Heavy Flavour Physics
Lecture 3 of 3

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Contents

Today I'd better cover Part 3

(no really)

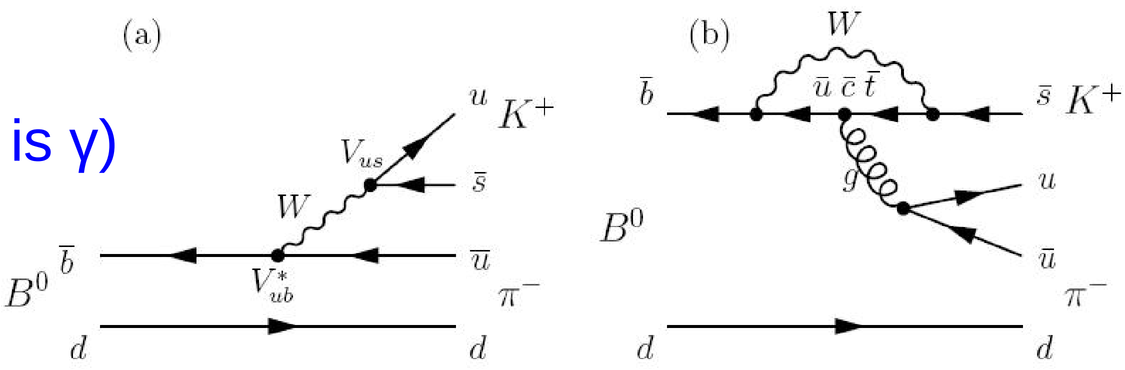
CP violation in decay

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

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

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

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

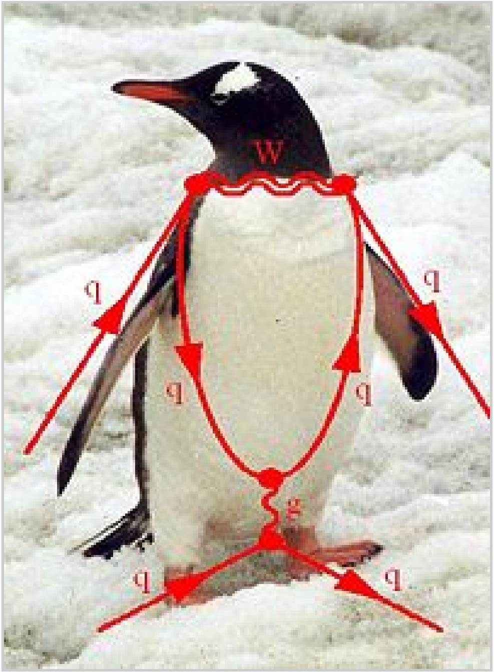
In quantum field theory, **penguin diagrams** are a class of Feynman diagrams which are important for understanding CP violating processes in the standard model. They were first isolated and studied by Mikhail Shifman, Arkady Vainshtein, and Valentin Zakharov.[1] The processes which they describe were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

Penguin diagram

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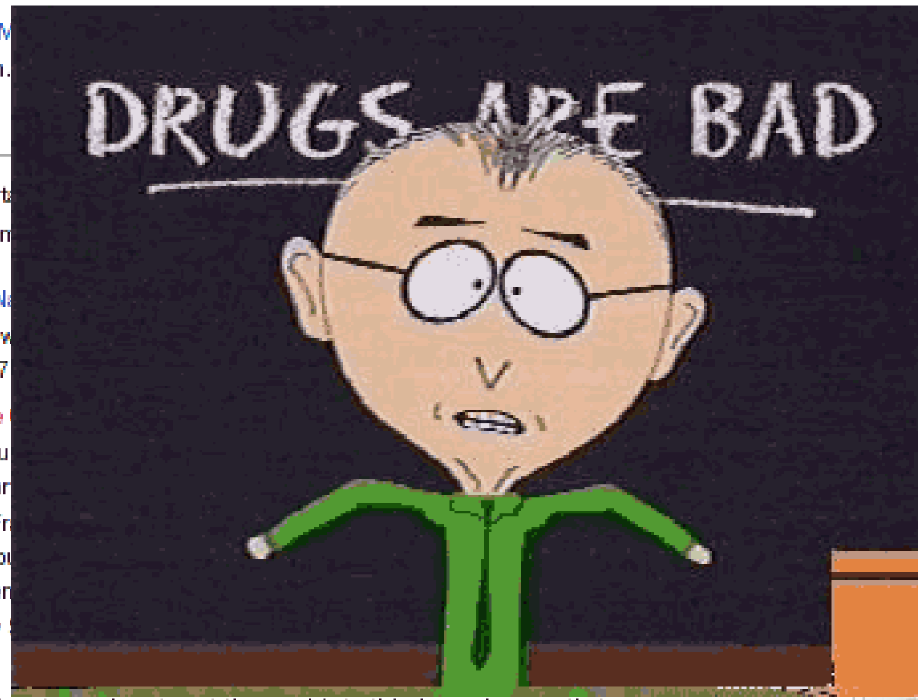

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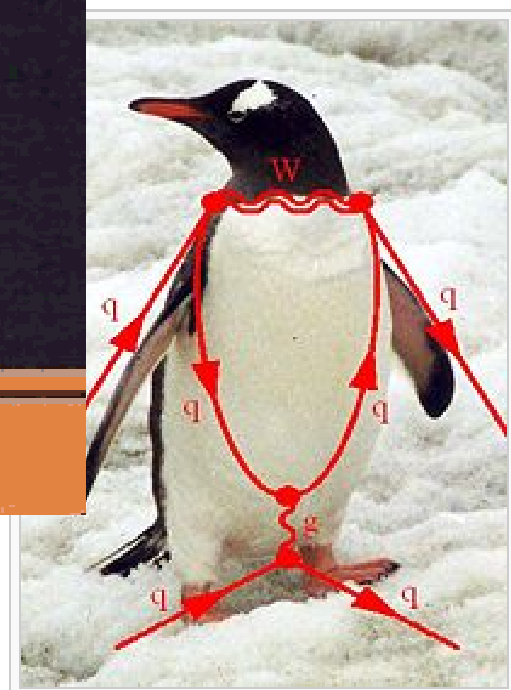
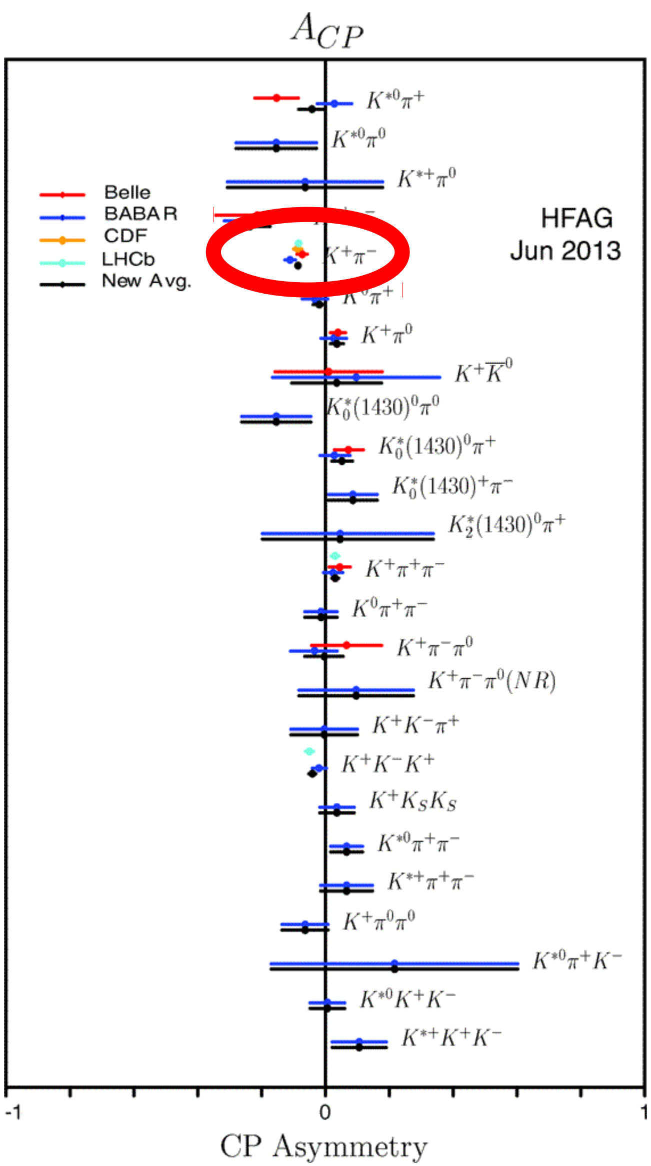
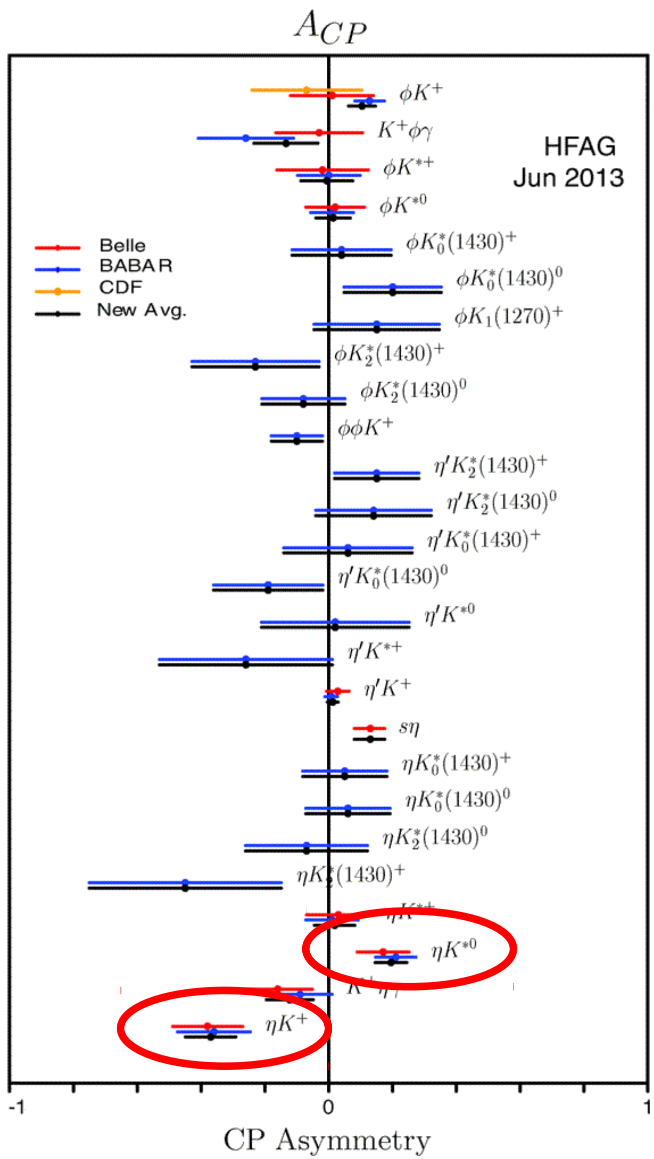
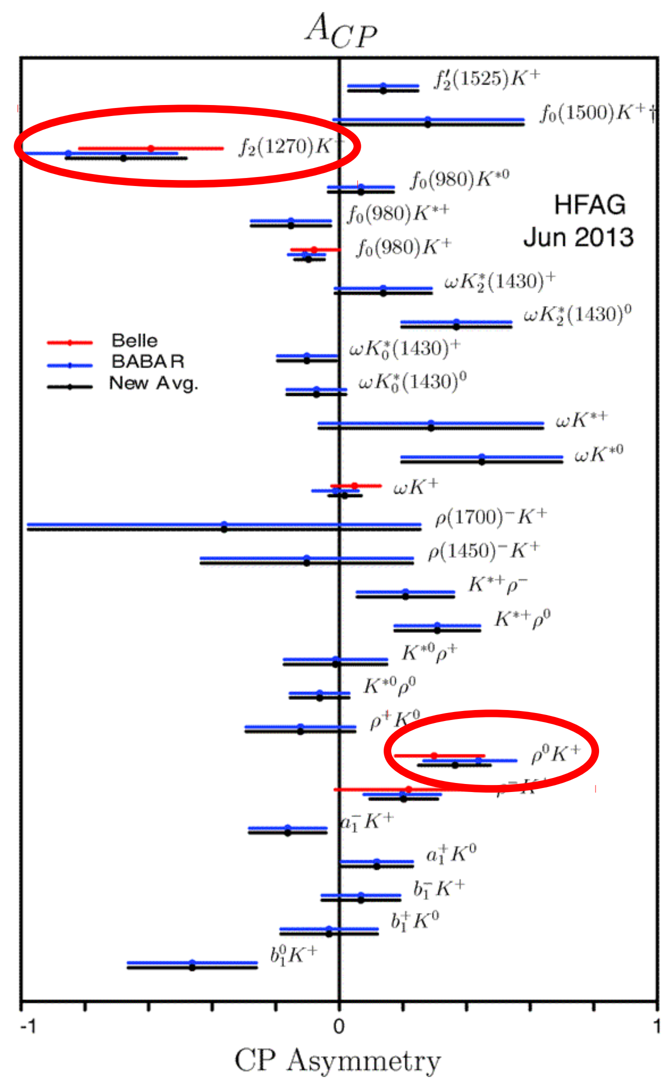


Example of a penguin diagram

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

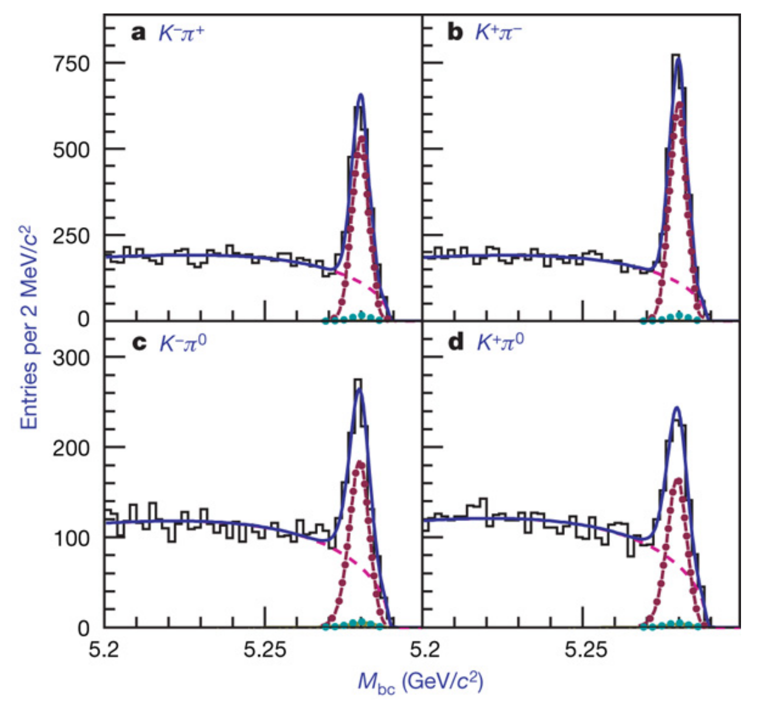
NB. interesting deviation from naïve expectation

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.)

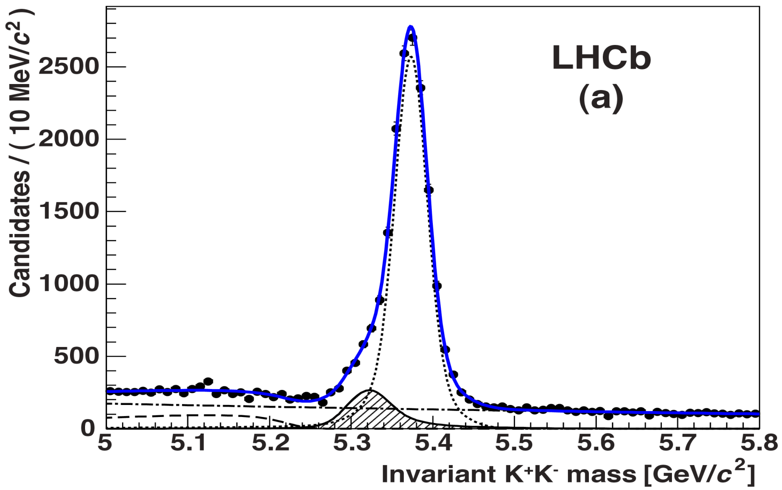
- Measure more $B_{u,d}\to K\pi$ decays & relate by isospin
- Perform similar analysis on $B\to K^*\pi$ &/or $B\to K\rho$
  - Dalitz plot analyses of $K\pi\pi$ final states extract both amplitudes and relative phases $\to$ more observables
- Measure $B_s\to KK$ decays & relate by U-spin
  - e.g. relation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

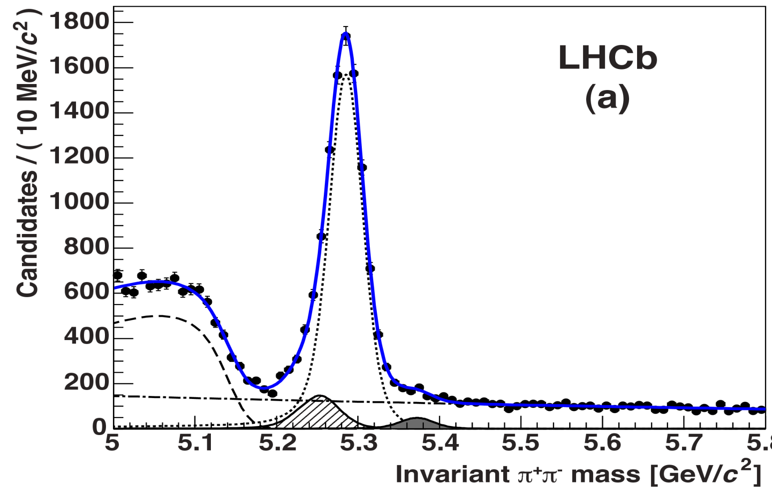
Note: flavour symmetries very useful
But, still get theory error from symmetry breaking (difficult to evaluate)
… data driven methods will win in the end (unless miracle breakthrough)

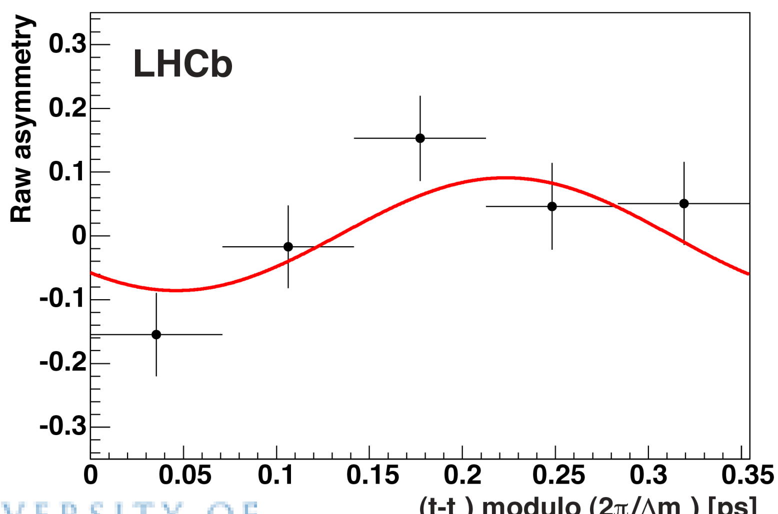
$B^0 \to \pi^+\pi^-$ & $B_s^0 \to K^+K^-$

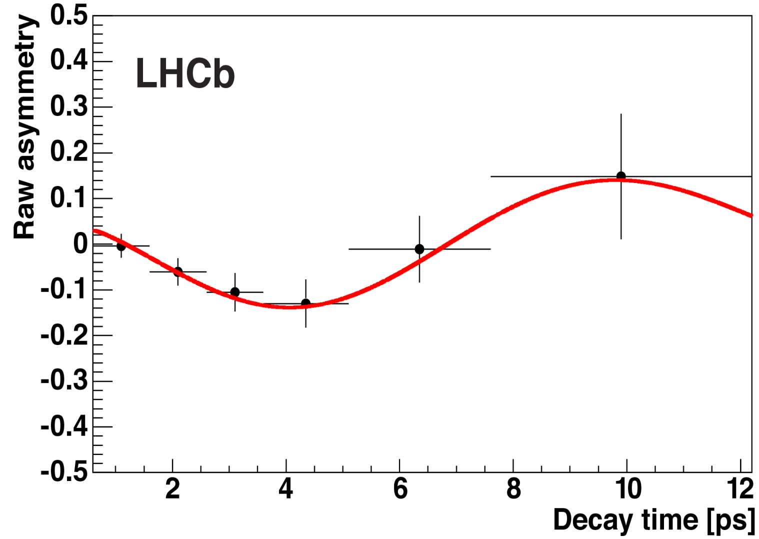
First CP violation measurements in these channels at a hadron collider ($B^0 \to \pi^+\pi^-$) / ever ($B_s^0 \to K^+K^-$)

JHEP 10 (2013) 183







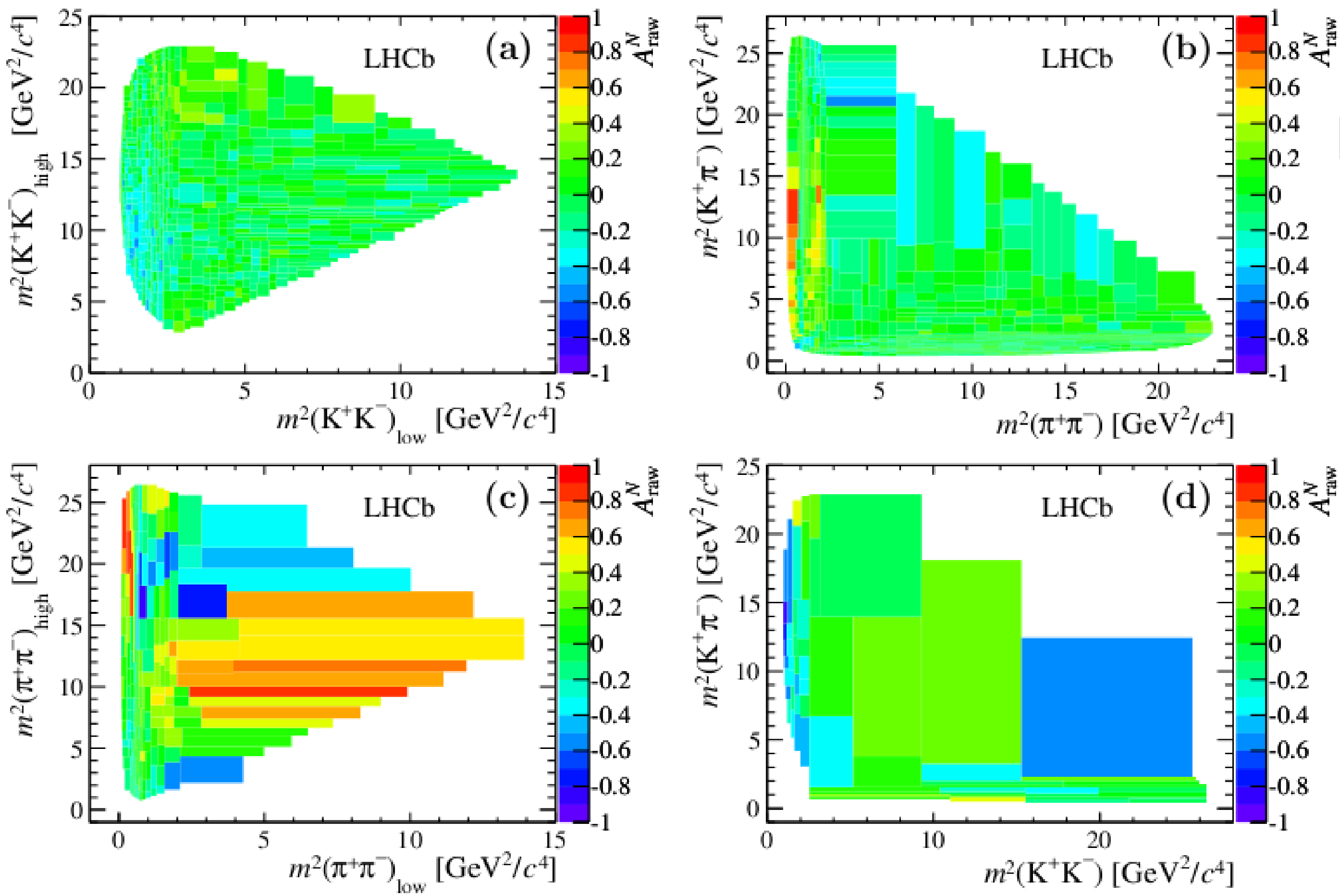


Latest results on multibody charmless B decays

PRD 90 (2014) 112004

B → KKK

B → Kππ



B → πππ

B → KKπ

Large CP violation effects with strong variation across the Dalitz plot

Detailed studies will be necessary to understand origin of these effects

Importance of γ from B → DK

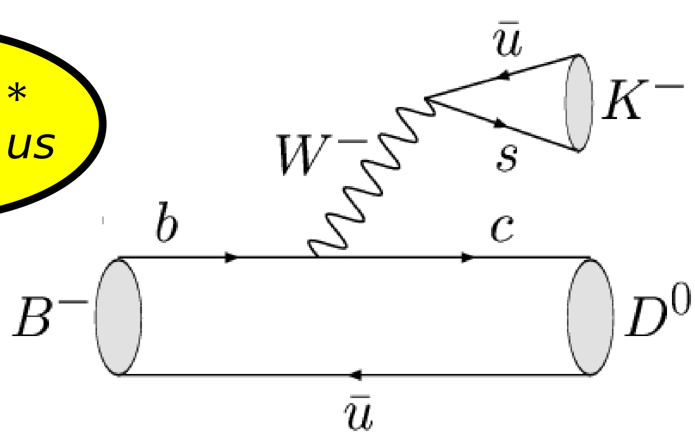
- γ plays a unique role in flavour physics

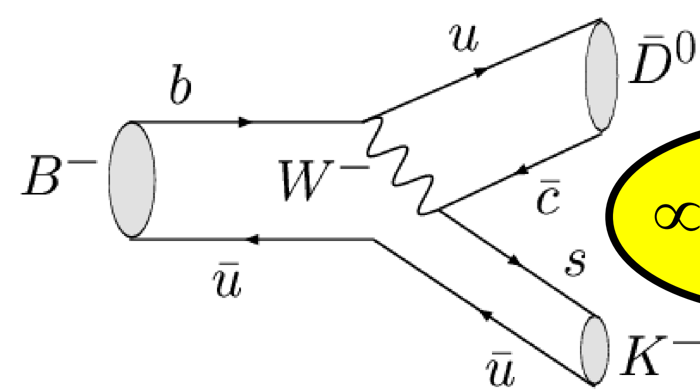
the only CP violating parameter that can be measured through tree decays (*)

(*) more-or-less

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

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





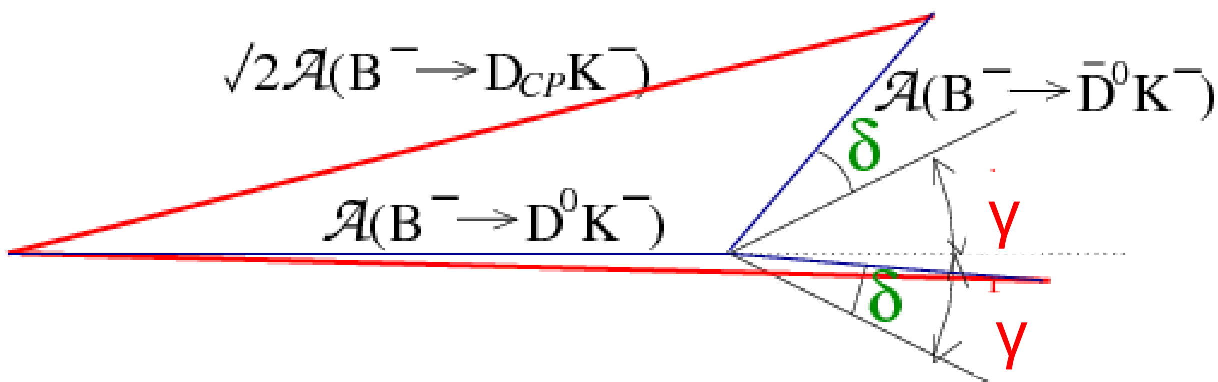
$\propto V_{ub} V_{cs}^{*}$

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)
  - $B^0 \to DK_S$, $B_s^0 \to D\phi$ (with or without time-dependence)
  - $B_s^0 \to D_sK$, $B^0 \to D^{(*)}\pi$ (time-dependent)

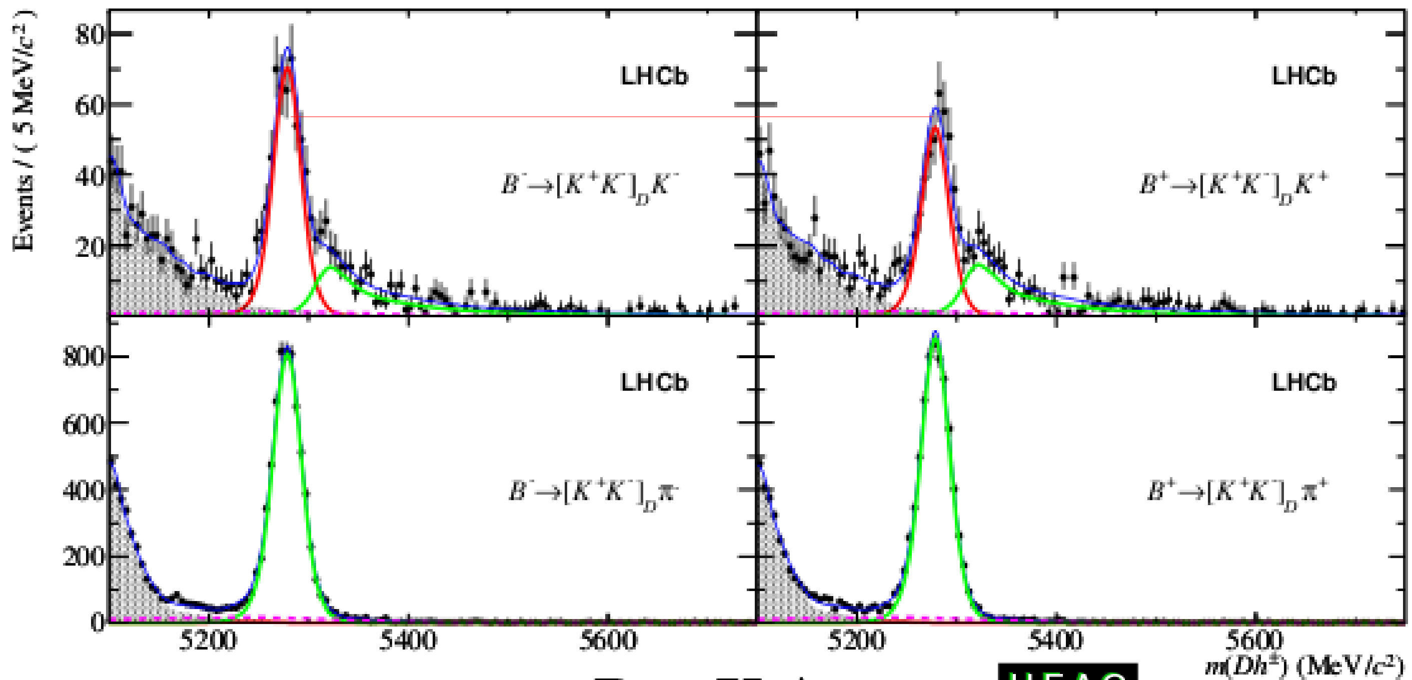
Search for CP violation in decay caused by $\gamma \neq 0$

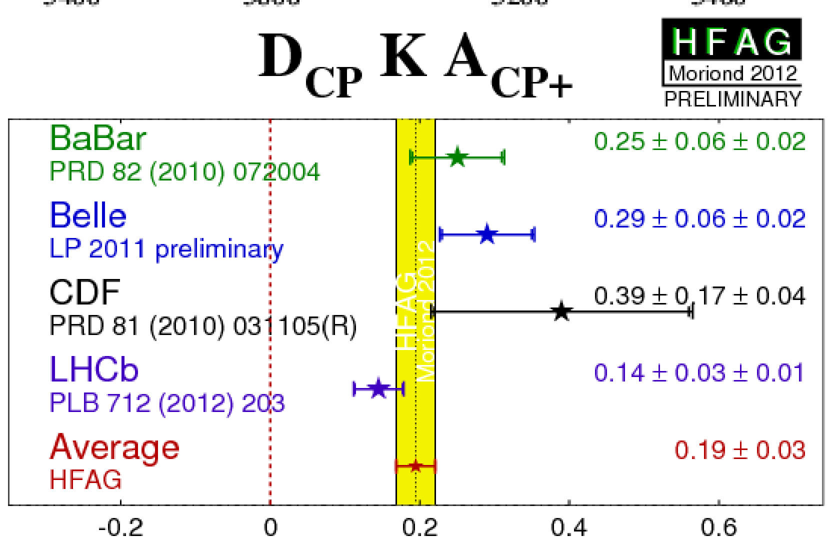
All parameters from data – no theory input needed

Latest results on B→DK : GLW

PLB 712 (2012) 203

Evidence for CP violation (γ≠0)





Observed CP violation effects

As listed in PDG 2014

- 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
  - $S_{\psi K0} = +0.682 \pm 0.019$
  - $S_{\eta' K0} = +0.63 \pm 0.06$, $S_{\varphi K0} = +0.74^{+0.11}_{-0.13}$, $S_{f0K0} = +0.69^{+0.10}_{-0.12}$, $S_{K+K-K0} = +0.68^{+0.09}_{-0.10}$
  - $S_{\pi+\pi-} = -0.66 \pm 0.06$, $C_{\pi+\pi-} = -0.31 \pm 0.05$
  - $S_{\psi\pi0} = -0.93 \pm 0.15$, $S_{D+D-} = -0.98 \pm 0.17$, $S_{D*+D*-} = -0.71 \pm 0.09$
  - $A_{K\mp\pi\pm} = -0.082 \pm 0.006$, $A_{Bs\to K\mp\pi\pm} = -0.082 \pm 0.006$
  - $A_{D(CP+)K\pm} = +0.19 \pm 0.03$, CP violation in the phase space of $B\to 3h$ decays

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

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

$$\times \left[\cosh \frac{\Delta\Gamma \, t}{2} + \mathcal{A}_{\rm CP}^{\rm dir} \, \cos(\Delta m \, t) + \mathcal{A}_{\Delta\Gamma} \, \sinh \frac{\Delta\Gamma \, t}{2} + \mathcal{A}_{\rm CP}^{\rm mix} \, \sin(\Delta m \, t) \right]$$

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

$$\times \left[\cosh \frac{\Delta\Gamma \, t}{2} - \mathcal{A}_{\rm CP}^{\rm dir} \, \cos(\Delta m \, t) + \mathcal{A}_{\Delta\Gamma} \, \sinh \frac{\Delta\Gamma \, t}{2} - \mathcal{A}_{\rm CP}^{\rm mix} \, \sin(\Delta m \, t) \right] .$$

Time-dependent CP Violation Formalism

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$$\times \left[\cosh\frac{\Delta\Gamma\, t}{2} - \mathcal{A}^{\rm dir}_{\rm CP} \cos(\Delta m\, t) + \mathcal{A}_{\Delta\Gamma} \sinh\frac{\Delta\Gamma\, t}{2} - \mathcal{A}^{\rm mix}_{\rm CP} \sin(\Delta m\, t) \right].$$

CP violating asymmetries

CP conserving parameter

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

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

Time-dependent CP Violation Formalism

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

- Untagged analyses still sensitive to some interesting physics

Time-dependent CP Violation Formalism

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

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

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

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

Time-dependent CP Violation Formalism

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

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

- In some channels, expect no CP violation in decay
- B_d case: $\Delta\Gamma$ negligible

Time-dependent CP Violation Formalism

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

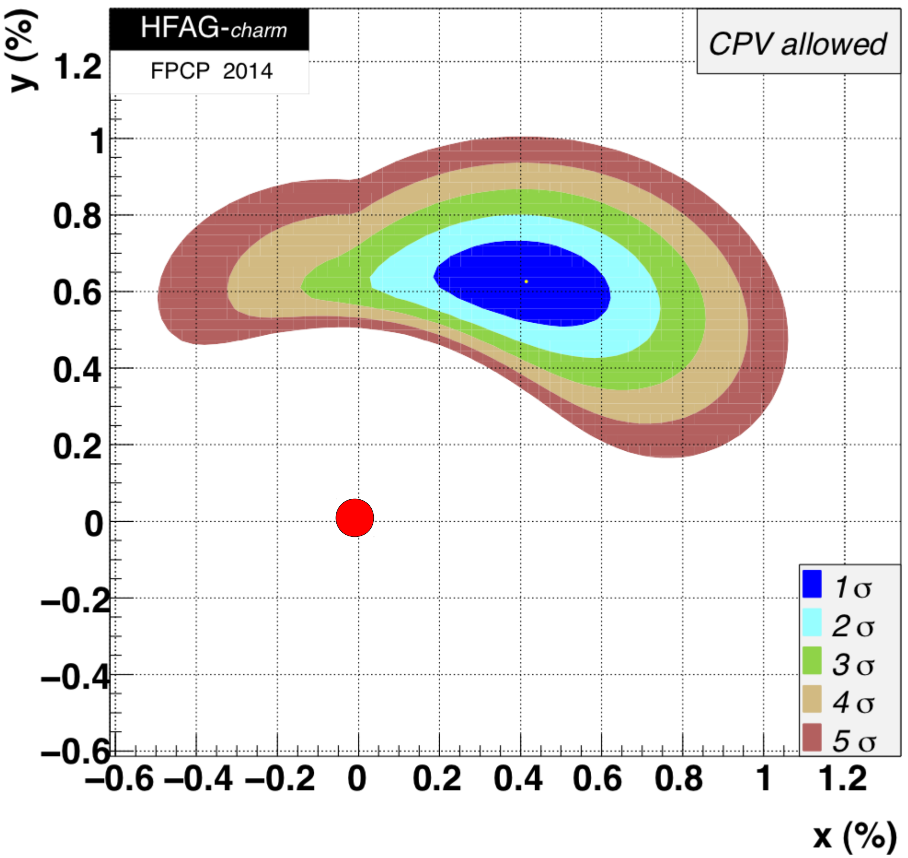
$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t} \times \left[1 + \mathcal{A}_{CP}^{dir} \; 1 + \mathcal{A}_{\Delta\Gamma} \; y\Gamma t + \mathcal{A}_{CP}^{mix} \; x\Gamma t \right]$$

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

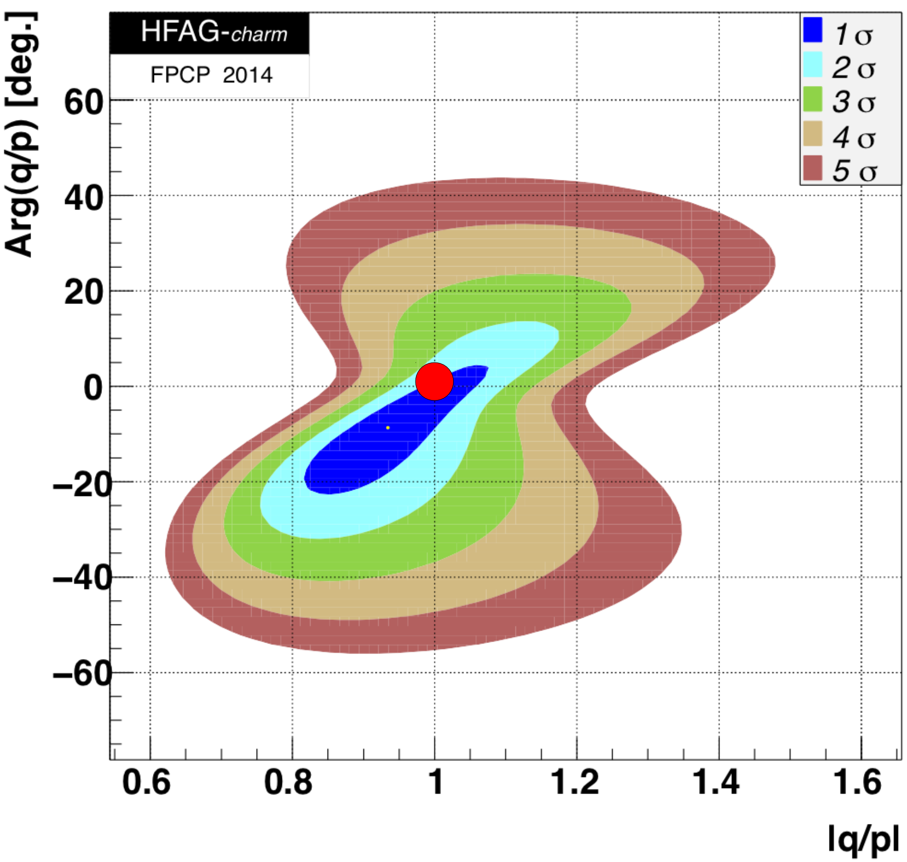
- In some channels, expect no CP violation in decay
- B_d case: ΔΓ negligible
- D^0 case: both x = Δm/Γ and y=ΔΓ/2Γ small

Charm mixing and CP violation

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



Inconsistent with no mixing point (0,0)



Consistent with no CP violation point (1,0)

CP violation in D decay?

e.g. PRL 108 (2012) 111602

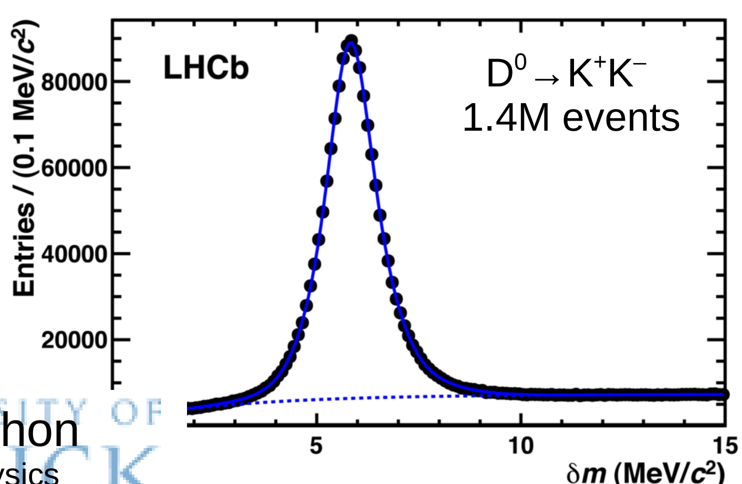
Measurement of CP asymmetry at pp collider requires knowledge of production and detection asymmetries; e.g. for $D^0 \rightarrow f$, where D meson flavour is tagged by $D^{*+} \rightarrow D^0\pi^+$ decay

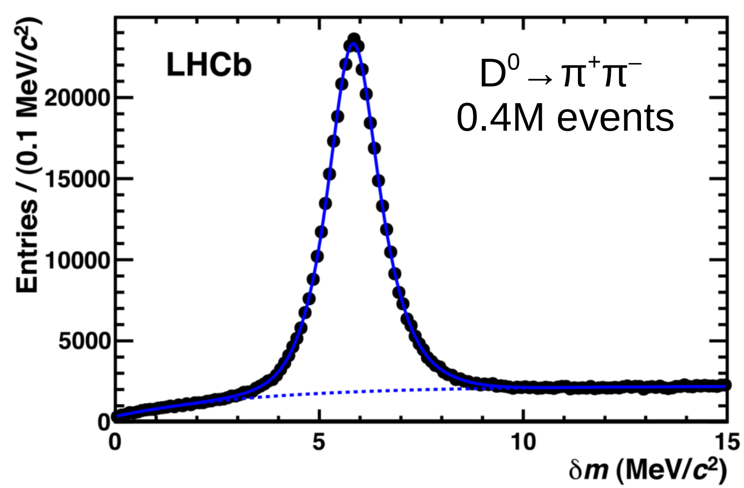
$$A_{\rm raw}(f) = A_{CP}(f) + A_{\rm D}(f) + A_{\rm D}(\pi_s^+) + A_{\rm P}(D^{*+}).$$

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)

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





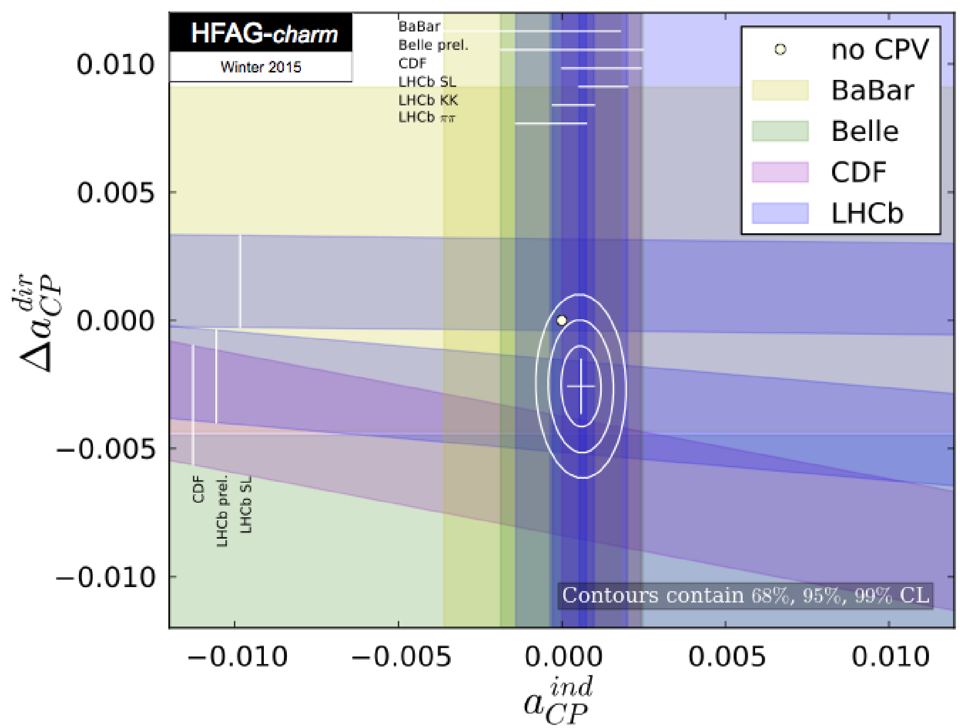
CP violation in D decays

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

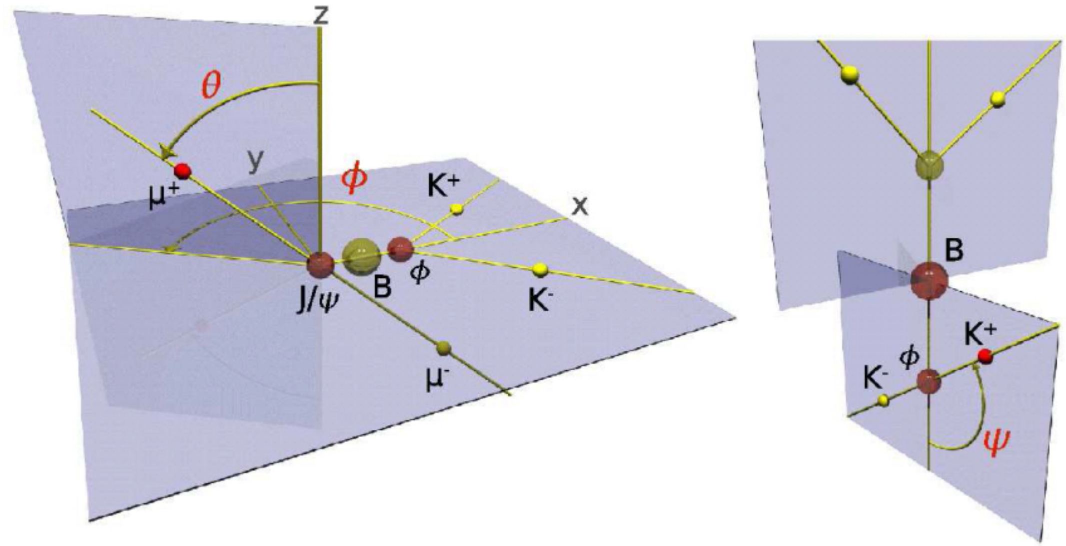
Singly Cabibbo-suppressed decays have tree and penguin contributions

Two body decays give largest yields – best sensitivity

Small contribution from “indirect” CP asymmetry due to non-perfect cancellation of decay time acceptance – also measured with decay-time-dependent methods



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



- 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 $\overline{\text{Bs}}$

$A_0(0) \to$ CP even
$A_{||}(0) \to$ CP even
$A_\perp(0) \to$ CP odd

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

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

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

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

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

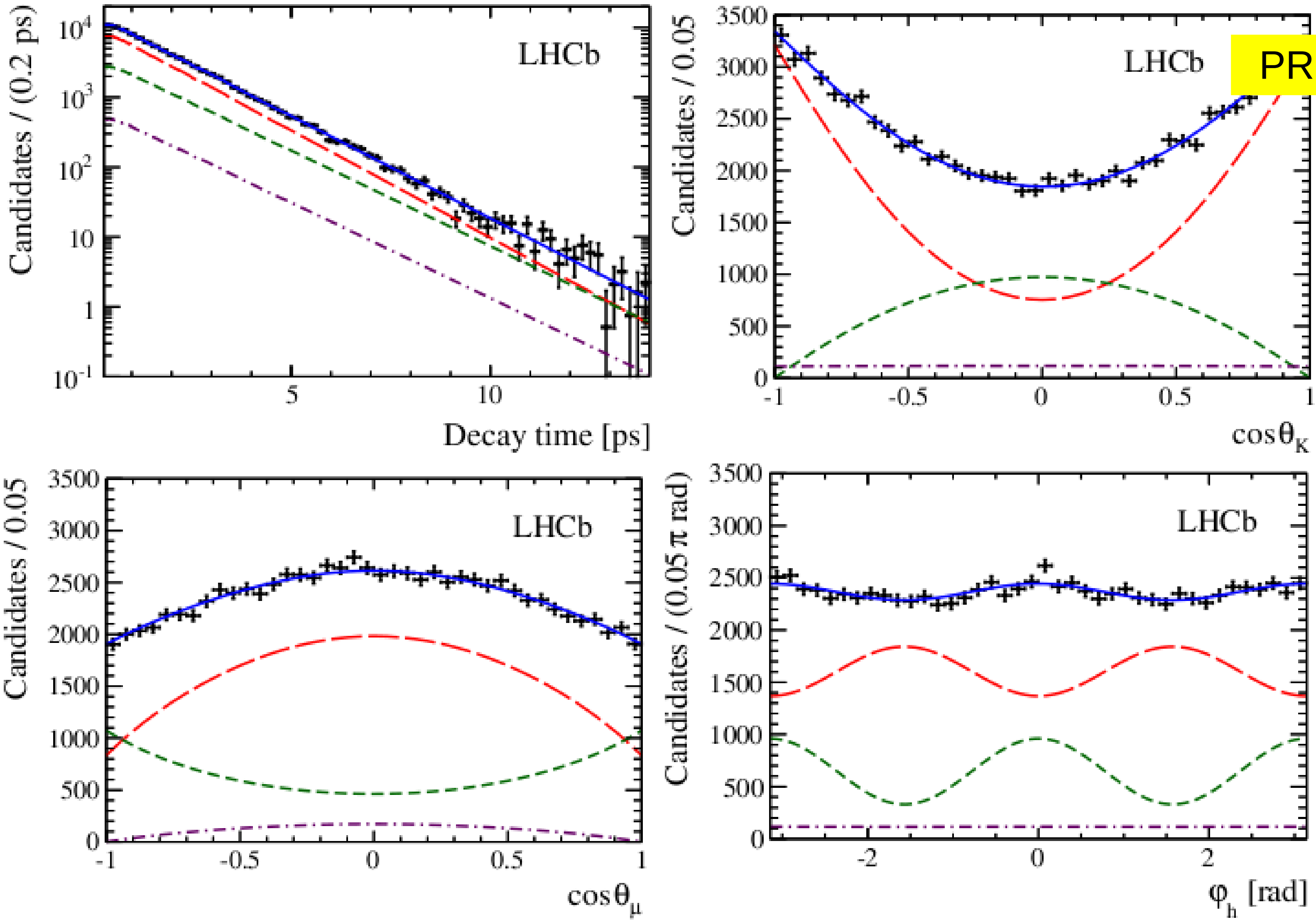
$$\Im\{\bar{A}_{||}^*(t)\bar{A}_\perp(t)\} = |\bar{A}_{||}(0)||\bar{A}_\perp(0)| e^{-\Gamma_s t}\Big[-\cos(\delta_\perp-\delta_{||})\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin(\delta_\perp-\delta_{||})\cos(\Delta m_s t) + \cos(\delta_\perp-\delta_{||})\cos\Phi\sin(\Delta m_s t)\Big],$$

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

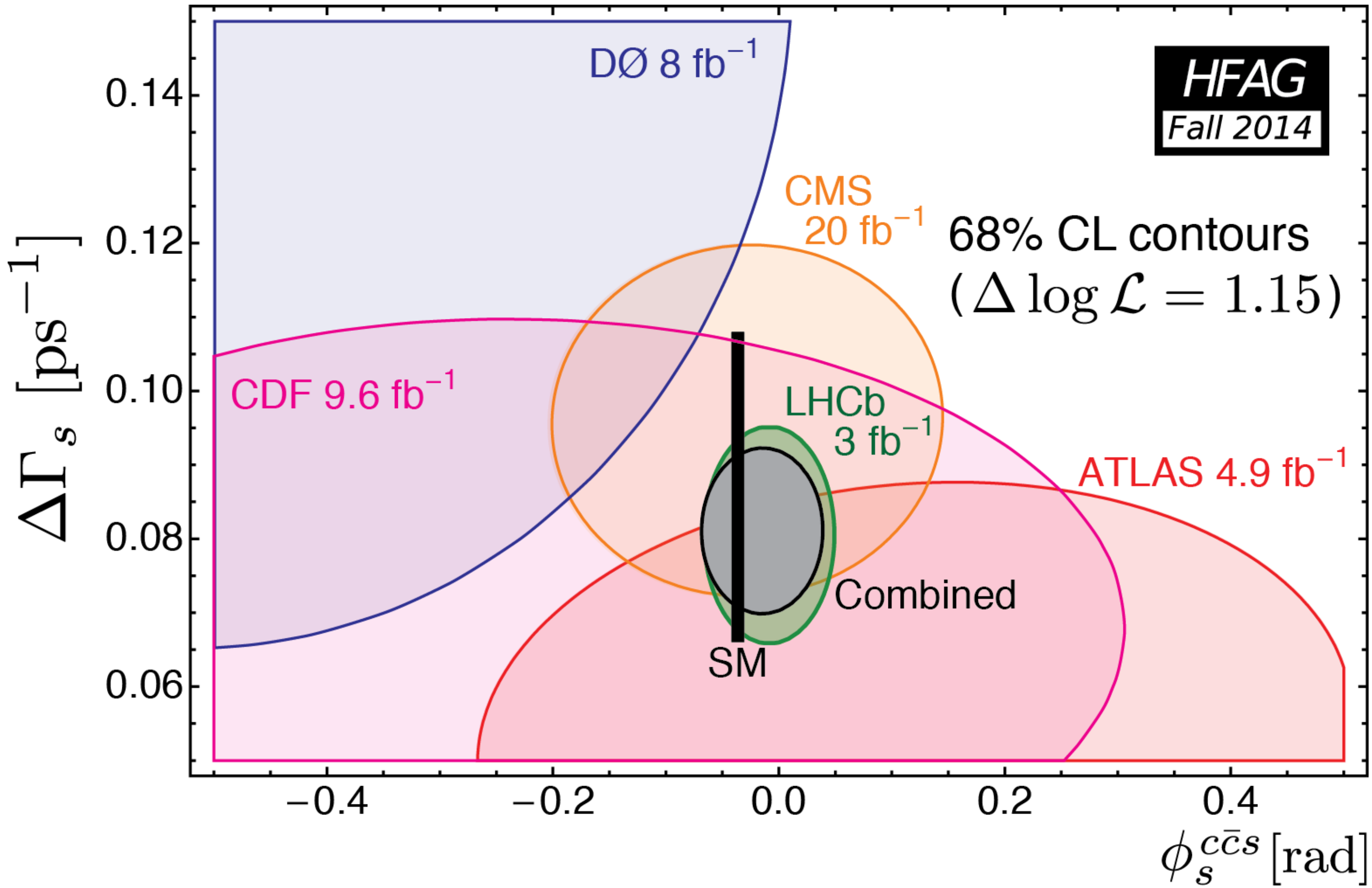
$$\Im\{\bar{A}_0^*(t)\bar{A}_\perp(t)\} = |\bar{A}_0(0)||\bar{A}_\perp(0)| e^{-\Gamma_s t}\Big[-\cos\delta_\perp\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\delta_\perp\cos(\Delta m_s t) + \cos\delta_\perp\cos\Phi\sin(\Delta m_s t)\Big].$$

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

PRL 114 (2015) 041801



CP violation in interference between B_s mixing and $b \to c\bar{c}s$ decay (φ_s)



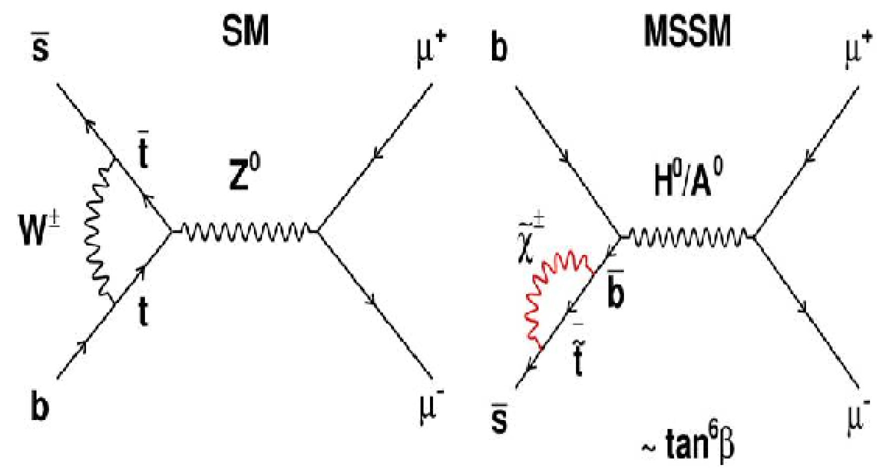
Looking forward to new Run 1 results from ATLAS & CMS

Rare Decays

$B_{(s)}^0 \to \mu^+\mu^-$

Killer app. for new physics discovery

- Very small in the SM
  - no tree-level FCNC
  - CKM suppression
  - helicity suppression

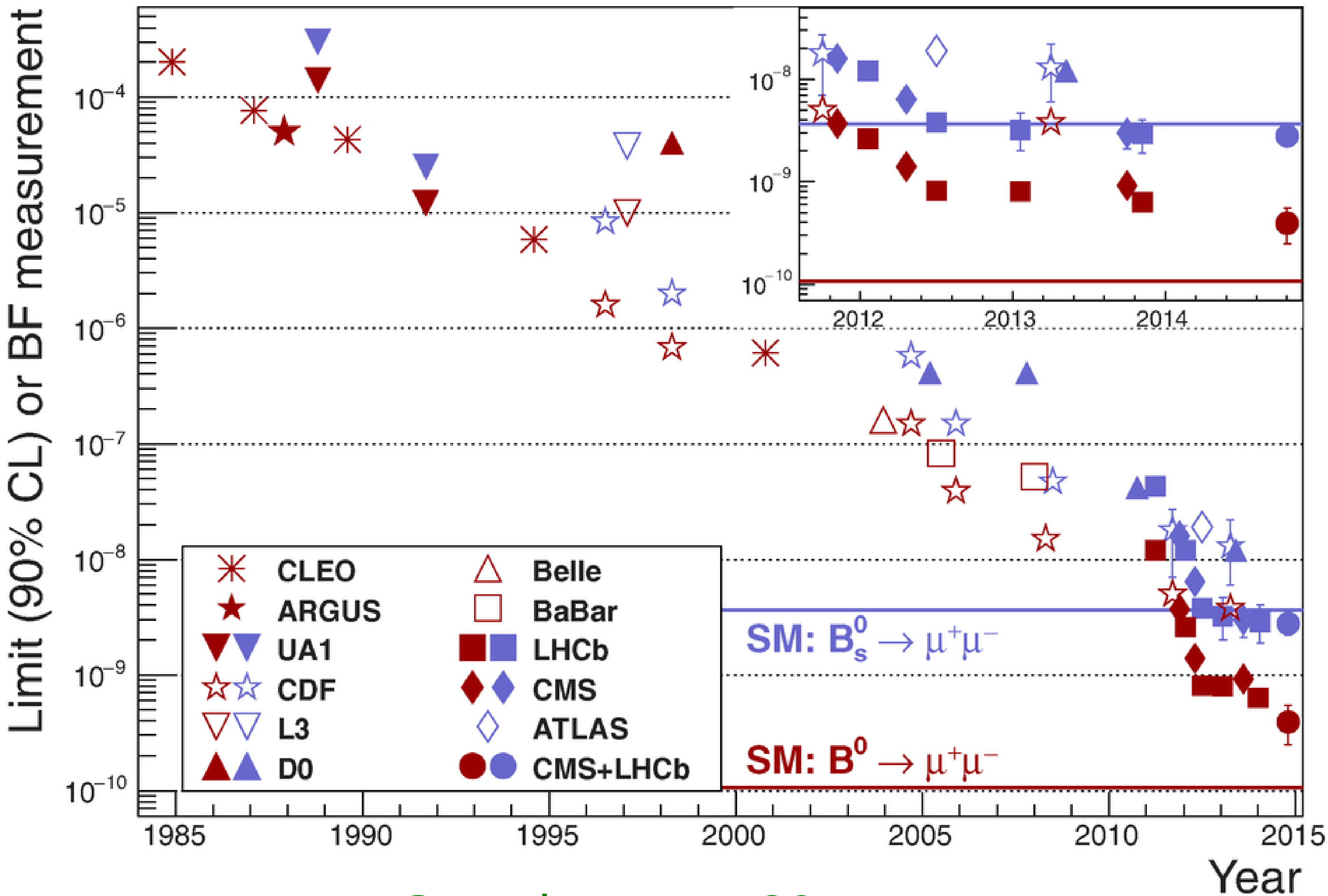


- Huge NP enhancement possible (tan β = ratio of Higgs vevs)

$$BR(B_s \to \mu^+\mu^-)^{SM} = (3.3 \pm 0.3) \times 10^{-9} \qquad BR(B_s \to \mu^+\mu^-)^{MSSM} \propto \tan^6\beta / M_{A0}^4$$

- Clean experimental signature

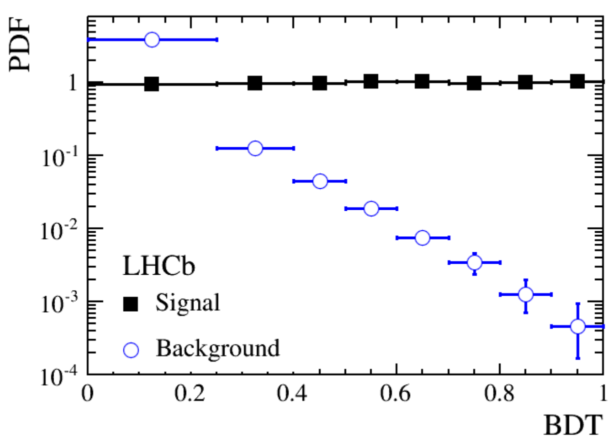
$B_{(s)}^0 \to \mu^+\mu^-$



Searches over 30 years

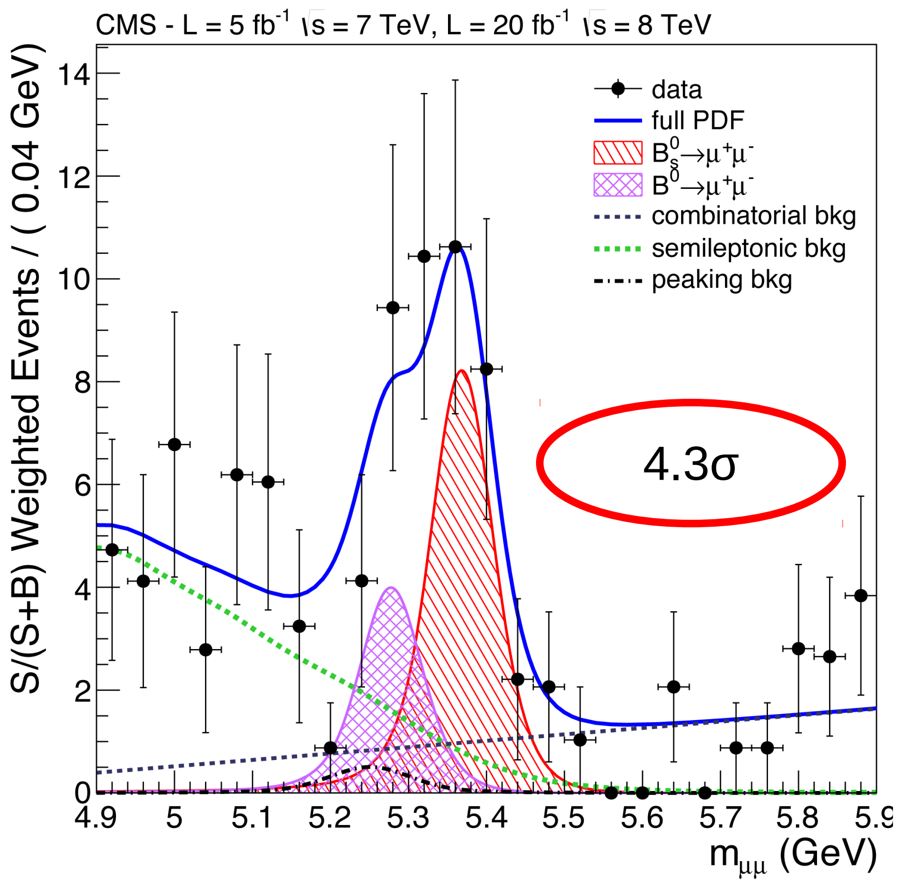
$B_{(s)}^0 \to \mu^+\mu^-$ – analysis ingredients

- Produce a very large sample of B mesons
- Trigger efficiently on dimuon signatures
- Reject background
  - excellent vertex resolution (identify displaced vertex)
  - excellent mass resolution (identify B peak)
    - also essential to resolve B^0 from B_s^0 decays
  - powerful muon identification (reject background from B decays with misidentified pions)
  - typical to combine various discriminating variables into a multivariate classifier
    - e.g. Boosted Decision Trees algorithm



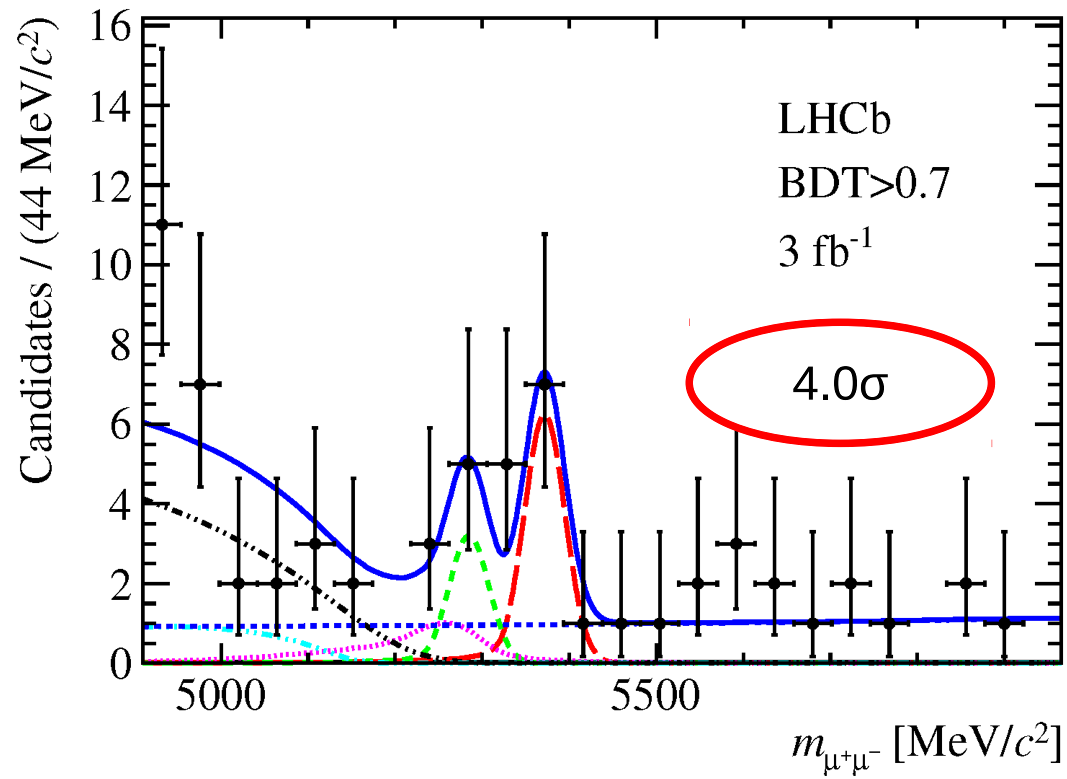
$B_{(s)}^0 \to \mu^+\mu^-$
latest results from CMS & LHCb

CMS PRL 111 (2013) 101804



Events weighted by S/(S+B)

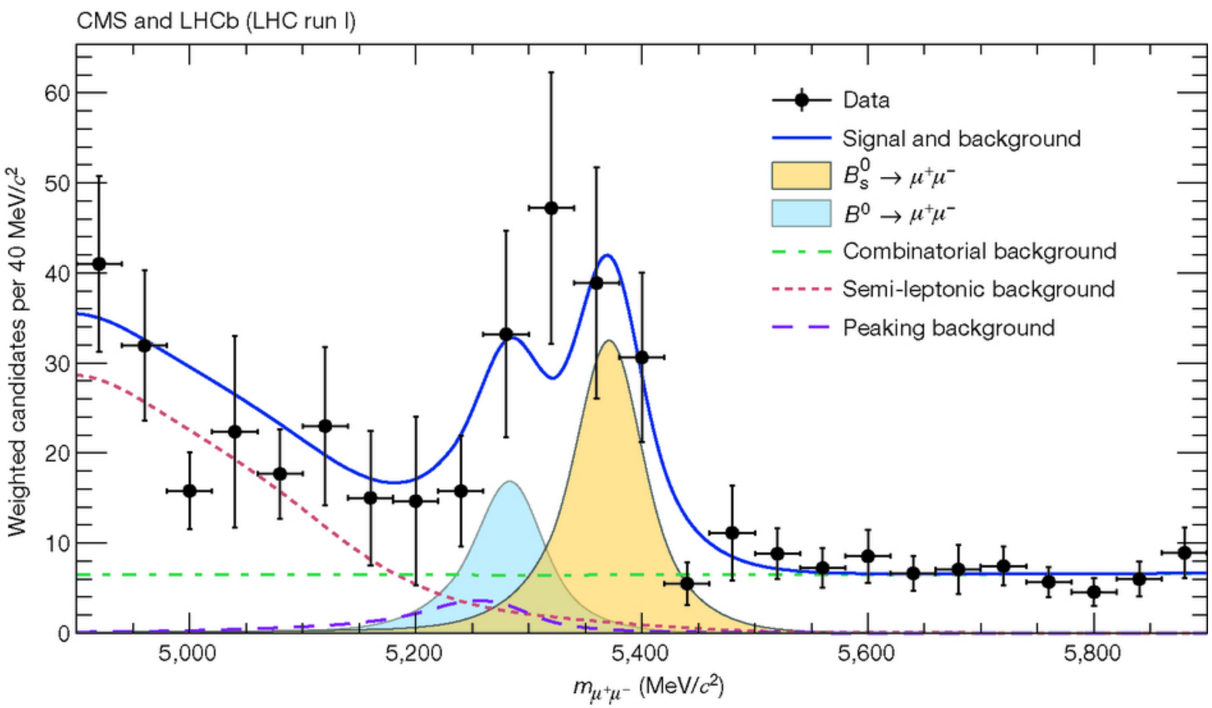
LHCb PRL 111 (2013) 101805



Only events with BDT > 0.7

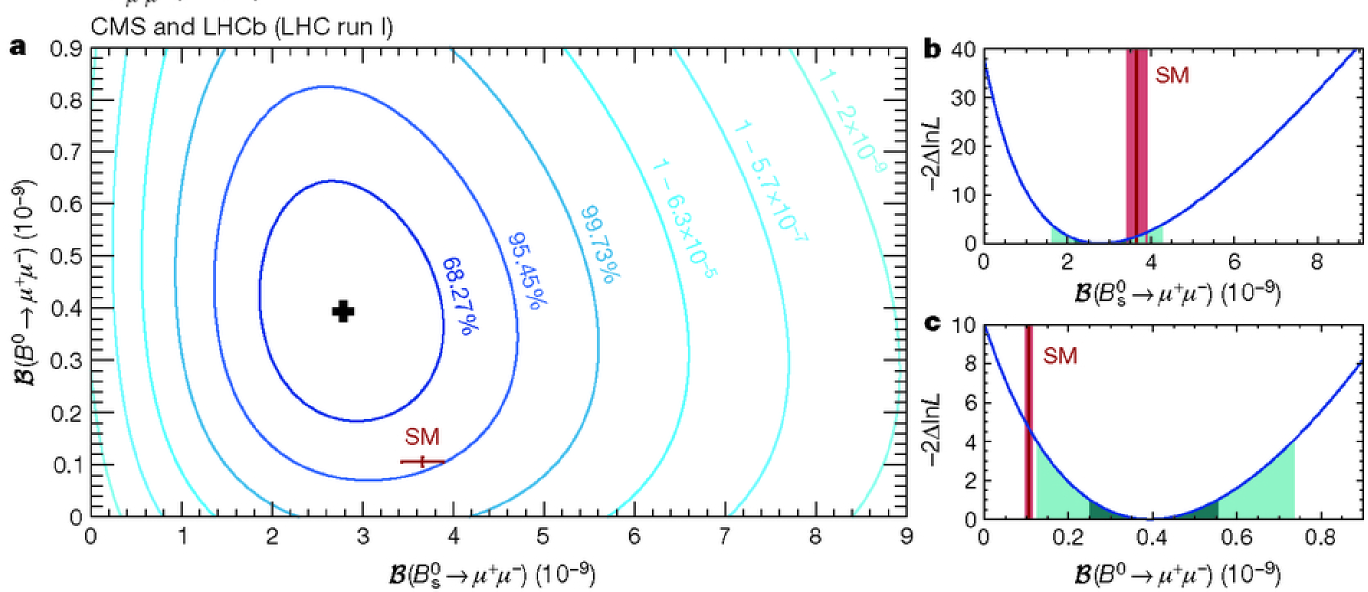
$B_s \to \mu^+\mu^-$

Nature 522 (2015) 68



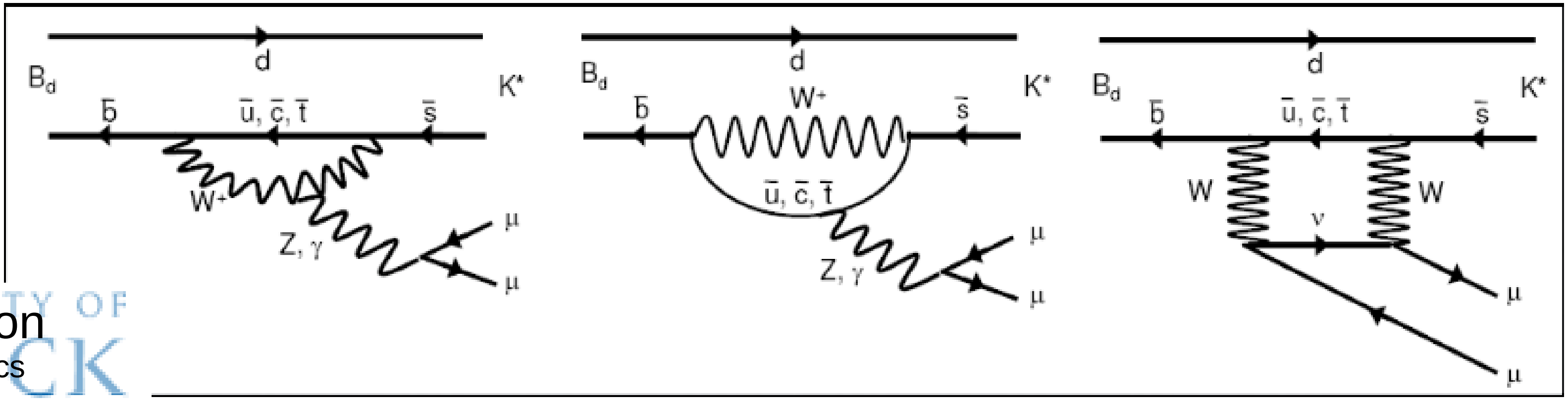
Combination of CMS and LHCb data results in first observation of $B_s \to \mu^+\mu^-$ and first evidence for $B^0 \to \mu^+\mu^-$

Results consistent with SM at 2σ level



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

- $b \to s l^+ l^-$ 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)

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

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

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

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

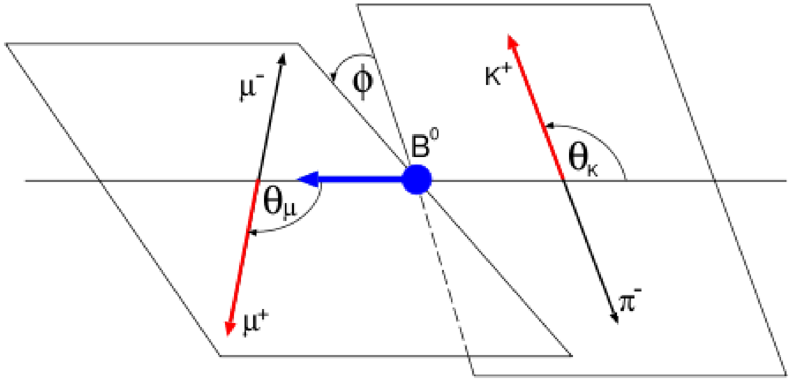
Four-fermion operators (except $Q_{7\gamma}$ & Q_{8g}) – dimension 6

Angular analysis of B→K*μ⁺μ⁻

LHCb-CONF-2015-002

- Differential decay distribution

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big].$$

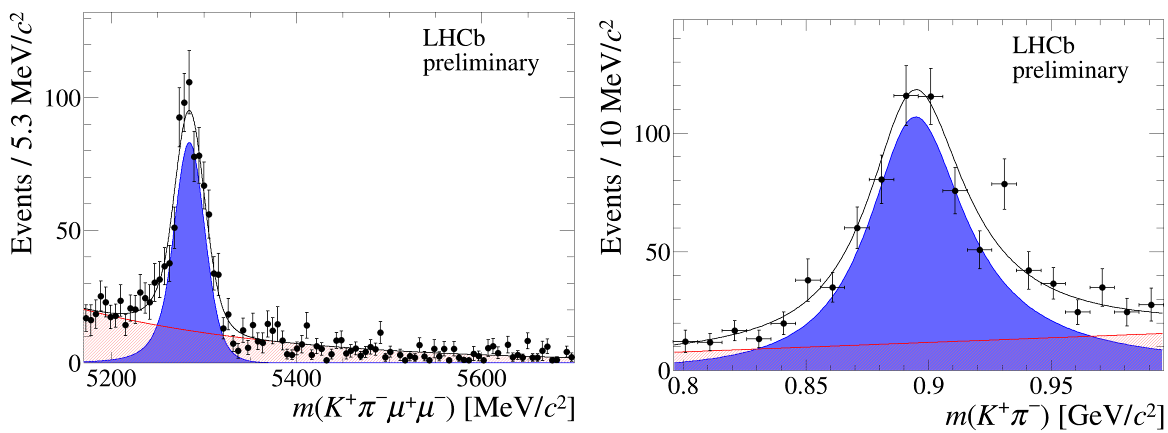


S_i terms related to Wilson coefficients and form factors

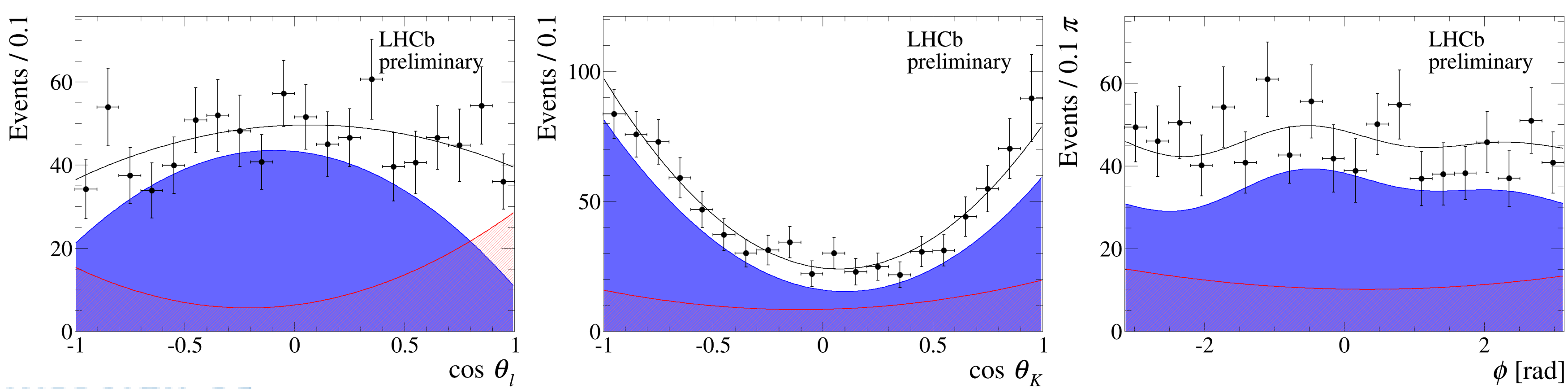
Full angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

LHCb-CONF-2015-002

- Example of fits, in $1.1 < q^2 < 6.0$ GeV^2 bin

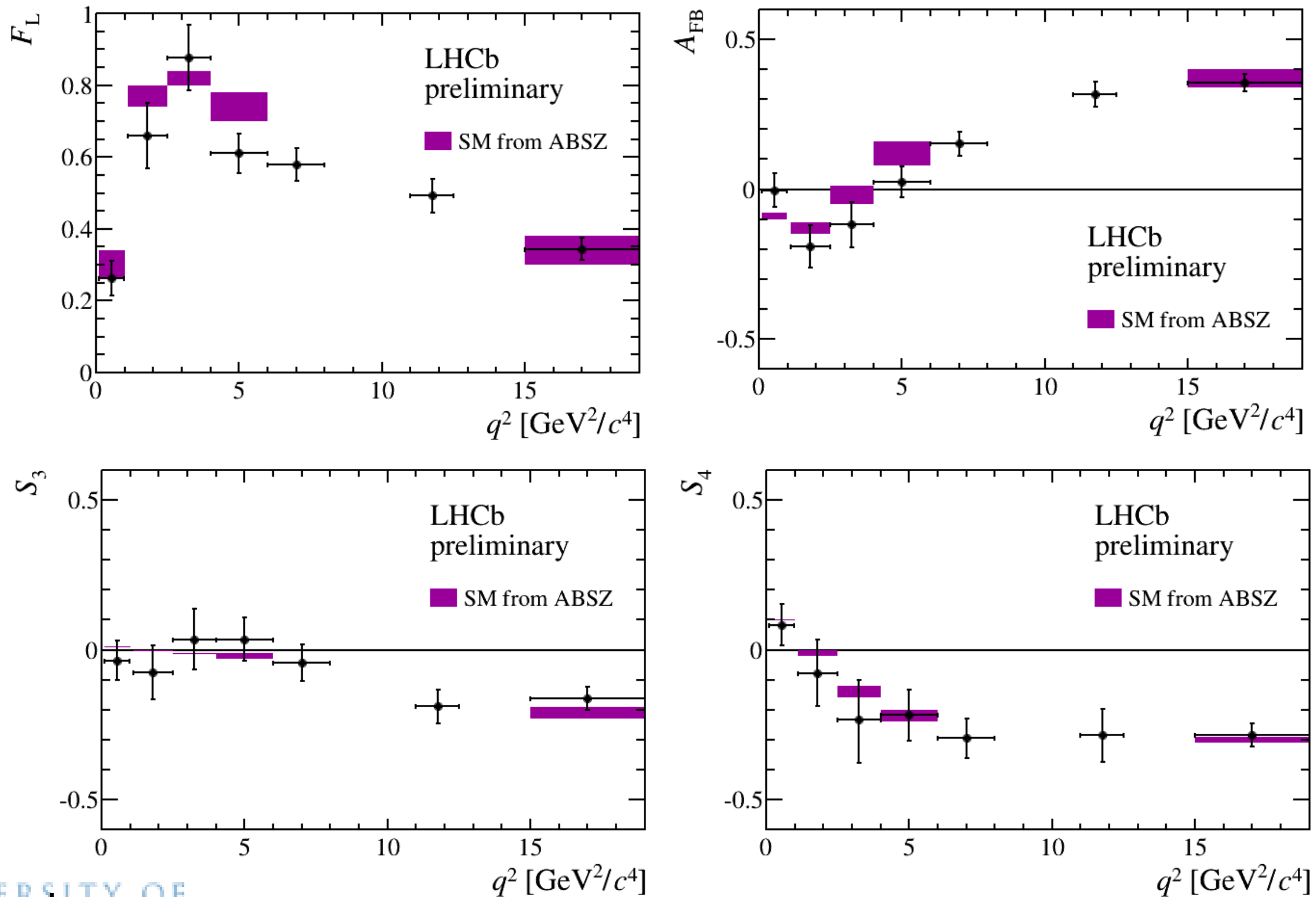


Angle and m(Kπ) projections in ± 50 MeV around B peak



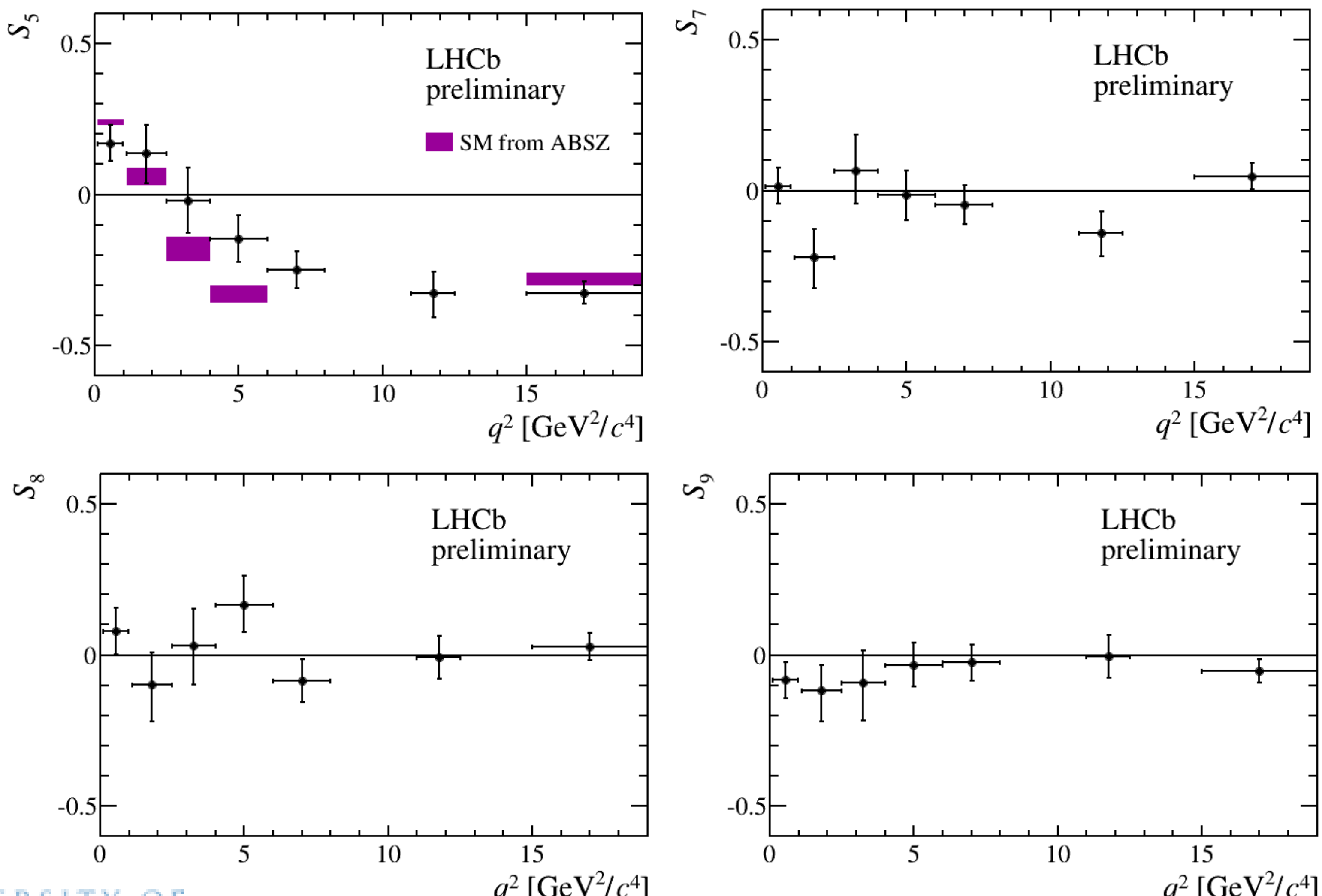
Full angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

LHCb-CONF-2015-002



Full angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

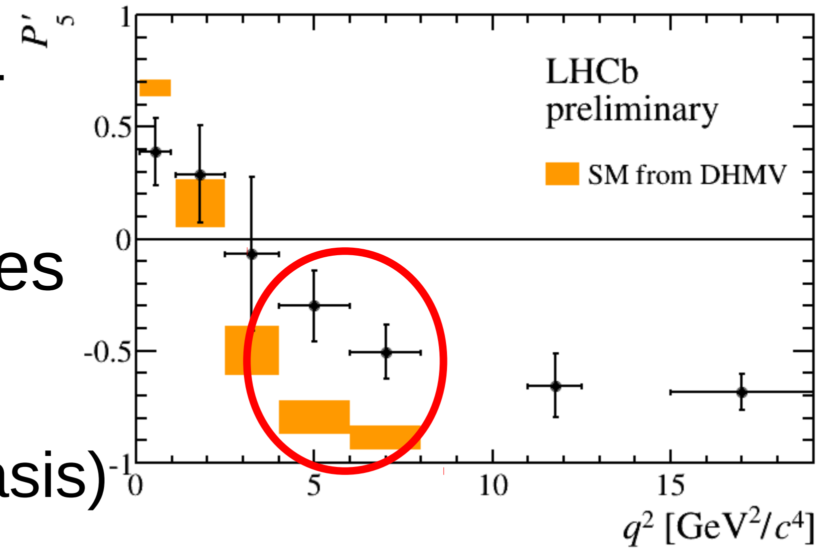
LHCb-CONF-2015-002



Tension in P_5'

LHCb-CONF-2015-002

- Dimuon pair is predominantly spin-1
  - either vector (V) or axial-vector (A)
- There are 6 non-negligible amplitudes
  - 3 for VV and 3 for VA
  - expressed as $A^{L,R}_{0,\perp,\parallel}$ (transversity basis)

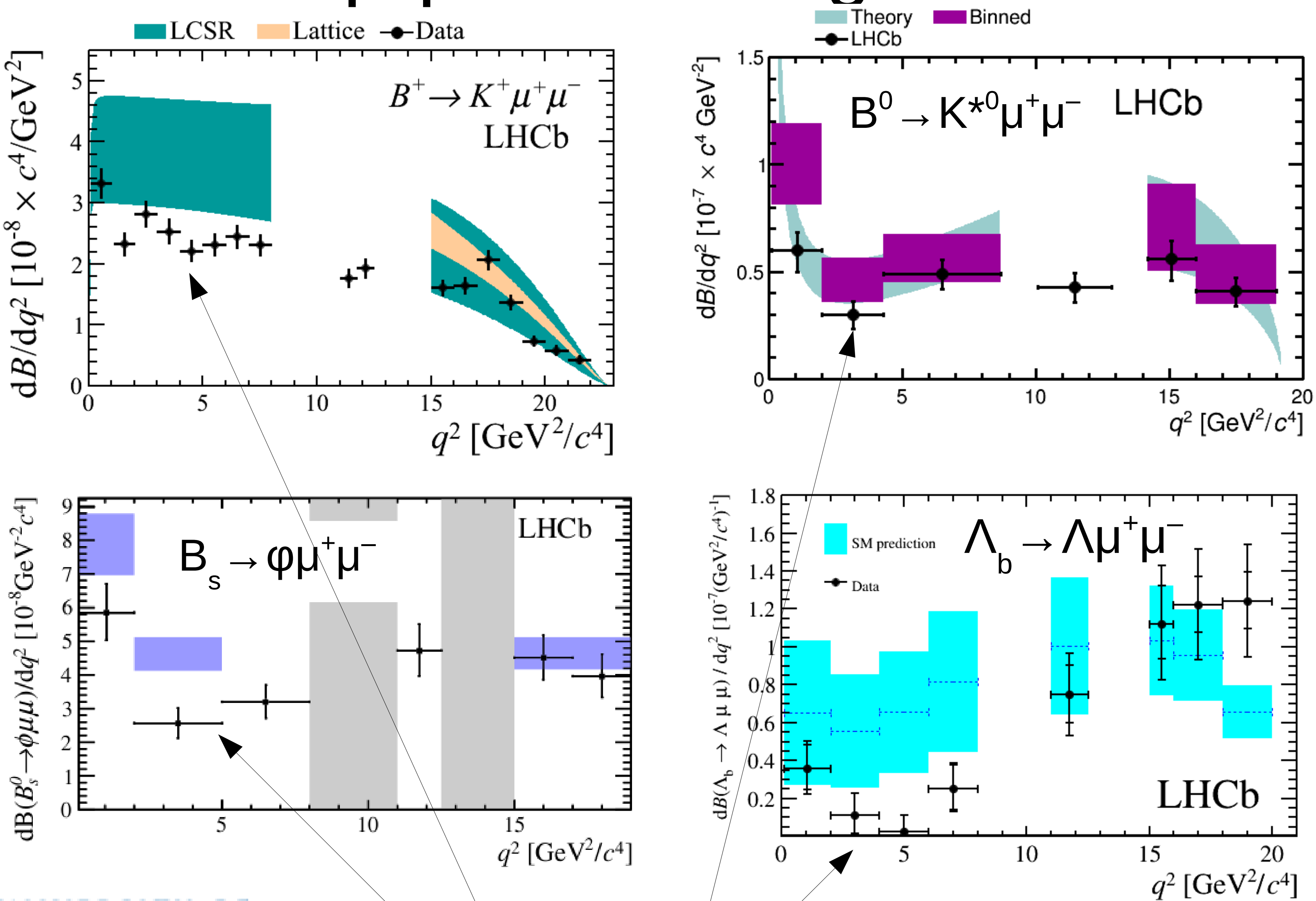


- P_5' related to difference between relative phase of longitudinal (0) and perpendicularly ($\perp$) polarised amplitudes for VV and VA
  - constructed so as to minimise form-factor uncertainties

$$P_5' = \sqrt{2}\frac{\mathrm{Re}\left(A_0^{\mathrm{L}}A_\perp^{\mathrm{L}*} - A_0^{\mathrm{R}}A_\perp^{\mathrm{R}*}\right)}{\sqrt{\left(|A_0^{\mathrm{L}}|^2 + |A_0^{\mathrm{R}}|^2\right)\left(|A_\parallel^{\mathrm{L}}|^2 + |A_\parallel^{\mathrm{R}}|^2 + |A_\perp^{\mathrm{L}}|^2 + |A_\perp^{\mathrm{R}}|^2\right)}}$$

Sensitive to NP in V or A couplings (Wilson coefficients $C_9^{(\prime)}$ & $C_{10}^{(\prime)}$)

$b \to s\mu^+\mu^-$ branching fractions

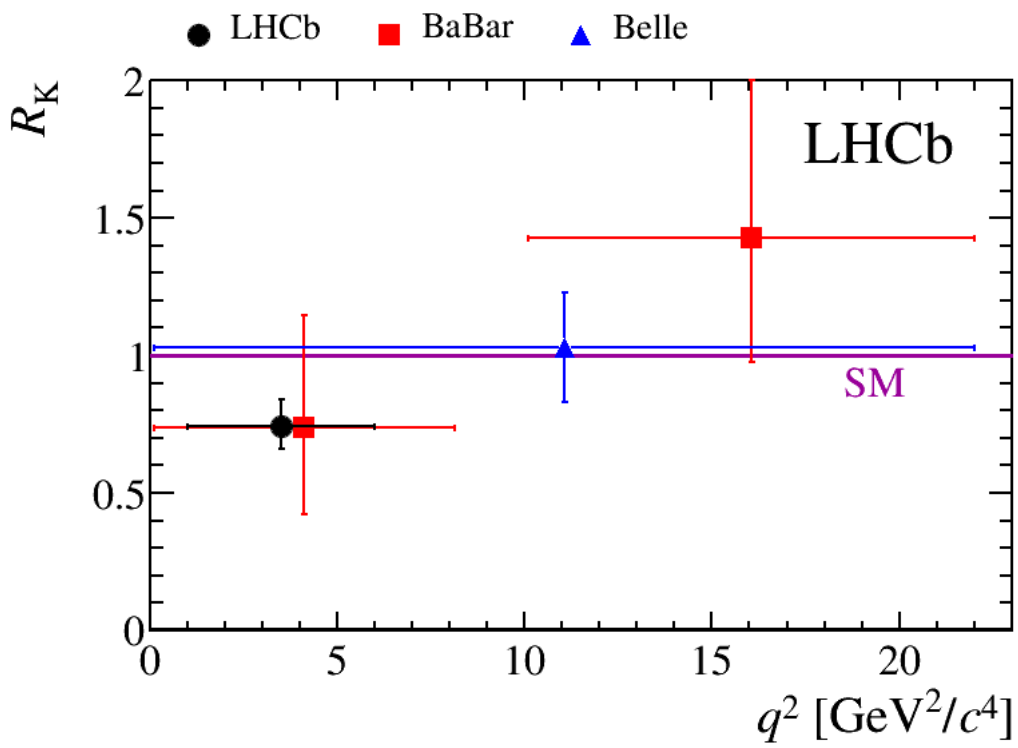


Trend to be below SM prediction at low q^2?

Lepton universality – R_K

PRL 113 (2014) 151601

Deficit of $B \to K\mu^+\mu^-$ compared to expectation
also seen in $K\mu^+\mu^-/Ke^+e^-$ ratio (R_K) – negligible theoretical uncertainty

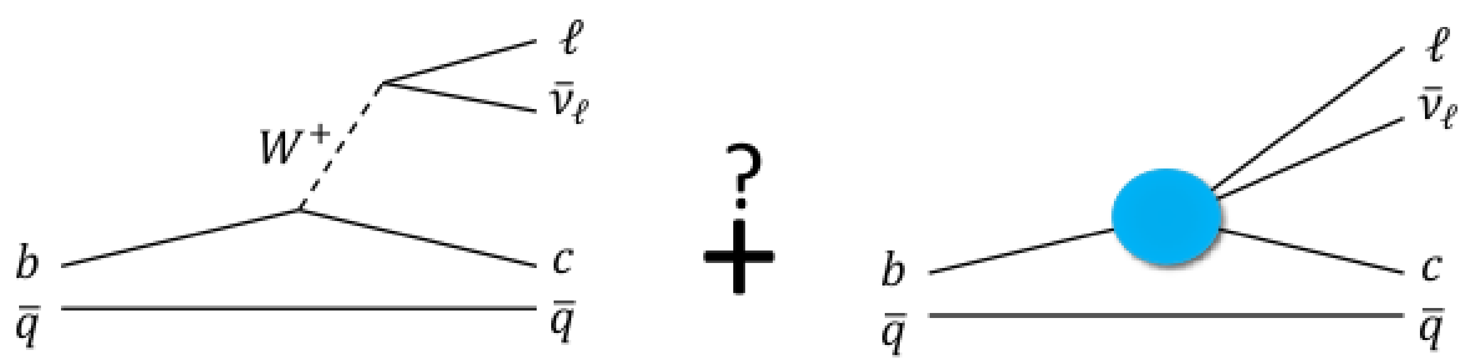


$$R_K(1 < q^2 < 6\ \mathrm{GeV}^2) = 0.745\,^{+0.090}_{-0.074} \pm 0.036$$

<3σ from SM but suggestive

$B \to D^{(*)}\tau\nu$

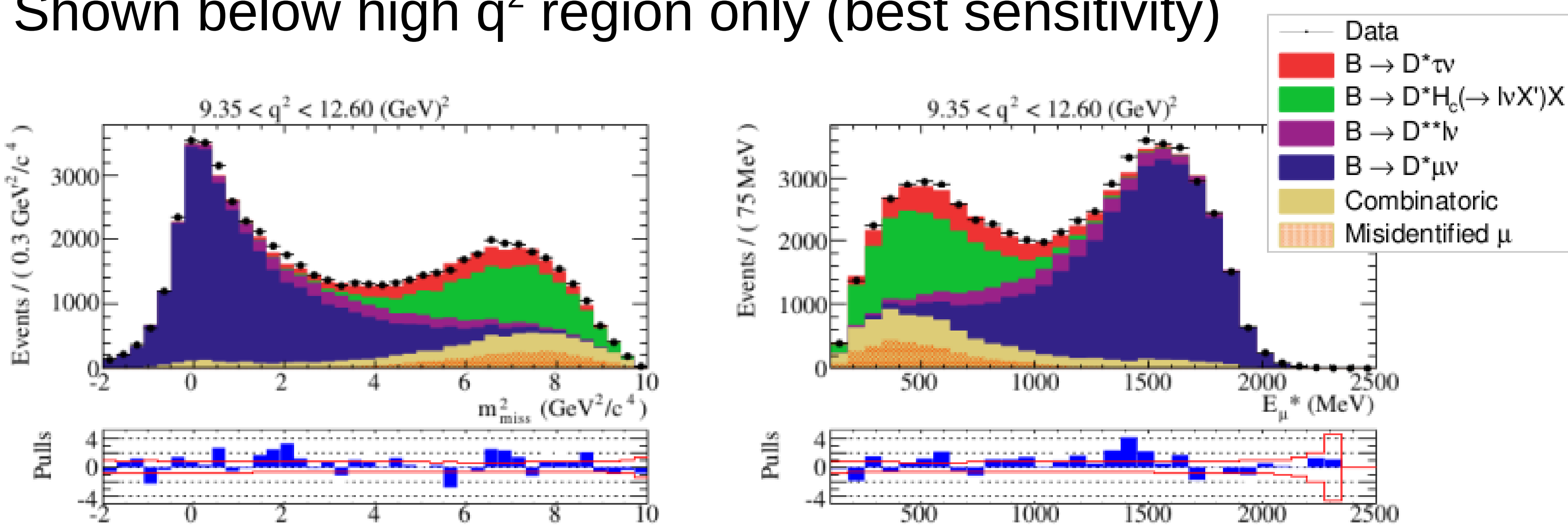
- Powerful channel to test lepton universality
  - ratios $R(D^{(*)}) = \mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}\mu\nu)$ could deviate from SM values, e.g. in models with charged Higgs
- Heightened interest in this area
  - anomalous results from BaBar
  - other hints of lepton universality violation, e.g. R_K , $H \to \tau\mu$



$B \to D^*\tau\nu$ at LHCb

LHCb-PAPER-2015-025

- Identify $B \to D^*\tau\nu$, $D^* \to D\pi$, $D \to K\pi$, $\tau \to \mu\nu\bar{\nu}$
  - Kinematic reconstruction to calculate $M_{miss}^2 = (p_B - p_{D^*} - p_\mu)^2$
  - Require significant B, D, τ flight distance & use isolation MVA
- Separate signal / background by fitting in M_{miss}^2, q^2 and E_μ
  - Shown below high q^2 region only (best sensitivity)

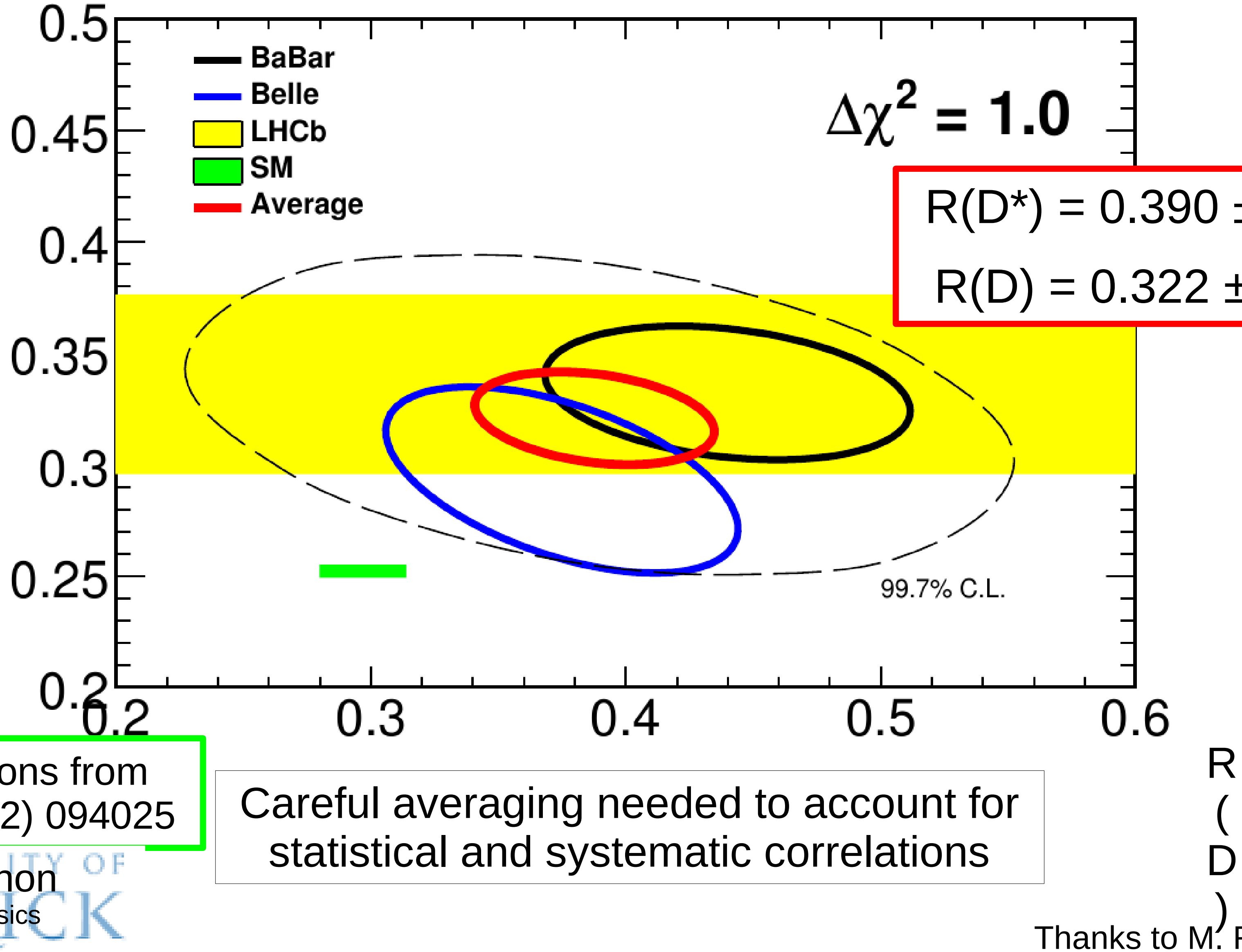


$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

$B \rightarrow D^{(*)}\tau\nu$

Tension with SM seems to persist

Very preliminary & unofficial average including new LHCb & Belle results



R(D*) = 0.390 ± 0.047

R(D) = 0.322 ± 0.021

SM predictions from PRD 85 (2012) 094025

Careful averaging needed to account for statistical and systematic correlations

Thanks to M. Rotondo

Summary of rare decays

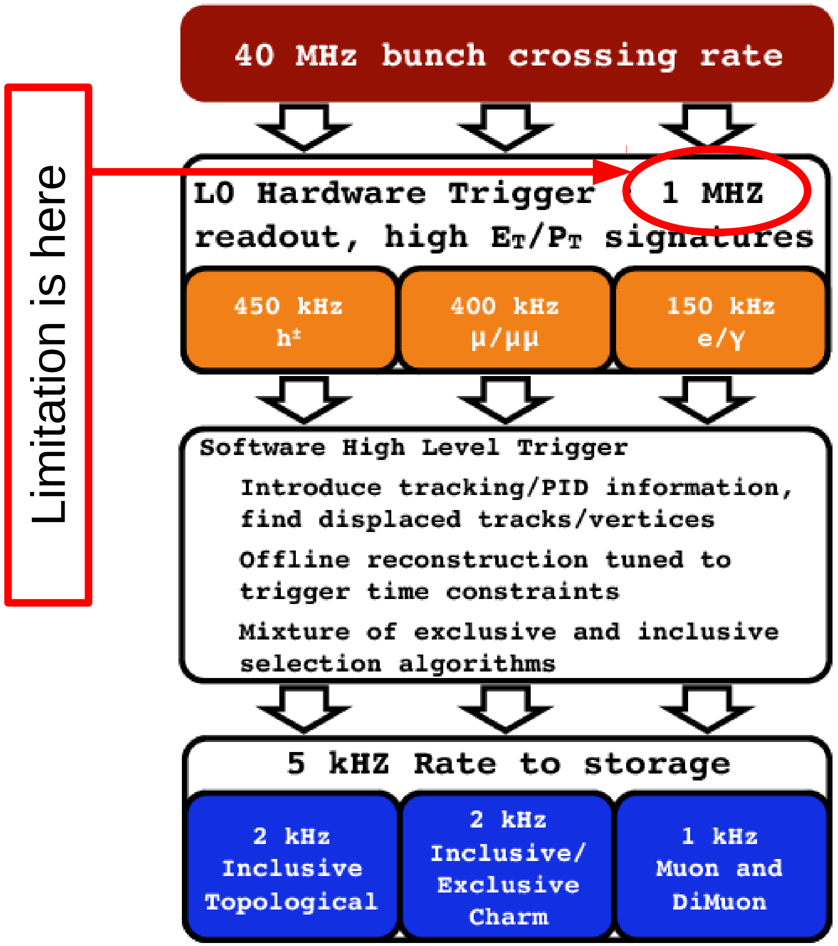
- Accumulating hints of non-SM effects?
  - in particular related to lepton universality
  - observables with negligible theoretical uncertainty
- It is easy to see patterns, yet there may be none
  - no single effect with 5σ significance
  - various models proposed that can explain effects
- Need more data!
  - many results still to come from Run I data
  - from ATLAS and CMS, as well as LHCb
  - … and Run II is happening

LHCb upgrade

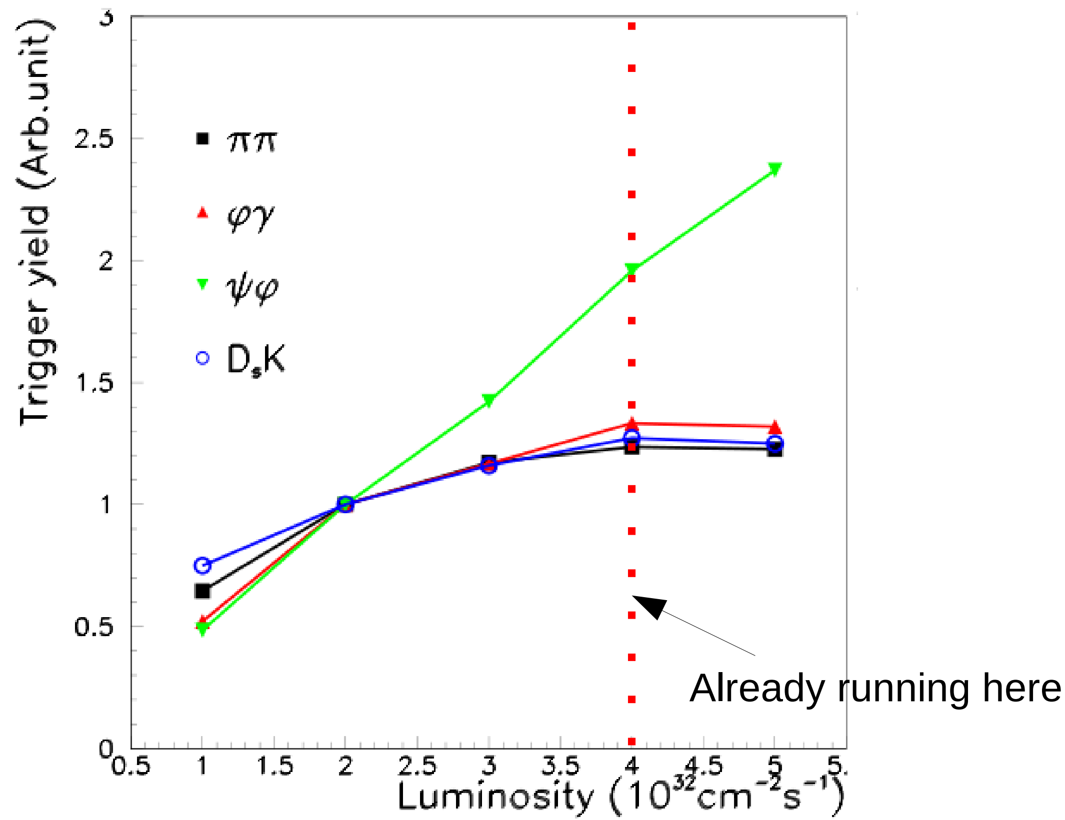
- To fully exploit LHC potential for heavy flavour physics will require an upgrade to LHCb
  - full readout & trigger at 40 MHz to enable high L running
  - "high L" = $10^{33}/cm^2/s$ (so independent of machine upgrade)
  - planned for 2018 shutdown

- 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)

LHC upgrade and the all important trigger

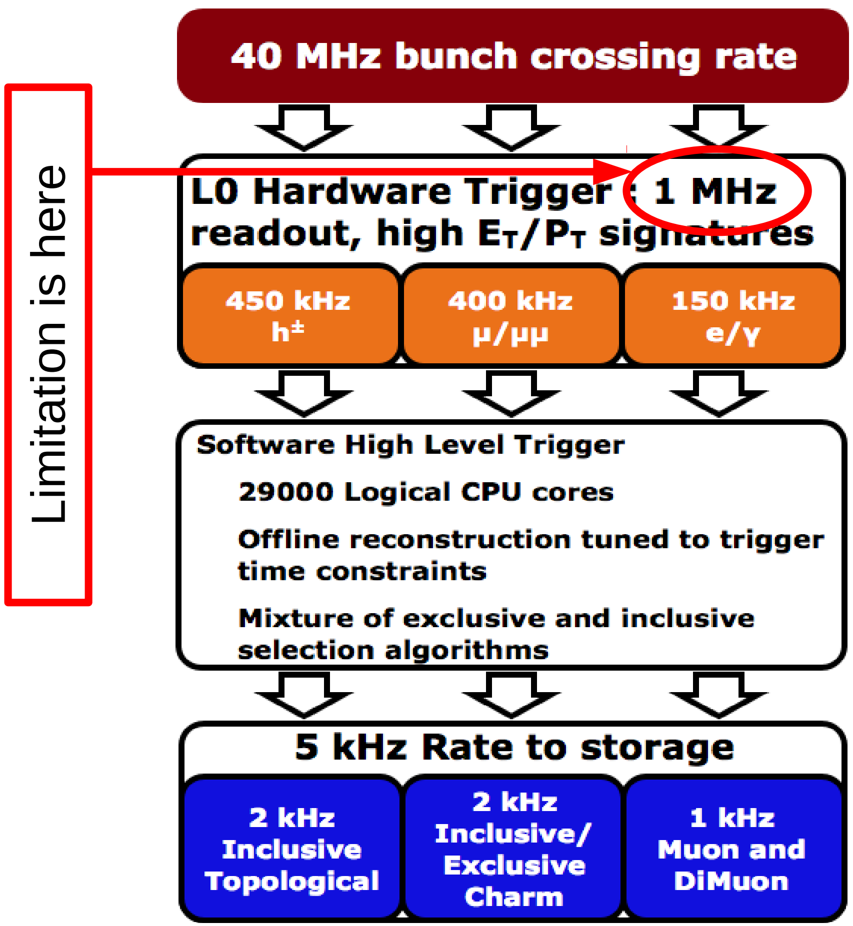


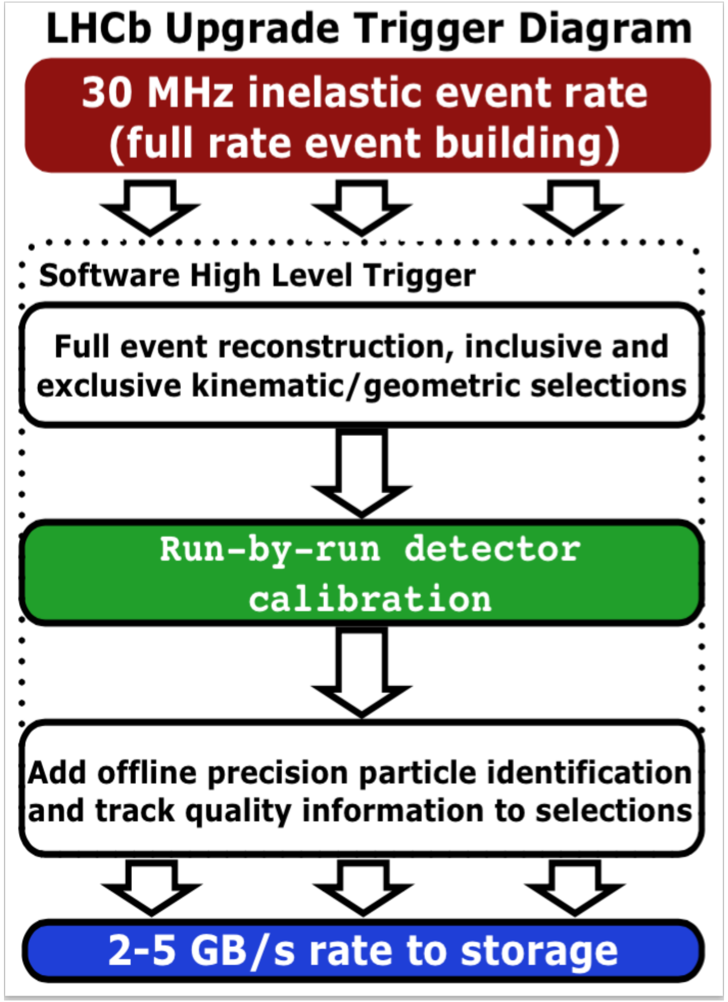
higher luminosity
→ need to cut harder at L0 to keep rate at 1 MHz
→ lower efficiency



- readout detector at 40 MHz
- implement trigger fully in software → efficiency gains
- run at L_{inst} up to 2 10^{33}/cm^2/s

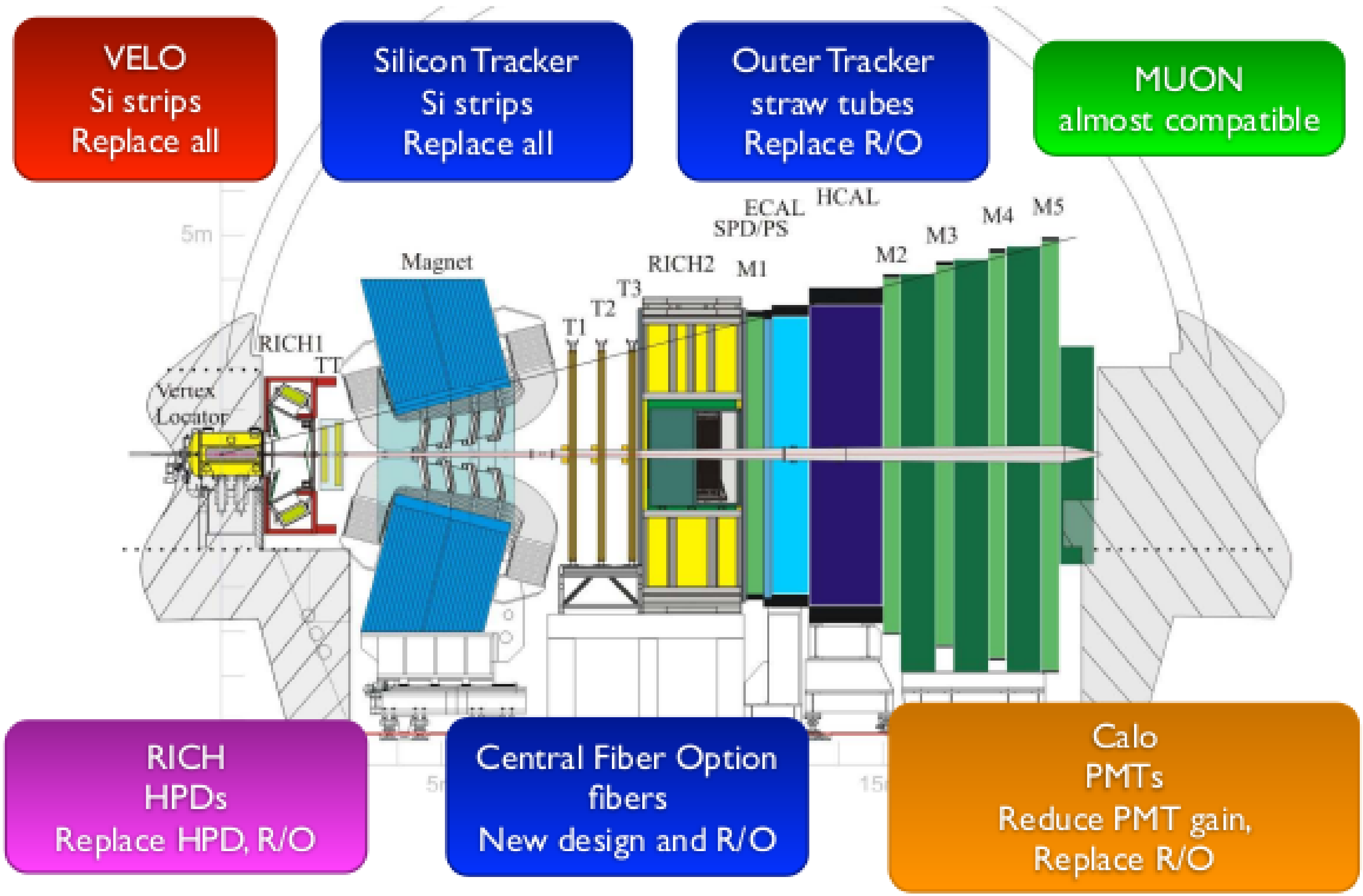
LHC upgrade and the all important trigger





- readout detector at 40 MHz
- implement trigger fully in software → efficiency gains
- run at L_{inst} up to 2 10^{33}/cm^2/s

LHCb detector upgrade



Other future flavour experiments

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

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

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

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

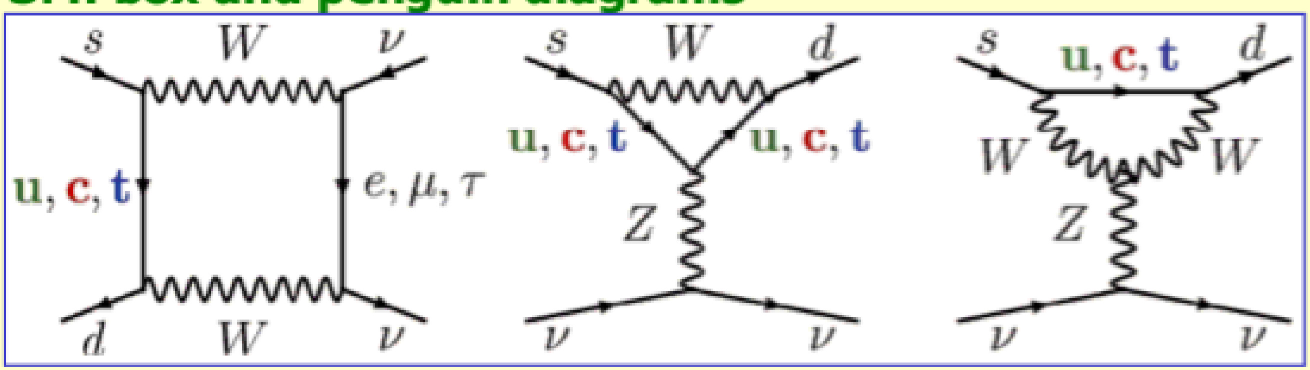
SM branching ratios

(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

- $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ (NA62, CERN)
- $K^0 \rightarrow \pi^0 \nu\bar{\nu}$ (K0T0, J-PARC)

The need for more precision

- "Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed"

  – A.Soni

- "A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L^0 \to \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the lab. The group was unlucky."

  – L.Okun

(remember: $B(K_L^0 \to \pi^+\pi^-) \sim 2\ 10^{-3}$)

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
- Will have continuing programme of flavour physics into the 2020s and perhaps beyond
  - 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)