Recent physics results from Belle

Youngjoon Kwon
Physics, Yonsei Univ.

ICPP, Dogus University, Istanbul, June 20-25, 2011
in memory of

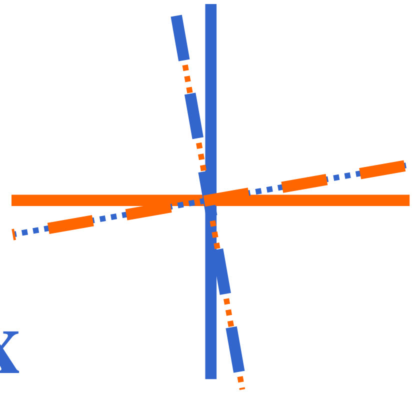
Outline

- Introduction
- Recent results*
  - *on CKM UT angles and sides*
  - *Rare B decays*
  - *results from Bs, Υ(nS)*
- Summary & Prospects

** not covering results in charm, charmonia & τ.*

Flavor mixing and CKM matrix

- For quarks,
  - weak interaction eigenstates ≠ mass eigenstates
  - mixing of quark flavors through a **unitary matrix**



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \left(V_{\mathrm{CKM}}\right)\begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Wolfenstein parametrization

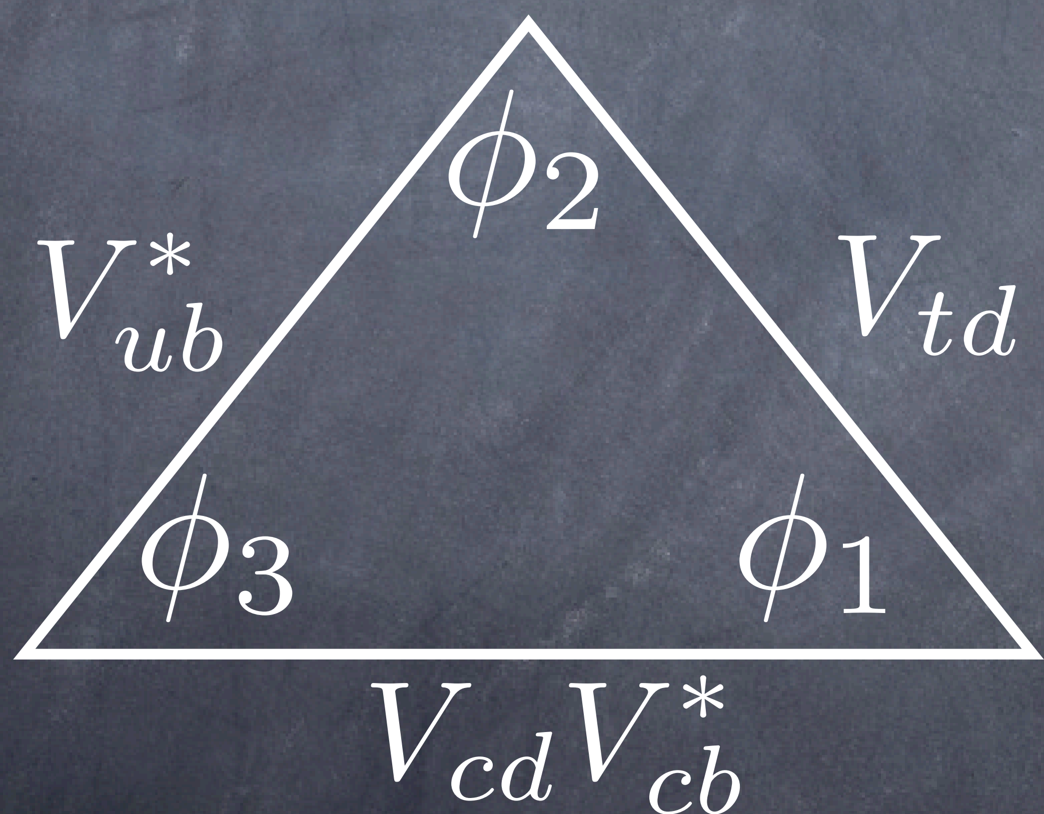
$$V_{\mathrm{CKM}} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$|\lambda| \approx O(0.1)$

3 real parameters (λ, A, ρ) and 1 phase (η)

the CKM UT angles

- Extract the UT angles through time-dependent A_{CP} measurement.



Unitarity triangle angles			
BABAR:	β	α	γ
BELLE:	ϕ_1	ϕ_2	ϕ_3
	易	難	魔

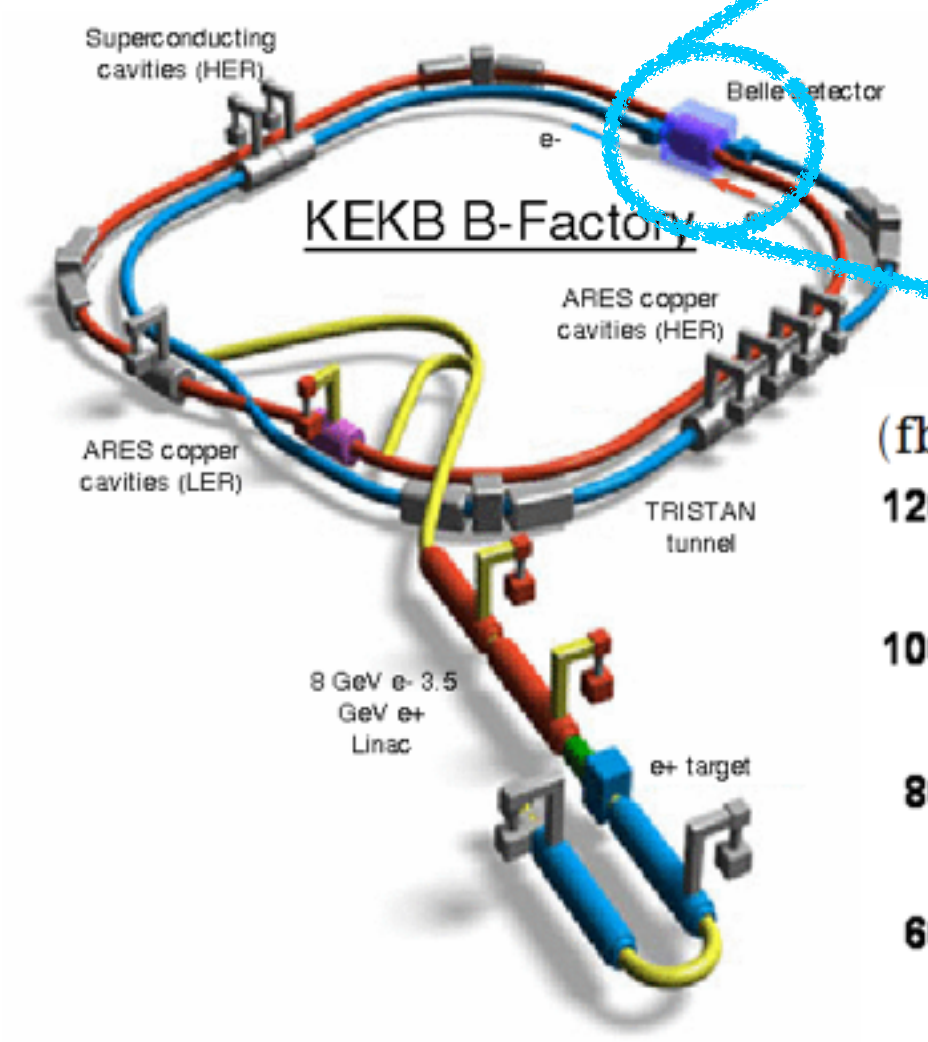
Z. Ligeti, ICHEP 2004

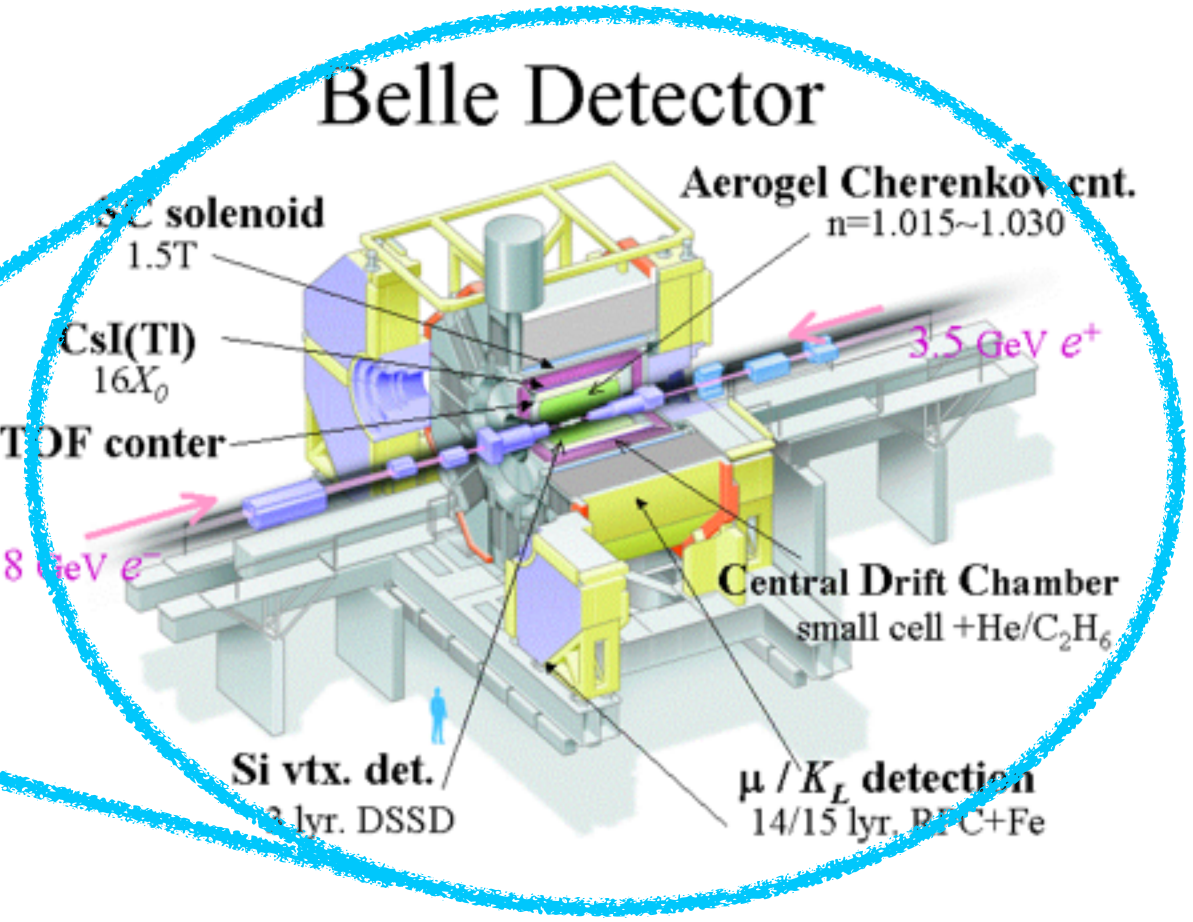
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

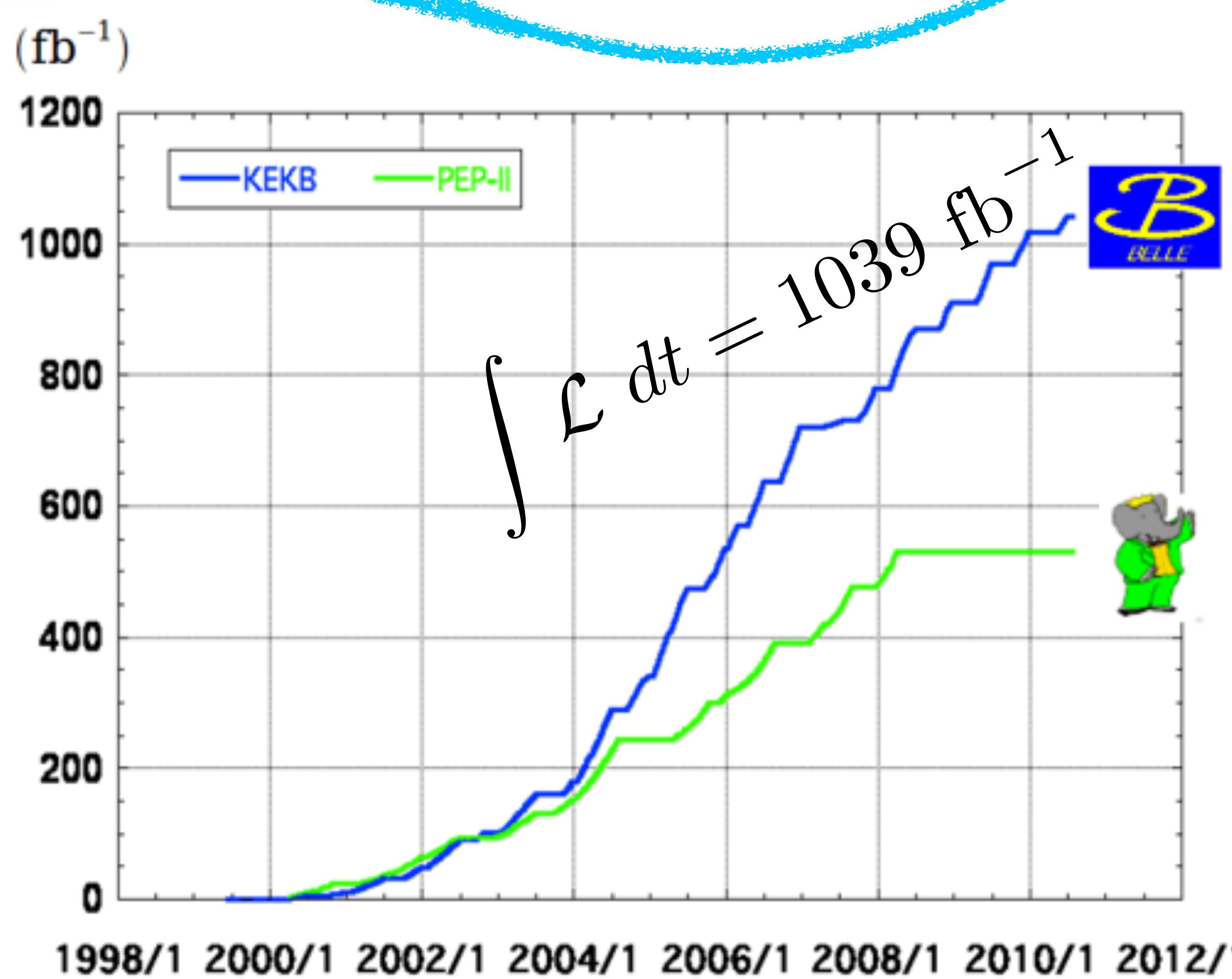
$$V_{ud} \simeq V_{tb} \simeq 1$$

13 countries
65 institues
~400 members

$\mathcal{L}_{\text{peak}} = 21.1\ \text{nb}^{-1}\text{s}^{-1}$



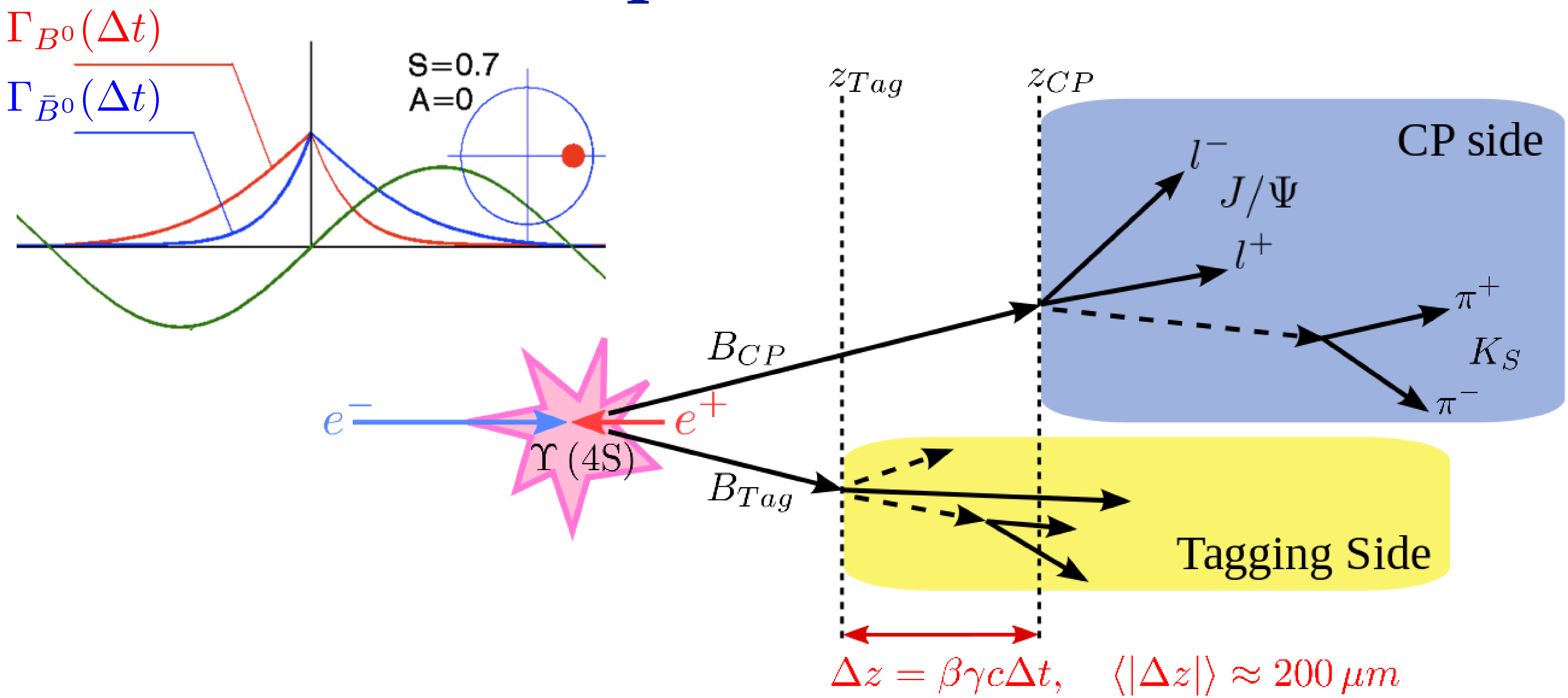




> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

time-dependent A_{CP} measurement



$$A_{CP}(\Delta t) = \frac{\Gamma\left(\bar{B}^0(\Delta t) \to f_{CP}\right) - \Gamma\left(B^0(\Delta t) \to f_{CP}\right)}{\Gamma\left(\bar{B}^0(\Delta t) \to f_{CP}\right) + \Gamma\left(B^0(\Delta t) \to f_{CP}\right)} = \mathcal{S}_f \sin(\Delta m \Delta t) + \mathcal{A}_f \cos(\Delta m \Delta t)$$

$$\mathcal{S}_f = \frac{2\,\mathrm{Im}(\lambda_f)}{|\lambda_f^2| + 1} \qquad \mathcal{A}_f = \frac{|\lambda_f^2| - 1}{|\lambda_f^2| + 1} \qquad \lambda_f = \frac{q}{p}\frac{\bar{A}(f_{CP})}{A(f_{CP})}$$

mixing-induced CPV

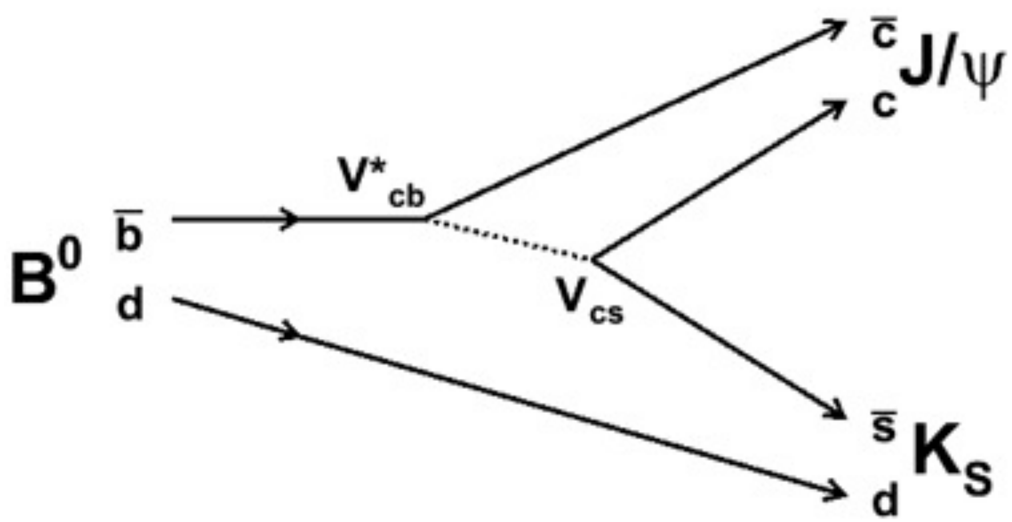
direct CPV

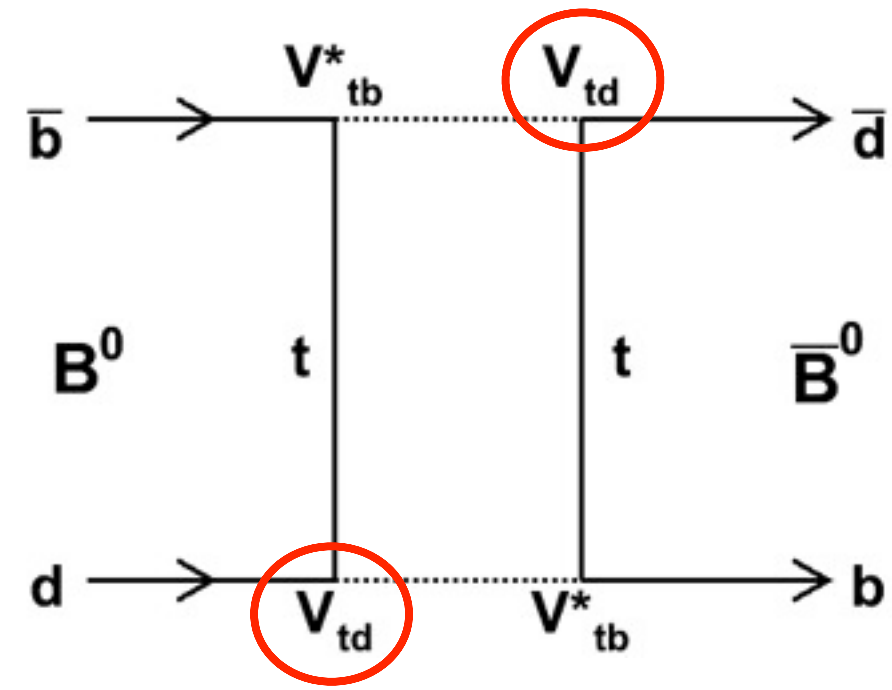
The Golden mode for ϕ_1

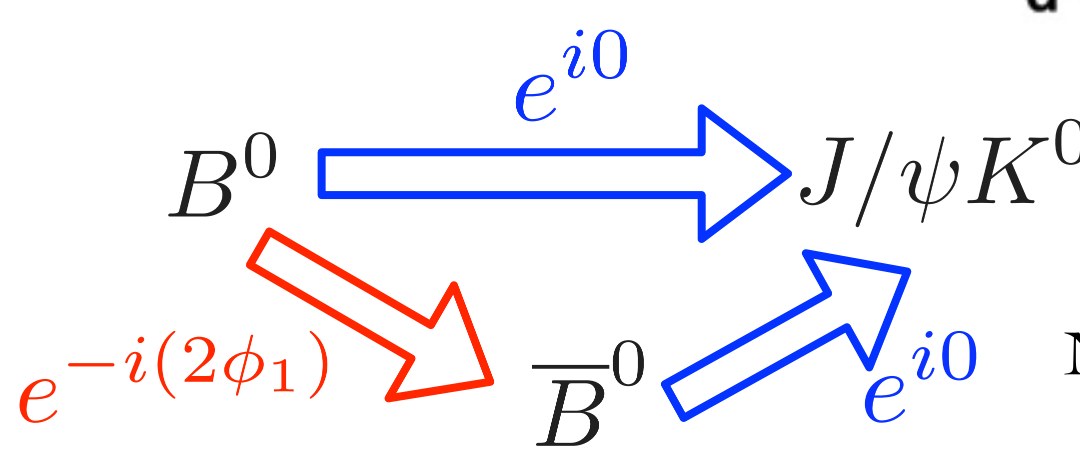
$B^0 \to J/\psi K^0$: high rate, theoretically clean

No CKM phase e^{i0}

Two V_{td} vertices $e^{-i(2\phi_1)}$



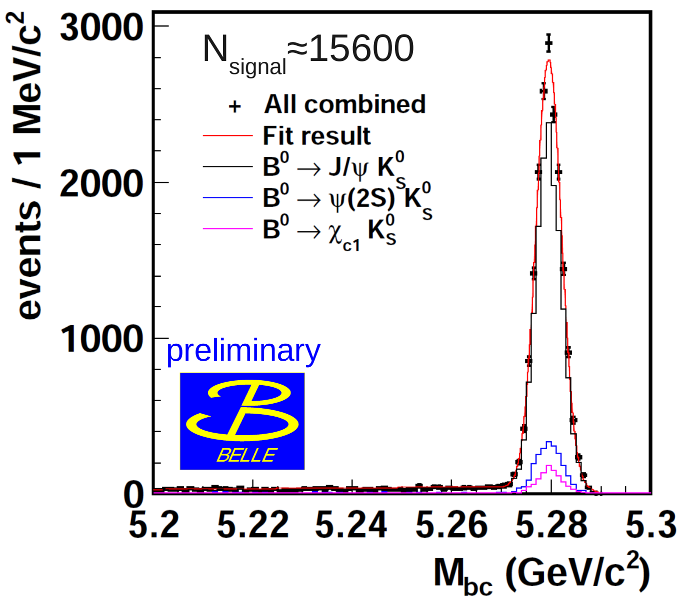


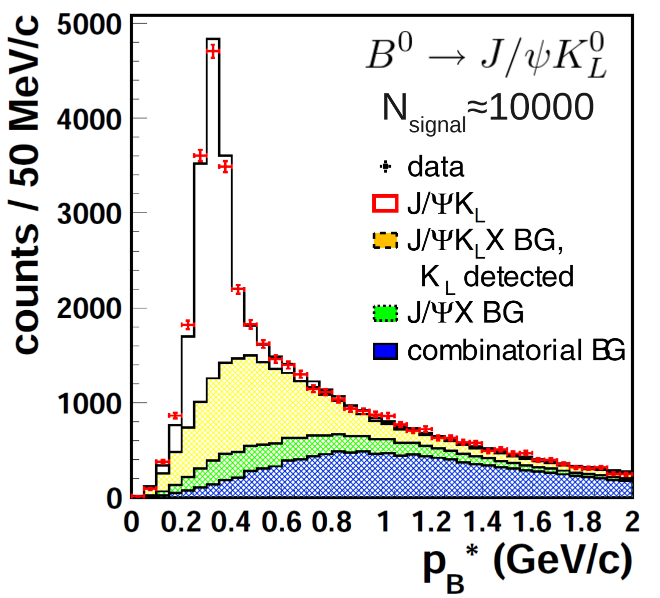


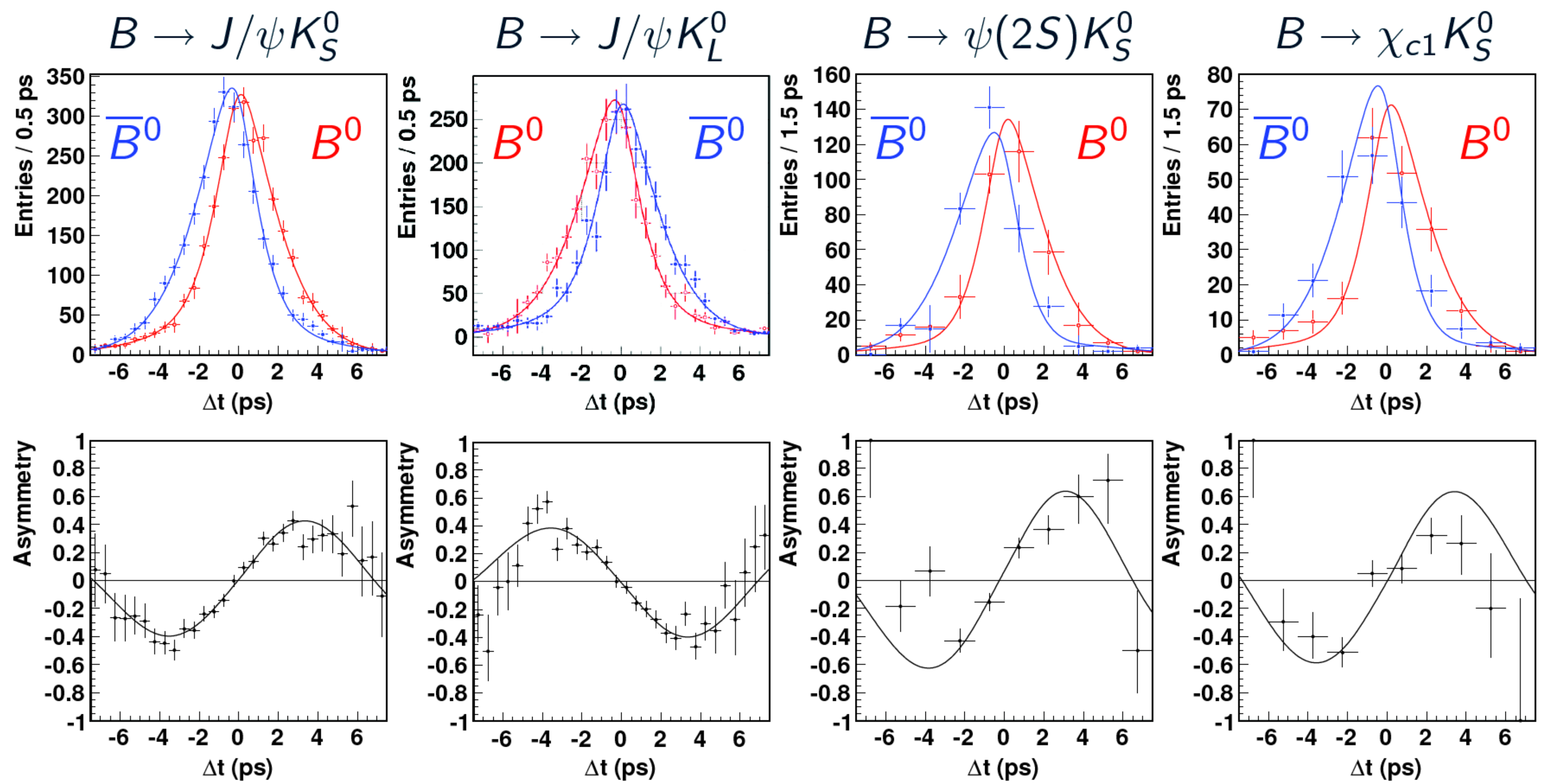
Note: true for any B^0 decay with no phase from decay amplitude

$$\Longrightarrow A_{CP}^{J/\psi K^0}(\Delta t) = -\xi_f \sin(2\phi_1) \sin(\Delta m \Delta t)$$

Belle's final result on $\sin(2\phi_1)$







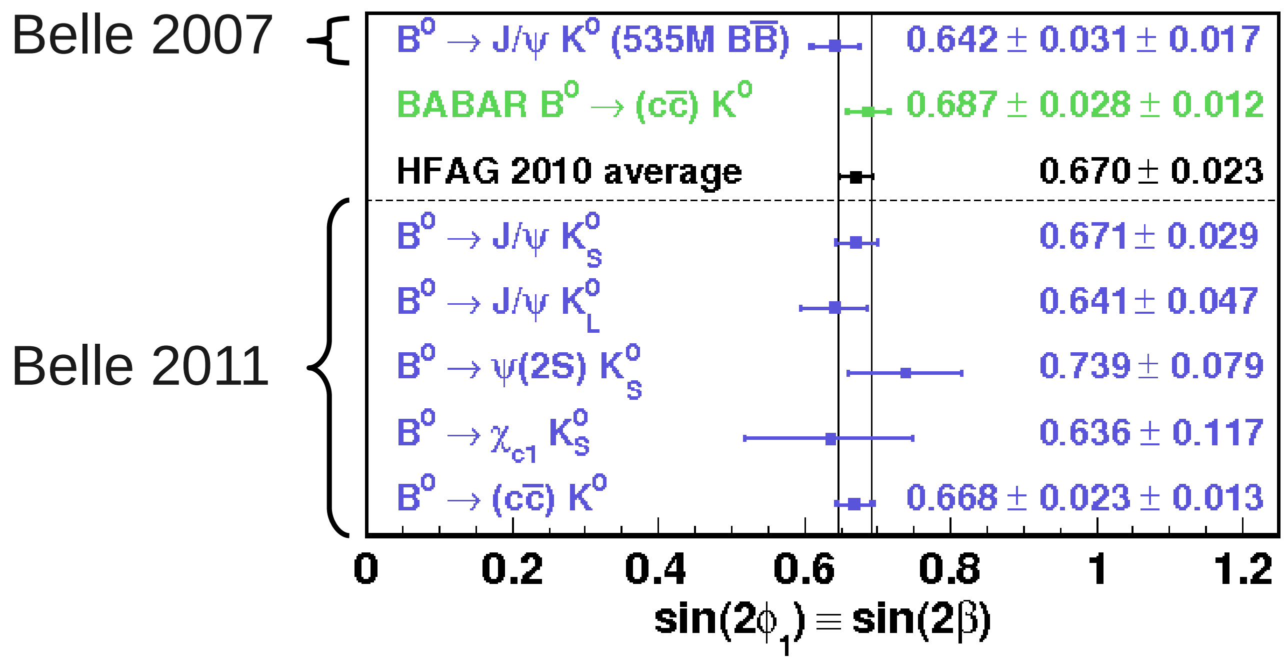
Belle with 772×10[6] BB:

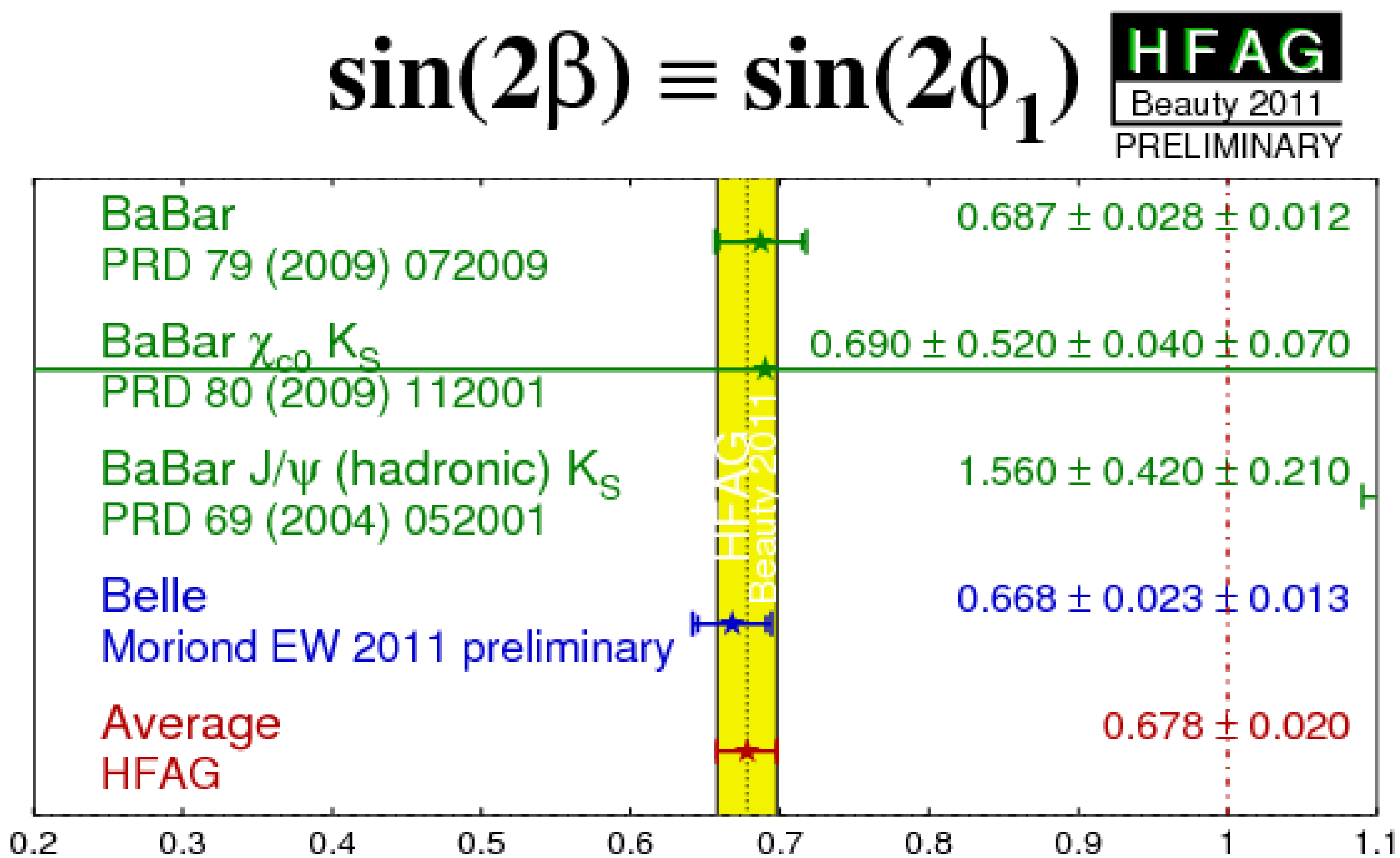
$$\mathcal{A} = 0.007 \pm 0.016\,(\mathrm{stat}) \pm 0.013\,(\mathrm{syst})$$

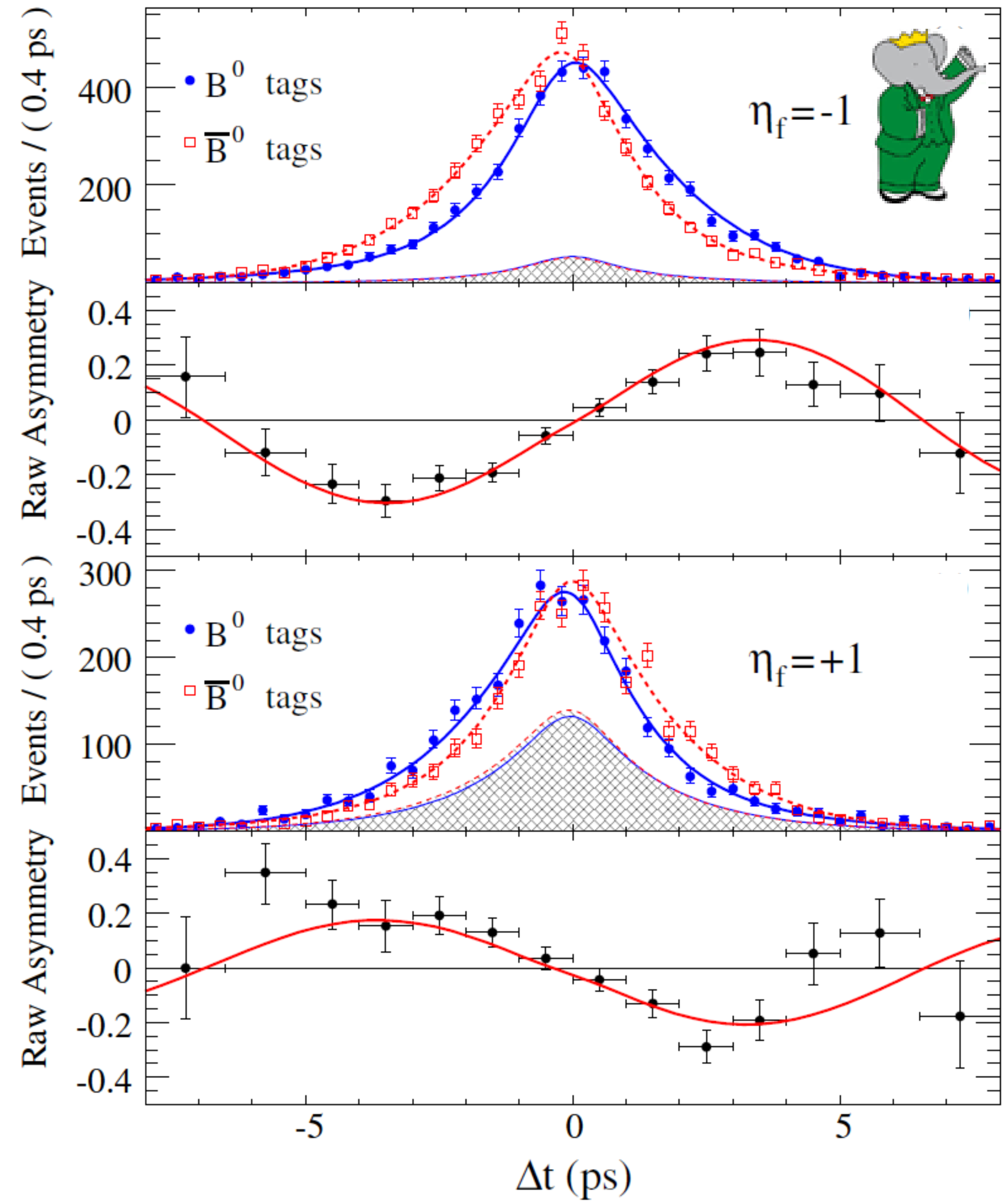
$$\sin(2\phi_1) = 0.668 \pm 0.023 \qquad \pm 0.013$$

preliminary

world's most precise value of $\sin(2\phi_1)$







CKMfitter
ICHEP 2010

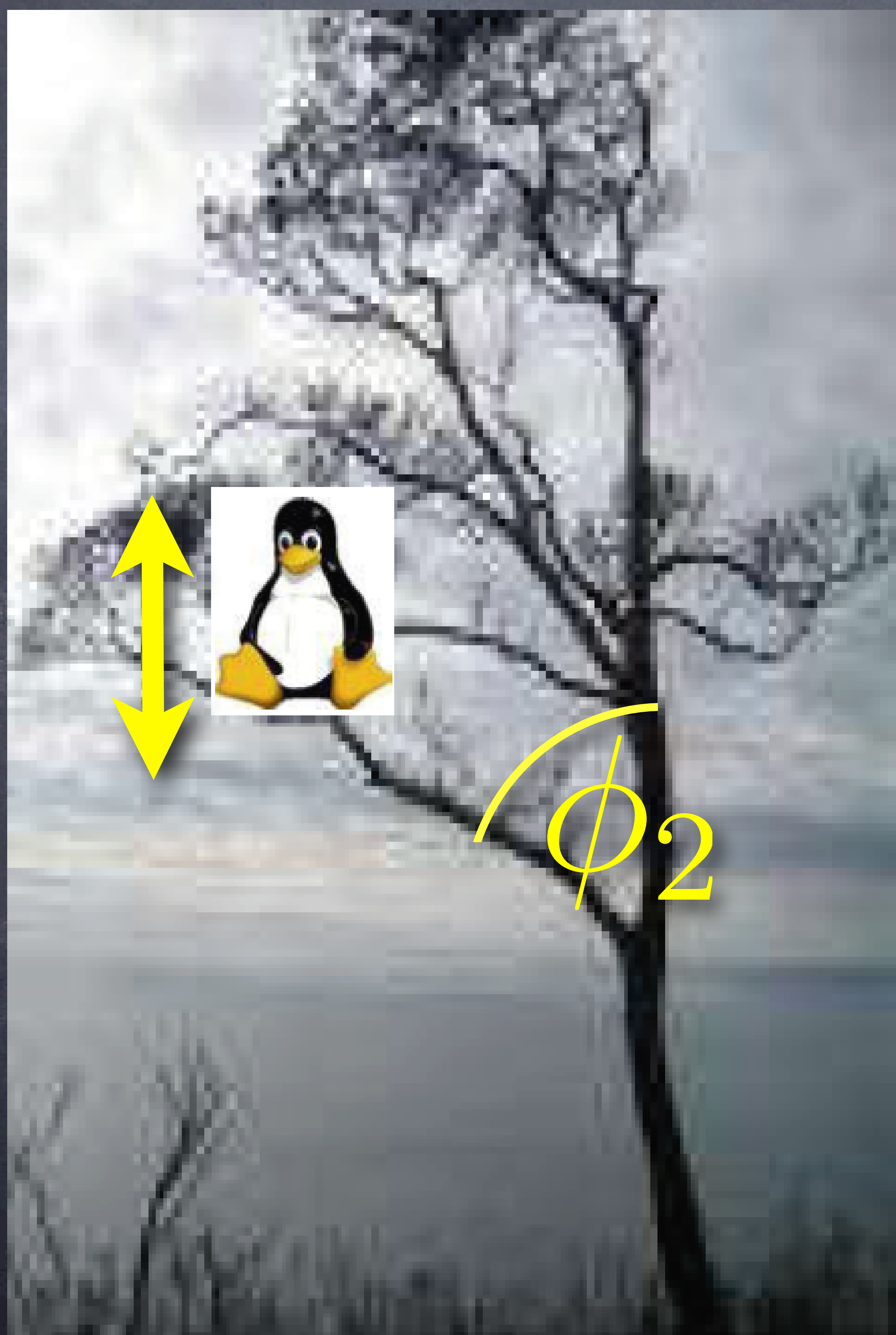
direct meas.: $\sin(2\phi_1) = 0.689^{+0.023}_{-0.021}$

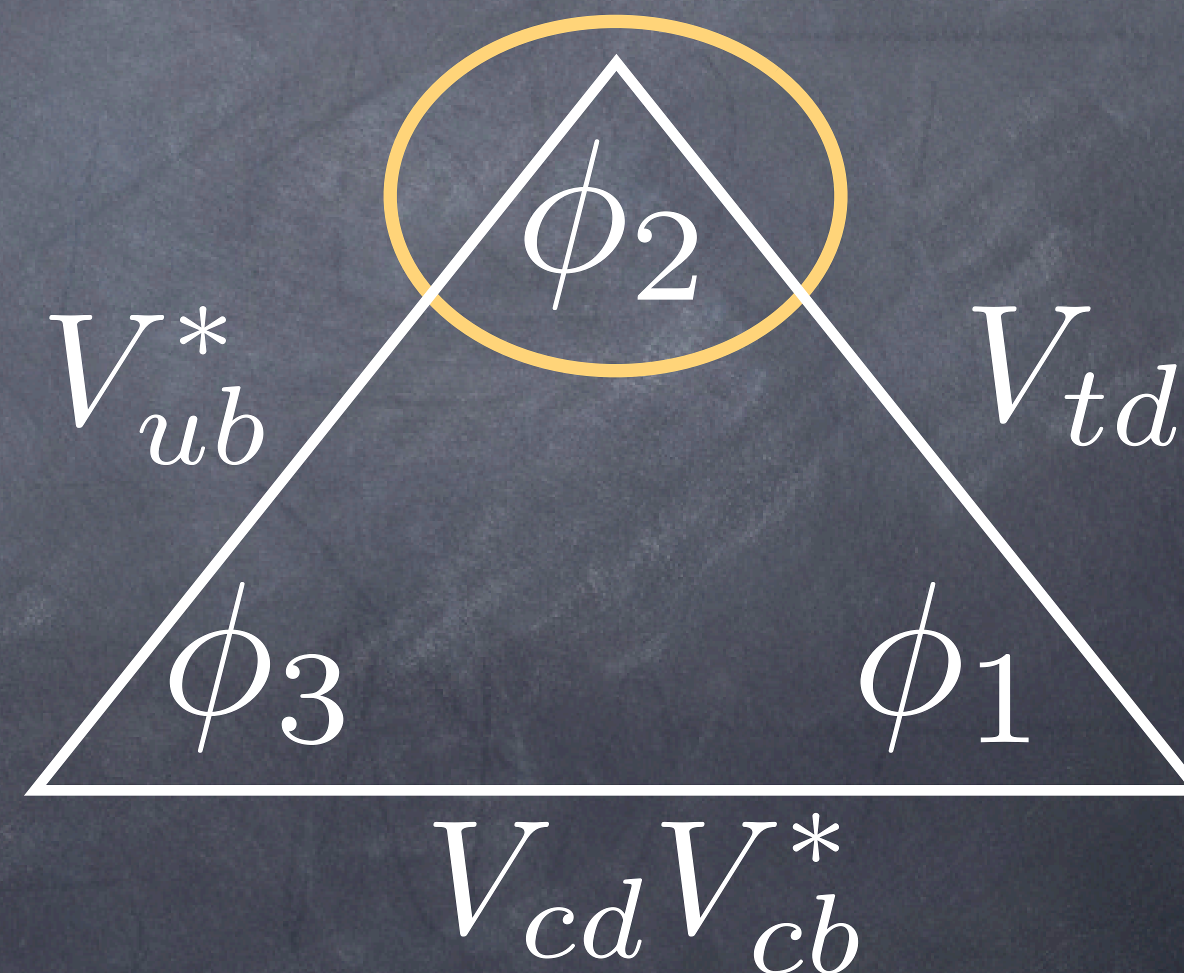
indirect fitting: $\sin(2\phi_1) = 0.830^{+0.013}_{-0.034}$

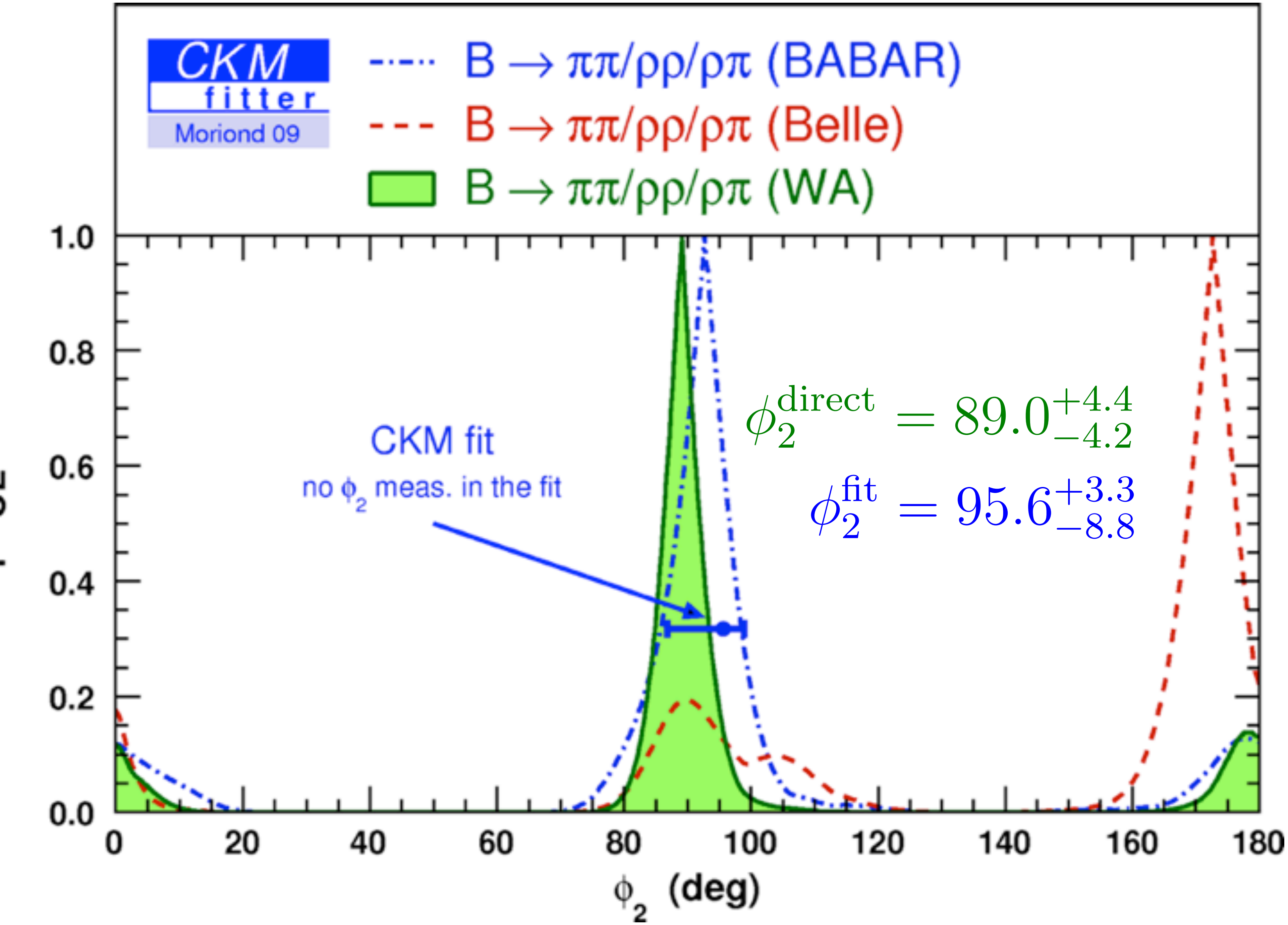
~3σ difference?

Other angles?

Unitarity triangle angles			
BABAR:	β	α	γ
BELLE:	ϕ_1	ϕ_2	ϕ_3
	易	難	魔







- ϕ_2 is dominated by $B \to \rho^+\rho^-$ (with isospin relation)

  ∵ The isospin triangle for $\rho\rho$ is almost flat

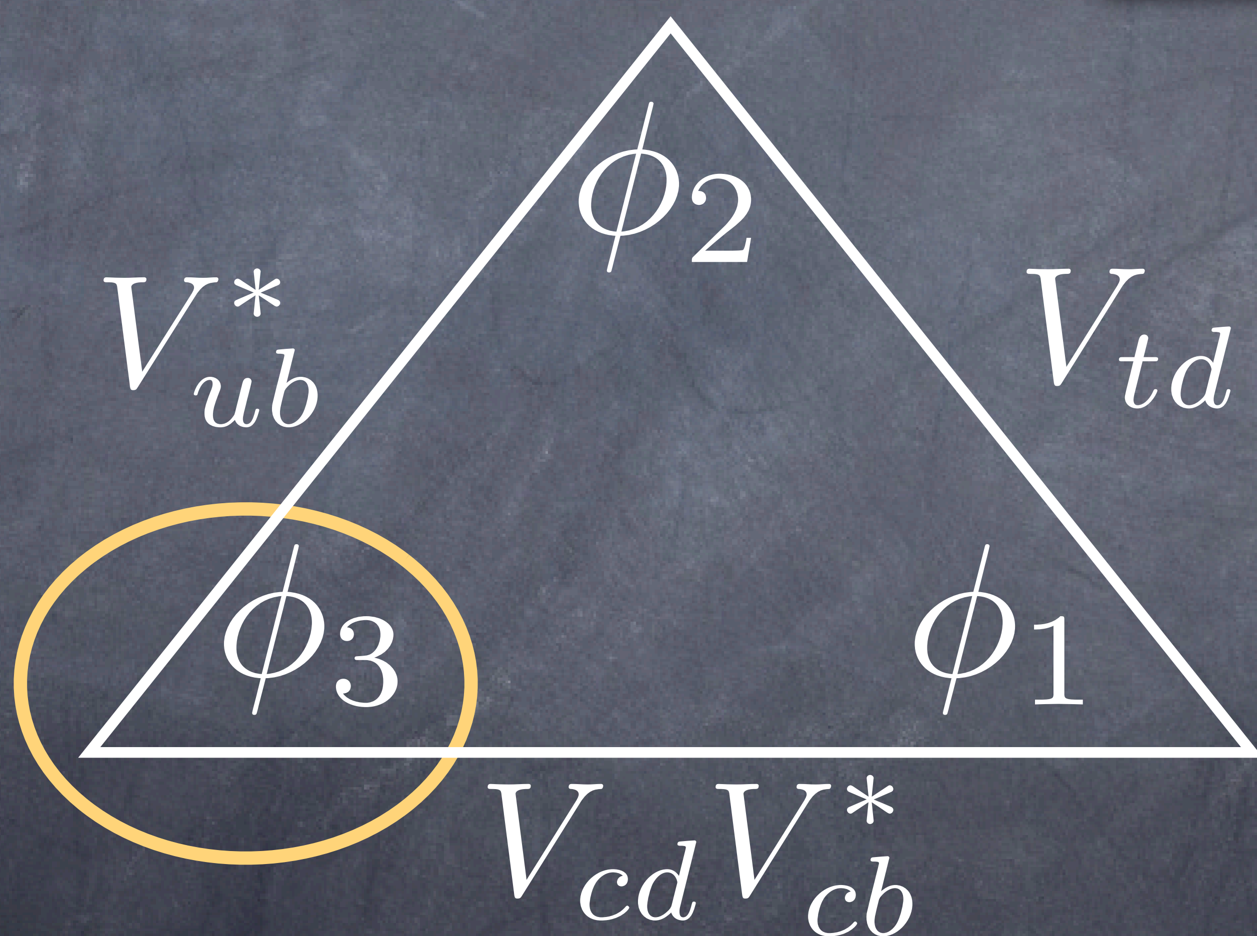
  - $\mathcal{B}(B^0 \to \rho^0\rho^0) \sim \mathcal{O}(10^{-6})$, much smaller than the others
  - New BaBar measurement (PRL 102, 141802 (2009)) of

$$\mathcal{B}(B^+ \to \rho^+\rho^0) = (23.7 \pm 1.4 \pm 1.4) \times 10^{-6}$$

  much improved the precision of the isospin triangle

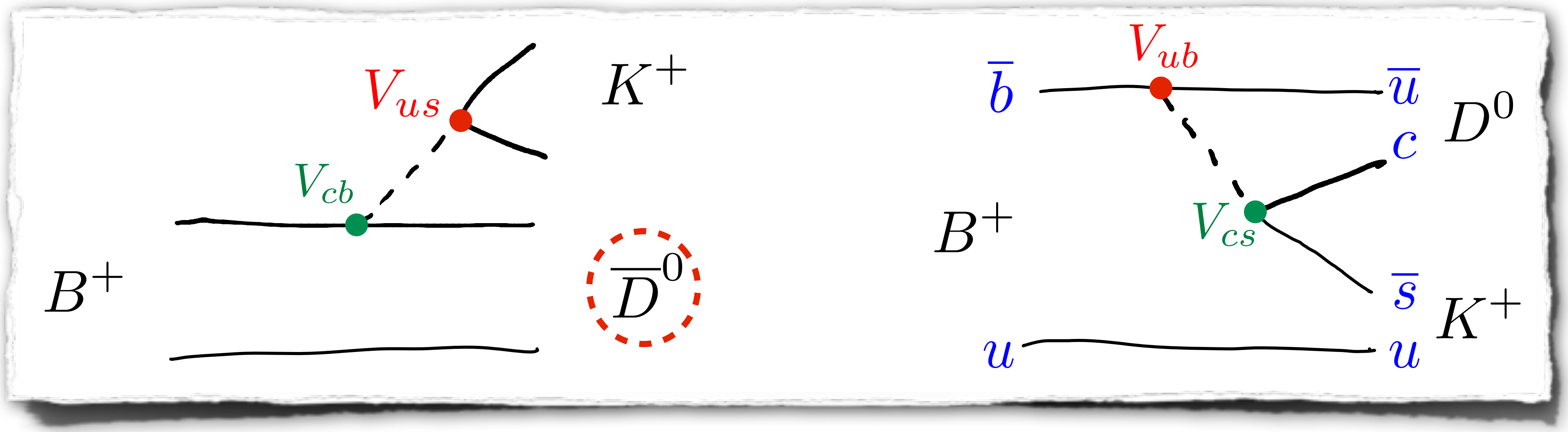
Other angles?

Unitarity triangle angles			
BABAR:	β	α	γ
BELLE:	ϕ_1	ϕ_2	ϕ_3
	易	難	魔



GLW: Gronau, London, Wyler (2001)
ADS: Atwood, Dunietz, Soni (1997)
GGSZ: Giri, Grossman, Soffer, Zupan (2003)

ϕ_3 from CPV in $B^+ \to D^{(*)}K^{(*)}$ (GGSZ)



- IF both D^0 and $\overline{D}^0$ decay into a common final state (e.g. $K_S\pi^+\pi^-$), then $B^+ \to D^0K^+$ and $B^+ \to \overline{D}^0K^+$ amplitudes interfere.

  Let $|\tilde{D}\rangle = |D^0\rangle + re^{i(\delta+\phi_3)}|\overline{D}^0\rangle$ be the mixed state.

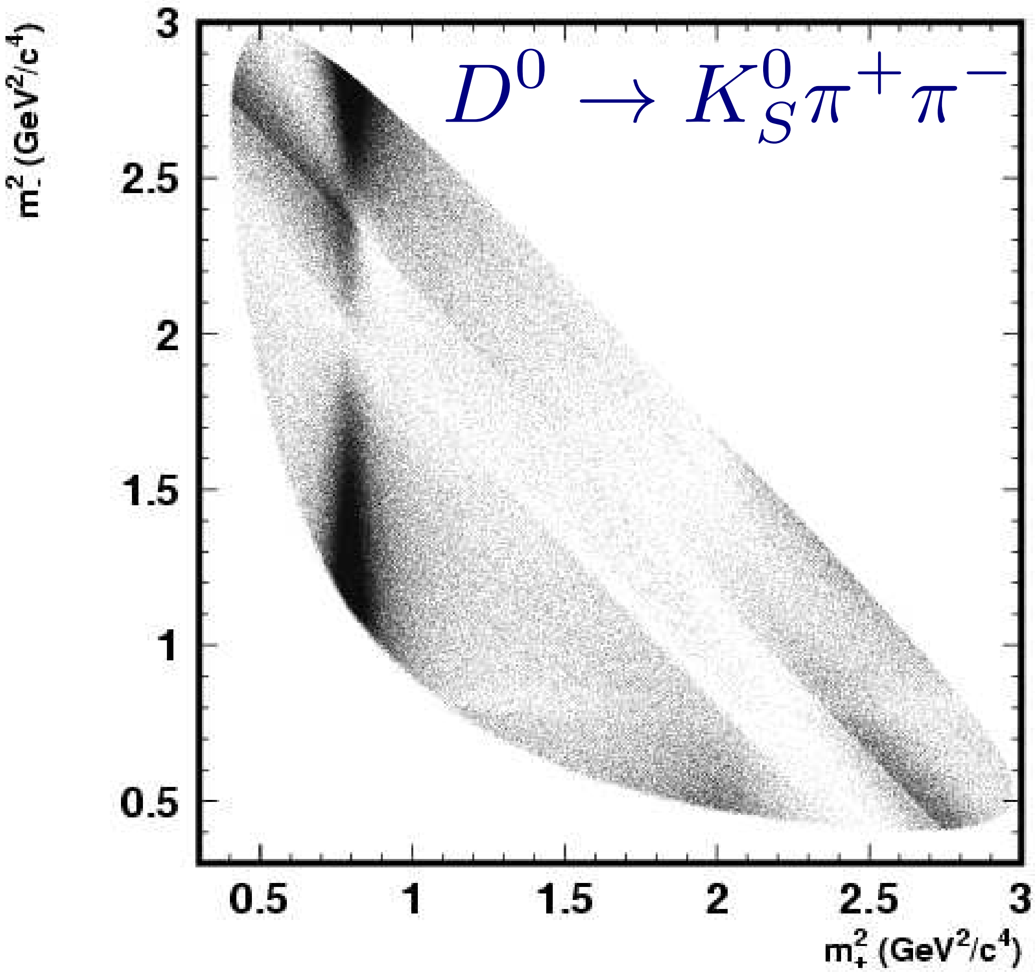
- The matrix element for the Dalitz plots are: $m_\pm = m(K_S\pi^\pm)$
  - $\mathcal{M}_+ = f(m_+^2, m_-^2) + re^{i(\delta+\phi_3)}f(m_-^2, m_+^2)$ for $B^+ \to \tilde{D}K^+$
  - $\mathcal{M}_- = f(m_-^2, m_+^2) + re^{i(\delta-\phi_3)}f(m_+^2, m_-^2)$ for $B^- \to \bar{\tilde{D}}K^-$

$$r = \left|\frac{A(B^- \to \overline{D}^0K^-)}{A(B^- \to D^0K^-)}\right| = \left|\frac{V_{ub}V_{cs}^*}{V_{cb}V_{us}^*}\right| \times [\text{color supp.}] \sim \mathcal{O}(10\%)$$

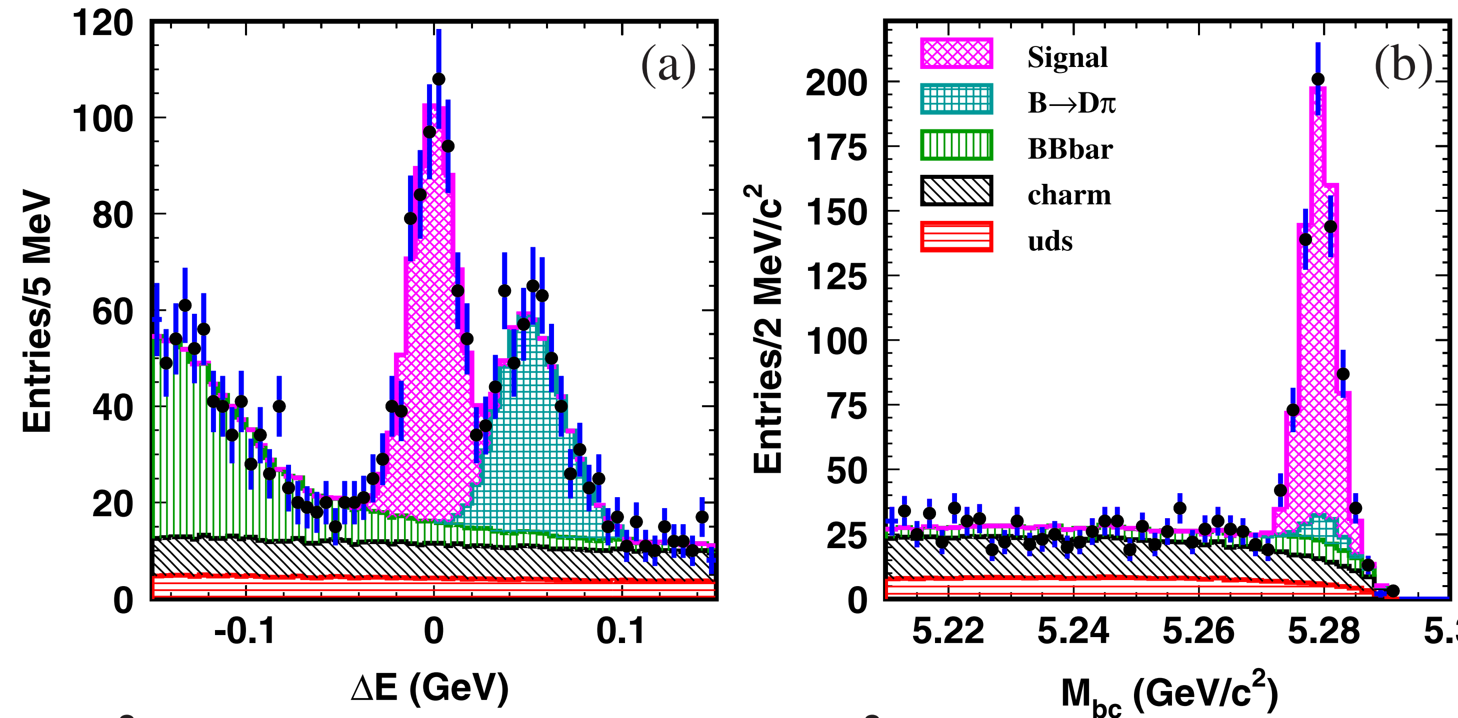
ϕ_3 from CPV in $B^+ \to D^{(*)}K^{(*)}$ (GGSZ)

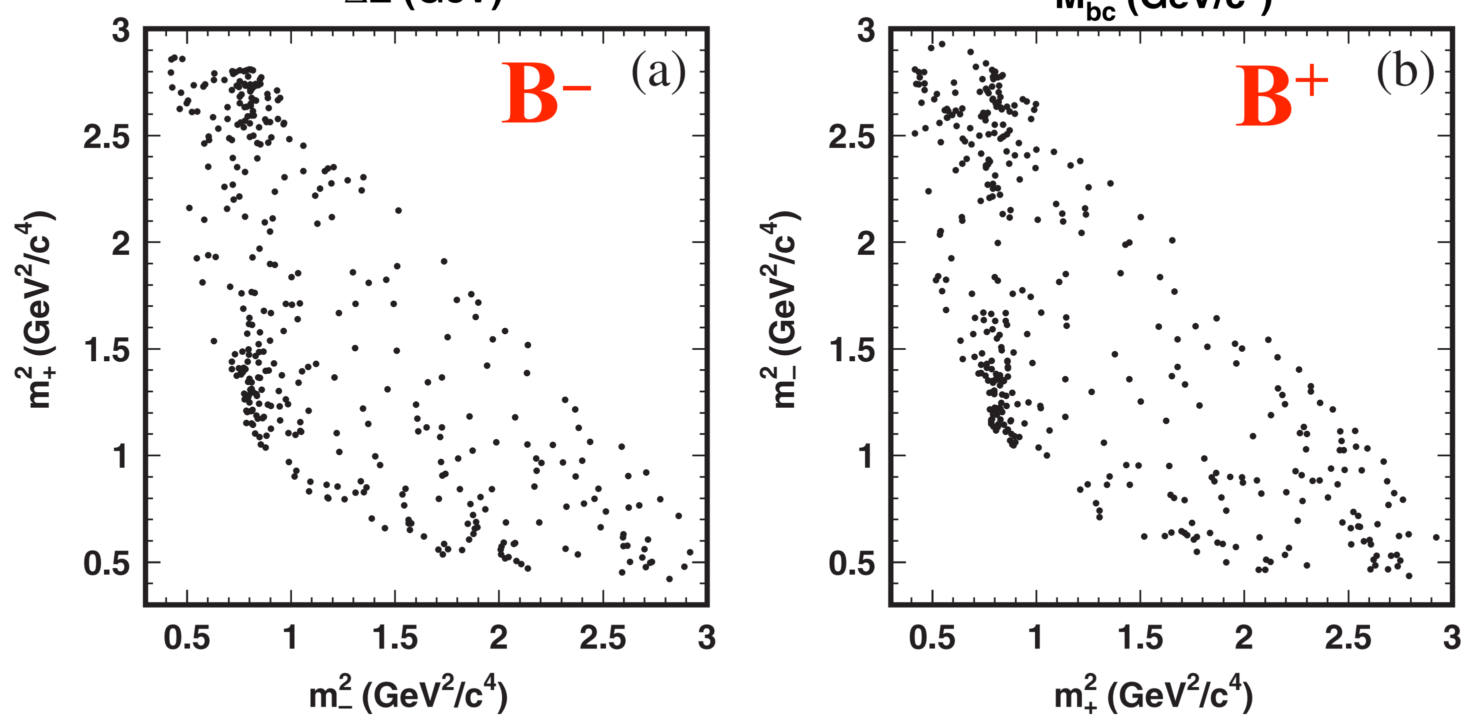
PRD 81, 112002 (2010)

Map out the Dalitz plot from all D^0 decays



Look for differences in $B^\pm \to D^0K^\pm$ plots





ϕ_3 from CPV in $B^+ \to D^{(*)}K^{(*)}$ (GGSZ)

in terms of measurables from $B^\pm$

$$x_\pm = r\cos(\delta_B \pm \phi_3)$$

$$y_\pm = r\sin(\delta_B \pm \phi_3)$$

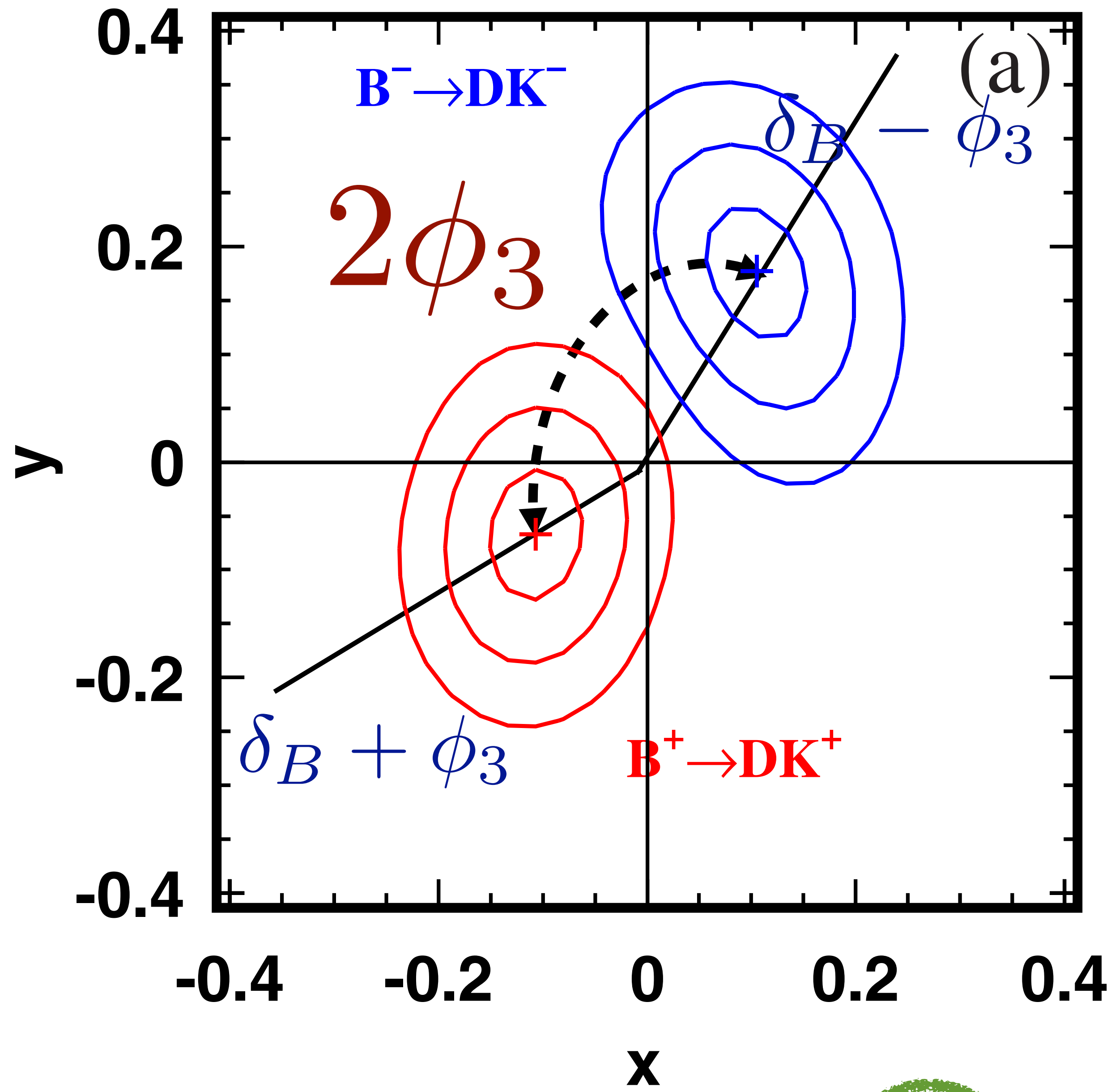
r : ratio of D/$\overline{\text{D}}$ ampl.
δ_B : D/$\overline{\text{D}}$ relative phase

Different r, δ_B for each mode $D^{(*)}K^{(*)}$

$$r_{DK} = 0.160^{+0.040}_{-0.038} \pm 0.011^{+0.050}_{-0.010}$$

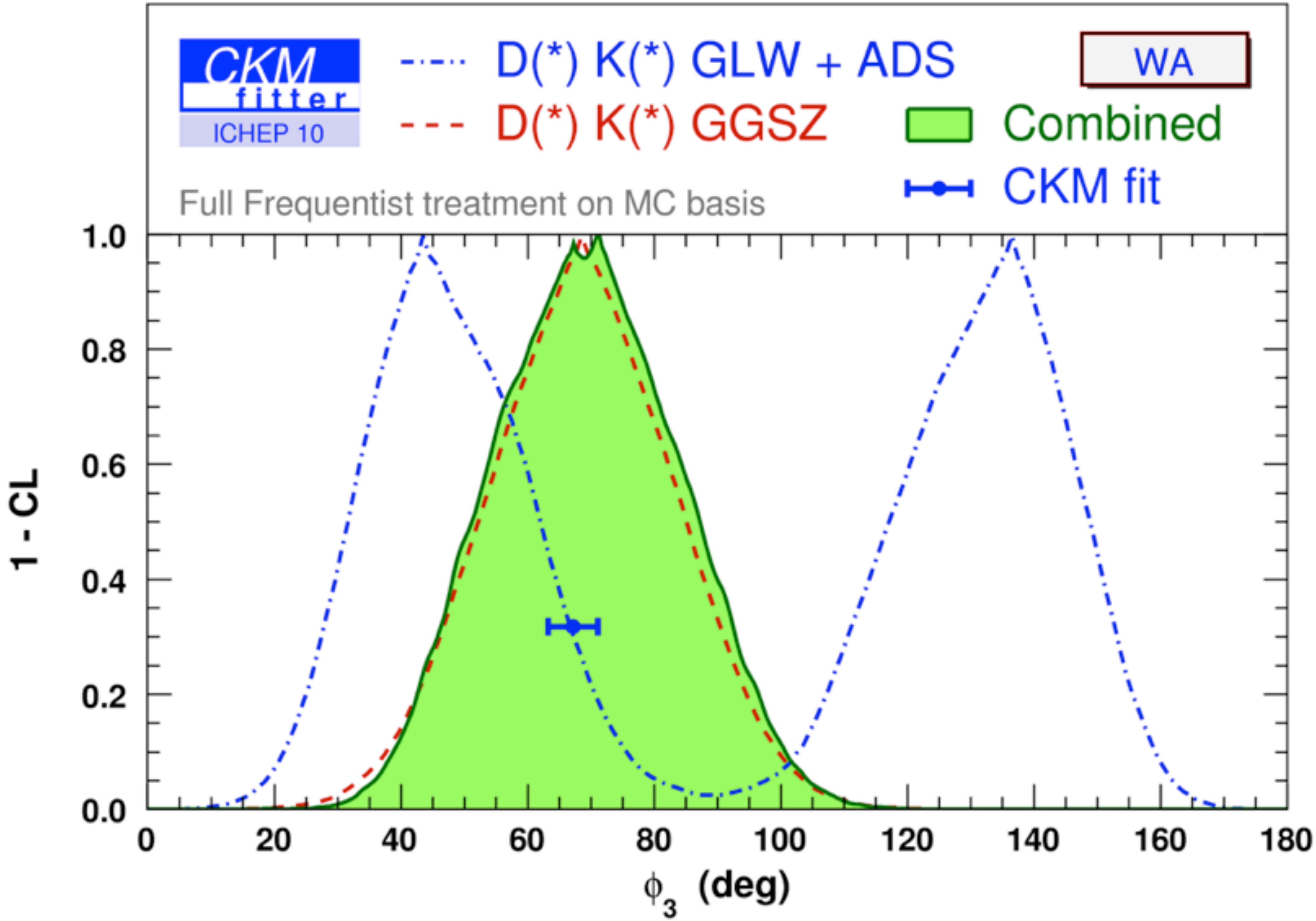
Evidence of direct CPV !!

PRD 81, 112002 (2010)



$$\phi_3 = 78.4^{+10.8}_{-11.6} \pm 3.6 \pm 8.9\,(^\circ)$$

Model-dep. error would dominate in the next-generation B-factory experiments

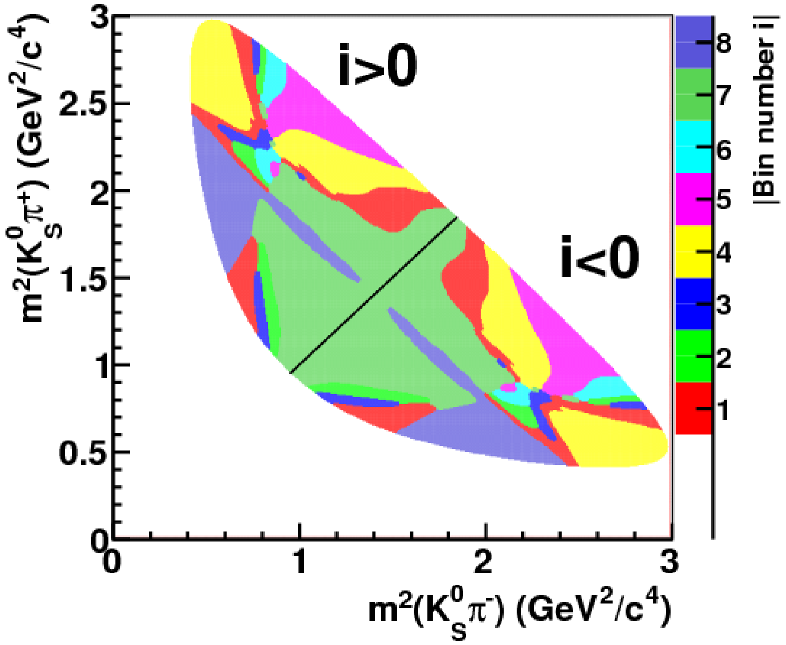


Indirect: $\phi_3 = 67.2 \pm 3.9(^\circ)$ Direct: $\phi_3 = 71^{+21}_{-25}\,(^\circ)$

(GGSZ) model-independent analysis

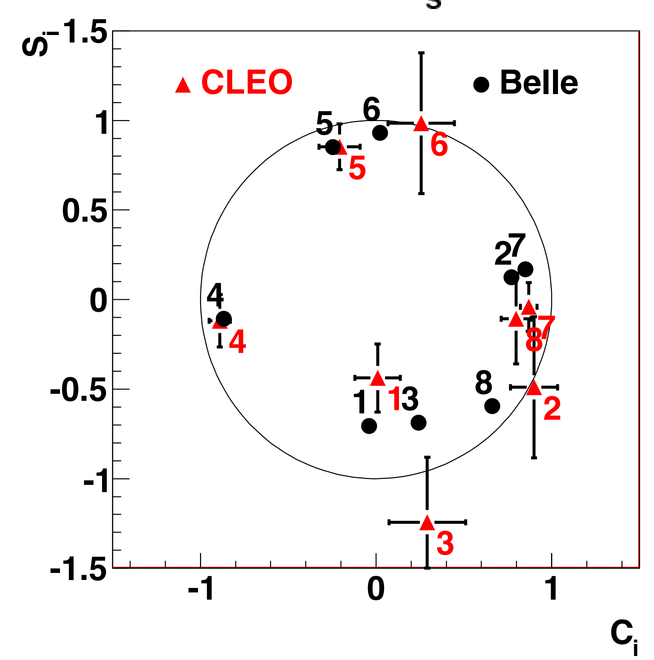
Bondar & Poluektov, EPJ C55, 51 (2008)

- fit over binned Dalitz plot
  - model-independent, but
  - reduced statistical power
  - compensate by smart choice of binning
    - "optimal binning" depends on model, but the resulting ϕ_3 does not --> no bias!



$$M_i^{\pm} = h\left\{K_i + r^2 K_{-i} + 2\sqrt{K_i K_{-i}}(x_\pm c_i + y_\pm s_i)\right\}$$

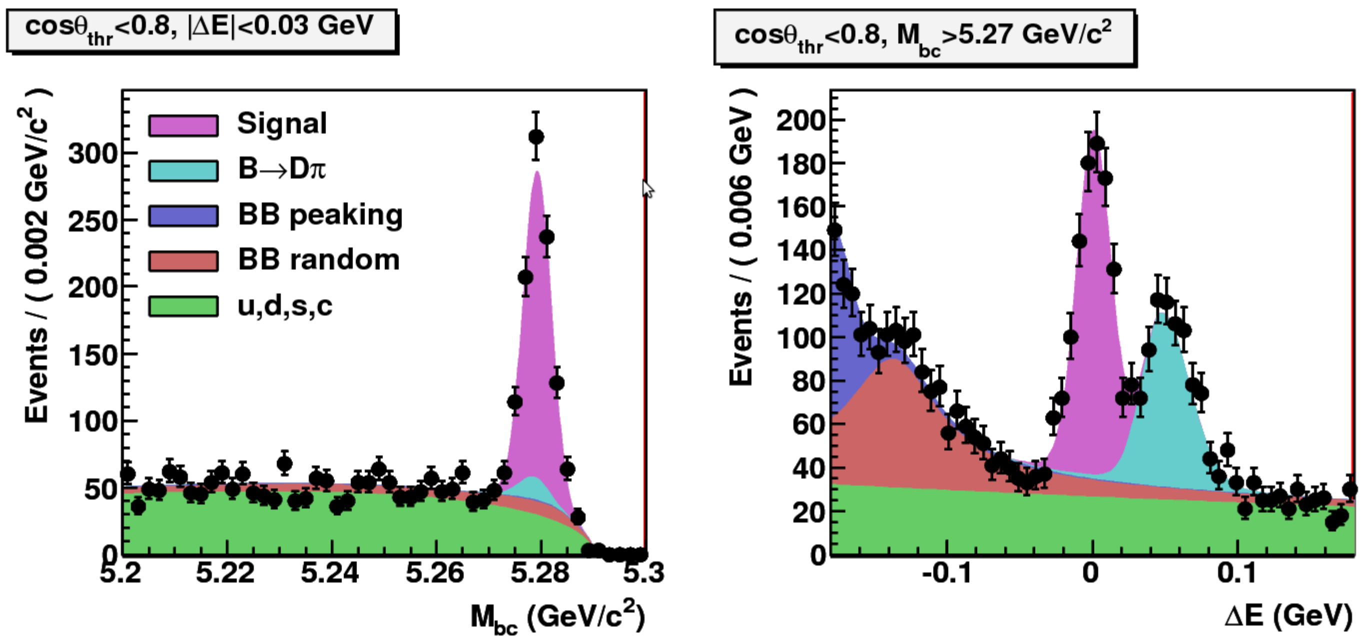
$$x_\pm = r\cos(\delta_B \pm \phi_3), \quad y_\pm = r\sin(\delta_B \pm \phi_3)$$



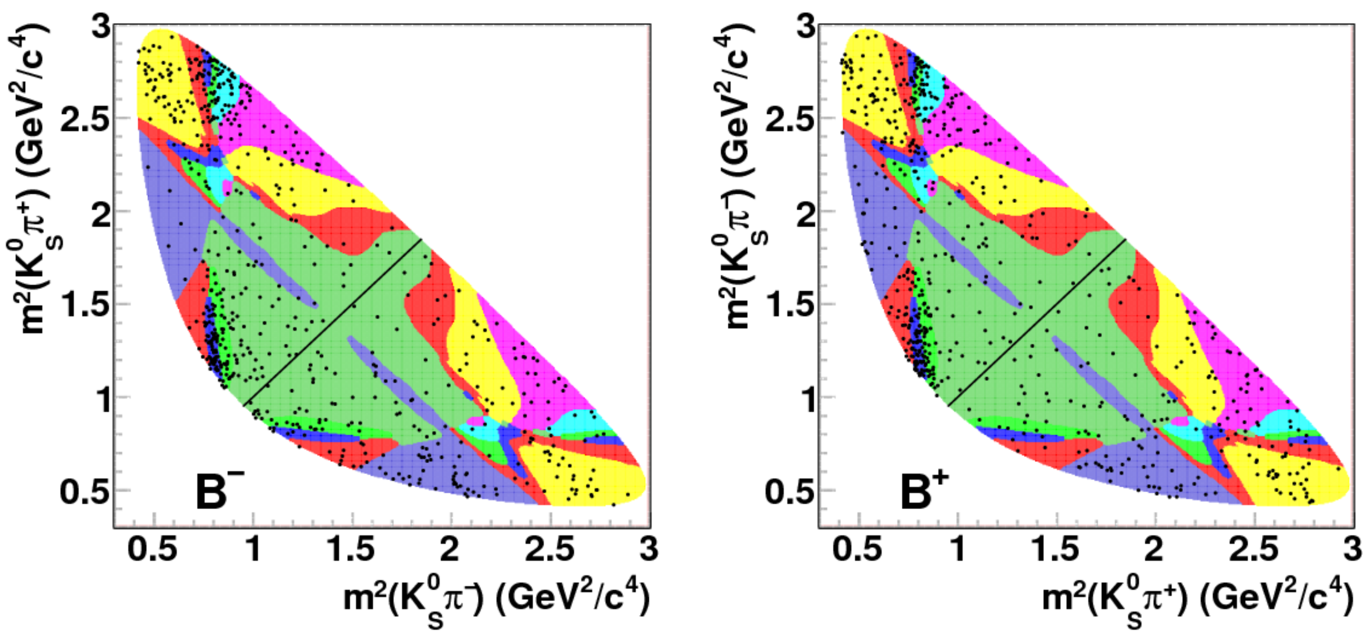
c_i & s_i contain info. about strong phase difference b/w symmetric D^0 decay Dalitz plot points;

use CLEO result in $\psi(3770) \to D^0\overline{D}^0$

(GGSZ) model-independent analysis

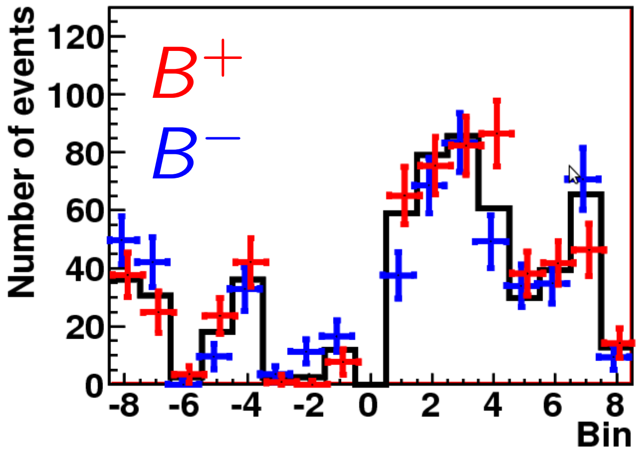


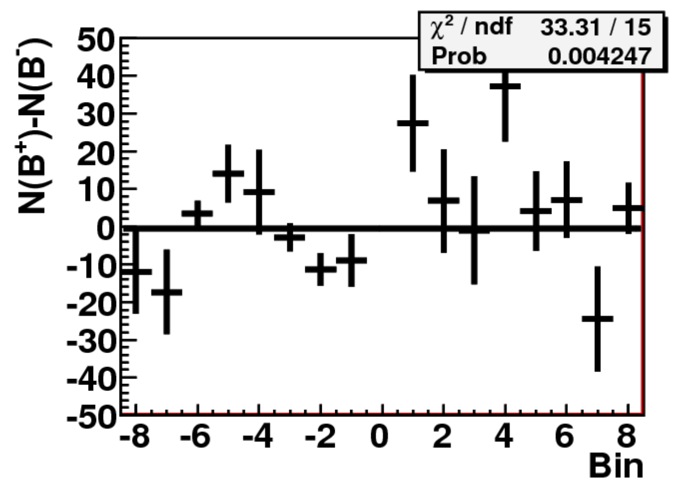
$B^- \to D^0 K^-$: $B^+ \to D^0 K^+$:



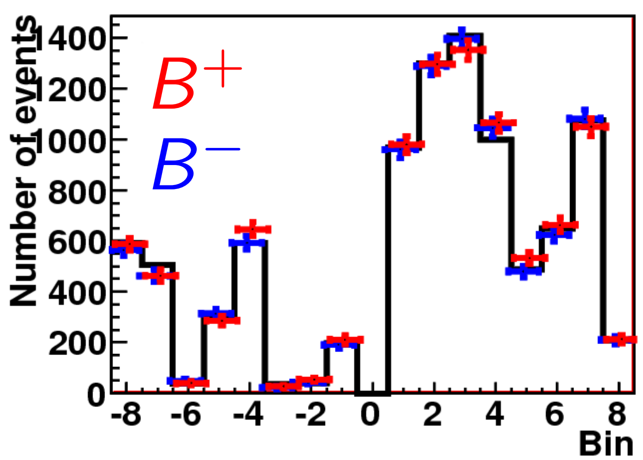
- Belle preliminary
  - N(BB) = 772M
  - much improved efficiency with reprocessed data
  - 4D unbinned fit for each Dalitz plot bin
  - N(sig) = 1176 ± 43

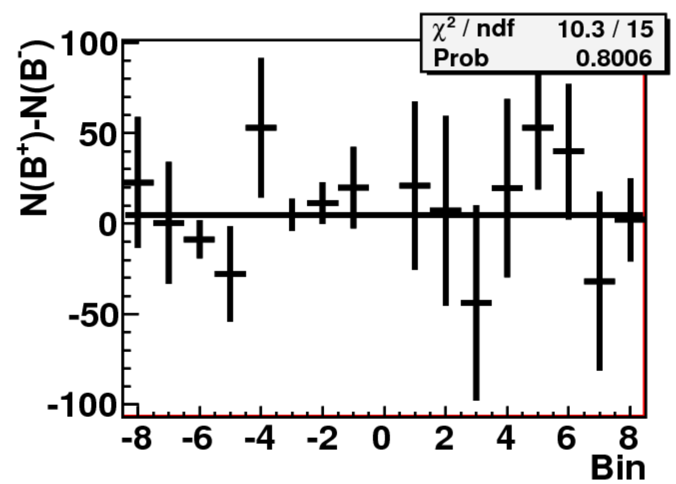
(GGSZ) model-independent analysis





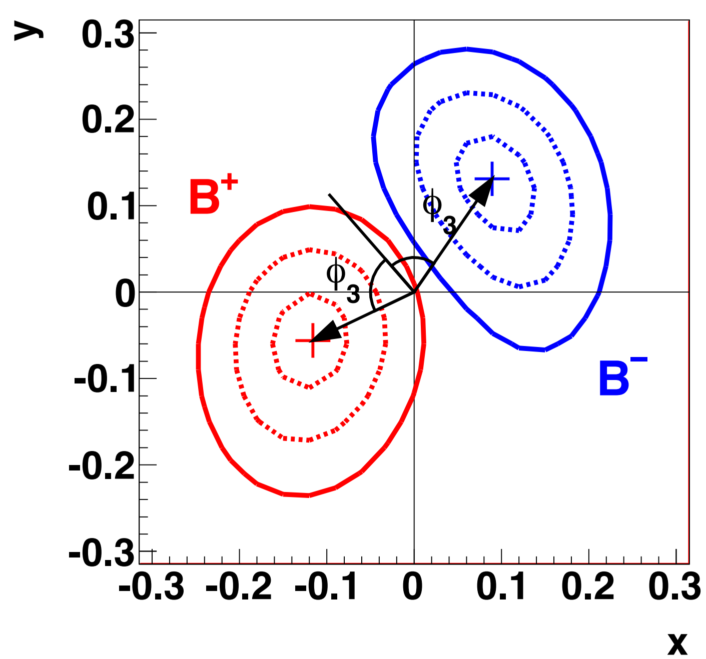
$B^{\pm} \to DK^{\pm}$





$B^{\pm} \to D\pi^{\pm}$

control sample



Belle preliminary

$$\phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.2 \pm 4.3)^{\circ}$$

$$\delta_B = (129.9 \pm 15.0 \pm 3.9 \pm 4.7)^{\circ}$$

$$r = 0.145 \pm 0.030 \pm 0.011 \pm 0.011$$

First evidence for the ADS mode

- **A**twood, **D**unietz, **S**oni, PRL 78, 3257 (1997)
  - *B* --> *D K*+ with “wrong-sign” [*K* π]*D*

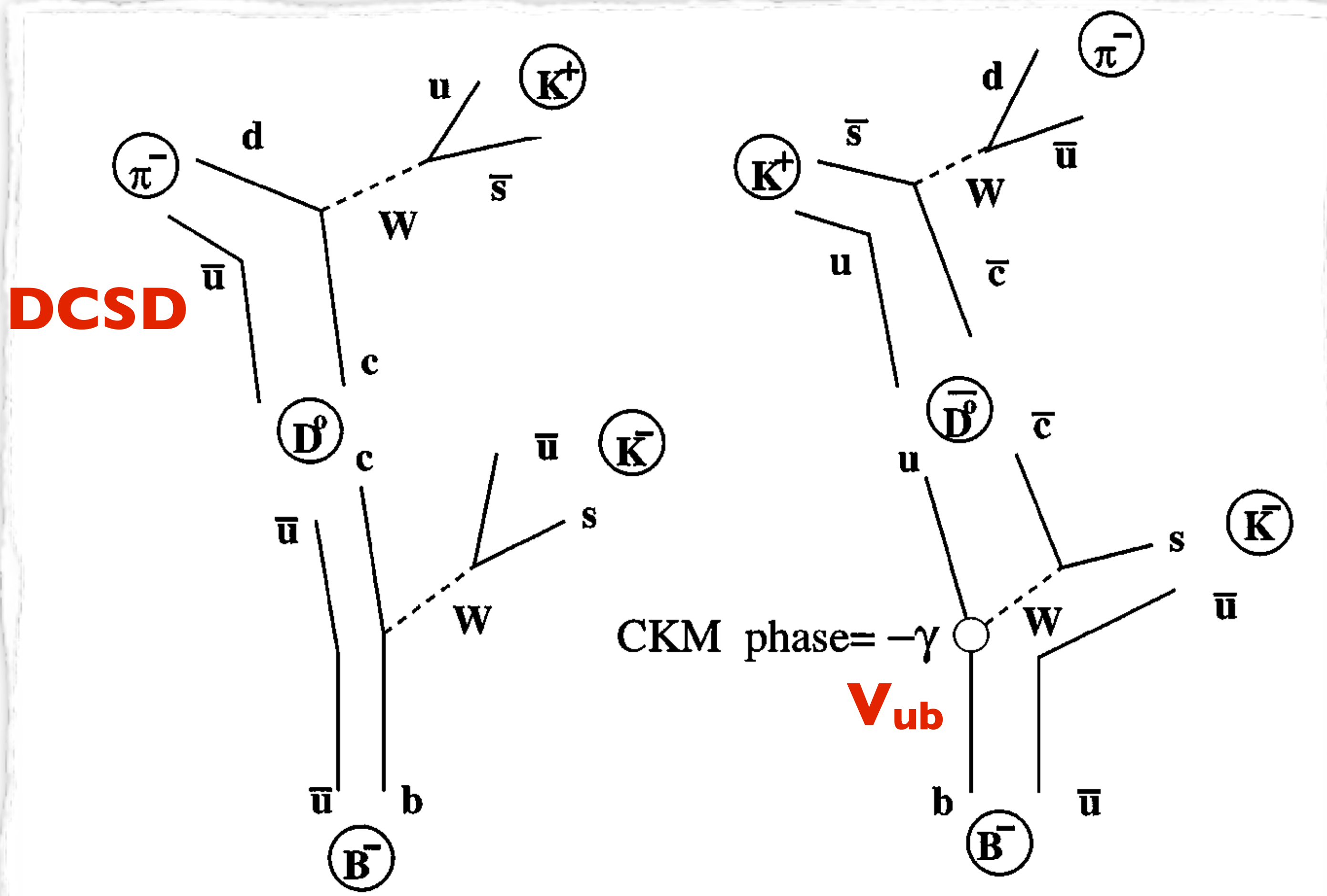


FIG. 1. Diagrams for the two interfering processes: $B^- \longrightarrow K^- D^0$ (color-allowed) followed by $D^0 \longrightarrow K^+\pi^-$ (doubly Cabibbo suppressed) and $B^- \longrightarrow K^-\overline{D}^0$ (color-suppressed) followed by $\overline{D}^0 \longrightarrow K^+\pi^-$ (Cabibbo allowed).

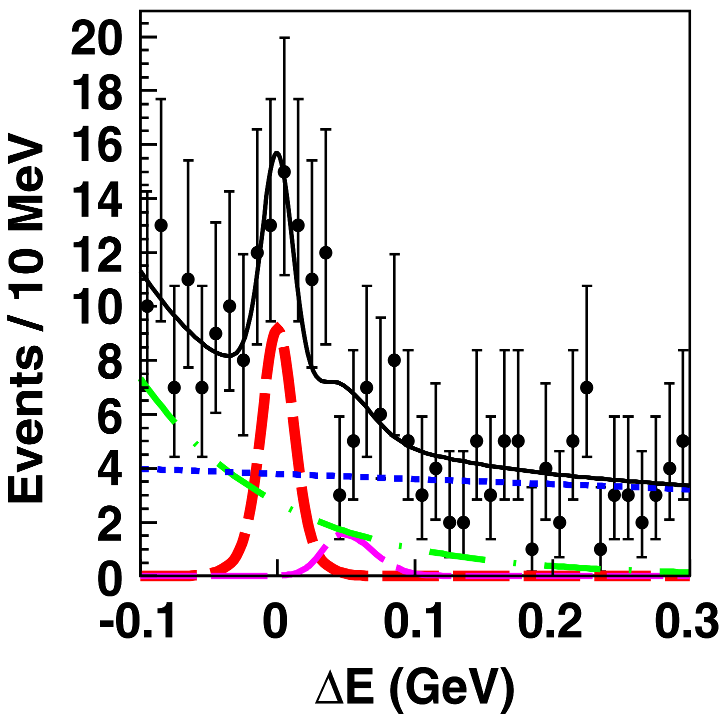
$$\mathcal{R}_{DK} \equiv \frac{\mathcal{B}([K^+\pi^-]_D K^-) + \mathcal{B}([K^-\pi^+]_D K^+)}{\mathcal{B}([K^-\pi^+]_D K^-) + \mathcal{B}([K^+\pi^-]_D K^+)}$$

$$\mathcal{A}_{DK} \equiv \frac{\mathcal{B}([K^+\pi^-]_D K^-) - \mathcal{B}([K^-\pi^+]_D K^+)}{\mathcal{B}([K^+\pi^-]_D K^-) + \mathcal{B}([K^-\pi^+]_D K^+)}$$

$$\mathcal{R}_{DK} = r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos\phi_3$$

$$\mathcal{A}_{DK} = 2 r_B r_D \sin(\delta_B + \delta_D)\sin\phi_3/\mathcal{R}_{DK},$$

First evidence for the ADS mode



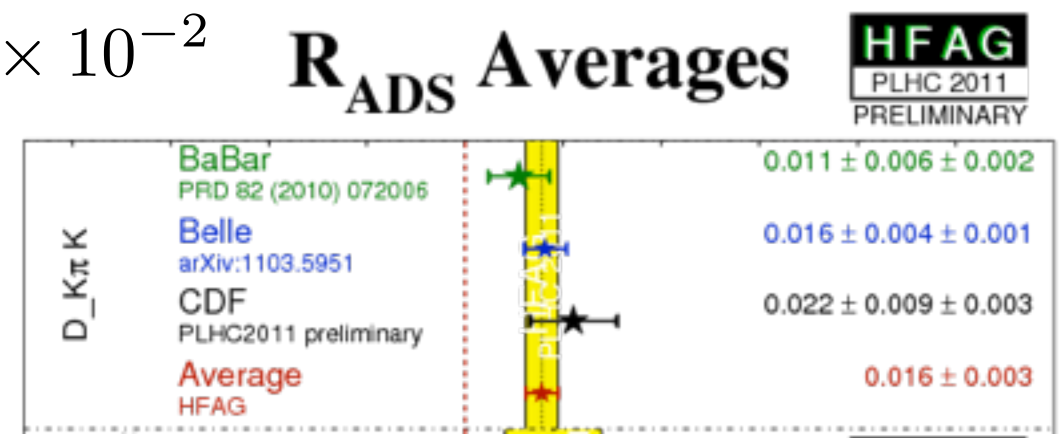
- First evidence (sig. = 4.1σ)

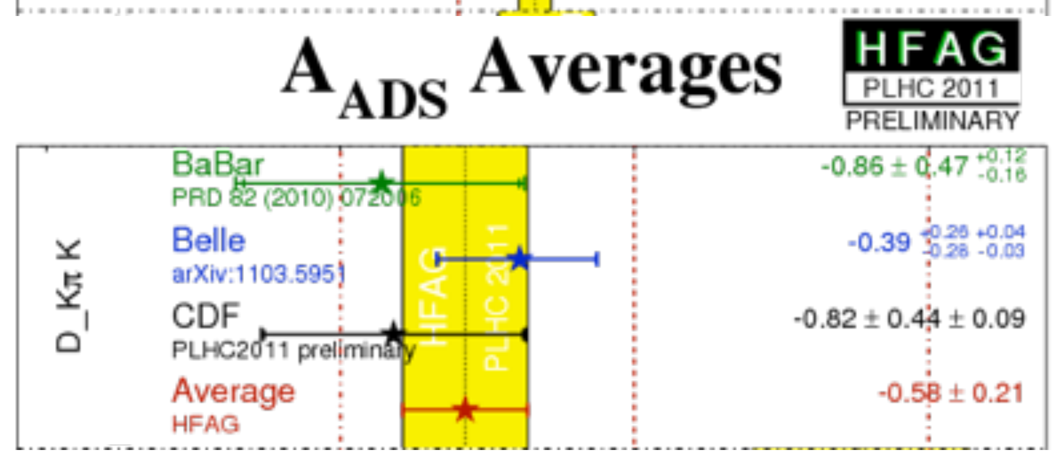
PRL 106, 231803 (2011)

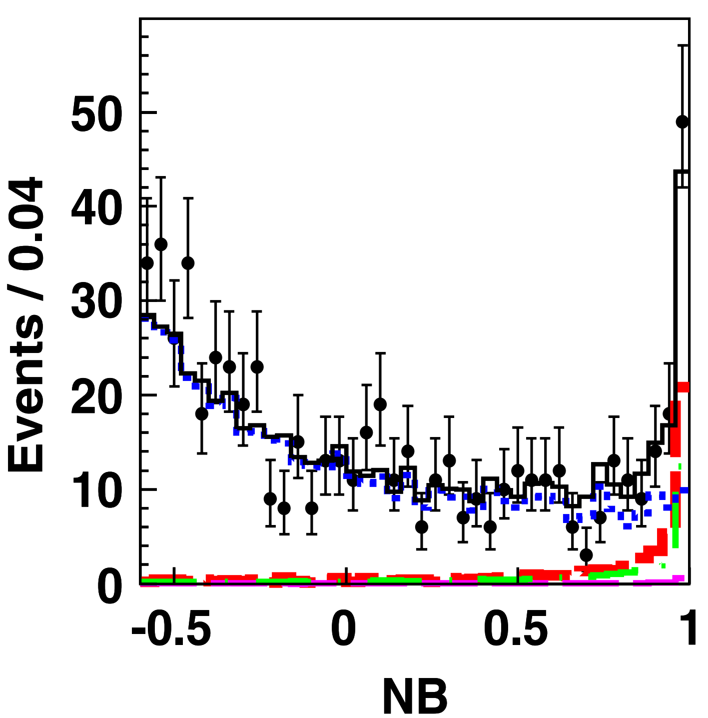
Mode	Yield	Efficiency (%)	Significance
$B^- \to [K^+\pi^-]_D K^-$	$56.0^{+15.1}_{-14.2}$	33.6 ± 0.4	4.1σ
$B^- \to [K^-\pi^+]_D K^-$	3394^{+68}_{-69}	33.2 ± 0.4	
$B^- \to [K^+\pi^-]_D \pi^-$	$165.0^{+19.1}_{-18.1}$	36.5 ± 0.4	9.2σ
$B^- \to [K^-\pi^+]_D \pi^-$	49164^{+245}_{-244}	35.7 ± 0.4	

$$\mathcal{R}_{DK} = (1.63^{+0.44+0.07}_{-0.41-0.13}) \times 10^{-2}$$

$$\mathcal{A}_{DK} = -0.39^{+0.26+0.04}_{-0.28-0.03}$$







Neural network (NB) for much improved continuum suppression

B decays for CKM UT sides

- $|V_{cb}|$ from $B^0 \to D^{*-}\ell^+\nu$
- $|V_{ub}|$ from $B^0 \to \pi^-\ell^+\nu$

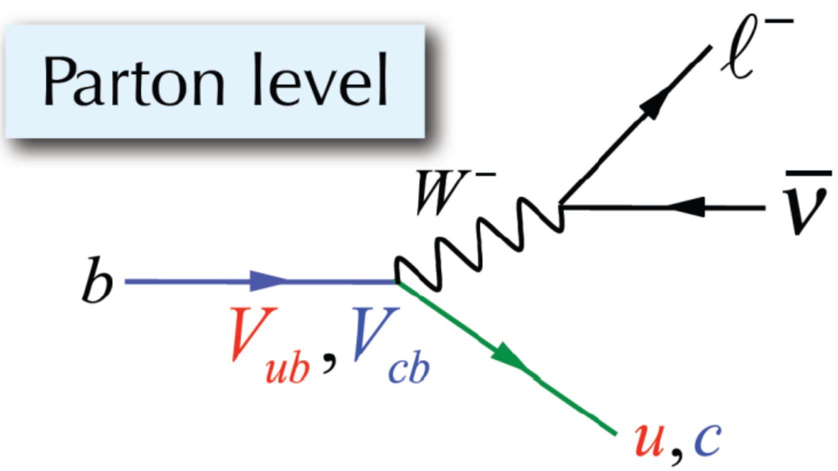
$B \to X\ell\nu$ and CKM

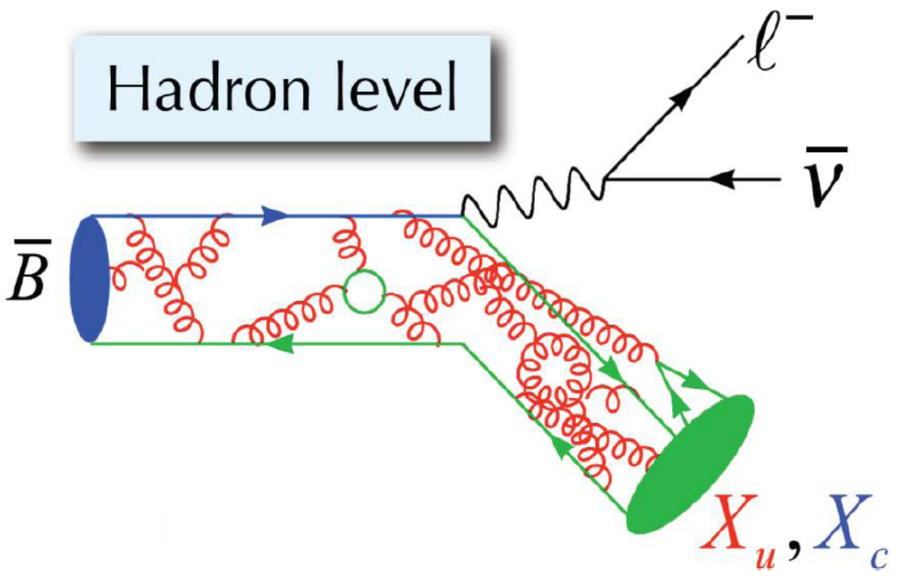
- Semileptonic B decays ($B \to X\ell\nu$)
  – directly related to CKM elements $|V_{cb}|$ and $|V_{ub}|$

$$\mathcal{M}(M_{Q\bar{q}} \to X_{q'\bar{q}}\,\ell\bar{\nu}) = -i\frac{G_F}{\sqrt{2}}V_{q'Q}\,L^{\mu}H_{\mu}$$

$$L^{\mu} = \bar{u}_{\ell}\gamma^{\mu}(1-\gamma_5)v_{\nu} \quad H_{\mu} = \langle X|\bar{q}'\gamma_{\mu}(1-\gamma_5)Q|M\rangle$$

- Understanding hadronic effects is the big challenge





- Independent theoretical approaches for inclusive (OPE) and exclusive (FF) decay processes

$|V_{cb}|$ from exclusive B decays

- based on differential decay rate of $B \to D\ell^+\nu_\ell$ and $D^*\ell^+\nu_\ell$
- limited by knowledge of $B \to D^{(*)}$ form factors
  but form factors become unity in the heavy-quark limit

$$\frac{d\Gamma}{dw}(\overline{B} \to D\ell\overline{\nu}_\ell) = \frac{G_F^2}{48\pi^3\hbar} M_D^3 (M_B + M_D)^2 (w^2 - 1)^{3/2} \mid V_{cb} \mid^2 \mathcal{G}^2(w)$$

$$w = v_B \cdot v_{D^{(*)}}$$

$$\frac{d\Gamma}{dw}(\overline{B} \to D^*\ell\overline{\nu}_\ell) = \frac{G_F^2}{48\pi^3} |V_{cb}|^2 m_{D^*}^3 (w^2 - 1)^{1/2} P(w) (\mathcal{F}(w))^2$$

in heavy quark limit,

$$\lim_{w \to 1} \mathcal{F}(w), \mathcal{G}(w) = 1$$

- $|V_{cb}|$ is extracted by extrapolating $d\Gamma/dw$ to $w \to 1$
  needs assumption about form factor shape

$B^0 \to D^{*-}\ell^+\nu_\ell$ for $|V_{cb}|$

PRD **82**, 112007 (2010)

- untagged analysis, based on full Belle sample ($\mathcal{L} = 711\ \mathrm{fb}^{-1}$)

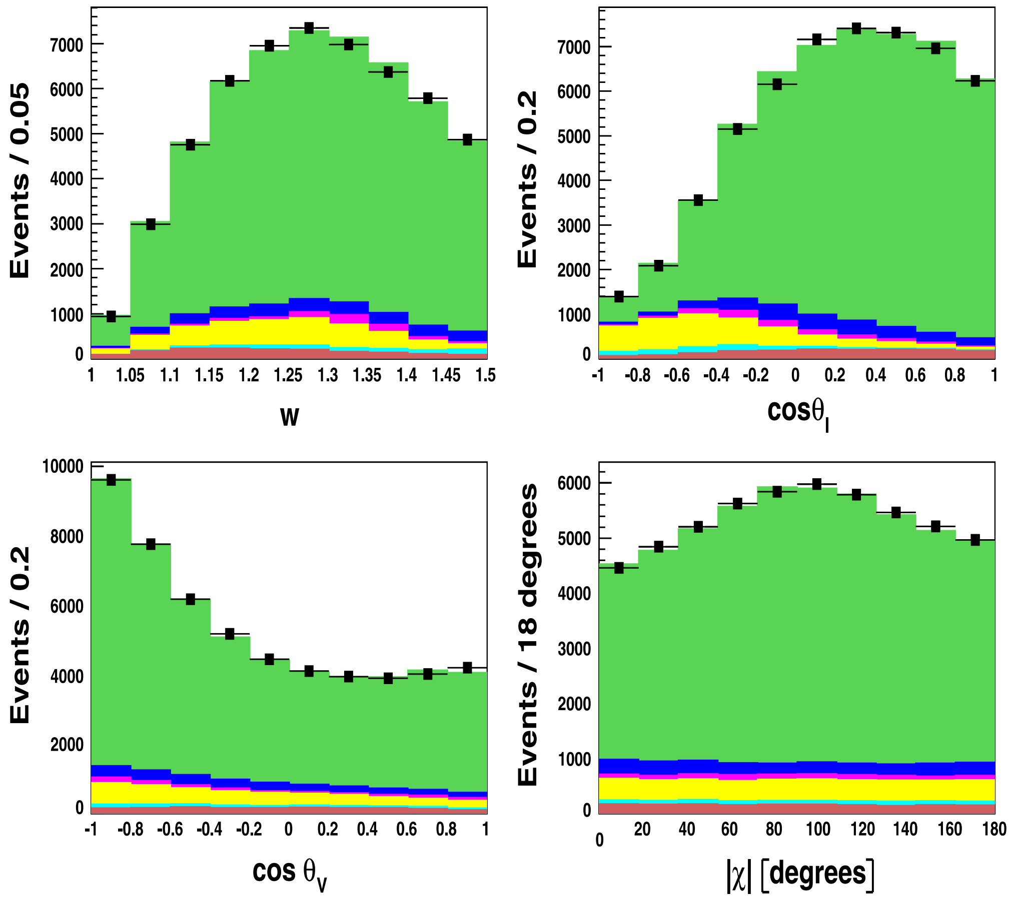
  updated from prelim. result ($140\ \mathrm{fb}^{-1}$)

- Reduced systematic error

  exploiting large statistics

  * use cleanest mode only $D^{*-} \to \bar{D}^0\pi^-, \quad \bar{D}^0 \to K^+\pi^-$ to reduce systematic error
  * 1/2 sample is used only for π_s efficiency calibration
  * uses the other 1/2 for analysis $\sim$ 120K $B^0 \to D^{*-}\ell^+\nu_\ell$ evts.

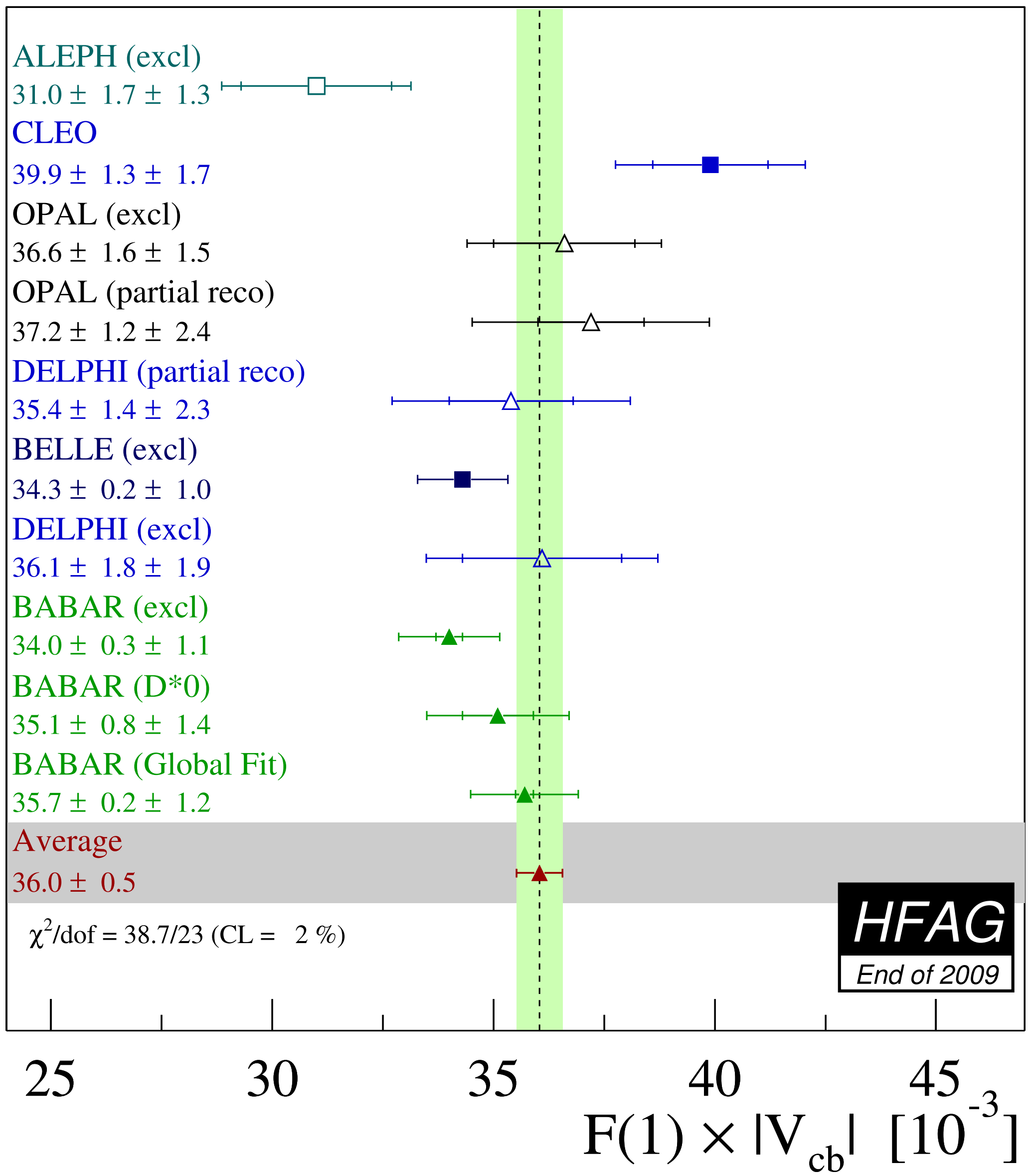
- BF and form factors, obtained from fits to $(w, \cos\theta_\ell, \cos\theta_\nu, \chi)$

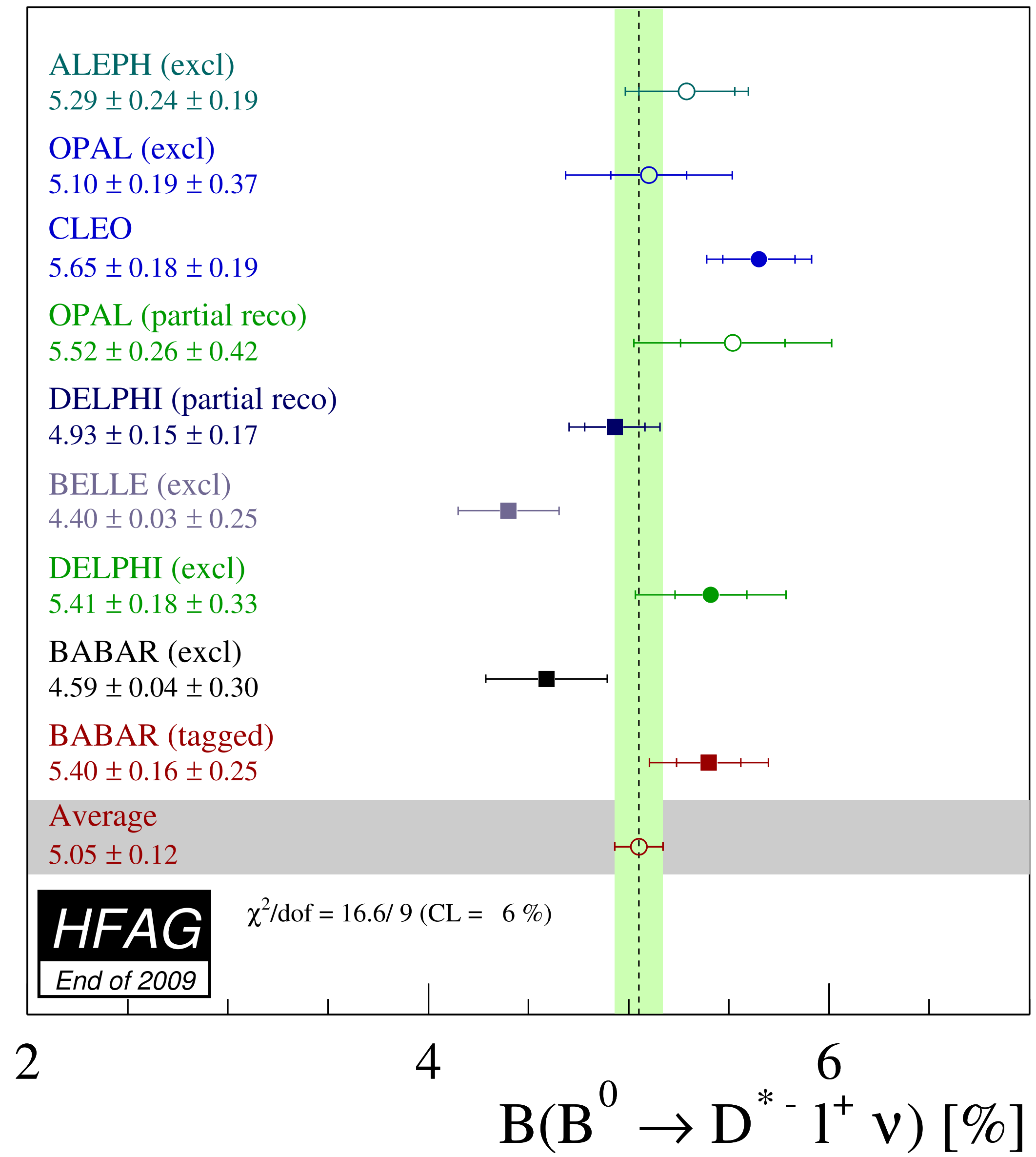


$$\mathcal{F}(1)|V_{cb}| = (34.6 \pm 0.2 \pm 1.0) \times 10^{-3}$$
$$\rho^2 = 1.214 \pm 0.034 \pm 0.009,$$
$$R_1(1) = 1.401 \pm 0.034 \pm 0.018,$$
$$R_2(1) = 0.864 \pm 0.024 \pm 0.008,$$
$$\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell) = (4.58 \pm 0.03 \pm 0.26)\%.$$

$|V_{cb}|$ from exclusive B decays

- world average

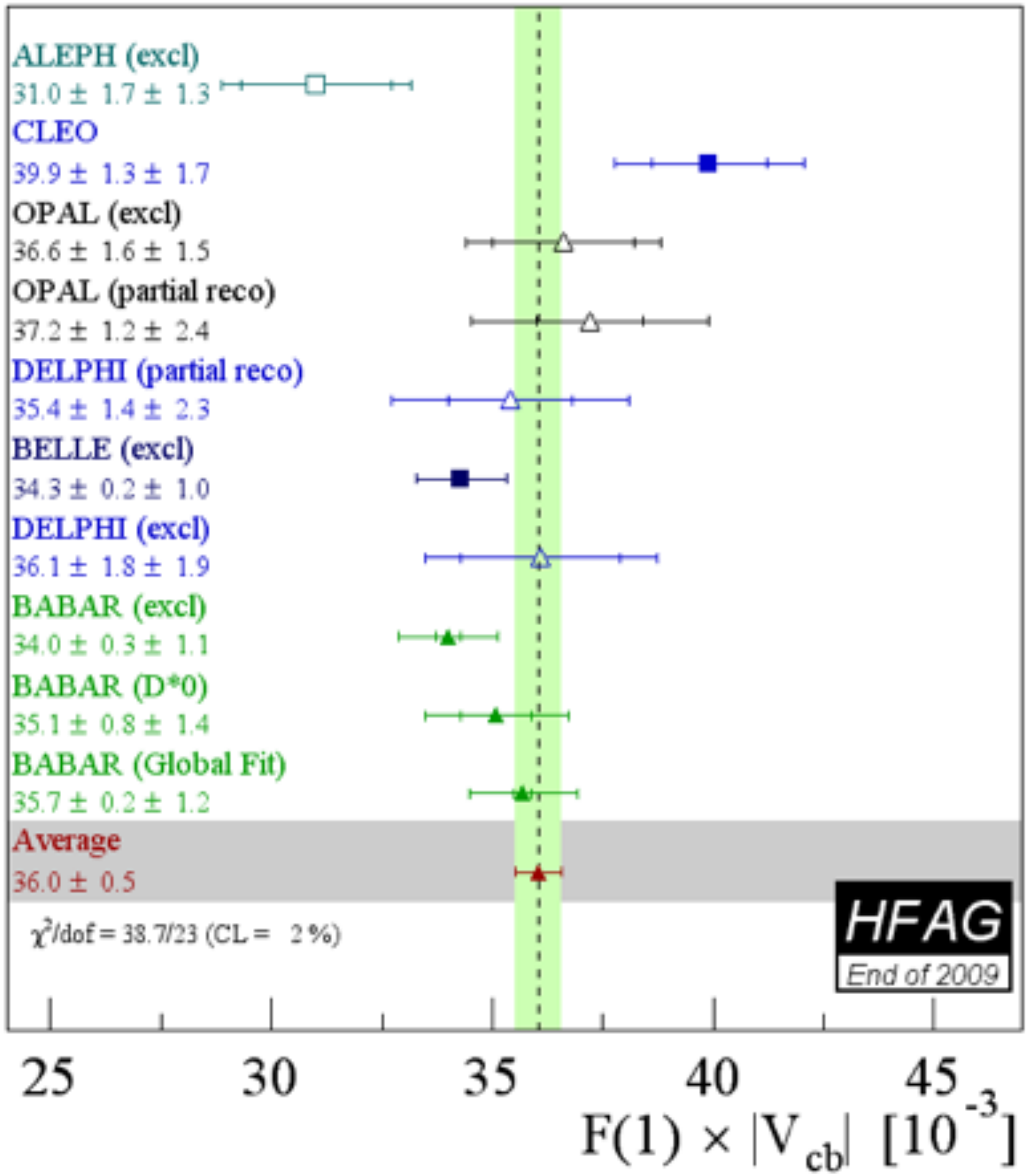


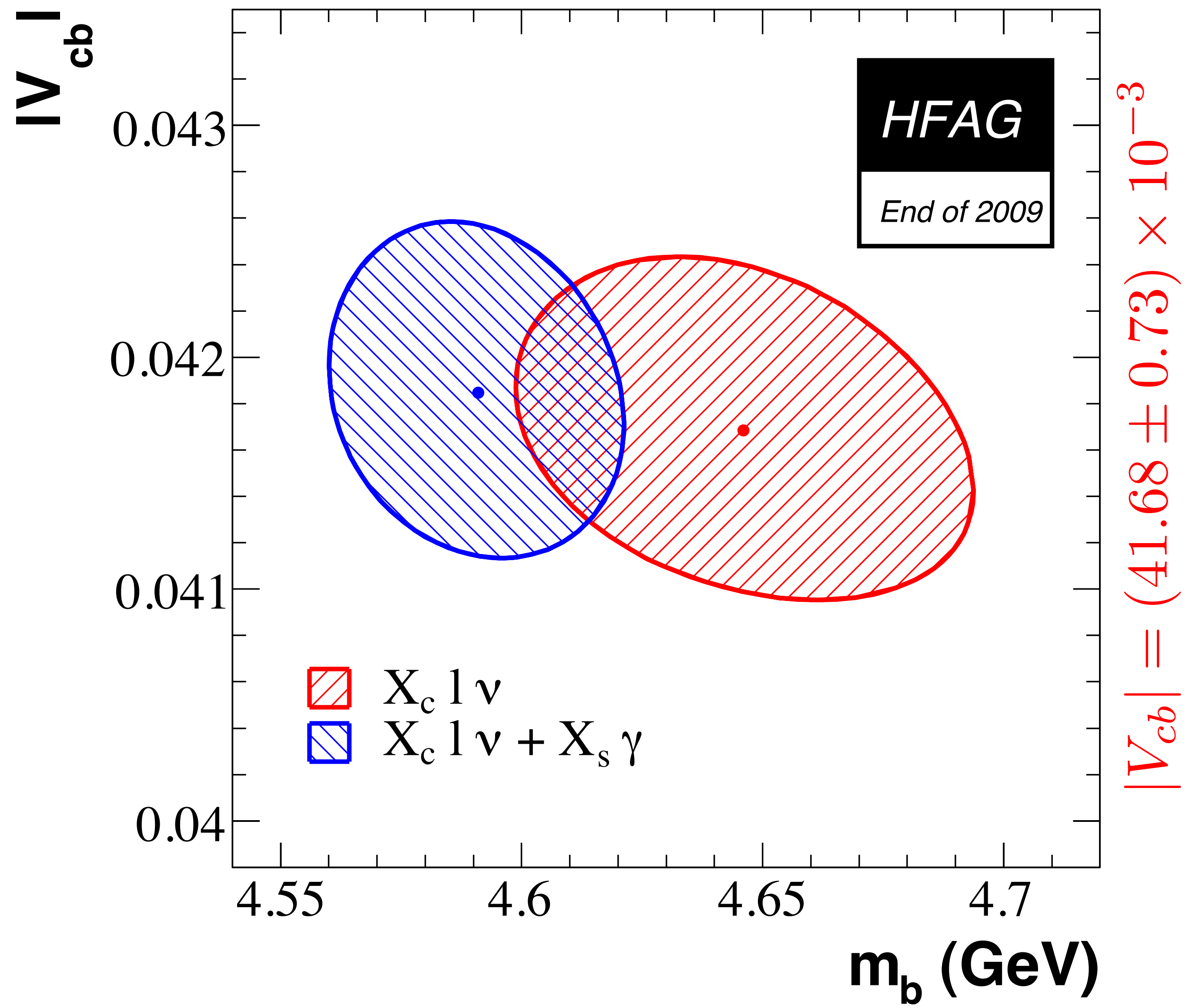


- on-going effort – looking for the missing pieces

  $B \to D_s^{(*)} K \ell^+ \nu_\ell$

Exclusive vs. Inclusive

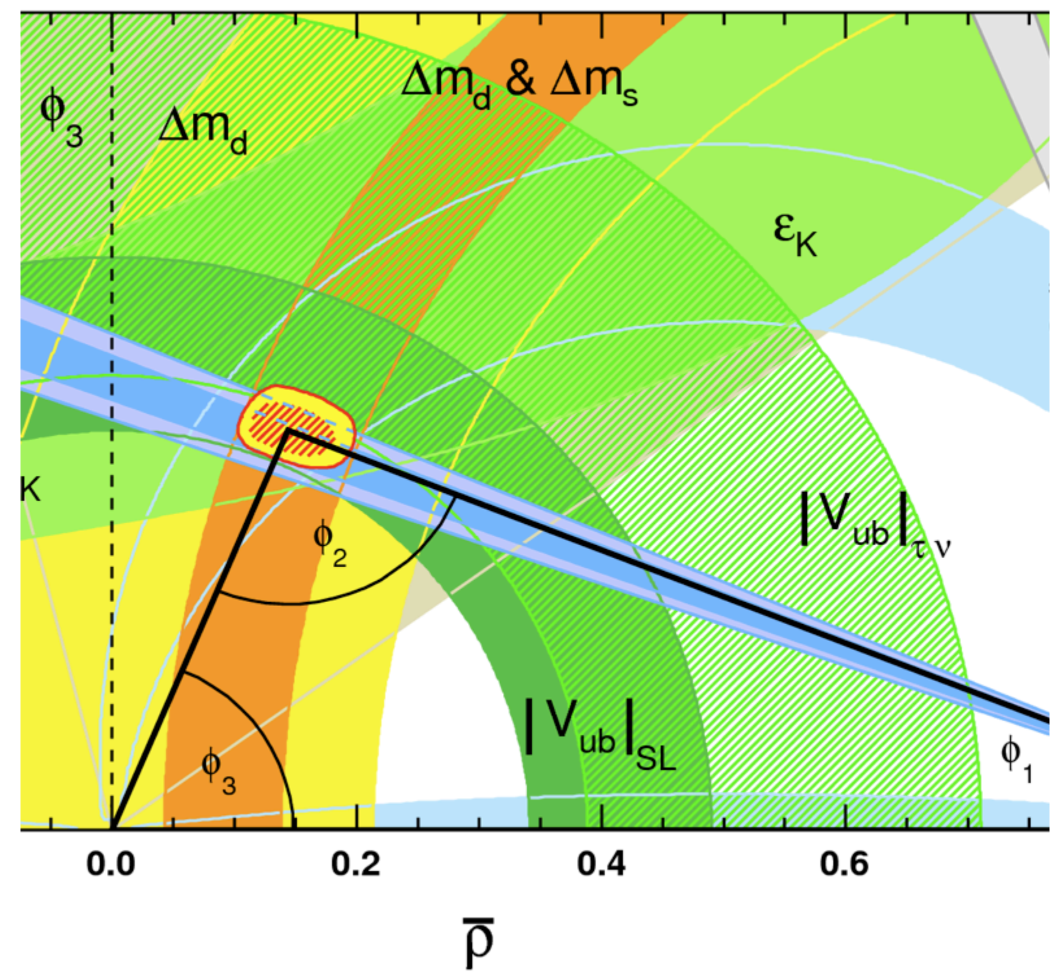




$> 2\sigma$ difference!

$|V_{ub}|$ from exclusive B decays

- a tension?
  - In the UT, $|V_{ub}|$ and $\sin 2\phi_1$ constrains each other.
  - $\exists$ slight tension b/w excl. & incl. determ'n of $|V_{ub}|$



- With exclusive $B \to X_u \ell^+ \nu_\ell$, $|V_{ub}|$ can be extracted from the *differential decay rate*

$$\frac{d\Gamma(B \to \pi \ell^+ \nu_\ell)}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} |p_\pi|^3 |f_+(q^2)|^2$$

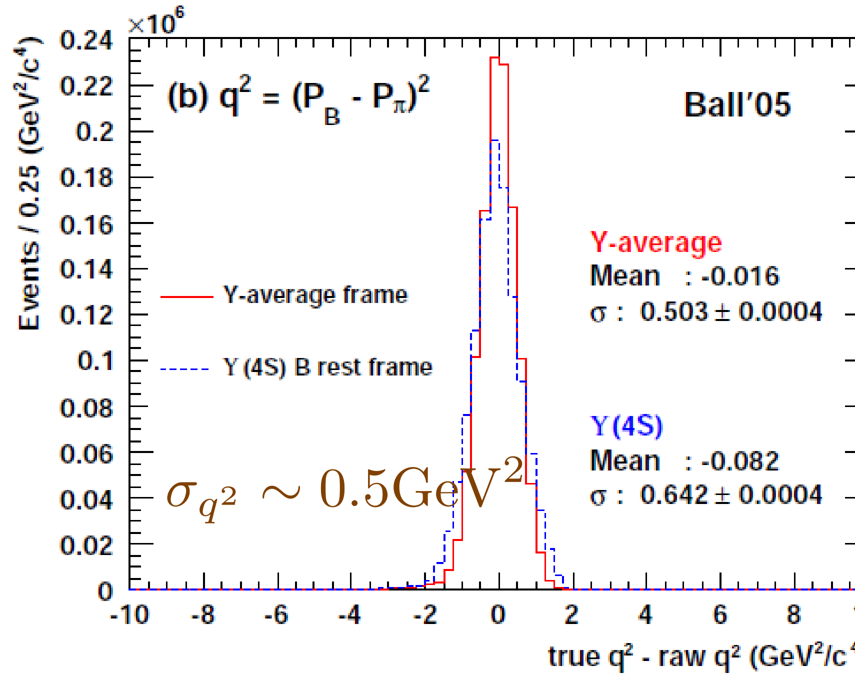
Theory input is needed to determine form factor $f_+(q^2)$.

- statistics is still important as we have various exclusive approaches at varying degree of efficiency vs. purity

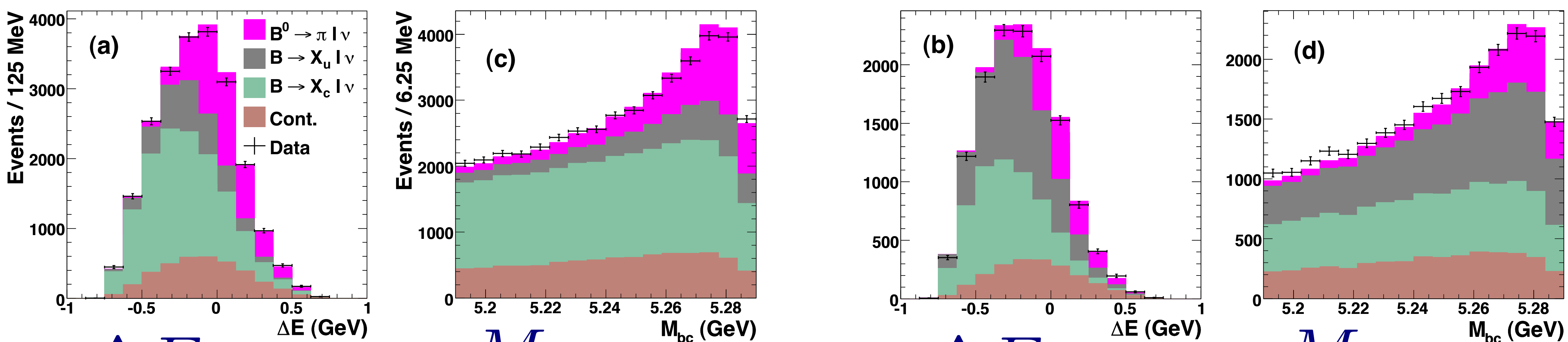
  e.g. untagged, SL-tagged, full-recon-tagged, etc.

$B^0 \to \pi^- \ell^+ \nu_\ell$ for $|V_{ub}|$

- based on $\mathcal{L} = 605\ \mathrm{fb}^{-1}$
  - * uses $\tilde{q}^2 \equiv \langle q^2 \rangle$ over B direction ambiguity
  - * extracts yield by fitting $(\Delta E, M_{\rm bc})$



$0 < q^2 < 16$ $\qquad$ $q^2 > 16$



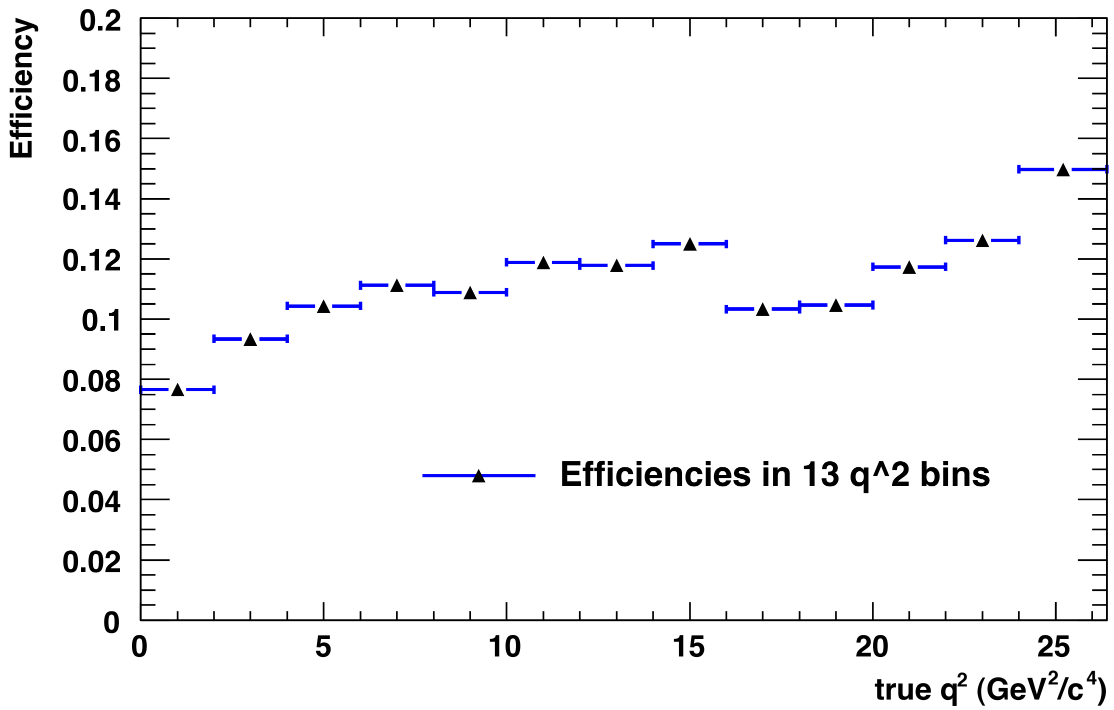
ΔE $\qquad$ $M_{\rm bc}$ $\qquad$ ΔE $\qquad$ $M_{\rm bc}$

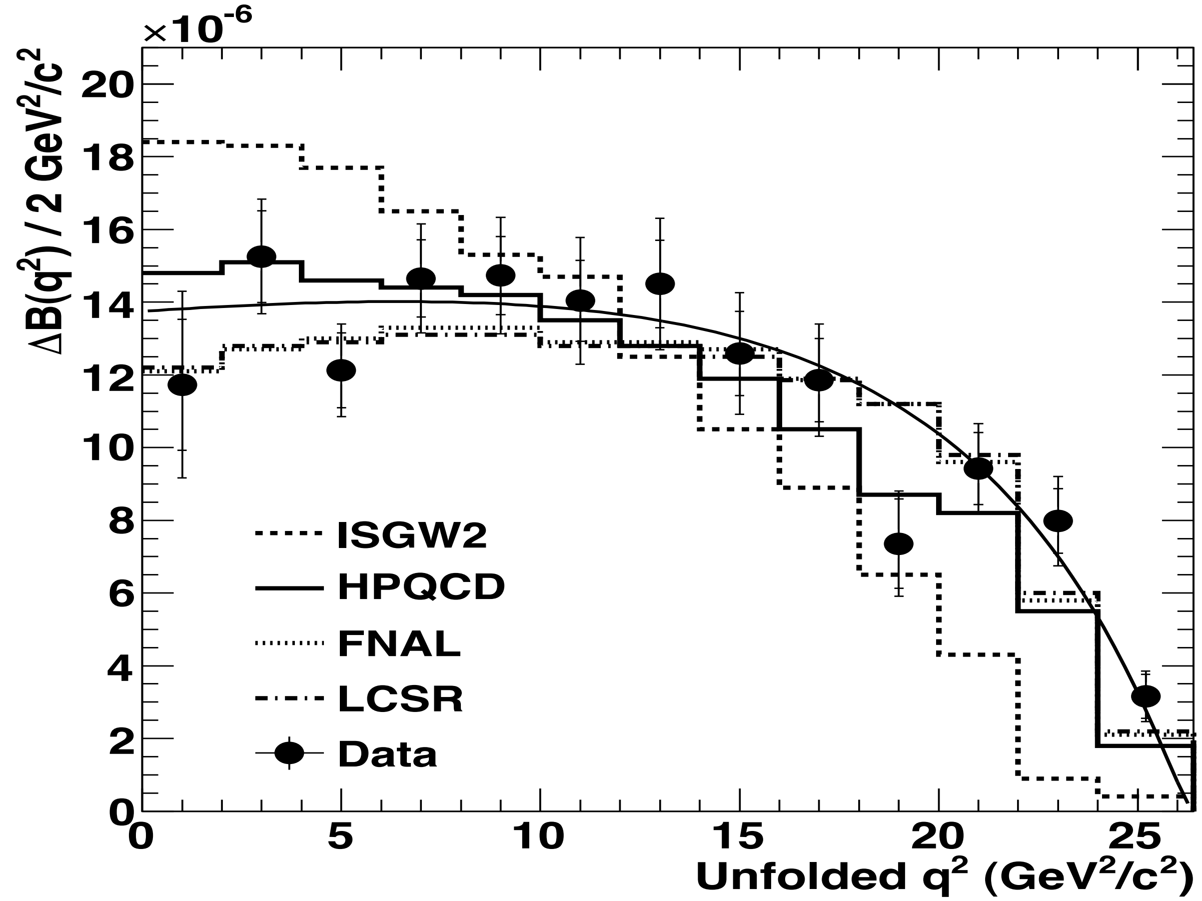
PRD 83, 071101 (2011)

$B^0 \to \pi^- \ell^+ \nu_\ell$ for $|V_{ub}|$

PRD 83, 071101 (2011)

efficiency as a function of q^2





- $d\Gamma/dq^2$ for unfolded q^2
  Models are tested by the shape – ISGW2 is disfavored

$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.49 \pm 0.04 \pm 0.07) \times 10^{-4}$$

- What about $|V_{ub}|$?

$|V_{ub}|$ from $B^0 \to \pi^- \ell^+ \nu_\ell$

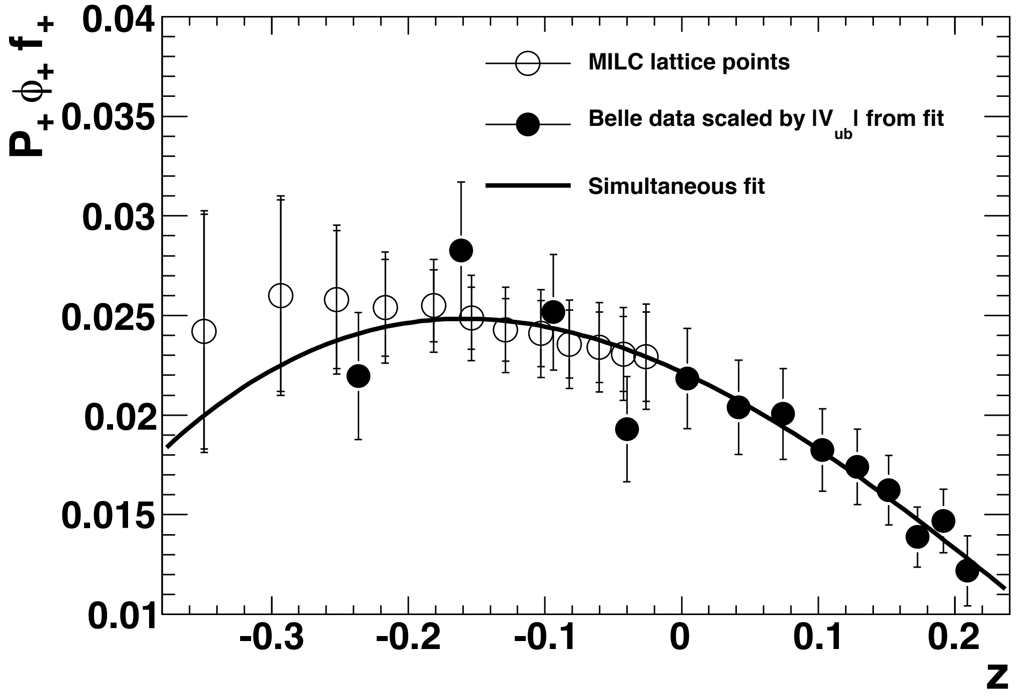
- Model-dependent: $|V_{ub}| = \sqrt{\Delta\mathcal{B}(q^2)/\tau_{B^0}\Delta\zeta}$

$f_+(q^2)$	q^2 (GeV$^2/c^2$)	$\Delta\zeta$ (ps^{-1})	$\lvert V_{ub}\rvert$ (10^{-3})
HPQCD [4]	> 16	2.07 ± 0.57	$3.55 \pm 0.13^{+0.62}_{-0.41}$
FNAL [5]	> 16	1.83 ± 0.50	$3.78 \pm 0.14^{+0.65}_{-0.43}$
LCSR [6]	< 16	5.44 ± 1.43	$3.64 \pm 0.11^{+0.60}_{-0.40}$

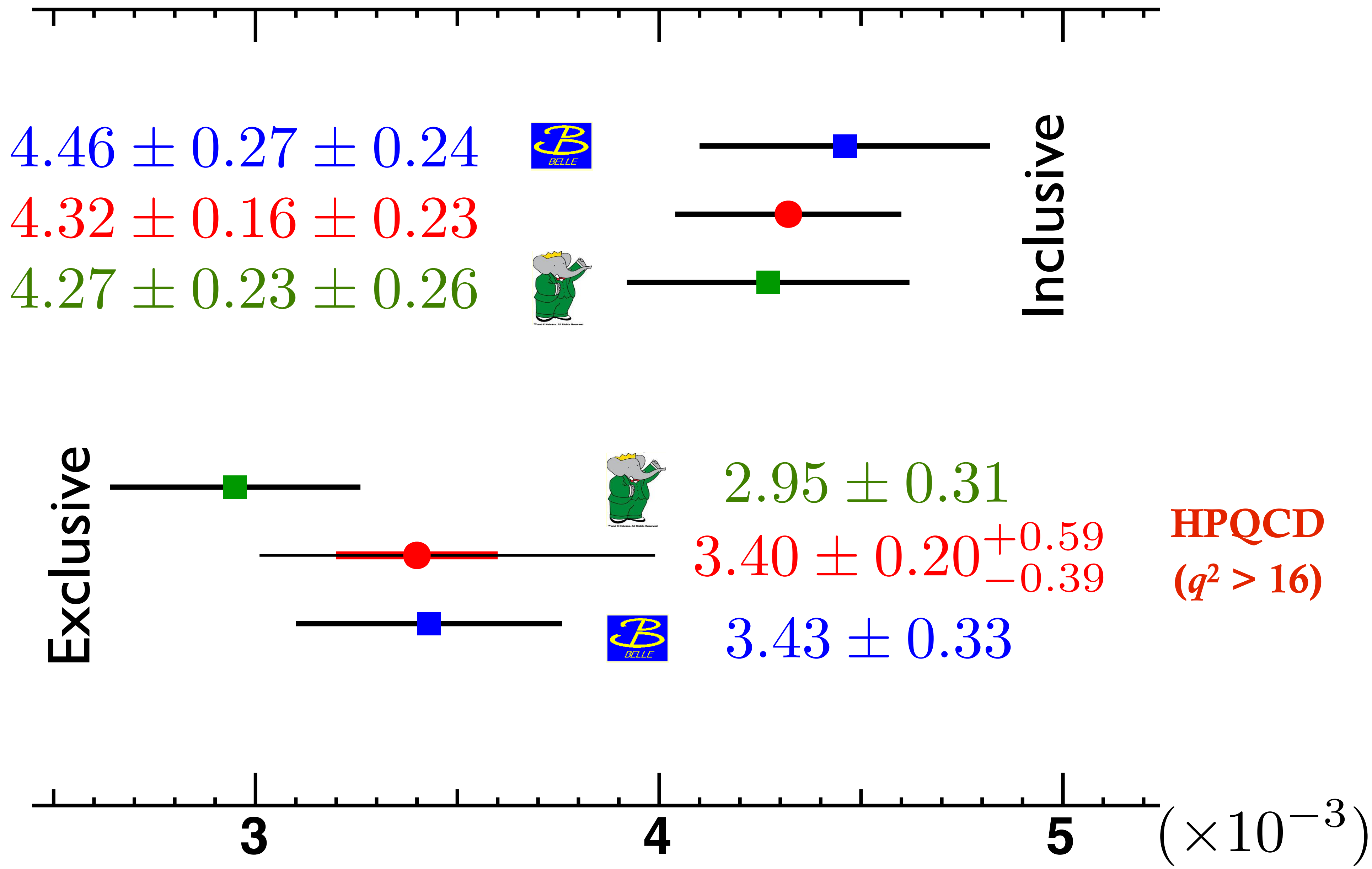
Form-factor uncertaintis give largest syst. error.

- Model-independent PRD **79**, 054507 (2009) simultaneous fit with
  - lattice result (MILC)
  - experimental data (Belle)

$$|V_{ub}| = (3.43 \pm 0.33) \times 10^{-3}$$

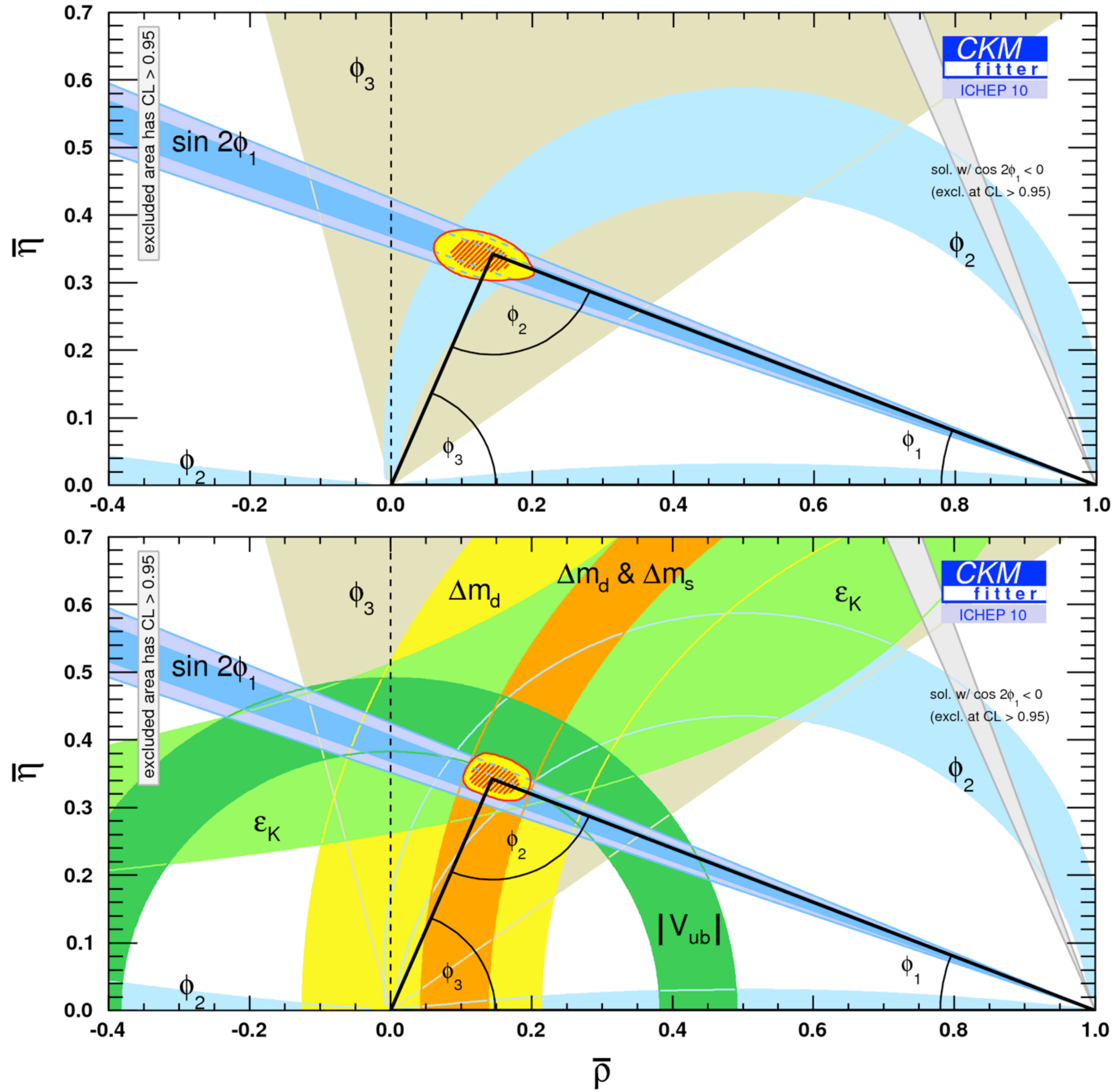


$|V_{ub}|$ summary



- Significant improvements in recent years
- But some discrepancy b/w inclusive and exclusive measurements persists

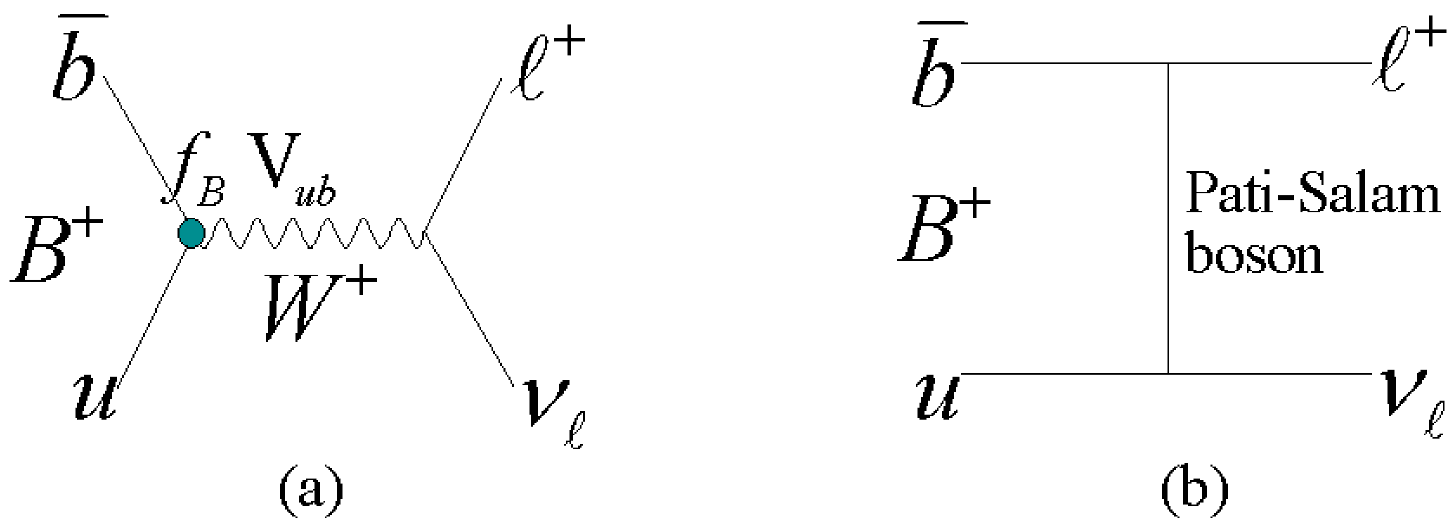
UT: current status



Rare B decays for New Physics

- SM is a very good approx. for reality
  i.e. $A_{\text{Nature}} \simeq A_{\text{SM}}$ for most processes
- Need to look where A_{SM} is small, in order to be sensitive to NP
  e.g. $b \to s$ penguins
- Compare A_{Nature} with A_{SM}, then
  Find new physics or learn new lessons!
- In particular, we will focus on:
  - * charged Higgs
  - * EWP and related
  - * exotic decays

$B^+ \to \ell^+ \nu_\ell$



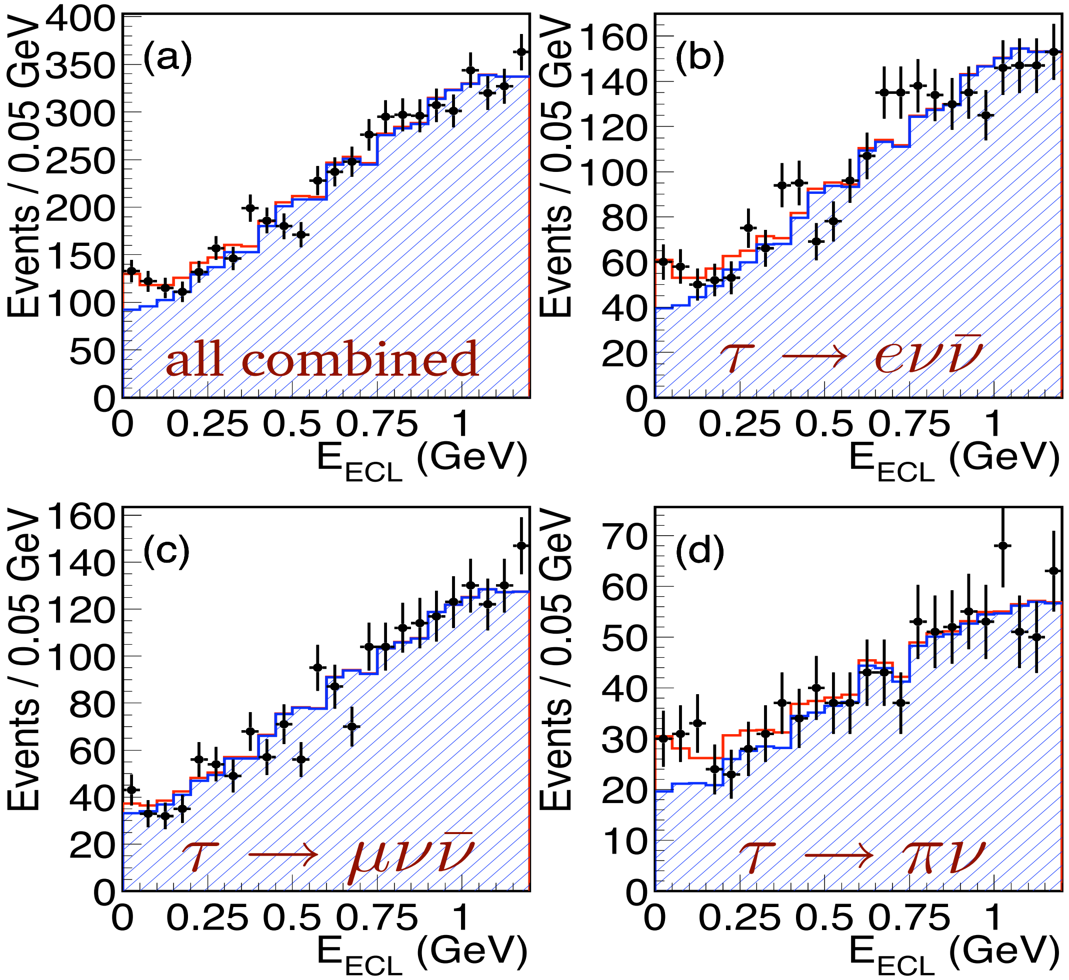
$$\Gamma(B^+ \to \ell^+ \nu_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi} \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2$$

- very clean place to measure f_B (or V_{ub}?) and/or search for new physics (e.g. H^+, LQ)
- but, helicity-suppressed: $\Gamma(B^+ \to e^+ \nu_e) \ll \Gamma(B^+ \to \mu^+ \nu_\mu) \ll \Gamma(B^+ \to \tau^+ \nu_\tau)$
- First evidnce for $B^+ \to \tau^+ \nu_\tau$ by Belle using hadronic tagging ("Full reconstruction")

PRL 97, 251802 (2006)

$B^+ \to \tau^+\nu_\tau$ by semileptonic tagging

PRD 82, 071101 (2010)



- tagged by $B^+ \to \overline{D}^{(*)}\ell^+\nu_\ell$
  - statistically independent from hadronic tagging analysis
- signal side
  - Use *1-prong* τ^- modes: $\ell^-\bar{\nu}\nu$, $\pi^-\nu$
  - $E_{\rm ECL}$ to extract $N_{\rm sig}$
- Significance: 3.6σ incl. syst. err.

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (1.54^{+0.38+0.29}_{-0.37-0.31}) \times 10^{-4}$$

$$f_B|V_{ub}| = (9.3^{+1.2}_{-1.1} \pm 0.9) \times 10^{-4}\ \text{GeV}$$

Decay Mode	Signal Yield	ε (10^{-4})	$\mathcal{B}$ (10^{-4})
$\tau^- \to e^-\nu\bar{\nu}_\tau$	73^{+23}_{-22}	5.9	$1.90^{+0.59+0.33}_{-0.57-0.35}$
$\tau^- \to \mu^-\nu\bar{\nu}_\tau$	12^{+18}_{-17}	3.7	$0.50^{+0.76+0.18}_{-0.72-0.21}$
$\tau^- \to \pi^-\nu_\tau$	55^{+21}_{-20}	4.7	$1.80^{+0.69+0.36}_{-0.66-0.37}$
Combined	146^{+36}_{-35}	14.3	$1.54^{+0.38+0.29}_{-0.37-0.31}$

$B^+ \to \tau^+\nu_\tau$ constraint on H^+

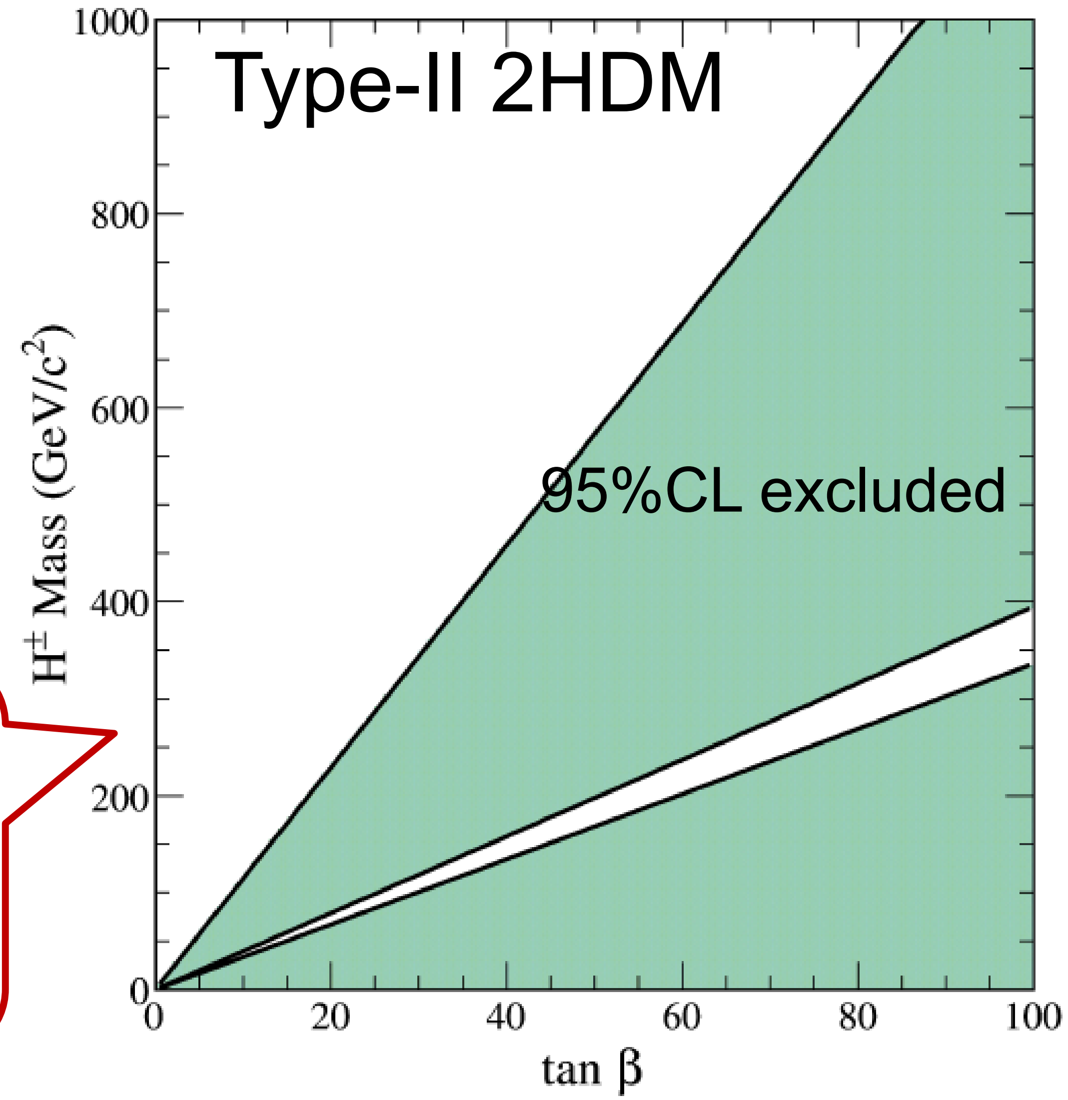
K. Trabelsi @ ICHEP2010

$Br(\tau\nu) = [1.68 \pm 0.31] \times 10^{-4}$ ⟺ $Br_{SM}(\tau\nu) = [1.20 \pm 0.25] \times 10^{-4}$

Based on fB from HPQCD and $|V_{ub}|$ from HFAG (BLNP, ICHEP08)

- Belle
  - Hadronic tag (449MBB) :
    $Br(\tau\nu) = [1.79^{+0.56+0.46}_{-0.49\,-0.51}] \times 10^{-4}$
  - Semileptonic tag (657MBB):
    $Br(\tau\nu) = [1.54^{+0.38+0.29}_{-0.37\,-0.31}] \times 10^{-4}$
- BaBar
  - Hadronic tag:
    $Br(\tau\nu) = [1.80^{+0.57}_{-0.54} \pm 0.26] \times 10^{-4}$
  - Semileptonic tag:
    $Br(\tau\nu) = [1.70 \pm 0.87 \pm 0.20] \times 10^{-4}$

Constraint on charged Higgs



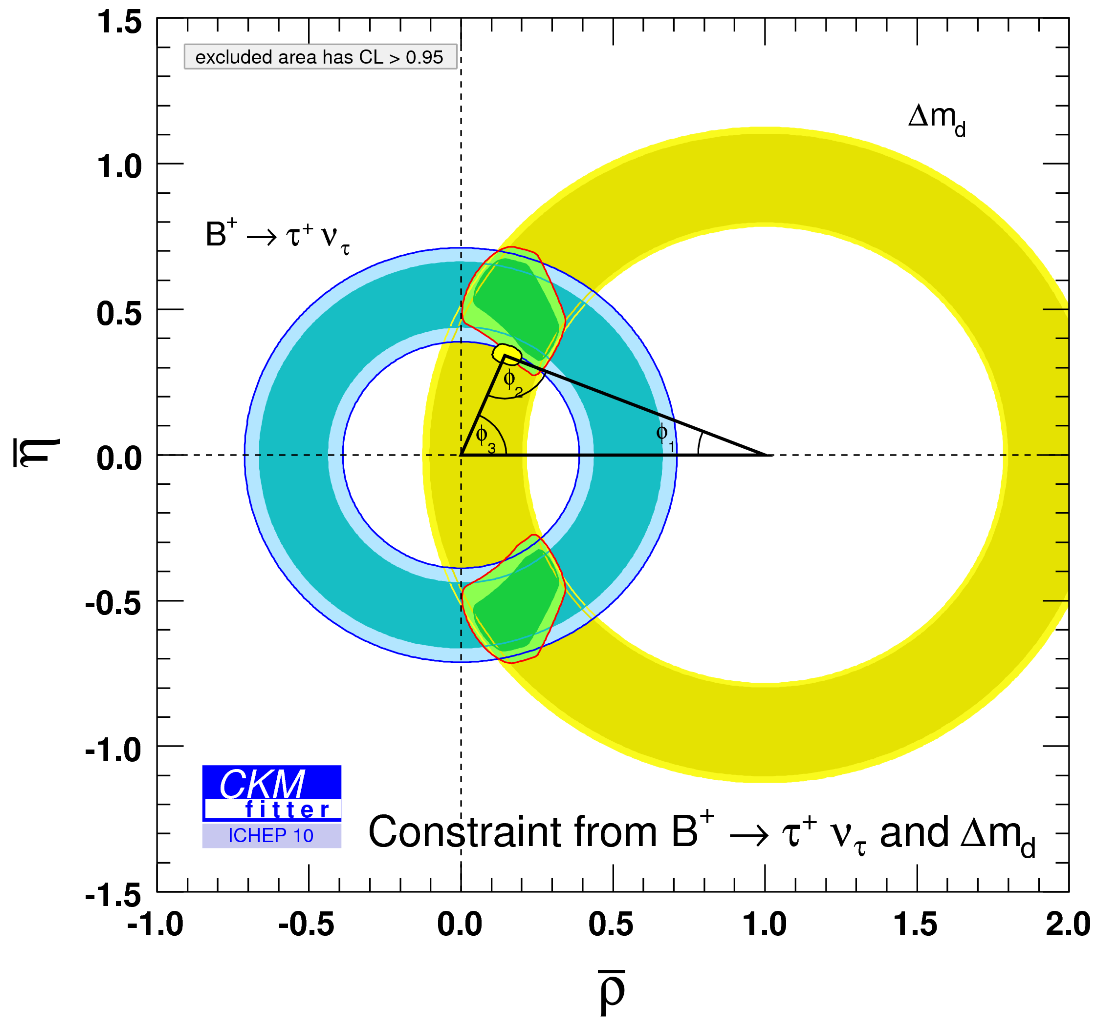
Effect of Charged Higgs (Type-II 2HDM)

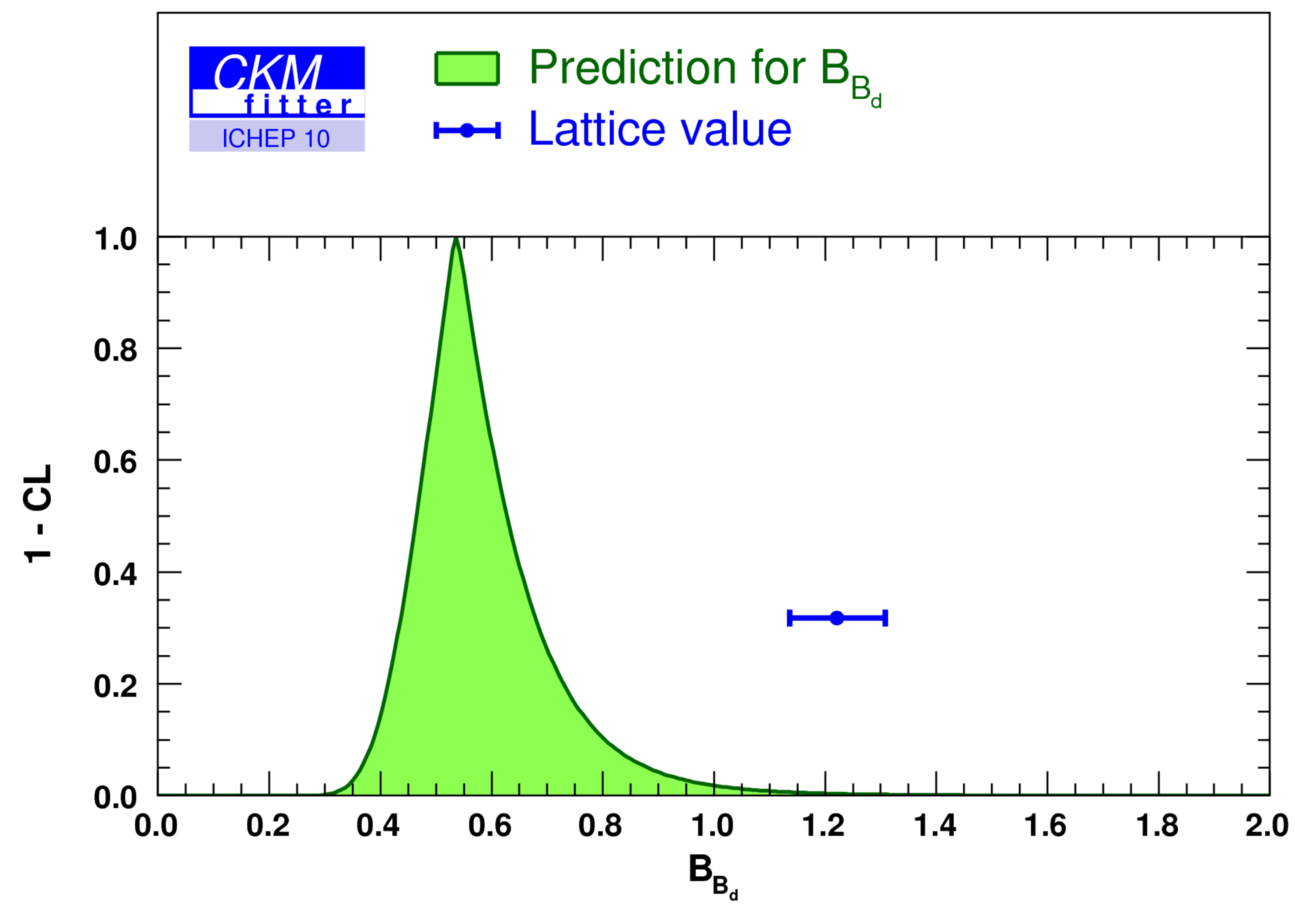
W. Hou, Phys. Rev. D48, 2342 (1993)

$$Br = Br_{SM} \times \left(1 - \frac{m_B^2 \tan\beta^2}{m_H^2}\right)^2$$

from a slide by T. Iijima for TAU2010

The "$B^+ \to \tau^+\nu_\tau$ puzzle"

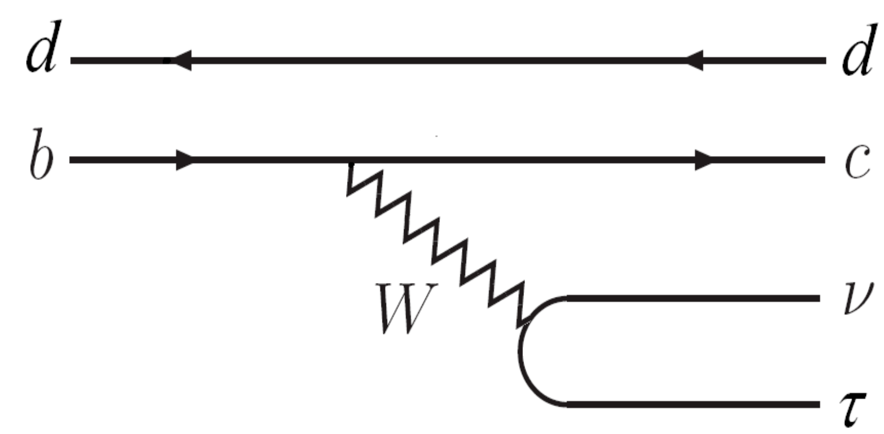




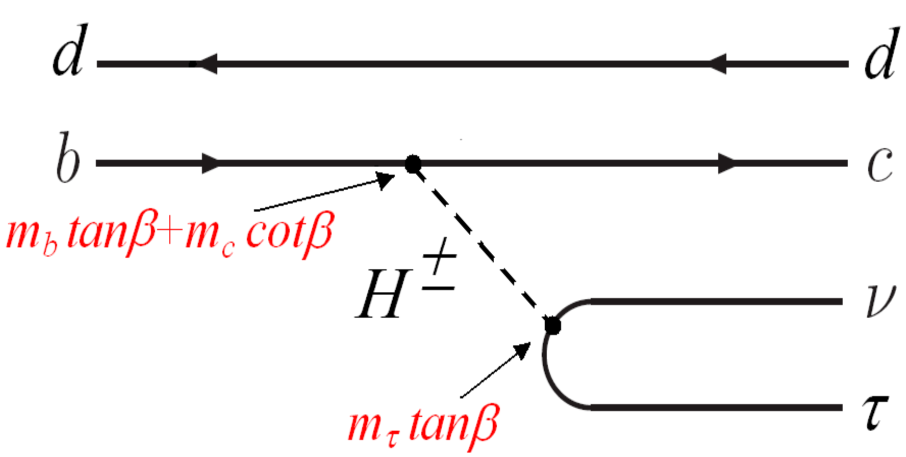
$$\frac{BR(B \to \tau\nu)}{\Delta m_d} = \frac{3\pi}{4} \frac{m_\tau^2}{m_W^2 S(x_t)} \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \tau_{B^+} \frac{1}{B_{B_d}} \frac{1}{|V_{ud}|^2} \left(\frac{\sin\beta}{\sin\gamma}\right)^2$$

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

- missing piece of B semileptonic decays
- good features
  - due to heavy m_τ, sensitive to H^+
  - $\mathcal{B}(B \to \overline{D}^{(*)} \tau^+ \nu_\tau) \gg \mathcal{B}(B^+ \to \tau^+ \nu_\tau)$
  - access to more dynamical info. through τ polarization



- but, very difficult for analysis
  - multiple ν's
  - large background from $B \to DX\ell^+\nu$
- $B \to \overline{D}^{(*)} \tau^+ \nu_\tau$ depends on form-factor
  - but, it can be deduced from $B^+ \to \overline{D}^{(*)} \ell^+ \nu_\ell$



- First observed by Belle (2007) PRL 99, 191807 (2007)

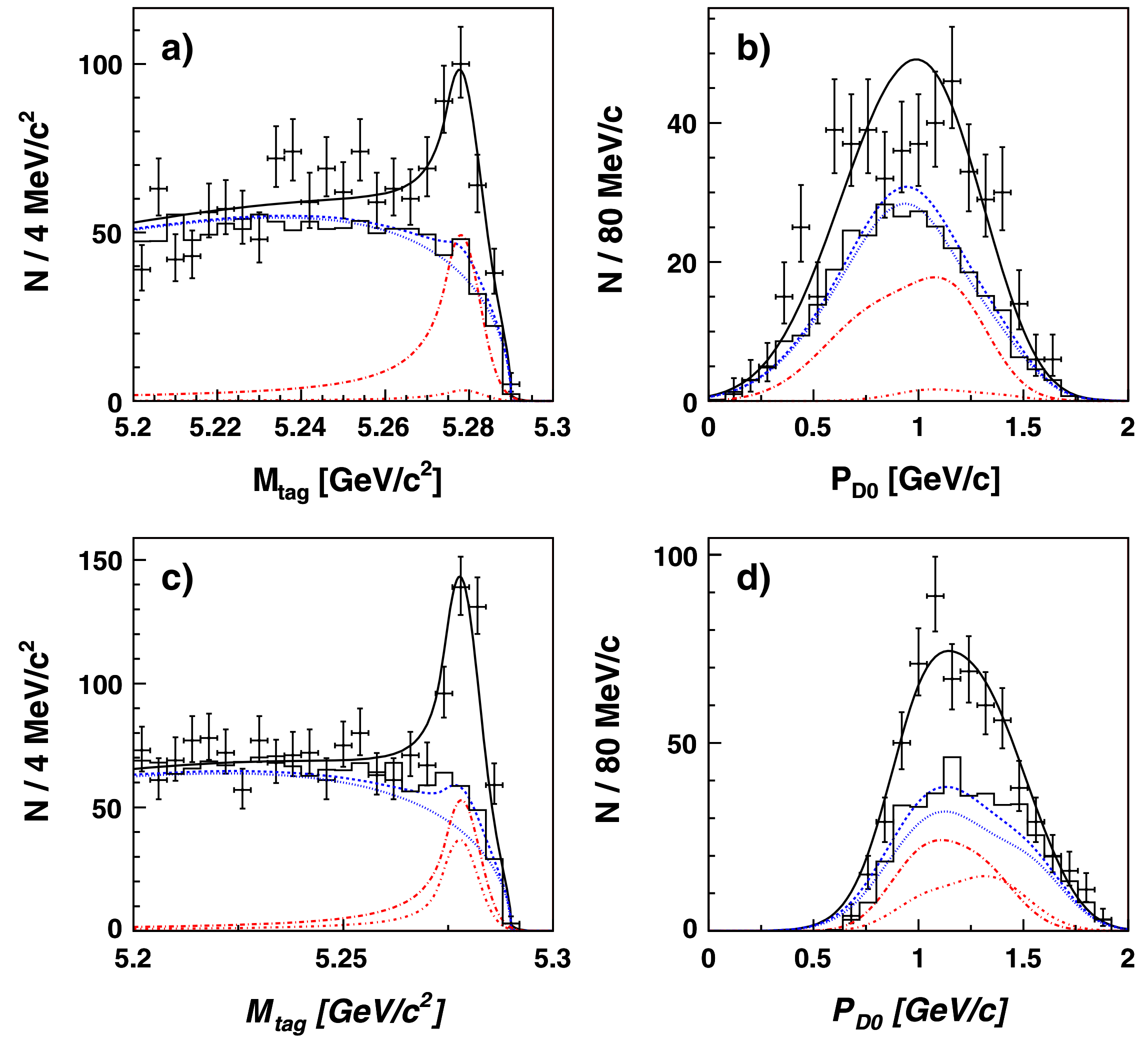
$$\mathcal{B}(B^0 \to D^{*-} \tau^+ \nu_\tau) = (2.02^{+0.40}_{-0.37} \pm 0.37)\%$$

(SM) $\mathcal{B}(B \to \overline{D}^{*} \tau^+ \nu_\tau) \approx 1.4\%, \quad \mathcal{B}(B \to \overline{D} \tau^+ \nu_\tau) \approx 0.7\%$

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

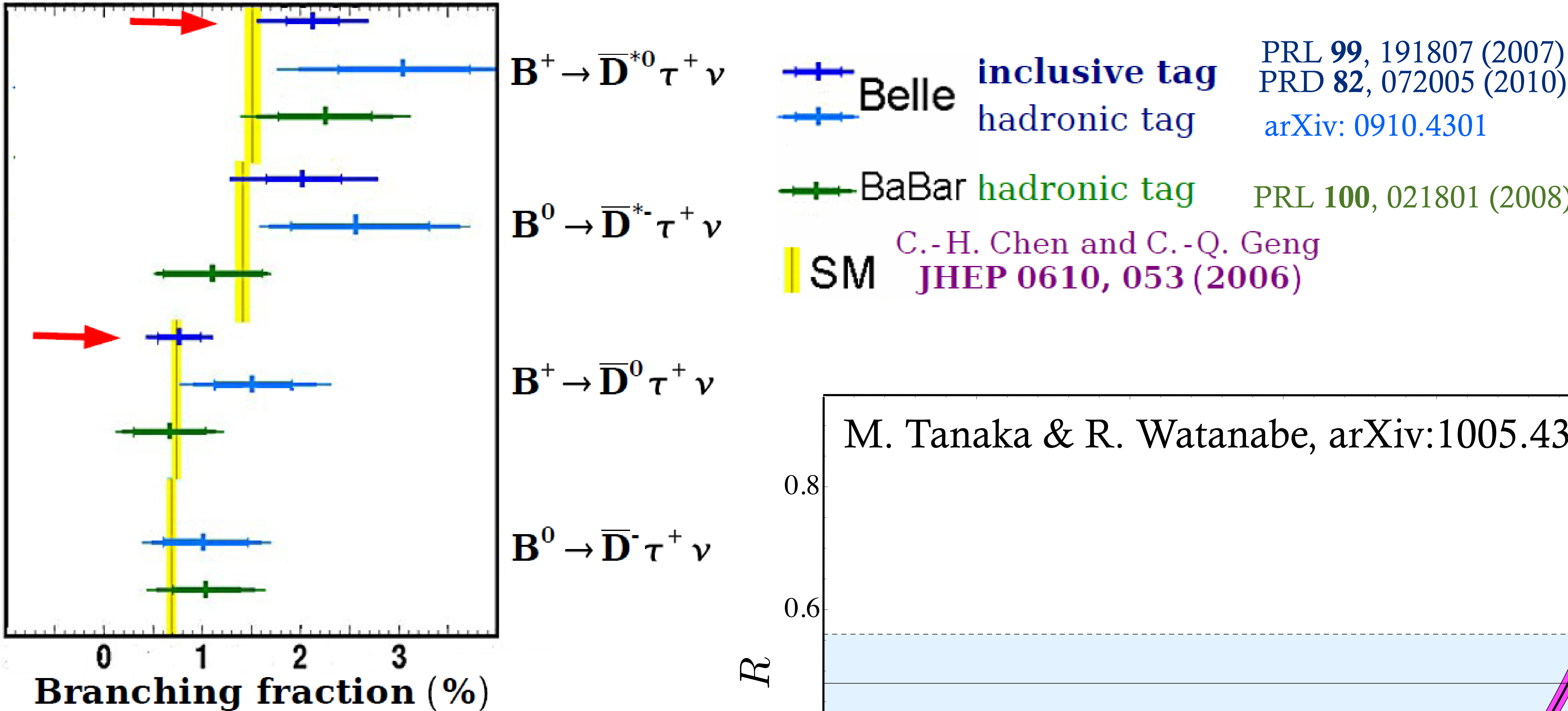
PRD 82, 072005 (2010)

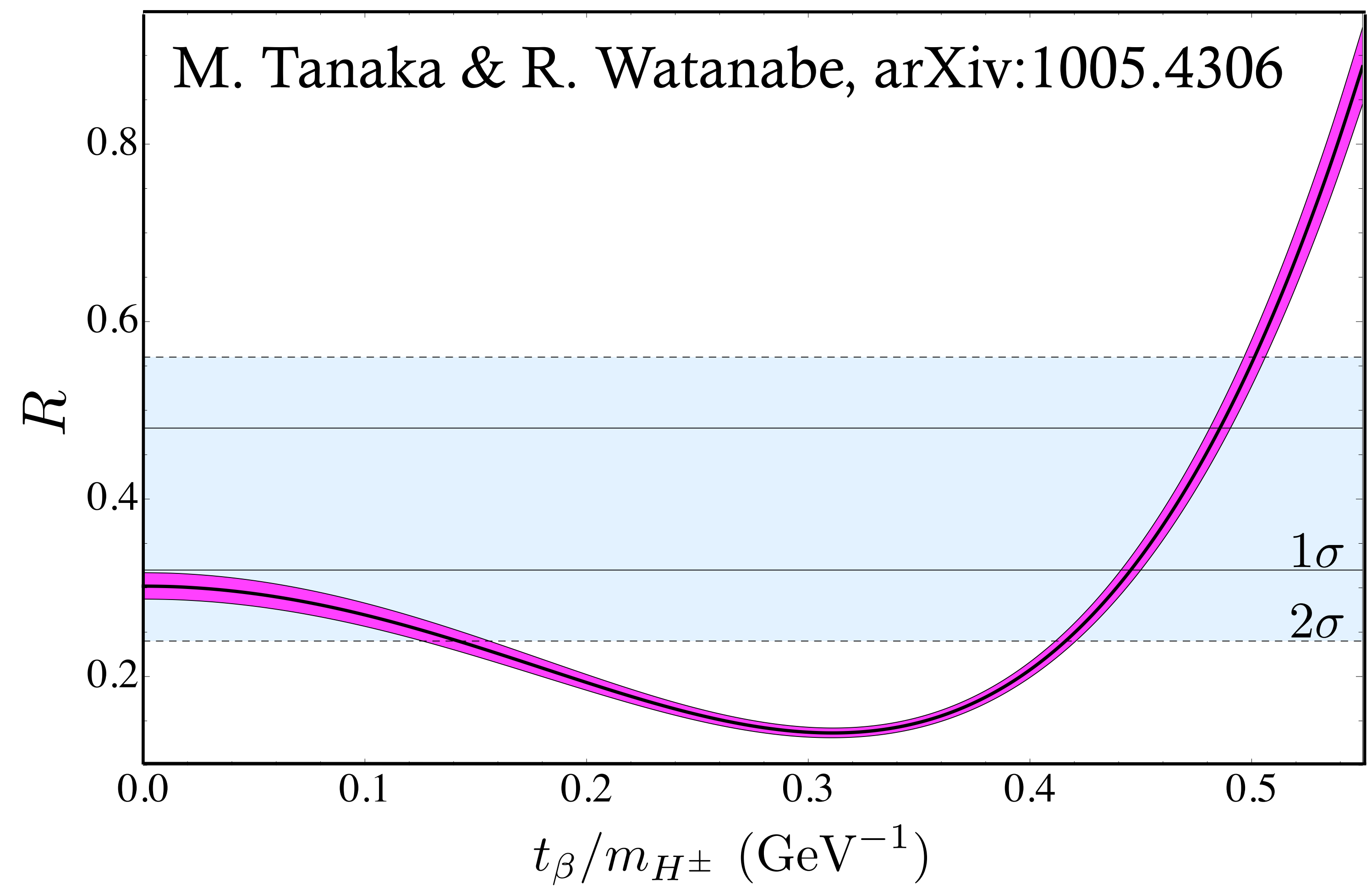
- New measurements by Belle (2010)
  $B^+ \to \bar{D}^{(*)0}\tau^+\nu_\tau$
  - First evidence for $\bar{D}^0$ mode
  - different EM final-state contributions expected for B^0 and B^+
  - loose "full recon"; same as used for 2007 discovery
  - simultaneous extraction of $\bar{D}^{(*)0}\tau^+\nu_\tau$ yields by 2D-fit on $(M_{\rm tag}, p_D)$



$$\mathcal{B}(B^+ \to \bar{D}^{*0}\tau^+\nu_\tau) = (2.12^{+0.28}_{-0.27} \pm 0.29)\%$$
$$\mathcal{B}(B^+ \to \bar{D}^{0}\tau^+\nu_\tau) = (0.77 \pm 0.22 \pm 0.12)\%$$

$B \to \overline{D}^{(*)}\tau^+\nu_\tau$ summary

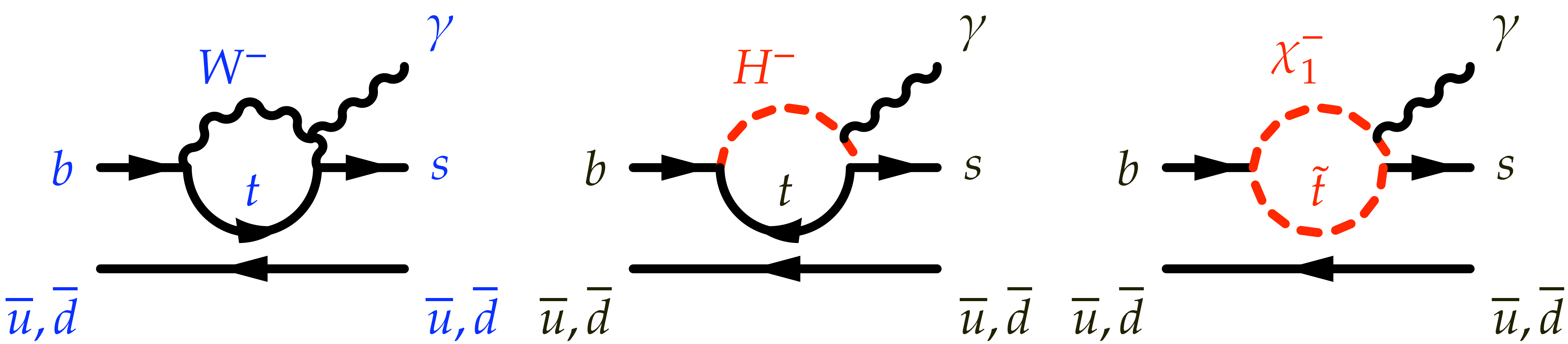




Combining Belle/BaBar, $R = \mathcal{B}(B \to D\tau\nu)/\mathcal{B}(B \to D\ell\nu) = 0.40 \pm 0.08$

EW penguin B decays

- one-loop penguin
  - suppressed in SM, hence sensitive to NP
  - (ex) H^+ in place of W^+ in the loop



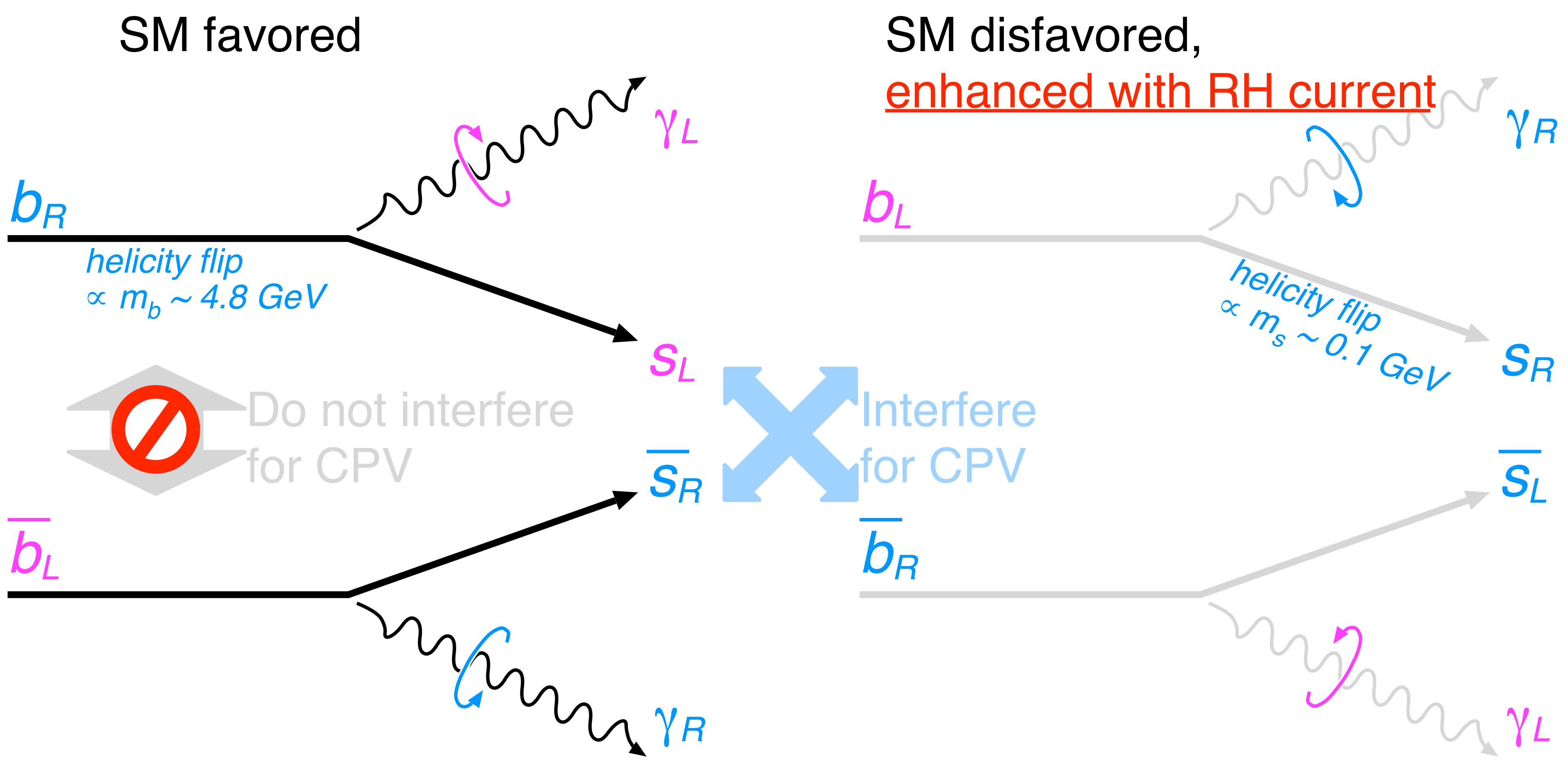
- CPV in radiative penguin can be a sensitie probe for NP
- It's cousin, $B \to X\ell^+\ell^-$ is interesting, too
  - rich structure
  - sensitive to several Wilson coeff's.

Belle's legacy on EWP

- First observation of $B \to K\ell^+\ell^-$ PRL **88**, 021801 (2002)
- First observation of $B \to K^*\ell^+\ell^-$ PRL **91**, 261601 (2003)
- First observation of $B \to X_s\ell^+\ell^-$ PRL **90**, 021801 (2003)
- First measurement of $A_{\rm FB}$ of $B \to K^*\ell^+\ell^-$ PRL **96**, 251801 (2006)

- First observations of several radiative modes, $\phi K\gamma$, $K_1\gamma$, etc.
- First observation of $B \to (\rho, \omega)\gamma$ PRL **96**, 221601 (2006)
- Most precise measurement of $B \to X_s\gamma$ covering the widest E_γ range PRL **103**, 241801 (2009)
- *and many more published results*

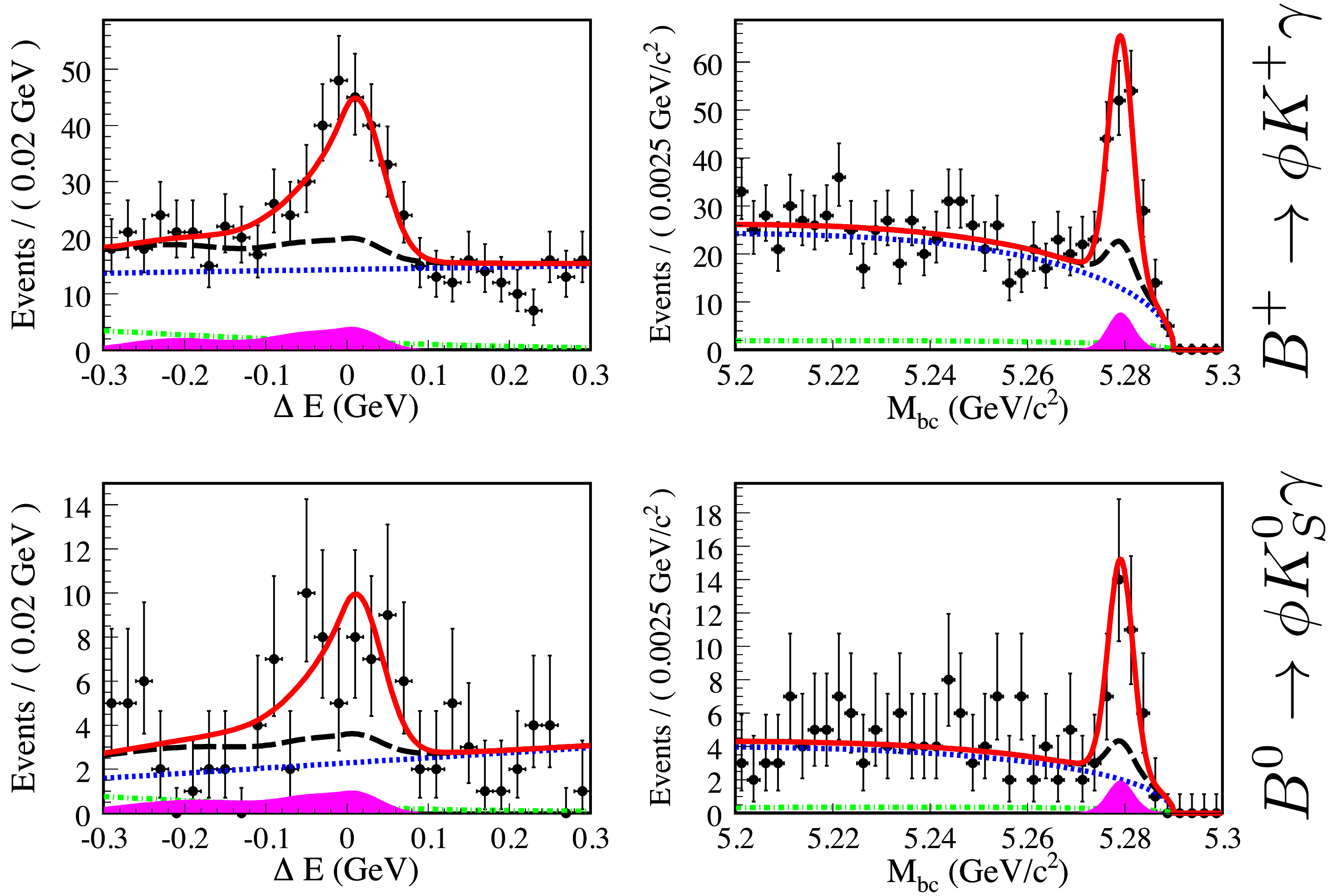
CPV in the radiative penguin

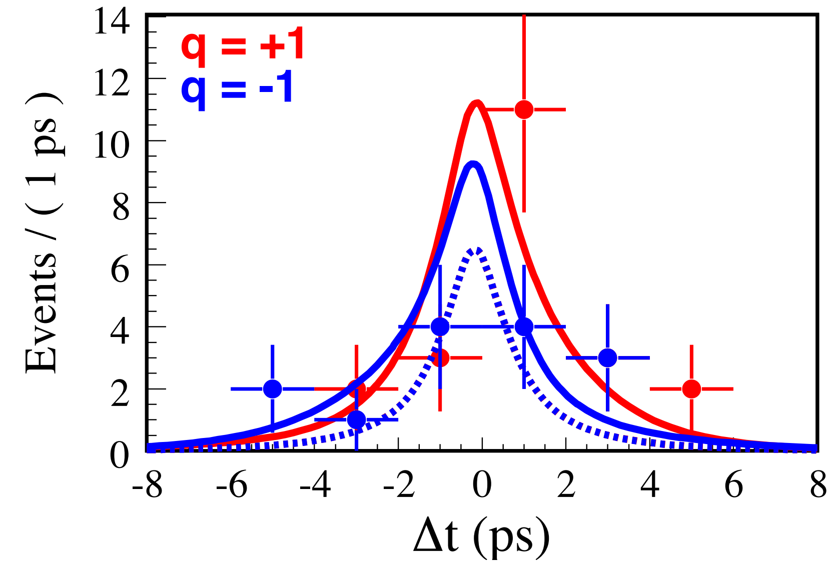


- CPV in SM is suppressed by $\mathcal{O}(m_s/m_b) \sim$ a few %
  - but can be enhanced if $\exists$ RH current
  - as in many NP models
- γ helicity measm’t is extremely difficult (*if not impossible*)
- but CPV may reveal photon polarization

CPV in $B \to \phi K \gamma$

arXiv:1104.5590

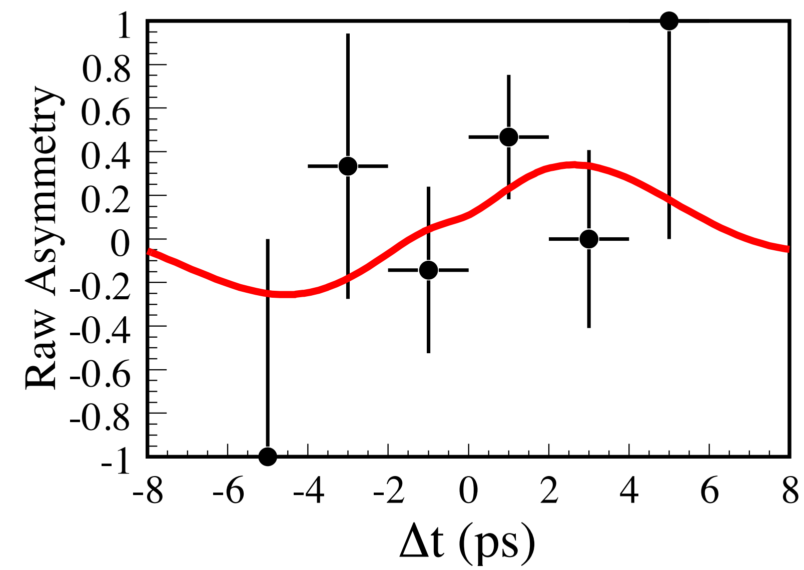


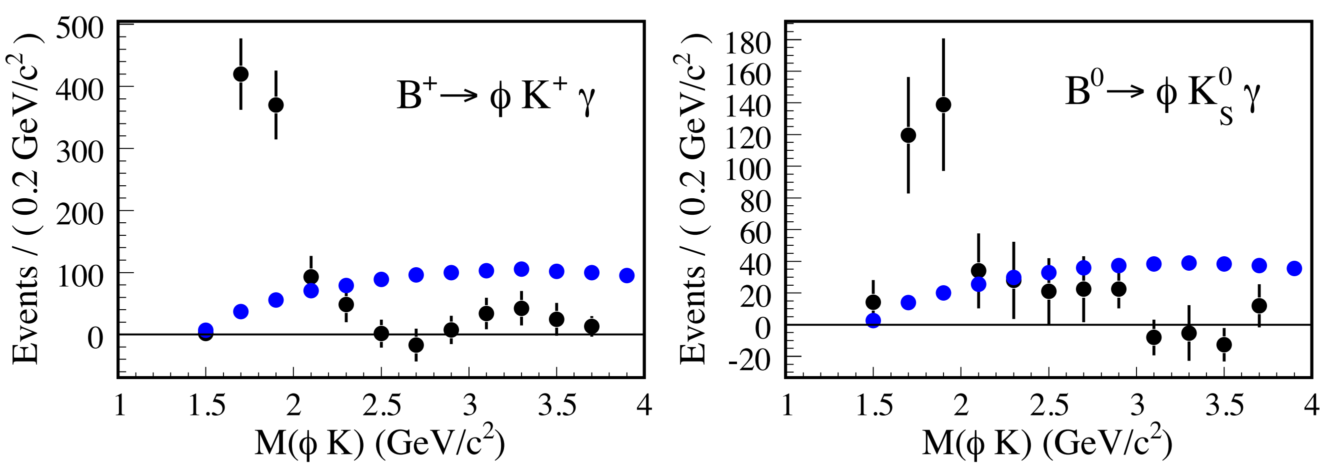


$$\mathcal{B}(B^+ \to \phi K^+ \gamma) = (2.48 \pm 0.30 \pm 0.24) \times 10^{-6}$$

$$\mathcal{B}(B^0 \to \phi K^0 \gamma) = (2.74 \pm 0.60 \pm 0.32) \times 10^{-6}$$

($\phi K^o \gamma$) first observation!





$$\mathcal{S} = +0.74^{+0.72+0.10}_{-1.05-0.24}$$

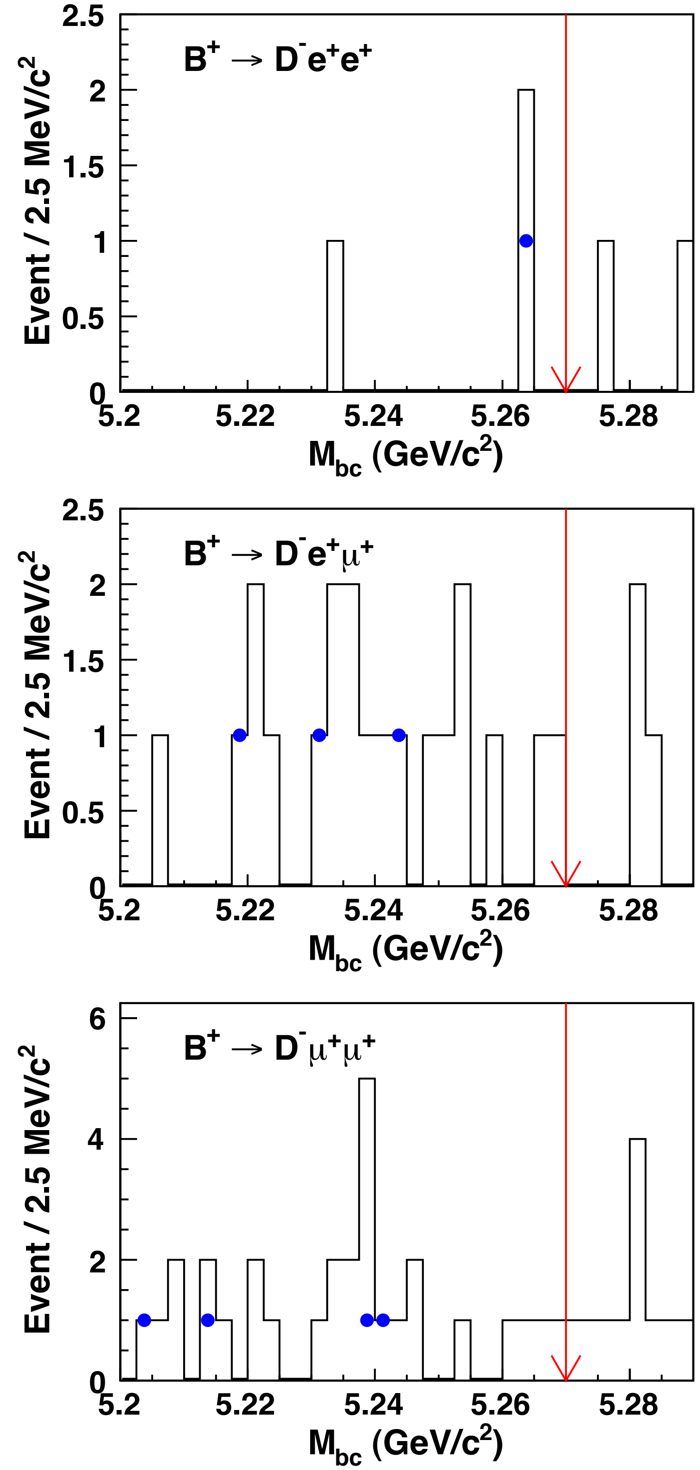
$$\mathcal{A} = +0.35 \pm 0.58^{+0.23}_{-0.10}$$

first measurements!

Search for $B^+ \to D^- \ell^+ \ell^+$

- LV ($\Delta L = 2$) process
  - * sensitive to Majorana-type ν
  - * "$0\nu 2\beta$ for B meson"
  - * expect $\mathcal{B} \sim \mathcal{O}(10^{-7})$ if $\exists$ a heavy Majorana ν with $m \in (2-4)$ GeV/c^2

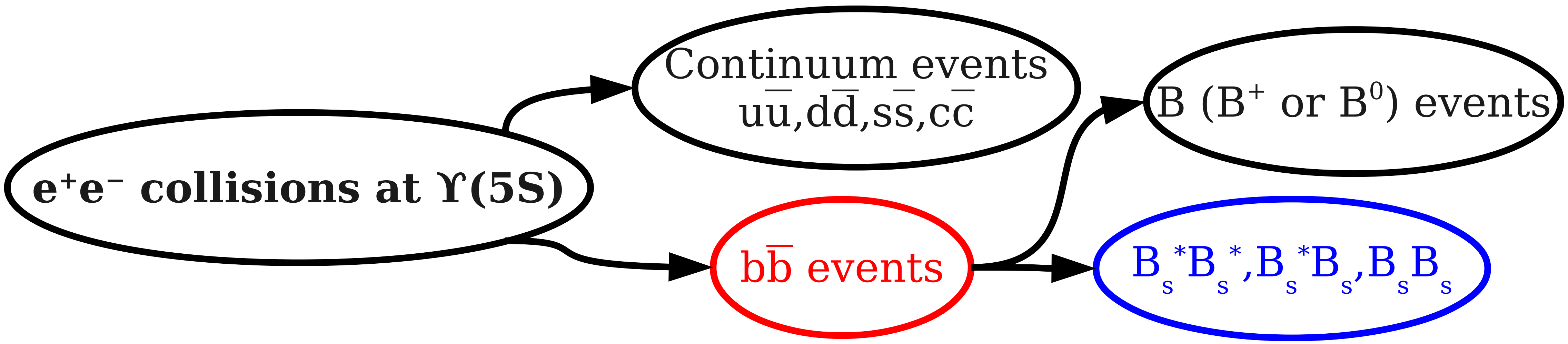
- Analysis
  - * event shape to suppress $e^+e^- \to q\bar{q}$ bkgd.
  - * $E_{\rm miss}$, δz to suppress $B\bar{B}$ bkgd.
  - * $\mathcal{B} < \mathcal{O}(10^{-6})$ @90% CL



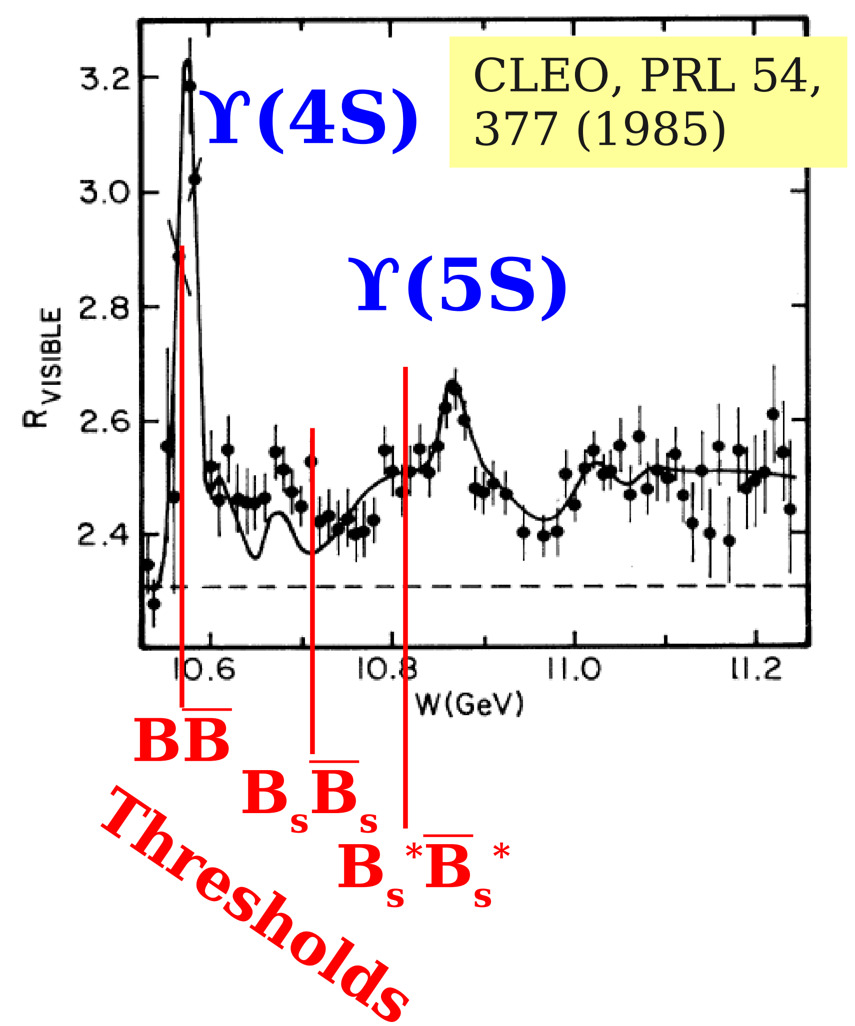
from non-$\Upsilon(4S)$

- new CP-eigenstate decays of B_s
- new results in the $b\bar{b}$ spectroscopy

Events at $\Upsilon(5S)$



- $\Upsilon(5S)$ is above $B_s^{(*)}B_s^{(*)}$ threshold
- Belle took ~ 140 fb^{-1} around $\Upsilon(5S)$
  - ~ 120 fb^{-1} at the resonance
  - ~ 20 fb^{-1} for scans
  - much larger than CLEO, BaBar; *but beware of LHCb!*



$B_s \to J/\psi f_0(980)$

- Silver-plated mode for LHCb to measure β_s
  - * $\mathcal{B}$ is $2 \sim 5$ times smaller than $B_s \to J/\psi\phi$, but is a pure CP eigenstate ($0 \to 0 \oplus 1$ vs. $0 \to 1 \oplus 1$)
  - * hence needing no angular analysis
- expected BF

$$0.2 \lesssim R_{f_0/\phi} \equiv \frac{\Gamma(B_s^0 \to J/\psi f_0(980); f_0(980) \to \pi^+\pi^-)}{\Gamma(B_s^0 \to J/\psi\phi; \phi \to K^+K^-)} \lesssim 0.5$$

$$\therefore 1.3 \times 10^{-4} \lesssim \mathcal{B}(B_s^0 \to J/\psi f_0(980); f_0(980) \to \pi^+\pi^-) \lesssim 3.2 \times 10^{-4}$$

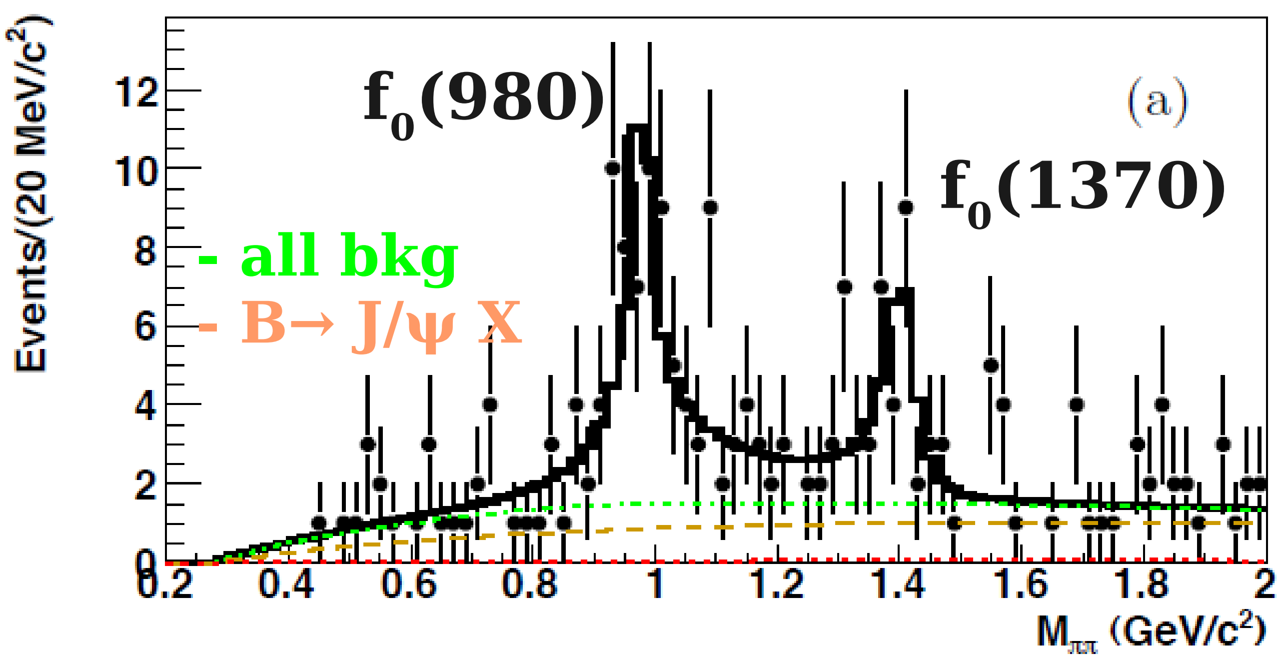
$\exists$ also theory calculation based on QCD sum rule (LO)

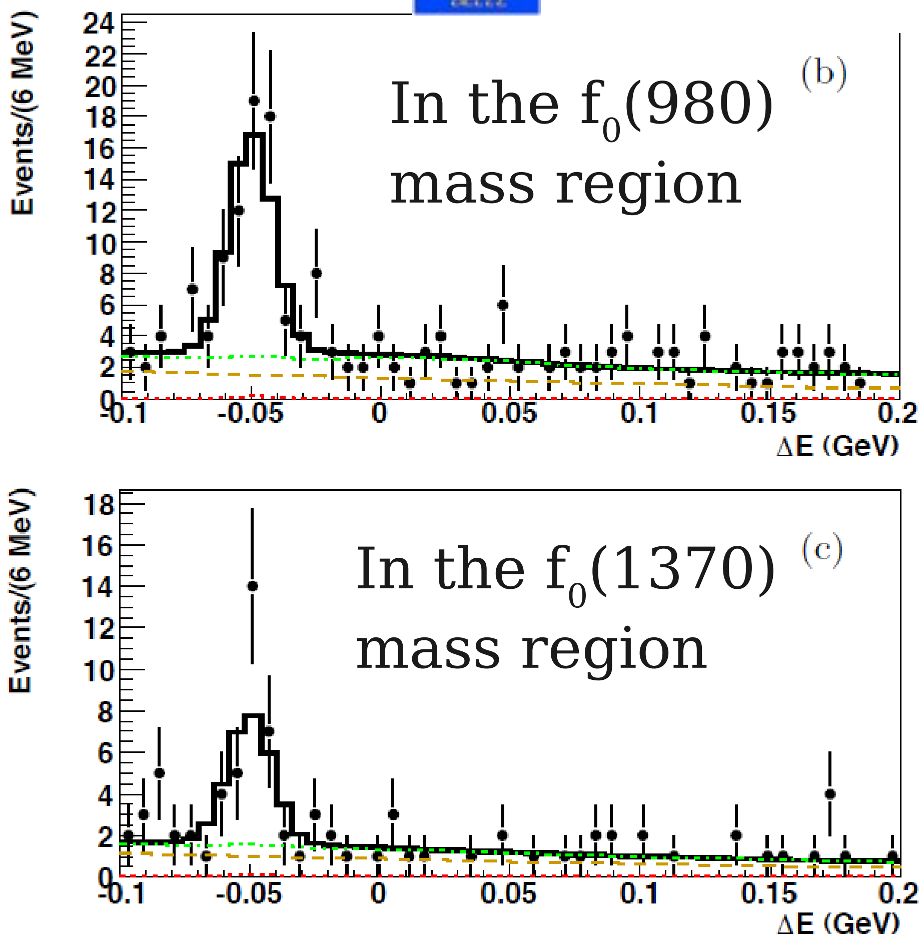
$B_s \to J/\psi f_0(980)$ Results

PRL 106, 121802 (2011)

63^{+16}_{-10} sig. events 19^{+6}_{-8} sig. events

8.4σ 4.2σ





$$\mathcal{B}(B_s^0 \to J/\psi f_0(980))\mathcal{B}(f_0(980) \to \pi^+\pi^-) = (1.16^{+0.31+0.15+0.26}_{-0.19-0.17-0.18}) \times 10^{-4}$$

$$\mathcal{B}(B_s^0 \to J/\psi f_0(1370))\mathcal{B}(f_0(1370) \to \pi^+\pi^-) = (0.34^{+0.11+0.03+0.08}_{-0.14-0.02-0.05}) \times 10^{-4}$$

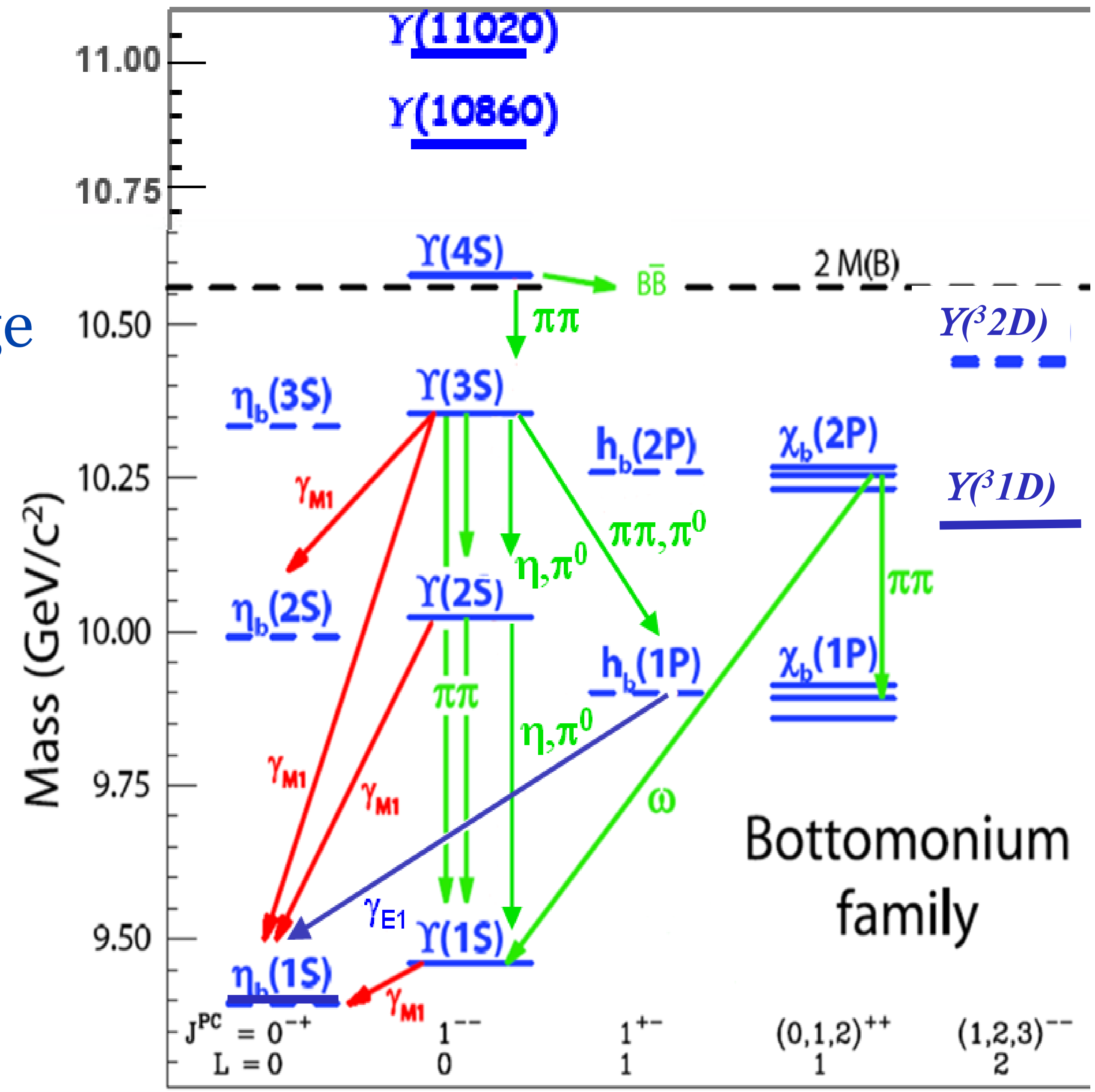
stat syst $N_{Bs^*Bs^*}$

First evidence of $B_s \to J/\psi\, f_0(1370)$

"Simultaneous" observation of $J/\psi\, f_0(980)$. LHCb:arXiv:1102.0206 [hep-ex]

$b\bar{b}$ spectroscopy

- an ideal lab. to study QCD
  - very rich bound states below the open-flavor threshold
  - nearly non-relativistic due to large b mass
- h_b : spin-singlet P wave states
  - testing the P-wave spin-spin interactions in the bb system
  - by $\Delta M_{\mathrm{HF}} \equiv \langle M(n^3P_J)\rangle - M(n^1P_1)$



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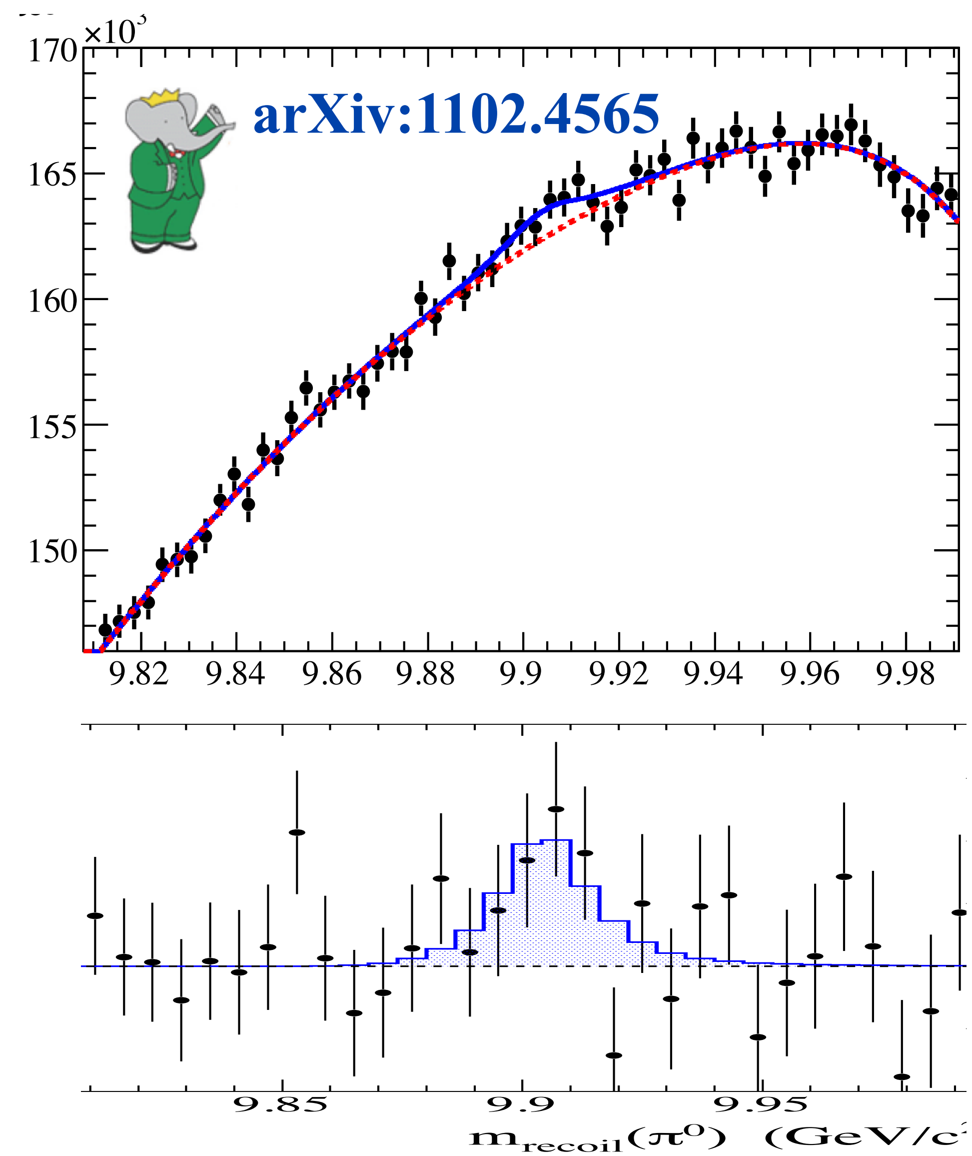
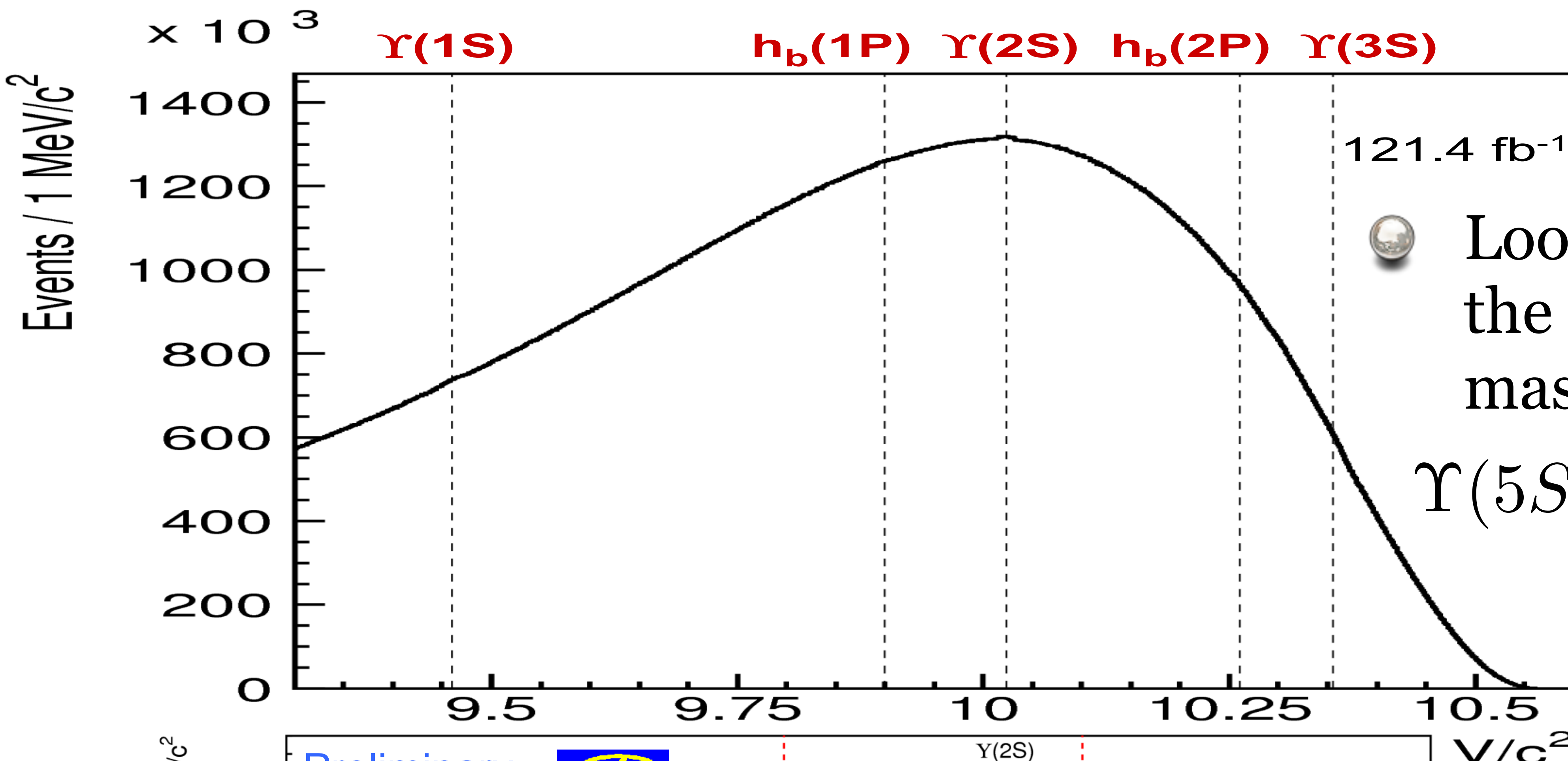
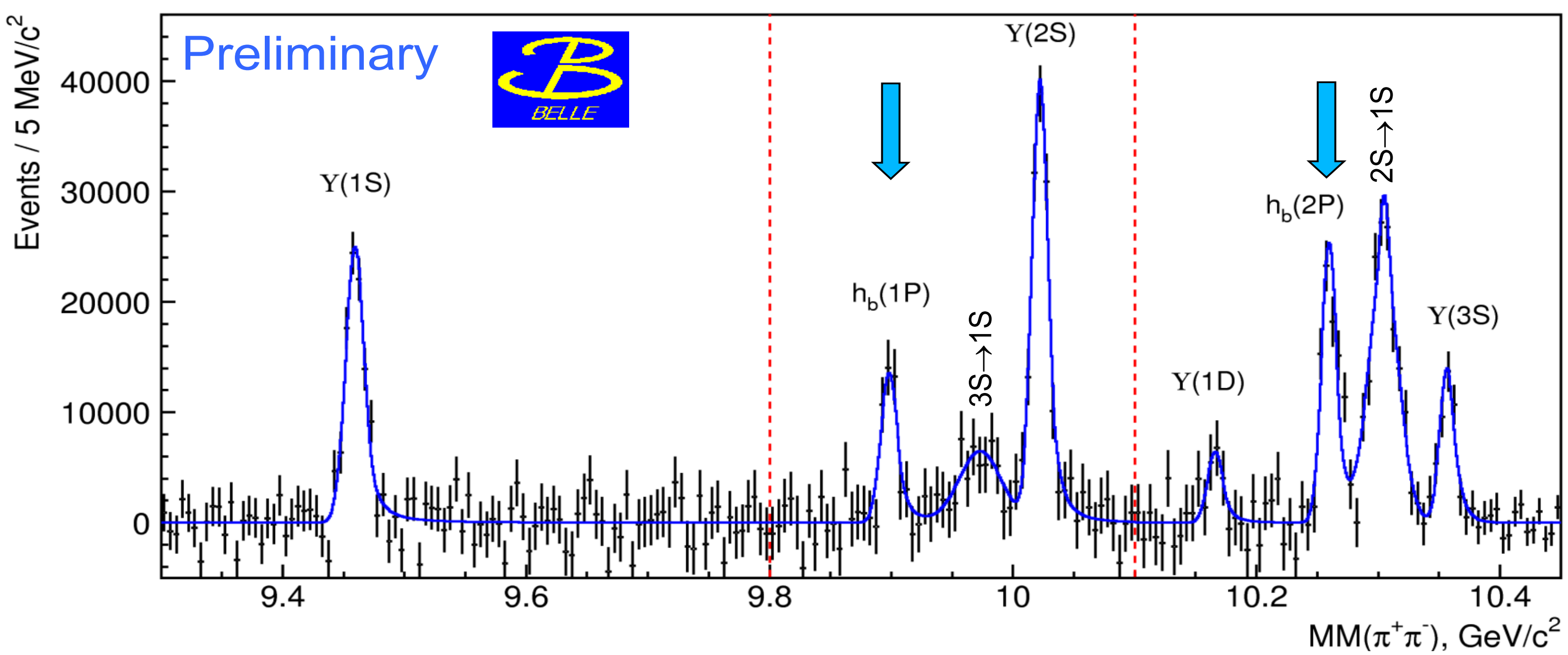
- Evidence for h_b(1P) from BaBar

$$\Upsilon(3S) \to \pi^0 h_b(1P) \to \pi^0 \gamma \eta_b(1P)$$



Observation of h_b states





- Look for signals in the missing (recoil) mass against $\pi^+\pi^-$

$$\Upsilon(5S) \rightarrow (\cdots)\pi^+\pi^-$$

Significance w/ systematics

$h_b(1P)$	5.5σ
$h_b(2P)$	11.2σ

Observation of h_b states

- ΔM_{HF} is consistent with zero, as expected
  - $\Delta M_{\mathrm{HF}}(1\mathrm{P}) = 1.62 \pm 1.52$ MeV/c^2
  - $\Delta M_{\mathrm{HF}}(2\mathrm{P}) = 0.48^{+1.57}_{-1.22}$ MeV/c^2
- The production rates are comparable to that of Υ(2S),

$$\frac{\Gamma[\Upsilon(5S) \to h_b(nP)\,\pi^+\pi^-]}{\Gamma[\Upsilon(5S) \to \Upsilon(2S)\,\pi^+\pi^-]} = \begin{cases} 0.407 \pm 0.079^{+0.043}_{-0.076} & \text{for } h_b(1P) \\ 0.78 \pm 0.09^{+0.22}_{-0.10} & \text{for } h_b(2P) \end{cases}$$

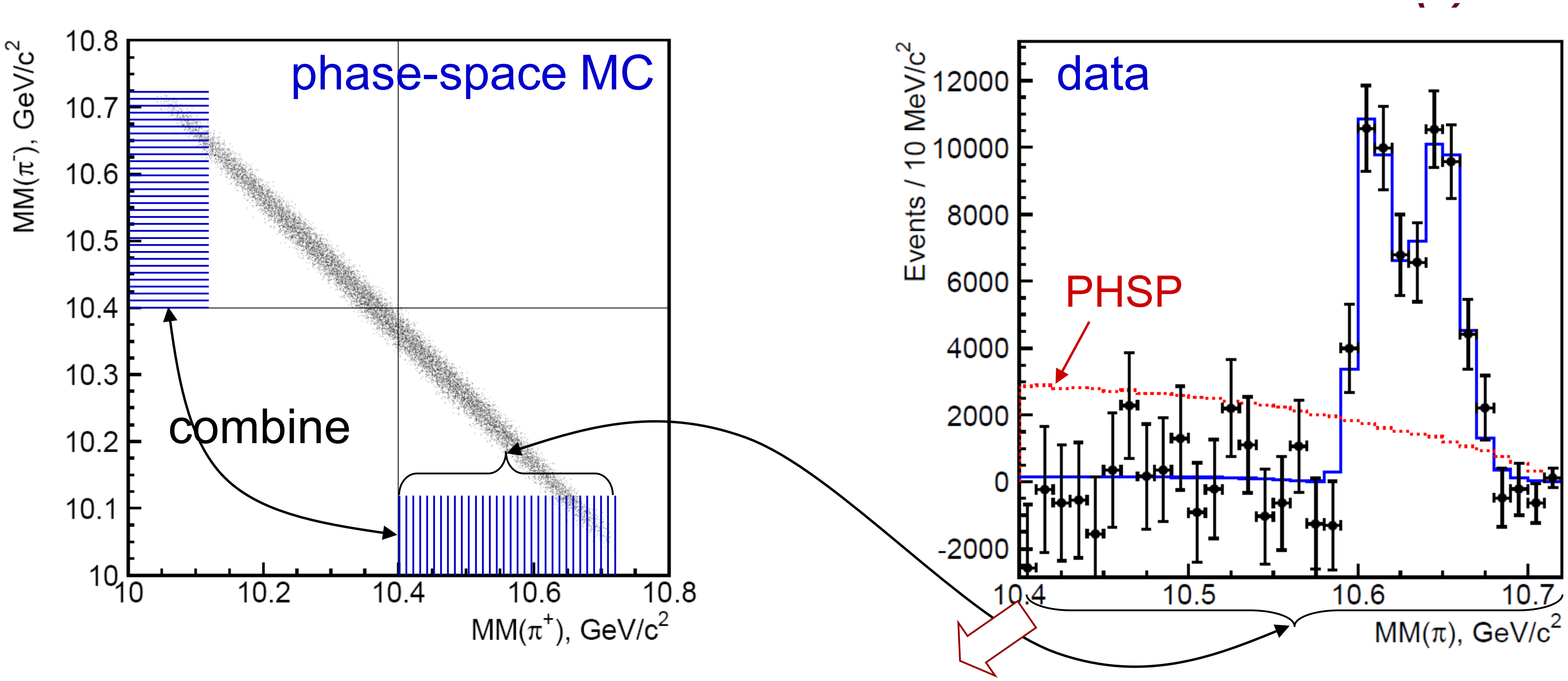
no flip   spin-flip

  - not consistent with naive argument of spin-flip suppression
  - moreover, no h_b signals from Υ(4S) decays
  - an exotic mechanism contributing to the Υ(5S) decays?
- A **motivation** to **study resonant substructure** of this process

preliminary

Observation of Z_b states

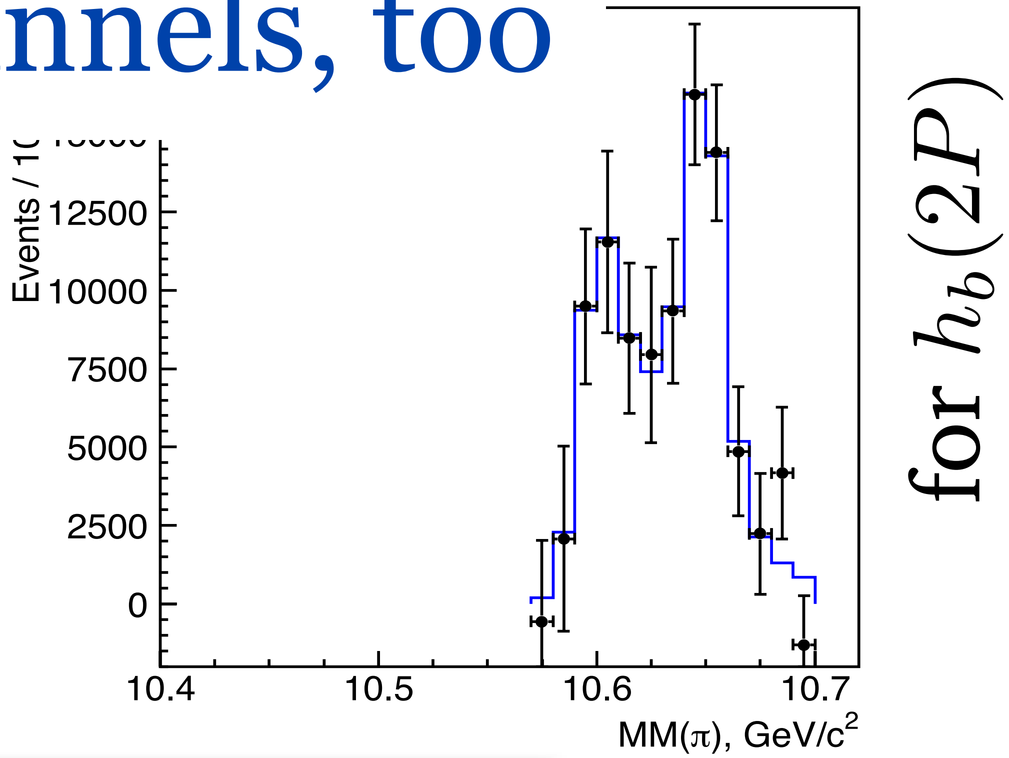
- Look for resonant substructure of $\Upsilon(5S) \to h_b(1P)\pi^+\pi^-$
  - $M(h_b\pi^\pm) = MM(\pi^\mp)$
  - combine the bins of $M(h_b\pi^\pm) = MM(\pi^\mp)$
  - measure $\Upsilon(5S) \to h_b(1P)\pi^+\pi^-$ yields in bins of $MM(\pi^\mp)$

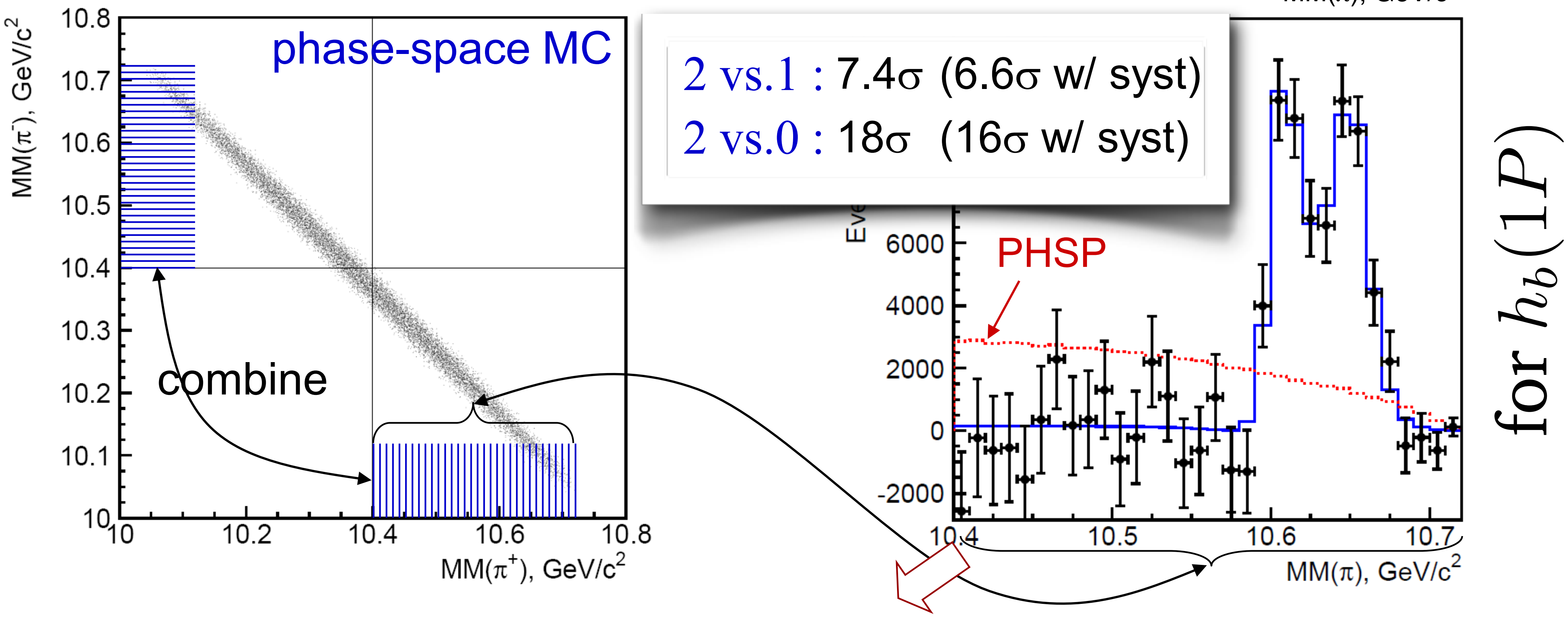


fit to $\left|BW_1^P(s) + ae^{i\phi}BW_2^P(s) + be^{i\psi}\right|^2 \frac{qp}{\sqrt{s}}$

Z_b in other channels, too

from angular analysis,
--> the two states $Z_b(10610)$ and $Z_b(10650)$ are both consistent with 1^+ hypothesis





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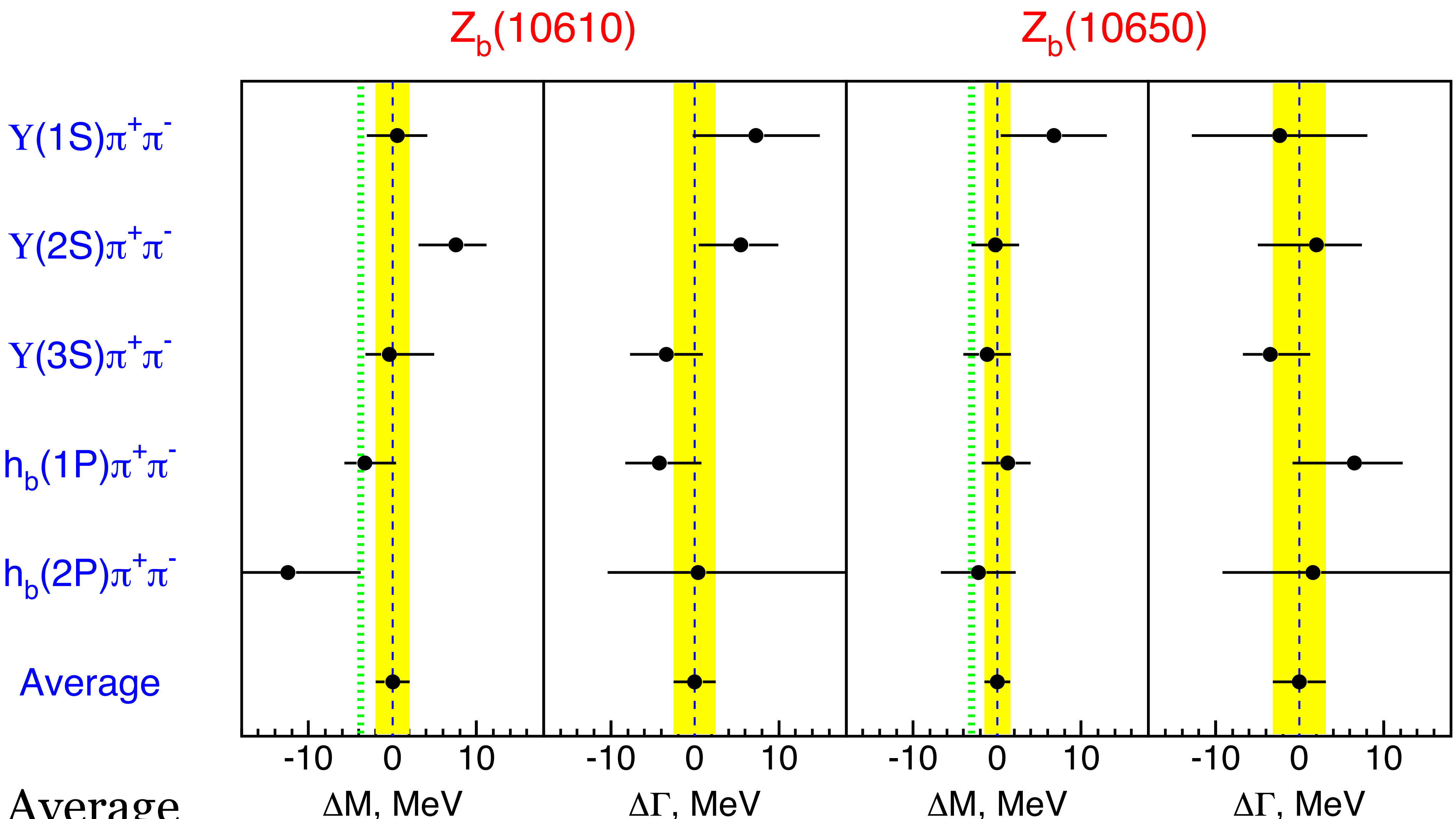
preliminary

Observation of Z_b states



Average M, Γ	10608.4 ± 2.0	15.6 ± 2.5	10653.2 ± 1.5	14.4 ± 3.2

What's ahead

- B physics experiments have taught us a lot
  - success of CKM paradigm for CPV (--> Physics Nobel 2008)
  - many interesting Rare B decay results
  - Yet, there are a few "tensions" & "puzzles"
- What's ahead
  - (*although I didn't say a word about it…*) The case for flavor physics in the LHC era is still compelling
  - LHC, esp. LHCb experiment will be great tools for heavy-flavor physics
  - But some physics modes, e.g. those with neutrino(s), will require next-generation B-factories (i.e. **Belle-II, SuperB**)

Future prospects

a news on Dec.27, 2010

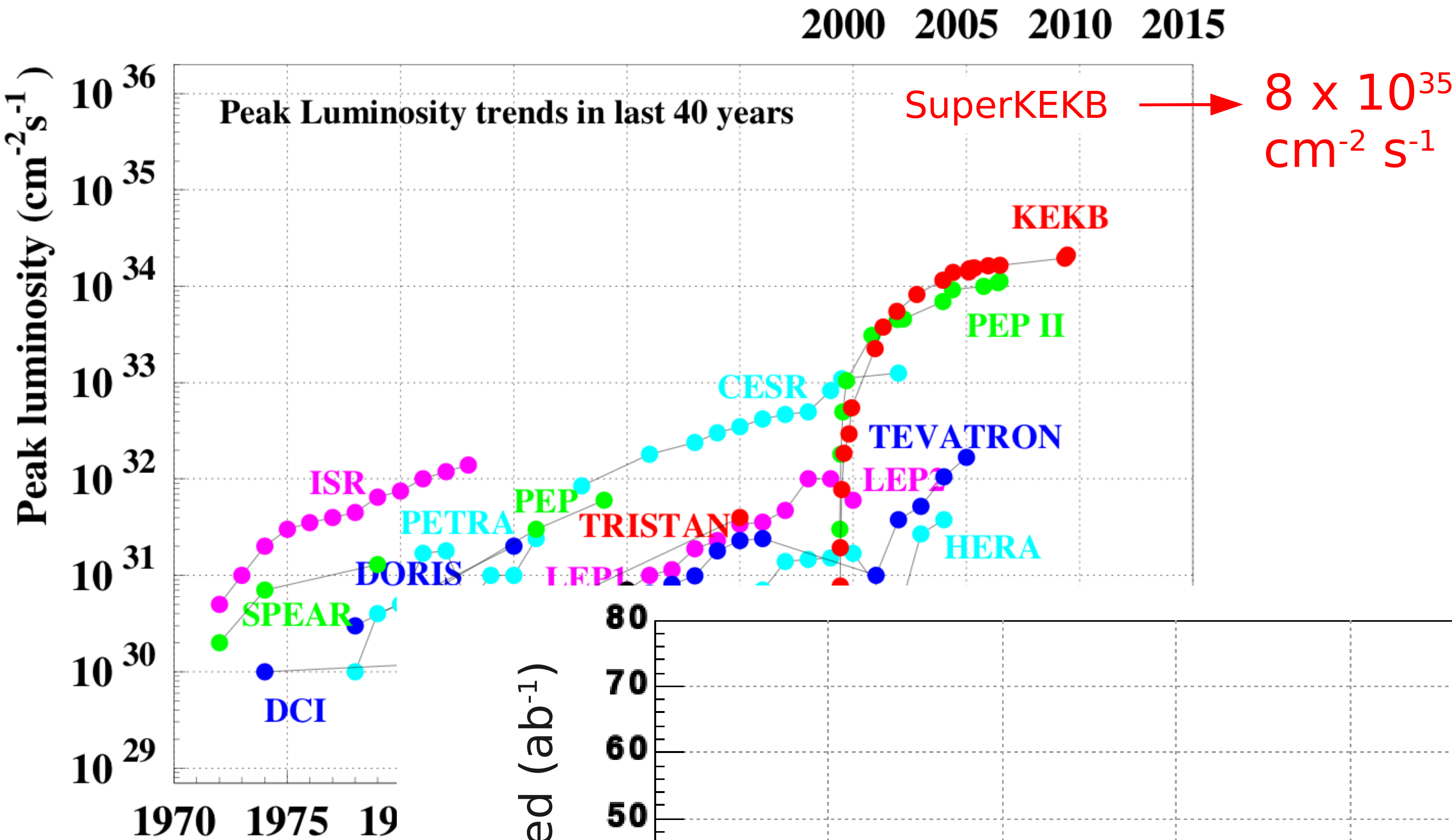
Dear Colleagues,

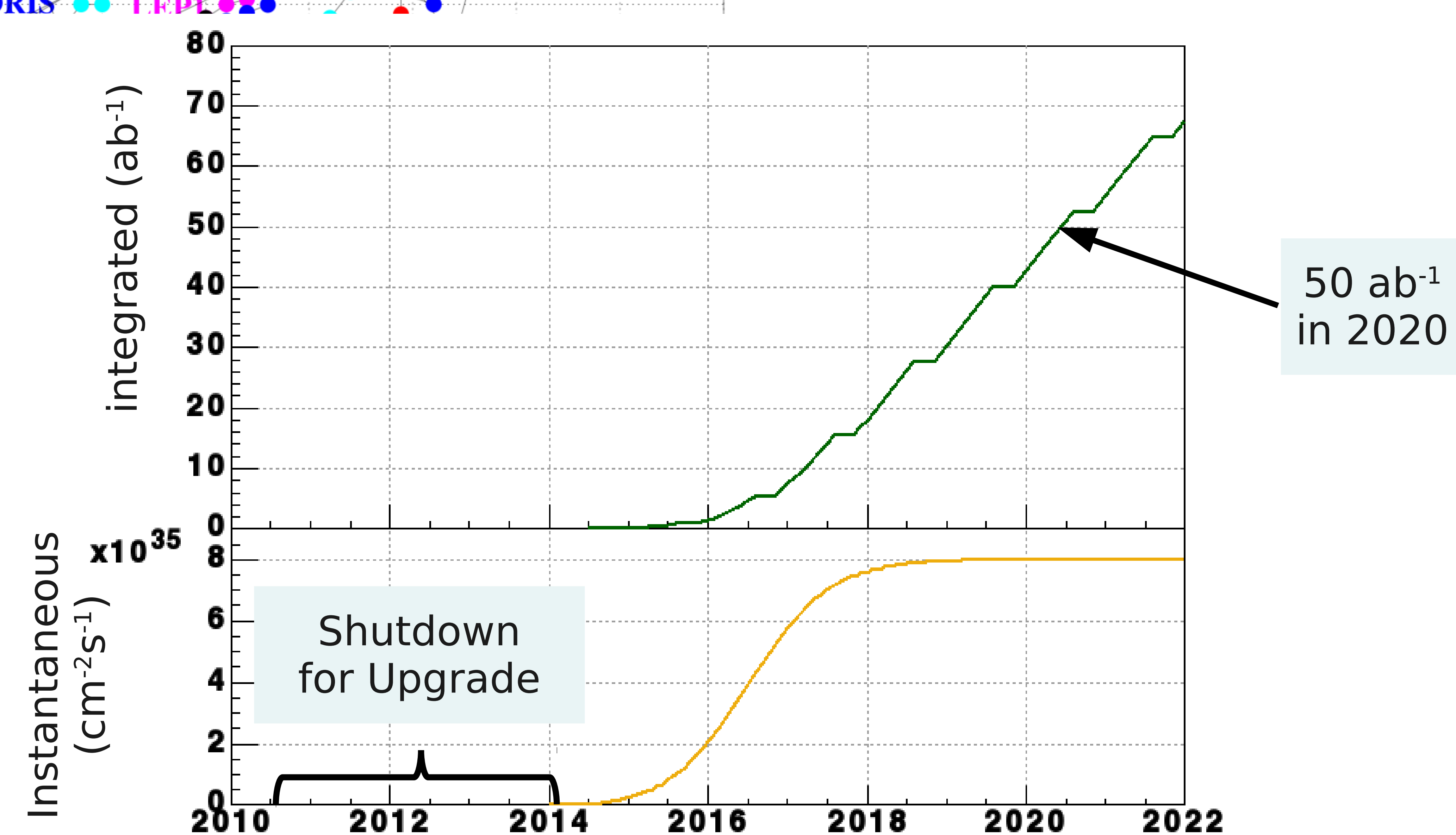
The Cabinet of Japan announced the national budget plan of JFY2011 last Friday, where SuperKEKB upgrade was approved as requested by MEXT.
This will be final decision of SuperKEKB after approval by the Japanese Diet.

Happy new year to you all!

M. Y.

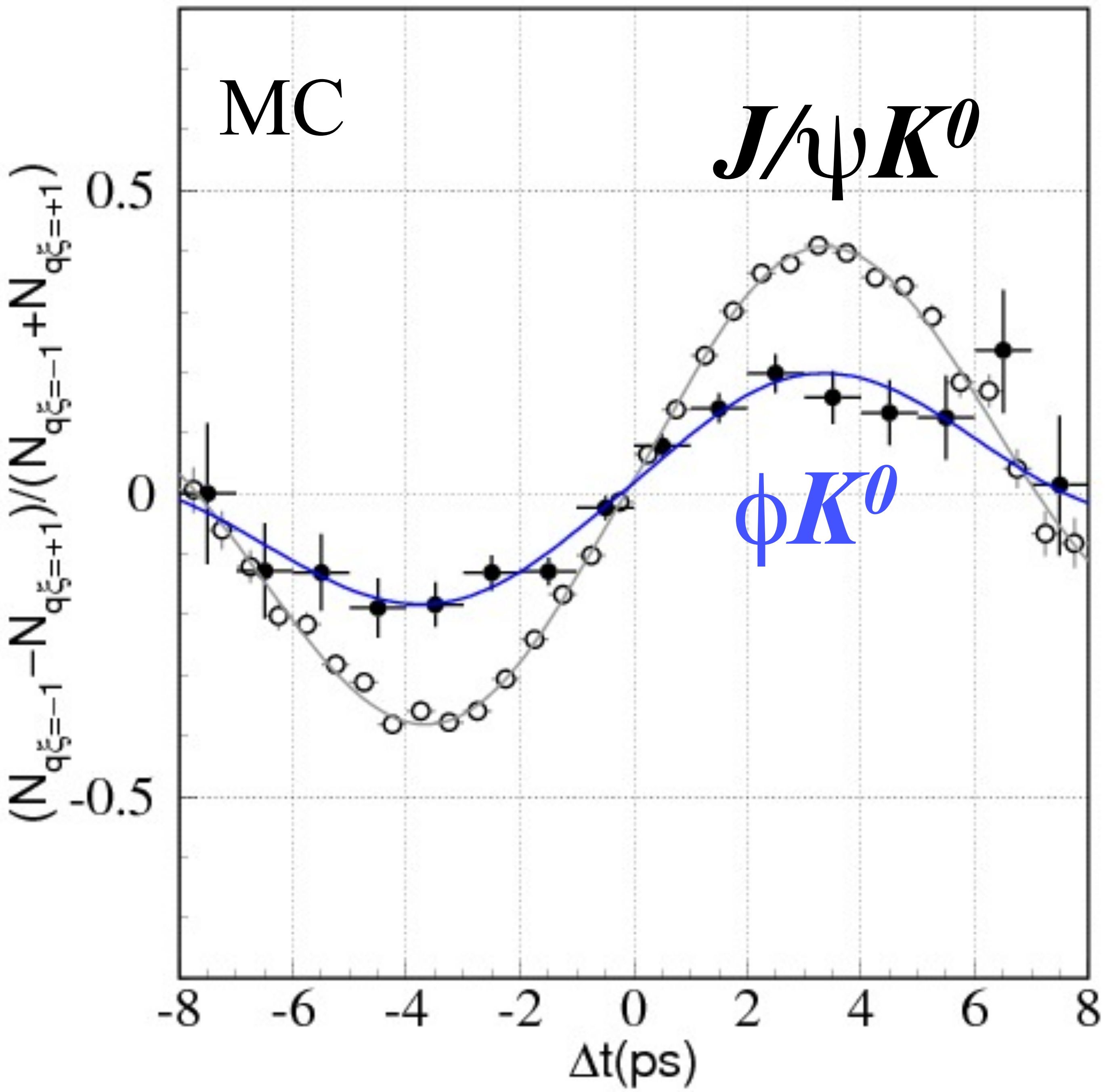
Future prospects





Extrapolation: $B \to \phi K^0$ at 50/ab

with present WA values



This would establish the existence of a NP phase

Compelling measurement in a clean mode

Epilogue

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

–A. Soni@Super KEKB proto-collaboration meeting

A lesson from history

"A special search at Dubna was carried out by E. Okonov and his group. They did not find a single $K_L \to \pi^+ \pi^-$ event among 600 decays into charged particles [12] (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the Lab. The group was unlucky."

-Lev Okun, "The Vacuum as Seen from Moscow"

$$(1964)\ \mathcal{B} = 2 \times 10^{-3}$$

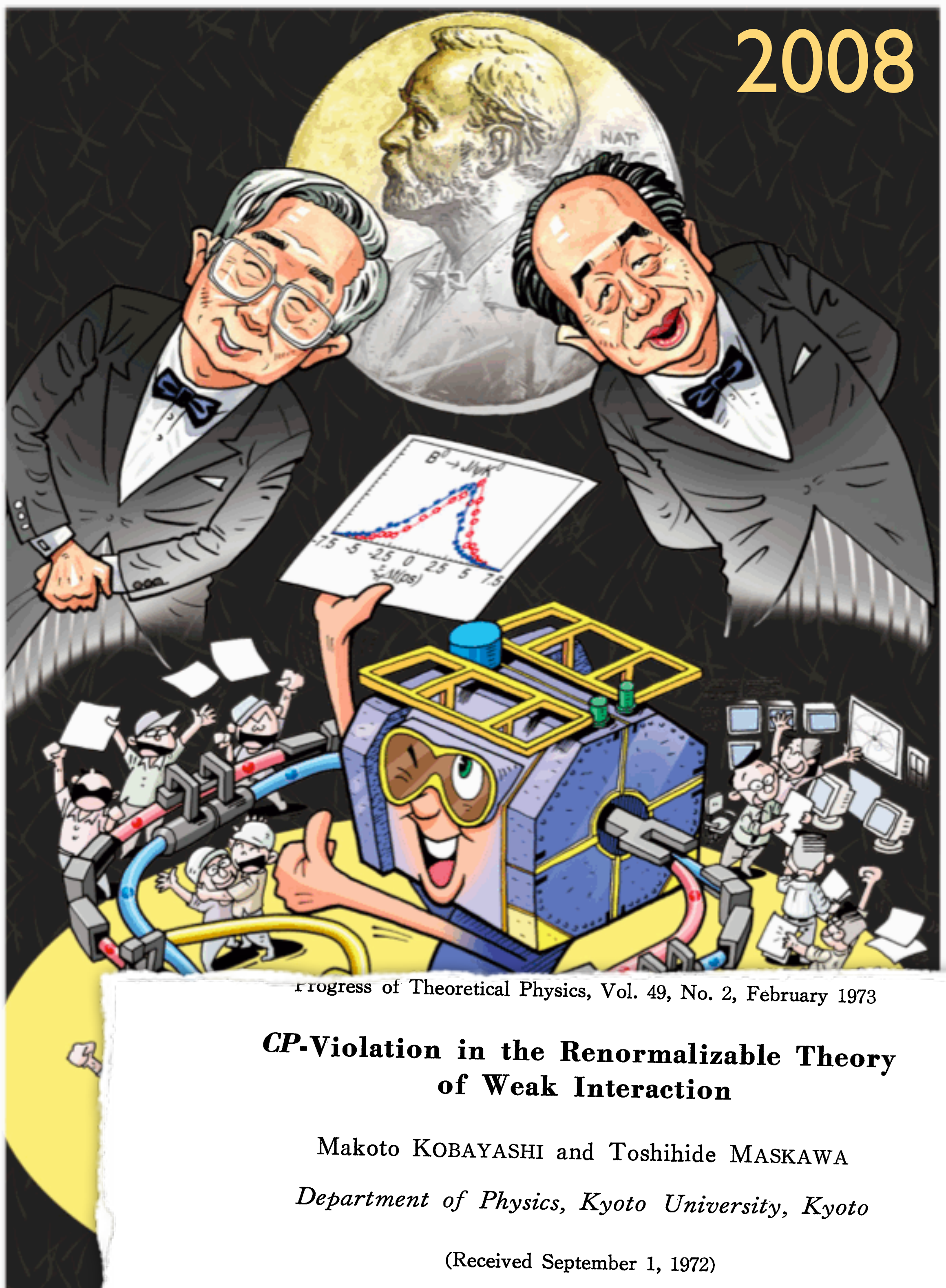
A failure of imagination, or lack of patience?

back-up slides

Historical Milestones

- 1957 Parity violation in ^{60}Co
- 1963 Cabibbo angle
- 1964 CP violation in K^0
- 1967 Sakharov's 3 conditions
- 1973 KM mechanism
- 1977 Discovery of b quark
- 1983 1st recon. of B meson
- 1987 B^0 mixing
- 1999 B-factories (Belle, BaBar) started
- 2001 CP violation in B^0
- 2004 Direct CP violation in B^0
- 2006 B_s mixing
- 2008 (1/2) Nobel Physics prize to K & M

N. Cabibbo
(1935-2010)



Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

When we apply the renormalizable theory of weak interaction[1] to the hadron system ...

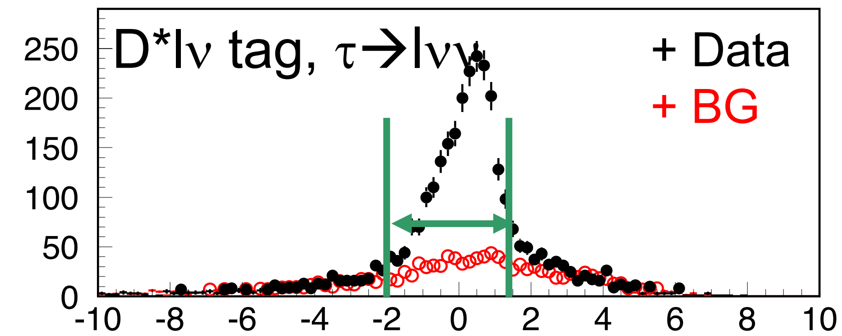
- Critical role of the *B*-factories in the verification of the KM hypothesis was recognized and cited by the Nobel Foundation
- A single irreducible phase in the weak int. matrix accounts for most of the *CP* violation observed in the *K*'s and in the *B*'s
- *CP*-violating effects in the B sector are $\mathcal{O}(1)$ rather than $\mathcal{O}(10^{-3})$ as in the K^0 system.

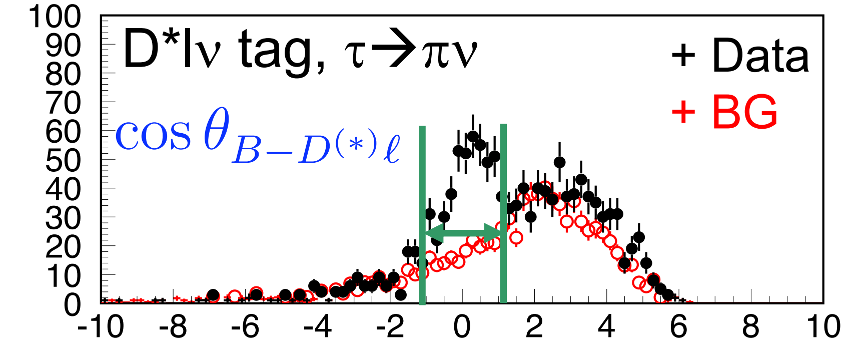
$B^+ \to \tau^+\nu_\tau$ by semileptonic tagging

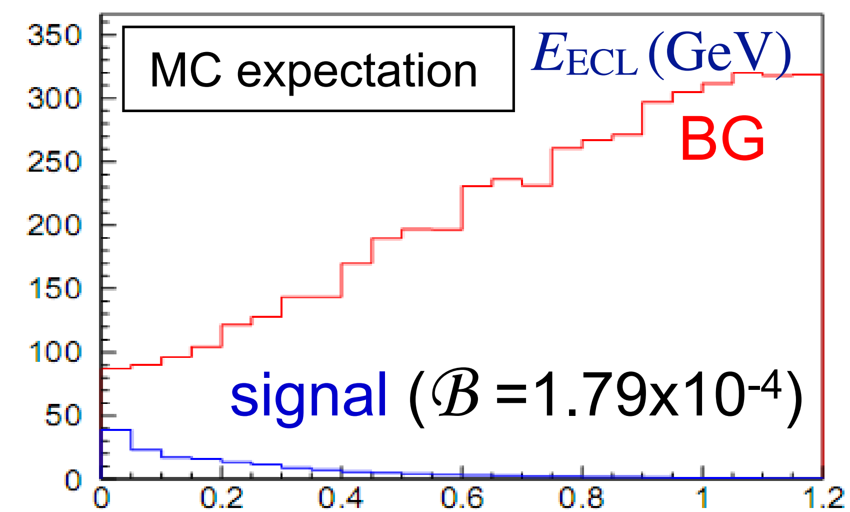
- Statistically independent sample from hadronic tagging
- Tagging side
  - Reconstruct $B^+ \to \overline{D}^{(*)}\ell^+\nu_\ell$
  - Kinematic relation for good-tag id.

$$\cos\theta_{B-\overline{D}^{(*)}\ell^+} = \frac{2E_B E_{\overline{D}^{(*)}\ell^+} - M_B^2 - M_{\overline{D}^{(*)}\ell^+}^2}{2P_B P_{\overline{D}^{(*)}\ell^+}}$$

- Signal side
  - Use *1-prong* τ^- modes: $\ell^-\bar{\nu}\nu$, $\pi^-\nu$
  - $E_{\rm ECL}$ to extract $N_{\rm sig}$

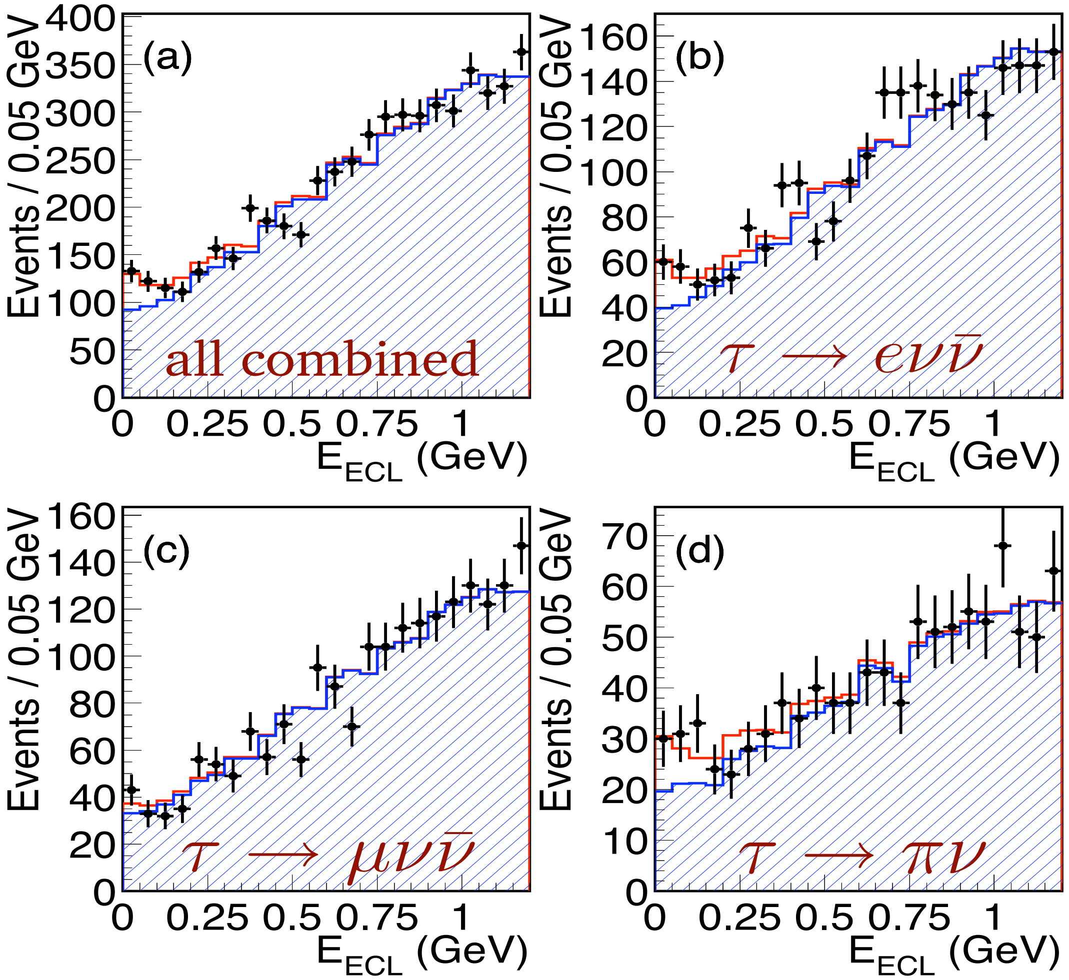






PRD 82, 071101 (2010)

$B^+ \to \tau^+ \nu_\tau$ by semileptonic tagging



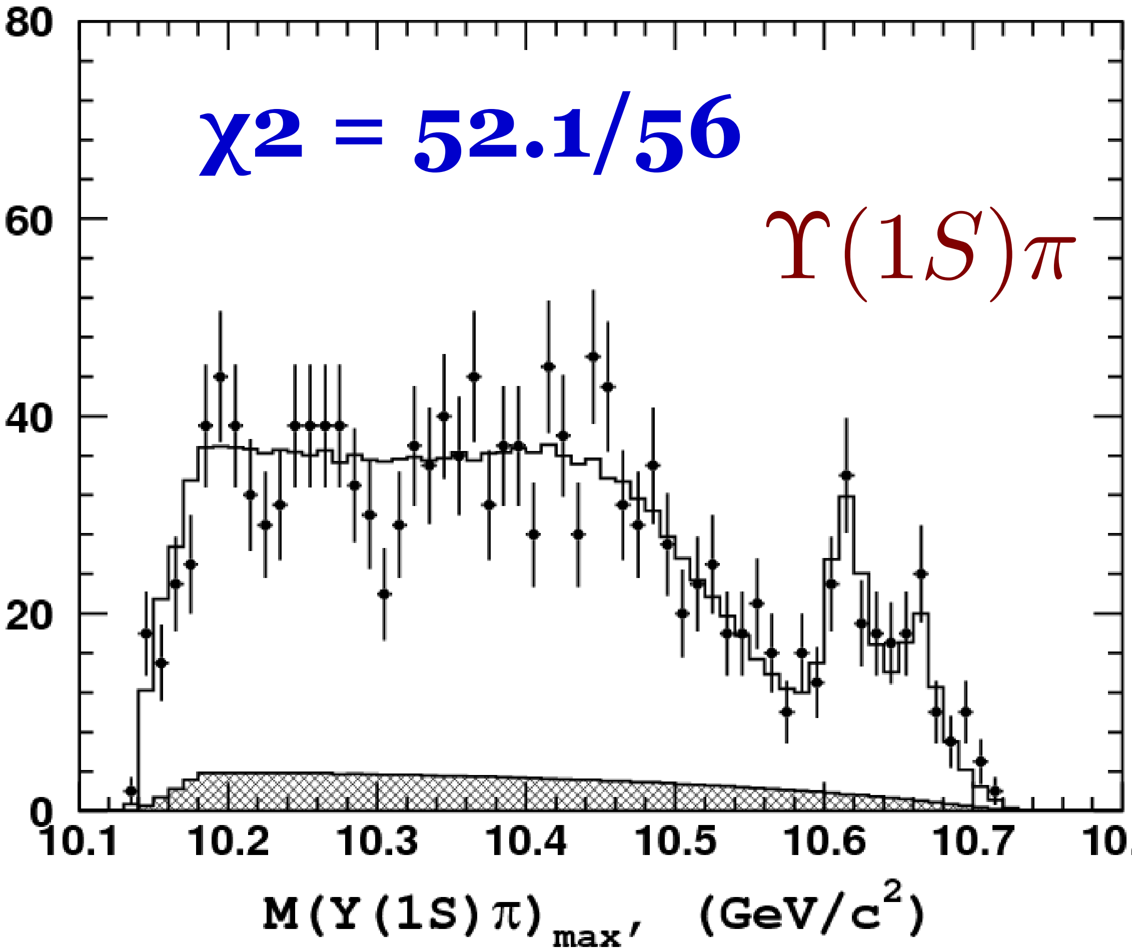
- Max. likelihood fit to $E_{\rm ECL}$ distribution
- Systematic err.
  - SL tagging efficiency (13.7%)
  - BG shape (+8.6%, -8.3%)
  - $\mathcal{B}$(peaking BG modes) (+4.5%, -8.8%)
  - $\mathcal{B}$(rare B modes) (+7.6%, -7.7%)
- Significance: 3.6σ incl. syst. err.

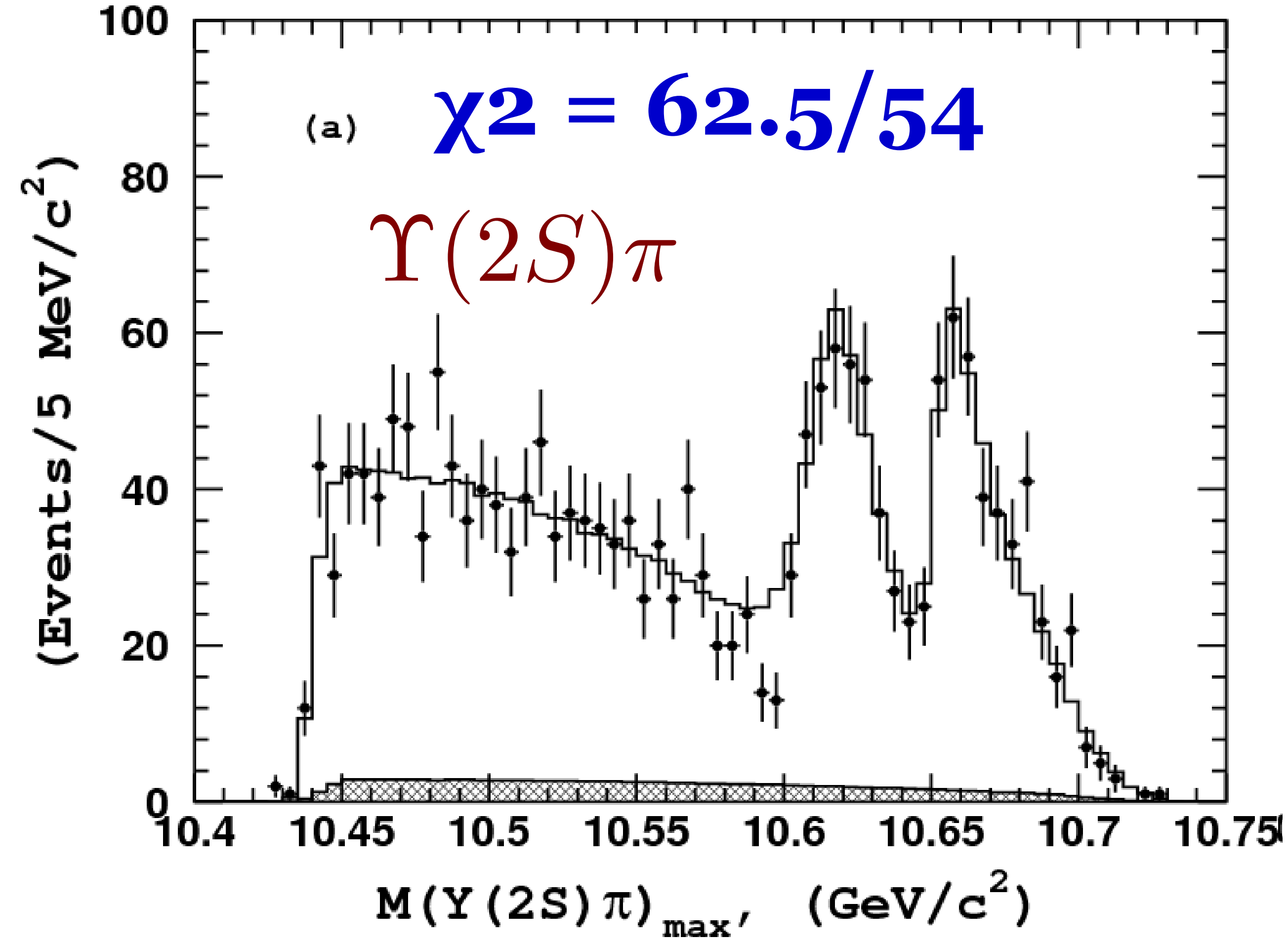
$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (1.54^{+0.38+0.29}_{-0.37-0.31}) \times 10^{-4}$$

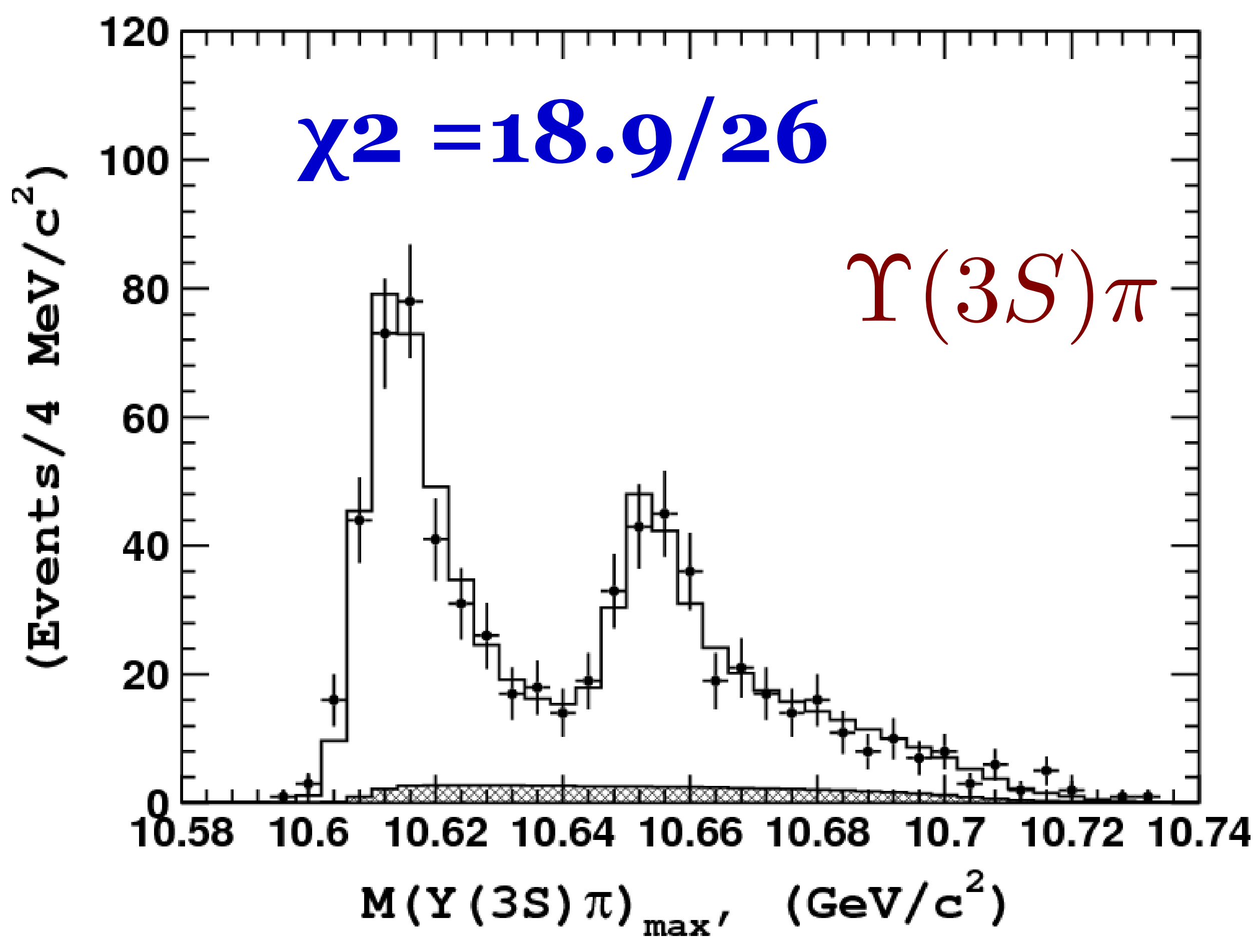
$$f_B|V_{ub}| = (9.3^{+1.2}_{-1.1} \pm 0.9) \times 10^{-4}\ \text{GeV}$$

PRD 82, 071101 (2010)

Decay Mode	Signal Yield	ε (10^{-4})	$\mathcal{B}$ (10^{-4})
$\tau^- \to e^-\nu\bar{\nu}_\tau$	73^{+23}_{-22}	5.9	$1.90^{+0.59+0.33}_{-0.57-0.35}$
$\tau^- \to \mu^-\nu\bar{\nu}_\tau$	12^{+18}_{-17}	3.7	$0.50^{+0.76+0.18}_{-0.72-0.21}$
$\tau^- \to \pi^-\nu_\tau$	55^{+21}_{-20}	4.7	$1.80^{+0.69+0.36}_{-0.66-0.37}$
Combined	146^{+36}_{-35}	14.3	$1.54^{+0.38+0.29}_{-0.37-0.31}$







consistent Z_b peaks in $\Upsilon(nS)\pi$