Recent Results from Belle: chipping away at the Standard Model

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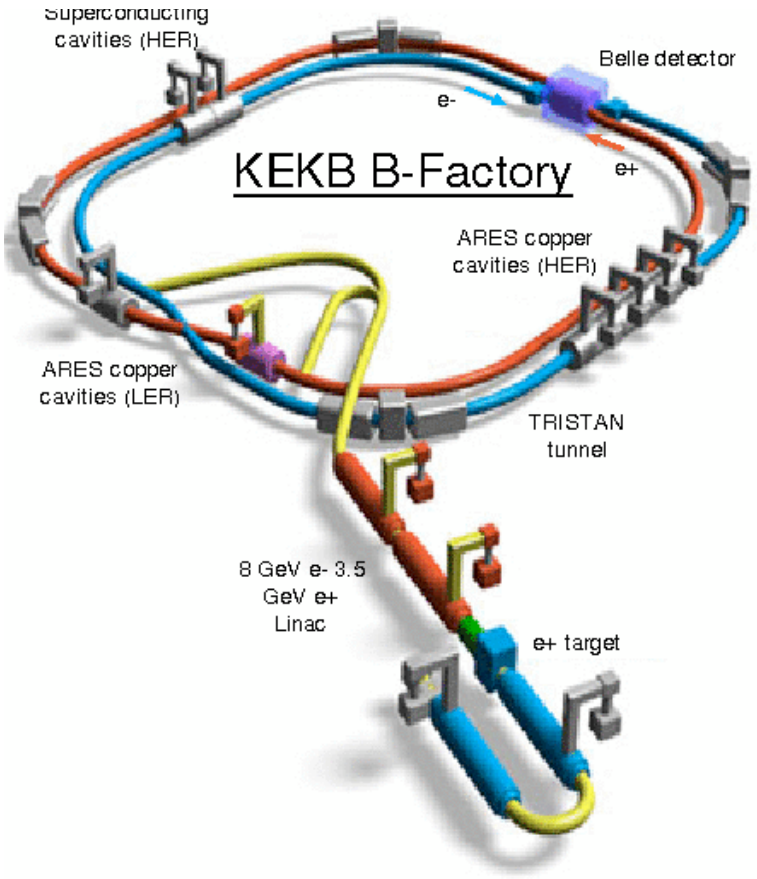
Topics: *(all recent, potential NP, not easy at LHC)*

- $B^+ \to \tau^+ \nu$, $B^+ \to D^* \tau^+ \nu$ *(charged Higgs)*
- $B \to X_s \gamma$ *(charged Higgs)*
- $B \to K^{(*)} \ell^+ \ell^-$ *(Wilson coefficients)*
- $B^0 \to K^0 \pi^0$ *(CKM ϕ_1, direct CPV)*
- $B \to X_u \ell^+ \nu$ *(CKM $|V_{ub}|$)*

The Belle experiment (@ KEKB)

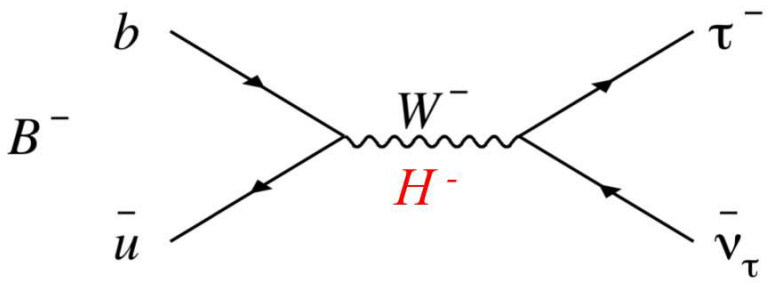
$e^+e^- \rightarrow \Upsilon(4S)$ $\Upsilon(5S)$ $\Upsilon(2S)$ $\rightarrow BB$



$\Upsilon(4S)$ 711 fb^{-1}
$\Upsilon(5S)$ 110 fb^{-1}
$\Upsilon(2S)$ 26 fb^{-1}
off peak 90 fb^{-1}
total ~1000 fb^{-1}

$B^+ \to \tau^+ \nu$:

Adachi et al., arXiv:0809.3834;
Ikado et al., PRL 97 251802 (1996) ← *first evidence, 3.5σ*



B meson decay constant, characterizes B wave-function at the origin

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

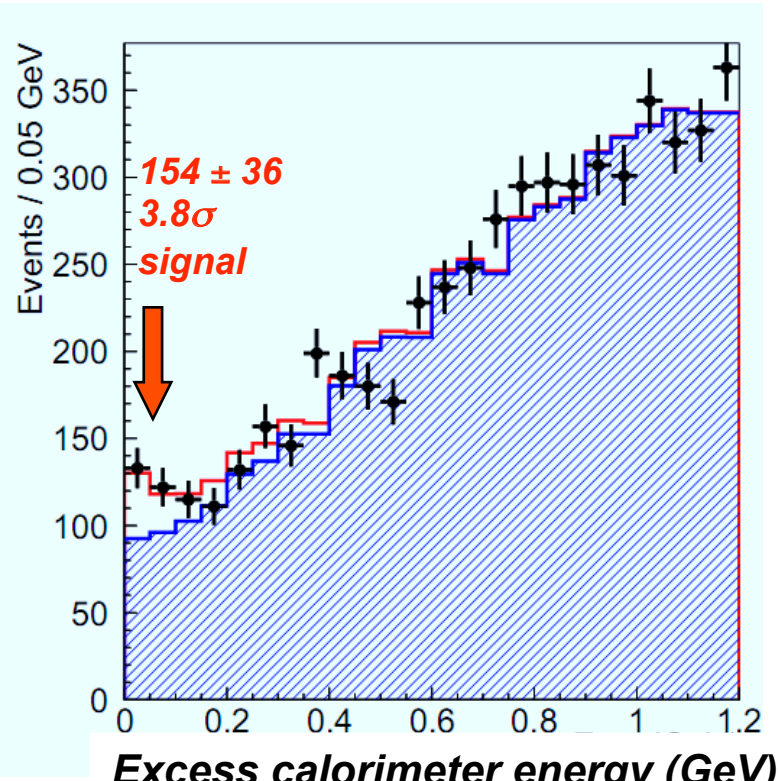
- ***Semileptonic tag:***

$B^+ \to D^{(*)0} \ell^+ \nu$, $D^{*0} \to D^0 \gamma$, $D^0 \pi^0$ $D^0 \to K\pi$, $K\pi\pi^0$, $K\pi\pi\pi$
$\tau \to \mu\nu\nu$, $e\nu\nu$, $\pi\nu$ (1 charged track) in signal hemisphere

- *Dominant backgrounds are $b \to c$ ($B\bar{B}$) and continuum*

- *Signal is obtained by fitting the ECL (electromagnetic calorimeter energy) distribution: peak new zero indicates $\tau \to \ell\nu\nu$, $\pi\nu$ decay.*

- *ECL simulation is validated with identically tagged $B^+ \to D^{(*)0} \ell^+ \nu$ control sample*



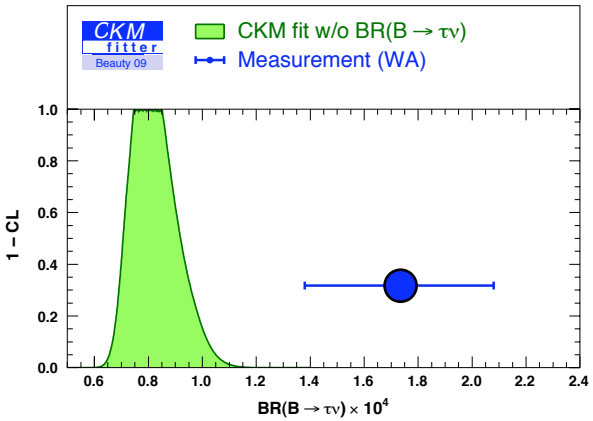
$B^+ \to \tau^+ \nu$

Adachi et al., arXiv:0809.3834;
Ikado et al., PRL 97 251802 (1996)

Belle semileptonic tag: $\mathcal{B}(B \to \tau\upsilon) = (1.65^{+0.38+0.35}_{-0.37-0.37}) \times 10^{-4}$

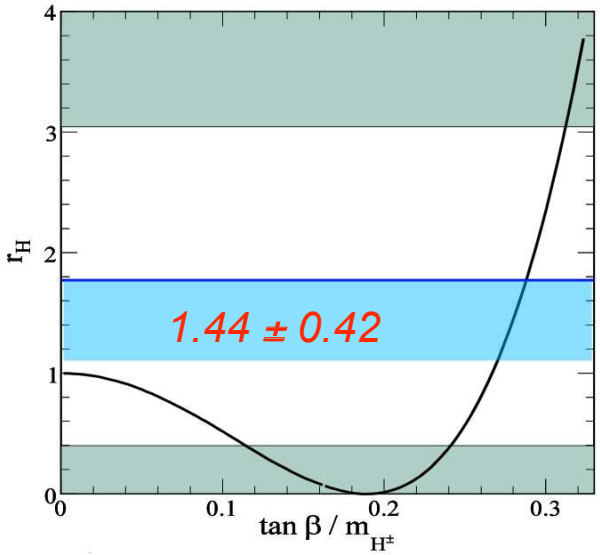
World average: $\mathcal{B}(B^+ \to \tau^+ \nu) = (1.73 \pm 0.35) \times 10^{-4}$

2.4σ discrepancy with the value predicted by the CKM fit:



Divide by $\mathcal{B}_{SM} = (1.20 \pm 0.25) \times 10^{-4}$ *to calculate*
$r_H = \mathcal{B}_{measured} / \mathcal{B}_{SM} = 1.44 \pm 0.42$

2-Higgs doublet model: $r_H = (1 - \frac{m_B^2}{m_H^2} \tan^2 \beta)^2$



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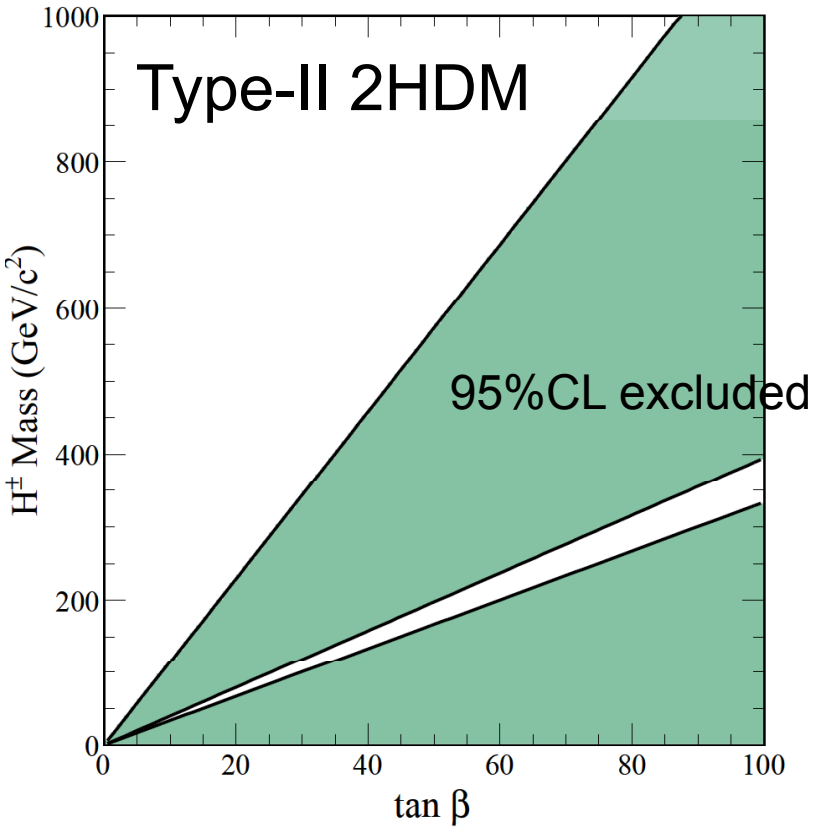
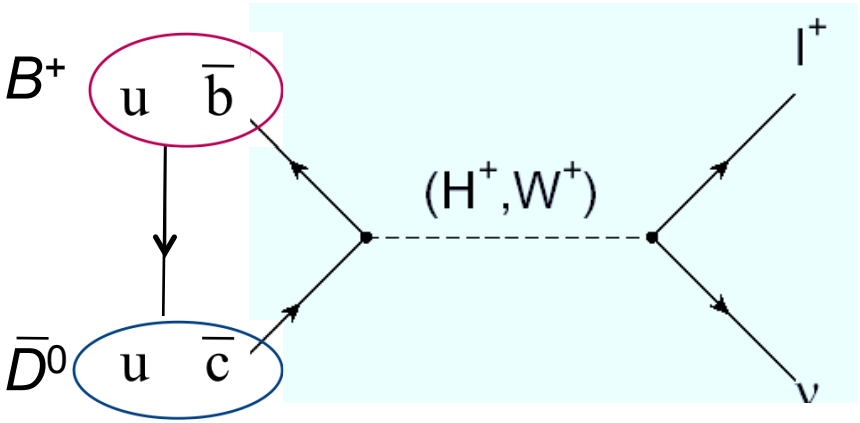


$B \to D^{(*)}\tau^+\nu$

605 fb^{-1}: Adachi et al., arXiv:0910.4301



$$M_{bc} \equiv \sqrt{E^2_{\rm beam} - p^2_B}$$
$$\Delta E \equiv E_B - E_{\rm beam}$$

- **Full reconstruction tag:**

$B^- \to$, $D^{(*)0}\pi^-$, $D^{(*)0}\rho^-$, $D^{(*)0}a_1^-$, $D^{(*)0}D_s^-$
$B^0 \to$, $D^{(*)+}\pi^-$, $D^{(*)+}\rho^-$, $D^{(*)+}a_1^-$, $D^{(*)+}D_s^-$
$D^{*0} \to D^0\gamma$, $D^0\pi^0$
$D^{*+} \to D^0\pi^+$, $D^+\pi^0$
$D^0 \to K^-\pi$, $K^-\pi\pi^0$, $K^-\pi\pi\pi$, $K_S\pi^0$, $K_S\pi\pi$, $K_S\pi\pi\pi^0$, K^+K^-
$D^+ \to K^-\pi^+\pi^+$, $K^-\pi\pi\pi^0$, $K_S\pi^-$, $K_S\pi\pi^0$, $K_S\pi\pi\pi$, $K^+K^-\pi^-$
$D_s^+ \to K^-K^+\pi^+$, K_SK^+

$5.27 < M_{bc} < 5.29$ GeV/c^2, $-0.08 < \Delta E < 0.06$ GeV

- **Signal hemisphere:**

$\tau \to \mu\nu\nu$, $e\nu\nu$
$D^0 \to K^-\pi$, $K^-\pi\pi^0$, $K^-\pi\pi\pi$, $K_S\pi^0$, $K_S\pi\pi$, $K_S\pi\pi\pi^0$
$D^+ \to K^-\pi^+\pi^+$, $K^-\pi\pi\pi^0$, $K_S\pi^-$

Fitting variables {

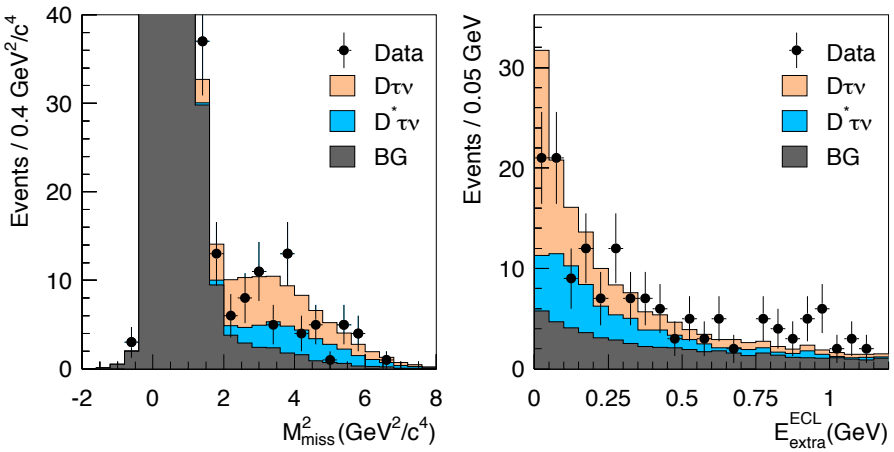
- cut on $M^2_{miss} = (E_{tag}-E_D-E_\tau)^2-(-\mathbf{p}_{tag}-\mathbf{p}_D-\mathbf{p}_\tau)^2$
- cut on E^{ECL}_{extra} (γ's not associated with signal or tag decay)
- cut on $p^{CM}_{e/\mu}$
- No extra tracks or π^0's

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

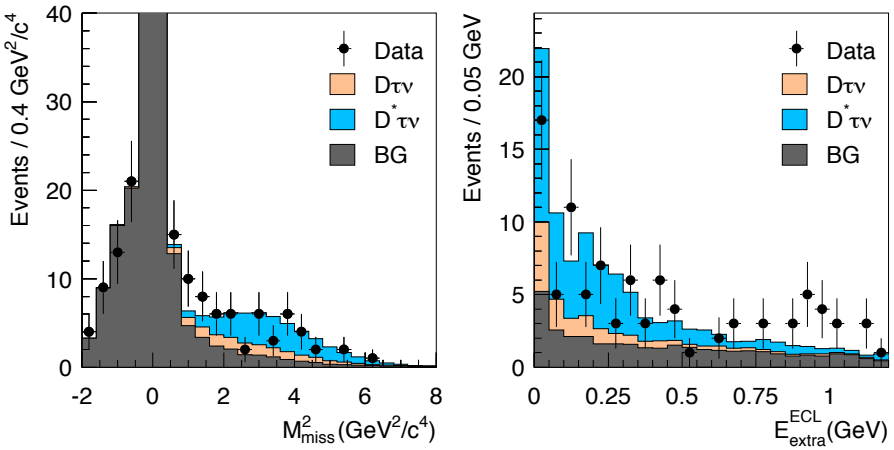
605 fb^{-1}: Adachi et al., arXiv:0910.4301

2D fit results for signal:

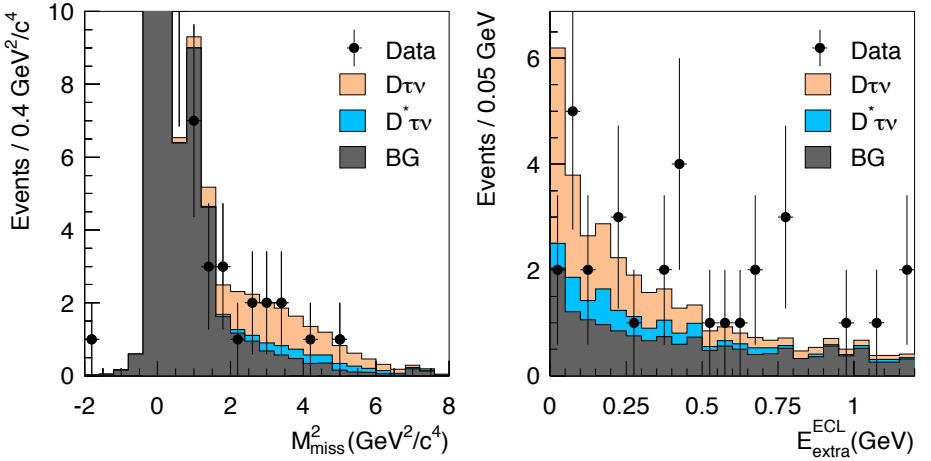
$B^+ \to D^0\tau^+\nu$ (Y=98.6)



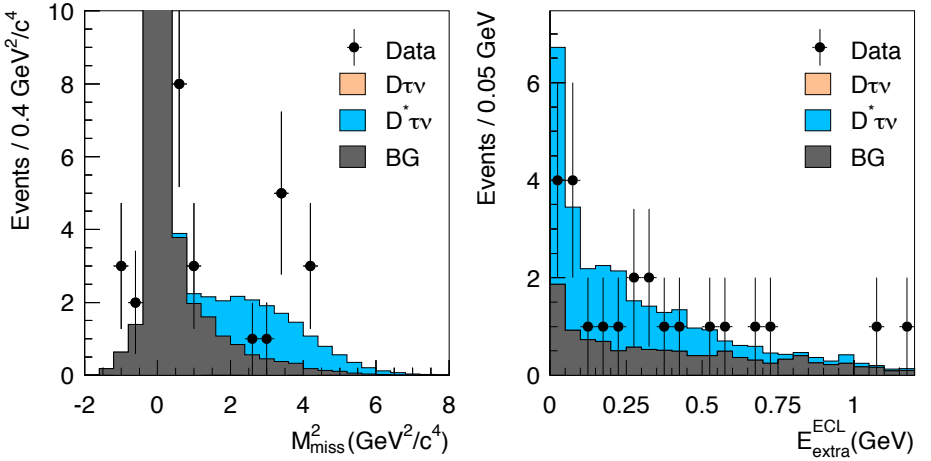
$B^+ \to D^{*0}\tau^+\nu$ (Y=99.8)



$B^0 \to D^-\tau^+\nu$ (Y=17.2)



$B^0 \to D^{*-}\tau^+\nu$ (Y=25.0)

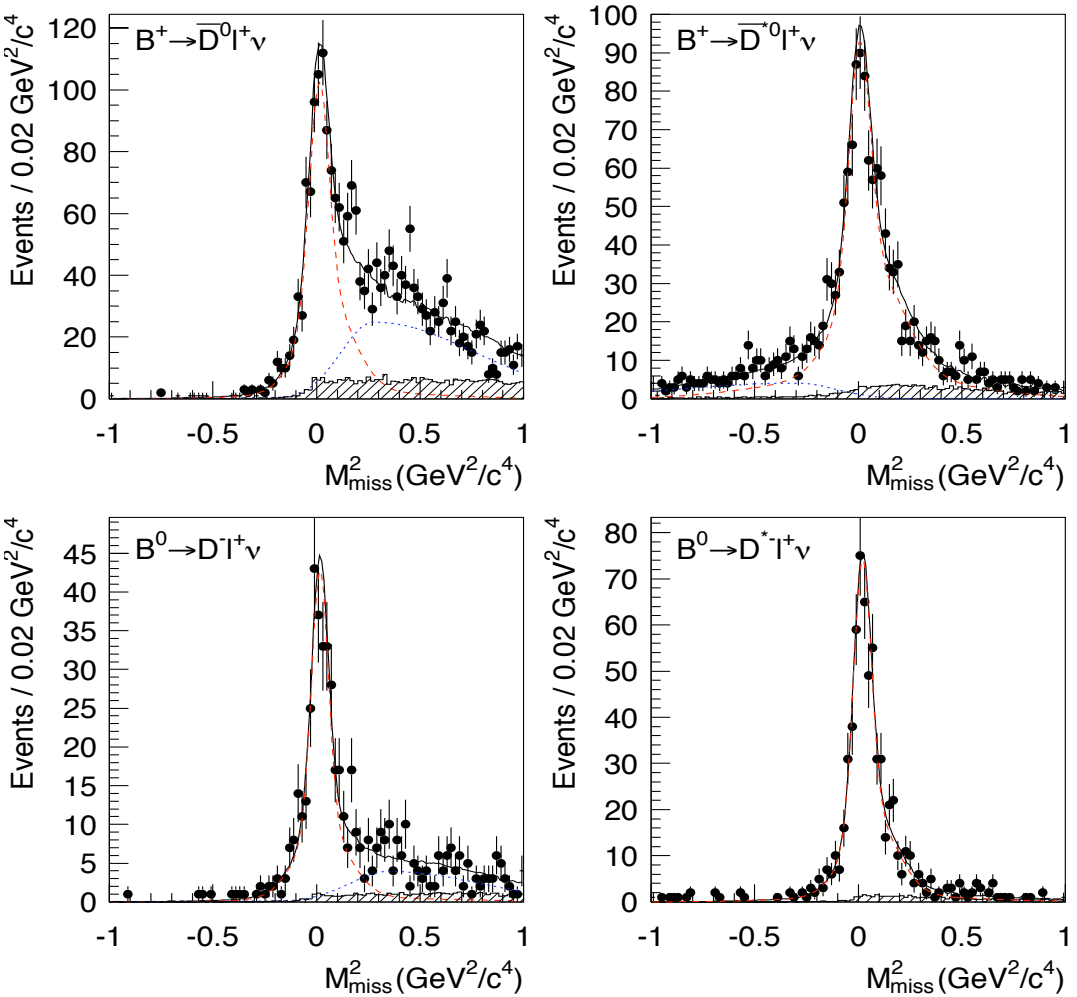


$B \to D^{(*)}\tau^+\nu$

605 fb^{-1}: Adachi et al., arXiv:0910.4301

Normalize to $B \to D^{(*)}\ell^+\nu$ to cancel systematics and form factor uncertainty:

$$R = \mathcal{B}(B \to D^{(*)}\tau^+\nu)/\mathcal{B}(B \to D^{(*)}\ell^+\nu)$$



Results:

$$\begin{aligned}
R(D^0) &= 0.70\,^{+0.19\,+0.11}_{-0.18\,-0.09} \quad (3.8\sigma)\\
R(D^{*0}) &= 0.47\,^{+0.11\,+0.06}_{-0.10\,-0.07} \quad (3.9\sigma)\\
R(D^-) &= 0.48\,^{+0.22\,+0.06}_{-0.19\,-0.05} \quad (2.6\sigma)\\
R(D^{*-}) &= 0.48\,^{+0.14\,+0.06}_{-0.12\,-0.04} \quad (4.7\sigma)
\end{aligned}$$

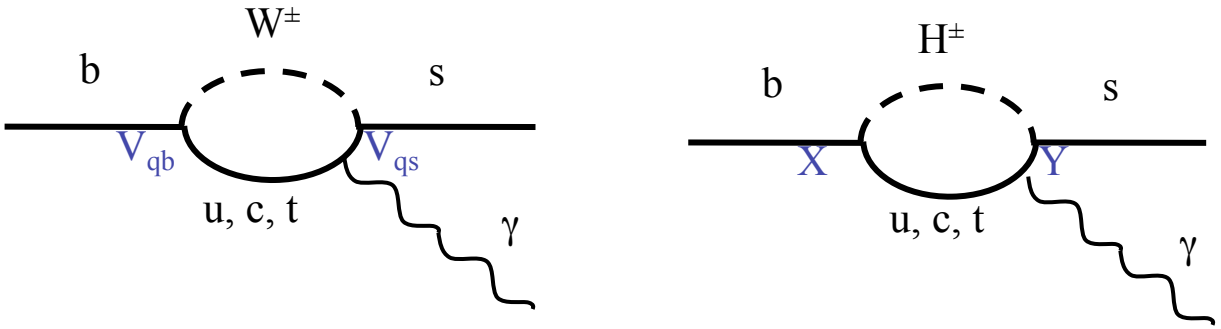
Using PDG values for $\mathcal{B}(B \to D^{(*)}\ell^+\nu)$:

$$\begin{aligned}
\mathcal{B}(B^+ \to \overline{D}^0\tau^+\nu) &= (1.51\,^{+0.41\,+0.24}_{-0.39\,-0.19} \pm 0.15)\%\\
\mathcal{B}(B^+ \to \overline{D}^{*0}\tau^+\nu) &= (3.04\,^{+0.69\,+0.40}_{-0.66\,-0.47} \pm 0.22)\%\\
\mathcal{B}(B^0 \to D^-\tau^+\nu) &= (1.01\,^{+0.46\,+0.13}_{-0.41\,-0.11} \pm 0.10)\%\\
\mathcal{B}(B^0 \to D^{*-}\tau^+\nu) &= (2.56\,^{+0.75\,+0.31}_{-0.66\,-0.22} \pm 0.10)\%
\end{aligned}$$

Inclusive $B \to X_s \gamma$

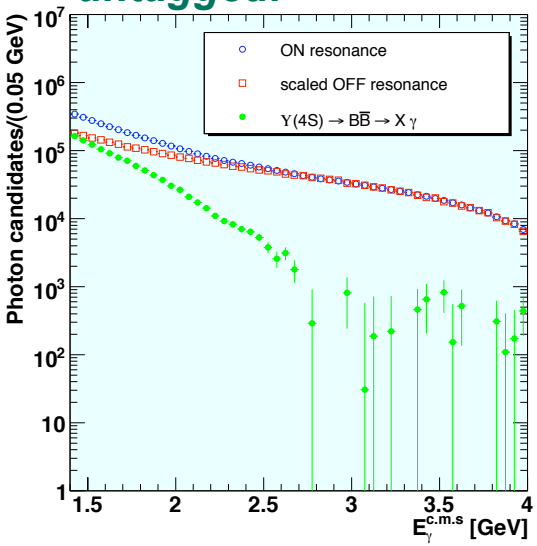
605 fb^{-1}: Limosani et al., PRL 103, 241801 (2009)

1-loop suppressed in SM ⇒ esp. sensitive to NP such as charged Higgs:

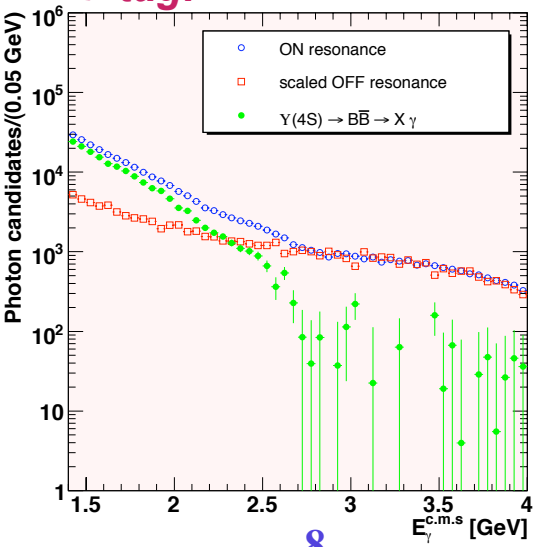


- **Two streams:**
  - *Semileptonic (e/μ) tag sample – low background, low statistics*
  - *Untagged sample – high background, high statistics (extra Fisher discriminant for qq background suppression)*
- **Select hard photon:**
  - *$E_\gamma^{cms} > 1.4$ GeV, no track, isolated ECL cluster*
  - *veto photons from π^0, η decays; veto events with opposing γ having $E_\gamma > 1$ GeV*
- **Subtract qq continuum spectrum:**
  - *spectrum obtained from 68 fb^{-1} qq sample recorded 60 MeV below $\Upsilon(4S)$ resonance, scaled for luminosity, energy, and cross section differences*

untagged:



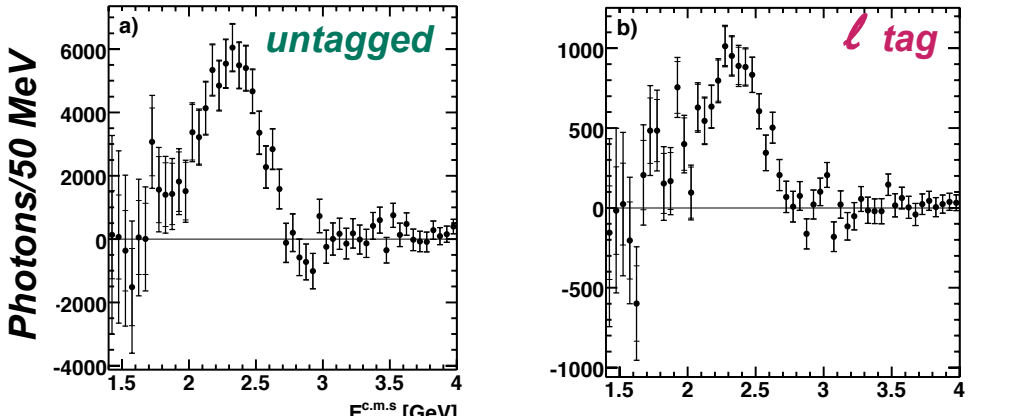
ℓ tag:

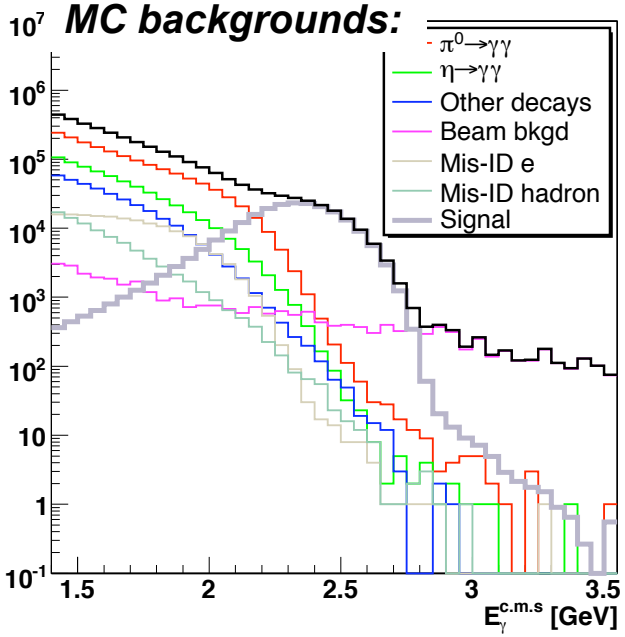


$B \to X_s \gamma$

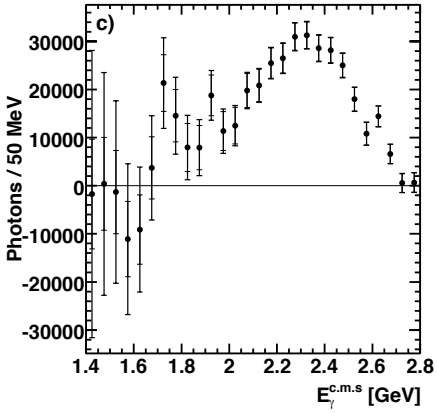
605 fb^{-1}: Limosani et al., PRL 103, 241801 (2009)

- ***Other backgrounds > signal for $E_\gamma^{cms} < 2.2$ GeV :***
  $\pi^0, \eta \to \gamma\gamma$; ω, η', $J/\psi \to \gamma X$; e, n, K_L faking ECL γ energy. The background spectra from MC are scaled by data/MC ratio of control samples, and subtracted off (e.g., n, K_L background doubled)





averaged & corrected by ε(cuts):

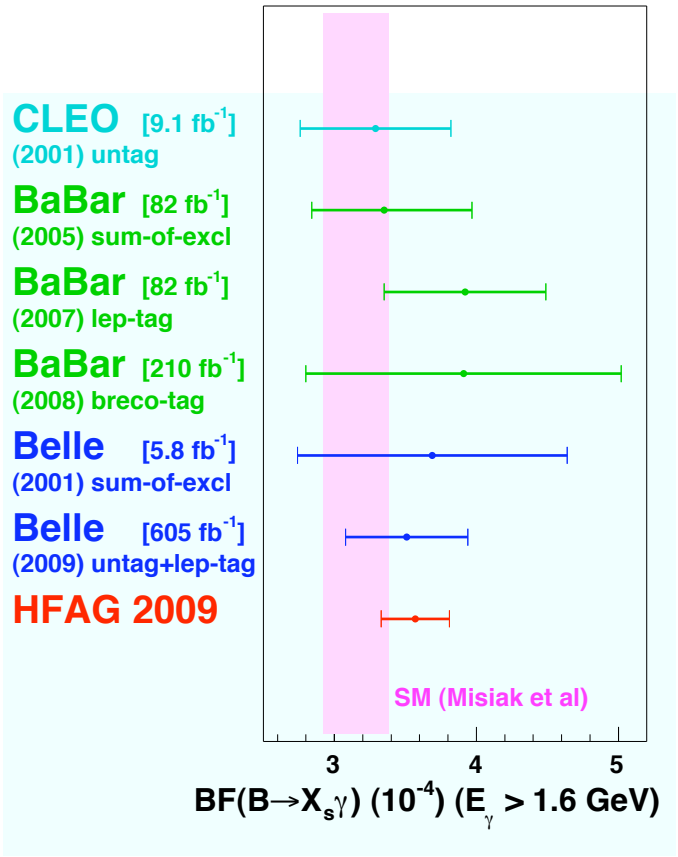


- ***Correct background-subtracted spectrum:***
  1. *divide by ε(cuts) given γ detected*
  2. *unfold γ spectrum (unfolding matrix from MC, calibrated using $\mu\mu\gamma$ control sample)*
  3. *divide by ε(γ detected)*

- ***Simple 4.5% subtraction for $B \to X_d \gamma$ contribution***
  [Hurth et al., Nucl. Phys. B704, 56 (2005); Charles et al., EPJ C41, 1 (2005)]

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

$B \to X_s \gamma$



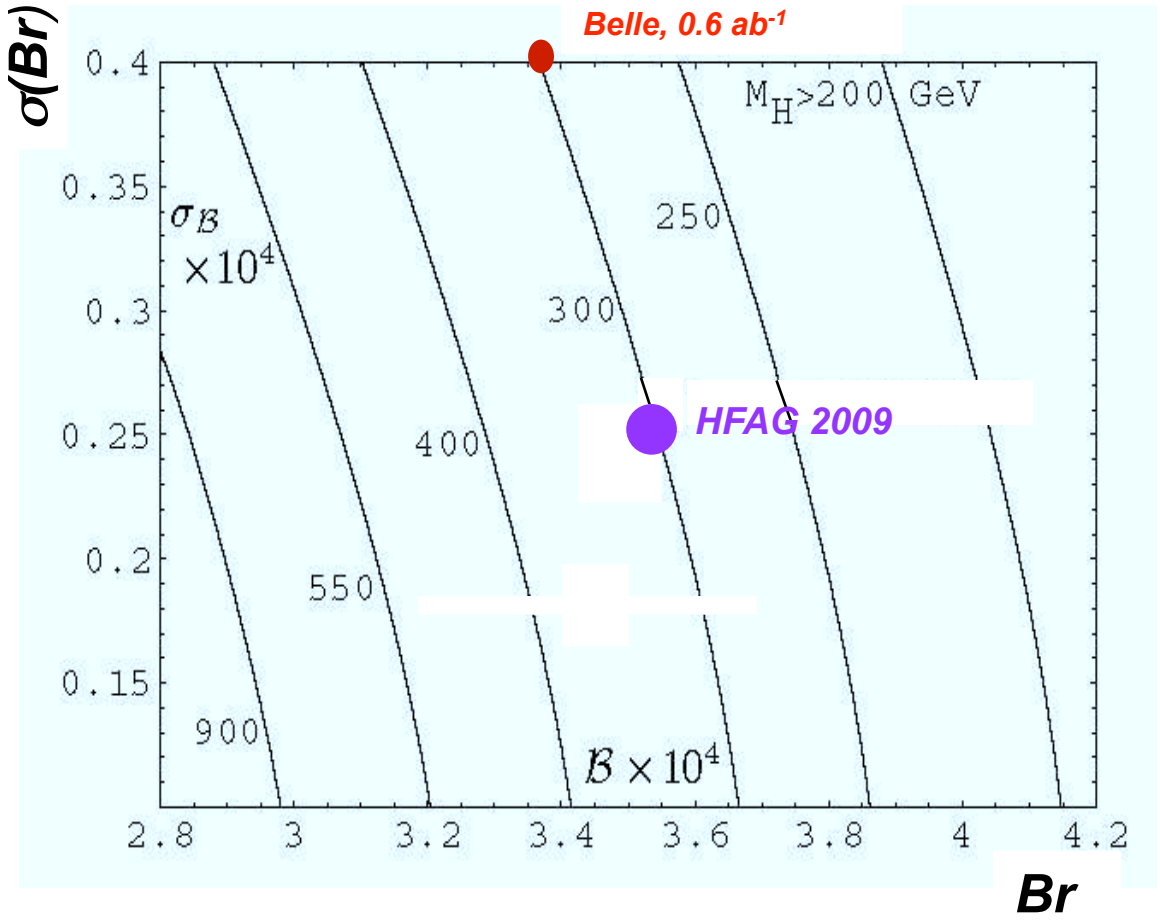
HFAG (summer 2009):

$\mathcal{B}(B \to X_s\gamma) = (3.57 \pm 0.24) \times 10^{-4}$

$(E\gamma > 1.6\ \text{GeV})$

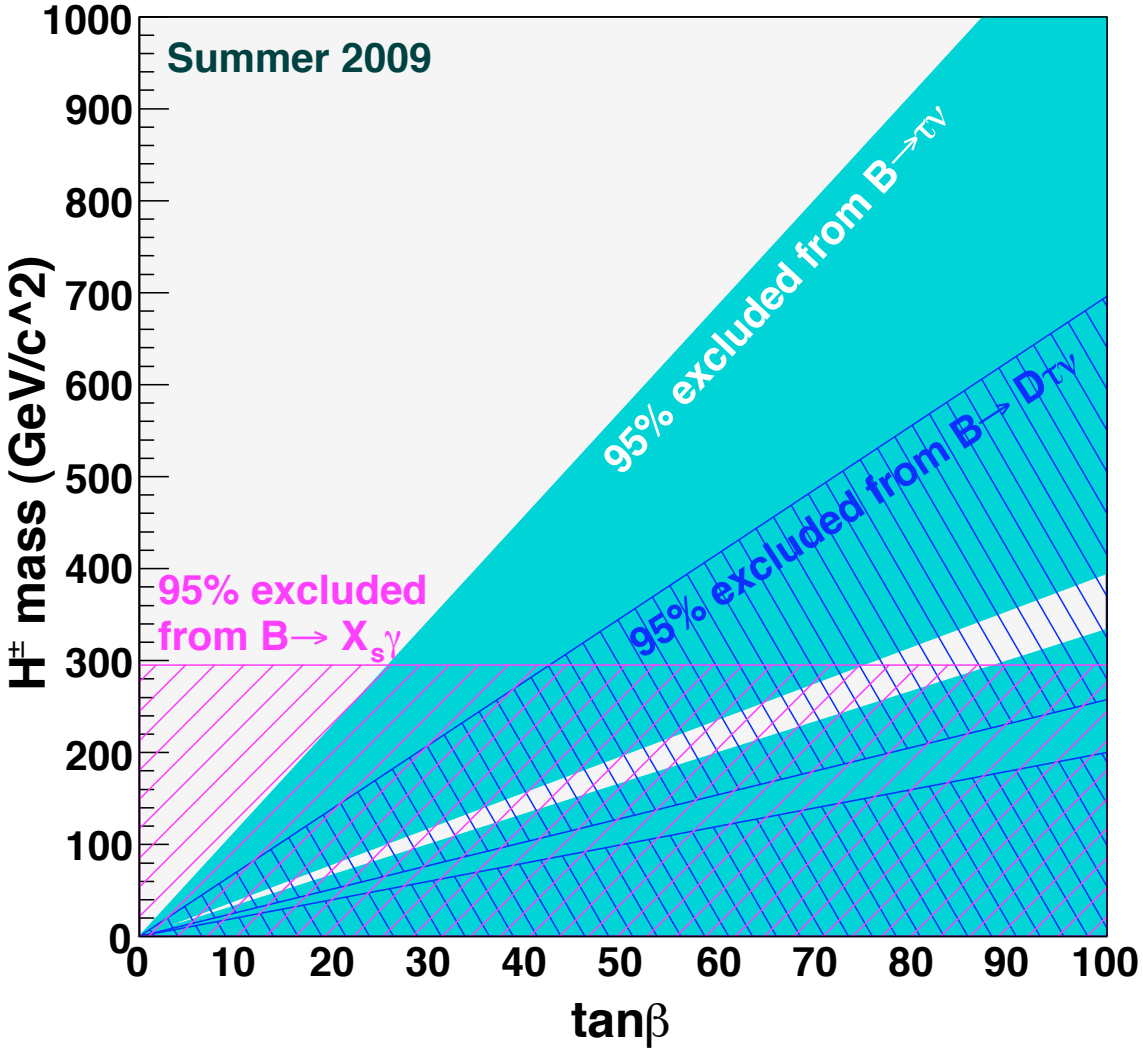
95% C.L. lower limit on m(H±), all tanβ

Misiak et al., PRL 98, 022002 (1997):

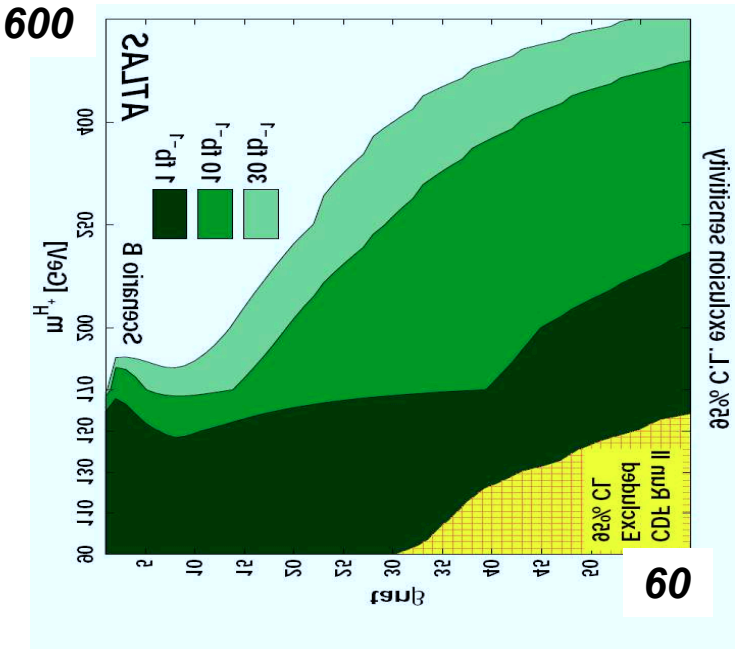


Current HFAG WA ⇒ $m_{H^+} > 300$ GeV (95% CL) for all tanβ *(complementary to hadron colliders)*

Constraining a charged Higgs



Compare to ATLAS:



$B \to K^{(*)}\, \ell^+\ell^-$

605 fb^{-1}: Wei et al., PRL 103, 171801 (2009)

- **Hadron final states:**

  $K^-\pi^+,\ K_S\pi^+,\ K^+\pi^0,\ K^+,\ K_S$

These are combined with $\mu^+\mu^-$ and e^+e^- pairs

$5.27 < M_{bc} < 5.29\ \mathrm{GeV}/c^2$
$-35(-55) < \Delta E < 35\ \mathrm{MeV}$
$|M_{K\pi} - M_{K^*}| < 80\ \mathrm{MeV}/c^2$

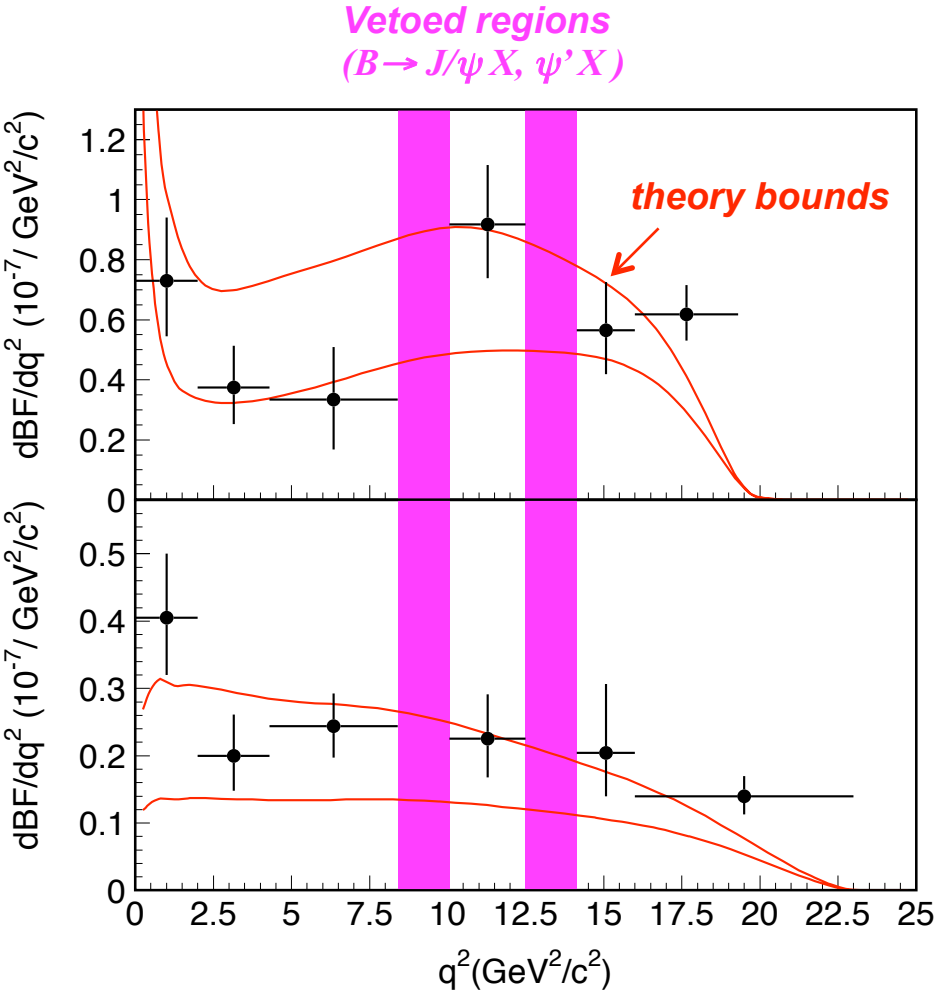
veto q^2 regions to eliminate $B \to J/\psi X,\ \psi' X$ background

Signal yield determined by 2d fit to M_{bc}-$M_{K\pi}$

For partial branching fractions, assume SM $\mu\mu/ee$ ratio and express results in terms of $B \to K^{(*)}\, \mu^+\mu^-$

Results:

$\mathcal{B}(B \to K^*\, \mu^+\mu^-) = (10.7 \pm 1.1 \pm 0.9) \times 10^{-7}$
$\mathcal{B}(B \to K\, \mu^+\mu^-) = (4.8 \pm 0.5 \pm 0.3) \times 10^{-7}$



$B \to K^{(*)}\, \ell^+\ell^-$

605 fb^{-1}: Wei et al., PRL 103, 171801 (2009)

Observables:

$$\frac{dN}{d\theta_K} = \frac{3}{2}F_L \cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K)$$

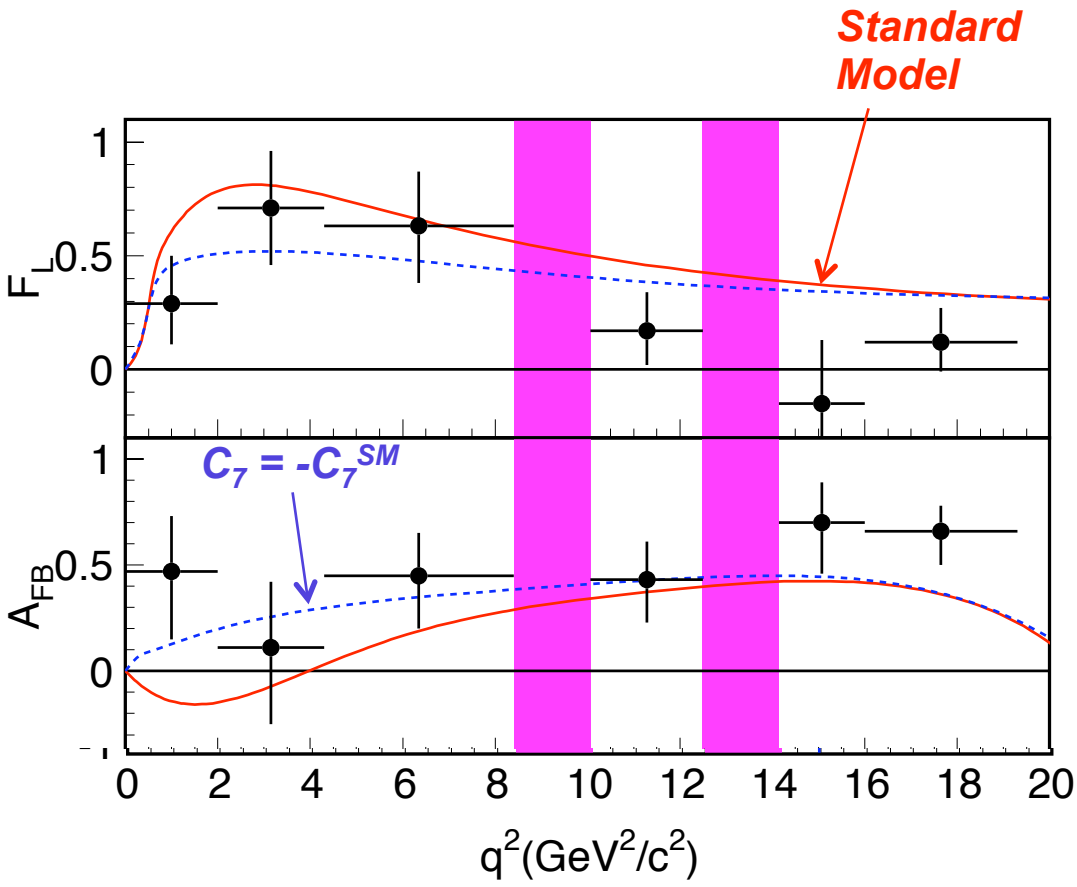
$$\frac{dN}{d\theta_\ell} = \frac{3}{4}F_L(1-\cos^2\theta_\ell) + \frac{3}{8}(1-F_L)(1+\cos^2\theta_\ell) + A_{FB}\cos\theta_\ell$$

Theory (operator product expansion):

$$A_{FB}(q^2) = -C_{10}^{\text{eff}}\,\xi(q^2)\left[Re(C_9^{\text{eff}})F_1 + \frac{1}{q^2}C_7^{\text{eff}}F_2\right]$$

- C_7 : magnetic moment operator $s\sigma^{\mu\nu}(1+\gamma_5)b\,F_{\mu\nu}$
- C_9 : V-A to vector operator $(bs)_{V\text{-}A}\,(\ell\ell)_V$
- C_{10} : V-A to axial vector operator $(bs)_{V\text{-}A}\,(\ell\ell)_A$

- distribution sensitive to sign of C_7
- theoretical uncertainty from form factors have only small effect



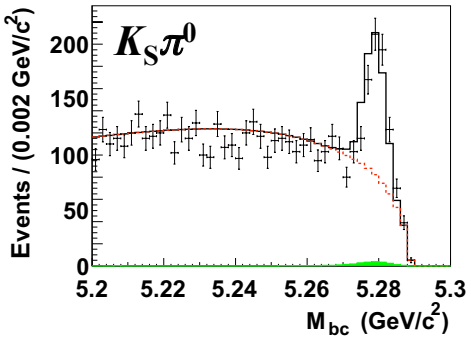
$A_{CP}(B \to K^* \mu^+\mu^-) = -0.10 \pm 0.10 \pm 0.01$
$A_{CP}(B \to K^+ \mu^+\mu^-) = 0.04 \pm 0.10 \pm 0.02$

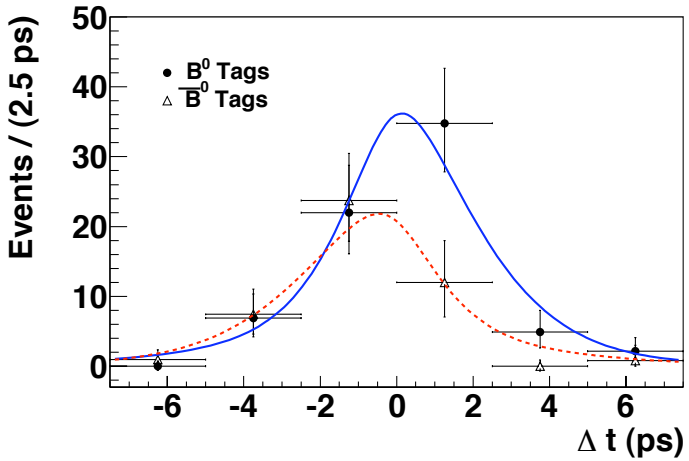
$B^0 \to K^0\pi^0$ CPV

605 fb^{-1}: Fujikawa et al., arXiv:0809.4366, to appear in PRD(RC)

- ***Use both K_S ($\to\pi^+\pi^-$) and K_L (shower in μ detector) samples***

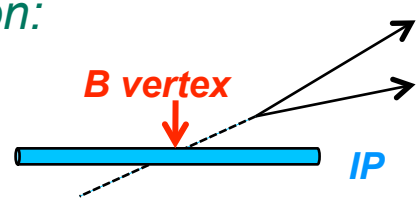
$5.27 < M_{bc} < 5.29$ GeV/c^2
$-0.15 < \Delta E < 0.10$ GeV



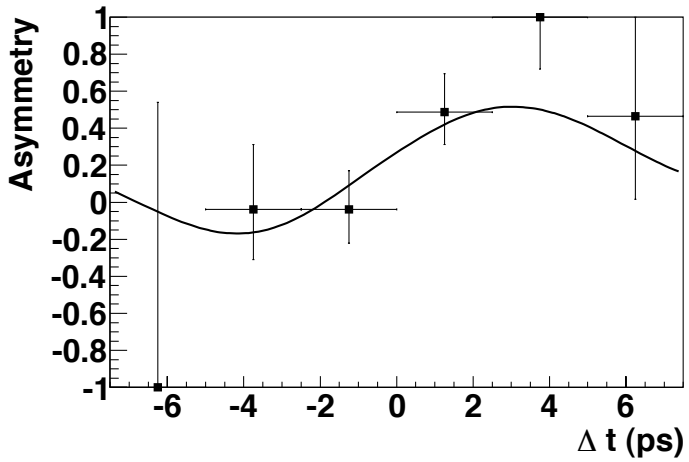


- ***Vertexing:***

extrapolate K_S momentum vector back to interaction profile to get z position:



Test method with $B^0 \to J/\psi\, K_S$ decays; method works!



- ***Fit for CPV parameters:***

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}\left[1 \pm \left(\mathcal{S}\sin(\Delta m \Delta t) + \mathcal{A}\cos(\Delta m \Delta t)\right)\right]$$

$$\mathcal{P}_{\text{integrated}} = \frac{1}{2}\left[1 \pm \frac{\mathcal{A}}{(1+\tau_B^2\,\Delta m^2)}\right]$$

Results:

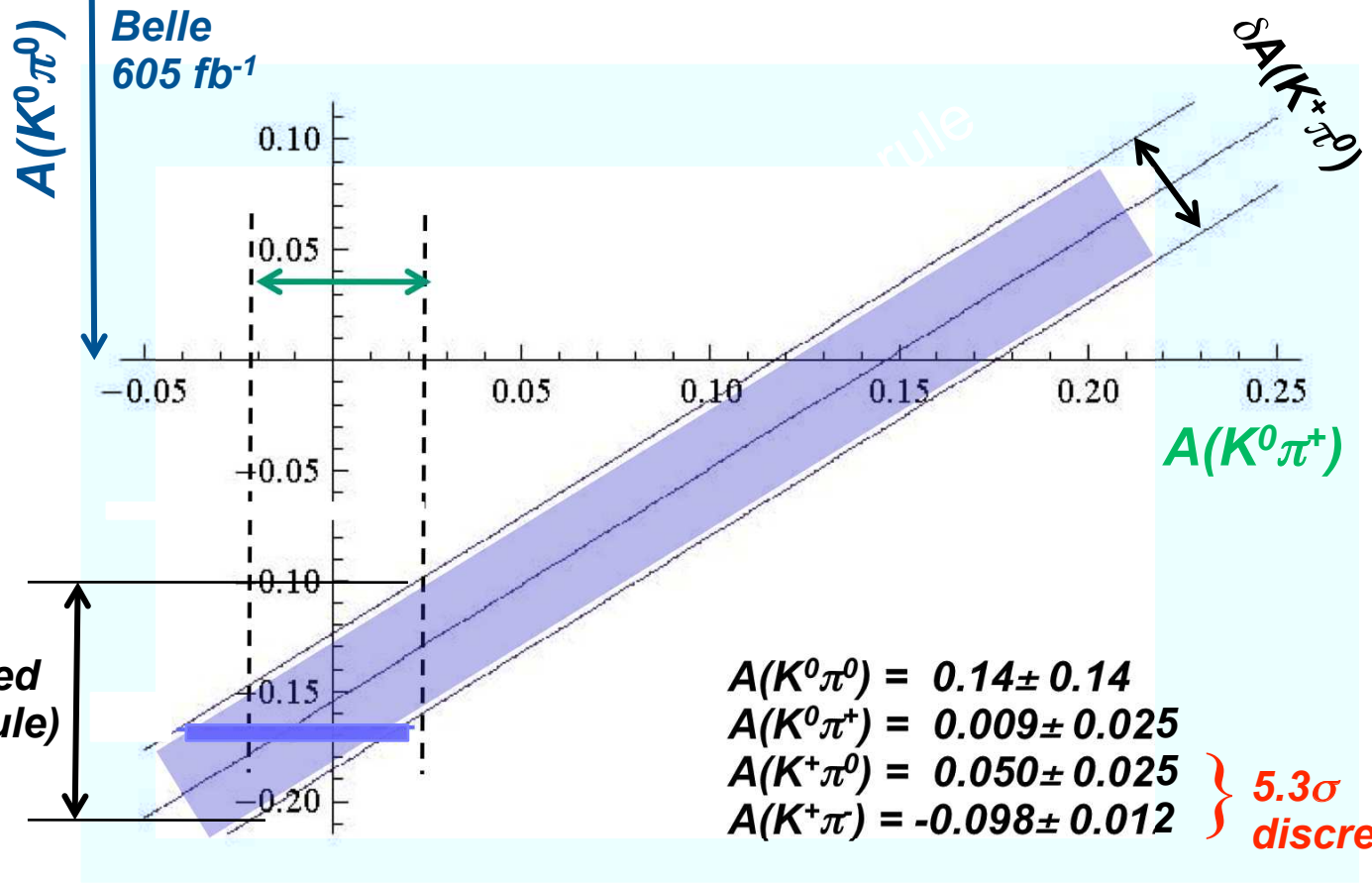
$\mathcal{B}(B \to K^0\pi^0)$	= (8.7 ± 0.5 ± 0.6) x 10^{-6}
A_{CP}	= +0.14 ± 0.13 ± 0.06
$\sin(2\phi_1)$	= 0.67 ± 0.31 ± 0.08

$B^0 \to K^0\pi^0$ CPV

Test ~model independent (SU(2) only) sum rule for all four modes:

Gronau, PLB 627, 82 (2005); Atwood & Soni, PRD 58, 036005 (1998):

$$\mathcal{A}_{CP}(K^+\pi^-) + \mathcal{A}_{CP}(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} = \mathcal{A}_{CP}(K^+\pi^0)\frac{2\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} + \mathcal{A}_{CP}(K^0\pi^0)\frac{2\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$



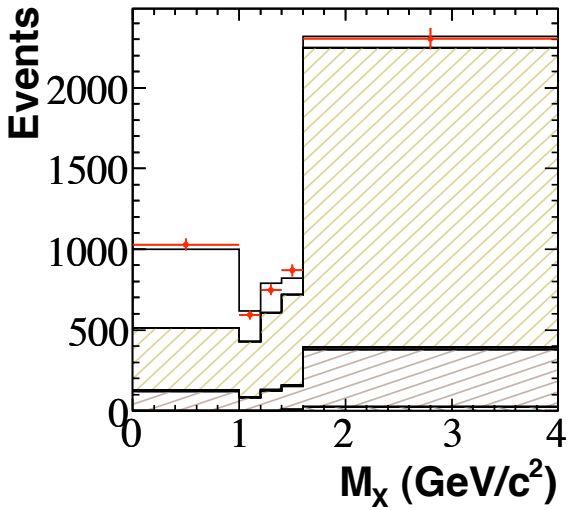
$B \to X_u \ell^+ \nu$

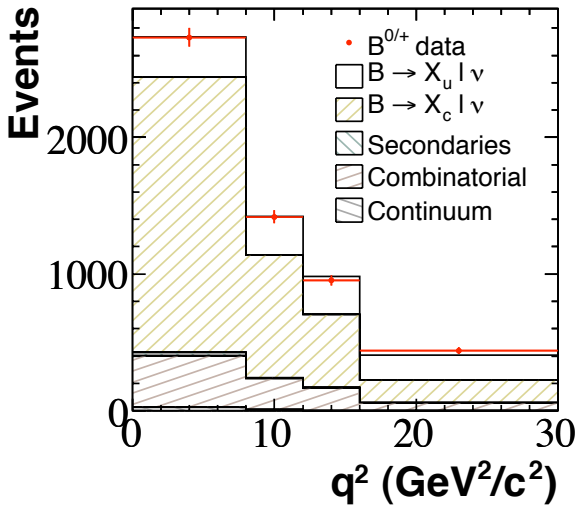
605 fb^{-1}: Urquijo et al., PRL 104, 021801 (2010)

- **Full reconstruction tag:**

$B^- \to$, $D^{(*)0}\pi^-$, $D^{(*)0}\rho^-$, $D^{(*)0}a_1^-$, $D^{(*)0}D_s^-$
$B^0 \to$, $D^{(*)+}\pi^-$, $D^{(*)+}\rho^-$, $D^{(*)+}a_1^-$, $D^{(*)+}D_s^-$
$D^{*0} \to D^0\gamma$, $D^0\pi^0$
$D^{*+} \to D^0\pi^+$, $D^+\pi^0$

$5.27 < M_{bc} < 5.29$ GeV/c^2
$-0.05 < \Delta E < 0.05$ GeV





Signal side:

require $p_\ell > 1.0$ GeV/c, then use Binary Decision Tree with 17 observables, e.g., q_{tot}, $M_{hadronic}$, $P_{hadronic}$, number of kaons, etc. Cut on BDT classifier (output)

2D fit events in $M_{hadronic}$ and q^2, calculate partial branching fraction from event yield:

$$\Delta\mathcal{B} = \left(\frac{N_{b\to u}}{2\varepsilon_{b\to u} N_{\rm tag}}\right)(1-\delta_{\rm rad})$$

Results:

$\mathcal{B}(B \to X_u \ell^+ \nu) = (1.963 \pm 0.173 \pm 0.159) \times 10^{-3}$

$|V_{ub}| \times 1000 = 4.37 \pm 0.26 \pm 0.23$ (BLNP)

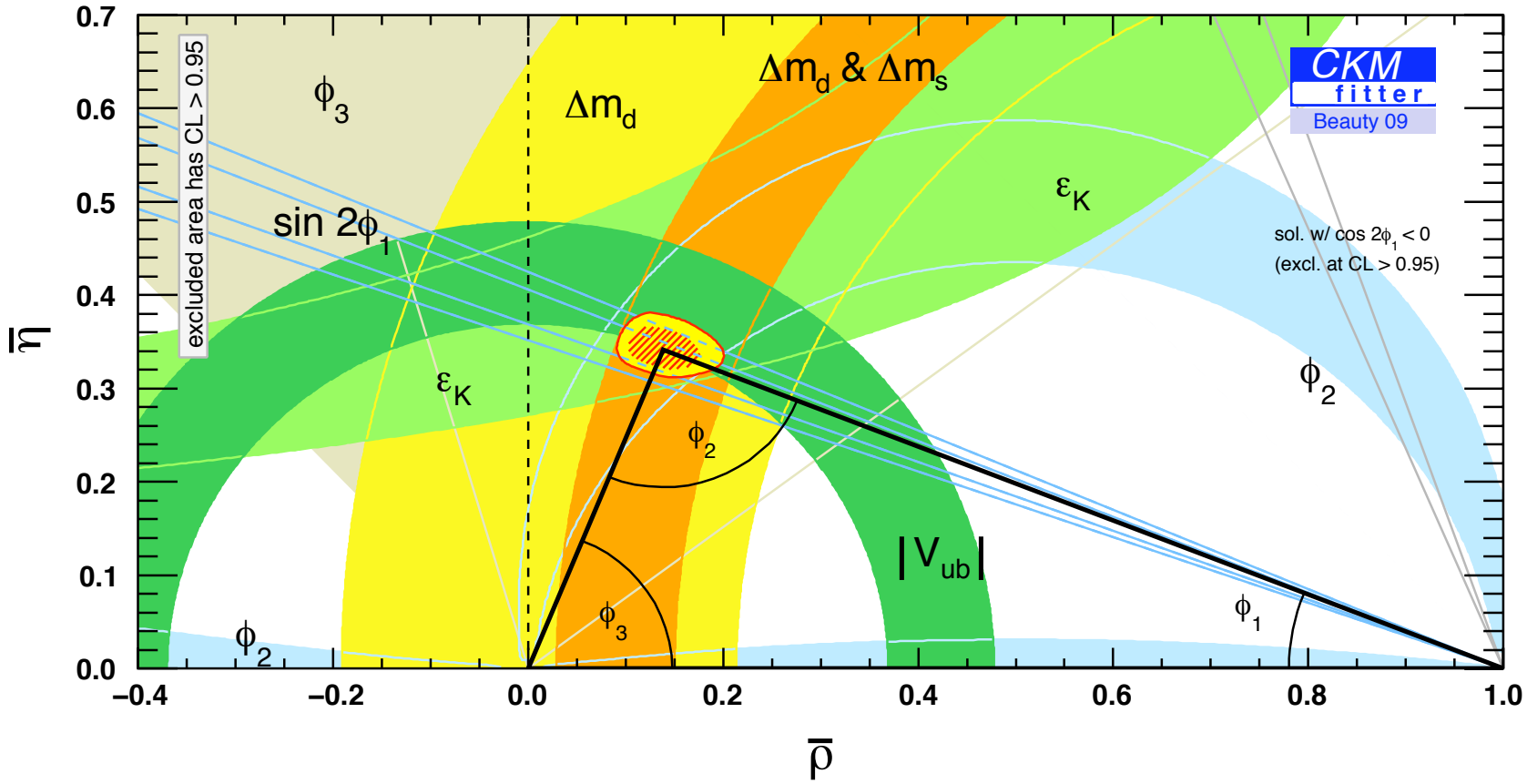
$|V_{ub}| \times 1000 = 4.46 \pm 0.26 \pm 0.16$ (DGE)

$|V_{ub}| \times 1000 = 4.41 \pm 0.26\ ^{+0.12}_{-0.22}$ (GGOU)

exper. error — theory error

$B \to X_u \ell^+ \nu$

Is $|V_{ub}|$ too large?
(now: differs by >1σ with global CKM fit)



Summary

- Belle has observed $B^+ \to \tau^+ \nu$ with 3.8σ significance using a semileptonic tag. Together with the previous Belle (hadronic tag) result and Babar results, this firmly establishes this mode. The branching fraction constrains M_{H+}

- Belle has made the most precise determination of $B \to D^{(*)}\tau^+ \nu$; the branching fraction constrains M_{H+}

- Belle has measured inclusive $B \to X_s \gamma$ with a very low E_γ threshold: 1.7 GeV. The branching fraction rules out H^+ with mass < 300 GeV/c^2 for all tanβ.

- Together, the above three modes rule out H^+ over most of ATLAS' phase space.

- Belle has measured the decay rate, CP asymmetry, and forward-backward asymmetry for $B \to K^{(*)} \ell^+\ell^-$ decays. The FB asymmetry is always positive, in contrast to SM expectation. Is this a non-SM contribution to C_7?

- Belle has measured the branching fraction, ϕ_1, and direct CPV in $B^0 \to K^0\pi^0$ decays. The ϕ_1 value agrees with that measured in other decays, but the $K\pi$ isospin-based sum rule is violated at the 1.9σ level.

- Belle has made the most precise measurement of inclusive $B \to X_u \ell^+\nu$ decays and used it to extract $|V_{ub}|$. Value is 1σ away from the CKM fit expectation.