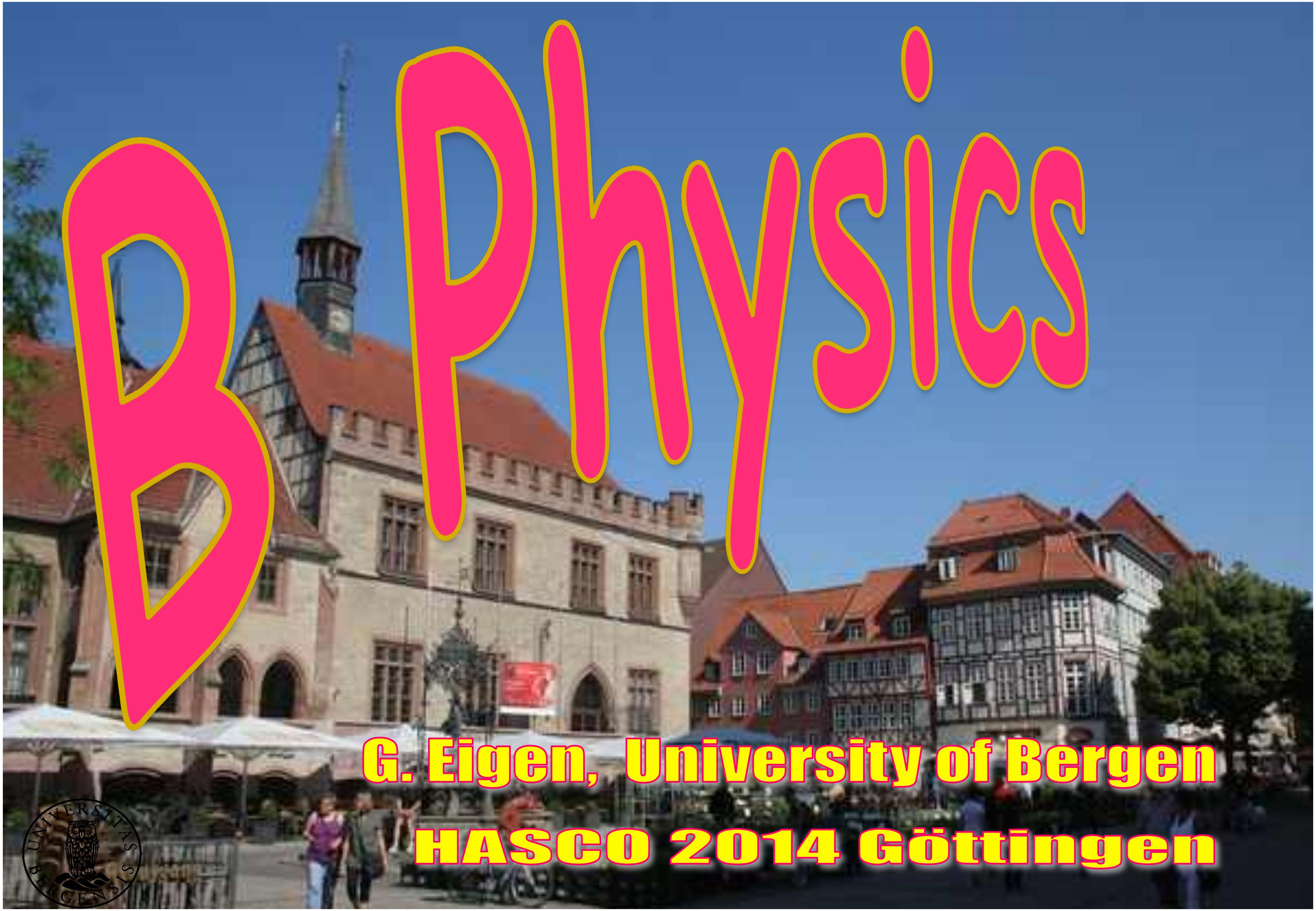
B Physics



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Introduction

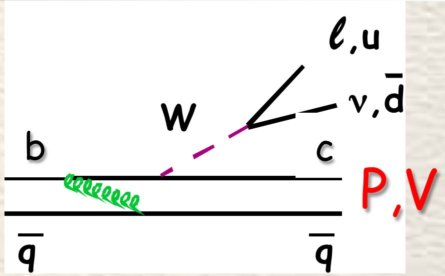
- The b quark is the heaviest quark that produces bound states, like the Υ resonances ($b\bar{b}$), B mesons ($\bar{b}q$) and B baryons (bqq', bbq, bbb), q,q'=u,d,s,c
  ➔ we focus here on B meson physics

- b quarks are produced in pairs
  - at e^+e^- colliders ➔ Υ(4S): CUSB, CLEO, BABAR, Belle, Belle II
    ➔ 90 GeV (LEP, SLC): ALEPH, DELPHI, L3, OPAL, SLD
  - at hadron colliders ➔ Tevatron: CDF, D0
    ➔ LHCb: LHCb, ATLAS, CMS

- At Υ(4S), b quark hadronizes into B^+ and B^0_d only with no additional pions
  - cross section is 1 nb ➔ need high luminosity get hundreds of 10^6 B mesons
  - excellent laboratory to study B mesons ➔ well-defined initial conditions

- At LEP, Tevatron and LHC, b quark hadronizes into B^+, B^0_d B^0_s, and b baryons in fractions of (0.402±0.007):(0.402±0.007):(0.105±0.006):(0.092±0.015)
  - cross section increases with $\sqrt{s}$ ➔ at 14 TeV $\sigma \cong 0.5$ b
  - initial conditions are not well defined, use p_T (conserved)

General Remarks

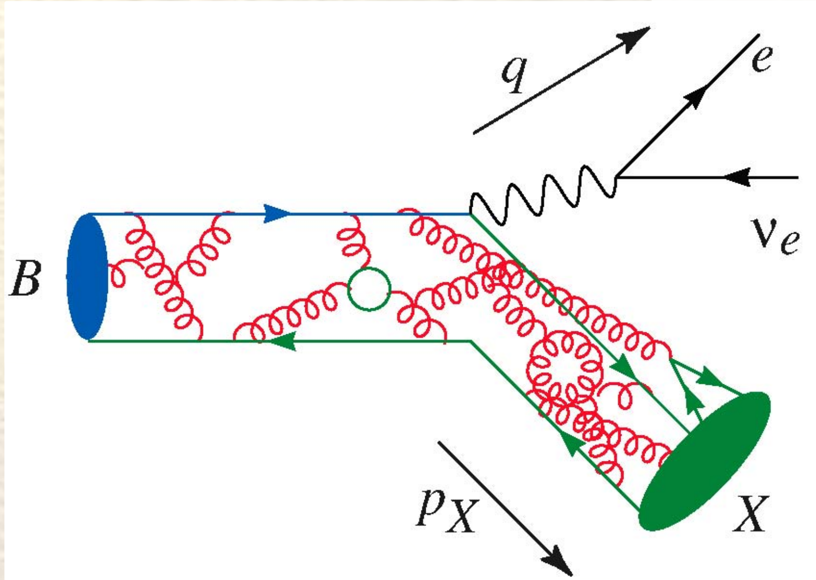


P: pseudoscalar meson
V: vector meson

- The reason why isospin is a good symmetry in QCD is that m_d-m_u«Λ_{QCD}≅200 MeV ≅1/r, where r=1 fm
- For heavy quarks it was noticed that there is another symmetry of QCD, m_Q» Λ_{QCD} (exact symmetry for $m_Q \rightarrow \infty$)
- This symmetry arises because once a quark becomes sufficiently heavy, its mass becomes irrelevant to the non perturbative dynamics of the light degrees-of-freedom (DOF) of QCD ➔ framework to calculate b→c transitions, also the spin of the heavy quark decouples from that of the light DOF
- In the heavy quark limit, an effective theory (HQET) exists that allows exact calculations of the 6 form factors in B→PW and B→VW in terms of a universal function ➔ since m_b is finite, corrections need to be included
- The heavy quark symmetry also justifies the calculation of hadronic decay properties in inclusive decays in terms of the quark decay properties plus an expansion in powers of $1/m_b$ (heavy quark expansion) ➔ for many quantities the $1/m_b$ term vanishes

General Remarks II

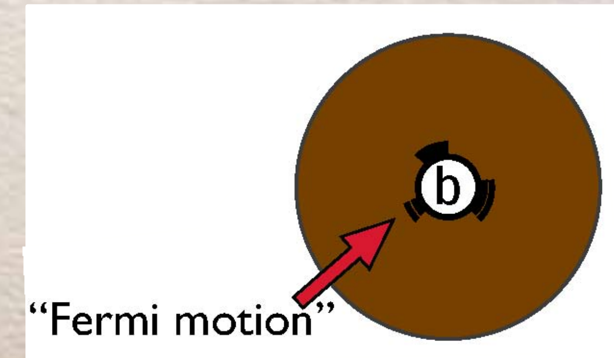
- As an example, lets look at B inclusive semileptonic decay rate



- The decay is at short distance ➔ calculable
- Hadronization occurs at long distance
  ➔ is non perturbative
- At leading order, short distance and long distance are cleanly separated and the probability to hadronize is 100%
- Thus, the semileptonic decay rate can be approximated by

$$\frac{d\Gamma}{d(\mathrm{LIPS})} \sim \frac{d\Gamma}{d(\mathrm{LIPS})}(\text{parton model}) + \sum_n z_n \left(\frac{\Lambda_{QCD}}{m_b}\right)^n \qquad (1)$$

- In this way, decay rate is calculated at ~1% accuracy
- Most of the time details of b-quark wave function are not relevant, only averages matter (k^2)

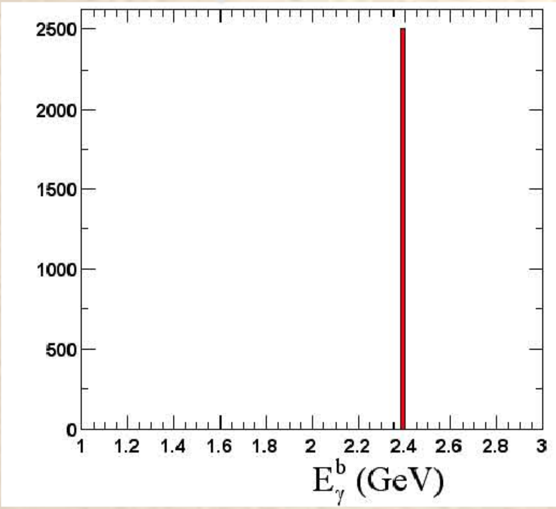


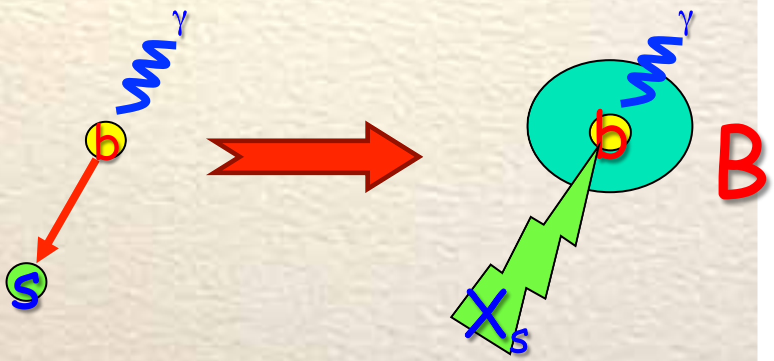
$k^{\mu} \sim \Lambda_{QCD}$

General Remarks III

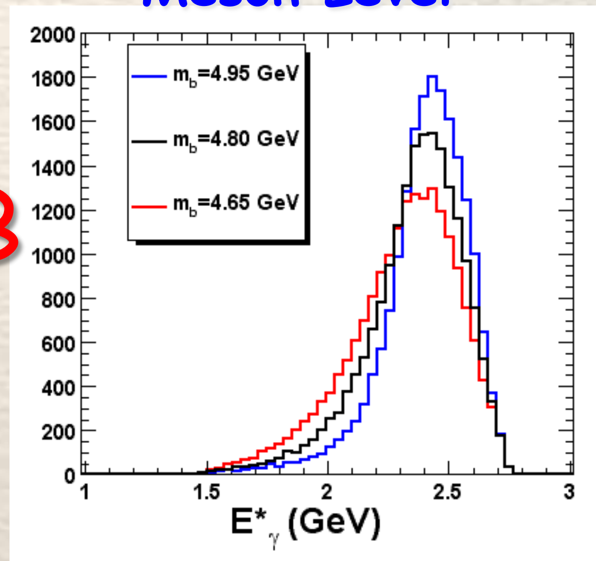
- Lets illustrate the effect of the Fermi motion in the decay $B \rightarrow X\gamma$
- The b-quark is confined inside the B meson ➔ the Fermi motion affects the shape of the photon energy spectrum (m_b)

Quark Level





Meson Level



- Since the b-quark motion is universal arising from hadronic b-quark interactions inside the B meson, we expect it to determine the dynamics of decays like $B \rightarrow X\gamma$ and $B \rightarrow X\ell\nu$ in the same way
- So for many effects, we need to deal with the motion of the b quark inside the B hadron

General Remarks IV

- Why is B physics so interesting?

- B decays have relatively simple decay topologies and a secondary vertex
  ➔so powerful criteria can be defined to discriminate signal from backgrounds
  ➔ particularly at the $\Upsilon(4S)$ with well-defined initial conditions
  ➔ dedicated experiments can fully exploit the physics

- For most observables predictions in the Standard Model (SM) are rather precise ➔ deviations would indicate new physics contributions

- With high statistics samples, measurements are rather precise to test the SM and check for new physics contributions

- There are many decays and observables that can be measured ➔ we get a complete picture which is important for deciding if an effect is real or is a fluctuation

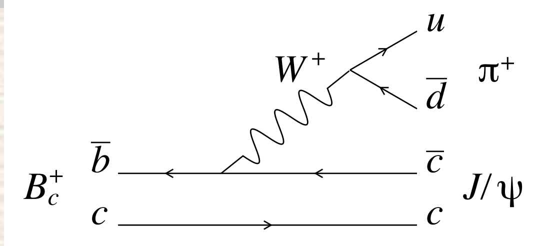
Outline

- Study of B^{+}_{c} Meson
- Rare Decays
  - $B \rightarrow X\gamma$
  - $B \rightarrow K\ell^{+}\ell^{-}$, $B \rightarrow K^{*}\ell^{+}\ell^{-}$, $B_{s} \rightarrow \phi\mu^{+}\mu^{-}$, and $B \rightarrow X_{s}\ell^{+}\ell^{-}$
  - $B \rightarrow \tau\nu$
  - $B \rightarrow \mu^{+}\mu^{-}$
- $B \rightarrow D^{(*)}\tau\nu$
- $B^{0}\bar{B}^{0}$ mixing
- CP violation
  - Direct CP violation
  - Measurement of β
  - Measurement of β_{s}
  - Measurement of α
  - Measurement of γ
  - Unitarity Triangle
- Summary and outlook

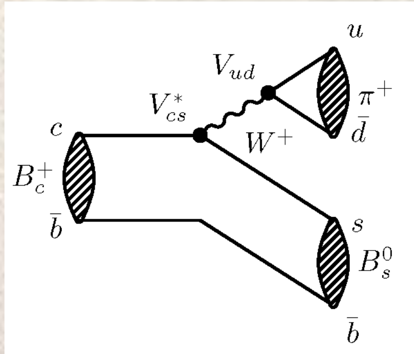
B^{+}_{c} Meson

Study of the B_c Meson

- The B_c (discovered by CDF in 1998) is only the B meson that consists of 2 decaying quarks thus shortening its lifetime wrt to that of other B mesons

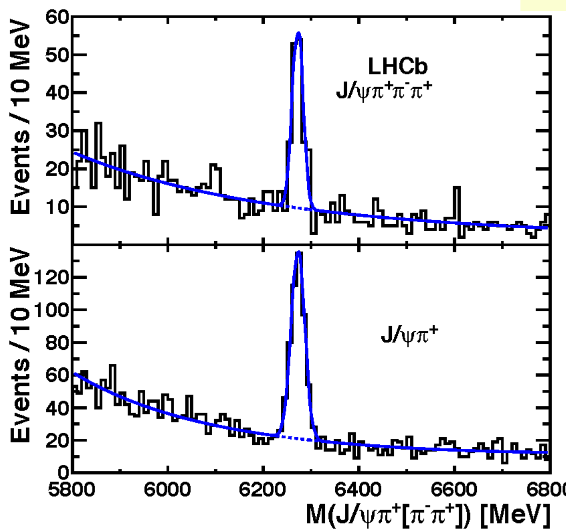


- LHCb observes 414±14 $J/\psi\pi^+$ events, and 145±14 $J/\psi\pi^+\pi^+\pi^-$ events (0.8 fb^{-1}) yielding a branching fraction ratio: $\frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+\pi^+\pi^-)} = 2.41 \pm 0.30 \pm 0.33$

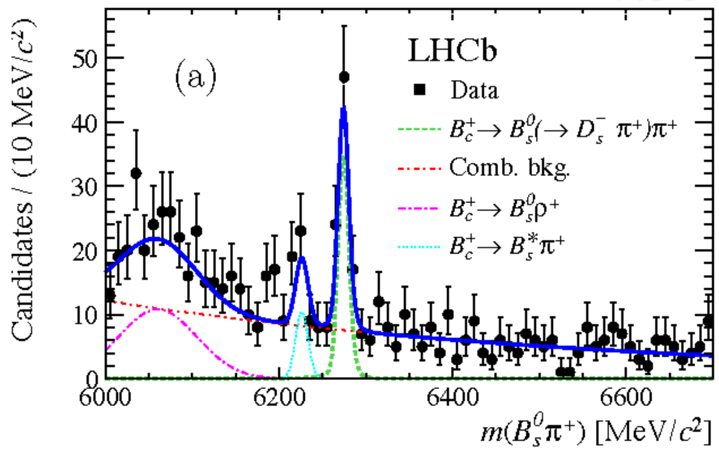


- LHCb observed for the first time the decay to $B_s\pi^+$ (3 fb^{-1}) measuring the ratio of B_c to B_s cross sections in the $B_s\pi^+$ mode:

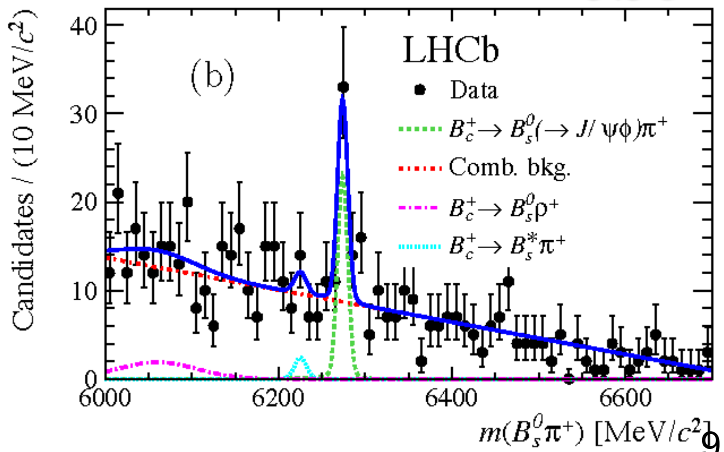
$$\frac{\sigma(B_c^+) \times \mathcal{B}(B_c^+ \to B_s^0\pi^+)}{\sigma(B_s^0)} = (2.37 \pm 0.31_{stat} \pm 0.11_{sys} \,{}^{+0.17}_{-0.13}{}_{\tau_{B_c^+}}) \times 10^{-3}$$



7.5σ

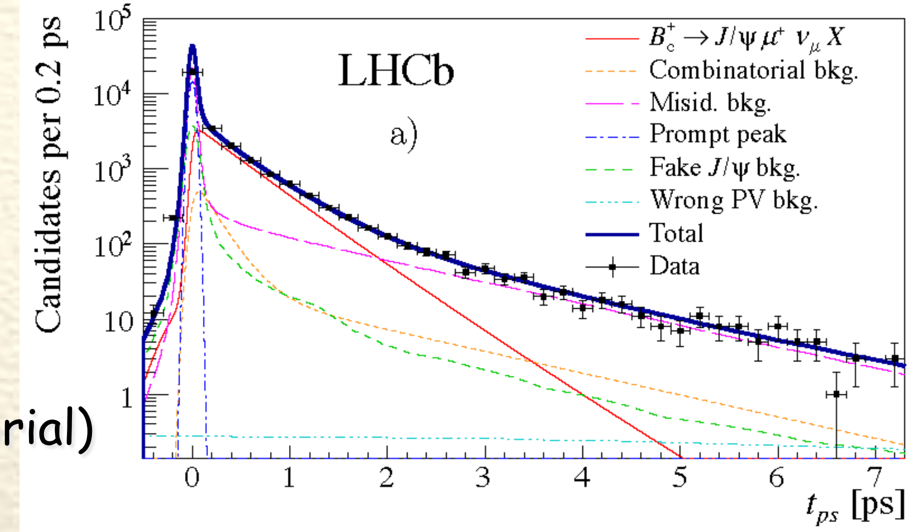


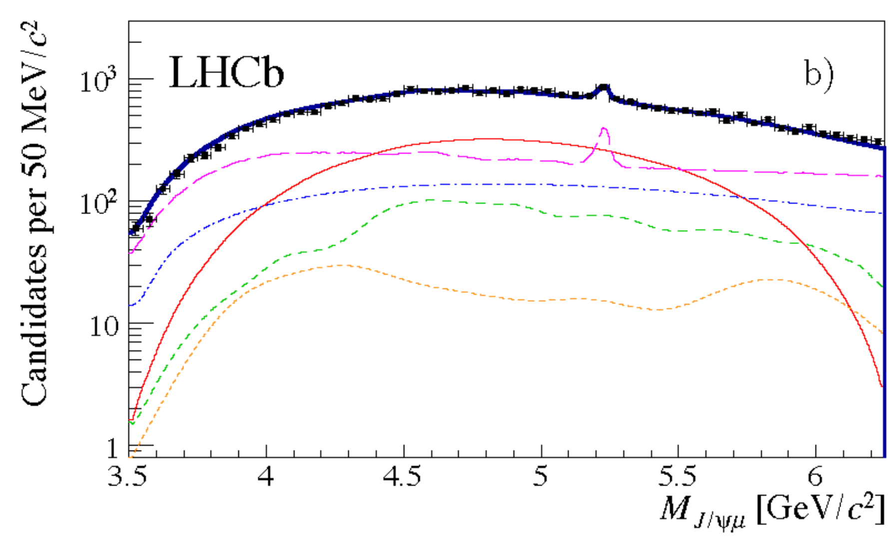
5.5σ



Study of the B_c Meson

- LHCb has also measured the B_c lifetime using a sample 2 fb^{-1} of $J/\psi X \mu\nu$ events
- Backgrounds:
  - J/ψ+ hadron misidentified as μ
  - false J/ψ + correct μ
  - J/ψ+ μ from primary vertex (prompt)
  - J/ψ+ μ from different vertices (combinatorial)
  - J/ψ+ μ from same vertex ($B \rightarrow 3\mu$)
- The lifetime is extracted from a 2D unbinned maximum likelihood fit to the lifetime and the $J/\psi\mu$ mass
- Signal t distribution is exponential, $J/\psi\mu$ mass is modeled from simulation
- Observe 8995±103 signal events



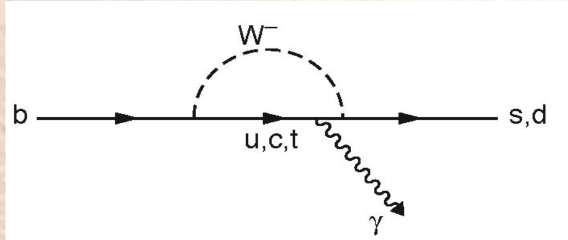


Measure B^+_c lifetime: $\tau_{B_c^+}$ = 0.5087 ± 0.0077 ps ➔ compared to $\tau_{B_s^0}$ = 1.516 ± 0.011 ps

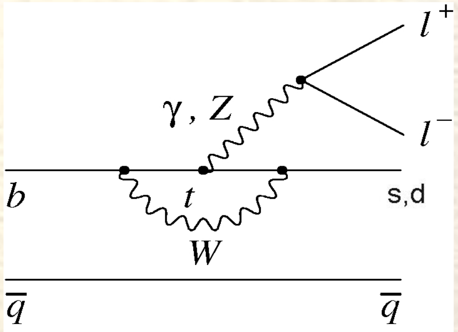
Rare Decays

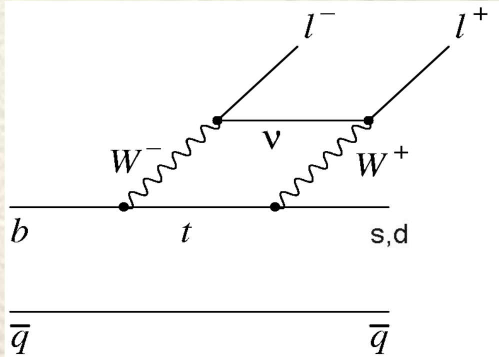
Rare Decays

- $B \to X\gamma$ & $B \to X\ell^+\ell^-$ are flavor-changing neutral current (FCNC) processes, forbidden in SM at tree level



C_7^{eff} (EM penguin)





C_9^{eff} & C_{10}^{eff} (V & A parts of weak penguin and box)

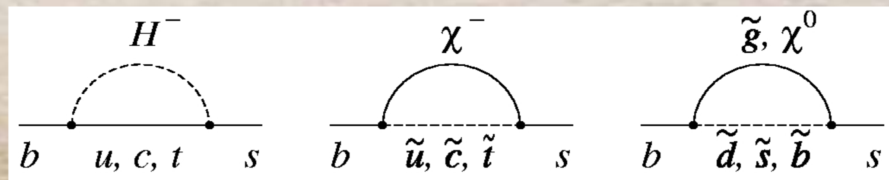
- Effective Hamiltonian factorizes short-distance from long-distance effects [$\mathcal{O}(\alpha_s)$]

$$H_{eff} = \frac{4G_F}{\sqrt{2}} \sum_i V^*_{tb} V_{ts,d} C_i(\mu)\mathcal{O}_i \qquad (2)$$

➔ 4 effective Wilson coefficient: C_7^{eff}, C_8^{eff}, C_9^{eff}, C_{10}^{eff}

- New physics adds new loops with new particles ➔ modifies SM values of Wilson coefficients and may introduce new terms, *e.g.* C_S and C_P

- Probe here new physics at a scale of a few TeV



$B \to \overline{X}_s\gamma$ Study

- The $\bar{B}\to X_s\gamma$ transition is dominated by the magnetic dipole operator $\mathcal{O}_{7\gamma}$ with $C_7^{eff}(SM)\approx -0.33$
  ➔ may be enhanced by new physics contributions

- In addition, $\mathcal{O}_1$ and $\mathcal{O}_{8G}$ contribute via mixing

- It is customary to use the spectator in which $\bar{B}\to X_s\gamma$ is approximated by the quark decay $b\to s\gamma$ that is then related to the inclusive semileptonic decay

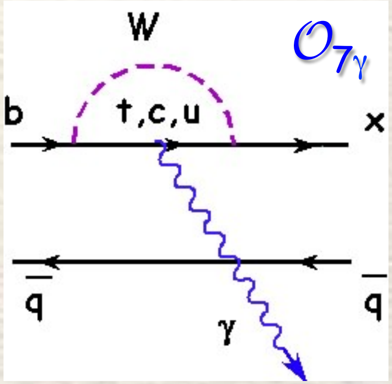
$$\mathcal{B}(\bar{B}\to X_s\gamma) \equiv \frac{\Gamma(\bar{B}\to X_s\gamma)}{\Gamma(\bar{B}\to X_c e\bar{\nu}_e)}\mathcal{B}(\bar{B}\to X_c e\bar{\nu}_\ell) \simeq \frac{\Gamma(b\to s\gamma)}{\Gamma(b\to ce\bar{\nu}_e)}\mathcal{B}(\bar{B}\to X_c e\bar{\nu}_\ell) \qquad (3)$$

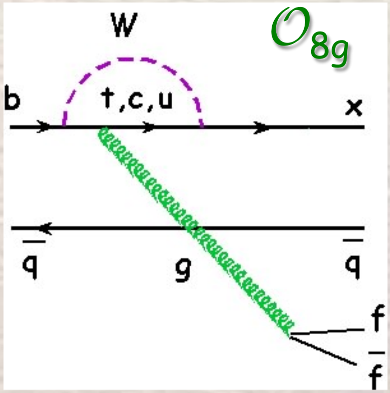
- Here short-distance QCD effects are included

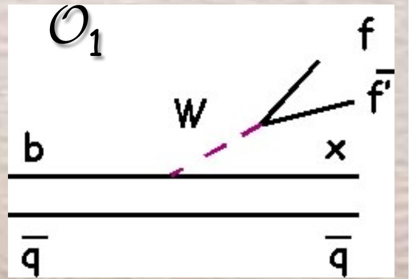
- Normalization to the semileptonic rate removes $(m_b)^5$ factor & reduces uncertainties in CKM parameters

- In NNLLO, the SM prediction yields

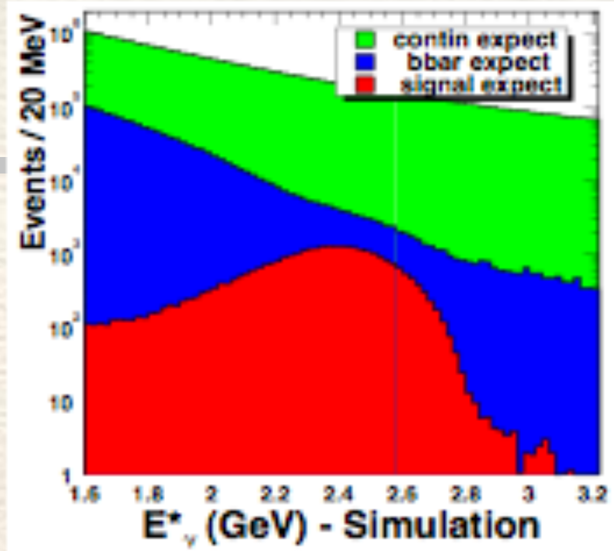
$$\mathcal{B}(\bar{B}\to X_s\gamma) = (3.15\pm 0.23)\times 10^{-4} \qquad E_\gamma > 1.6\ \text{GeV}$$







$\bar{B} \to X_s\gamma$ Results

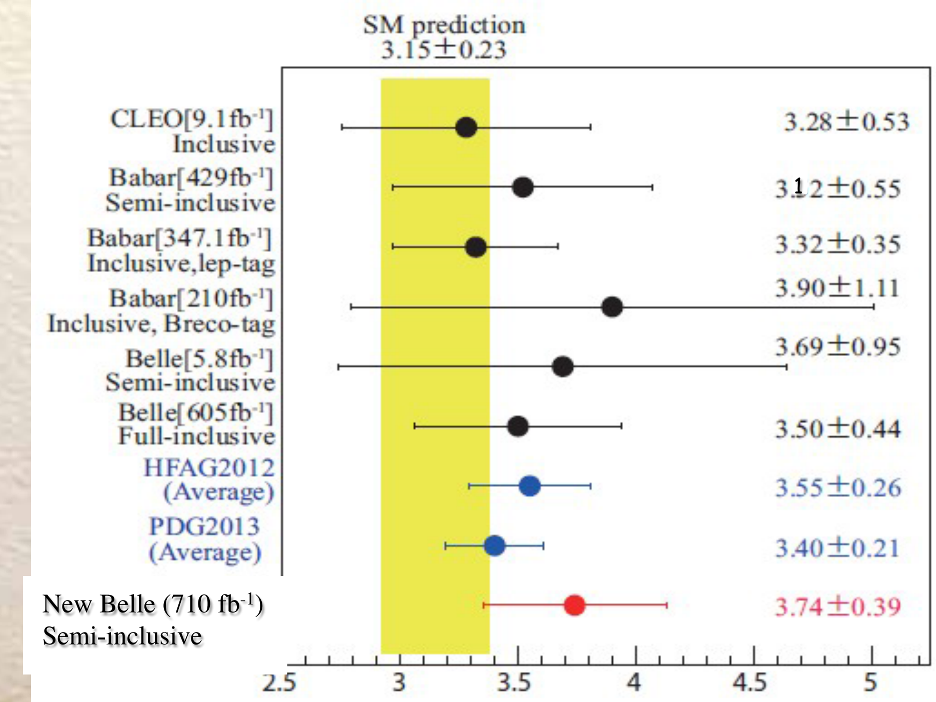


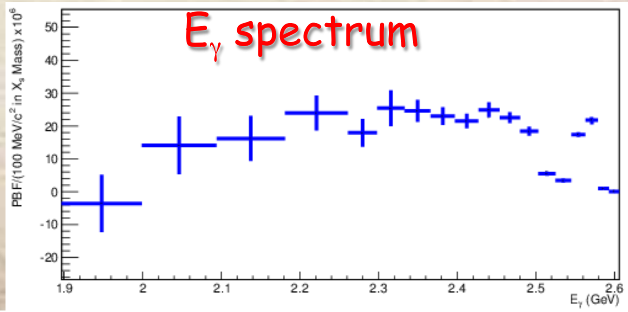
- Experimental challenge is to remove γs from π^0 and η decays
- Thus, use 2 approaches
  - fully inclusive method with B tag on opposite side and stringent π^0 and η vetoes
  - sum of exclusive final states, 1 $K^\pm$ (K^0_S) plus 4π ($\leq 1\ \pi^0$) ➔38 final states
- Measured branching fraction (WA)

$$\mathcal{B}(\bar{B} \to X_s\gamma) = \left(3.43 \pm \underbrace{0.21}_{\text{stat+sys}} \pm \underbrace{0.07}_{\text{shape function}}\right) \times \underbrace{10^{-4}}_{b\to d\gamma}$$

agrees well with the SM prediction

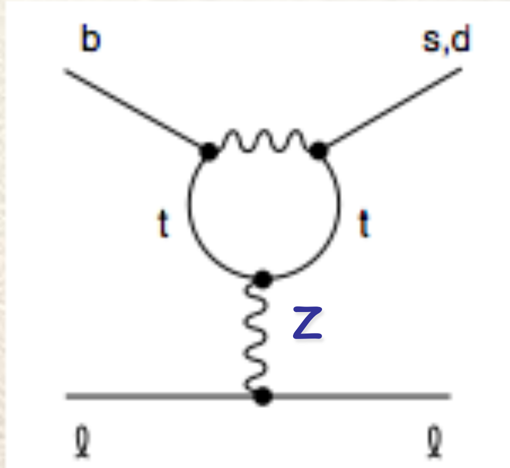
- We will see constraints in m_H-tan β plane



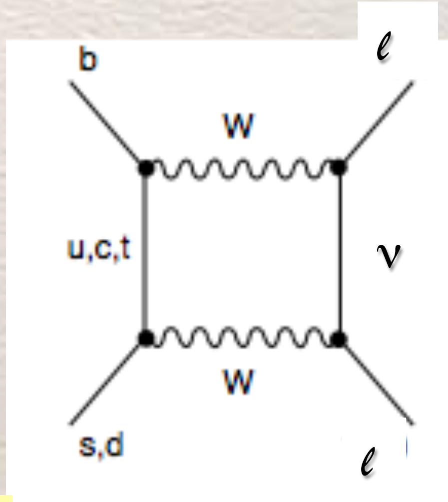


$B \to K\ell^+\ell^-$ and $B \to K^*\ell^+\ell^-$ Expectations

- In addition to the magnetic dipole operator $\mathcal{O}_{7\gamma}$, the weak penguin and box diagrams contribute, where the linear combination of vector currents form $\mathcal{O}_9$ and that of the axial-vector currents form $\mathcal{O}_{10}$



- So we encounter 2 new Wilson coefficients $C_9^{eff}(q^2)$ and C_{10}^{eff}
  $C_9^{eff}(q^2)-Y(q^2)=4.211$, $C_{10}^{eff}=-4.103$,
  $Y(q^2)$ increases faster than exponential for $q^2< 5.76$
  for $q^2>5.76$ decreases ~ exponentially



- The decay rate is again normalized to the semileptonic rate

- Predictions for $1<q^2<6$ GeV^2 and for $q^2> 14.2$ GeV^2 have smallest uncertainties

- SM prediction (for $1<q^2<6$ GeV^2) $\mathcal{B}(B \to K^*\ell^+\ell^-) = \left(2.60^{+1.82}_{-1.34}\right)\times 10^{-7}$

$\mathcal{B}(B^0 \to K^0_S\ell^+\ell^-) = \left(1.59^{+0.59}_{-0.35}\right)\times 10^{-7}$ $\mathcal{B}(B^+ \to K^+\ell^+\ell^-) = \left(1.75^{+0.64}_{-0.38}\right)\times 10^{-7}$

$B \to K\ell^+\ell^-$ and $B \to K^*\ell^+\ell^-$ Branching Fractions

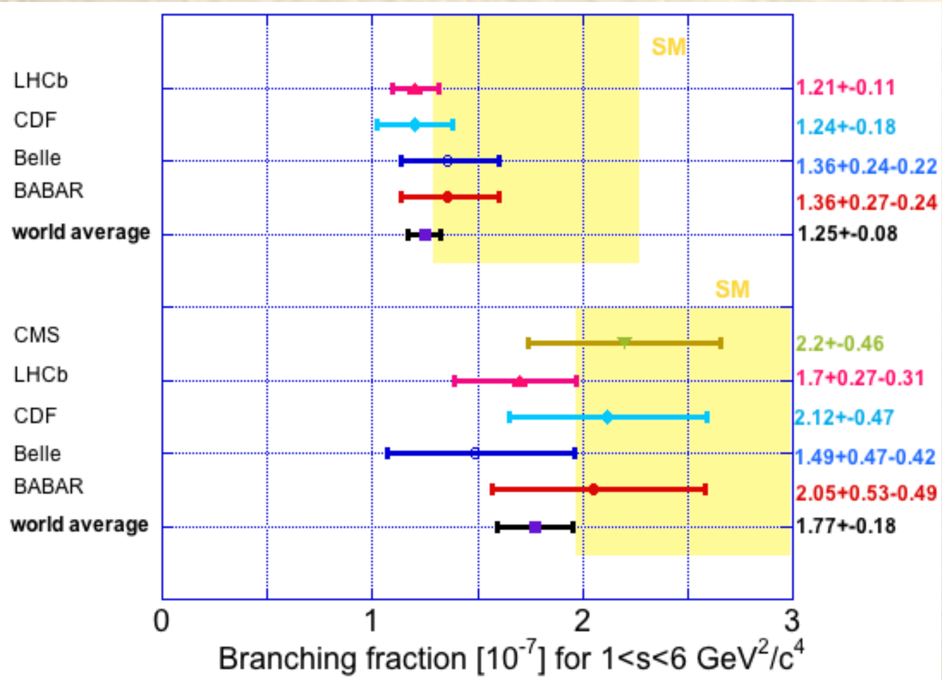
- BABAR, Belle, CDF, LHCb and CMS measured differential branching fractions of $B \to K\ell^+\ell^-$ & $B \to K^*\ell^+\ell^-$ decays

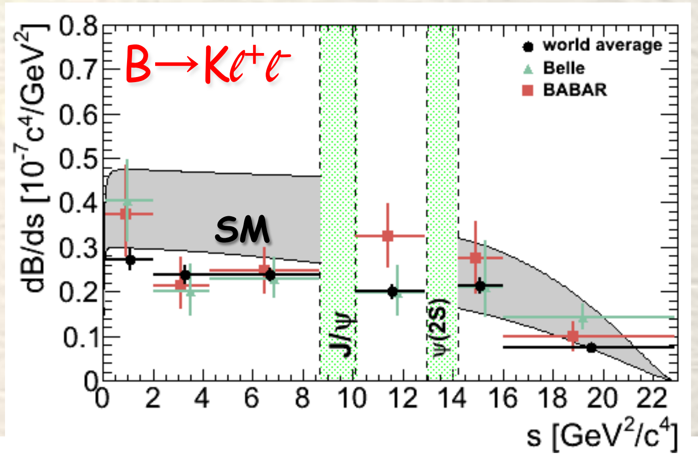
WA is dominated by LHCb

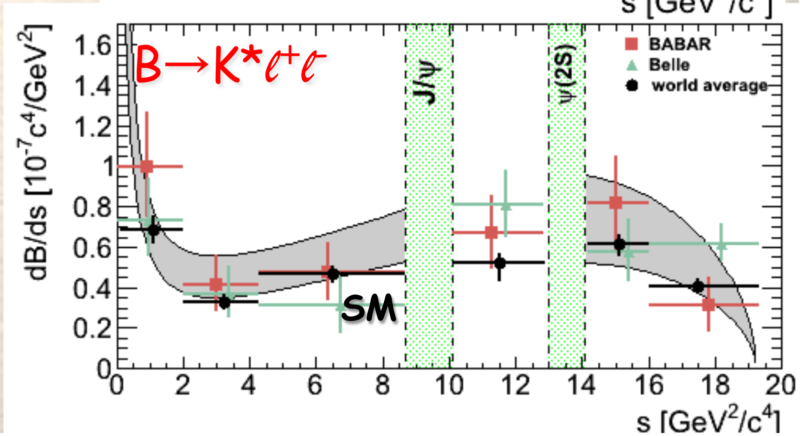
- Branching fractions for $1<s<6$ GeV^2

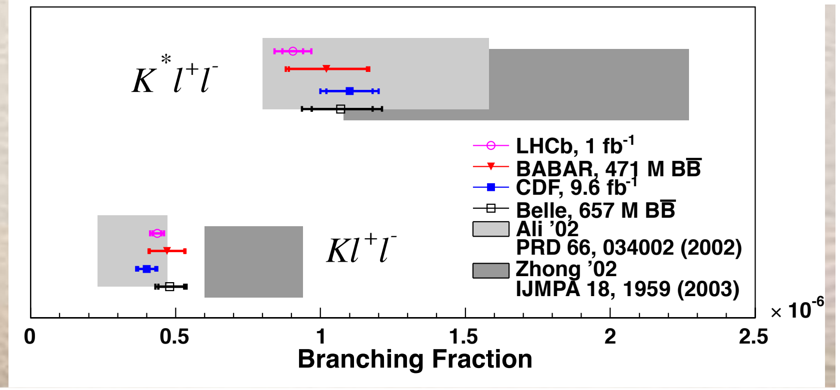
$$\mathcal{B}(B \to K\ell^+\ell^-) = (1.25 \pm 0.08) \times 10^{-7}$$

$$\mathcal{B}(B \to K^*\ell^+\ell^-) = (1.77 \pm 0.18) \times 10^{-7}$$



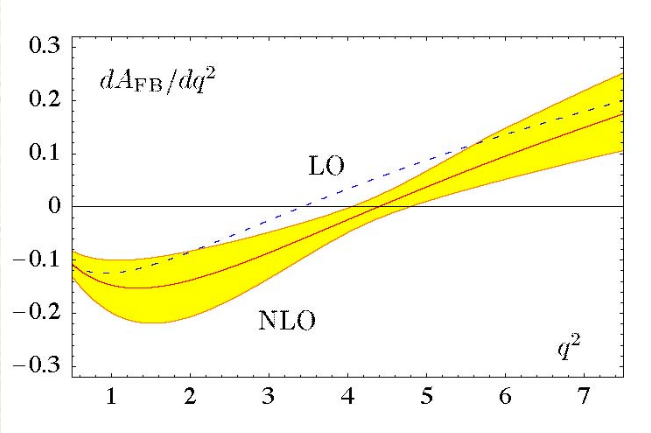




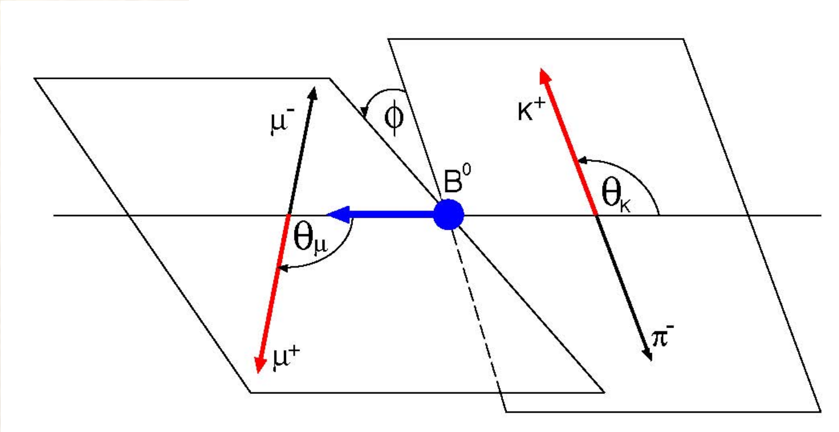


$B \to K\ell^+\ell^-$ and $B \to K^*\ell^+\ell^-$ Angular Analysis

- From angular distributions we can measure the forward-backward asymmetry $\mathcal{A}_{FB}$ (ℓ^+ is in same -opposite hemisphere of the B meson) and the K* longitudinal polarization $\mathcal{F}_L$



- 3 angles determine the decay rate:
  - θ_l: angle between ℓ^+ & B momenta in the $\ell^+\ell^-$ CM frame
  - θ_K: angle between K & B momenta in K* rest frame
  - ϕ: angle between 2 decay planes



- We extract parameters from the 1-dimensional angular distributions

$$W(\cos\theta_K) = \tfrac{3}{2}\mathcal{F}_L\cos^2\theta_K + \tfrac{3}{4}(1-\mathcal{F}_L)\sin^2\theta_K \tag{4}$$

$$W(\cos\theta_\ell) = \tfrac{3}{4}\mathcal{F}_L\sin^2\theta_\ell + \tfrac{3}{8}(1-\mathcal{F}_L)(1+\cos^2\theta_\ell) + \mathcal{A}_{FB}\cos\theta_\ell \tag{5}$$

$B \rightarrow K^* \ell^+ \ell^-$ Forward-backward Asymmetry

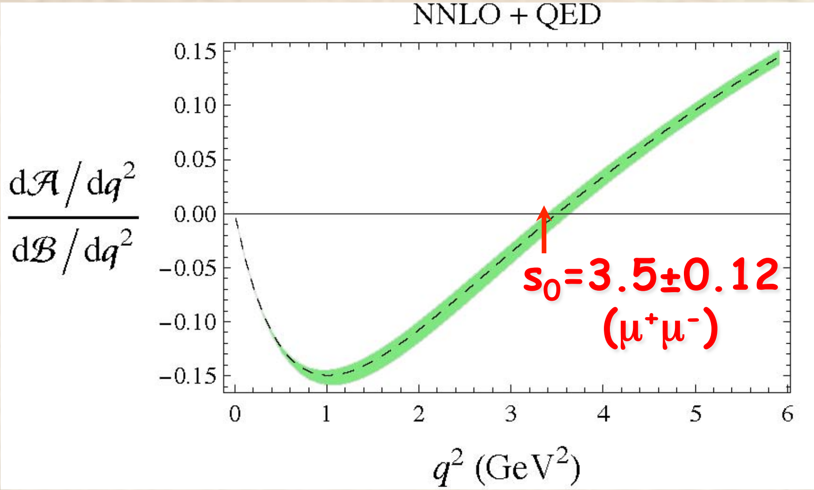
- In $\mathcal{O}(1)$ the lepton forward-backward asymmetry is

$$\frac{d\mathcal{A}_{FB}(q^2)}{ds} \propto -\left\{ \mathrm{Re}\left[C_9^{eff}(q^2) C_{10} \right] V(q^2) A_1(q^2) + \frac{m_b m_B}{q^2} \mathrm{Re}\left[C_7^{eff} C_{10} \right] \left[V(q^2) T_2(q^2) \left(1 - \frac{m_{K^*}}{m_B} \right) + A_1(q^2) T_1(q^2) \left(1 + \frac{m_{K^*}}{m_B} \right) \right] \right\} \quad (6)$$

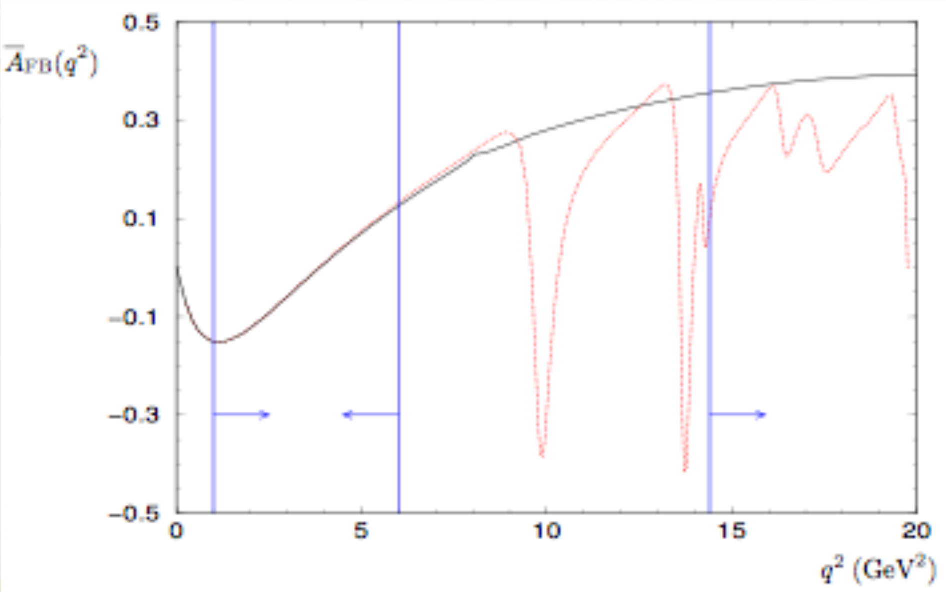
- $\mathcal{A}_{\mathcal{FB}}$ has a zero crossing that provides a powerful signature for searching for new physics effects

$V(q^2)$, $A_1(q^2)$, $T_1(q^2)$, $T_2(q^2)$ are form factors that increase with q^2 in a monopole or dipole form and are positive

- In $\mathcal{O}(\alpha_s)$ the scale dependence is small

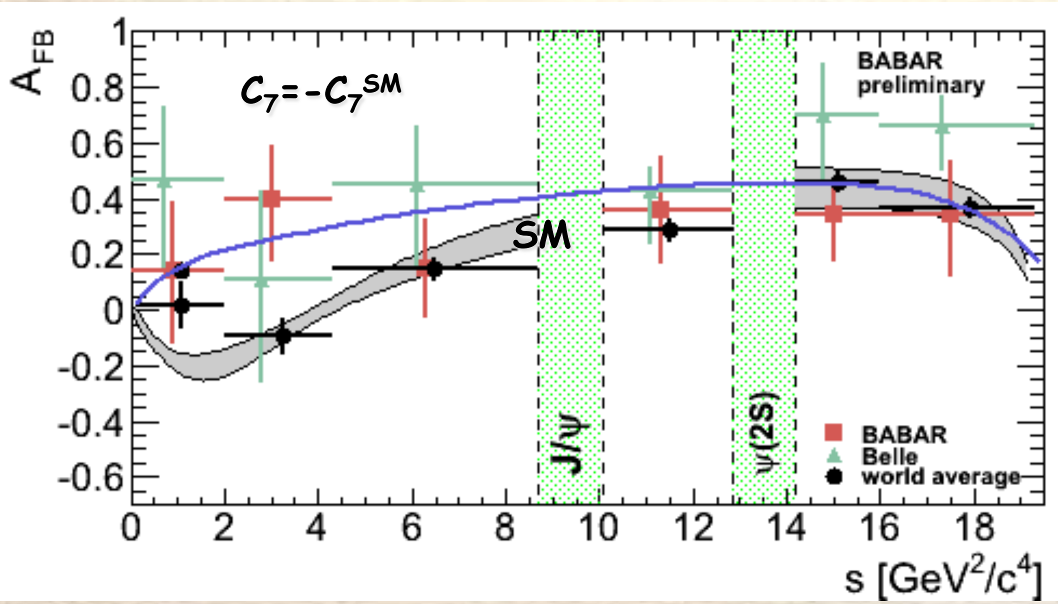


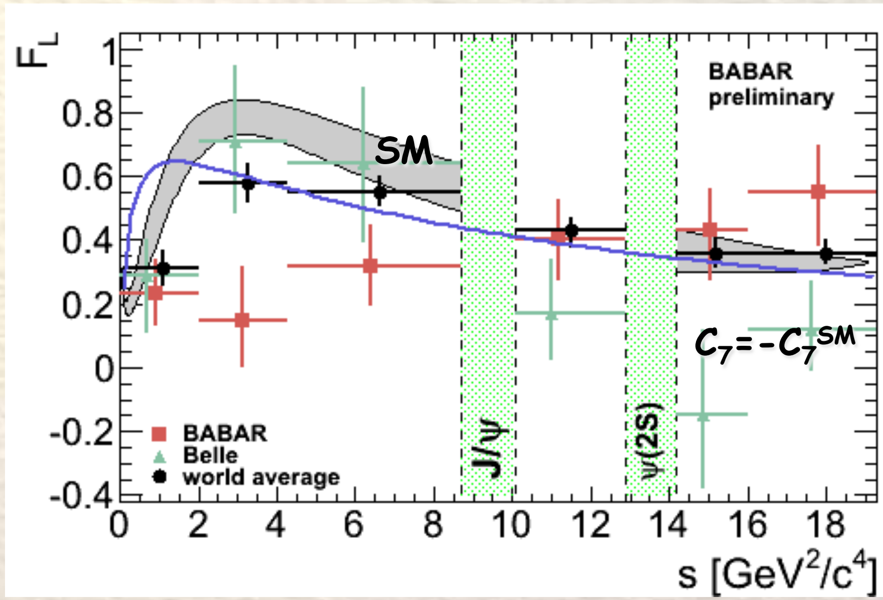
Huber, Hurth & Lunghi hep-ph/0712.3009



$B \to K^* \ell^+ \ell^-$ Results for $\mathcal{A}_{FB}$ and $\mathcal{F}_L$

- BABAR, Belle, CDF, LHCb, CMS & ATLAS measured $\mathcal{A}_{FB}$ & $\mathcal{F}_L$ in 6 bins of q^2





- In the low q^2 region, the $\mathcal{A}_{FB}$ and $\mathcal{F}_L$ averages over all measurements yield

$$\mathcal{A}_{FB}^{WA}(K^* \ell\ell) = -0.074^{+0.047}_{-0.048} \quad \text{and} \quad \mathcal{F}_L = 0.523^{+0.047}_{-0.044}$$

WA is dominated by LHCb

- This is in good agreement with the SM prediction

$$\mathcal{A}_{FB}^{SM} = -0.0494^{+0.0281}_{-0.0252} \left(K^{*0} \ell^+ \ell^-\right) \quad \text{and} \quad \mathcal{F}_L^{SM} = 0.735^{+0.06}_{-0.07} \left(K^{*0} \ell^+ \ell^-\right)$$

$B \to K^* \ell^+ \ell^-$ Angular Observables

- The full angular distribution for $B \to K^* \ell^+ \ell^-$ is given by

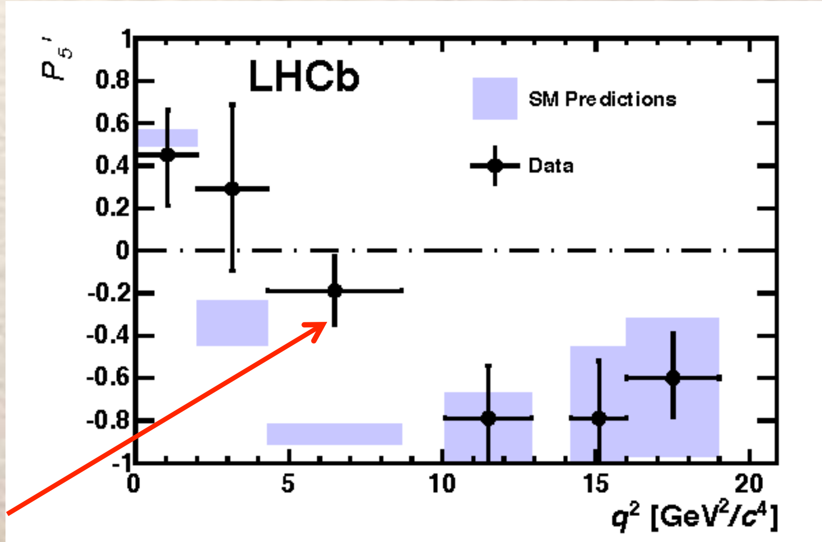
$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_\ell \, d\cos\theta_K \, d\phi \, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K \sin 2\theta_\ell$$
$$- F_L\cos^2\theta_K \cos 2\theta_\ell + S_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi$$
$$+ S_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + S_5 \sin 2\theta_K \sin\theta_\ell \cos\phi \qquad (7)$$
$$+ S_6 \sin^2\theta_K \cos\theta_\ell + S_7 \sin 2\theta_K \sin\theta_\ell \sin\phi$$
$$+ S_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + S_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi\Big]$$

- Define new observables in 6 bins of q^2

$$P'_{4,5,6,8} = \frac{S_{4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

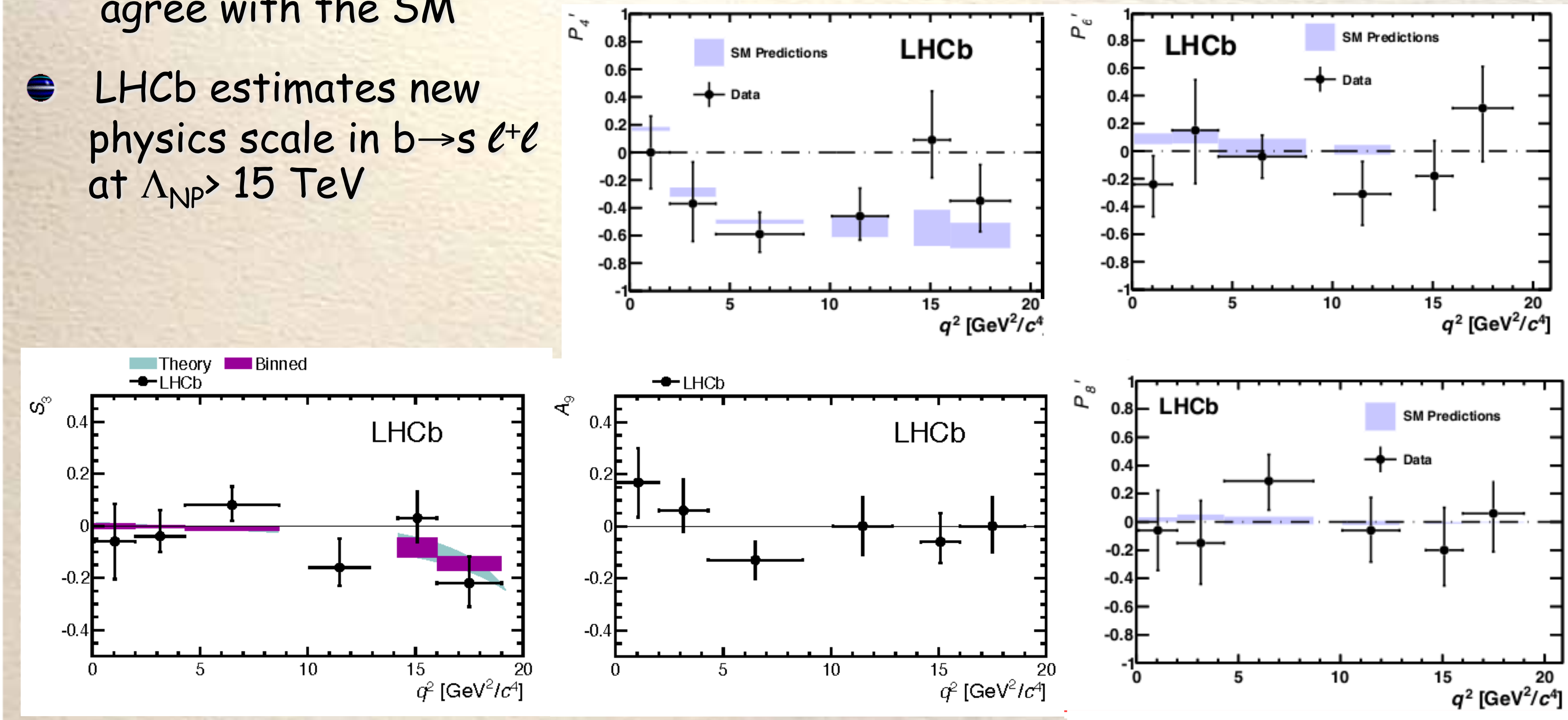
- At low q^2, observables are free from form factor uncertainties

- LHCb explored individual S_i/P'_i distributions
  ➔ P'_5 shows a deviation from the SM in bin 3



Measurement of $B \rightarrow K^* \ell^+ \ell^-$ Angular Observables

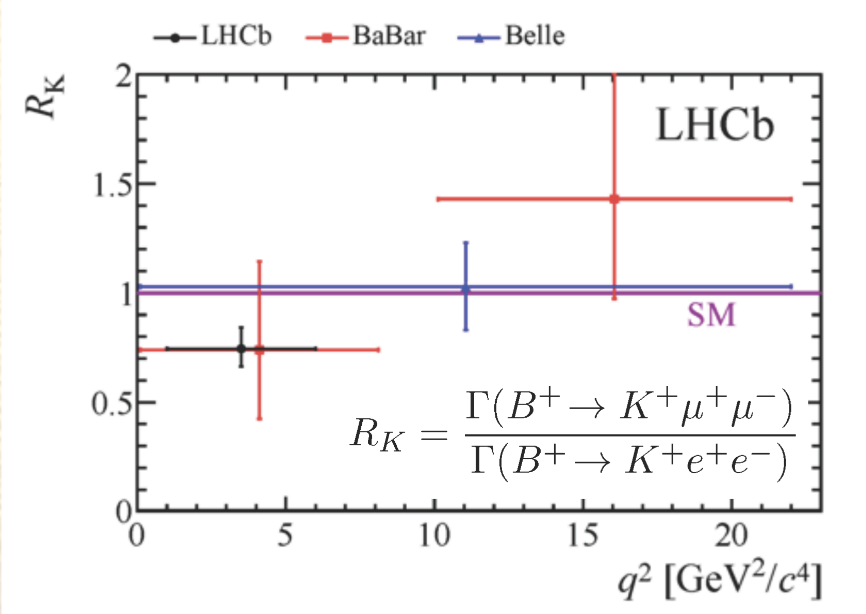
- Other distributions agree with the SM
- LHCb estimates new physics scale in $b \rightarrow s\ \ell^+ \ell$ at Λ_{NP}> 15 TeV



$B \to K\ell^+\ell^-$ and $B \to K^*\ell^+\ell^-$ Lepton Flavor Ratio

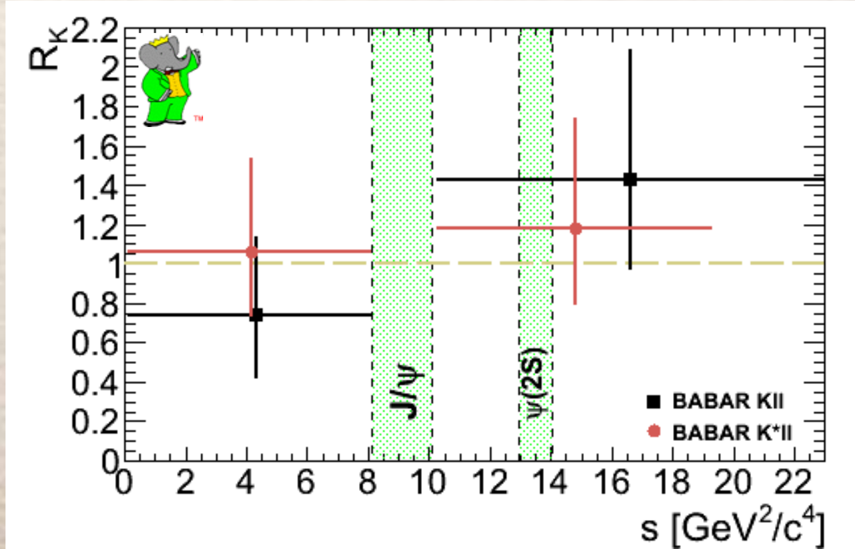
- Since $B \to K^{(*)}e^+e^-$ and $B \to K^{(*)}\mu^+\mu^-$ may receive different contributions from new physics, it is interesting to look at the lepton flavor ratios

$$\mathcal{R}_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \qquad q^2 \geq (2 {*} m_\mu)^2$$



- LHCb has measured R_K below the J/ψ resonance

- BABAR measured both R_K and R_{K^*} below and above the J/ψ resonance

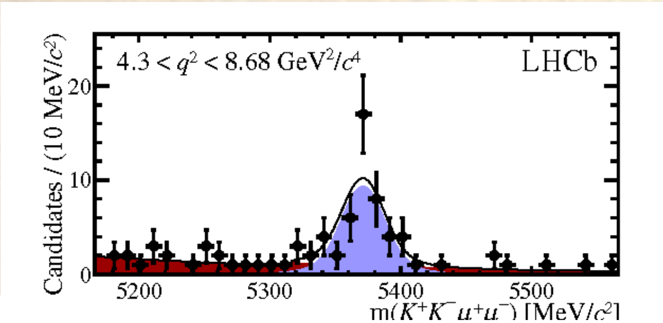


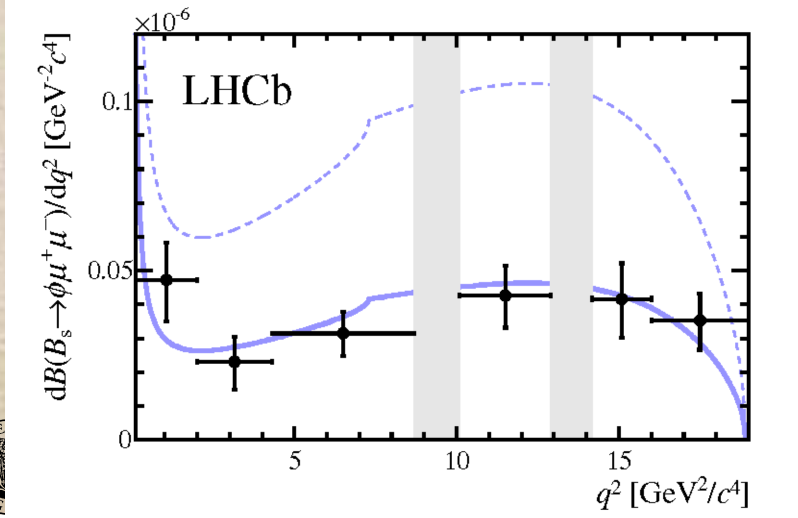
- BABAR $R_{K(*)}$ results are consistent and agree with the SM prediction

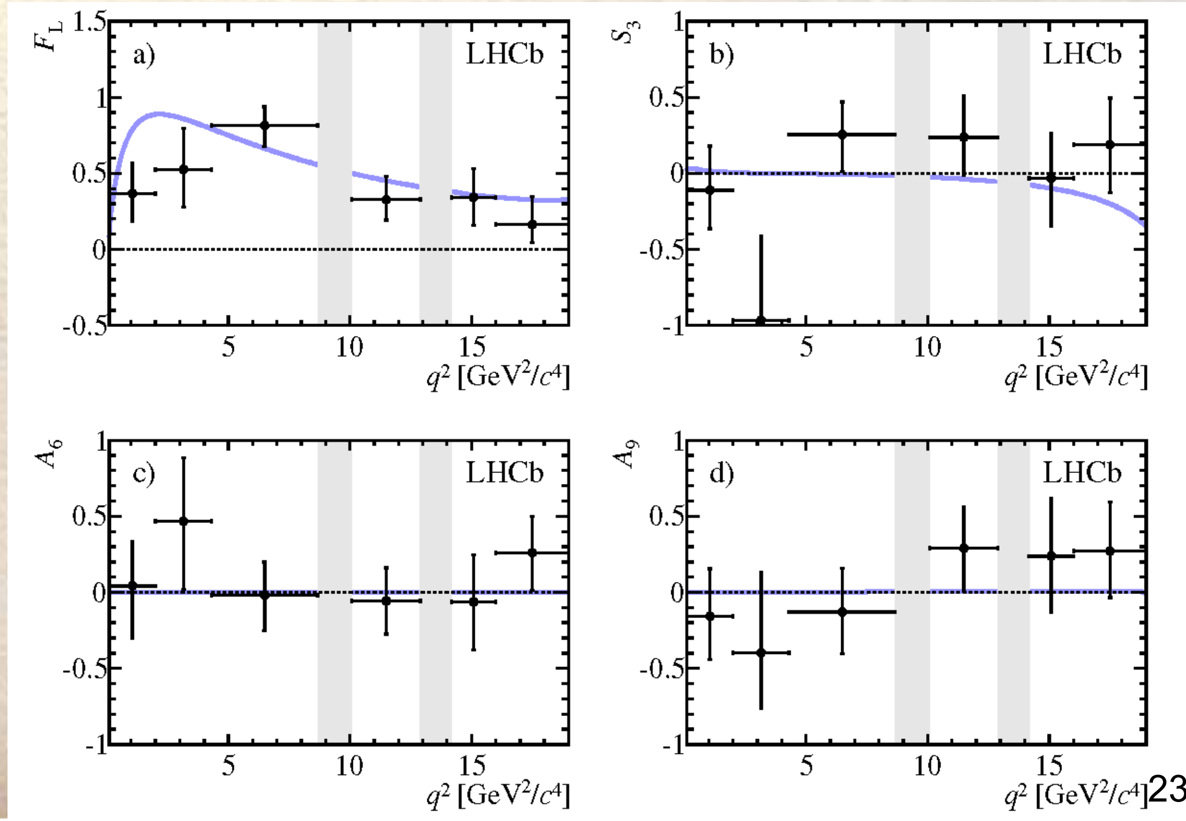
- The LHCb R_K result is consistent with the SM within 2σ

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

- Replacing the spectator d quark with and s quark yields $B_s \rightarrow \phi\mu^+\mu^-$
- LHCb has observed $B_s \rightarrow \phi\mu^+\mu^-$ measuring differential branching fractions and angular observables in 6 bins of q^2
- All results agree with the SM prediction
- The total branching fraction is $\mathcal{B}\left(B_s \rightarrow \phi\mu^+\mu^-\right) = \left(7.07^{+0.64}_{-0.56} \pm 0.17 \pm 0.71\right) \times 10^{-7}$



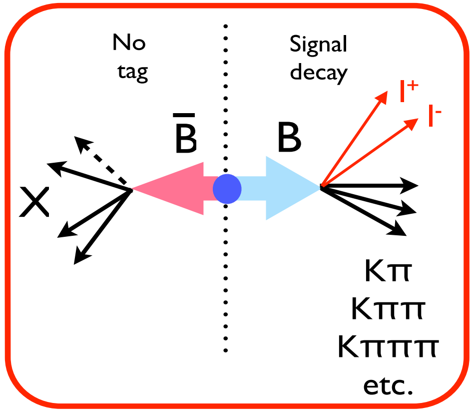




$B \to X_s \ell^+ \ell^-$

- Reconstruct 20 exclusive final states with K ($K^0_S \to \pi^+\pi^-$), $\leq 2\pi^\pm$ & $\leq 1\pi^0(\to\gamma\gamma)$ for branching fraction and 14 self-tagging modes (red) for CP asymmetry measurements

- The 20 exclusive modes represents 70% of the inclusive rate with m_{X_s} < 1.8 GeV accounting for K^0_L modes, $K^0_S \to \pi^0\pi^0$ and π^0 Dalitz decays

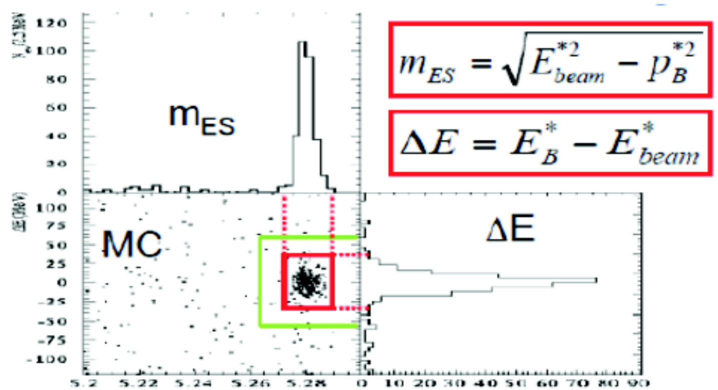


- Extrapolate for the missing modes and those with m_{X_s} > 1.8 GeV using JETSET fragmentation and theory predictions

- Kinematic constraints
  - m_{ES}>5.225 GeV
  - $-0.1 < \Delta E < 0.05$ for X_s ee
  - $-0.05 < \Delta E < 0.05$ for X_s μμ

- Use no tag for B

Kinematics of fully reconstructed B



$B^0 \to K^0_S \mu^+\mu^-$
$B^+ \to K^+\mu^+\mu^-$
$B^0 \to K^0_S e^+e^-$
$B^+ \to K^+e^+e^-$
$B^0 \to K^{*0}(K^0_S\pi^0)\mu^+\mu^-$
$B^+ \to K^{*+}(K^+\pi^0)\mu^+\mu^-$
$B^+ \to K^{*+}(K^0_S\pi^+)\mu^+\mu^-$
$B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$
$B^0 \to K^{*0}(K^0_S\pi^0)e^+e^-$
$B^+ \to K^{*+}(K^+\pi^0)e^+e^-$
$B^+ \to K^{*+}\left(K^0_S\pi^+\right)e^+e^-$
$B^0 \to K^{*0}(K^+\pi^-)e^+e^-$
$B^0 \to K^0_S\pi^+\pi^0\mu^+\mu^-$
$B^+ \to K^+\pi^-\pi^0\mu^+\mu^-$
$B^+ \to K^0_S\pi^+\pi^-\mu^+\mu^-$
$B^0 \to K^+\pi^+\pi^-\mu^+\mu^-$
$B^0 \to K^0_S\pi^+\pi^0e^+e^-$
$B^+ \to K^+\pi^+\pi^0e^+e^-$
$B^+ \to K^0_S\pi^+\pi^-e^+e^-$
$B^0 \to K^+\pi^+\pi^-e^+e^-$

$B \to X_s \ell^+\ell^-$

- For $1 < q^2 < 6$ GeV^2 BABAR measures

$$\mathcal{B}(B \to X_s \mu^+\mu^-) = (0.66^{+0.82+0.30}_{-0.76-0.24} \pm 0.07) \times 10^{-6}$$
$$\mathcal{B}(B \to X_s e^+e^-) = (1.93^{+0.47+0.21}_{-0.45-0.16} \pm 0.18) \times 10^{-6}$$
$$\mathcal{B}(B \to X_s \ell^+\ell^-) = (1.60^{+0.41+0.17}_{-0.39-0.13} \pm 0.18) \times 10^{-6}$$

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- Agrees well with the SM prediction

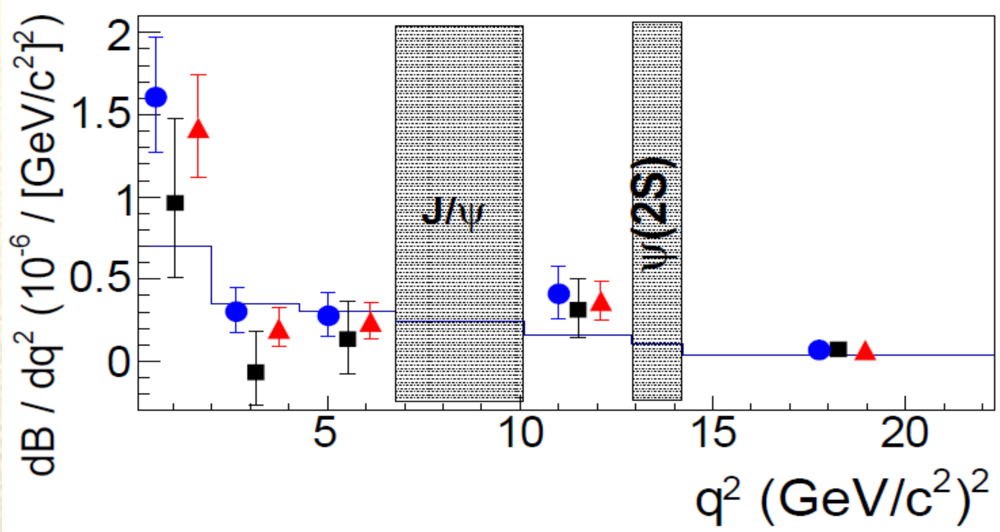
$$\mathcal{B}(B \to X_s \mu^+\mu^-) = (1.59 \pm 0.11) \times 10^{-6}$$
$$\mathcal{B}(B \to X_s e^+e^-) = (1.64 \pm 0.11) \times 10^{-6}$$

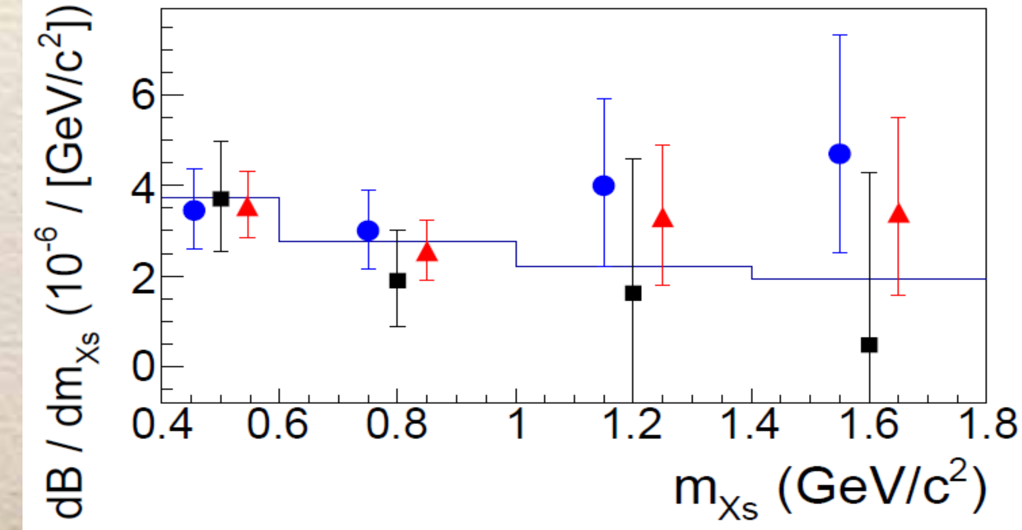
- For $q^2 > 14.2$ GeV^2 BABAR measures

$$\mathcal{B}(B \to X_s \mu^+\mu^-) = (0.60^{+0.31+0.05}_{-0.29-0.04} \pm 0.00) \times 10^{-6}$$
$$\mathcal{B}(B \to X_s e^+e^-) = (0.56^{+0.19+0.03}_{-0.18-0.03} \pm 0.00) \times 10^{-6}$$
$$\mathcal{B}(B \to X_s \ell^+\ell^-) = (0.57^{+0.16+0.03}_{-0.15-0.02} \pm 0.00) \times 10^{-6}$$

- Consistent with SM prediction at ~1σ

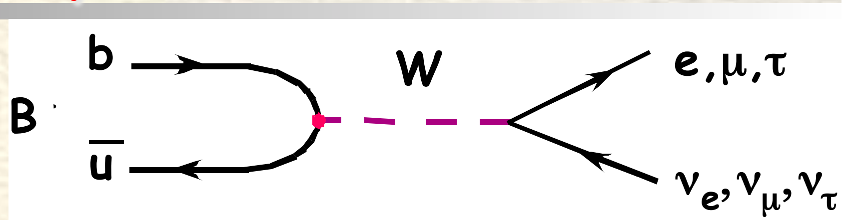
$$\mathcal{B}(B \to X_s \mu^+\mu^-) = (0.25^{+0.07}_{-0.06}) \times 10^{-6}$$





Leptonic Decays

- Pure leptonic decays are mediated by W annihilation



- The relevant ME here is $\left\langle 0 \middle| J_\mu^{V-A} \middle| B \right\rangle$ (8)

- The vector current vanishes while the axial vector currents yields

$$\left\langle 0 \middle| \bar{u}\gamma_\mu \gamma_5 b \middle| B \right\rangle = i f_B p_\mu^B \qquad (9)$$

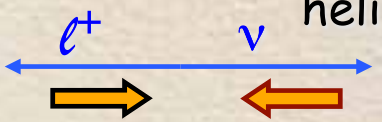
f_B: B decay constant
p_B: B momentum

- With this relation of the hadronic ME to the decay constant we can express the branching fraction by

$$\mathcal{B}(B^+ \to \ell^+ \nu_\ell) = \frac{G_F^2}{8\pi} \left| V_{ub} \right|^2 f_B^2 \tau_B m_B m_\ell^2 \left[1 - \frac{m_\ell^2}{m_B^2} \right]^2 \qquad (10)$$

helicity suppression

phase space



L=0, since B is pseudoscalar

- In the SM, the branching fractions are predicted to be

$$\mathcal{B}_{SM} = 1.0 \times 10^{-11} \quad \text{for } \ell = e$$
$$\mathcal{B}_{SM} = 3.5 \times 10^{-7} \quad \text{for } \ell = \mu$$
$$\mathcal{B}_{SM} = 1.1 \times 10^{-4} \quad \text{for } \ell = \tau$$

Measurement of $B^+ \to \tau^+ \nu$

- New Physics may enhance the branching fraction by a factor of

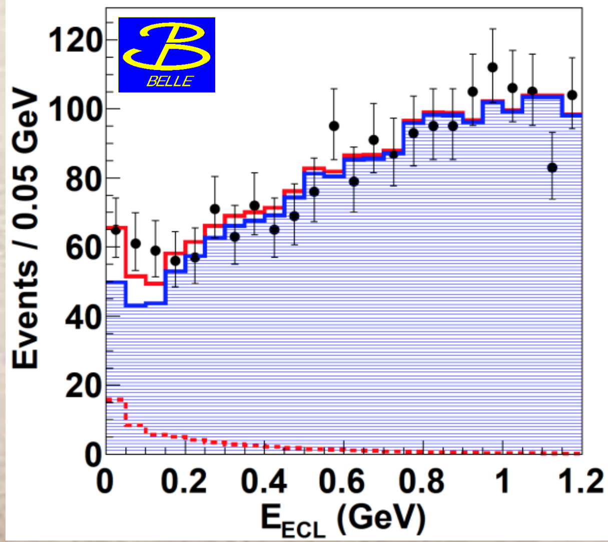
$$r_H = \left(1 - \frac{m_B^2}{m_H^2} \frac{\tan^2\beta}{1 + 0.01 \times \tan\beta}\right)^2 \quad (11)$$

m_H: charged Higgs mass
$\tan\beta$: ratio of vacuum expectation values for the 2 higgs doublets

- BABAR and Belle have observed $B^+ \to \tau^+ \nu$ and measured its branching fraction
- With reconstructing the other B meson fully in an exclusive final state, no additional particles should appear in the decay besides the τ decay products
- So BABAR and Belle examine the extra energy measured in the calorimeter
- BABAR observes 89±44 signal events
- Belle sees 62^{+23}_{-22} events
- The branching fractions measurements yield

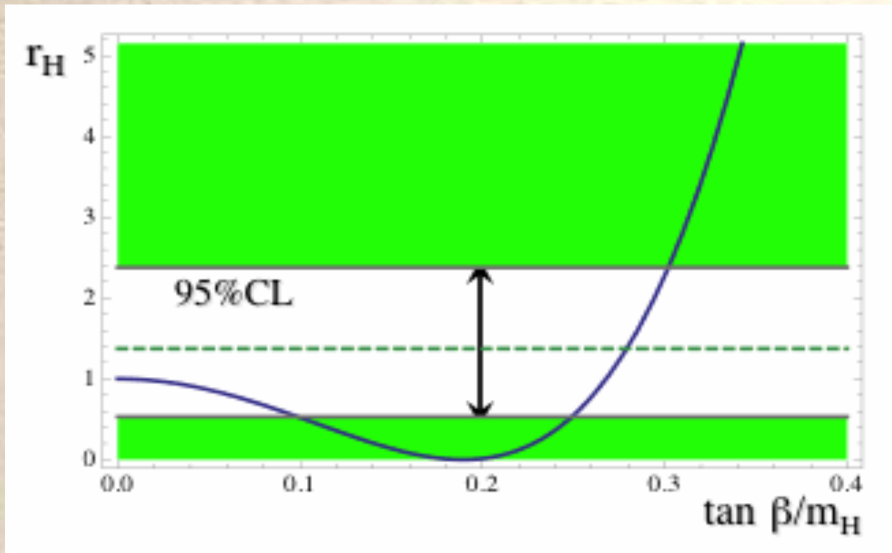
$$\mathcal{B}(B \to \tau\nu) = (1.76 \pm 0.49) \times 10^{-4}$$

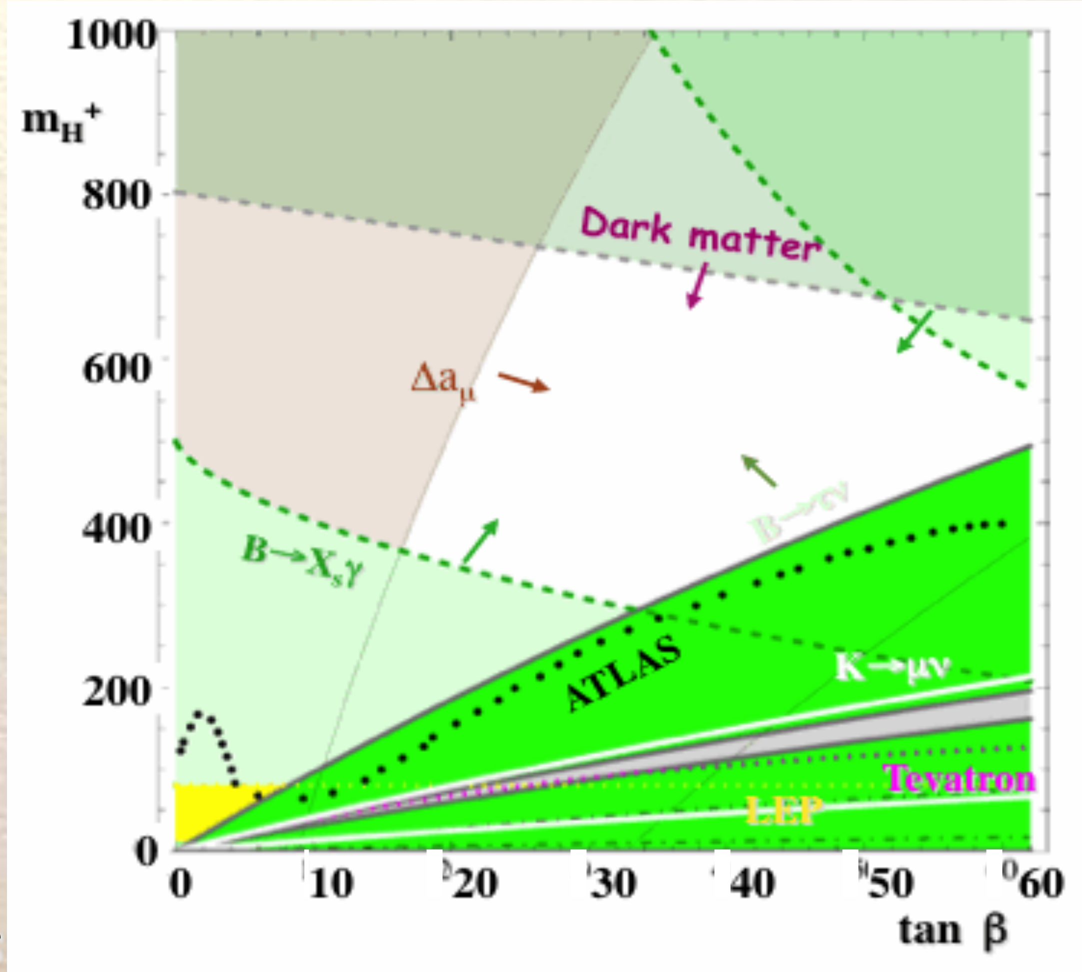
$$\mathcal{B}(B \to \tau\nu) = (0.72^{+0.27+0.11}_{-0.25-0.11}) \times 10^{-4}$$



Implications of $B^+ \to \tau^+\nu$ Measurements

- $B^+ \to \tau^+\nu$ is a useful probe to search for new physics contributions
- Extra contributions may arise from a charged Higgs boson increasing $\mathcal{B}(B^+ \to \tau^+\nu)_{SM}$ by r_H

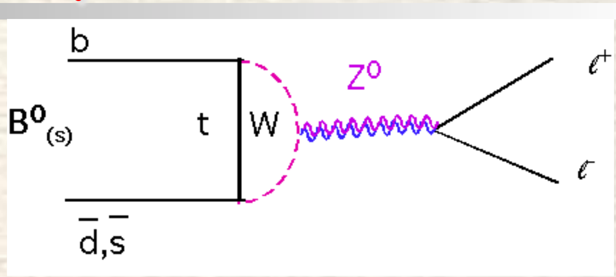


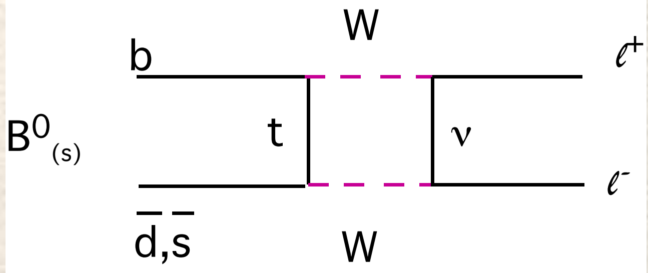


- Using the present WA of $\mathcal{B}(B^+ \to \tau^+\nu) = (1.15 \pm 0.23) \times 10^{-4}$, we can set a limit on the $H^\pm$ mass vs tanβ
- $\mathcal{B}(B^+ \to \tau^+\nu)$ plus other measurements impose stringent constraints on the $H^\pm$ -tanβ plane

Study of $B \to \mu^+\mu^-$ Decays

- The B^0_d and B^0_s mesons can also decay to $\mu^+\mu^-$, which proceeds via a weak penguin or box diagram





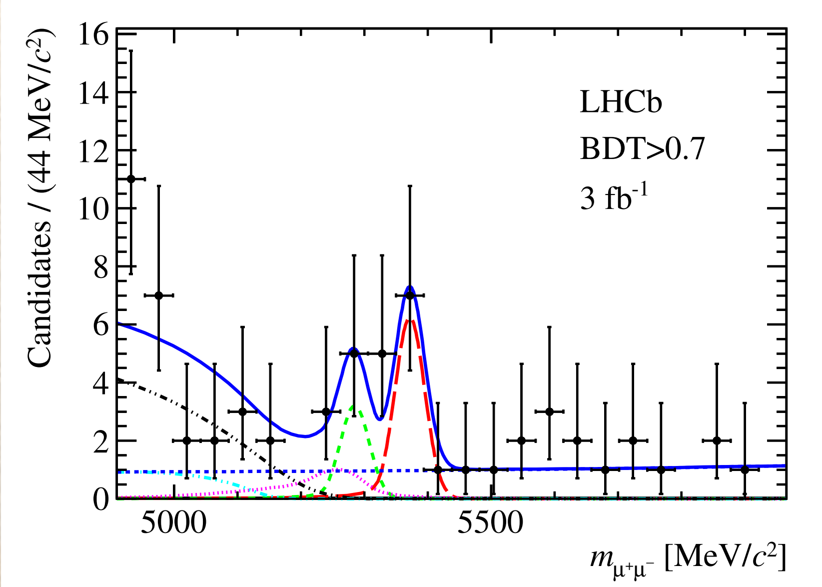
- In the Standard Model, the branching fractions are predicted to be

$$B(B^0_s \to \mu^+\mu^-) = (3.25 \pm 0.17) \times 10^{-9}$$

$$B(B^0_d \to \mu^+\mu^-) = (0.107 \pm 0.010) \times 10^{-9}$$

- LHCb found the first evidence for $B^0_s \to \mu^+\mu^-$ at the 4.0σ level yielding

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(2.9^{+1.1}_{-1.0}(\text{stat})^{+0.3}_{-0.1}(\text{sys})\right) \times 10^{-9}$$



- CMS has confirmed the LHCb result at 4.3σ

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(3.0^{+0.9}_{-0.8}(\text{stat})^{+0.6}_{-0.4}(\text{sys})\right) \times 10^{-9}$$

- The measured branching fractions agree well with the SM prediction

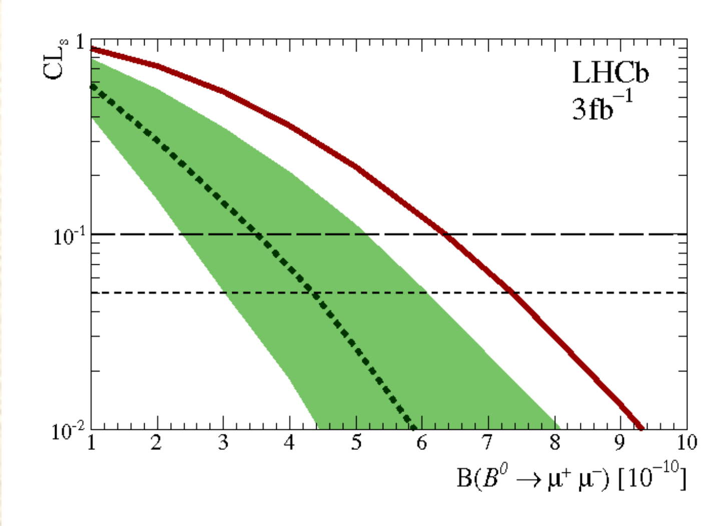
WA $\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(2.9 \pm 0.7\right) \times 10^{-9}$

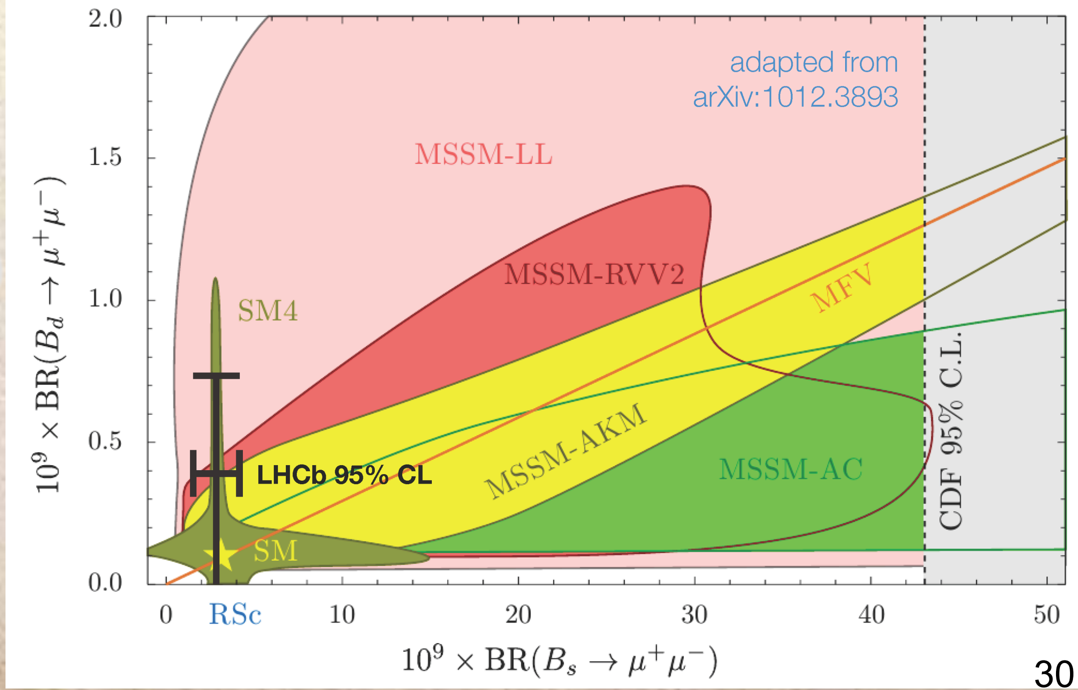
Implications of $B \to \mu^+\mu^-$ Measurements

- For B^0_d, LHCb has derived the lowest branching fraction upper limit

  $\mathcal{B}(B^0_d \to \mu^+\mu^-) < 7.4 \times 10^{-10}$ @ 95% CL

- The LHCb $\mathcal{B}(B^0_s \to \mu^+\mu^-)$ and $\mathcal{B}(B^0_d \to \mu^+\mu^-)$ measurements are shown in comparison to predictions of
  - The Standard Model
  - Minimum Flavor Violation Model
  - 4 SUSY models
  - ➔ Only left-handed currents (LL)
  - ➔ Agashe and Carone (AC)
  - ➔ Ross, Velasco-Sevilla, Vives (RVV2)
  - ➔ Antusch, King, Malinsky (AKM)





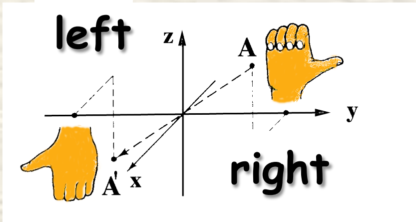
- The $\mathcal{B}(B^0_s \to \mu^+\mu^-)$ measurements place strong constraints on the parameter space of New Physics Models

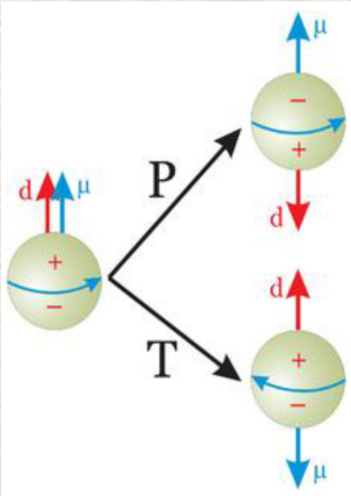
CP Violation in the B System

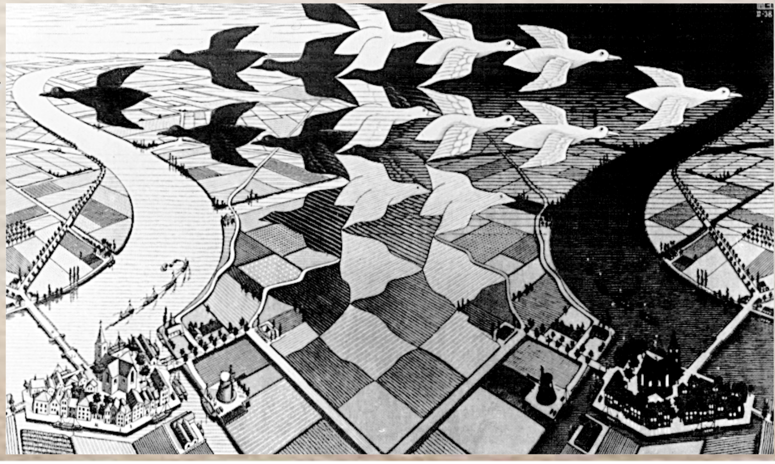
CP Violation

- Particle physics use many internal symmetries, *e.g.* C, P, T
- *P*: parity transforms:
  left-handed state ←→ right-handed state
- *C*: C-parity transforms
  particle ←→ antiparticle
- *T*: time reversal transforms:
  forward moving time ←→ backward moving time
- *CP*: transforms:
  left-handed particle particle ←→ right-handed antiparticle
- *CP* is conserved in strong and electromagnetic interactions
- *CP* is violated in weak processes

$\vec{x} \longrightarrow -\vec{x}$







CP Violation in the B System

- States produced in strong and electromagnetic interactions are the flavor eigenstates, *e.g.* $|B^0\rangle$ & $|\overline{B^0}\rangle$

- However, they decay weakly as $|B^0_H\rangle$ and $|B^0_L\rangle$ that can be expressed as linear combinations of the flavor eigenstates:

$$\left|B^0_L\right\rangle = p\left|B^0_d\right\rangle + q\left|\bar{B}^0_d\right\rangle \qquad \text{with} \qquad |q|^2 + |p|^2 = 1 \qquad (22)$$
$$\left|B^0_H\right\rangle = p\left|B^0_d\right\rangle - q\left|\bar{B}^0_d\right\rangle$$

- Since individual decay channels have small branching fractions $\mathcal{O}(10^{-3})$ that contribute with alternating signs, both states have the same lifetime: $\Gamma_H=\Gamma_L=\Gamma$

- $|B^0_H\rangle$ is the heavier state, $|B^0_L\rangle$ is the lighter state

- Their mass difference $\Delta M=M_H-M_L$ represents the B^0_d-$\overline{B^0}_d$ oscillation frequency

- The ratio q/p represents a phase factor for the mixing; in the SM $|q/p|=1$

- The 2-particle system is described by a Schrödinger equation with mass matrix M and decay matrix Γ

B Decay Rate and λ

- We want to look at decays of $|B^0\rangle$ & $|\bar{B}^0\rangle$ into CP eigenstates f_{CP} as a function of time

- Thus, we define the amplitudes $A(t) \equiv \langle f_{CP} | H | B^0(t) \rangle$ and $\bar{A}(t) \equiv \langle f_{CP} | H | \bar{B}^0(t) \rangle$ (23)

- The figure of merit for *CP* violation is where η denotes the *CP* eigenvalue of the *CP* eigenstate

$$\lambda = \eta \frac{q}{p} \frac{\bar{A}}{A} \qquad (24)$$

- The time-dependent decay rates are

$$\Gamma\left(\begin{matrix} B^0_{phys}(t) \\ \bar{B}^0_{phys}(t) \end{matrix} \to f_{CP} \right) = |A|^2 \exp\{-\Gamma t\} \times \left[\frac{1+|\lambda|^2}{2} \pm \frac{1-|\lambda|^2}{2} \cos(\Delta M t) \mp \Im m\lambda \sin(\Delta M t) \right] \qquad (25)$$

- We define the time-dependent *CP* asymmetry

$$\mathcal{A}_{f_{CP}}(t) \equiv \frac{\Gamma\left(\bar{B}^0_{phys}(t) \to f_{CP}\right) - \Gamma\left(B^0_{phys}(t) \to f_{CP}\right)}{\Gamma\left(\bar{B}^0_{phys}(t) \to f_{CP}\right) + \Gamma\left(B^0_{phys}(t) \to f_{CP}\right)} \qquad (26)$$

Time-dependent *CP* Asymmetry

- For the $B^0\,\overline{B^0}$ system, we obtain

$$\mathcal{A}_{f_{CP}}(t) = \frac{-\left(1-|\lambda|^2\right)\cos\left(\Delta M t\right) + 2\Im m\lambda \sin\left(\Delta M t\right)}{\left(1+|\lambda|^2\right)} \qquad (27)$$

- The first term represents direct CP violation; the second term results from the interference of decays with and without $B^0\,\overline{B^0}$ mixing

- If in addition, $|\overline{A}/A|=1$ ➔ $|\lambda|=1$ and the *CP* asymmetry reduces to

$$\mathcal{A}_{f_{CP}}(t) = +\Im m\lambda \sin\left(\Delta M t\right) \qquad (28)$$

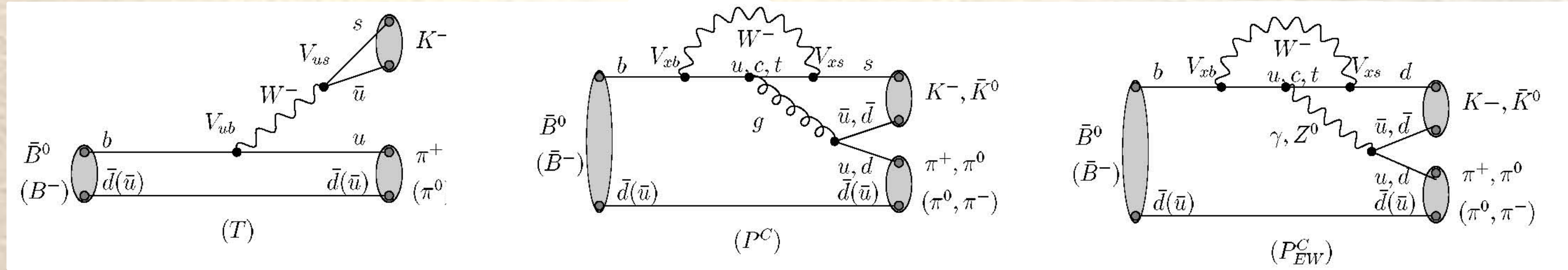
- Note that λ is directly related to CKM matrix elements

- At the $\Upsilon(4S)$, a $B^0\overline{B^0}$ pair is produced that is entangled until one B decays ➔ however, the equations (27) and (28) still hold if t is replaced with $t_{fCP}-t_{tag}$ where t_{fCP} is the decay time of one B meson into the CP eigenstate and t_{tag} is the decay time of the other B into a state that identifies the B flavor

- Since B mesons produced at the $\Upsilon(4S)$ are nearly at rest ($p_B \approx 340$ MeV), the $\Upsilon(4S)$ system needs to be boosted ➔ at PEP II boost is $\beta\gamma=0.56$

Direct *CP* Violation in $B^0 \to K^+\pi^-$

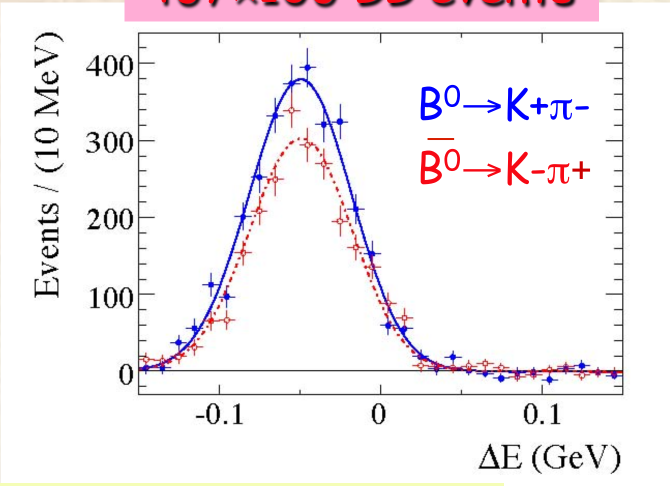
- We observe a huge decay asymmetry between $B^0 \to K^+\pi^-$ & $\bar{B}^0 \to K^-\pi^+$



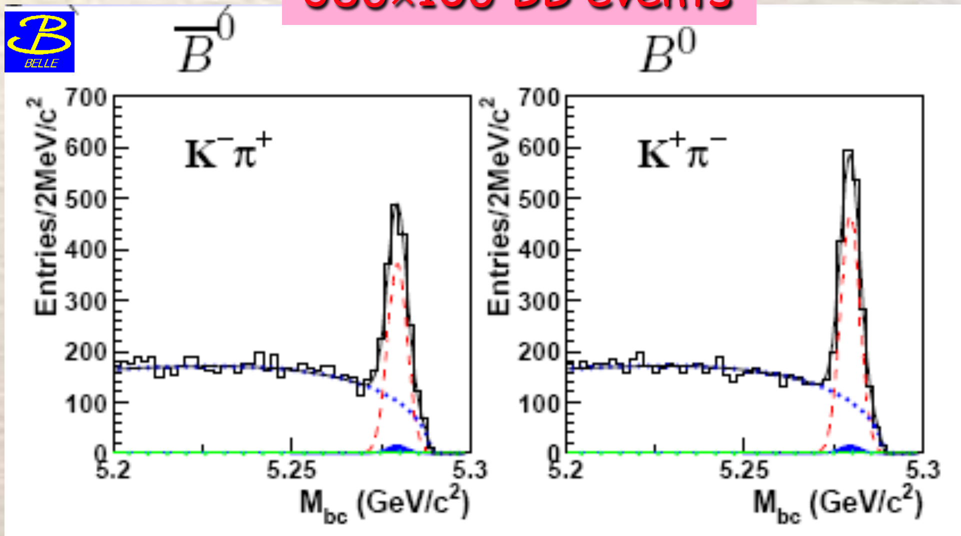
- The world average is $\mathcal{A}_{CP}(B^0 \to K^+\pi^-) = -0.82 \pm 0.006$

- LHCb also observes large *CP* in $B^0_s \to K^+\pi^-$ Decays

467×106 $B\bar{B}$ events



386×106 $B\bar{B}$ events



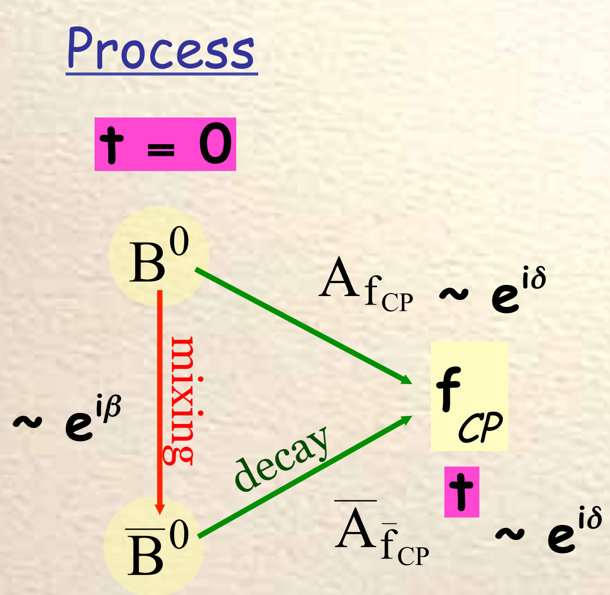
$$\mathcal{A}_{CP}(B^0_s \to K^+\pi^-) = 0.27 \pm 0.04 \pm 0.01$$

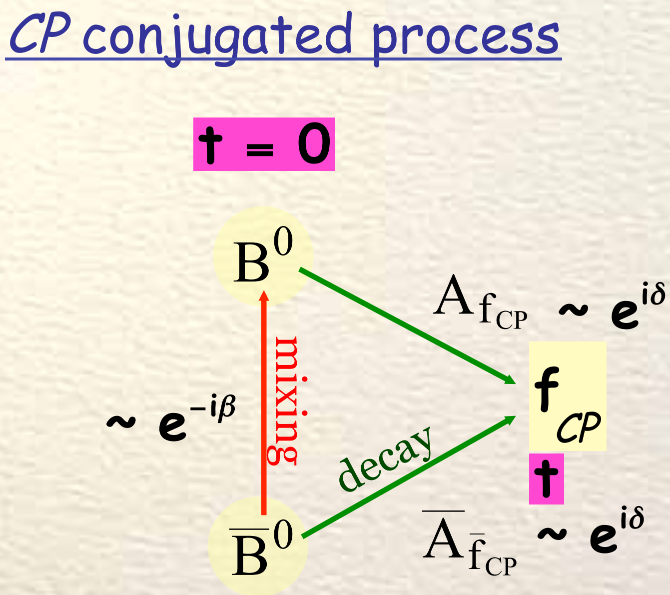
$$\mathcal{A}_{CP}(B^+ \to K^+\pi^0) = 0.040 \pm 0.021$$

- This effect is not seen in charged B decays

$$\mathcal{A}_{CP}(B^+ \to K^0\pi^+) = -0.015 \pm 0.019$$

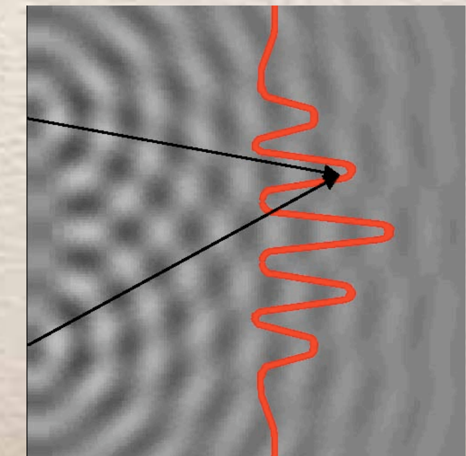
CP Violation caused by Interference of Decays with and without B⁰B⁰ Mixing





- Decay rate ≠ *CP*-conjugated decay rate

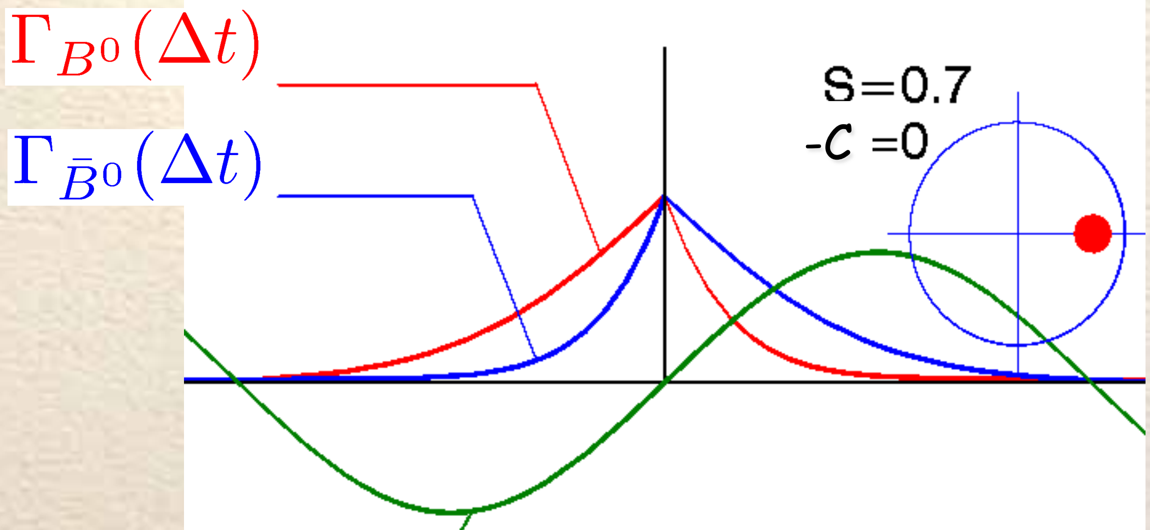
  ➔ *CP* Violation is caused by the interference between mixing & decay



- Typically, we need to measure the time dependence of the *CP* asymmetry as the time-integrated asymmetry vanishes

Illustration of time-dependent *CP* Violation

- Lets look at the time dependence of the B^0 and B^0 decay rates and the *CP* asymmetry



$$\mathcal{A}_{f_{CP}}(\Delta t) \equiv \frac{\Gamma_{\bar{B}^0}(\Delta t) - \Gamma_{B^0}(\Delta t)}{\Gamma_{\bar{B}^0}(\Delta t) + \Gamma_{B^0}(\Delta t)}$$

$$\mathcal{A}_{f_{CP}}(\Delta t) = S \cdot \sin \Delta m \cdot \Delta t - C \cdot \cos \Delta m \cdot \Delta t$$

Mixing-induced CP

Direct CPV

Unitarity Conditions of the CKM Matrix

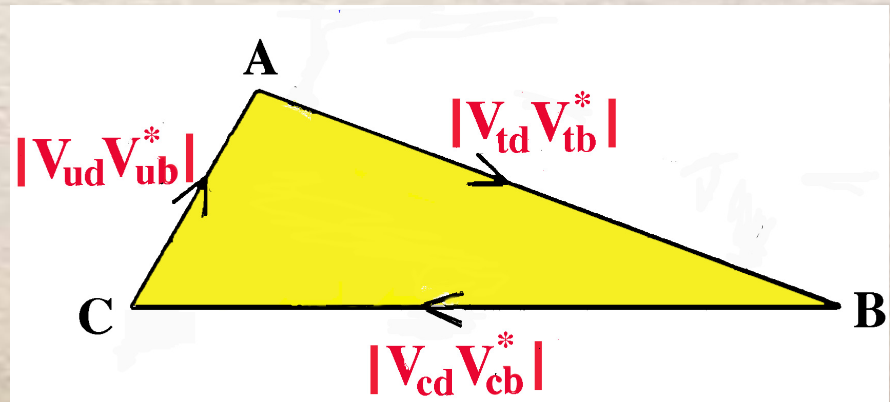
- In the Standard Model, the CKM matrix produces *CP* violation
- The unitarity conditions of the CKM matrix yields 6 triangular relations
- Physics-wise most interesting is the relation

$$\underset{1}{\underset{\Uparrow}{V_{ud}}}V_{ub}^{*}+\underset{-\sin\theta_c}{\underset{\Uparrow}{V_{cd}}}V_{cb}^{*}+\underset{1}{\underset{\Uparrow}{V_{td}}}V_{tb}^{*} = 0 \qquad (29)$$

$$\begin{array}{ccc} \Downarrow & & \Downarrow^{*} \\ \multicolumn{3}{c}{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}} \\ \Uparrow & & \Uparrow \end{array}$$

- The graphical representation of this relation yields the so-called Unitarity Triangle
- All 6 triangles have the same area
  $A \propto J = \Im m(V_{ij}V_{kl}V^{*}_{il}V^{*}_{kj}) \neq 0$
  for any $i \neq k$ and $j \neq l$
  (Jarlskog determinant)
  $J=(3.01\pm0.19)\times10^{-5}$

~~*CP*~~



The Unitarity Triangle

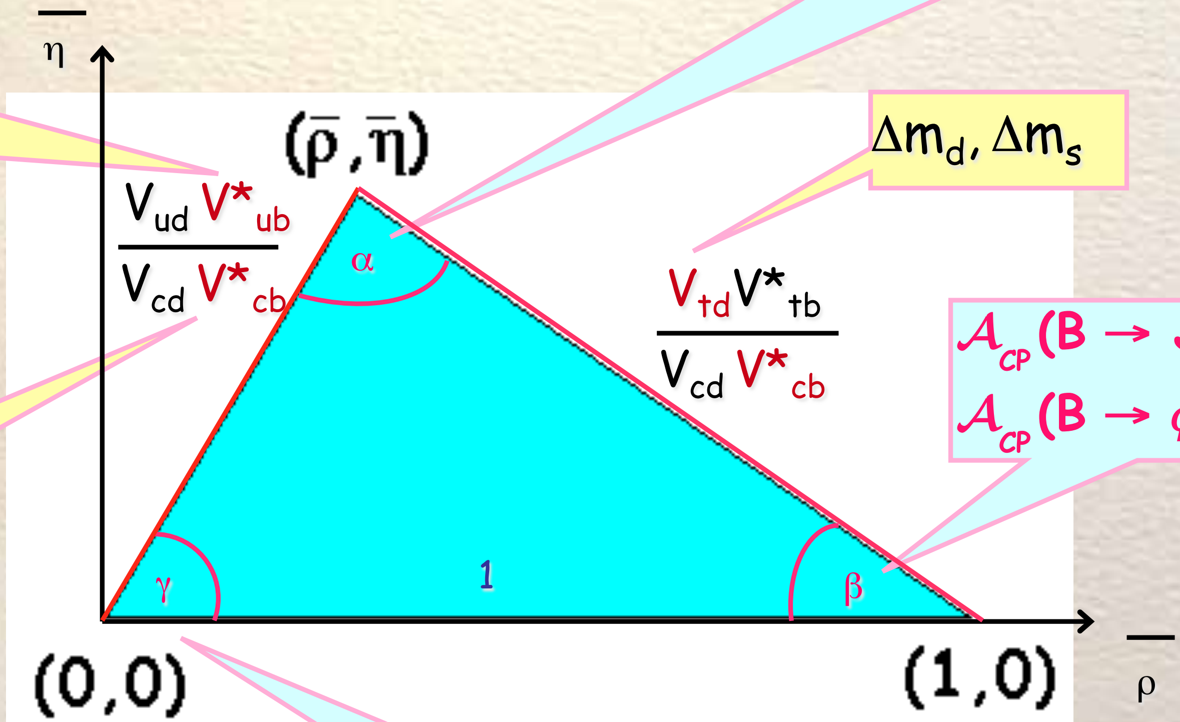
- B factories measure 4 CKM elements & 3 phases
  - ➔ overconstrains unitarity triangle
  - ➔ test of Standard Model

$\mathcal{A}_{CP}(B \to \rho^+\rho^-, \rho^\pm\pi^\mp, \pi^+\pi^-)$

$\mathcal{B}(B \to X_u l \nu)$
$\mathcal{B}(B \to \pi,\rho l \nu)$

$\Delta m_d, \Delta m_s$

$$\alpha \equiv Arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$



$\mathcal{A}_{CP}(B \to J/\psi K^0_S)$
$\mathcal{A}_{CP}(B \to \phi K^0_S)$

$\mathcal{B}(B \to X_c l \nu)$
$\mathcal{B}(B \to D^* l \nu)$

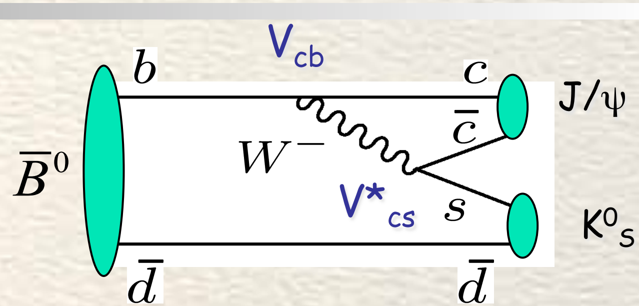
$\mathcal{B}(B^\pm \to [D^0, \bar{D}^0]K^\pm)$

$$\gamma \equiv Arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

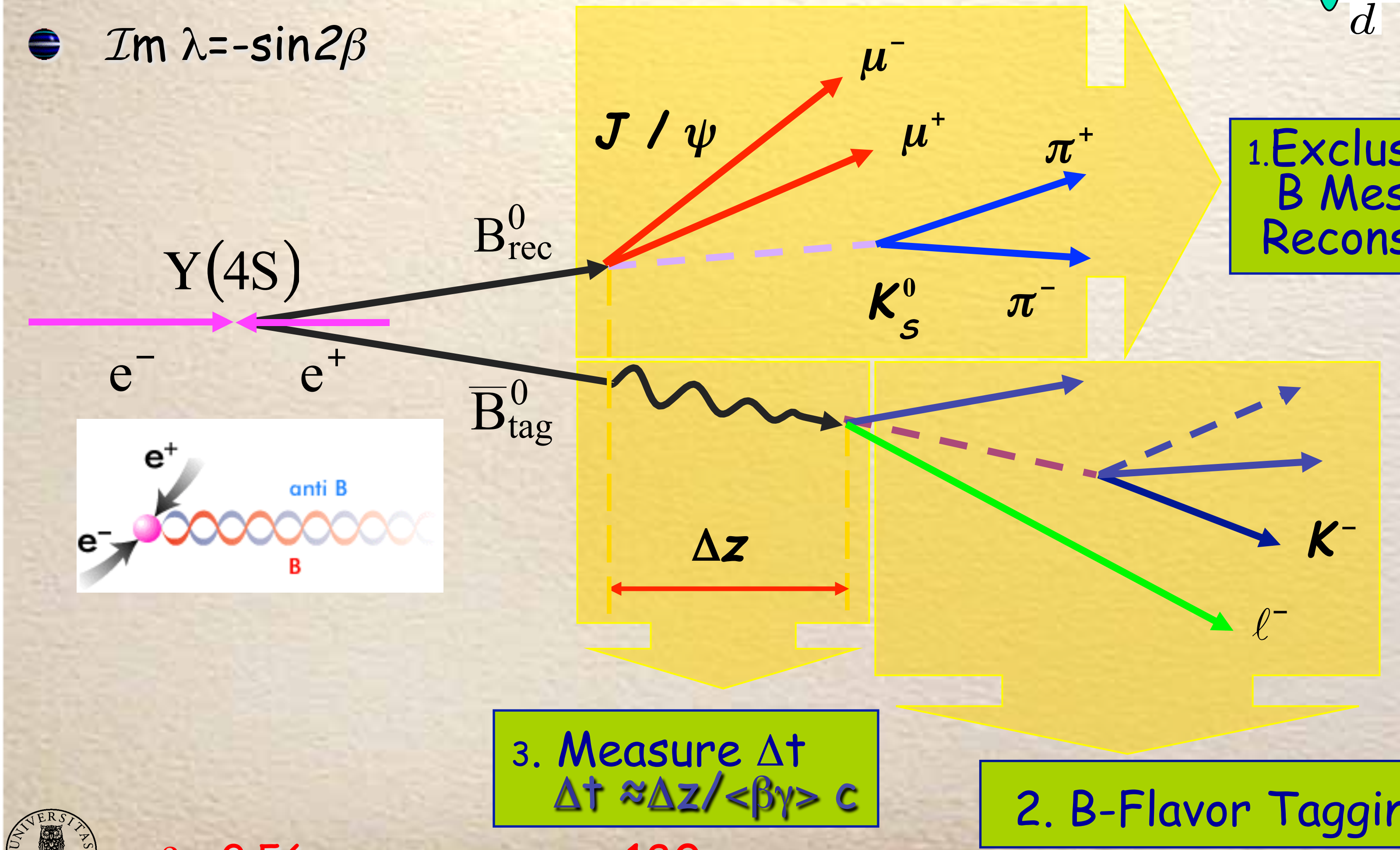
$$\beta \equiv Arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

Measurement of *sin2β* in $(c\bar{c})K^0$ Modes

- We need to measure 3 quantities to determine the *CP* asymmetry in $B^0 \to J/\psi K^0$



- $\mathcal{I}m\ \lambda = -\sin 2\beta$



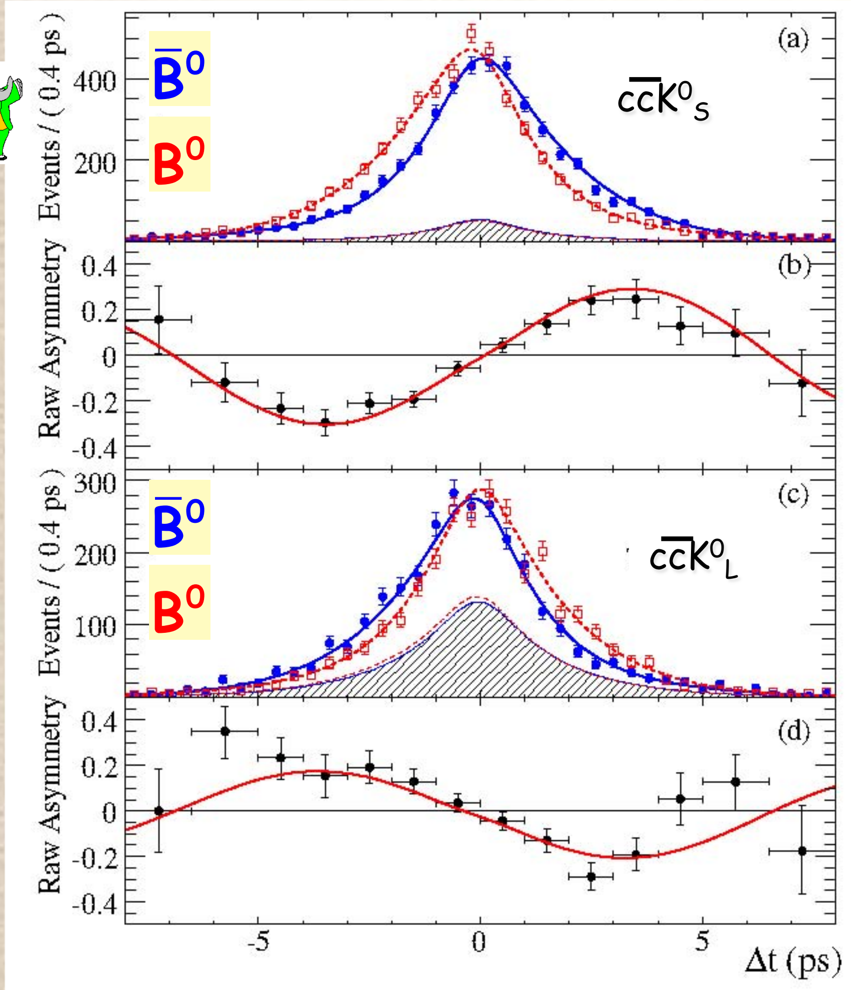
Tagging quality
$Q=31.2\pm0.3\%$,
$\varepsilon=(74.37\pm0.1)\%$

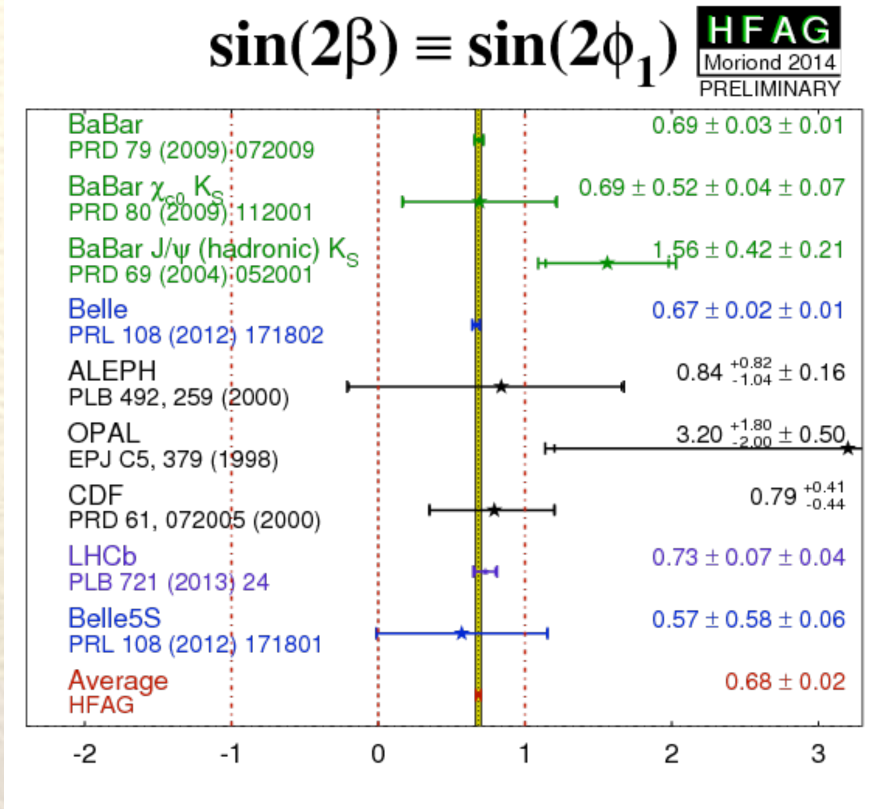
$\beta\gamma=0.56$

$\sigma_{\Delta z}=180\ \mu m$

sin2β Measurements

- 15481 tagged events (465 M $B\overline{B}$)



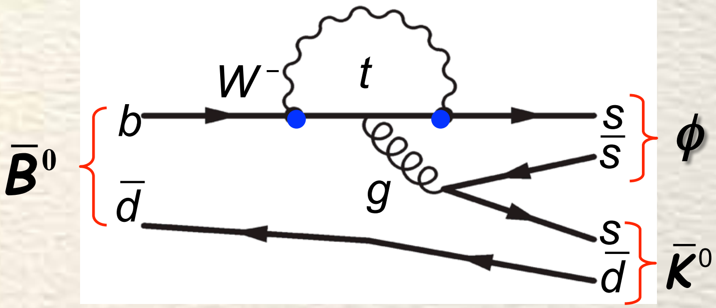


sin 2β=0.687±0.028±0.012
C=0.024±0.020±0.016

- sin 2β world average is 0.68±0.02
  ➔ $\beta=(21.5^{+0.8}_{-0.7})°$
- Cosine term is consistent with zero
  0.005±0.017

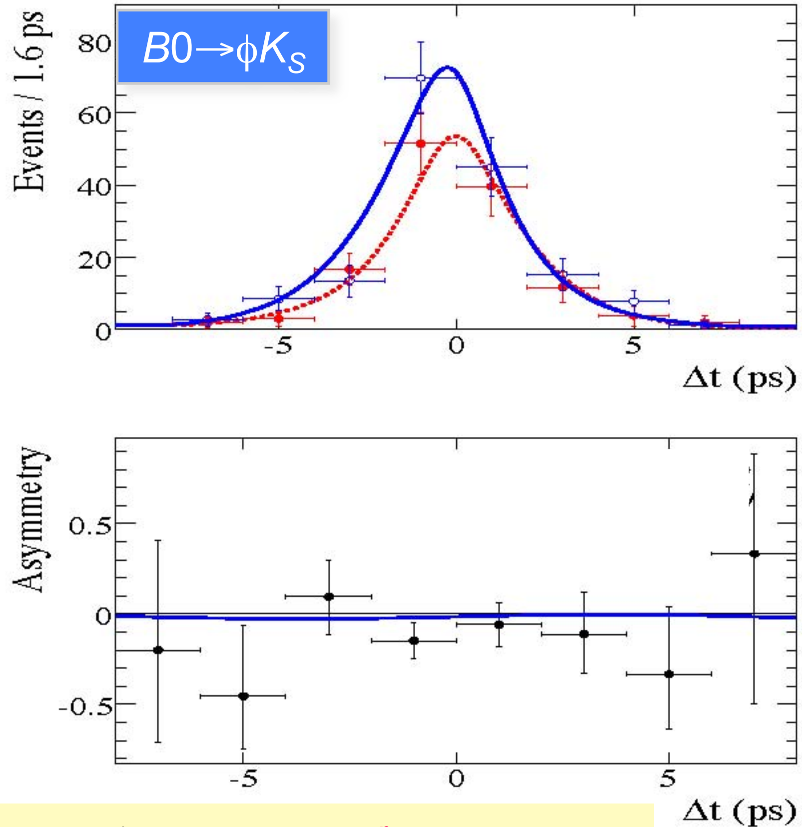
Measurement of sin2β in $B\to\phi K^0$

- In the *Standard Model*, *CP* violating asymmetries from $B\to J/\psi K^0$ & $B\to\phi K^0$ modes yield the same value of "sin 2β"



- Using 465×10^6 (383×10^6) $B\bar{B}$ events, BABAR observed 381±23 ϕK^0_S & (151±22 ϕK^0_L events)

- Using 535×10^6 $B\bar{B}$ events, Belle observed 307±21 ϕK^0_S & 114±17 ϕK^0_L events



- The *CP* asymmetry measurements from BABAR & Belle yield:

$S_{\phi K^0} = +0.74^{+0.11}_{-0.13}$ $C_{\phi K^0} = 0.01 \pm 0.14$

- This agrees well with the SM prediction

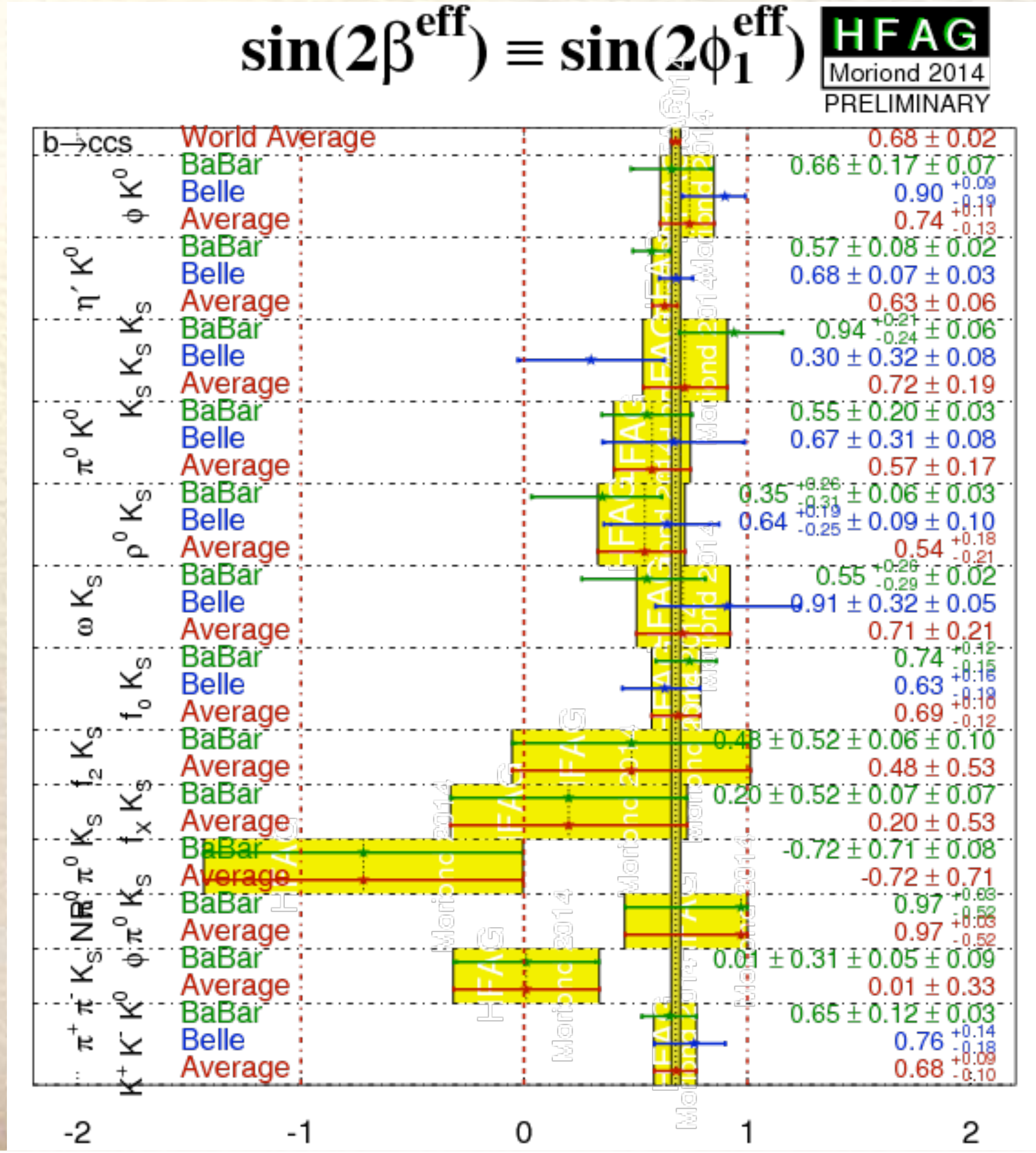
- Another related mode is $B\to\eta' K^0$ yielding

$S_{\eta' K^0} = +0.59 \pm 0.07$ $C_{\eta' K^0} = -0.05 \pm 0.05$ $\mathcal{A}_{f_{CP}}(\Delta t) = S\cdot\sin\Delta m\cdot\Delta t - C\cdot\cos\Delta m\cdot\Delta t$

Comparison of sin2β in Penguin-Dominated Modes

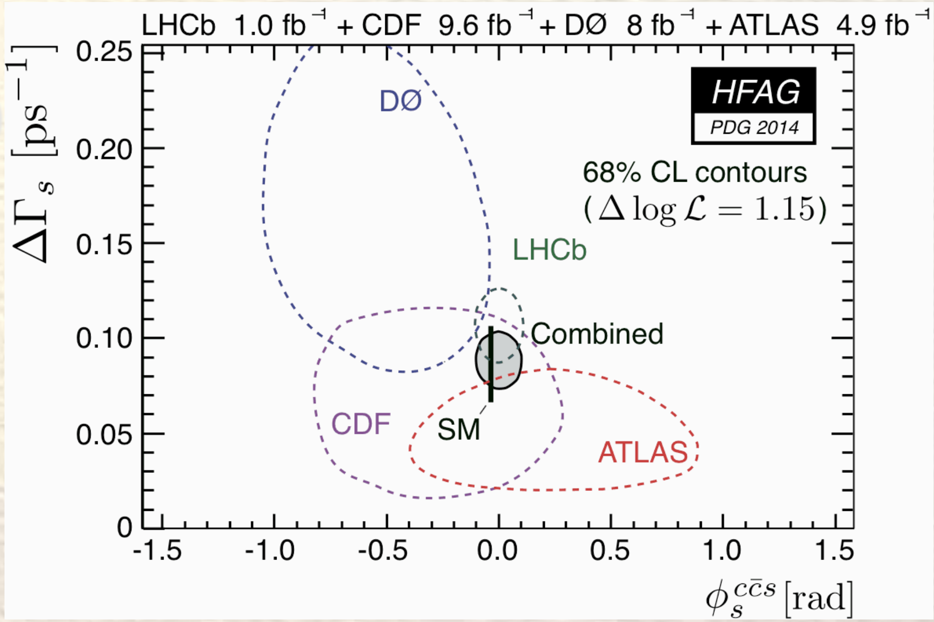
- For the penguin-dominated rare hadronic decays BABAR and Belle yield consistent results

- For most penguin-dominated rare hadronic decays, the measured value of $\sin 2\beta^{eff}$ agrees with the $\sin 2\beta$ world average obtained from $B \to \bar{c}cK^0$ modes



CP Violation in the B_s System

- The phase difference between the B_s mixing amplitude and $b \to c\bar{c}s$ decay amplitude of B_s meson is $\phi_s = 2\beta_s$, where in SM $\beta_s = \arg\left(-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)\right) \sim 1^o$ (35)



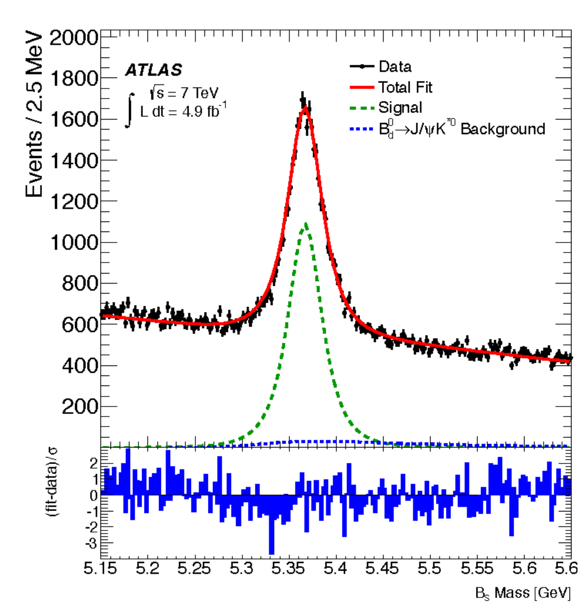
- This is defined in analogy to β for B_d decays
- CDF, D0, CMS ATLAS and LHCb have measured β_s using the decay $B_s \to J/\psi\phi$
- LHCb added $B_s \to J/\psi\pi^+\pi^-$ modes
- Perform a 2-D fit in the β_s-$\Delta\Gamma_s$ plane w & w/o other constraints
- Present world average is $\phi_s = 2\beta_s = (0.00 \pm 0.07)$ rad
- At ICHEP 2014, LHCb showed updated result with 3 fb^{-1} of $B_s \to J/\psi\pi^+\pi^-$ data
  ➔ LHCb average $\phi_s = (0.07 \pm 0.055)$ rad
- LHCb also measured ϕ_s in $B_s \to \phi\phi$ (3 fb^{-1}) yielding $\phi_s = (-0.17 \pm 0.15 \pm 0.03)$ rad

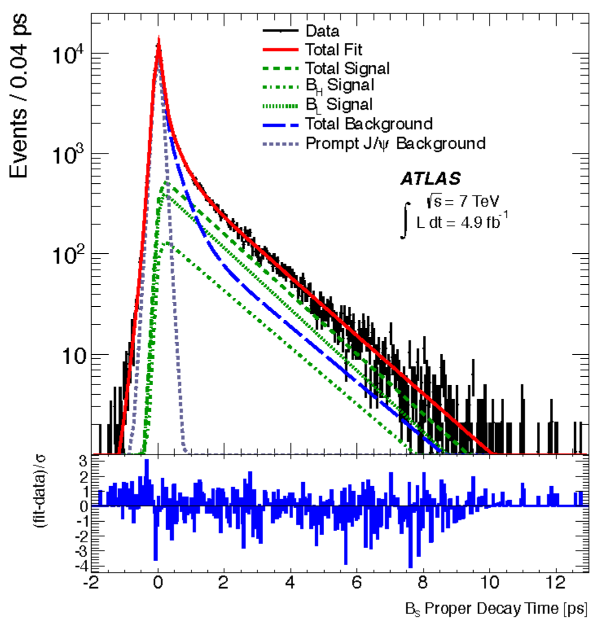
Study of the B_s Meson

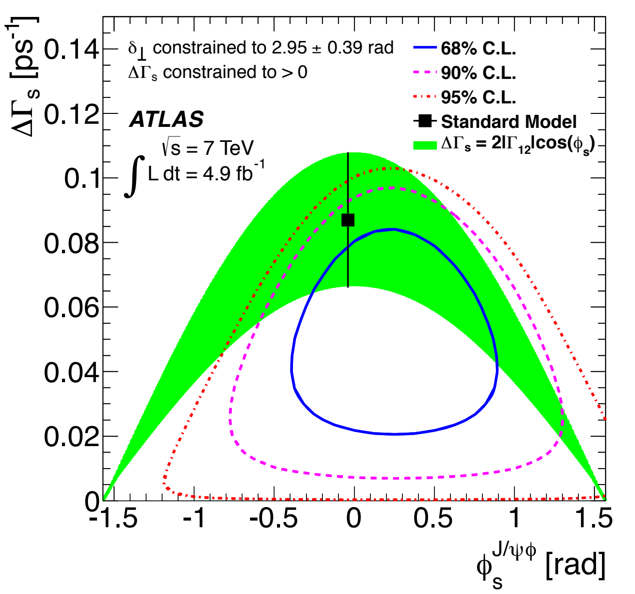
- ATLAs performed a time-dependent full angular analysis of $B_s \rightarrow J/\psi\phi$ (26 parameter ML fit) to extract amplitudes, strong phases, Γ_s, $\Delta\Gamma_s$ and ϕ_s

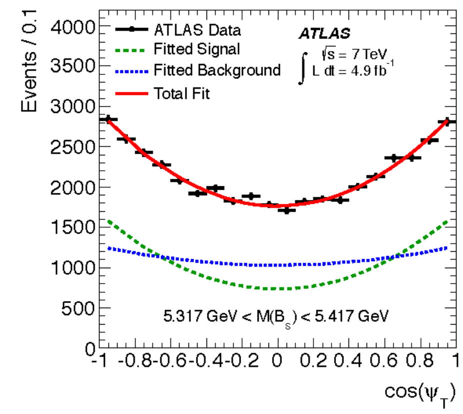
$$\phi_s = (0.22 \pm 0.41 \pm 0.10)\ \mathrm{rad}$$
$$\Delta\Gamma_s = (0.053 \pm 0.021 \pm 0.010)\ \mathrm{ps}^{-1}$$
$$\Gamma_s = (0.677 \pm 0.007 \pm 0.004)\ \mathrm{ps}^{-1}$$

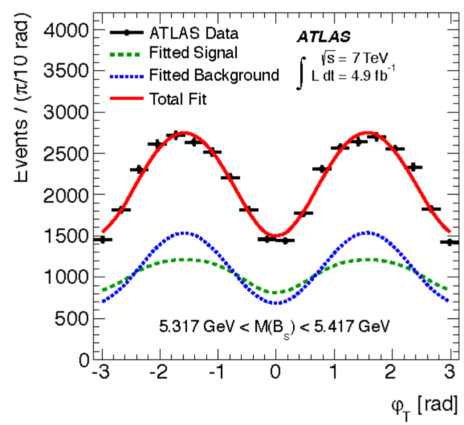
- This agrees with results from CMS and LHCb and the SM predictions

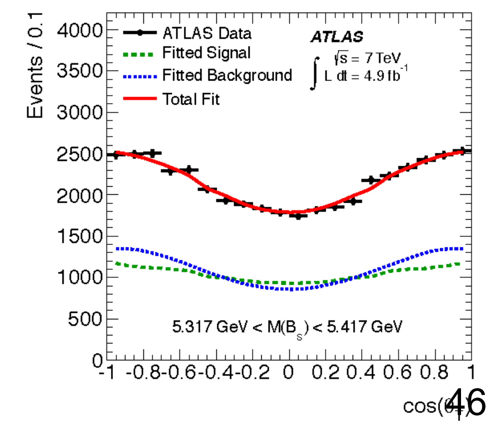








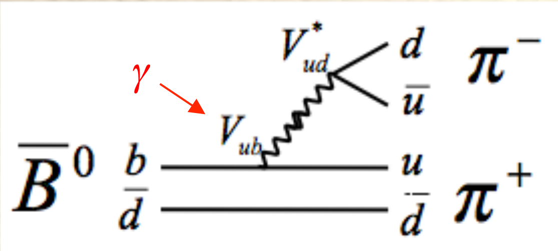




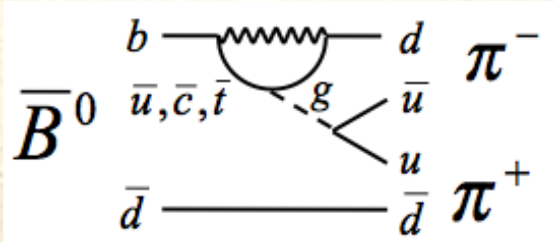
Measurement of $\sin 2\alpha$

- Interference of $b \to u\bar{u}d$ decay w&w/o $B^0\bar{B}^0$ mixing yields angle α

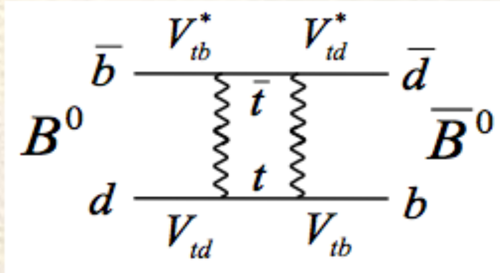
tree



penguin



B0 B0 mixing



- Thus we need to measure Δt-dependent *CP* asymmetries of $b \to u\bar{u}d$ processes, such as $B \to \pi\pi, \rho\pi, \rho\rho$, ...

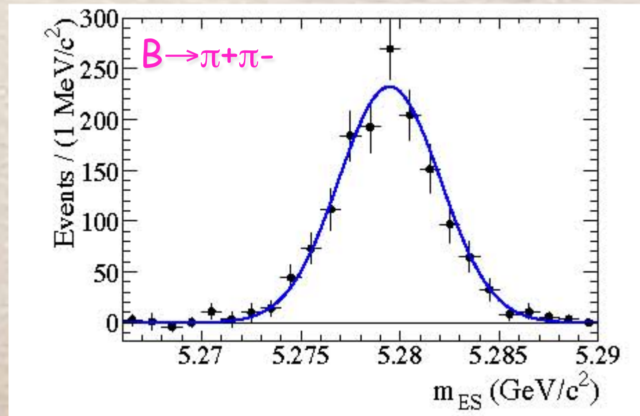
- However, penguin pollution complicates extraction of α ➔ measure $\sin 2\alpha_{eff}$

- Since $|\lambda| \neq 1$, *CP* asymmetry has form

$$\mathcal{A}_{\pi\pi}(\Delta t) = -C_{\pi\pi} \cos \Delta m_d \Delta t + S_{\pi\pi} \sin \Delta m_d \Delta t$$

$$S_{\pi\pi} = 2\Im m\lambda = \sin 2\alpha \qquad (36)$$

1394±54 events



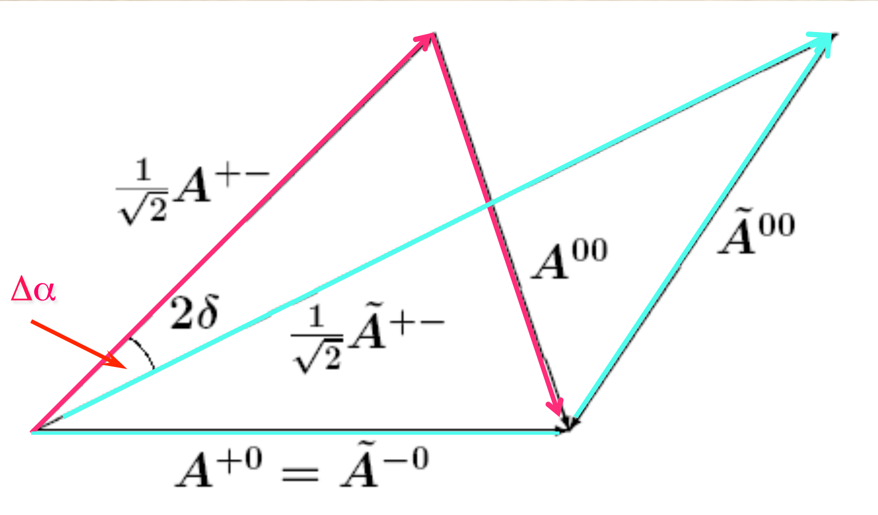
The Gronau-London Method

- $S_{\pi\pi}$ measures $2\alpha_{eff} = 2\alpha + \Delta\alpha$, where $\Delta\alpha$ can be determined using the Gronau-London method

- The decays $B \rightarrow \pi^+ \pi^-, \pi^+\pi^0, \pi^0\pi^0$ are related by SU(2)
  ➔ Have isospin relations between amplitudes A_{+-}, A_{+0}, A_{00}

- Central observation is that $\pi\pi$ states can have I=2 or 0, while gluonic penguins only contribute to I = 0 (ΔI = ½ rule)
  ➔ $\pi^+\pi^0$ is pure I = 2, so only tree amplitude $\rightarrow$ $|A+0| = |A-0|$

B→ππ isospin analysis

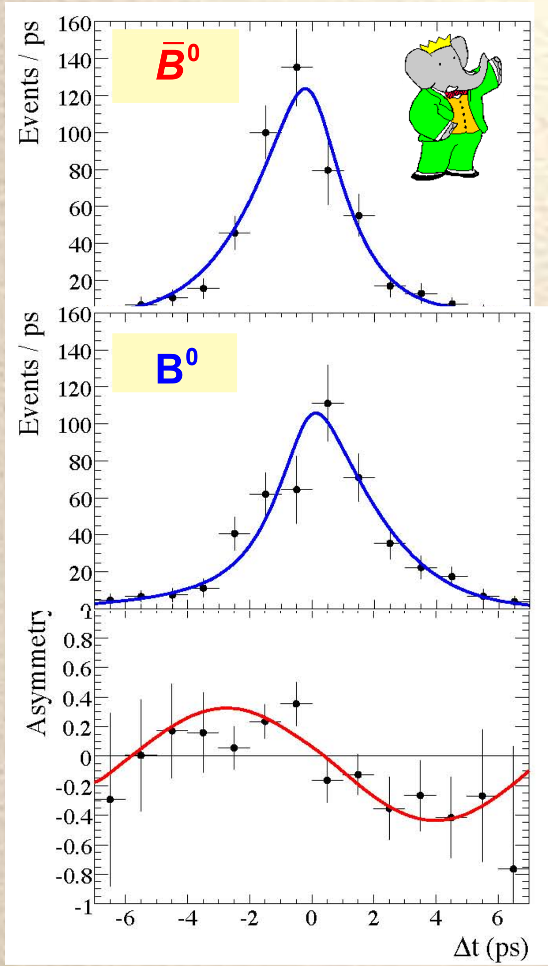


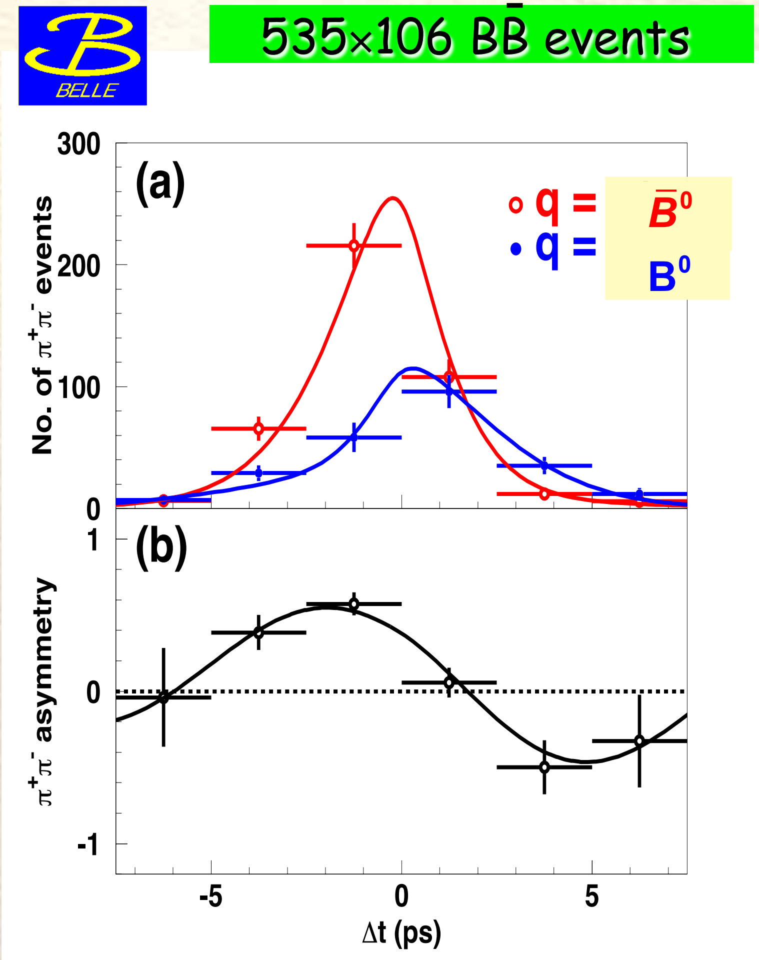
- **Need to measure:**
  C_{+-}, C_{00} (amplitudes in Cos terms for $\pi^+\pi^-$ & $\pi^0\pi^0$), & A_{00}, A_{+0}
  ➔ **Effective isospin analysis requires A_{00} & A_{00} very large, or very small!**

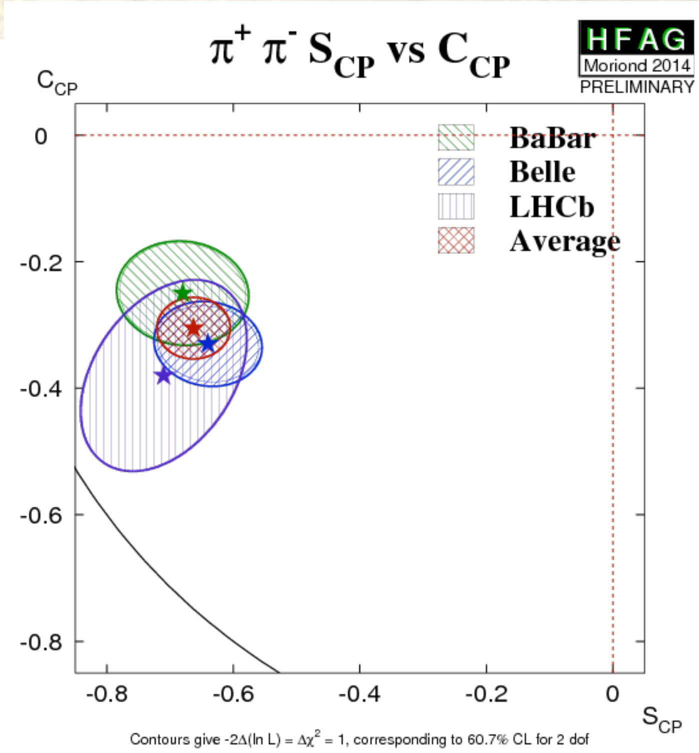
Measurement of sin2α in B→ππ

- Compare results on B→ππ from BABAR, Belle and LHCb

467×106 $B\bar{B}$ events







LHCb

$S_{\pi\pi} = -0.68 \pm 0.10 \pm 0.03$
$C_{\pi\pi} = -0.25 \pm 0.08 \pm 0.02$

$S_{\pi\pi} = -0.64 \pm 0.08 \pm 0.03$
$C_{\pi\pi} = -0.33 \pm 0.06 \pm 0.03$

$S_{\pi\pi} = -0.71 \pm 0.13 \pm 0.02$
$C_{\pi\pi} = -0.31 \pm 0.15 \pm 0.02$

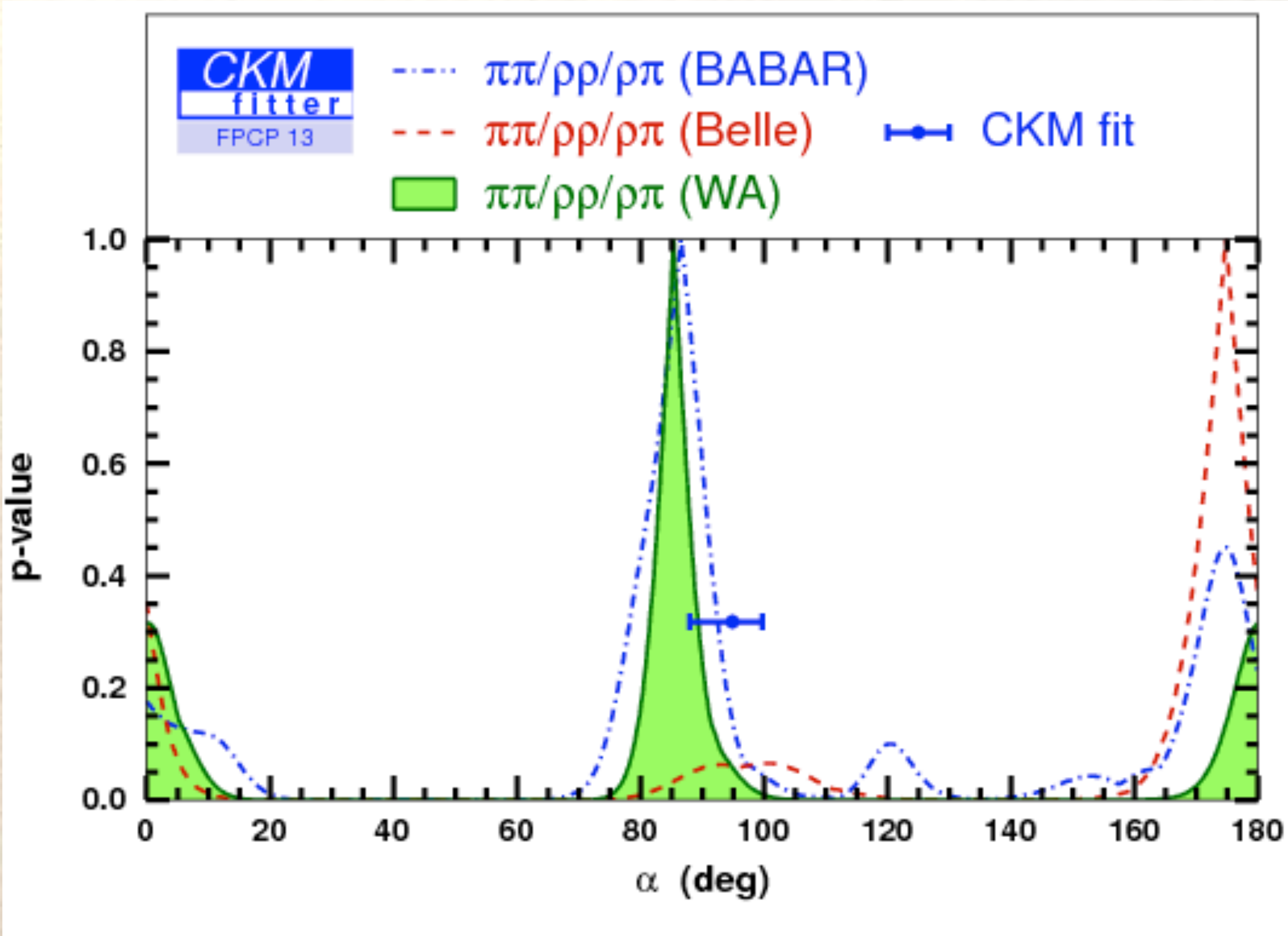
Summary of α Measurements

- Summary on α measurements
- From combined $\pi\pi$, $\rho\pi$, $\rho\rho$ results constrain α to:

  $\alpha = [85.4\ ^{+4.0}_{-3.9}]^{\circ}$

- Best constraints from $B\to\rho\rho$
- Mirror solutions are disfavored
- CKM indirect constraint yields:

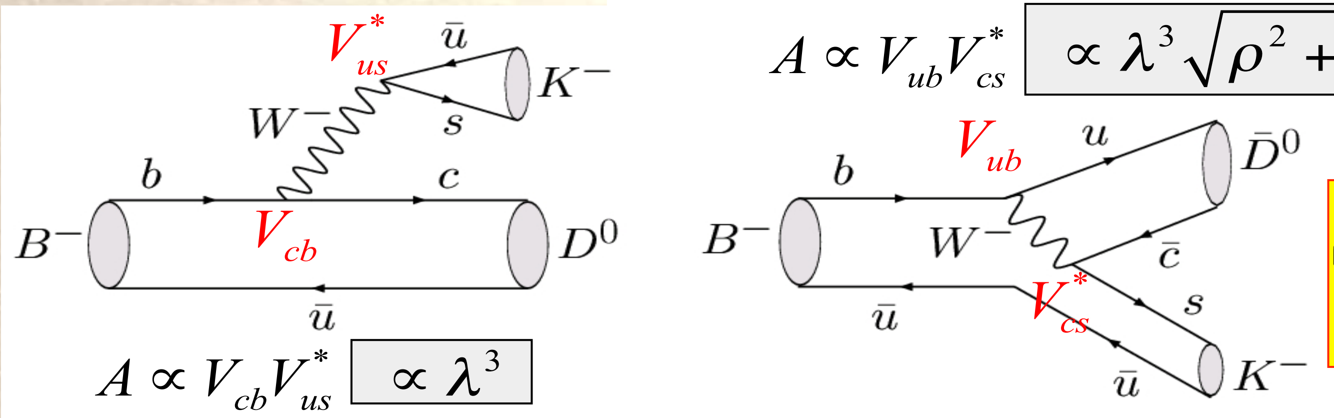
  $\alpha = [94.9^{+4.8}_{-6.8}]^{\circ}$



Very good agreement

Measurement of Angle γ

- The angle γ is measurable via interference between $B^- \to D^0 K^-$ & $B^- \to \bar{D}^0 K^-$ decays, where the D^0 / $\bar{D}^0$ decay to common final state



$A \propto V_{cb} V_{us}^* \quad \boxed{\propto \lambda^3}$

$A \propto V_{ub} V_{cs}^* \quad \boxed{\propto \lambda^3 \sqrt{\rho^2 + \eta^2}} \; e^{i(\delta B - \gamma)}$

$$r_B^{(*)} = \frac{|A(B^- \to \bar{D}^{(*)0} K^-)|}{|A(B^- \to D^{(*)0} K^-)|} \sim 0.1 - 0.3$$

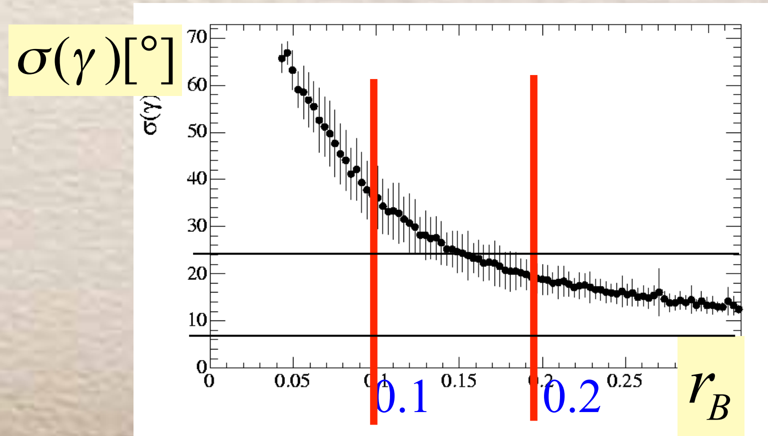
- Use 3 different methods:
  - Gronau-London-Wyler (GLW 1991)

    Use $B^- \to D^0_{CP\pm} K^-$ decays
  - Atwood-Dunietz-Soni (ADS 2001)

    Use $B^- \to D^{(*)0}(K^- \pi^+) K^-$ decays
  - Giri, Grossman, Soffer Zupan (GGSZ) D^0 Dalitz plot analysis

    Use $B^- \to D^0(K^0_S \pi^+ \pi^-) K^-$ decays

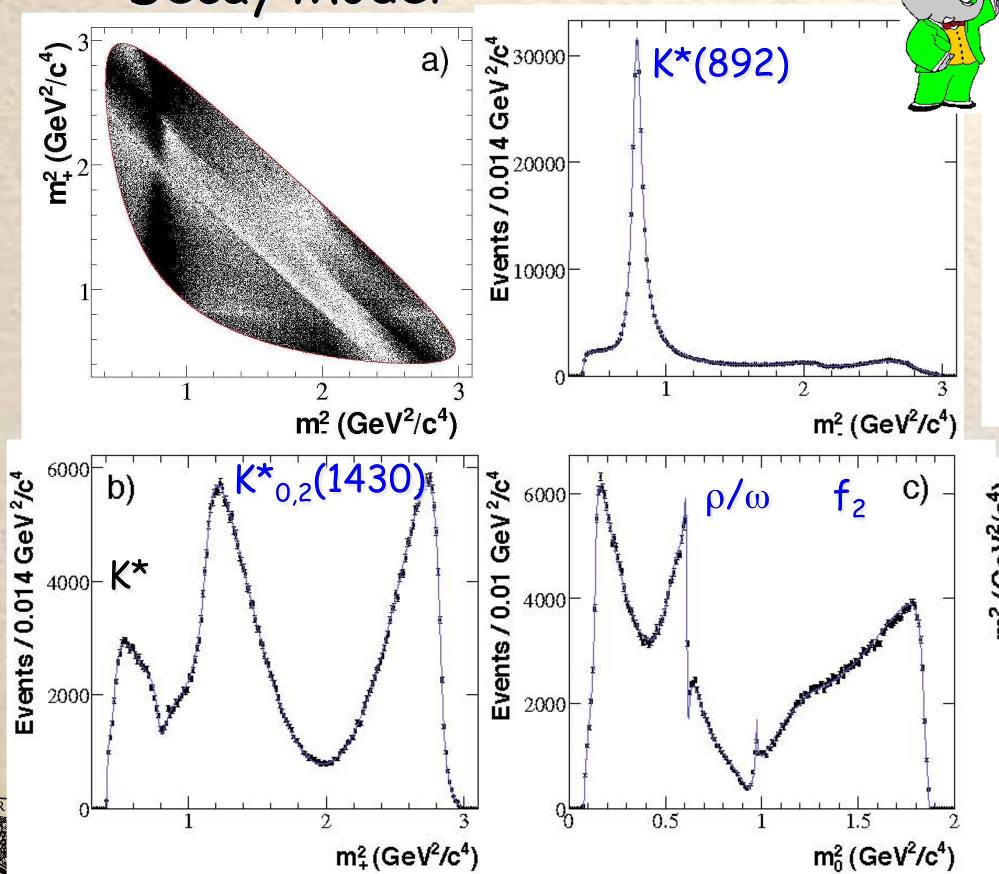
Size of the CP asymmetry & error on γ depends on $r^{(*)}_B$



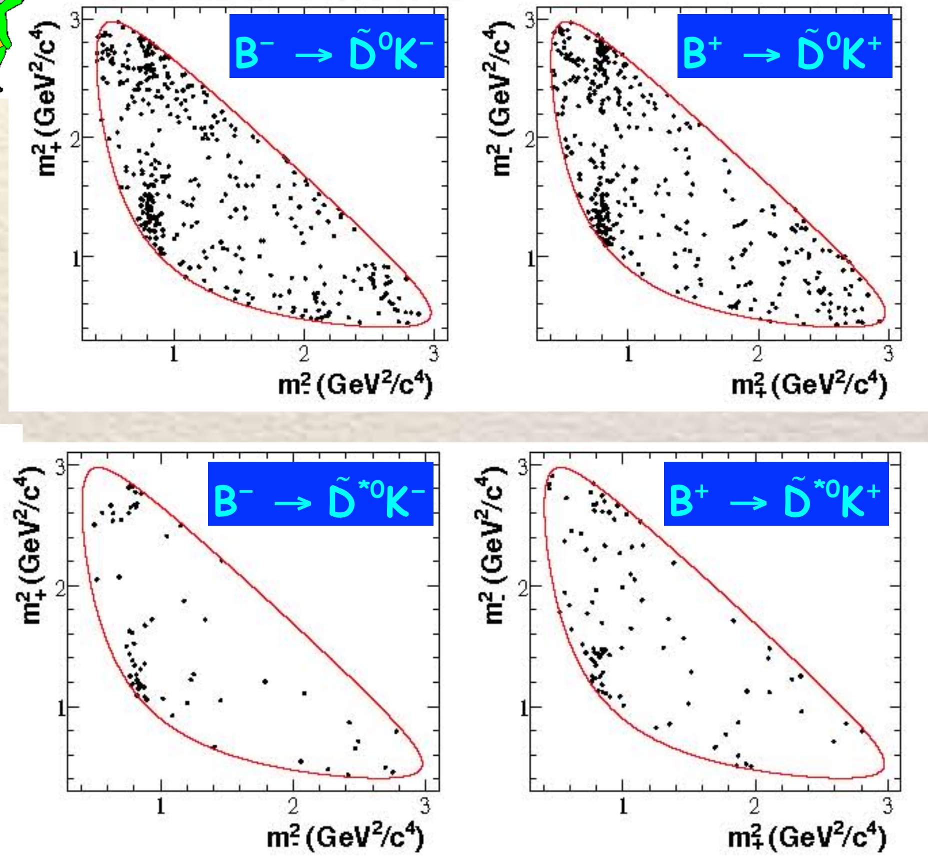
Dalitz Plot in $B^- \rightarrow D^0 (K^0_s \pi^+ \pi^-) K^-$

- Decay model of $K_S \pi^+ \pi^-$: coherent sum of 10 Breit-Wigner amplitudes: 7 distinct resonances $K^*(892)$, $K^*_0(1430)$, $K^*_2(1430)$, $K^*(1680)$ (4 Cabibbo-allowed and 3 DCS), $\rho(770)$, $\omega(782)$, $f_2(1270)$ (CP-ES) plus 1 non-resonant term ($\pi\pi$ S-Wave)

Decay Model

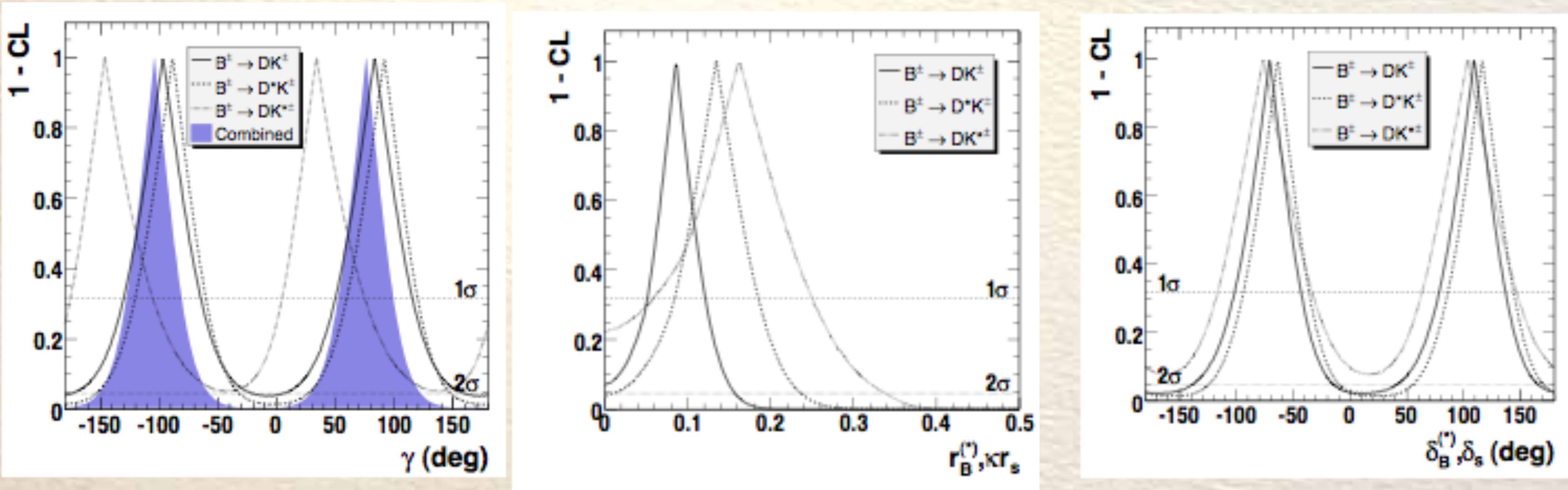


Measurements



Measurement of Angle γ in $B^- \rightarrow D^0 (K^0_s \pi^+ \pi^-) K^-$

- From the $B^- \rightarrow D^{(*)0} K^-$ & corresponding decays BABAR extracts γ, r_B and δ_B



- We get 2-fold ambiguity: $(\gamma, \delta(^*)_B) \rightarrow (\gamma+\pi, \delta(^*)_B+\pi)$

$$r_B = 0.085 \pm 0.035 \pm 0.010 \pm 0.011$$

$$r_B^* = 0.135 \pm 0.051 \pm 0.011 \pm 0.005$$

$$\delta_B = (109^{+28}_{-31\,stat} \pm 4_{sys} \pm 7_{Dalitz})^\circ$$

$$\delta_B^* = (63^{+28}_{-30\,stat} \pm 5_{sys} \pm 4_{Dalitz})^\circ$$

$$\gamma = (76 \pm 22_{stat} \pm 5_{sys} \pm 5_{Dalitz\ model})^\circ$$

$$\gamma = (76^{+12}_{-13} \pm 4_{sys} \pm 9_{Dalitz\ model})^\circ$$

Summary of γ Measurements

- Combining all 3 methods for $B^- \to D^{(*)0}K^{(*)-}$ yields first measurement of γ

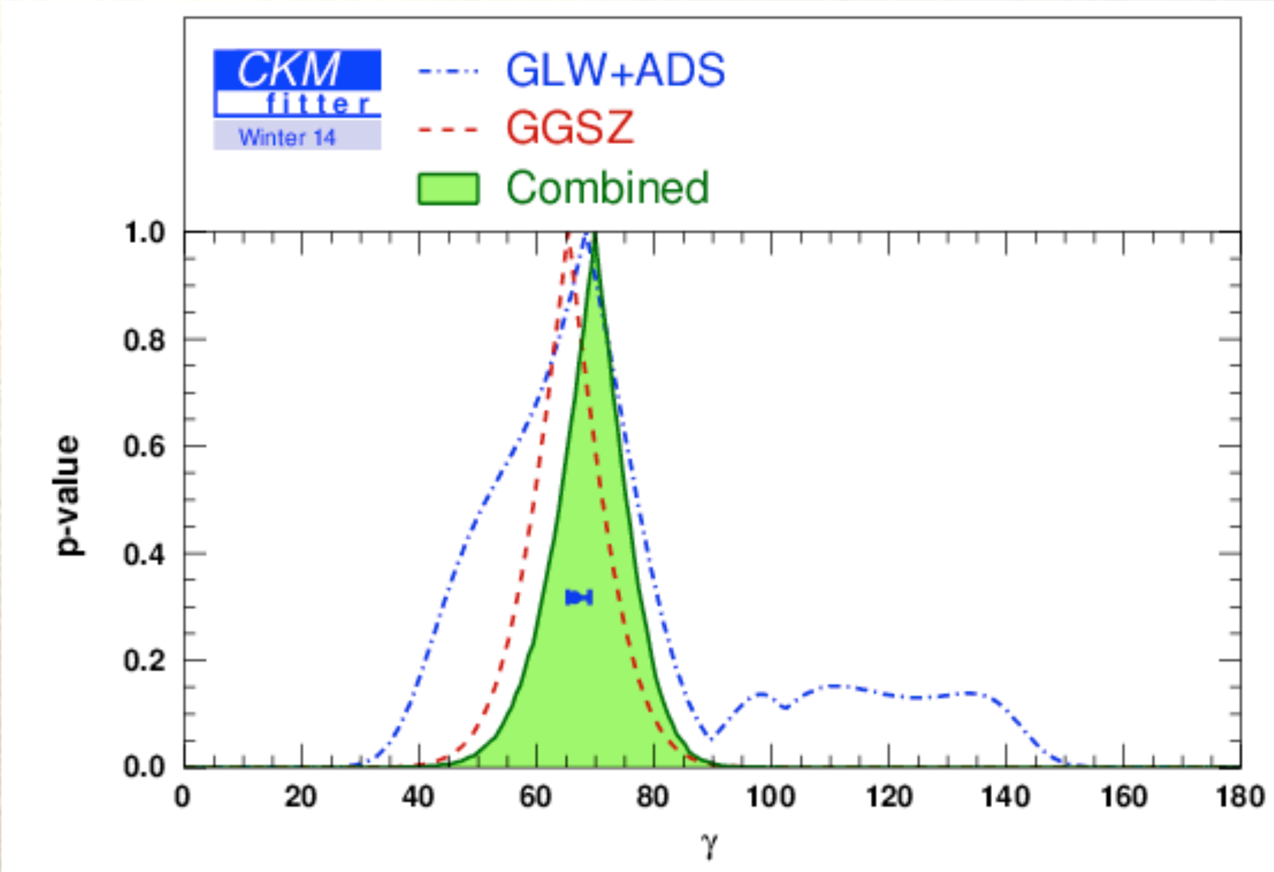
- A few years ago this was thought to be impossible

- From combined analysis

  $\gamma = [70.0\ ^{+7.7}_{-9.0}]^\circ$

- From indirect constraints

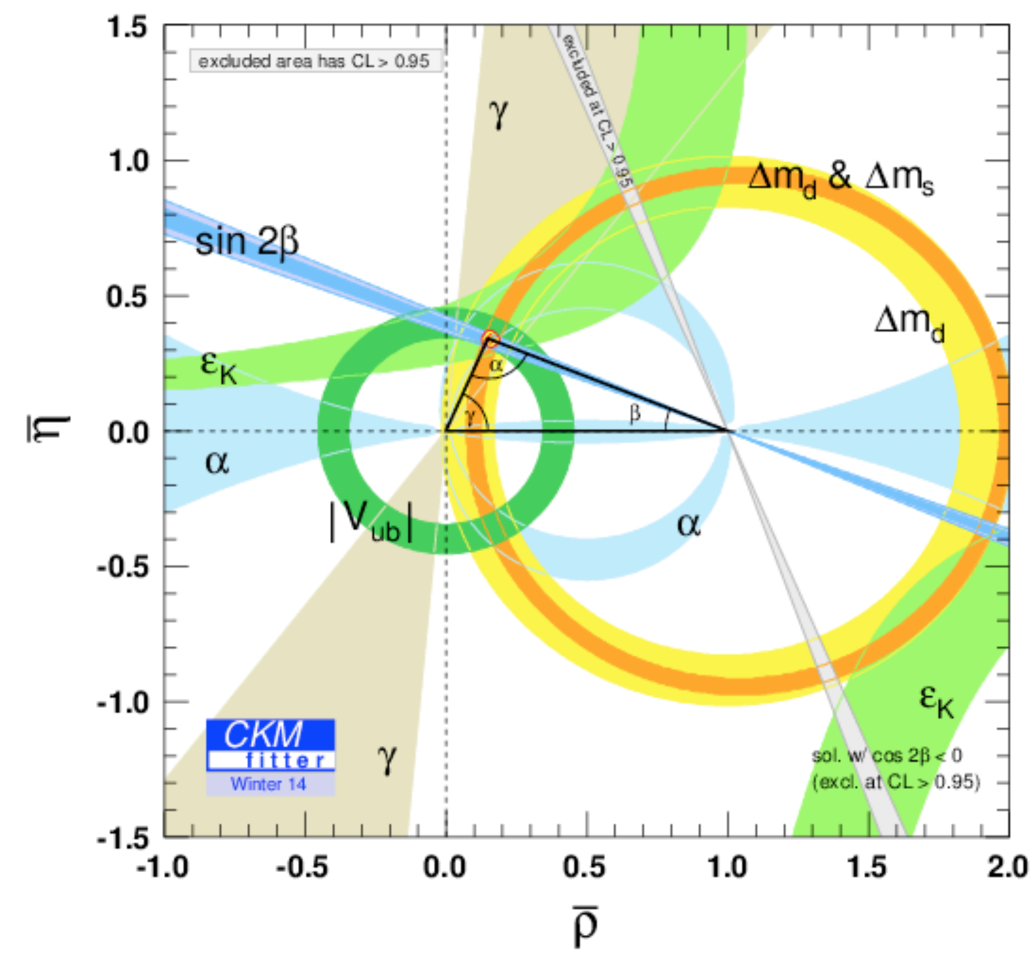
  $\gamma = [66.4\ ^{+1.2}_{-3.3}]^\circ$



- **γ measurements obtained from 2 independent methods are in good agreement (errors are still large)**

Present Status of Unitarity Triangle

- Global fit in ρ-η plane using V_{ub}, V_{cb}, Δm_d, Δm_s, ε_K, $\sin 2\beta$, $\cos 2\beta$, $\sin 2\alpha$, γ
- Measurements of 3 sides agree with measurements of the 3 angles
  ➔ expect this in the *SM*
  ➔ no $\mathcal{O}(1)$ New Physics effects
- Since the SM works so well, look for New Physics as a correction to the *SM* at $\mathcal{O}(0.1)$



$88.9^\circ < \alpha < 97.3^\circ$ @ 95% CL

$20.5^\circ < \beta < 23.5^\circ$ @ 95% CL

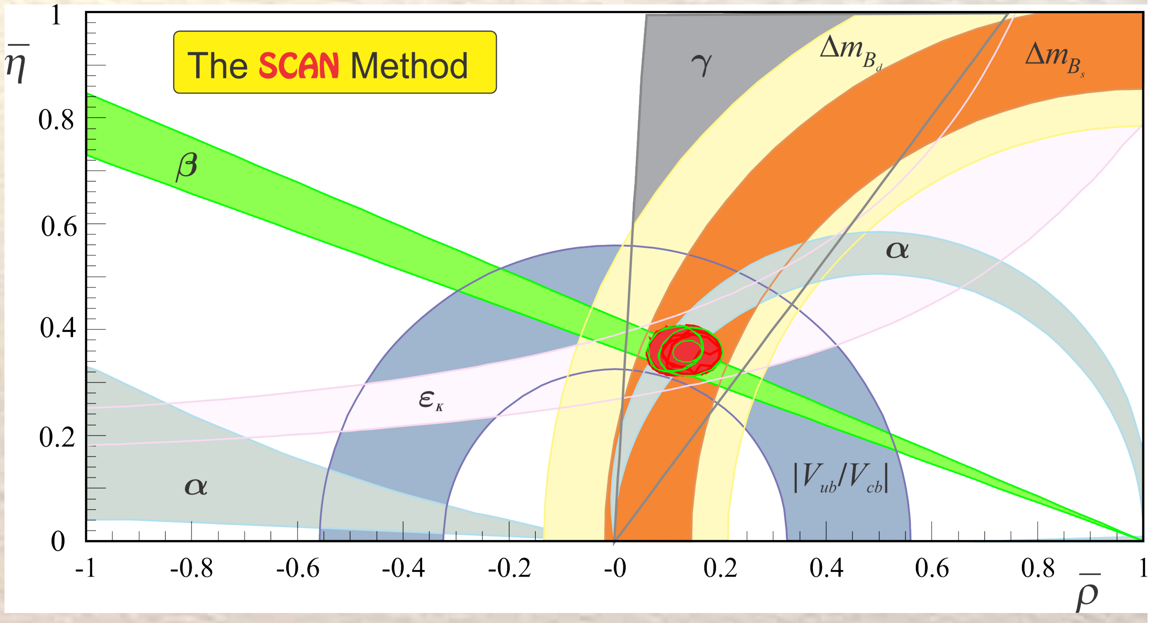
$61.4^\circ < \gamma < 68.9^\circ$ @ 95% CL

$0.133 < \bar{\rho} < 0.182$ @ 95% CL

$0.318 < \bar{\eta} < 0.366$ @ 95% CL

Present Status of Unitarity Triangle in Scan Method

- Perform a fit using 256 measurements and 114 parameters
  - ➔ use all available $\mathcal{B}$ and $\mathcal{A}_{CP}$ measurements in $B \to PP$, PV, VV, a_1P for α
  - ➔ use $\mathcal{B}$ & $\mathcal{A}_{CP}$ measurements in $B^- \to D^{(*)0}K^-(\pi^-)$, $B^- \to D^0 K^{*-}(\rho^-)$ for γ
  - ➔ use ε_K, Δm_d, Δm_s, $\sin 2\beta$, $\mathcal{B}(B \to \tau^\pm \nu)$, m_t, m_c and CKM matrix elements
- Theory uncertainties δ in V_{ub}, V_{cb}, f_{Bd}, B_{Bd}, f_{Bs}, B_{Bs}, B_K have a non-Gaussian part that we scan over
- So we select particular values within $\pm 1\delta$ and perform a fit
- For $P(\chi^2) > 5\%$, we plot contours in the $\bar{\rho}-\bar{\eta}$ plane
  - ➔ allowed range is envelope of all contours



$81.1^\circ < \alpha < 93.3^\circ$ @ 95% CL

$19.0^\circ < \beta < 25.8^\circ$ @ 95% CL

$62.8^\circ < \gamma < 79.8^\circ$ @ 95% CL

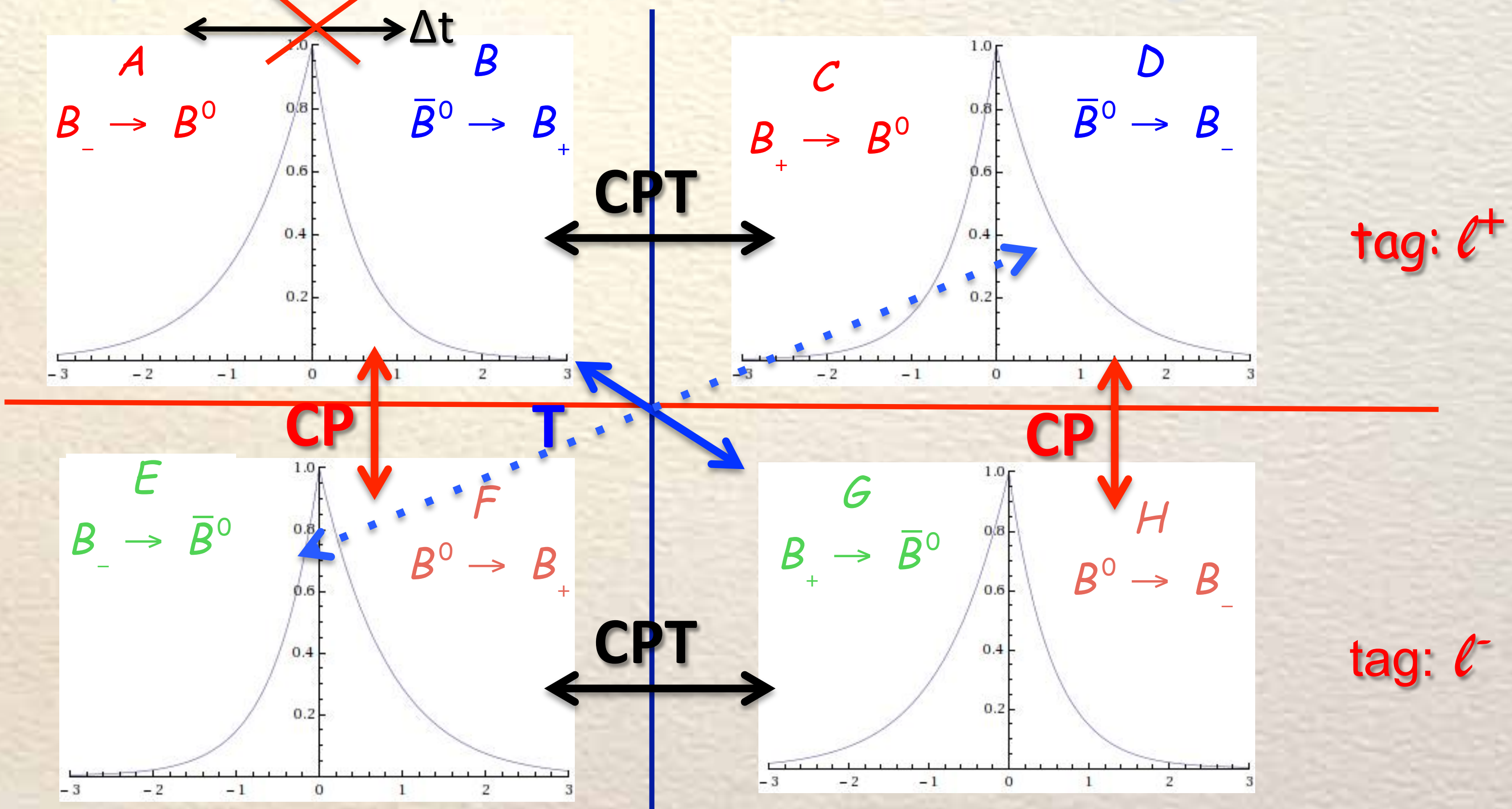
$0.058 < \bar{\rho} < 0.191$ @ 95% CL

$0.314 < \bar{\eta} < 0.406$ @ 95% CL

T Violation in the B System

T Violation

- The $B^0\overline{B}^0$ system produced at the ϒ4S) is unique for measuring *T* violation
- Use the decay *B→J/ψK⁰* and explore time distribution
- Define
  B₊: *CP even*
  B₋: *CP odd*



Decay: J/ψ K_L (*CP*=+1)   Decay: J/ψ K_S (CP=-1)

- We construct:

$$\Delta S_T^+ = S_{\ell^-,K_L^0}(\Delta t<0) - S_{\ell^+,K_S^0}(\Delta t>0)$$
$$\Delta S_T^- = S_{\ell^-,K_L^0}(\Delta t>0) - S_{\ell^+,K_S^0}(\Delta t<0)$$

$$\Delta C_T^+ = C_{\ell^-,K_L^0}(\Delta t<0) - C_{\ell^+,K_S^0}(\Delta t>0)$$
$$\Delta C_T^- = C_{\ell^-,K_L^0}(\Delta t>0) - C_{\ell^+,K_S^0}(\Delta t<0)$$

where $S_{X,Y}$ and $C_{X,Y}$ come from time-dep asymmetries as $\mathcal{A}_{CP}$

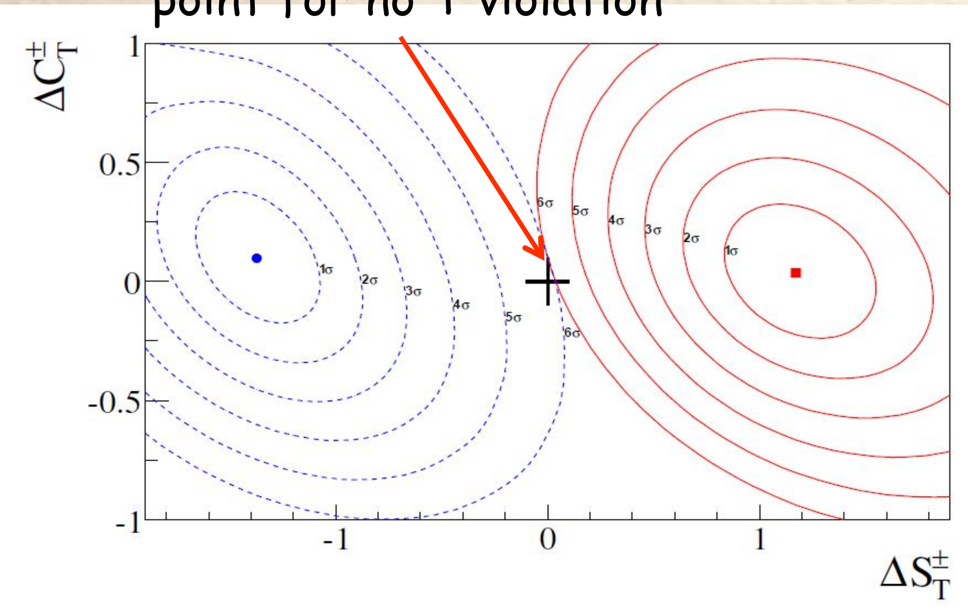
T Violation Asymmetries

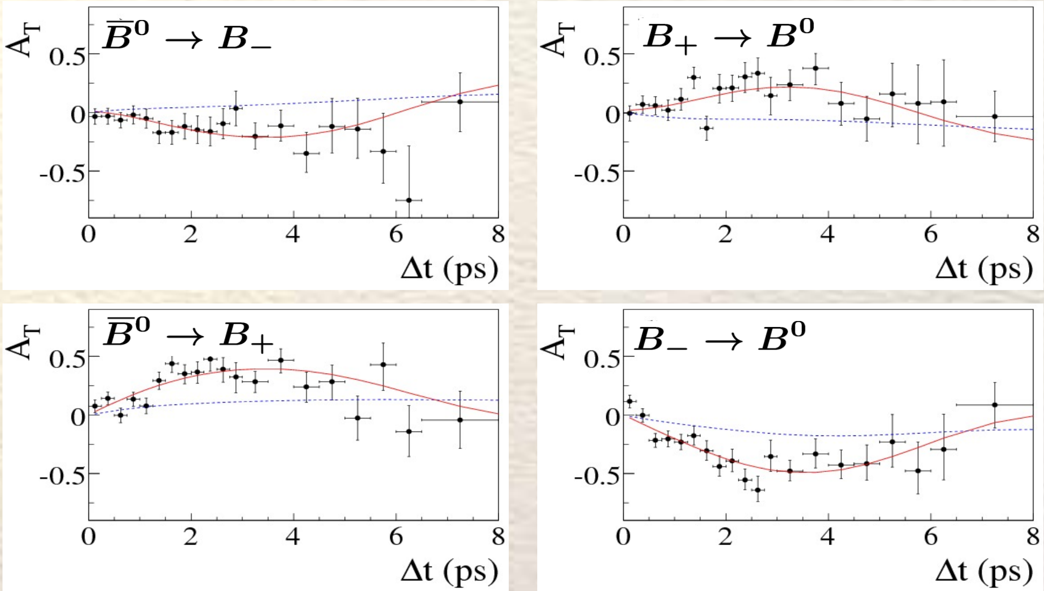
- Define 4 asymmetries, e.g.

$$A_T = \frac{N(B_+ \to \bar{B}^0) - N(\bar{B}^0 \to B_+)}{N(B_+ \to \bar{B}^0) + N(\bar{B}^0 \to B_+)} \approx \frac{\Delta C_T^+}{2} \cos \Delta m \Delta t + \frac{\Delta S_T^+}{2} \sin \Delta m \Delta t \quad (37)$$

- The A_T asymmetries clearly show the expected T violation
- Plot of $\Delta C^{\pm}_T$ versus $\Delta S^{\pm}_T$ shows a 14σ effect

point for no T violation



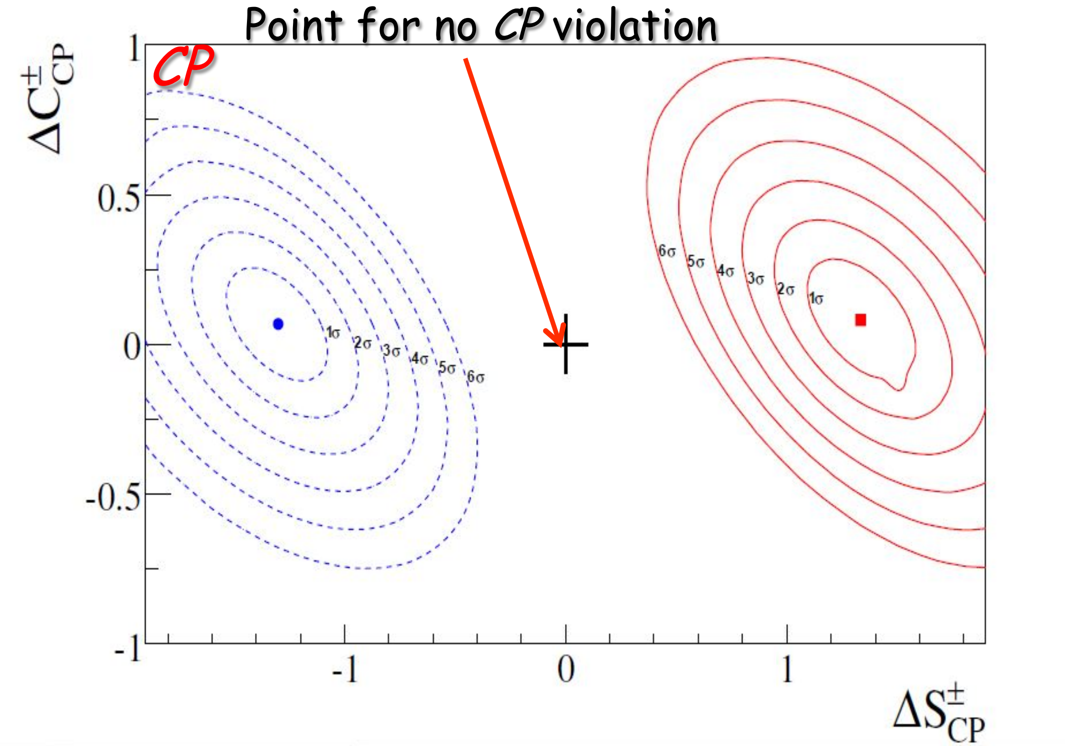


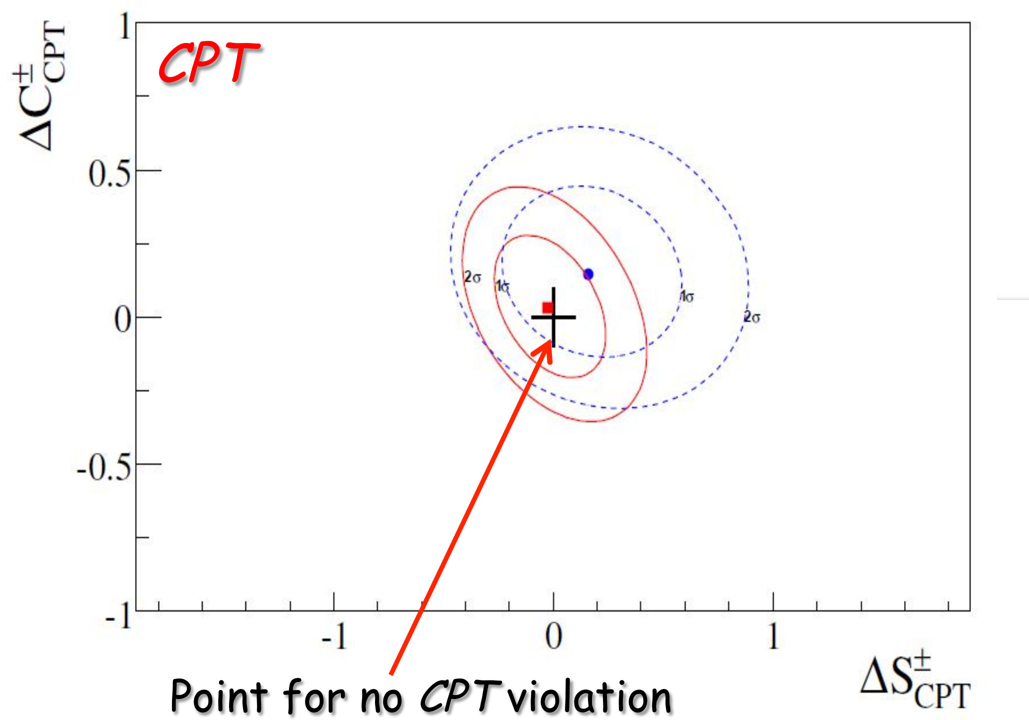
$$\begin{aligned}
\Delta S_T^+ &= -1.37 \pm 0.14 \pm 0.06 \\
\Delta S_T^- &= 1.17 \pm 0.18 \pm 0.11 \\
\Delta C_T^+ &= 0.10 \pm 0.16 \pm 0.08 \\
\Delta C_T^- &= 0.04 \pm 0.16 \pm 0.08
\end{aligned}$$

Check for *CP* Violation and *CPT* Conservation

- Define in similar way ($\Delta C^{\pm}_{CP}$, $\Delta S^{\pm}_{CP}$) and ($\Delta C^{\pm}_{CPT}$, $\Delta S^{\pm}_{CPT}$) pairs

$$\begin{aligned}
\Delta S^{+}_{CP} &= -1.30 \pm 0.10 \pm 0.07 \\
\Delta S^{-}_{CP} &= 1.33 \pm 0.12 \pm 0.06 \\
\Delta C^{+}_{CP} &= 0.07 \pm 0.10 \pm 0.03 \\
\Delta C^{-}_{CP} &= 0.08 \pm 0.09 \pm 0.04
\end{aligned}$$





$$\begin{aligned}
\Delta S^{+}_{CPT} &= 0.16 \pm 0.20 \pm 0.09 \\
\Delta S^{-}_{CPT} &= -0.03 \pm 0.13 \pm 0.06 \\
\Delta C^{+}_{CPT} &= 0.15 \pm 0.17 \pm 0.07 \\
\Delta C^{-}_{CPT} &= 0.03 \pm 0.14 \pm 0.08
\end{aligned}$$

- Measure *T* and *CP* violation and CPT conservation in the same sample

Conclusion and Outlook

- B physics has produced many interesting results and is still a very active field
- The Belle II upgrade is in full progress ➔expect data taking 2016?
- LHCb is planning a full detector upgrade for the 2018 shutdown
- In the next decade, LHCb and Belle II will make many more precision measurements

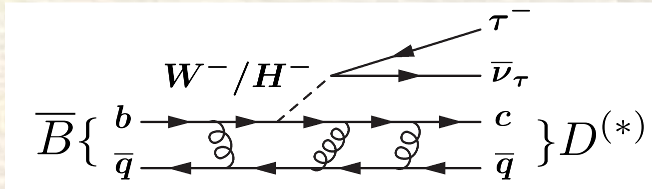
Type	Observable	Current precision (Spring 2012)	LHCb 2018 (7-8 fb^{-1})	**Upgrade** (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s(B_s^0 \to J/\psi\phi)$	0.10 [139]	0.025	0.008	$\sim$0.003
Gluonic penguins	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\overline{K}^{*0})$	–	0.13	0.02	< 0.02
Right-handed currents	$2\beta_s^{\text{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	$<$0.01
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [68]	0.025	0.008	0.02
	$s_0 A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [68]	6 %	2 %	7 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim$100 %	$\sim$35 %	$\sim$5 %
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	$\sim$10–12° [252, 266]	4°	0.9°	negligible
	$\gamma(B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta(B^0 \to J/\psi K_S^0)$	0.8° [44]	0.6°	0.2°	negligible

Backup Slides

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

$B^- \to D\tau^-\nu$ Decay Rate

- For $B \to D(*)\tau\nu$, the differential decay rate in the SM is



$$\frac{d\Gamma(B \to D^{(*)}\tau\nu)}{dq^2} = \frac{G_F^2 \left|V_{cb}\right|^2 p^*_{D^{(*)}} q^2}{96\pi^3 m_B^2}\left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left[\left(\left|H_+\right|^2 + \left|H_-\right|^2 + \left|H_0\right|^2\right)\left(1 - \frac{m_\tau^2}{q^2}\right) + \frac{3m_\tau^2}{2q^2}\left|H_s\right|^2\right] \qquad (12)$$

$$H_\pm(q^2) = \left(m_B + m_V\right)A_1(q^2) \mp \frac{2m_B\left|\vec{p}_V\right|}{m_B + m_V}V(q^2) \qquad (13)$$

$$H_s(q^2) = \frac{2m_B\left|p^*_{D^*}\right|}{\sqrt{q^2}}A_0\left(q^2\right) \qquad (15)$$

where H_i are the helicity amplitudes that are functions of formfactors

$$H_0(q^2) = \frac{m_B + m_V}{2m_V\sqrt{q^2}}\left[\left(m_B^2 - m_V^2 - q^2\right)A_1(q^2) - \frac{4m_B^2\left|\vec{p}_V\right|^2}{\left(m_B + m_V\right)^2}A_2(q^2)\right] \qquad (14)$$

- Charged Higgs decays may enhance the decay rate

- In the 2Higgs Doublet Model (2HDM) type II the decay rate is multiplied by

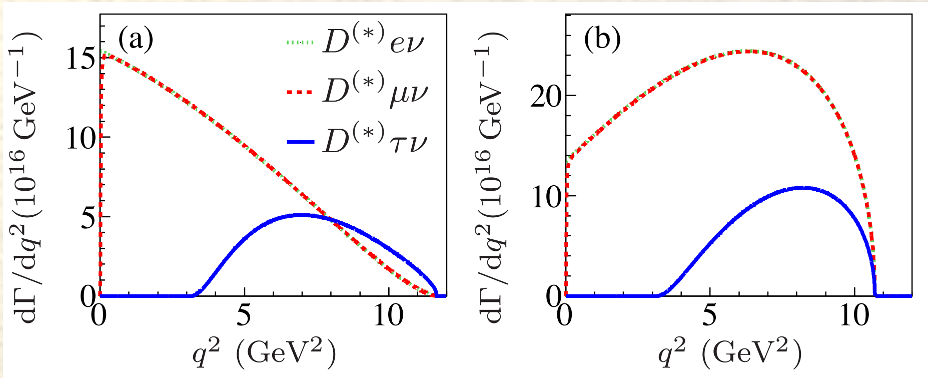
$$\left(1 - \frac{\tan^2\beta}{m_{H^\pm}^2}\frac{q^2}{1 \mp \frac{m_c}{m_b}}\right)^2 \qquad (16)$$

where β is the ratio of the VEVs of the 2 doublets

B→Dτν Higgs Contribution

- B→D(*)τν may get sizable contributions from H^- compared to B→D(*)μν due to the large τ mass that also reduces the B→D(*)τν phase space

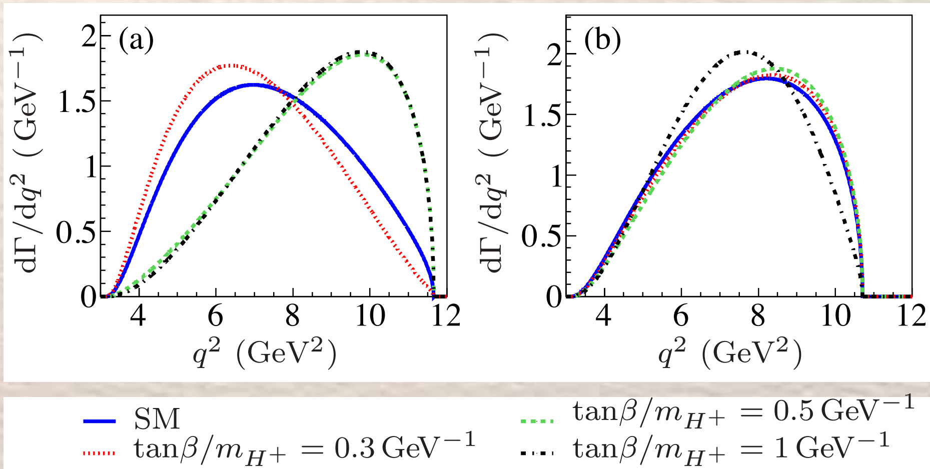
- The shape of the q^2 spectrum is modified by $H^\pm$ contributions



- The strategy is to measure the ratios

$$R(D) = \frac{\mathcal{B}\left(\bar{B} \to D\tau^-\bar{\nu}\right)}{\mathcal{B}\left(\bar{B} \to D\ell^-\bar{\nu}\right)} \qquad \ell = e,\mu$$

$$R(D^*) = \frac{\mathcal{B}\left(\bar{B} \to D^*\tau^-\bar{\nu}\right)}{\mathcal{B}\left(\bar{B} \to D^*\ell^-\bar{\nu}\right)}$$



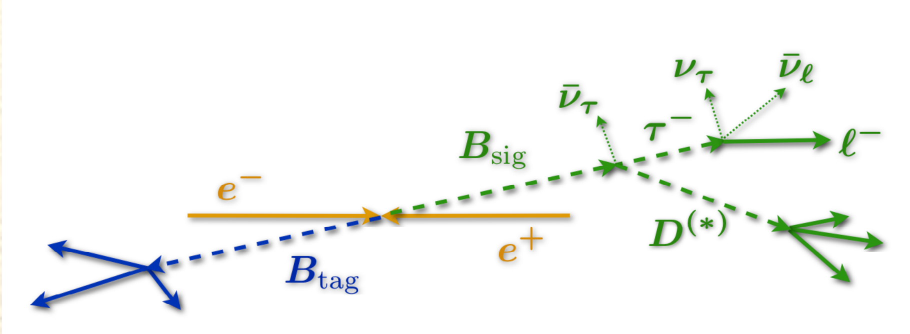
- The ratios are independent of $|V_{cb}|$ & to a large extent to hadronic matrix elements

- In the SM

$$R(D) = 0.297 \pm 0.017 \qquad R(D^*) = 0.252 \pm 0.003$$

$B \to D\tau\nu$ Analysis

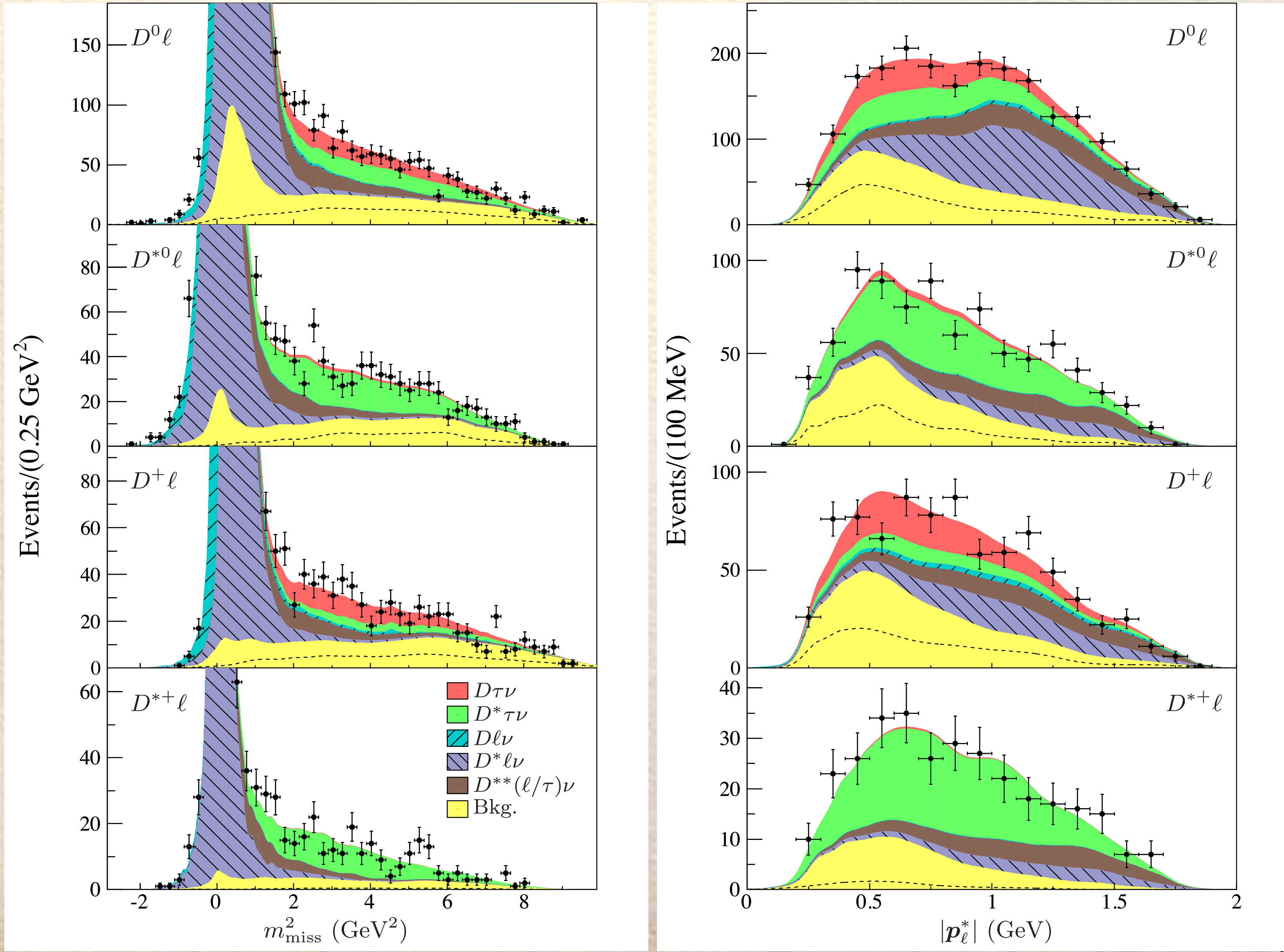
- Experimentally, we reconstruct one B in a hadronic final state using 2968 individual modes, called B_{tag}



- For each B_{tag}, we look for a semileptonic decay, i.e. a lepton and a D or D^*
- We reconstruct the τ only in leptonic decays, ➔ get signal and normalization modes
- The D^0 (D^+) is reconstructed in 5 (7) final states, the D^{*+} in $D^0\,\pi^+$, $D^+\pi^0$ and D^{*0} in $D^0\,\pi^0$, $D^0\gamma$
- Backgrounds originate from $B \to D^{**}\tau/\ell\nu$, generic BB and qq continuum
- For signal events, there are three neutrinos ➔ we look at various kinematic observables: q^2, p_l (lepton momentum), m^2_{miss} (missing mass squared), $\Delta E = E_{tag} - E_{beam}$, $m_{ES} = (E2_{beam} - p2_{tag})1/2$, E_{extra} (extra neutral E in calormeter)

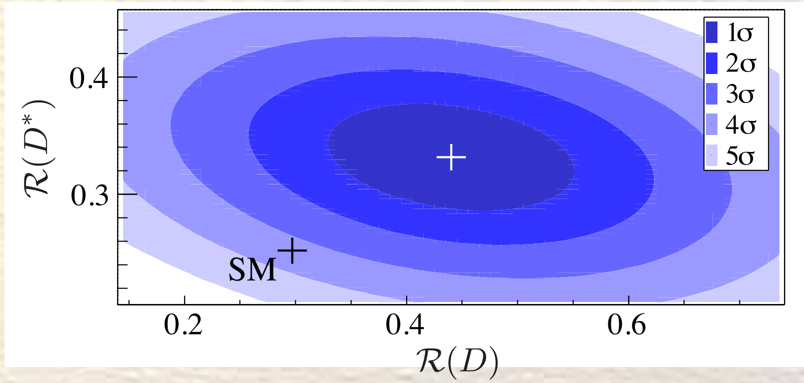
B→Dτν m^2_{miss} and p_ℓ Distributions

- 4 final states
  - $D^0\ell$
  - $D^{*0}\ell$
  - $D^+\ell$
  - $D^{*+}\ell$

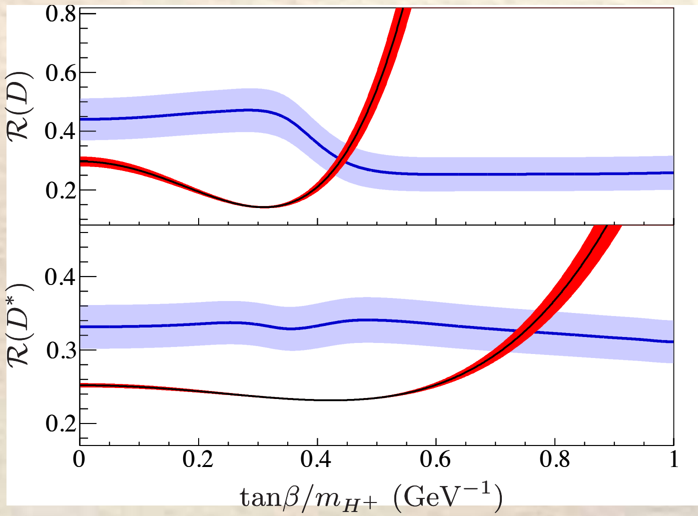


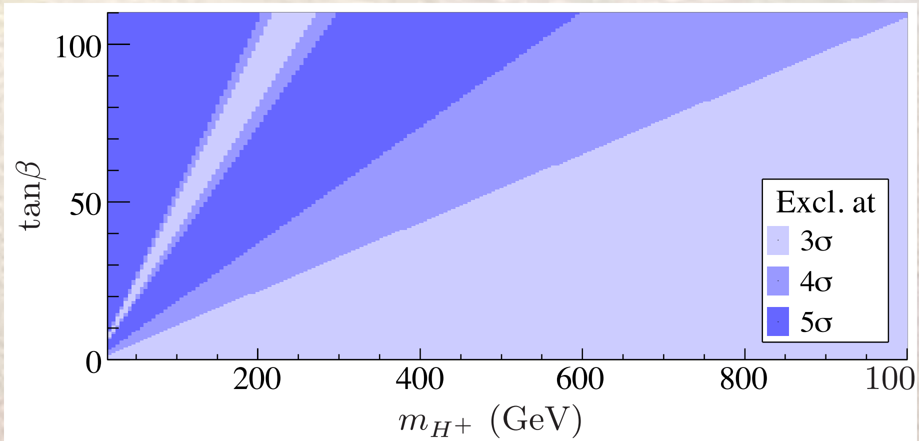
B→Dτν Implications on 2HDM

- Measure **R(D) = 0.440 ± 0.058 ± 0.042** **R(D*) = 0.332 ± 0.024 ± 0.018**
- This is much higher than the SM prediction, disagreement of R(D) and R(D*) with the SM is 3.4σ



- We can compare the measurements with the predictions of 2HDM





- The combination of R(D) and R(D*) excludes 2HDM, since allowed regions 0.44±0.02 GeV-1 and 0.75±0.02 GeV-1 do not overlap
- The type III 2HDM still has two solutions

$B \rightarrow D\tau\nu$

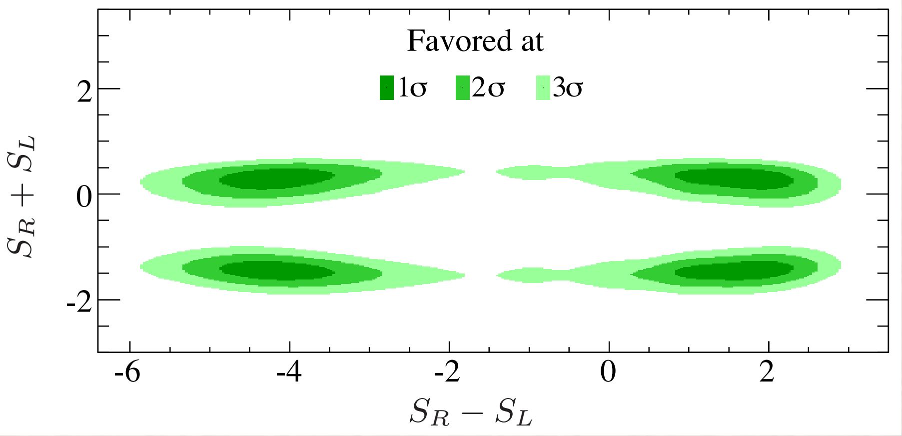
- Lets look at a type III 2HDM including scalar and pseudoscalar contributions

$$H_{eff} = \frac{4G_F V_{cb}}{\sqrt{2}}\Big[\left(\bar{c}\gamma_\mu P_L b\right)\left(\bar{\tau}\gamma^\mu P_L \nu_\tau\right) + S_L\left(\bar{c}P_L b\right)\left(\bar{\tau}P_L\nu_\tau\right) + S_R\left(\bar{c}P_R b\right)\left(\bar{\tau}P_R\nu_\tau\right)\Big] \quad (17)$$

- This modifies R(D) and R(D*)

$$R(D) = R(D)_{SM} + A'_D \,\mathrm{Re}(S_R + S_L) + B'_D \left|S_R + S_L\right|^2 \quad (18)$$

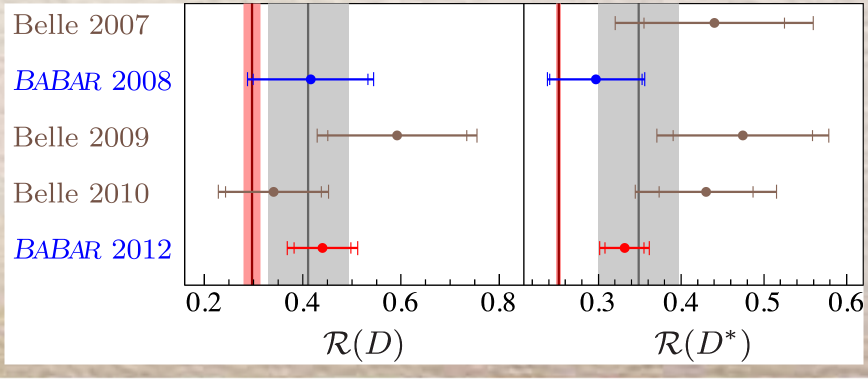
$$R(D^*) = R(D^*)_{SM} + A'_{D^*} \,\mathrm{Re}(S_R - S_L) + B'_{D^*} \left|S_R - S_L\right|^2 \quad (19)$$



- There are 4 solutions, the q^2 spectra disfavor those at $S_R+S_L=-1.5$

- BABAR results are in good agreement with other measurements

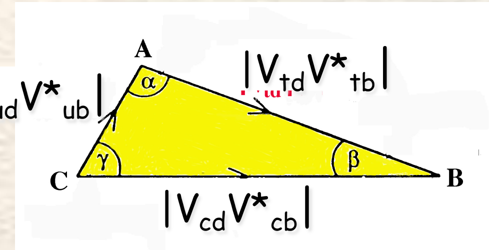
- Is this a hint for new physics?



Unitarity Conditions of the CKM Matrix

- CP asymmetries in B0 decays into CP eigenstates provide a good way to measure the 3 angles of the Unitarity Triangle, defined by

$$\alpha \equiv Arg\left(-\frac{V_{td}V^*_{tb}}{V_{ud}V^*_{ub}}\right), \quad \beta \equiv Arg\left(-\frac{V_{cd}V^*_{cb}}{V_{td}V^*_{tb}}\right), \quad \gamma \equiv Arg\left(-\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right)$$

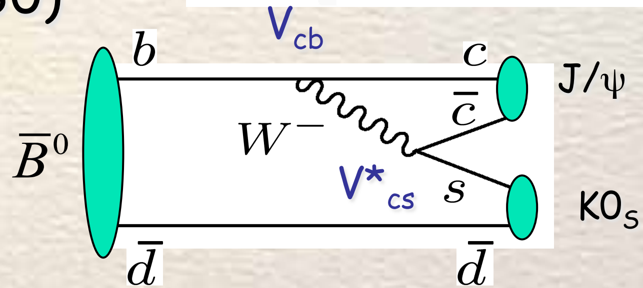


- Lets consider some examples

(30)

$B \rightarrow J/\psi K^0_s$:

$$\lambda_{\psi K^0_S} = \left(\frac{V^*_{tb}V_{td}}{V_{tb}V^*_{td}}\right)\left(\frac{\cancel{V^*_{cs}}V_{cb}}{\cancel{V_{cs}}V^*_{cb}}\right)\left(\frac{V^*_{cd}\cancel{V_{cs}}}{V_{cd}\cancel{V^*_{cs}}}\right) \Rightarrow \Im m\lambda = -\sin 2\beta$$

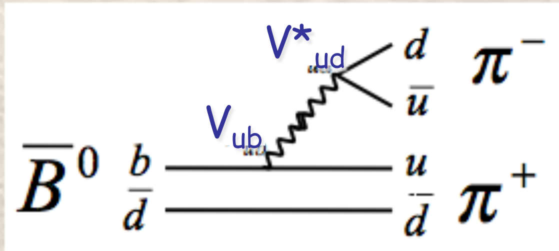


$B \rightarrow \pi^+\pi^-$:

(31)

$$\lambda_{\pi\pi} = \left(\frac{V^*_{tb}V_{td}}{V_{tb}V^*_{td}}\right)\left(\frac{V^*_{ud}V_{ub}}{V_{ud}V^*_{ub}}\right) \Rightarrow \Im m\lambda = \sin 2\alpha$$

(32)



- Measurement of γ is more complicated (see later)

- The goal is to make many independent measurements of both sides and angles of the Unitarity Triangle to overconstrain it ➔ test SM

CP Violation in the B System

- There are many useful constraints from B and K decays

$$R_u = \left|\frac{V_{ud}^* V_{ub}}{V_{cd}^* V_{cb}}\right| = \sqrt{\bar{\rho}^2 + \bar{\eta}^2}$$

➔ small blue circle

$$R_t = \left|\frac{V_{td}^* V_{tb}}{V_{cd}^* V_{cb}}\right| = \sqrt{(1-\bar{\rho})^2 + \bar{\eta}^2}$$

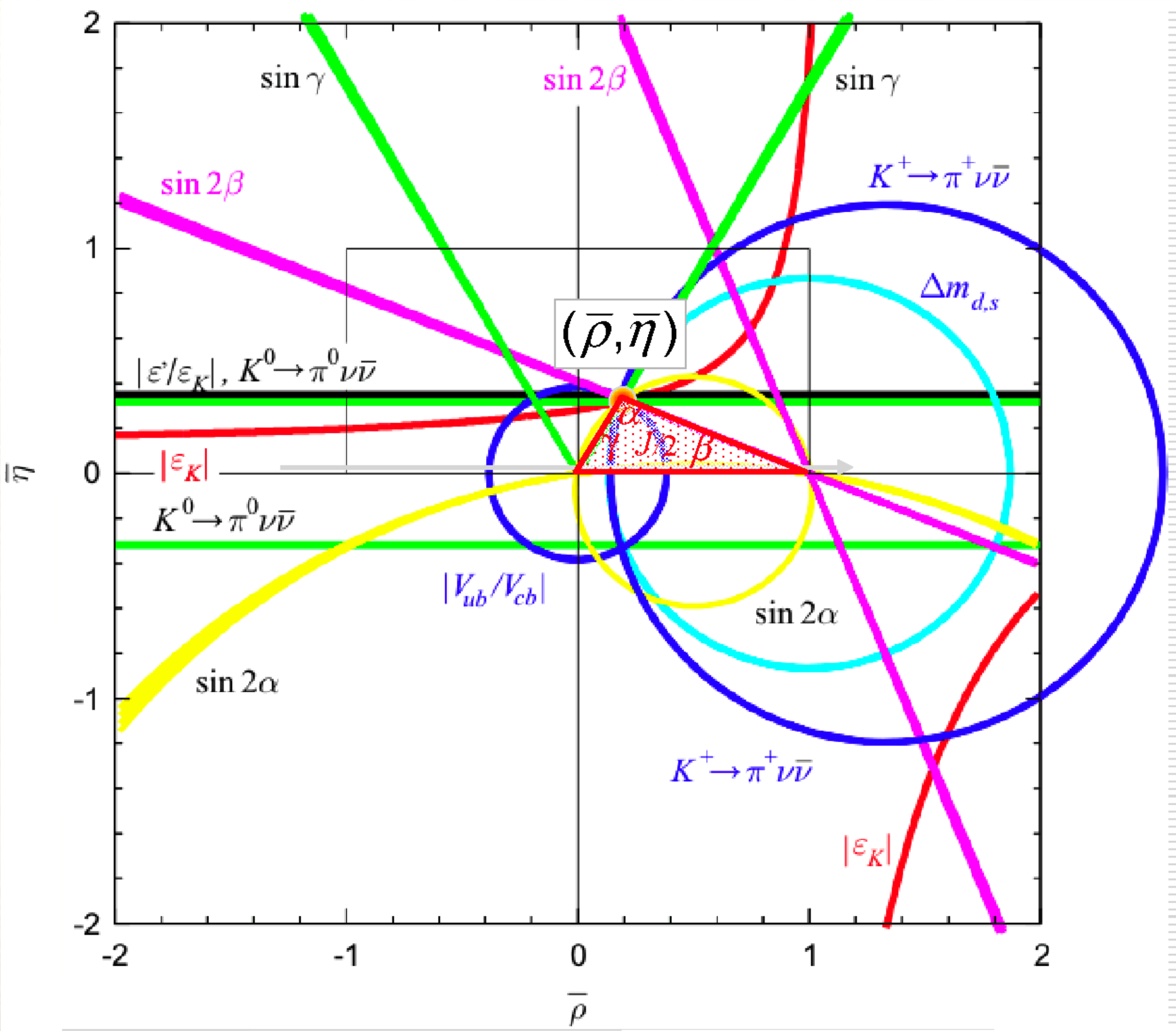
➔ cyan circle

$$\sin 2\alpha = \frac{2\bar{\eta}\left[R_u^2 - \bar{\rho}\right]}{R_t^2 R_u^2}$$

➔ yellow circles

$$\sin 2\beta = \frac{2\bar{\eta}\left[1 - \bar{\rho}\right]}{R_t^2}$$

➔ magenta rays

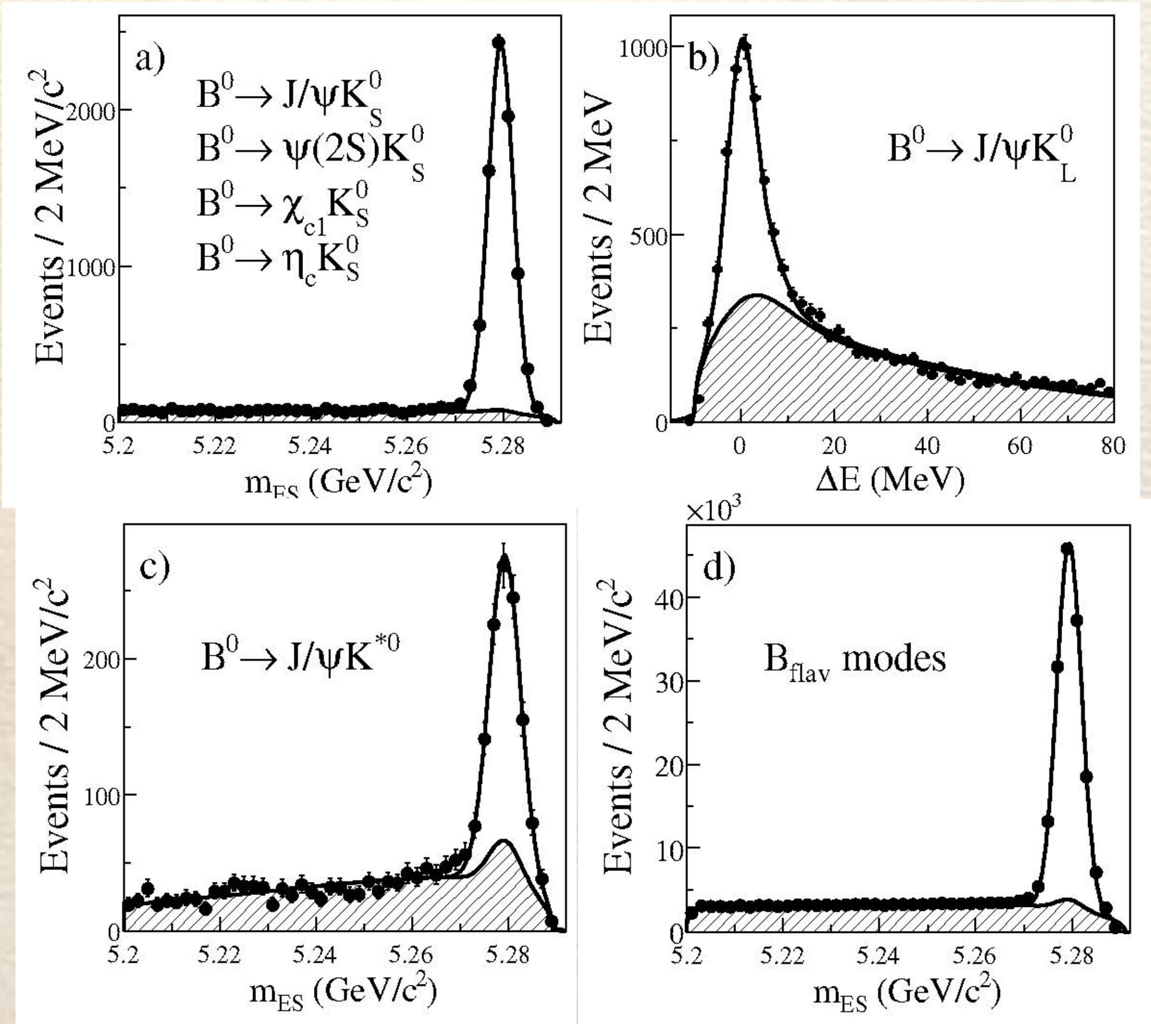


CP Violation in the B System

- We measured different samples

9377 tagged events

5813 tagged events



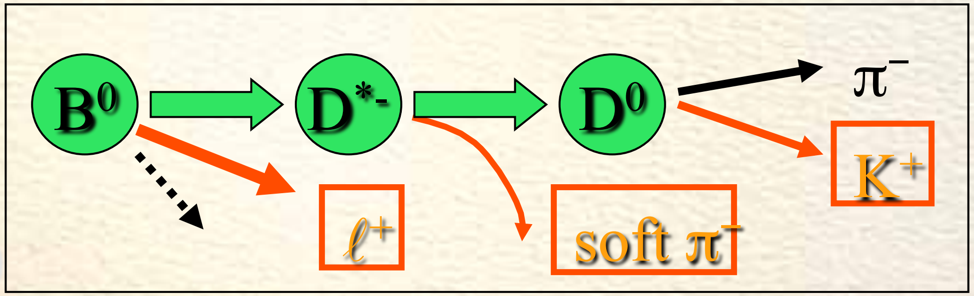
1291tagged events

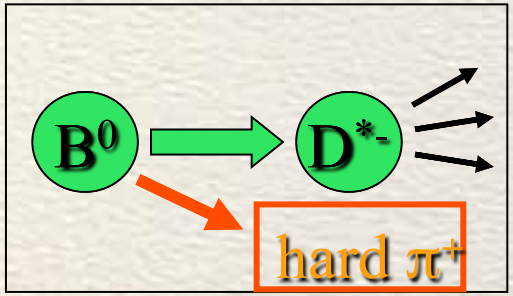
166276 flavor tags

- Control sample has the same mistag rate and Δt resolution as *CP* sample
  (Δt error dominated by recoil side) ➔ use in fit as well

Tagging and Δt Reconstruction

- Tag 2nd B by





- Tagging quality

$$Q = \varepsilon(1-2\omega)^2 \quad (33)$$

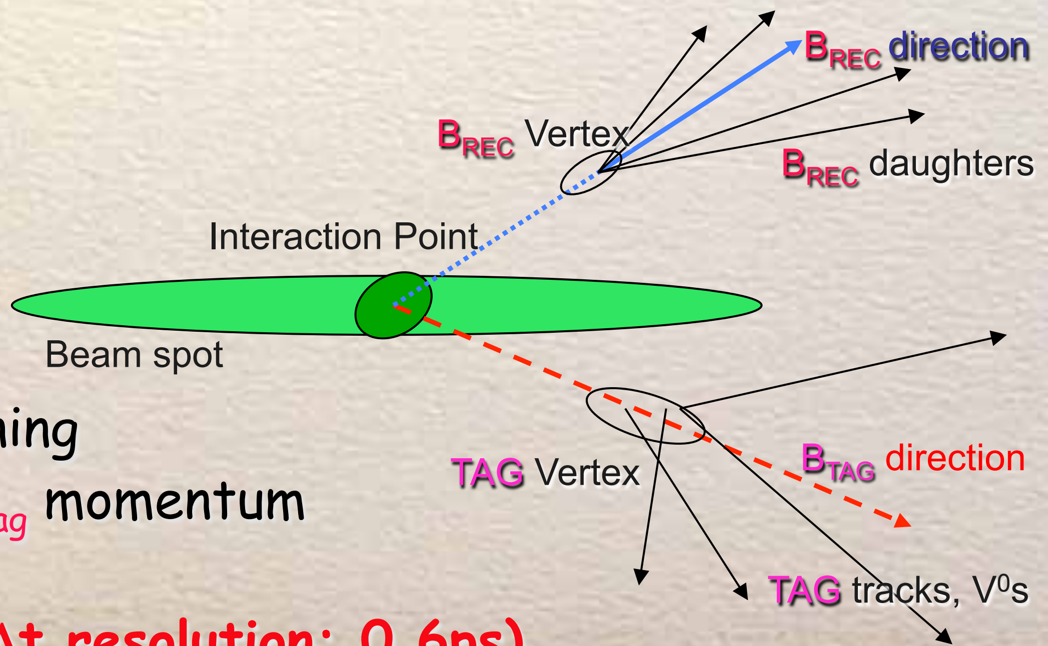
- Error on sin2β depends on tagging quality

$$\sigma(\sin 2\beta) \propto \frac{1}{\sqrt{Q}} \quad (34)$$

- Error on sin2β depends on tagging quality: Q=31.2±0.3%, ε=(74.37±0.1)%
- Δt reconstruction:
- Get B_{rec} vertex from charged daughter tracks

$\sigma_z(B_{rec})$=65 μm ➲ B_{rec} momentum

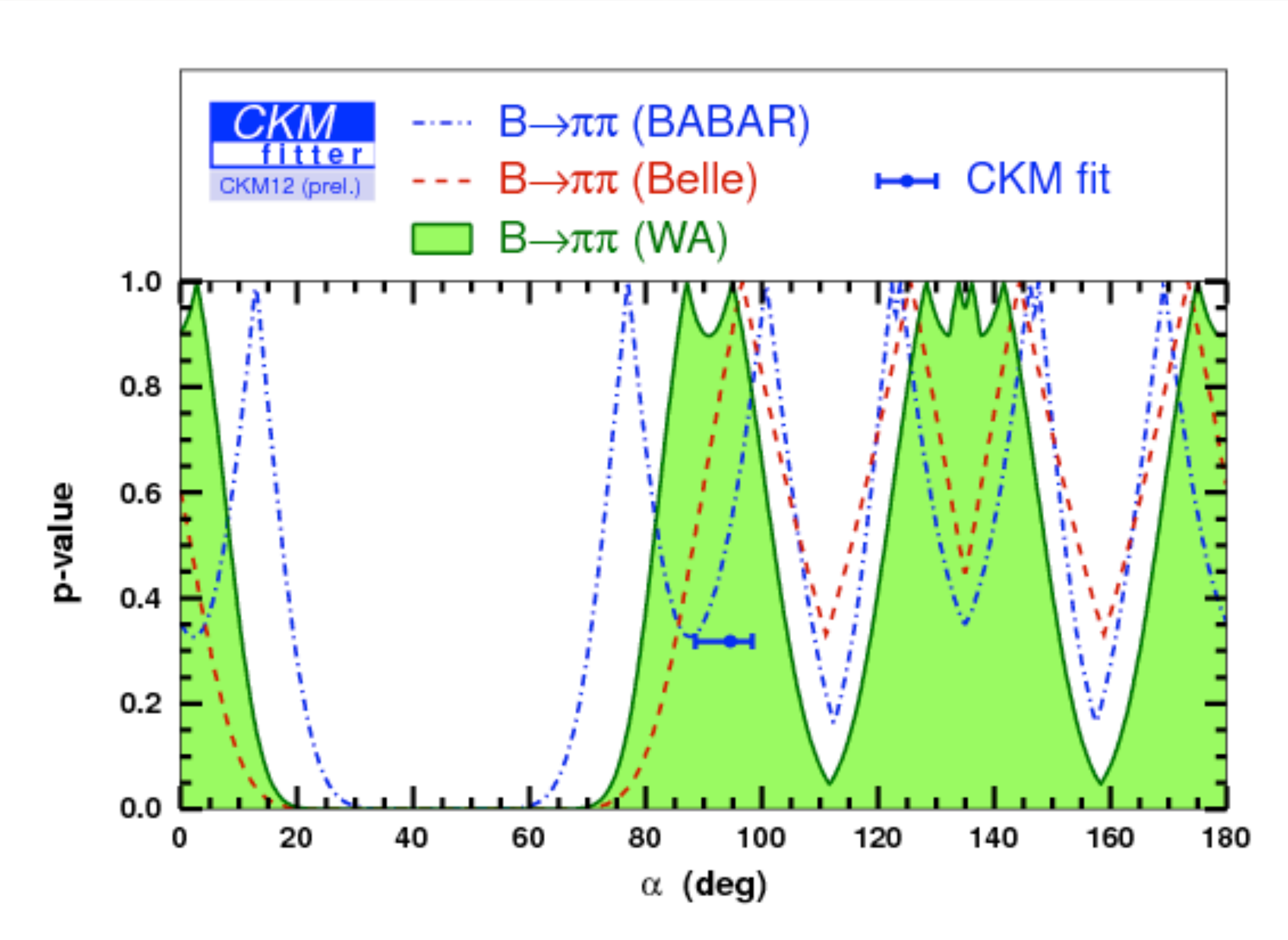
- Determine B_{tag} vertex from remaining charged tracks ➲ B_{tag} vertex & B_{tag} momentum



Average Δz resolution: 180 μm (Δt resolution: 0.6ps)

Extraction of α from $B \to \pi\pi$

- Use as inputs:
  $\mathcal{B}(B0 \to \pi+\pi-)$
  $\mathcal{B}(B0 \to \pi0\pi0)$
  $\mathcal{B}(B\pm \to \pi\pm\pi0)$
  $S_{\pi+\pi-}$
  $C_{\pi+\pi-}$
  $C_{\pi0\pi0}$



- For $B \to \pi\pi$ obtain no stringent constraint on α
  ➔ Need either also measurements from $B \to \rho\pi$, $B \to \rho\rho$, & $B \to a_1\pi$
  ➔ or need to combine all measured $B \to PP$ modes

Direct CP Violation in $B \rightarrow X_s\gamma$

- In the SM, direct CP violation in $B \rightarrow X_s\gamma$ is predicted to be small: $-0.6\% < \mathcal{A}_{CP}(X_s\gamma) < 2.8\%$
- Its measurement is performed by using exclusive self-tagging decays
- Using 16 such modes in a sample of 471×10^6 $B\bar{B}$ events, BABAR measured

$$\boxed{\mathcal{A}_{CP}(X_s\gamma) = \left(1.7 \pm 1.9_{stat} \pm 1.0_{sys}\right)\%}$$

➔ most precise $\mathcal{A}_{CP}$ result

arXiv:1406.0534

- The difference for charged and neutral B decays is

$$\boxed{\Delta\mathcal{A}_{CP}(X_s\gamma) = \mathcal{A}_{CP}(B^+ \rightarrow X_s^+\gamma) - \mathcal{A}_{CP}(B^0 \rightarrow X_s^0\gamma)}$$

- $\Delta\mathcal{A}_{CP}(B \rightarrow X_s\gamma)$ depends on $C_{7\gamma}$ and C_{8g}:

$$\boxed{\Delta\mathcal{A}_{CP}(X_s\gamma) \approx 4\pi^2\alpha_s \frac{\bar{\Lambda}_{78}}{m_b} \Im m \frac{C_8^{eff}}{C_7^{eff}} \approx 0.12 \frac{\bar{\Lambda}_{78}}{100\text{ MeV}} \Im m \frac{C_8^{eff}}{C_7^{eff}}}$$

$$\boxed{17\text{ MeV} < \bar{\Lambda}_{78} < 190\text{ MeV}}$$

Benzke *et al.*, PRL106, 141801 (2011)

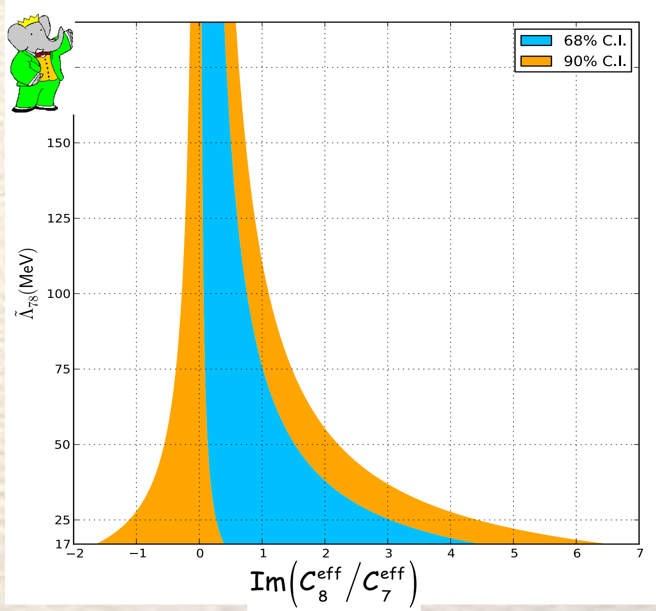
- In the SM, C_7^{eff} and C_8^{eff} are real ➔ $\Delta\mathcal{A}_{CP}(X_s\gamma)=0$
  - This may be modified by new physics contributions
- BABAR measures $\boxed{\Delta\mathcal{A}_{CP}(X_s\gamma) = \left(5.0 \pm 3.9_{stat} \pm 1.5_{sys}\right)\%}$ ➔ first $\Delta\mathcal{A}_{CP}(B \rightarrow X_s\gamma)$ result

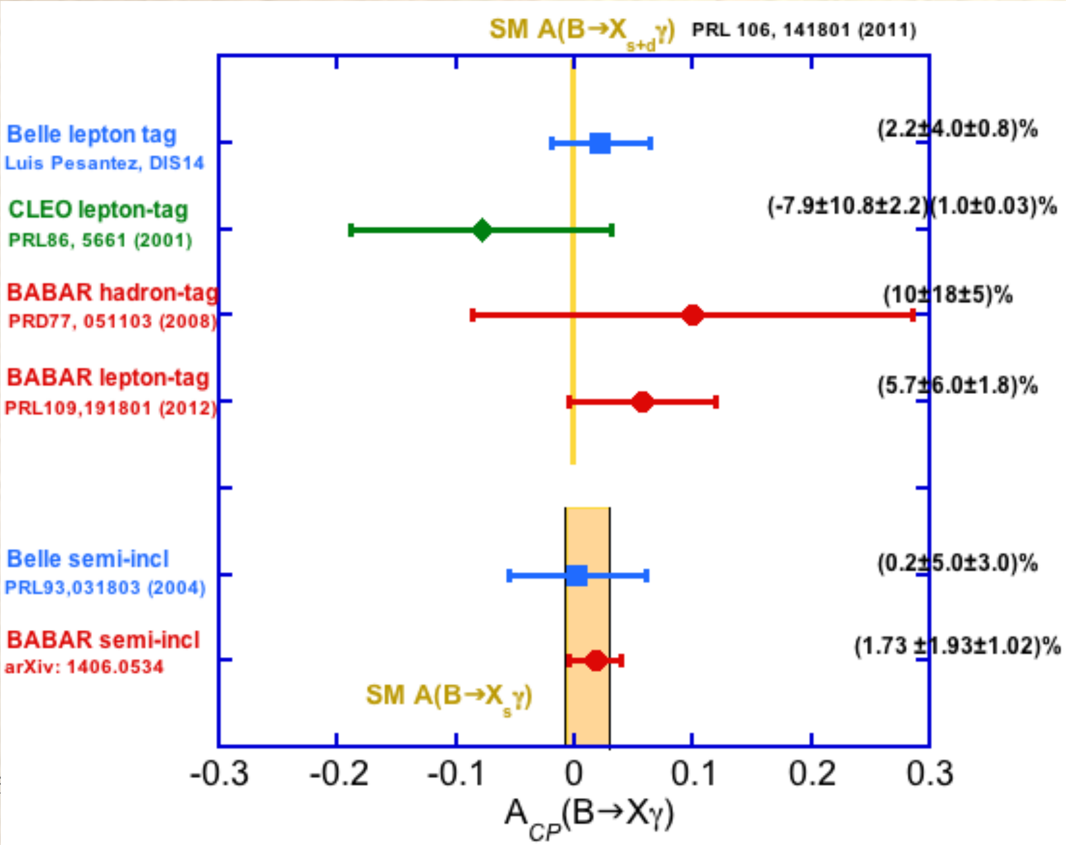
Direct CP Violation in $B \to X_s \gamma$

- This yields a 90% CL constraints on $\mathcal{I}m\,(C_8^{eff}/C_7^{eff})$

$$\boxed{-1.64 < \mathrm{Im}\left(C_8^{eff}/C_7^{eff}\right) < 6.52 \text{ @90\% CL}}$$

- This is the first constraint on the ratio of Wilson coefficients C_8^{eff}/C_7^{eff} in this process



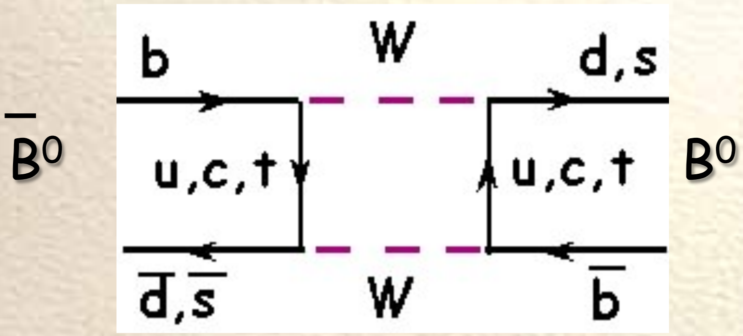


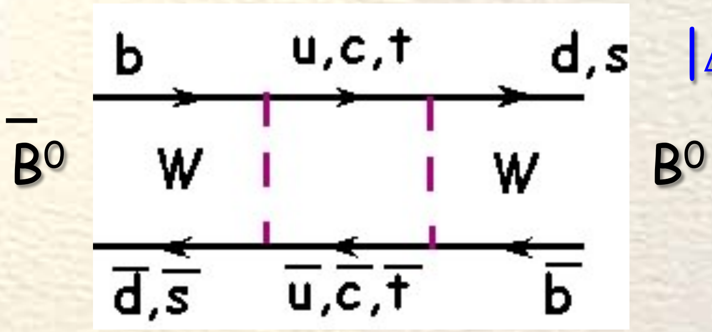
- In the fully inclusive analysis, $\mathcal{A}_{CP}$ *has* $b \to s\gamma$ & $b \to d\gamma$ contributions
- In the SM, $\mathcal{A}_{CP}(B \to X_{s+d})=0$
- Determine B/$\overline{\mathrm{B}}$ from charge of tag
- *All results agree well with the SM*

B^0-$\overline{B^0}$ Mixing

$B^0\bar{B}^0$ Mixing

- B^0_d and B^0_s can oscillate into their antiparticles $\bar{B}^0_d$ and $\bar{B}^0_s$, respectively





$|\Delta B|=2$ transition

box diagrams

- The Hamiltonian of the $B^0\bar{B}^0$ system has a mass matrix M and a decay matrix Γ
  ➔ M corresponds to a phase in the wave function while Γ corresponds to a probability density, which decays exponentially with time and has the characteristic decay width

- By diagonalizing the Hamiltonian, we obtain 2 *CP* eigenstates whose
- masses differ by

$$\Delta M = 2\Re e\sqrt{\left(M_{12} - \tfrac{1}{2}\Gamma_{12}\right)\left(M^*_{12} - \tfrac{1}{2}\Gamma^*_{12}\right)} \quad (20)$$

where M_{12} & Γ_{12} are the off diagonal matrix elements of M and Γ, respectively

- For B^0_d, $\Gamma_{12}\approx 0$

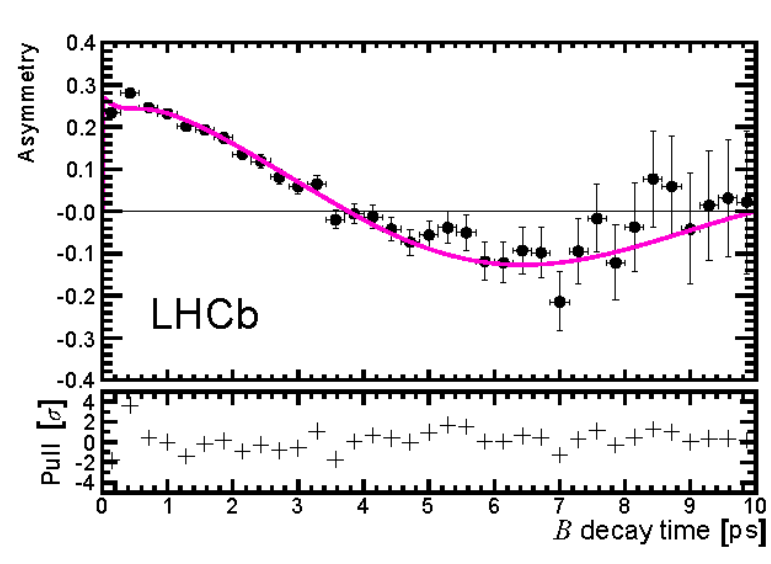
$B^0_d\,\overline{B^0}_d$ and $B^0_s\,\overline{B^0}_s$ Oscillation

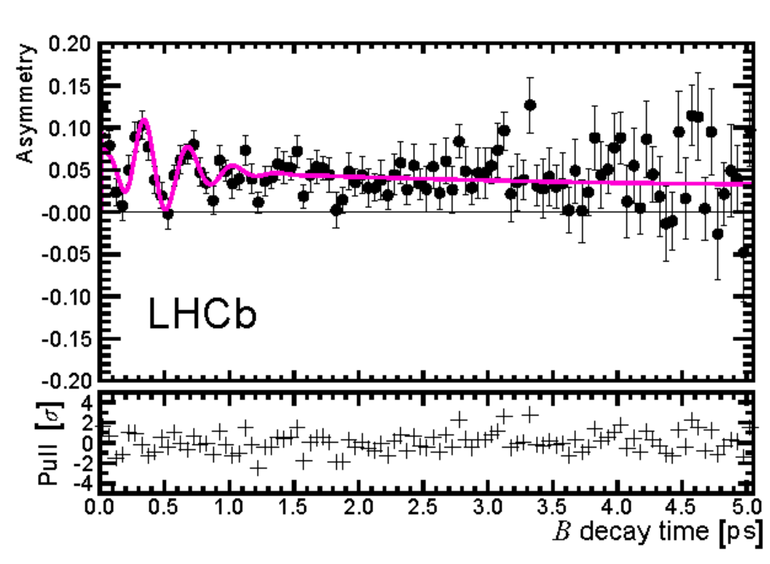
- For a top quark in the box diagram, the $|\Delta B|=2$ weak Hamiltonian yields a mass difference of

$$\Delta M = \frac{G_F}{6\pi^2} B_B f_B^2 m_B \left|V_{td}^* V_{tb}\right|^2 M_W^2 S_0(x_t)\eta_B \qquad (21)$$

where G_F is the Fermi constant, f_B is the B^0_d decay constant, B_B is the bag factor, V_{tb} and V_{td} are CKM matrix elements, m_B is the B^0_d mass, M_W is the W boson mass, $S_0(m_t^2/M_W^2)$ is the function of the box, m_t is the top quark mass and η_B is a QCD factor ➔ f_B & B_B have theory uncertainties

- For B^0_s, ΔM is gotten from eq (21) by replacing f_B, B_B, m_B, and $|V^*_{td}V_{tb}|^2$ with the corresponding B^0_s quantities





$B^0\overline{B}^0$ Mixing Measurements

- For B^0_d, the world average for ΔM is

$$\Delta M_{B^0_d} = (0.51 \pm 0.004)\ ps^{-1}$$

- For B^0_s, the world average for ΔM is

$$\Delta M_{B^0_s} = 17.671 \pm 0.022\ ps^{-1}$$