Inclusive radiative electroweak penguin decays: $b \to s\gamma$

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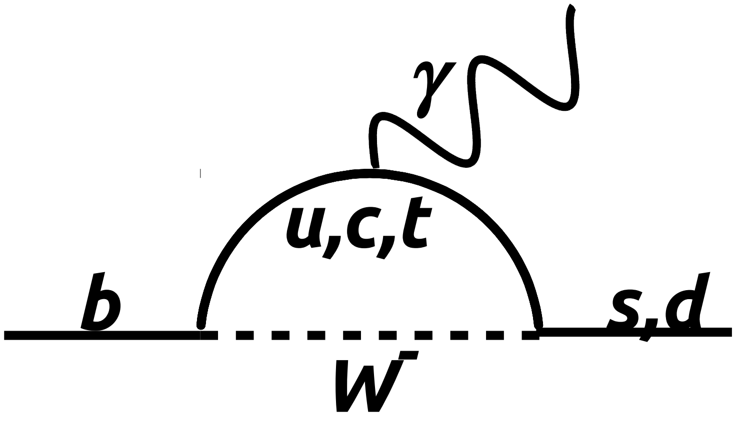
25/05/15

Contents

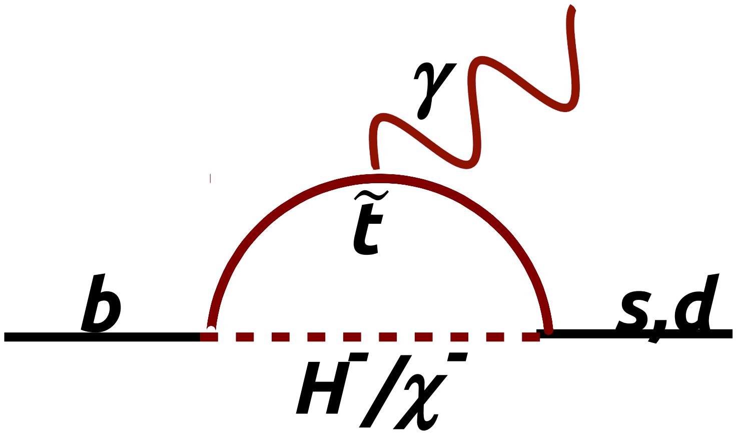
- Electroweak penguins
  - SM predictions & New Physics
- Experimentally
  - Observables: branching fraction and CP asymmetries
    - $\mathcal{B}(B \to X_s\gamma)$, $\mathcal{B}(B \to X_{s+d}\gamma)$, $A_{CP}(B \to X_s\gamma)$, $A_{CP}(B \to X_{s+d}\gamma)$, ΔA_{CP}
- Belle II
- Limits on 2HDM-II

Introduction

- Electroweak penguins: **b→s/d γ** are FCNC, forbidden at tree level in SM
- In NP models, new heavy particles could enter the loop (in 2HDM-II it is the H^-)
  - Modify observables (**BF**, **A_{CP}**, **…**)
- Most precise predictions are for inclusive **b→s γ**
  - Motivates inclusive or semi-inclusive analyses
- Challenges: large BG, missing exclusive modes, fragmentation modeling, etc.
- Suppression for **b→dγ** with respect to **b→sγ** of order: $|V_{td}/V_{ts}|^2 \approx 1/20$



Standard Model



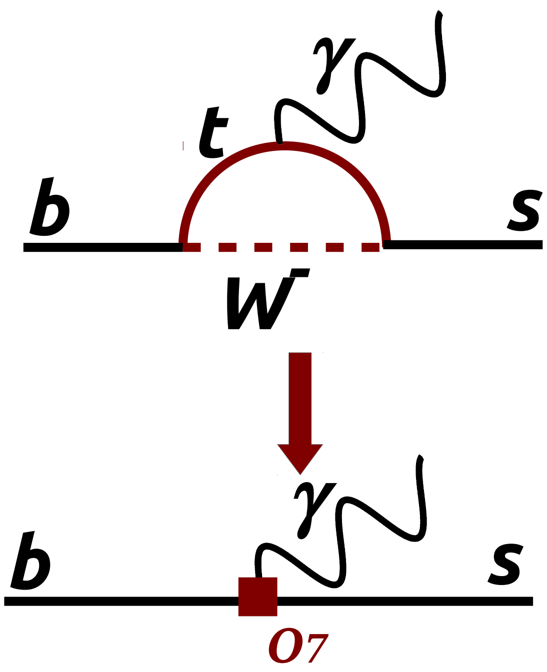
New Physics

The inclusive rate

- HQET Hamiltonian: $$H_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i C_i(\mu_b) O_i(\mu_b)$$
  - ***m_W, m_t >> μ_b***
- ***Ci & Oi*** are the Wilson coefficients and operators. ***C7*** and ***C8*** are the relevant contributions

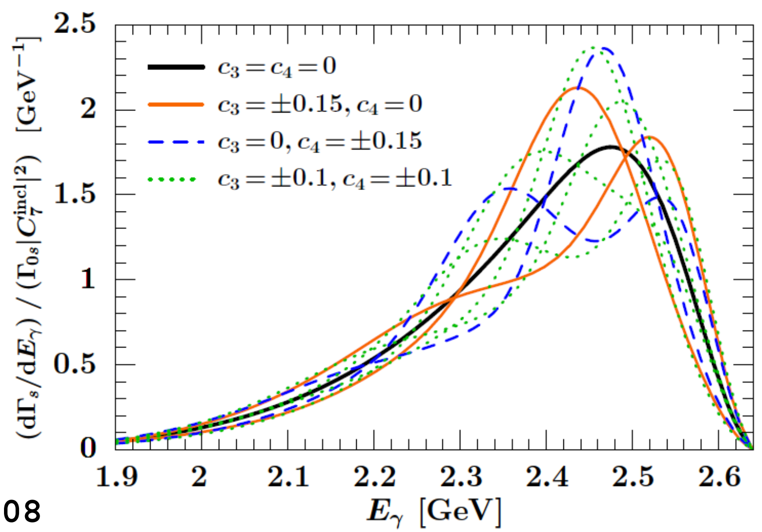
$$\mathcal{O}_7 = \frac{e m_b}{16\pi^2} \bar{s}_L \sigma_{\mu\nu} F^{\mu\nu} b_R$$

$$\mathcal{O}_8 = \frac{g m_b}{16\pi^2} \bar{s}_L \sigma_{\mu\nu} T^a b_R G_a^{\mu\nu}$$



With NP: ***Ci → Ci + Ci'***

- Photon energy or ***Xs*** mass spectra, described by two parameters: $m_b,\ \mu_\pi^2$
- Strong dependence on input parameters and model
  - Use cut-off E_γ>1.6 GeV
  - Large uncertainty for low E_γ



Phys.Rev.D78:114014,2008

BF($B \to X_{s/d}\,\gamma$) calculation

- Recent update: complete NNLO calculation (***E*γ**>1.6 GeV) **arxiv:1503.01789[hep-ph]**
- Central value increased by **6.4%** with respect to 2006 value

$$\mathcal{B}(B \to X_s\gamma) = (3.36 \pm 0.23) \times 10^{-4}$$
$$\mathcal{B}(B \to X_d\gamma) = (1.73^{+0.12}_{-0.22}) \times 10^{-5}$$

  - Total uncertainty is **~7%** for $\boldsymbol{\mathcal{B}(B \to X_s\gamma)}$
  - Room for improvement: interpolation for ***m_c=0*** in new NNLO terms.
- Limit on 2HDM-II charged Higgs mass, based on 2014 HFAG average

$$\mathcal{B}(B \to X_s\gamma)^{\mathrm{exp}} = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$$
$$M(H^-) > 480 \text{ GeV at } 95\% \text{ CL}$$

Direct CP asymmetry

- Direct **CP** Asymmetry: non-vanishing for exclusive cases

$$\mathrm{A_{CP}} = \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)}$$

$$f = X_{s,d}\gamma$$

Channel	$\mathrm{A_{CP}}$(SM)
$\mathrm{B}\to X_s\gamma$	[-0.6% , +2.8%]
$\mathrm{B}\to X_d\gamma$	[-62% ,+14%]
$\mathrm{B}\to X_{s+d}\gamma$	0

PRL 106, 141801 (2011)

- Cancellation for ***X_{s+d}*** due to **CKM** unitarity, theory error becomes negligibly small

$$A_{\mathrm{CP}} = \frac{\Delta\Gamma_q}{2\Gamma(B\to f_q)} \quad \longrightarrow \quad \Delta\Gamma_q \propto \Im(V_{ub}V_{cb}^{*}V_{cq}V_{uq}^{*})$$

$$\Delta\Gamma_s = -\Delta\Gamma_d$$

Nucl.Phys.B704(2005) 56-74

- Difference of ***ACP*** between charged and neutral modes gives information on Wilson coefficients C_7 and C_8:

$$\Delta A_{CP} \equiv A_{CP}(B^+ \to X_s^+\gamma) - A_{CP}(B^0 \to X_s^0\gamma)$$

$$\Delta A_{CP} \approx 4\pi^2\alpha_s \frac{\bar{\Lambda}_{78}}{m_b} \mathrm{Im}\frac{\mathrm{C}_8^{\mathrm{eff}}}{\mathrm{C}_7^{\mathrm{eff}}}$$

Experimental part

The B-factories

- Asymmetric ***e***$^+$***e***$^-$ colliders @ **10.58 GeV** center of mass energy

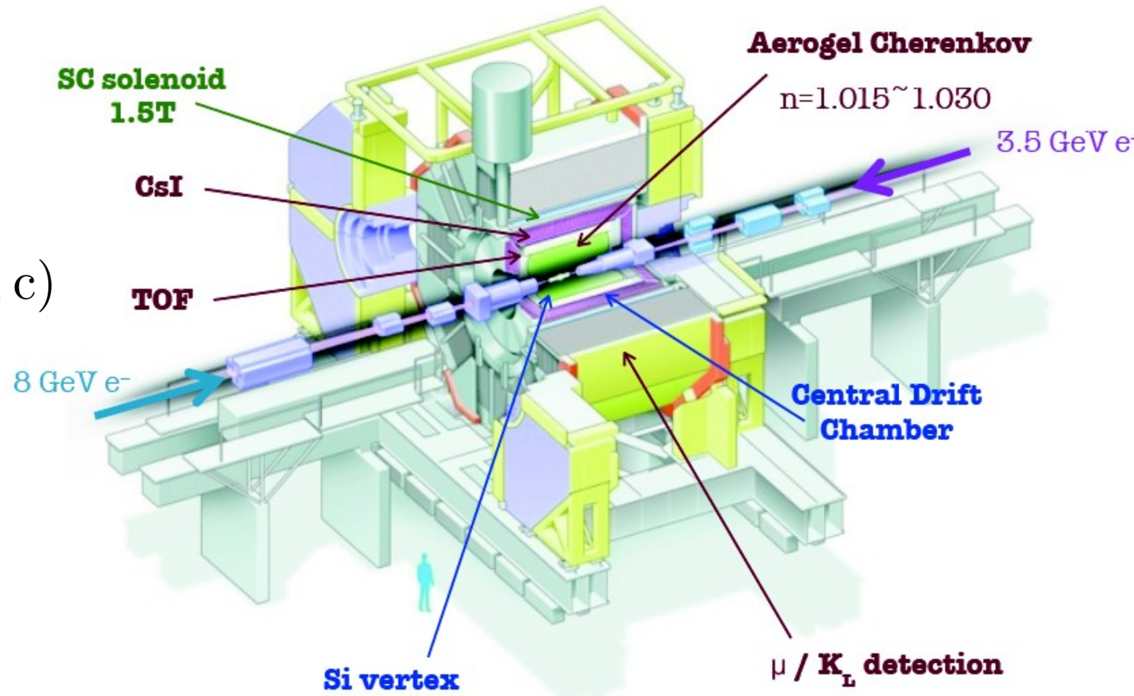
- On resonance:

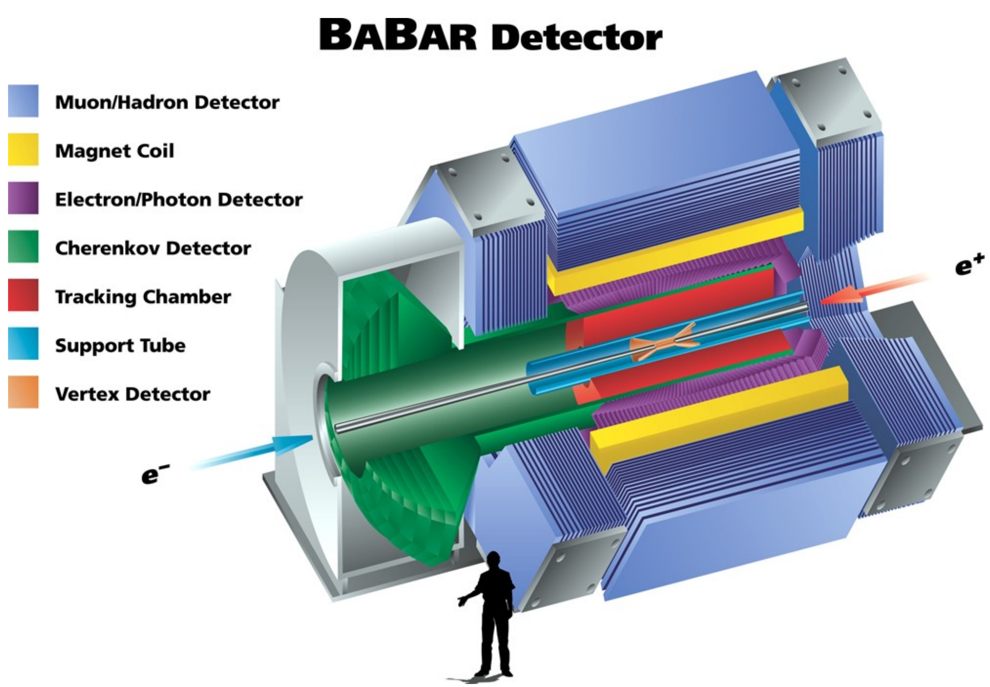
$$\sqrt{s} = 10.58\text{GeV} \quad e^+e^- \to \Upsilon(4S) \to B\overline{B}$$

- Continuum:

$$\sqrt{s} \text{ below } \Upsilon(4S) \quad e^+e^- \to q\overline{q}(q = u, d, s, c)$$

  - Continuum is ~3 times more abundant than ***BB***





- Belle + BABAR: 711fb^{-1}+433fb^{-1} on ***Y(4S):***
  Over 1 billion ***BB*** pairs!
- Continuum: 90fb^{-1}+44fb^{-1}

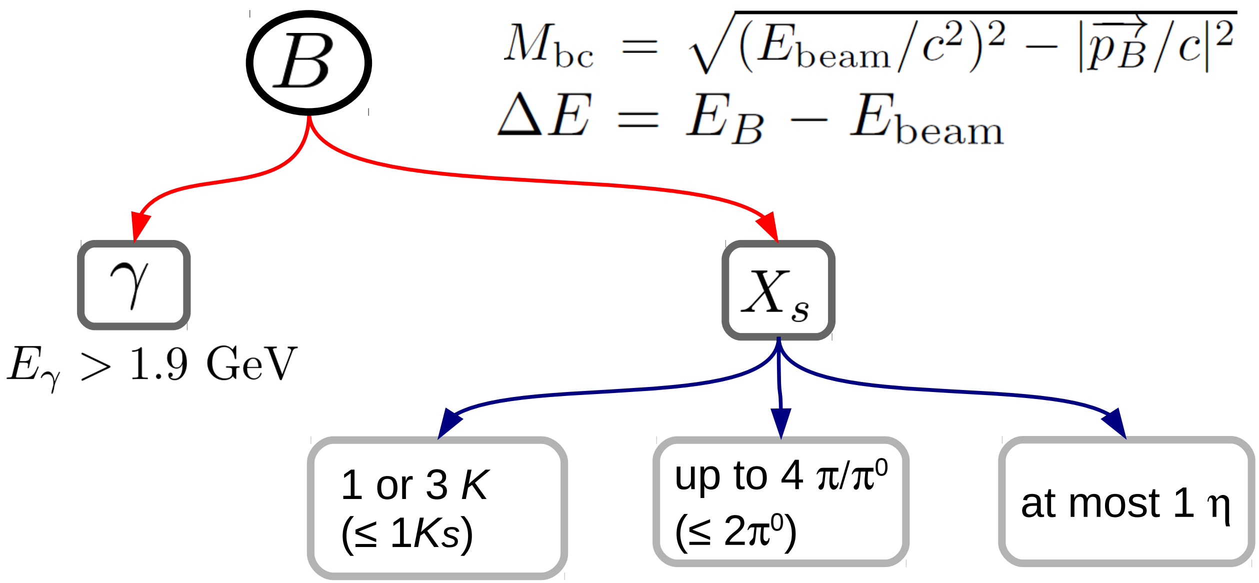
Semi-inclusive method: reconstruction

- Reconstruct as many final states as possible

Belle: Phys. Rev. D 91, 052004(2015)

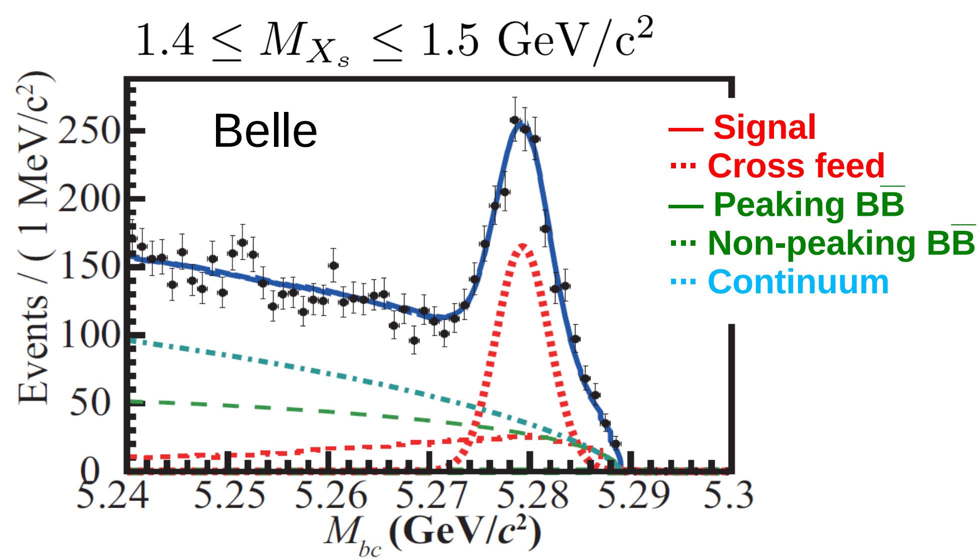
BABAR: Phys. Rev. D 86, 052012(2012)

$$M_{\rm bc} = \sqrt{(E_{\rm beam}/c^2)^2 - |\vec{p_B}/c|^2}$$
$$\Delta E = E_B - E_{\rm beam}$$



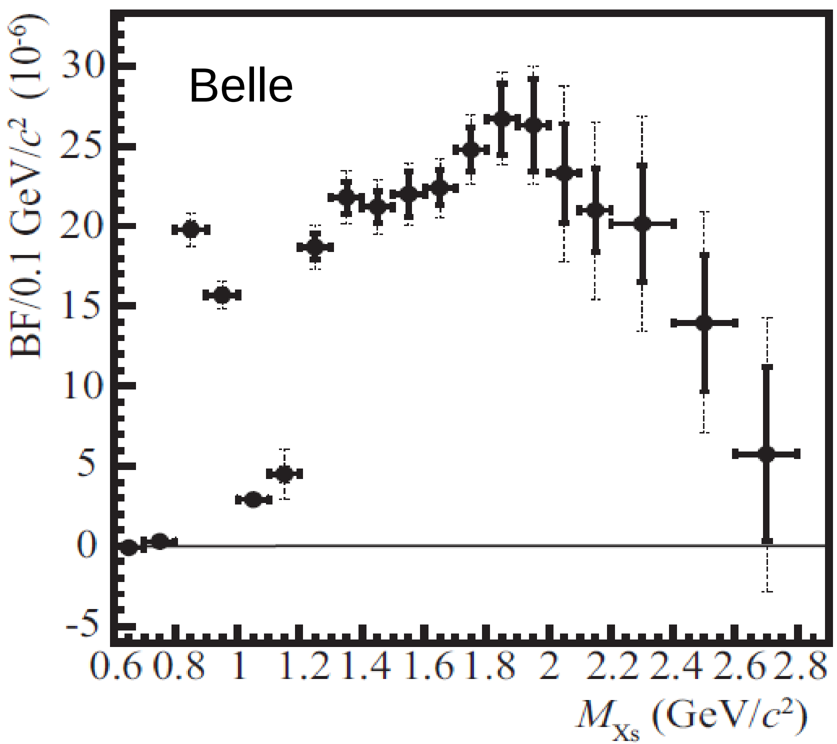
- 38 exclusive ***Xs*** states
- Large combinatoric BG and cross-feed
- ***Xs*** selection efficiencies hard to determine
- **70% of total BF**

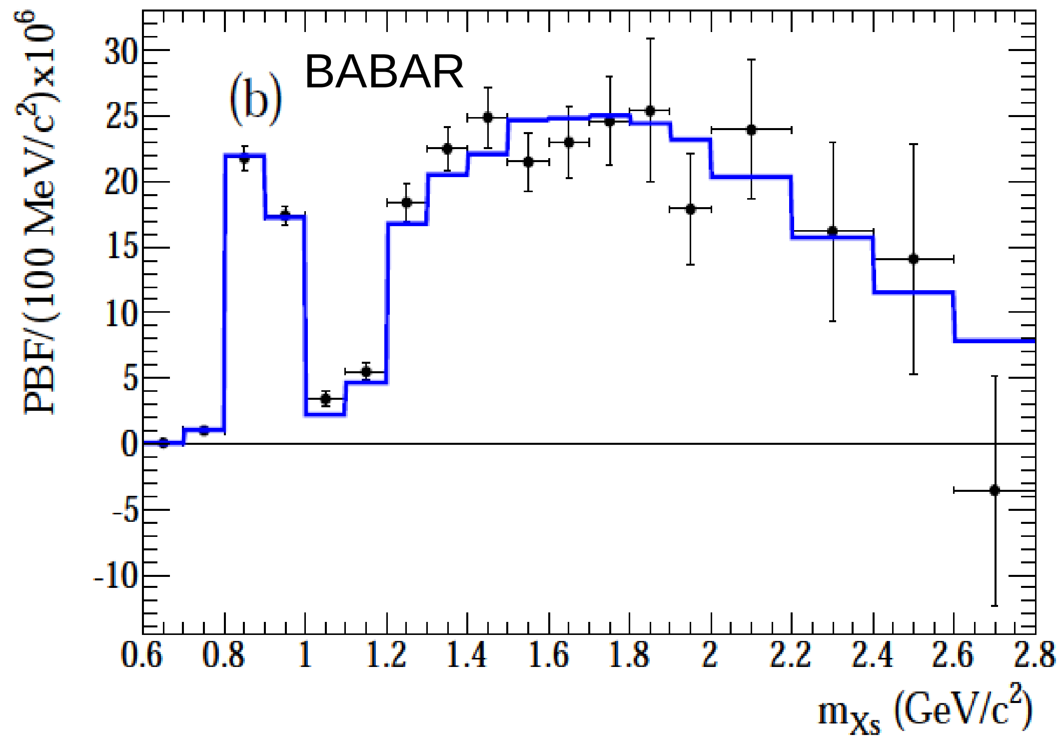
- Use of ***MVAs*** to reduce background
- Selection efficiencies and fraction of missing modes estimated using JETSET and PYTHIA



Semi-inclusive method: reconstruction

- **BF** extracted in hadronic mass ***M(Xs)*** bins: $0.6 \leq M_{X_s} \leq 2.8\ \mathrm{GeV/c^2}$
- Partial **BF:**





- Integrated **BF** >1.9GeV

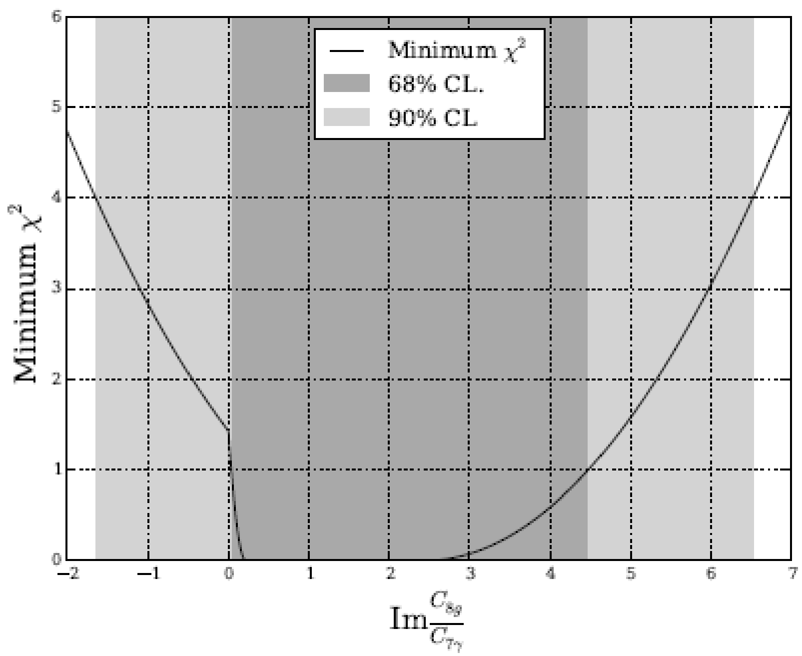
$$\text{Belle:} \quad \mathcal{B}(B \to X_s\gamma) = (3.51 \pm 0.17 \pm 0.33) \times 10^{-4}$$
$$\text{BABAR:} \quad \mathcal{B}(B \to X_s\gamma) = (3.29 \pm 0.19 \pm 0.48) \times 10^{-4}$$

- Systematics: missing modes (1%-30%), background fitting (~4%), detector response (~3%)

Semi-inclusive method: A_{CP} and ΔA_{CP}

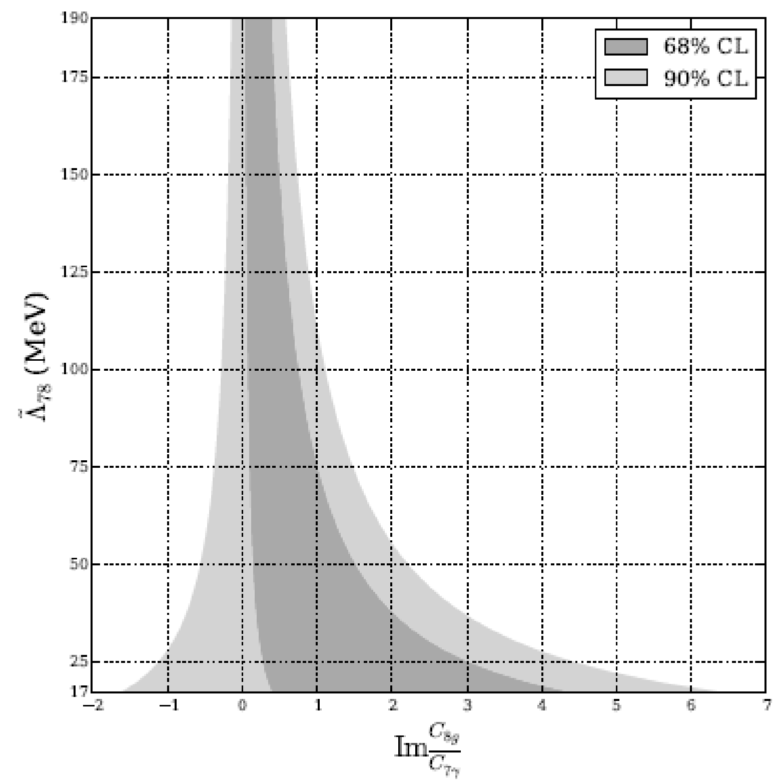
- BABAR uses 16 self-tagging modes
- Consistent with SM $B \to X_s\gamma: \quad -0.6\% < A_{CP}^{\mathrm{SM}} < 2.8\%$ $\qquad A_{CP}^{\mathrm{meas}} = (1.7 \pm 1.9 \pm 1.0)\%$
- $\Delta A_{CP} \equiv A_{CP}(B^+ \to X_s^+\gamma) - A_{CP}(B^0 \to X_s^0\gamma)$

  $\Delta A_{CP} \approx 0.12 \frac{\bar{\Lambda}_{78}}{100\mathrm{MeV}} \mathrm{Im}(\mathrm{C}_8/\mathrm{C}_7)$, where $17\ \mathrm{MeV} < \bar{\Lambda}_{78} < 190\ \mathrm{MeV}$
- From $\Delta A_{CP} = (5.0 \pm 3.9 \pm 1.5)\%$ confidence intervals for ***C8/C7*** can be derived



$$0.07 \le \mathrm{Im}\,\frac{C_{8g}}{C_{7\gamma}} \le 4.48, \quad 68\%\ \mathrm{CL},$$

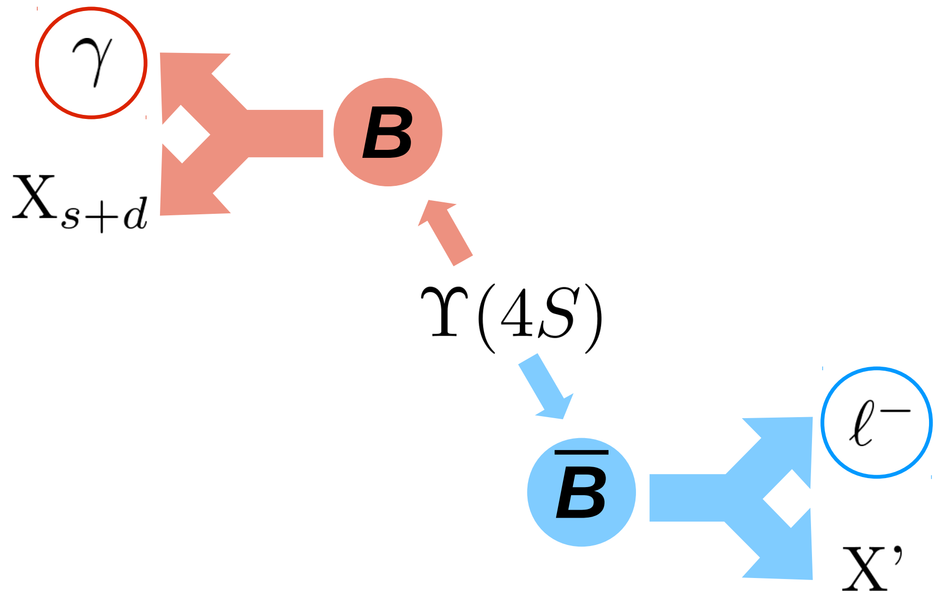
$$-1.64 \le \mathrm{Im}\,\frac{C_{8g}}{C_{7\gamma}} \le 6.52, \quad 90\%\ \mathrm{CL}.$$



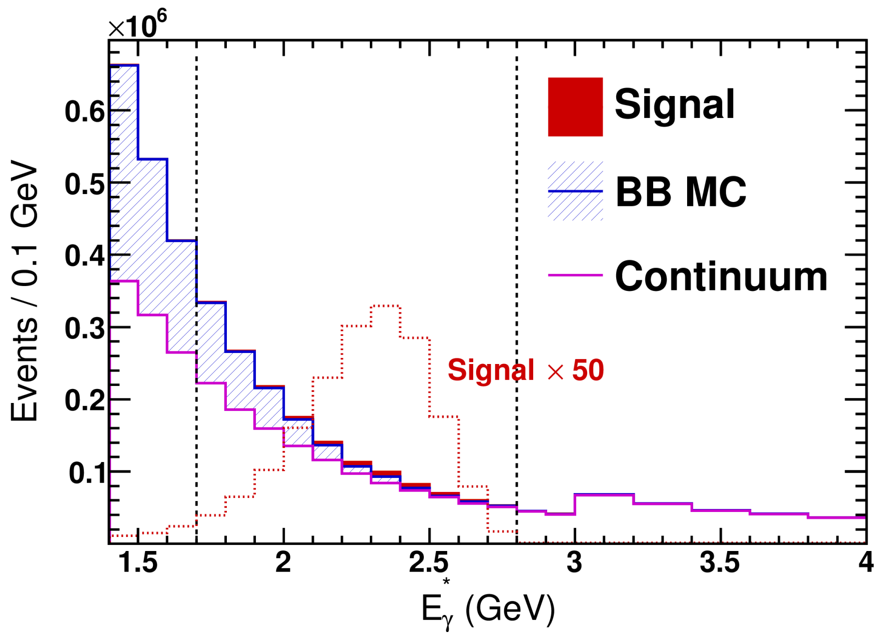
BABAR:Phys. Rev. D 90, 092001 (2014)

Inclusive method: reconstruction

- Inclusive analysis:
  - High energy **photon** $E_\gamma > 1.7\ \mathrm{GeV}$
  - High momentum **lepton**
    - Continuum suppression and flavor tagging (for ***A*CP**)



- Veto light meson decays $\pi^0(\eta) \to \gamma\gamma$
- Statistics are limiting factor (continuum data subtraction)
- Does not distinguish $b \to s\gamma$ from $b \to d\gamma$
- Large background: need for **MVAs**



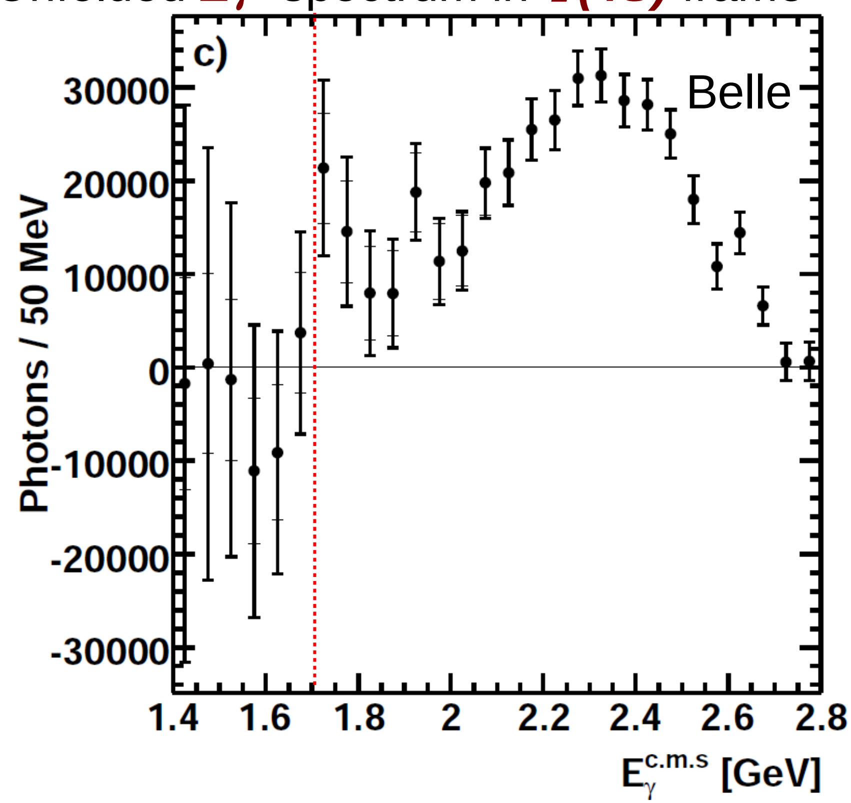
Inclusive method: BF

Belle:Phys.Rev.Lett.103:241801(2009)

BABAR:Phys.Rev.D.86,112008 (2012)

- Important issues
  - **MVA** for continuum suppression
  - Normalization of **π/η** background
  - Unfolding
- BABAR, main systematics from:
  - BB background modeling (7.8%)
  - Selection efficiency uncertainty (3.1%)
- Belle measured **BF** with and without lepton tag (and ***E*γ> 1.7 GeV**).
  - 7.5% uncertainty from continuum
  - 7.5% uncertainty from BB

Unfolded ***E*γ*** spectrum in ***Υ(4S)*** frame



Belle 657M $B\bar{B}$ BABAR 383M $B\bar{B}$

$\mathcal{B}(B\to X_s\gamma)$	E_γ >1.7 GeV
Belle	$(3.45 \pm 0.15 \pm 0.40) \times 10^{-4}$
$\mathcal{B}(B\to X_s\gamma)$	E_γ >1.9 GeV
Belle	$(3.21 \pm 0.11 \pm 0.16) \times 10^{-4}$
BABAR	$(3.00 \pm 0.14 \pm 0.19 \pm 0.06) \times 10^{-4}$

Inclusive method: $A_{CP}(B \to X_{s+d}\gamma)$

- Number of events tagged by a positive or negative lepton:

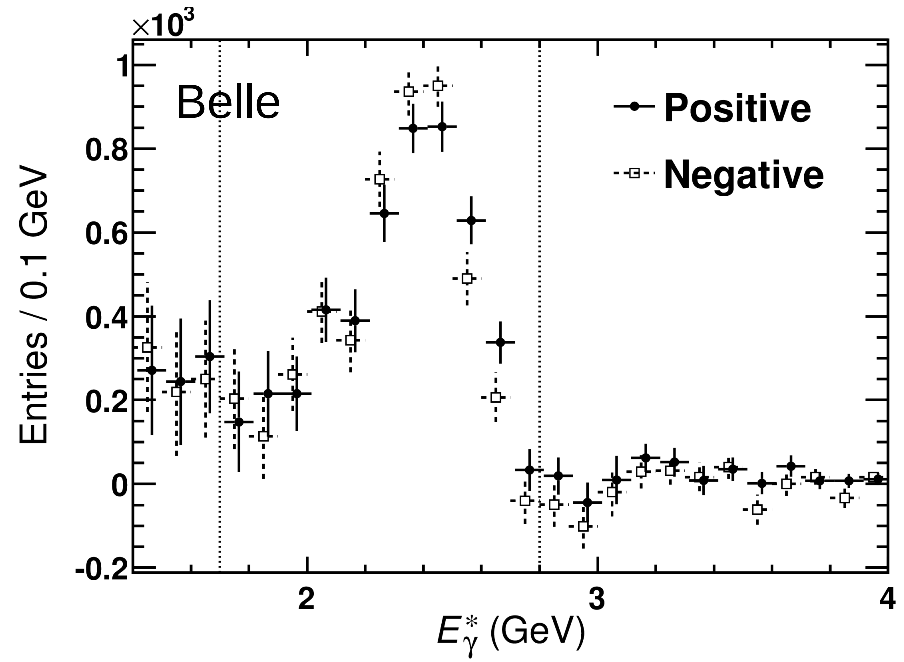
$$A_{CP}^{\mathrm{meas}} = \frac{N(\ell^+) - N(\ell^-)}{N(\ell^+) + N(\ell^-)}$$

- Correct for various effects:

$$A_{CP}^{\mathrm{true}} = \frac{1}{1-2\omega}(A_{CP}^{\mathrm{meas}} - A_{\mathrm{bkg}} - A_{\mathrm{det}})$$

  - Wrong tag factor ω $\approx 14\%$: oscillation, secondaries, fakes
  - Detector asymmetry ***Adet*** $\approx (0.0 \pm 0.3)\%$: tag and probe, mapping of the whole detector, use $B \to XJ/\psi(\ell^+\ell^-)$
  - Background asymmetry $\approx (0.0 \pm 0.7)\%$: in data Eγ<1.7 GeV

- Independent of choice of E*γ threshold.



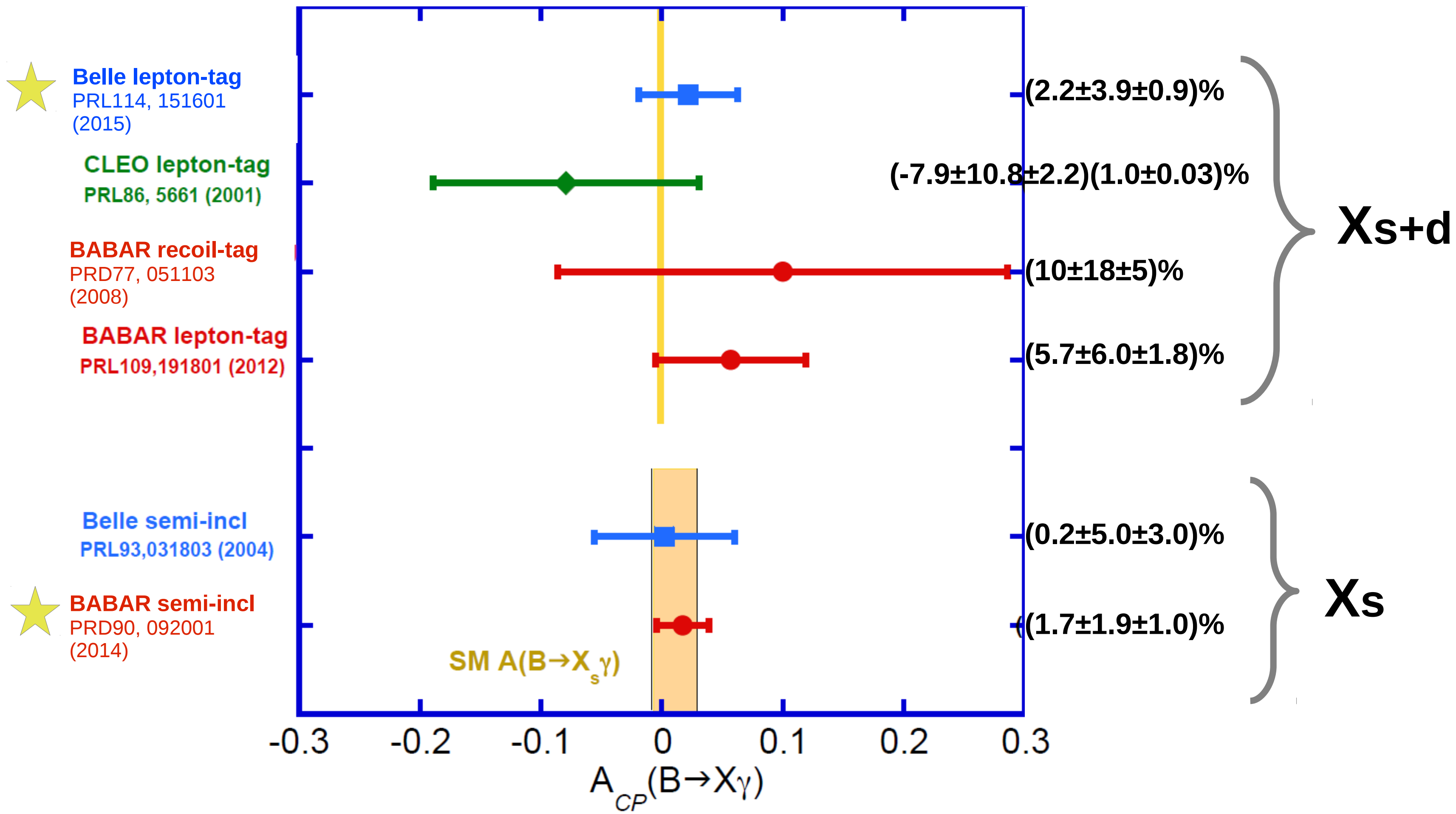
	$E^*_\gamma > 2.1\mathrm{GeV}$ $A_{CP}(X_{s+d}\gamma)$
Belle	$(2.2 \pm 3.9 \pm 0.9)\%$
BABAR	$(5.7 \pm 6.0 \pm 1.8)\%$

Belle:Phys.Rev.Lett.114,151601 (2015)

BABAR:Phys.Rev.D.86,112008 (2012)

Direct A_{CP} in $B \to X_{s+d}\gamma$ and $B \to X_s\gamma$

- Precision greatly affected by statistics → can be improved in Belle II
  - Most systematics cancel
- No deviation from Standard Model

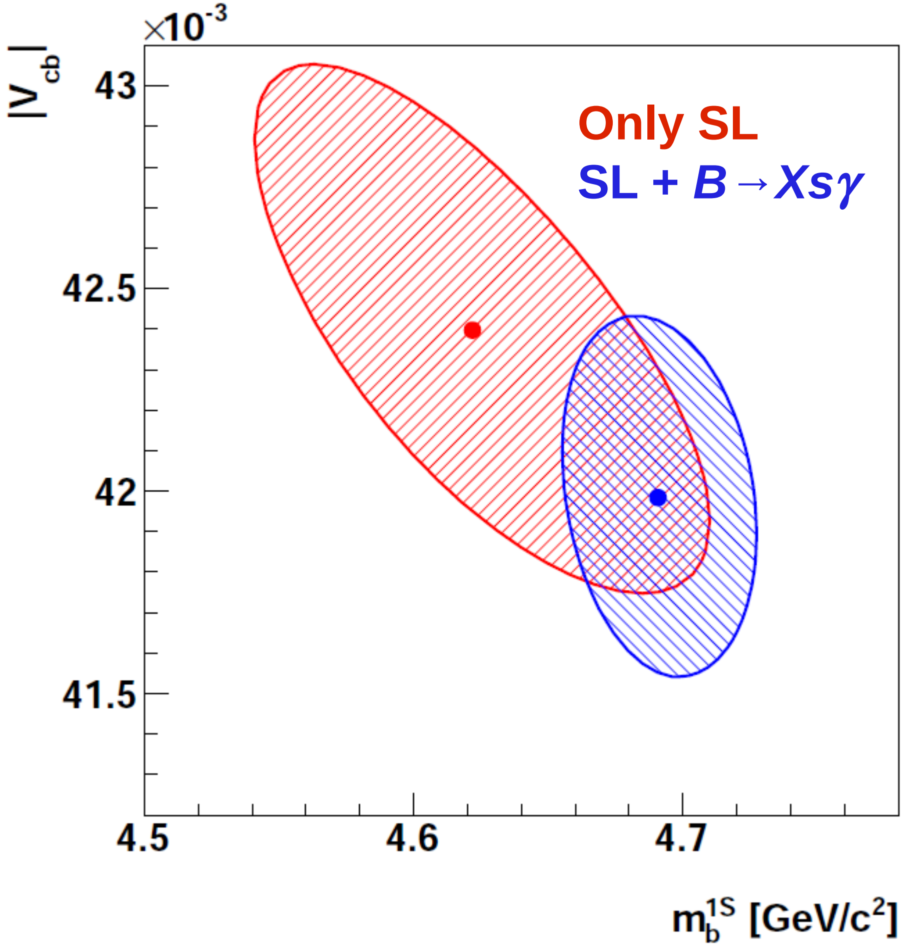


Using the $B \to X_s\gamma$ spectrum

- Example: 1st and 2nd moments can be used to constrain **m_b** in the **1S scheme.** Input from BABAR, Belle and CLEO

$$\mathrm{E}_1 : \langle E_\gamma \rangle$$
$$\mathrm{E}_2 : \langle (E_\gamma - \langle E_\gamma \rangle)^2 \rangle$$

- More precise determination of **$|V_{cb}|$**, respect to only semileptonic inputs



	m_b^{1S} (GeV/c^2)
SL	4.62 ± 0.09
SL+$B \to X_s\gamma$	4.69 ± 0.04

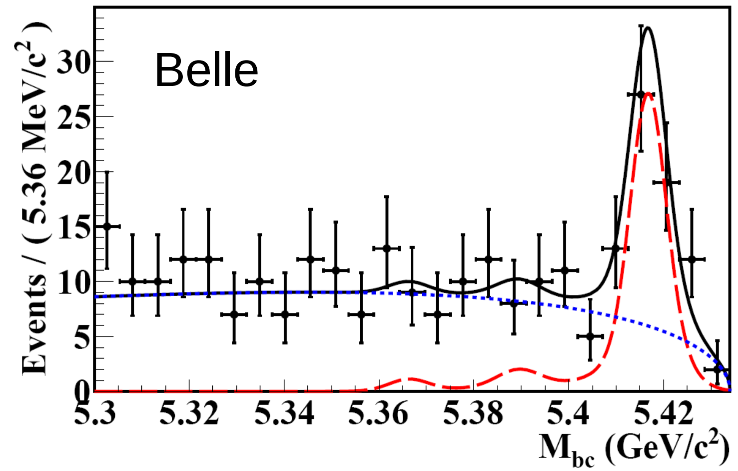
	$\lvert V_{cb}\rvert \times 10^3$
SL	42.40 ± 0.65
SL+$B \to X_s\gamma$	41.98 ± 0.45

Phys.Rev.D78:032016,2008

HFAG14:arXiv:1412.7515

Exclusive decays : $B_s \to \phi(K^-K^+)\gamma$

- Rare decay: $\mathcal{B}(B_s \to \phi\gamma)^{SM} = (3.9 \pm 1.1 \pm 0.5-) \times 10^{-5}$ **Phys.Rev.D75:054004,2007**
- Belle's 121fb^{-1} on ***Y(5S)***
- NN for continuum suppression and fitting (***C_{NB}***)
- 4-D extended maximum likelihood fit: ***M_{bc}, ΔE, $\cos\theta_{hel}$, C_{NB}***. (Show 2 projections)

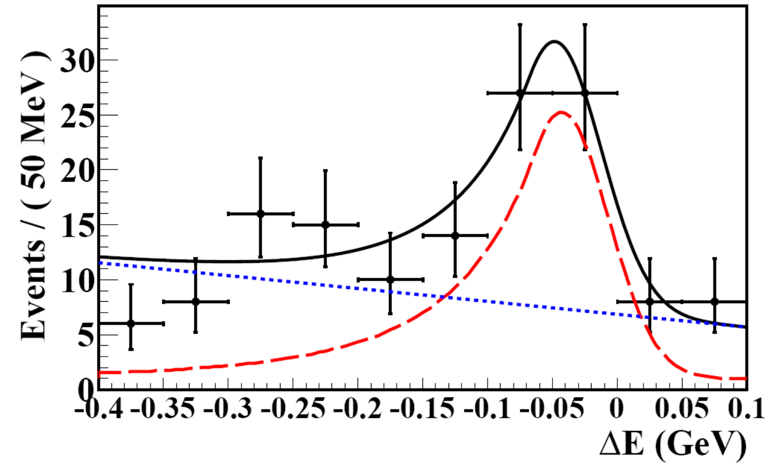


- Find 91^{+14}_{-13} candidates, $\varepsilon = (36.1 \pm 0.1)\%$

$$\mathcal{B}(B_s \to \phi\gamma) = (3.6 \pm 0.5(\mathrm{st.}) \pm 0.3(\mathrm{sys.}) \pm 0.6(\mathrm{f_s})) \cdot 10^{-5}$$

Belle: PRD 91, 011101(R) (2015)

fraction of ***B_s*** and ***bb*** cross section at ***Y(5S)*** (17%, 4.7%), NN requirement (4.8%)



- Consistent with SM and LHCb:

$$\mathcal{B}(B_s \to \phi\gamma) = (3.5 \pm 0.4) \cdot 10^{-5}$$

LHCb: Nucl.Phys.B867,1 (2013)

Best measurement of $\sigma\left(e^+e^- \to B_s^{(*)}\bar{B}_s^{(*)}\right)$ with half the uncertainty

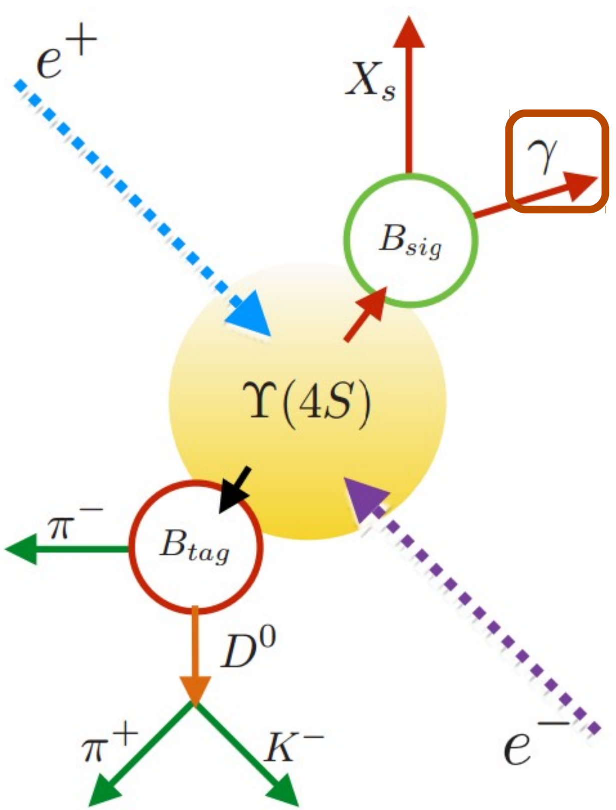
Belle arXiv:1504.02004

Prospects for Belle II

- Statistical uncertainties and several systematics will be improved:

	ΔA_{CP}	$A_{CP}(X_s\gamma)$	$A_{CP}(X_{s+d}\gamma)$
Now	5%	2%	4%
Belle II 50 ab^{-1}	$\sim 0.7\%$	$\sim 0.5\%$	$\sim 0.6\%$

- Total uncertainty in **BF** could be halved
  - Different approach: hadronic tag



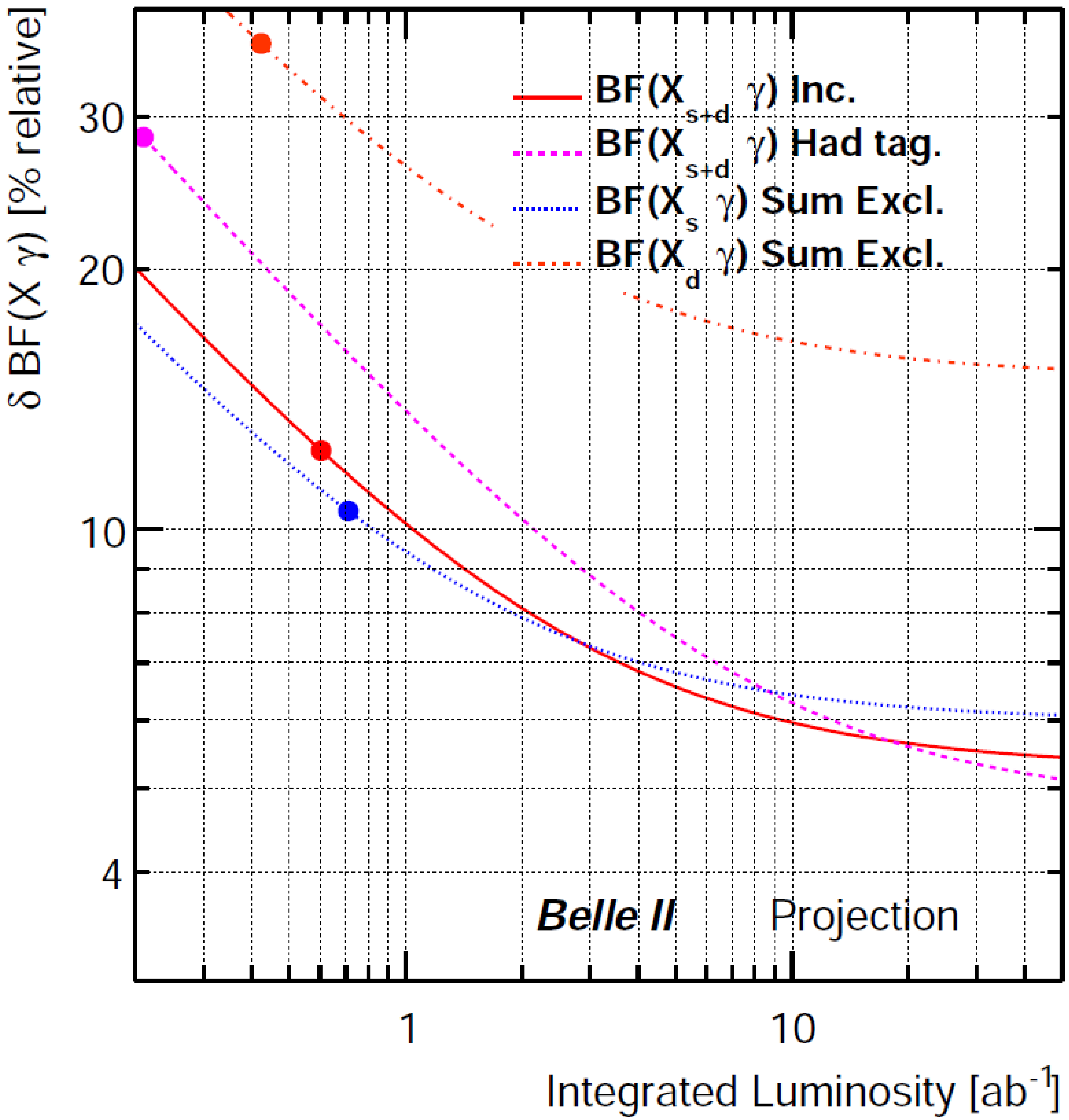
- Not yet feasible → low efficiency
- No continuum, lower model dependence
- Measures for ***B***⁺ and ***B⁰*** independently
- BABAR: 210 fb^{-1} and ~27% uncertainty
  Phys.Rev.D77,051103, (2008)

$$\mathcal{B}(B \to X_s\gamma) = (3.91 \pm 0.91 \pm 0.64) \times 10^{-4}$$
$$E_\gamma > 1.6 \text{ GeV}$$

  - Systematics: background modeling (12%), fit parameters (7.5%), detector response (11%)
  - 5% uncertainty for Belle-II 50 ab^{-1}

Prospects for Belle II

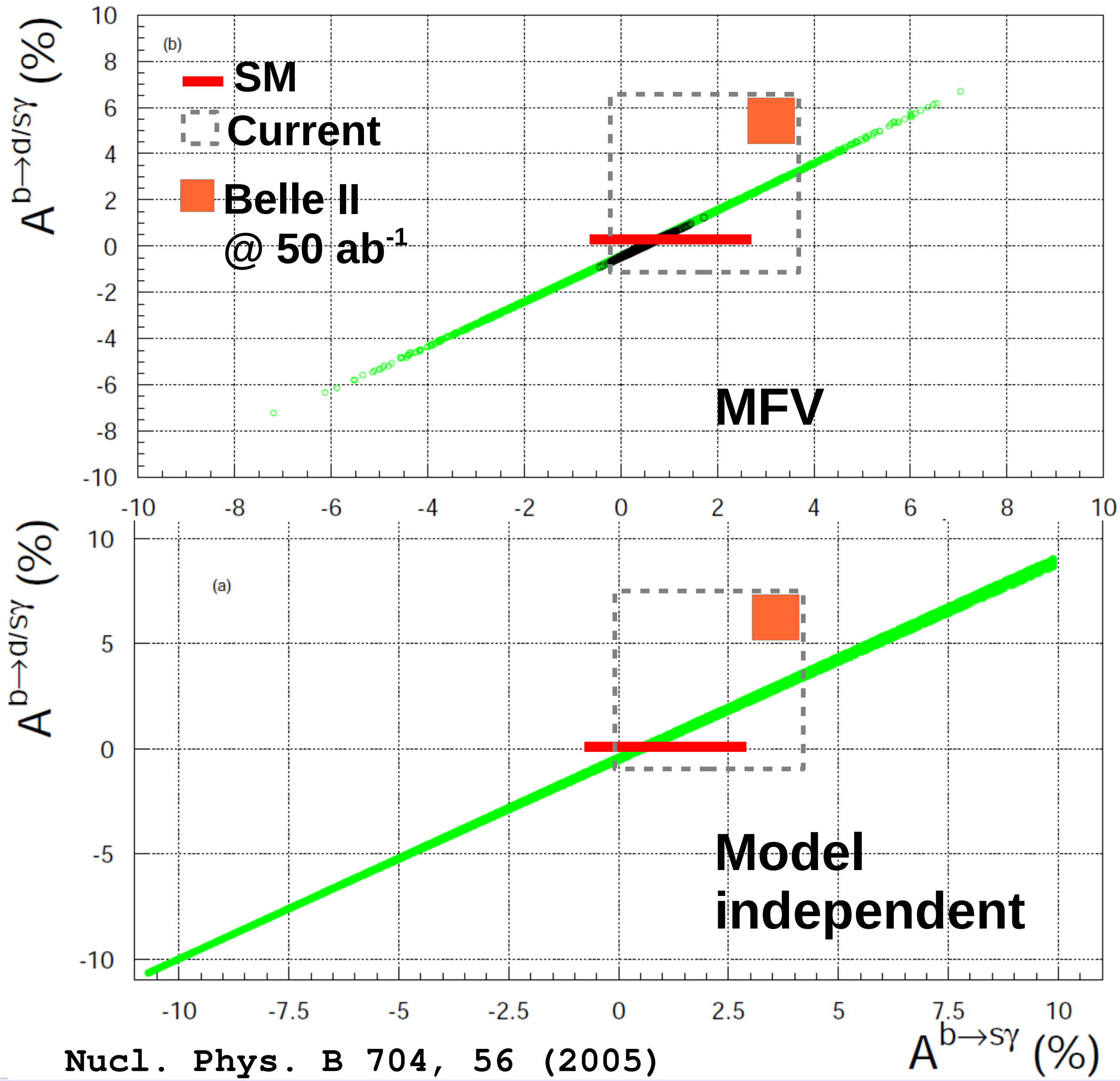
- Projection of uncertainty in ***BF*** for Belle II



New Physics

Beyond SM - MFV

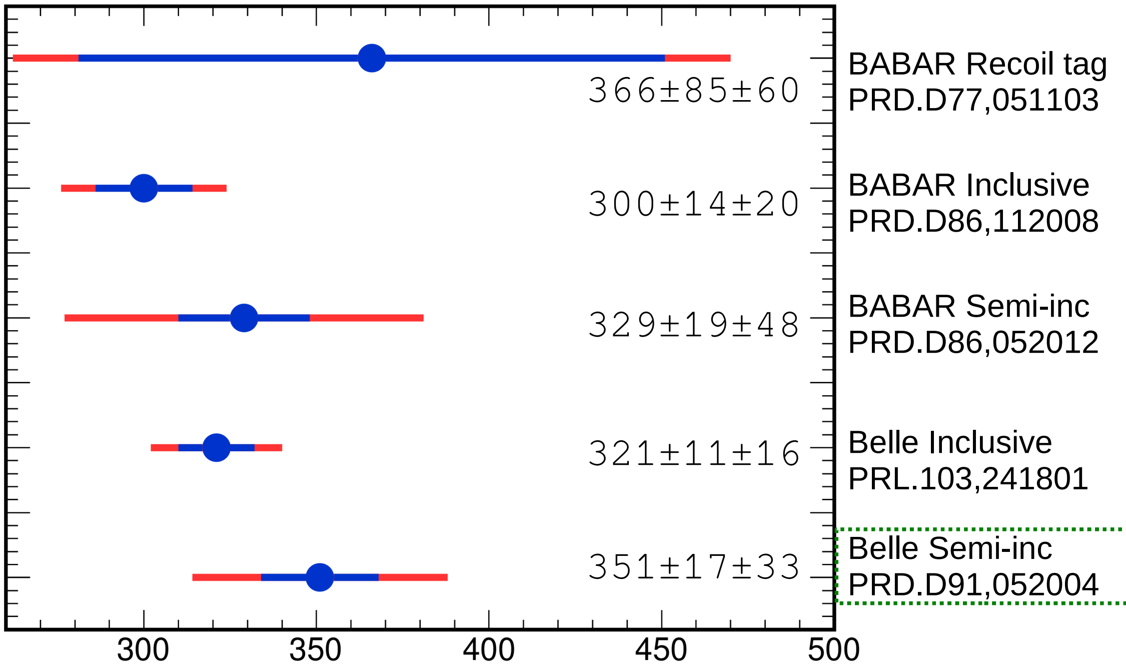
- Strict proportionality between tagged and untagged **A_{CP}**.
- In MFV ~2%, more generic approaches allow for **A_{CP}** as large as 10%



Nucl. Phys. B 704, 56 (2005)

- If **A_{CP}≠0**, current experimental precision does not suffice to distinguish between these scenarios

Beyond SM - 2HDM-II



$\mathcal{B}_{X_s\gamma} \times 10^6$ for $E^*_\gamma > 1.9\text{GeV}$

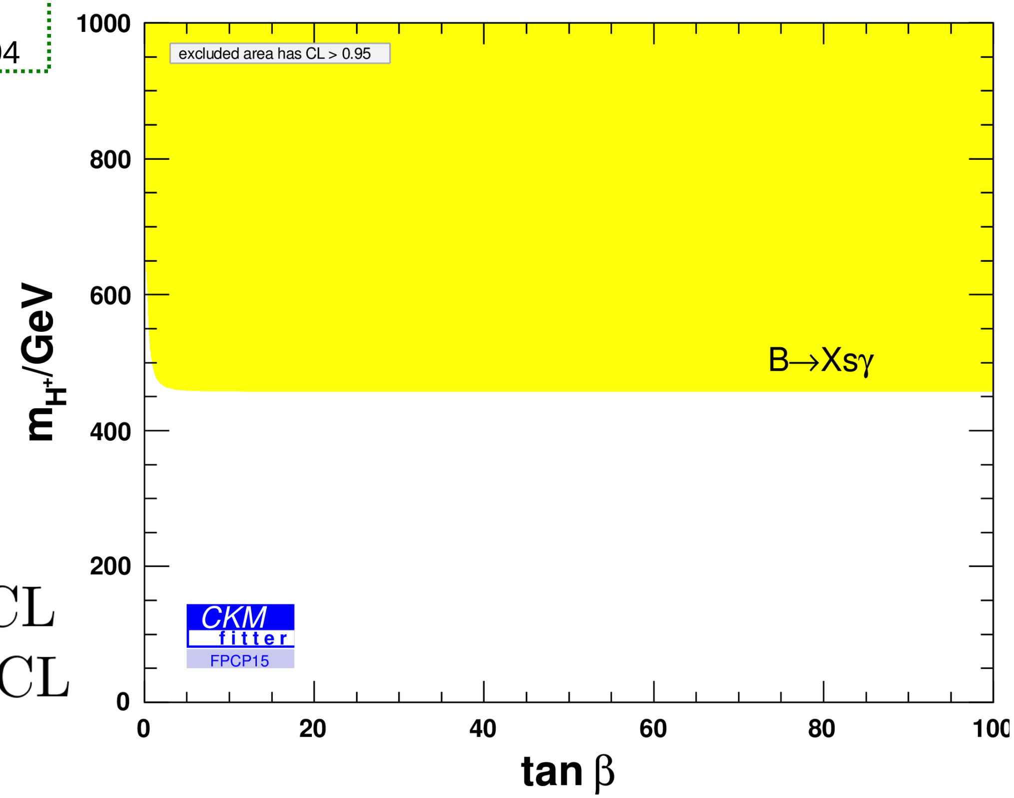
- ***BF(B→Xsγ)*** for 1.9 GeV photon energy threshold (and excluding CLEO)
- Extrapolate to 1.6 GeV using kinetic scheme

Phys.Rev.D73:073008 (2006)

$$\mathcal{B}^{SM}_{X_s\gamma} = (336 \pm 23) \times 10^{-6}$$
$$\mathcal{B}^{exp}_{X_s\gamma} = (341 \pm 16(\text{exp}) \pm 4(\text{extrap})) \times 10^{-6}$$

- For charged Higgs in 2HDM of type II:

$$\text{2014 avg:} \quad M(H^-) > 480 \text{ GeV at } 95\% \text{ CL}$$
$$\text{1.9 GeV avg:} \quad M(H^-) > 540 \text{ GeV at } 95\% \text{ CL}$$

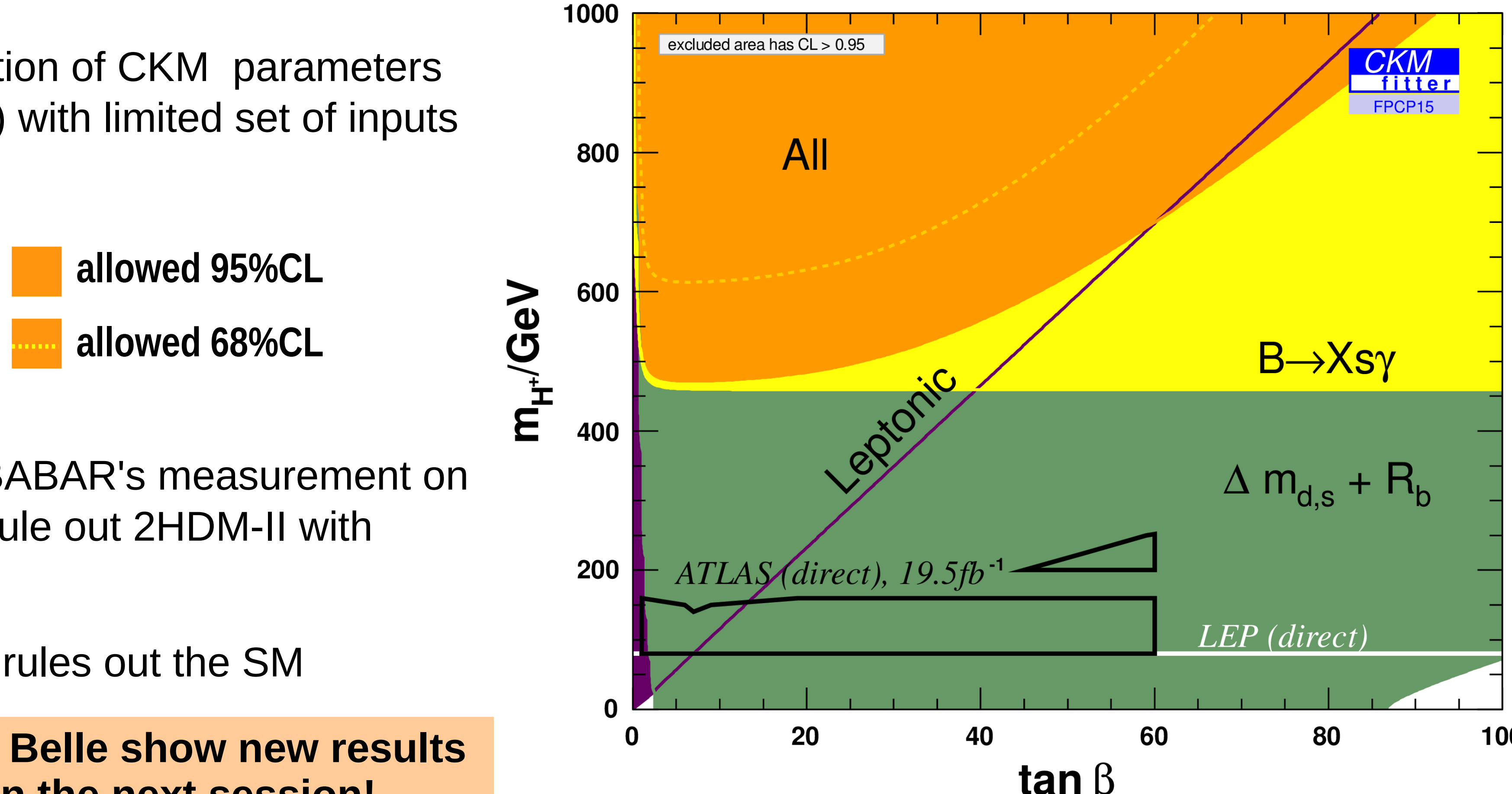


Beyond SM - 2HDM-II

$$\text{Leptonic}: \frac{K\to\ell\nu}{\pi\to\ell\nu} \;\&\; \frac{\tau\to K\nu}{\tau\to\pi\nu}, \frac{K\to\pi\mu\nu}{K\to\pi e\nu}, \mathcal{B}(Ds\to\mu\nu), \mathcal{B}(D\to\mu\nu), \mathcal{B}(B\to\tau\nu)$$

$$\text{Box and loop}: \frac{\mathcal{B}(B\to X_s\gamma)}{\mathcal{B}(B\to X_c\ell\nu)}, R_b = \frac{Z\to b\bar{b}}{Z\to \text{hadrons}}, B_{s,d}\bar{B}_{s,d} \text{ oscillation frequencies}$$

- Determination of CKM parameters (***A, λ, ρ, η***) with limited set of inputs



- However BABAR's measurement on **$B\to D^{(*)}\tau\nu$** rule out 2HDM-II with 99.8% CL
  - But also rules out the SM
- **LHCb and Belle show new results on *$R(D^{(*)})$* in the next session!**

ATLAS(arXiv:1412.6663)
LEP (arxiv:1301.6065)

Summary & Outlook

- **Flavor can provide valuable information for SM and NP**
  - **BF($B \to X_s\gamma$)** is calculated and measured with 7% precision
    - Improvements in SM calculations and experiment put ***m(H⁻)>540*** **GeV**
- **Belle II prospects are very exciting**
  - Direct **A_{CP}** measurements greatly limited by statistics: room for improvement
  - Full hadronic tag approach will be feasible
  - Several systematics do scale with statistics
- **Understanding of *f_s* and *bb* cross section currently limits *Y(5S)* studies**
  - New and more precise ***B_s*** measurements are being produced.

BACKUP

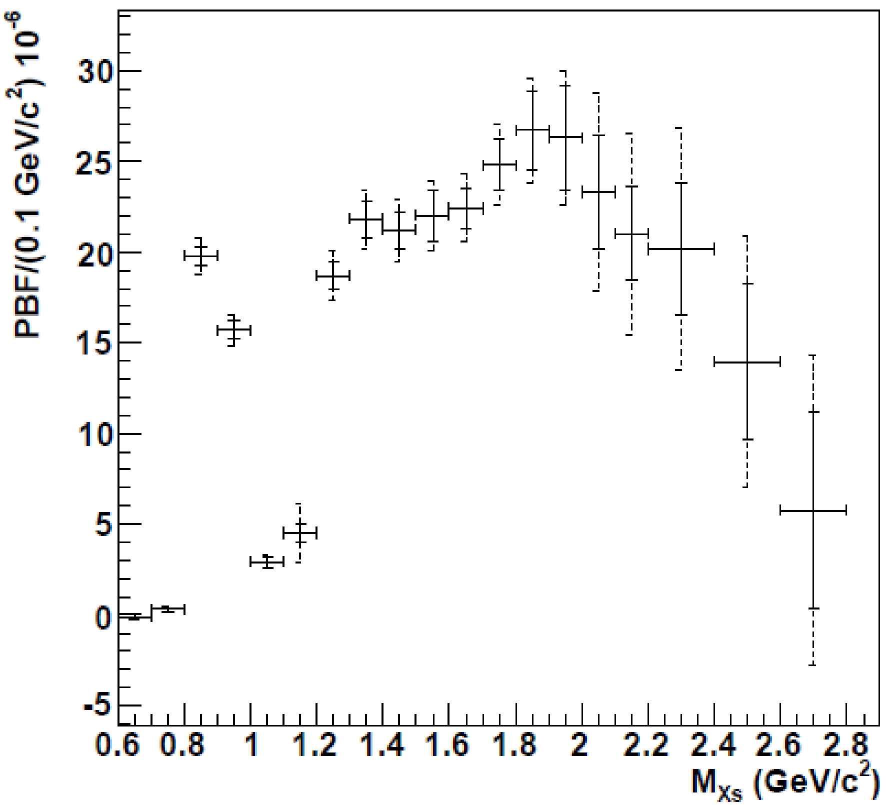
Reconstructed $B \to X_s \gamma$ modes

Mode ID	Final state	Mode ID	Final state	Mode ID	Final state
1	$K^+\pi^-$	16	$K_s\pi^+\pi^+\pi^-\pi^0$	31	$K^+\eta\pi^-\pi^0$
2	$K_s\pi^+$	17	$K^+\pi^0\pi^0$	32	$K_s\eta\pi^+\pi^0$
3	$K^+\pi^0$	18	$K_s\pi^0\pi^0$	33	KKK
4	$K_s\pi^0$	19	$K^+\pi^-\pi^0\pi^0$	34	KKK_s
5	$K^+\pi^+\pi^-$	20	$K_s\pi^+\pi^0\pi^0$	35	KK_sK_s
6	$K_s\pi^+\pi^-$	21	$K^+\pi^+\pi^-\pi^0\pi^0$	36	$K^+K^+K^-\pi^-$
7	$K^+\pi^+\pi^0$	22	$K_s\pi^+\pi^-\pi^0\pi^0$	37	$K^+K^-K_s\pi^+$
8	$K_s\pi^+\pi^0$	23	$K^+\eta$	38	$K^+K^+K^-\pi^0$
9	$K^+\pi^+\pi^-\pi^-$	24	$K_s\eta$		
10	$K_s\pi^+\pi^+\pi^-$	25	$K^+\eta\pi^-$		
11	$K_s\pi^+\pi^0$	26	$K_s\eta\pi^+$		
12	$K_s\pi^+\pi^0$	27	$K^+\eta\pi^0$		
13	$K^+\pi^+\pi^+\pi^-\pi^-$	28	$K_s\eta\pi^0$		
14	$K_s\pi^+\pi^+\pi^-\pi^-$	29	$K^+\eta\pi^+\pi^-$		
15	$K_s\pi^+\pi^+\pi^-\pi^0$	30	$K_s\eta\pi^+\pi^-$		

Partial $B \to X_s \gamma$ BF

Table 9.12: The partial branching ratio on M_{X_s}

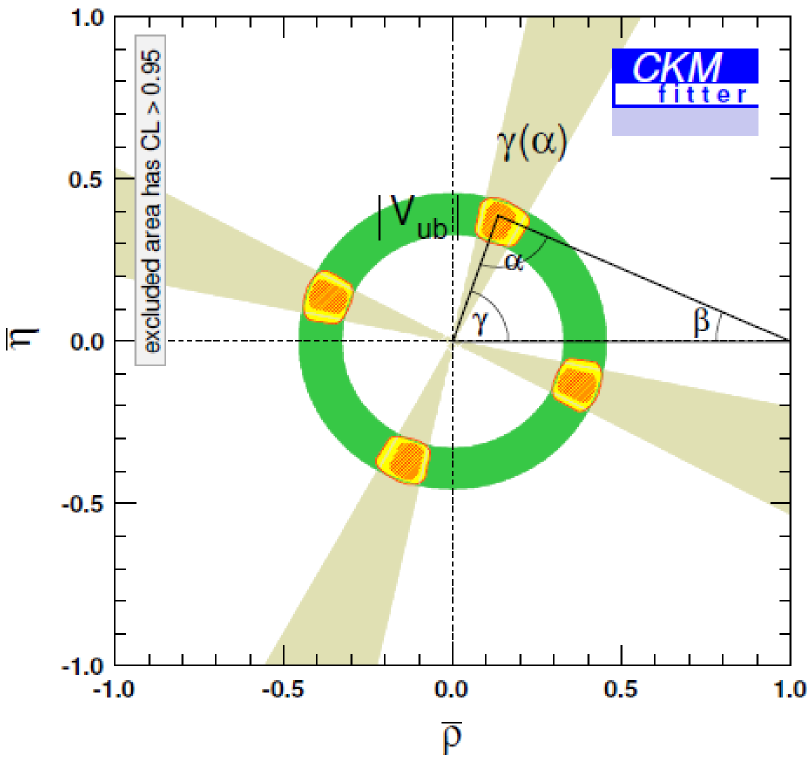
M_{X_s} bin(GeV/c^2)	$\mathcal{BR}(10^{-6})$
0.6-0.7	-0.1±0.1±0.0
0.7-0.8	0.3±0.1±0.1
0.8-0.9	19.8±0.5±0.9
0.9-1.0	15.7±0.5±0.7
1.0-1.1	2.9±0.3±0.2
1.1-1.2	4.8±0.5±1.5
1.2-1.3	18.7±0.8±1.1
1.3-1.4	21.8±1.0±1.3
1.4-1.5	21.2±1.0±1.4
1.5-1.6	22.0±1.4±1.3
1.6-1.7	22.4±1.1±1.5
1.7-1.8	24.8±1.4±1.7
1.8-1.9	26.7±2.2±1.9
1.9-2.0	26.3±2.9±2.3
2.0-2.1	23.3±3.1±4.5
2.1-2.2	21.0±2.6±4.9
2.2-2.4	40.3±7.2±11
2.4-2.6	27.9±8.6±11
2.6-2.8	11.5±11±13



(a) Partial branching ratio.The first solid error is the statistical one and the second dashed error is a quadratic sum of the statistical and systematic errors.

SM inputs for 2HDM-II limits

Inputs must not be sensitive to NP, so take tree-level processes where the ratio $m_{q1} \cdot m_{q2} / m^2_{H+}$ is negligibly small:



- λ from $|V_{ud}|$ (super-allowed β decays)
- A from $|V_{cb}|$ (semileptonic $b \to c$ decays), and λ
- $\rho + i\eta$:
  - from γ from $\alpha + \beta$ (don't use γ from $B \to DK$)
  - $|V_{ub}|$ (semileptonic $b \to u$ decays)

Less powerful than global fit