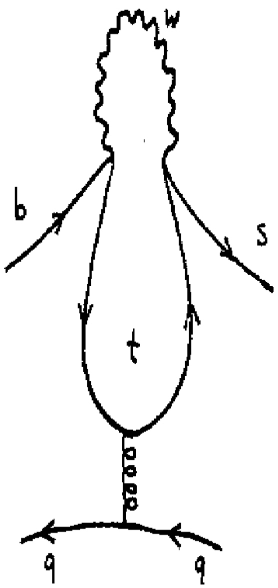
Radiative Penguin Decays at BaBar

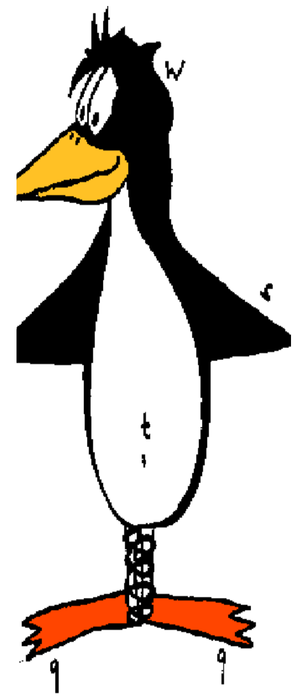


Colin Jessop

University of Notre Dame

Representing the BaBar Collaboration

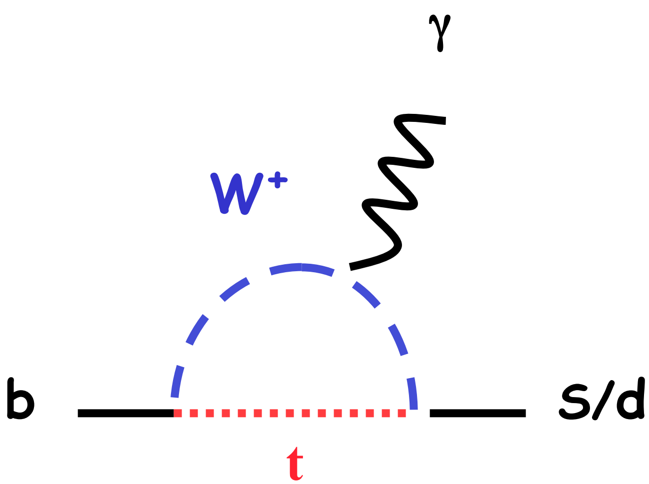
at ICHEP 2008



Motivation to Study Radiative Penguins

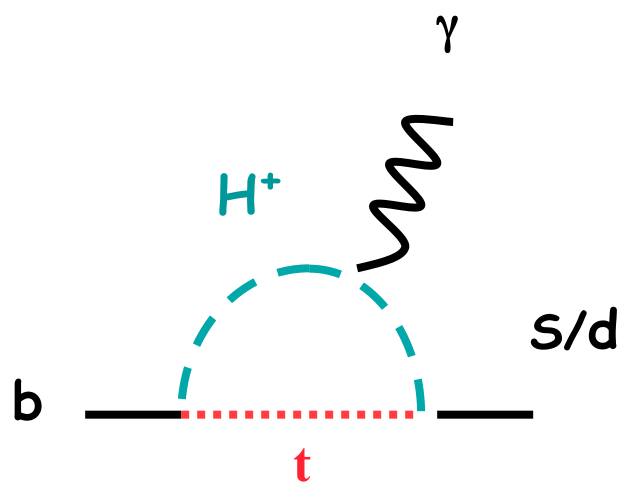
New Physics enters at same order (1-loop) as Standard Model

SM



+

SUSY

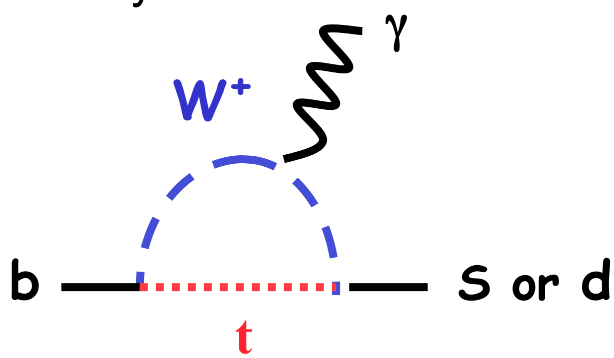


+ ..

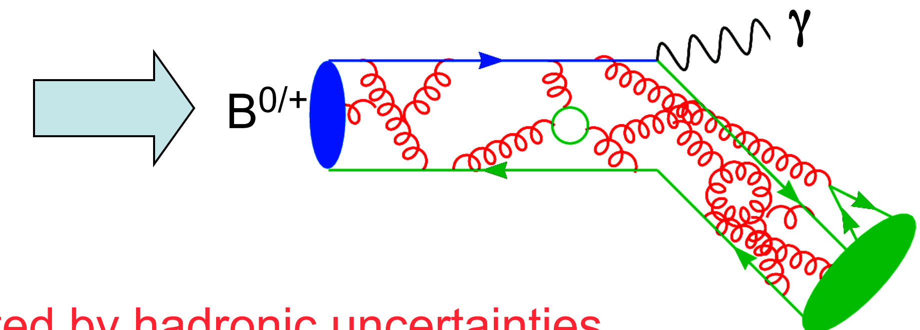
Sensitive to many models – very extensive literature

Hadronic Uncertainties

What you can calculate reliably



What you actually observe



Sensitivity to New Physics limited by hadronic uncertainties.

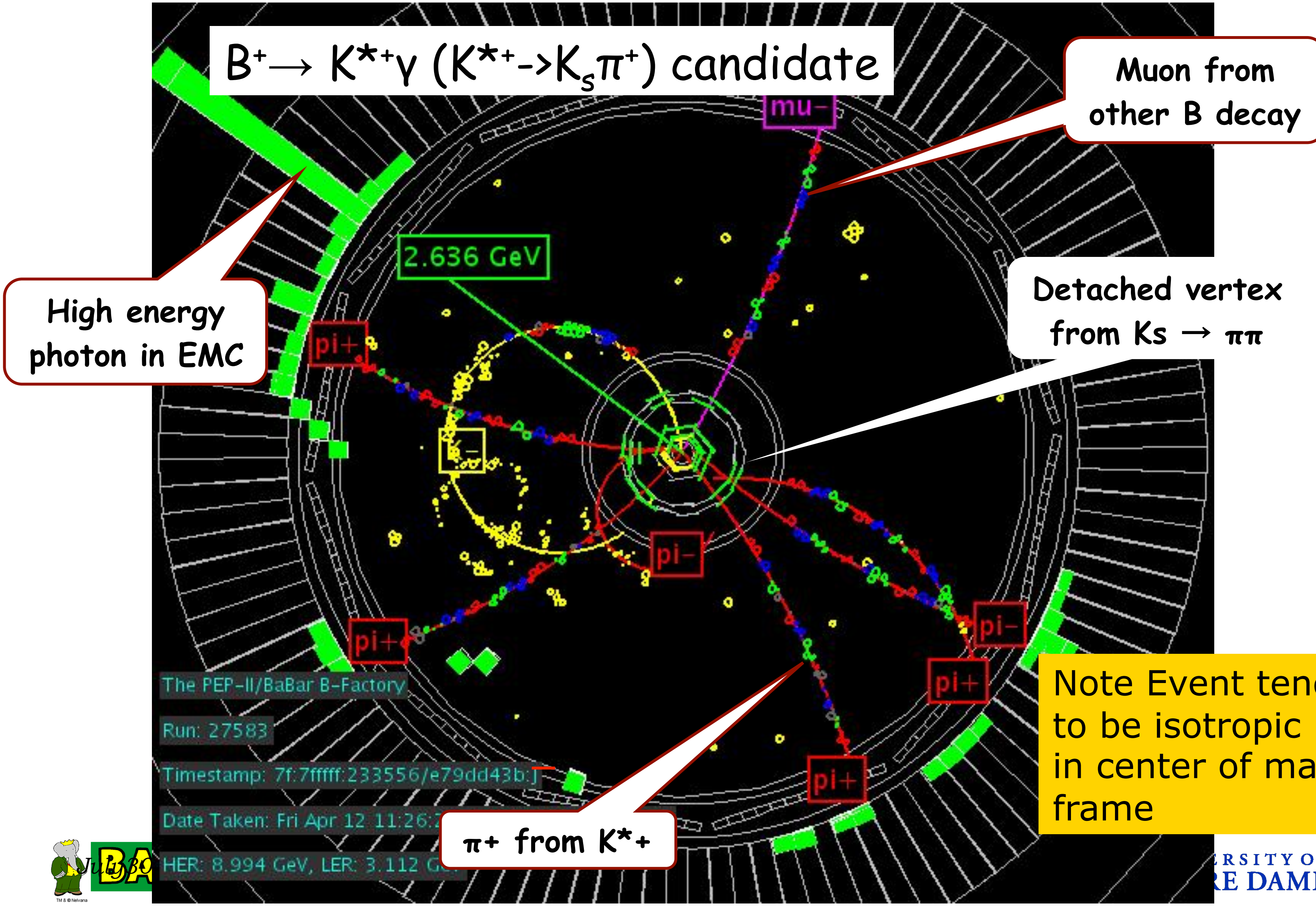
Reduce by:

1.) Measuring inclusive production $X_{s,d}$ (Quark-Hadron duality)

2.) Asymmetries or ratios of exclusive states where uncertainties may cancel

Also exclusive measurements alone can test hadronic (QCD) calculations

Analysis Technique illustrated with updated $B \rightarrow K^*(892)\gamma$



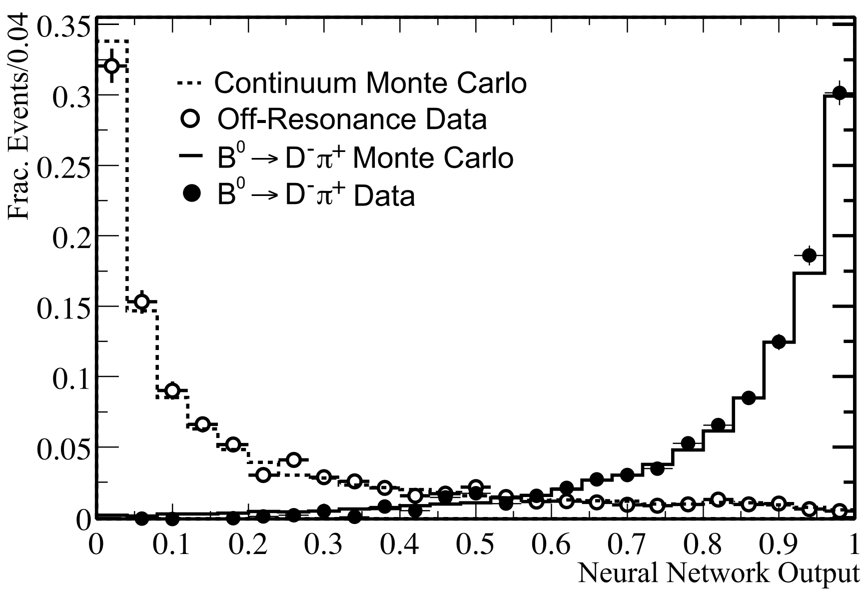
Note Event tends to be isotropic in center of mass frame

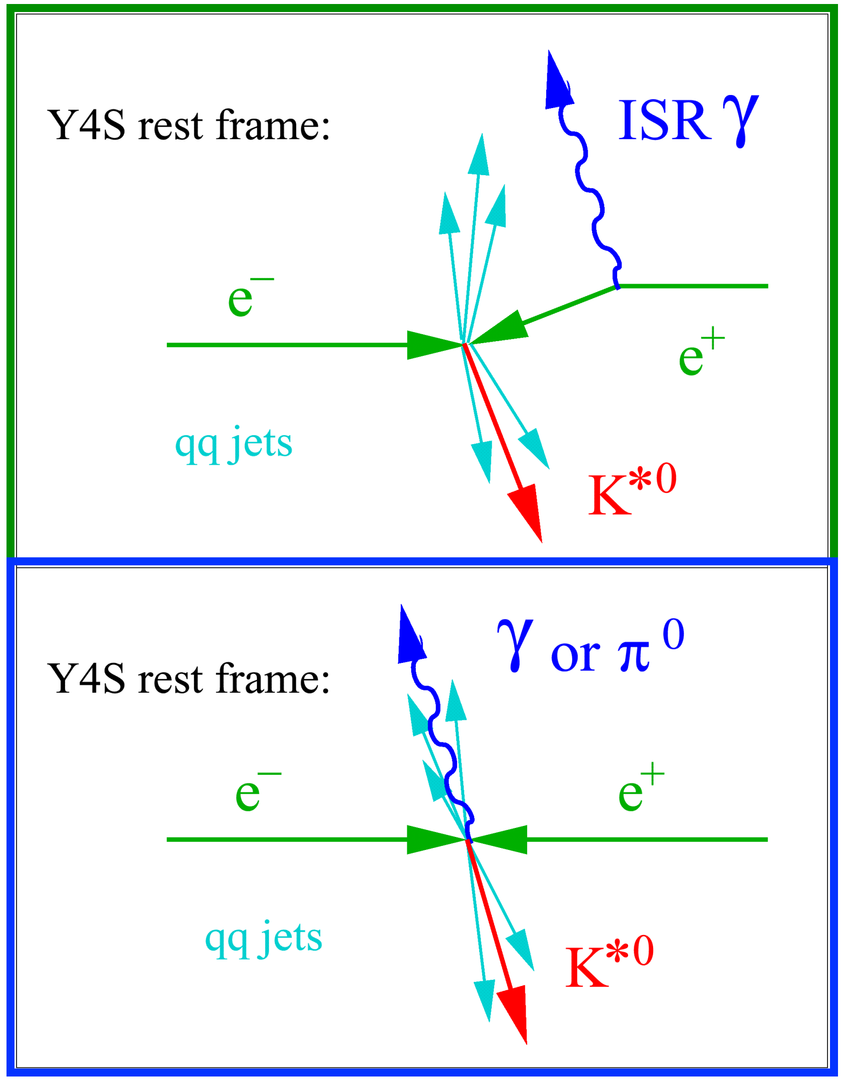
Reducing Continuum Backgrounds

Continuum Production of u,d,s,c quark and τ pairs underneath Υ(4S)

Jet-like topology in contrast to isotropic BB events.

Use multivariate event topology discriminants which are validated in data control samples





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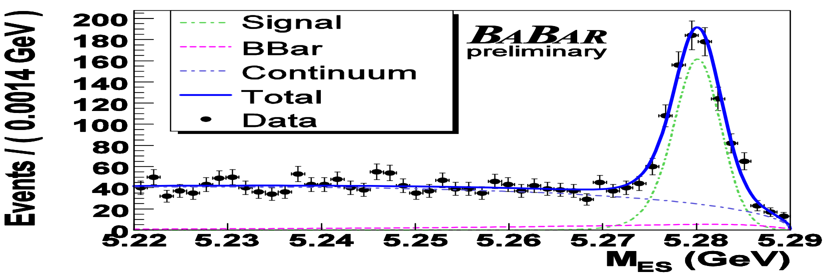
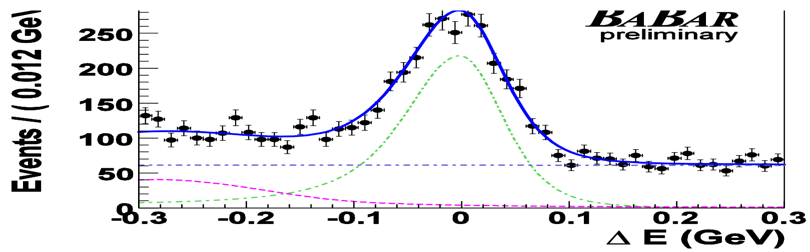
Signal Variables for Exclusive Reconstruction analyses

Energy Substituted Mass

$B^0 \to K^*(K^+\pi^-)\gamma$

Reconstructed Energy – beam Energy





M_{ES} (GeV)

ΔE (GeV)

$$M_{ES} = \sqrt{\left(E_{beam}^{*2} - p_B^{*2}\right)}$$

$$\Delta E^* = E_B^* - E_{beam}^*$$

(* = computed in $\Upsilon(4S)$ rest frame)

Sensitivity enhanced by performing multi-dimensional likelihood fits. to signal and background. M_{es} and ΔE projections are shown

Updated $B \to K^*(892)\gamma$ Results

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By Mode

Mode	B(x10^{-5}) ± stat ±sys	Acp ± stat ±sys
$K^+\pi^-$	4.55 ± 0.11 ± 0.16	-0.023 ± 0.022 ± 0.011
$K_S\pi^0$	5.01 ± 0.40 ± 0.37	N/A
$K^+\pi^0$	5.05 ± 0.22 ± 0.27	0.033 ± 0.039 ± 0.011
$K_S\pi^+$	4.56 ± 0.20 ± 0.17	-0.006 ± 0.041 ± 0.011

Combined

$B^0 \to K^{*0}\gamma$	4.58 ± 0.10 ± 0.16	−0.009 ±0.017 ±0.011
$B^+ \to K^{*+}\gamma$	4.73 ± 0.15 ± 0.17	

Isospin Asymmetry

± stat ±sys ± (B^+/B^0 prod. sys.)

Δ_{0+} 0.029 ±0.019 ±0.016 ±0.018

Theory

$$A_{cp} = \frac{\Gamma(B\to\bar{K}^*\gamma)-\Gamma(B\to K^*\gamma)}{\Gamma(B\to\bar{K}^*\gamma)+\Gamma(B\to K^*\gamma)}$$

< 0.01 in SM

(Greub,Simma,Wyler
Nuc Phys B 434 39 1995)

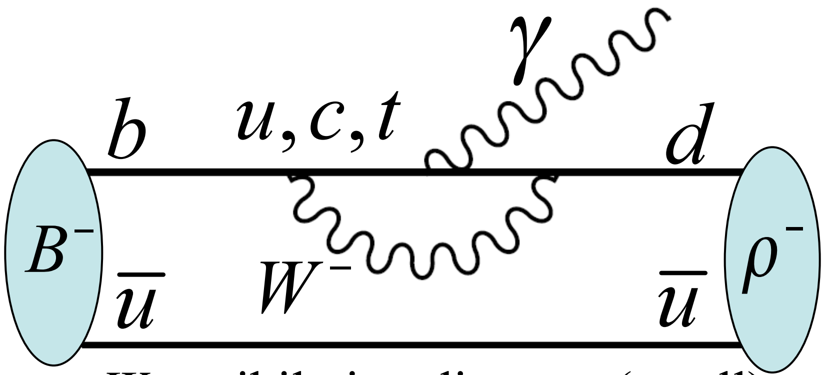
$$\Delta_{0+} = \frac{\Gamma(B^0\to K^{0*}\gamma)-\Gamma(B^+\to K^{*+}\gamma)}{\Gamma(B^0\to K^{0*}\gamma)+\Gamma(B^+\to K^{*+}\gamma)}$$

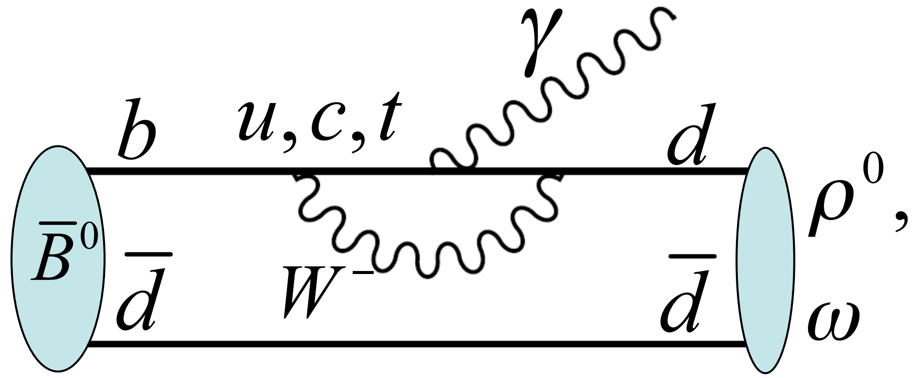
$\Delta_{0+} = +0.026 \pm 0.008$ in SM

Matsumori, Sanda, Keum
PRD 72, 014013 (2005)

Results Consistent with SM expectations and previous measurements

Measurement of $B \to \rho/\omega\gamma$ and Extraction of $|V_{td}/V_{ts}|$





+ W annihilation diagram (small)

$$\frac{\mathcal{B}(B \to \rho,\omega\gamma)}{\mathcal{B}(B \to K^*\gamma)} = S \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{\left(m_B^2 - m_\rho^2\right)^3}{\left(m_B^2 - m_{K^*}^2\right)^3} \left(\frac{T_1^\rho(0)}{T_1^{K^*}(0)}\right)^2 (1+\Delta R)$$

S=1 for ρ^+ 1/2 for ρ^0 or ω

Form Factors $1/\xi^2$

(annihilation contribution)

$$\Gamma(B \to \rho^+\gamma) = 2\frac{\tau_{B^0}}{\tau_{B^+}}\Gamma(B^0 \to \rho^0\gamma) = 2\frac{\tau_{B^+}}{\tau_{B^0}}\Gamma(B^0 \to \omega^0\gamma)$$

I-spin (ρ), quark model (ω). Expect small I-spin violation:(1.1+/-3.9)%.

Updated $B \to \rho/\omega\gamma$ Results

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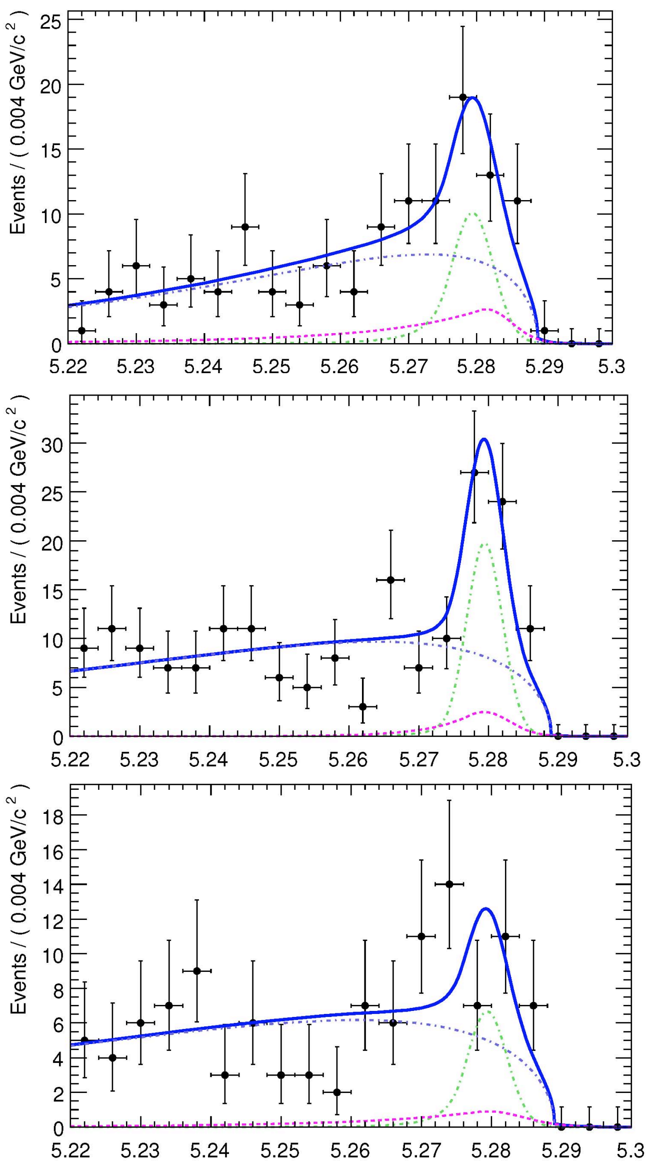


M_{ES}

	Significance	B(x10^{-6}) ± stat ± sys
$B^+ \to \rho^+\gamma$	3.2σ	$1.20^{+0.42}_{-0.37} \pm 0.20$
$B^0 \to \rho^0\gamma$	5.4σ	$0.97^{+0.24}_{-0.22} \pm 0.06$
$B^0 \to \omega^0\gamma$	2.2σ	$< 0.9(90\%C.L.)$ or $0.50^{+0.27}_{-0.23} \pm 0.09$

Results Consistent with SM and previous measurements

V_{td}/V_{ts} and Isospin asymmetry

Theory: Expect $\Delta\rho$ =-0.05 ±0.03 for CKM $\gamma = 60^0$ (Ball,Jones Zwicky PRD 75 054004 2007)

$$\Delta_\rho = \frac{\Gamma(B^+ \to \rho^+\gamma)}{2\Gamma(B^0 \to \rho^0\gamma)} - 1 = -0.43^{+0.25}_{-0.22} \pm 0.10$$

Using averaged $\rho+,\rho^0$ results and

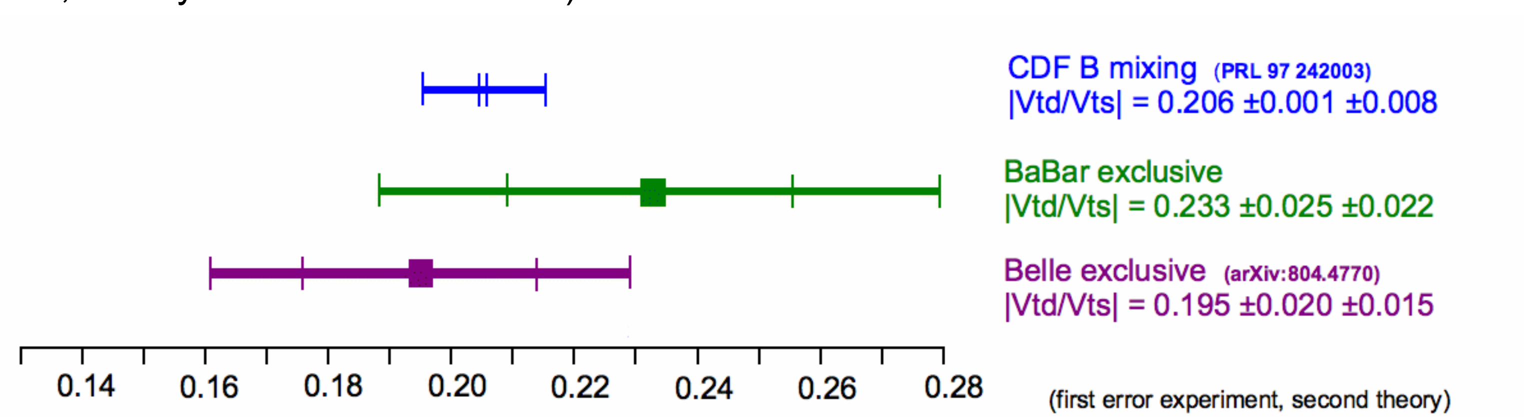
$$\Delta R_{\rho^+,\rho^0} = 0.057^{+0.057}_{-0.055}, 0.006^{+0.046}_{-0.043}$$

(Ali and Parkhomento hep-ph/0610149 2006)

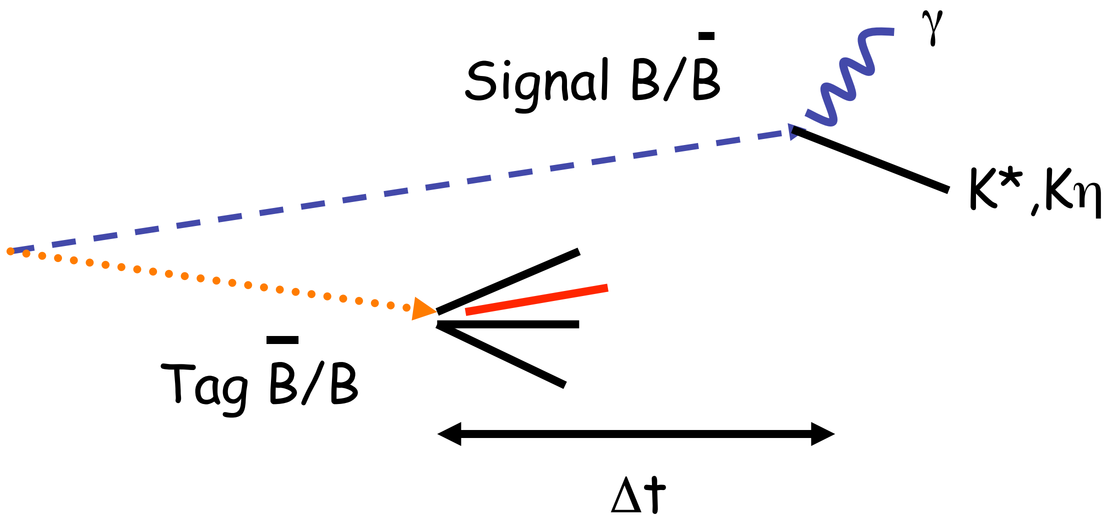
$$1/\zeta = 1.17 \pm 0.09$$

(Ball,Jones, Zwicky PRD 75 054004 2007)

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.235^{+0.026}_{-0.025}(\mathrm{exp.}) \pm 0.020(th.)$$



Time Dependent CPV with $B \to K_s \eta\gamma$ and $B \to K^*(K_s\pi^0)\,\gamma$



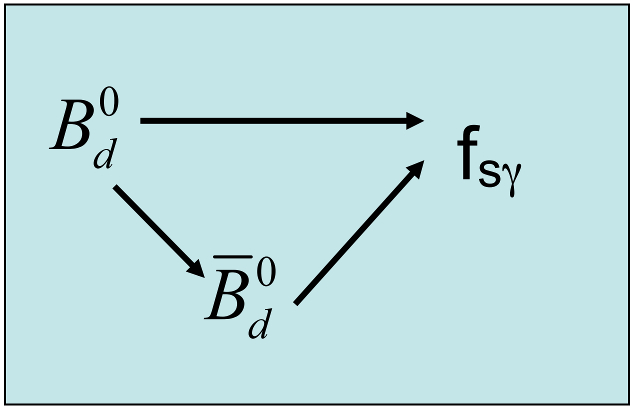
$$P_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left[1 \pm S\sin(\Delta m \Delta t) \mp C\cos(\Delta m \Delta t)\right]$$

≈ 0 In SM

C = Direct CP violation < 0.01 in SM for b → sγ

(Greub,Simma,Wyler Nuc Phys B 434 39 1995)

Time Dependent CPV with $B \to K\eta\gamma$ and $B \to K^*(K_s\pi^0)\,\gamma$



In SM photon is left handed in $b \to s\gamma$

right $\bar{b} \to \bar{s}\gamma$

So no common $f_{s\gamma}$ so $S \sim 0$

$$P_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left[1 \pm S\sin(\Delta m \Delta t) \mp C\cos(\Delta m \Delta t)\right]$$

≈ 0 ≈ 0 In SM

BUT in extensions to the standard model with a different helicity structure such as Left Right Symmetric model or SUSY S can be large while still being consistent with $\Gamma(b \to s\gamma)$ measurements (Atwood,Soni,Gronau PRL 79,185 1997)

Time Dependent CPV in $B \rightarrow K^*(K_s\pi^0)\,\gamma$

arXiv:0807.3103

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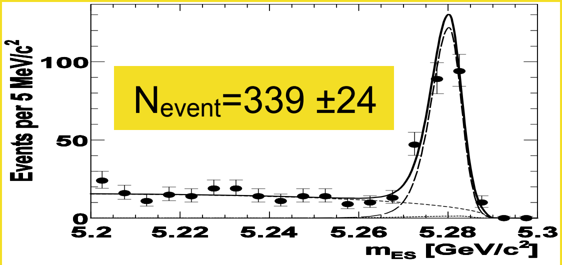


K* Region

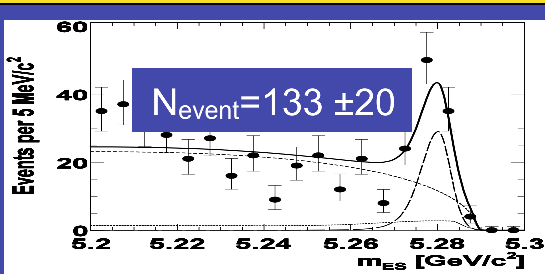
$$0.8 < M_{K_s^0\pi^0} < 1.0 \quad GeV$$

$$S = -0.03 \pm 0.29(stat) \pm 0.03(sys)$$

$$C = -0.14 \pm 0.16(stat) \pm 0.03(sys)$$

M_{ES} (GeV)

Δt (ps)



$$1.1 < M_{K_s^0\pi^0} < 1.8 \quad GeV$$

$$S = -0.78 \pm 0.59(stat) \pm 0.09(sys)$$

$$C = -0.36 \pm 0.33(stat) \pm 0.04(sys)$$

M_{ES} (GeV)

Δt (ps)

Updated Measurements consistent with previous measurements and no CPV

Time Dependent CPV with $B^0 \rightarrow K_s^0\eta\gamma$

arXiv:0807.1317

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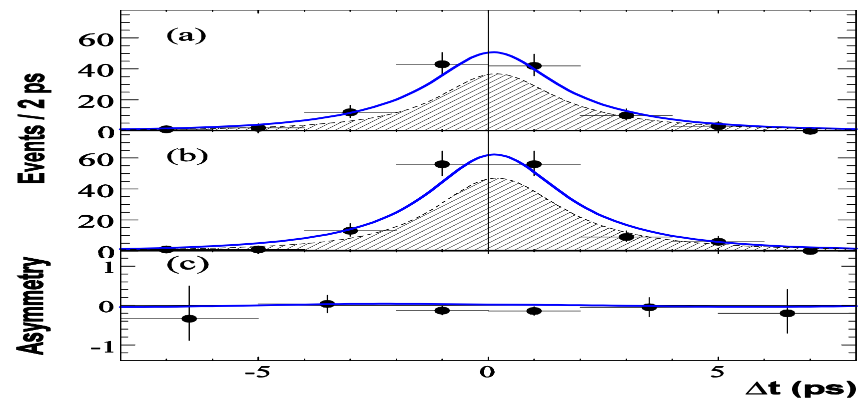
$\eta \rightarrow \gamma\gamma, \eta \rightarrow \pi^+\pi^-\pi^0$

5.2 $N_{events} = 82^{+23}_{-22}$ m_{ES} (GeV/c²) 5.28 5.29



M_{ES} (GeV)

$B(B^0 \rightarrow K_s^0\eta\gamma) = 7.1^{+2.1}_{-2.0}(stat) \pm 0.4(sys) \times 10^{-6}$

Δt (ps)

$S = 0.18^{+0.49}_{-0.46}(stat) \pm 0.12(sys)$

$C = -0.32^{+0.40}_{-0.39}(stat) \pm 0.07(sys)$

No CPV – First Measurement

B.F. and Time Integrated CPV with $B^+ \to K^+\eta\gamma$

arXiv:0807.3103

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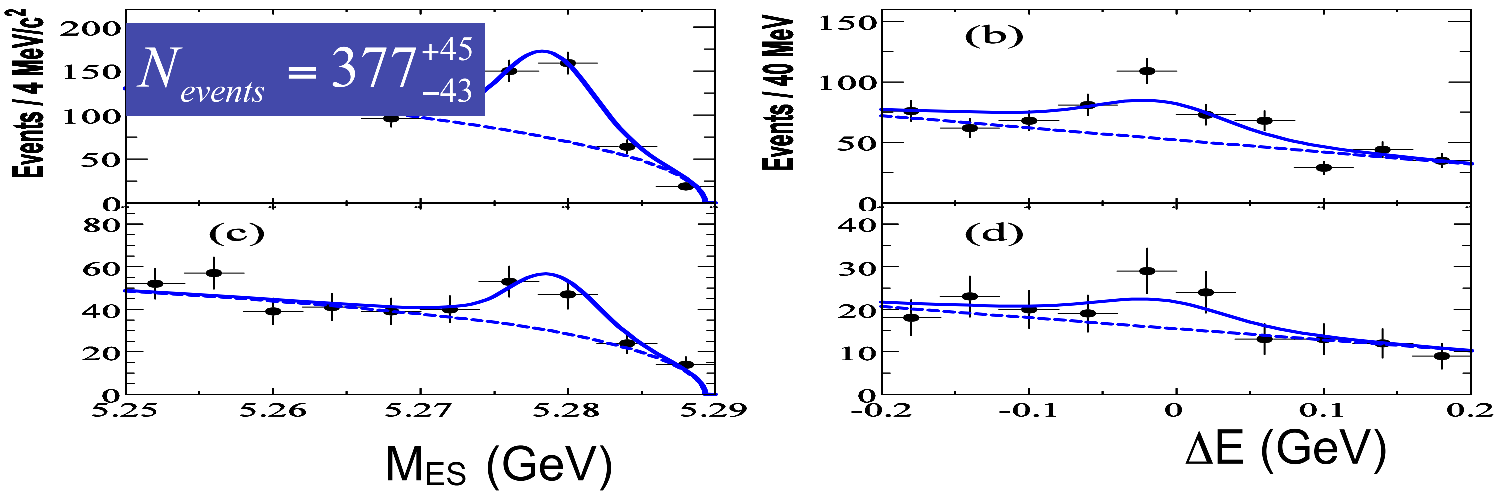


$$B(B^+ \to K^+\eta\gamma) = 7.7 \pm 1.0(stat) \pm 0.4(sys) \times 10^{-6}$$

$$A_{cp} = \frac{\Gamma(B^- \to K^-\eta\gamma) - \Gamma(B^+ \to K^+\eta\gamma)}{\Gamma(B^- \to K^-\eta\gamma) + \Gamma(B^+ \to K^+\eta\gamma)} = -9.0^{+10.4}_{-9.8}(stat) \pm 1.4(sys) \times 10^{-2}$$

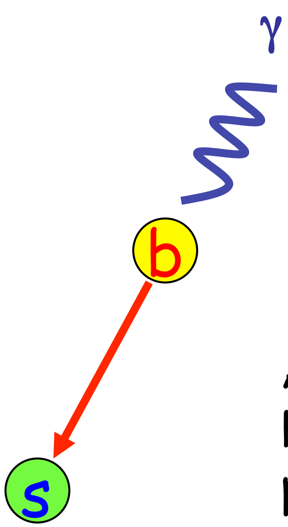
Update measurements consistent with previous measurements and no CPV

Inclusive Measurements

Quarks

Quark-Hadron Duality

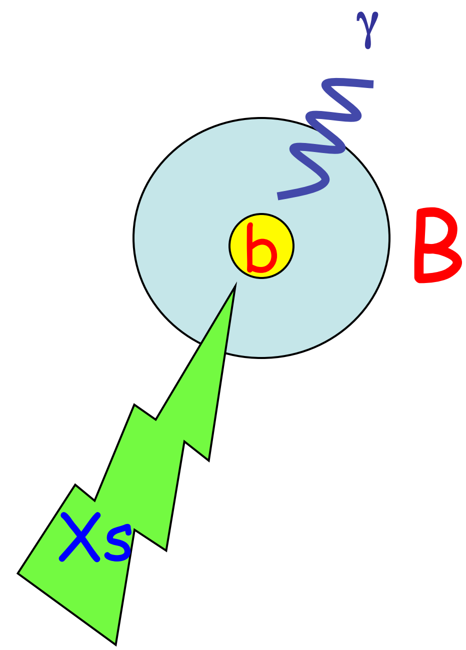
Hadrons



$$\Gamma(b \to s\gamma) = \Gamma(B \to X_s\gamma) + \Delta_{non\text{-}pert}$$

($\Delta_{non\text{-}pert}$ a few percent)

A fully inclusive measurement can be related directly to a reliable parton calculation



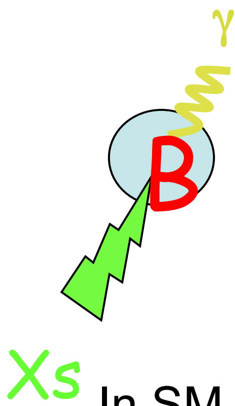
SM Theoretical Predictions:

$\Gamma(b \to s\gamma)$: Misiak etal PRL 98 022002 2007 Acp($b \to s\gamma$) Kagan and Neubert PRD 98 094012 1998

$\Gamma(b \to d\gamma)$, Acp($b \to d\gamma$) Ali,Asatrian & Greub PLB 429,87,1998

Experimentally difficult to achieve fully inclusive measurements due to backgrounds

Time Integrated *CP* Asymmetry with $B \rightarrow X_s\gamma$

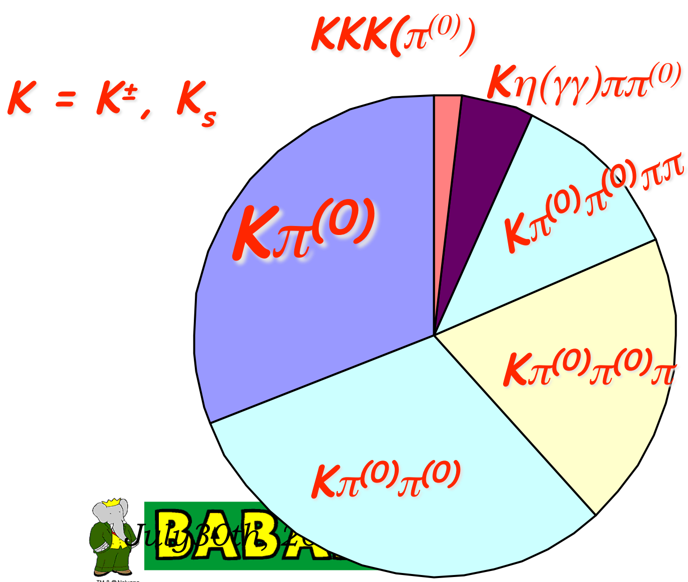


$$A_{cp} = \frac{\Gamma(\bar{B}\rightarrow\bar{X}_s\gamma)-\Gamma(B\rightarrow X_s\gamma)}{\Gamma(\bar{B}\rightarrow\bar{X}_s\gamma)+\Gamma(B\rightarrow X_s\gamma)}$$

In SM Acp < 1% due to CKM & GIM suppression but models with non-minimal Flavor violation (e.g SUSY) may have of order 10%-15% asymmetry

(Kagan and Neubert PRD 98 094012)

Reconstructed Final States ~55%



Exclusively Reconstruct 16 final states of Xs :

Covers ~55% of possible Xs states

Self-tagging

Time Integrated CP Asymmetry with $B \to X_s\gamma$

arXiv:0805.4796

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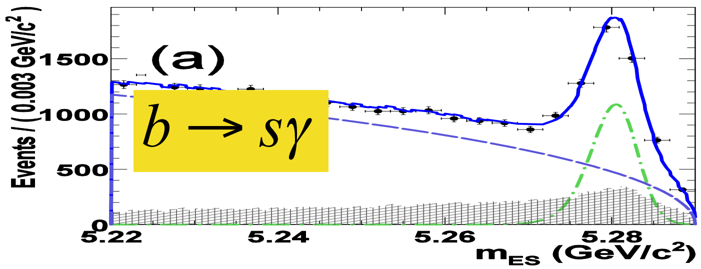
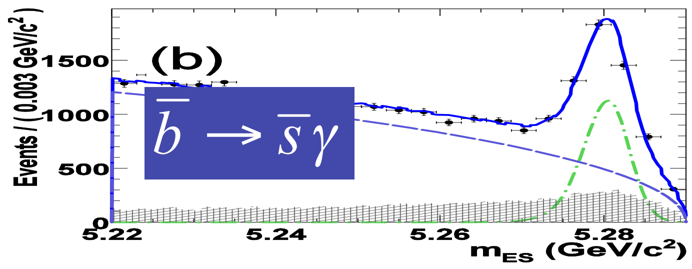




$q\bar{q}$

$B\bar{B}$

M_{ES} (GeV)

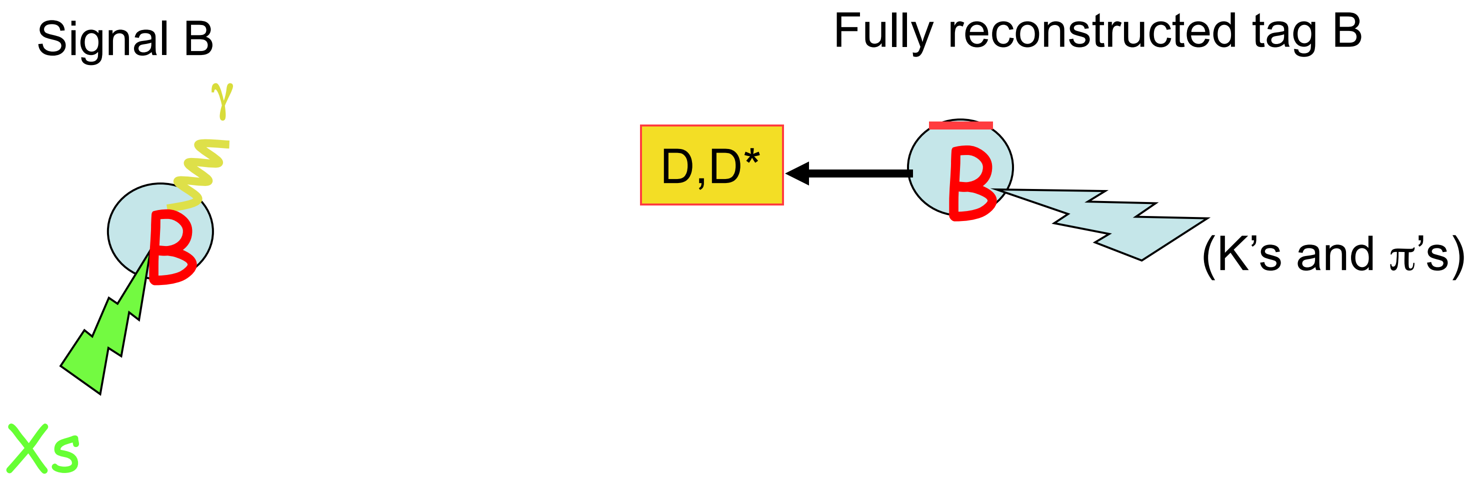
M_{ES} (GeV)

Detector asymmetry A_{det}=-.007 ±0.005

$$A_{cp} = -0.011 \pm 0.030(stat) \pm 0.014(sys)$$

Most precise measurement to date of $A_{cp}(B \to X_s\gamma)$. Consistent with no CPV

$B \rightarrow X_s\gamma$ *with B recoil method*



Fully reconstruct the tag B in order to suppress continuum background, tag charge and flavor, and identify B rest frame.

Fully inclusive X_s but low efficiency (5% of B's reco'd) and large BB background

$B \to X_s\gamma$ *with B recoil method*

PRD 77:051103 2008

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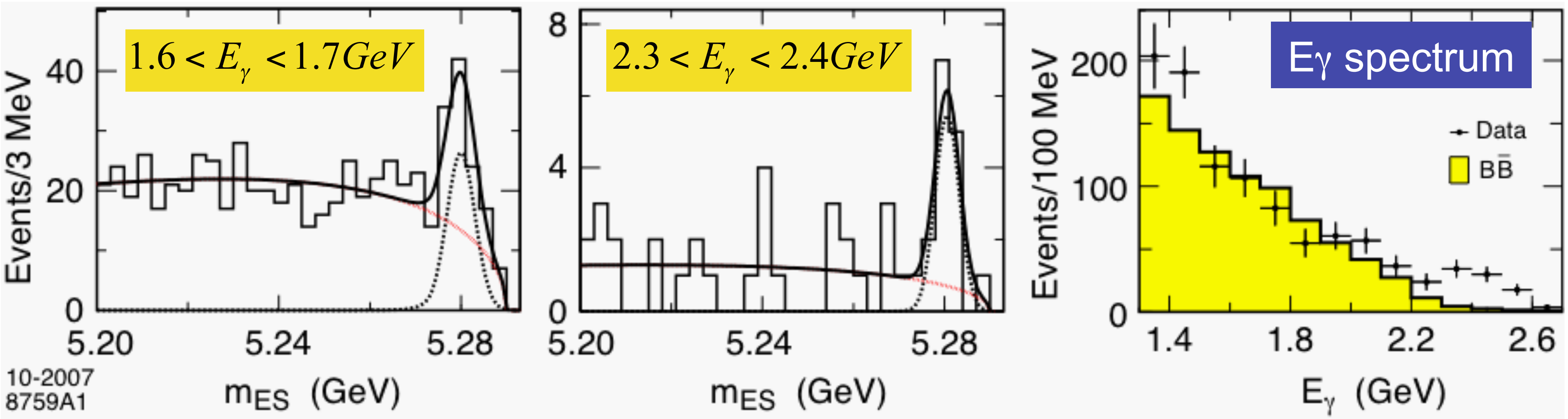

$$B(B \to X_s\gamma, E_\gamma > 1.9 GeV) = 3.66 \pm 0.85(stat) \pm 0.60(sys) \times 10^{-4}$$

$$\langle E_\gamma \rangle (E_\gamma > 1.9 GeV) = 2.289 \pm 0.058 \pm 0.027 GeV$$

$$\langle (E_\gamma - \langle E_\gamma \rangle)^2 \rangle = 0.0334 \pm 0.0124 \pm 0.0062 GeV^2$$

Results consistent with previous measurements and SM prediction
(Technique will be more competitive at Super B factories)

Measurement of $B(B \to X_d\gamma)$ and $|V_{td}/V_{ts}|$

Reconstruct 7 final states of X_d *(~50%)* and corresponding states in X_s (~30%) with $\pi \to K$

$B \to X_d\gamma$	$B \to X_s\gamma$
$B^0 \to \pi^+\pi^-\gamma$	$B^0 \to K^+\pi^-\gamma$
$B^+ \to \pi^+\pi^0\gamma$	$B^+ \to K^+\pi^0\gamma$
$B^+ \to \pi^+\pi^-\pi^+\gamma$	$B^+ \to K^+\pi^-\pi^+\gamma$
$B^0 \to \pi^0\pi^-\pi^+\gamma$	$B^0 \to K^0\pi^-\pi^+\gamma$
$B^0 \to \pi^+\pi^-\pi^+\pi^-\gamma$	$B^0 \to K^+\pi^-\pi^+\pi^-\gamma$
$B^+ \to \pi^+\pi^-\pi^+\pi^0\gamma$	$B^+ \to K^+\pi^-\pi^+\pi^0\gamma$
$B^+ \to \pi^+\eta\gamma$	$B^+ \to K^+\eta\gamma$

Two mass regions studied

$0.6 < M_{Xd/s} < 1.0$ GeV ($B \to \rho/\omega\gamma$ *region)*

$1.0 < M_{Xd/s} < 1.8$ GeV

Many systematics cancel in the ratio but uncertainty in fraction of modes not measured is the dominant error.

Measurement of $B(B \to X_d\gamma)$ and $|V_{td}/V_{ts}|$

arXiv:0807.4975

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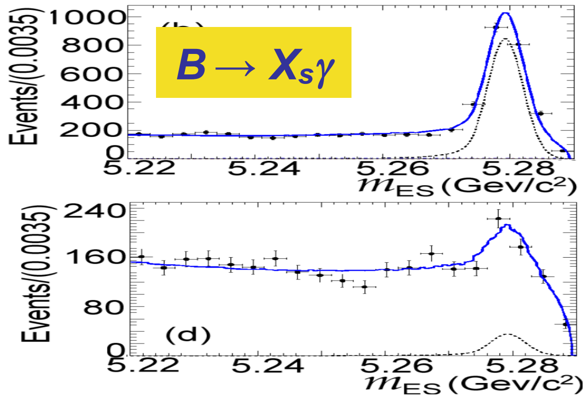
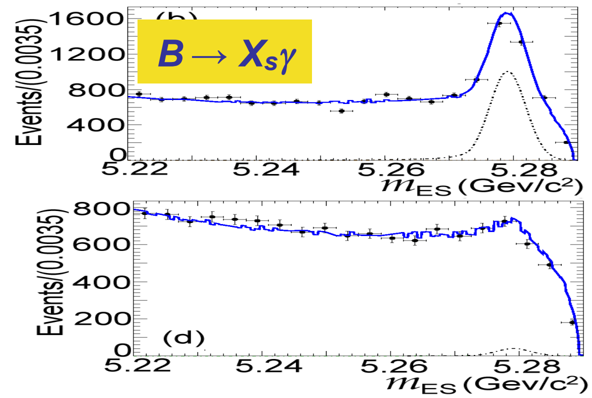
$0.6 < M_{Xd/s} < 1.0$ GeV



$B \to X_d\gamma$

$1.0 < M_{Xd/s} < 1.8$ GeV



$N_{events} = 107 \pm 47$

$B \to X_d\gamma$

Consistency with previous $B \to \rho/\omega\gamma$,
$B \to X_s\gamma$ measurements as control check

$$\frac{\Gamma(B \to X_d\gamma)}{\Gamma(B \to X_s\gamma)} = 0.033 \pm 0.013(stat.) \pm 0.009(sys.)$$

$$(0.6 < M_{X_{s,d}} < 1.8\ GeV)$$

$|V_{td}/V_{ts}|$ from $B \to X_d\gamma$

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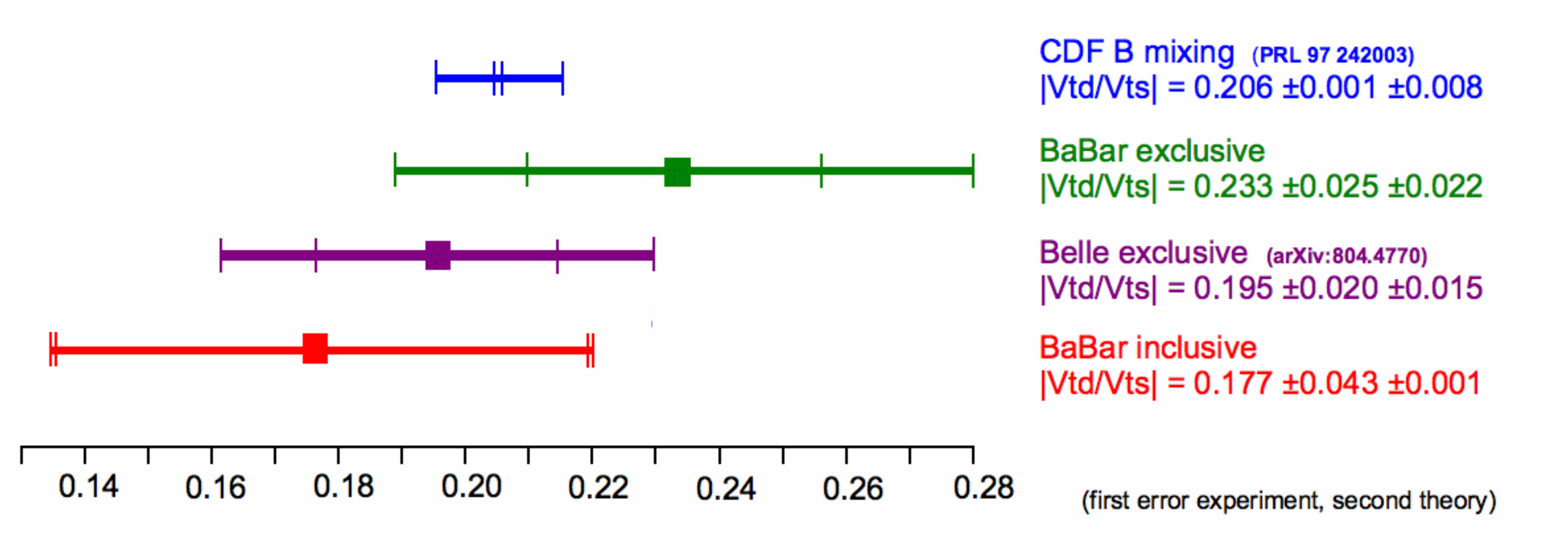
$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.177 \pm 0.043(\text{exp.}) \pm 0.001(th.)$$

(Using theory: Ali,Asatrian & Greub PLB 429,87,1998)*



*Theory error in BaBar $B \to X_d\gamma$ does not include error for using ~50% of states

- i.e does heavy quark duality still hold ?

Summary

Updated Measurements of B($B \to K^*(892)\gamma$), B($B \to \rho/\omega\gamma$), B($B \to K\eta\gamma$)

Updated Time dependent CPV measurement for $B \to K^*(K_s\pi^0)\,\gamma$

First Measurement of Time dependent CPV in $B^0 \to K^0\eta\gamma$

Updated measurements of time integrated CPV in $B \to X_s\gamma$, $B^+ \to K^+\eta\gamma$

B reco recoil method applied to $B \to X_s\gamma$

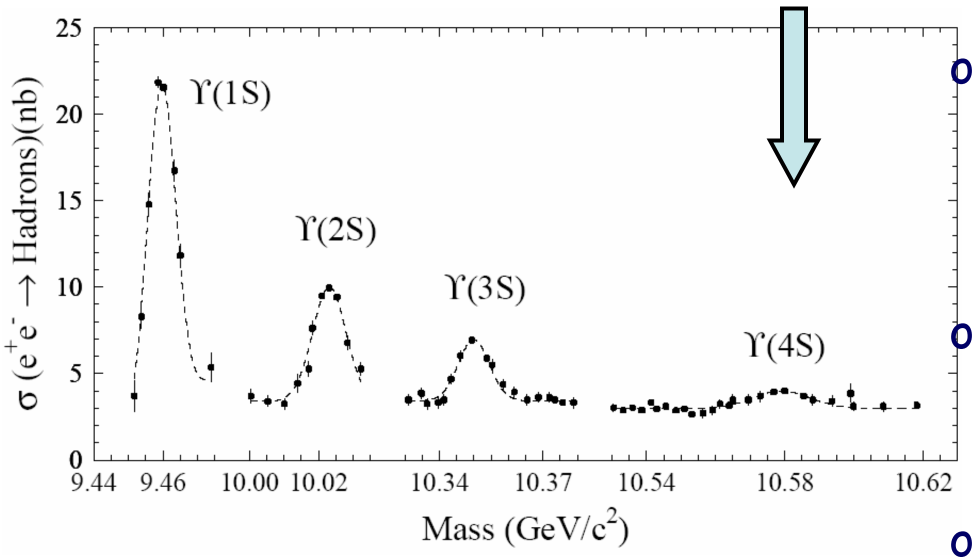
Measurement of $B \to X_d\gamma$

Extraction of $|V_{td}/V_{ts}|$ from inclusive and exclusive $b \to d\gamma$

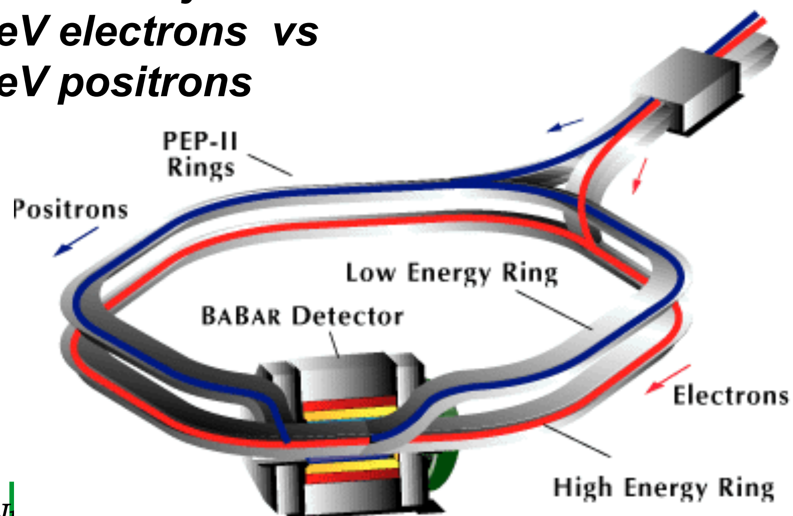
All measurements consistent with SM and previous results !

Backup Slides

B factories: $e^+e^- \to \Upsilon(4S) \to B\bar{B}$

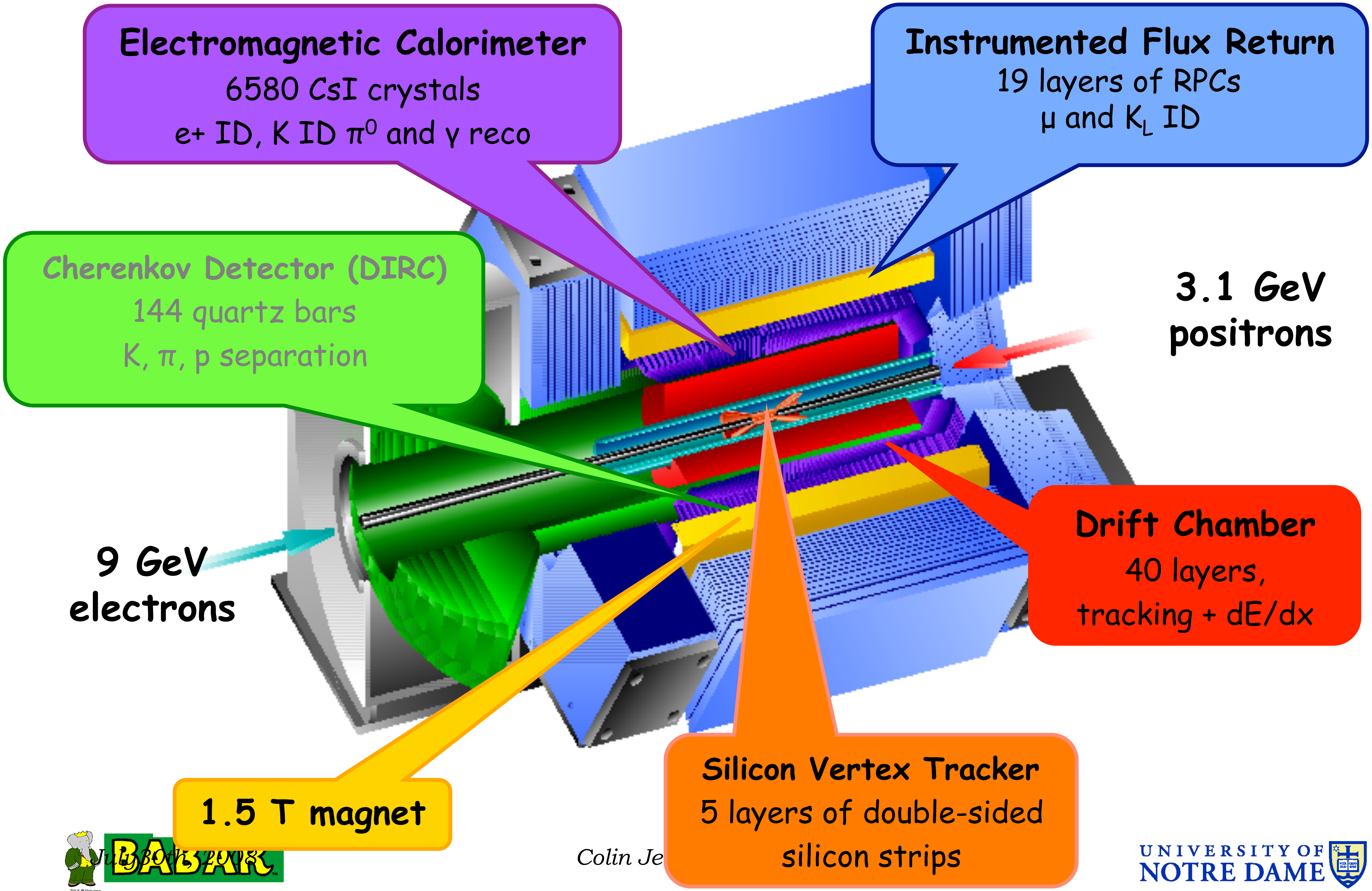


PEP-II is an asymmetric collider
9.0 GeV electrons vs
3.1 GeV positrons



- BaBar finally collected 423 fb^{-1} at $\Upsilon(4S)$ resonance (10.58 GeV) and 41 fb^{-1} just below the $\Upsilon(4S)$
- hadronic cross sections: udsc:bb = 3.4:1.1 nb
- In the $\Upsilon(4S)$ frame the B mesons are practically at rest
- The asymmetry boosts the $\Upsilon(4S)$ to facilitate time-dependent CP violation measurements

The BaBar detector



Isospin Asymmetry

- Hadronic and experimental uncertainties partially cancel in ratios (theory uncertainties large for branching fractions)
- Both measurements are sensitive to new physics

$$\mathcal{A} = \frac{\Gamma(\overline{B} \to \overline{K}^{*}\gamma) - \Gamma(B \to K^{*}\gamma)}{\Gamma(\overline{B} \to \overline{K}^{*}\gamma) + \Gamma(B \to K^{*}\gamma)}$$

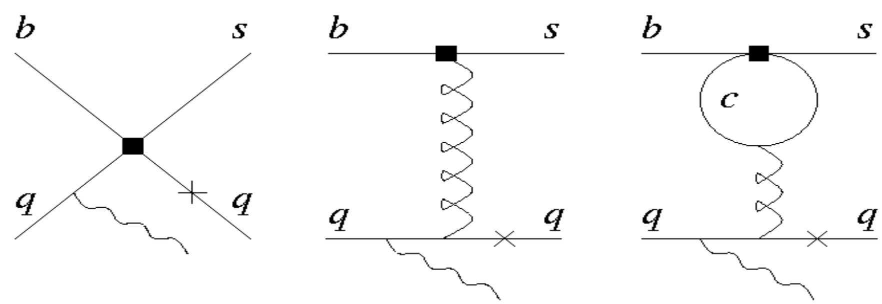
- Decay dominated by one operator
  SM: $A_{CP} < 1\%$

SM: $\Delta_{0+} = +(2.6 \pm 0.8)\text{x } 10^{-2}$

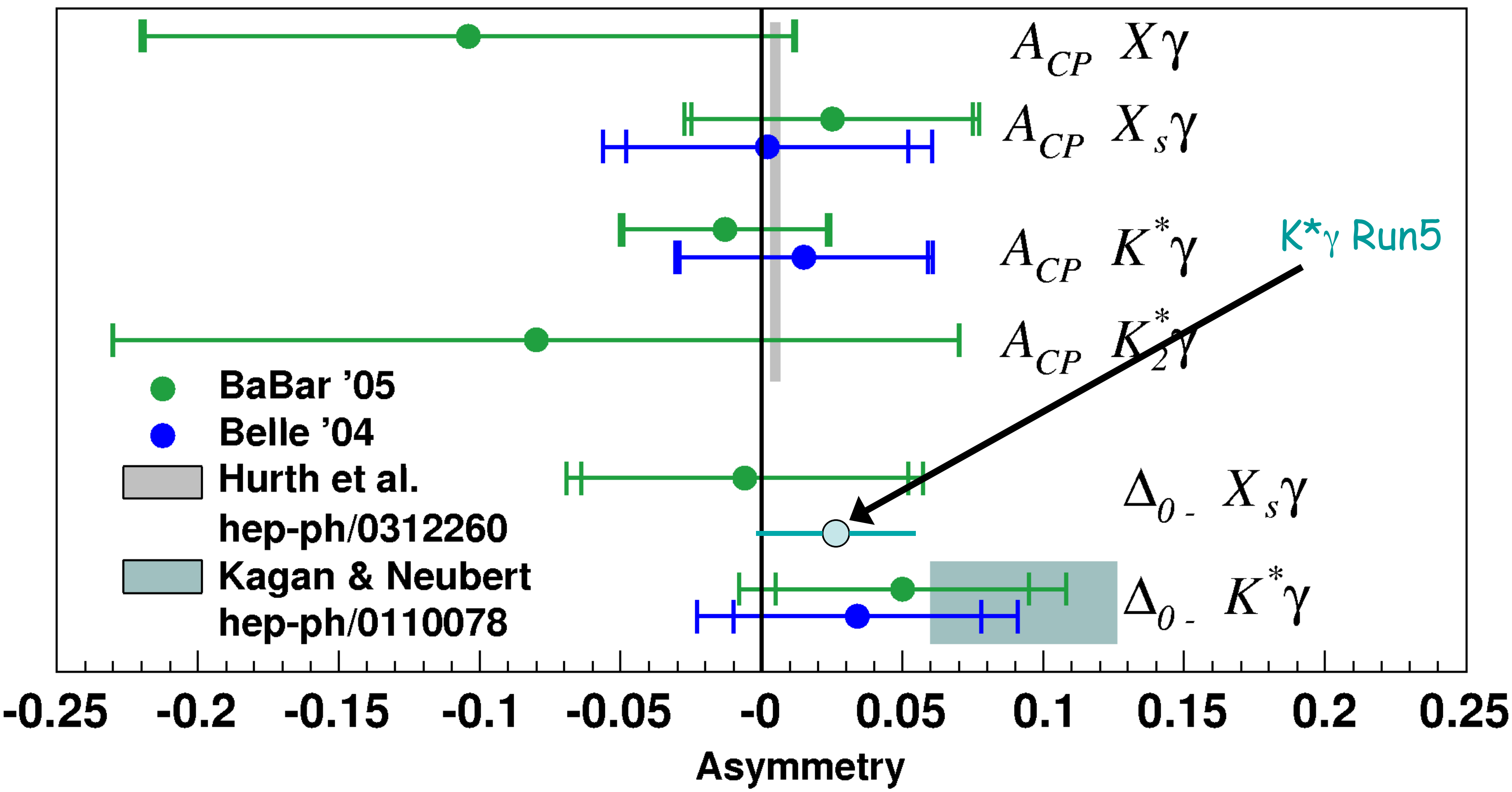
Matsumori, Sanda, Keum
PRD 72, 014013 (2005)

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

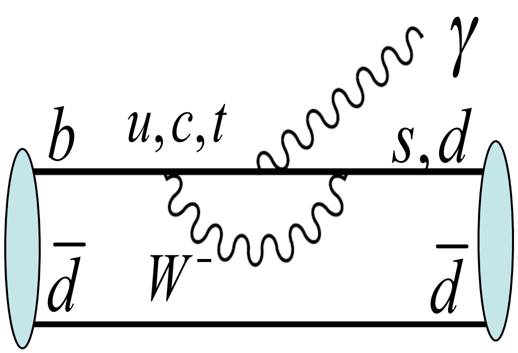
- Isospin breaking diagrams



Summary of B->K*γ asym measurements



A Colony of Penguins

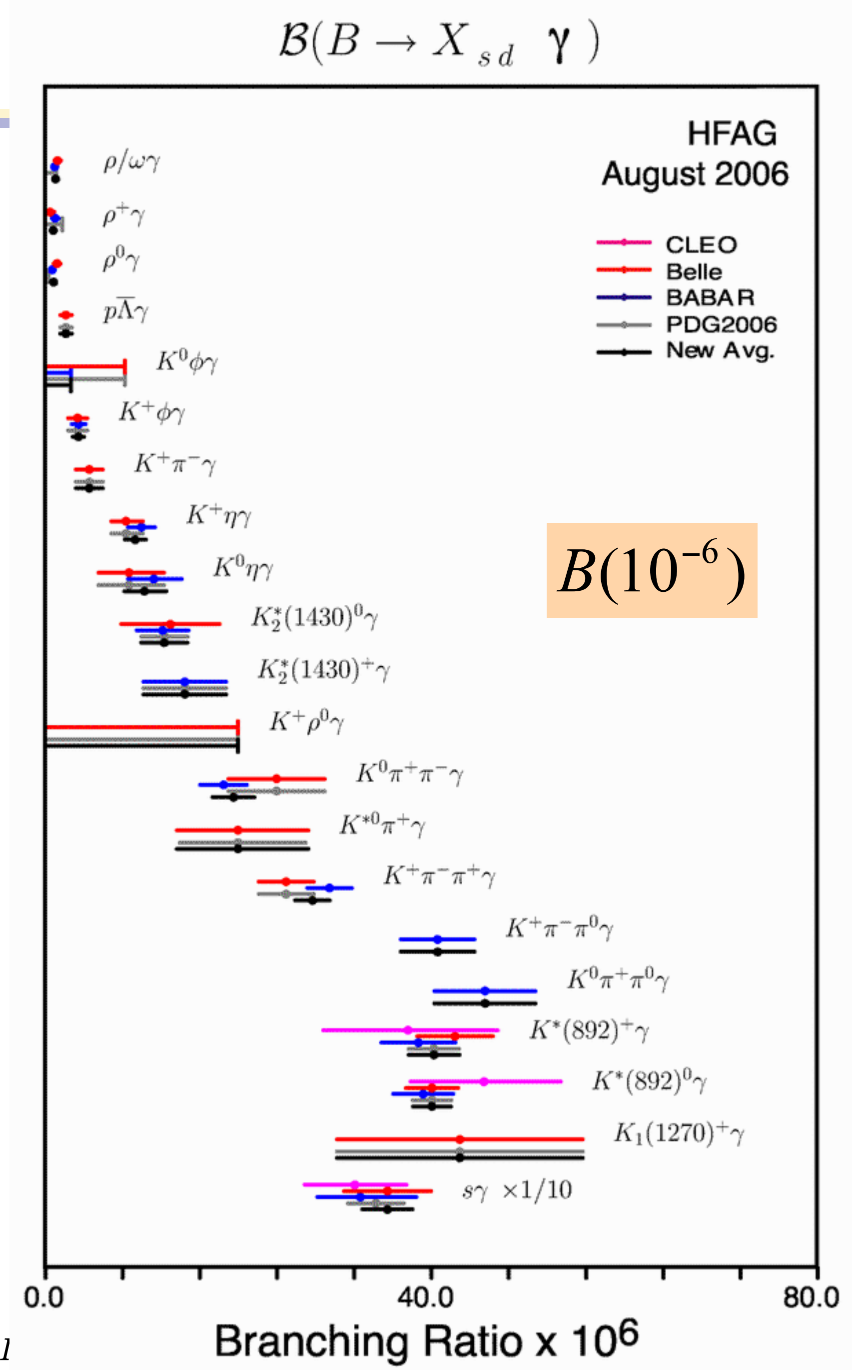


ρ,ω

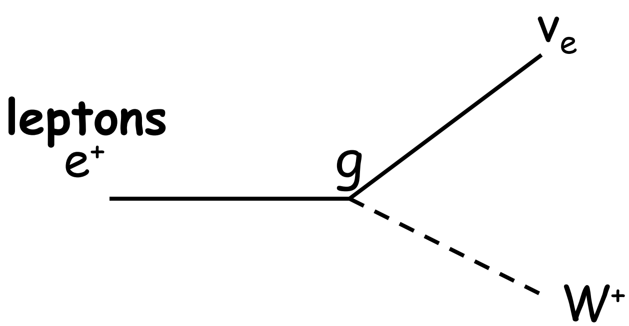
dd (V_{td})

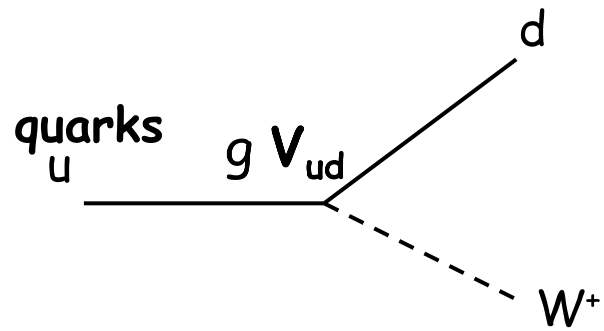
sd (V_{ts})

K*(892)
K_1(1270)
K_2(1430)
...



The CKM matrix





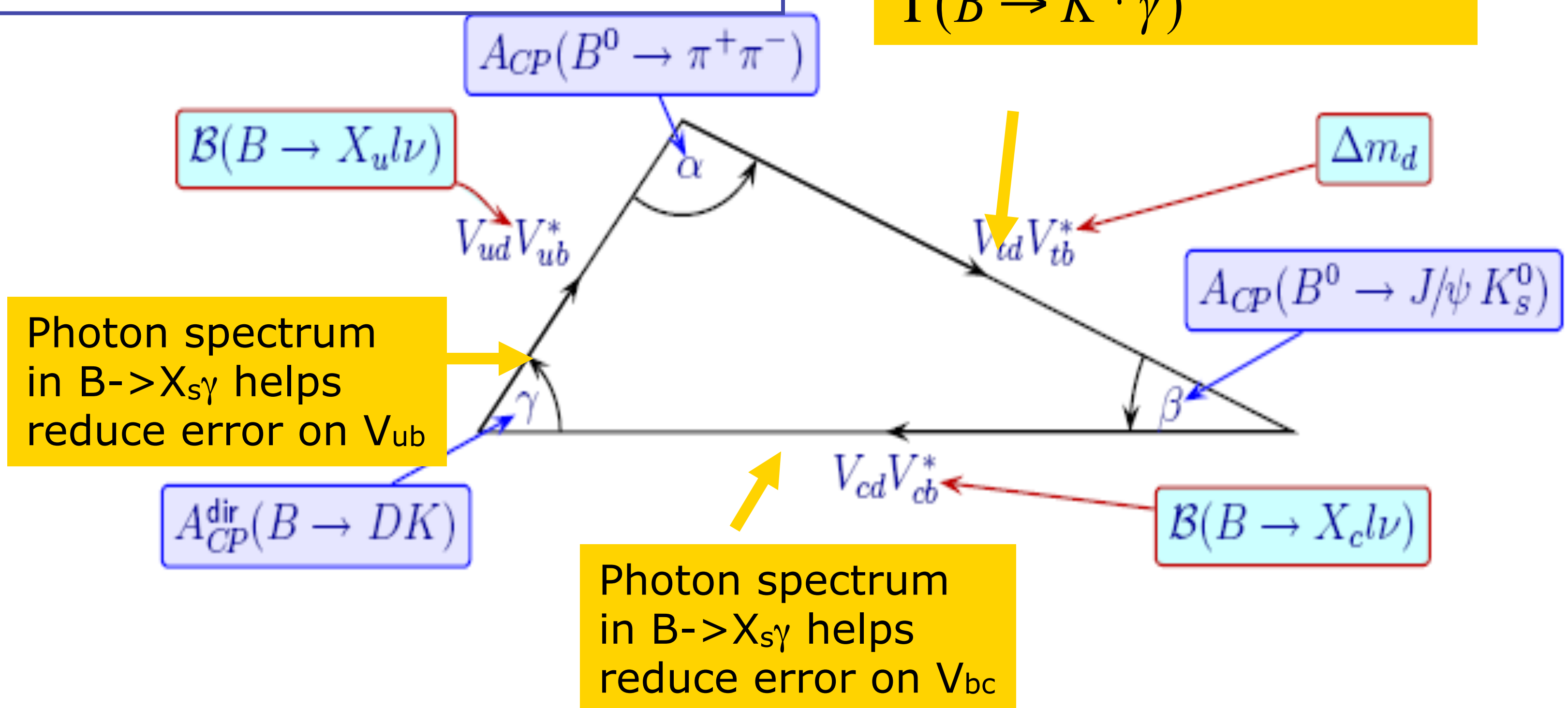
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

Standard model explanation of CP violation is a single phase in the CKM matrix V.

The unitarity triangle

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

$$\frac{\Gamma(B \to \rho\gamma, \omega\gamma)}{\Gamma(B \to K^*\gamma)} \text{ measures } V_{td}$$



Overconstraining the triangle may reveal new sources of CP violation.

Extracting $|V_{td}/V_{ts}|$ from $b \to d\gamma$ Decays

Belle, PRL 96, 221601 (2006).

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.199^{+0.026+0.018}_{-0.025-0.015}$$

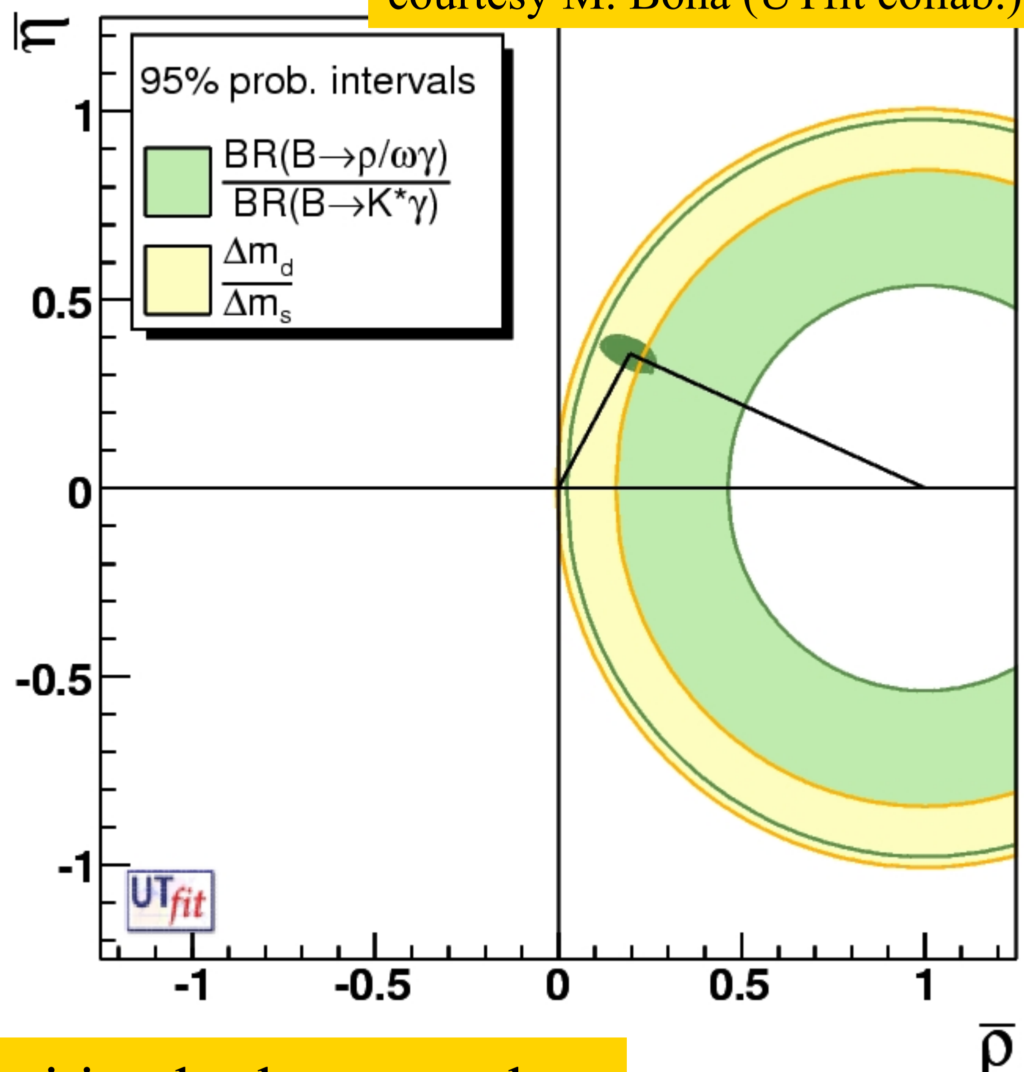
BABAR, hep-ex/0607099 (preliminary)

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.171^{+0.018+0.017}_{-0.021-0.014}$$

CDF, hep-ex/0606027 (preliminary)

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.208^{+0.001+0.008}_{-0.002-0.006}$$

courtesy M. Bona (UTfit collab.)



Consistent within errors.

Theoretical uncertainties limiting both approaches.

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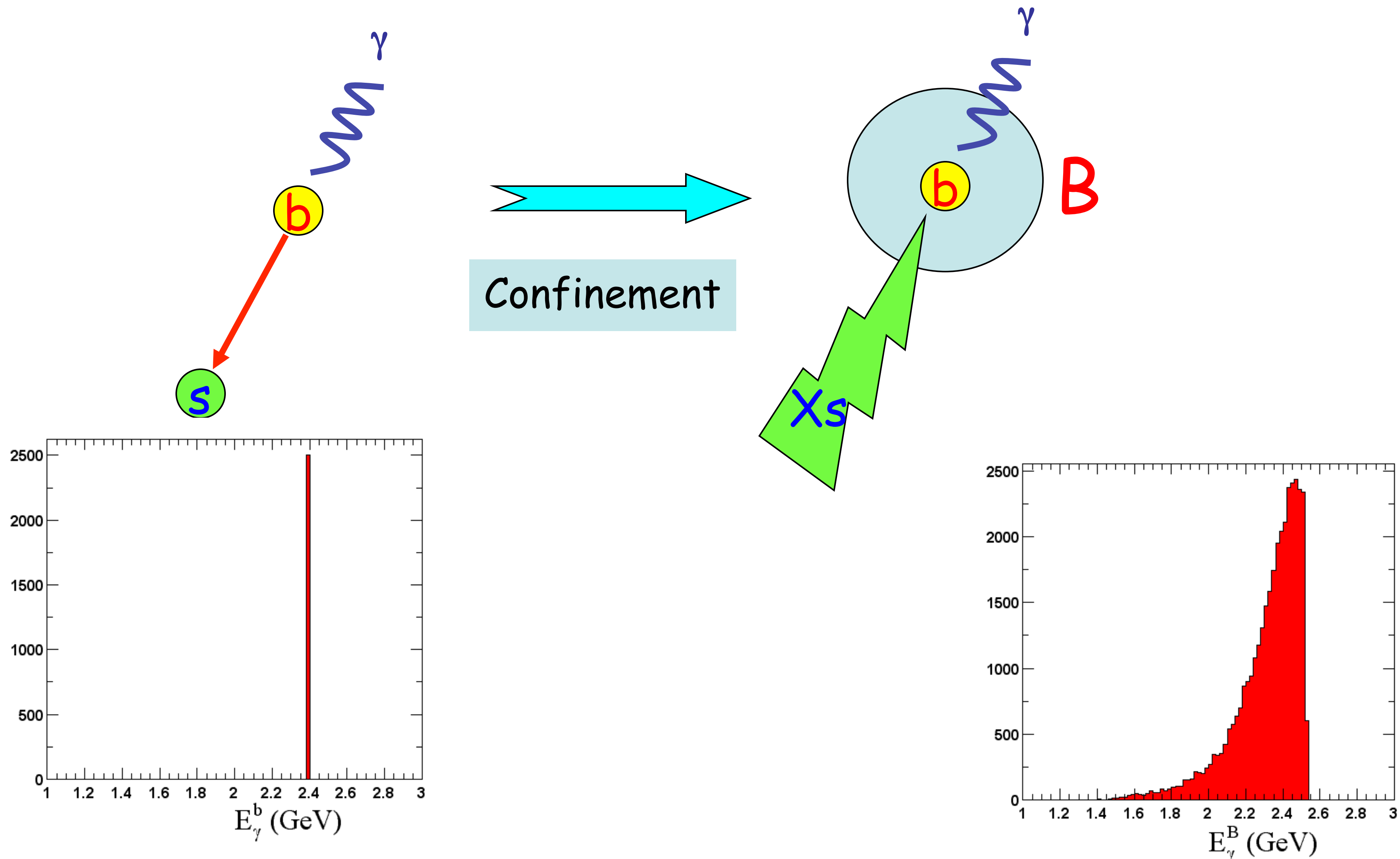
Inclusive Photon Spectrum



To be fully inclusive must measure all the photon spectrum

Errors in *Measurement of B(B → $X_d\gamma$) and $|V_{td}/V_{ts}|$*

Error in X_d/X_s Ratio

K/π misid	2.0 %
Fit PDF's	8.7 %
Backgrounds	5.4%
Fit Bias	3.0%
Fragmentation	8.5%
Missing >5 body	21.0%
Other Missing States	5.0%
Total	26.1%

Missing states corrected for using JETSET. Vary fractions of missing states by 50% from phase space fragmentation – but get cancellation in ratio