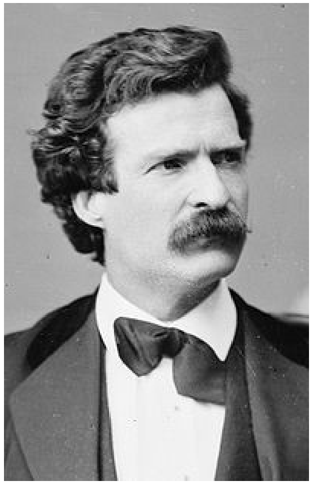
What We've Learned from Experiments

Tim Gershon
University of Warwick & CERN

CKM2012, University of Cincinnati

29th September 2012

The most permanent lessons in morals are those which come, not of booky teaching, but of experience.



Mark Twain, A Tramp Abroad

What We've Learned from Experiments

Heavy Flavour

since CKM2010

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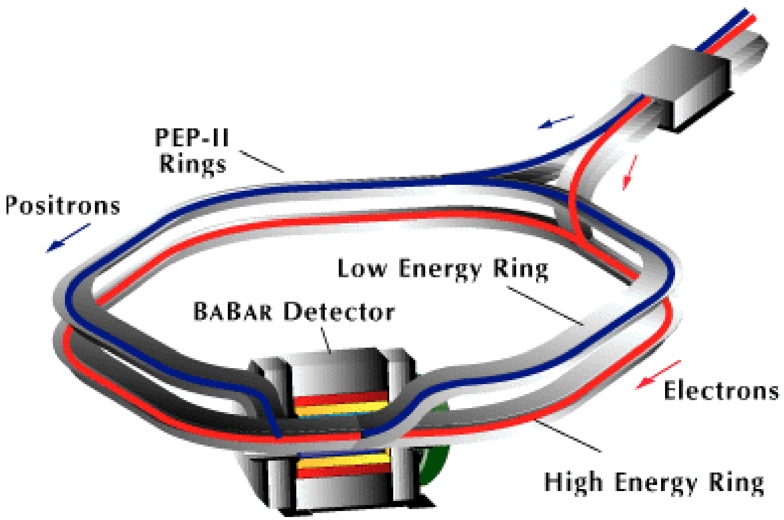
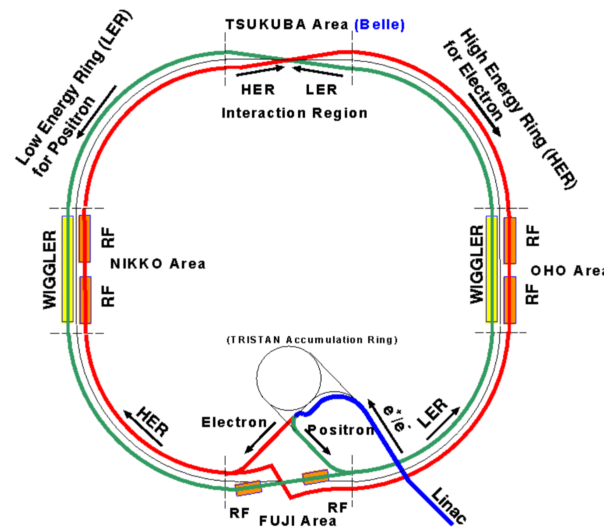
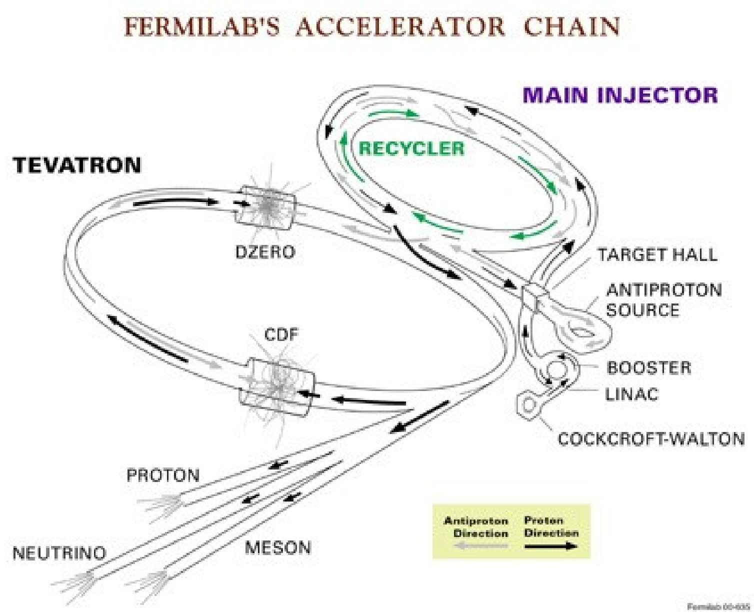
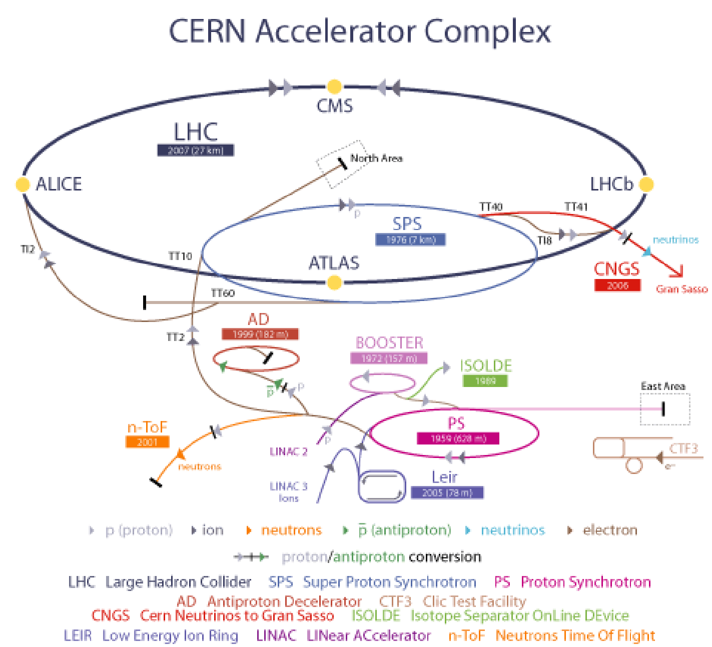
First key to success: excellent accelerator performance

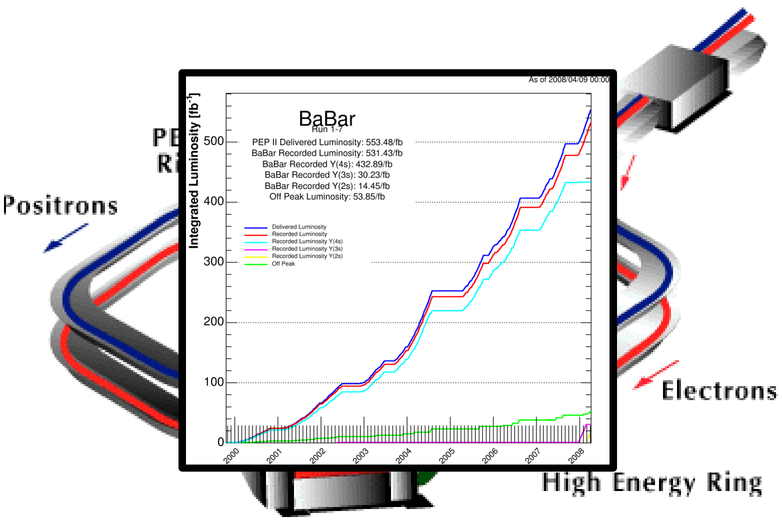




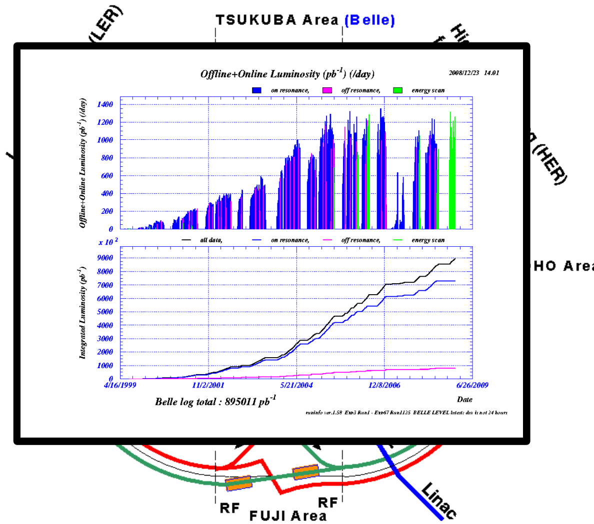




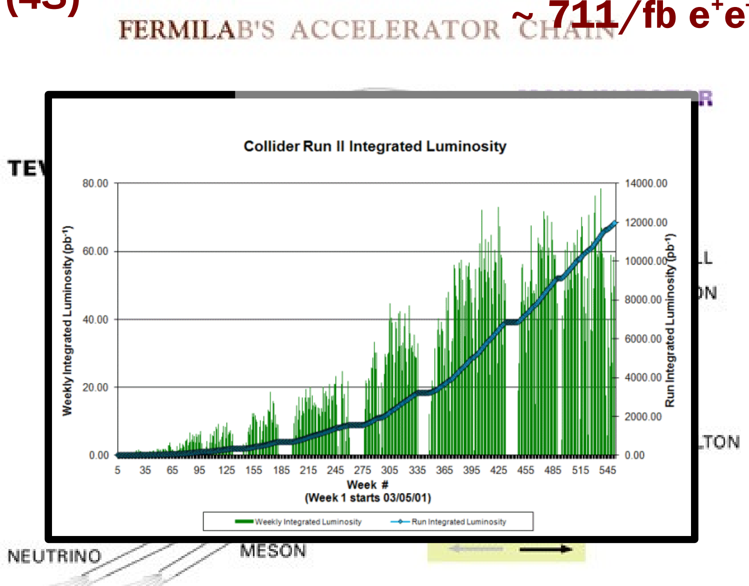
First key to success: excellent accelerator performance



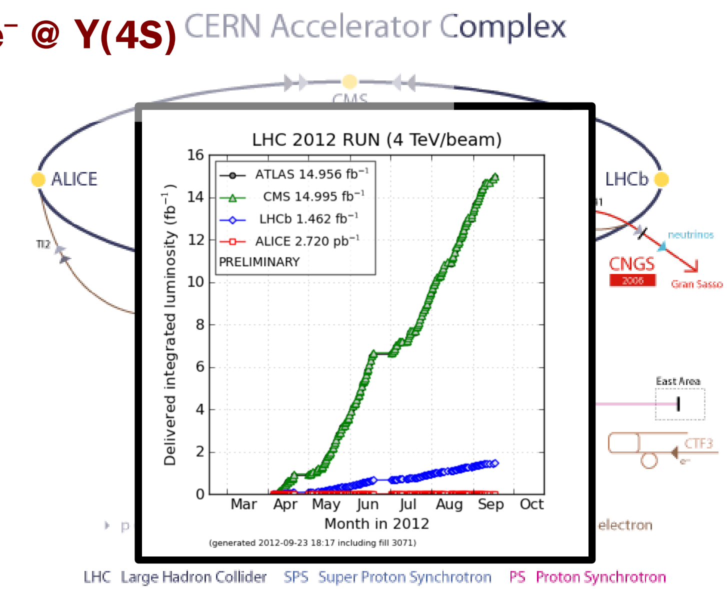
~ 433/fb e^+e^- @ Y(4S)



~ 711/fb e^+e^- @ Y(4S)



~ 12/fb 1.96 TeV $p\bar{p}$ collisions per experiment

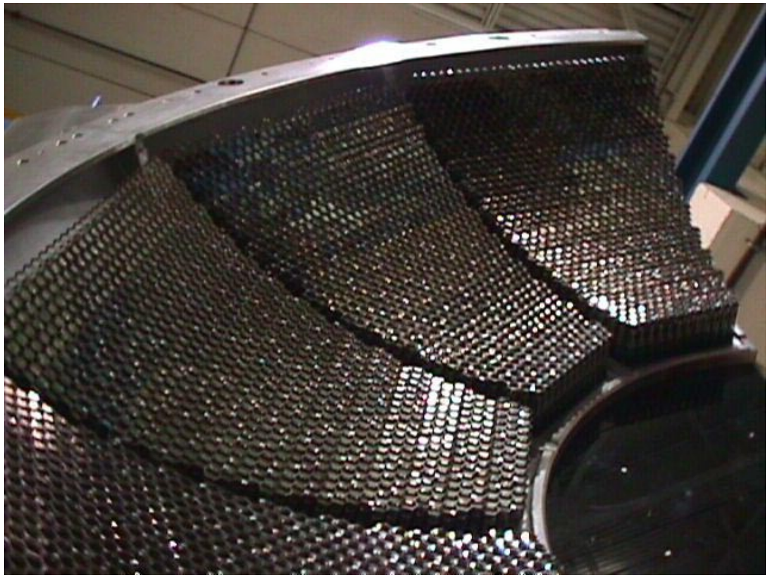


ATLAS & CMS ~ 6/fb 7 TeV + 15/fb 8 TeV
LHCb ~ 1.2/fb 7 TeV + 1.5/fb 8 TeV pp collisions

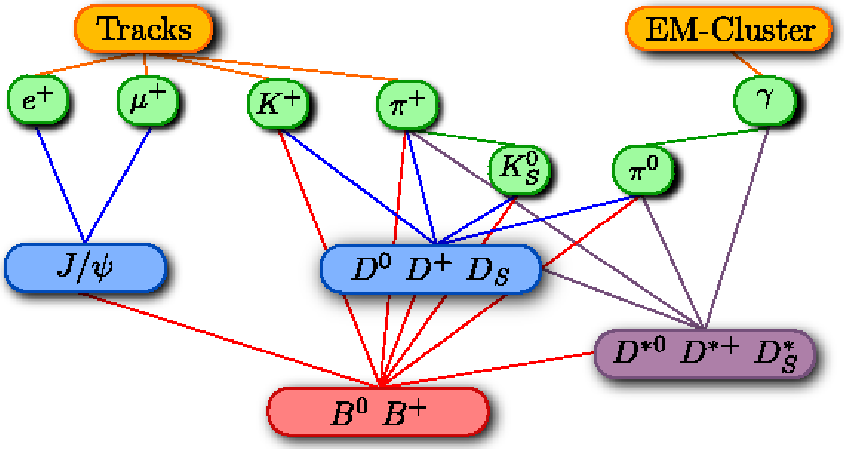
Novel detectors & analysis techniques

(just some examples from many)

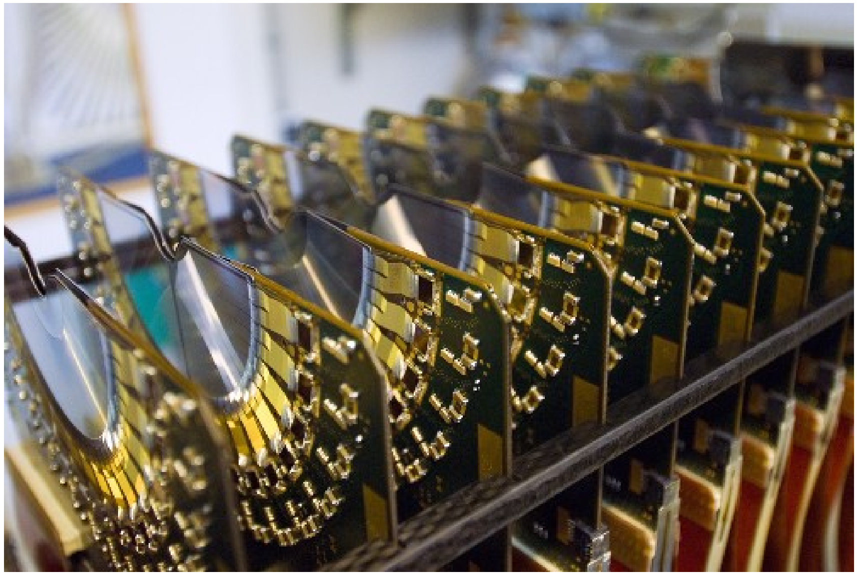
BaBar DIRC detector for K/π ID



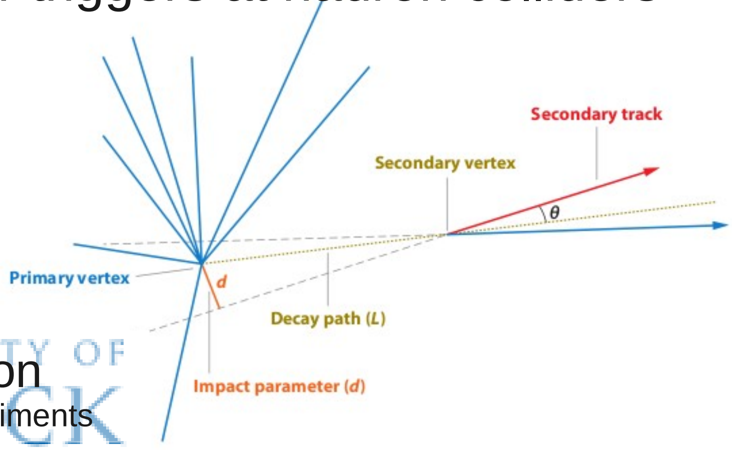
Neutral network based event reconstruction in Belle



LHCb VErtex LOcator



Heavy flavour triggers at hadron colliders



What do we know about CP violation?

Observed (5σ) CP violation effects

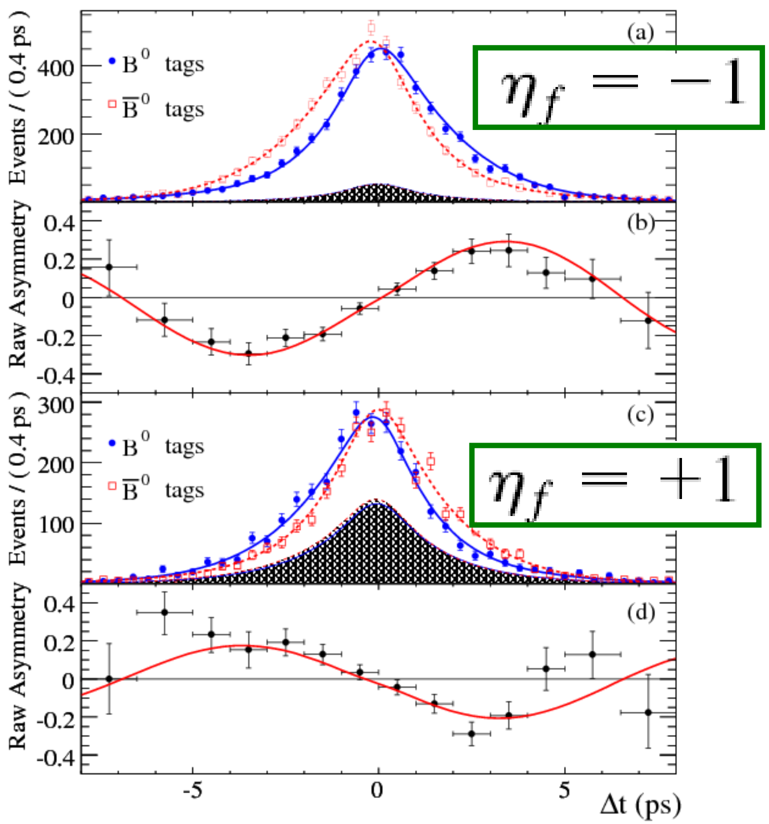
As listed in PDG 2012

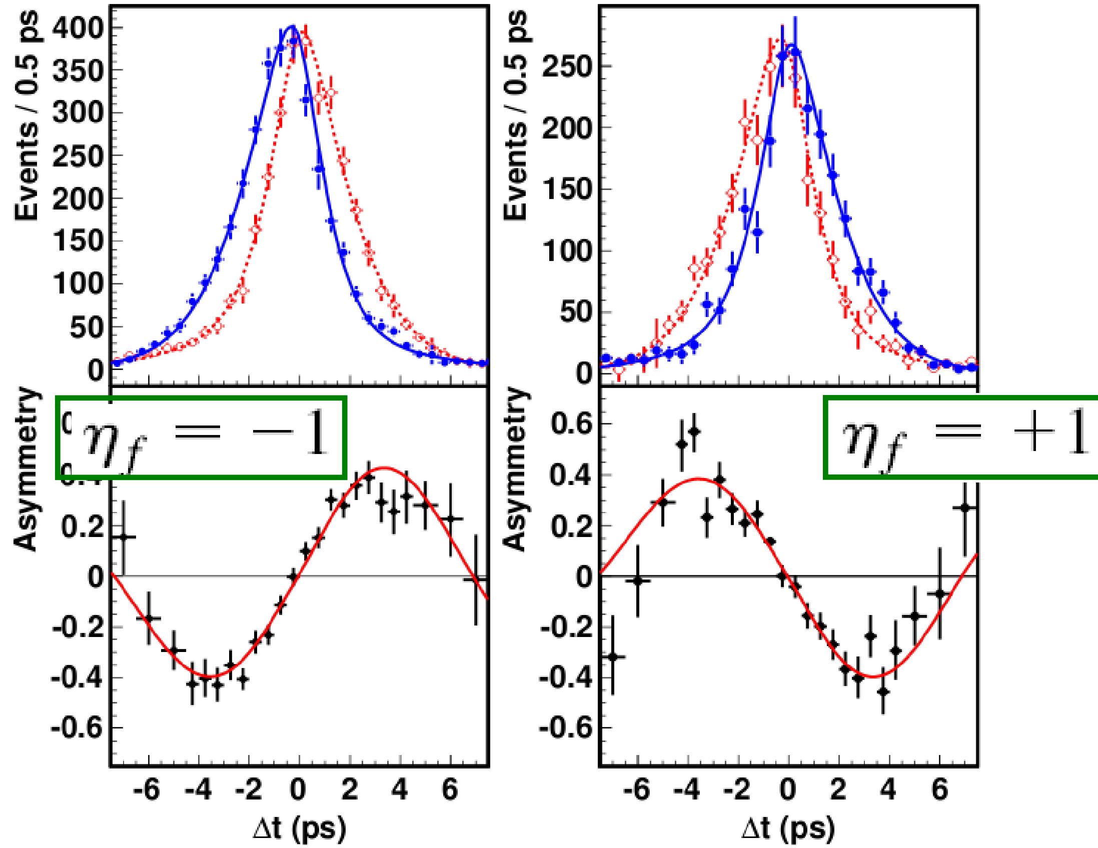
- Kaon sector
  - $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$
  - $\mathrm{Re}(\varepsilon'/\varepsilon) = (1.65 \pm 0.26) \times 10^{-3}$
- B sector
  - $b \to c\bar{c}s$: $S_{\psi K0} = +0.679 \pm 0.020$
  - $b \to q\bar{q}s$: $S_{\eta' K0} = +0.59 \pm 0.07$, $S_{\phi K0} = +0.74^{+0.11}_{-0.13}$, $S_{f0K0} = +0.69^{+0.10}_{-0.12}$, $S_{K+K-K0} = +0.68^{+0.09}_{-0.10}$
  - $b \to u\bar{u}d$: $S_{\pi+\pi-} = -0.65 \pm 0.07$, $C_{\pi+\pi-} = -0.36 \pm 0.06$
  - $b \to c\bar{c}d$: $S_{\psi\pi0} = -0.93 \pm 0.15$, $S_{D+D-} = -0.98 \pm 0.17$, $S_{D*+D*-} = -0.77 \pm 0.10$
  - $b \to u\bar{u}s$: $A_{K\mp\pi\pm} = -0.087 \pm 0.008$
  - $b \to c\bar{u}s$ / $u\bar{c}s$: $A_{D(CP+)K\pm} = +0.19 \pm 0.03$

Only one in charged B mesons!
Nothing yet in baryons, charm, leptons, ...

Large CP violation effects exist
$\sin(2\beta)$ from $B^0 \rightarrow J/\psi K^0_S$

BABAR **BELLE**





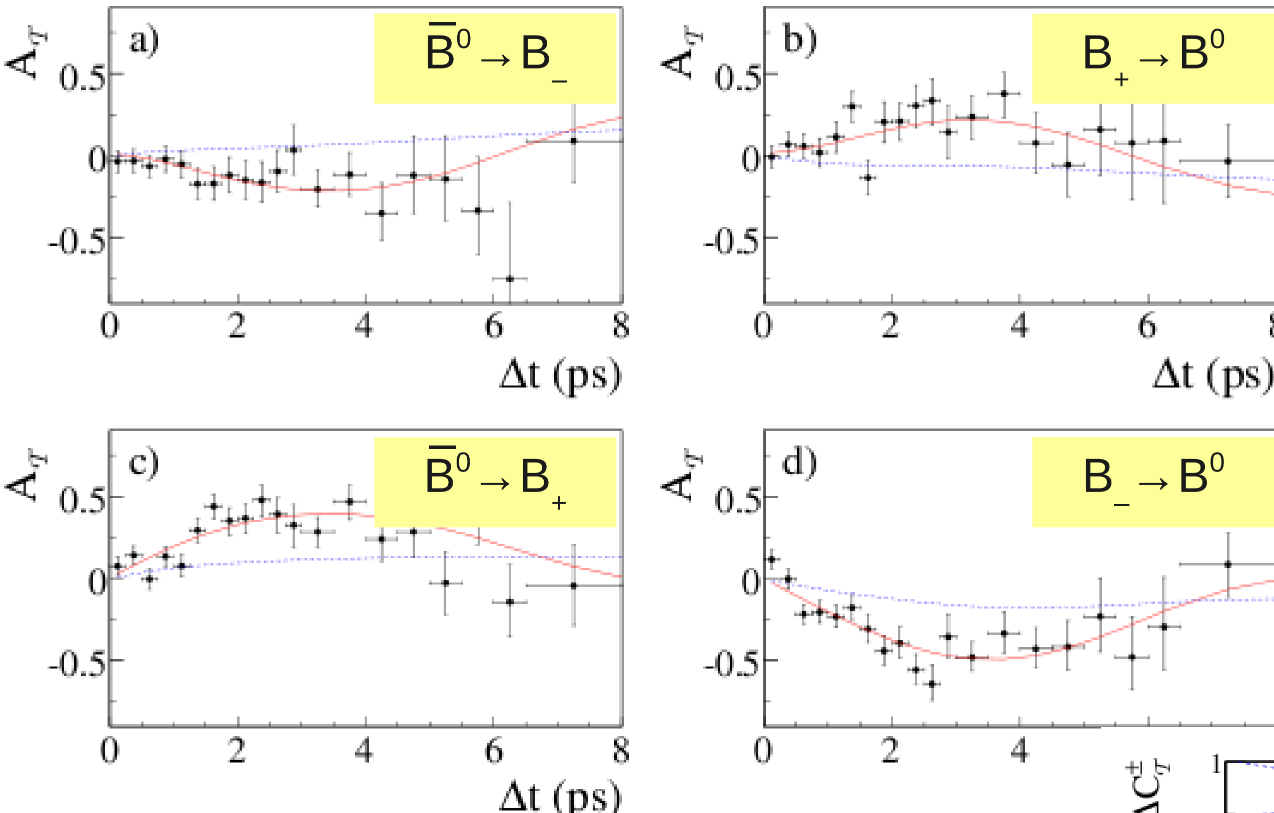
PRD 79 (2009) 072009

PRL 108 (2012) 171802

World average: $\sin(2\beta) = 0.679 \pm 0.020$

New results from LHCb to be presented in WGIV

… and T is also violated, as expected



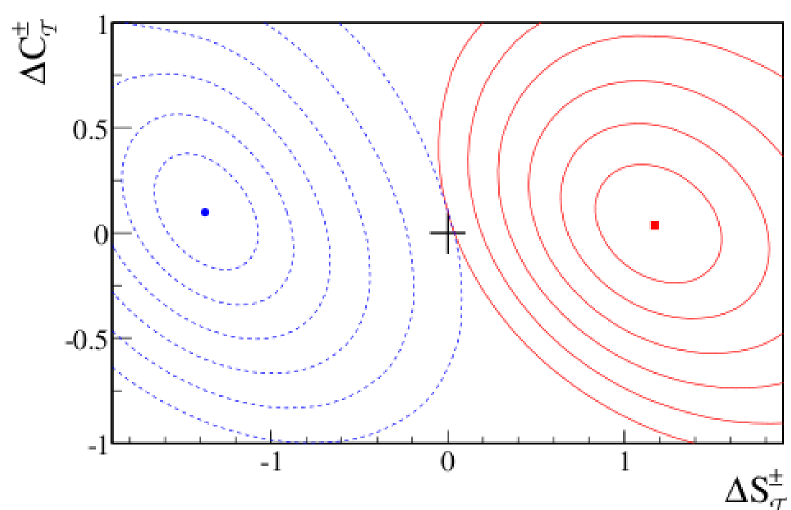
BaBar arXiv:1207.5832

Generalisation of usual sin(2β) analysis allowing for separate CP, T and CPT violating terms

No significant sign of CPT violation in any test

e.g. $A_T(\bar{B}^0 \rightarrow B_-)$ between (l^- tag, $J/\psi K_S$, $\Delta t > 0$) and (l^+ tag, $J/\psi K_L$, $\Delta t < 0$)

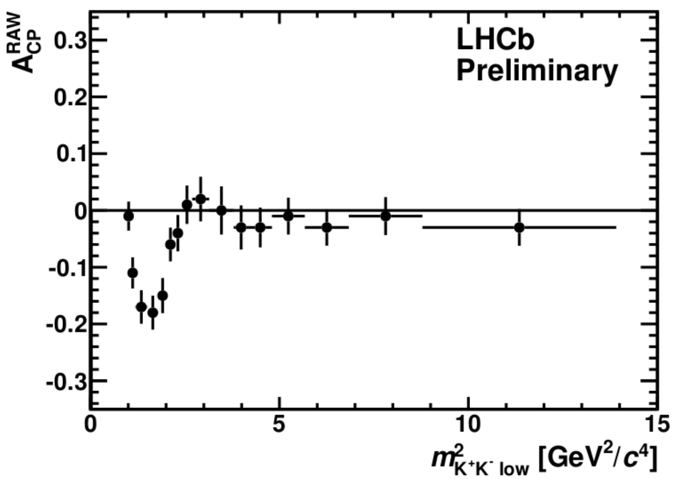
$\sim \frac{1}{2}(\Delta S_T^+ \sin(\Delta m_d \Delta t) + \Delta C_T^+ \cos(\Delta m_d \Delta t))$

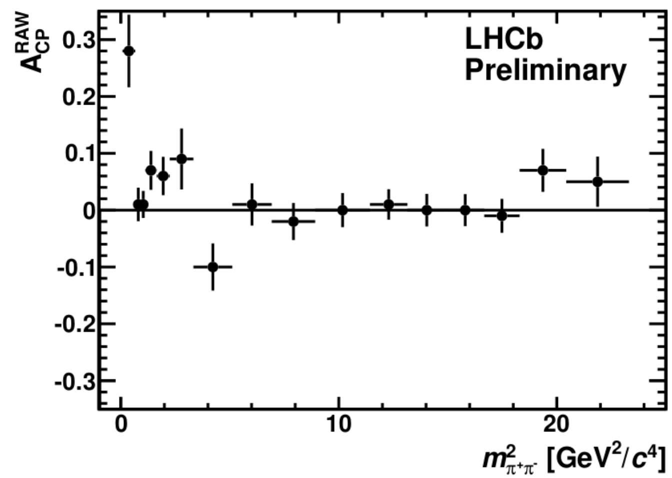


Large *direct* CP violation effects also exist

LHCb-CONF-2012-018

$B \to KKK$





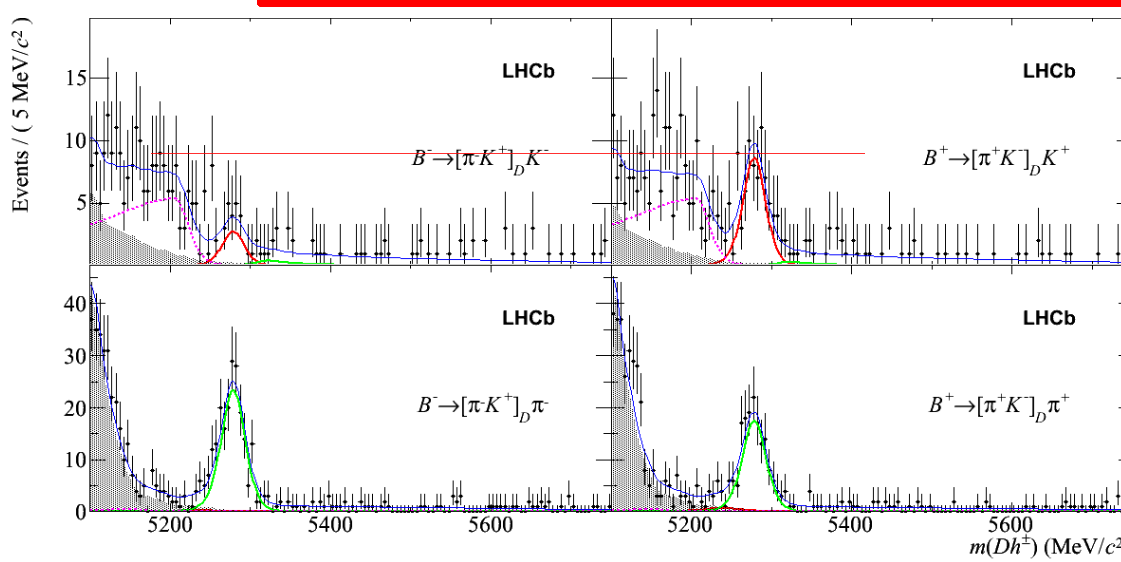
$B \to K\pi\pi$

Large CP violation effects with strong variation across the Dalitz plot

Detailed studies will be necessary to understand origin of these effects

New results from LHCb to be presented in WGV

PLB 712 (2012) 203



$B \to D_{ADS}K$

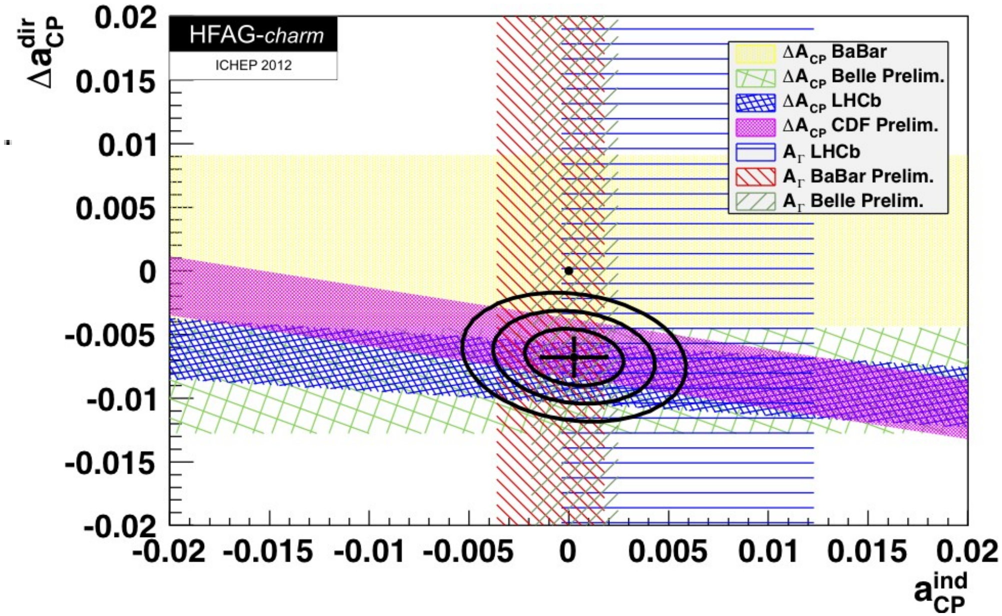
Is there CP violation in the charm system?

(and if so, where does it come from?)

LHCb PRL 108 (2012) 111602
CDF PRL 109 (2012) 111801
Belle ICHEP preliminary

To reduce systematics and (perhaps) enhance CP violation effect, experiments measure

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



ΔA_{CP} related mainly to direct CP violation

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

$$\Delta a_{CP}^{\rm dir} = (-0.68 \pm 0.15\ )\%$$

Naïvely expected to be much smaller in the Standard Model

Must prepare ourselves for ‰ level measurements

… are we too naïve?
Or can we discover NP by better understanding of QCD?

Is there CP violation in B mixing?

Semileptonic asymmetries in both B_d and B_s systems negligibly small in the SM

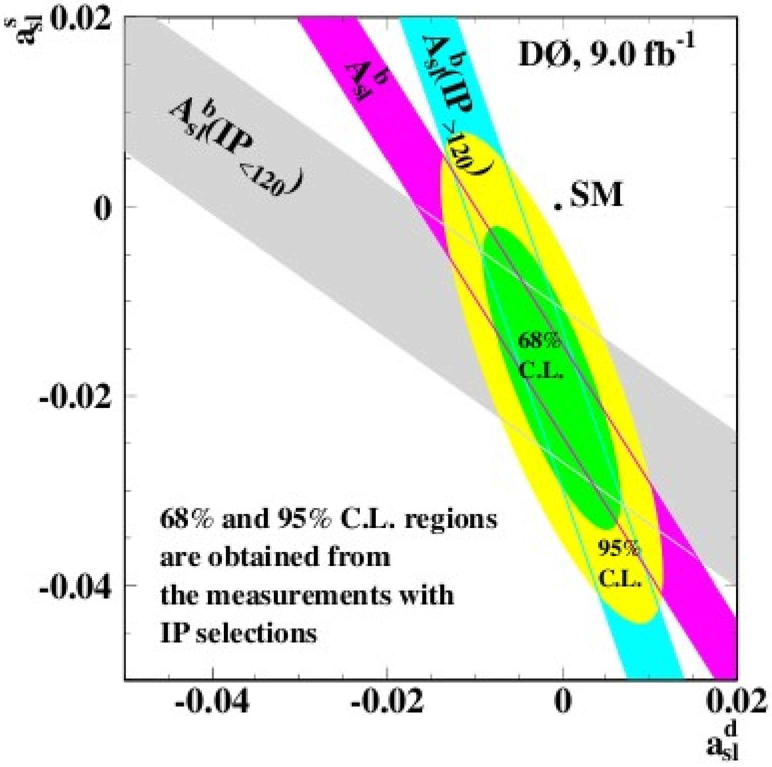
D0 PRD 84 (2011) 052007
arXiv:1207.1769, arXiv:1208.5813
LHCb-CONF-2012-022

Results of inclusive dimuon asymmetry analysis 3.9σ from SM

Systematics reduced by magnet polarity inversions, and from use of control samples, such as single muon sample

$$A_{sl}^{b} = (0.594 \pm 0.022)\, a_{sl}^{d} + (0.406 \pm 0.022)\, a_{sl}^{s}$$

Constraint in a_{sl}^{d}–a_{sl}^{s} plane obtained from oscillated B_d or B_s enriched samples (cutting on impact parameter)



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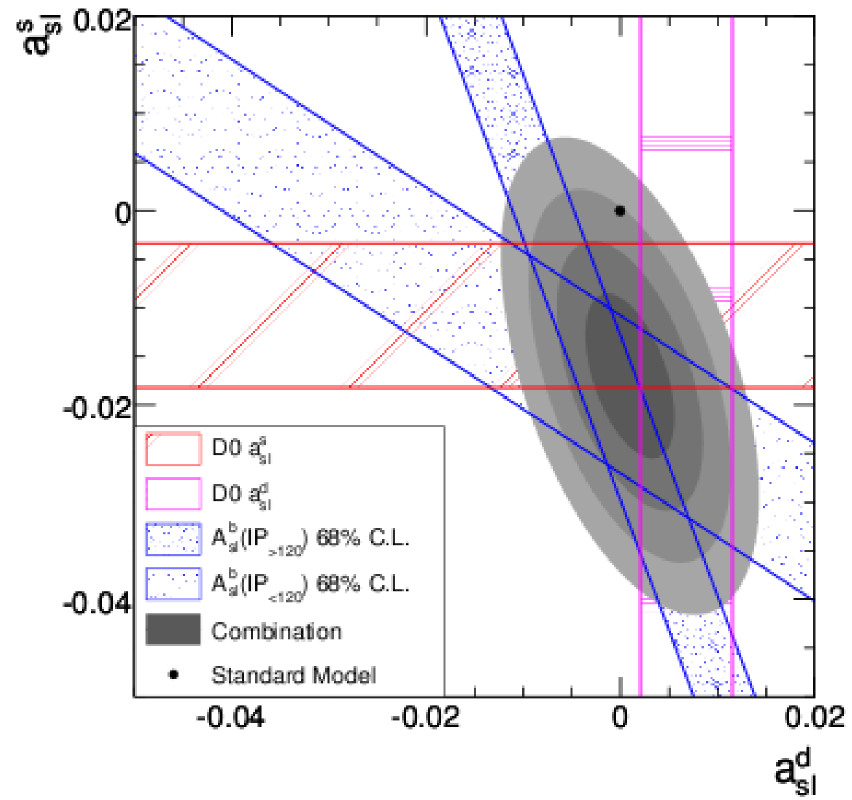
Including results on a_{sl}^d and a_{sl}^s individually (from $D^{(*)+}\mu^-\nu X$ and $D_s^+\mu^-\nu X$ samples) puts combination at 2.9σ from SM



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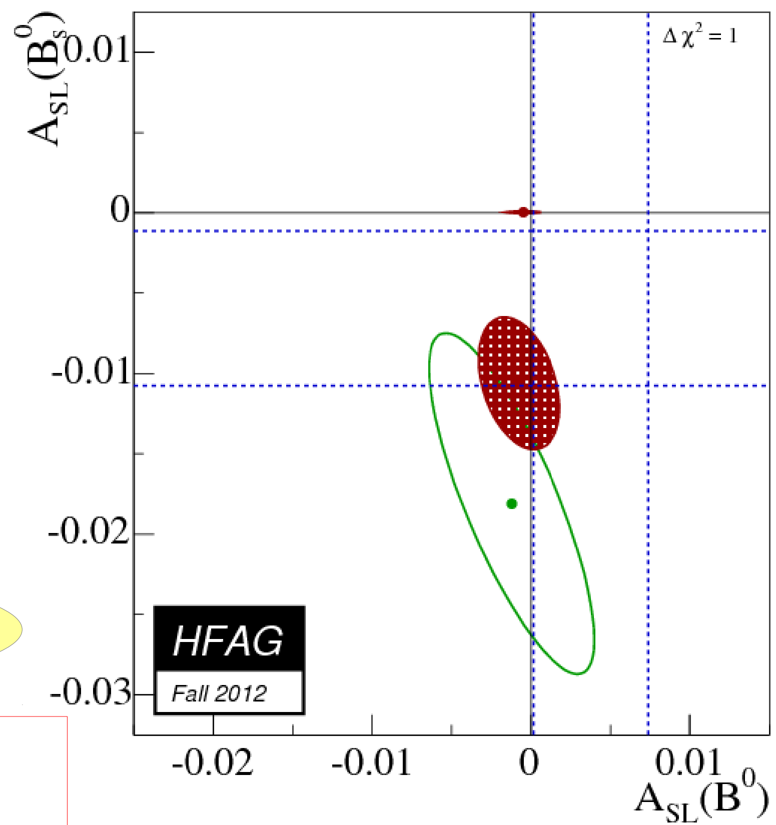
Including B factory a_{sl}^d and LHCb a_{sl}^s results give average 2.4σ from the SM

Situation unclear –
improved measurements needed

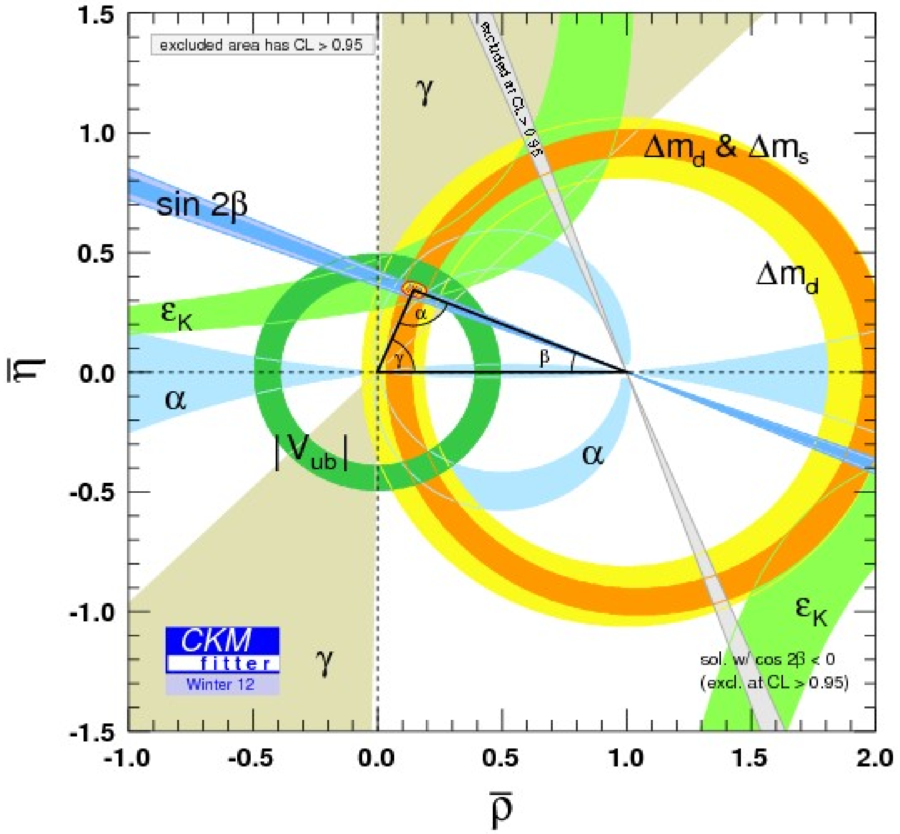


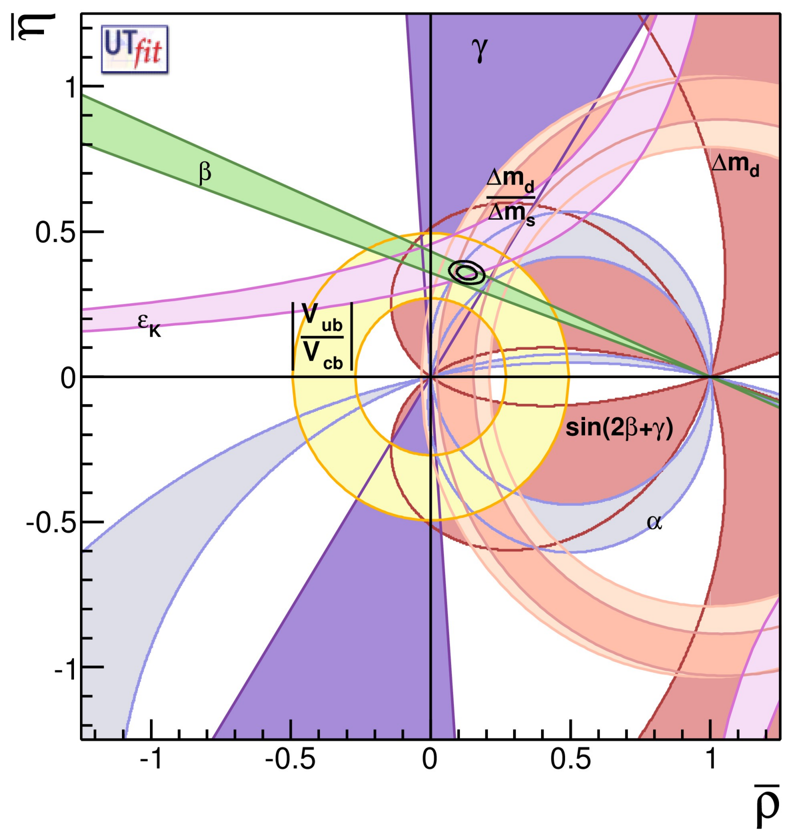
Warning: scale changed from previous slide

Must prepare ourselves for ‰ level measurements

New results from BaBar to be presented in WGIV

The Unitarity Triangle

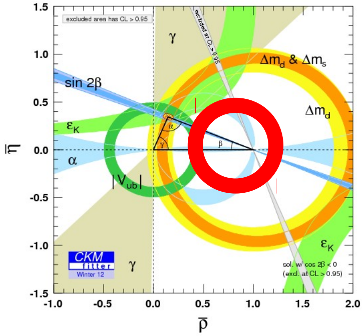




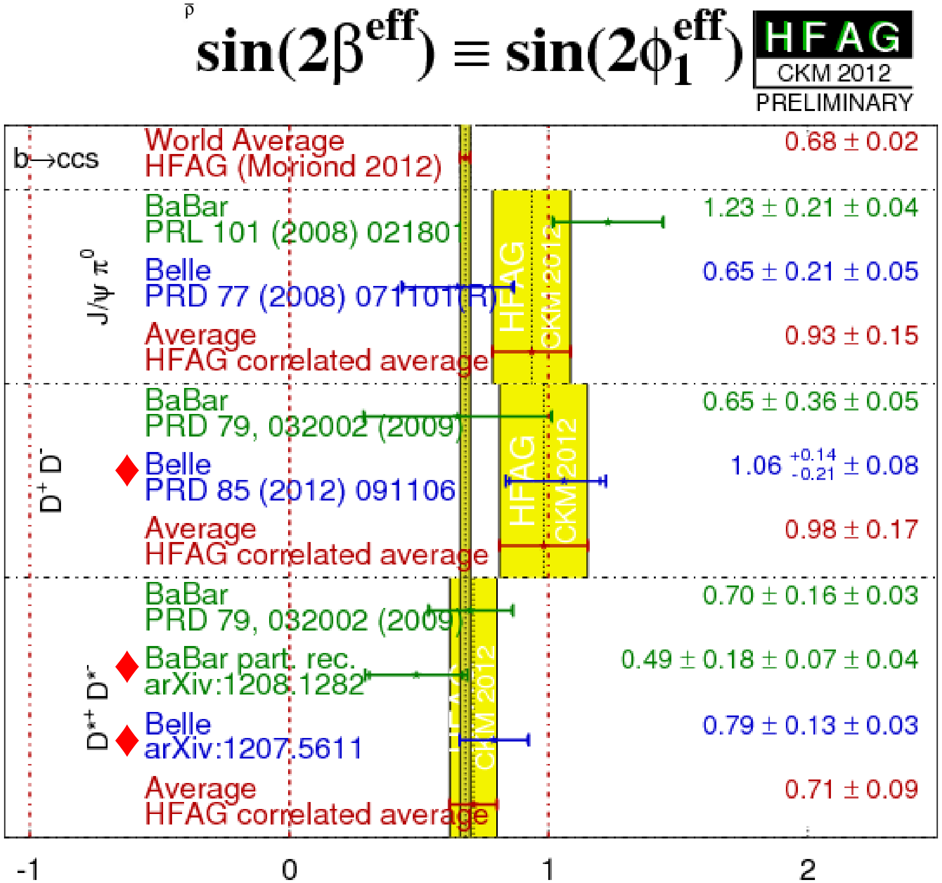
Disclaimer (I): other fitter groups are available

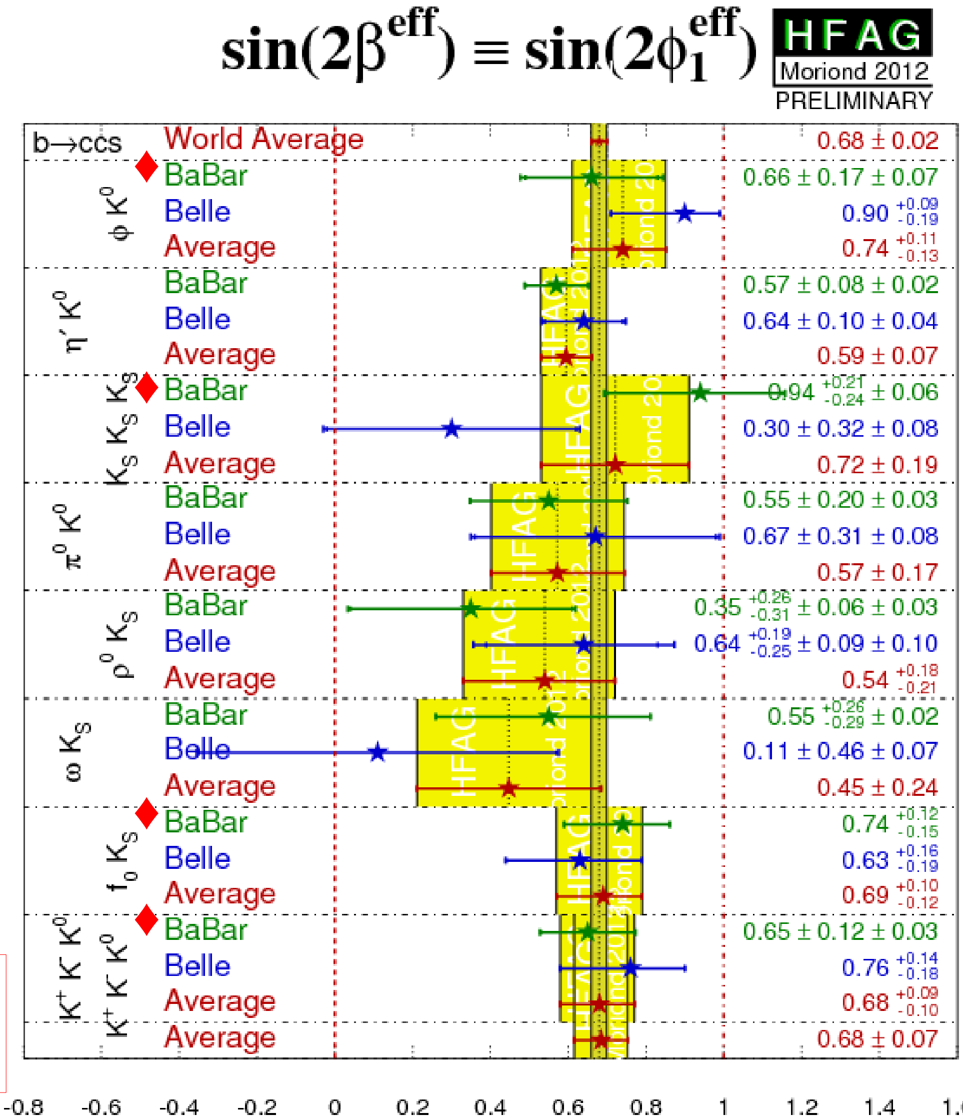
Disclaimer (ii): other Unitarity Triangles are available

(but this one really does deserve to be called “The” Unitarity Triangle)



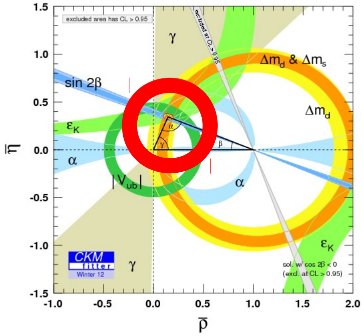
$\beta \equiv \phi_1$





Many ways to measure β
… and all agree within current uncertainties

♦ ≡ new since CKM2010

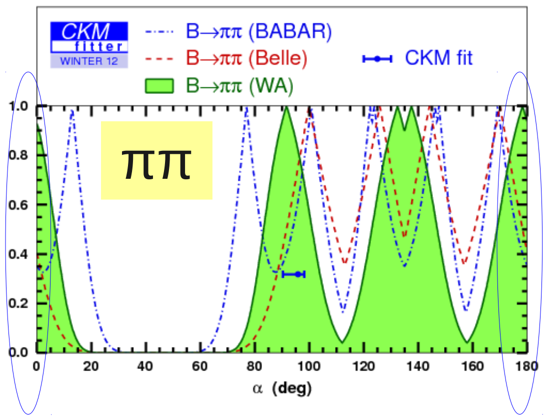


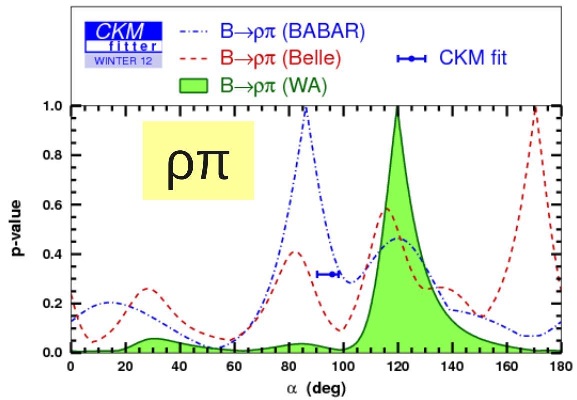
$\alpha \equiv \varphi_2$

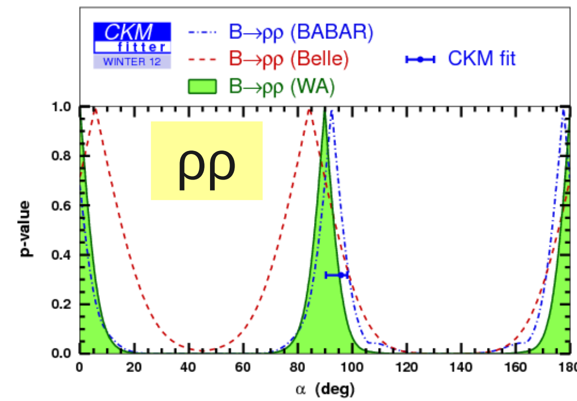
$\equiv \pi - \beta - \gamma \equiv \pi - \varphi_1 - \varphi_3$

Constraints from ππ, ρπ, ρρ (also $a_1\pi$). Combination dominated by ρρ – strong influence of single measurement of $B^+ \to \rho^+\rho^0$

Solutions at α = 0,π ruled out by observation of direct CP violation in $B^0 \to \pi^+\pi^-$

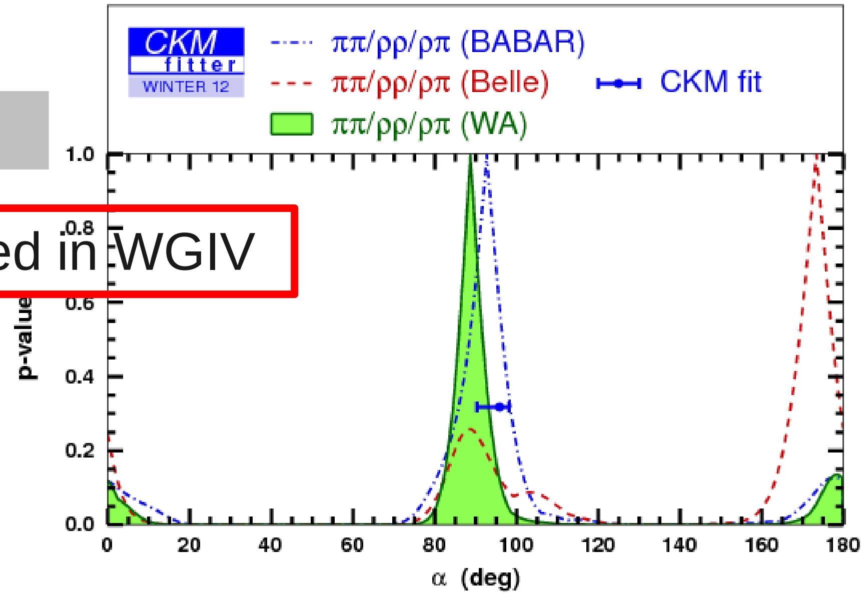


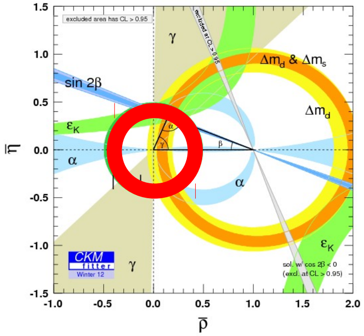




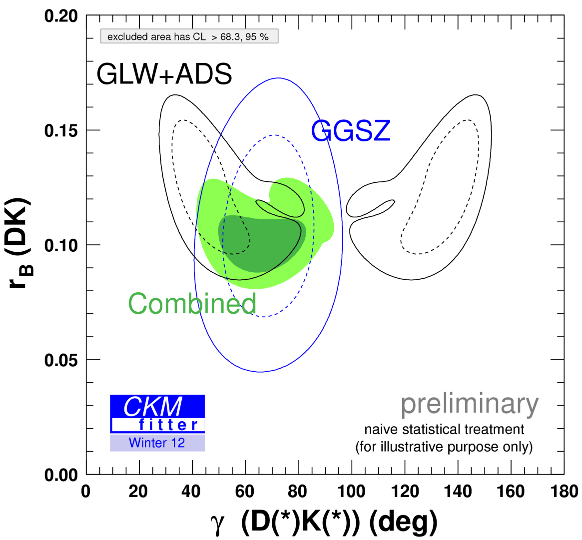
How well do we really know α?

New results from BaBar to be presented in WGIV



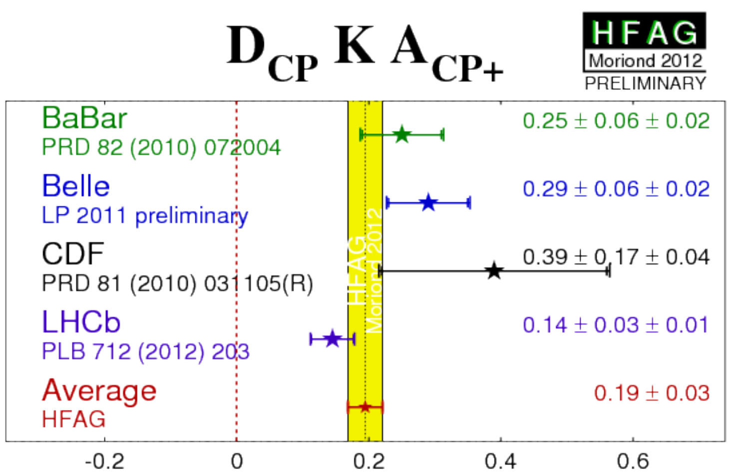


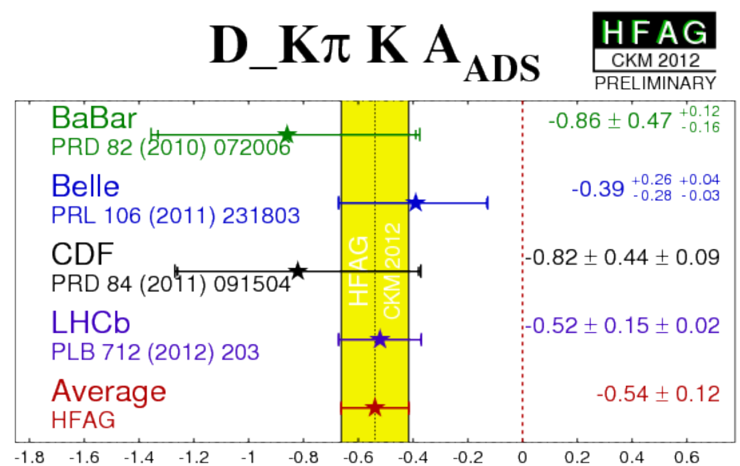
$\gamma \equiv \varphi_3$



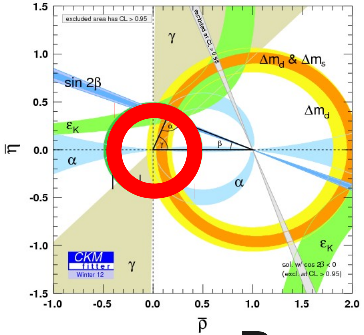
Precision on γ from tree-level decays ($B \to DK$) has stubbornly refused to go below 10° despite great efforts

Precise measurements of several key observables now exist … are we on the verge of more precise knowledge of γ?





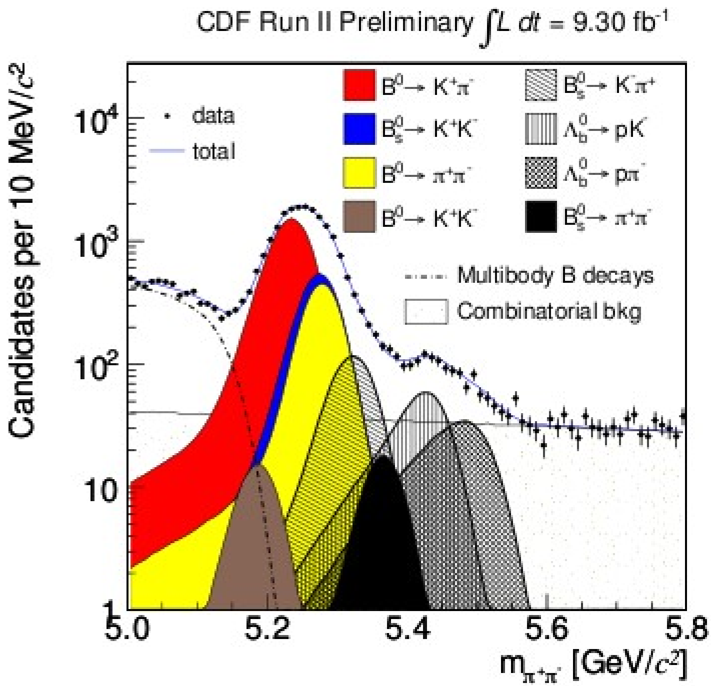
New results from BaBar & LHCb to be presented in WGV



$\gamma \equiv \varphi_3$

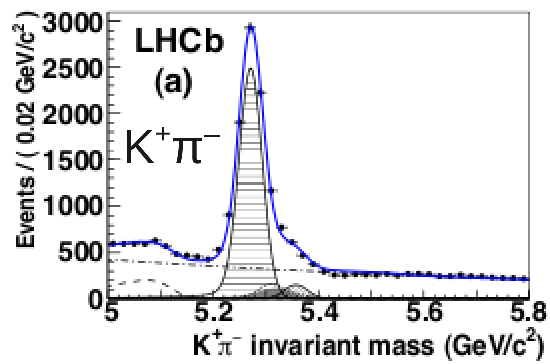
Perennial question for CKM workshops: how to extract clean (but still NP sensitive) weak phase information from hadronic B decays?

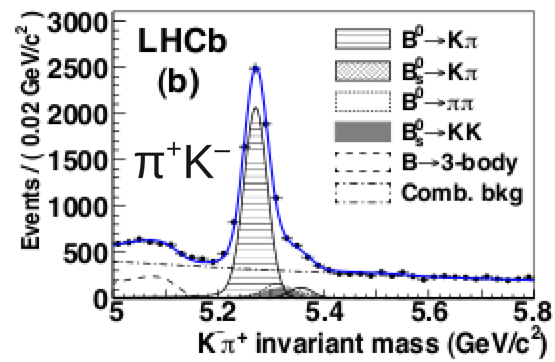
$A_{CP}(K^-\pi^+) - A_{CP}(K^-\pi^0) \neq 0$ puzzle persists

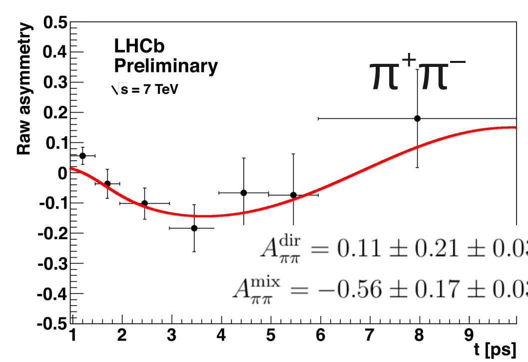


CDF note 10726

LHCb PRL 108 (2012) 201601

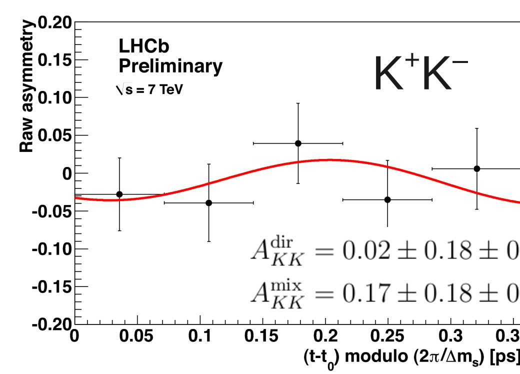






$A^{\rm dir}_{\pi\pi} = 0.11 \pm 0.21 \pm 0.03,$

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



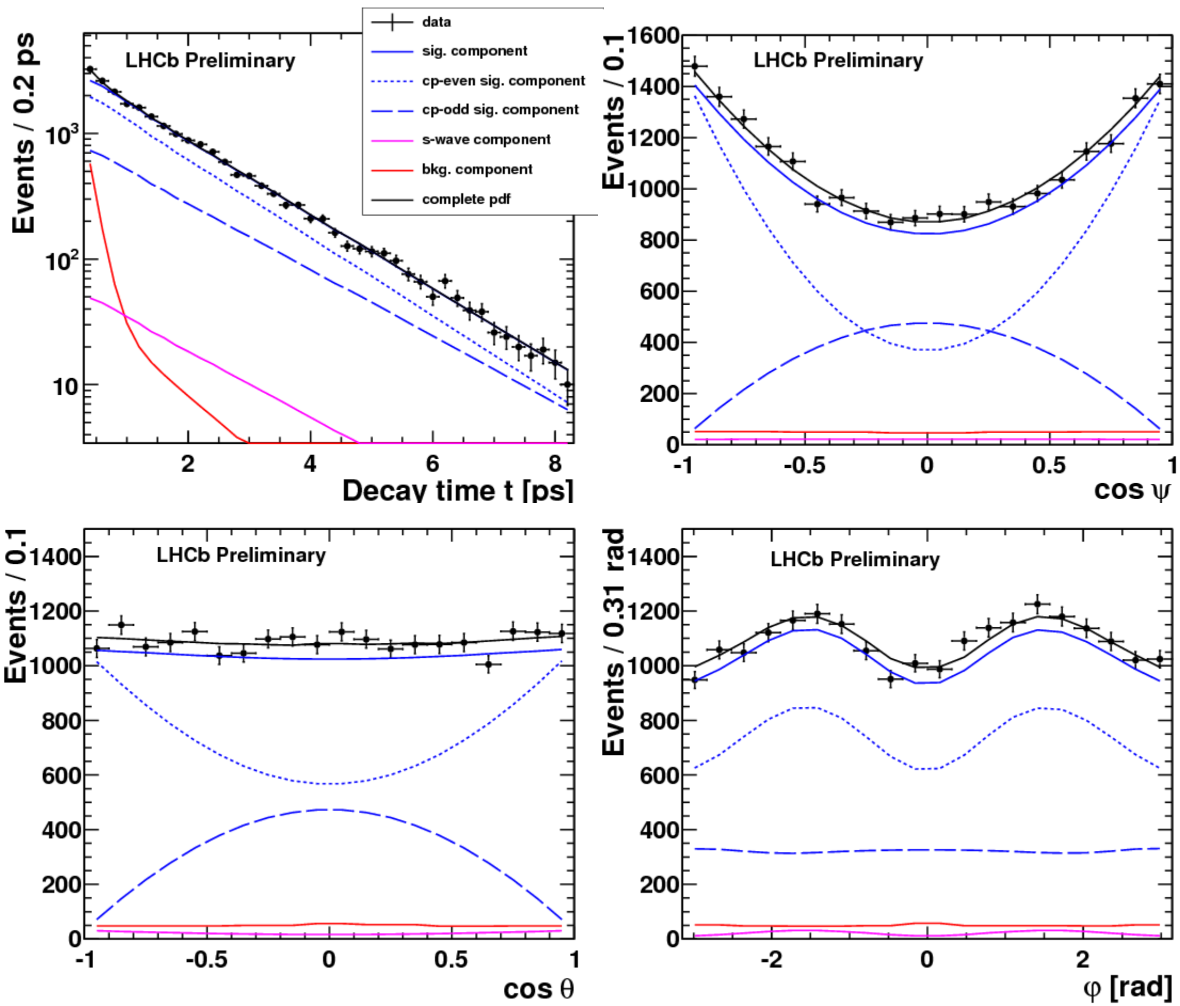
$A^{\rm dir}_{KK} = 0.02 \pm 0.18 \pm 0.04,$

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

LHCb-CONF-2012-007

Suggestion in arXiv:1205.4948 to combine information in $B \to \pi\pi$ with $B_s \to K^+K^-$ – blurs boundary between α and γ

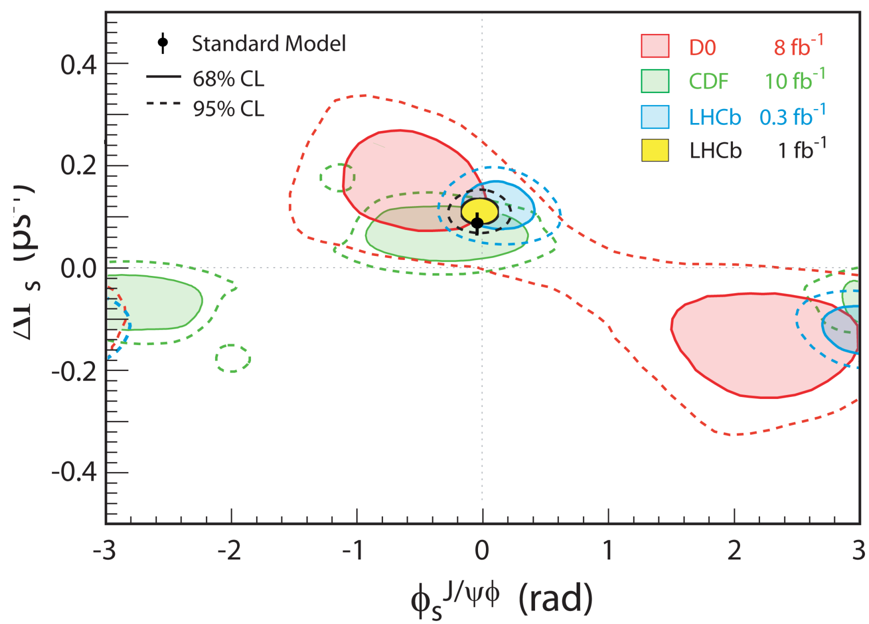
β_s from $B_s \to J/\psi\phi$ & $J/\psi\pi\pi$



CDF arXiv:1208.2967
D0 PRD 85 (2012) 032006
LHCb-CONF-2012-002
LHCb PLB 713 (2012) 378
Also ATLAS arXiv:1208.0572

Significant improvements in precision ($\Delta\Gamma_s$>0 now established)

Earlier hints of large anomalous effects not confirmed

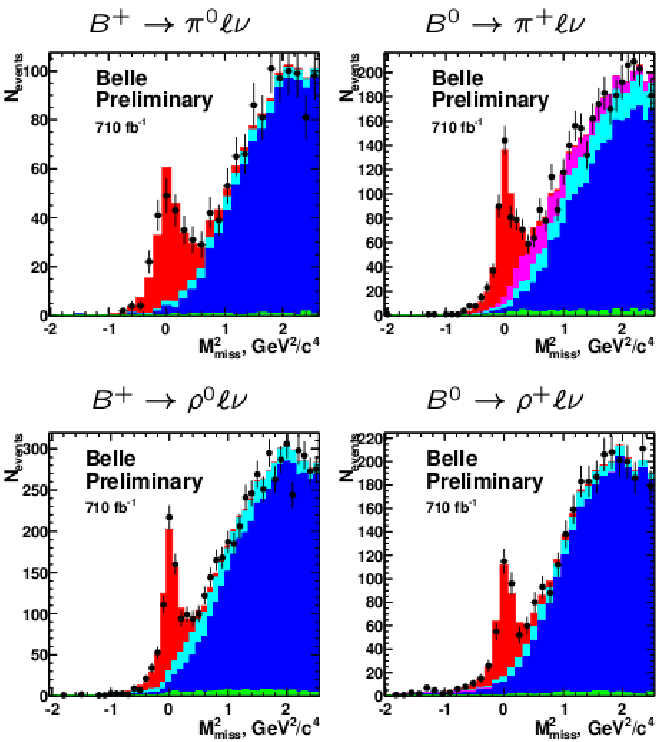


n.b. $\sigma(\beta_s) \sim 4\sigma(\beta)$

The sides of the UT

Continued progress on measurements sensitive to $|V_{ub}|$, $|V_{cb}|$, $|V_{td}|$ & $|V_{ts}|$

Belle LLWI preliminary



BaBar arXiv:1208.1253

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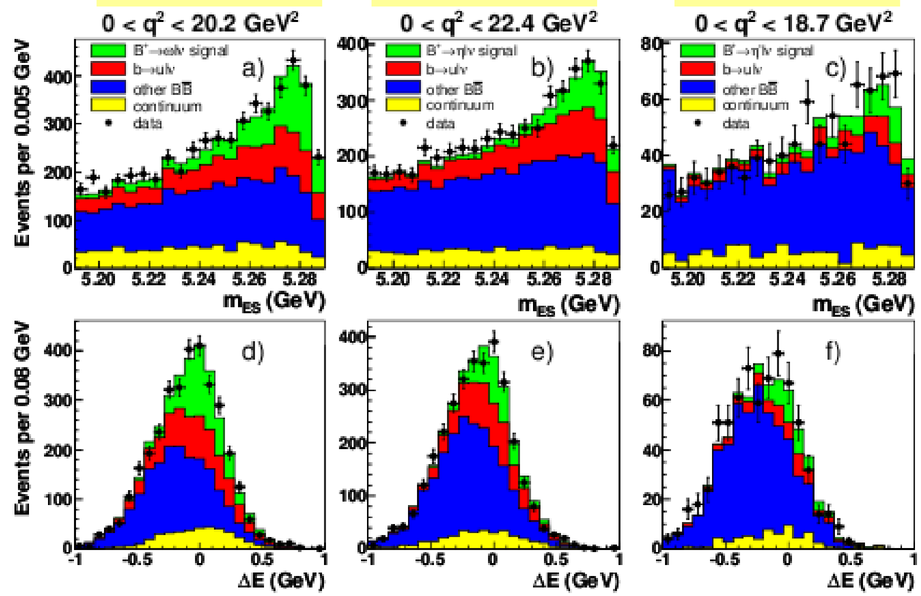
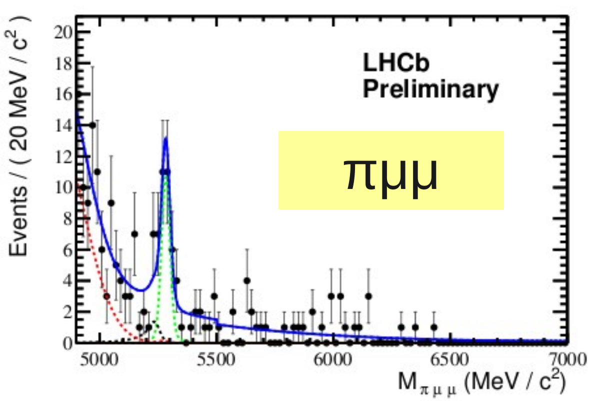


LHCb-CONF-2012-006

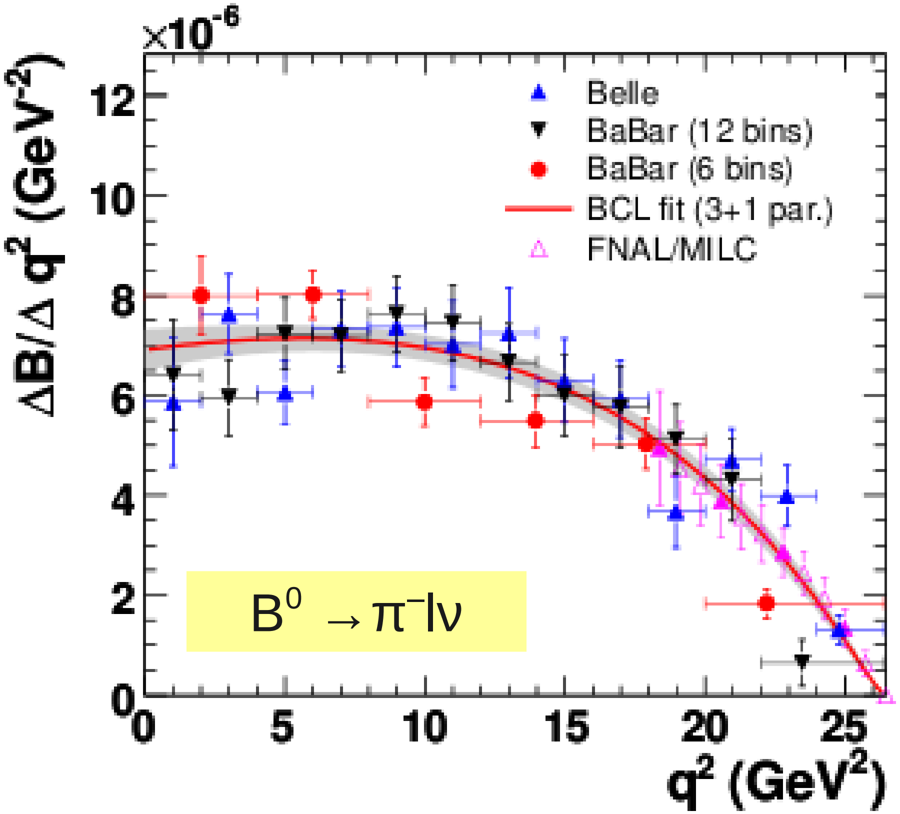


Updated LHCb results to be shown in WG3

Can we measure $|V_{td}|$ & $|V_{ts}|$ from semileptonic decays?

$|V_{ub}|$ from {in,ex}clusive semileptonic decays

PBFLB based on
BaBar PRD 83 (2011) 052011 &
PRD 83 (2011) 032007
Belle PRD 83 (2011) 071101(R)



Some tension between exclusive and inclusive results. PBFLB concludes:

$$|V_{ub}|_{excl} = [3.23\ (1 \pm 0.05_{exp} \pm 0.08_{th})] \times 10^{-3}$$
$$|V_{ub}|_{incl} = [4.42\ (1 \pm 0.045_{exp} \pm 0.034_{th})] \times 10^{-3}.$$

This average has a probability of $P(\chi^2) = 0.003$. Thus we scale the error by $\sqrt{\chi^2} = 3.0$ and arrive at

$$|V_{ub}| = [3.95\ (1 \pm 0.096_{exp} \pm 0.099_{th})] \times 10^{-3}$$

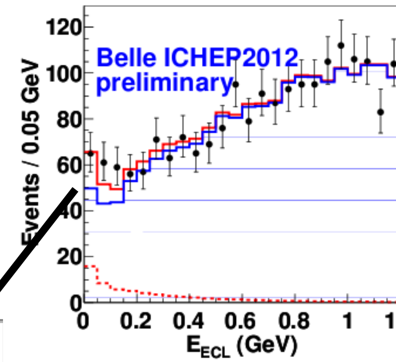
Similar tension also for $|V_{cb}|$

Better understanding needed to reduce uncertainty

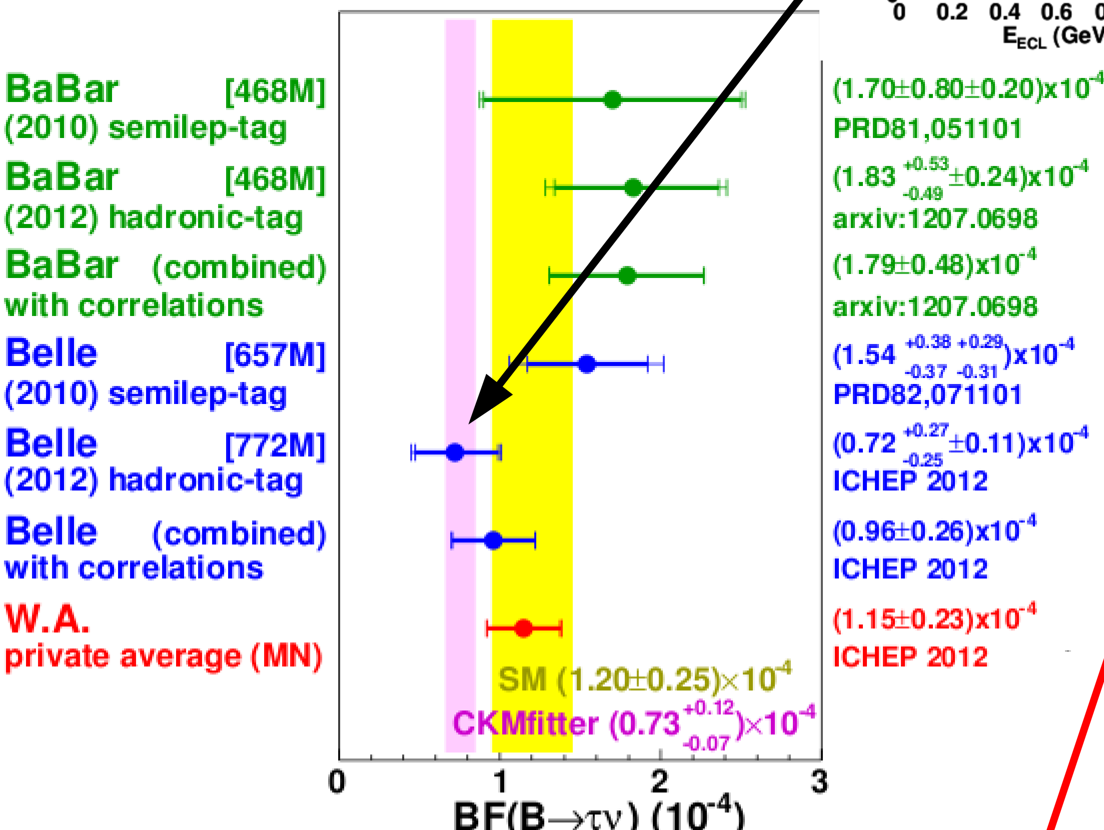
lattice uncertainty

$B \to \tau\nu$ & $B \to D(*)\tau\nu$

BaBar arXiv:1207.0698
Belle arXiv:1208.4678
M. Nakao @ ICHEP



BaBar PRL 109 (2012) 101802
Belle PRD82 (2010) 072005

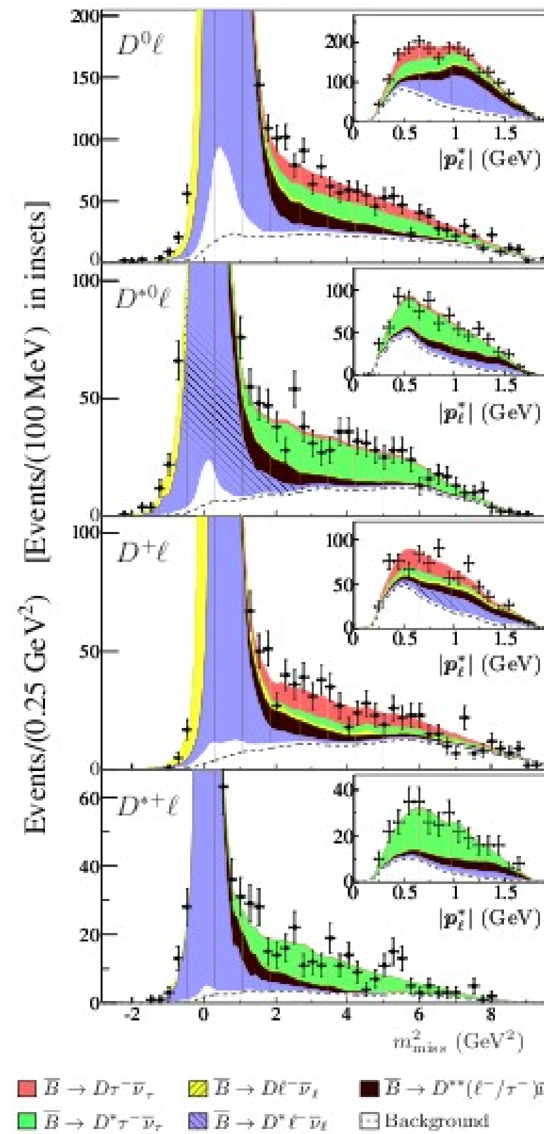


2.3σ

3.8σ

3.6σ

3.0σ



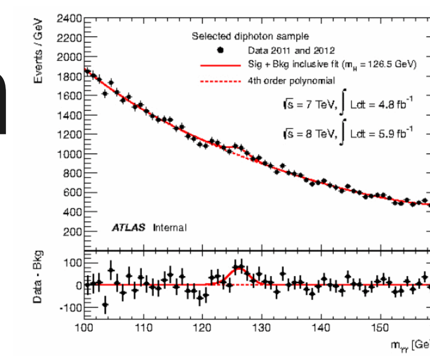
BaBar rates 3.4σ above the SM, and inconsistent with 2HDM

Significance (from 0) below the usual threshold to claim observation

What do we know about rare decays?

Two routes to heaven

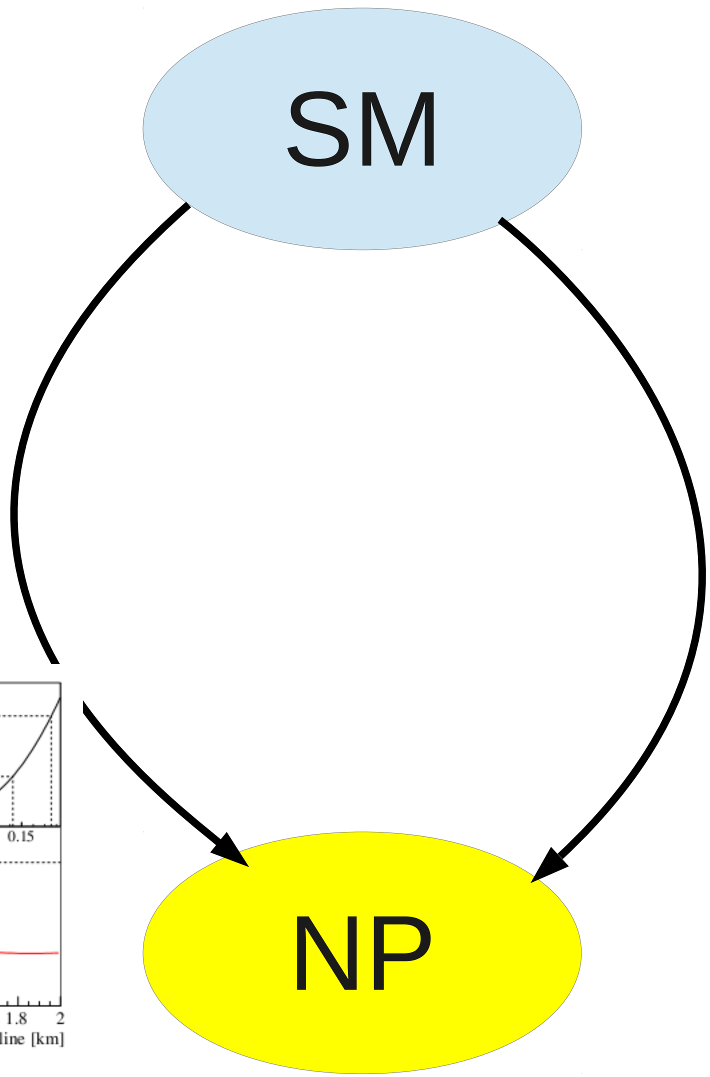
for heavy quark flavour physics



~250th google image hit for "Higgs boson"

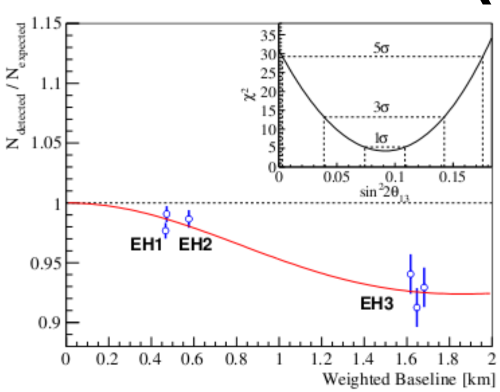
CP violation
(extra sources must exist)

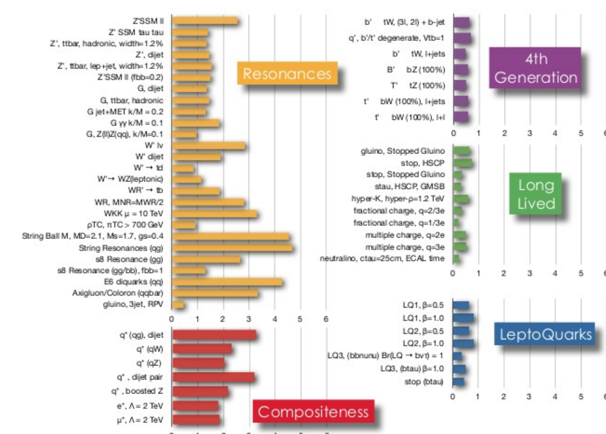
But
- No guarantee of the scale
- No guarantee of effects in the quark sector
- Realistic prospects for CPV measurement in νs due to large θ_{13}



Rare decays
(strong theoretical arguments)

But
- How high is the NP scale?
- Why have FCNC effects not been seen?





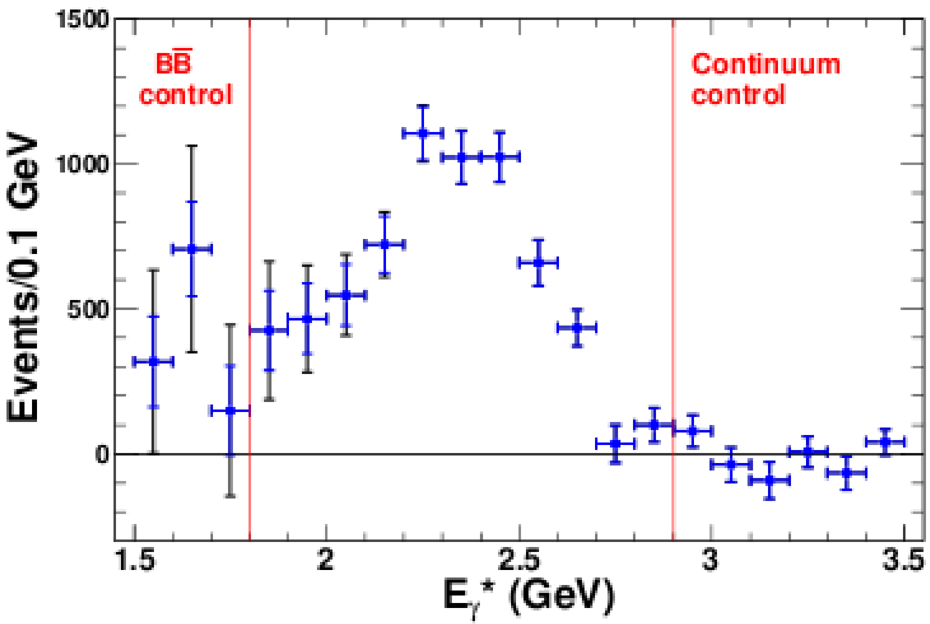
Tim Gershon
Learned from Experiments

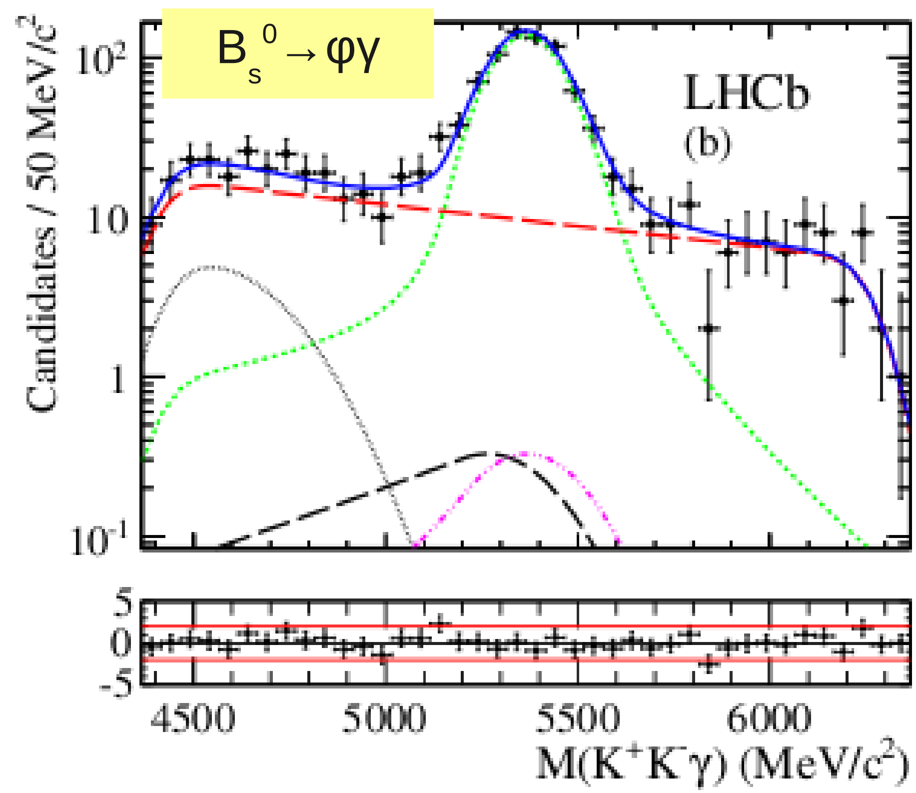
$b \to s\gamma$

The archetypal FCNC decay
New results on both inclusive properties and exclusive modes

BaBar arXiv:1207.5772

LHCb arXiv:1209.0313

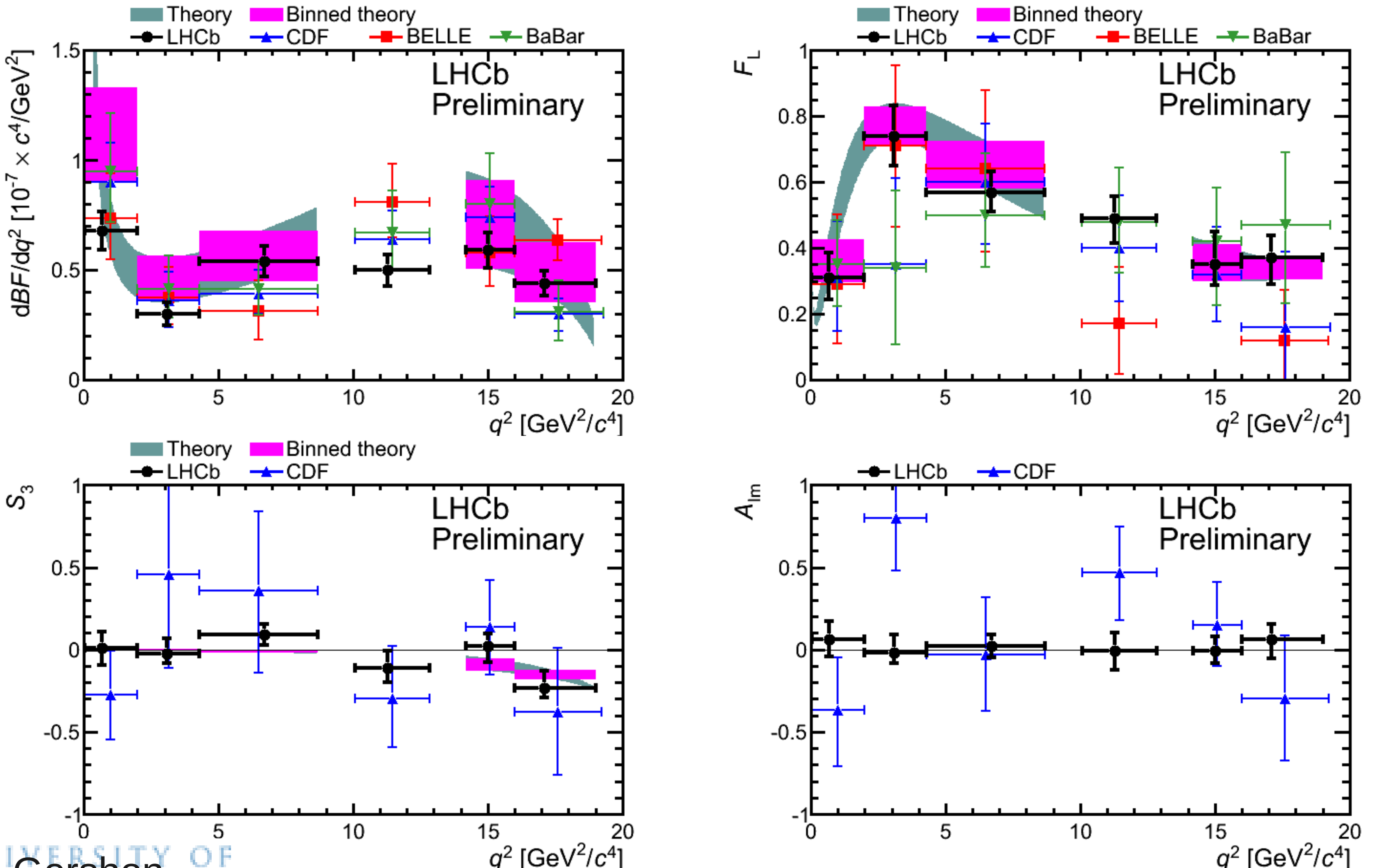




>15 year old hint for NP in $b \to s\gamma$ long since gone ...
… but still interesting possibilities for NP searches

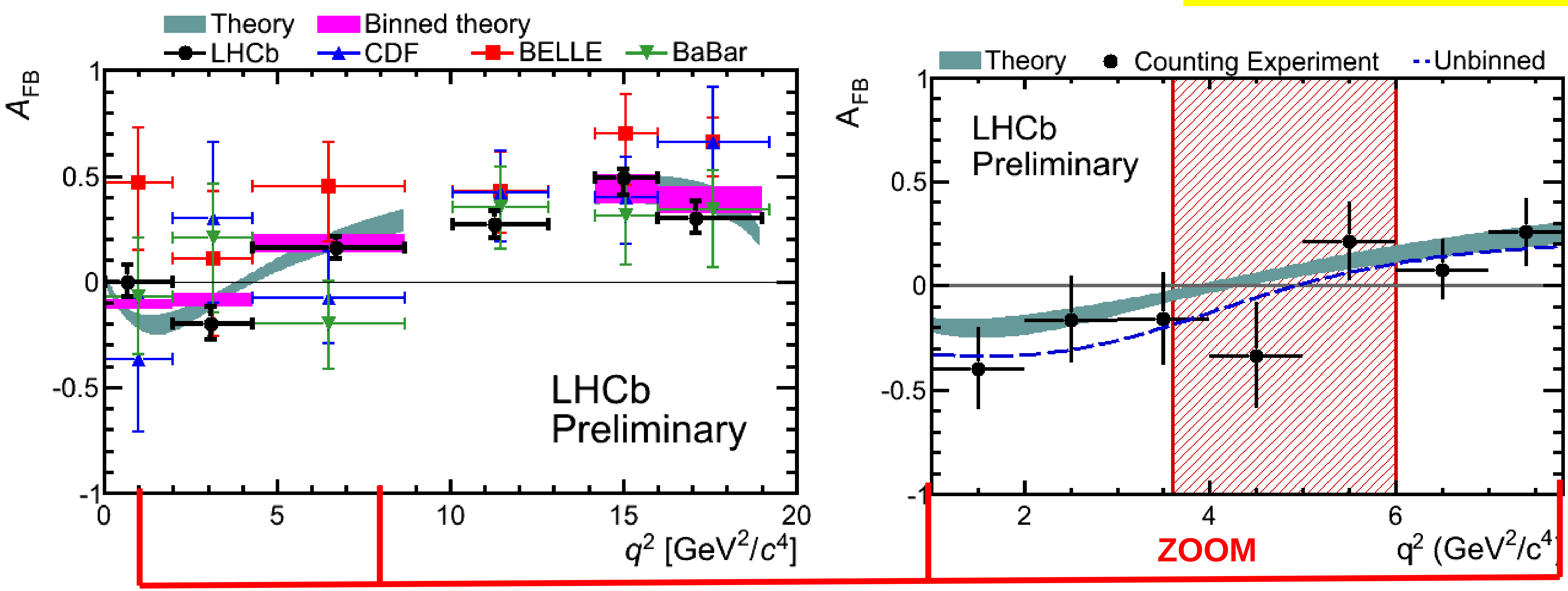
$B^0 \to K^{*0}\mu^+\mu^-$

LHCb-CONF-2012-008
BaBar Lake Louise preliminary, also
CDF ICHEP preliminary



$A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)$

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

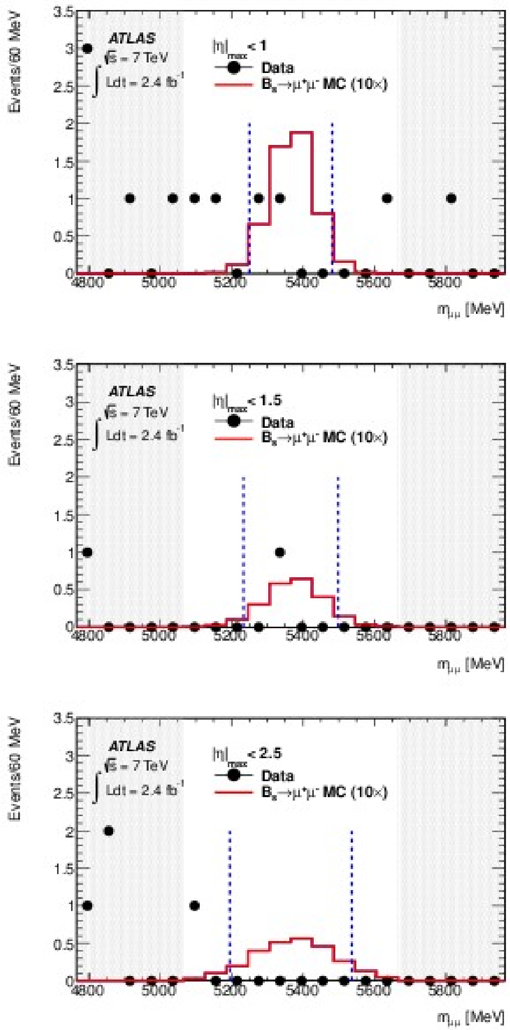
(SM predictions in the range 4.0 – 4.3 GeV^2)

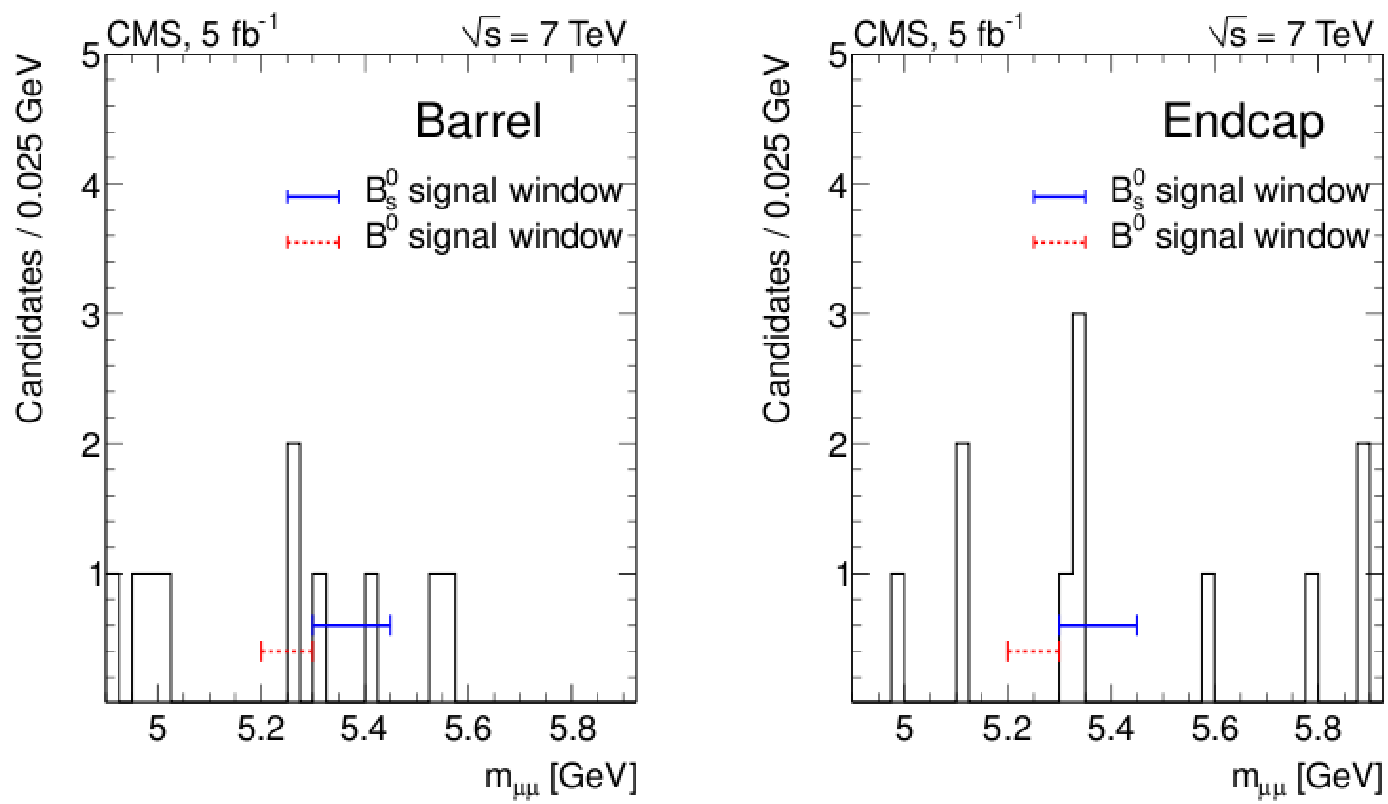
Updates hotly anticipated

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

ATLAS (2.4/fb) PLB 713 (2012) 387

CMS (5/fb) JHEP 04 (2012) 033



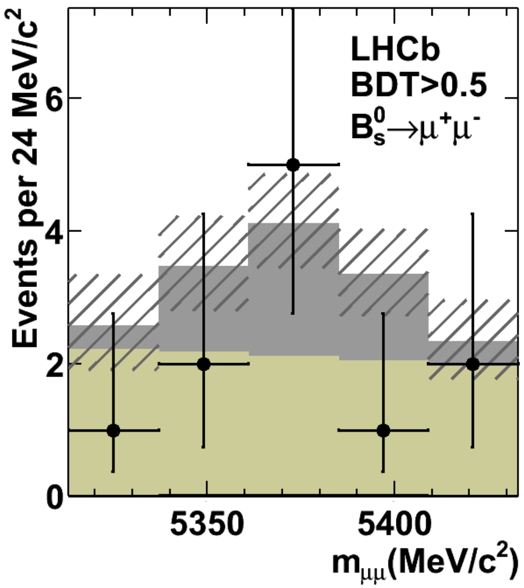


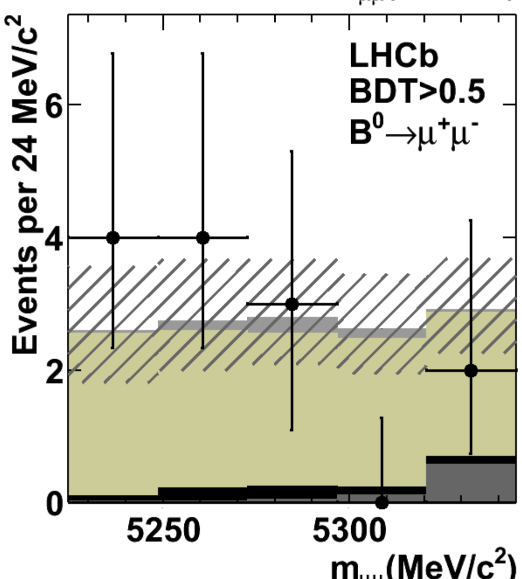
ATLAS $B(B_s \to \mu^+\mu^-) < 2.2\ (1.9) \times 10^{-8}$ @ 95% (90%) CL

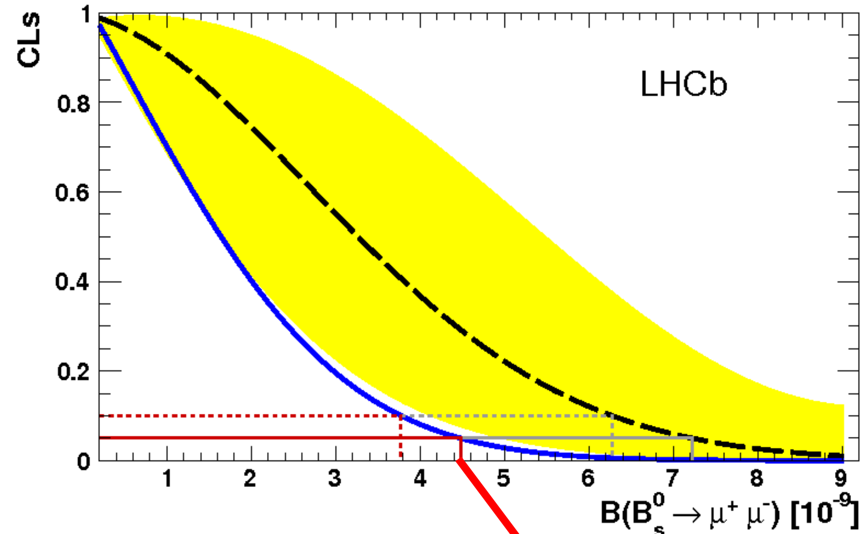
CMS $B(B_s \to \mu^+\mu^-) < 7.7\ (6.4) \times 10^{-9}$ @ 95% (90%) CL

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

LHCb (1/fb) PRL 108 (2012) 231801







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}

LHC combination: $B(B_s^0 \to \mu^+\mu^-) < 4.2\ 10^{-9}$

Standard Model expectation, e.g. $(3.2 \pm 0.3) \times 10^{-9}$
Buras et al, arXiv:1208.0934

N.B. Should be corrected up by 9% since time-integrated branching fraction is measured (arXiv:1204.1737)

Don't forget the bread and butter

- Most hadron collider heavy flavour results are ratios
  - e.g.

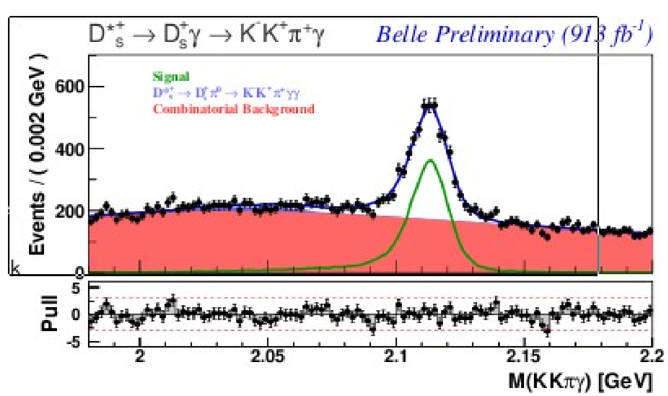
    $B(B_s^0 \to \mu^+\mu^-) = B(B^+ \to J/\psi K^+) \times B(J/\psi \to \mu^+\mu^-) \times f_s/f_d \times$

    $\{ [N(B_s^0 \to \mu^+\mu^-)/\varepsilon(B_s^0 \to \mu^+\mu^-)] / [N(B^+ \to J/\psi K^+)/\varepsilon(B^+ \to J/\psi K^+)] \}$
  - where

    $f_s/f_d = \{ [N(B_s^0 \to D_s^-\mu^+X)/\varepsilon(B_s^0 \to D_s^-\mu^+X)] / [N(B^0 \to D^-\mu^+X)/\varepsilon(B^0 \to D^-\mu^+X)] \} \times$

    $[\tau(B^0)/\tau(B_s^0)] \times [B(D^- \to K^+\pi^-\pi^-)/B(D_s^- \to K^+K^-\pi^-)]$

    (simplified expressions given here; other methods to determine f_s/f_d also rely on $B(D_s^- \to K^+K^-\pi^-)$)
  - Limiting factor will become uncertainty on $B(D_s^- \to K^+K^-\pi^-)$
  - Improved measurements of basic quantities can have significant impact



Belle Charm 2012 preliminary
(spin-off of $D_s \to \tau\nu$ analysis)

Some morals

- Worship the accelerator gods
- Investment in detectors & techniques brings rewards
- Interesting effects might be very big …

  … or very small → be prepared to be precise

  … but it seems like there are no O(1) deviations from the SM
- Clean theoretical predictions are to be treasured ...

  … data-driven methods to control uncertainties also to be valued
- 3σ often goes away, but 5σ seems to stay

  … but investigating anomalies is worth the effort
  - sure to learn something (about physics, systematics or statistics)
- Bread and butter can be needed before a feast
- New physics just might be around the corner ...

  … plenty to look forward to in CKM2012 … and beyond