$b \to s\gamma$ and $b \to d\gamma$ (B factories)

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(on behalf of Babar* and Belle)

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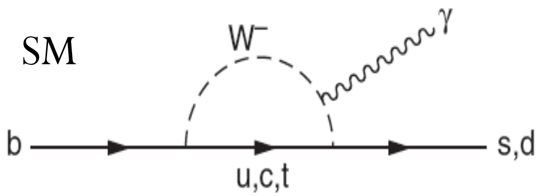
Outline

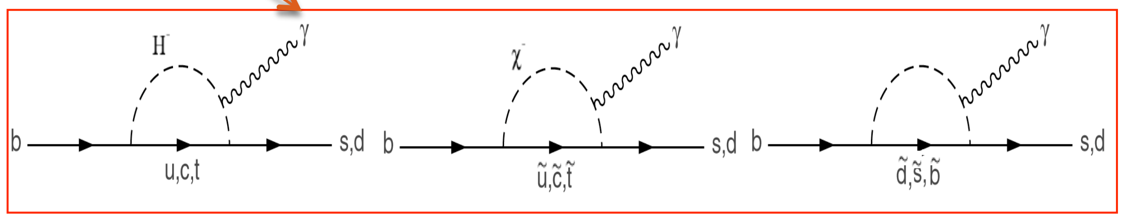
- Introduction
- Direct CP asymmetry (A_{CP}) in $B \to X_{s+d}\, \gamma$ New
- Inclusive $b \to s\gamma$ branching fraction & spectral moments
- Measurement of $b \to d\gamma$ and determination of $|V_{td}/V_{ts}|$ New
- Summary

Motivation

❖ $b \to s(d)\gamma$, flavor-changing neutral currents, forbidden at tree-level in Standard Model (SM)—lowest order requires one loop.

Ideal process for indirect search for New Physics (NP).





➢ Branching fraction: SM prediction Next-to-Next-Leading-Log

$$\left(B \to X_s\gamma\right)_{E_\gamma^B > 1.6GeV} = (3.15 \pm 0.23)\times 10^{-4}$$

(Misiak et al. Phys.Rev.Lett.98:022002,2007)

➢ Direct CP asymmetry

$$A_{CP}(B \to X_s\gamma) \approx +0.0044$$
$$A_{CP}(B \to X_d\gamma) \approx -0.102$$
$$A_{CP}(B \to X_{s+d}\gamma) \sim 10^{-6}$$

$$A_{CP}(B \to X_q\gamma) = \frac{\Gamma(\bar{B} \to X_q\gamma) - \Gamma(B \to X_{\bar{q}}\gamma)}{\Gamma(\bar{B} \to X_q\gamma) + \Gamma(B \to X_{\bar{q}}\gamma)}$$

(Hurth etal, Nucl.Phys.B704:56-74,2005)

➢ Spectral moments => Heavy quark parameters: m_b , μ_π^2.

Experimental technique

- ❖Exclusive: Fully reconstructed resonance states, e.g. $K^*\gamma$, $(\rho, \omega)\gamma$,
  low background,
  large theoretical uncertainty from form factors.

- ❖Inclusive: Better theoretical control from quark-hadron duality.

  - ➢Sum of exclusive: reconstruct as many as possible exclusive modes, background understood, extrapolation of missing modes.

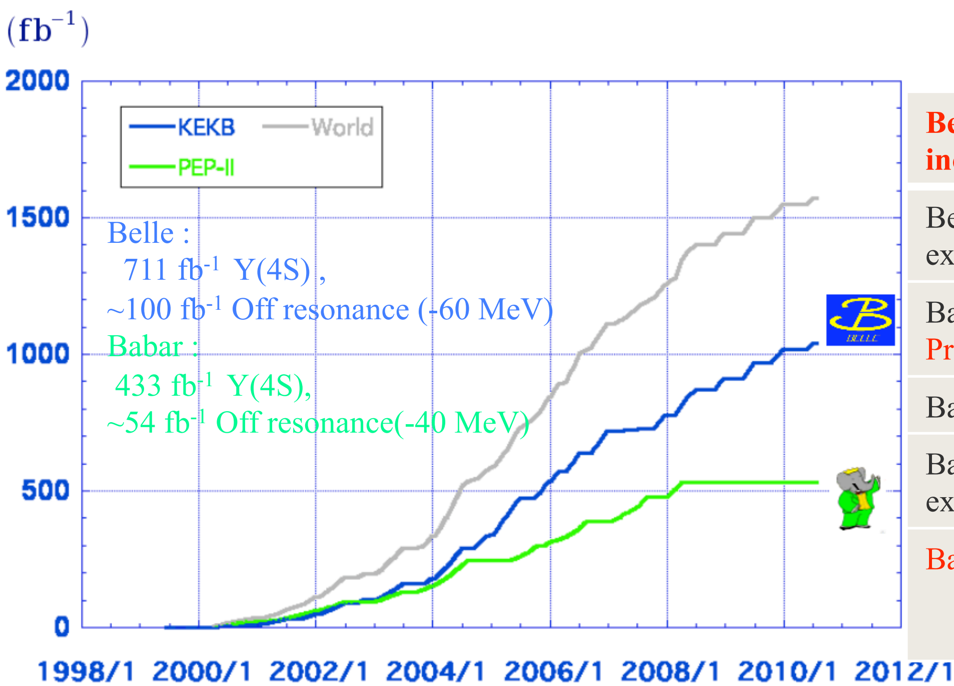
  - ➢Fully Inclusive: identify one high energy photon, no missing modes, estimation of very large background is challenging.

.

Inclusive $b \to s(d)\gamma$ & B factories

- $b \to s(d)\gamma$ pioneered by CLEO
  PRL 74: 2885 (1995), PRL 87:251807 (2001)
- Huge datasets from B factories (Babar & Belle)

Luminosity at B factories



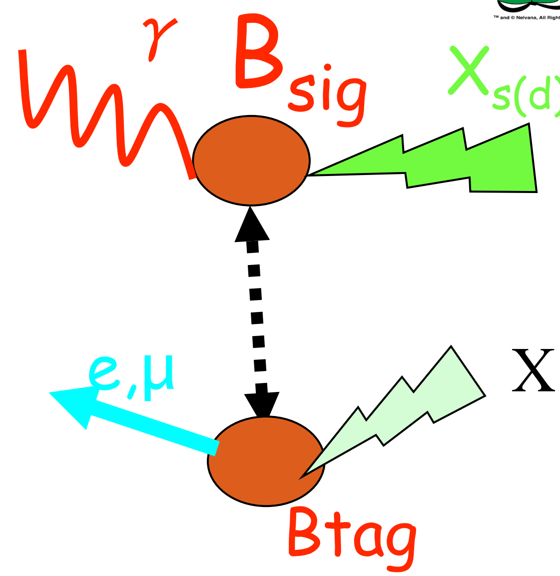
Belle inclusive*	**PRL 103:241801(2009)** **PRL 93:061803(2004)**	**605 fb^{-1}** **140 fb^{-1}**
Belle Σ exclusive	PL B511:151(2001)	5.8 fb^{-1}
Babar l-tagged Preliminary*	PRL 97:171803(2006) ******	81fb^{-1} 347 fb^{-1}
Babar B-tagged	PRD77:151103 (2008)	210 fb^{-1}
Babar Σ exclusive	PR D72:052004(2005)	82 fb^{-1}
Babar Xs(d) *	PRL 102: 161803(2009) **arXiv:1005.4087** **(accepted by PRD-RC)**	347 fb^{-1} 433fb^{-1}

*after CKM2008

Babar: $B \to X_s \gamma$ (New, preliminary)

347 fb^{-1} $\Upsilon(4S)$ Data and 36 fb^{-1} Off resonance Data

- Signal signature:
  One isolated High Energy photon (γ_{HE}), do not reconstruct the hadronic system. Veto γ_{HE} from π^0/η.



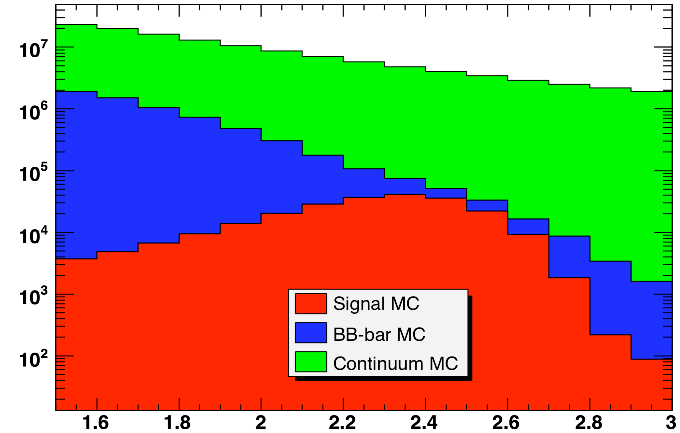
- Lepton tag and event topology criteria used to suppress continuum.

- Measurements
  - Branching fraction
    Does not distinguish X_s and X_d, ~4% X_d subtracted at the end.
  - CP asymmetry A_{CP} ($B \to X_{s+d}\gamma$): Lepton charge identifies B flavor.
  - Spectral moments.

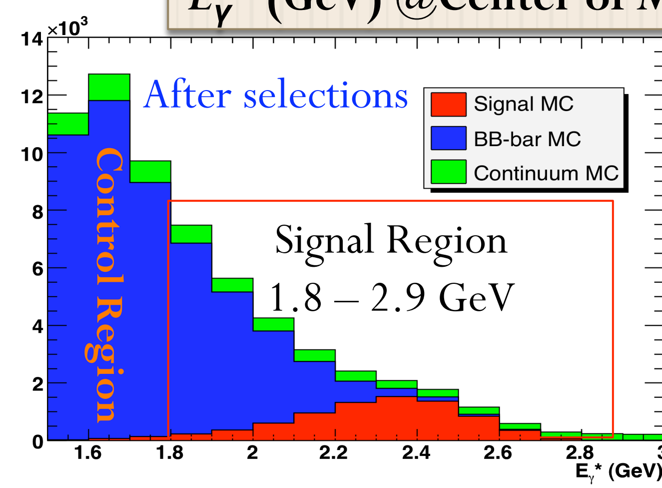
Present today

Analysis method

Monte Carlo (MC) after select HE photons + reject QED events



E_γ* (GeV) @Center of Mass



Key of this analysis is to subtract backgrounds.

❖Continuum

Event selection optimized, by lepton tagging and by exploiting event topology (Neural Network). Remained subtracted with off resonance data (scaled).

⇒dominant statistical uncertainty.

Continuum control region (2.9-3.5)GeV.

❖$B\bar{B}$ background (non-signal)

Rely on MC, correct each component with data control sample.

⇒dominant systematic uncertainty.

$B\bar{B}$ control region (1.53-1.8 GeV).

B$\bar{B}$ background components

MC truth		Control region		Signal region	
Truth-match	Parent	MC fraction	Corr. factor	MC fraction	Corr. factor
Photon	π^0	0.5390	1.05	0.6127	1.09
	η	0.2062	0.79	0.1919	0.75
	ω	0.0386	0.80	0.0270	0.80
	η'	0.0112	0.52	0.0082	1.13
	B	0.0362	1.00	0.0194	1.00
	J/ψ	0.0061	1.00	0.0071	1.00
	$e^{\pm}$	0.0967	1.07	0.0619	1.07
	Other	0.0035	1.00	0.0032	1.00
	Total	0.9375	– – – –	0.9315	– – – –
$e^{\pm}$	Any	0.0411	1.65	0.0333	1.68
$\bar{n}$	Any	0.0170	0.35	0.0243	0.15
Other	Any	0.0029	1.00	0.0028	1.00
None		0.0015	1.00	0.0079	1.00

❖Largest π^0 +η: 75-80%:

❖ ω,/η' ~5%

❖Electron bremsstrahlung,

❖Fake photon ~6-7%

➢Electron mismatched or track lost.

➢Cluster produced by $\bar{n}$.

❖ Nearly all components corrected/checked with various data control sample.

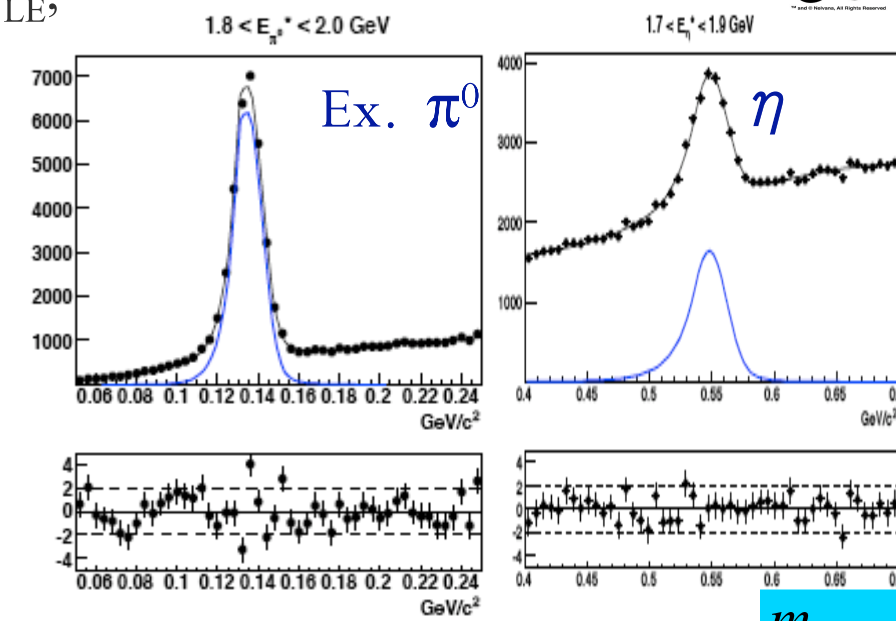
$B\bar{B}$ background components--π^0/η

❖Control sample $B \to X\pi^0(\eta)$, $\pi^0(\eta) \to \gamma_{HE}\gamma_{LE}$, same selection applied except the veto.

❖Yield fitted in $E^*_{\pi 0(\eta)}$ bins, translated into E^*_γ. Bins.

❖Corrections for data/MC differences including:

- ➢Produced yield after selection;
- ➢Efficiency of high energy photon;
- ➢Efficiency of lepton tag.



$m_{r_{HE} r_{LE}}$

Veto: ($115 < m_{\gamma\gamma} < 155$ GeV, $508 < m_{\gamma\gamma} < 588$ GeV)

❖ **However, $\pi^0(\eta)$ samples (Low Energy photon found)**

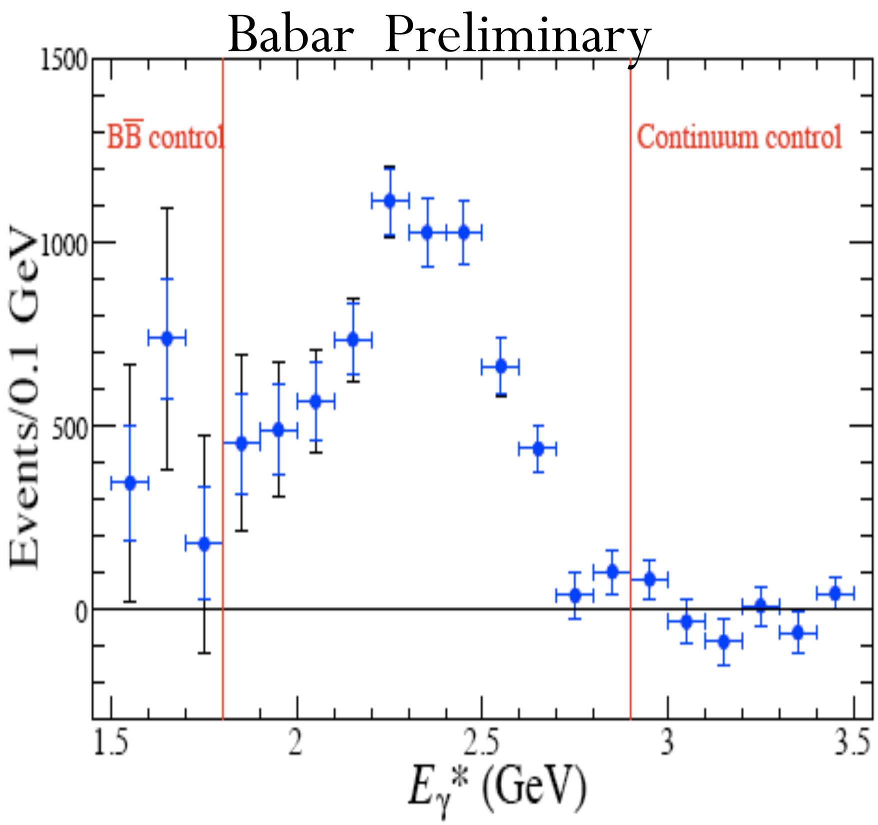
⇒ the $\pi^0(\eta)$ events pass the π^0/η vetoes (mostly true LE photon NOT found).

Any data/MC difference on LE photon efficiency

⇒ opposite direction in control sample and normal sample,

Additional correction applied.

Unblinded spectrum after bg. subtraction



❖ Continuum Control Region:

OnPeak On – Off Data:

1825 => -100 ± 138 events

❖ $B\bar{B}$ Control Region:

OnPeak On – Off Data – BB MC

3.6×10^4 =>1252 ± 272 ± 841

(1.4σ IF no signal)

a tail of signal ~100-400 (models)

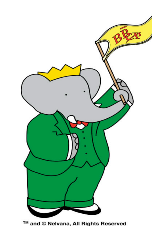
⇒0.9-1.3σ

❖Control region checks show good understanding of backgrounds.

❖**A_{CP} is insensitive to photon energy cut, statistical optimization**

=> (2.1-2.8) GeV for the A_{CP} .

$A_{CP}(B \rightarrow X_{s+d}\gamma)$ measurement



❖Lepton charge gives the flavor of B.

❖Sometimes mistags B by mistag rate (ω):

$$A_{CP} = \frac{A_{CP}^{meas}}{1-2\omega}$$

	ω±Δω
$B^0-\bar{B}^0$ oscillation	(0.1824±0.0024)/2
$B^0\bar{B}^0$:B^+B^-	0.000 ±0.0030
Non-direct-semileptonic	0.0318±0.0035
Fake ID	0.0073±0.0037
sum	0.131±0.0064

❖Statistical errors, dominated by off peak data subtraction.

❖Most of the systematic uncertainties in the branching fraction measurement are common for +/- leptons, cancelled for A_{CP}.

❖Potential bias (ΔA_{CP}) from

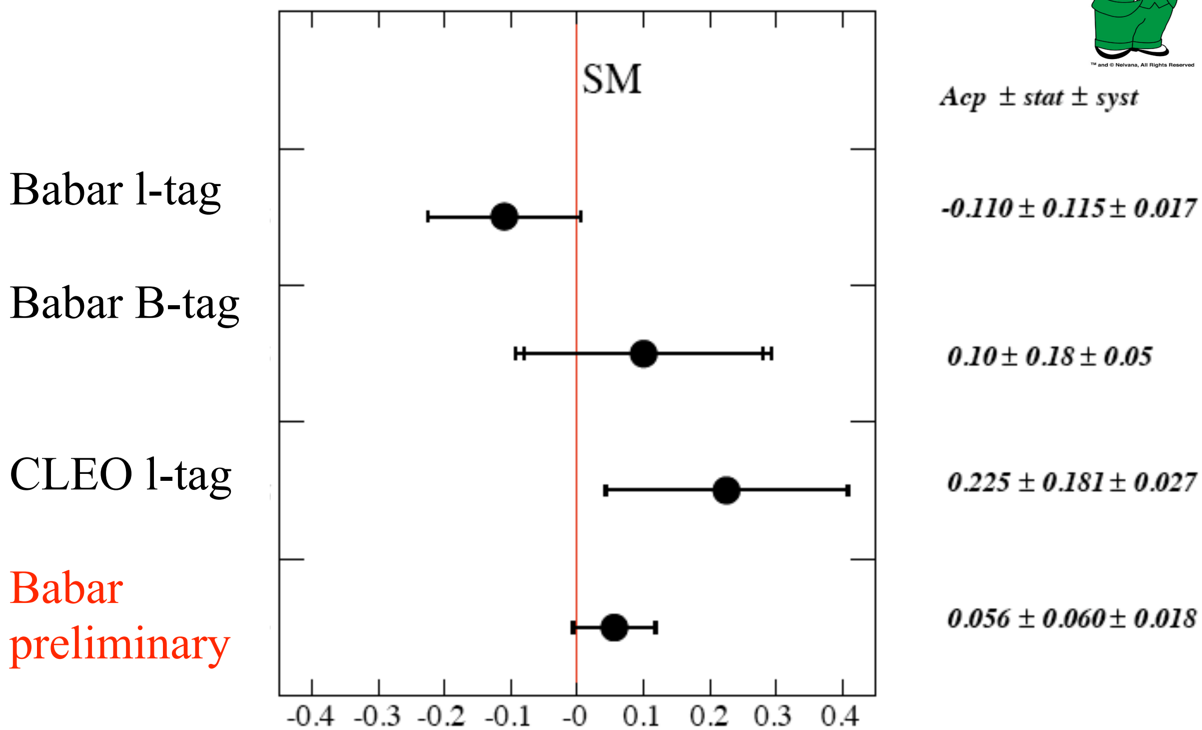
- BB Background subtraction, estimated from control region.
- Detector charge asymmetry: Lepton ID.

	ΔA_{CP} (10^{-2})
$B\bar{B}$ background	-0.4±0.6
Detection asymmetry	0.0±1.1
Sum	-0.4±1.3

$A_{CP}(B \to X_{s+d}\gamma)$ preliminary

$N(l^+) = 2623 \pm 158$
$N(l^-) = 2397 \pm 151$

Babar preliminary
$A_{CP} = 0.056 \pm 0.060 \pm 0.018$

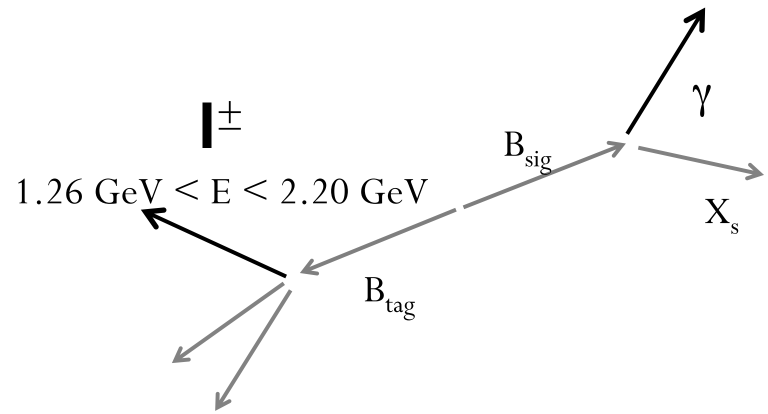


- ✓No significant asymmetry is observed, most precise to date.
- ✓Consistent with SM and previous measurements.
- ✓All measurements dominated by statistical uncertainty.

Belle: Fully Inclusive $b \to s\gamma$

Phys.Rev.Lett.103:241801,2009.

- 657M $B\bar{B}$ and 68 fb^{-1} offpeak (60MeV below).
- Only high energy γ reconstructed, veto π^0/η.
- Mix of two sub samples:
  - Tagged: similar to Babar method, well defined electron/muon.



  - Untagged: Fischer discriminant based on energy flow and event-shape for continuum suppress.

- Two methods: Similar sensitivity, largely statistically independent, profit from combination.
- Remaining background
  - Continuum taken from off-peak data;
  - $B\bar{B}$ estimated from MC.

$B\bar{B}$ Background

❖ BB Background: 6 background categories taken from MC.

Phys.Rev.Lett.103:241801,2009.

1.7-2.8 GeV, photon sources ($B\bar{B}$)

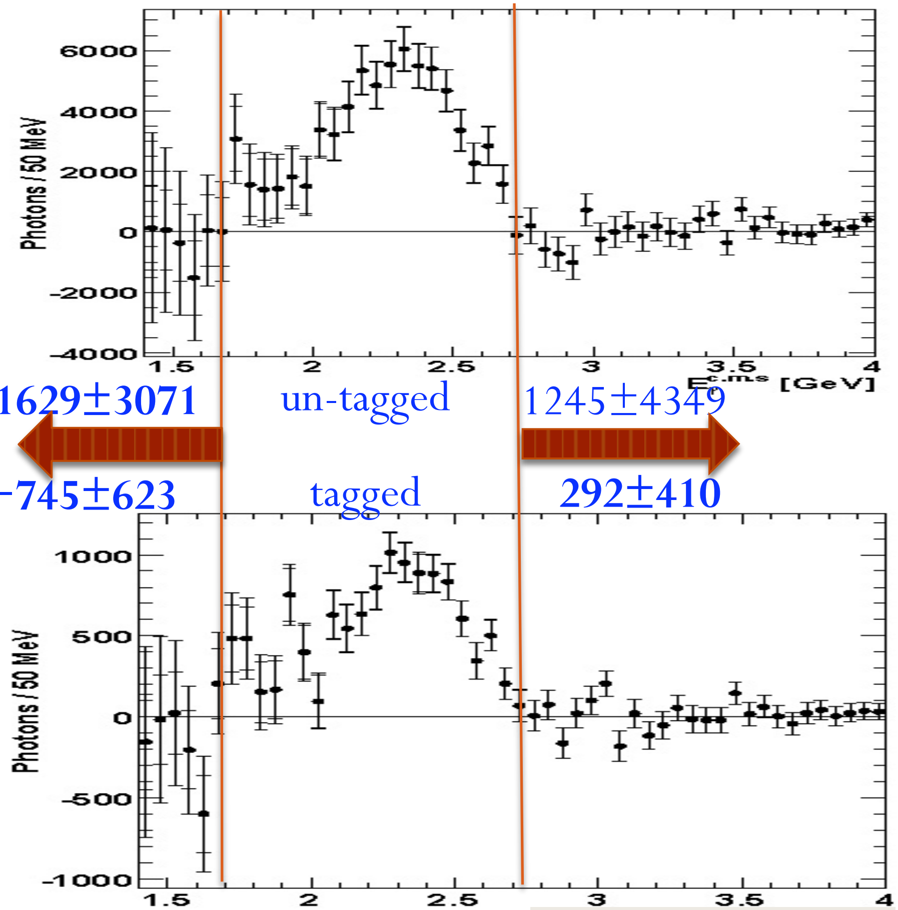
	Untagged (%)	Tagged(%)
π^0	47.4	48.0
η	16.3	16.0
ω η' J/Ψ	8.1	8.9
K_L, $\bar{n}$	1.7	1.6
Electron	6.1	3.3
Beam bg	1.3	2.6
Signal	19.1	19.7

➢inclusive $B\to X\pi^0(\eta)$ samples reconstructed in data and MC => correct MC yield;
veto efficiency measured by partially reconstructed $D^0 \to K^-\pi^+\pi^0$;

➢Others B components,
shape and yield corrected by data control samples,
±20% assigned to systematic uncertainty ⇒ largest systematic.

❖ ~60% of data with EM cluster timing information used to remove overlapping events (hadronic + Bhabha).

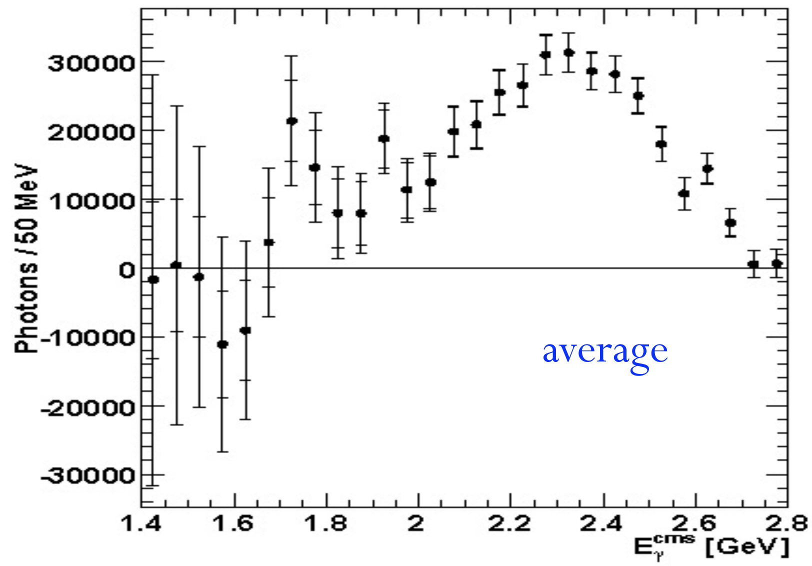
Measured spectra



$(Belle)E_\gamma^{cms} = (Babar)E_\gamma^*$

❖Corrected and combined spectra

correct for select efficiency ($\varepsilon_{untag} \sim 15\%$, $\varepsilon_{tag} \sim 2.5\%$); statistic correlation into account.



❖control region

- ➢High-energy region (2.8-4.0 GeV): agree with zero <0.5 σ
- ➢ Low-energy region (1.4-1.7 GeV) : 0.5 σ (untagged 1.2 σ if no signal

Branching fraction

E_γ^B (GeV)	>1.7	>1.8	>1.9	>2.0
BF ($b \to s\gamma$)	3.45	3.36	3.21	3.02
Statistical error	4.4%	3.9%	3.4%	3.3%
Systematic error	11.6%	7.4%	5.0%	3.6%
Sum	12.4%	8.4%	6.0%	4.9%
HFAG extrapolation (%)	98.5±0.4	96.7±0.6	93.6±1.0	89.4±1.6

- Smallest total measured error is 5% for >2.0GeV.
- First time down to 1.7 GeV, cover more than 98% of Xs, smallest model error, systematic error increased by a factor of 3, from large B background subtraction.

$b \to s\gamma$ Branching Fractions

	E^{min} (GeV)	$B(E_\gamma{}^B > E^{min})$ ($\times 10^{-4}$)
CLEO (2001)	2.0	$3.06 \pm 0.41 \pm 0.26$
Belle Σ exclusive (2001)	2.24	$3.36 \pm 0.53 \pm 0.42^{+0.50}_{-0.54}$
Babar Σ exclusive(2005)	1.9	$3.27 \pm 0.18^{+0.56}_{-0.41}{}^{+0.04}_{-0.09}$
Babar l-tag (2006)	1.9	$3.67 \pm 0.29 \pm 0.34 \pm 0.29$
Babar B-tag (2008)	1.9	$3.66 \pm 0.85 \pm 0.60$
Bell inclusive (2009)	1.7	$3.45 \pm 0.15 \pm 0.40$
HFAG average (2010)	**1.6**	$3.55 \pm 0.24 \pm 0.09$
SM NNLL	**1.6**	3.15 ± 0.23

1.2σ

- ❖Good agreement with SM prediction.
- ❖Provide stringent constraints on NP: e.g. M_{H+}>295GeV@95%CL.
- ❖Babar lepton tag (New) results will come soon.
- ❖Important to measure the $B \to X_s\gamma$ with reduce error in future!

$b \to s\gamma$ spectral moments

❖Ideal laboratory for the studying dynamics of b-quark inside the B meson, because of the universal motion of b-quark inside the B meson =>apply to B semileptonic decays.

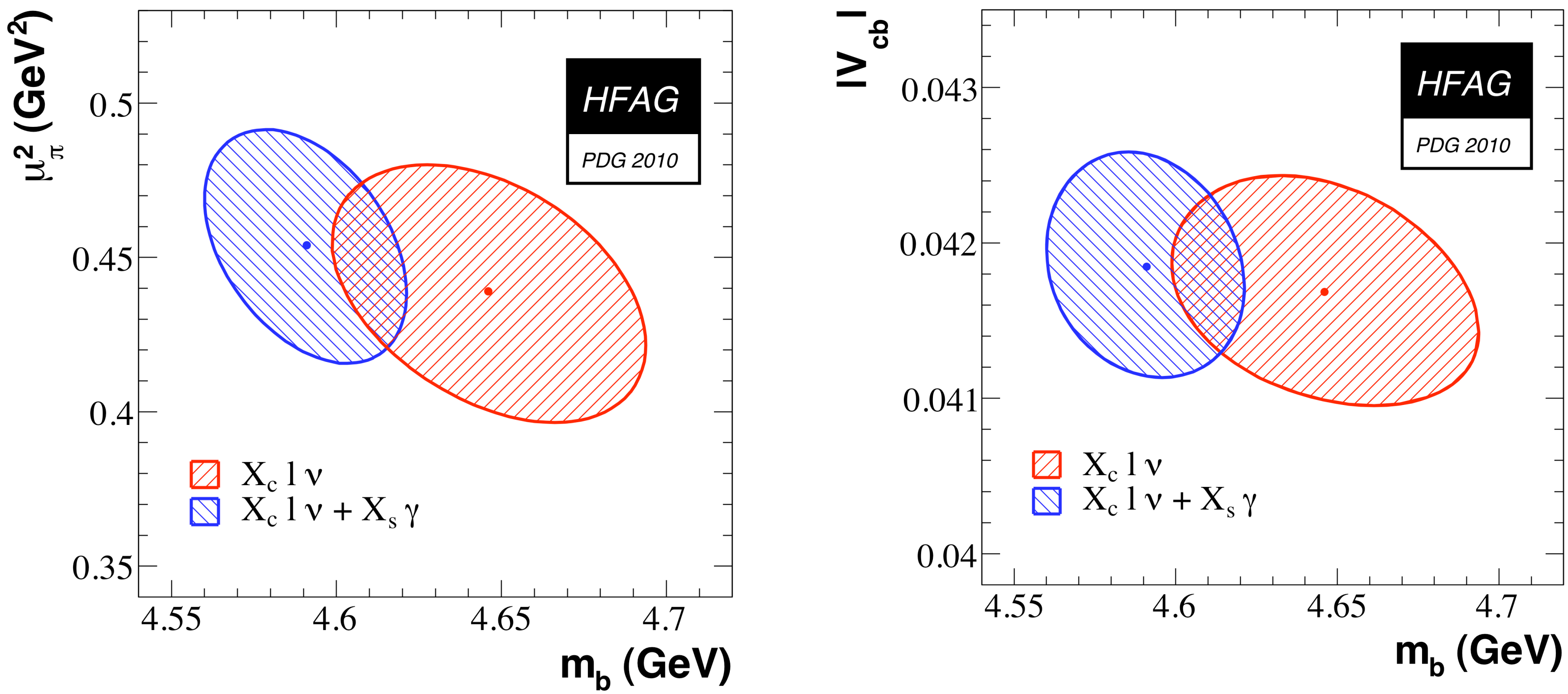
First Moments $< E_\gamma >$ in GeV $\times 10^3$

E_γ threshold	> 1.7	> 1.8	> 1.9	> 2.0	> 2.1
Belle inclusive	2282 ± 53	2294 ± 30	2311 ± 18	2334 ± 11	2350 ± 14
BaBar l-tagged			2288 ± 33	2316 ± 22	2355 ± 19
BaBar B-tagged			2289 ± 64	2315 ± 41	2371 ± 27
BaBar Σ exclusive			2321 ± 47	2314 ± 31	2357 ± 21
B factory average	2282 ± 53	2294 ± 30	2304 ± 16	2324 ± 10	2357 ± 10

Second Moments $< E_\gamma^2 - < E_\gamma >^2 >$ in GeV$^2 \times 10^4$

E_γ threshold	> 1.7	> 1.8	> 1.9	> 2.0	> 2.1
Belle inclusive	428 ± 207	370 ± 86	302 ± 36	230 ± 21	170 ± 22
BaBar l-tagged			328 ± 60	266 ± 34	191 ± 25
BaBar B-tagged			334 ± 139	265 ± 62	142 ± 39
BaBar Σ exclusive			253 ± 107	273 ± 40	183 ± 25
B factory average	428 ± 207	370 ± 86	305 ± 32	253 ± 17	174 ± 13

$b \to s\gamma$ spectral moments & Global Fit



Input	m_b(GeV)	μ_π^2(GeV^2)	$\lvert V_{cb}\rvert$ (10^{-3})
$X_c l \nu$	4.646±0.047	0.439±0.042	$41.68 \pm 0.44_{fit} \pm 0.09_{\tau B} \pm 0.58_{th}$
$X_c l \nu + X_s l \nu$	4.591±0.031	0.454±0.038	$41.85 \pm 0.42_{fit} \pm 0.09_{\tau B} \pm 0.59_{th}$

$B \rightarrow X_d \gamma$ Analysis & $|V_{td}/V_{ts}|$

- $b \rightarrow d\gamma$ suppressed by a factor of ~20 w.r.t. $b \rightarrow s\gamma$ in the SM. New Physics may appear differently for $b \rightarrow s\gamma$ and $b \rightarrow d\gamma$, change the branching fraction ratio.

- The ratio used to extract $|V_{td}/V_{ts}|$.

$$\frac{\Gamma(b \rightarrow d\gamma)}{\Gamma(b \rightarrow s\gamma)} = \xi^2 \left|\frac{V_{td}}{V_{ts}}\right|^2 (1 + \Delta R)$$

Ali eta al PRB 429,87 (1998)

  - ξ is the remaining SU(3) breaking effects and ΔR is the annihilation amplitudes correction, often calculated in term of CKM parameters (ρ and η), both related to $|V_{td}/V_{ts}|$;
  - Reformulate the equation to express the ratio as function of $|V_{td}/V_{ts}|$ and a orthogonal coordinate, i.e. well-known CKM angle β.

- Independent check of value from B_s vs. B_d mixing
- Study from exclusive decay well established ~7% theory uncertainty; inclusive decay ~1% theory uncertainty.

Babar: $B \to X_d \gamma$ Analysis

arXiv:1005.4087
(accepted by PRD-RC)

- 471M $B\bar{B}$ (full Babar dataset), supersedes the previous measurements with 383 M BB: PRL102:161803 (2009)

- Measure the partial branching fraction of sum of seven modes: X_d and X_s

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

X_s and X_d related by kaon-pion substitution

Charge conjugation implied throughout

- Extrapolate to inclusive BF, to include un-reconstructed decay modes, requires knowledge of fragmentation of hadronic systems

$B \to X_d \gamma$ Fit to data

- Yield determined from simultaneous fit to m_{ES} (below) and ΔE
- Two mass bins to cover 0.5-2.0 GeV

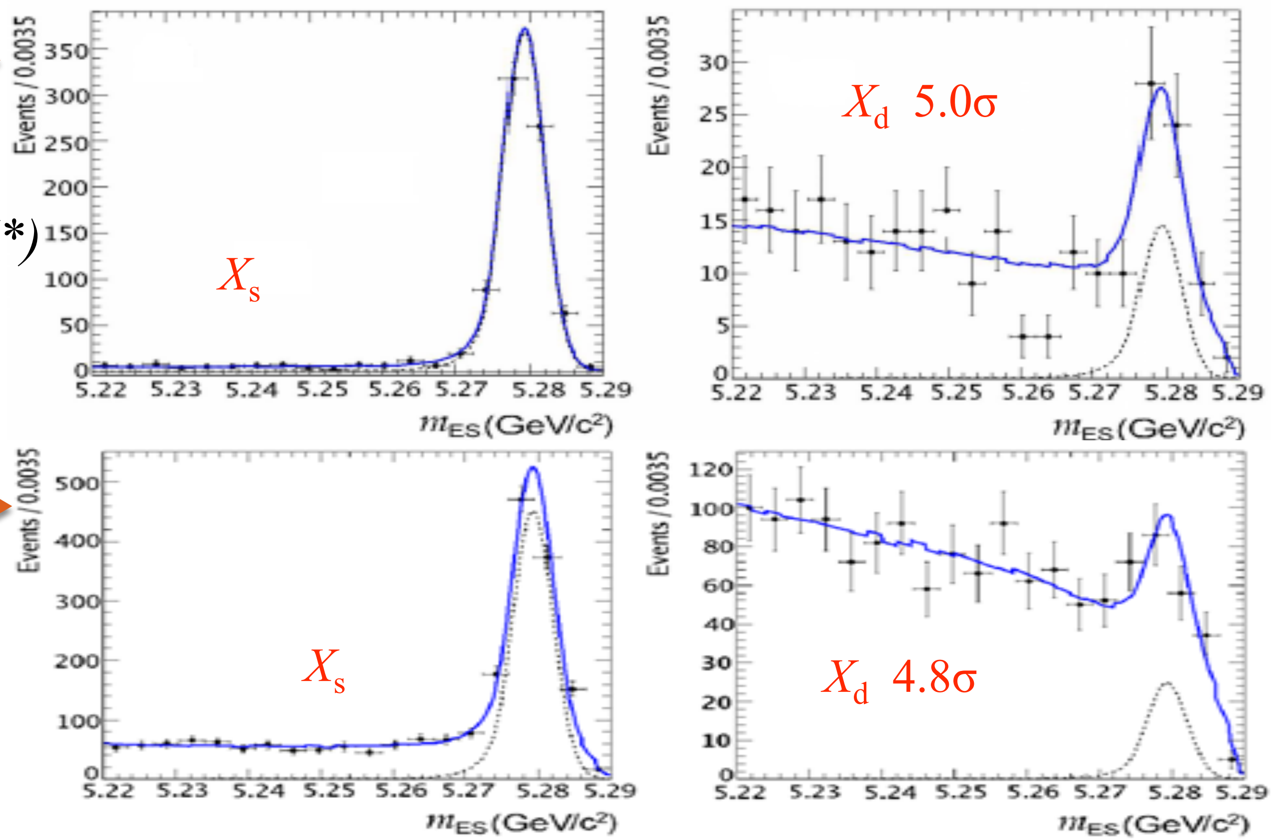
$$m_{ES} = \sqrt{E_{Beam}^2 - p_B^2}$$

$$\Delta E = E_B - E_{Beam}$$

$-0.15 < \Delta E < 0.1$GeV

Top:
Low mass bin
0.5 -1.0 GeV/c^2
Dominated by ρ/ω (K^*)
resonances

Bottom:
High mass bin
1.0 -2.0 GeV/c^2
Non-resonant



- **Large signal yield Xs, allow to study the fragmentation of the non-resonant decay, adjust MC.**
- **First significant observation of $b \to d\gamma$ in non-resonant modes.**

Systematic errors

- Systematic error on the measured partial branching fraction calculated from data/MC comparisons.

- To extrapolate to inclusive BF, correct the missing states

  - Low mass region: resonance dominated, simply correct unreconstructed $\rho/\omega(K^*)$

  - High mass region: based on MC fragmentation model, corrected for measured $b \to s\gamma$.

  - Vary fragmentation with physics-motivated bounds to obtain uncertainty =>Largest systematic errors.

Systematic Error Source	$M(X_s)$ 0.5-1.0	$M(X_s)$ 1.0-2.0	$M(X_d)$ 0.5-1.0	$M(X_d)$ 1.0-2.0
Error on partial $\mathcal{B}$	4.0%	9.0%	9.3%	14.2%
Missing ≥ 5 body		9.6%		18.2%
Other missing states		7.5%		15.3%
Spectrum Model		1.8%		1.6%
Error on inclusive $\mathcal{B}$	4.0%	15.2%	9.3%	27.7%

$B \to X_d \gamma$ Results

	Branching Fraction
$b \to s\gamma$ low mass	$3.83 \pm 0.16 \pm 0.15 \times 10^{-5}$
$b \to s\gamma$ high mass	$19.2 \pm 0.8 \pm 1.7 \pm 2.3 \times 10^{-5}$
$b \to s\gamma\ (m_{had} < 2.0\,\mathrm{GeV}/c^2)$	$23.0 \pm 0.8 \pm 1.9 \pm 2.3 \times 10^{-5}$
$b \to d\gamma$ low mass	$1.25 \pm 0.32 \pm 0.12 \times 10^{-6}$
$b \to d\gamma$ high mass	$7.90 \pm 1.98 \pm 1.12 \pm 1.88 \times 10^{-6}$
$b \to d\gamma\ (m_{had} < 2.0\,\mathrm{GeV}/c^2)$	$9.15 \pm 2.01 \pm 1.24 \pm 1.88 \times 10^{-6}$
$\frac{B\to(\rho,\omega)\gamma}{B\to K^*\gamma}$	$0.033 \pm 0.009 \pm 0.003$
$\frac{b\to d\gamma}{b\to s\gamma}\ (m_{had} < 2.0\,\mathrm{GeV}/c^2)$	$0.040 \pm 0.009 \pm 0.005 \pm 0.010$

World Average (HFAG):

BF(B->$K^*\gamma$)=$(4.21\pm0.18)\times10^{-5}$

BF(B->$(\rho,\omega)\gamma$)=$(1.30\pm0.19)\times10^{-5}$

Combined: the first measurement <2.0 GeV

Unchanged for the full spectra

$$|V_{td}/V_{ts}|=0.199 \pm 0.022_{stat} \pm 0.012_{syst} \pm 0.027_{extrap} \pm 0.002_{th}$$

B-Mixing average : $|V_{td}/V_{ts}|=0.2059 \pm 0.001_{stat} \pm 0.008_{th}$

- Consistent with previously measured results.
- Smaller theoretical uncertainty!

Summary

- Babar: New CP asymmetry ($B \to X_{s+d}\gamma$) measurement: consistence with SM, the most precise to date.
- Belle provides the best experimental measurements on the branching fraction& spectral moments, first experiment down to 1.7GeV, the smallest experimental error >2.0GeV.
- Babar: Sum of exclusive $b \to d\gamma$ measurement. First significant measurement of non-resonant $b \to d\gamma$. |Vtd/Vts|, comparable with previous measurements, smallest theoretical uncertainty
- No significant evidence for NP from B factories, BaBar and Belle, consistent with SM predictions within experimental error.

  =>CKM is the dominant (only?) source of CP violation in B decay.
- LHC-b and Super B factories! Hope for the future!

Backup

- Extract $X=|V_{td}/V_{ts}|$ from ratio of inclusive BFs
  - Use NLO calculation of Ali, *et al.* [Phys. Lett. B429 87]

$$R = \lambda^2[1+\lambda^2(1-2\bar{\rho})]\left[(1-\bar{\rho})^2+\bar{\eta}^2+\frac{D_u}{D_t}(\bar{\rho}^2+\bar{\eta}^2)+\frac{D_r}{D_t}(\bar{\rho}(1-\bar{\rho})-\bar{\eta}^2)\right]$$

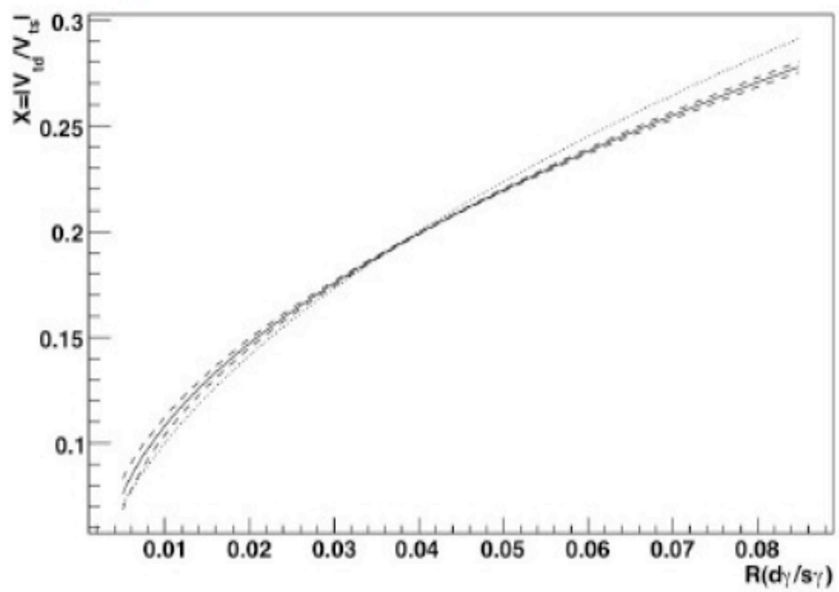
  - Rewrite in terms of X and UT angle β

$$R = \kappa_1 X^2 + \kappa_2 X + \kappa_3,$$

$$\kappa_1 = 1+\frac{D_u}{D_t}\left(1-2\lambda^2\cos^2\beta\right)-\frac{D_r}{D_t}\left(\lambda^2\cos^2\beta+1\right),$$

$$\kappa_2 = \lambda\cos\beta\left[\frac{D_u}{D_t}\left(3\lambda^2-2\right)+\frac{D_r}{D_t}\left(1+\frac{\lambda^2}{2}\right)\right],$$

$$\kappa_3 = \lambda^2\frac{D_u}{D_t}\left(1-\lambda^2\right).$$



  - Uncertainties from PDG and numerical calculations of D factors