FLAVOR PHYSICS
(PART III: the arrival of LHC)

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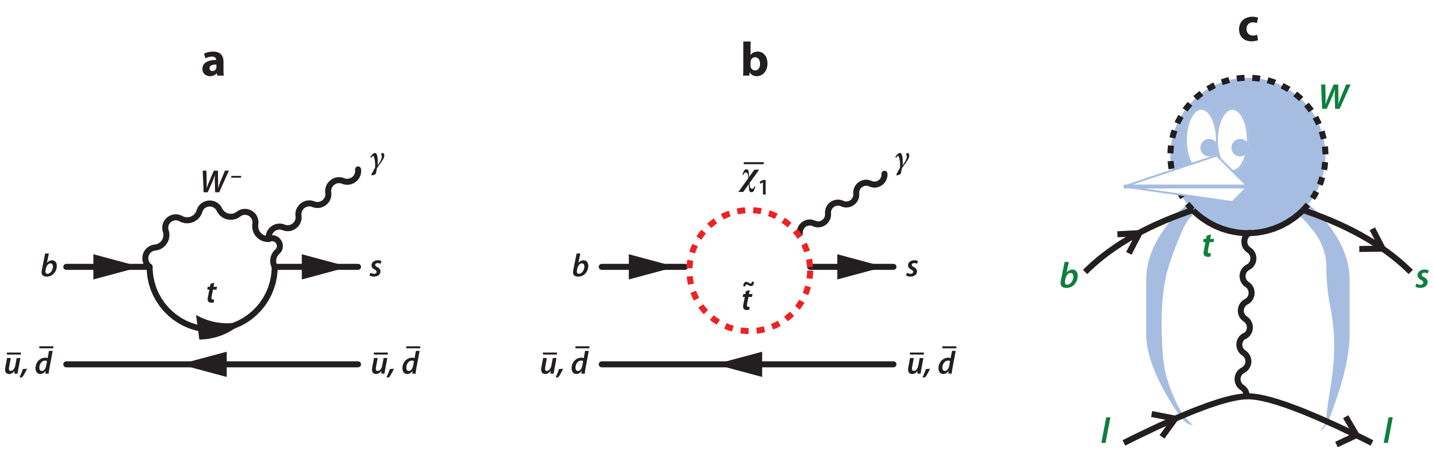
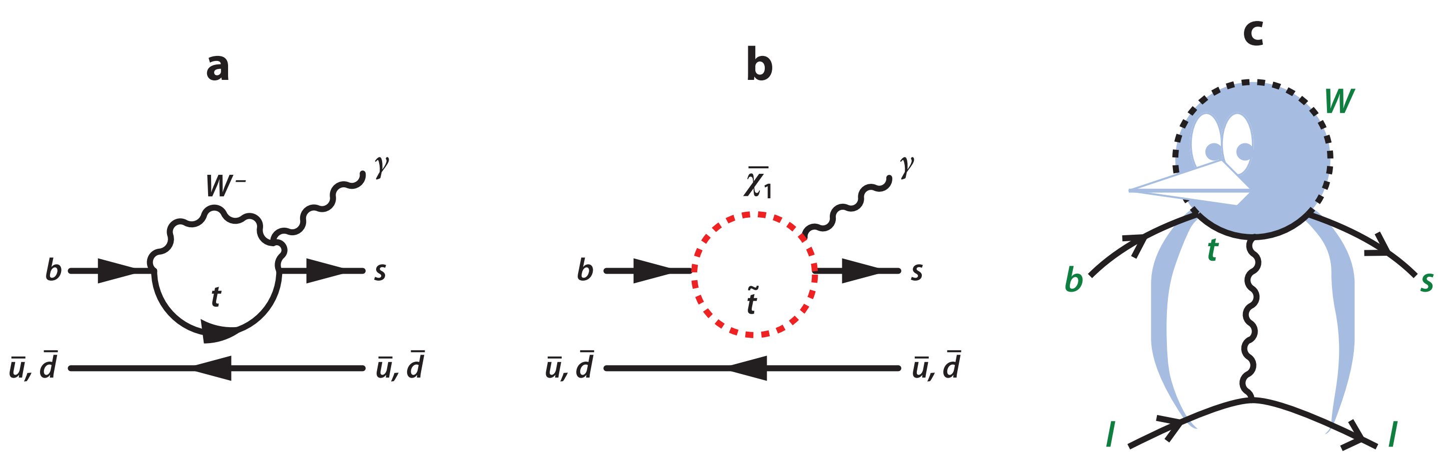
Radiative decays

- Radiative decays are flavor-changing neutral current (FCNC) processes, and occur only via loop diagrams
  - two categories:
    - radiative penguin decays: emission of a photon (a,b)
    - electroweak penguin decays: emission of a lepton pair (c)



Radiative decays in the SM and beyond

- In the SM, radiative decays are well understood, and accurate predictions can be made (branching fractions, photon energy spectrum)
- New physics heavy particles can enter the loop and couple to the SM particles (quarks, photon)
  => modification to the SM-predicted values
  => sensitive laboratory for new physics



Electroweak effective Hamiltonian

- Rare B decays: interplay between weak and strong interactions. To first order:
    - weak interactions govern the decay
    - strong interactions govern the hadronization
- Effective theory in B-meson decays
  - integrate out the heavy particles:
    - the top quark
    - and the electroweak bosons ($W^{\pm}$, Z^0)
  - we obtain an effective 5-quark low-energy theory (*u,d,s,c,b*)
- The operator product expansion (OPE) method allows separation of
  - long distance contributions (operator matrix elements)
  - short-distance physics ("Wilson coefficients")

Electroweak effective Hamiltonian

- The electroweak effective Hamiltonian

$$\mathcal{H}_{\mathrm{eff}} = \frac{4G_F}{\sqrt{2}} \sum_i C_i(\mu, M)\mathcal{O}_i(\mu)$$

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- can be calculated with perturbative methods

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The operator matrix elements

- for inclusive decays: use quark-hadron duality
  - i.e. calculations at quark level (+corrections): $b \to s\gamma$
- for exclusive decays: need matrix elements between meson states.
  - various approaches, based on heavy-quark limit:
    - QCD factorizations (QCDF)
    - soft-collinear effective theory (SCET)

Effective Hamiltonian for radiative decays

- The electroweak effective Hamiltonian for radiative decays:

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} \left[\lambda_q^t \sum_{i=1}^{10} C_i \mathcal{O}_i + \lambda_q^u \sum_{i=1}^{2} C_i (\mathcal{O}_i - \mathcal{O}_i^u) \right]$$

- The CKM matrix elements enter in the λ_q parameters

$$\lambda_q^t = V_{tb} V_{tq}^*$$
$$\lambda_q^u = V_{ub} V_{uq}^*$$

with unitarity relations $\lambda_q^c = -\lambda_q^t - \lambda_q^u$

- The operators are:

trees →

$$\mathcal{O}_1 = (\bar{s}_L \gamma_\mu T^a c_L)(\bar{c}_L \gamma^\mu T^a b_L), \qquad \mathcal{O}_2 = (\bar{s}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L),$$
$$\mathcal{O}_1^u = (\bar{s}_L \gamma_\mu T^a u_L)(\bar{u}_L \gamma^\mu T^a b_L), \qquad \mathcal{O}_2^u = (\bar{s}_L \gamma_\mu u_L)(\bar{u}_L \gamma^\mu b_L),$$

penguins →

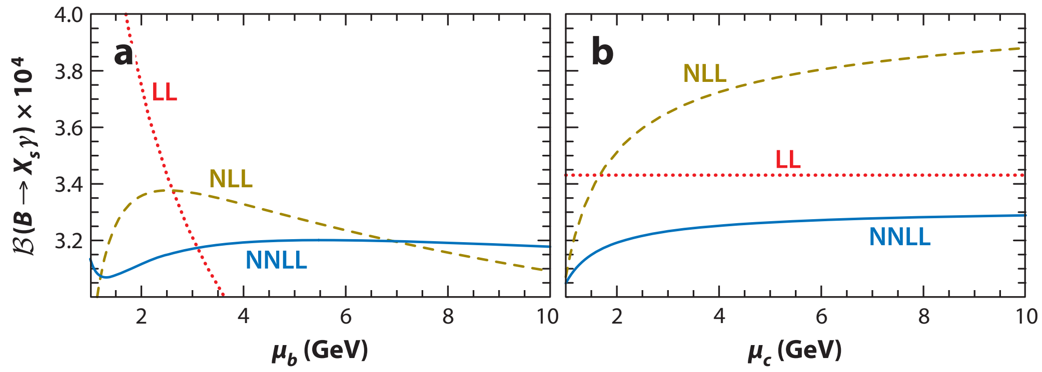
$$\mathcal{O}_3 = (\bar{s}_L \gamma_\mu b_L) \sum_q (\bar{q} \gamma^\mu q), \qquad \mathcal{O}_4 = (\bar{s}_L \gamma_\mu T^a b_L) \sum_q (\bar{q} \gamma^\mu T^a q),$$
$$\mathcal{O}_5 = (\bar{s}_L \Gamma b_L) \sum_q (\bar{q} \Gamma' q), \qquad \mathcal{O}_6 = (\bar{s}_L \Gamma T^a b_L) \sum_q (\bar{q} \Gamma' T^a q),$$
$$\mathcal{O}_7 = e/16\pi^2 m_b (\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu}, \qquad \mathcal{O}_8 = g_s/16\pi^2 m_b (\bar{s}_L \sigma^{\mu\nu} T^a b_R) G^a_{\mu\nu},$$

semileptonic →

$$\mathcal{O}_9 = e^2/16\pi^2 (\bar{s}_L \gamma_\mu b_L) \sum_\ell (\bar{\ell} \gamma^\mu \ell), \quad \mathcal{O}_{10} = e^2/16\pi^2 (\bar{s}_L \gamma_\mu b_L) \sum_\ell (\bar{\ell} \gamma^\mu \gamma_5 \ell),$$

Calculating the $b \to s\gamma$ branching fraction

- Three steps:
  1. match the effective theory to the W mass scale ($\mu = m_W$)
     - small QCD corrections to the Wilson coefficients
     - LL at $O(\alpha_s)$ or NNLL at $O(\alpha_s^2)$ level
  2. evolution of C_i from $\mu = m_W$ down to $\mu = m_b$
     - with help of renormalization group
  3. apply corrections (e.g. bremsstrahlung)
- For $b \to s\gamma$ calculations:

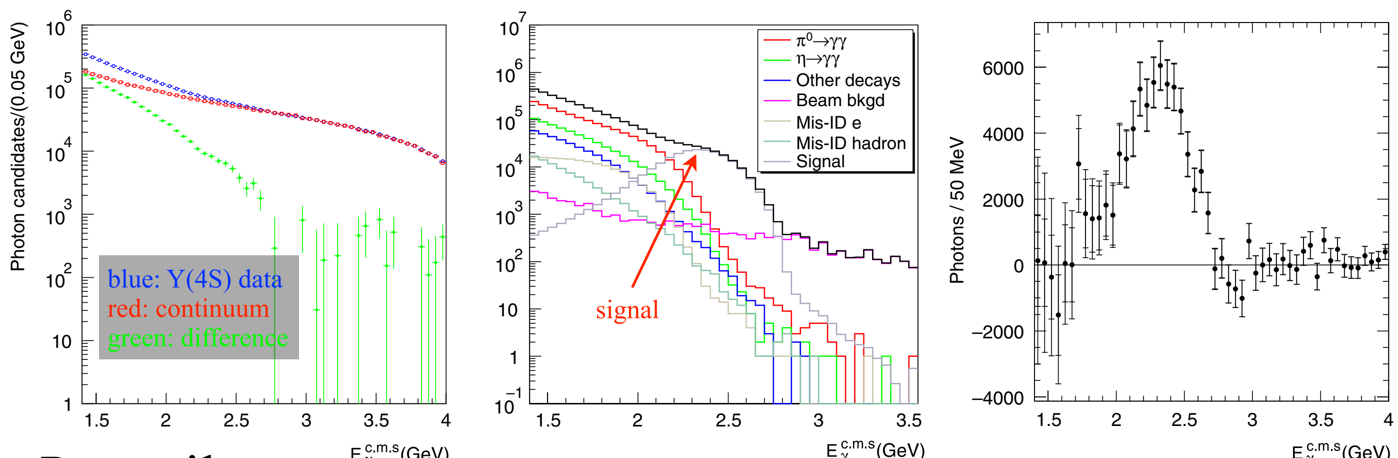


$$BF(b \to s\gamma, E_\gamma > 1.6 GeV) = (3.15 \pm 0.23) \times 10^{-4}$$

Misiak et.al., PRL 98 (2007) 022002

$b \to s\gamma$ branching fraction measurements

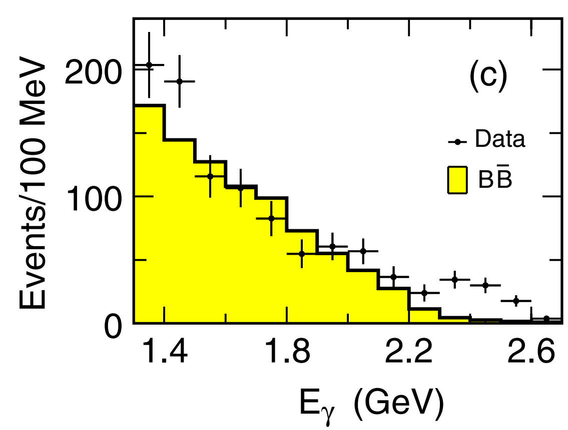
- 3 methods to measure the $b \to s\gamma$ branching fraction
  1. semi inclusive: sum of several exclusive final states ($B \to X_s\gamma$)
  2. fully inclusive: subtract continuum and other B-decay photon energy spectrum from on-resonance $Y(4S)$ data
     - full statistics can be exploited, but large backgrounds



BELLE, PRD 78 (2008) 032016

  3. B recoil
     - very clean, but relatively small statistics

BABAR, PRD 77 (2008) 051103



$b \to s\gamma$ branching fraction: results

- CLEO, Belle and BABAR measured the branching fraction for $b \to s\gamma$ (in units of 10^{-6}), above the photon energy E_γ

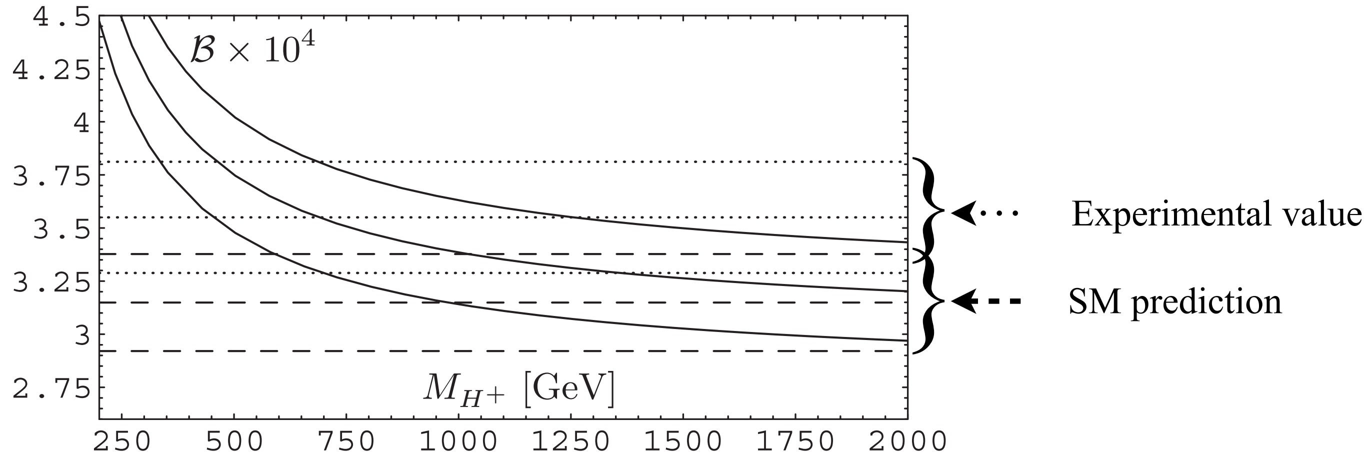
Method	Data set	$E_\gamma^{\min}$	$\mathcal{B}(E_\gamma > E_\gamma^{\min})$	$\mathcal{B}(E_\gamma > 1.6\text{GeV})$
CLEO fully inclusive	9	2.0	$305 \pm 41 \pm 26$	329 ± 53
BABAR fully inclusive	82	1.9	$367 \pm 29 \pm 34 \pm 29$	392 ± 56
BABAR semi-inclusive	82	1.9	$327 \pm 18\,^{+55}_{-40}\,^{+4}_{-9}$	349 ± 57
BABAR *B*-recoil	210	1.9	$366 \pm 85 \pm 60$	391 ± 111
Belle semi-inclusive	6	2.24	–	369 ± 94
Belle fully inclusive	605	1.7	$332 \pm 16 \pm 37 \pm 1$	337 ± 43
Average	–	–	–	$352 \pm 23 \pm 9$
Theory prediction	–	–	–	315 ± 23

- the fully inclusive method gives the better accuracy
- all results are in agreement within their uncertainties
- global average: $\mathcal{B}(B \to X_s\gamma) = (352 \pm 23_{\text{stat+syst}} \pm 9_{E_\gamma > 1.6GeV}) \times 10^{-6}$
- the difference with the theory calculation is not significant...

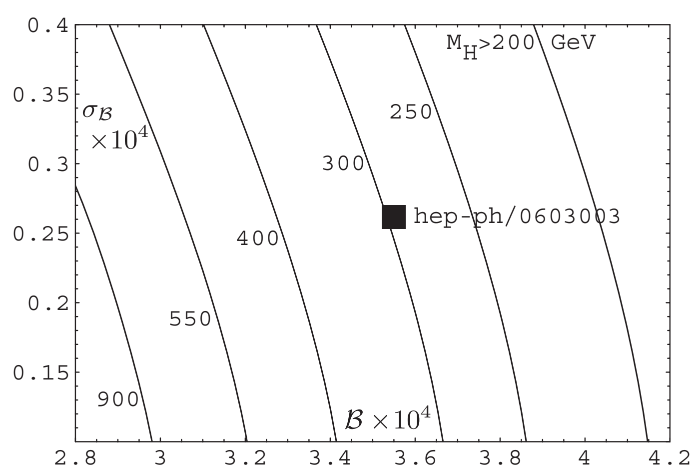
=> no obvious departure from SM predictions

$b \to s\gamma$: sensitivity to charged Higgs

- Calculation of the $b \to s\gamma$ branching fraction as a function of the charged Higgs mass



  - allows determination of the *95% CL* lower bound on the charged Higgs mass M_H



Misiak et.al., PRL 98 (2007) 022002

Exclusive $B \rightarrow K^{*}\gamma$ decays

- Belle and BABAR measured $B \rightarrow K^{*}\gamma$
  - HFAG averages

$$\mathcal{B}(B^+ \to K^{*+}\gamma) = (42.1 \pm 1.8) \times 10^{-6}$$
$$\mathcal{B}(B^0 \to K^{*0}\gamma) = (43.3 \pm 1.5) \times 10^{-6}$$

  - Remarks:
    - the $K^{*}\gamma$ final states correspond to approximately 12% of the inclusive $b \rightarrow s\gamma$ rate
    - SM predictions are consistent, but have large uncertainties (30%-50%) due to $B \rightarrow K^{*}$ form factors
    - CP asymmetries in these channels are all consistent with zero

$b \to d\gamma$ and $|V_{td}/V_{ts}|$

- Exclusive decays are (also) affected by hadronic uncertainties
- But they can provide a measurement of $|V_{td}/V_{ts}|$ via

$$\frac{\mathcal{B}(B^0 \to \rho^0\gamma)}{\mathcal{B}(B^0 \to K^{*0}\gamma)} = \frac{1}{2\xi^2}\left|\frac{V_{\rm td}}{V_{\rm ts}}\right|^2 \left[1 - 2R_{ut}\epsilon_0 \cos\alpha \cos\theta_0 + R_{ut}^2\epsilon_0^2\right]$$

  - all parameters can be calculated
  - largest uncertainty from the ratio of form factors parameter ξ

- Results ($\times 10^6$) :

	Belle	BABAR
$B^+ \to \rho^+\gamma$	$0.87\,^{+0.29}_{-0.27}\,^{+0.09}_{-0.11}$	$1.20\,^{+0.42}_{-0.37} \pm 0.20$
$B^0 \to \rho^0\gamma$	$0.78\,^{+0.17}_{-0.16}\,^{+0.09}_{-0.10}$	$0.97\,^{+0.24}_{-0.22} \pm 0.06$
$B^0 \to \omega\gamma$	$0.40\,^{+0.19}_{-0.17} \pm 0.13$	$0.50\,^{+0.27}_{-0.23} \pm 0.09$

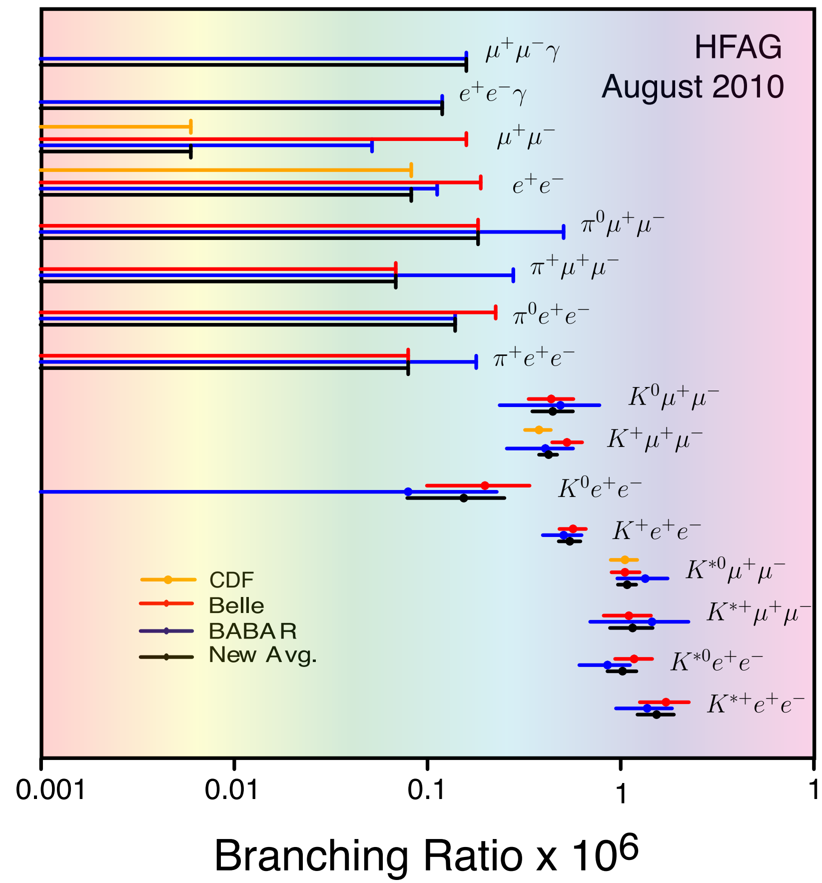
=> Belle: $|V_{td}/V_{ts}| = 0.195^{+0.020}_{-0.019}{}_{\rm exp} \pm 0.015_{\rm theory}$

=> BABAR: $|V_{td}/V_{ts}| = 0.233^{+0.025}_{-0.024}{}_{\rm exp} \pm 0.021_{\rm theory}$

Radiative decays: $b \rightarrow s l^+ l^-$

- $B \rightarrow K^{(*)} e^+ e^-$ and $B \rightarrow K^{(*)} \mu^+ \mu^-$ decays have been first observed at BABAR and Belle
  - decay topology similar to $J/\psi K_S$ => well suited for B factories ...and for LHCb!
  - background levels are low
- Results:
  - branching fractions are at the level of 10^{-6} or below
  - consistent with SM expectations

$\mathcal{B}(B \longrightarrow X_s \ell^+ \ell^-)$



$B \to K^{(*)} l^+ l^-$ isospin asymmetry

- Isospin asymmetry

$$\Delta_{0+}(B \to K^* \ell^+ \ell^-) = \frac{\Gamma(B^0 \to K^{*0}\ell^+\ell^-) - \Gamma(B^+ \to K^{*+}\ell^+\ell^-)}{\Gamma(B^0 \to K^{*0}\ell^+\ell^-) + \Gamma(B^+ \to K^{*+}\ell^+\ell^-)}$$

  - Measurements (HFAG): $\Delta_{0+} = -0.45 \pm 0.10$
  - SM prediction is essentially zero

=> $3\text{-}4\sigma$ effect in data!

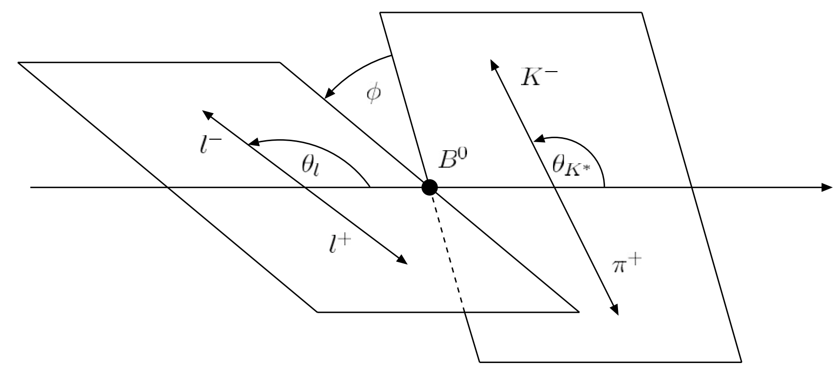
Parameter	PDG2010 Avg.	BABAR	Belle	New Avg.
$\Delta_{0-}(X_s\gamma)$	-0.01 ± 0.06	-0.01 ± 0.06		-0.01 ± 0.06
$\Delta_{0-}(K^*\gamma)$	0.066 ± 0.030	$0.066 \pm 0.021 \pm 0.022$	$0.012 \pm 0.044 \pm 0.026$	0.052 ± 0.026
$\Delta_{\rho\gamma}$	-0.46 ± 0.17	$-0.43^{+0.25}_{-0.22} \pm 0.10$	$-0.48^{+0.21+0.08}_{-0.19-0.09}$	$-0.46^{+0.17}_{-0.16}$
$\Delta_{0-}(K\ell\ell)\dagger$	$-0.40^{+0.34}_{-0.30}$	$-1.43^{+0.56}_{-0.85} \pm 0.05$	$-0.31^{+0.17}_{-0.14} \pm 0.08$	$-0.40^{+0.16}_{-0.15}$
$\Delta_{0-}(K^*\ell\ell)\dagger$	-0.44 ± 0.13	$-0.56^{+0.17}_{-0.15} \pm 0.03$	$-0.29 \pm 0.16 \pm 0.09$	$-0.44^{+0.13}_{-0.12}$
$\Delta_{0-}(K^{(*)}\ell\ell)\dagger$	-0.45 ± 0.17	$-0.64^{+0.15}_{-0.14} \pm 0.03$	$-0.30^{+0.12}_{-0.11} \pm 0.08$	-0.45 ± 0.10

$\dagger m_{\ell\ell} < m_{J/\psi}$

HFAG 2010

$B \to K^{(*)} l^+ l^-$ asymmetries

- 4-body final state ($K\pi ee$ or $K\pi\mu\mu$) => angular distributions



  - differential decay rate (summed over spin states)

$$\frac{d^4\Gamma_{\bar{B}}}{dq^2\, d\theta_\ell\, d\theta_K\, d\phi} = \frac{9}{32\pi} I(q^2, \theta_\ell, \theta_K, \phi) \sin\theta_\ell \; \sin\theta_K$$

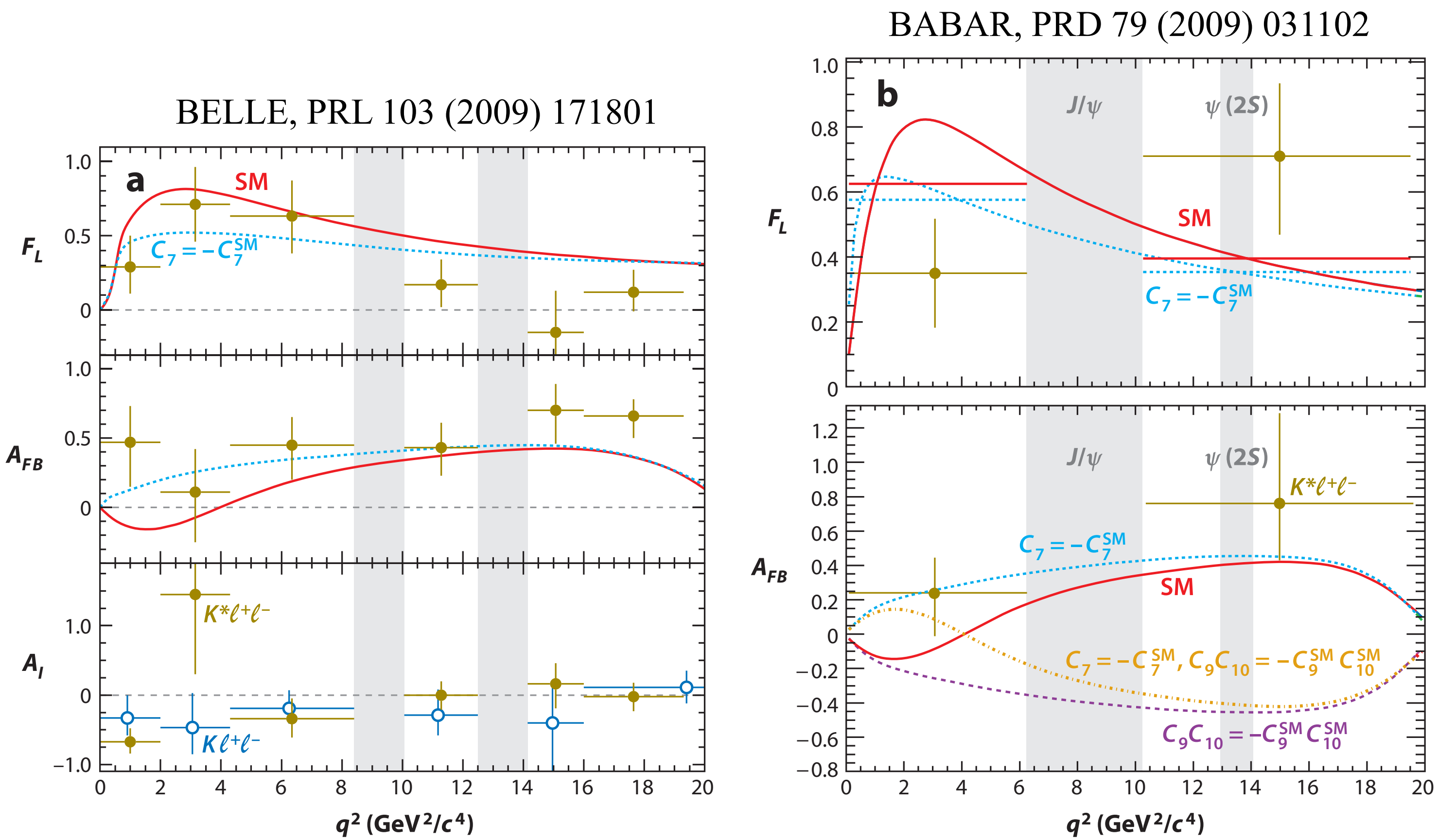
  - integrating over angles, we define the longitudinal polarization F_L, and the forward-backward asymmetry A_{FB}

$$\frac{d\Gamma'}{d\theta_K} = \frac{3\Gamma'}{4} \sin\theta_K \left(2F_L \cos^2\theta_K + (1-F_L)\sin^2\theta_K\right)$$

$$\frac{d\Gamma'}{d\theta_\ell} = \Gamma' \left(\frac{3}{4}F_L \sin^2\theta_\ell + \frac{3}{8}(1-F_L)(1+\cos^2\theta_\ell) + A_{FB}\cos\theta_\ell\right) \sin\theta_\ell .$$

- Measure these asymmetries as a function of the lepton-pair invariant mass squared q^2

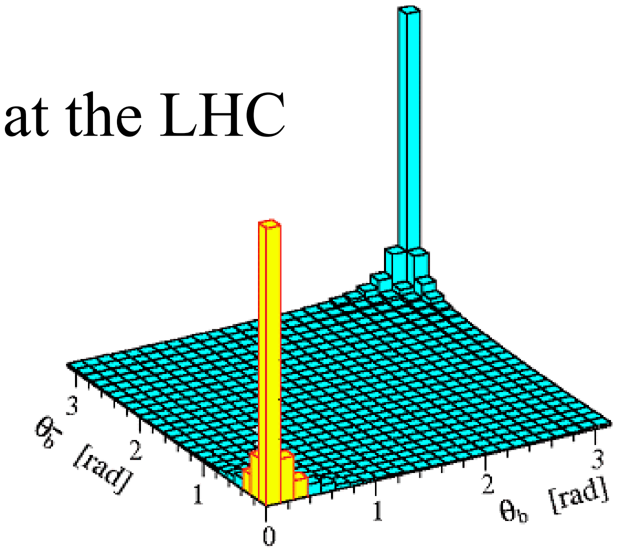
$B \to K^{(*)} l^+ l^-$ measured asymmetries

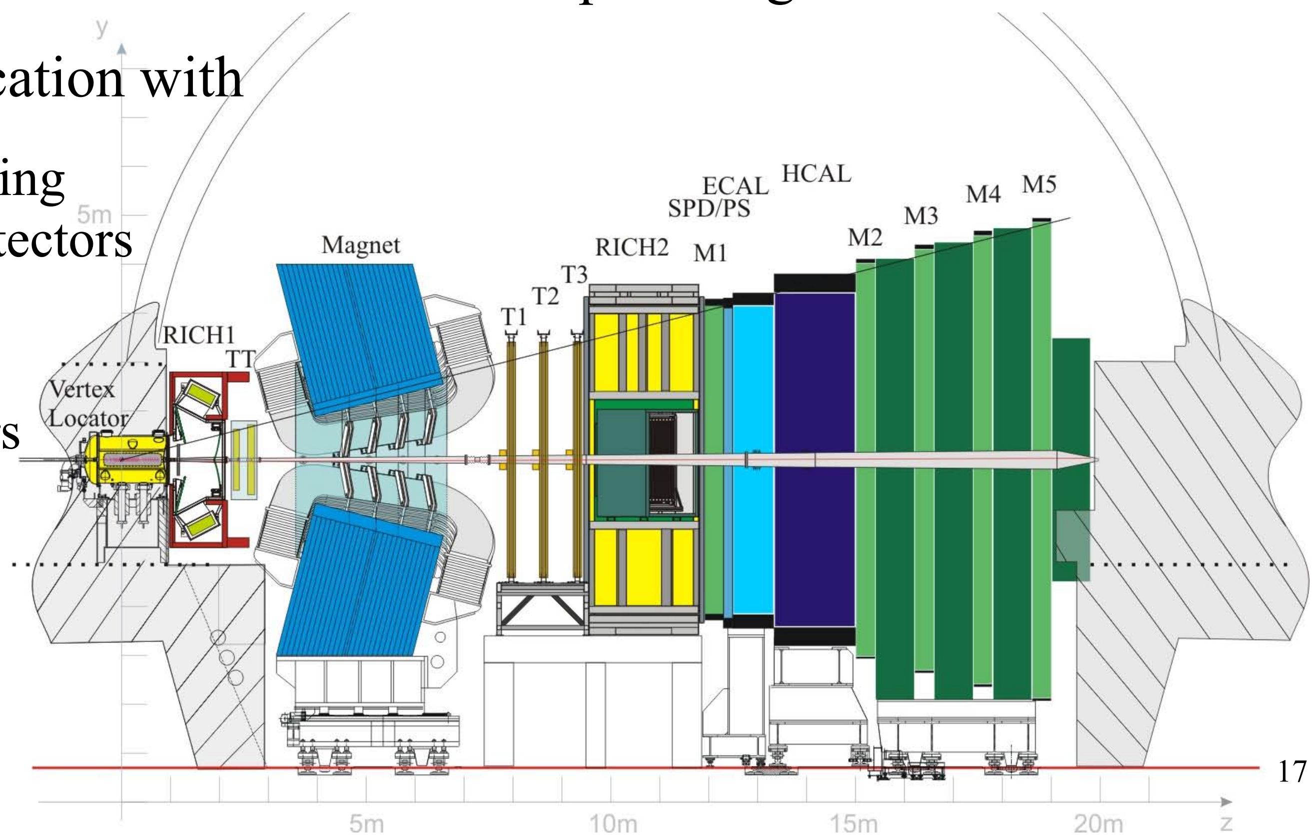


- measurements are confronted to SM predictions and alternative scenarios => constraints on Wilson coefficients
  - (marginally) compatible with SM
  - negative-sign C_7 coefficient is a possibility => new physics?
- More statistics is needed => LHCb...

The LHCb detector

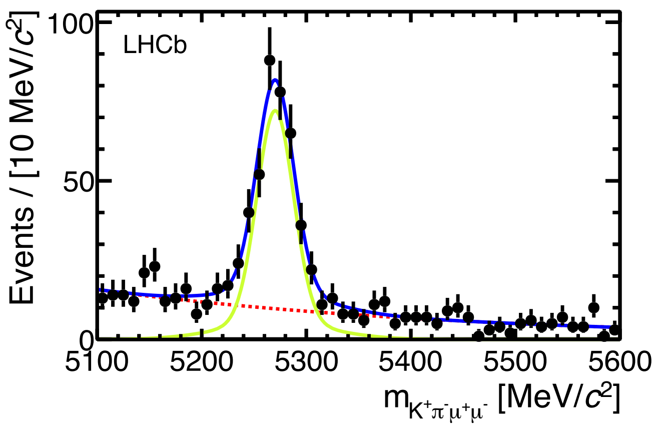
- LHCb is a single-arm forward spectrometer at the LHC
  - rapidity range: $1.9 < \eta < 4.9$
- Fully instrumented in the forward region
  - excellent vertex resolution (+boost)
    → ~50fs lifetime resolution
  - tracking stations before and after 4Tm dipole magnet
  - particle identification with
    - two ring-imaging Cherenkov detectors
    - calorimetry
    - muon detectors



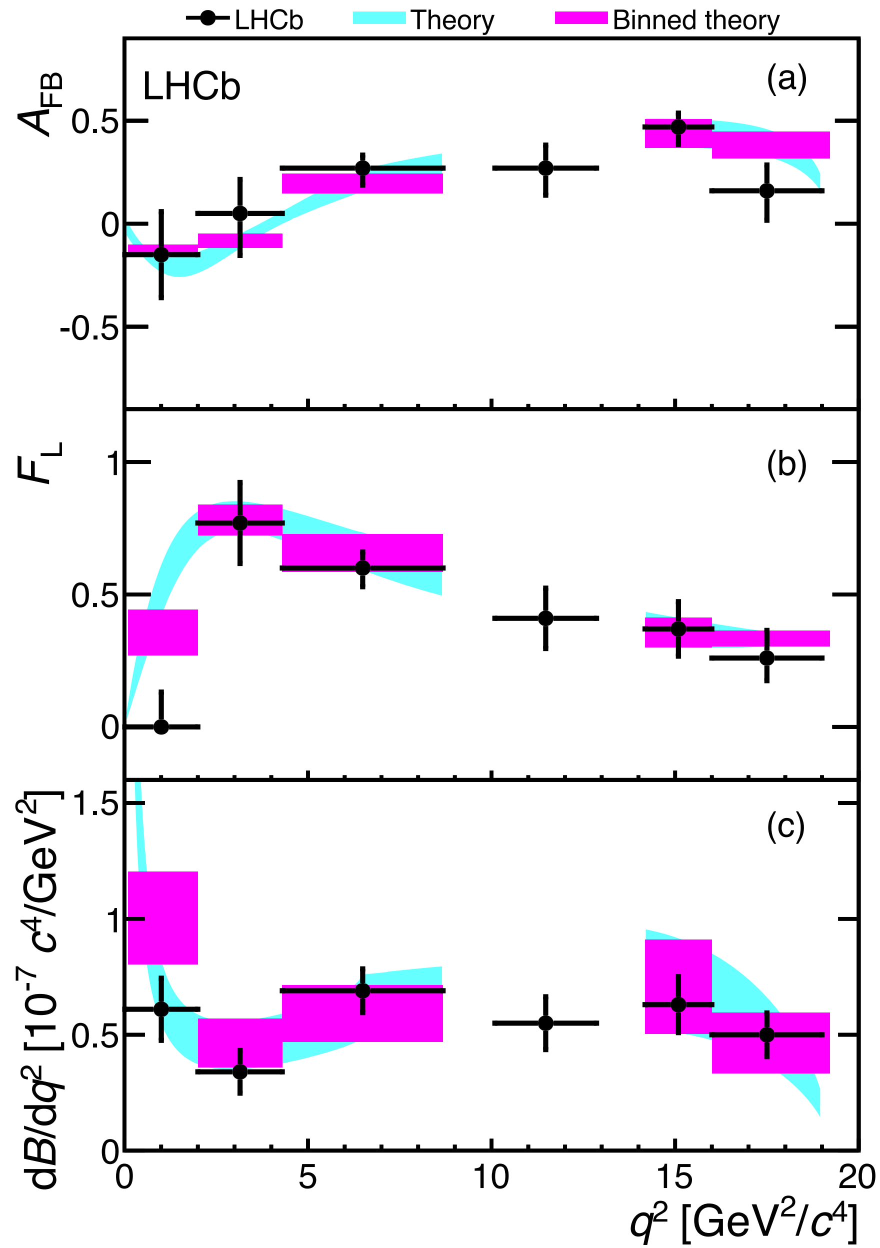


$B \to K^{(*)} l^+ l^-$ at LHCb

- LHCb has been optimized for these types of decays
- $L_{int} = 370 pb^{-1}$
- Simultaneous fit to mass and angles



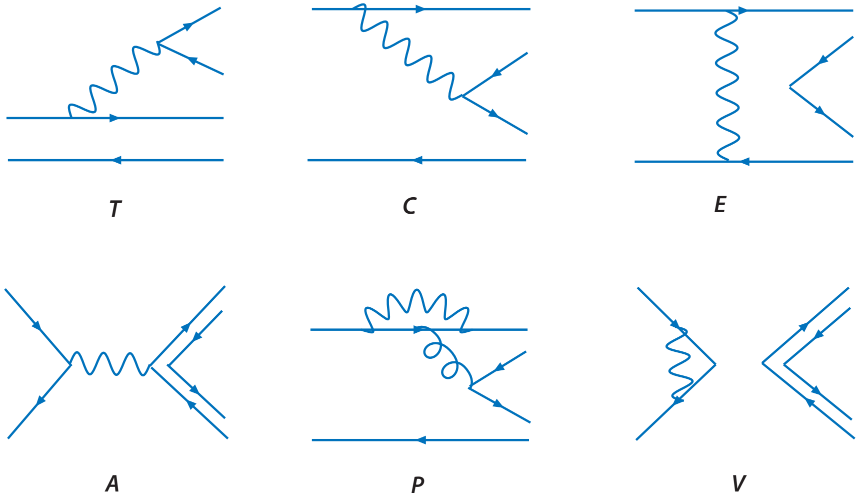
- 337±21 signal events => best single result
- Results in good agreement with SM! unfortunately :-(



LHCb, arXiv:1112:3515

Charmless hadronic B decays

- Charmless hadronic *B* decays concern decays which do not contain valence charm quarks in the final state
- At the quark level, the $B \to M_1 M_2$ transitions can be expressed in term of 6 topological diagrams
  - external (T) and color-suppressed (C) tree
  - electroweak and gluonic penguin (P)
  - $W^{\pm}$-exchange (E)
  - $W^{\pm}$-annihilation (A)
  - vertical $W^{\pm}$-loop (V)
- Remarks: these are not Feynman diagrams, as the QCD effects are included



Charmless hadronic B decays

- The decay amplitudes are written as functions of the topological diagrams

$$A(B^0 \to \pi^+\pi^-) = T + P + \frac{2}{3}P^c_{\rm EW} + E + V,$$

$$A(B^0 \to \pi^0\pi^0) = -\frac{1}{\sqrt{2}}\left(C - P + P_{\rm EW} + \frac{1}{3}P^c_{\rm EW} - E - V\right)$$

$$A(B^+ \to \pi^+\pi^0) = \frac{1}{\sqrt{2}}(T + C + P_{\rm EW} + P^c_{\rm EW}),$$

$$A(B^0 \to K^+K^-) = E + P_A,$$

$$A(B^0 \to K^0\bar{K}^0) = P - \frac{1}{3}P^c_{\rm EW} + P_A,$$

$$A(B^+ \to K^+\bar{K}^0) = A + P - \frac{1}{3}P^c_{\rm EW},$$

$$A(B^0 \to K^+\pi^-) = P' + T' + \frac{2}{3}P'^c_{\rm EW} + P'_A,$$

$$A(B^0 \to K^0\pi^0) = \frac{-1}{\sqrt{2}}\left(P' - C' + P'_{\rm EW} + \frac{1}{3}P'^c_{\rm EW} + P'_A\right),$$

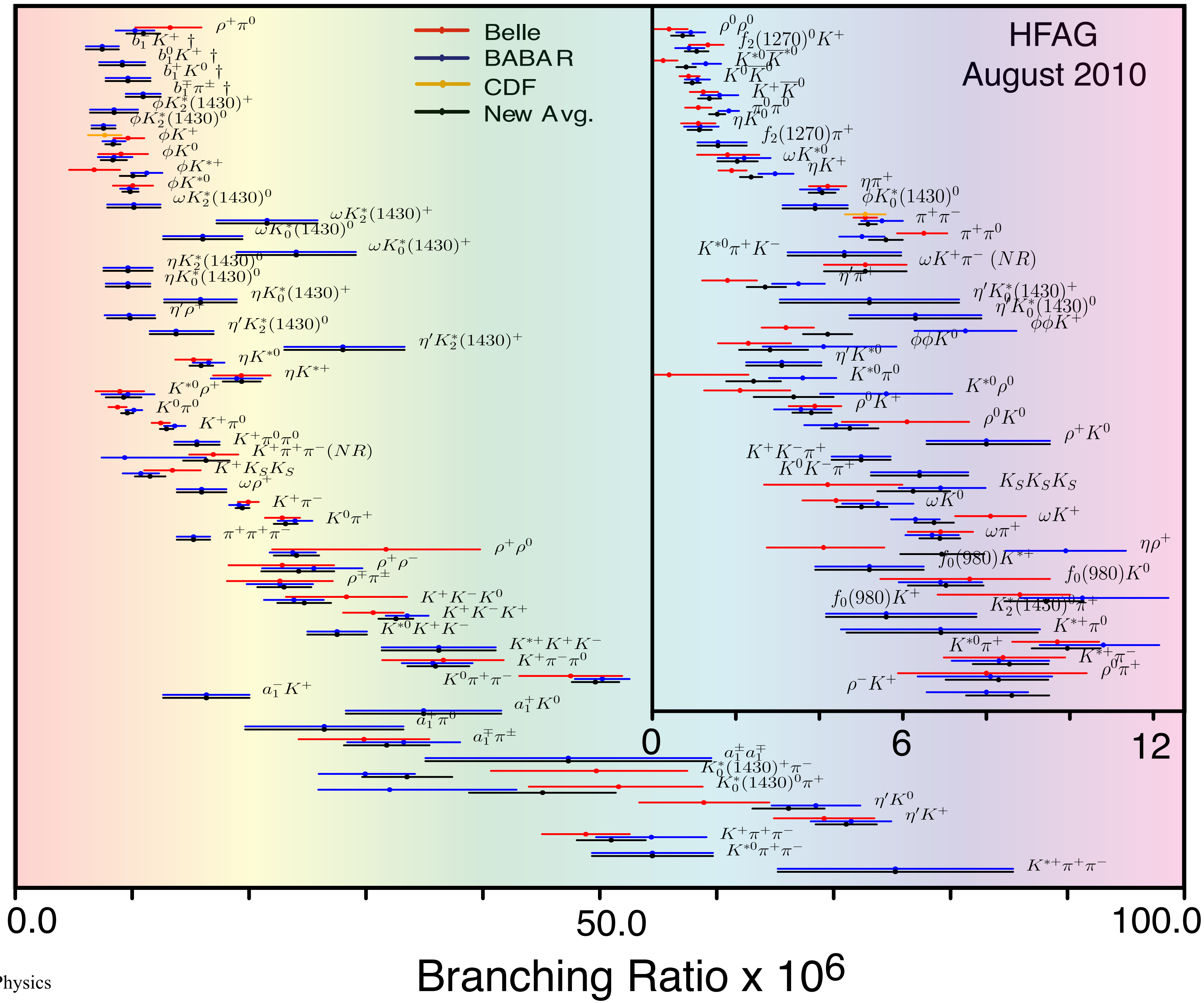
$$A(B^+ \to K^0\pi^+) = P' - \frac{1}{3}P'^c_{\rm EW} + A' + P'_A, \quad \text{and}$$

$$A(B^+ \to K^+\pi^0) = \frac{1}{\sqrt{2}}\left(P' + T' + C' + P'_{\rm EW} + \frac{2}{3}P'^c_{\rm EW} + A' + P'_A\right)$$

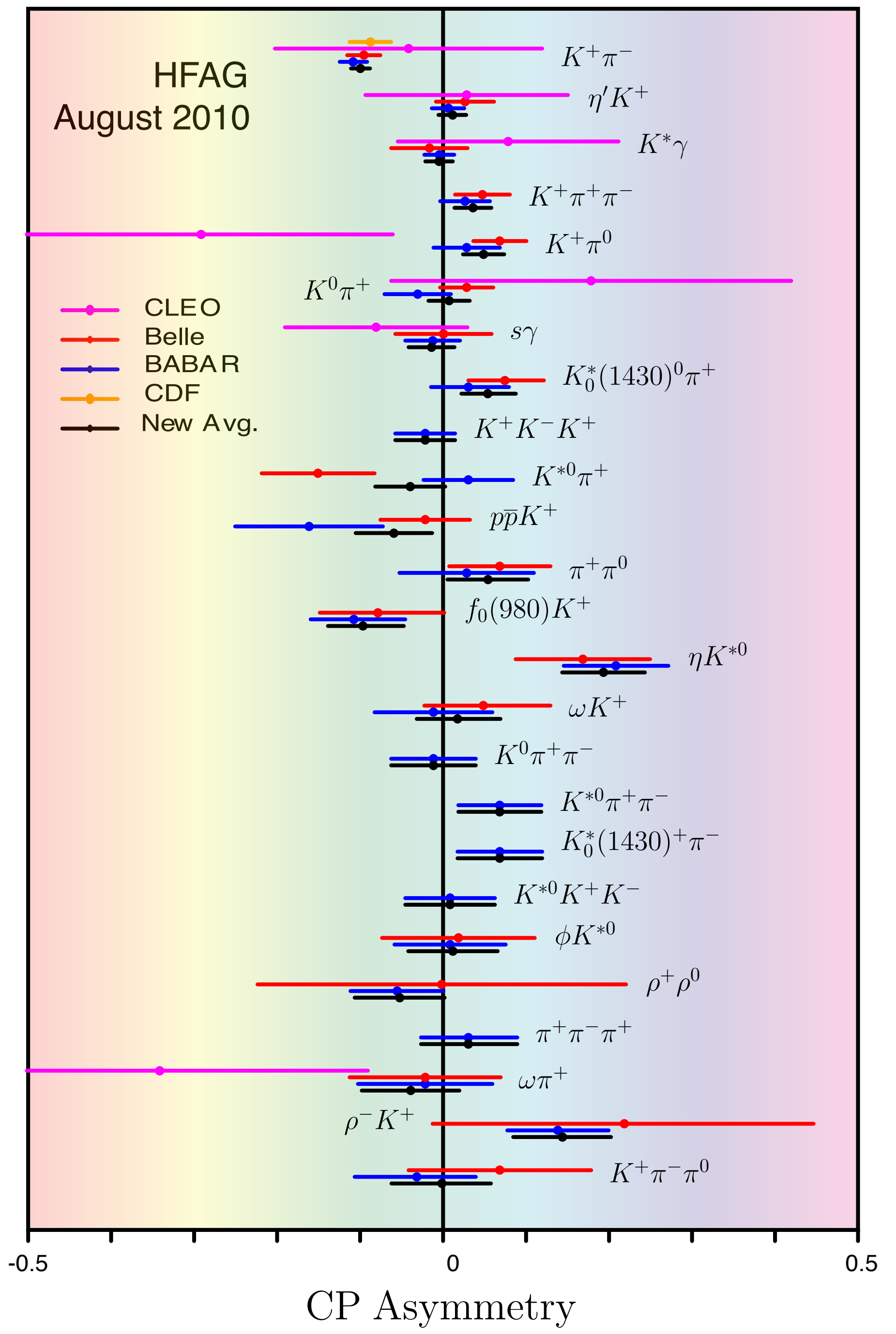
- From measured branching fractions and CP asymmetries, and assuming *SU(3)* flavor symmetry
  => constrain and determine the topological amplitudes

- The amplitudes can then be used to compute the value of $sin2\beta_{\rm eff}$ measured in charmless B decays

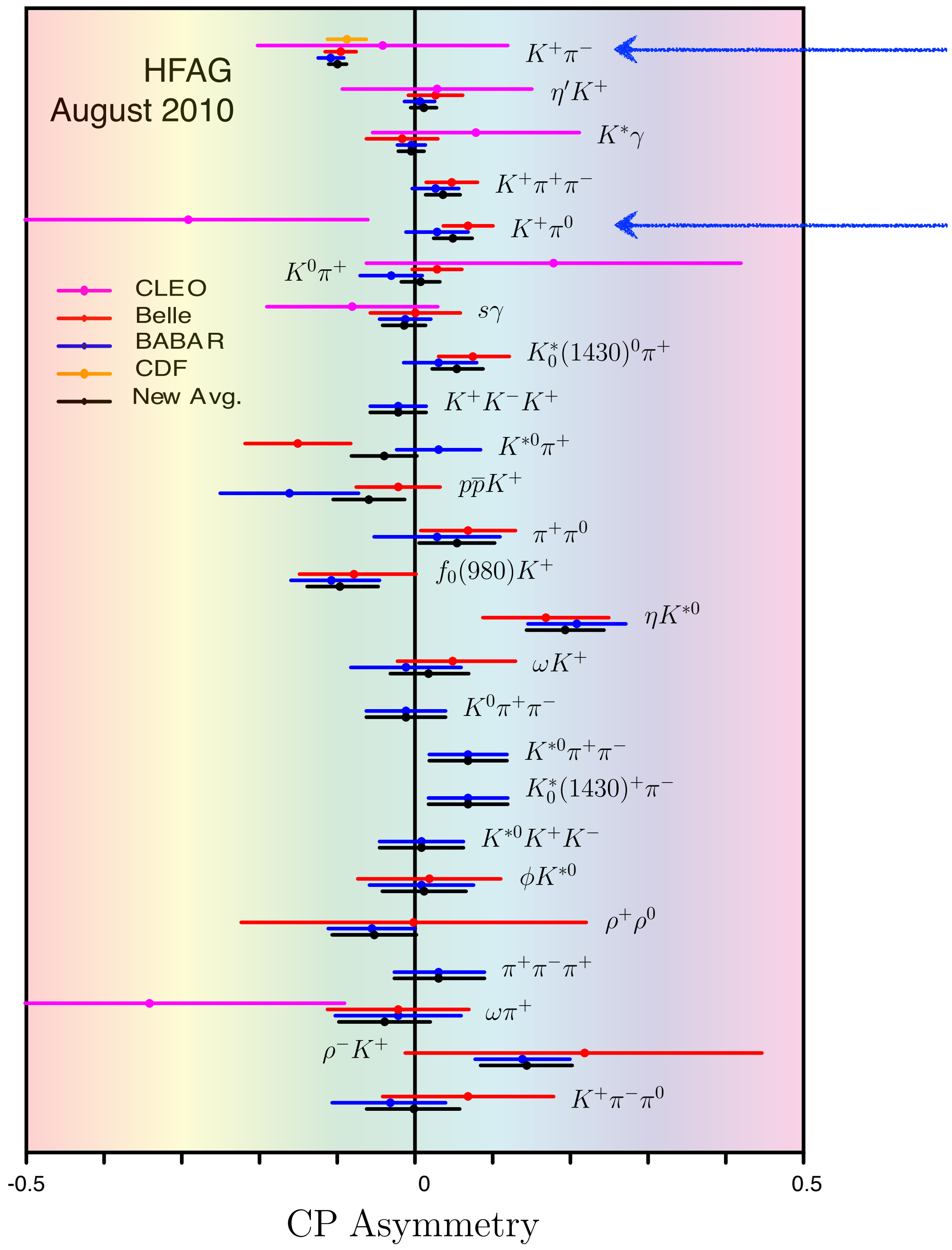
$B^{0,\pm}$ charmless decays: branching fractions



$B^{0,\pm}$ charmless decays: CP asymmetries



$B^{0,\pm}$ charmless decays: CP asymmetries



A_{CP} in $B^0 \rightarrow K^+\pi^-$

- Significant ($>5\sigma$) CP asymmetry observed in $B^0 \rightarrow K^+\pi^-$

$$A_{CP} = -0.098 \pm 0.012$$

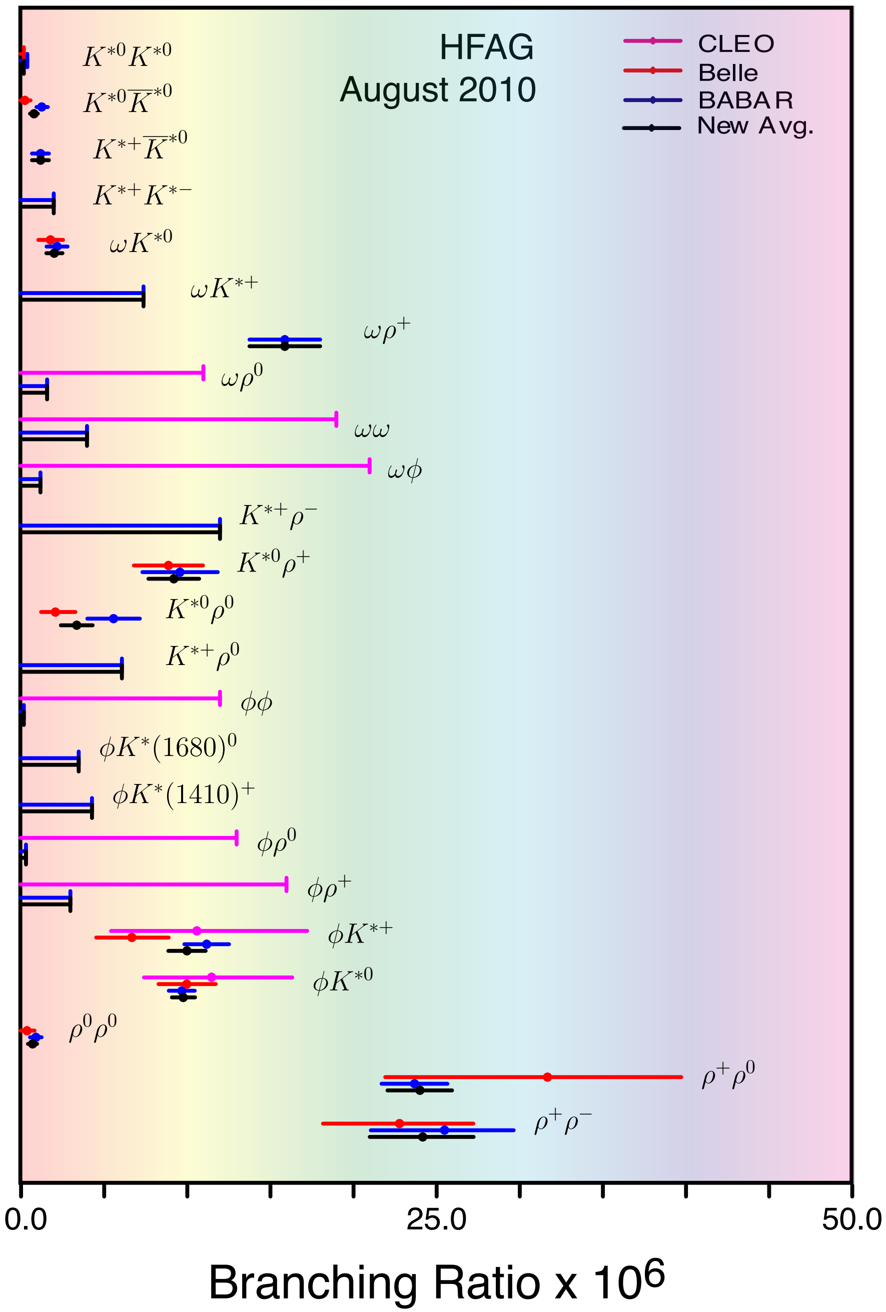
- If the color-suppressed, EW penguin, and annihilation diagrams can be neglected

$$\Rightarrow A(B^0 \rightarrow K^+\pi^-) = \sqrt{2} \times A(B^+ \rightarrow K^+\pi^0)$$

$$\Rightarrow \text{expect } A_{CP}(B^0 \rightarrow K^+\pi^-) = A_{CP}(B^+ \rightarrow K^+\pi^0)$$

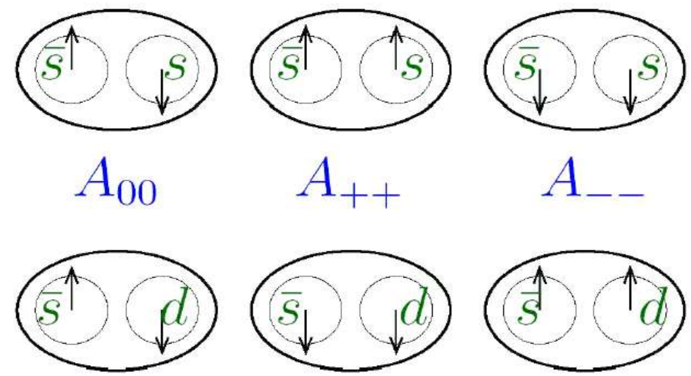
- Experimentally, the charge asymmetries differ by 5.3σ
=> either large color-suppressed or EW penguin amplitude
  - various scenarios have been proposed
  - it should be noted that a large color-suppressed amplitude, with large relative phase to the tree amplitude would:
    - solve the apparent A_{CP} puzzle, and
    - explain the large $B^0 \rightarrow \pi^0\pi^0$ branching ratio

$B \to VV$: branching ratios



$B \to VV$: polarization fraction

- From helicity conservation, expect the longitudinal polarization to dominate over the transverse amplitudes
  - amplitudes reduced by factors of (Λ_{QCD}/m_b)
  - A_{00} dominates over A_{++} and A_{--}



[helicity conservation]

- Define the polarization fraction

$$f_L = \frac{|A_0|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}$$

where the transversity amplitudes are

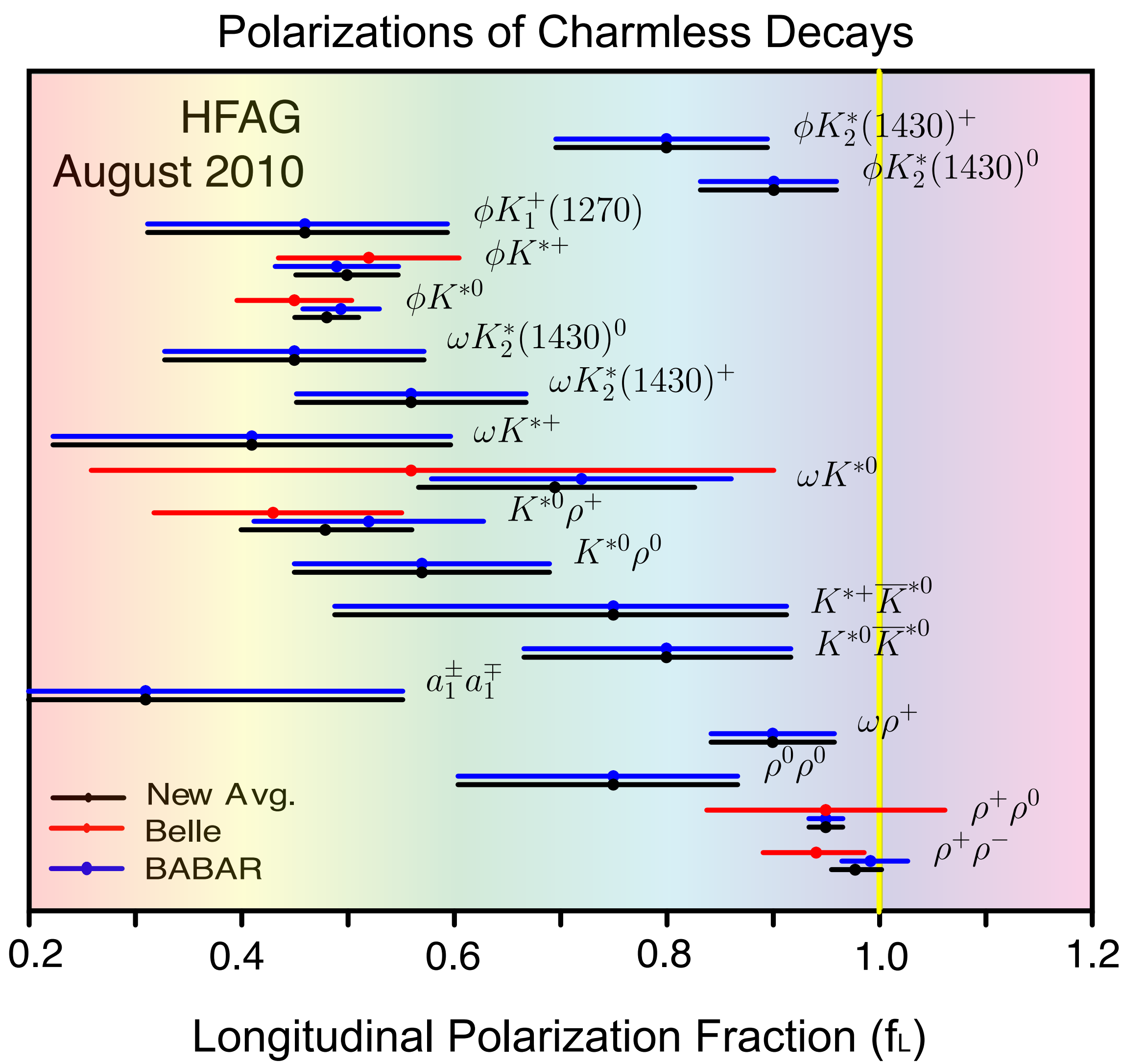
$$A_\parallel = \frac{A_+ + A_-}{\sqrt{2}}$$

$$A_\perp = \frac{A_+ - A_-}{\sqrt{2}}$$

- Expectation:

$$1-f_L \approx (m_V/m_B)^2 \approx 0.04$$

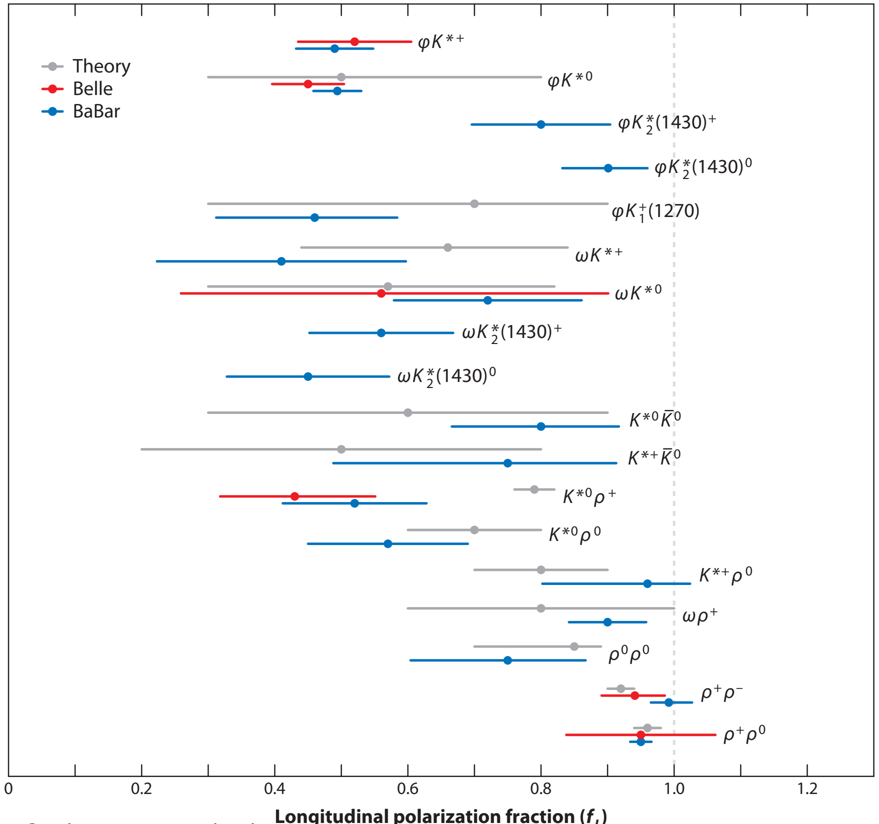
B→VV polarization: results



- $B \to \rho\rho$ modes: $f_L \approx 1$
- $B \to K^*\rho$ and $B \to \varphi K^*$ modes: $f_L \approx 0.5$ Why????

$B \rightarrow VV$ polarization puzzle

- Various mechanisms have been proposed to explain the f_L puzzle:
  - large penguin-annihilation contributions
  - final state interactions
  - form factor tuning
  - new physics (!)
- But next-to-leading-order (NLO) corrections may well be the explanation
  - non-factorizable corrections and hard spectator scattering increases the positive-helicity amplitude (A_+) of some VV modes

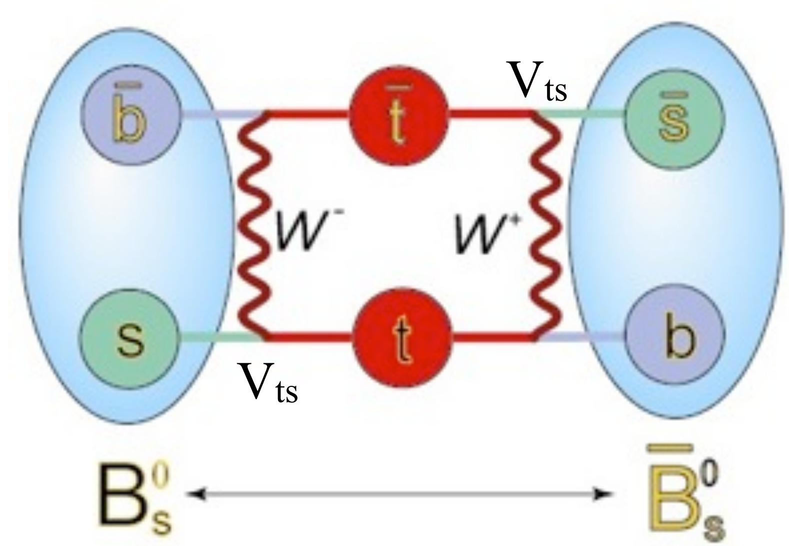


- Problem solved?
  - no, still need to test other predictions of the model
    - e.g. $f_L(K^{*+}\rho^0) > f_L(K^{*+}\rho^-) > f_L(K^{*0}\rho^+) > f_L(K^{*0}\rho^0).$

Measurements with the B_s meson

B_s mixing

- Observation of B_s mixing is probably the most significant contribution to flavor physics from the Tevatron experiments (*B* factories running at the *Y(4S)* do not have B_s samples)

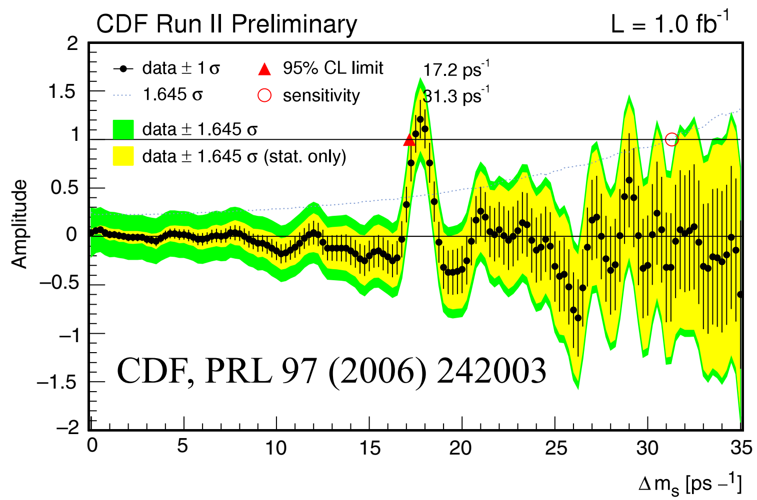


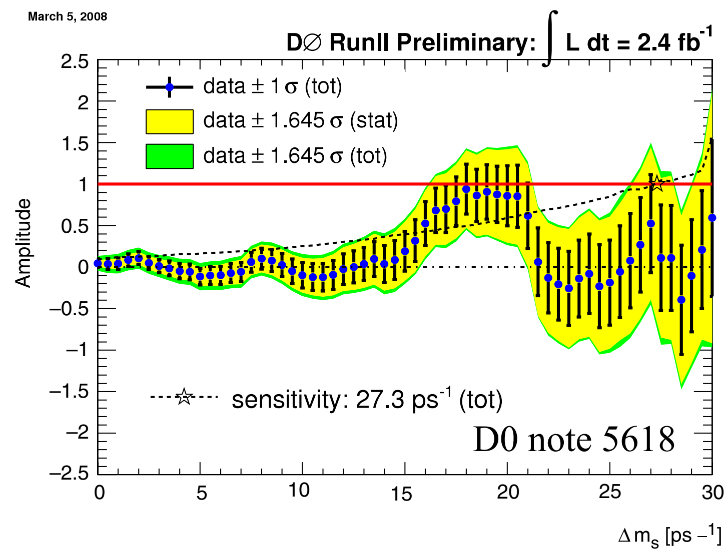
- B_s high oscillation frequency ($\approx 18 ps^{-1}$) requires proper time reconstruction resolution better than the oscillation period
- The method used is an "amplitude scan" (similar to Fourier transform)
  1. refit the data for the amplitude with fixed probe frequencies
  2. report the amplitude as a function of the probe frequency
  3. signal where the amplitude is significantly different from zero

Moser and Roussarie, NIM A384 (1997) 491

B_s mixing: Tevatron results

- B mixing first observed at CDF and D0





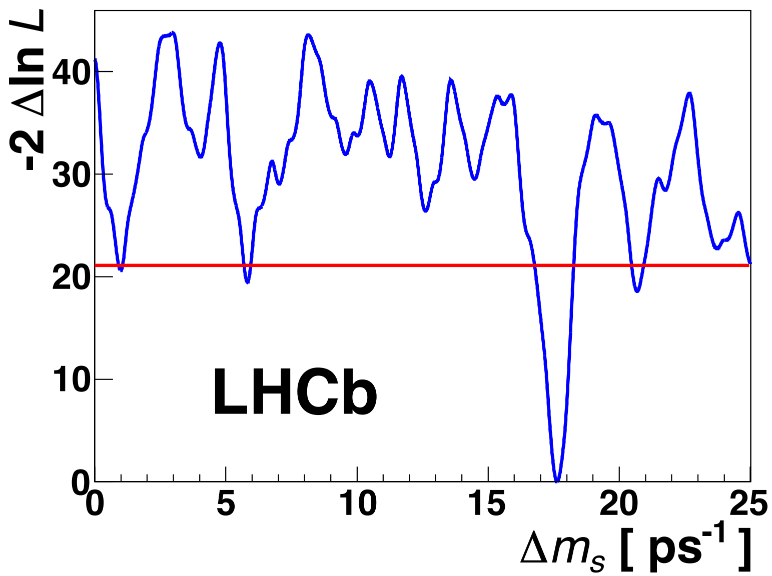
The sensitivity of the measurement is defined by the maximum value of Δm_s where A=1 is excluded at 95% C.L. if the measured value of A were zero.

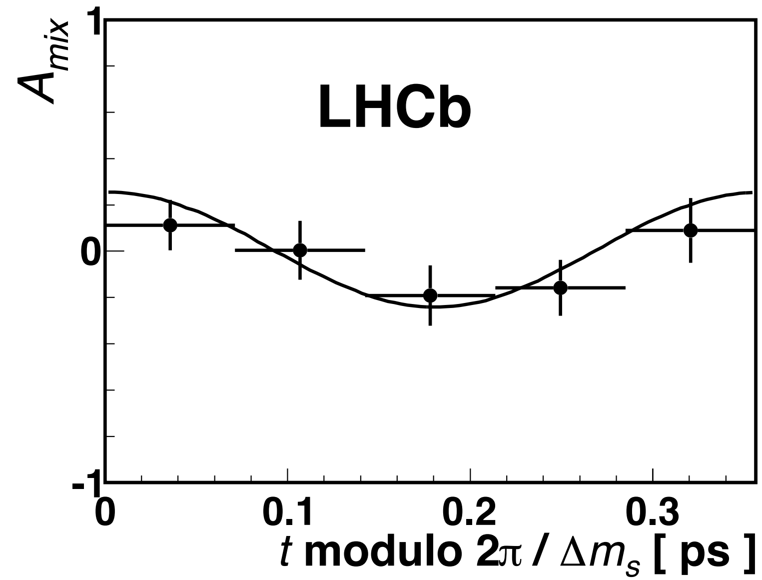
$$\Delta m_s = (17.77 \pm 0.10_{\rm stat} \pm 0.07_{\rm syst})\mathrm{ps}^{-1} \ \ (5.9\sigma, \mathrm{CDF})$$

$$\Delta m_s = (18.53 \pm 0.93_{\rm stat} \pm 0.30_{\rm syst})\mathrm{ps}^{-1} \ \ (2.9\sigma, \mathrm{D0})$$

B_s mixing: LHCb results

- With 36pb^{-1} (2010 dataset) LHCb measures Δm_s in the channels $B_s \rightarrow D_s^-(3)\,\pi$
- 1381 signal events
- Result: $\Delta m_s = 17.63 \pm 0.11 \pm 0.02$ ps^{-1}





LHCb, arXiv:1112:4311

B_s mixing => determination of $|V_{td}/V_{ts}|$

- Relation between oscillation frequencies in B_d and B_s systems allows an accurate determination of $|V_{td}/V_{ts}|$

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \left| \frac{V_{ts}}{V_{td}} \right|^2$$

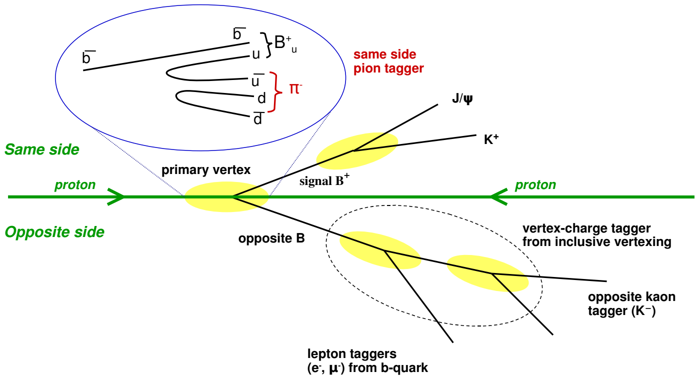
  - the ξ factor accounts for *SU(3)*-breaking effects $\xi = 1.210^{+0.047}_{-0.035}$

- Provides a theoretically clean ratio (here with Tevatron Δm_s)

$$\left| \frac{V_{td}}{V_{ts}} \right| = 0.2061 \pm 0.0012_{\rm exp} \pm {}^{+0.0080}_{-0.0060}{}_{\rm theo}$$

Phase of $V_{ts} \Rightarrow \varphi_s$ in B_s decays

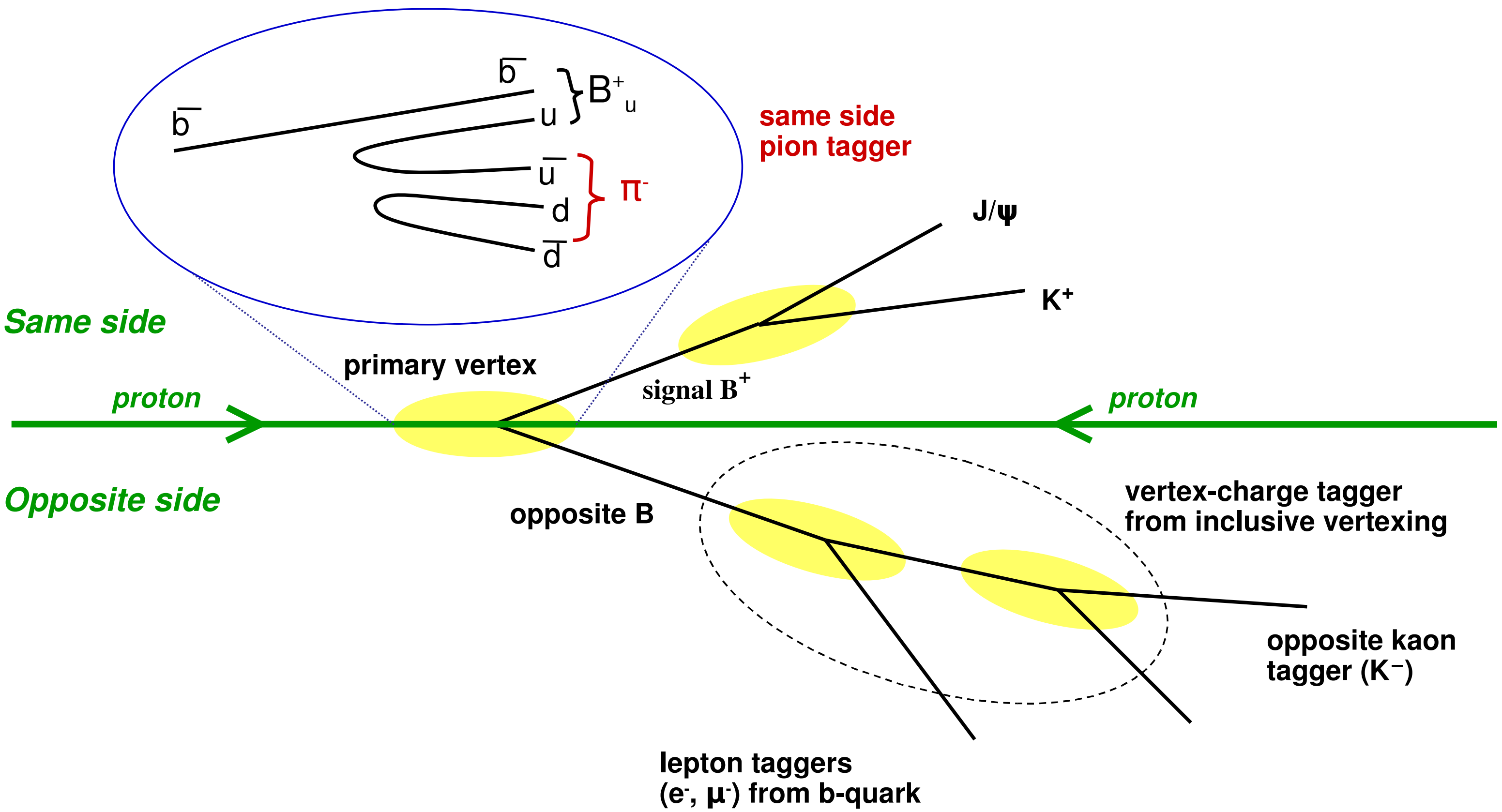
- φ_s is the phase of V_{ts}, like β is the phase of V_{td}
- φ_s can be measured in B_s decays to CP eigenstates
- Golden mode: $B_s \rightarrow J/\psi\varphi$
  - vector-vector final state
    $\Rightarrow$ angular analysis to separate
    CP-even and CP-odd amplitudes
- Tagging at the time of production of the b quark, using the flavor of the associate anti-b quark (opposite-side tagging)



  - tagging efficiency $\varepsilon = 24.9\%$
  - dilution $D = 0.277$
  - effective tagging efficiency $\varepsilon_{tag} = (1.91 \pm 0.23)\%$
    (compare to ≈30% tagging efficiency at B factories)

LHCb, arXiv:1112:3183

Tagging at LHCb



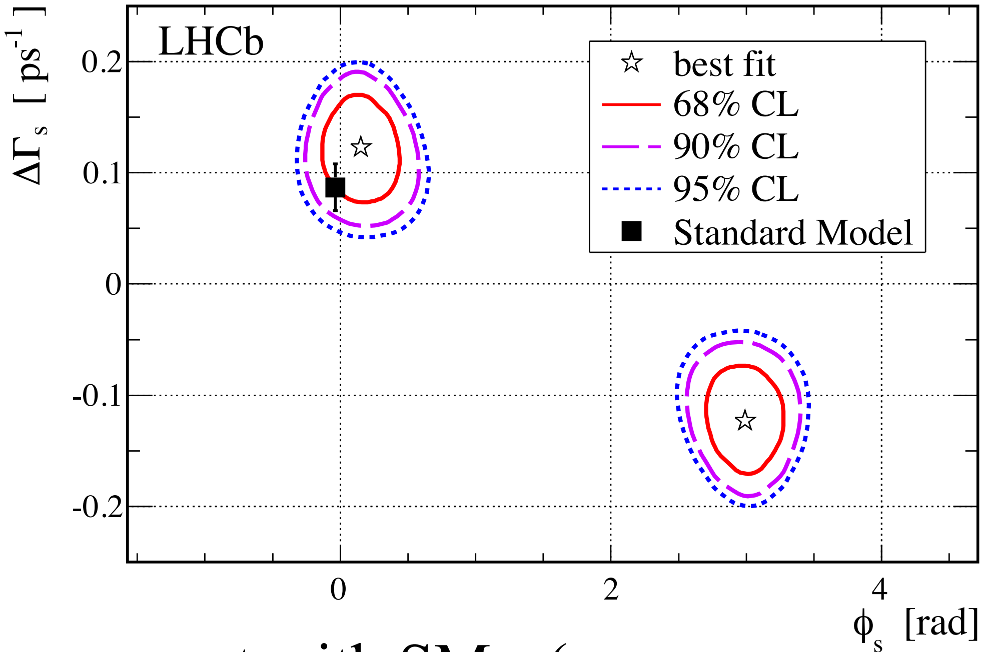
LHCb: φ_s results

- SM prediction:

$$\Delta\Gamma_s = 0.087 \pm 0.021 \text{ ps}^{-1}$$
$$\varphi_s = -0.0363 \pm 0.0017 \text{ rad}$$

- With 370pb^{-1}, LHCb measures:

$$\mathbf{\Delta\Gamma_s = 0.123 \pm 0.029 \pm 0.011 \text{ ps}^{-1}}$$
$$\mathbf{\varphi_s = 0.15 \pm 0.18 \pm 0.06 \text{ rad}}$$



⇒ good agreement with SM :-(
...but plenty of room for NP :-)

LHCb, arXiv:1112:3183

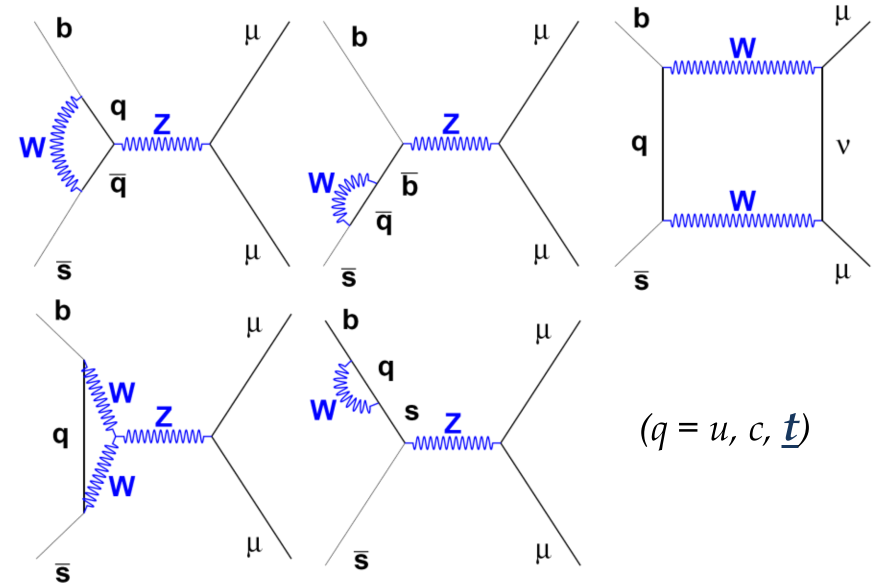
$B_s \rightarrow \mu^+\mu^-$

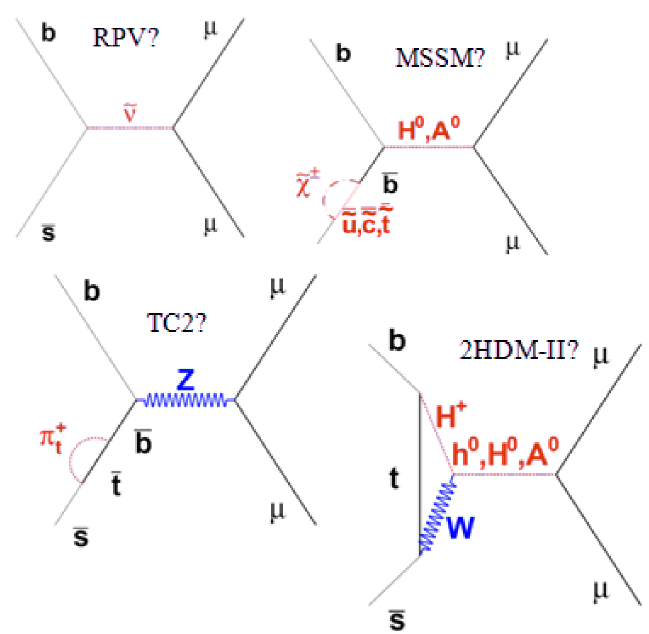
- Decay suppressed in the SM

  $BF(B_s \rightarrow \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$

  (small BF, with small SM error ⇒ sensitivity to deviations!)

- Possible large enhancement from New Physics
  - scalar sector, SUSY high tanβ ⇒ BF≫SM
  - extra dimensions ⇒ BF≠SM
  - but negative interference with SM in some models
  - in all cases, constraints on the parameter space





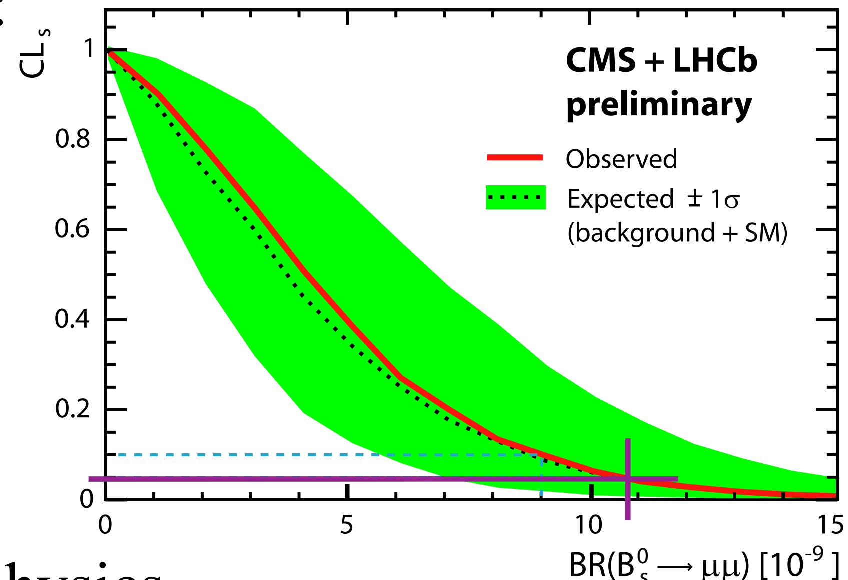
$B_s \to \mu^+\mu^-$ results

- Measurements from CDF, CMS, and LHCb

	Luminosity	95% CL upper limit	
CDF	$7 fb^{-1}$	$<4.0\times10^{-8}$	arXiv:1107.2304 (2011)
CMS	$1.14 fb^{-1}$	$<1.9\times10^{-8}$	PRL 107, 191802 (2011)
LHCb	$0.34 fb^{-1}$	$<1.5\times10^{-8}$	arXiv:1112.1600 (2011)

- Combined CMS and LHCb results:

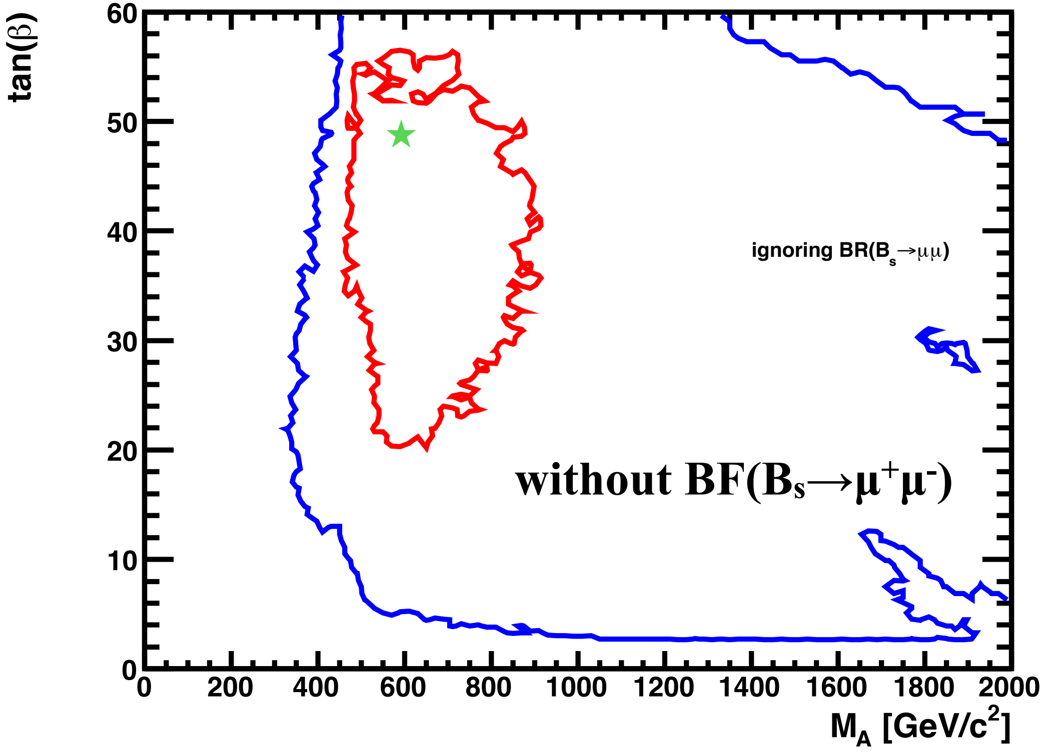
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \;<\; 1.08 \times 10^{-8} \text{ at } 95\,\% \text{ CL},$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \;<\; 0.90 \times 10^{-8} \text{ at } 90\,\% \text{ CL},$$



⇒ no large deviation from the SM
...but still plenty of room for new physics

$B_s \to \mu^+\mu^-$: constraints on New Physics

- Effect of $B_s \to \mu^+\mu^-$ on SUSY (NUHM model):
  - constraint on the high $\tan\beta$ region
  - complementary to the direct searches



arXiv:1110:3568

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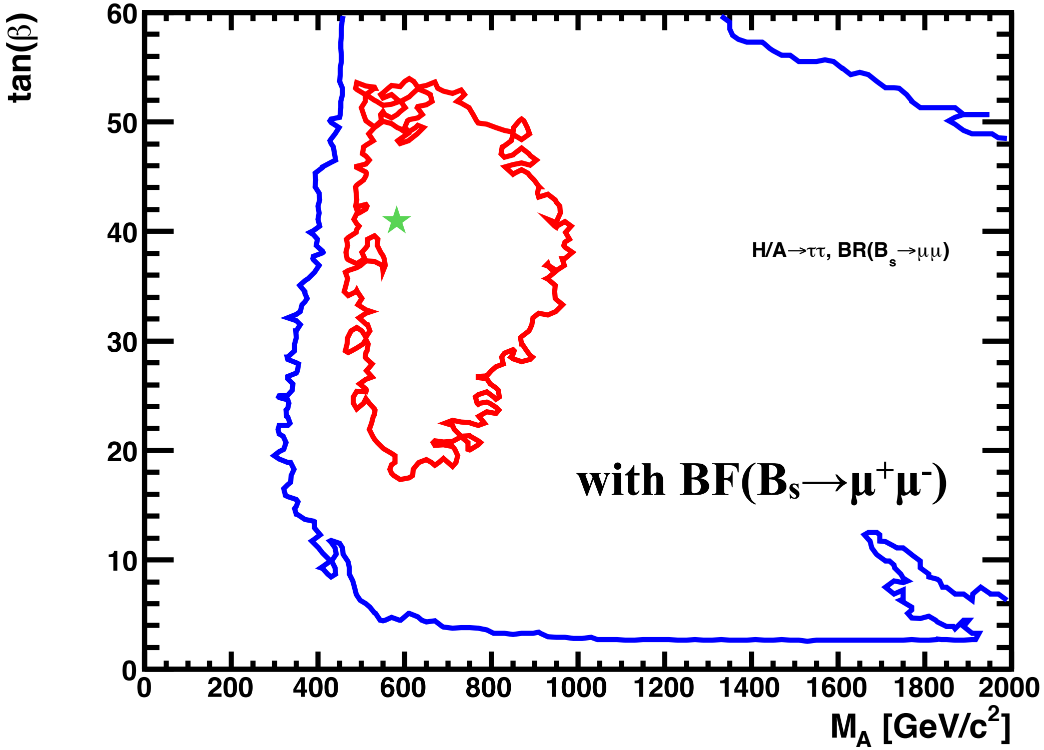


arXiv:1110:3568

CP violation in charm decays (LHCb)

- Measurement of direct CP violation (≡CP in the decay)

$$A_{CP}(f) = \frac{\Gamma_{D^0\to f} - \Gamma_{\bar{D}^0\to f}}{\Gamma_{D^0\to f} + \Gamma_{\bar{D}^0\to f}}$$

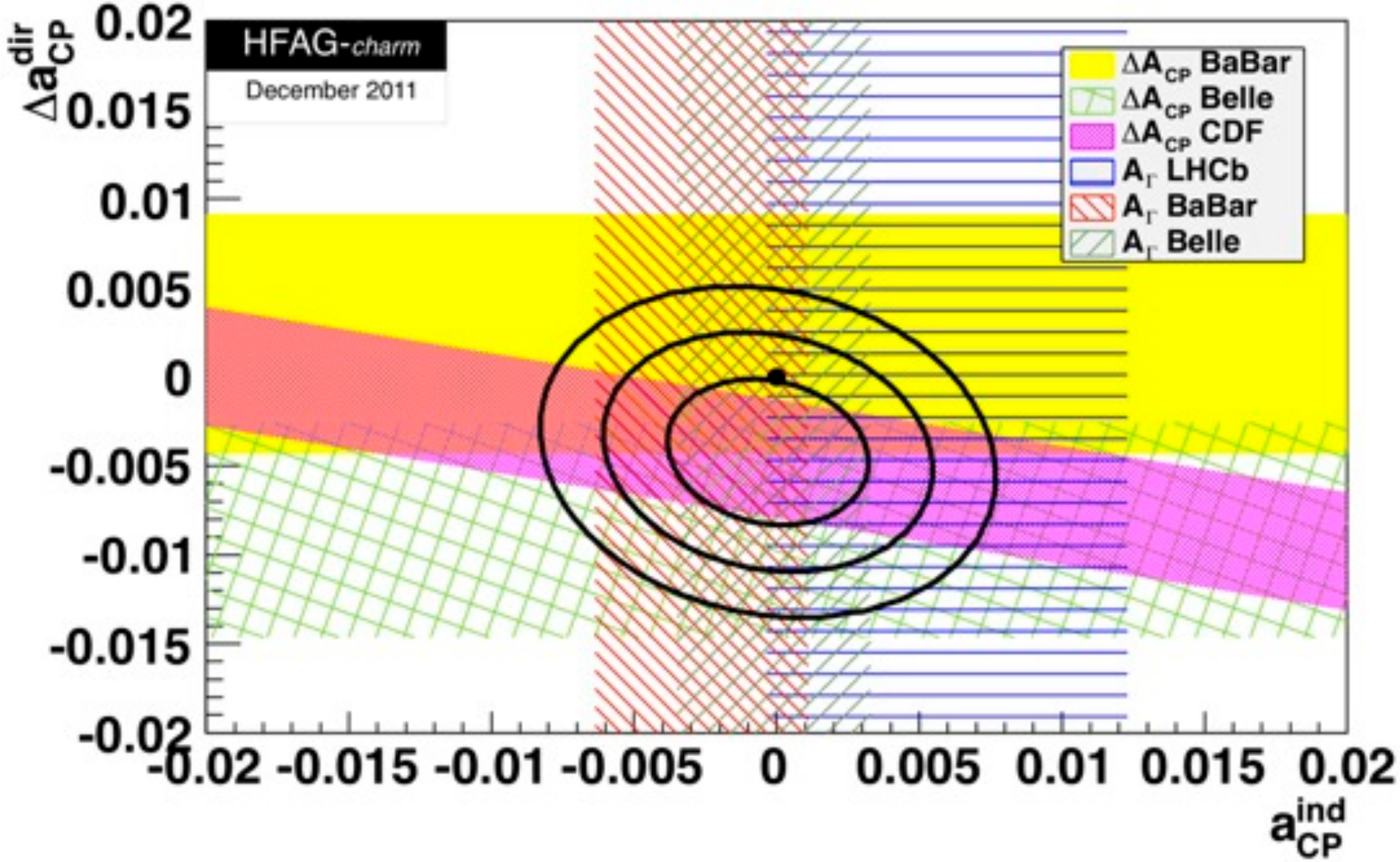
- To cancel experimental systematic errors, measure instead

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

- U-spin symmetry
  => $A_{CP}(KK) = -A_{CP}(\pi\pi)$
  => ΔA_{CP} is essentially sum of two effects

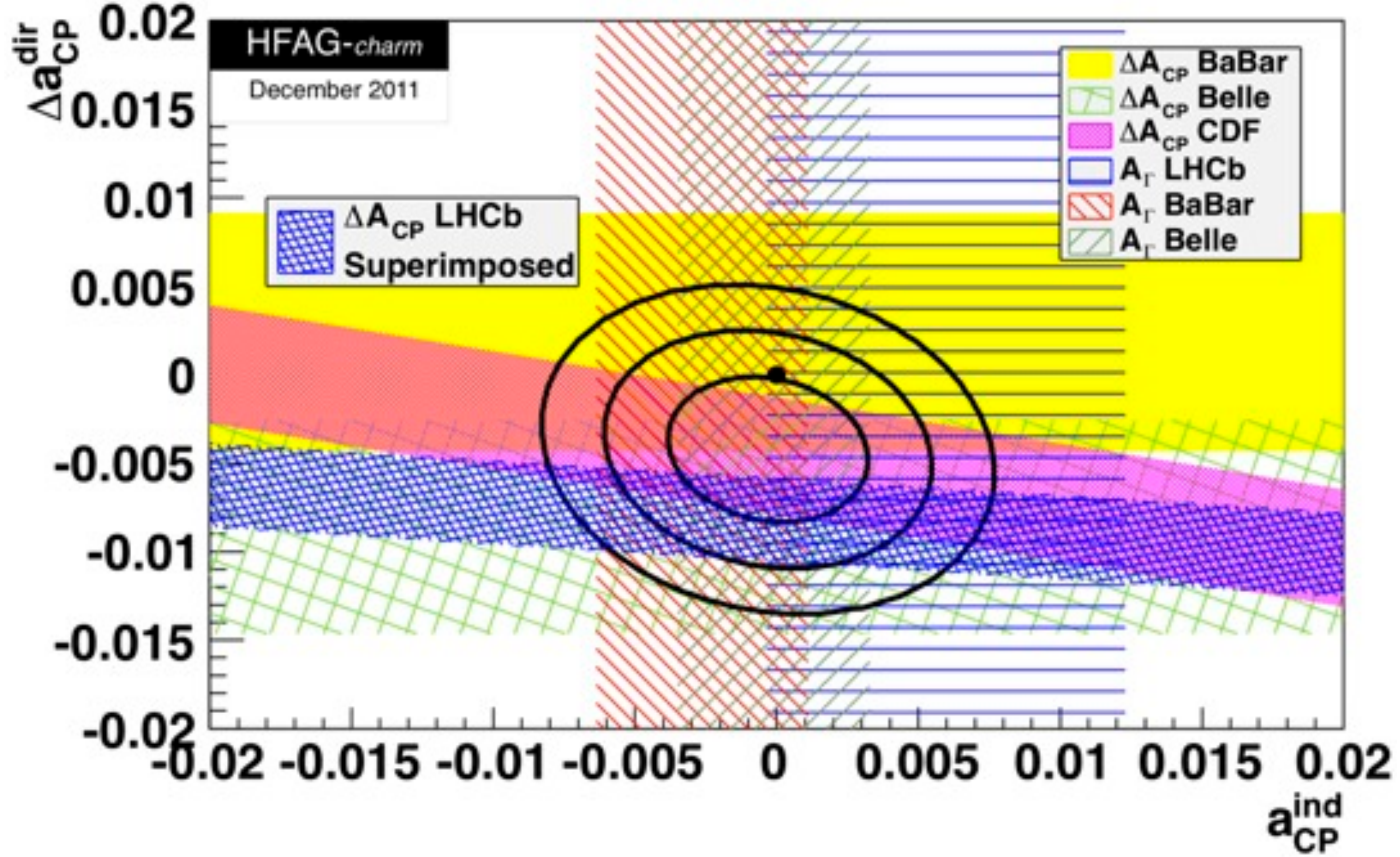
- Time-integrated quantities
  => CP violation in mixing is integrated out
  => essentially a measurement of direct CP violation

ΔA_{CP} in D^0 decays



- LHCb result: $\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%$ => 3.5σ significant
- Combined result (all exp.): $\Delta a_{CP}^{dir} = (-0.645 \pm 0.180)\%$
- Is this a fluctuation, or sign of New Physics? (à suivre...)

ΔA_{CP} in D^0 decays



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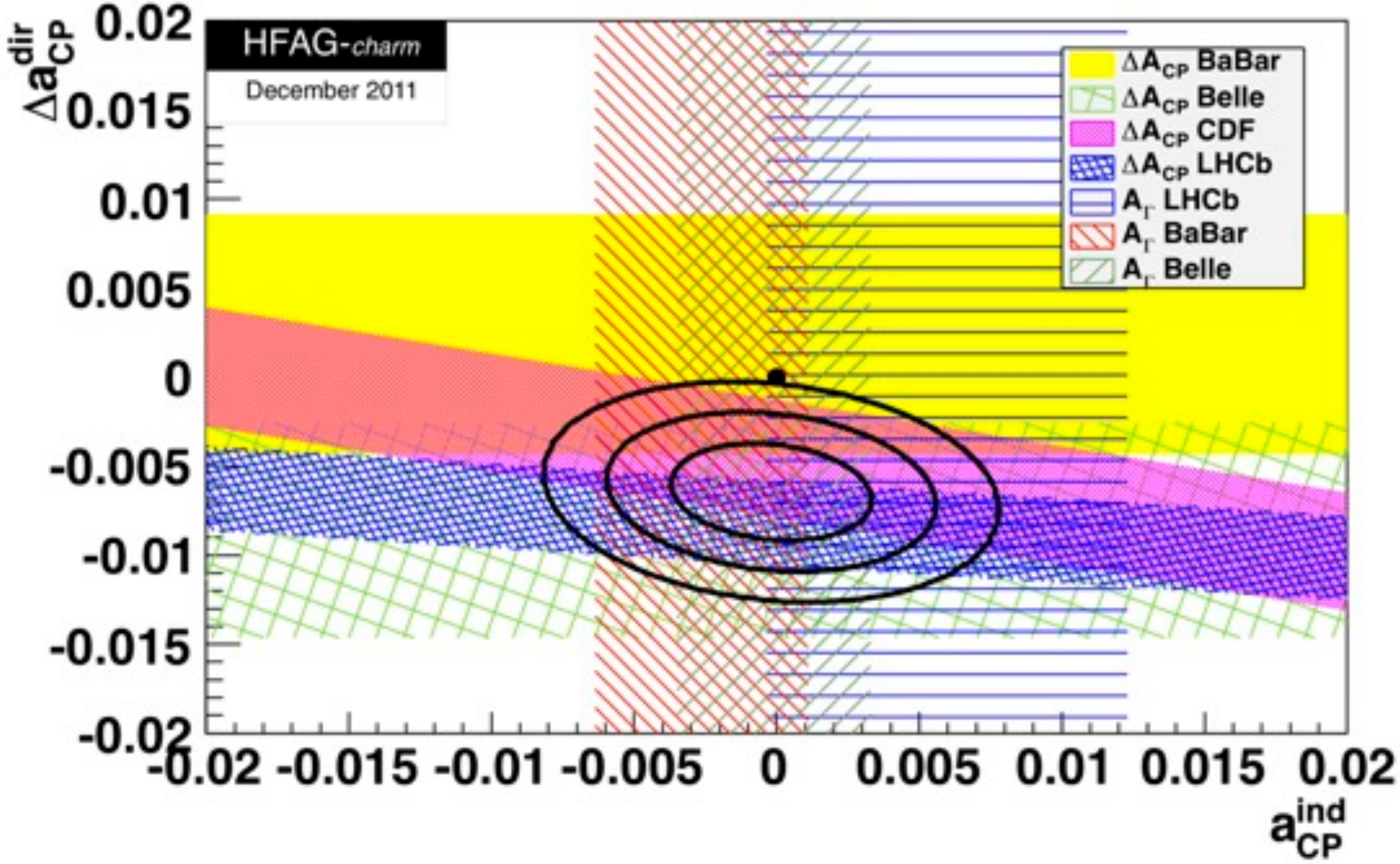

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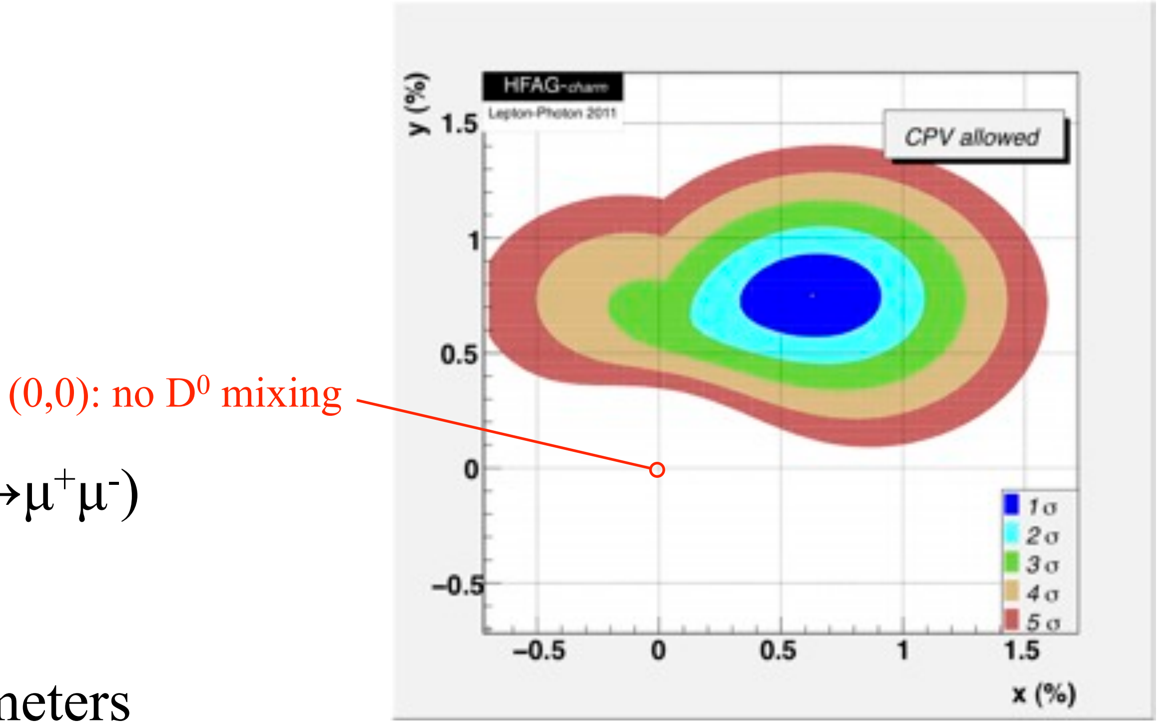
Many other topics (not covered here)!

- B_s physics at Belle
- charm physics
  - Dalitz analyses
  - D^0 mixing
  - rare decays (e.g. $D^0 \to \mu^+\mu^-$)
- τ physics:
  - decay (Michel) parameters
  - lepton-flavor violation (LFV) searches
- 2-photon physics
- neutrino-less double beta decays
  => Majorana vs Dirac neutrinos?
- ...



Future of flavor physics @ LHC

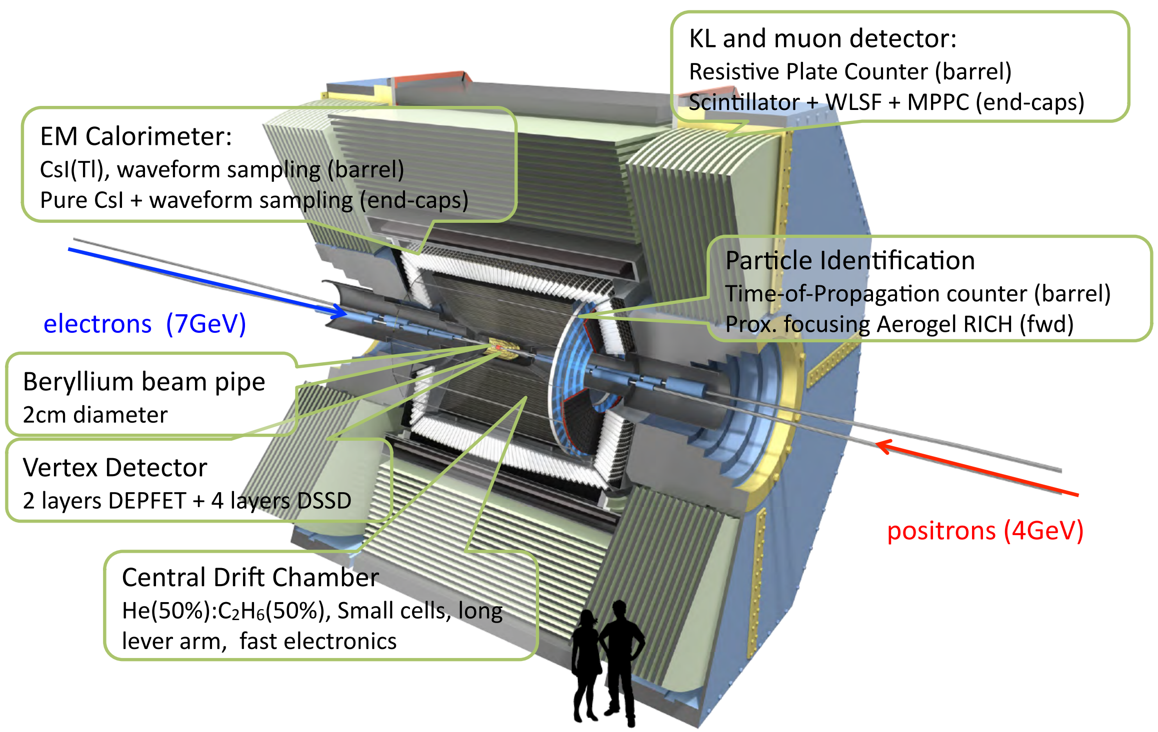
- LHCb is dedicated to the study of flavor physics at the LHC
  - LHC is a hadron machine => 1. large statistics, 2. large backgrounds, 3. access to all flavor mesons (e.g. B_d, B_s, B_c,...)
  - LHCb is expected to provide unique measurements of:
    - the weak phase of V_{ts} (in $B_s \to J/\psi\varphi$ decays)
    - $B_s \to \mu^+\mu^-$, with sensitivity to new physics
    - CKM angle γ

- CMS and ATLAS will also contribute to flavor physics
  - much larger dataset
    - significant contributions to $B_s \to \mu^+\mu^-$
  - but more challenging signal reconstruction

Future of flavor physics @ B factories

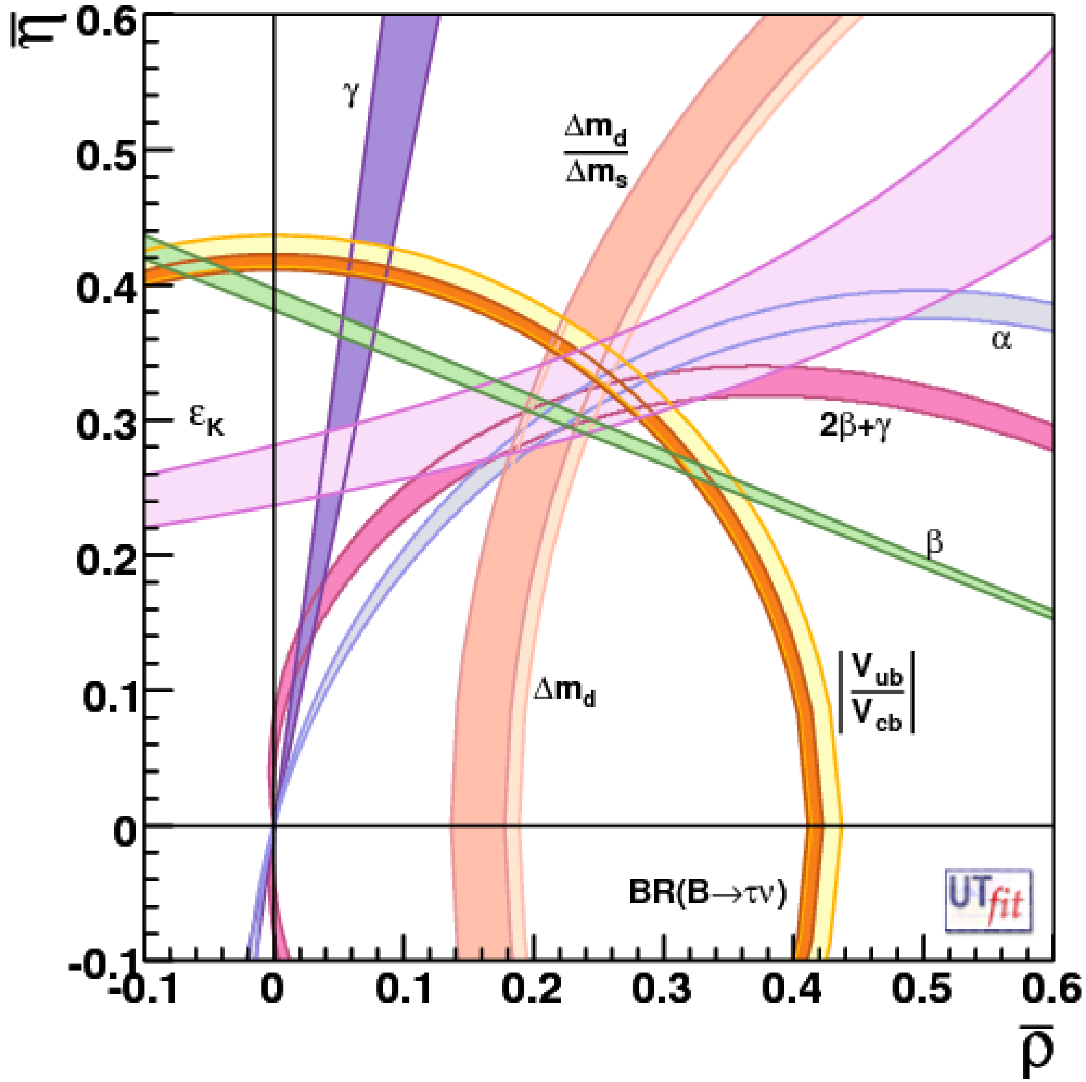
- Belle-2 (approved) and Super-B (in the process of approval) plan to run at high luminosity B factories
  - increase the total integrated luminosity to *50-100ab^{-1}*
    - Belle-II expects to start in 2014, and have ≈50ab^{-1} by 2020
  - sensitivity to rare decays => $\tau^+ \nu$, $X_s l^+ l^-$, etc...
  - should answer the questions related to the value of V_{ub}

Belle II Detector



Future of Flavor Physics

- Can we dream of this?



Summary

- Flavor physics has proven a very useful tool to study the standard model and to search for new physics
- In the past 10 years, the CKM paradigm in the SM was proven to be an excellent low-energy description of the weak interactions in the quark sector
  - several measurements allowed to strongly over-constraint the model => good agreement is observed
  - these conclusions lead to the Nobel prize for Kobayashi and Maskawa

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

- We have now started a new era at the LHC
  - no clear sign yet of new physics...
  - but we still have a few 2-3σ deviations from the SM
  - many more results expected soon!

The search for new physics continues...