Radiative B Decays

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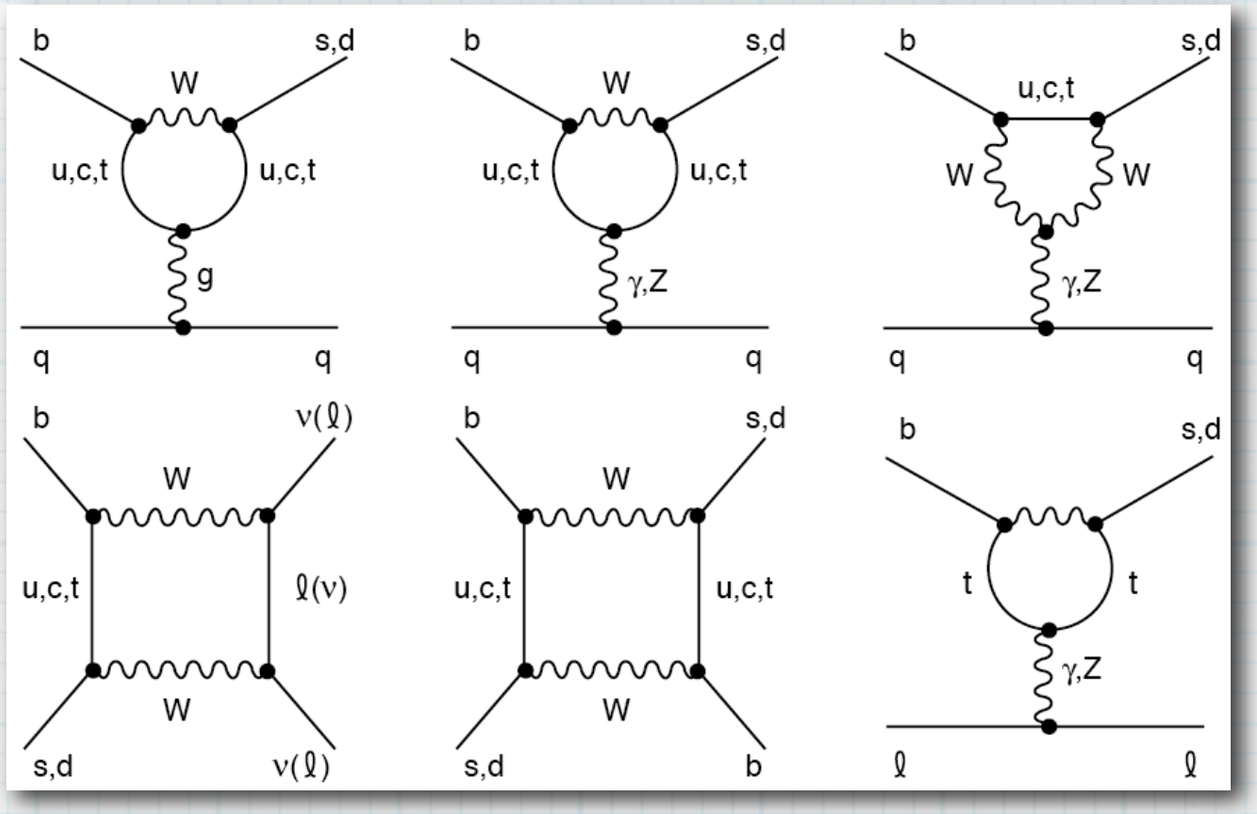
Outline

- Basic Theory
- Radiative B decays to leptons
- Radiative B decays to photons
- Summary

Neutral Currents in SM

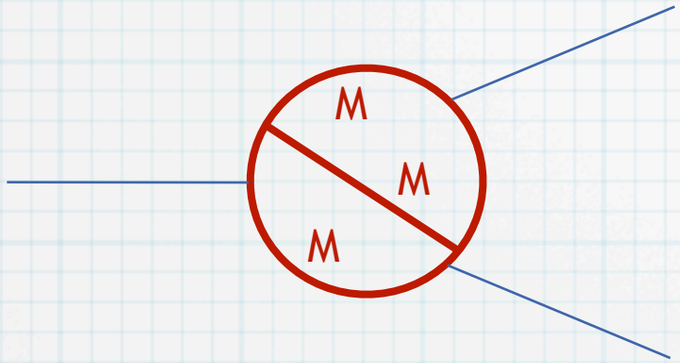
$$\mathcal{L}_{\rm nc} = \frac{g_2}{\cos\theta_W} Z^\mu \sum_f \left[\bar{f}_L U_f^\dagger \left(T_f^3 \frac{1-\gamma_5}{2} - Q_f \sin^2\theta_W \right) U_f f_L \right.$$
$$\left. + \bar{f}_R W_f^\dagger \left(-Q_f \sin^2\theta_W \right) W_f f_R \right]$$

* Perfect cancellation of contributions
* No generation-changing current interactions at tree level
* Multitude of loop processes mimic neutral currents
* How can we calculate their rates?

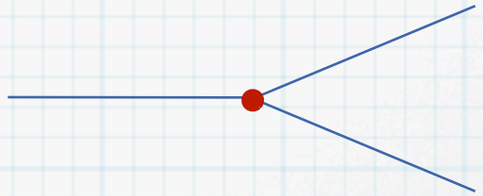


Effective Field Theory

- At low energies, the exchange of heavy, virtual particles (M»E) leads to local effective interactions

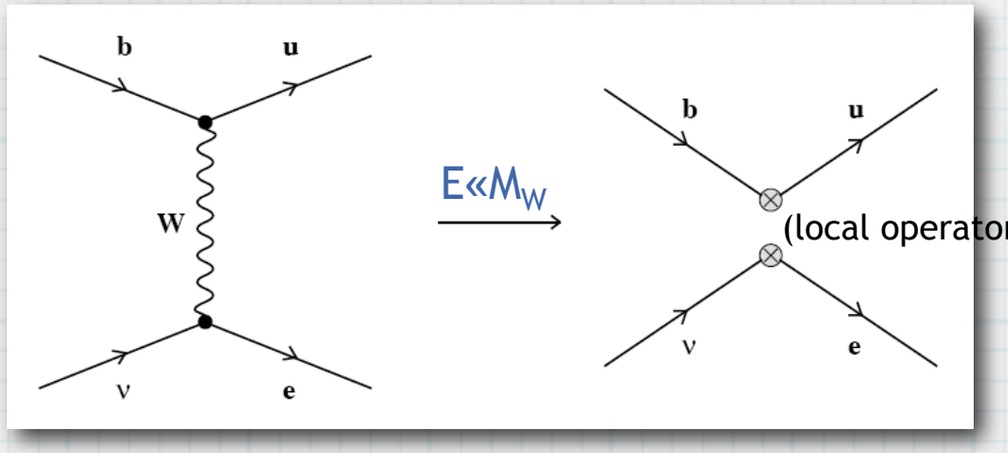


exchange of heavy, virtual particles between light SM particles



induced, effective local interactions at low energies

- An Effective field theory offers systematic description of effects of channels with large virtualities through an expansion in local operators



$G_F/\sqrt{2} = g_2^2/8M_W^2$

Effective Field Theory II

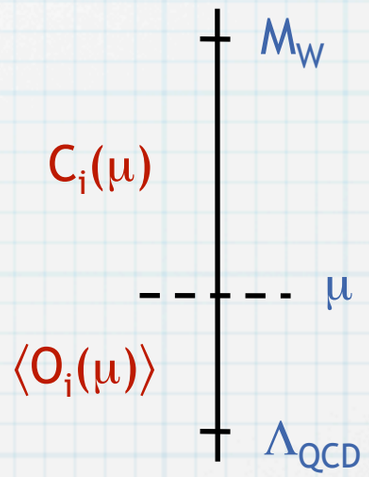
$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} \left[\sum_{q=u,c} V_{qb} V_{qs}^* \left(C_1 \, Q_1^{(q)} + C_2 \, Q_2^{(q)} \right) - V_{tb} V_{ts}^* \sum_{i=3,\ldots,10,7\gamma,8g} C_i \, Q_i \right]$$

W-boson exchange

penguin and box graphs

- **Separation of high and low energy effects**

$$\int_{-p^2}^{M_W^2} \frac{dk^2}{k^2} = \int_{\mu^2}^{M_W^2} \frac{dk^2}{k^2} + \int_{-p^2}^{\mu^2} \frac{dk^2}{k^2}$$



- **Sensitivity to known and unknown heavy particles can be explored using perturbative methods**

$$C_i(\mu) = C_i^{SM}(M_W, m_t, \mu) + C_i^{NP}(M_{NP}, g_{NP}, \mu)$$

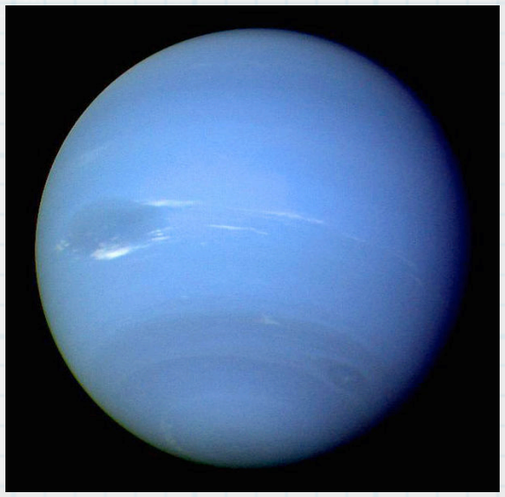
Strategy

- Use Effective Field Theory to make accurate predictions of observables related to loop processes

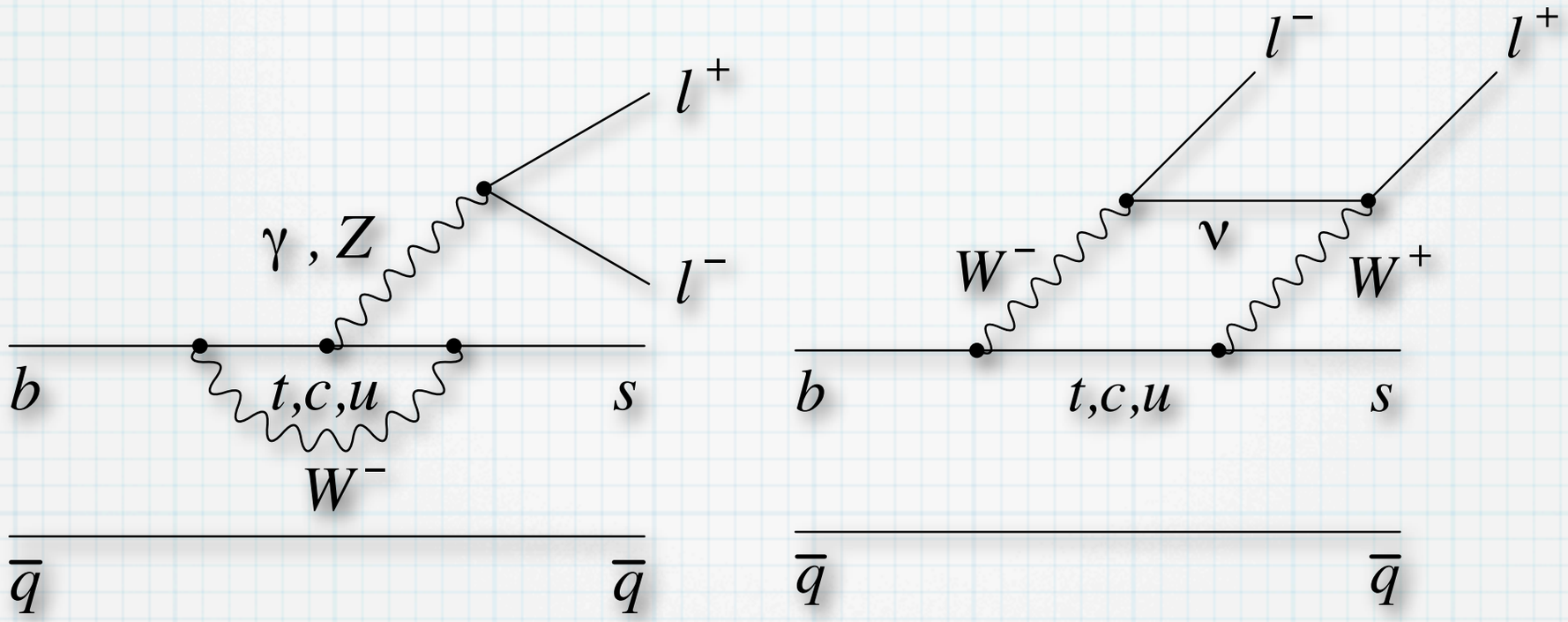
- Perform accurate measurements of these observables

- Do the prediction and measurement agree?

- Remember unexpected changes that were observed in the orbit of Uranus led to the discovery of the Neptune



Radiative Decay to Lepton-Pairs



- Decay width and q^2 distribution
- Longitudinal polarisation
- Isospin and Forward/Backward Asymmetry
- Lepton universality

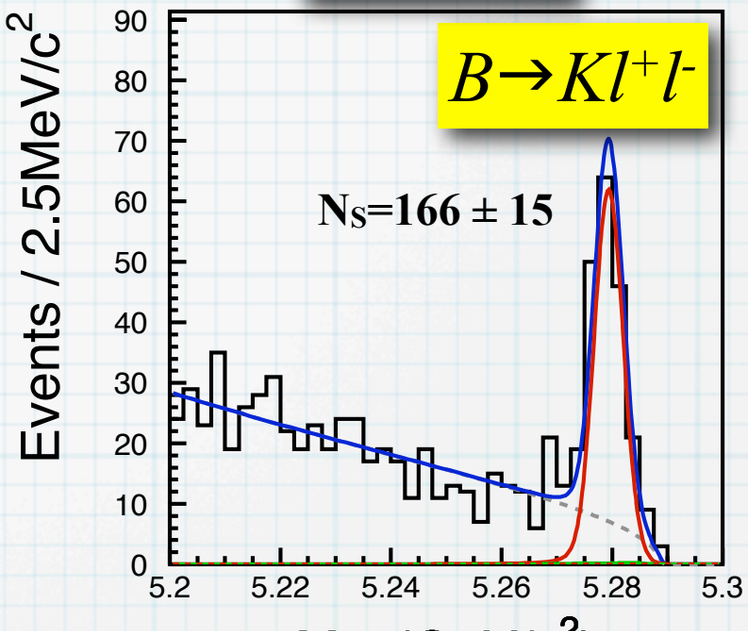
$$A_{FB}(q^2) = -C_{10}^{eff}\xi(q^2)\left[Re(C_9^{eff})F_1 + \frac{1}{q^2}C_7^{eff}F_2\right]$$

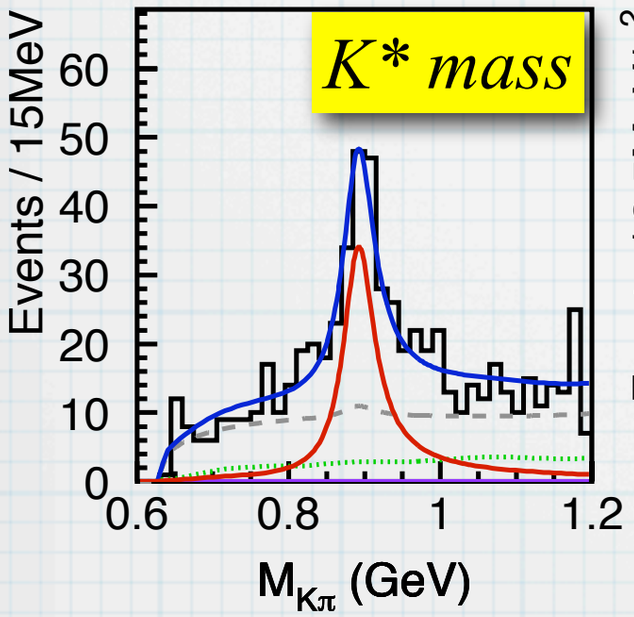
B -> K(*)ll Analysis

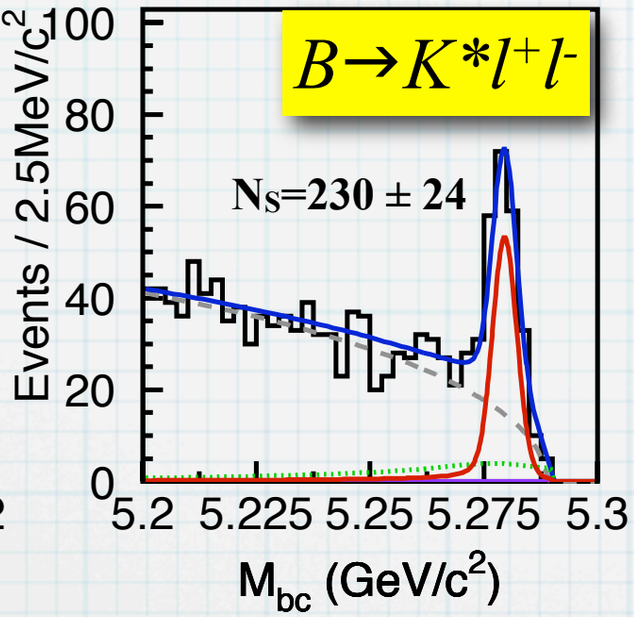
- Full Reconstruction of B-meson momentum from decay products
- Main background: continuum and semileptonic B decays
- Veto e/μ -pairs from J/ψ (ψ') from B's
- 2D Fit M(bc)-M(Kπ) B->K*ll, 1D Fit M(bc) B->Kll

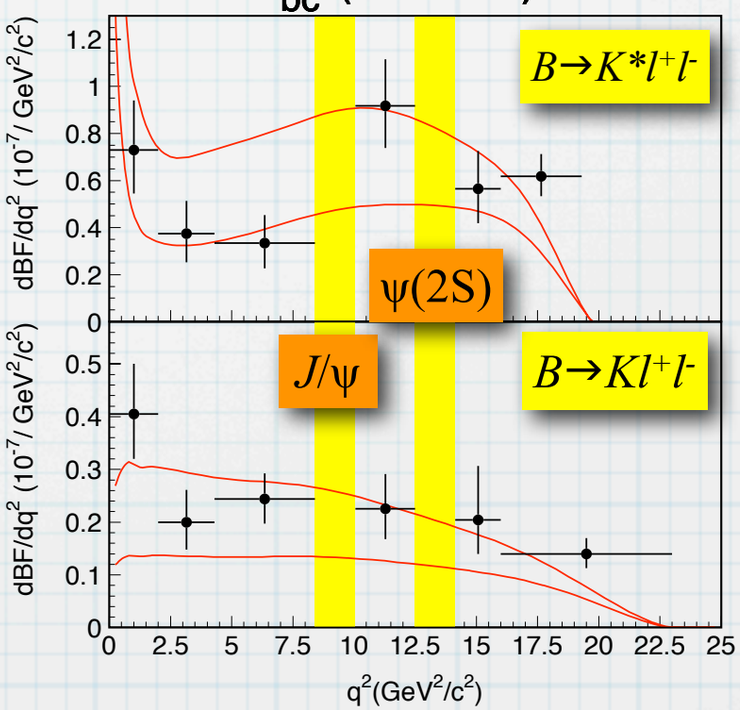
arXiv:0904.0770 Just accepted by PRL

657M B-pairs









$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

Standard Model Prediction
R(K*) = 0.75 & R(K) = 1

R(K*) = 0.83 +/- 0.17 +/- 0.05
R(K) = 1.03 +/- 0.19 +/- 0.06

R(K*) = 1.37 +0.53-0.04 +/- 0.09 BABAR
R(K) = 0.96 +0.44-0.34 +/- 0.05 BABAR

PRD79, 031102(R) 2008

Theory
Ali,A. et al PRD61, 074024 (2000)
Ali,A. et al PRD66, 034002 (2002)

B->K(*)ll Branching Fraction

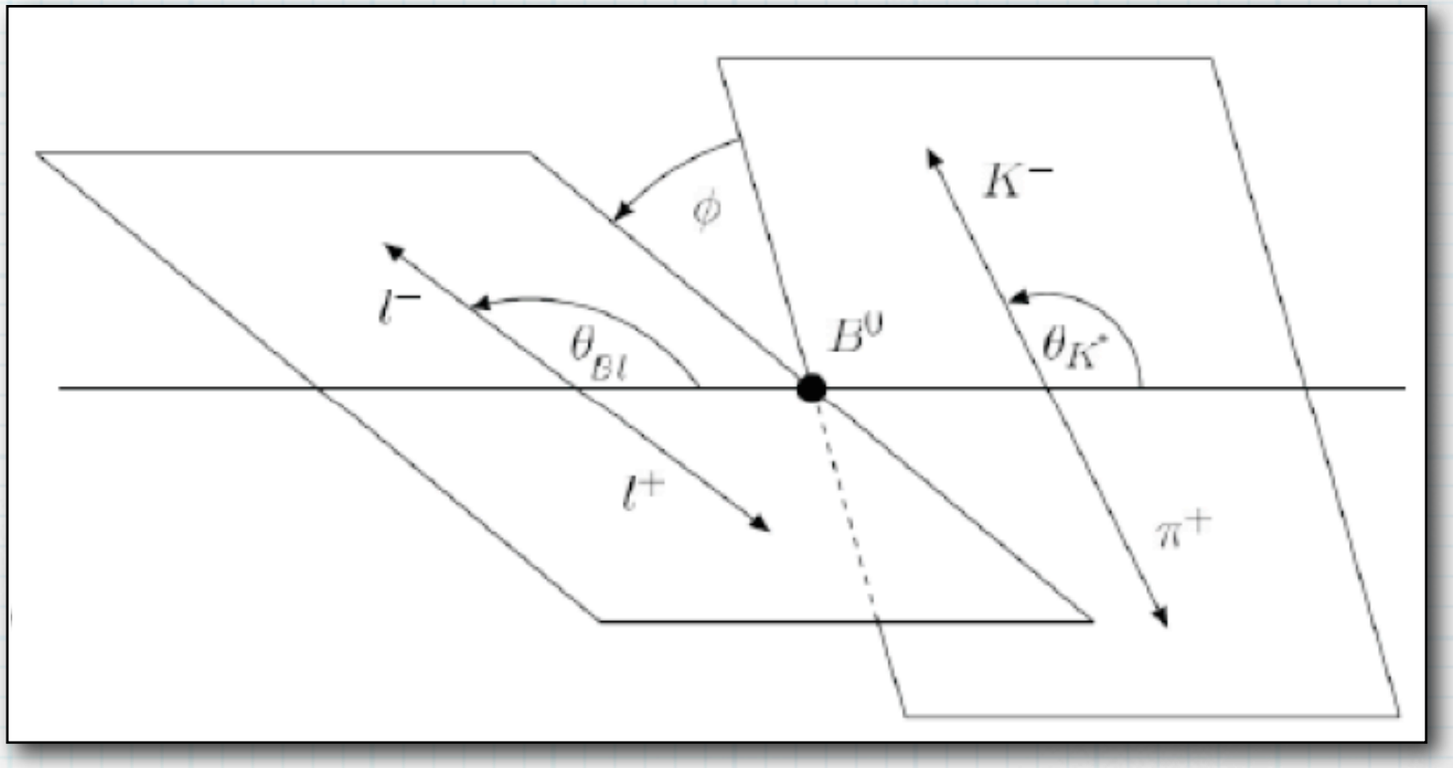
	BF($B \to K^* ll$) 10^{-7}	BF($B \to Kll$) 10^{-7}	
Belle 657M B-pairs	$10.7 \pm 1.1 \pm 0.9$	$4.8 \pm 0.5 \pm 0.3$	Accepted PRL arXiv:0904.0770 (2009)
BABAR 384M B-pairs	$7.8 \pm 1.9 \pm 1.1$	$3.4 \pm 0.7 \pm 0.2$	PRD79 031102(R) (2008)
CDF 924/pb	$8.1 \pm 3.0 \pm 1.0$	$5.9 \pm 1.5 \pm 0.4$	PRD79 011104 (2008)
Prediction	11.9 ± 3.9 $q^2>0.1$ GeV^2	3.5 ± 1.2	PRD66 034002 (2002)
HFAG	10.1 ± 1.1	4.3 ± 0.4	

B->K(*)ll Asymmetries

F_L : K* longitudinal polarization fraction

Angle θ_K between K and the B directions in the K* rest frame

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



A_{FB} : Forward Backward Asymmetry
Angle θ_l between l+ and the B directions in the l+l- rest frame

$$\frac{3}{4}F_L(1-\cos^2\theta_\ell)+\frac{3}{8}(1-F_L)(1+\cos^2\theta_\ell)+\mathcal{A}_{FB}\cos\theta_\ell$$

Isospin Asymmetry

$$A_I \equiv \frac{(\tau_{B^+}/\tau_{B^0})\times\mathcal{B}(K^{(*)0}\ell^+\ell^-)-\mathcal{B}(K^{(*)\pm}\ell^+\ell^-)}{(\tau_{B^+}/\tau_{B^0})\times\mathcal{B}(K^{(*)0}\ell^+\ell^-)+\mathcal{B}(K^{(*)\pm}\ell^+\ell^-)}$$

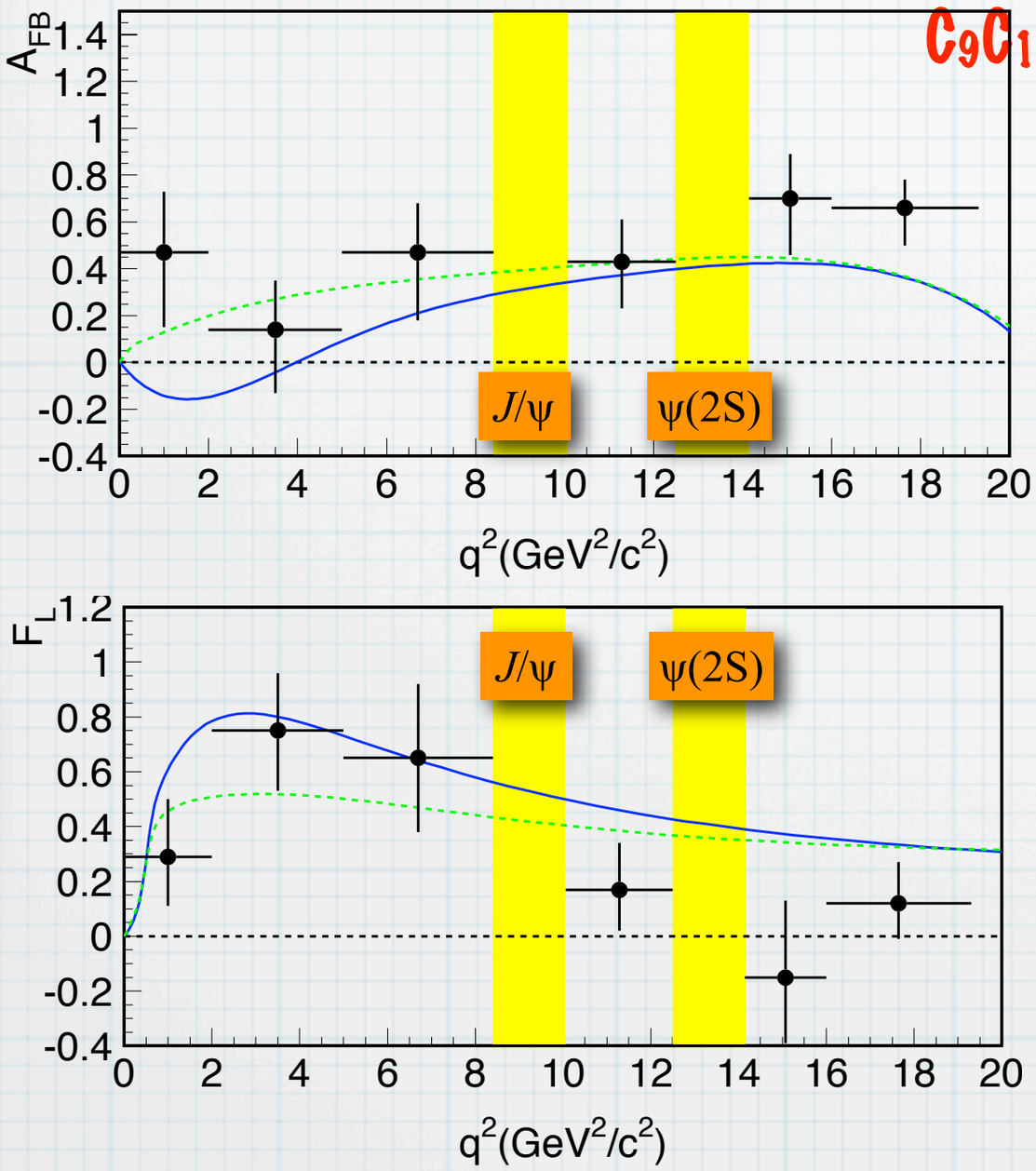
Polarisation /FB Asymmetry

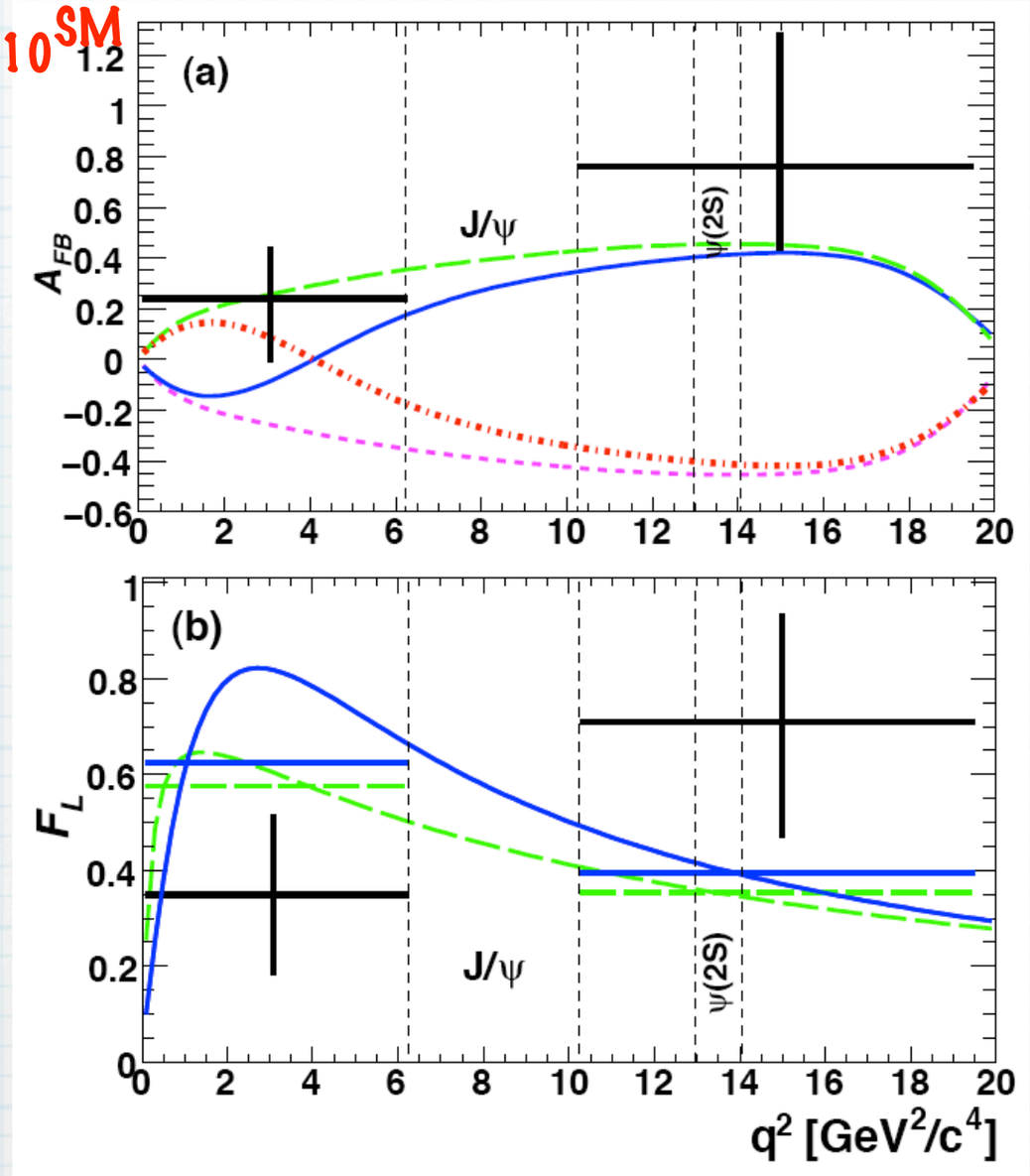
$$\frac{3}{4}F_L(1-\cos^2\theta_\ell)+\frac{3}{8}(1-F_L)(1+\cos^2\theta_\ell)+\mathcal{A}_{FB}\cos\theta_\ell$$

SM

$C_7=-C_7^{SM}$

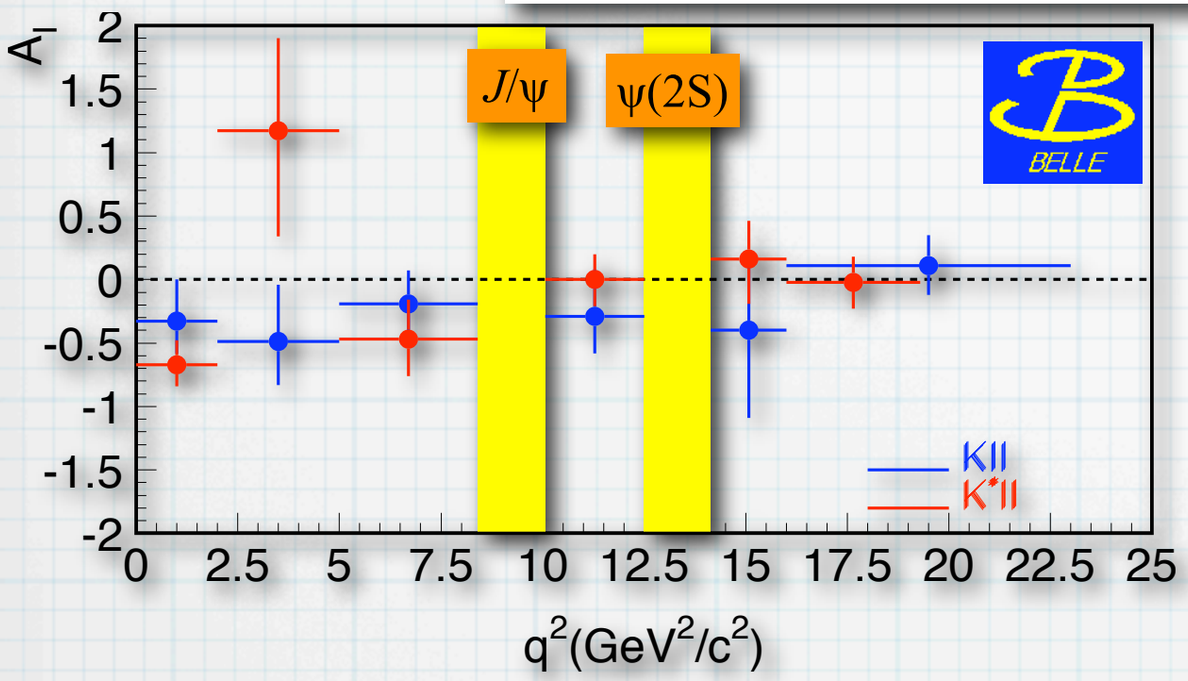
$C_9C_{10}=-C_9C_{10}^{SM}$

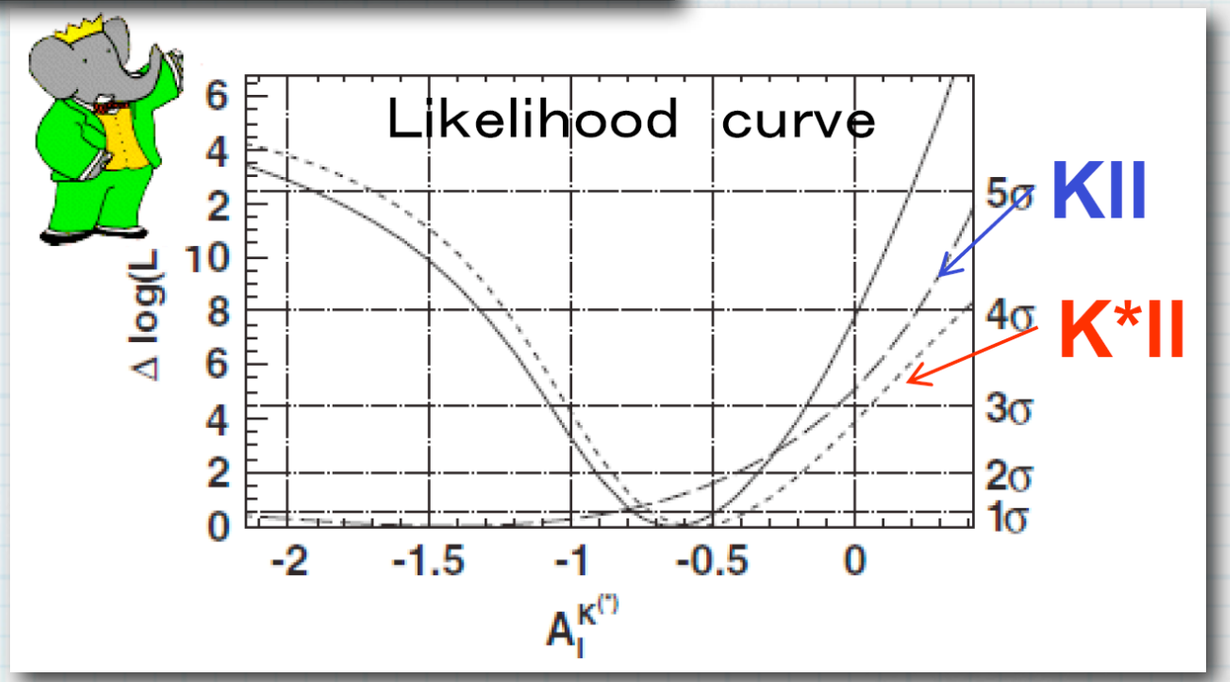




Isospin Asymmetry

$$A_I \equiv \frac{(\tau_{B^+}/\tau_{B^0}) \times \mathcal{B}(K^{(*)0}\ell^+\ell^-) - \mathcal{B}(K^{(*)\pm}\ell^+\ell^-)}{(\tau_{B^+}/\tau_{B^0}) \times \mathcal{B}(K^{(*)0}\ell^+\ell^-) + \mathcal{B}(K^{(*)\pm}\ell^+\ell^-)}$$





$q^2 < 8.68$ GeV$^2/c^2$

$A_I(B\to K^*l^+l^-) = -0.29 \pm 0.16 \pm 0.03$ (1.4σ)

$A_I(B\to Kl^+l^-) = -0.31 \pm 0.17 \pm 0.05$ (1.7σ)

$A_I(B\to K^{(*)}l^+l^-) = -0.30 \pm 0.12 \pm 0.04$ (2.2σ)

$q^2 = 0.10\text{-}7.02$ GeV$^2/c^2$

$A_I(B\to K^*l^+l^-) = -0.56 \pm 0.17 \pm 0.03$ (2.7σ)

$A_I(B\to Kl^+l^-) = -1.43\ {}^{+0.56}_{-0.85} \pm 0.05$ (3.2σ)

$A_I(B\to K^{(*)}l^+l^-) = -0.64 \pm 0.15 \pm 0.03$ (3.9σ)

* A_I expected to be zero with SM, as $q^2 \to 0$ $A_I = +10\%$

B->Xs ll

$$\frac{d\Gamma(b \to s\ell^+\ell^-)}{dq^2} = \left(\frac{\alpha_{\rm em}}{4\pi}\right)^2 \frac{G_F^2 m_b^5 \left|V_{ts}^* V_{tb}\right|^2}{48\pi^3}(1-q^2)^2$$
$$\times\left[(1+2q^2)\left(|C_9^{\rm eff}|^2+|C_{10}^{\rm eff}|^2\right)+4\left(1+\frac{2}{q^2}\right)|C_7^{\rm eff}|^2+12{\rm Re}\left(C_7^{\rm eff}C_9^{\rm eff}\right)\right]$$

* Sensitive to Wilson Coefficients
* less theoretical uncertainty than K(*)ll
* Technique is sum up exclusive states

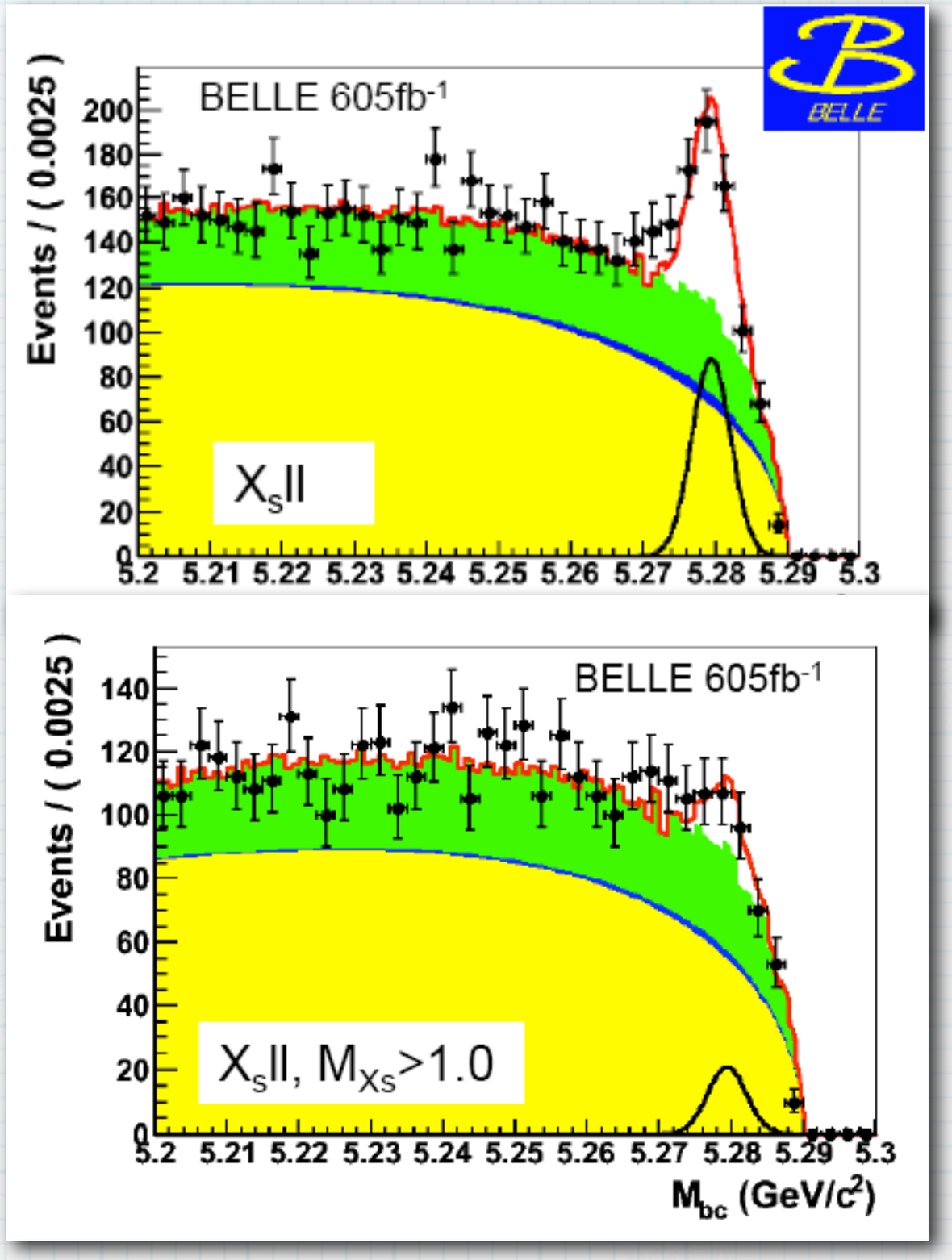
B->Xs ll data

- 657 M B-pairs
- Sum of exclusive states K/Ks + <=4π
- Improved Background Rejection

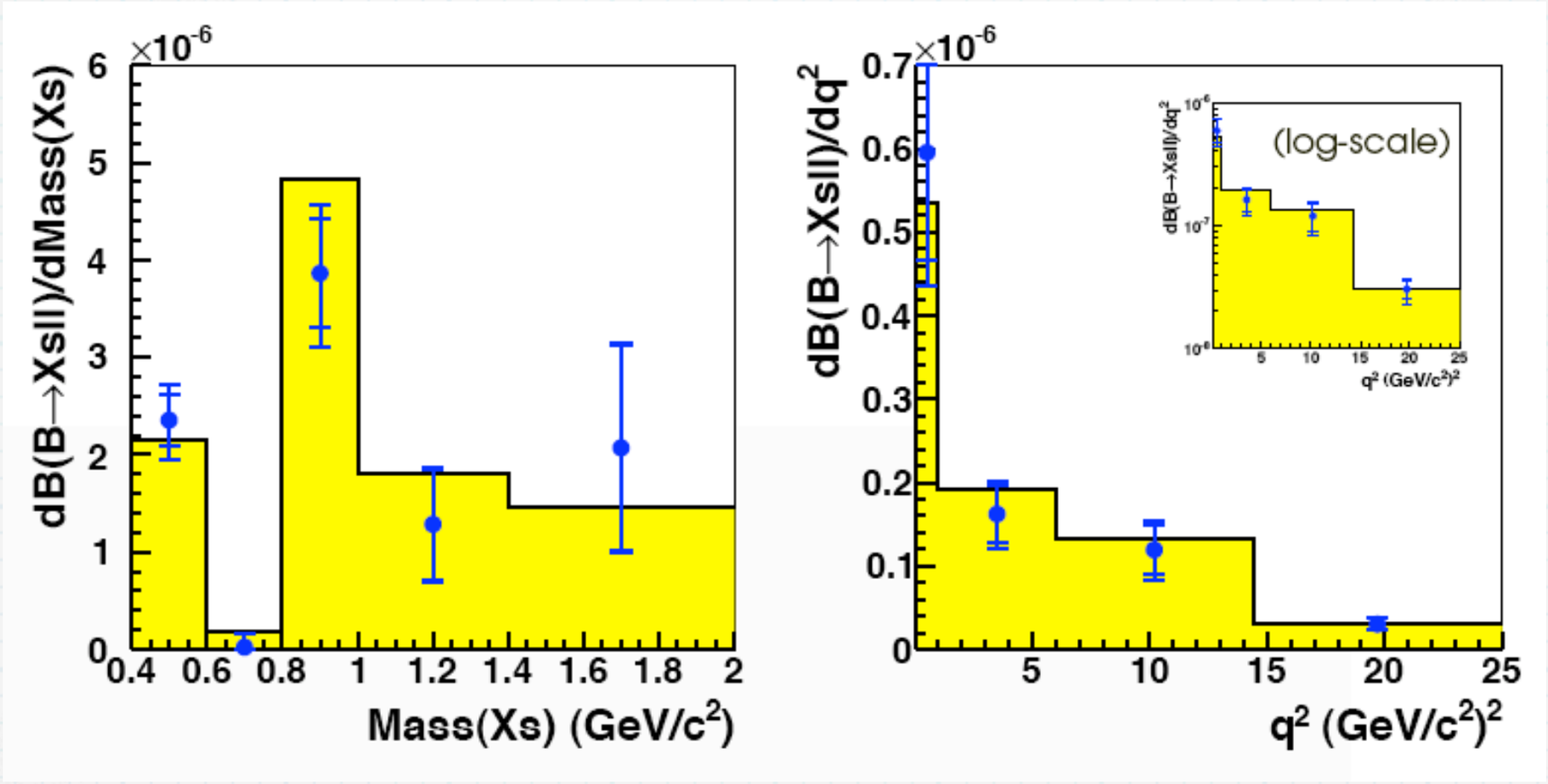
Mode	N_{sig}	Signif.
Xs e^+ e^-	121.6±19.3±2.0	7.0
Xs μ^+ μ^-	118.5±17.3±1.5	7.9
Xs l^+ l^-	238.3±26.4±2.3	10.1

For M_{Xs}>1.0GeV/c^2

Mode	N_{sig}	Signif.
Xs l^+ l^-	56.2±19.6±0.5	3.0



Distributions q^2 & M_X



$BF(B \to X_s l^+ l^-) = (3.33 \pm 0.80 + 0.19 - 0.24) \times 10^{-6}$

HFAG average

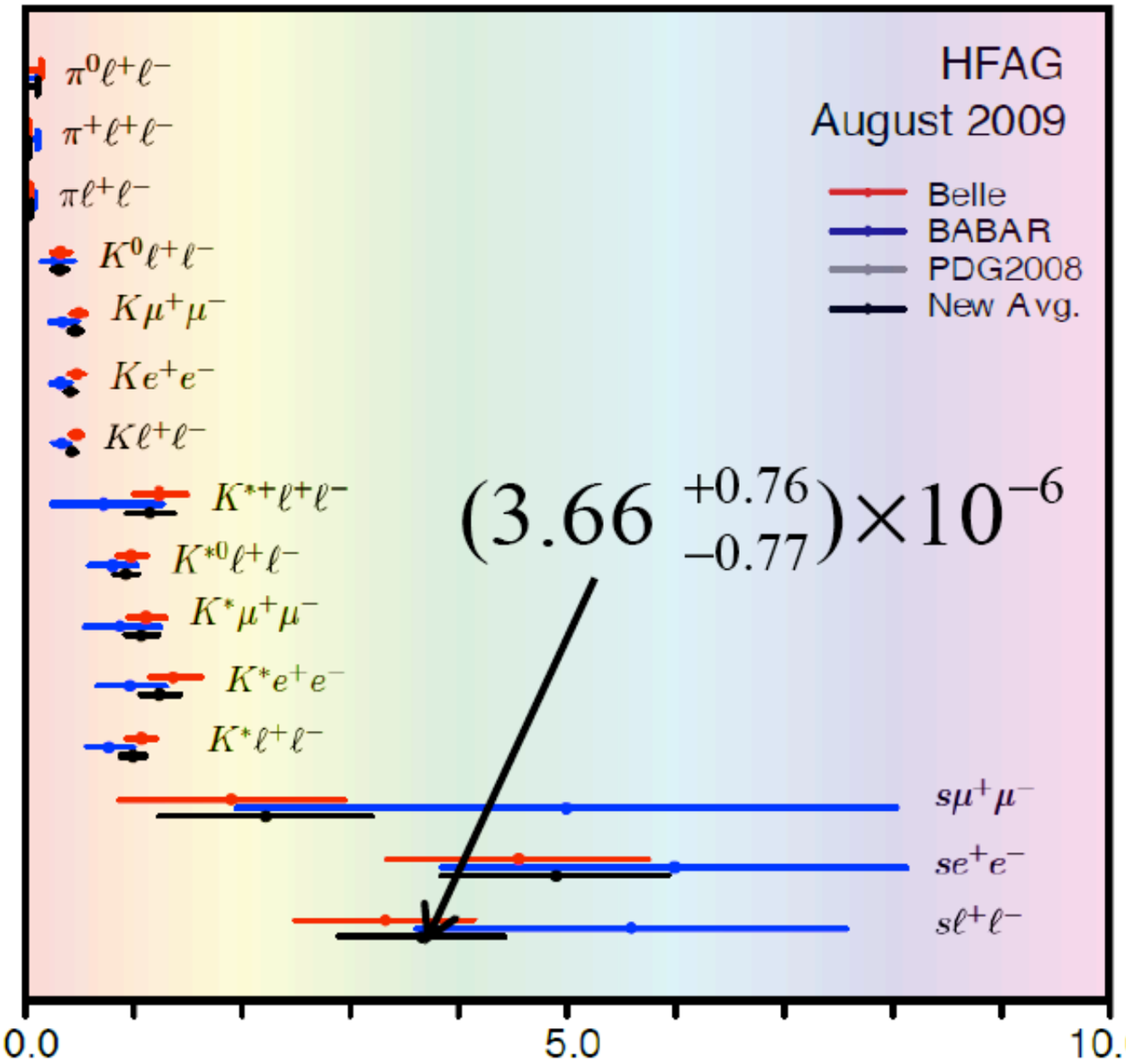
$= (3.66 \pm 0.77) \times 10^{-6}$

SM expectation Ali et al. CERN-TH/2002-284 (2002)

$= (4.2 \pm 0.7) \times 10^{-6}$

B->Xs ll

$$\mathcal{B}(B \to X_s \ell^+ \ell^-)$$



New Exclusive Channels (Belle)

$B \to K\varphi\gamma$

772M B-pairs

Preliminary

$BF(B^+ \to K^+\varphi\gamma) = (2.34 \pm 0.29 \pm 0.23) \times 10^{-6}$

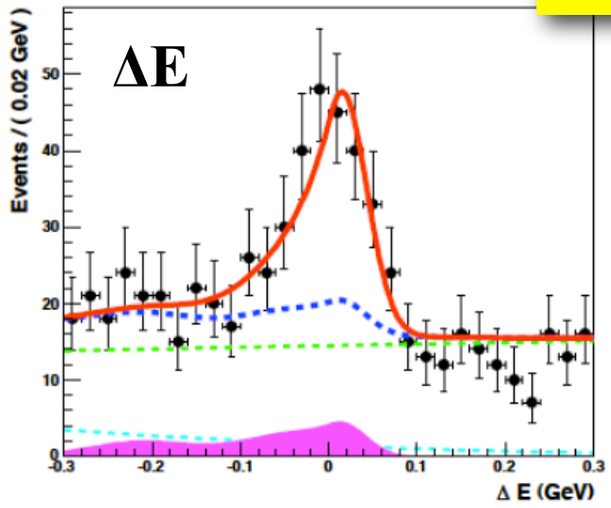
$N_S = 136 \pm 17$ (10.5σ statistical)

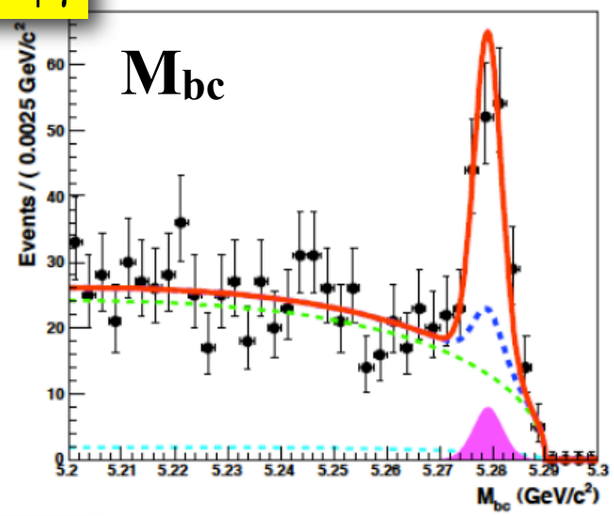
$BF(B^0 \to K^0\varphi\gamma) = (2.66 \pm 0.60 \pm 0.32) \times 10^{-6}$

$N_S = 35 \pm 8$ (5.8σ statistical)

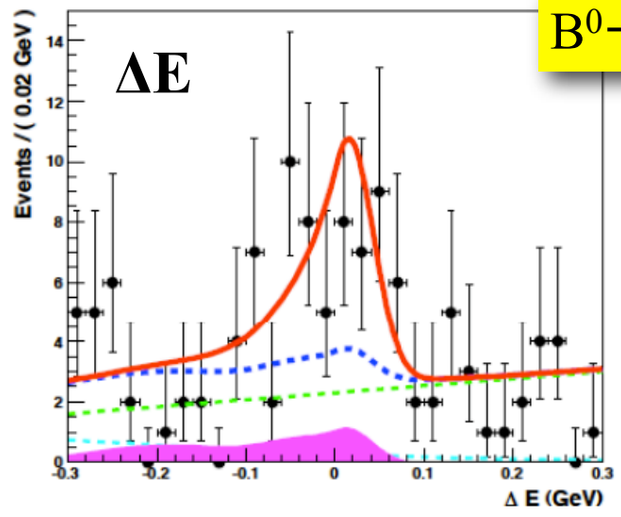
Suitable for measurement of time-dependent CP violation

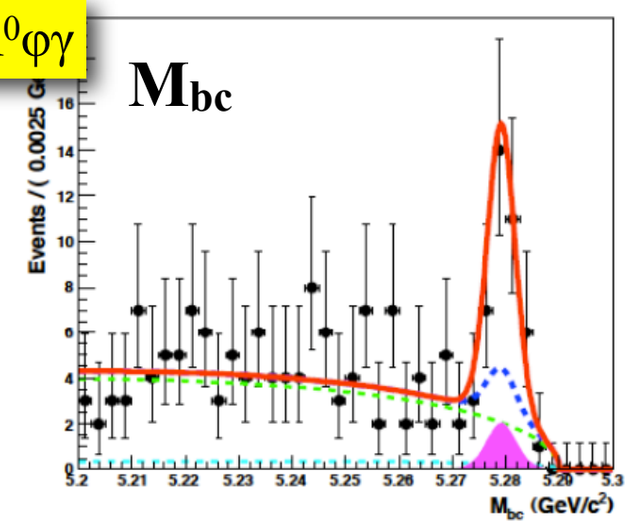
$B^+ \to K^+\varphi\gamma$





$B^0 \to K^0\varphi\gamma$



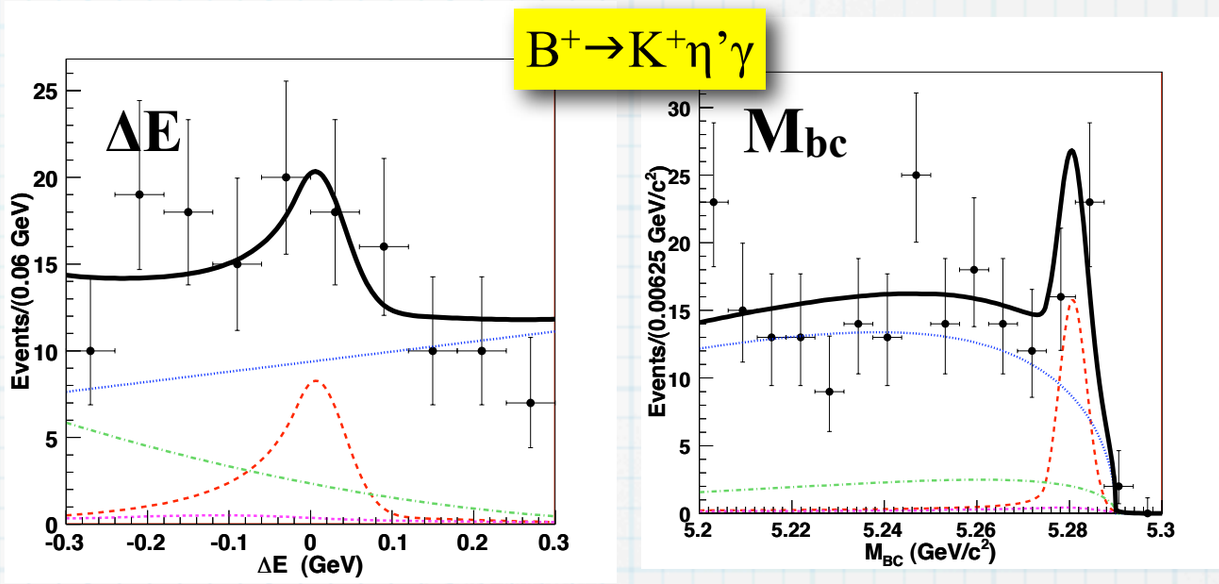


New Exclusive Channels II (Belle)

$B \to K\eta'\gamma$

657M B-pairs

$B^+ \to K^+\eta'\gamma$



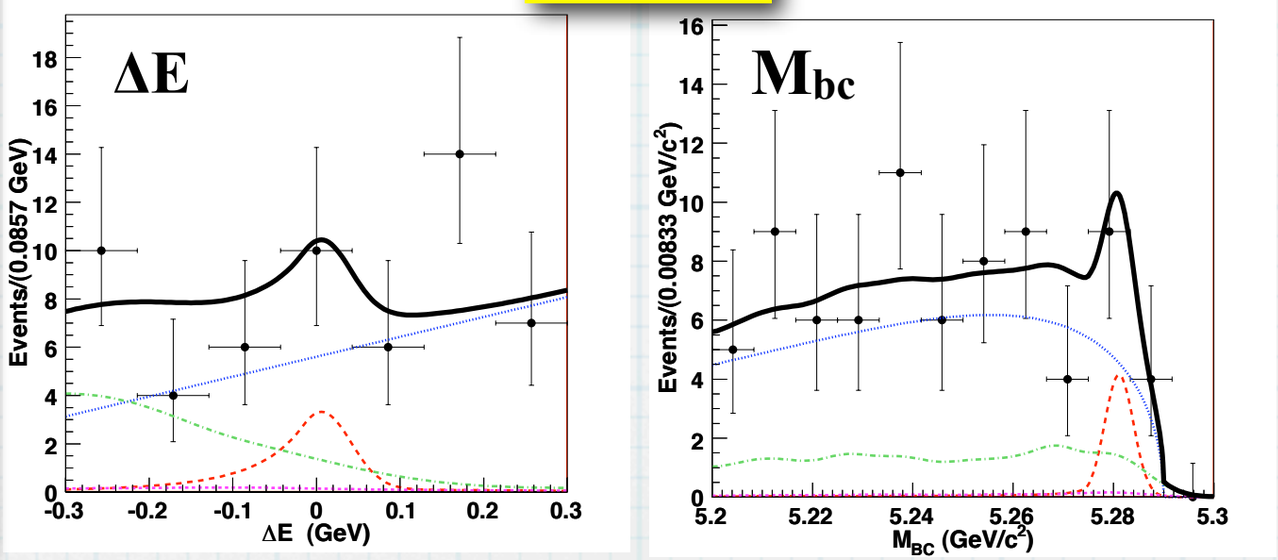
$BF(B^+ \to K^+\eta'\gamma) = (3.6 \pm 1.2 \pm 0.4) \times 10^{-6}$

$N_S = 33 \pm 12$ (3.3σ statistical)

$BF(B^0 \to K^0\eta'\gamma) < 6.4 \times 10^{-6}$

90% CL

$B^0 \to K^0\eta'\gamma$



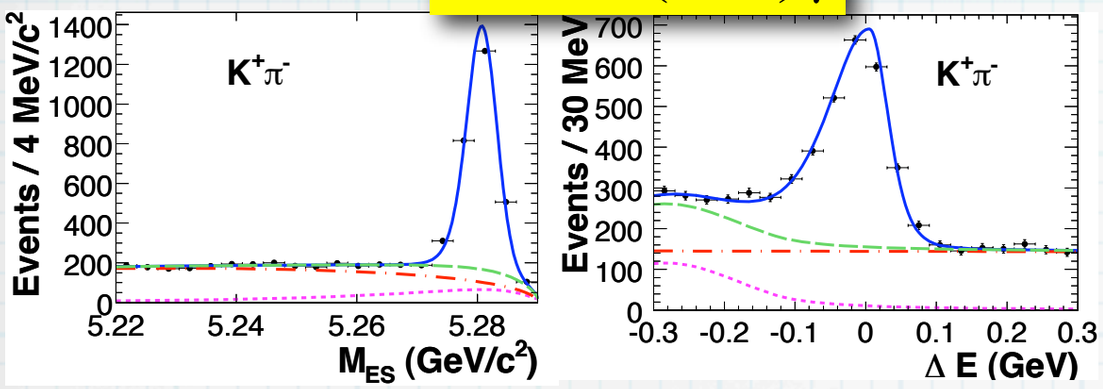
arXiv:0810.0804 Submitted to PRD (RC)

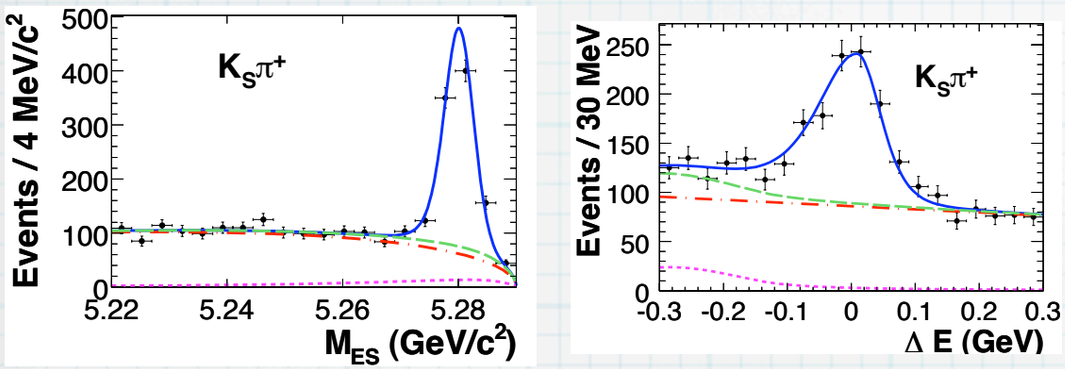
Improved Exclusive Channel (BABAR)

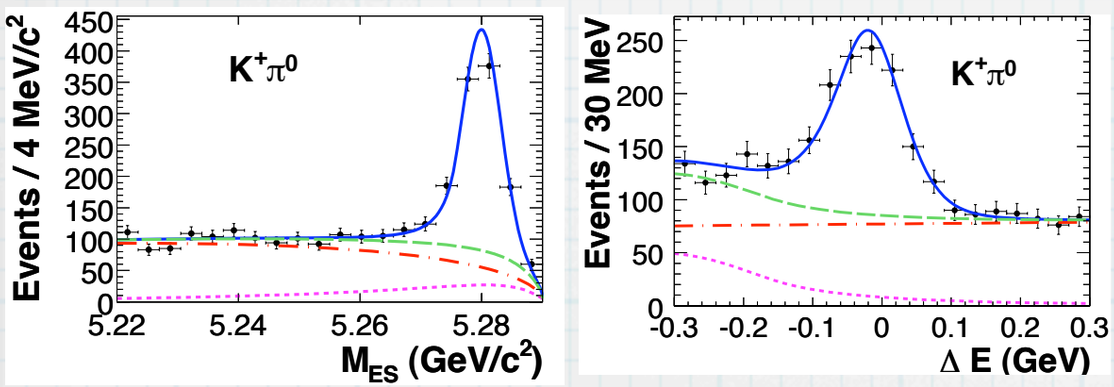
$B \to K^*(892)\gamma$

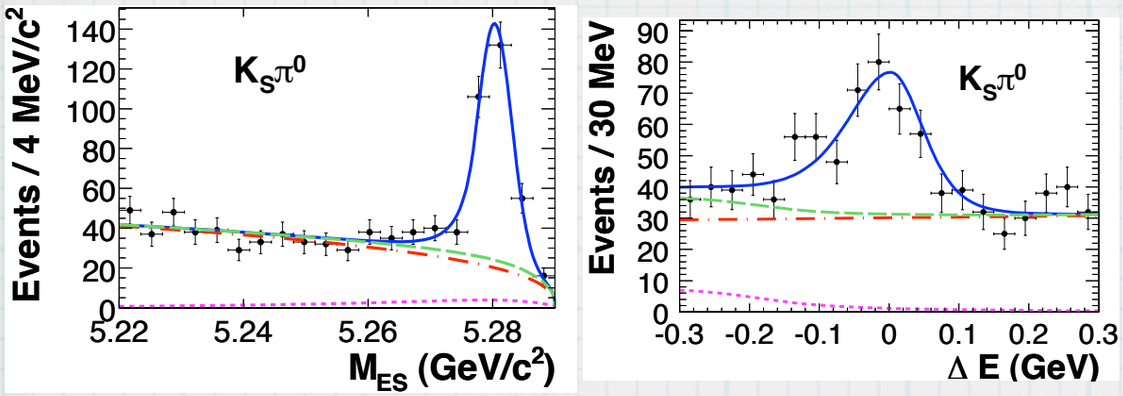
383M B-pairs

arXiv.0906.2177, submitted to PRL









Branching Fraction

$BF(B^0 \to K^{*0}\gamma) = (4.47 \pm 0.10 \pm 0.16) \times 10^{-5}$

$BF(B^+ \to K^{*+}\gamma) = (4.22 \pm 0.14 \pm 0.16) \times 10^{-5}$

ISOSPIN ASYMMETRY

$\Delta_{0-}(B \to K^*\gamma) = 0.066 \pm 0.021 \pm 0.022$

$-0.017 < \Delta_{0-}(B \to K^*\gamma) < 0.116 \quad 90\%CL$

CP ASYMMETRY

$A_{CP}(B \to K^*\gamma) = -0.003 \pm 0.017 \pm 0.007$

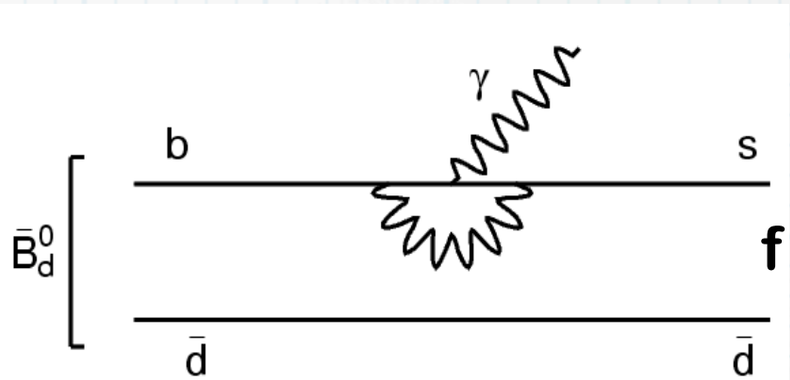
$-0.033 < A_{CP}(B \to K^*\gamma) < 0.028 \quad 90\%CL$

Search for Right-Handed currents

- Standard Model (SM) : Left handed γ in $b \to s\gamma$,

Right handed for anti-b quark decay

$$\frac{\Gamma[\bar{B}^0(t) \to f\gamma] - \Gamma[B^0(t) \to f\gamma]}{\Gamma[\bar{B}^0(t) \to f\gamma] + \Gamma[B^0(t) \to f\gamma]} = S_{f\gamma} \sin(\Delta m\, t) - C_{f\gamma} \cos(\Delta m\, t)$$



- f = K* decay to CP eigenstate (SM : |S| = 0.04)
- f can include multibody states composed of pseudoscalars

Atwood, Gronau & Soni. Phys Rev Lett. 79, 185 (1997)
Atwood, Gershon, Hazumi & Soni.
Phys Rev D71. 076003
Grinstein, Grossman, Ligeti and Prijol.
Phys Rev D71 011504(R)
Grinstein & Pirjol. Phys Rev D73. 014013

New Physics models : somewhat ambidextrous γ

may enhance the CP asymmetry "S"

NEW PHYSICS if |S| is larger than expected!

TCPV in B -> K η γ

B→Kηγ

BABAR

465 M B-pairs

$BF(B^0 \to K_s \eta\gamma) = (7.1 \pm 2.1 \pm 0.4) \times 10^{-6}$

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

$A_{CP}(B \to K_s \eta\gamma) = -0.003 \pm 0.017 \pm 0.007$

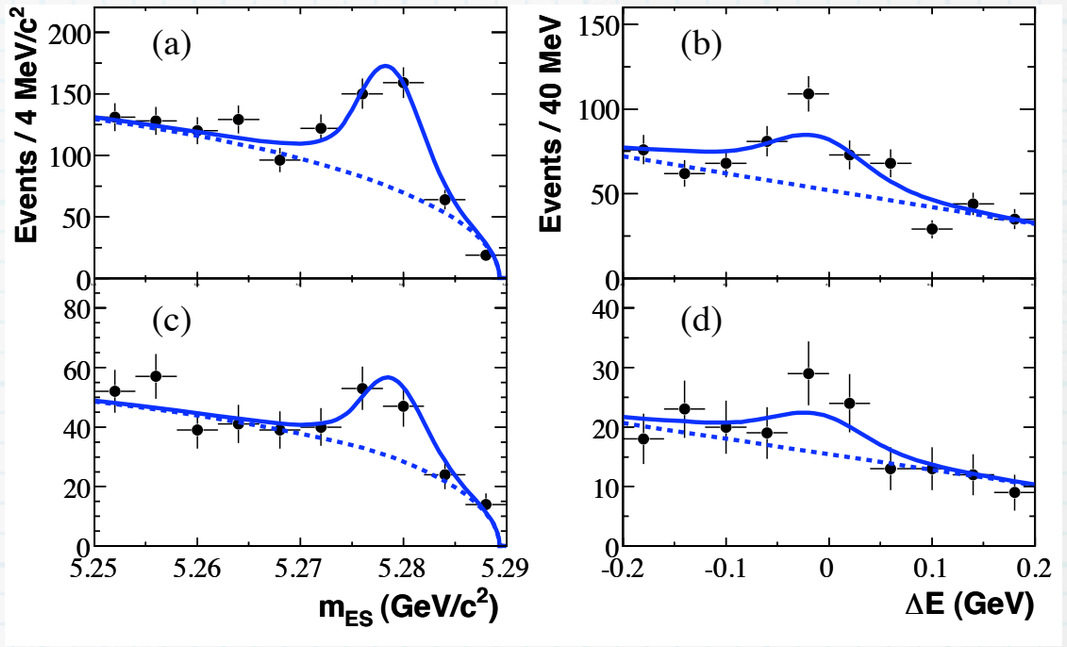
$S = -0.18 \pm 0.49 \pm 0.12$

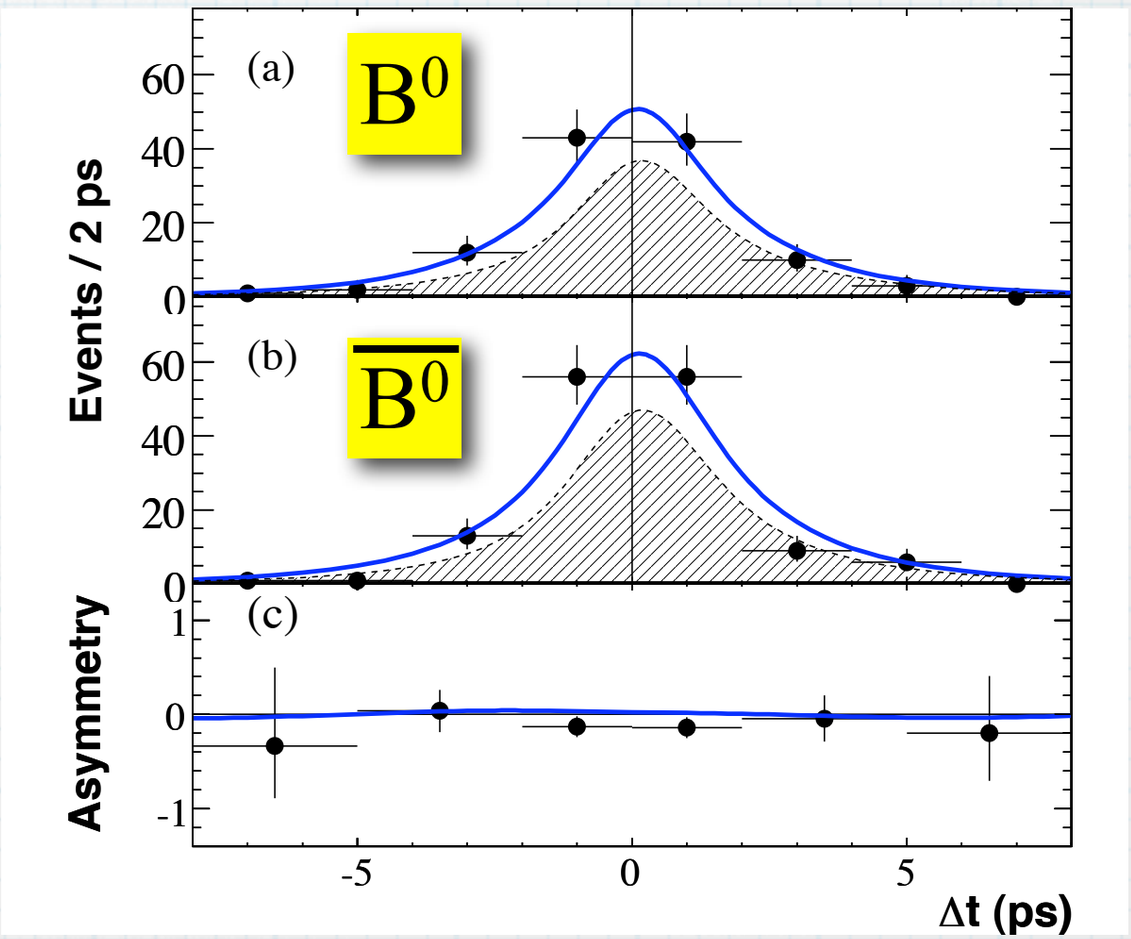
$C = -0.32 \pm 0.40 \pm 0.07$

PRD79, 011102(R) 2009

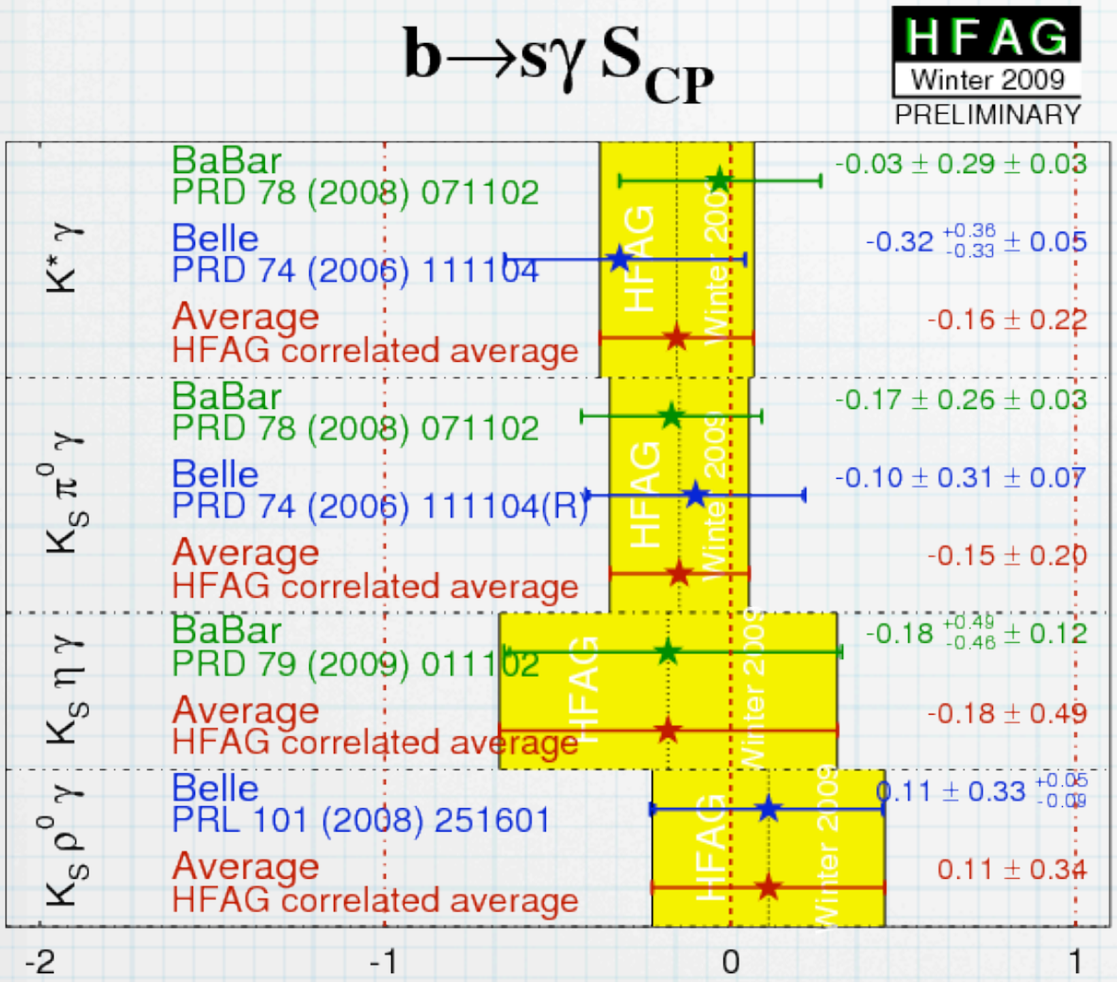
First Time dependent CPV result for this mode

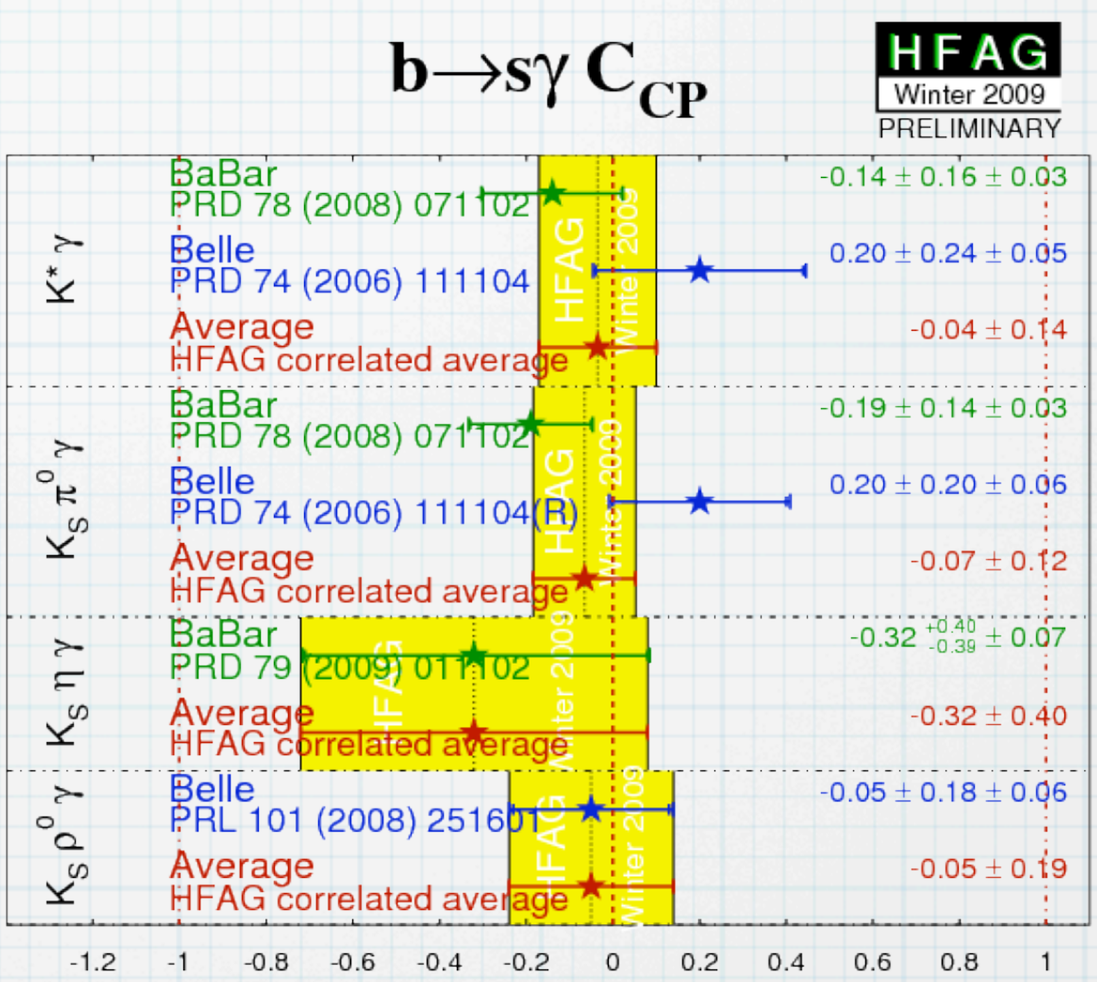
f





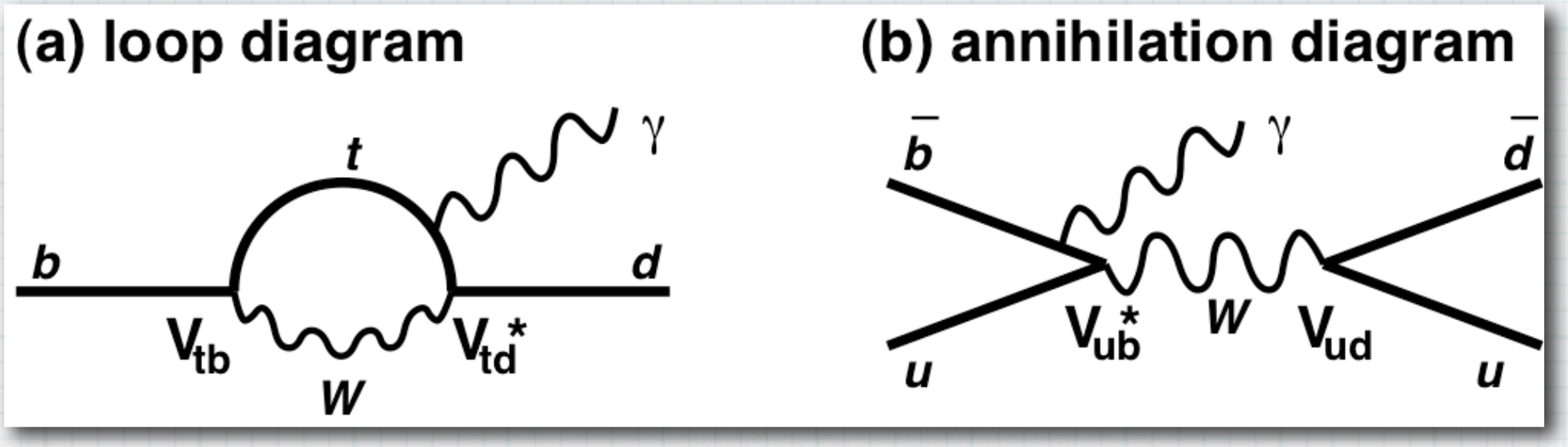
TCPV Radiative Summary





- All consistent with the expectation of the SM

$B \to X_d \gamma$



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

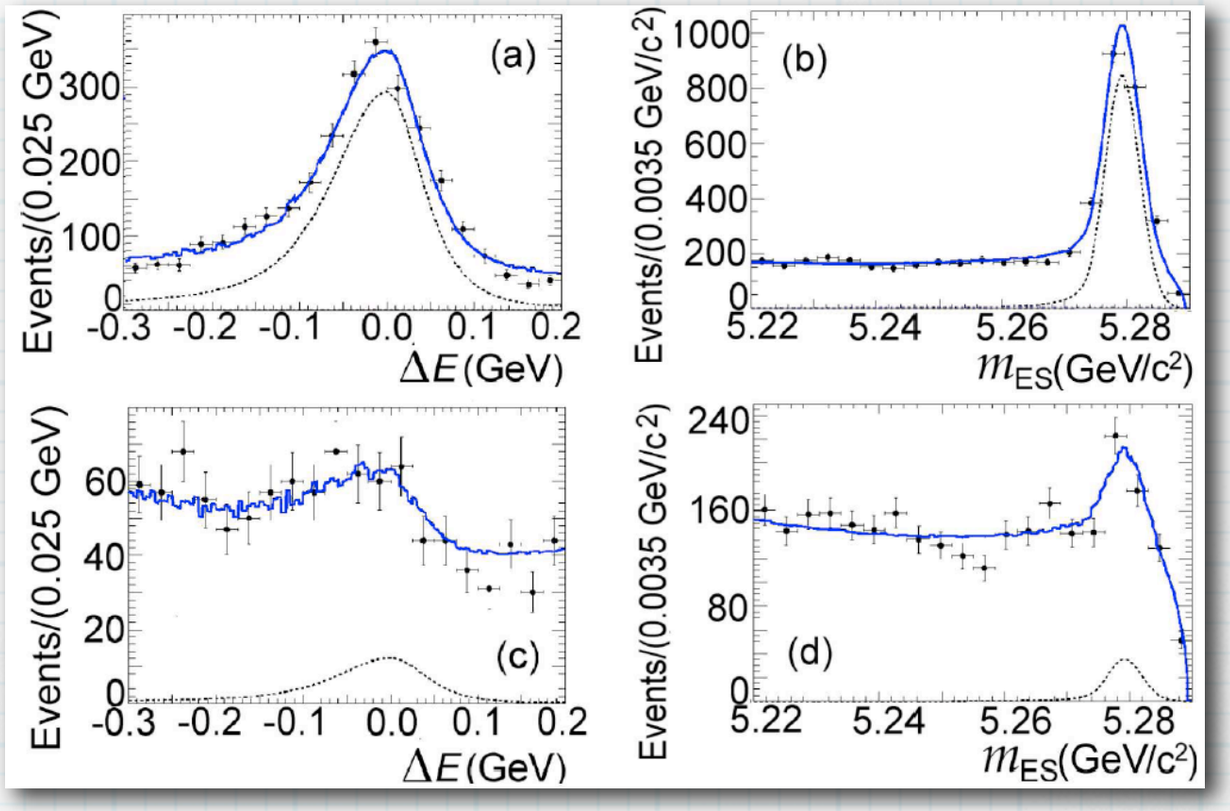
Physics beyond the Standard Model could affect differently $B \to X_d \gamma$ and B_d/B_s mixing!

Exclusive B->$X_{s/d}\,\gamma$ (BABAR)

383 M B-pairs

Phys.Rev.Lett.102:161803,2009

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



$$|V_{td}/V_{ts}| = 0.177 \pm 0.043 \pm 0.001$$

Phys.Rev.Lett.97:242003,2006 1/fb

$$|V_{td}/V_{ts}| = 0.2060 \pm 0.0007\ (\text{exp})\ ^{+0.0081}_{-0.0060}\ (\text{theor})$$

Phys.Rev.Lett.101:111801,2008, Erratum-ibid.101:129904,2008.

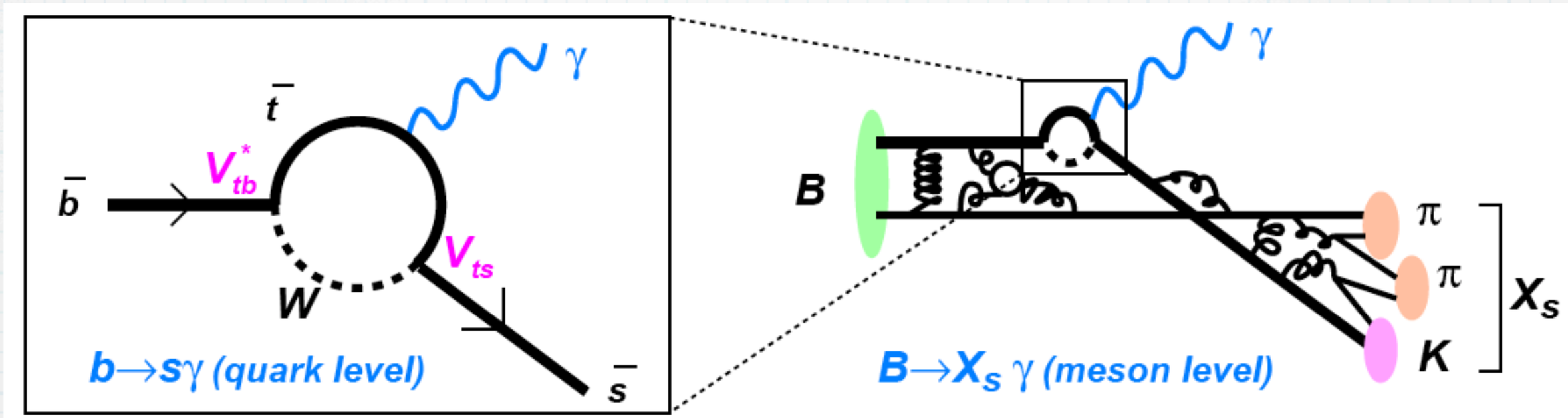
$$|V_{td}/V_{ts}| = 0.195\ ^{+0.020}_{-0.019}(\text{exp.}) \pm 0.015(\text{th.})$$

657M B-pairs

Phys.Rev.D78:112001,2008 465M B-pairs

$$|V_{td}/V_{ts}|_{\rho} = 0.235^{+0.026}_{-0.025} \pm 0.020$$
$$|V_{td}/V_{ts}|_{\rho/\omega} = 0.233^{+0.025+0.022}_{-0.024-0.021}.$$

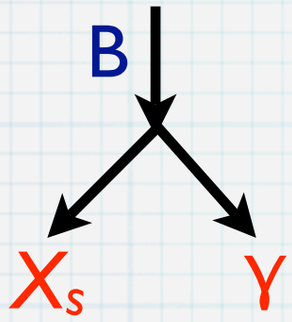
Inclusive B -> $X_s \gamma$

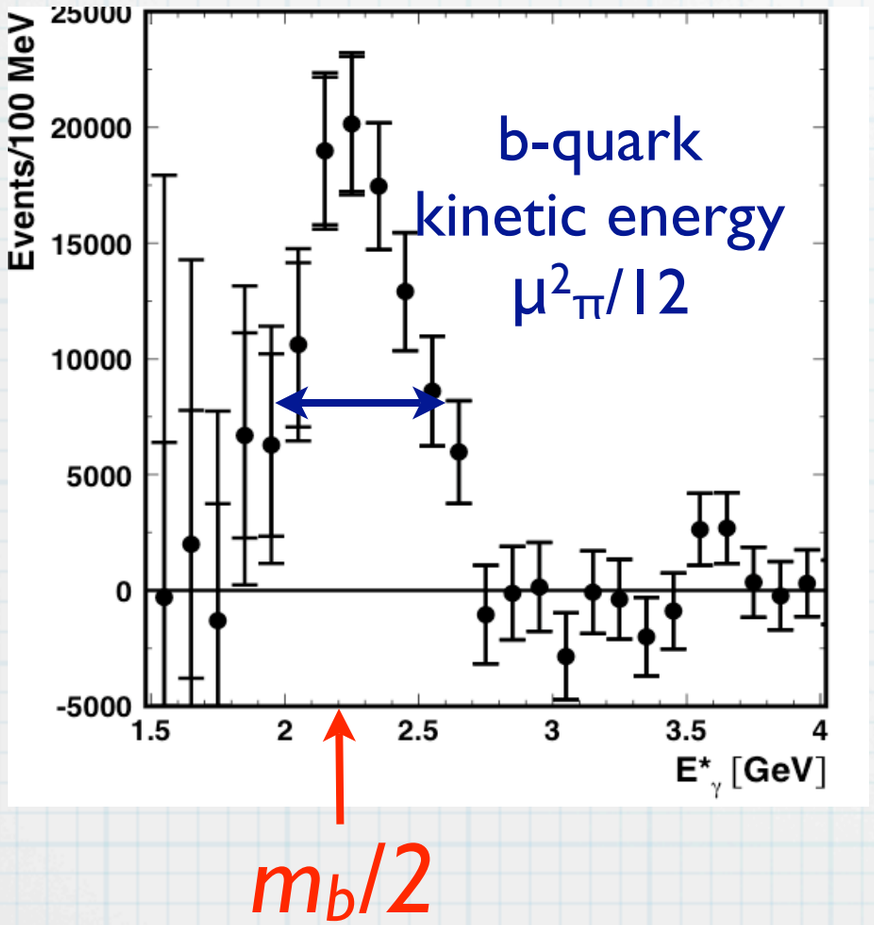


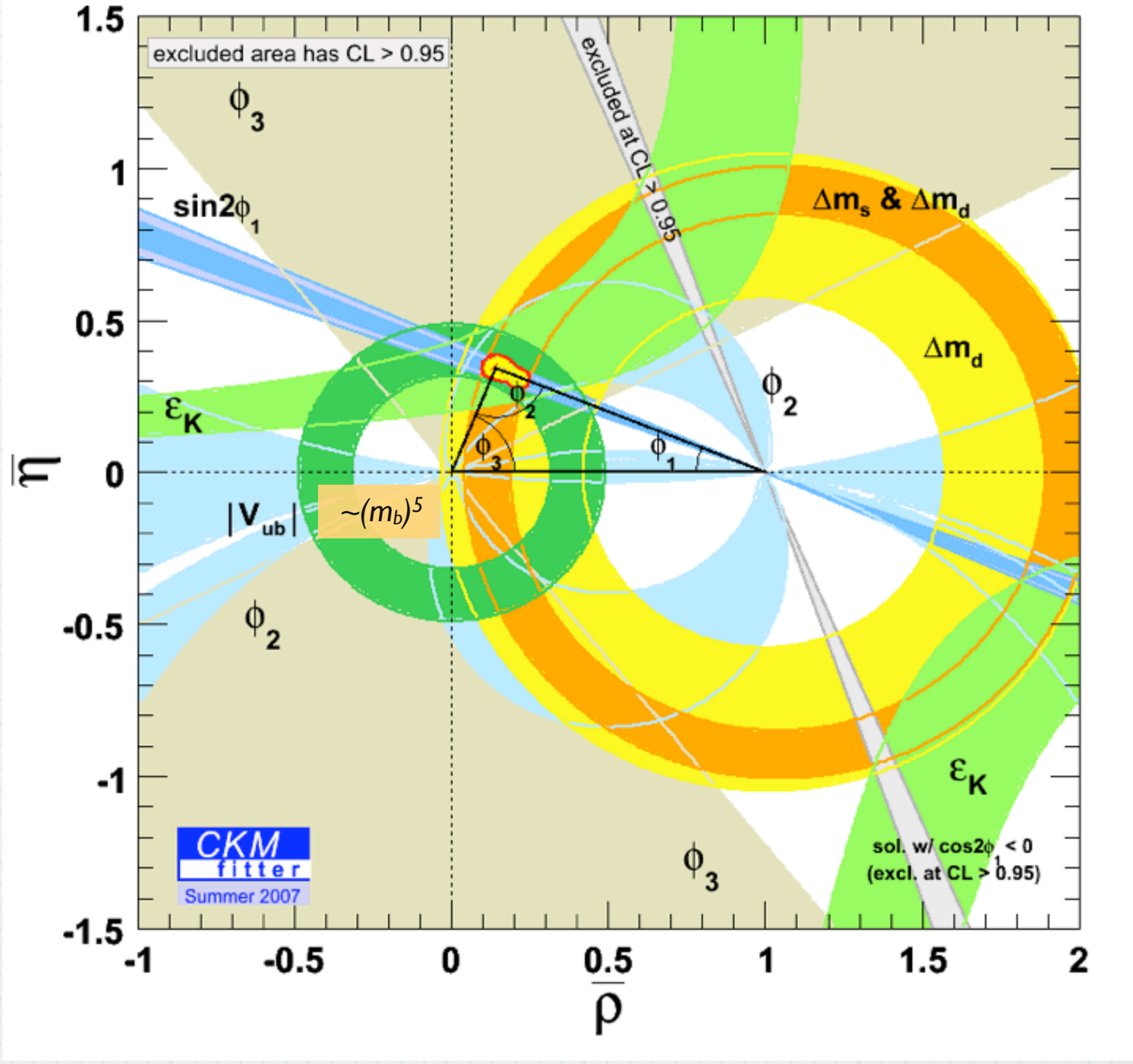
Total Decay rate and CP Asymmetry : Probe for the New Physics e.g. charged Higgs, SUSY, LR models

Differential Decay rate : Photon as a messenger of the dynamics of the b-quark properties e.g mass needed for V_{ub} and V_{cb}

Unitarity Triangle







Time integrated CP Asymmetry

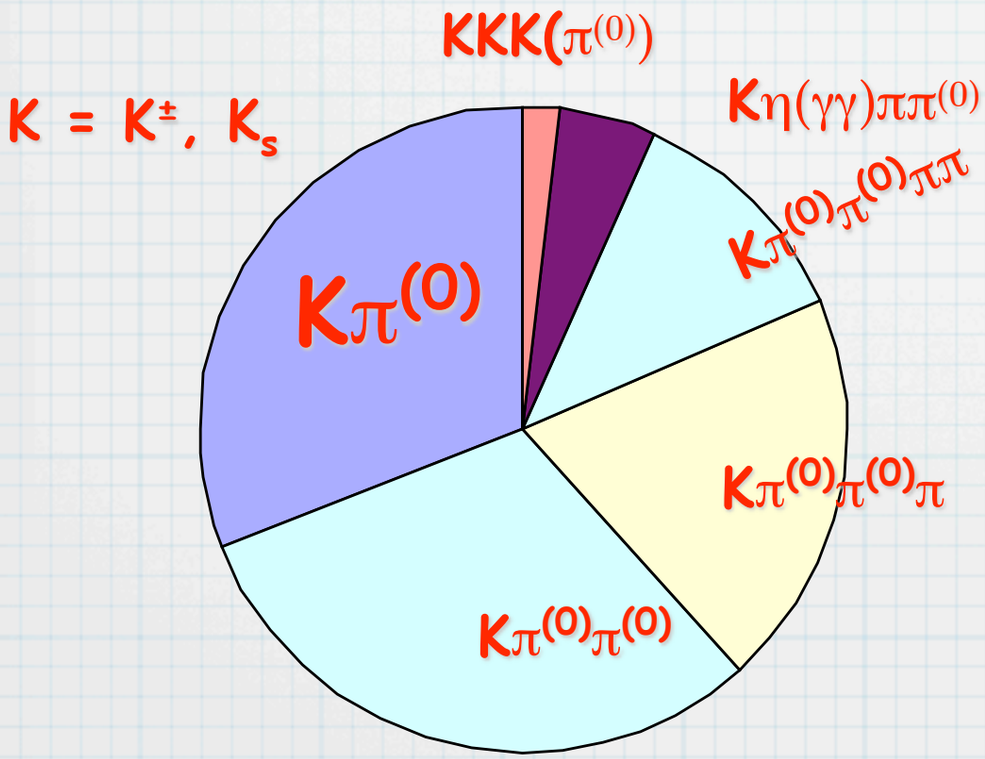
$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{X}_s\gamma) - \Gamma(B \to X_s\gamma)}{\Gamma(\bar{B} \to \bar{X}_s\gamma) + \Gamma(B \to X_s\gamma)}$$

- A_{CP} < 1% due to CKM & GIM suppression in SM

Wolfenstein & Wu PRL73 2809(1994)
Asatrian & Ioannisian PRD54, 5642 (1996)
Ciuchini, Gabrielli, Giudice PLB388 353 1996
Kagan and Neubert PRD 98 094012

- Models with non-minimal Flavor violation (e.g SUSY) A_{CP} ~10%-15%

Reconstructed Final States



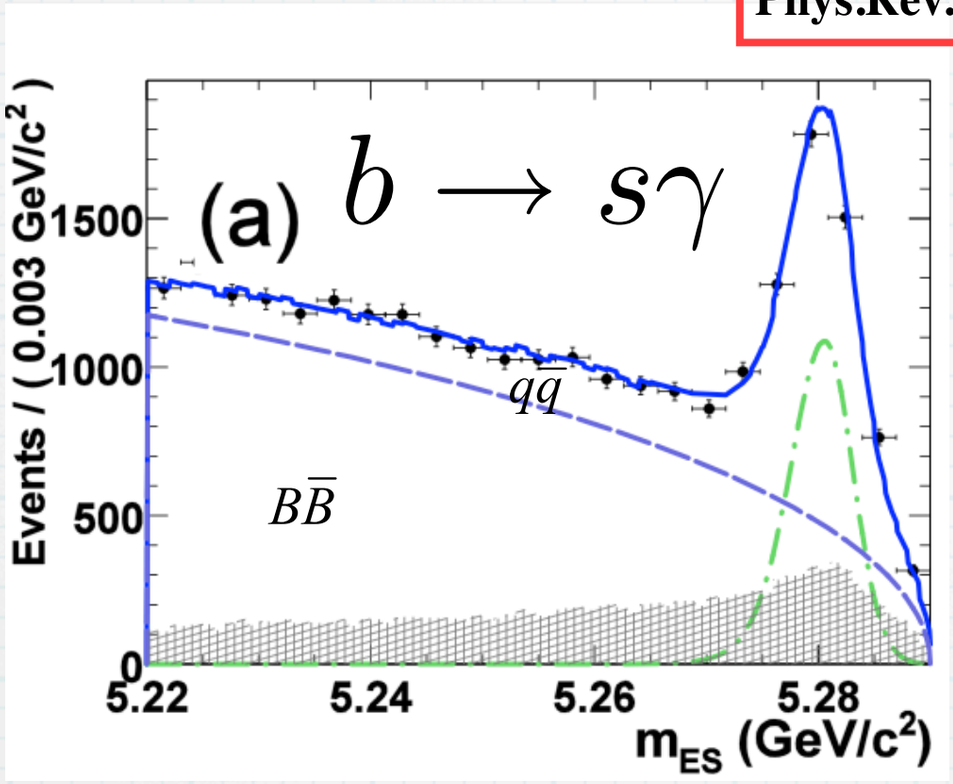
Exclusively Reconstruct 16 final states of X_s :

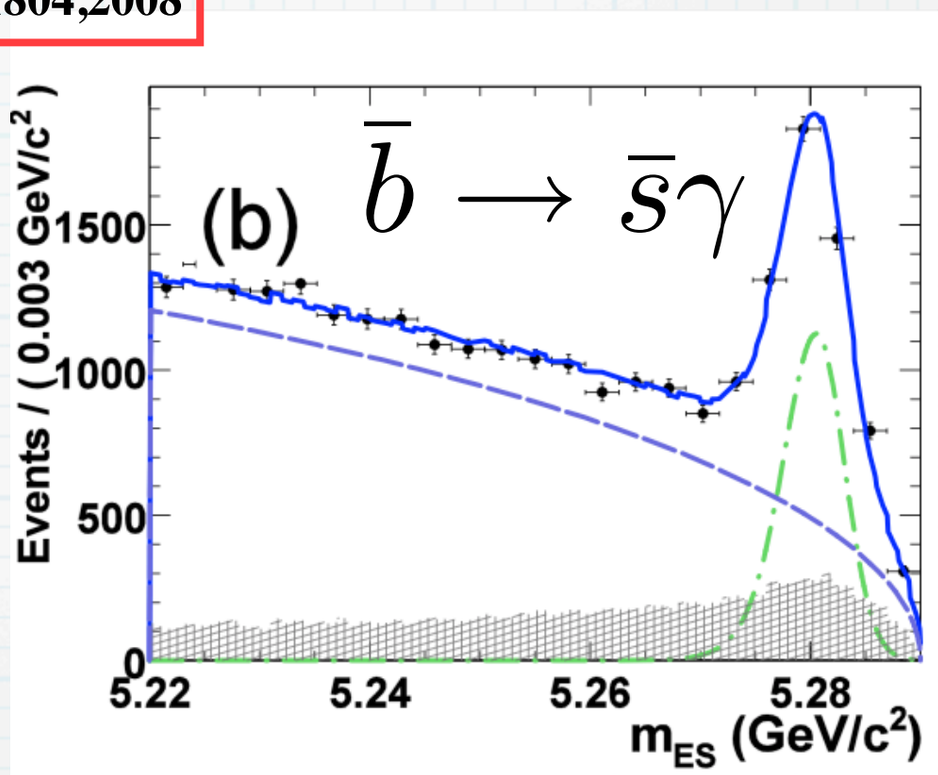
Covers ~55% of possible Xs states

Self-tagging

Results@423 fb^{-1}

Phys.Rev.Lett.101:171804,2008





Detector asymmetry A_{det}=-0.007±0.005

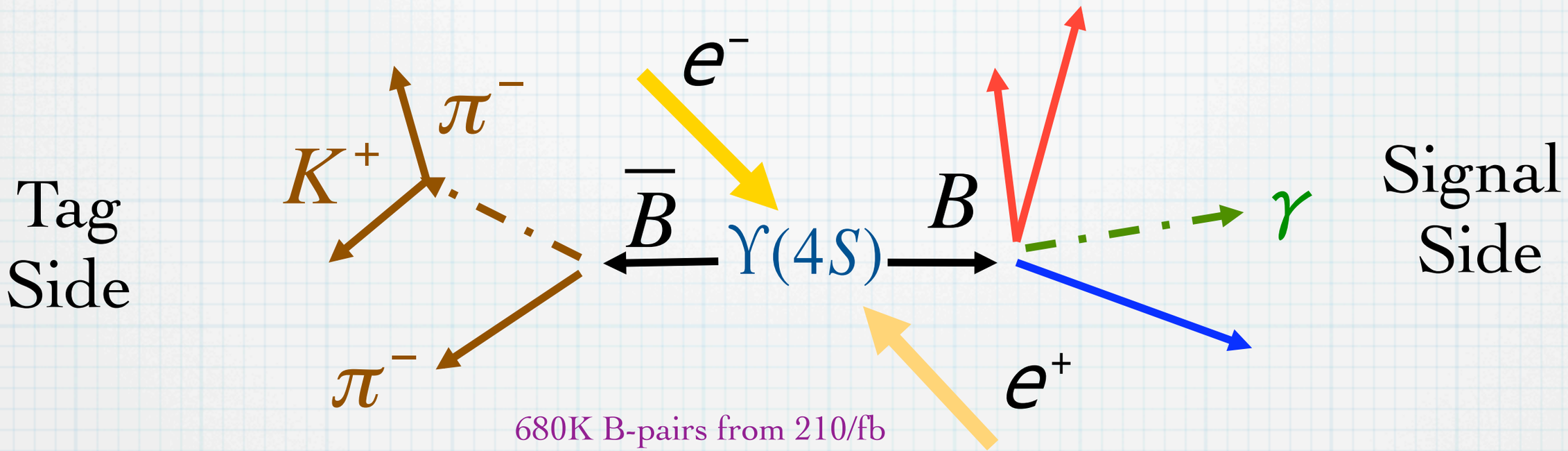
$$A_{CP} = -0.011 \pm \underbrace{0.030}_{\text{stat}} \pm \underbrace{0.014}_{\text{sys}}$$

$$0.6 < M_{X_s}/(\text{GeV}/c^2) < 2.8$$

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

B-recoil Method

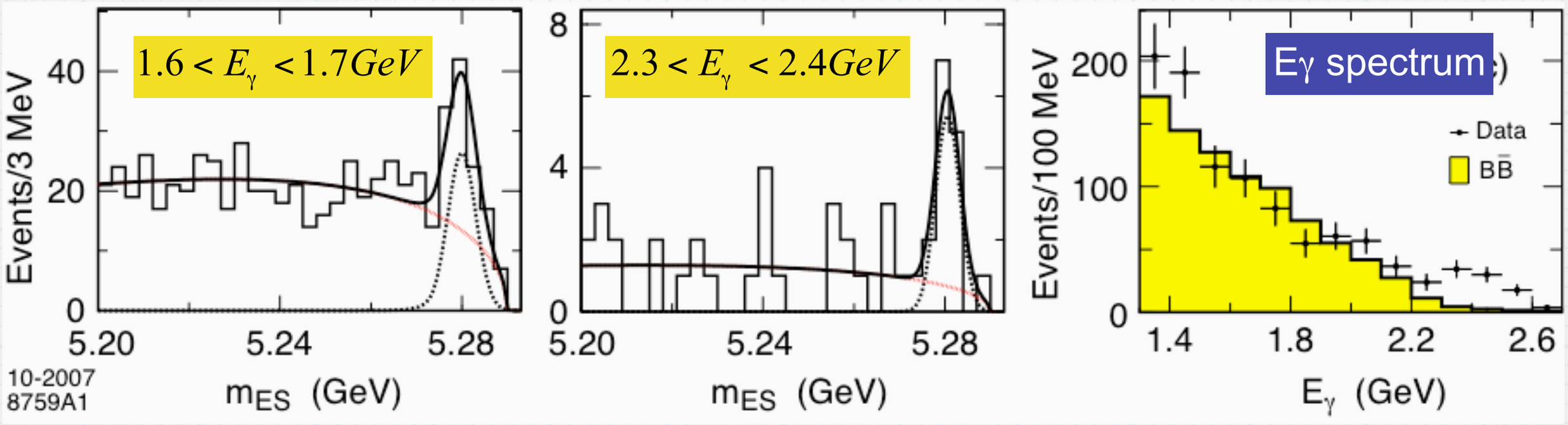
Tag B is fully reconstructed in a hadronic mode
Search for an isolated photon from the rest of the event



680K B-pairs from 210/fb
1114 modes ~about 5% of the total width of B decays

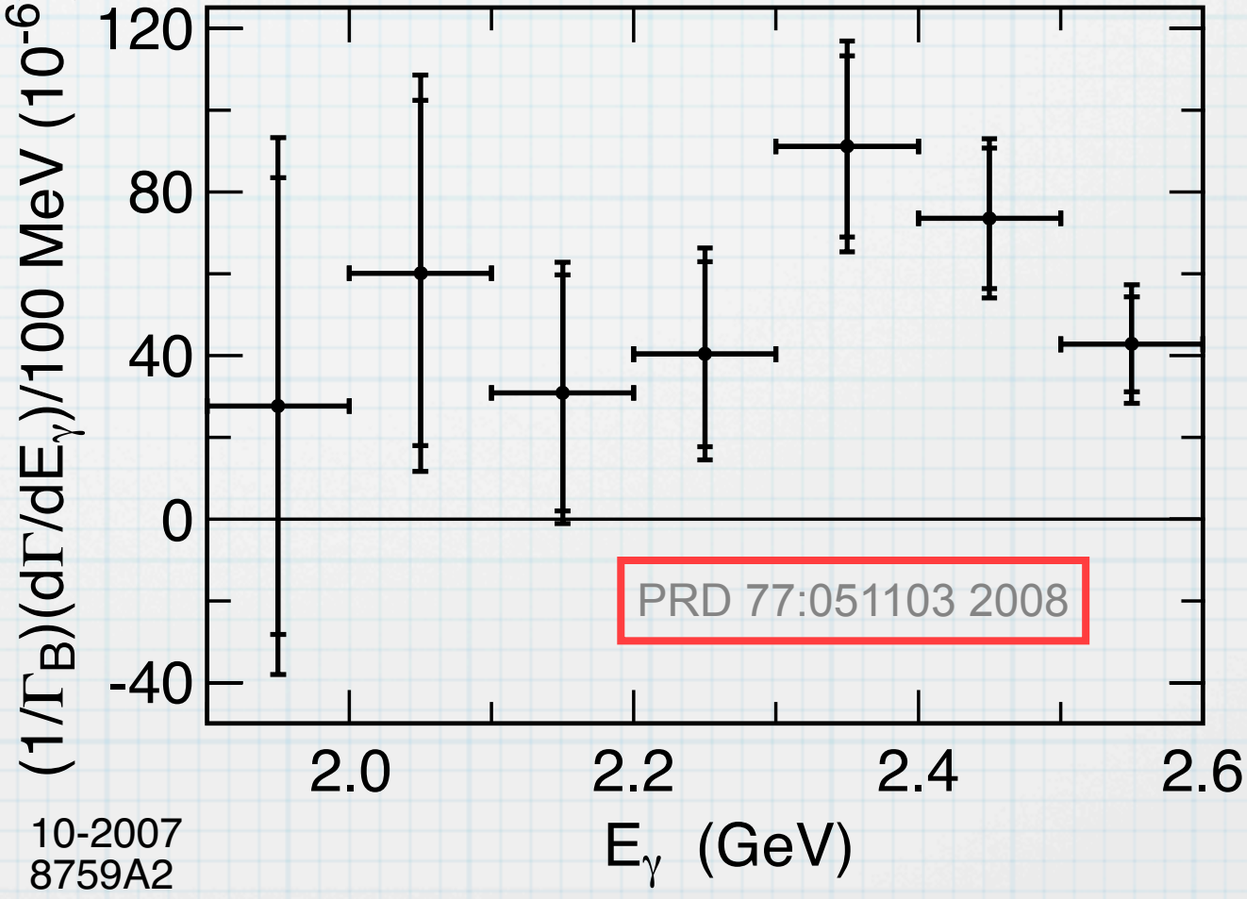
Advantages
Rest frame of the B, negligible continuum background
Access to B flavour, charge and momentum
Disadvantages
Low efficiency for fully reconstructing B (~0.3%)

Photon Spectrum



$$\frac{1}{\Gamma_B}\frac{d\Gamma_i}{dE_\gamma} = \frac{N_i - b_i}{\varepsilon_i N_B}$$

$$\varepsilon_i = \frac{N_{\mathrm{found},i}/N_{\mathrm{sim}}}{N_{\mathrm{true},i}/N_{\mathrm{gen}}}\, C_{\mathrm{tag}}$$



Results@210 fb^{-1}

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

$$\langle E_\gamma \rangle|_{E_\gamma > 1.9\,\mathrm{GeV}} = 2.289 \pm 0.058 \pm 0.027\,\mathrm{GeV}$$

$$\left(\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2\right)|_{E_\gamma > 1.9\,\mathrm{GeV}} = 0.0334 \pm 0.0124 \pm 0.0062\,\mathrm{GeV}^2$$

$$\begin{aligned} \Delta_{0-} &= \frac{\Gamma(\overline{B}^0 \to X_{s,d}\gamma) - \Gamma(B^- \to X_{s,d}\gamma)}{\Gamma(\overline{B}^0 \to X_{s,d}\gamma) + \Gamma(B^- \to X_{s,d}\gamma)} \\ &= -0.06 \pm 0.15_{\text{stat}} \pm 0.07_{\text{stat}} \end{aligned}$$

$E_\gamma > 2.2\,\mathrm{GeV}$

$$A_{CP} = 0.10 \pm 0.18_{\text{stat}} \pm 0.05_{\text{stat}}$$

$$m_b = 4.46^{+0.21}_{-0.23}\,\mathrm{GeV}/c^2$$

$$\mu_\pi^2 = 0.64^{+0.39}_{-0.38}\mathrm{GeV}^2/c^2$$

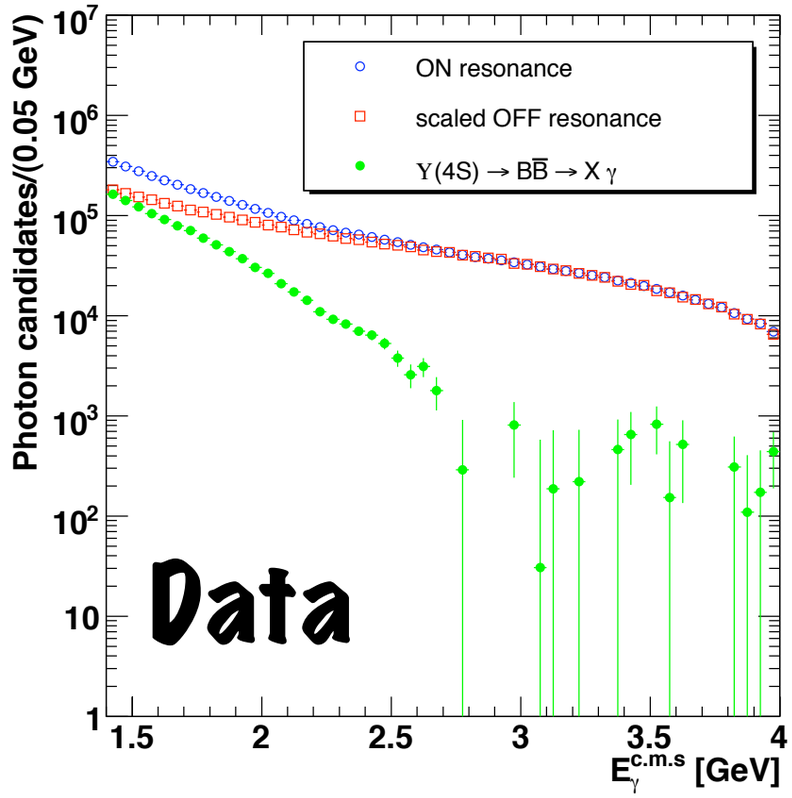
- Consistent with previous measurements and the SM prediction
- First look at the future : expect more from Super-B factory
- Both statistical and systematic uncertainties to decrease with more statistics

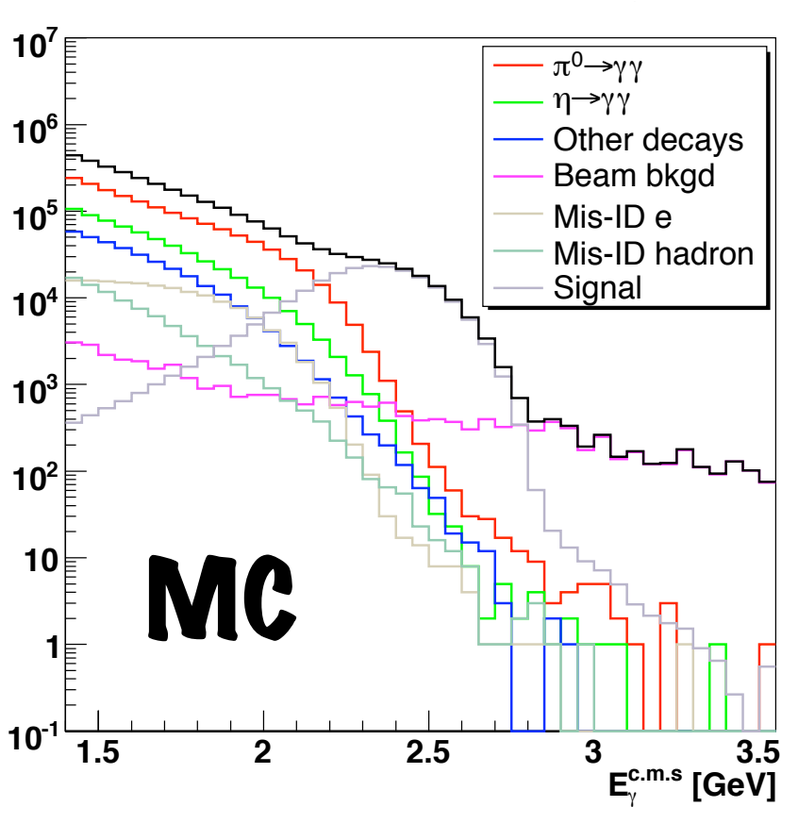
Fully Inclusive Method

$B \to X_s \gamma$

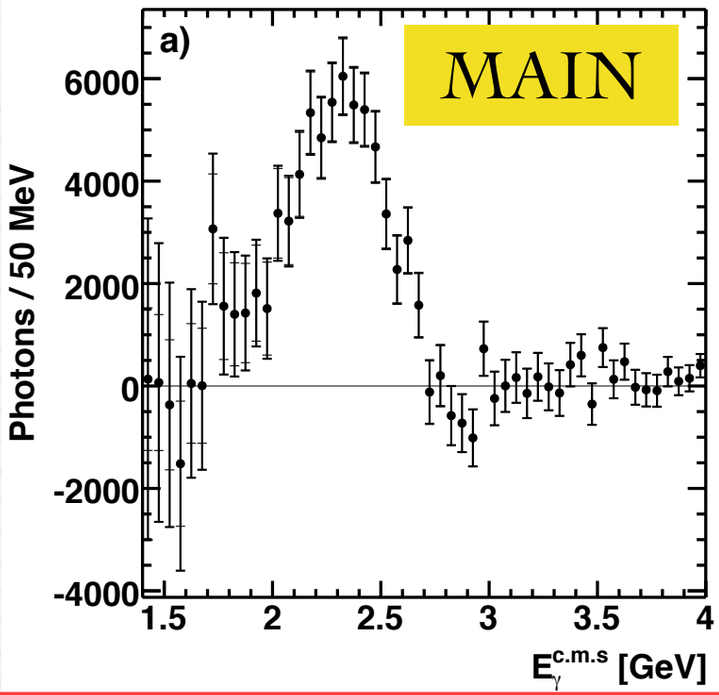
657 M B-pairs

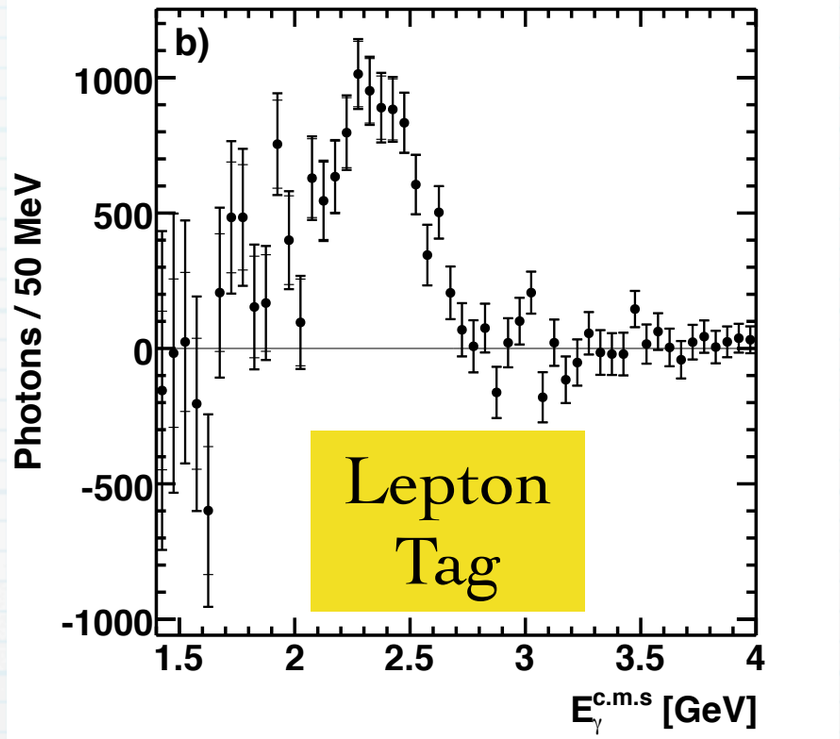
- Find isolated clusters in the EM calorimeter
- High energy E(c.m.s) > 1.4 GeV
- Veto γ from π, η & Bhabha and use event topology to suppress continuum
- Estimate continuum using OFF resonance data : Two sets of cuts i.e. two analysis streams with and without
- "Lepton Tag"
- Estimate B decays using "corrected" MC sample : Measure $B \to X (\eta/\pi^0)$





Photon Energy Spectrum





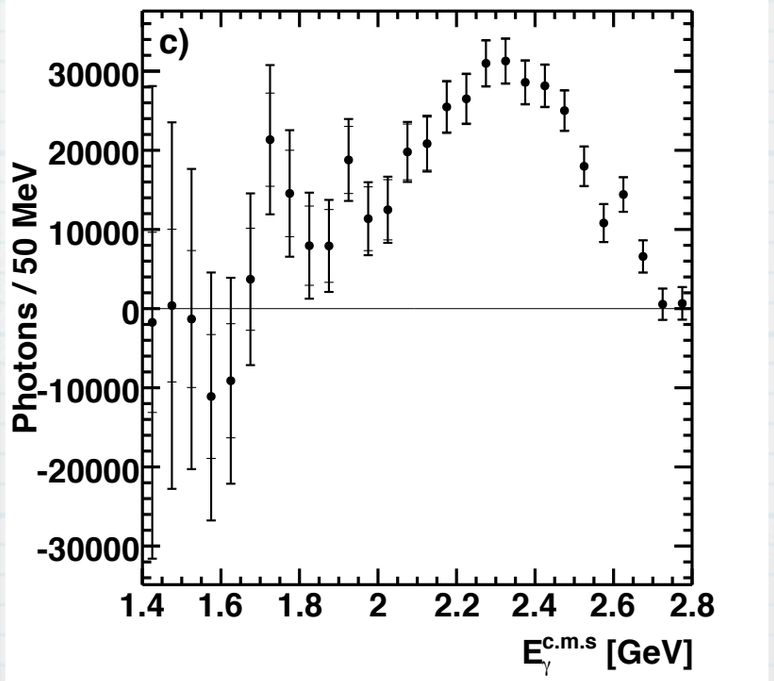
arXiv:0804.1580 Proc, Moriond EW, 2008

arXiv:0907.1384 submitted to PRL

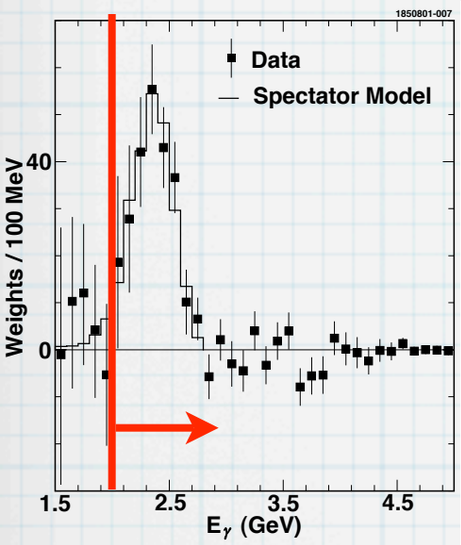
After efficiency correction
MAIN and LT streams are averaged

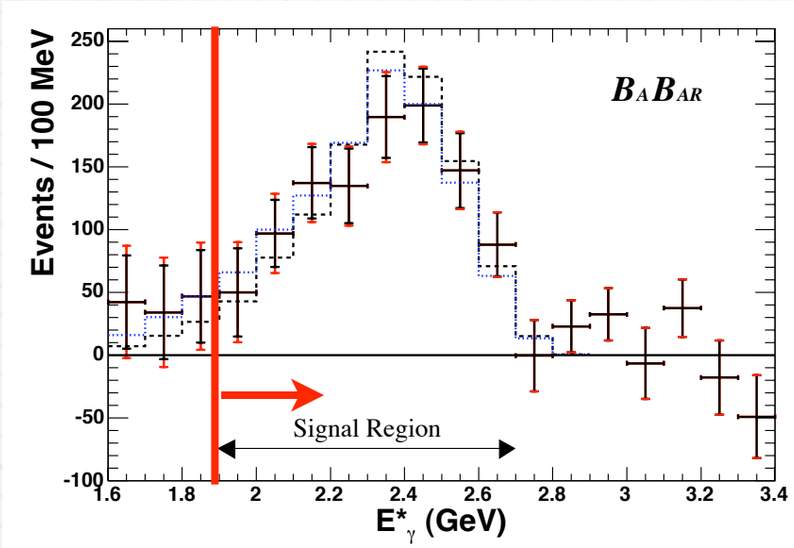
*** Small Statistical correlation**

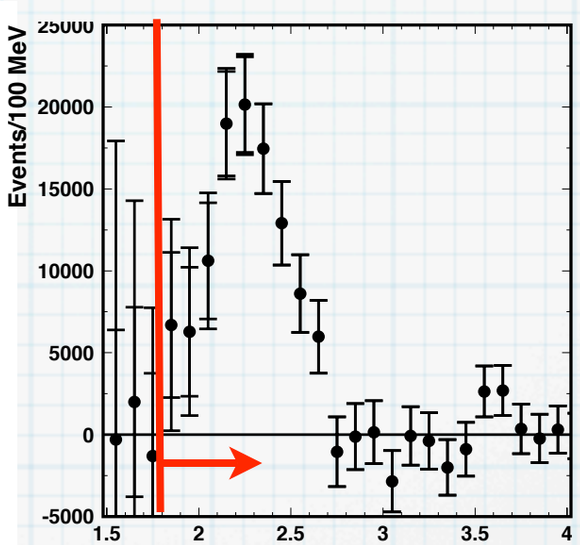
Overall effect reduces stat error

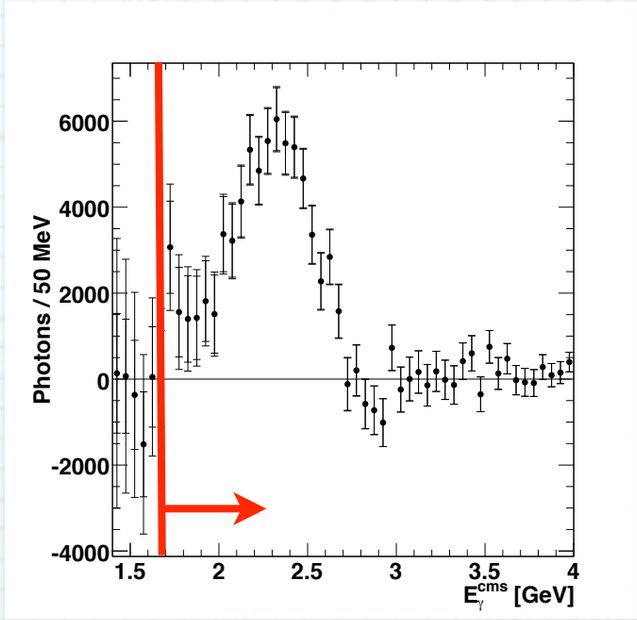


Summary of Fully Inclusive





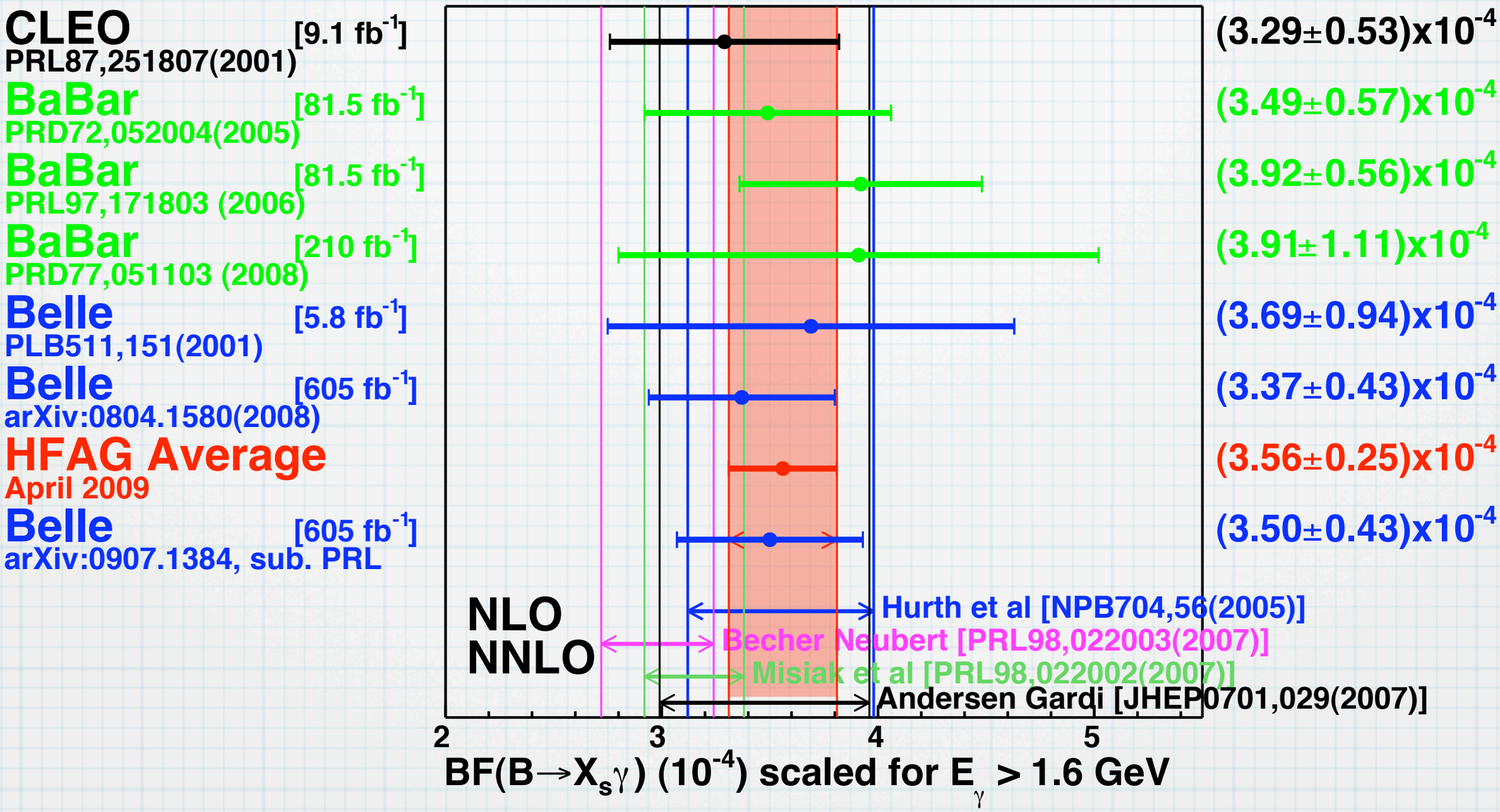




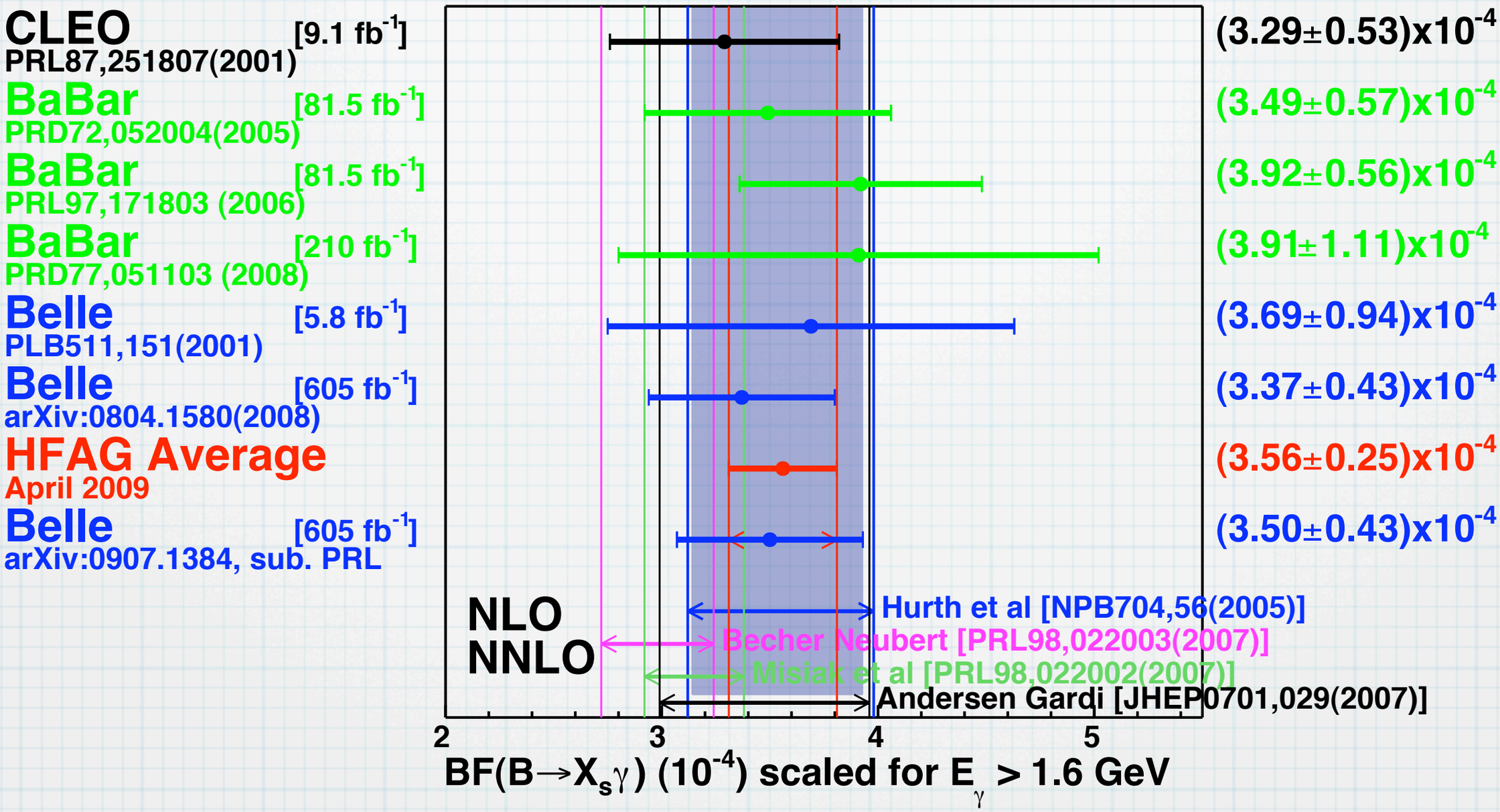
CLEO	*BABAR*	*Belle*	*Belle*
9.1/fb ON 4.4/fb OFF $E_\gamma > 2.0$ GeV	81.5/fb ON 9.6/fb OFF $E_\gamma > 1.9$ GeV	140/fb ON 15/fb OFF $E_\gamma > 1.8$ GeV	605/fb ON 68/fb OFF $E_\gamma > 1.7$ GeV
PRL87, 251807(2001)	PRL97, 171803(2006)	PRL93, 061803(2004)	arXiv:0804.1580 (2008)

More data, lower the photon energy cut

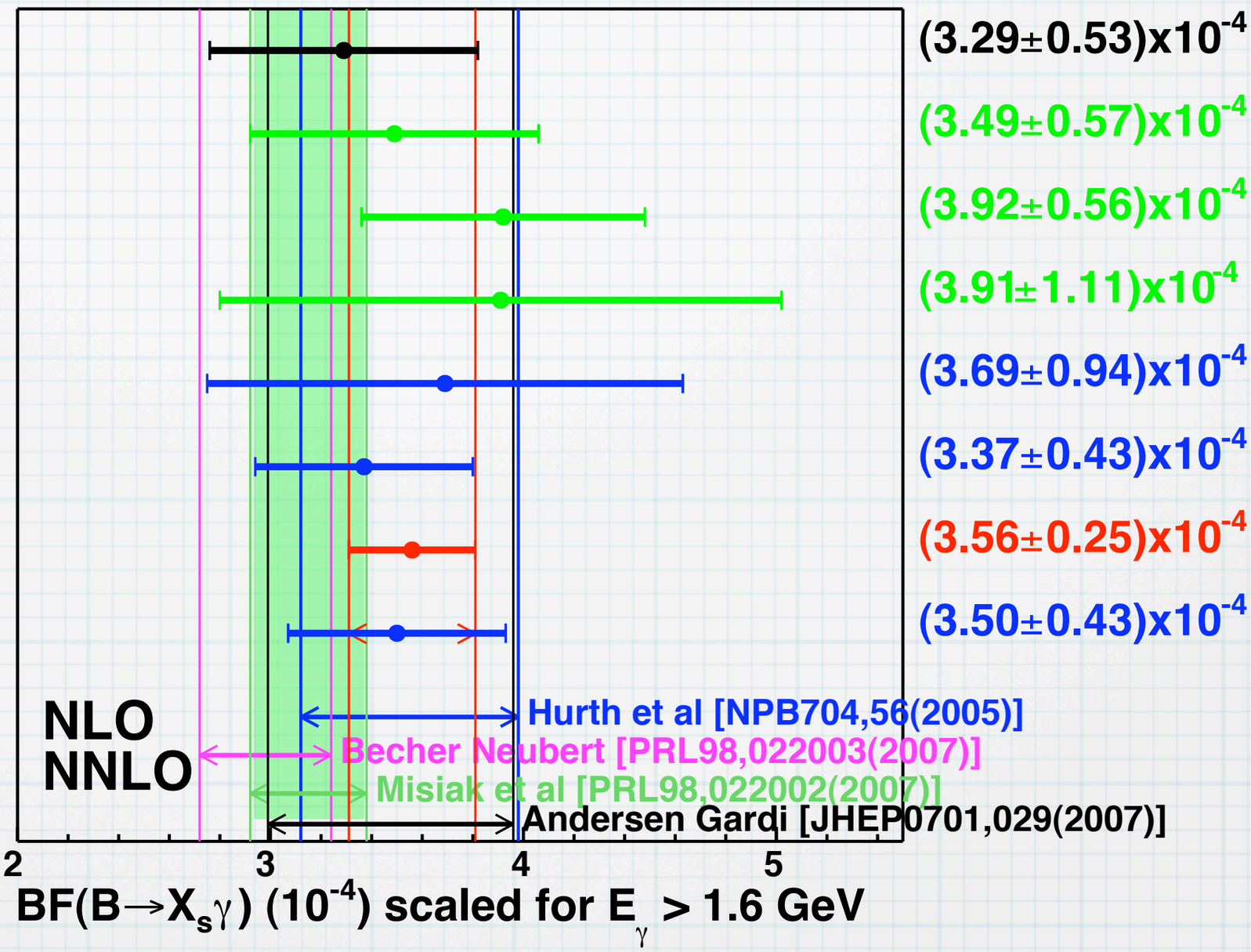
Branching fraction (Exp)



Branching fraction (NLO)



Branching fraction (NNLO)

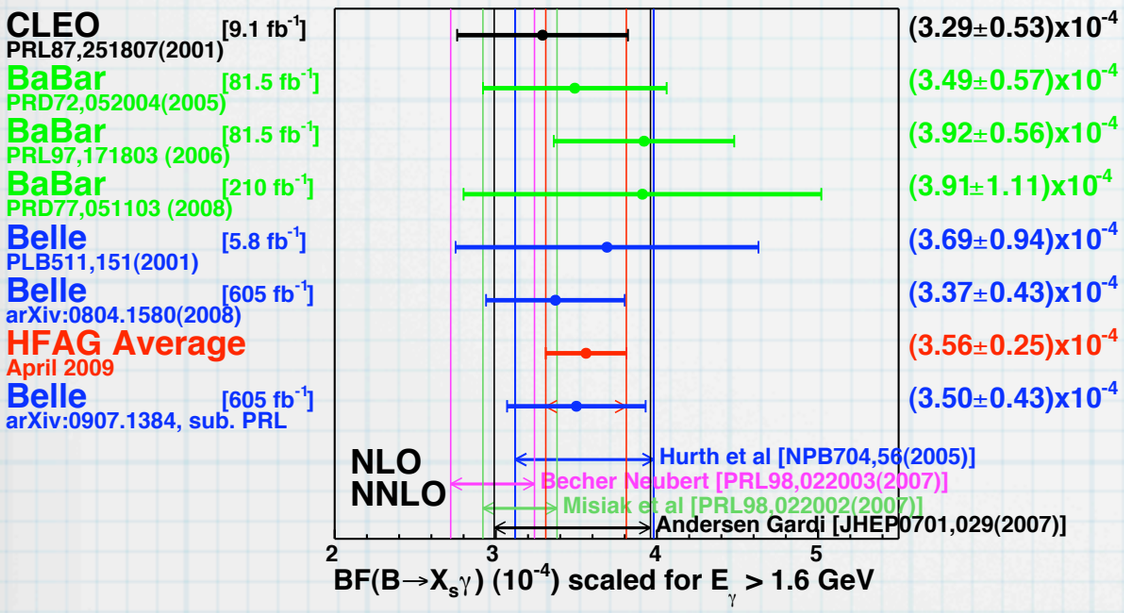


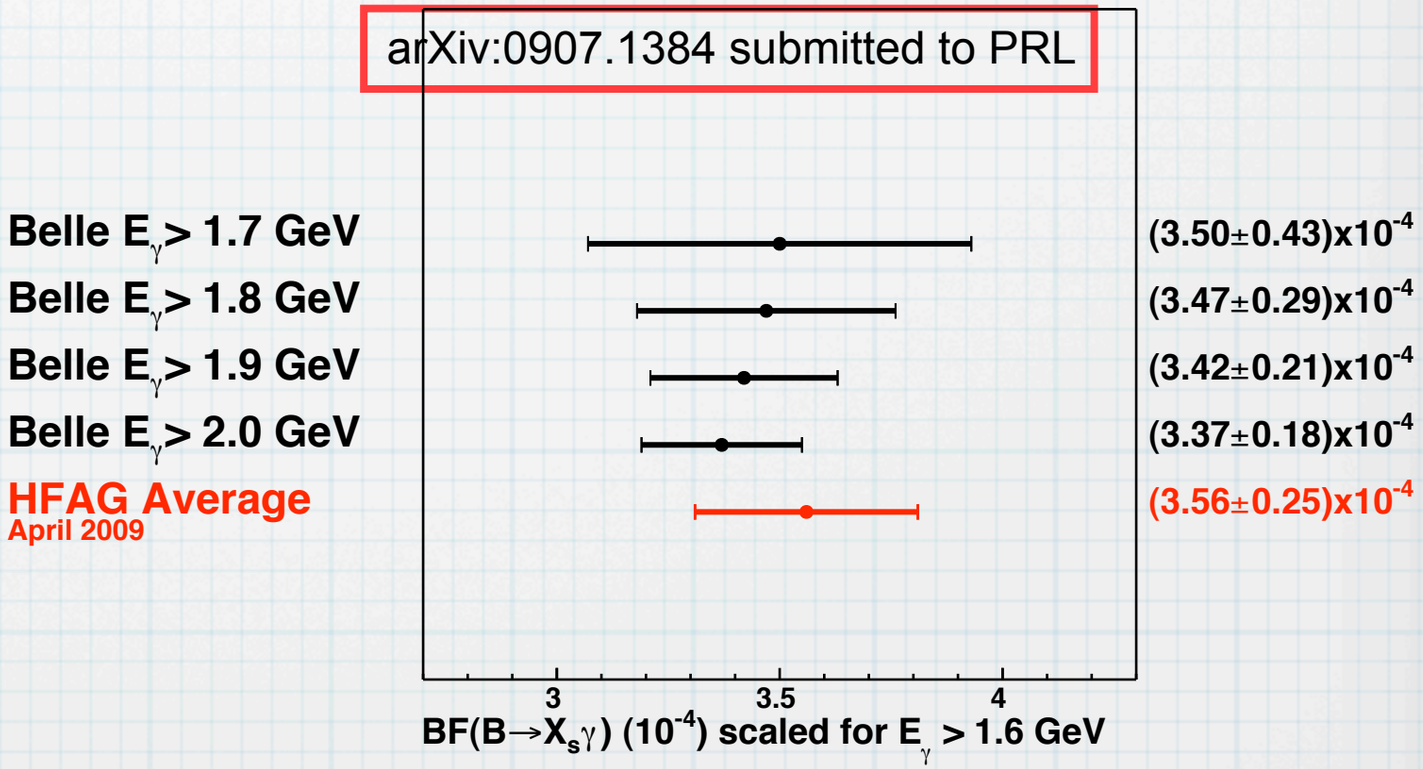
Problems with W.A.

Extrapolation factors used by HFAG from Buchmuller & Flacher PRD73 073008 (2006)

Table 1: Extrapolation factor in various scheme with various minimum photon energy requirement (in GeV).

Scheme	$E_\gamma < 1.7$	$E_\gamma < 1.8$	$E_\gamma < 1.9$	$E_\gamma < 2.0$	$E_\gamma < 2.242$
Kinetic	0.986 ± 0.001	0.968 ± 0.002	0.939 ± 0.005	0.903 ± 0.009	0.656 ± 0.031
Neubert SF	0.982 ± 0.002	0.962 ± 0.004	0.930 ± 0.008	0.888 ± 0.014	0.665 ± 0.035
Kagan-Neubert	0.988 ± 0.002	0.970 ± 0.005	0.940 ± 0.009	0.892 ± 0.014	0.643 ± 0.033
Average	0.985 ± 0.004	0.967 ± 0.006	0.936 ± 0.010	0.894 ± 0.016	0.655 ± 0.037

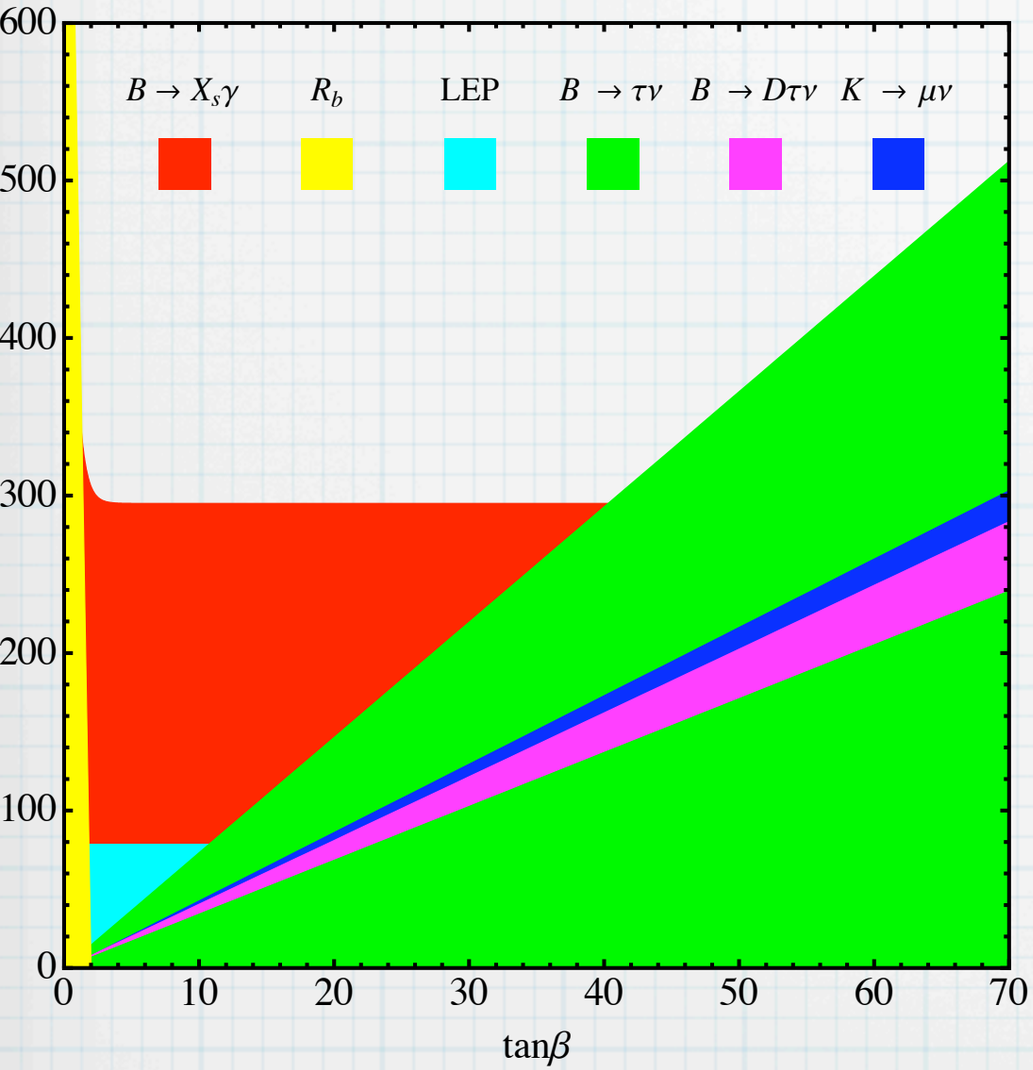


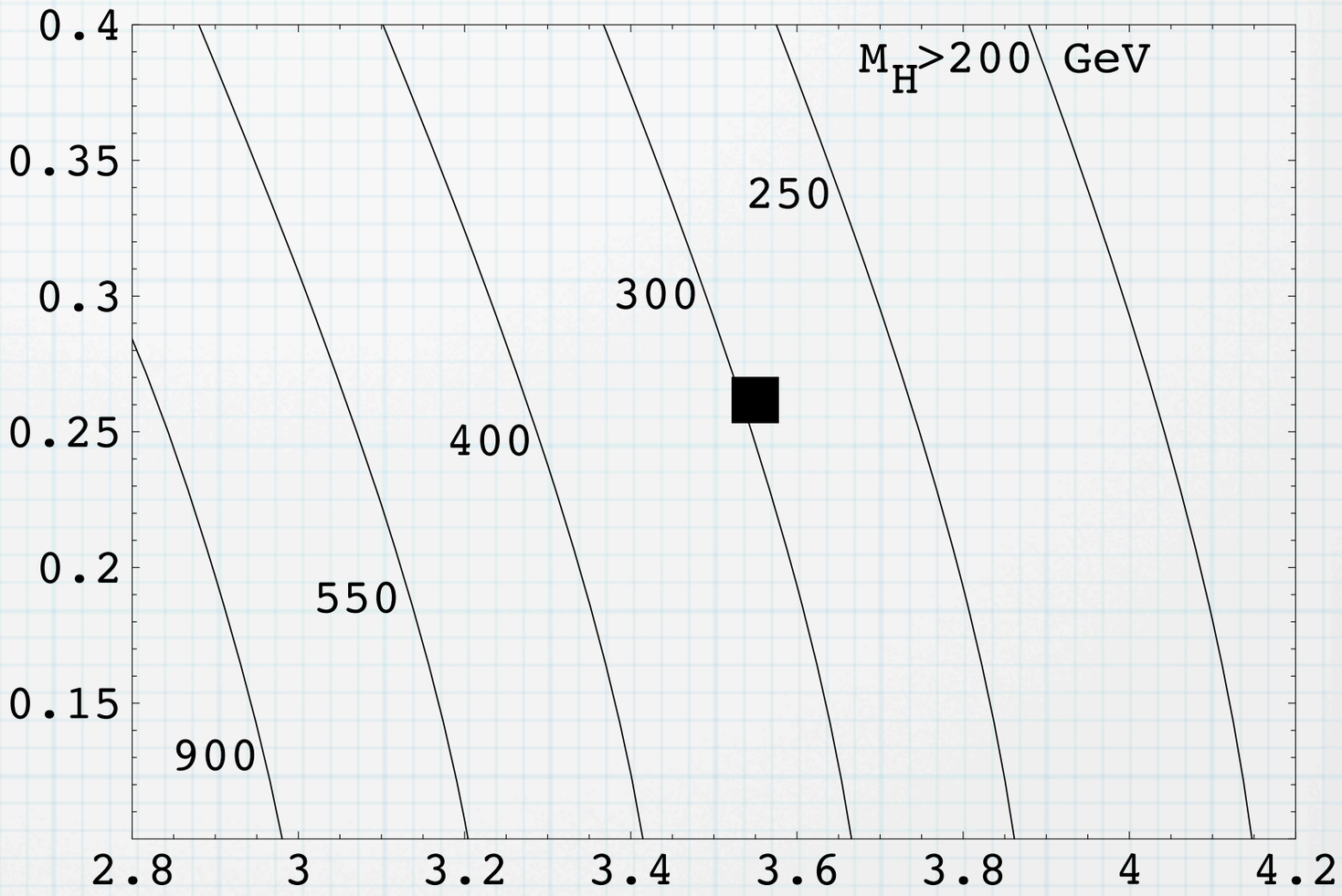


Much lower uncertainty if E>2.0 GeV cut is used!
Old measurements have a disproportionate weight in the average!

Constraints on New Physics

Type-II 2HDM





M(H$^\pm$) > 300 GeV @ 95% CL

Summary

Since the advent of B-factories knowledge of Radiative B decays has significantly increased

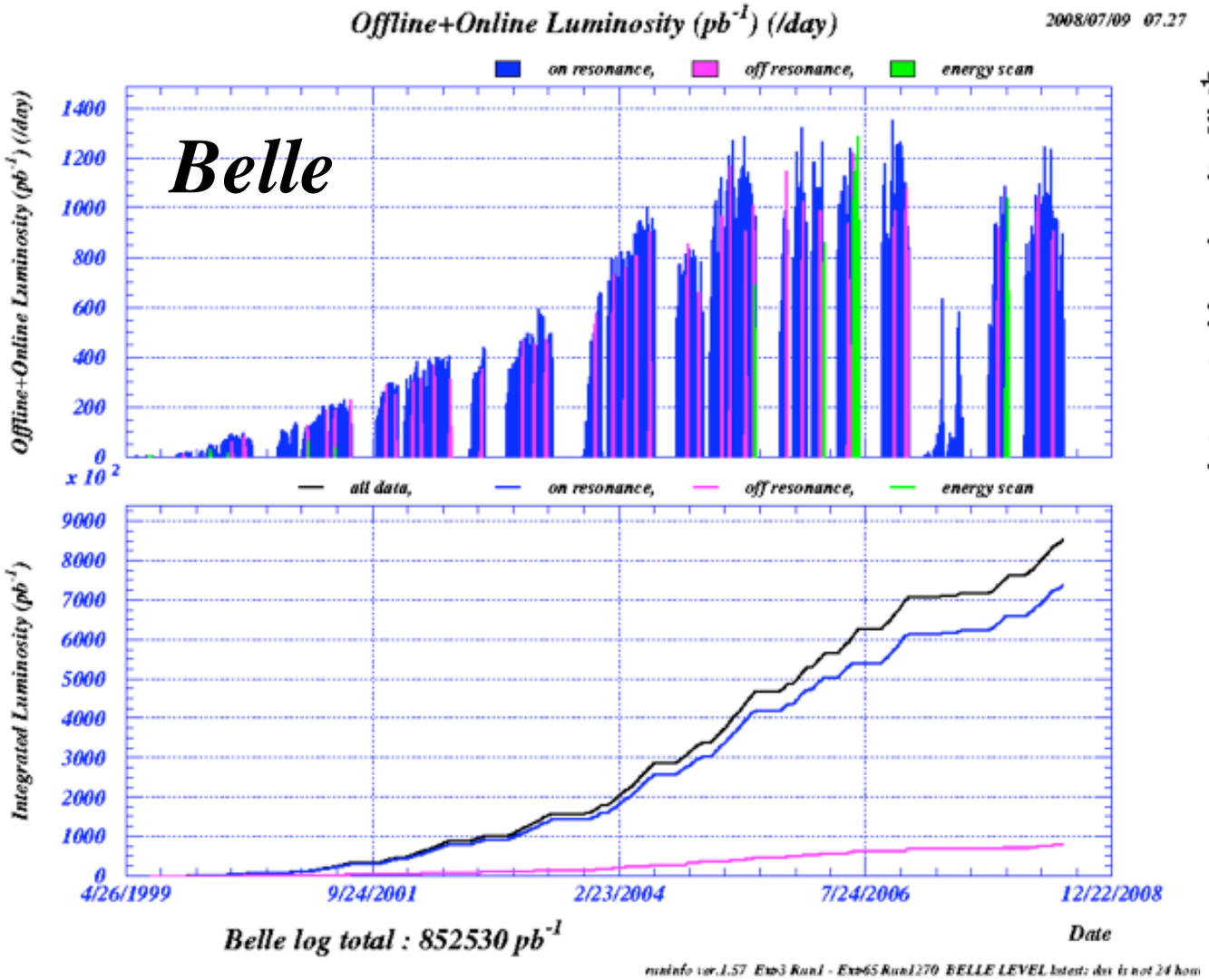
Many measurements translate to a high number of tests of the Standard Model

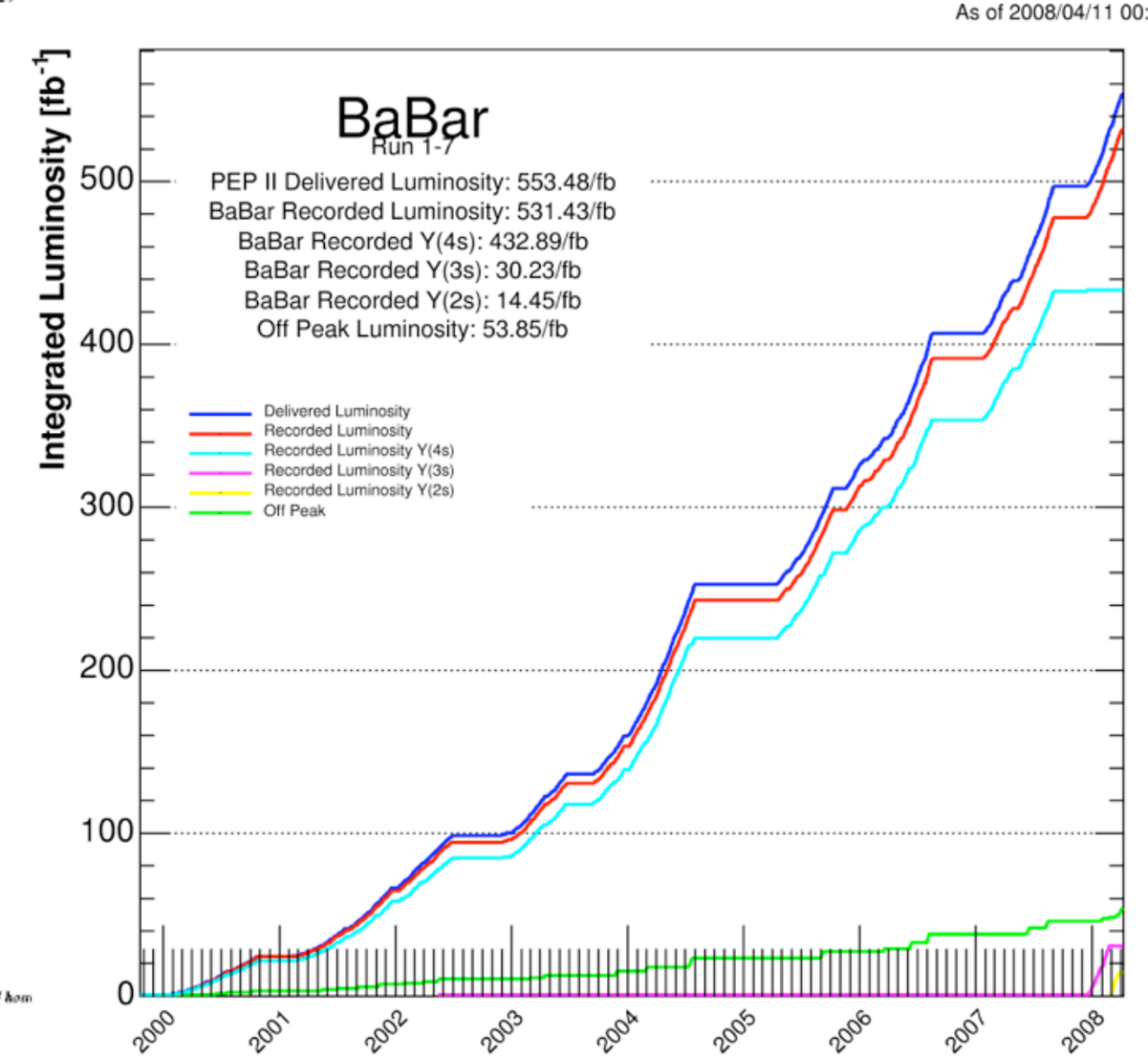
As yet no significant deviation from expection, but the small differences seem to persist as our measurements gain in accuracy

Is the discovery of "Neptune" just around the corner? We'll need a bigger B-factory to map the "orbit" of Radiative B decays

Backup

Data Sets





BELLE

BABAR™

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