Radiative B Decays at BaBar Belle

color code: blue for Belle, green for BaBar.

Mikihiko Nakao (KEK)

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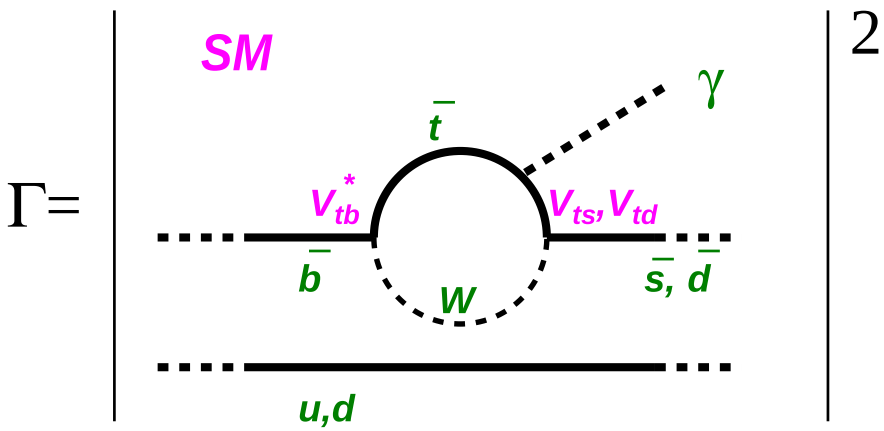
Radiative B decays

Flavor changing neutral current (FCNC)



Unique tool to study quark-level couplings

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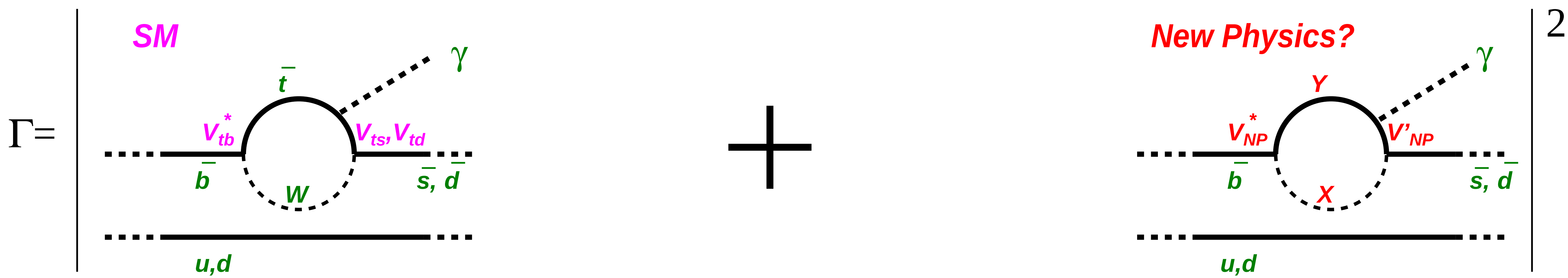

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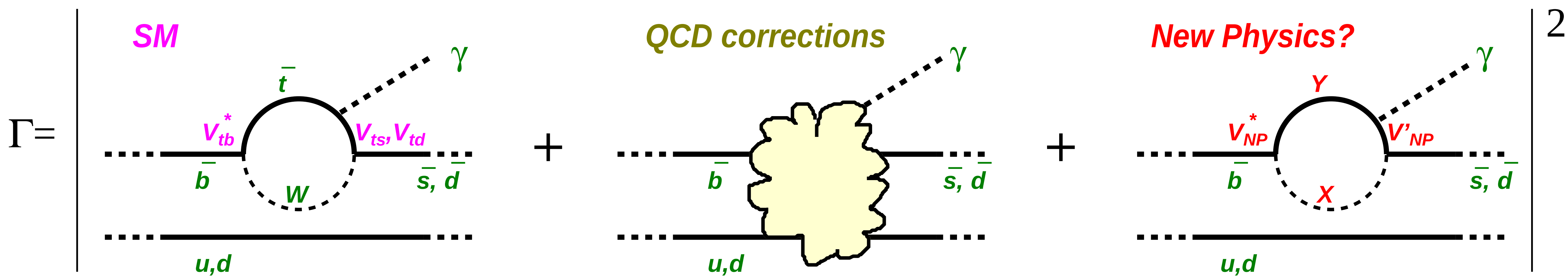

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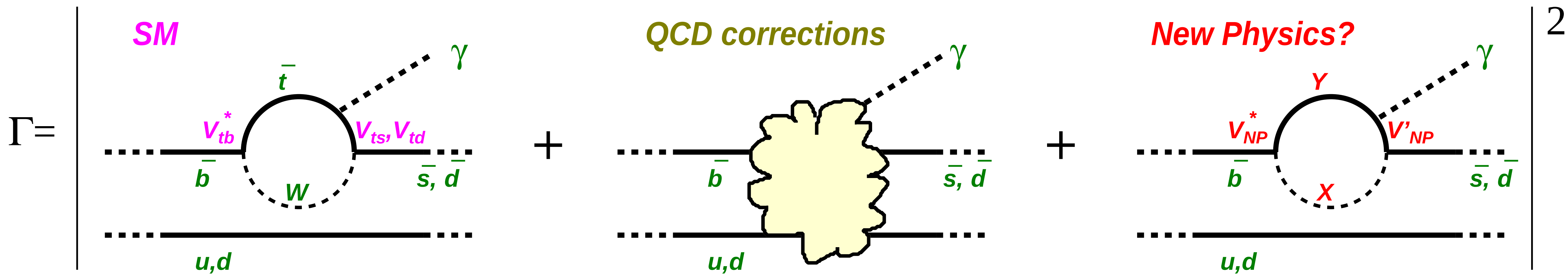

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Outline — new/recent results on. . .

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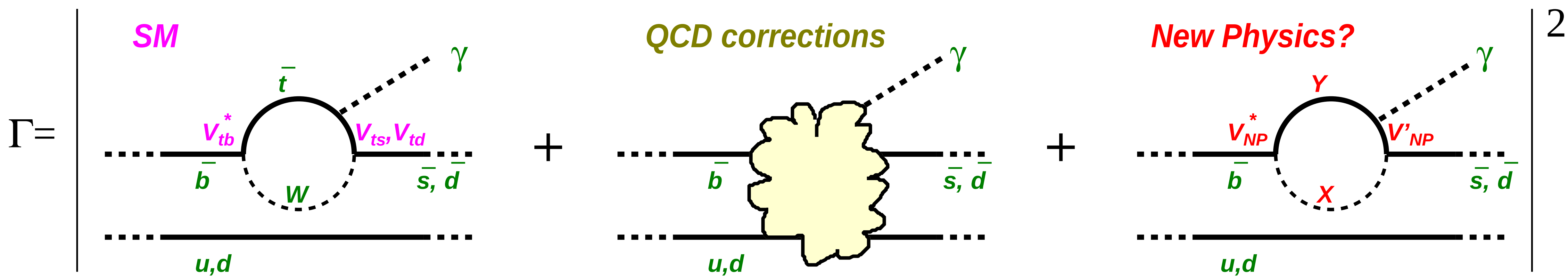


Unique tool to study quark-level couplings (search for new physics)
Unique tool to study QCD corrections (probe for the murky hadron)

Outline — new/recent results on. . .

- First observation of the $b \to d\gamma$ process
- Inclusive $b \to s\gamma$ precision measurements
- Searches for CPV in $b \to s\gamma$ and exotic radiative modes

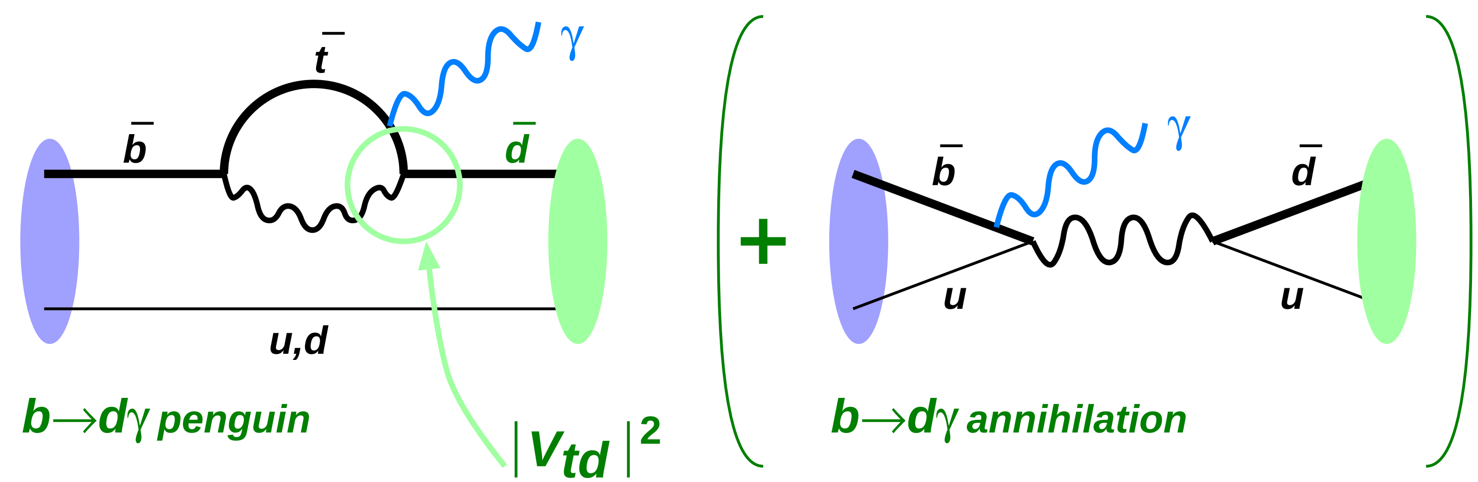
(note the studies on radiative decays are not limited to the topics above)

$b \to d\gamma$

The first observation

$b \to d\gamma$ in exclusive processes

- Three major roles of $b \to d\gamma$
  - Sensitive to $|V_{td}|$, or to $|V_{td}/V_{ts}|$ w.r.t. corresponding $b \to s\gamma$
  - Sensitive to new physics assuming $|V_{td}|$ from CKM fits could be very sensitive since the SM amplitude is suppressed
  - Large direct CPV is expected



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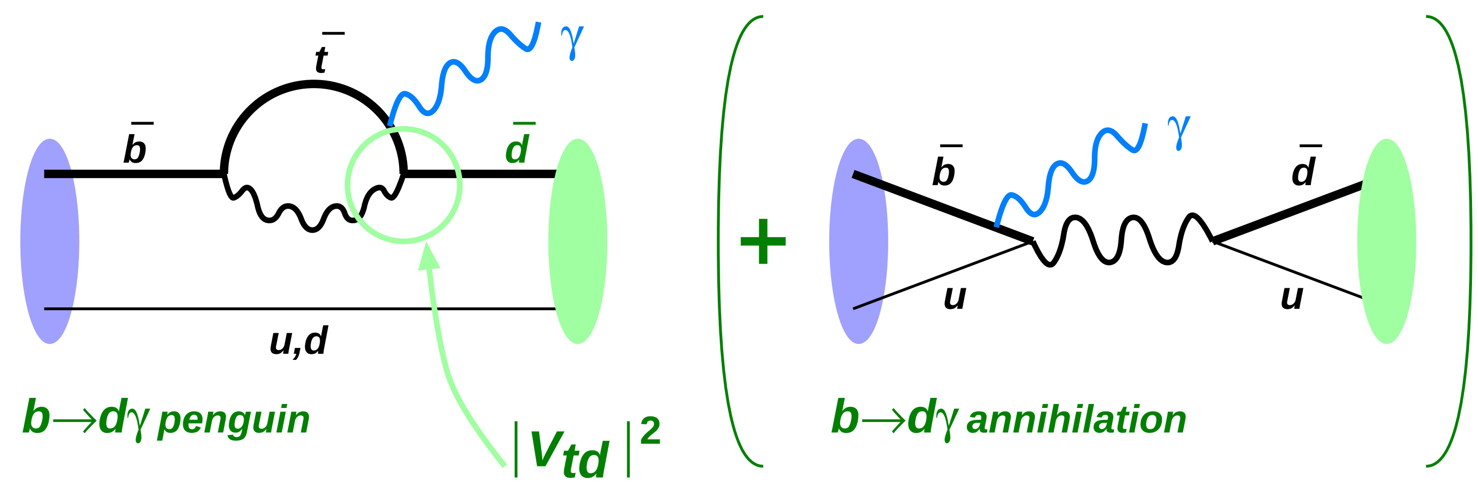
- Exclusive processes: $B^- \to \rho^-\gamma$, $\overline{B}^0 \to \rho^0\gamma$, $\overline{B}^0 \to \omega\gamma$



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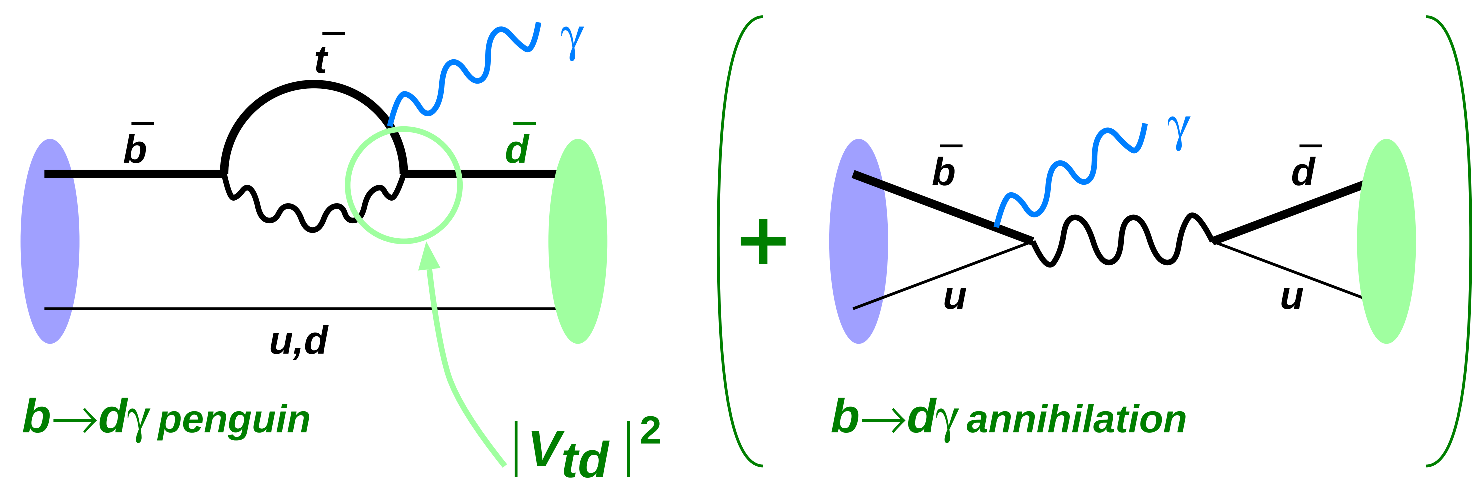


- Pros and cons of exclusive modes
  - Straightforward reconstruction — standard technique ($M_{\mathrm{bc(ES)}}$, ΔE)
  - Hadronic uncertainty ($\sim 30\%$) — no way to reduce? (inclusive $B \to X_d\gamma$ only for future (> 1 ab^{-1}))

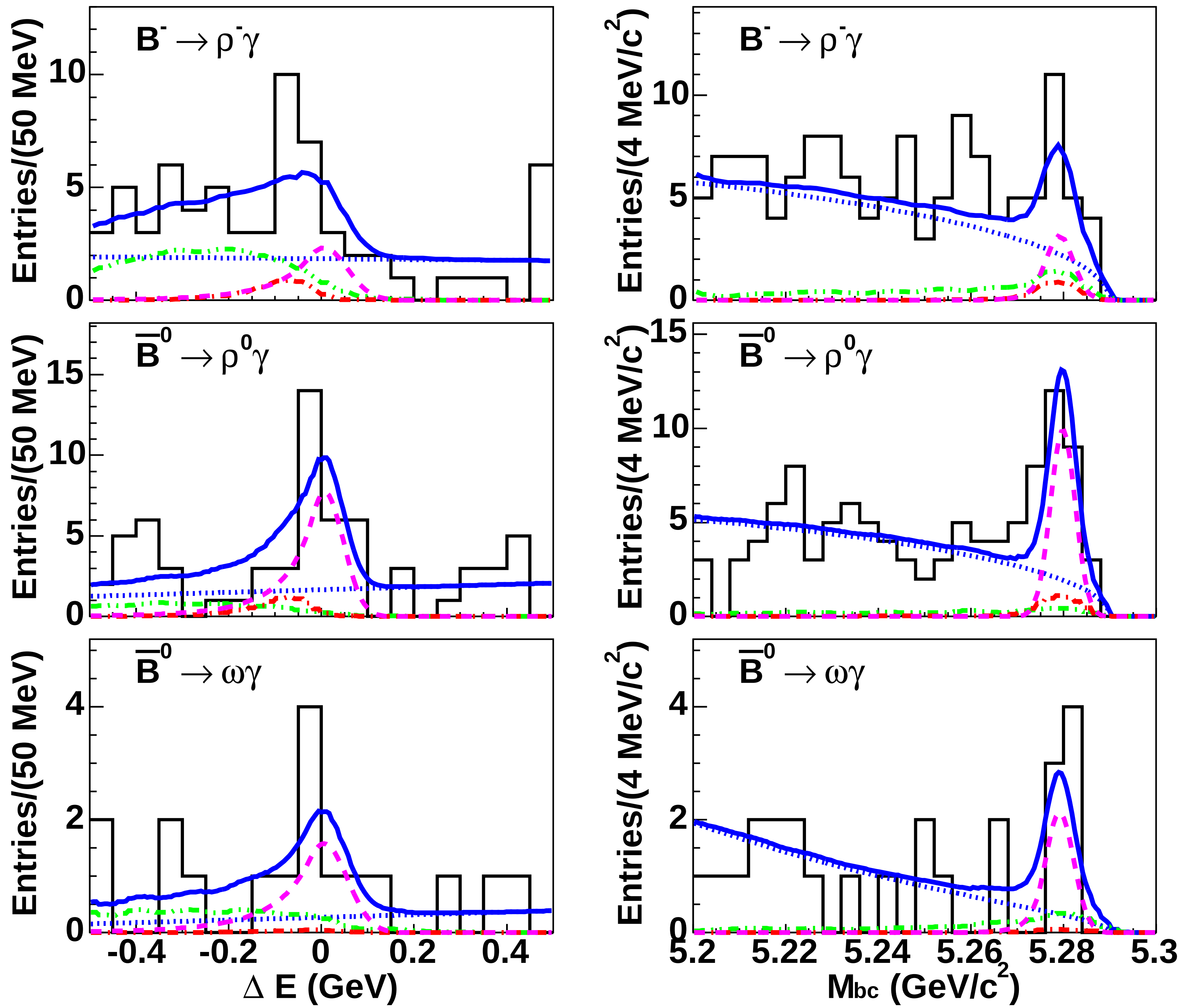
$B \to \rho\gamma$ and $B \to \omega\gamma$ analysis challenges

Many background sources due to the smallness of the signal!

- $B \to K^*\gamma$ backgrounds (×30 than the signal!)
  Particle ID ($\sim 1/10$), $M(\text{“}K\text{''}\pi)$, separation in ΔE
  Good control sample: signal shape, analysis cross-check
- Other $B \to X_s\gamma$
- $B \to (\rho,\omega)\pi^0$ and $B \to (\rho,\omega)\eta$
  π^0/η rejection, decay helicity angle of (ρ,ω)
- Other rare B decays with ρ or ω
- Huge continuum background
  Event shape, Δz, B meson direction ⇒ likelihood ratio
  Flavor-tag algorithm to suppress continuum (not $B/\overline{B}$ like)

Maximize $N_S/\sqrt{N_B}$ where N_B is the sum of all backgrounds

$B \to \rho\gamma$ and $B \to \omega\gamma$ signal



$B^- \to \rho^-\gamma$ (1.6σ)

8.5 events

$\mathcal{B} = (0.55\,^{+0.42}_{-0.36}\,^{+0.09}_{-0.08}) \times 10^{-6}$

$\overline{B}^0 \to \rho^0\gamma$ (5.2σ)

20.7 events

$\mathcal{B} = (1.25\,^{+0.37}_{-0.33}\,^{+0.07}_{-0.06}) \times 10^{-6}$

$\overline{B}^0 \to \omega\gamma$ (2.3σ)

5.7 events

$\mathcal{B} = (0.56\,^{+0.34}_{-0.27}\,^{+0.05}_{-0.10}) \times 10^{-6}$

Belle 386M $B\overline{B}$
hep-ex/0506079
submitted to PRL

Fit: Signal, $K^*\gamma$ background, other B, and continuum

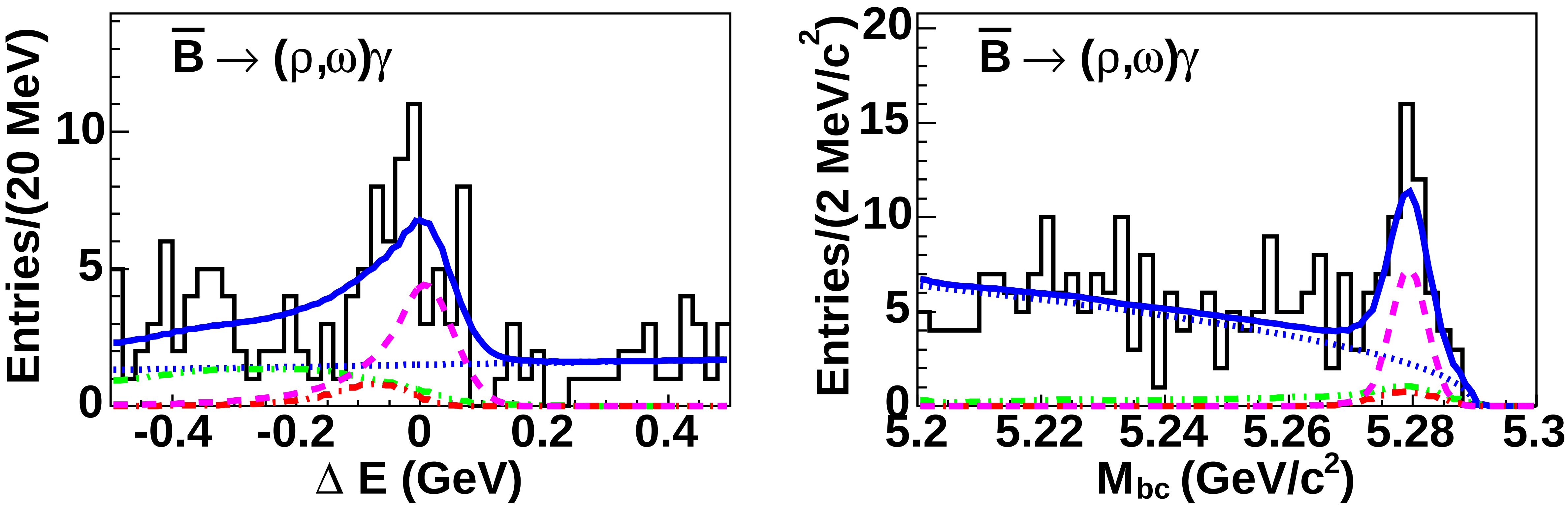
Combined fit — isospin relation

Combined branching fraction to establish the $b \to d\gamma$ signal:

$$\Gamma(B \to (\rho,\omega)\gamma) \equiv \Gamma(B^- \to \rho^-\gamma) = 2\times\Gamma(\overline{B}^0 \to \rho^0\gamma) = 2\times\Gamma(B \to \omega\gamma)$$

Simultaneous fit (Belle), first observation!

$$\mathcal{B}(B \to (\rho,\omega)\gamma) = (1.32\,^{+0.34}_{-0.31}(\text{stat.})\,^{+0.10}_{-0.09}(\text{syst.})) \times 10^{-6}\ (5.1\sigma)$$



similar analysis by BaBar (211M $B\overline{B}$, PRL94,011801(2005)):

$\mathcal{B}(B \to (\rho,\omega)\gamma) = (0.6 \pm 0.3 \pm 0.1) \times 10^{-6}$ (2.1σ) $< 1.2 \times 10^{-6}$ (90%CL)

$|V_{td}/V_{ts}|$ from branching fraction ratio

- Relation between branching fraction ratio and $|V_{td}/V_{ts}|$

$$\frac{\mathcal{B}(B \to (\rho,\omega)\gamma)}{\mathcal{B}(B \to K^*\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{(1 - m^2_{(\rho,\omega)}/m^2_B)^3}{(1 - m^2_{K^*}/m^2_B)^3} \zeta^2 [1 + \Delta R]$$

(form factor ratio $\zeta = 0.85 \pm 0.10$, $SU(3)$-breaking correction $\Delta R = 0.1 \pm 0.1$)

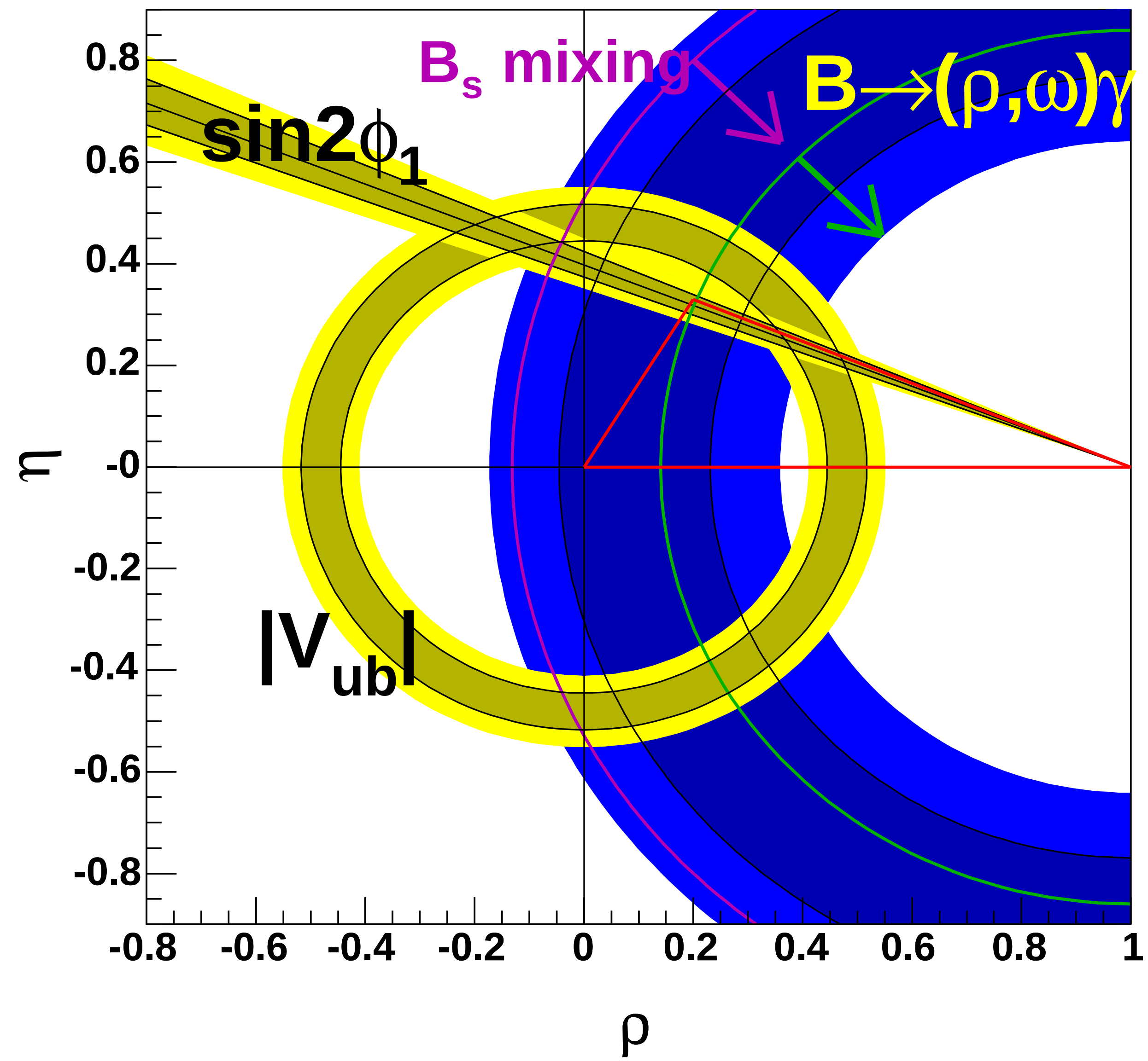
- Ratio from a simultaneous fit to $B \to K^*\gamma$ and $B \to (\rho,\omega)\gamma$
  - Belle result: ratio $= 0.032 \pm 0.008 \pm 0.002$
  - BaBar result: ratio < 0.029 (90%CL)
- Complementary to $B^0_s - \overline{B}^0_s$ mixing at LEP/Tevatron/LHCb
  No lattice-QCD involved (although lattice may help on the form factor)
- Cautions:
  - Theory errors above may be underestimated
    (similarly predicted $B \to K^*\gamma$ rate is a lot higher than measurement)
  - Isospin relation is controversial for precise determination

$|V_{td}/V_{ts}|$ results

$$|V_{td}/V_{ts}| = 0.199\ ^{+0.026}_{-0.025}(\text{exp.})\ ^{+0.018}_{-0.015}(\text{theo.})$$ (Belle)

$0.142 < |V_{td}/V_{ts}| < 0.259$
(Belle 95% CL)

$|V_{td}/V_{ts}| < 0.19$
(BaBar 90% CL)



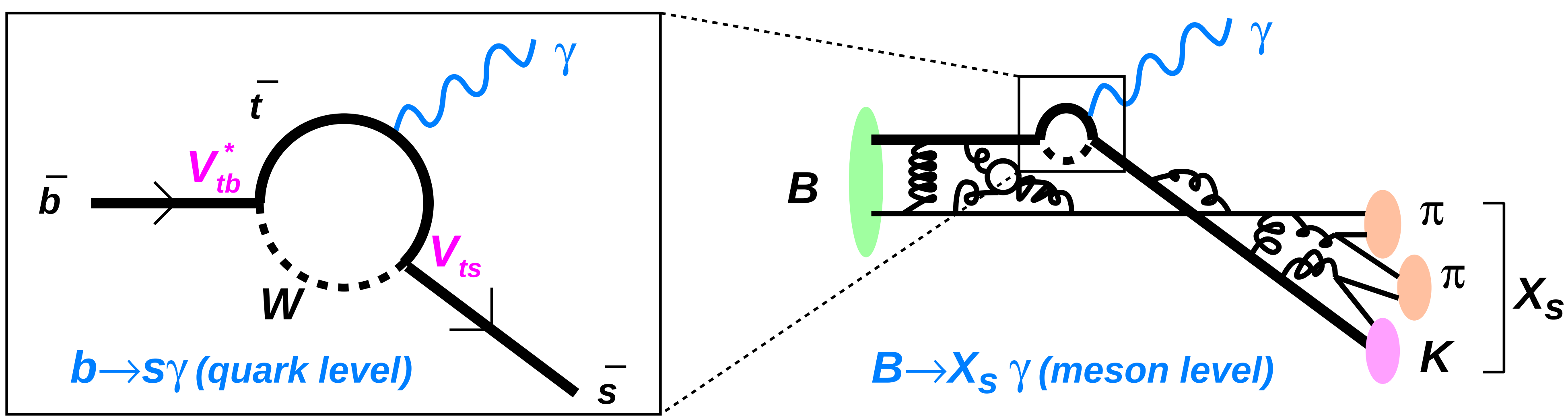
- $|V_{td}/V_{ts}|$ is as expected
- No hint of new physics
- Mode for future CPV study

SM has passed another non-trivial test in $b \to d$ transition!

Inclusive $b \to s\gamma$ precision measurements

Inclusive $b \to s\gamma$ measurement

- Three major roles of $b \to s\gamma$
  - Photon as a probe for B decay properties (universal parameters to improve V_{cb}, V_{ub} and $b \to s\gamma$)
  - Sensitive to new physics (Charged Higgs, SUSY, Left-right symmetric model. . .)
  - To measure $|V_{ts}|$ (without assuming CKM unitarity)



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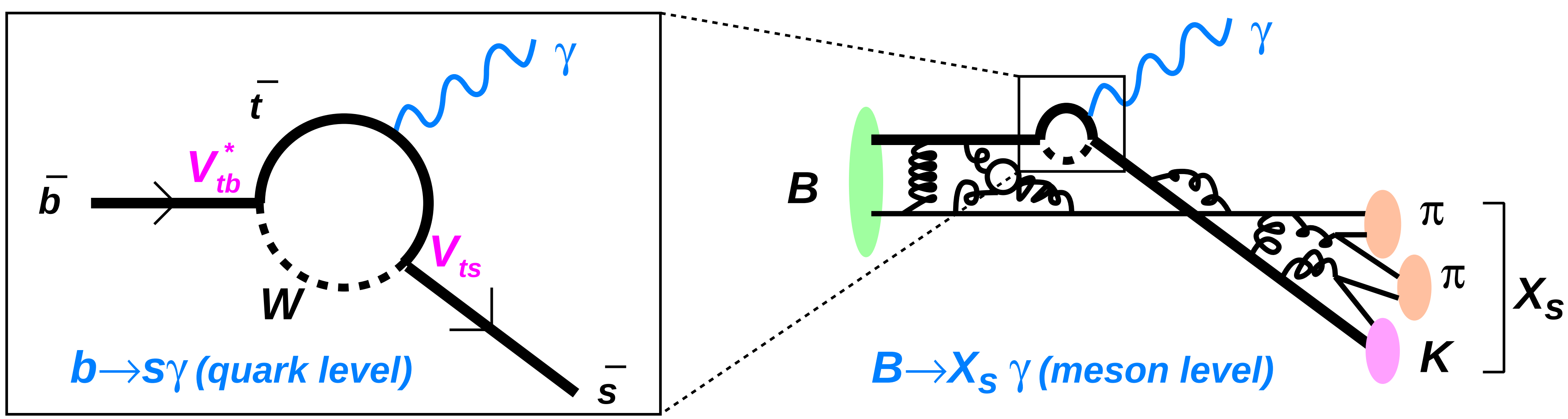
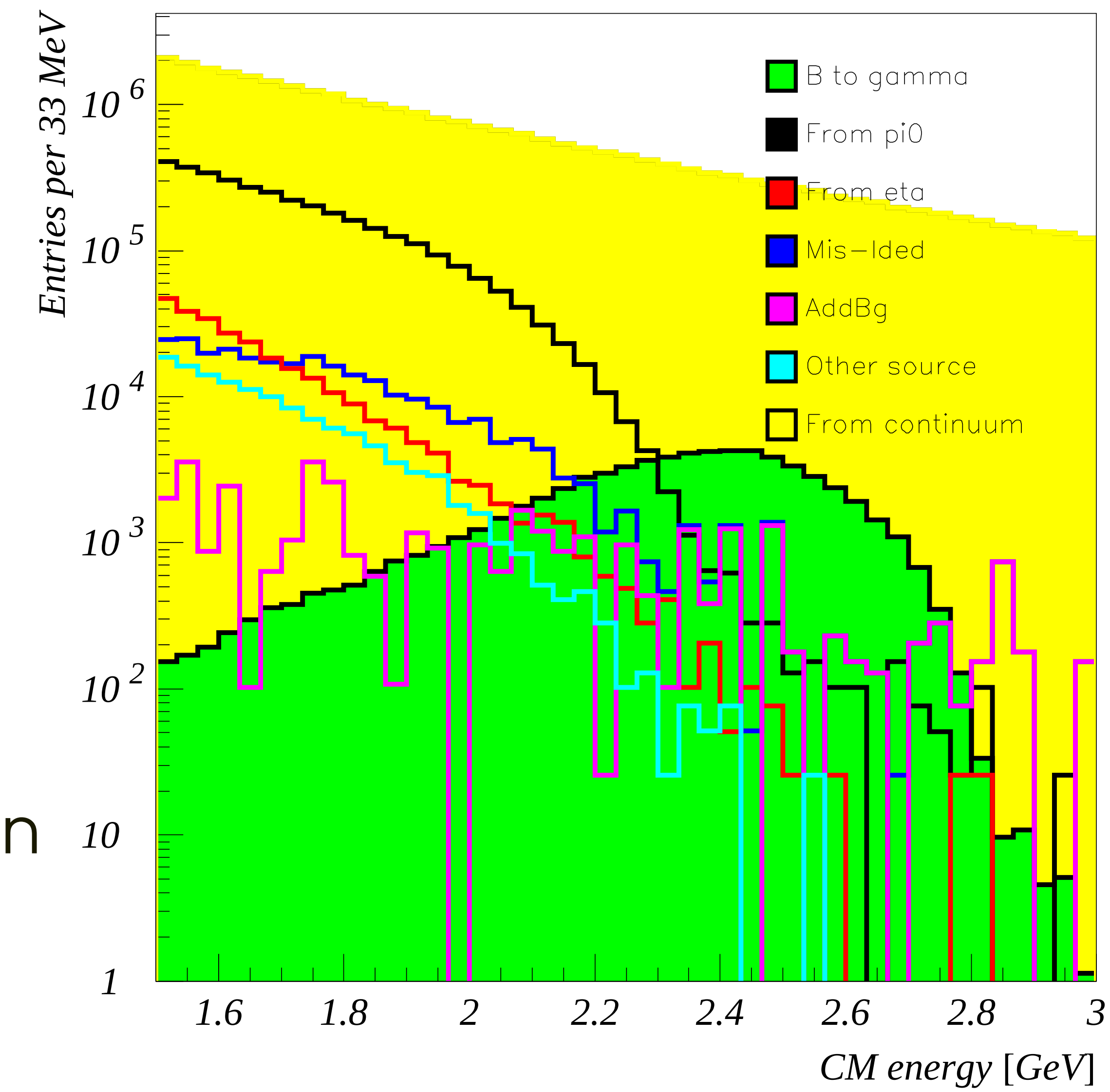


- Plenty of inclusive $B \to X_s\gamma$ events now
  - more than 10 years since first measured by CLEO ('95)
  - Precise measurements, and precise theories in NLO

Two inclusive $B \to X_s\gamma$ methods

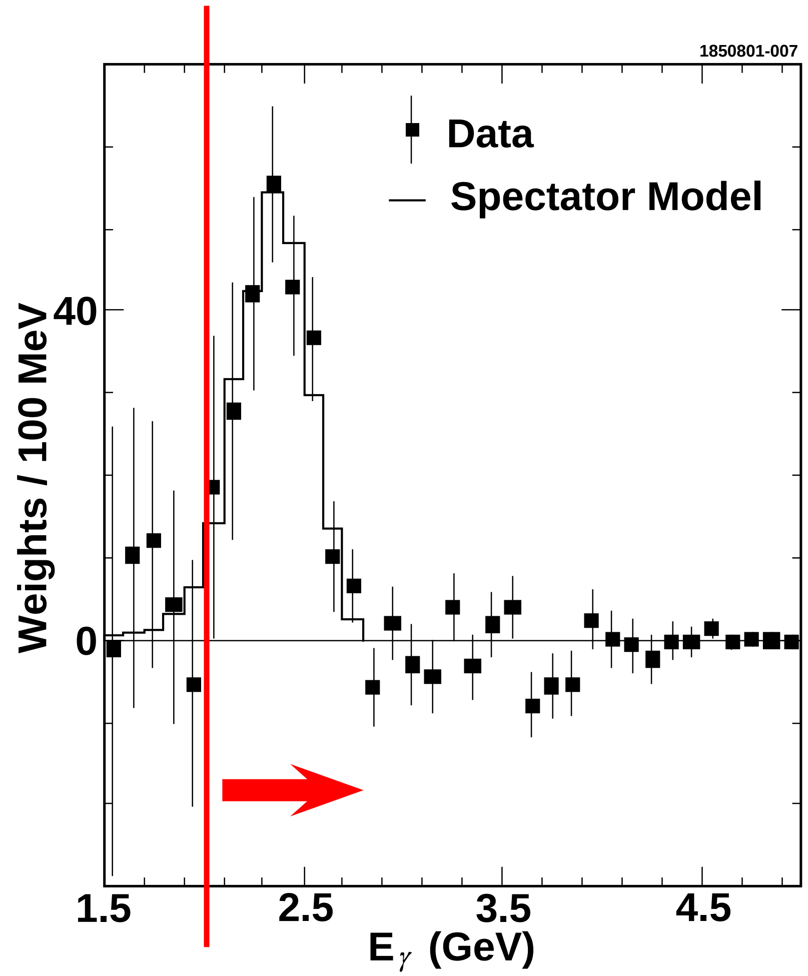
- **Full-inclusive**
  - Photon only, no B reconstruction
  - Off-resonance subtraction (huge continuum background)
  - $B \to X\pi^0$, $\pi^0 \to \gamma\gamma$ subtraction
  - Smeared by B momentum
- **Semi-inclusive**
  - Standard $M_{\mathrm{bc(ES)}}$-ΔE reconstruction
  - Sum up as many modes (e.g., $B \to K\pi\pi\pi\gamma$)
  - Still many modes are not included

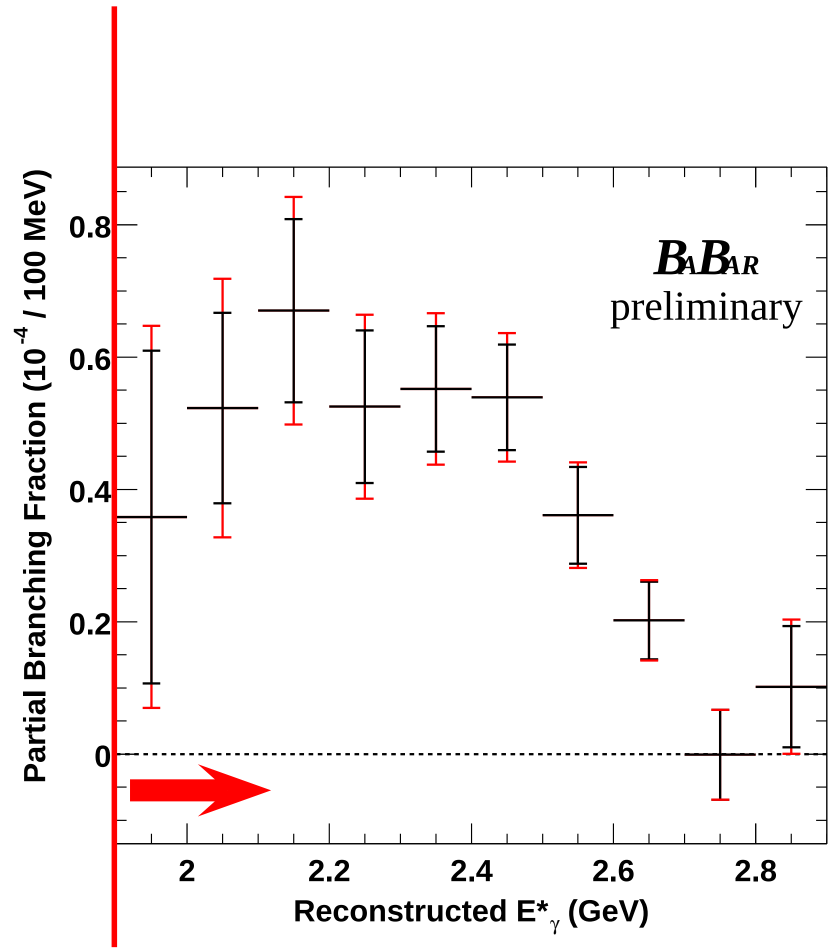


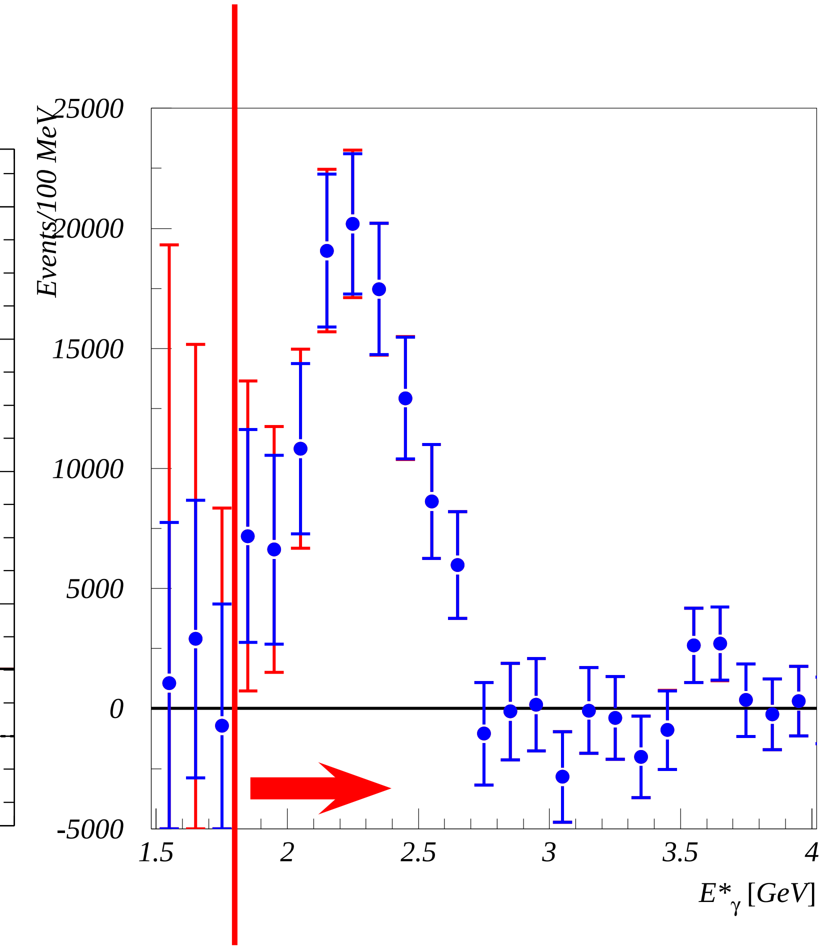
- **Trade-off on the minimum photon energy cut**

  Large background ⇔ reduced model dependence as E_γ cut is lowered

E_γ spectrum (full-inclusive)







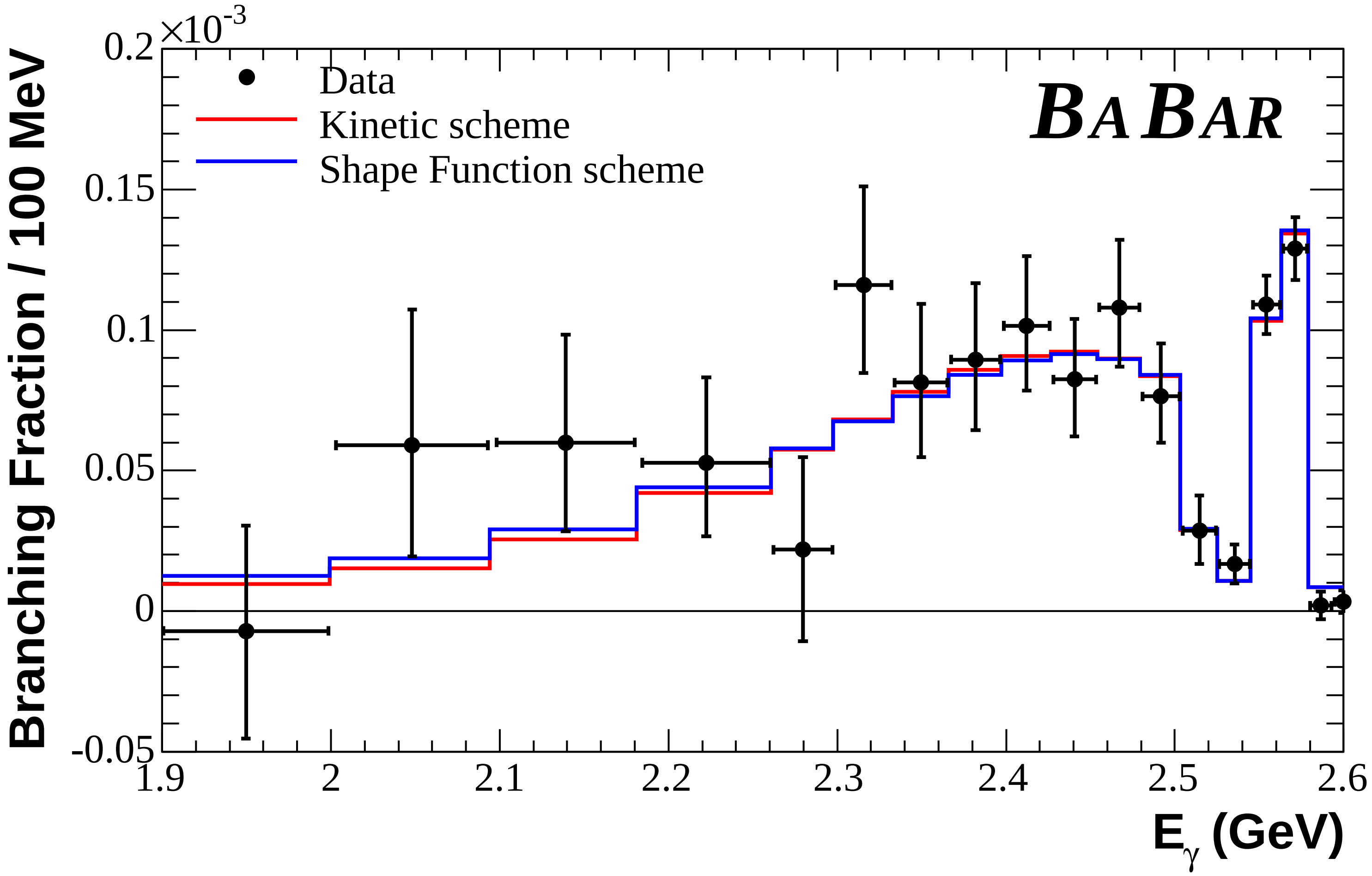
CLEO
9.1 fb^{-1} on $\Upsilon(4S)$
-4.4 fb^{-1} off-resonance
$E_\gamma > 2.0$ GeV
(PRL87,251807(2001))

BaBar
81.5 fb^{-1} on $\Upsilon(4S)$
-9.6 fb^{-1} off-resonance
$E_\gamma > 1.9$ GeV
(hep-ex/0507001)

Belle
140 fb^{-1} on $\Upsilon(4S)$
-15 fb^{-1} off-resonance
$E_\gamma > 1.8$ GeV
(PRL93,061803(2004))

More data, lower photon energy cut

E_γ spectrum (semi-inclusive)



BaBar 81.5 fb^{-1}

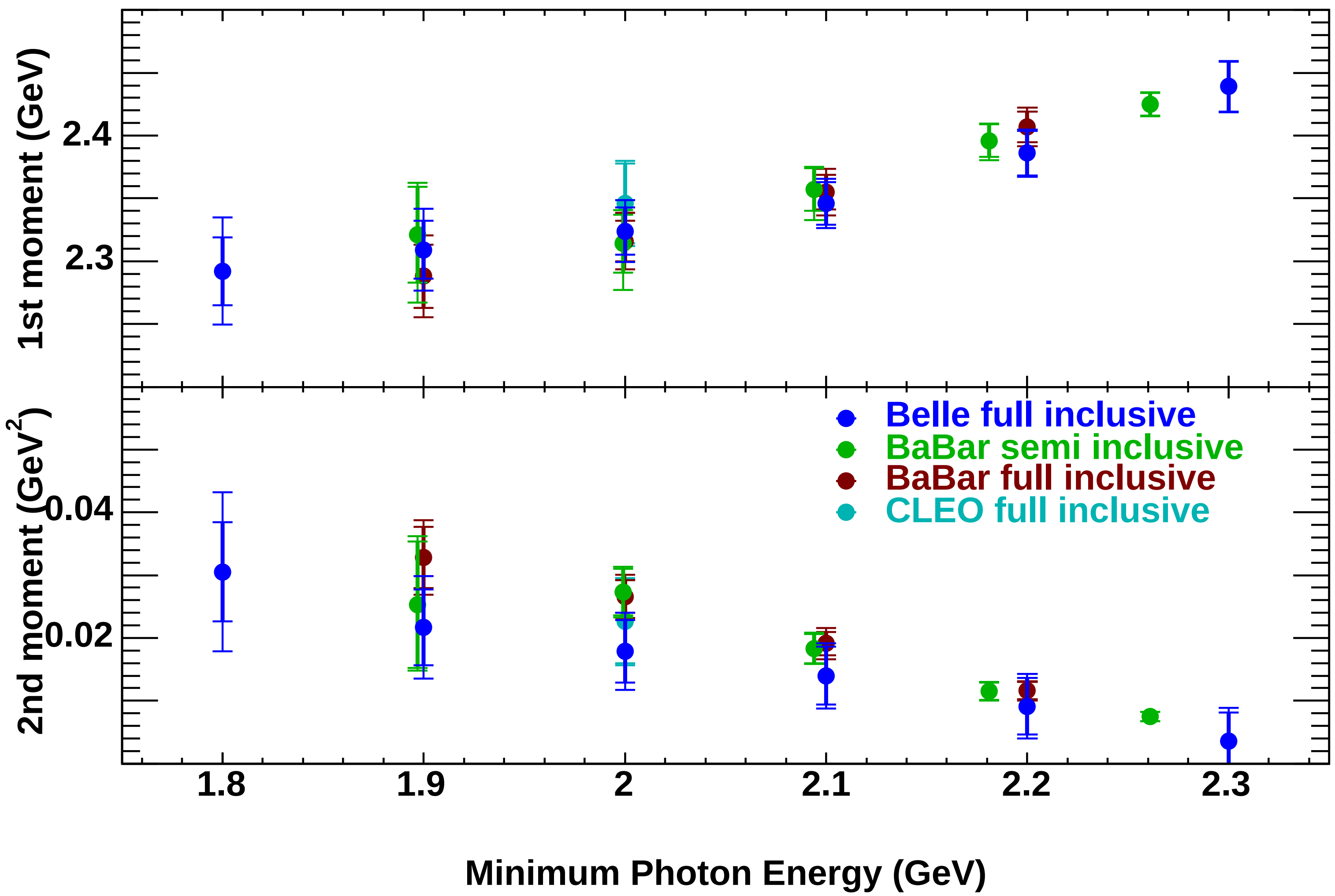
$B \to K\pi\gamma, K\pi\pi\gamma,$
$K\pi\pi\pi\gamma, K\pi\pi\pi\pi\gamma,$
$K\eta(\pi(\pi))\gamma, KKK(\pi)\gamma$

$E_\gamma > 1.9$ GeV
($M(X_s) < 2.8$ GeV)
(PRD72,052004(2005))

Belle measured $\mathcal{B}$ with
6 fb^{-1} for $M(X_s) < 2.1$ GeV

- Spectrum measured in 0.1 GeV bin of $M(X_s)$
  $\Rightarrow$ equivalent to E_γ in B rest frame
- Much better resolution (1–5 MeV) compared with E_γ from calorimeter ($\sim$ 40 MeV), no $p(B)$ smearing
- Large fragmentation uncertainty (due to missing modes)

Moments

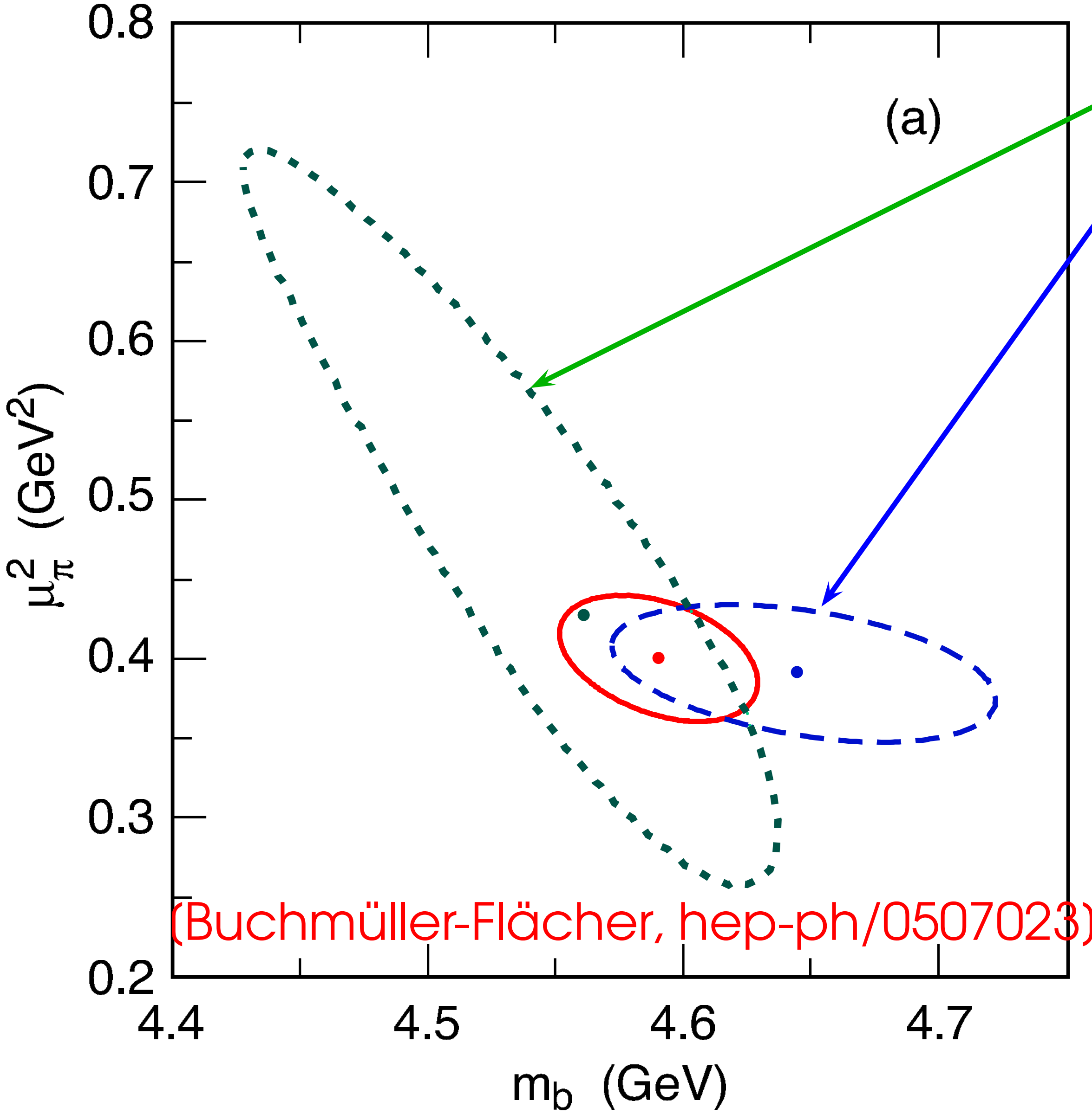


1st moment:
$\langle E_\gamma \rangle$

2nd moment:
$\langle ((\langle E_\gamma \rangle - E_\gamma)^2 \rangle$
(3rd moments are also measured by BaBar)

- Observables to be directly compared with predictions
- Universal parameters in operator product expansion (OPE)
  (several available schemes: kinetic scheme, shape function scheme. . .)
- Kinetic scheme: m_b (b quark mass), μ_π^2 (Fermi momentum)^2

A fit of OPE parameters (kinetic scheme)



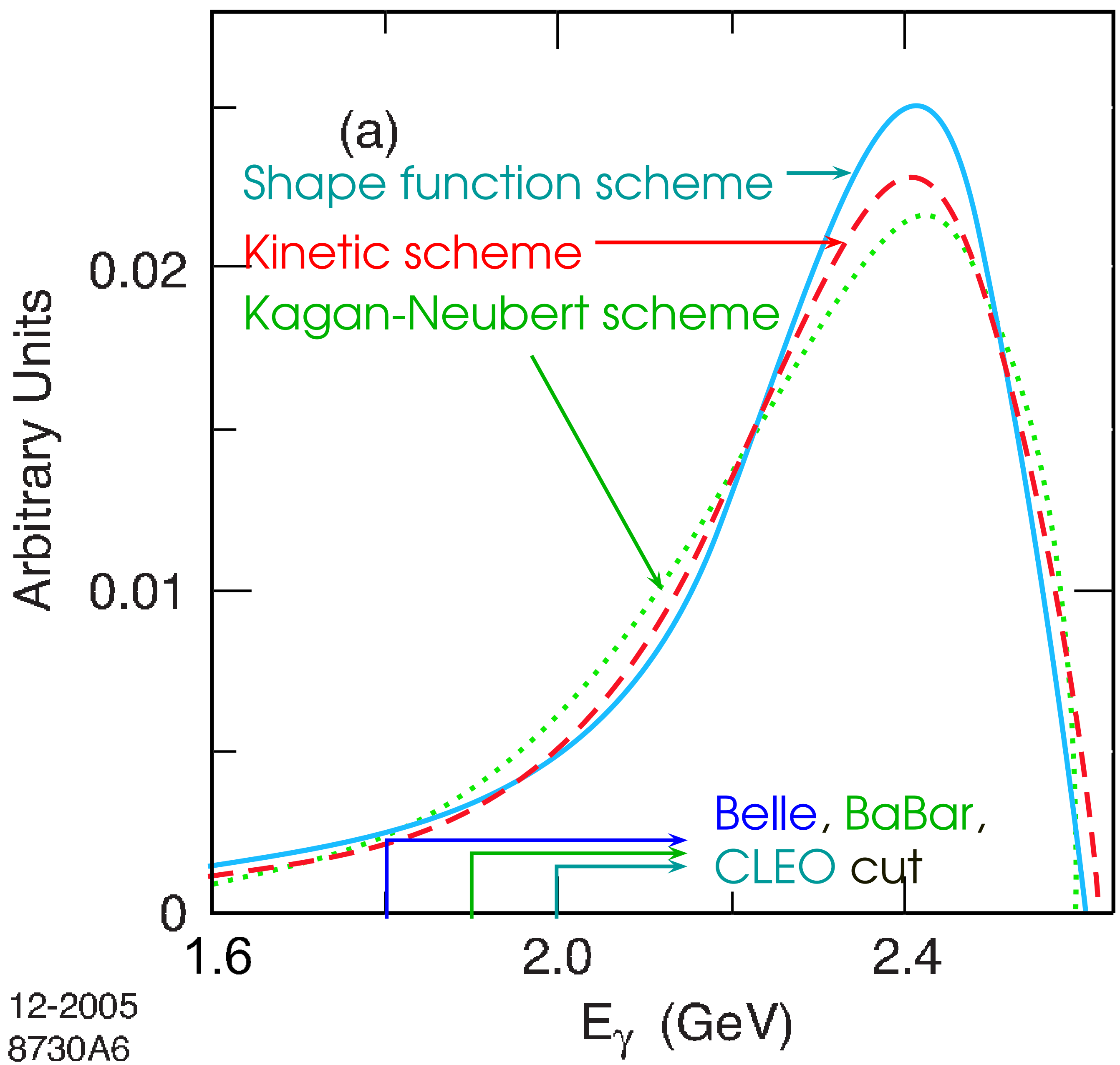
Global fit (CLEO, Belle, BaBar data)
to the moments from $B \to X_s\gamma$
to the moments from $B \to X_c\ell\nu$

- Parameters are universal
- Fits to $B \to X_c\ell\nu$ and $B \to X_s\gamma$ are complimentary
- Input to V_{ub} from $B \to X_u\ell\nu$ that recently reduced the $|V_{ub}|$ error significantly

- Combined fit results — m_b to less than 1% accuracy!

$m_b = 4.590 \pm 0.025$(exp) $\pm\, 0.030$(OPE) GeV, $\mu_\pi^2 = 0.401 \pm 0.019$(exp) $\pm\, 0.035$(OPE) GeV^2

E_γ extrapolation



- OPE fit also improves the $b \to s\gamma$ measurement
- Very small model dependence

  frac($E_\gamma > 1.8$ GeV) $= 96.7 \pm 0.6\%$

  frac($E_\gamma > 1.9$ GeV) $= 93.6 \pm 1.0\%$

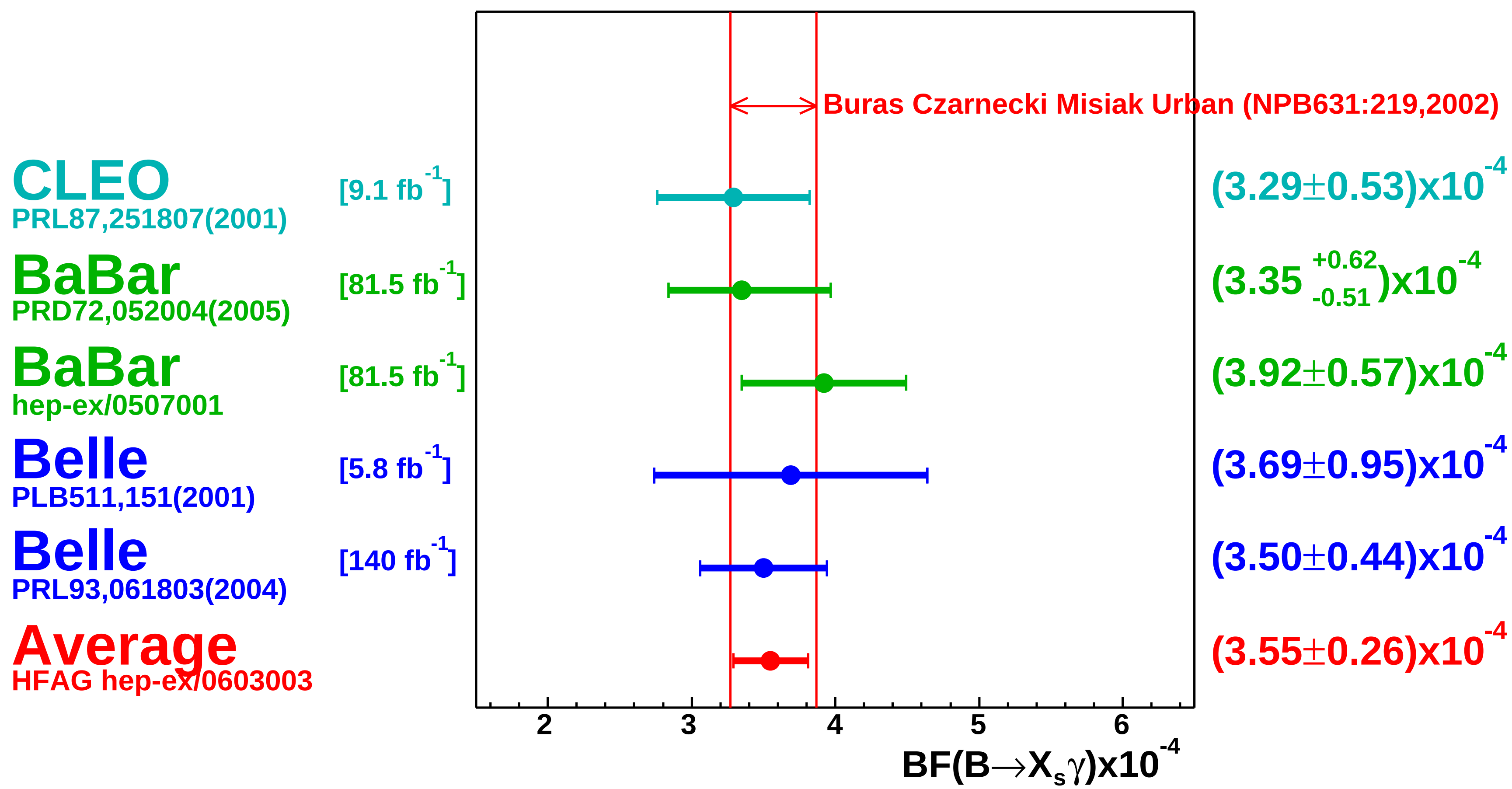
  frac($E_\gamma > 2.0$ GeV) $= 89.4 \pm 1.6\%$
- Allow us to make an average at any E_γ cut to compare with theory (1.6 GeV is suitable now)

Nevertheless, lower E_γ cuts are crucial to verify the predictions

$B \to X_s\gamma$ branching fraction

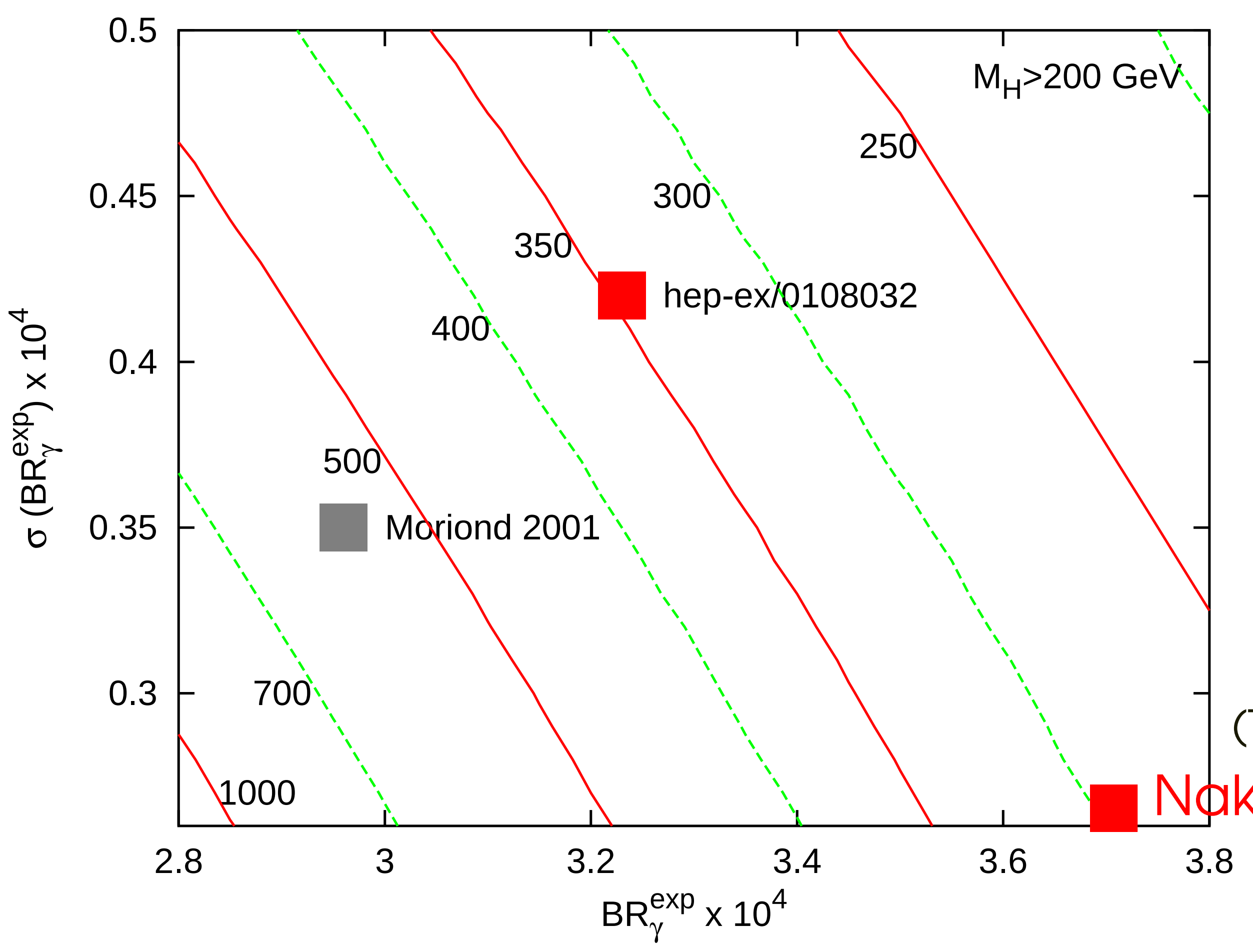
- All measurements are scaled to $E_\gamma = 1.6$ GeV
- Then, average branching fraction is calculated
  (Heavy Flavor Averaging Group (HFAG), hep-ex/0603003)

$$\mathcal{B}(B \to X_s\gamma;\ E_\gamma > 1.6\ \text{GeV}) = (355 \pm 24\,^{+9}_{-10} \pm 3) \times 10^{-6}$$



Very consistent with SM expectations, e.g., $(357 \pm 30) \times 10^{-6}$

An example of constraint on new physics



- Lower limit on type-II charged Higgs mass for any $\tan\beta$
- Previously the limit was unnecessarily high, since the measured rate was lower than the prediction

(This plot is made for $\mathcal{B}_{\text{th}} = 3.73 \pm 0.31$)

Branching fraction in 10^{-4}:

2001: $3.23 \pm 0.42_{(\text{exp})} - 3.73 \pm 0.31_{(\text{th})} = -0.50 \pm 0.52$ (for full E_γ spectrum)

2006: $3.55 \pm 0.26_{(\text{exp})} - 3.57 \pm 0.30_{(\text{th})} = -0.02 \pm 0.40$ (for $E_\gamma > 1.6$ GeV)

(caution: depends on the choice of the SM value/error)

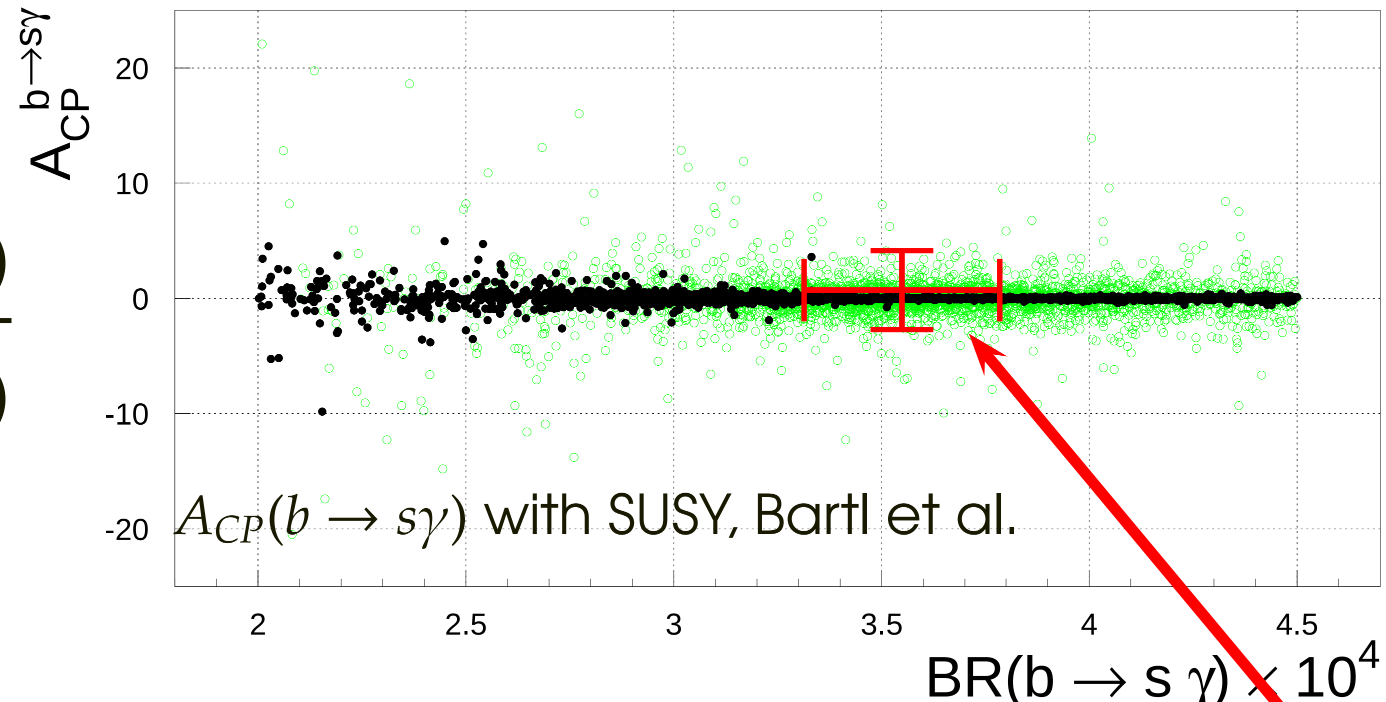
- Still worthwhile decreasing the experimental error
- Need to squeeze the theory error — NNLO calculation

More searches for new physics

CPV in $b \to s\gamma$ and exotic radiative modes

Direct CP asymmetry

$$A_{CP} = \frac{\Gamma(b \to s\gamma) - \Gamma(\bar{b} \to \bar{s}\gamma)}{\Gamma(b \to s\gamma) + \Gamma(\bar{b} \to \bar{s}\gamma)}$$



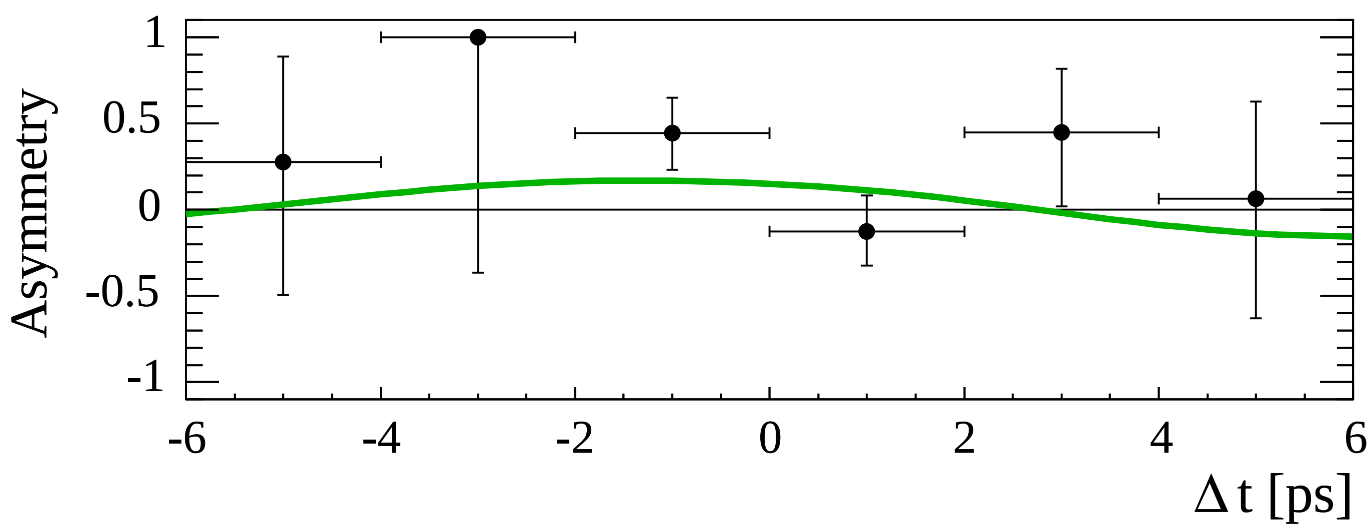
- Precisely measured: HFAG $A_{CP}(B \to X_s\gamma) = (5 \pm 36) \times 10^{-3}$
  Belle 140 fb^{-1}: $(2 \pm 50 \pm 30) \times 10^{-3}$, BaBar 82 fb^{-1}: $(25 \pm 50 \pm 15) \times 10^{-3}$
  but extremely small in SM: e.g., $A_{CP} = (4.2\,^{+1.7}_{-1.2}) \times 10^{-3}$ (T.Hurth et al)
  Only up to a few percent even in SUSY (with EDM constraints)
- BaBar 82 fb^{-1}: $A_{CP}(B \to X_{(s+d)}\gamma) = (-110 \pm 115 \pm 17) \times 10^{-3}$
  $b \to s\gamma$ and $b \to d\gamma$ are not separated — even smaller SM CPV (canceling)

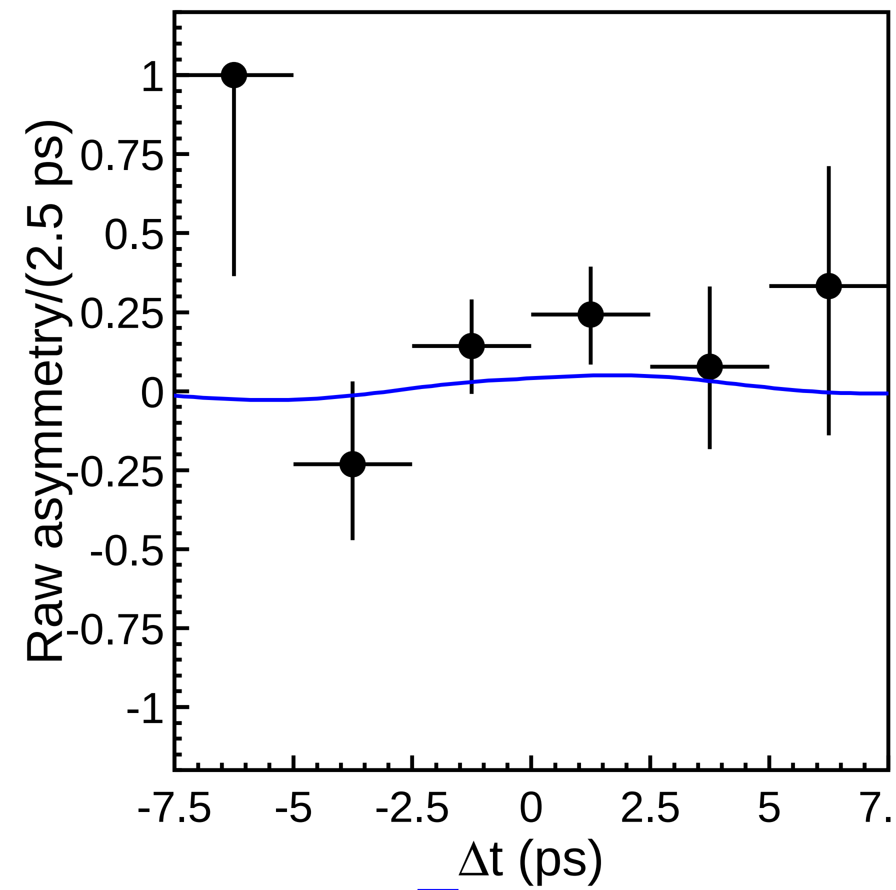
Time dependent CP asymmetry

$$A_{CP}(\Delta t) = \frac{\Gamma(\overline{B}^0(t) \to K_S^0\pi^0\gamma) - \Gamma(B^0(t) \to K_S^0\pi^0\gamma)}{\Gamma(\overline{B}^0(t) \to K_S^0\pi^0\gamma) + \Gamma(B^0(t) \to K_S^0\pi^0\gamma)} = S \sin \Delta m \Delta t + A \cos \Delta m \Delta t$$

$$A_{\mathrm{Belle}} = -C_{\mathrm{BaBar}}$$

- SM left handed coupling gives $S \sim 0.04$–0.10, any large S is due to non-SM right handed coupling





BaBar 232M $B\overline{B}$ PRD72,051103R:

$S_{K^{*0}\gamma} = -0.21 \pm 0.40 \pm 0.05$

$A_{K^{*0}\gamma} = +0.40 \pm 0.23 \pm 0.04$

Belle 386M $B\overline{B}$ hep-ex/0507059

$S_{\mathrm{all}\ K_S^0\pi^0\gamma} = +0.08 \pm 0.41 \pm 0.10$

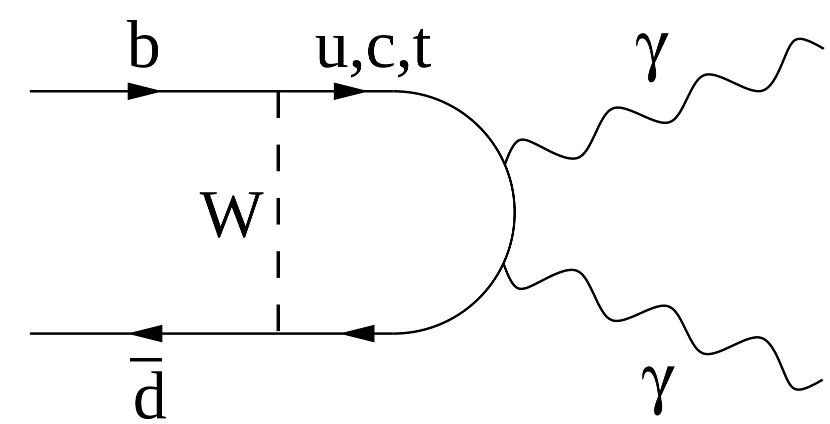
$A_{\mathrm{all}\ K_S^0\pi^0\gamma} = +0.12 \pm 0.27 \pm 0.10$

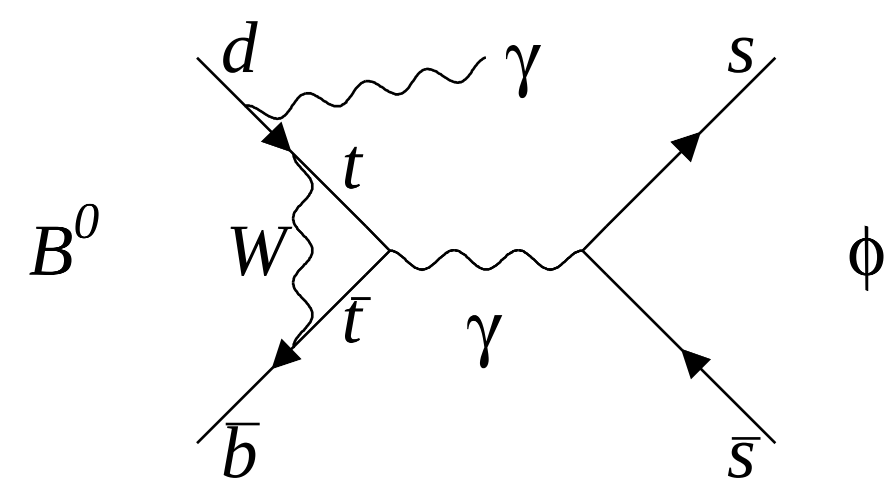
- Error on S is ~ 0.4, still long way to the precision of the SM

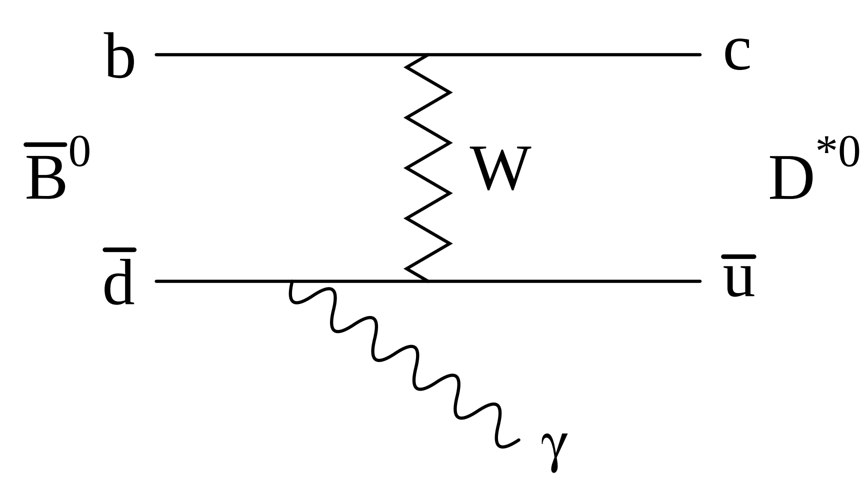
Exotic radiative decays

Simple signal topology,
heavily suppressed in the SM

- $B \to \gamma\gamma$
  SM expects $\mathcal{B} \sim 3 \times 10^{-8}$
  Belle finds $\mathcal{B} < 6.2 \times 10^{-7}$ (90% CL)
  ($104\ \mathrm{fb}^{-1}$, hep-ex/0507036)
- $B \to \phi\gamma$
  SM expects $\mathcal{B} \sim 4 \times 10^{-12}$
  BaBar finds $\mathcal{B} < 8.5 \times 10^{-7}$ (90% CL)
  ($113\ \mathrm{fb}^{-1}$, PRD72,091103(2005))
- $B \to D^{*0}\gamma$
  SM expects $\mathcal{B} \sim O(10^{-6})$
  BaBar finds $\mathcal{B} < 2.5 \times 10^{-5}$ (90% CL)
  ($80\ \mathrm{fb}^{-1}$, PRD72,051106(2005))







Summary

- First observation of $b \to d\gamma$ by Belle
  in the combined $B \to \rho\gamma$ and $B \to \omega\gamma$ exclusive modes.

$$\mathcal{B}(B \to (\rho,\omega)\gamma) = (1.32\,^{+0.34}_{-0.31}(\text{stat.})\,^{+0.10}_{-0.09}(\text{syst.})) \times 10^{-6}$$

  $|V_{td}/V_{ts}|$ is in agreement with the SM unitarity triangle

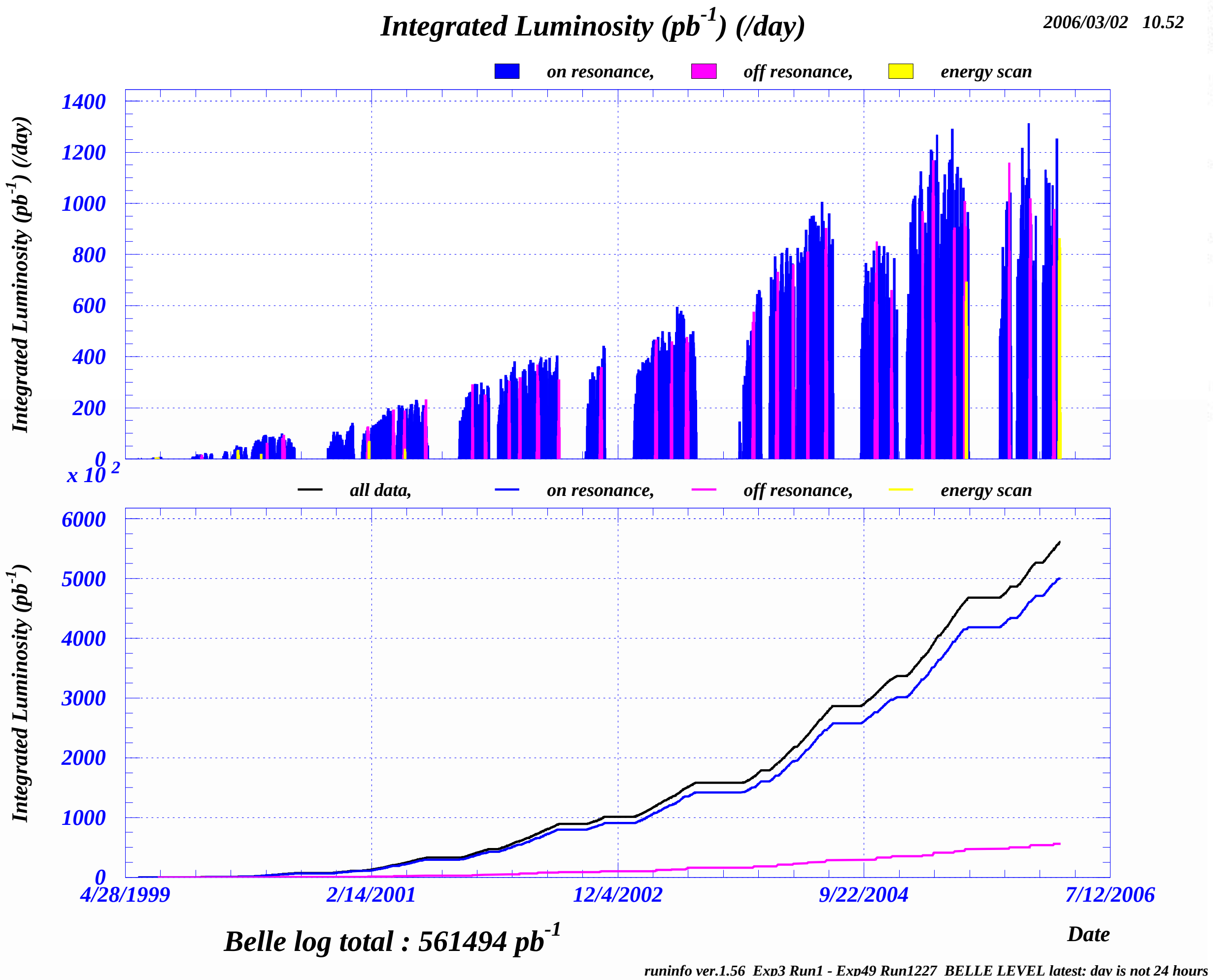
- Huge efforts and new developments on inclusive $b \to s\gamma$
  A new HFAG average in very good agreement with SM

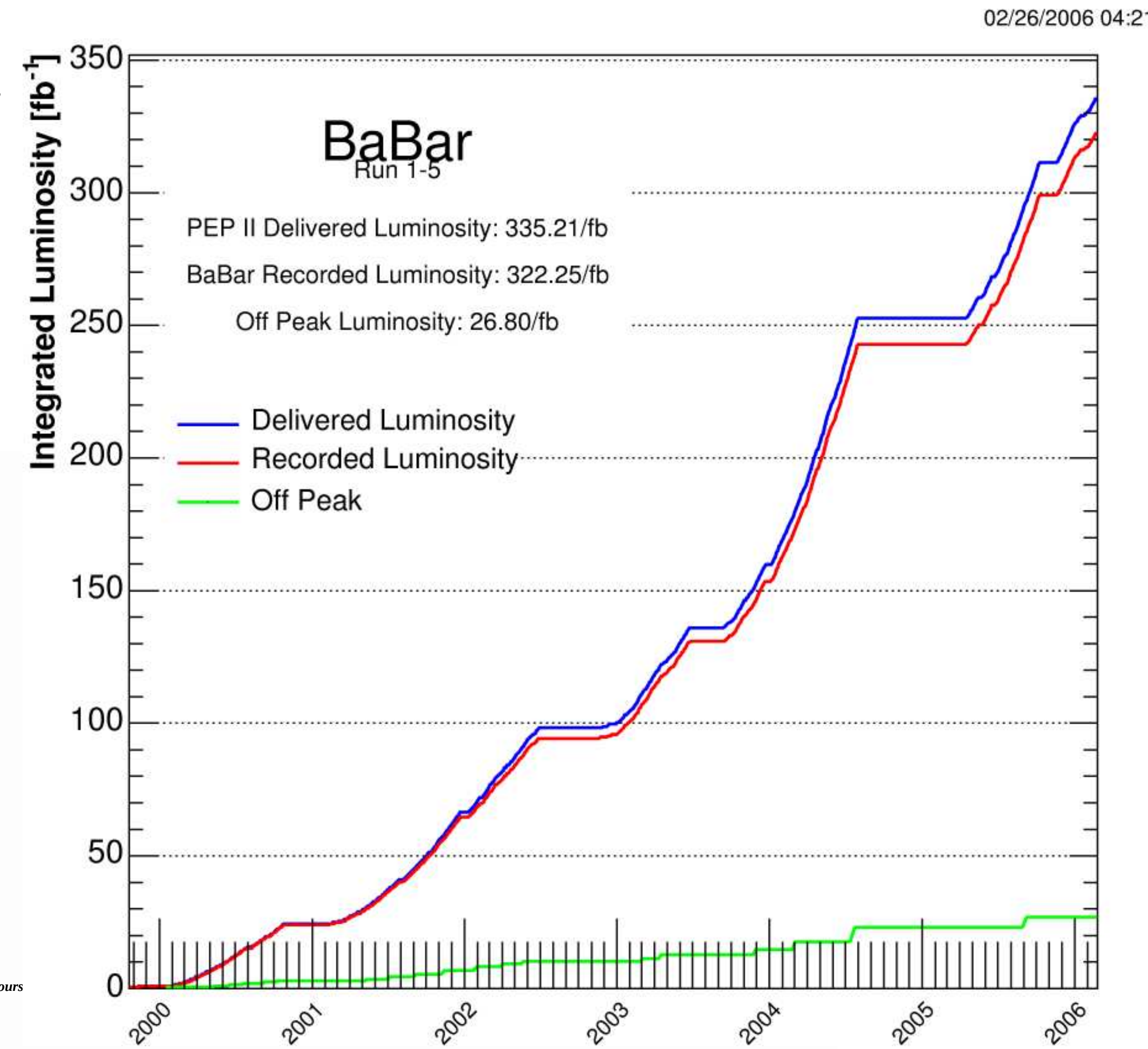
$$\mathcal{B}(B \to X_s\gamma;\, E_\gamma > 1.6\,\text{GeV}) = (355 \pm 24\,^{+9}_{-10} \pm 3) \times 10^{-6}$$

- Search for new physics continues
  in $b \to s\gamma$ asymmetries
  in other decay modes
  with more data coming

Backup slides

Dataset





KEKB/Belle

560 fb^{-1} collected

(Now in shutdown for crab-cavity)

Analyzed: 104–357 fb^{-1} ($\Upsilon(4S)$)

PEP-II/BaBar

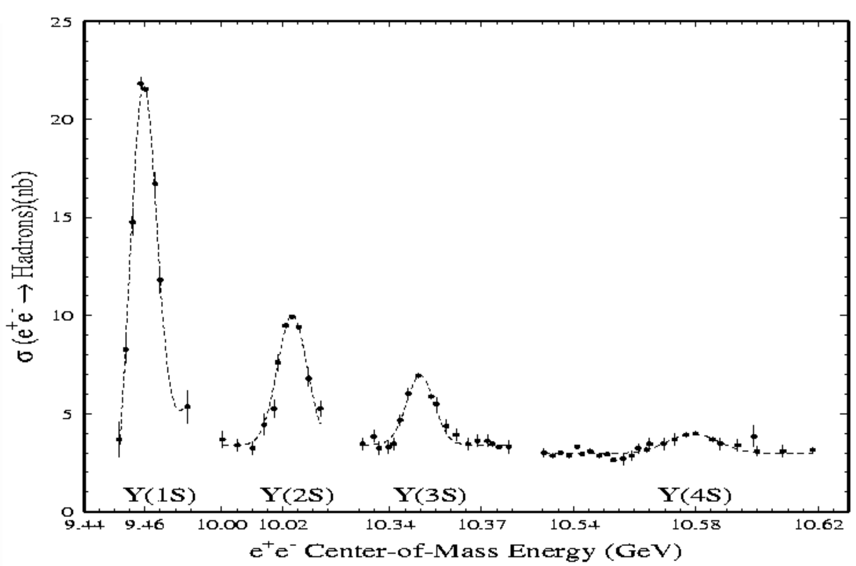
322 fb^{-1} collected

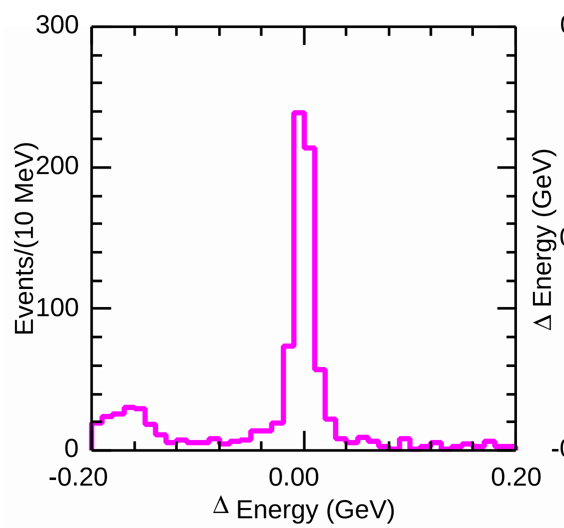
Analyzed: 80–211 fb^{-1} ($\Upsilon(4S)$)

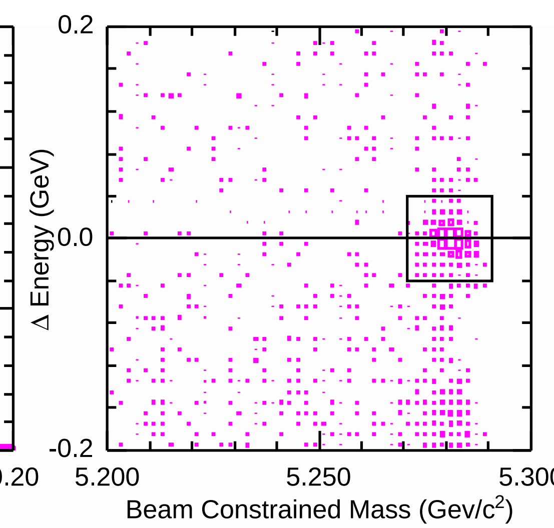
1 fb^{-1} $\sim$ 1.1M $B\overline{B}$ events, $\sim$10% off-resonance taken

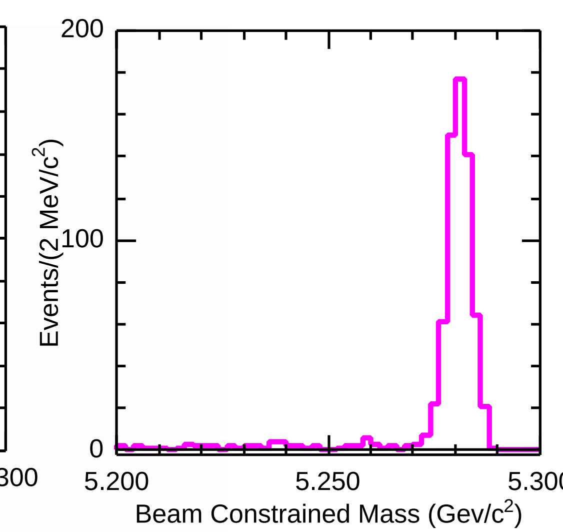
Exclusive B decay analysis

- Reconstruction: photon, tracking, π/K id
- $\Upsilon(4S)$ constraint: $M_{bc(ES)} = \sqrt{{E^*_{\rm beam}}^2 - p_B^2}$, $\Delta E = E_B - E^*_{\rm beam}$
  Unbinned fit to $M_{\rm bc}$-ΔE to extract the signal

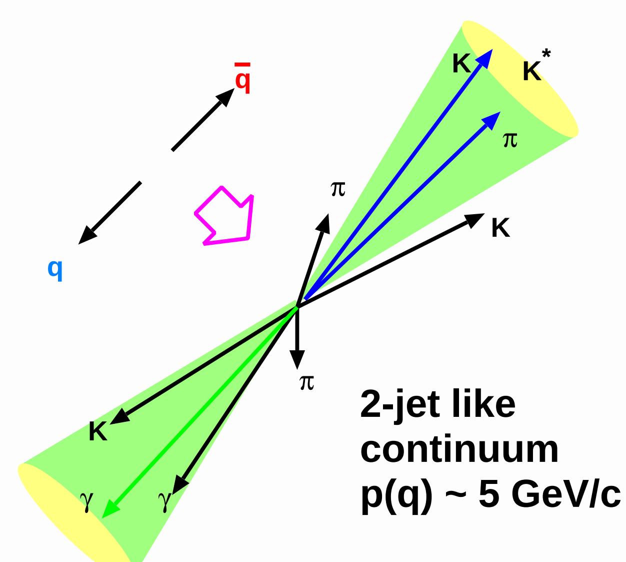


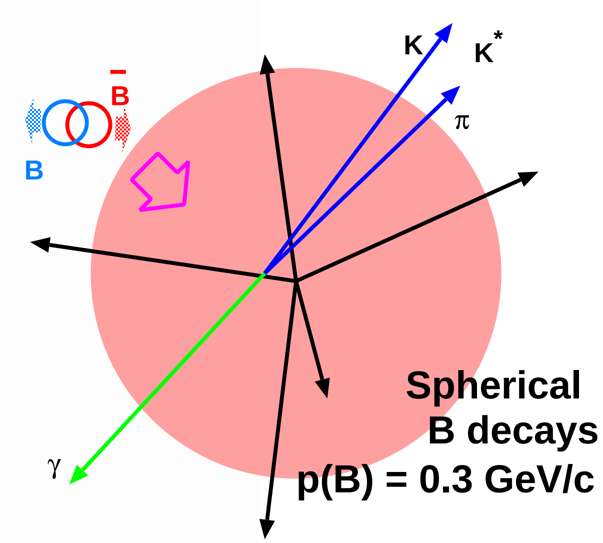






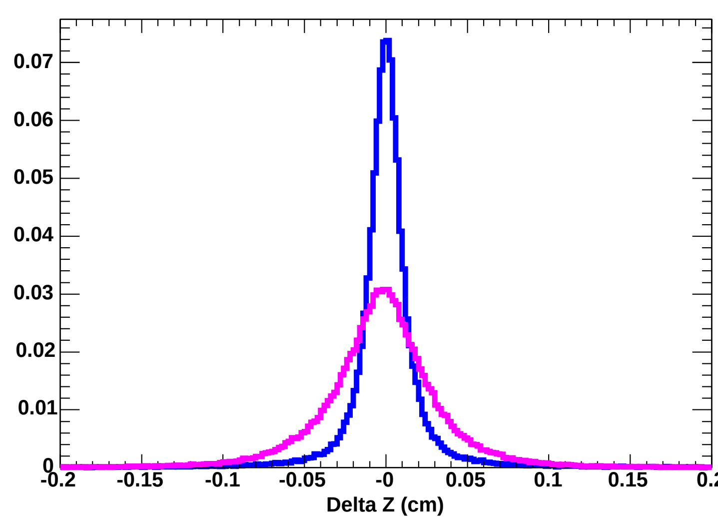
- Continuum suppression:
  event topology
  for discrimination
  (Fisher discriminant)





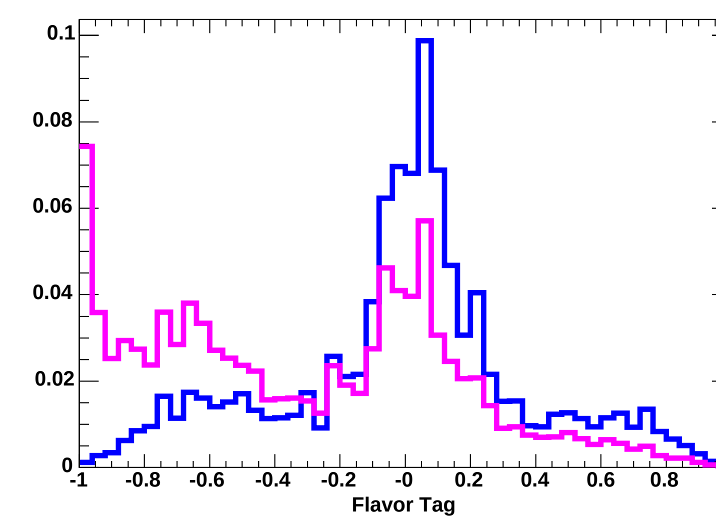
$B \to \rho\gamma$ and $B \to \omega\gamma$ analysis

- More specific background suppression (Belle's analysis)
  1. π^0 and $\eta \to \gamma\gamma$ rejection (copious!)
  2. K^* veto in $M(``K"\pi)$ (to suppress $B \to K^*\gamma$)
  3. Helicity angle of ρ/ω decay (discriminate $\rho\gamma$ vs $\rho\pi^0$, etc)
  4. B meson direction $(1 - \cos^2\theta_B$ for $\Upsilon(4S) \to B\overline{B})$
  5. Vertex displacement (Δz) from other B ($\Delta z \sim 0$ for $q\overline{q}$)
  6. Flavor-tag algorithm of the other B ($q\overline{q}$ is neither B or $\overline{B}$-like)
- Combine 4, 5 and event-shape Fisher into a likelihood ratio, and flavor-tag quality dependent cut on it (BaBar uses neural net)



$\Leftarrow$ Δz for signal and continuum

Flavor-tag quality $\Rightarrow$



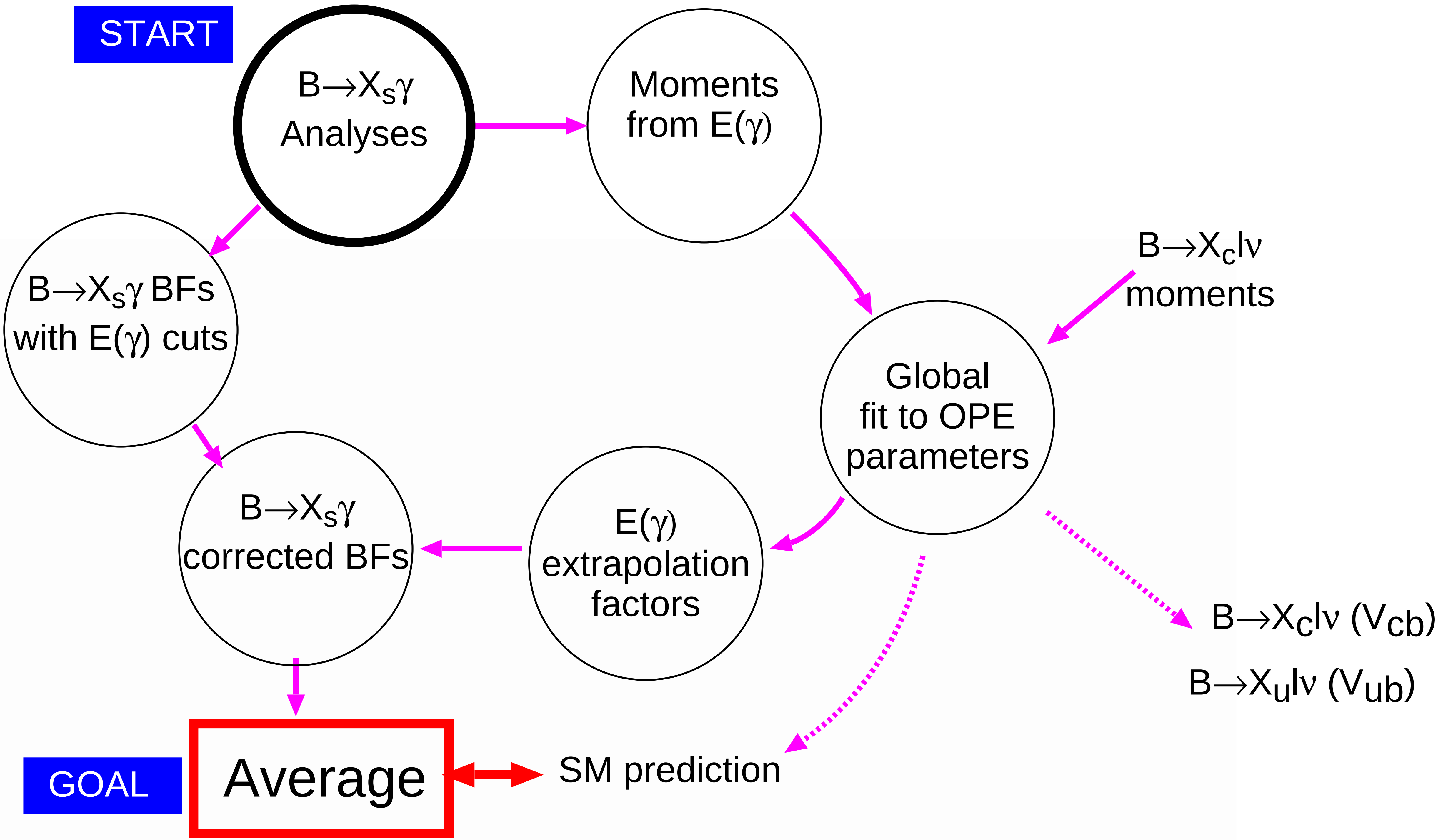
Belle's $b \to d\gamma$ analysis finalized since LP05

- Belle has reported the observation of $b \to d\gamma$ at LP05 (hep-ex/0506079v1), with a 5.5σ significance
- Systematic errors are finalized:
  - Control sample fit ($B \to K^*\gamma$) was redone for the signal shape
  - Further sub-divisions of the B decay backgrounds
  - Efficiency correction factors were updated
  - A few more missing small systematic errors were added
- More conservative systematic error in the significance
  - Statistical error is assumed to be Gaussian and convolved in the likelihood function
  - Significance drops from 5.4σ (stat only) to 5.1σ

Systematics tests on Belle's $b \to d\gamma$

- Possible isospin violation effect?
  - $\mathcal{B}(\overline{B}^0 \to \rho^0\gamma) \sim 2\mathcal{B}(B^- \to \rho^-\gamma)$ while $\mathcal{B}(B^- \to \rho^-\gamma) \sim 2\mathcal{B}(\overline{B}^0 \to \rho^0\gamma)$ is expected
    $\mathcal{B}(\overline{B}^0 \to \rho^0\gamma) \sim 2\mathcal{B}(B \to \omega\gamma)$ while $\mathcal{B}(\overline{B}^0 \to \rho^0\gamma) \sim \mathcal{B}(B \to \omega\gamma)$ is expected
  - Using a toy MC study assuming isospin symmetry, the probability to observe a deviation equal to or larger is 4.9% (2σ effect)
- Consistency with the previous results? (253 fb^{-1}, PRD72,011101)
  - Due to the changes in the continuum suppression variables, the overlap of the events are rather small (especially for background)
  - For the same sample, $\overline{B}^0 \to \rho^0\gamma$ has the largest deviation of about 2σ, after the overlapped events are taken into account
  - Newly added data includes more $\overline{B}^0 \to \rho^0\gamma$ signal events, and makes the deviation for $\overline{B}^0 \to \rho^0\gamma$ larger
  - Other modes and combined results are consistent

Flowchart to average $B \to X_s\gamma$



$B \to X_s\gamma$ branching fraction table

Correction factor for the E_γ spectrum is obtained from fit to the $b \to s\gamma$ and $b \to c\ell^-\overline{\nu}$ data $\Rightarrow$ corrected for $\mathcal{B}$ with $E_\gamma > 1.6$ GeV

	$E_\gamma^{\rm min}$	Reported $\mathcal{B}$ (10^{-4})	Corrected $\mathcal{B}$ (10^{-4})
CLEO full	2.0	$321 \pm 43 \pm 27\,^{+18}_{-10}$	$329 \pm 44 \pm 28 \pm 6 \pm 6$
Belle semi	2.24	$336 \pm 53 \pm 42\,^{+50}_{-54}$	$369 \pm 58 \pm 46\,^{+56}_{-60}$
Belle full	1.8	$355 \pm 32\,^{+30}_{-31}\,^{+11}_{-7}$	$350 \pm 32\,^{+30}_{-31} \pm 2 \pm 2$
BaBar semi	1.9	$335 \pm 19\,^{+56}_{-41}\,^{+4}_{-9}$	$349\,^{+2}_{-0}\,^{+59}_{-46}\,^{+4}_{-9}$
BaBar full	1.9	-	$392 \pm 31 \pm 36 \pm 30 \pm 4 \pm 6$

Then, average branching fraction is calculated

$$\mathcal{B}(B \to X_s\gamma;\, E_\gamma > 1.6\ \text{GeV}) = (355 \pm 24\,^{+9}_{-10} \pm 3) \times 10^{-6}$$

(Heavy Flavor Averaging Group (HFAG), hep-ex/0603003)

Time dependent CPV in $b \to s\gamma$

- $K^{*0}\gamma(\overline{K}^{*0}\gamma) \to K_S^0\pi^0\gamma$ final state, from both B and $\overline{B}$
- Not necessarily to be from the K^* resonance
- Experimental challenges:
  - Small $K^{*0} \to K_S^0(\to \pi^+\pi^-)\pi^0$ fraction (11%)
  - Extrapolating B-vertex from displaced K_S^0 decay