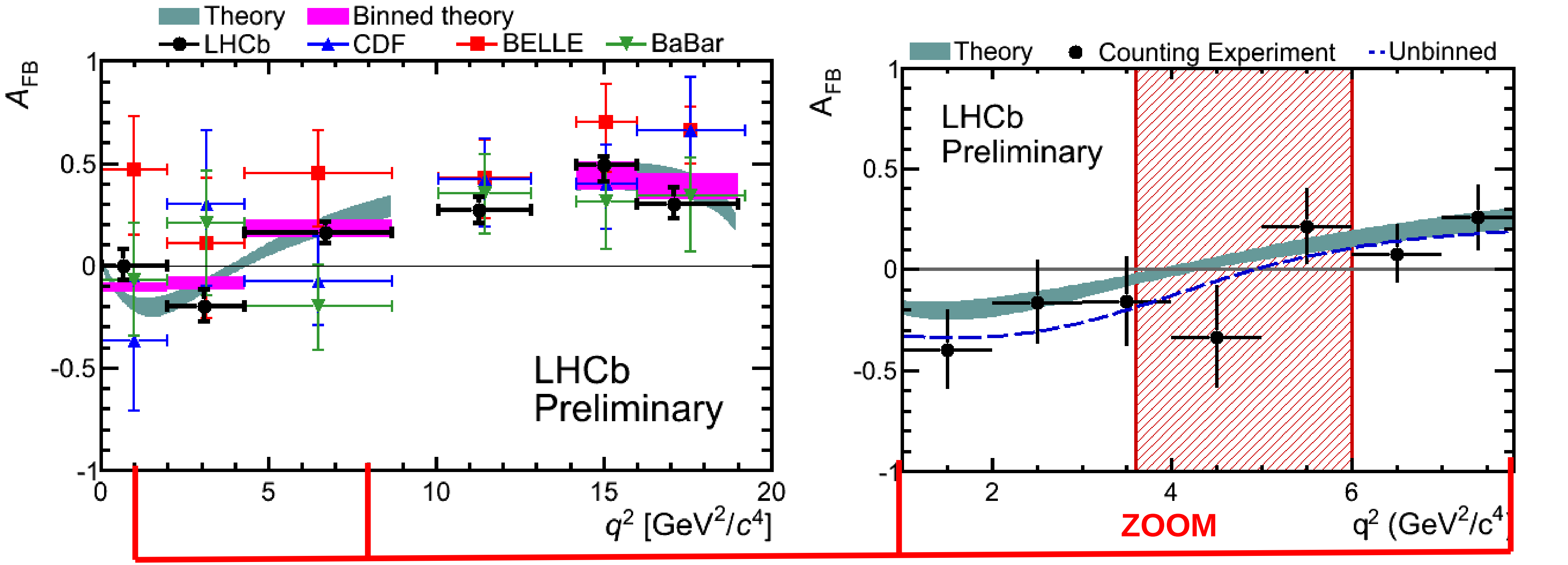
Differential branching fraction and angular analysis of the $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decay

LHCb-CONF-2012-008



Differential branching fraction and angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay

LHCb-CONF-2012-008



First measurement of the zero-crossing point of the forward-backward asymmetry

$q^2_0 = (4.9^{+1.1}_{-1.3})$ GeV^2

(SM predictions in the range 4.0 – 4.3 GeV^2)

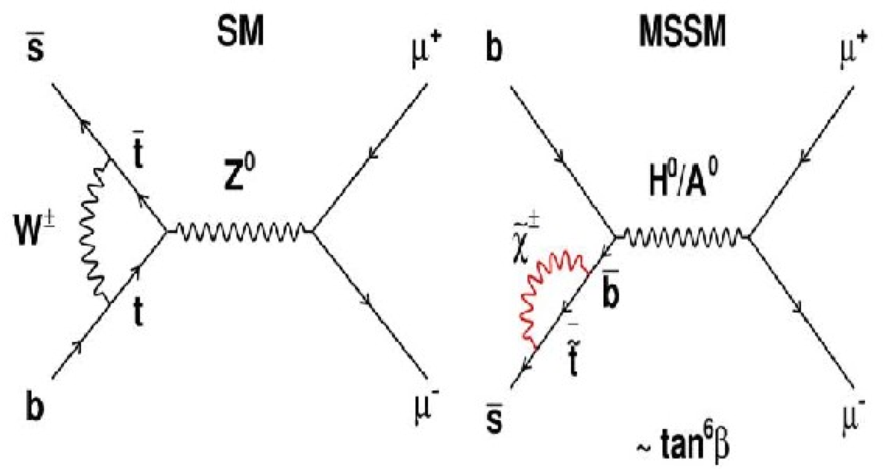
$B_s \to \mu^+\mu^-$

Killer app. for new physics discovery

- Very small in the SM
- Huge NP enhancement

(tan β = ratio of Higgs vevs)

- Clean experimental signature

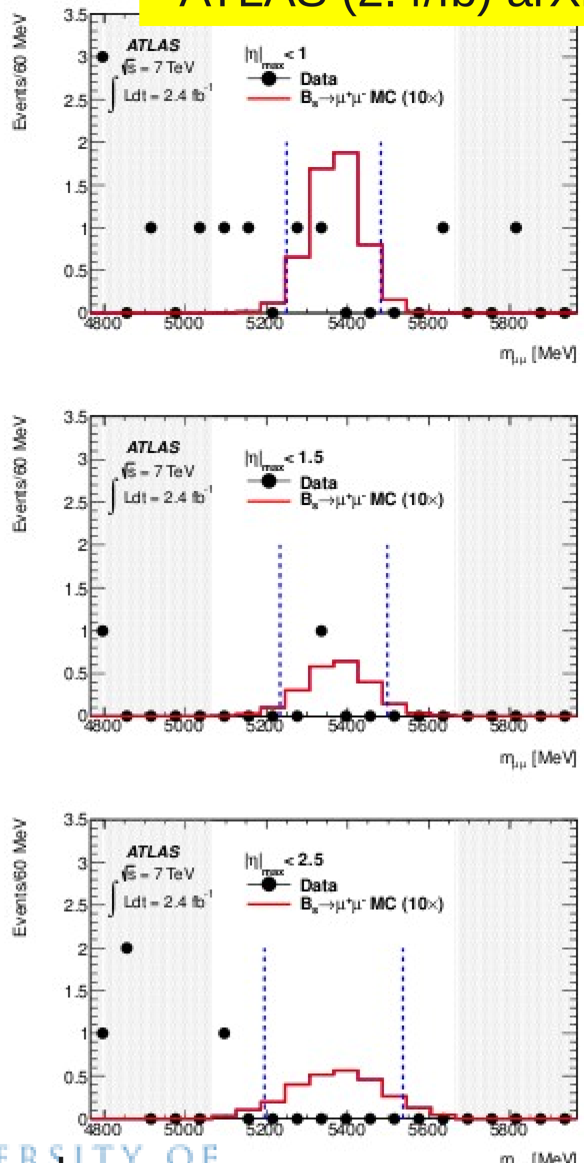


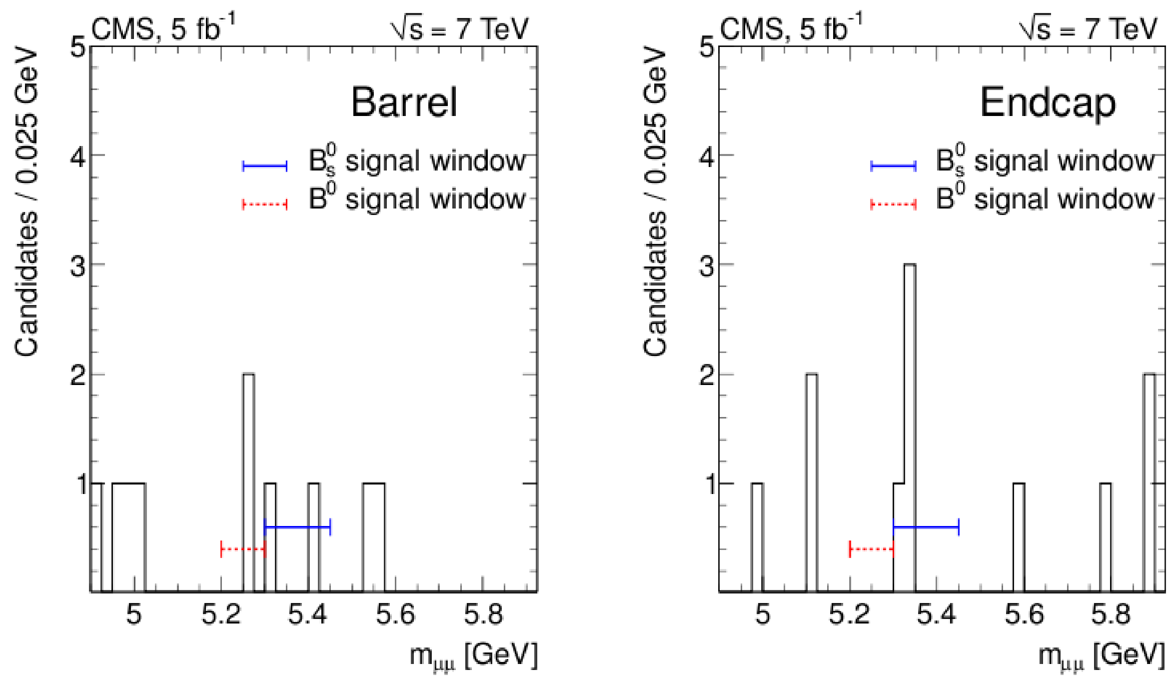
$$BR(B_s \to \mu^+\mu^-)^{SM} = (3.3 \pm 0.3) \times 10^{-8} \qquad BR(B_s \to \mu^+\mu^-)^{MSSM} \propto \tan^6\beta / M_{A0}^4$$

Latest results on $B_s \to \mu^+\mu^-$

ATLAS (2.4/fb) arXiv:1204.0735

CMS (5/fb) arXiv:1203.3976



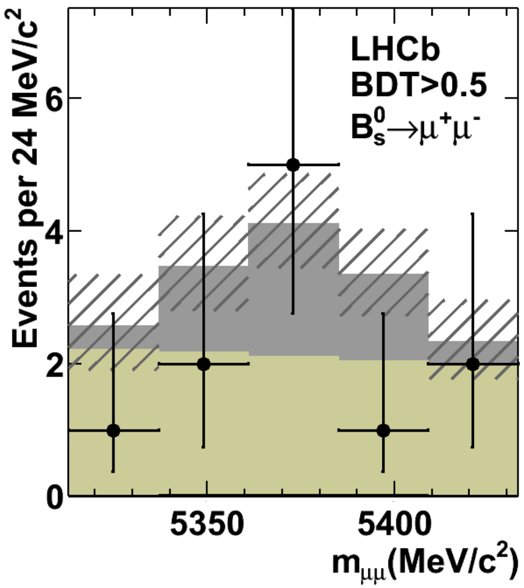


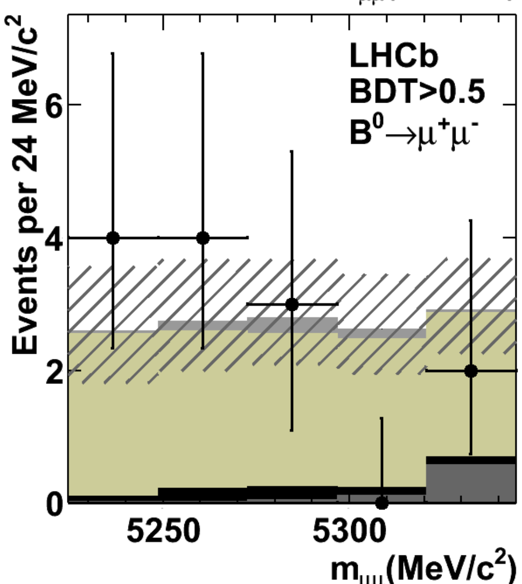
ATLAS $B(B_s \to \mu^+\mu^-) < 2.2\ (1.9) \times 10^{-8}$ @ 95% (90%) CL

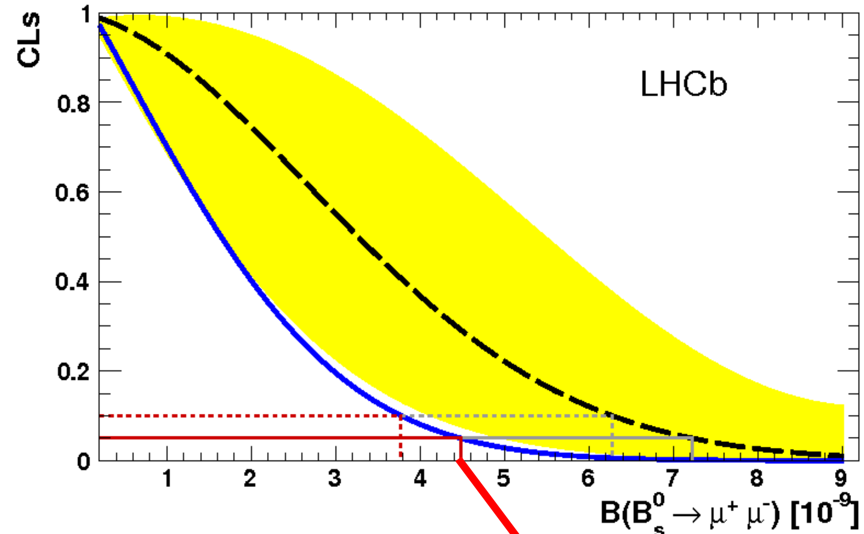
CMS $B(B_s \to \mu^+\mu^-) < 7.7\ (6.4) \times 10^{-9}$ @ 95% (90%) CL

Latest results on $B_s \to \mu^+\mu^-$

LHCb (1/fb) arXiv:1203.4493







Mode	Limit	at 90 % CL	at 95 % CL
$B_s^0 \to \mu^+\mu^-$	Exp. bkg+SM	6.3×10^{-9}	7.2×10^{-9}
	Exp. bkg	2.8×10^{-9}	3.4×10^{-9}
	Observed	3.8×10^{-9}	4.5×10^{-9}
$B^0 \to \mu^+\mu^-$	Exp. bkg	0.91×10^{-9}	1.1×10^{-9}
	Observed	0.81×10^{-9}	1.0×10^{-9}

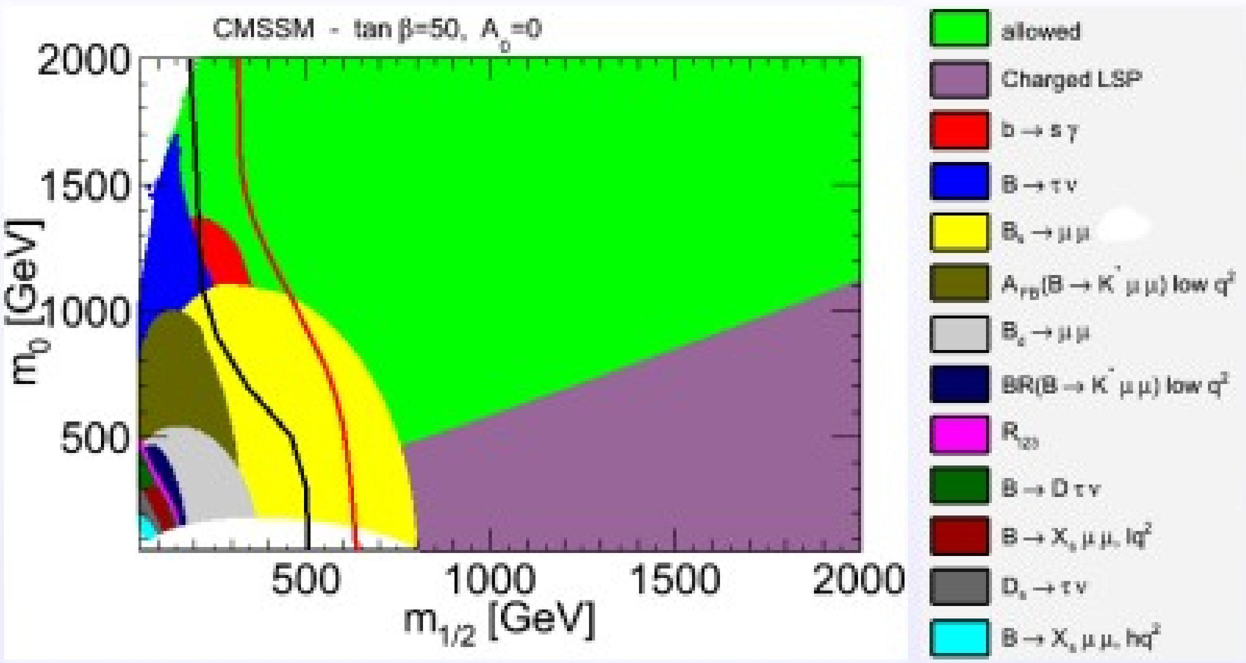
Standard Model expectation, e.g. $(3.2 \pm 0.2) \times 10^{-9}$
Buras, arXiv:1012.1447

Why does LHCb get a better limit than ATLAS/CMS?

Implications

G.Dissertori Moriond QCD summary talk:

"Numbers most often mentioned: 3.2 x 10^{-9} and 125"



Black line: CMS exclusion limit with 1.1 fb^{-1} data

Red line: CMS exclusion limit with 4.4 fb^{-1} data

… before ...

Superlso v3.2+

N. Mahmoudi at Moriond

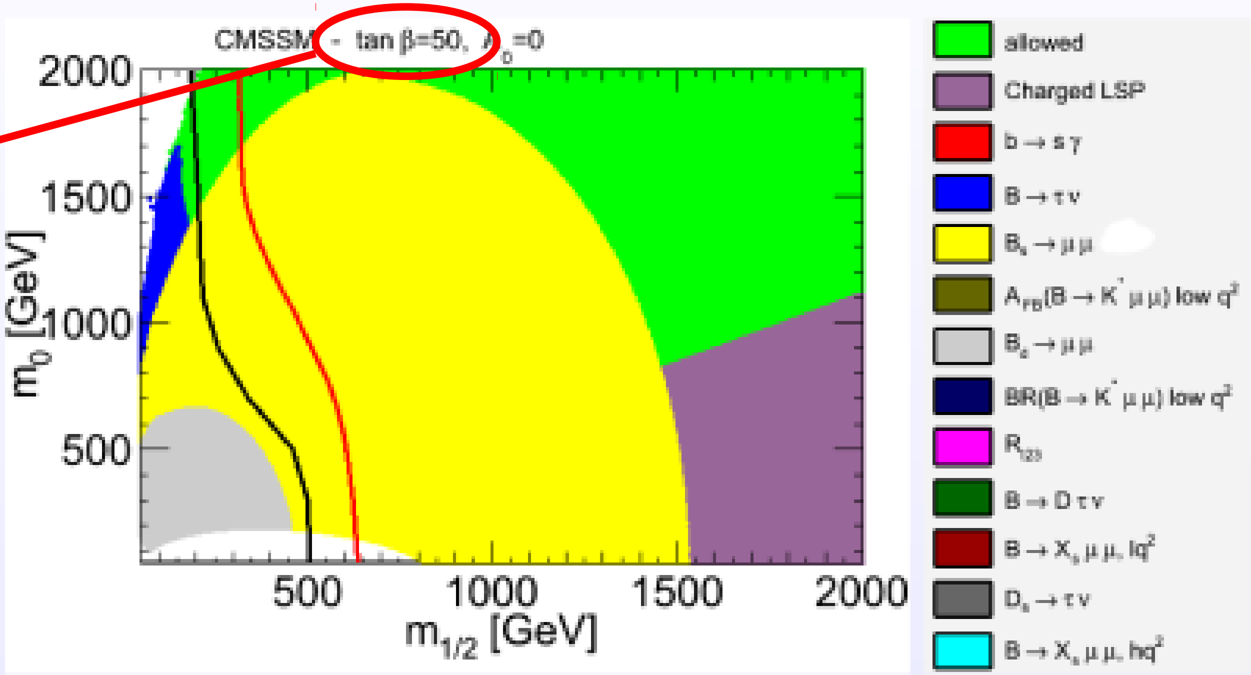
Implications

G.Dissertori Moriond QCD summary talk:

"Numbers most often mentioned: 3.2 x 10^{-9} and 125"

"the wow plot"

Simple TeV-scale models with large tan β ~ ruled out



Black line: CMS exclusion limit with 1.1 fb^{-1} data

Red line: CMS exclusion limit with 4.4 fb^{-1} data

New LHCb limits for $BR(B_s \to \mu^+\mu^-)$ and $BR(B_d \to \mu^+\mu^-)$

… after ...

Superlso v3.2+

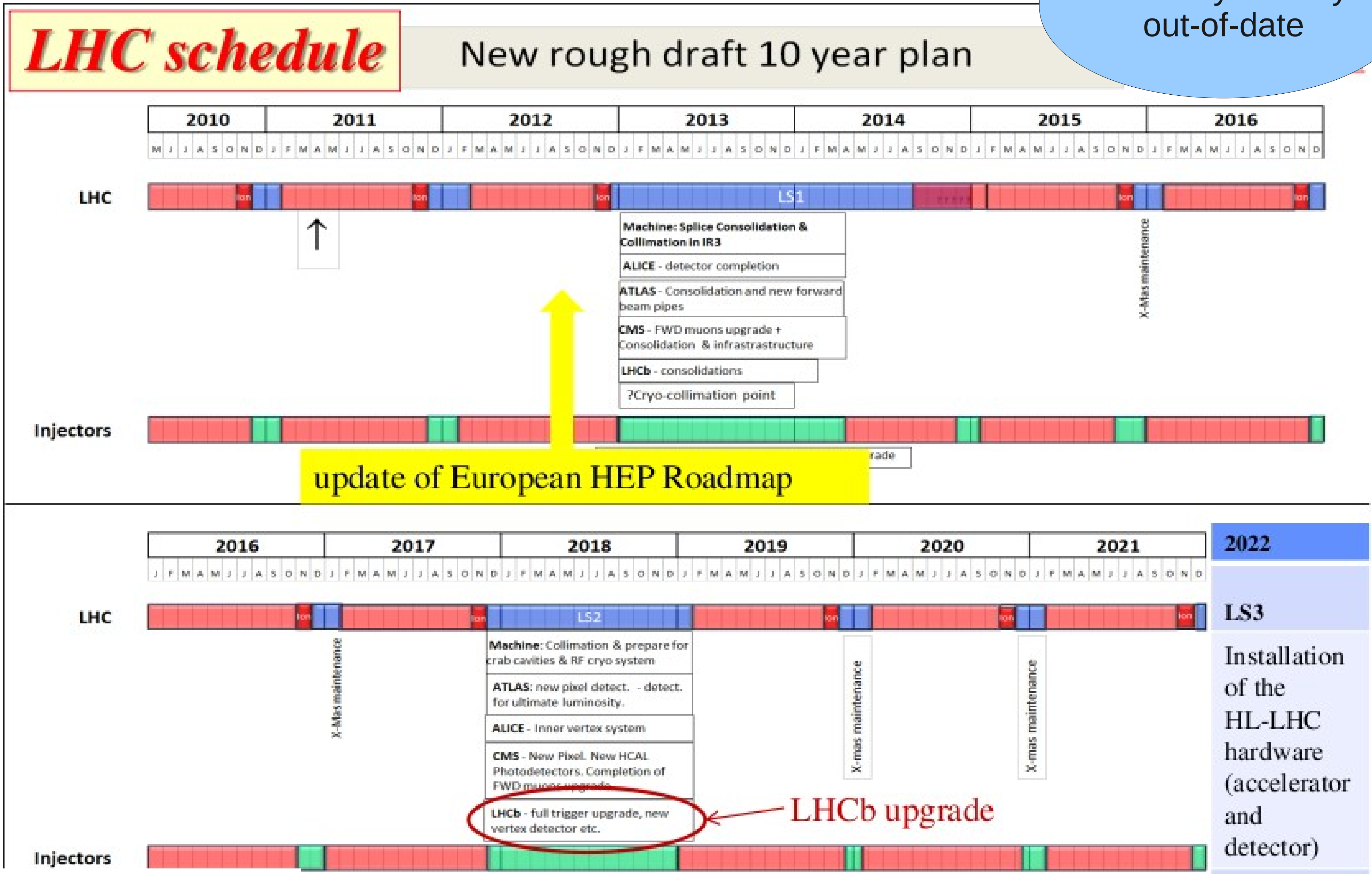
N. Mahmoudi at Moriond

LHCb upgrade

- To fully exploit LHC potential for heavy flavour physics will require an upgrade to LHCb
  - full readout & trigger at 40 MHz to enable high L running
  - “high L” = 10^{33}/cm^{2}/s (so independent of machine upgrade)
  - planned for 2018 shutdown

What is the LHC era?

Probably already out-of-date



… it is the foreseeable future!

Other future flavour experiments

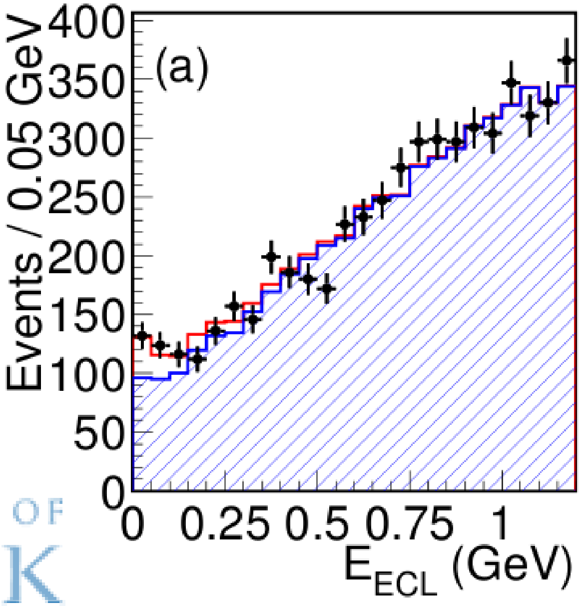
- SuperKEKB/Belle2 & SuperB
  - $B \to \tau\nu$, inclusive measurements, τ physics, …
- Rare kaon decays
  - $K^+ \to \pi^+\nu\nu$ (NA62, CERN); $K^0 \to \pi^0\nu\nu$ (K0T0, J-PARC)
- Muon to electron conversion (charged lepton flavour violation)
  - COMET/PRIME (J-PARC); mu2e (FNAL)

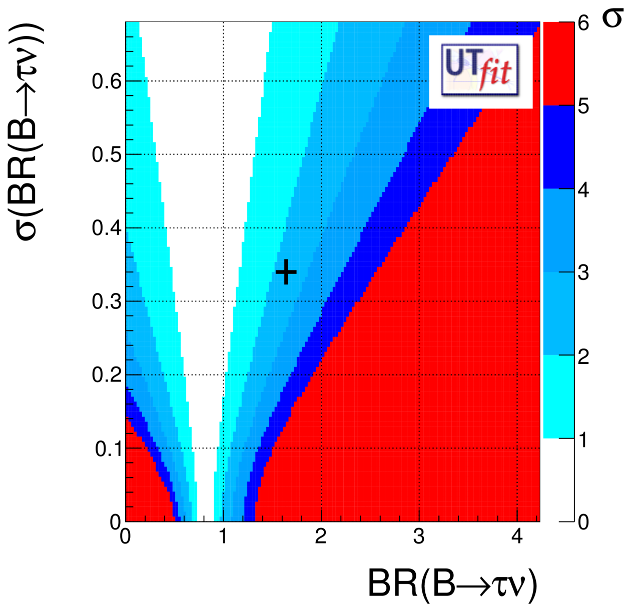
$B \to \tau\nu$ and charged Higgs limits

- Pure leptonic decays of charged B mesons very clean
  - clean SM prediction
  - clean effect of charged Higgs (2HDM or SUSY)

$$BR(B^+ \to l^+ \nu)^{SM} = \frac{G_F m_B}{8\pi} m_l^2 \left(1 - \frac{m_l^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B \qquad BR(B^+ \to l^+ \nu)^{NP} = BR(B^+ \to l^+ \nu)^{SM} \left(1 - \frac{m_B^2}{m_H^2} \tan^2\beta\right)^2$$

Belle PRD 82 (2010) 071101





The holy grail of kaon physics: $K \rightarrow \pi\nu\nu$

Highest CKM suppression of the $s \rightarrow d$ coupling:

$$A \sim (m_t/m_W)^2 |V_{ts}^* V_{td}| \sim \lambda^5$$

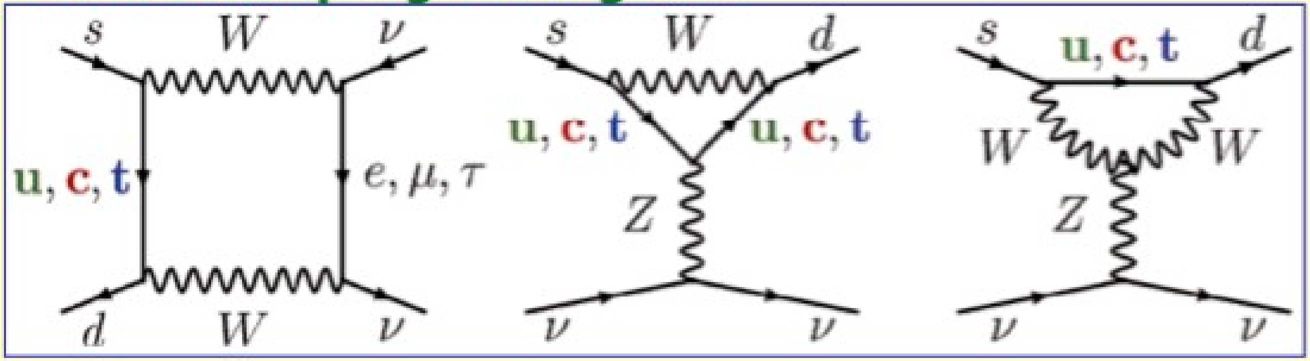
SM branching ratios

(Brod, Gorbahn, Stamou; PRD83 (2011) 034030)

Mode	$BR_{SM} \times 10^{11}$
$K^+ \rightarrow \pi^+ \nu\bar{\nu}(\gamma)$	$7.81 \pm 0.75 \pm 0.29$
$K_L \rightarrow \pi^0 \nu\bar{\nu}$	$2.43 \pm 0.39 \pm 0.06$

CKM parametric (mainly $|V_{ts}|$) — Intrinsic

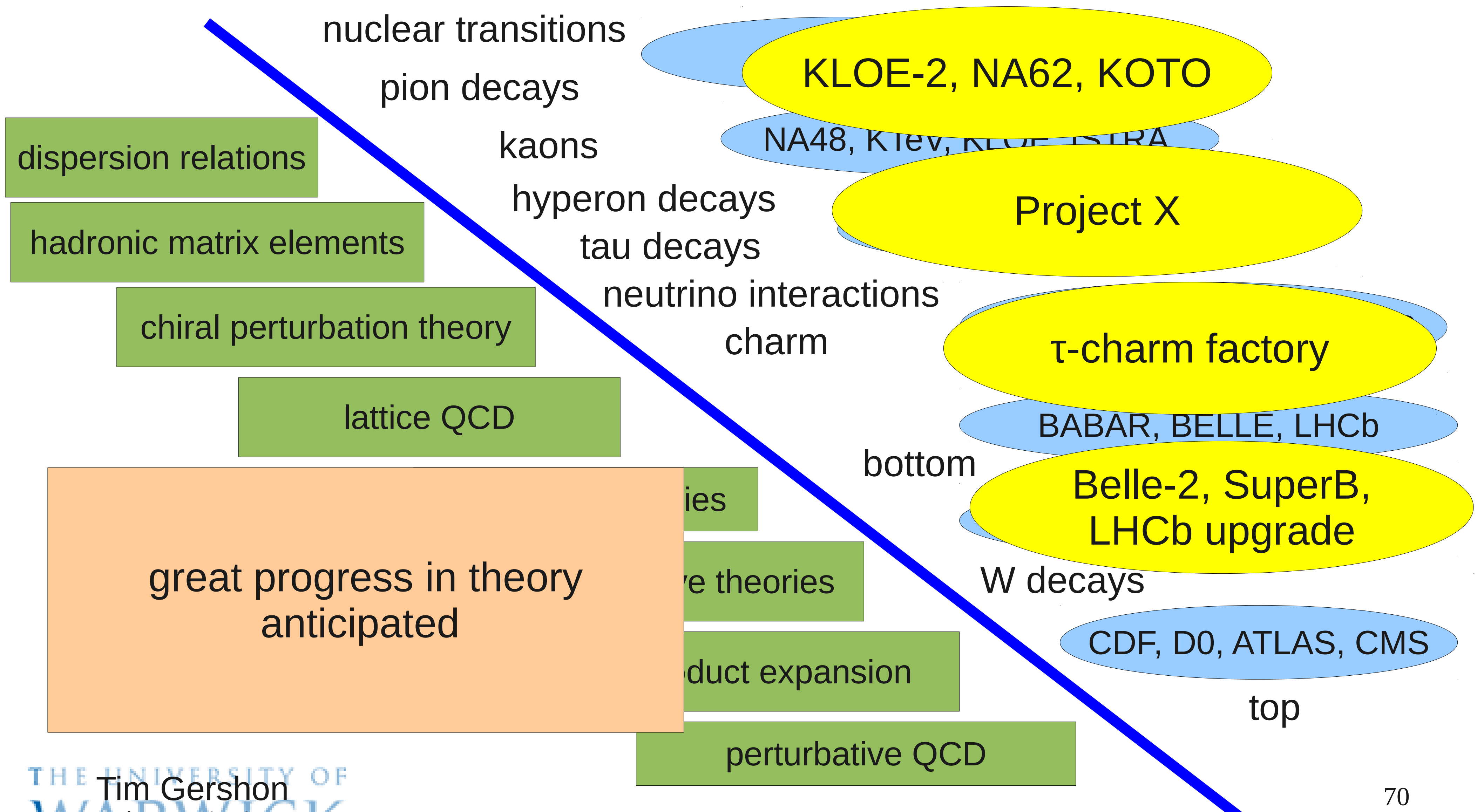
SM: box and penguin diagrams



Next generation experiments should measure these decays for the 1st time

- $K^+ \rightarrow \pi^+\nu\nu$ (NA62, CERN)
- $K^0 \rightarrow \pi^0\nu\nu$ (K0T0, J-PARC)
- Proposals also at FNAL

Future projects



Summary

- We still don't know:
  - why there are so many fermions in the SM
  - what causes the baryon asymmetry of the Universe
  - where exactly the new physics is …
  - … and what it's flavour structure is
- Prospects are good for progress in the next few years
- We need a continuing programme of flavour physics into the 2020s
  - complementary to the high-p_T programme of the LHC

References and background reading

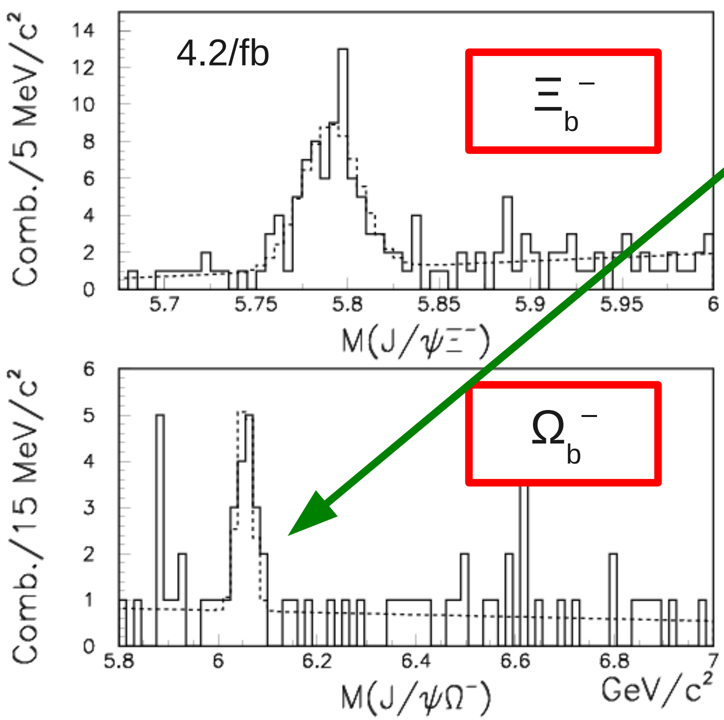
- Reviews by the Particle Data Group
  - http://pdg.lbl.gov/
- Heavy Flavour Averaging Group (HFAG)
  - http://www.slac.stanford.edu/xorg/hfag/
- CKMfitter & UTfit
  - http://ckmfitter.in2p3.fr/ & http://www.utfit.org/
- Review journals (e.g. Ann. Rev. Nucl. Part. Phys.)
  - http://nucl.annualreviews.org
- Proceedings of CKM workshops
  - Phys.Rept. 494 (2010) 197, eConf C100906
- Books
  - CP violation, I.I.Bigi and A.I.Sanda (CUP)
  - CP violation, G.C.Branco, L.Lavoura & J.P.Silva (OUP)

Back up

b hadron spectroscopy – Observation of the Ω_b

CDF PRD 80 (2009) 72003

D0 PRL 101 (2008) 232002

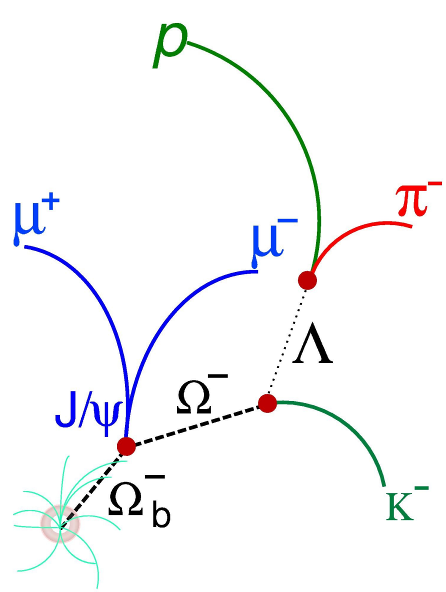


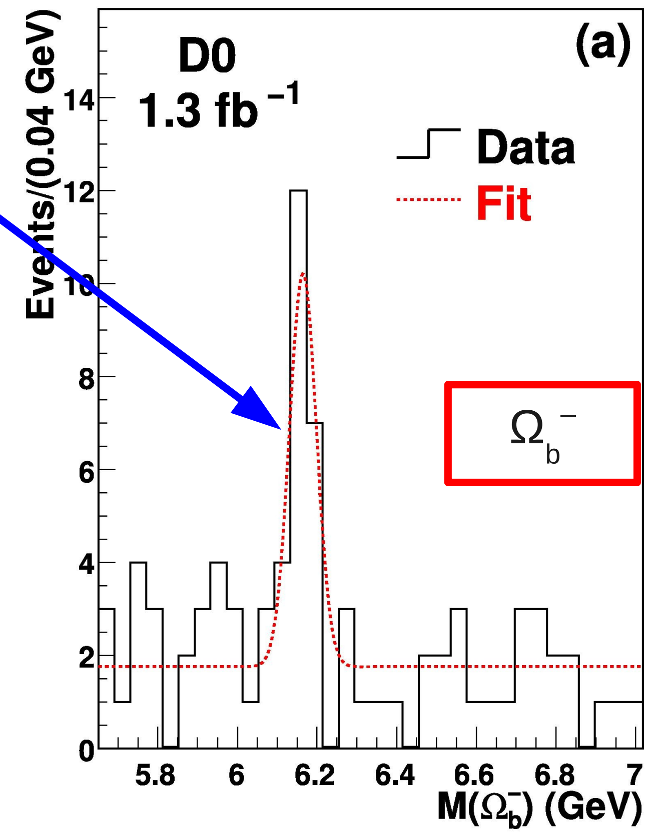
$m(\Omega_b)$ =

6054.4 ± 6.8 (stat.) ± 0.9 (syst.) MeV

6165 ± 10 (stat) ± 13(syst.) MeV

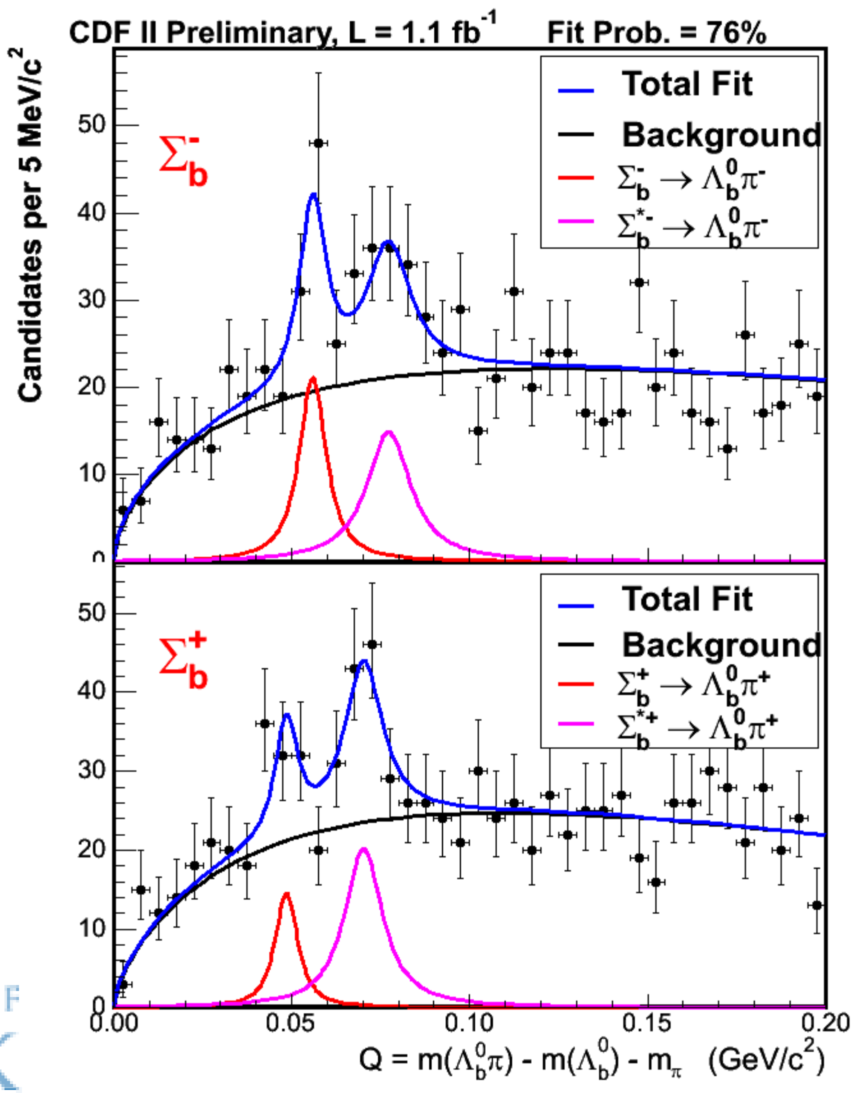
significant discrepancy to be understood





b hadron spectroscopy – Observation of the Σ_b

CDF PRL 99 (2007) 202001



Fully hadronic decay chain:

$\Sigma_b^{(*)\pm} \to \Lambda_b^0 \pi^\pm$

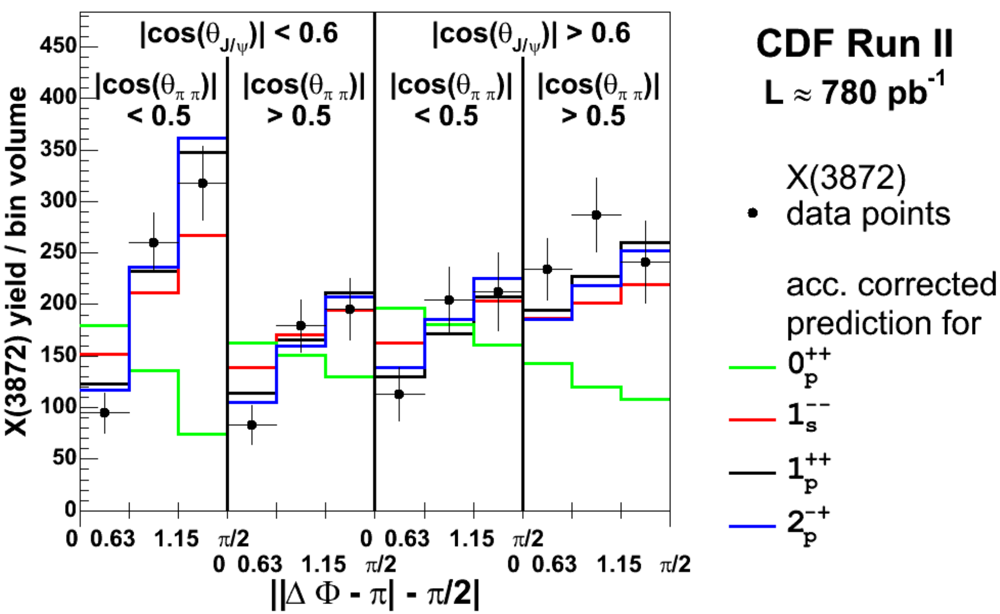
$\Lambda_b^0 \to \Lambda_c^+ \pi^-$

$\Lambda_c^+ \to p K^- \pi^+$

Impressive demonstration of B physics potential with hadronic triggers

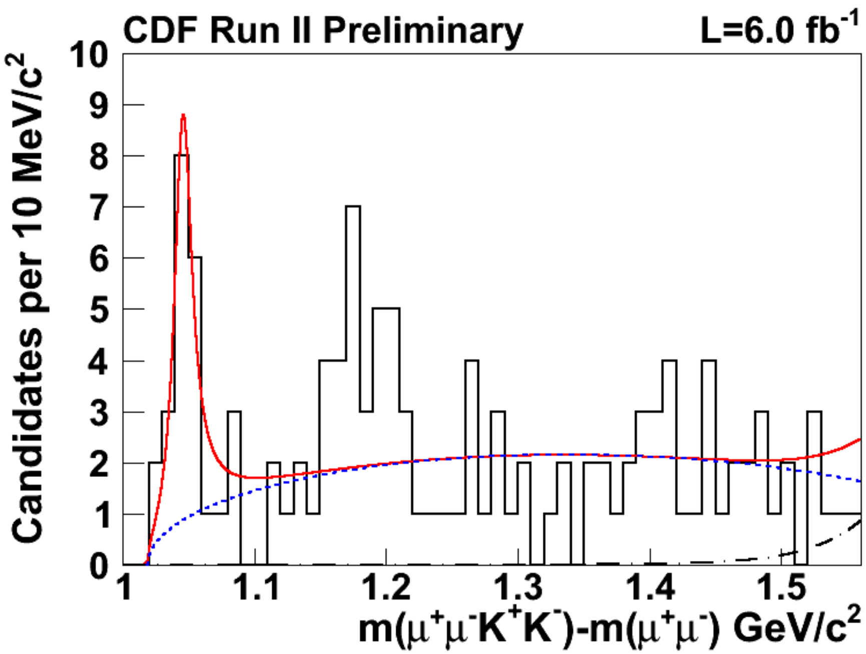
More b hadron spectroscopy

Study of the quantum numbers of X(3872)



PRL 98 (2007) 132002

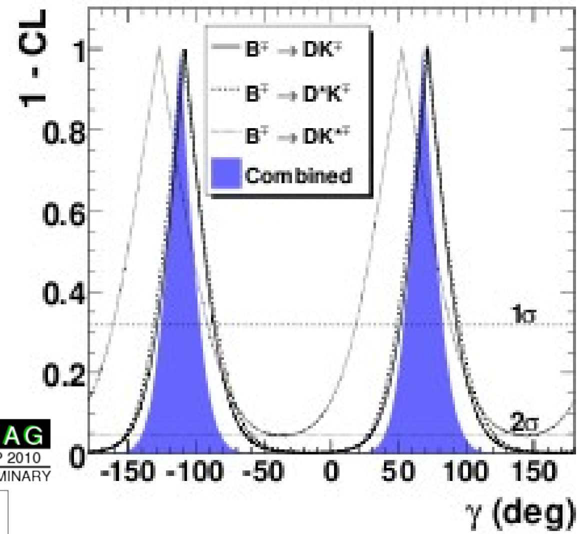
Discovery of the Y(4140) in $B \to J/\psi\varphi K$



CDF Note 10244 & PRL 102 (2009) 242002

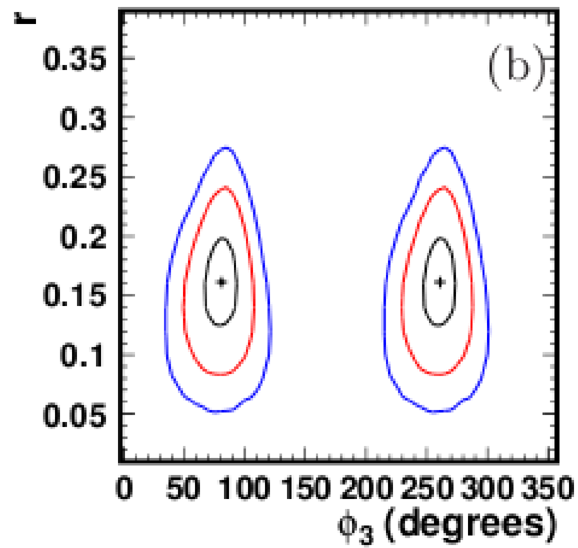
Latest results on B→DK : GGSZ

BABAR arXiv:1005.1096



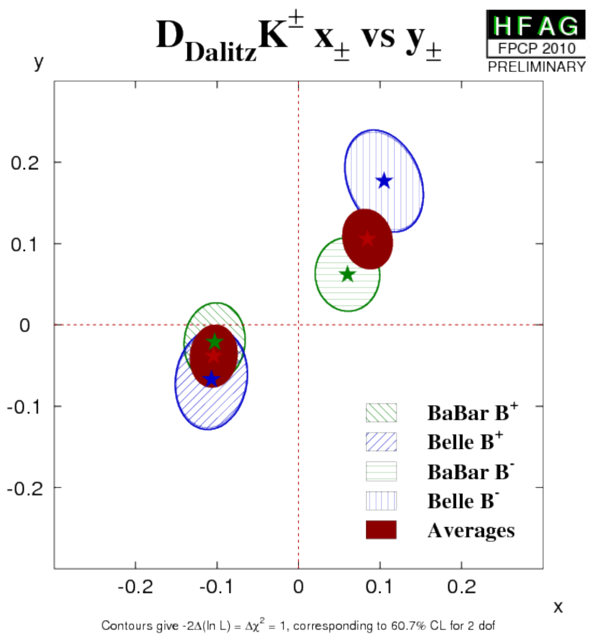
$\gamma = (68\,^{+15}_{-14} \pm 4 \pm 3)°$

BELLE PRD 81 (2010) 112002



$\Phi_3 = (78\,^{+11}_{-12} \pm 4 \pm 9)°$

Evidence for direct CP violation (γ≠0)



Uncertainty due to assumed $D \to K_S\pi^+\pi^-$ decay model

Model independent B→DK Dalitz measurements

- Use CP-tagged CLEOc data to measure average D^0–$\bar{D}^0$ phase difference

A.Powell at Beauty 2009

CLEO-c Results: c_i & s_i

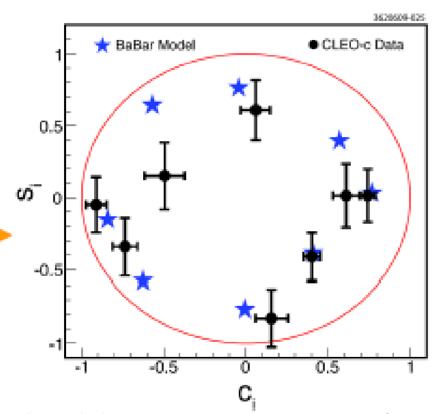
NEW

[Phys Rev. D 80, 032002 (2009)]

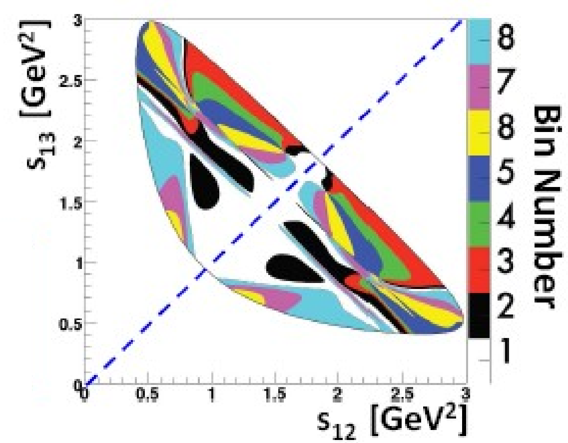
- Result ± stat ± sys ± ($K_L\pi\pi$ $K_S\pi\pi$ syst)

i	c_i	s_i
1	$0.743 \pm 0.037 \pm 0.022 \pm 0.013$	$0.014 \pm 0.160 \pm 0.077 \pm 0.045$
2	$0.611 \pm 0.071 \pm 0.037 \pm 0.009$	$0.014 \pm 0.215 \pm 0.055 \pm 0.017$
3	$0.059 \pm 0.063 \pm 0.031 \pm 0.057$	$0.609 \pm 0.190 \pm 0.076 \pm 0.037$
4	$-0.495 \pm 0.101 \pm 0.052 \pm 0.045$	$0.151 \pm 0.217 \pm 0.069 \pm 0.048$
5	$-0.911 \pm 0.049 \pm 0.032 \pm 0.021$	$-0.050 \pm 0.183 \pm 0.045 \pm 0.036$
6	$-0.736 \pm 0.066 \pm 0.030 \pm 0.018$	$-0.340 \pm 0.187 \pm 0.052 \pm 0.047$
7	$0.157 \pm 0.074 \pm 0.042 \pm 0.051$	$-0.827 \pm 0.185 \pm 0.060 \pm 0.036$
8	$0.403 \pm 0.046 \pm 0.021 \pm 0.002$	$-0.409 \pm 0.158 \pm 0.050 \pm 0.002$

- Statistical uncertainties dominant
- c_i better determined than s_i
- Results also available for c_i' & s_i'
- Broad agreement with model predictions



[Model = BABAR PRL 95 121802 (2005)]



[Model = BABAR PRL 95 121802 (2005)]

- γ **Uncertainty:** $\sigma_{\text{CLEO-input}}(\gamma) = 1.7°$
  (recall model error = 7°)