Flavour Physics in the LHC Era

Lecture 3 of 3

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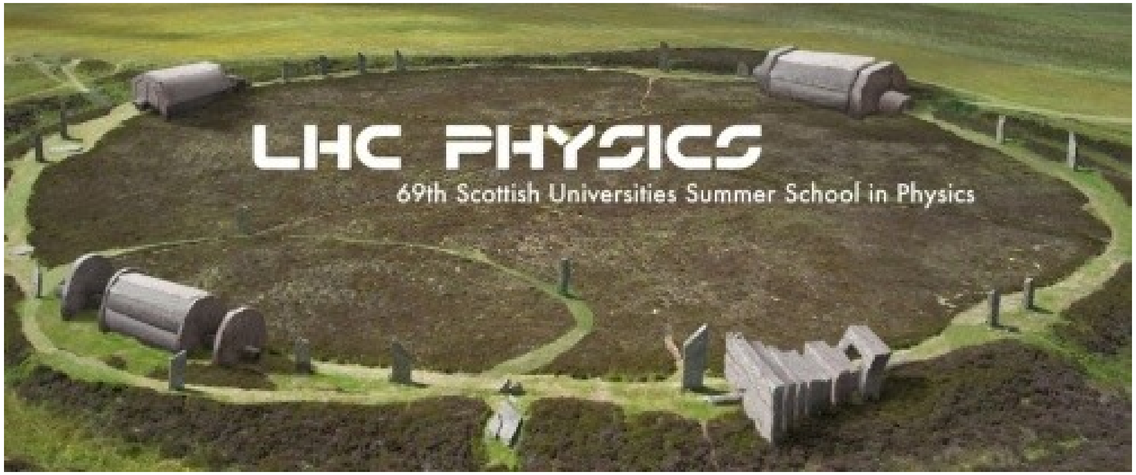
SUSSP 2012

25th August 2012



Contents

- Part 1
  - Why is flavour physics interesting?
- Part 2
  - What do we know from previous experiments?
- Part 3
  - What do we hope to learn from current and future heavy flavour experiments?

Today I'd better cover Part 3

(no really)

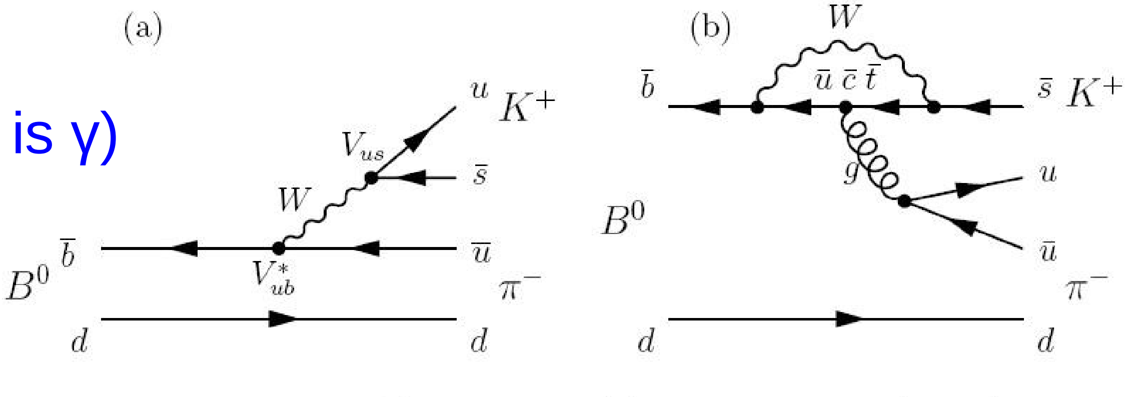
Direct CP violation

- 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

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

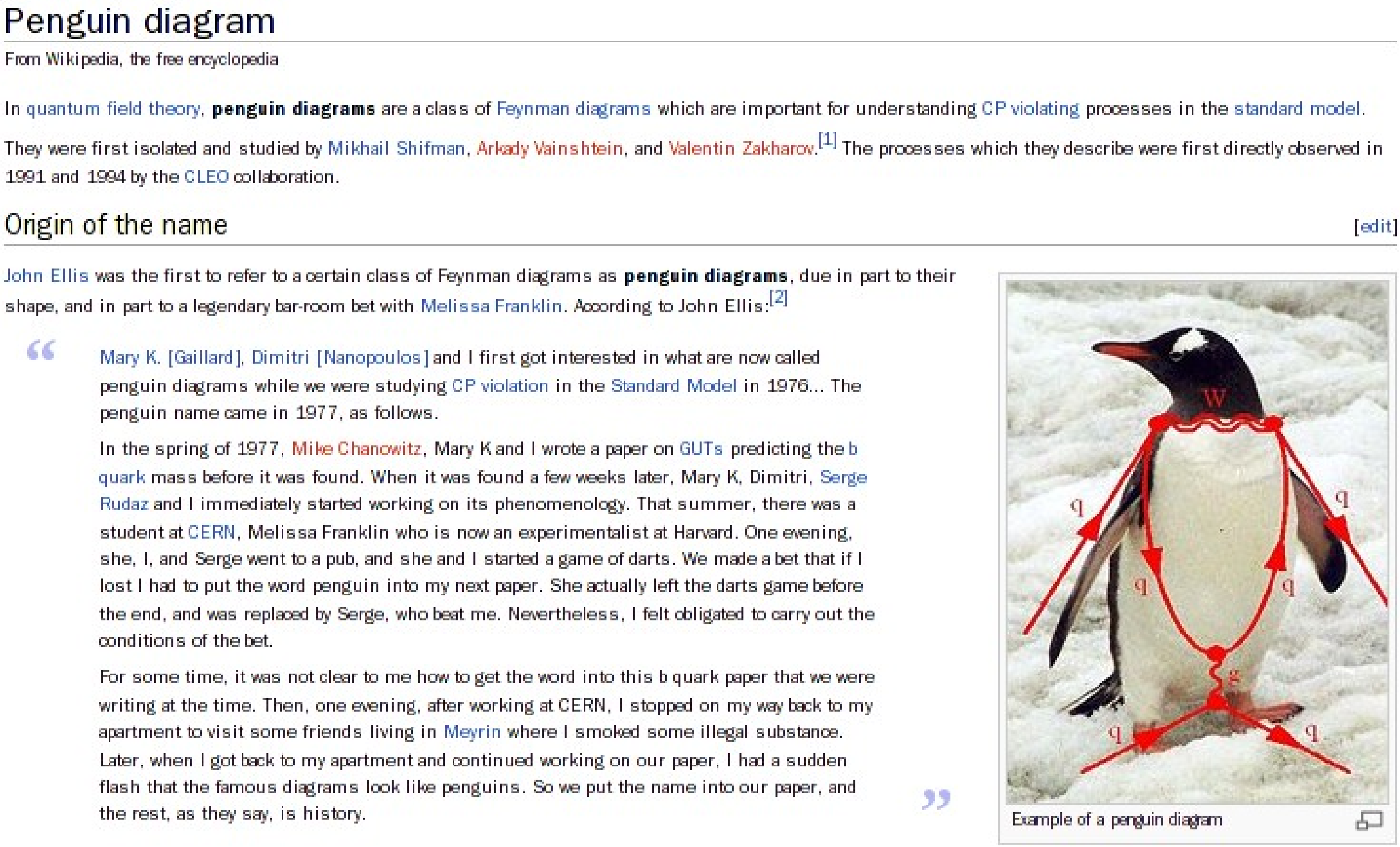
$$A_{CP} = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} = \frac{2\,|T||P| \sin(\delta_T - \delta_P) \sin(\phi_T - \phi_P)}{|T|^2 + |P|^2 + 2\,|T||P| \cos(\delta_T - \delta_P) \cos(\phi_T - \phi_P)}$$

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

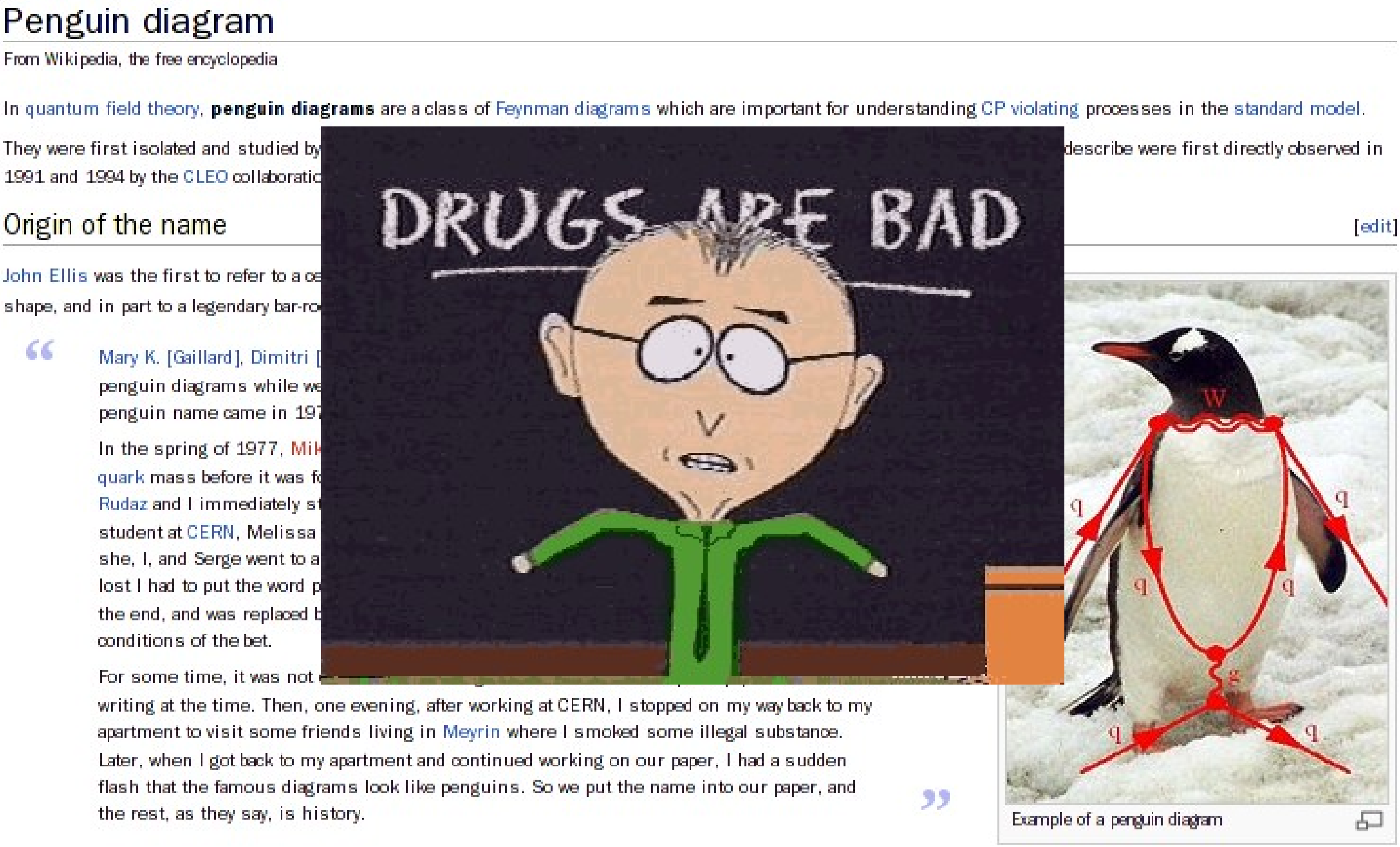
[edit]

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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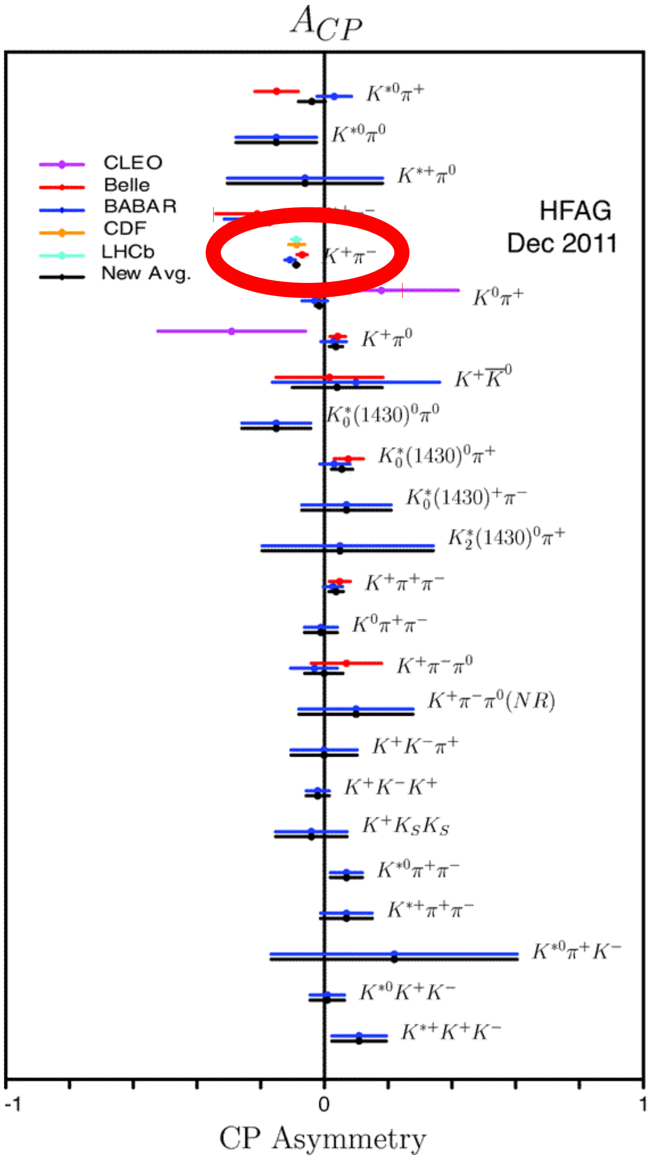
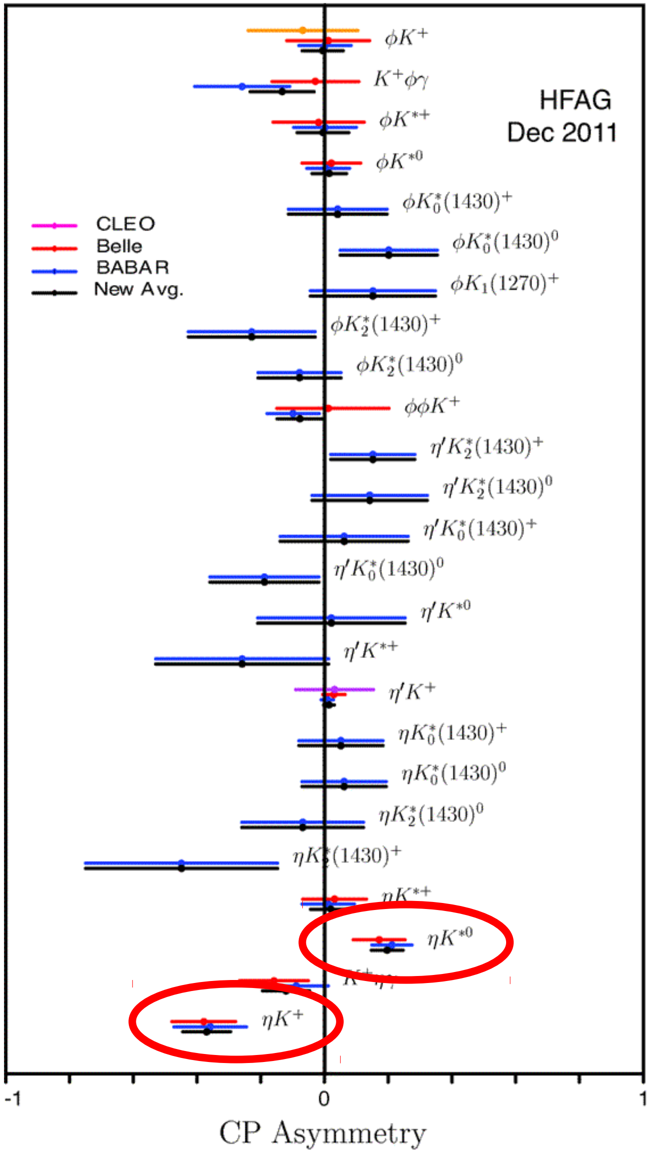
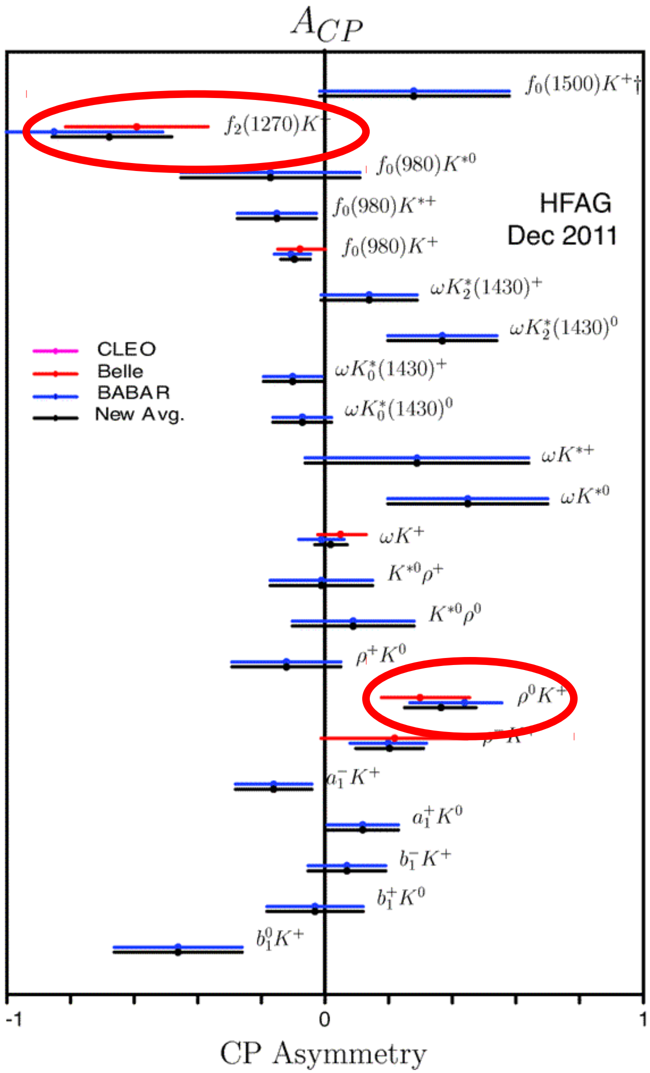
Example of a penguin diagram

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

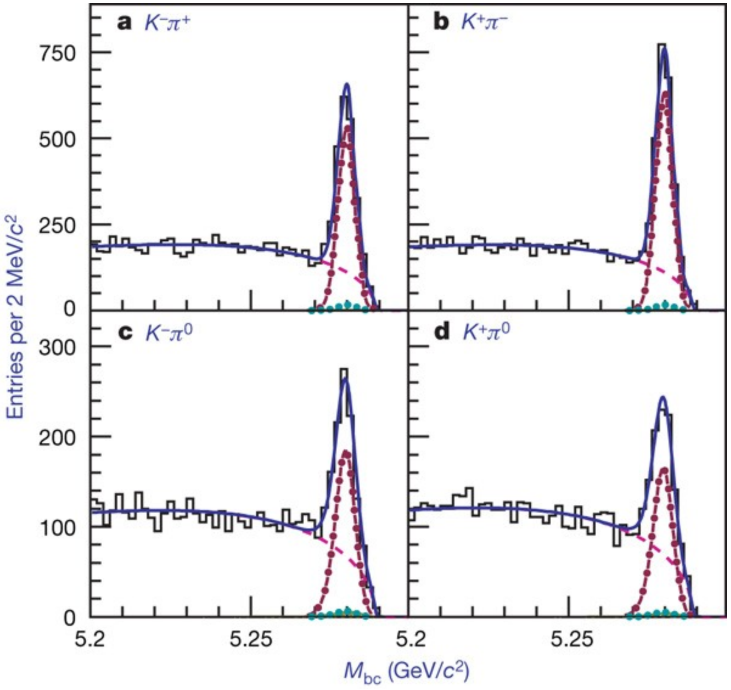
“Kπ puzzle”

$$A_{CP}(K^-\pi^+) = -0.087 \pm 0.008$$
$$A_{CP}(K^-\pi^0) = +0.037 \pm 0.021$$

HFAG averages

Could be a sign of new physics …
… first need to rule out possibility of
larger than expected QCD corrections

Belle Nature 452 (2008) 332



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

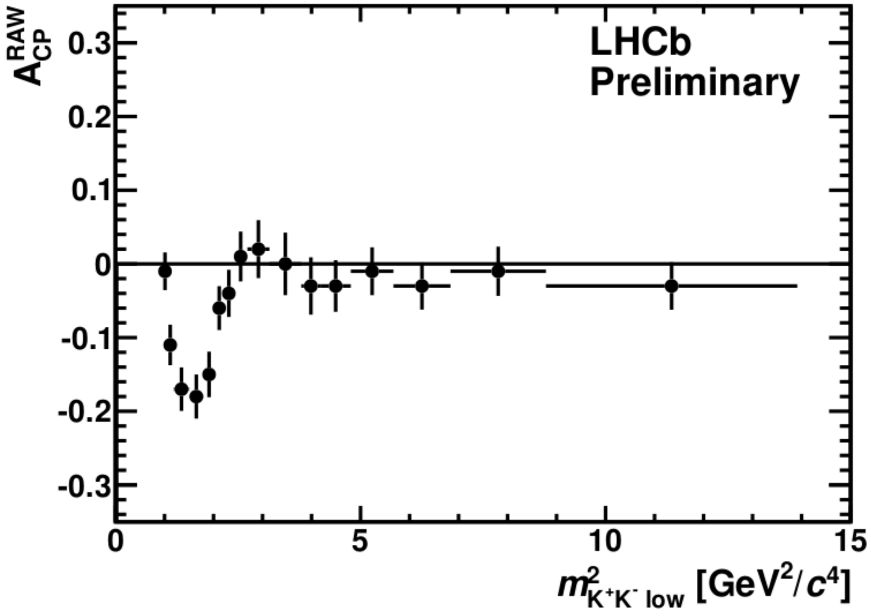
- Measure more $B_{u,d} \to K\pi$ decays & relate by isospin
- Perform similar analysis on $B \to K^*\pi$ &/or $B \to K\rho$
  - Dalitz plot analyses of $K\pi\pi$ final states extract both amplitudes and relative phases → more observables
- Measure $B_s \to KK$ decays & relate by U-spin
  - e.g. relation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

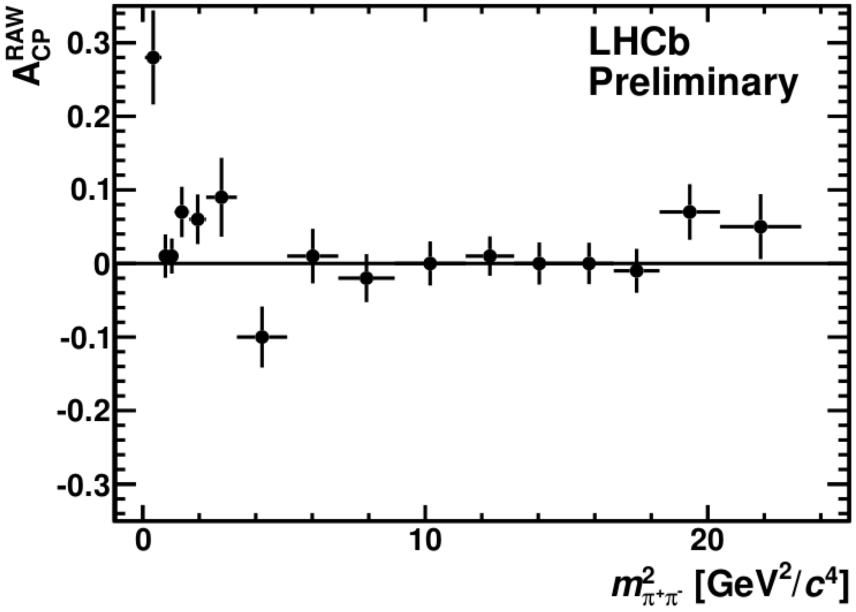
Latest results on multibody charmless B decays

LHCb-CONF-2012-018

B → KKK



B → Kππ

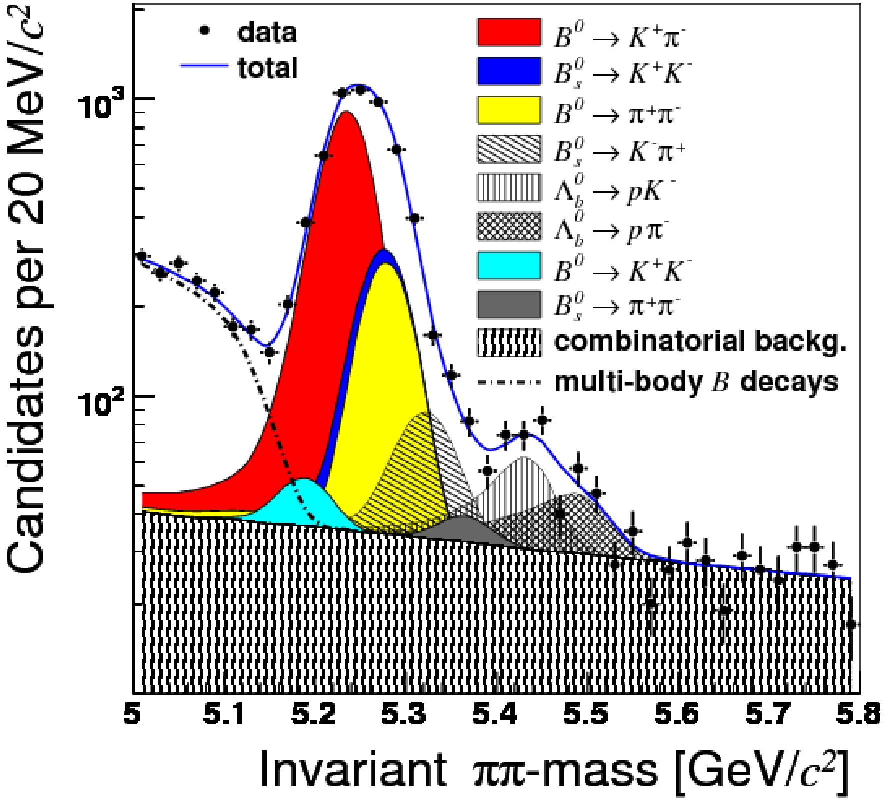


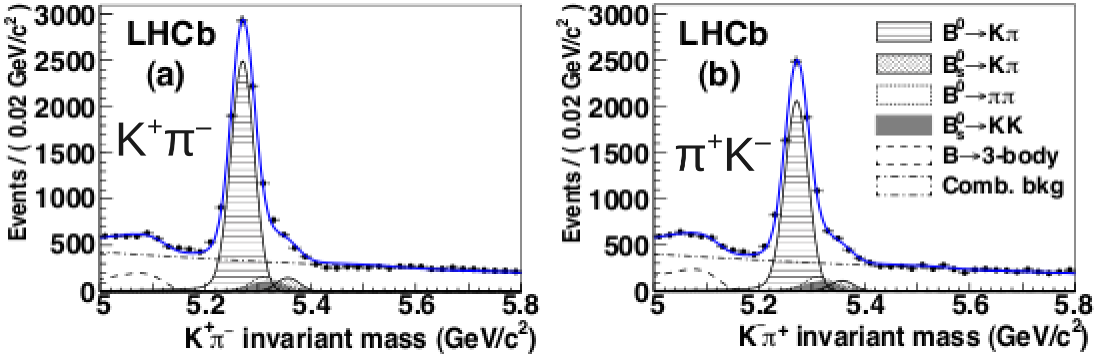
Large CP violation effects with strong variation across the Dalitz plot
Detailed studies will be necessary to understand origin of these effects

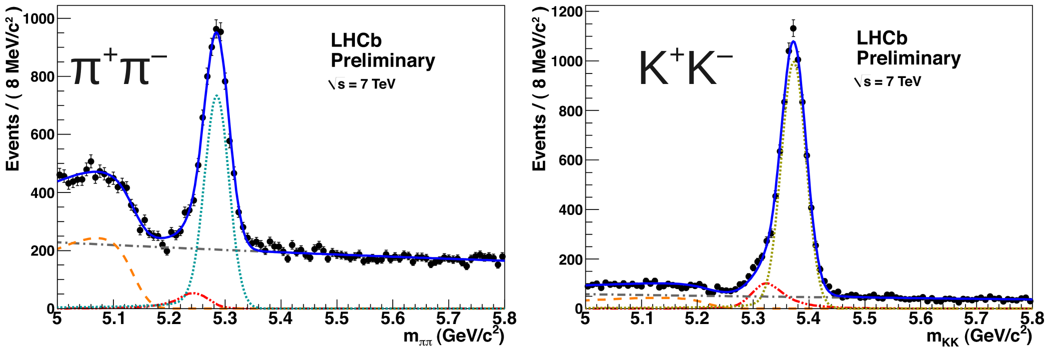
$B \to h^+h'^-$ at hadron colliders

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

LHCb arXiv:1202.6251







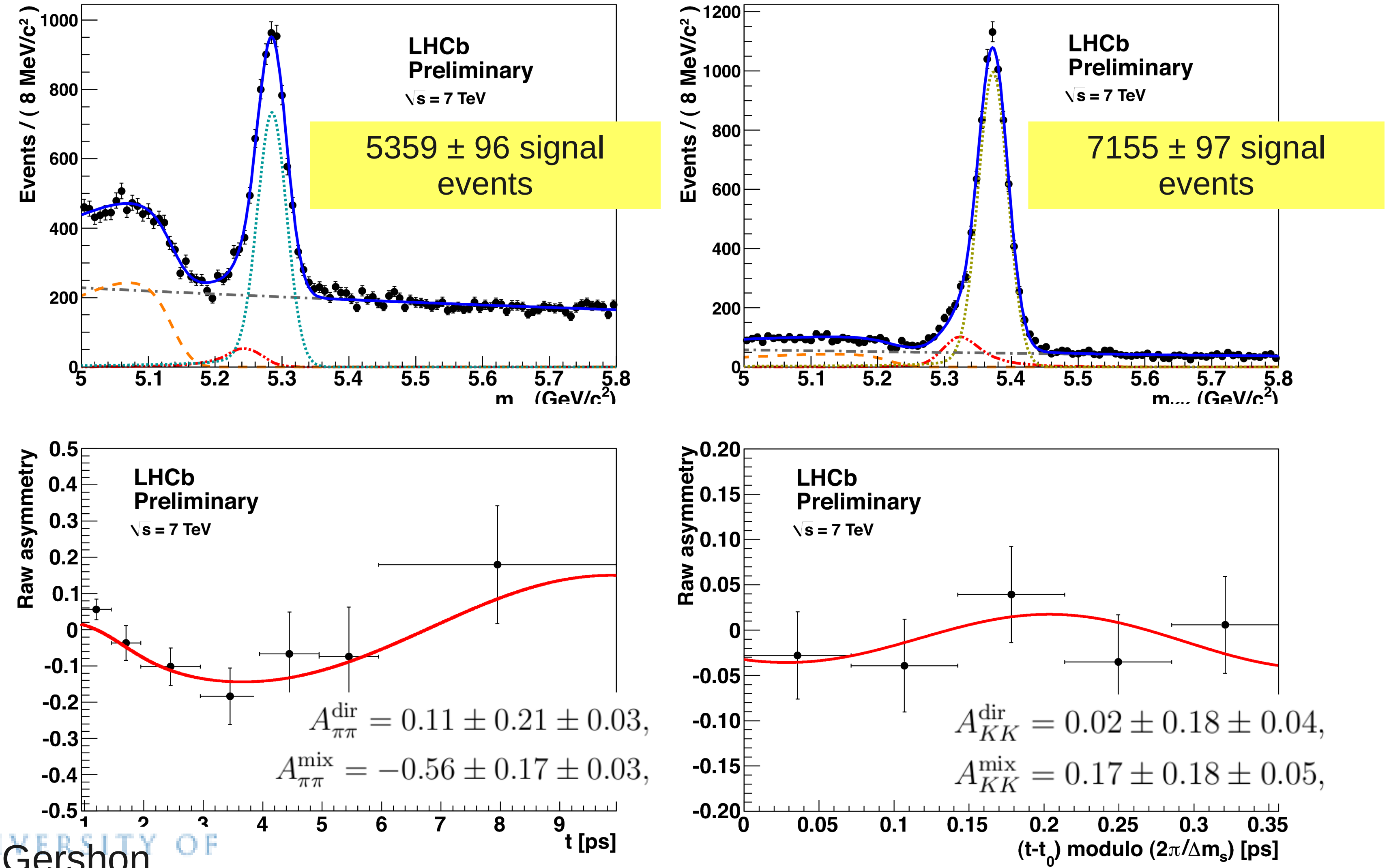
LHCb-CONF-2012-007

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



5359 ± 96 signal events

7155 ± 97 signal events

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

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

Importance of γ from B → DK

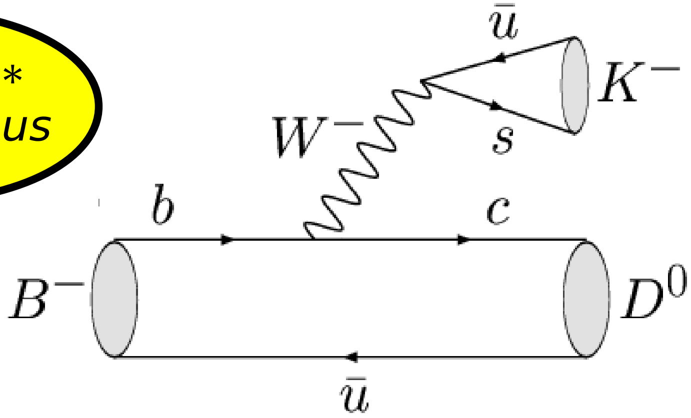
- γ plays a unique role in flavour physics

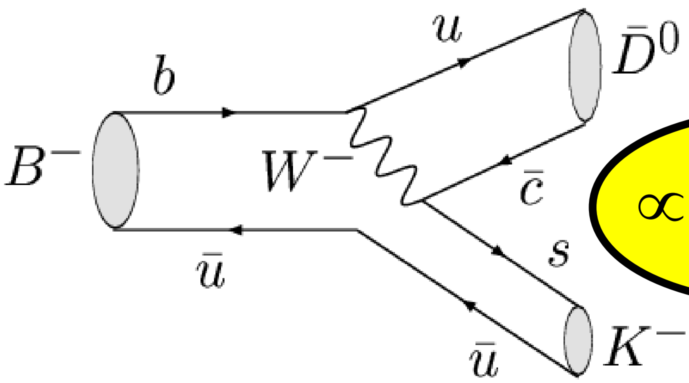
the only CP violating parameter that can be measured through tree decays (*)

(*) more-or-less

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

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



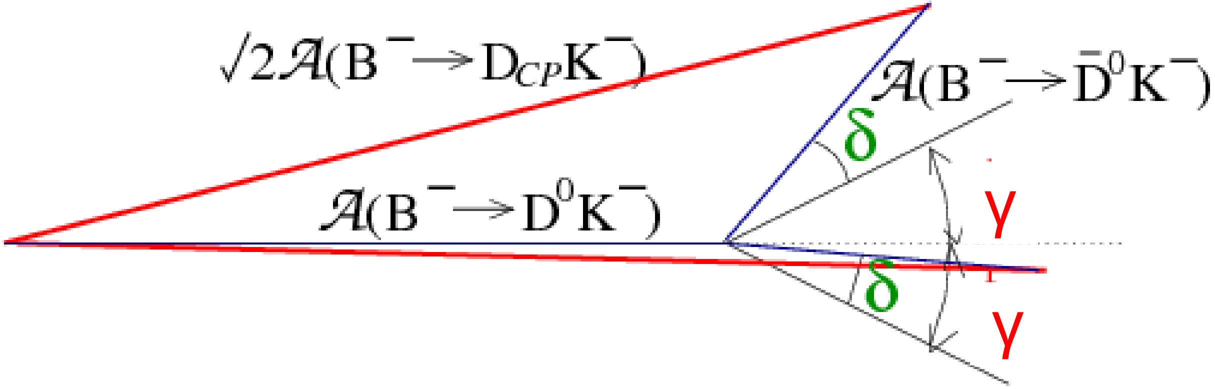


$\propto V_{ub} V^*_{cs}$

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

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

never studied before (or not much)

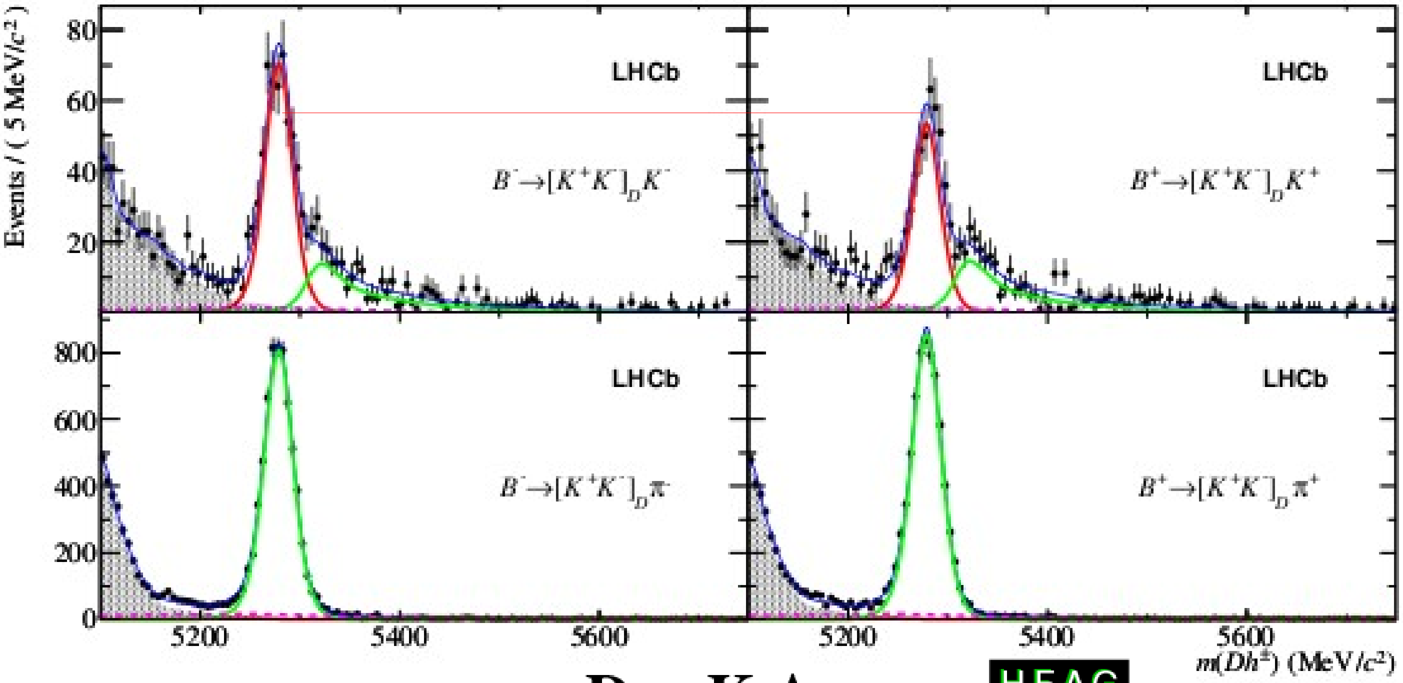
Search for direct CP violation caused by $\gamma \neq 0$

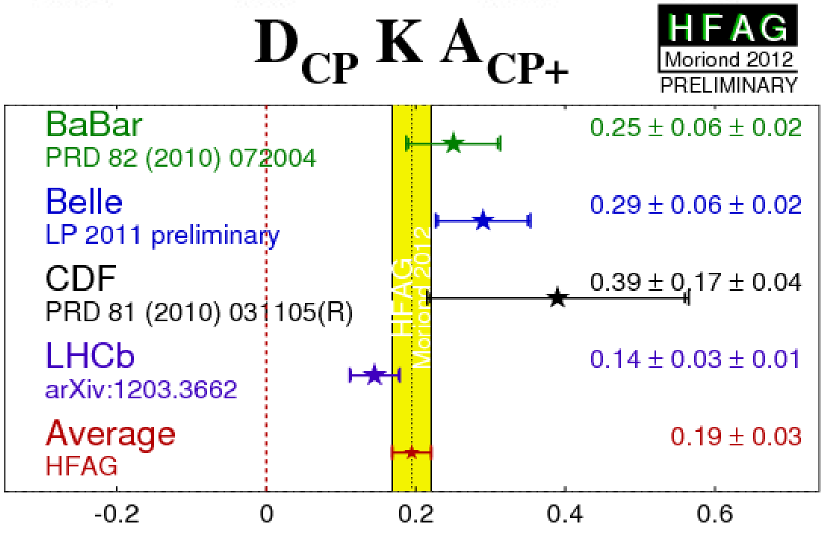
All parameters from data – no theory input needed

Latest results on B → DK : GLW

LHCb arXiv:1203.3662

Evidence for direct CP violation (γ≠0)





Observed 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
    - $S_{\psi K0} = +0.679 \pm 0.020$
    - $S_{\eta' K0} = +0.59 \pm 0.07$, $S_{\varphi K0} = + 0.74^{+0.11}_{-0.13}$, $S_{f0K0} = +0.69^{+0.10}_{-0.12}$, $S_{K+K-K0} = +0.68^{+0.09}_{-0.10}$
    - $S_{\pi+\pi-} = -0.65 \pm 0.07$, $C_{\pi+\pi-} = -0.36 \pm 0.06$
    - $S_{\psi\pi0} = -0.93 \pm 0.15$, $S_{D+D-} = -0.98 \pm 0.17$, $S_{D*+\,D*-} = -\,0.77 \pm 0.10$
    - $A_{K\mp\pi\pm} = -0.087 \pm 0.008$
    - $A_{D(CP+)K\pm} = +0.19 \pm 0.03$

Only one in charged B mesons!

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 ($x_D = \Delta m_D/\Gamma_D$ & $y_D = \Delta\Gamma_D/2\Gamma_D$) 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

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

CP violating asymmetries

CP conserving parameter

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

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

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

- 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

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t}$$

$$\times \left[\boxed{1} + \mathcal{A}_{\rm CP}^{\rm dir} \cos(\Delta m \, t) + \boxed{0} + \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta m \, t) \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1+a) \, e^{-\Gamma t}$$

$$\times \left[\boxed{1} - \mathcal{A}_{\rm CP}^{\rm dir} \cos(\Delta m \, t) + \boxed{0} - \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta m \, t) \right] .$$

- 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

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, e^{-\Gamma t}$$

$$\times \left[1 + \mathcal{A}_{\rm CP}^{\rm dir}\ 1 + \mathcal{A}_{\Delta\Gamma}\ y\Gamma t + \mathcal{A}_{\rm CP}^{\rm mix}\ x\Gamma t \right]$$

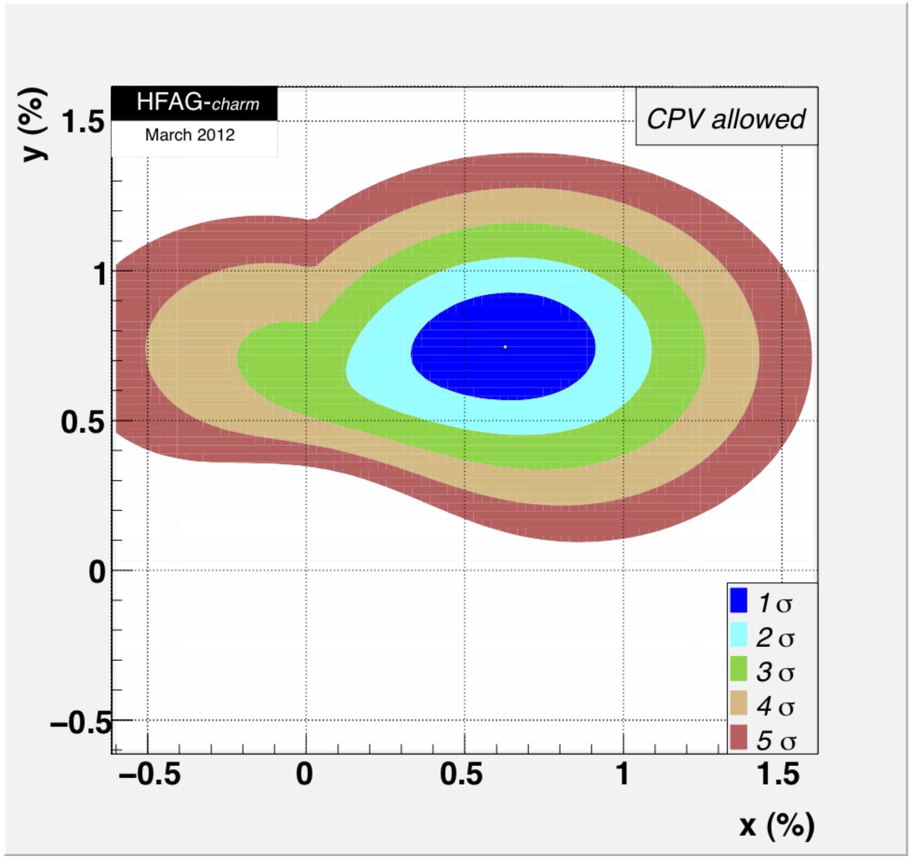
$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f\, |A_f|^2\, \frac{1+|\lambda_f|^2}{2}\, (1+a)\, e^{-\Gamma t}$$

$$\times \left[1 - \mathcal{A}_{\rm CP}^{\rm dir}\ 1 + \mathcal{A}_{\Delta\Gamma}\ y\Gamma t - \mathcal{A}_{\rm CP}^{\rm mix}\ x\Gamma t \right] .$$

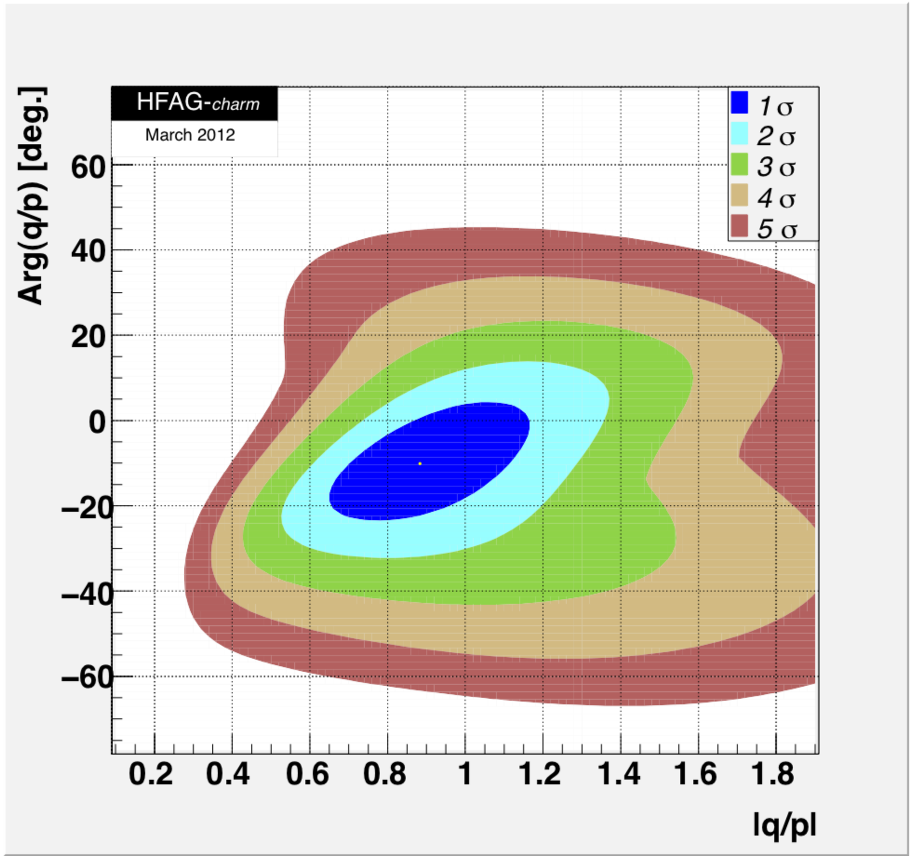
- In some channels, expect no direct CP violation
- B_d case: ΔΓ negligible
- D^0 case: both $x = \Delta m/\Gamma$ and $y=\Delta\Gamma/2\Gamma$ small

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

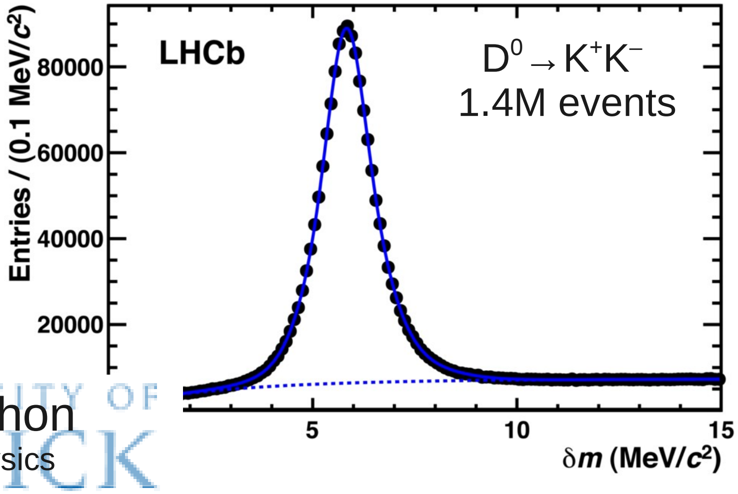
Measurement of CP asymmetry at pp collider requires knowledge of production and detection asymmetries; e.g. for $D^0 \rightarrow f$, where D meson flavour is tagged by $D^{*+} \rightarrow D^0\pi^+$ decay

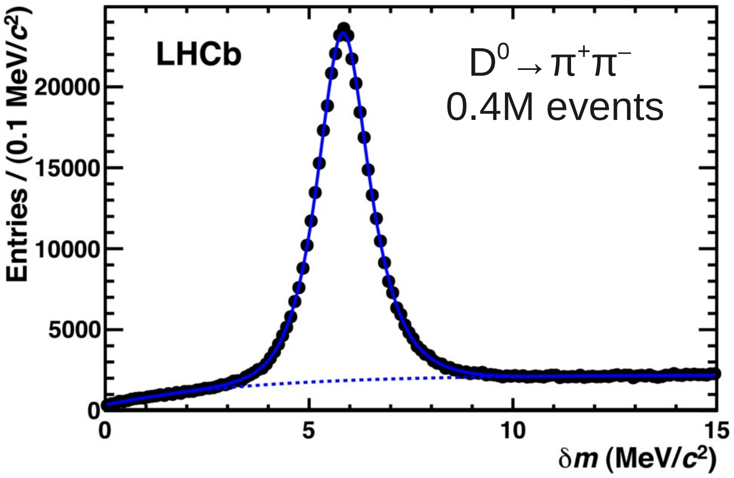
$$A_{\rm raw}(f) = A_{CP}(f) + A_{\rm D}(f) + A_{\rm D}(\pi_{\rm s}^+) + A_{\rm P}(D^{*+}).$$

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)

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

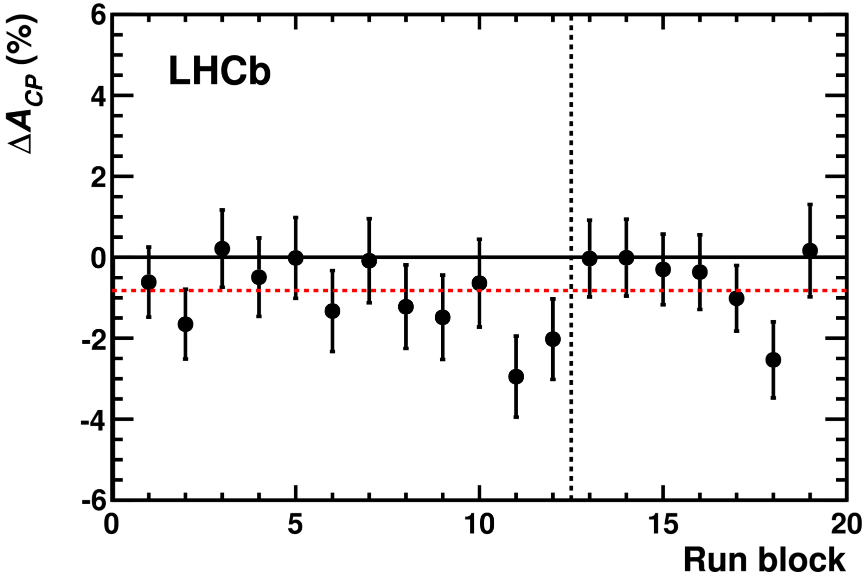




Evidence for CP violation in D → h^+h^- decays

LHCb PRL 108 (2012) 111602

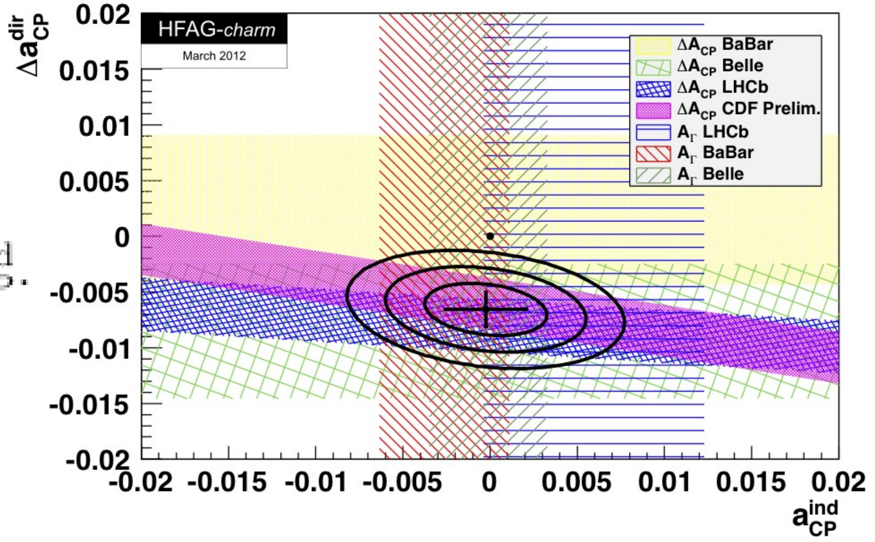
Result, based on 0.62/fb of 2011 data
ΔA_{CP} = [−0.82 ± 0.21(stat.) ± 0.11(syst.)]%



ΔA_{CP} related mainly to direct CP violation

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

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

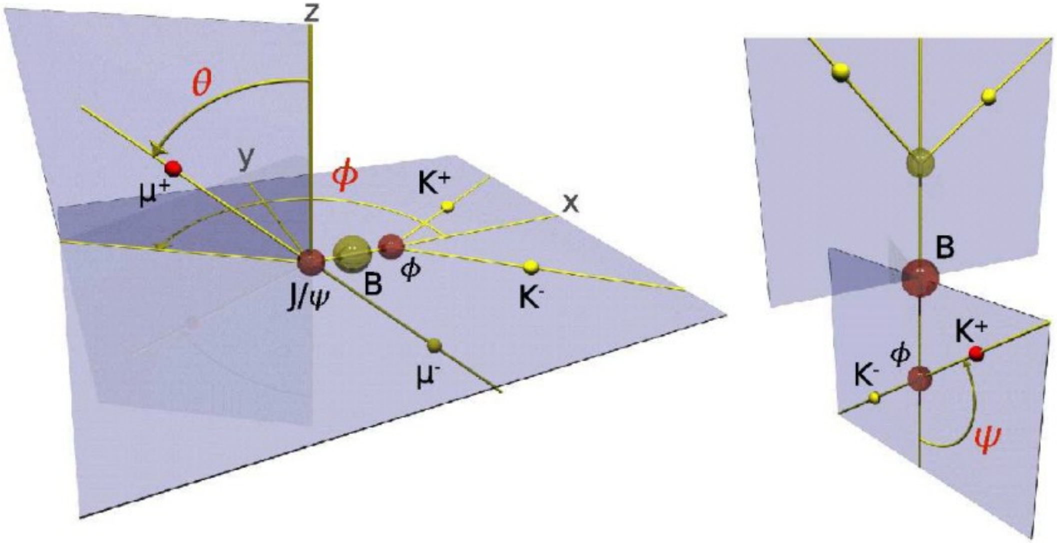


Evidence for CP violation in D → h^+h^- decays

- 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→π+π− and D0→K+K− arXiv:1203.3131
    - A consistent picture for large penguins in D → 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

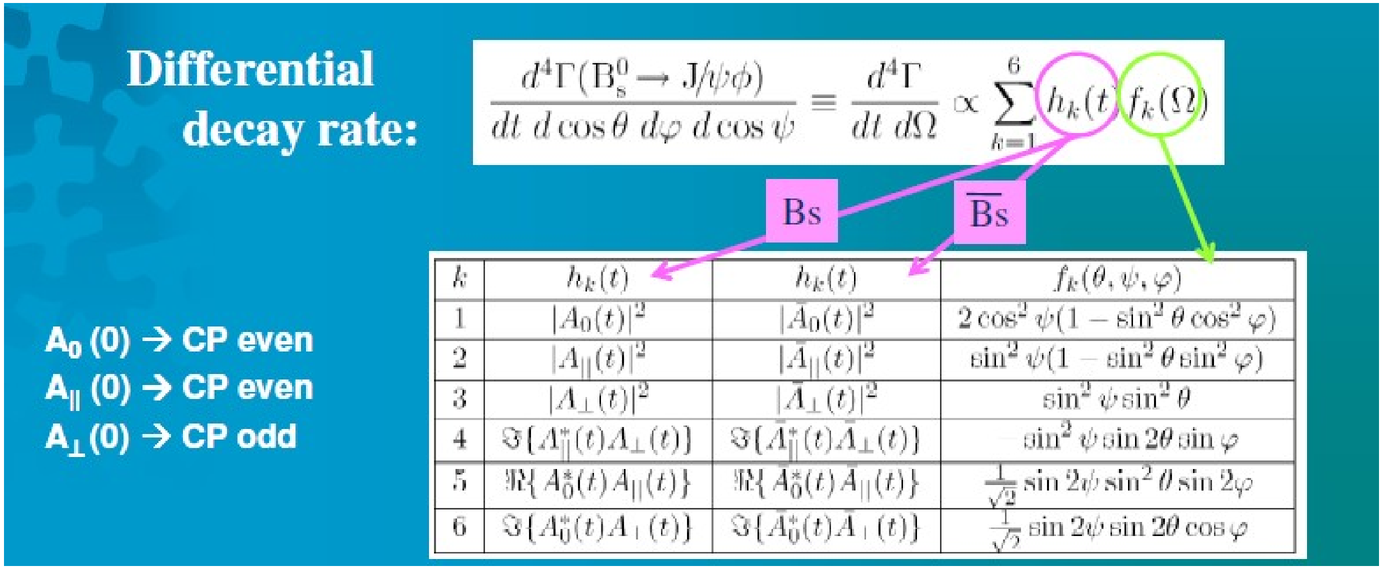
  → additional sensitivity

  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:

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

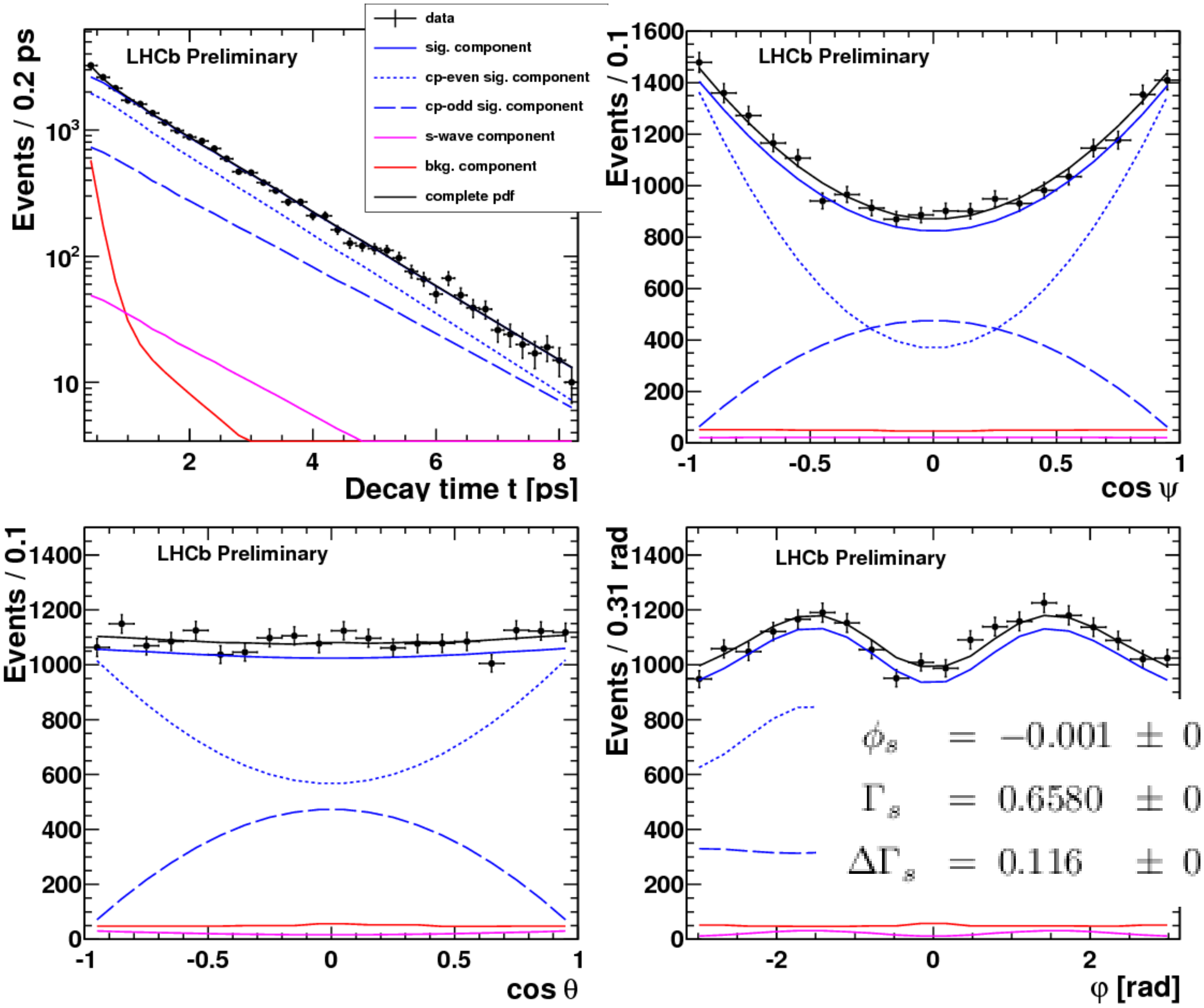
k	$h_k(t)$	$h_k(t)$	$f_k(\theta,\psi,\varphi)$
1	$\|A_0(t)\|^2$	$\|\bar{A}_0(t)\|^2$	$2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)$
2	$\|A_\parallel(t)\|^2$	$\|\bar{A}_\parallel(t)\|^2$	$\sin^2\psi(1-\sin^2\theta\sin^2\varphi)$
3	$\|A_\perp(t)\|^2$	$\|\bar{A}_\perp(t)\|^2$	$\sin^2\psi\sin^2\theta$
4	$\Im\{A_\parallel^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_\parallel^*(t)\bar{A}_\perp(t)\}$	$-\sin^2\psi\sin 2\theta\sin\varphi$
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 $\bar{B}_s$

$$\begin{aligned}
|\bar{A}_0(t)|^2 &= |\bar{A}_0(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\Phi\sin(\Delta m_s t)\right], \\
|\bar{A}_\parallel(t)|^2 &= |\bar{A}_\parallel(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\Phi\sin(\Delta m_s t)\right], \\
|\bar{A}_\perp(t)|^2 &= |\bar{A}_\perp(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\Phi\sin(\Delta m_s t)\right], \\
\Im\{\bar{A}_\parallel^*(t)\bar{A}_\perp(t)\} &= |\bar{A}_\parallel(0)||\bar{A}_\perp(0)|e^{-\Gamma_s t}\left[-\cos(\delta_\perp-\delta_\parallel)\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right. \\
&\quad \left. - \sin(\delta_\perp-\delta_\parallel)\cos(\Delta m_s t) + \cos(\delta_\perp-\delta_\parallel)\cos\Phi\sin(\Delta m_s t)\right], \\
\Re\{\bar{A}_0^*(t)\bar{A}_\parallel(t)\} &= |\bar{A}_0(0)||\bar{A}_\parallel(0)|e^{-\Gamma_s t}\cos\delta_\parallel\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right. \\
&\quad \left. - \sin\Phi\sin(\Delta m_s t)\right] \text{ and} \\
\Im\{\bar{A}_0^*(t)\bar{A}_\perp(t)\} &= |\bar{A}_0(0)||\bar{A}_\perp(0)|e^{-\Gamma_s t}\left[-\cos\delta_\perp\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right. \\
&\quad \left. - \sin\delta_\perp\cos(\Delta m_s t) + \cos\delta_\perp\cos\Phi\sin(\Delta m_s t)\right].
\end{aligned}$$

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



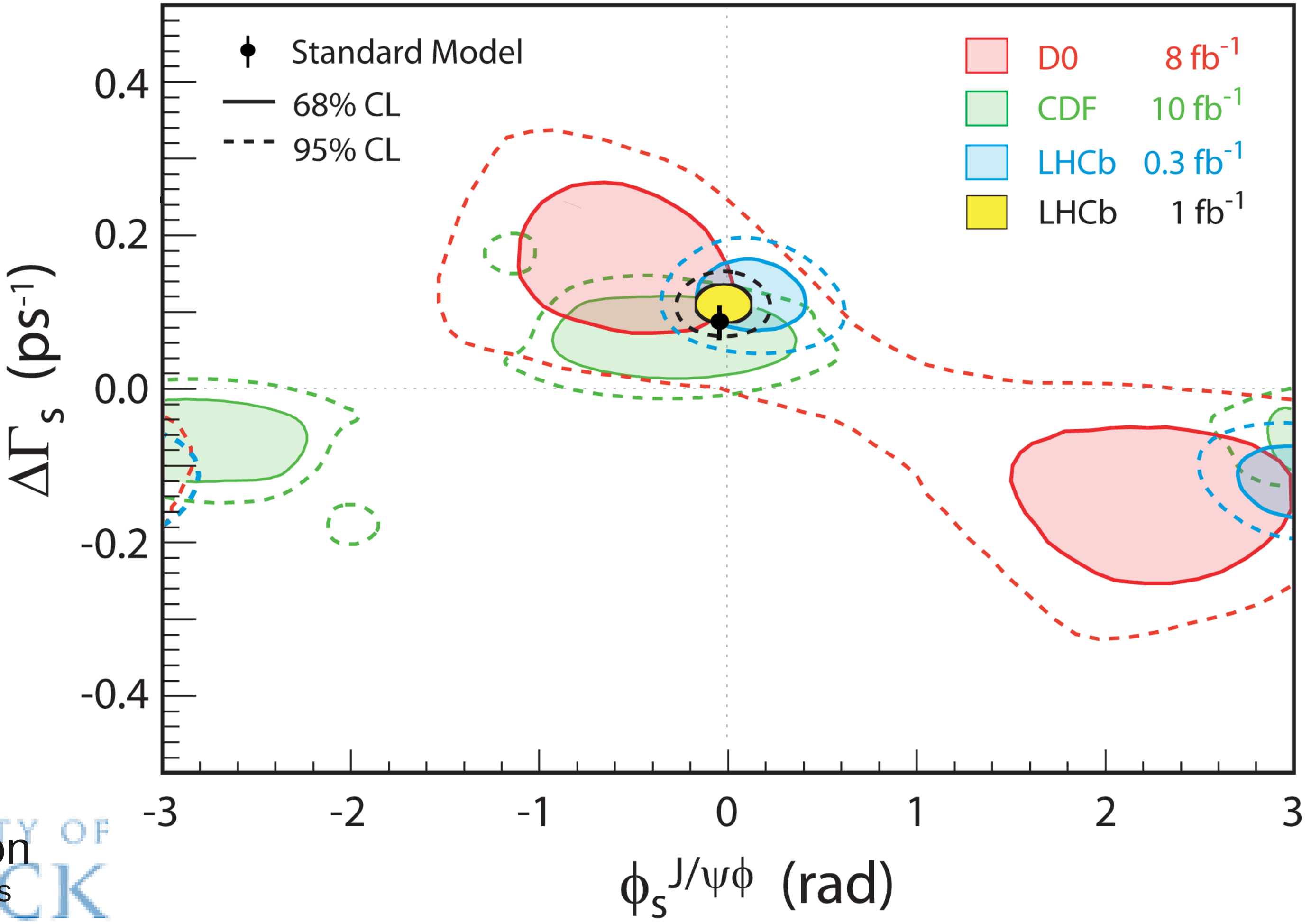
LHCb-PAPER-2011-028
0.37/fb
LHCb-CONF-2012-002
LHCb-PAPER-2012-005
LHCb-PAPER-2012-006
All 1/fb

LHCb-CONF-2012-002

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

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

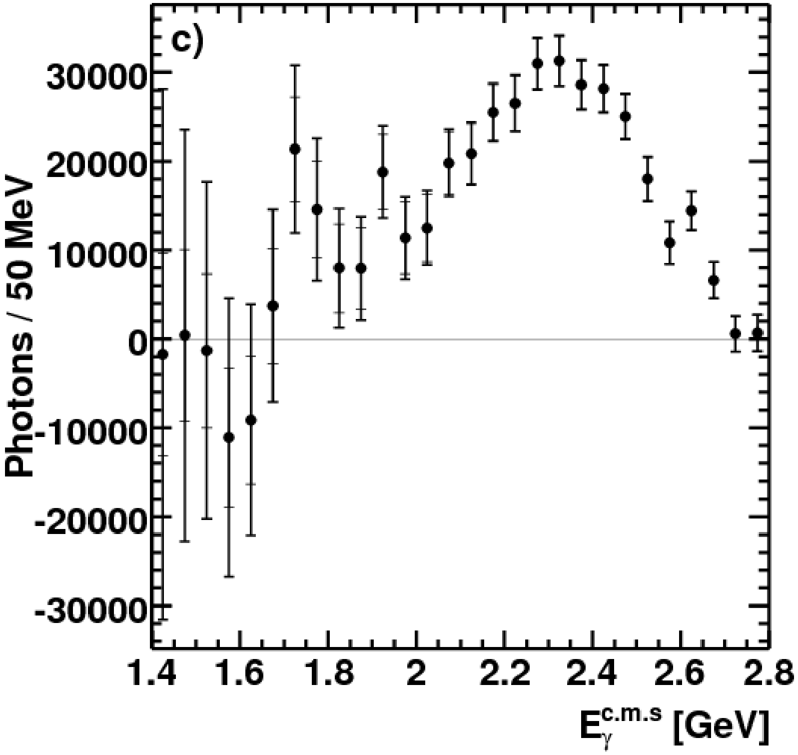
- Ambiguity resolution ↔ LHCb-PAPER-2011-028
- Tagged time-dependent angular analysis of $J/\psi\phi$ with 1/fb ↔ LHCb-CONF-2012-002
- Amplitude analysis to determine CP content of $J/\psi\pi\pi$ ↔ LHCb-PAPER-2012-005
- Tagged time-dependent analysis of $J/\psi\pi\pi$ ↔ LHCb-PAPER-2012-006



Rare Decays

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

Archetypal FCNC probe for new physics



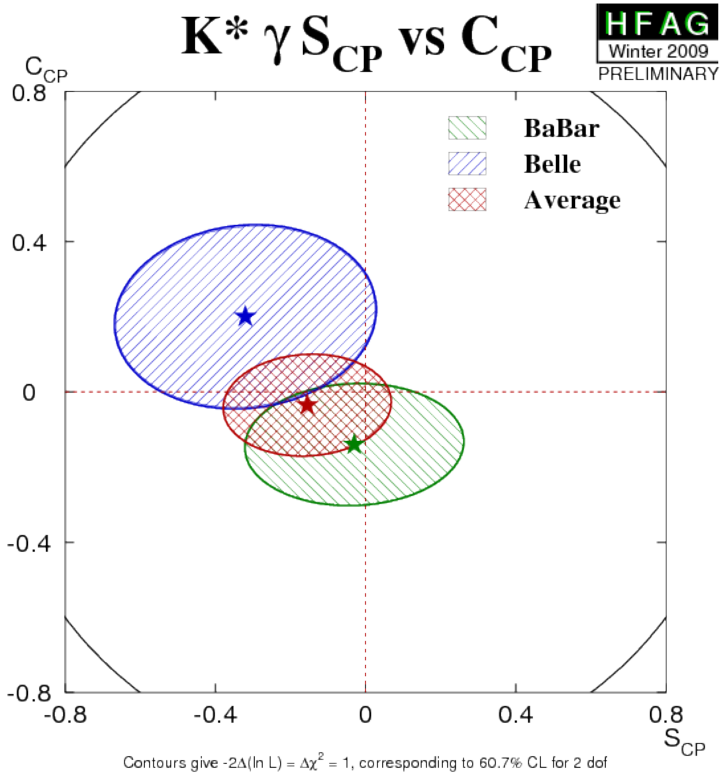
Belle PRL 103 (2009) 241801

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

consistent with the SM prediction

b→sγ photon polarisation measurement

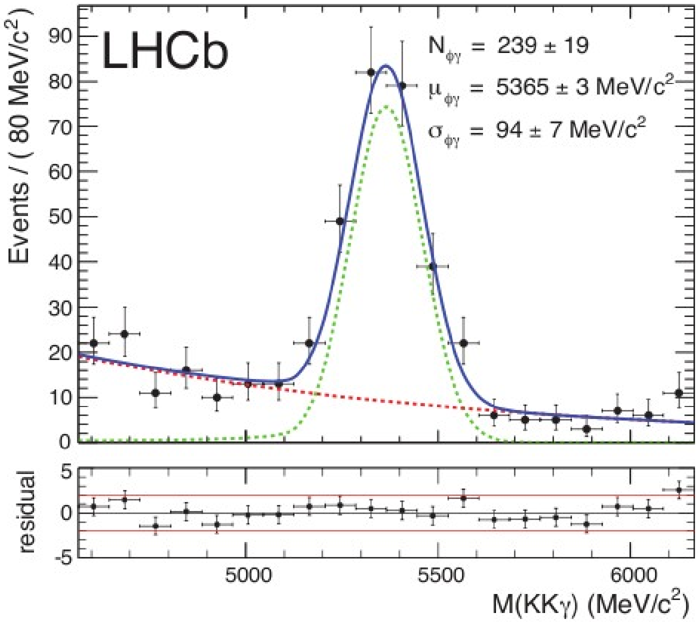
- Search for time-dependent asymmetry
- Observable effect requires NP: left-handed current & new CP phase



Contours give $-2\Delta(\ln L) = \Delta\chi^2 = 1$, corresponding to 60.7% CL for 2 dof

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

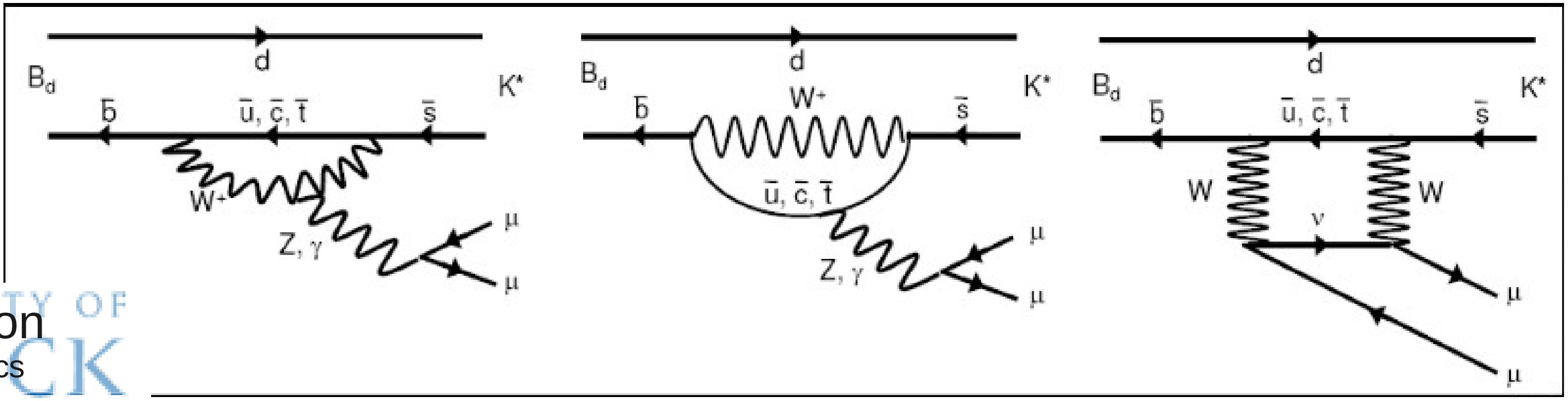
LHCb arXiv:1202.6267



Can also use, eg., $B \rightarrow K^* e^+ e^-$ (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)

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

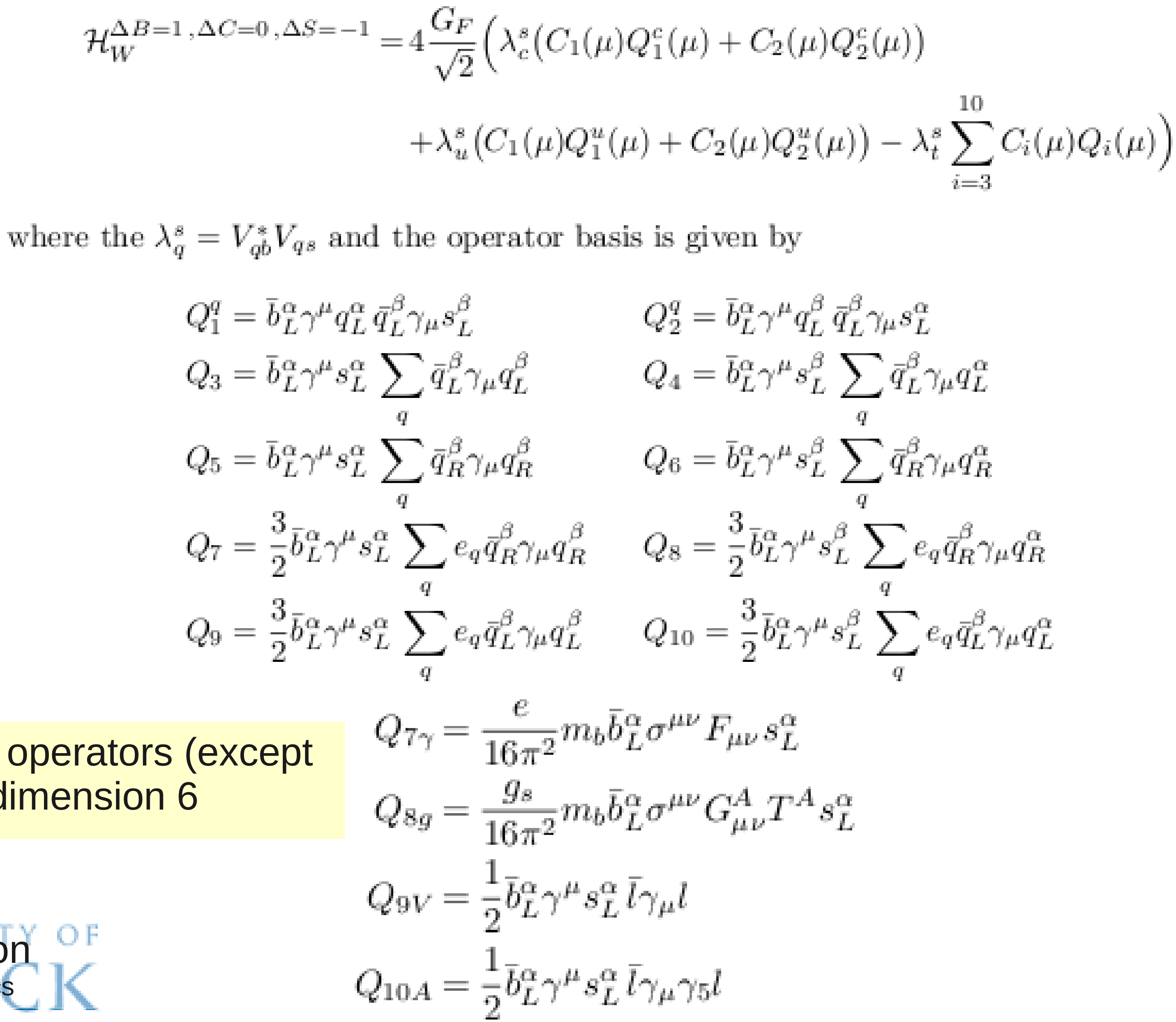
Q_n – local interaction terms (operators), C_n – coupling constants (Wilson coefficients)

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→sγ), 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

$$Q_1^q = \bar{b}_L^\alpha \gamma^\mu q_L^\alpha \, \bar{q}_L^\beta \gamma_\mu s_L^\beta \qquad Q_2^q = \bar{b}_L^\alpha \gamma^\mu q_L^\beta \, \bar{q}_L^\beta \gamma_\mu s_L^\alpha$$

$$Q_3 = \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q \bar{q}_L^\beta \gamma_\mu q_L^\beta \qquad Q_4 = \bar{b}_L^\alpha \gamma^\mu s_L^\beta \sum_q \bar{q}_L^\beta \gamma_\mu q_L^\alpha$$

$$Q_5 = \bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q \bar{q}_R^\beta \gamma_\mu q_R^\beta \qquad Q_6 = \bar{b}_L^\alpha \gamma^\mu s_L^\beta \sum_q \bar{q}_R^\beta \gamma_\mu q_R^\alpha$$

$$Q_7 = \frac{3}{2}\bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q e_q \bar{q}_R^\beta \gamma_\mu q_R^\beta \qquad Q_8 = \frac{3}{2}\bar{b}_L^\alpha \gamma^\mu s_L^\beta \sum_q e_q \bar{q}_R^\beta \gamma_\mu q_R^\alpha$$

$$Q_9 = \frac{3}{2}\bar{b}_L^\alpha \gamma^\mu s_L^\alpha \sum_q e_q \bar{q}_L^\beta \gamma_\mu q_L^\beta \qquad Q_{10} = \frac{3}{2}\bar{b}_L^\alpha \gamma^\mu s_L^\beta \sum_q e_q \bar{q}_L^\beta \gamma_\mu q_L^\alpha$$

$$Q_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{b}_L^\alpha \sigma^{\mu\nu} F_{\mu\nu} s_L^\alpha$$

$$Q_{8g} = \frac{g_s}{16\pi^2} m_b \bar{b}_L^\alpha \sigma^{\mu\nu} G_{\mu\nu}^A T^A s_L^\alpha$$

$$Q_{9V} = \frac{1}{2}\bar{b}_L^\alpha \gamma^\mu s_L^\alpha \, \bar{l}\gamma_\mu l$$

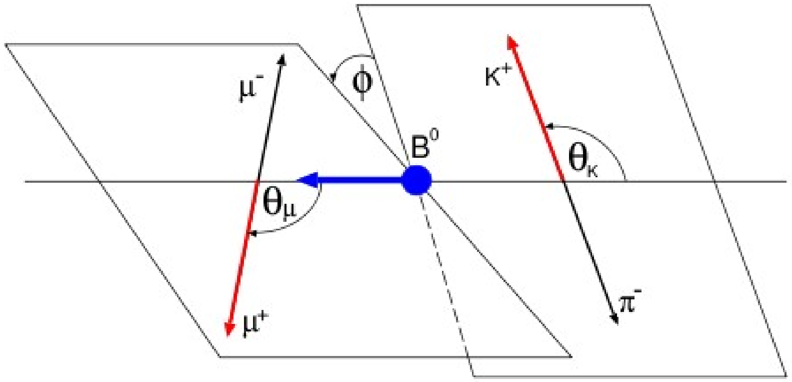
$$Q_{10A} = \frac{1}{2}\bar{b}_L^\alpha \gamma^\mu s_L^\alpha \, \bar{l}\gamma_\mu \gamma_5 l$$

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

Theory of B → K*$\mu^+\mu^-$

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

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



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

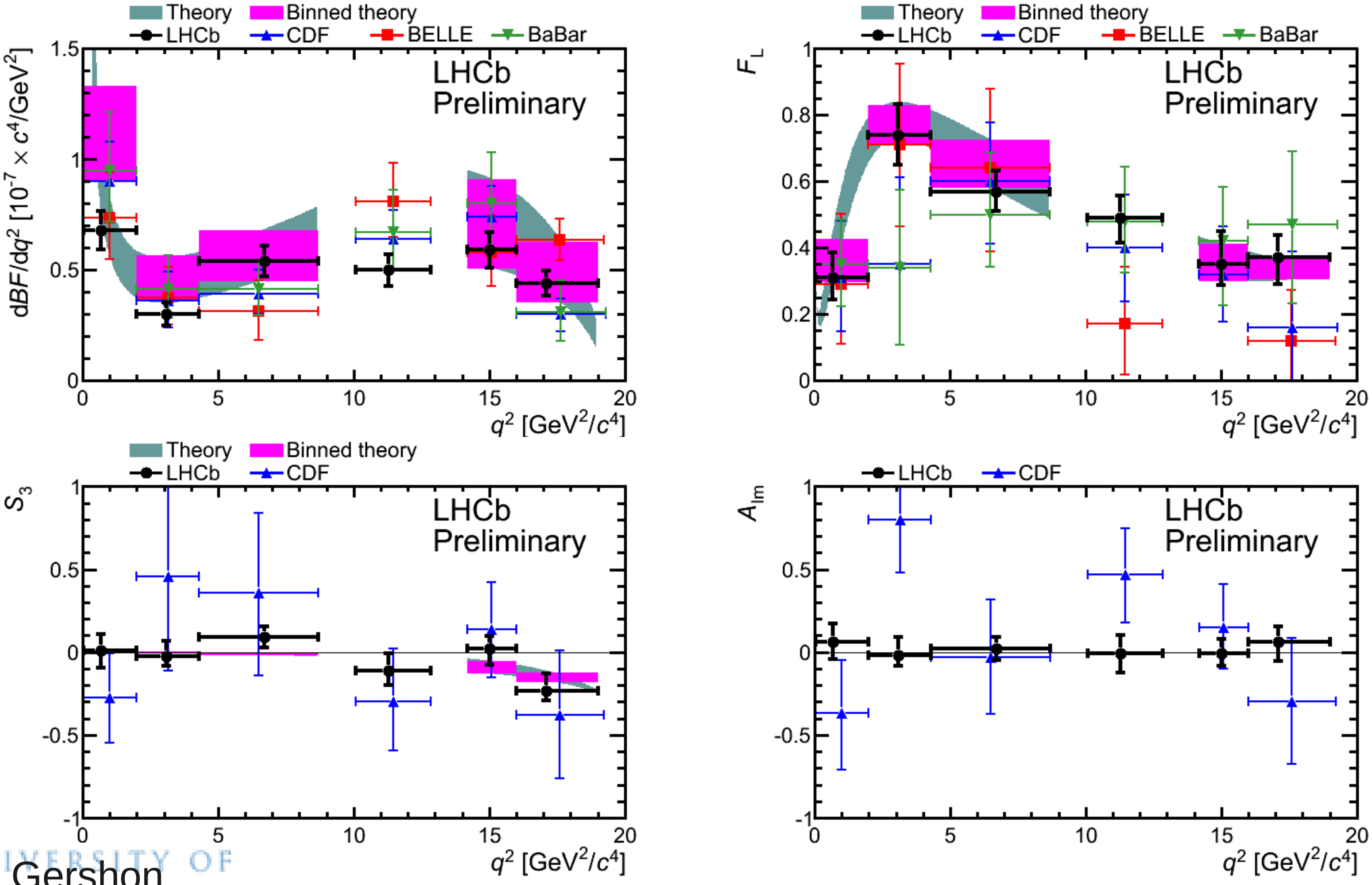
$$H_A(q^2) \propto -4q^2 C_{10}\left(C_9 + 2C_7\,\frac{m_b^2}{q^2}\right),$$

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

This term gives a forward-backward asymmetry

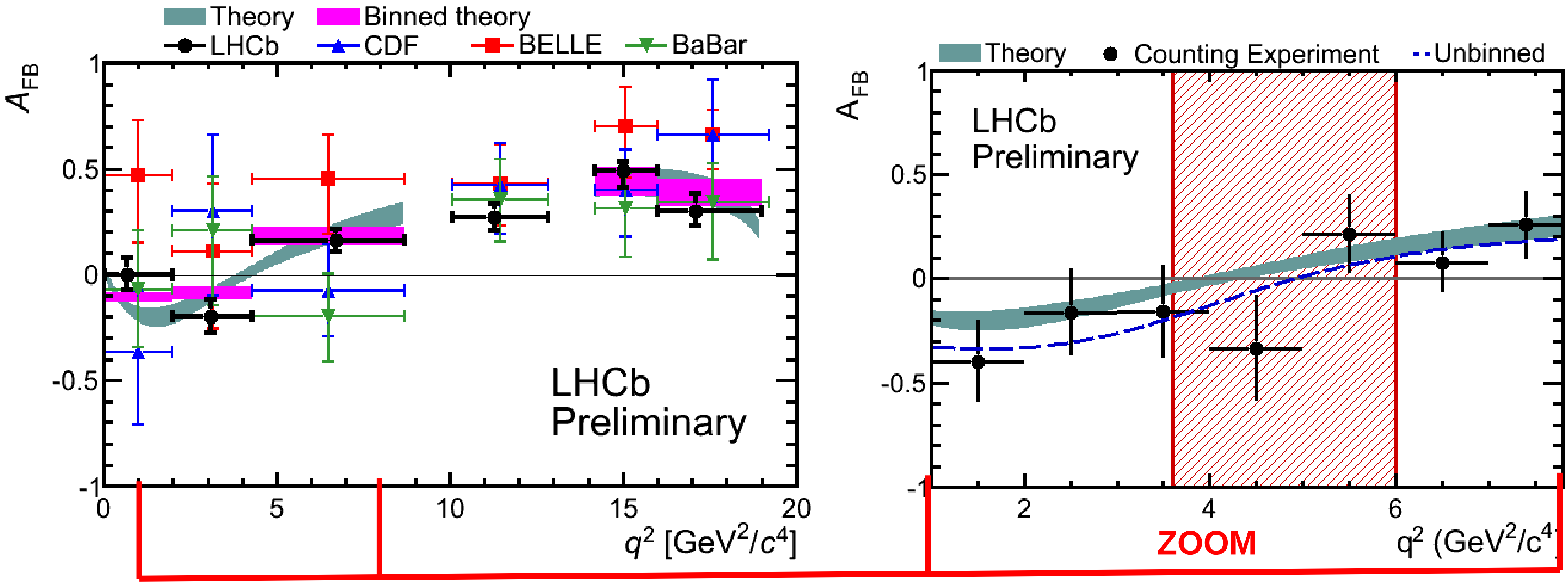
Differential branching fraction and angular analysis of the $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decay

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)

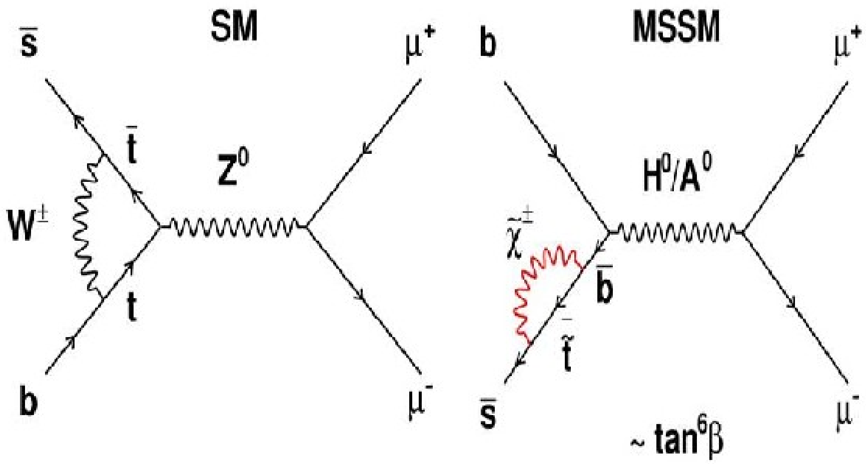
$B_s \to \mu^+\mu^-$

Killer app. for new physics discovery

- Very small in the SM
- Huge NP enhancement

(tan β = ratio of Higgs vevs)

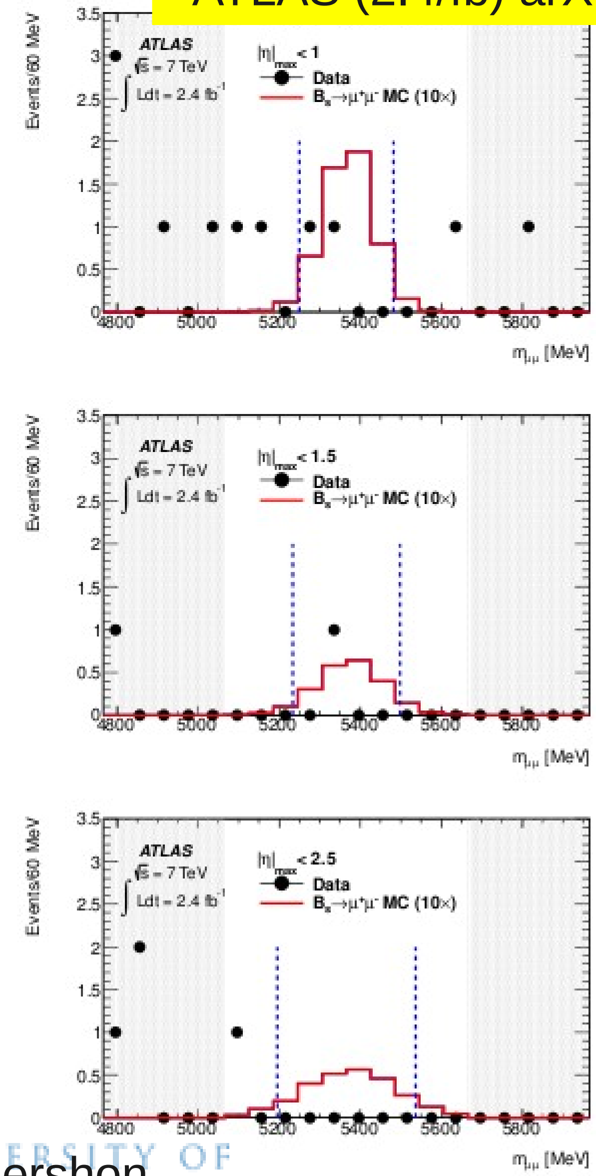
- Clean experimental signature



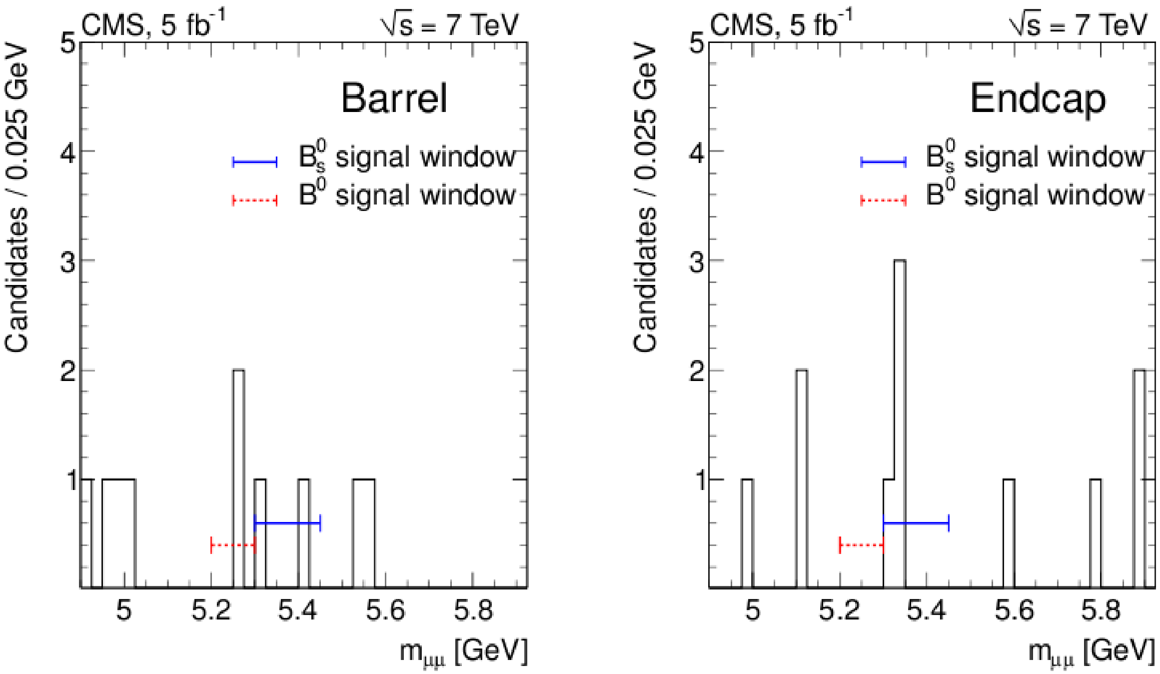
$$BR(B_s \to \mu^+\mu^-)^{SM} = (3.3 \pm 0.3) \times 10^{-8} \qquad BR(B_s \to \mu^+\mu^-)^{MSSM} \propto \tan^6\beta / M^4_{A0}$$

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

ATLAS (2.4/fb) arXiv:1204.0735



CMS (5/fb) arXiv:1203.3976

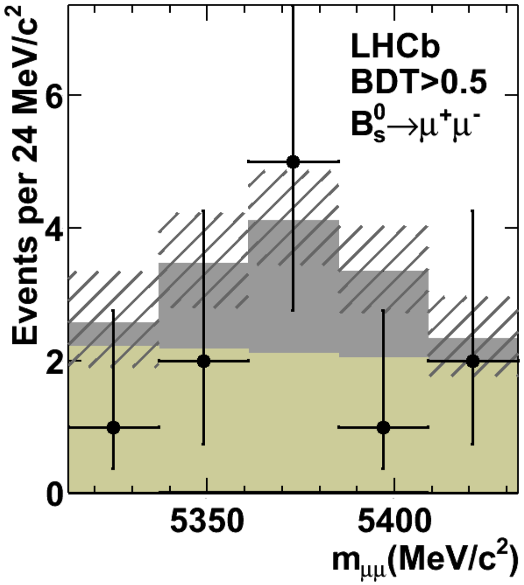


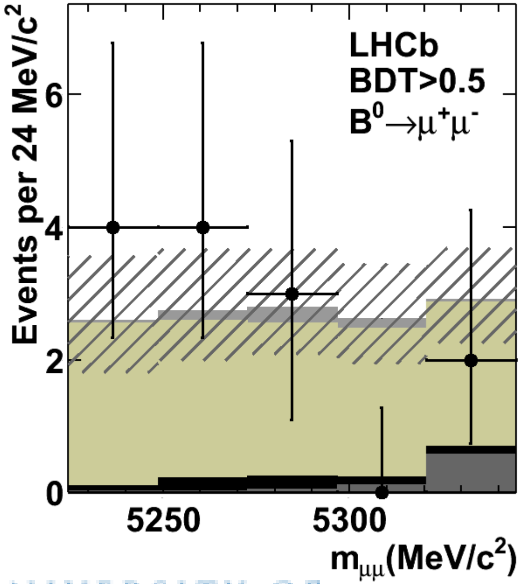
ATLAS $B(B_s \rightarrow \mu^+\mu^-) < 2.2\ (1.9) \times 10^{-8}$ @ 95% (90%) CL

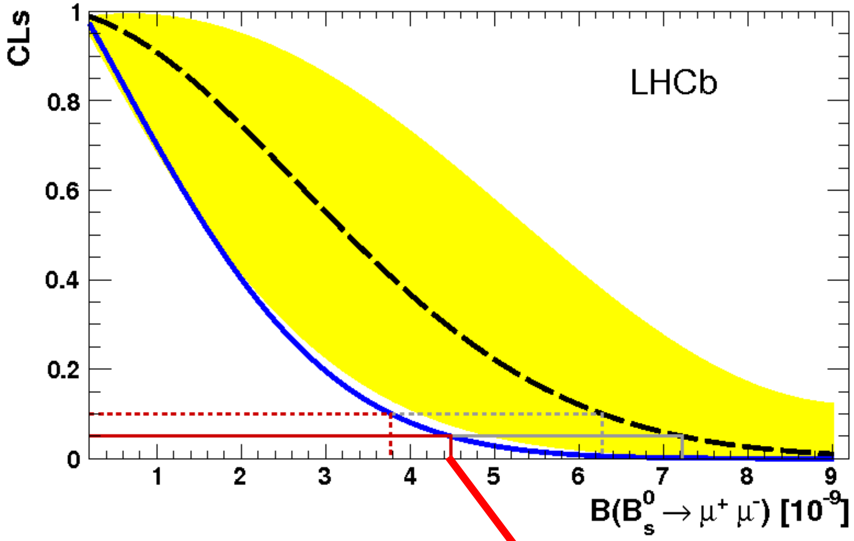
CMS $B(B_s \rightarrow \mu^+\mu^-) < 7.7\ (6.4) \times 10^{-9}$ @ 95% (90%) CL

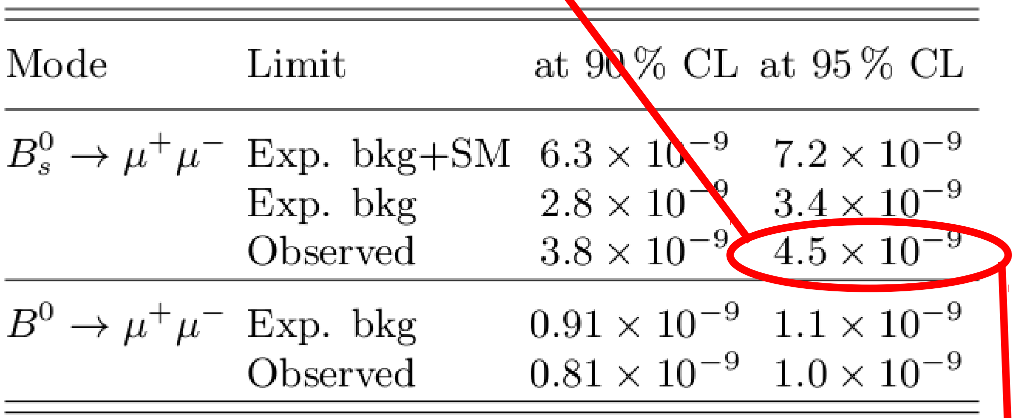
Latest results on $B_s \rightarrow \mu^+\mu^-$

LHCb (1/fb) arXiv:1203.4493









Mode	Limit	at 90 % CL	at 95 % CL
$B_s^0 \rightarrow \mu^+\mu^-$	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}
$B^0 \rightarrow \mu^+\mu^-$	Exp. bkg	0.91×10^{-9}	1.1×10^{-9}
	Observed	0.81×10^{-9}	1.0×10^{-9}

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

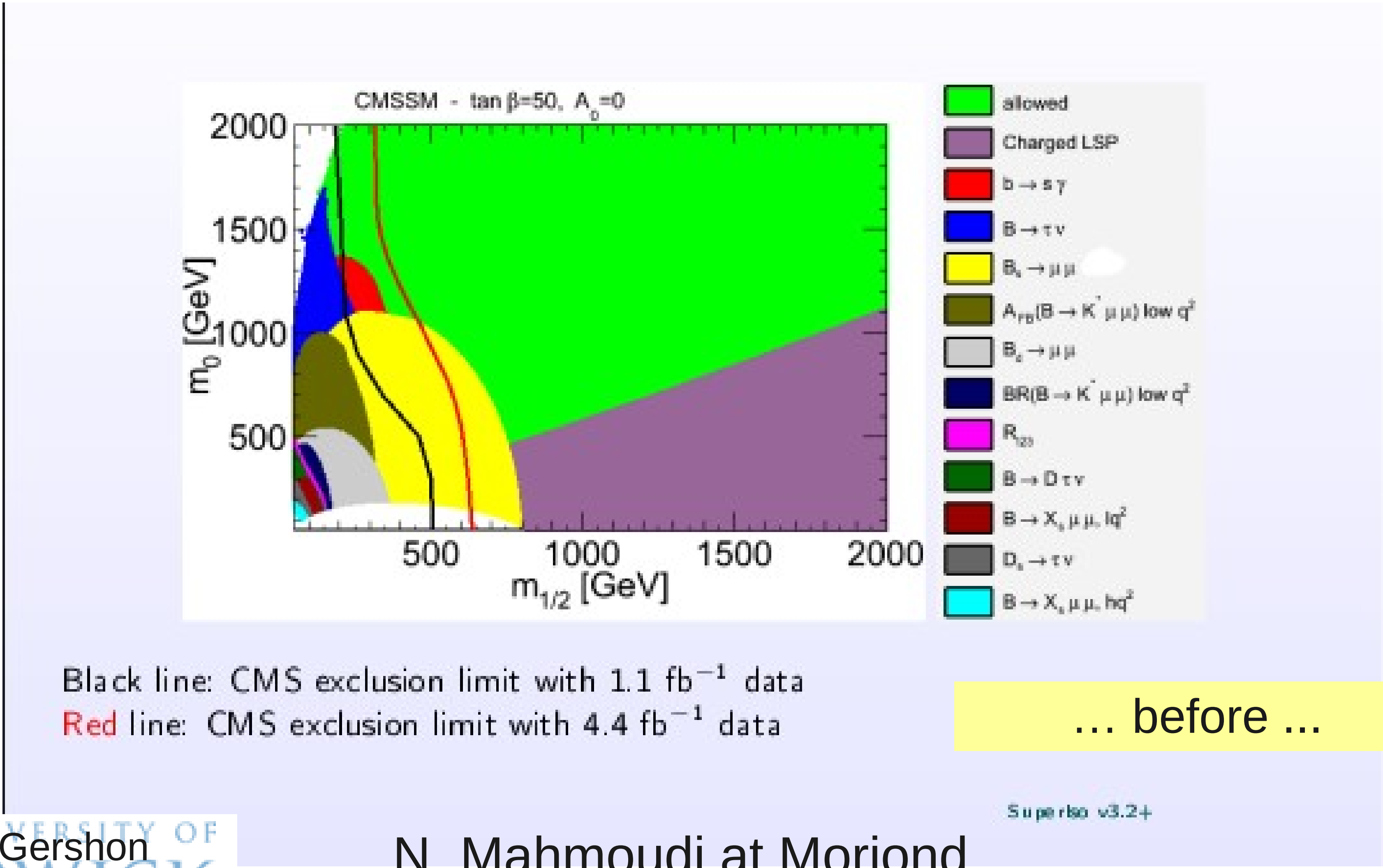
Buras, arXiv:1012.1447

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

Implications

G.Dissertori Moriond QCD summary talk:

"Numbers most often mentioned: 3.2×10^{-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

SuperIso v3.2+

… before ...

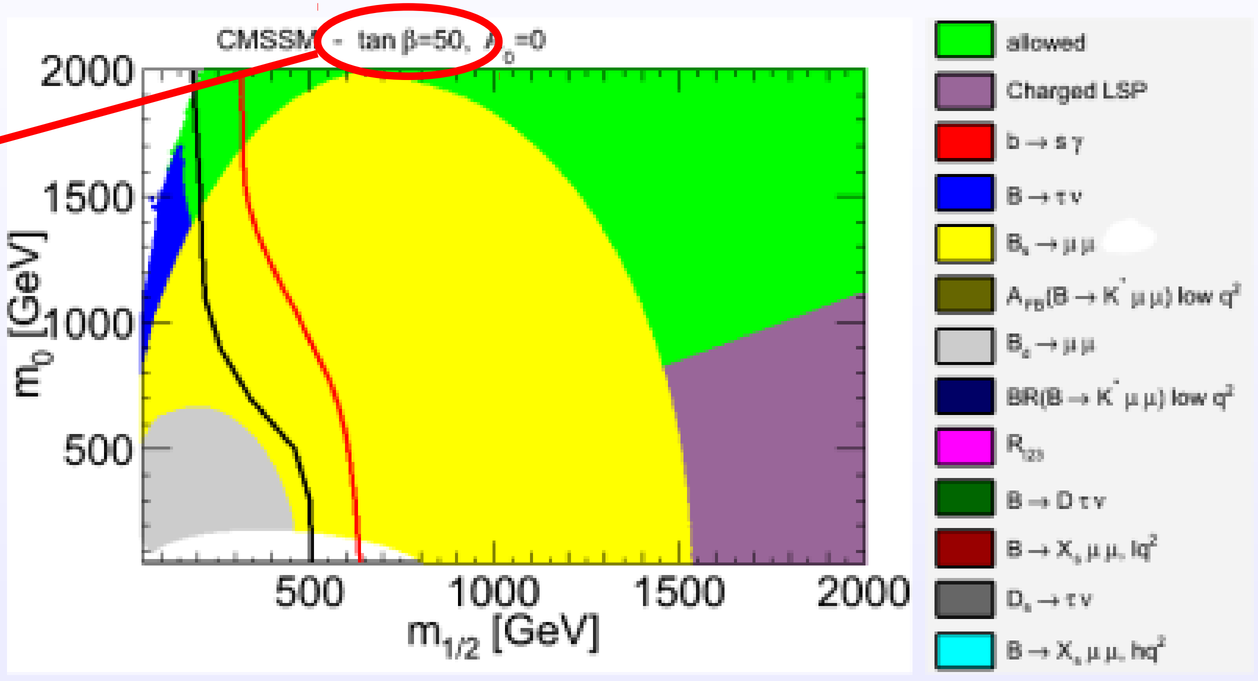
N. Mahmoudi at Moriond

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

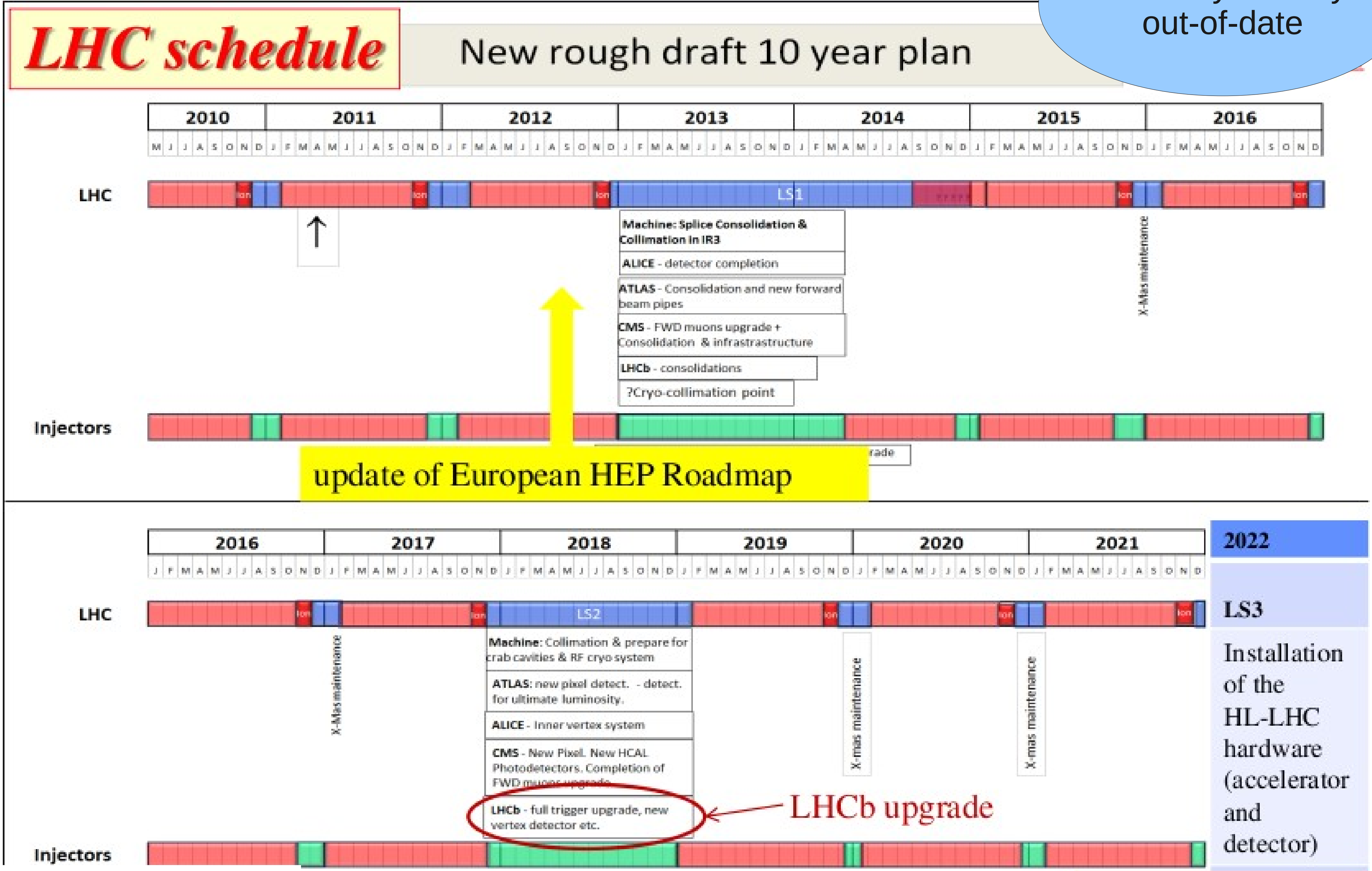
LHCb upgrade

- 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

- Physics case:
  - “exploration” of 1st phase will become “precision studies”
  - new opportunities for exploration open up (e.g. testing consistency of CP violation in tree vs. loop processes)

What is the LHC era?

Probably already out-of-date



LHC schedule

New rough draft 10 year plan

Machine: Splice Consolidation & Collimation in IR3

ALICE - detector completion

ATLAS - Consolidation and new forward beam pipes

CMS - FWD muons upgrade + Consolidation & infrastrastructure

LHCb - consolidations

?Cryo-collimation point

update of European HEP Roadmap

Machine: Collimation & prepare for crab cavities & RF cryo system

ATLAS: new pixel detect. - detect. for ultimate luminosity.

ALICE - Inner vertex system

CMS - New Pixel. New HCAL Photodetectors. Completion of FWD muons upgrade

LHCb - full trigger upgrade, new vertex detector etc.

LHCb upgrade

Installation of the HL-LHC hardware (accelerator and detector)

… it is the foreseeable future!

Other future flavour experiments

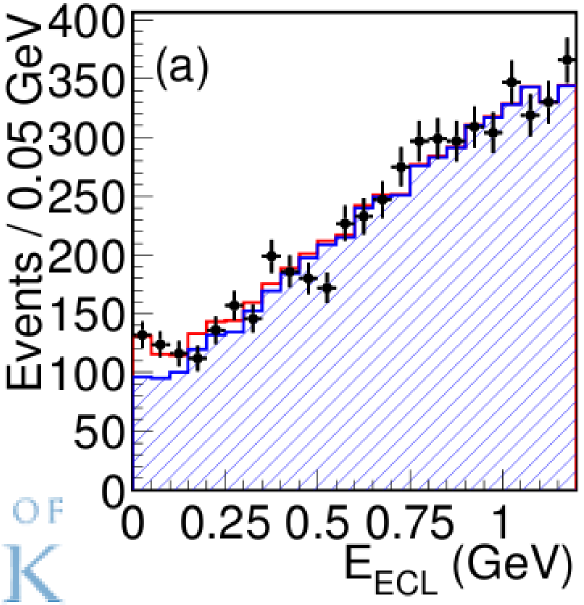
- SuperKEKB/Belle2 & SuperB
  - $B \to \tau\nu$, inclusive measurements, τ physics, …
- Rare kaon decays
  - $K^+ \to \pi^+\nu\nu$ (NA62, CERN); $K^0 \to \pi^0\nu\nu$ (K0T0, J-PARC)
- Muon to electron conversion (charged lepton flavour violation)
  - COMET/PRIME (J-PARC); mu2e (FNAL)

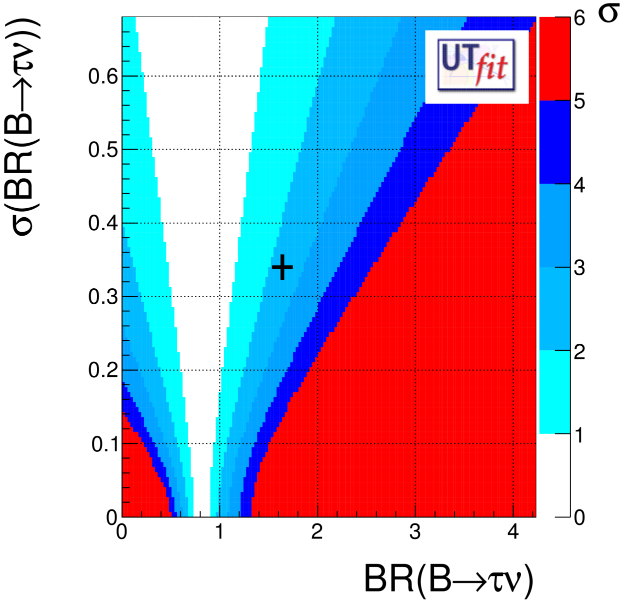
B → τν and charged Higgs limits

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

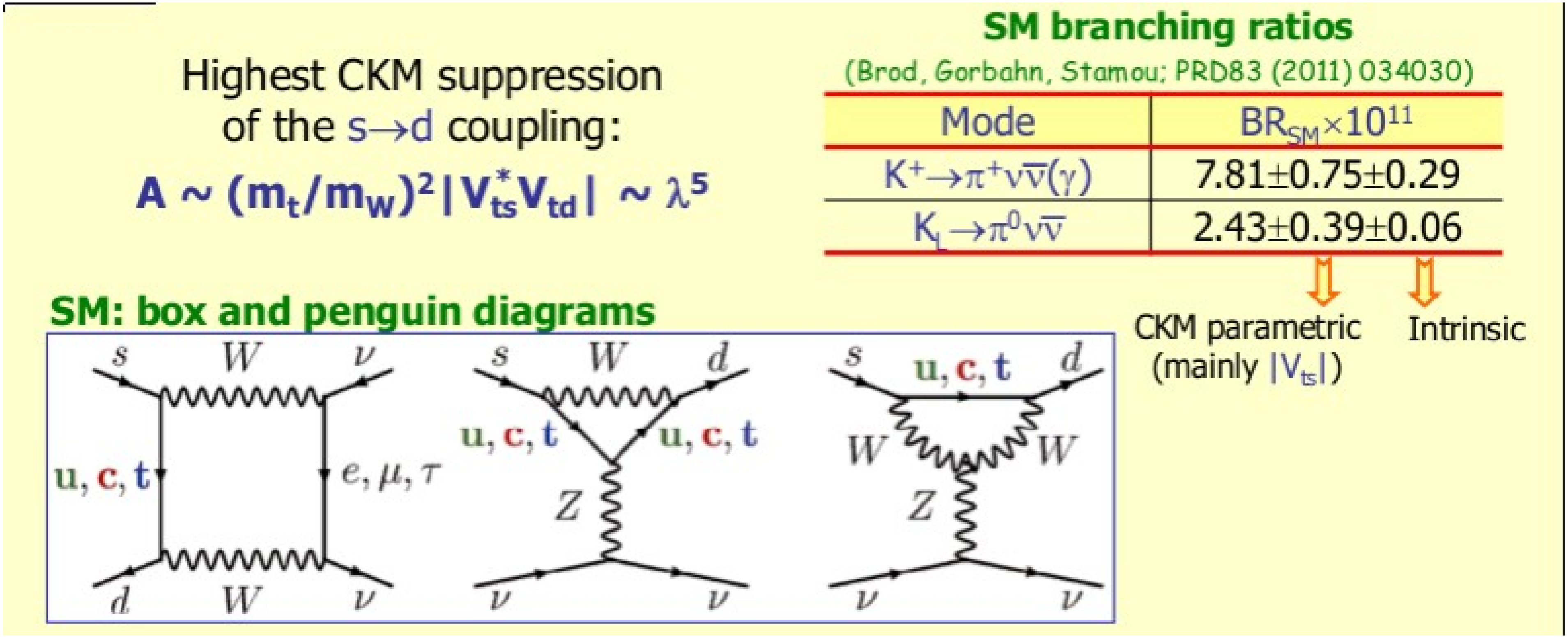
$$BR(B^+ \to l^+ \nu)^{SM} = \frac{G_F\, m_B}{8\pi} m_l^2 \left(1 - \frac{m_l^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B \qquad BR(B^+ \to l^+ \nu)^{NP} = BR(B^+ \to l^+ \nu)^{SM} \left(1 - \frac{m_B^2}{m_H^2} \tan^2\beta\right)^2$$

Belle PRD 82 (2010) 071101





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



Highest CKM suppression of the s→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	$BR_{SM} \times 10^{11}$
$K^+ \to \pi^+ \nu\bar{\nu}(\gamma)$	$7.81 \pm 0.75 \pm 0.29$
$K_L \to \pi^0 \nu\bar{\nu}$	$2.43 \pm 0.39 \pm 0.06$

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

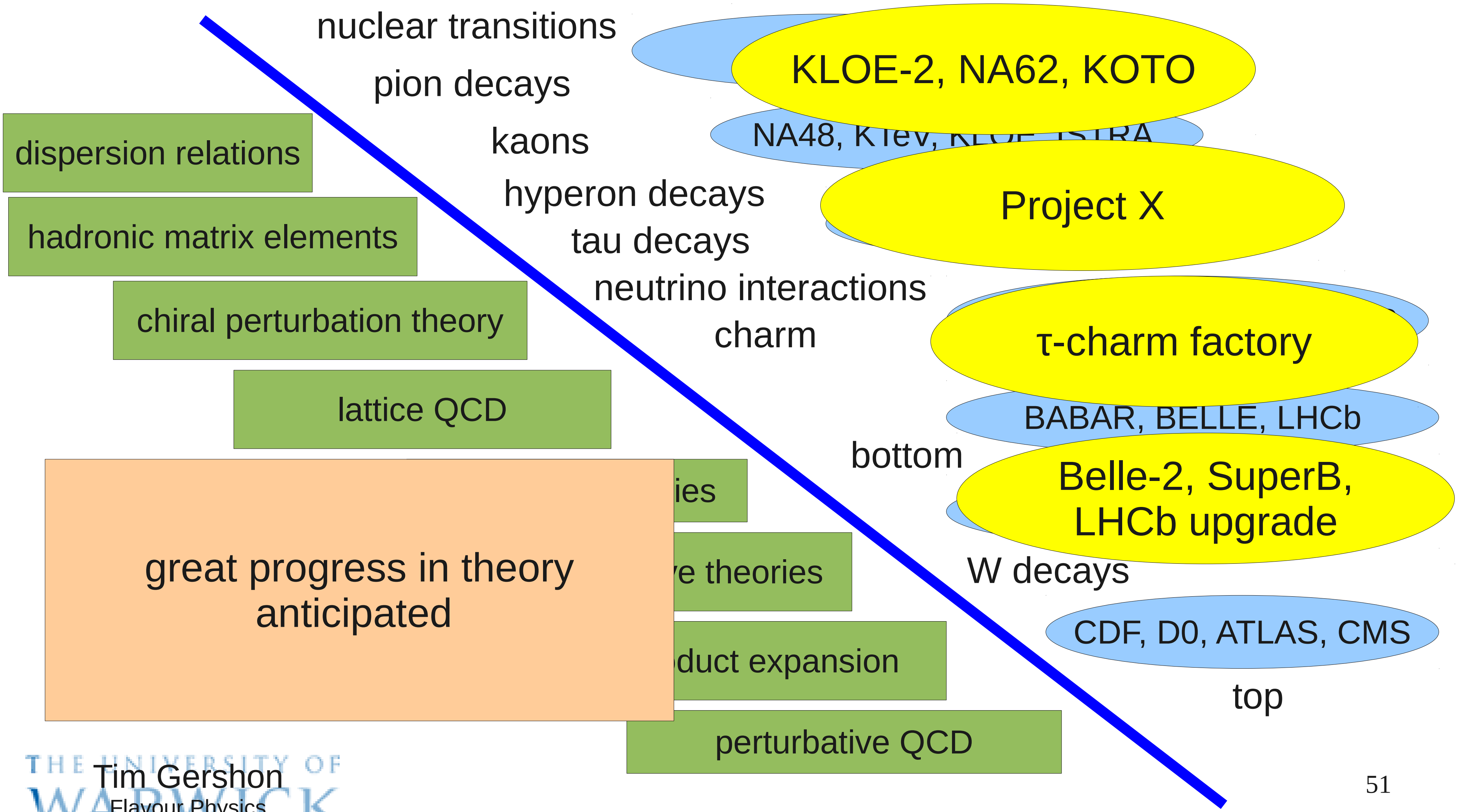
Intrinsic

SM: box and penguin diagrams

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

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

Future projects



nuclear transitions

pion decays

kaons

hyperon decays

tau decays

neutrino interactions

charm

bottom

W decays

top

KLOE-2, NA62, KOTO

NA48, KTeV, KLOE ISTRA

Project X

τ-charm factory

BABAR, BELLE, LHCb

Belle-2, SuperB, LHCb upgrade

CDF, D0, ATLAS, CMS

dispersion relations

hadronic matrix elements

chiral perturbation theory

lattice QCD

ies

e theories

duct expansion

perturbative QCD

great progress in theory anticipated

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)