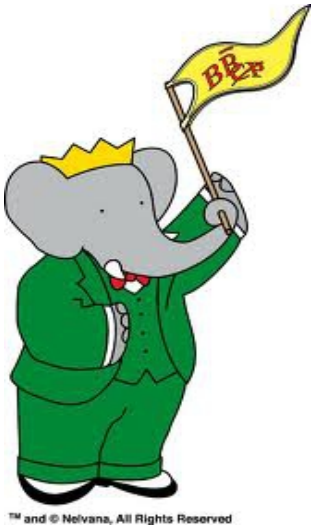
Xth Rencontres du Vietnam

Flavour Physics Conference ICISE

Quy Nhon Vietnam – 27th July - 2rd August 2014

Probing BSM Physics with Rare B Decays @ BaBar



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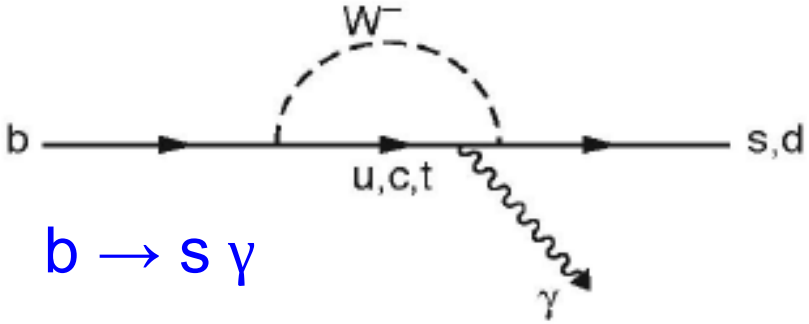
Marcello Rotondo

I.N.F.N. Padova

Rare B decays: New Physics probes

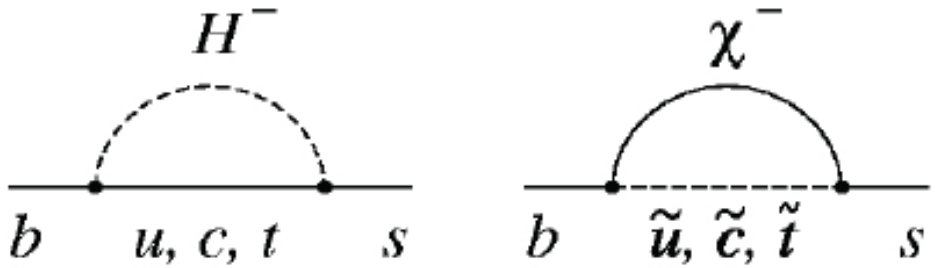
- CMS and ATLAS search for direct production of new particles predicted in many extensions of the Standard Model (SM)
- New particles also contribute to heavy mesons decays
  - Search for deviations from SM predictions due to virtual contributions of new heavy particles in loop processes
  - Complementary to the direct search at LHC
- The most interesting processes are those that are strongly suppressed in the SM: FCNC processes (but also LFV, CPV in $B_{d,s}$ mixing...)
  - NP could increase the expectations by orders of magnitude
  - Rare B decays can probe mass scales beyond the direct reach of LHC

Standard Model contribution



$b \to s\,\gamma$

New Physics loops



Rare B decays: New Physics probes

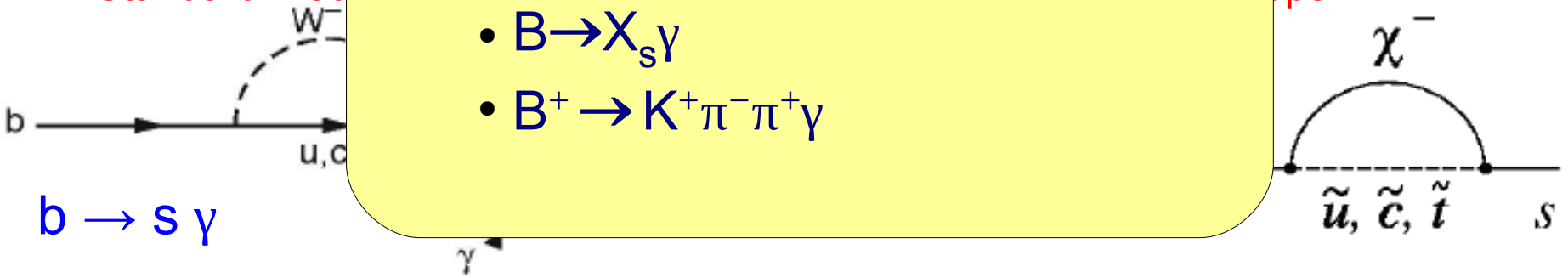
- CMS and ATLAS search for direct production of new particles predicted in many extensions of the Standard Model (SM)
- New particles also contribute to heavy mesons decays
  - Search for deviations from SM predictions due to virtual contributions of new heavy particles in loop processes
  - Complementa
- The most intere y suppressed in the SM: FCNC ng...)
  - NP could incr
  - Rare B decay ach of LHC

Outline

I will focus on recent measurements on radiative & EW penguin decays

- $B \to X_s \ell^+ \ell^-$
- $B \to X_s \gamma$
- $B^+ \to K^+ \pi^- \pi^+ \gamma$

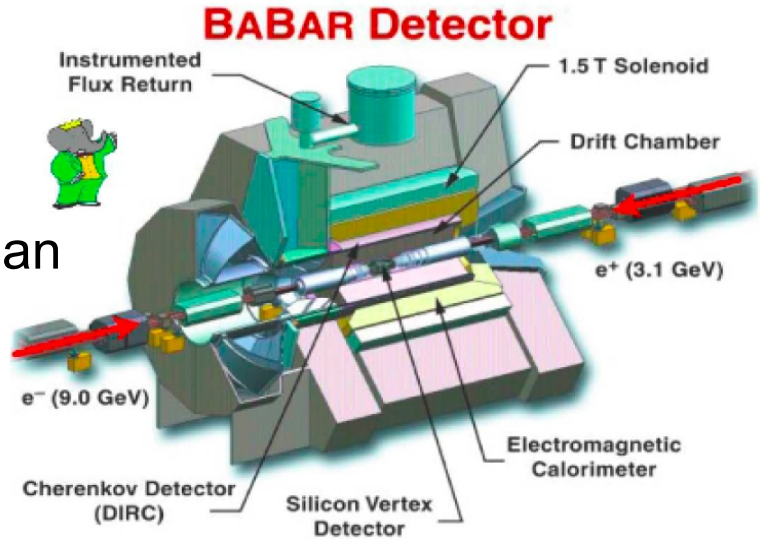
Standard Mod ops



$b \to s \gamma$

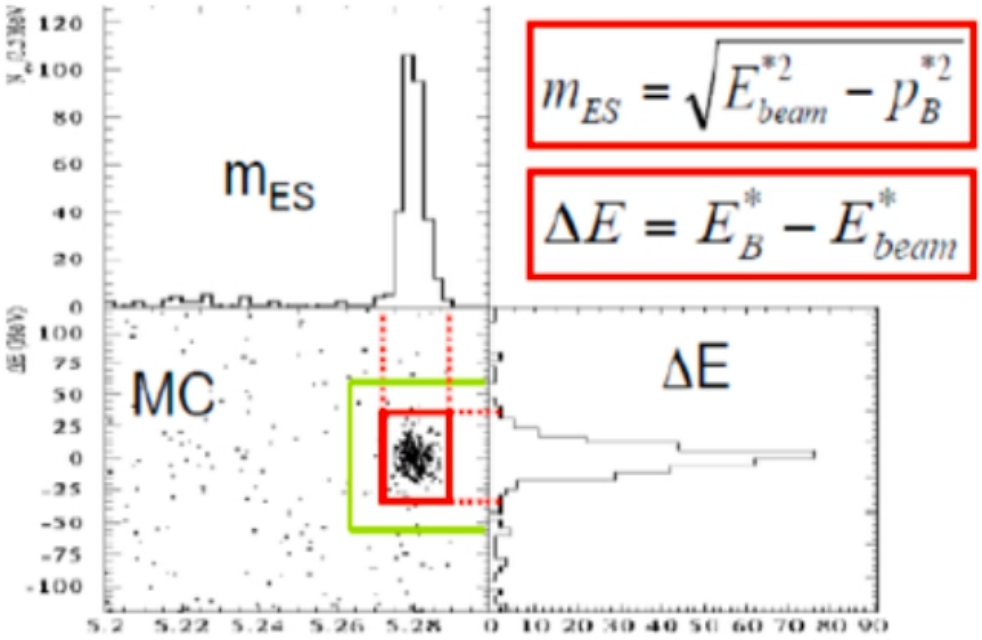
BaBar in a nutshell

- Operation: 05/1999-04/2008 (BaBar, **PEP-II**)
- e^+e^- machines run at Y(4S) resonance:
  - Y(4S) decays only in $B^0\underline{B}^0$ and B^+B^- (very clean environment)
  - Cross section is relatively high: 1.06nb
  - Backgrounds from $e^+e^- \rightarrow q\underline{q}$ (~3 nb)



~470 x 10^6 BB pairs

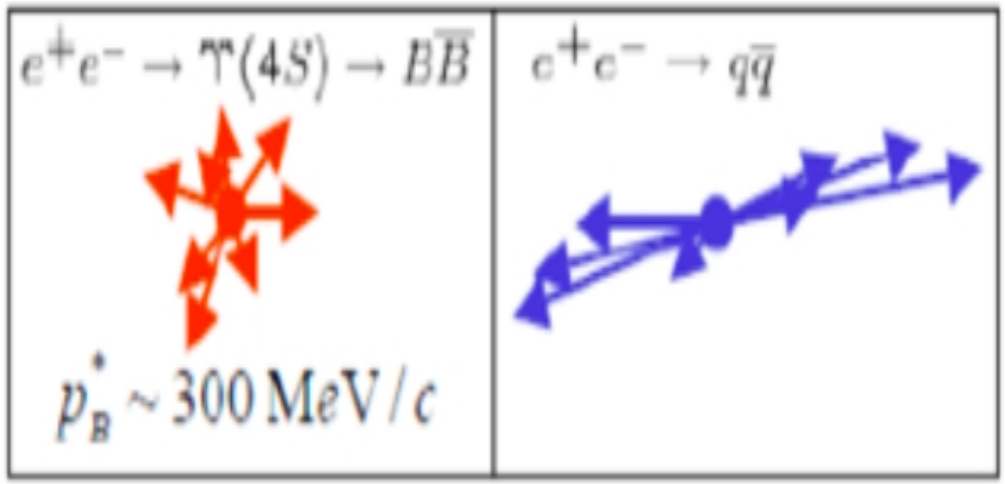
Kinematics of fully reconstructed B



$$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_B}$$

$$\Delta E = E^*_B - E^*_{beam}$$

Background discrimination



$B \to X_s \ell^+ \ell^-$

- "Measurement of the $B \to X_s \ell^+ \ell^-$ branching fraction and search for direct CP violation from a sum of exclusive final states"

- Phys. Rev. Lett. 112, 211802 (2014)

$B \to X_s \ell^+ \ell^-$ (1/4)

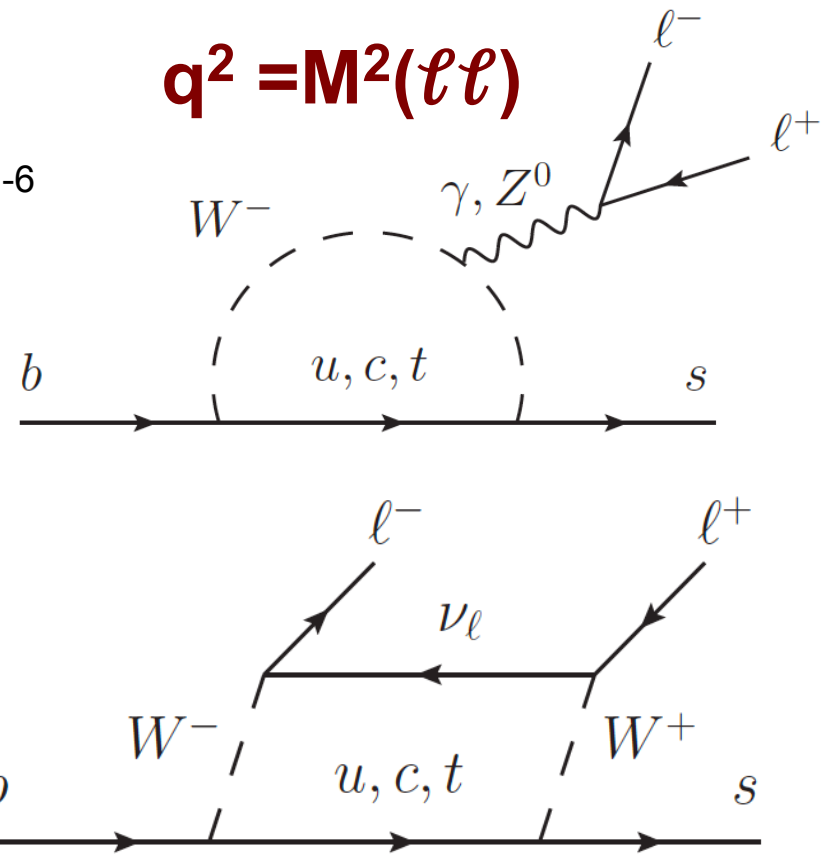
Nucl.Phys.B802,40 (2008)
Phys.Rev.D 54,882

- Sensitive to NP effects in photon, vector and axial-vector coupling
  - FCNC process forbidden at tree level: BF~10^{-6}
  - NP enter at the SM level

- $1 < q^2 < 6$ GeV^2 → $BR_{SM} = (1.59 \pm 0.11) \cdot 10^{-6}$
- $q^2 > 14.4$ GeV^2: → $BR_{SM} = (0.24 \pm 0.07) \cdot 10^{-6}$
- Direct CP violation: SM predicts $A_{CP} << 1\%$ in exclusive and inclusive transitions

- Large extent complementary to $B_s \to \mu^+\mu^-$

$q^2 = M^2(\ell\ell)$



- Decay amplitudes expressed using OPE in terms of perturbatively calculable effective coefficients:
  - Short distance Wilson coefficients: C_7^{eff}, C_9^{eff}, C_{10}^{eff}
  - Theoretical uncertainties: ~7-30% (in different q^2 regions)

$B \to X_s \ell^+ \ell^-$ (2/4)

- Measurement performed using a sum of 20 fully reconstructed modes

X_s modes

ℓ=e/μ

- 0 pions: K^+, K_s
- 1 pion: $K^+\pi^0$, $K^+\pi^-$, $K_s\pi^+$, $K_s\pi^0$
- 2 pions: $K^+\pi^-\pi^0$, $K^+\pi^-\pi^-$, $K_s\pi^+\pi^0$, $K_s\pi^+\pi^-$

Not used in the A_{CP} measurement

- Reconstructed states account for 70% of inclusive rate: extrapolation to total rate from MC (JETSET fragmentation and theoretical
- B decays to J/ψ and ψ(2S) have same final state particles: explicit mass vetoes applied → vetoed events make excellent control sample

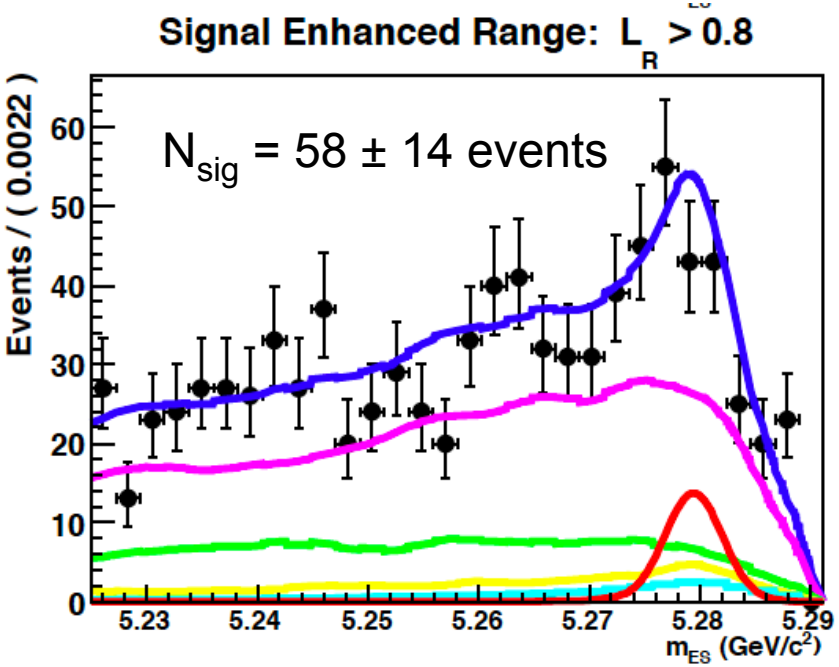
- $B \to X_s \ell^+ \ell^-$ yields extracted in hadronic mass (M_x) and q^2 bins

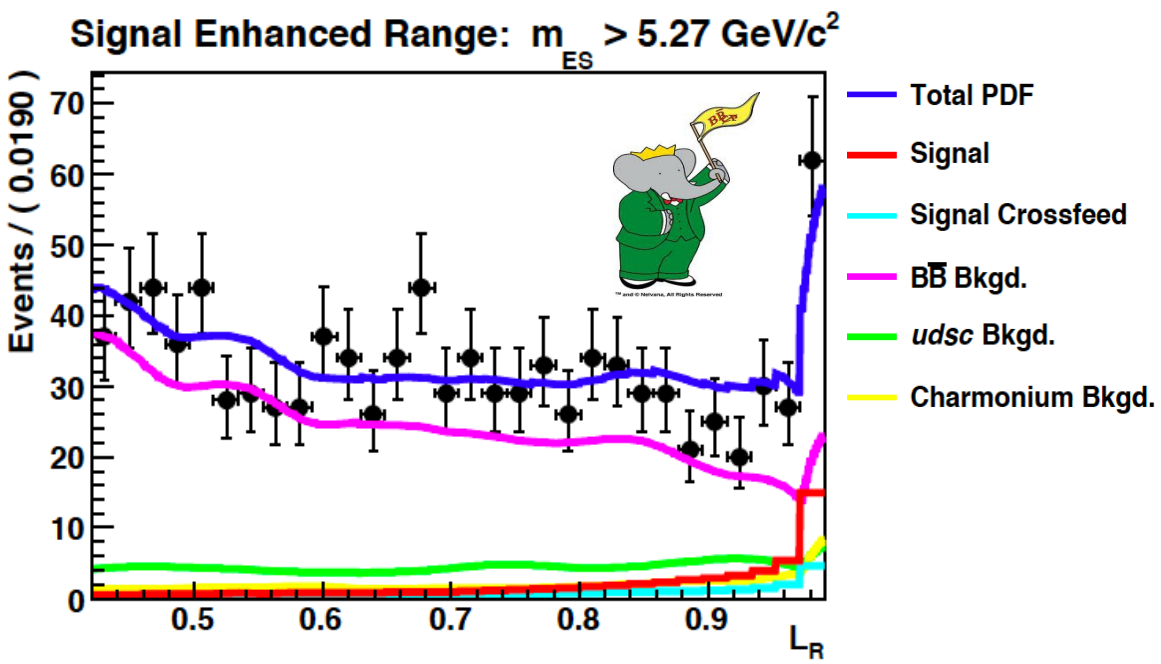
$$\frac{d\mathcal{BR}}{dq^2} \quad \frac{d\mathcal{BR}}{dM_x} \quad \mathcal{BR} \quad \frac{dA_{CP}}{dq^2}$$

$B \to X_s \ell^+ \ell^-$ (3/4)

- Yields extracted in various q^2 & M_x bins by 2D (m_{ES}, L_R) fit
  - $m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_B} \quad \Delta E = E^*_B - E^*_{beam}$
  - BB combinatorial background using a Likelihood Ratio (L_R) defined from outputs of eights BDTs exploiting kinematical and topological quantities

$B \to X_s e^+ e^-$: $1 < q^2 < 6$ GeV^2





$B \to X_s \ell^+ \ell^-$ (4/4)

- Observed BR scaled to full rate based on simulation

$$BR = (6.73\ ^{+0.70}_{-0.64}\ ^{+0.34}_{-0.25}\ \pm 0.50) \cdot 10^{-6}$$

$$BR_{SM} = (4.6 \pm 0.8) \cdot 10^{-6}$$

Huber et al. NPB802,40 (2008)

- **I**: $1 < q^2 < 6$ GeV^2

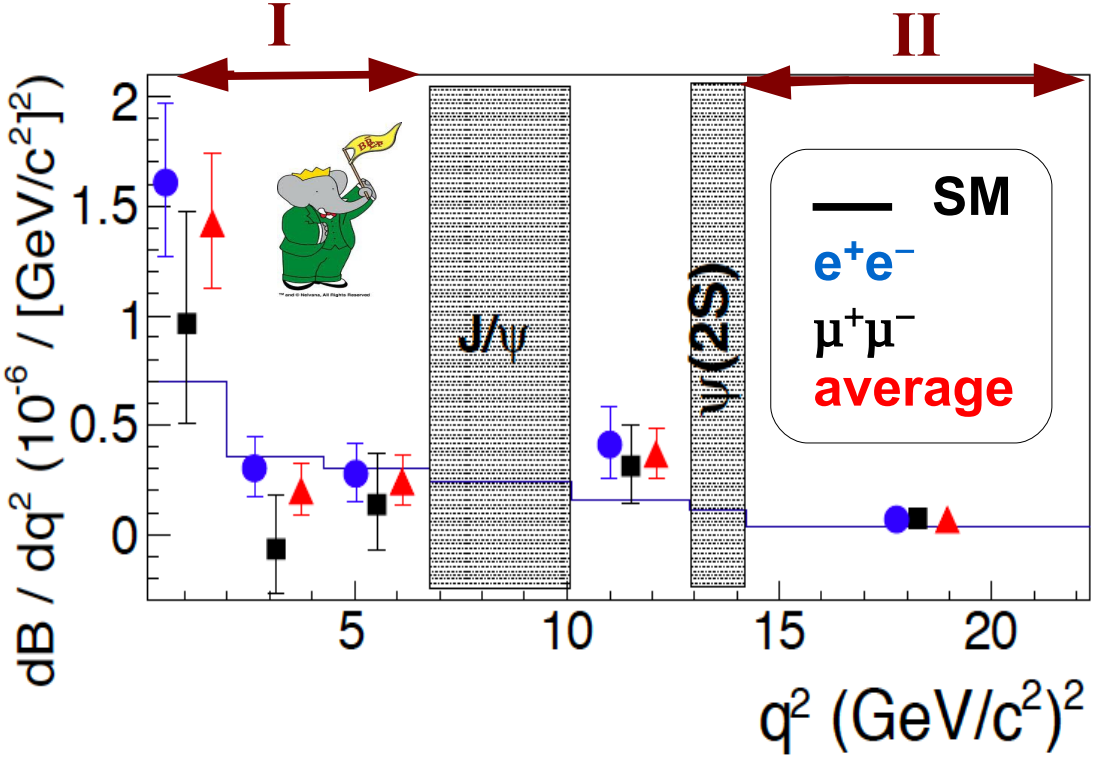
$$BR = (1.60\ ^{+0.44}_{-0.39}\ ^{+0.17}_{-0.13} \pm 0.18) \cdot 10^{-6}$$

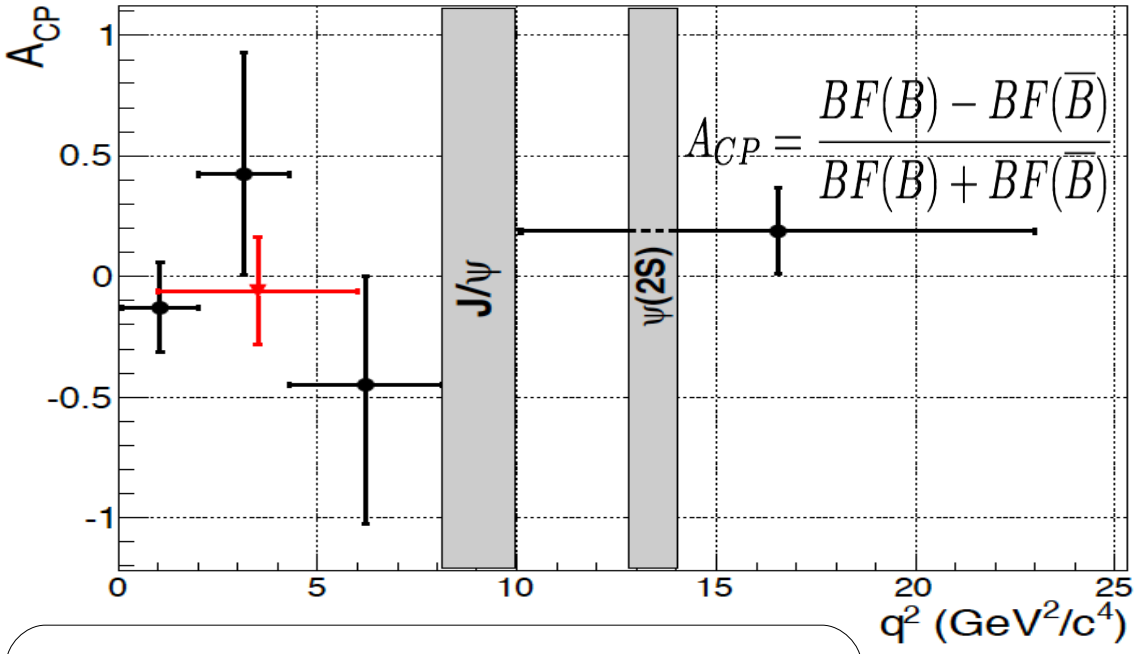
$$BR_{SM} = (1.59 \pm 0.11) \cdot 10^{-6}$$

- **II**: q^2 above $\psi(2S)$

$$BR = (0.57\ ^{+0.16}_{-0.15}\ ^{+0.03}_{-0.02} \pm 0.0) \cdot 10^{-6}$$

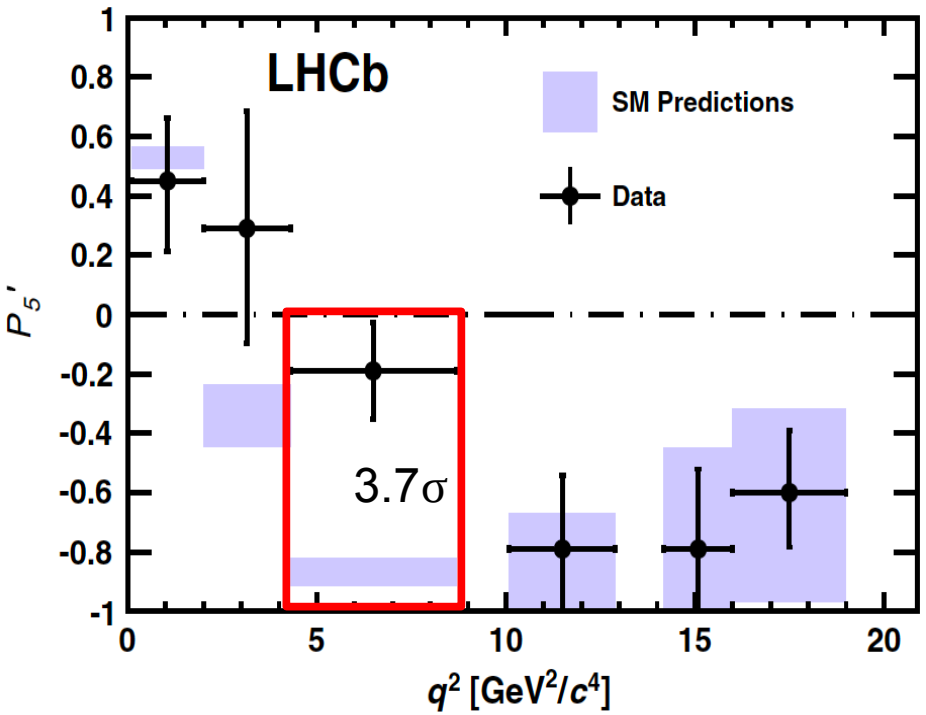
$$BR_{SM} = (0.25 \pm 0.07) \cdot 10^{-6}$$





$$A_{CP} = 0.04 \pm 0.11_{stat} \pm 0.01_{syst}$$

$B \to K \pi \ell^+ \ell^-$ & $B \to X_s \ell^+ \ell^-$



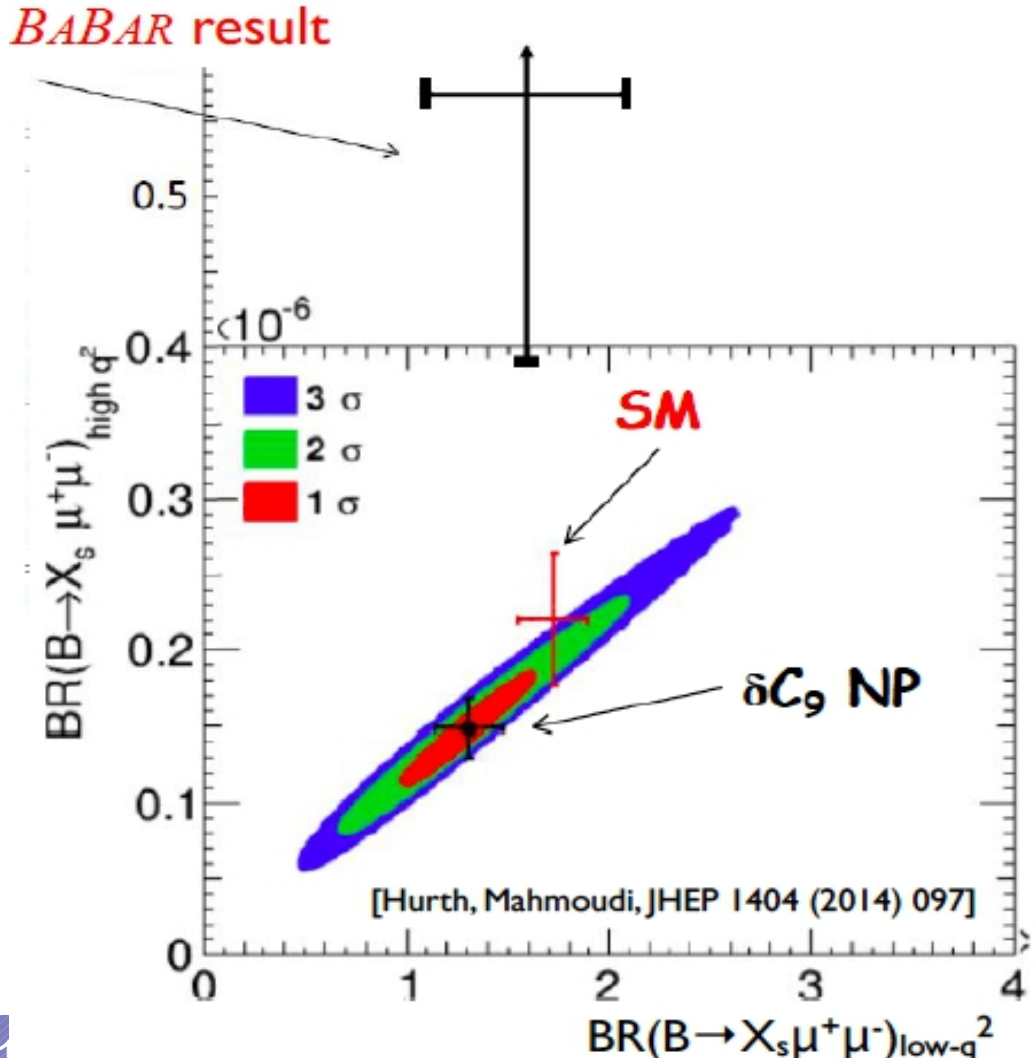
- LHCb measurement of observables "free" from Form Factor contributions

PRL111,191801(2013)

- Global fits to recent b → sll and b→ sγ data favor decreased value of Wilson coefficient $C_{9:}$: indication of NP?

JHEP1305,043 (2013), PRD88,074002(2013)

- This leads to a reduced value of inclusive B($B \to X_s \ell^+ \ell^-$)
- However, our measurement of BF at high-q^2 does not support this hypothesis



$B \rightarrow X_s \gamma$

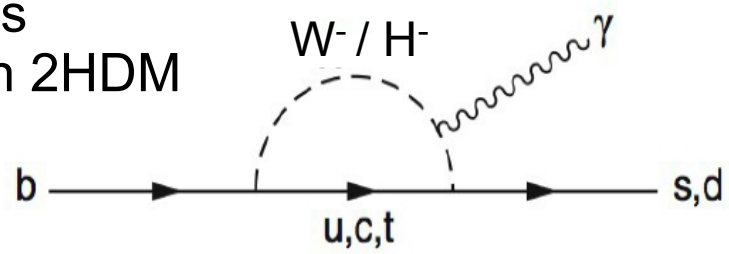
- "Measurement of Direct CP asymmetry in $B \rightarrow X_s \gamma$ decays using sum of Exclusive decays"

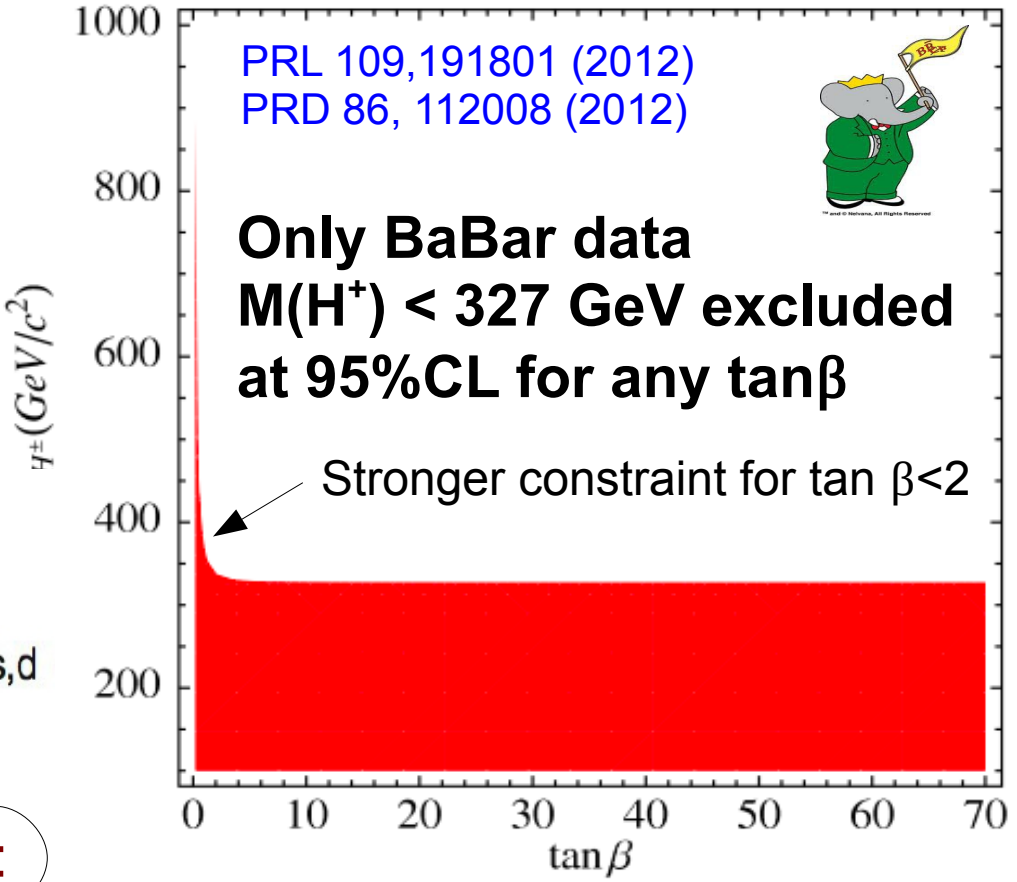
- Submitted to Phys. Rev. D. arXiv: 1406.0534

$B \to X_s \gamma$ (1/4)

- Measurement of the BF of <u>inclusive</u> $B \to X_s \gamma$ decay is extremely powerful to constrain NP

Charged Higgs Contribution in 2HDM





- New observables in inclusive decays:

Direct CP violation

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

- Expected small in the SM

$-0.6\ \% < A_{CP}^{SM} < 2.8\%$

- New particles in the loop could enhance A_{CP} up to 15%

Difference of CP asymmetry

$$\Delta A_{CP} = A_{CP}(B^{\pm}) - A_{CP}(B^0) \propto Im(\frac{C_7}{C_8})$$

- Allows access to Wilson coefficients C_8

Benzke et al. PRL106,141801
Hurt at al. Nucl.Phys.B 704 56
Wolfenstein et.al PRL73,2809

$B \to X_s \gamma$ (2/4)

- Measurement performed using a sum of 38 reconstructed modes
  - 16 self-tagged modes for A_{CP} measurement

- K and π using charge PID, veto $\pi^0/\eta \to \gamma\gamma$
- Selection criteria:
  - $1.6 < E_\gamma < 3.0$ GeV
  - $0.6 < m_{Xs} < 2.0$ GeV
  - $\Delta E > 0.15$ GeV
  - $M_{ES} > 5.24$ GeV/c^2

- Two multivariate classifiers to:
  - Select the best candidate
  - Reduce continuum background

Charge modes

$K_S^0\ \pi^+\ \gamma$
$K^+\ \pi^0\ \gamma$
$K^+\ \pi^+\ \pi^-\ \gamma$
$K_S^0\ \pi^+\ \pi^0\ \gamma$
$K^+\ \pi^0\ \pi^0\ \gamma$
$K_S^0\ \pi^+\ \pi^-\ \pi^+\ \gamma$
$K^+\ \pi^+\ \pi^-\ \pi^0\ \gamma$
$K_S^0\ \pi^+\ \pi^0\ \pi^0\ \gamma$
$K^+\ \eta\ \gamma$
$K^+\ K^-\ K^+\ \gamma$

Neutral modes

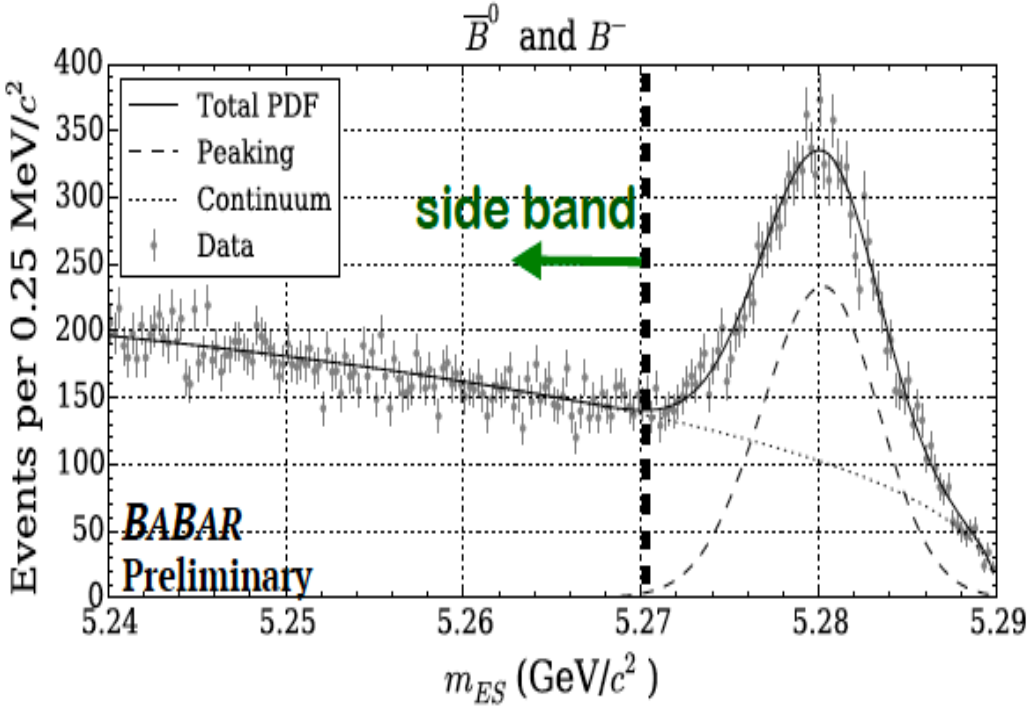
$K^+\ \pi^-\ \gamma$
$K^+\ \pi^-\ \pi^0\ \gamma$
$K^+\ \pi^+\ \pi^-\ \pi^-\ \gamma$
$K^+\ \pi^-\ \pi^0\ \pi^0\ \gamma$
$K^+\ \eta\ \pi^-\ \gamma$
$K^+\ K^-\ K^-$

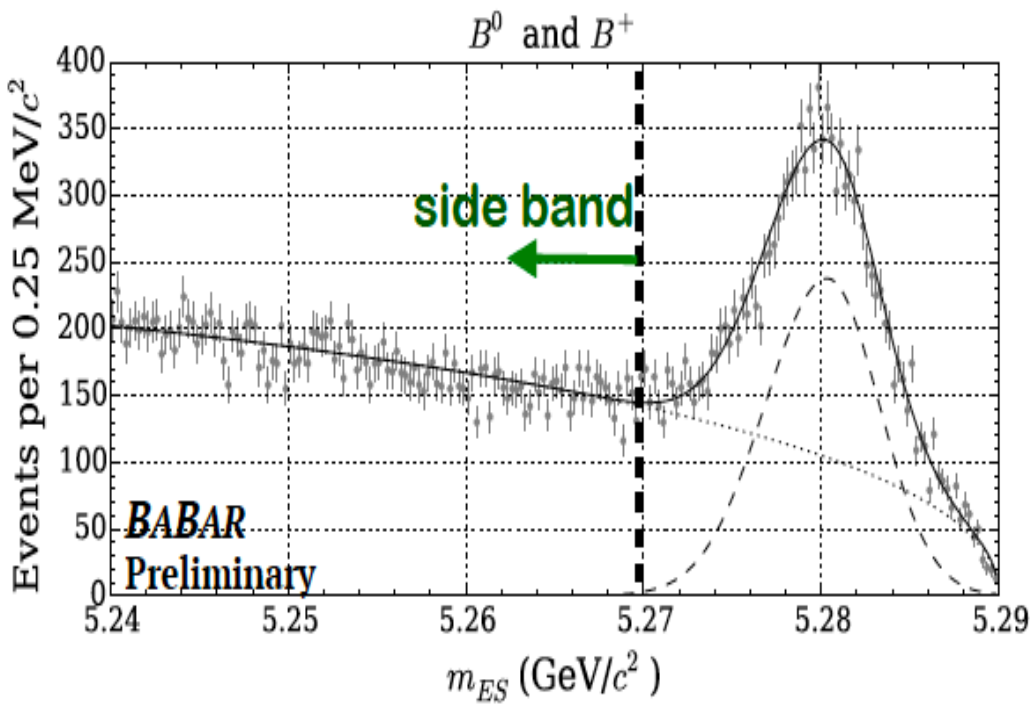
$B \to X_s \gamma$ (3/4)

- Simultaneous m_{ES} fit of charged and neutral B
  - A_{CP} decomposed in three components:

$$A_{CP} = A_{peak} - A_{det} + D$$

    - A_{peak}: fitted asymmetry from raw fitted yields of m_{ES} distribution
    - A_{det}:: detector asymmetry (due to efficiency difference in K+ and K-)
      - Extracted from m_{ES} side band A_{det}=(-1.4 +- 0.7)%
    - D: dilution due to peaking background contamination or wrongly reconstructed $B \to X_s \gamma$ (cross feed)
      - Accounted for as systematic uncertainty: δA_{CP}=0.9%





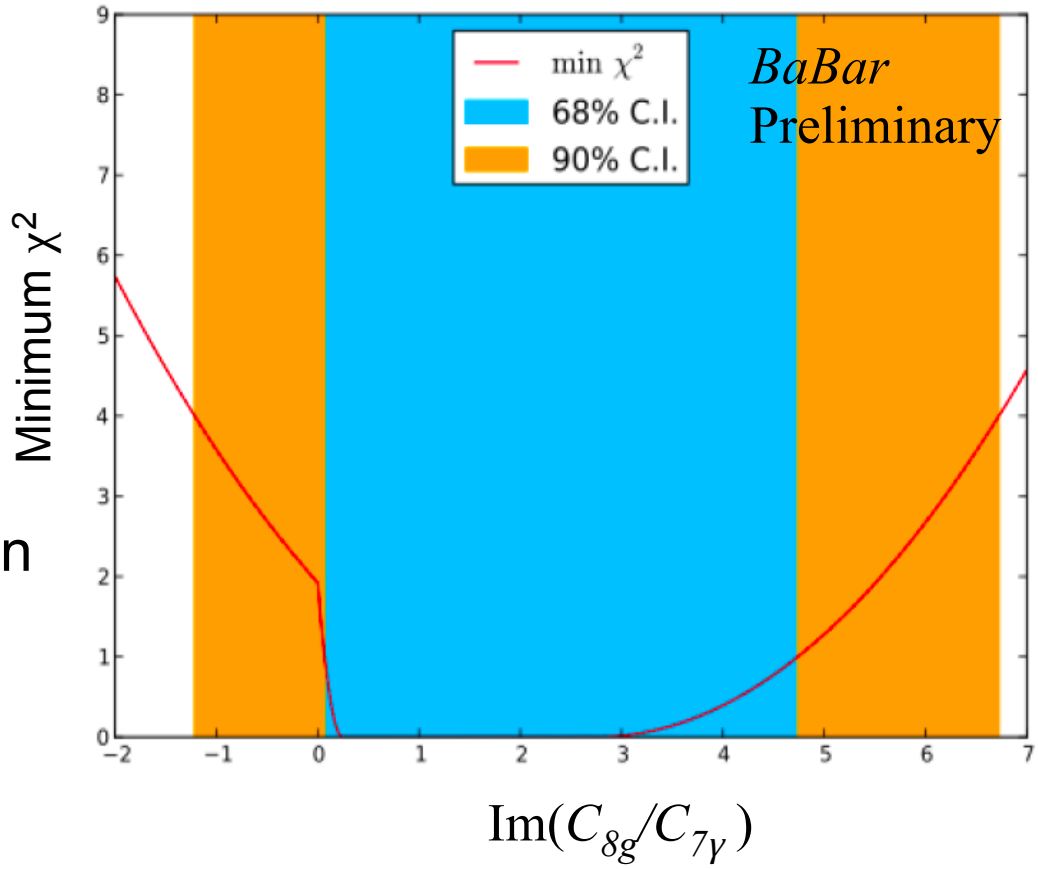
$B \to X_s \gamma$ (4/4)

B Sample	A_{peak}	D	A_{det}	A_{CP}
All B	$+(0.33 \pm 1.87)\%$	$\pm 0.88\%$	$-(1.40 \pm 0.49 \pm 0.51)\%$	$+(1.73 \pm 1.93 \pm 1.02)\%$
Charged B	$+(3.14 \pm 2.86)\%$	$\pm 0.80\%$	$-(1.09 \pm 0.67 \pm 0.51)\%$	$+(4.23 \pm 2.93 \pm 0.95)\%$
Neutral B	$-(2.48 \pm 2.47)\%$	$\pm 0.97\%$	$-(1.74 \pm 0.72 \pm 0.51)\%$	$-(0.74 \pm 2.57 \pm 1.10)\%$

- CP asymmetry for all B mesons:
  - A_{CP} = + (1.7 ± 1.9 ± 1.0)%
- Isospin difference of A_{CP}:
  - $\Delta A_{X_s\gamma}$ = + (5.0 ± 3.9 ± 1.5)%
- $\Delta A_{X_s\gamma}$ provides limits on poorly known Wilson Coefficient C_8:

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

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



A_{CP} and $\Delta A_{X\gamma}$ in agreement with SM

Benzke et al. PRL106,141801

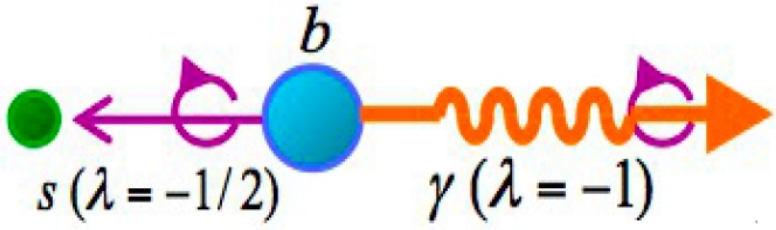
$B \rightarrow K\pi^-\pi^+\gamma$

- "Time-dependent analysis of $B^0 \rightarrow K_s\pi^-\pi^+\gamma$ and studies of the $K^+\pi^-\pi^+$ system in $B^+ \rightarrow K^+\pi^-\pi^+\gamma$ decays"

- Paper to be submitted to Phy.Rev.D

$B \to K_s \pi\pi\gamma$ (1/5)

- Radiative b→s γ
  - described in the SM as interaction between left-handed quark and right-handed antiquarks
  - In SM: predominance of left-handed photons
  - NP particles: enhancement of the right-handed photons contribution



Helicity: $\lambda = \frac{\vec{S}\cdot\vec{p}}{|\vec{p}|}$

- Method to probe the photon polarization:
  - Measurement of CP asymmetry parameters in radiative $B^0 \to K_s \rho^0 \gamma$ decay

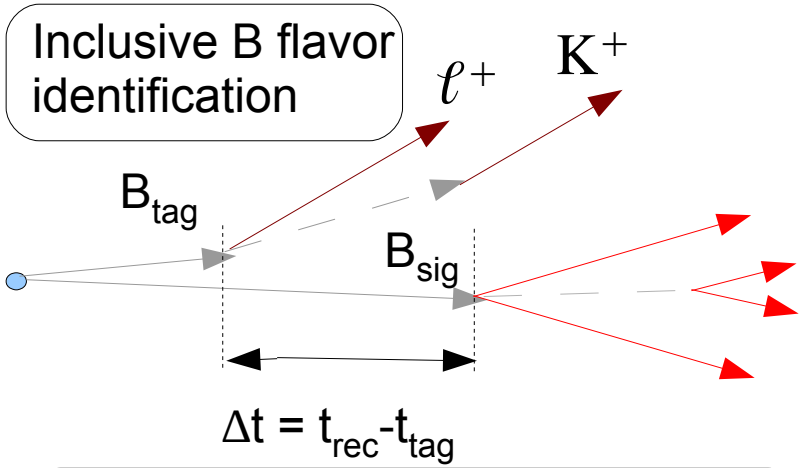
$$\mathcal{A}_{CP}(\Delta t) = \frac{\Gamma(\overline{B}^0(\Delta t) \to f_{CP}\gamma) - \Gamma(B^0(\Delta t) \to f_{CP}\gamma)}{\Gamma(\overline{B}^0(\Delta t) \to f_{CP}\gamma) + \Gamma(B^0(\Delta t) \to f_{CP}\gamma)} = \mathcal{S}_{f_{CP}} \sin(\Delta m_d \Delta t) - \mathcal{C}_{f_{CP}} \cos(\Delta m_d \Delta t)$$

In the SM

$$\mathcal{S}_{fCP} \propto \frac{m_s}{m_b} \approx 0.02$$

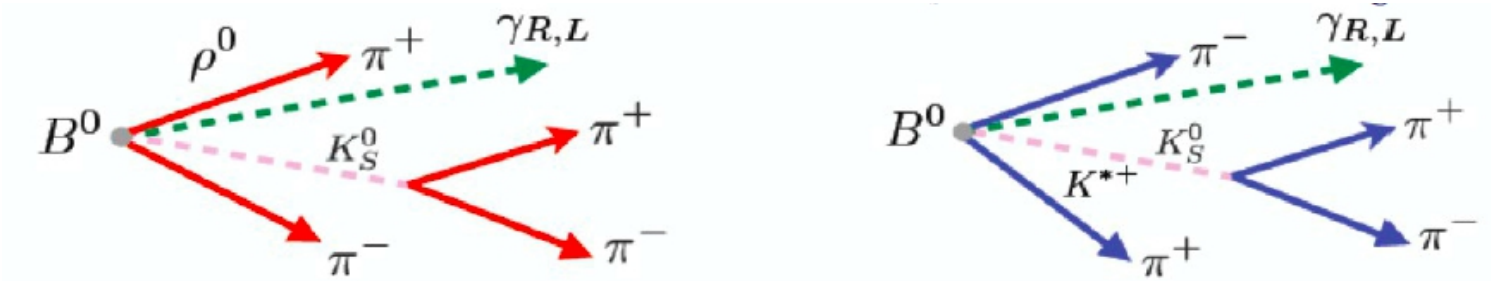
$B \to K_s \pi\pi\gamma$ (2/5)

Inclusive B flavor identification



Δt from distance between the two B^0 decay vertices in the event

- Extract the parameter $S_{ks\rho\gamma}$ in $B^0 \to K_s \rho^0 \gamma$
- Experimentally: time dependent analysis of $B^0 \to K_s \pi\pi\gamma$
  - Rare decays: BF = (9.8 ± 1.1)·10^{-6}
  - Dilution from irreducible BKG from non CP eigenstates
    - $B^0 \to K_s \rho^0 \gamma$
    - $B^0 \to K^*(K_s\pi)\pi\gamma$



  - Measure an effective value of S: $S_{ks\pi\pi\gamma}$
  - The value of $S_{Ks\rho\gamma}$ is diluted

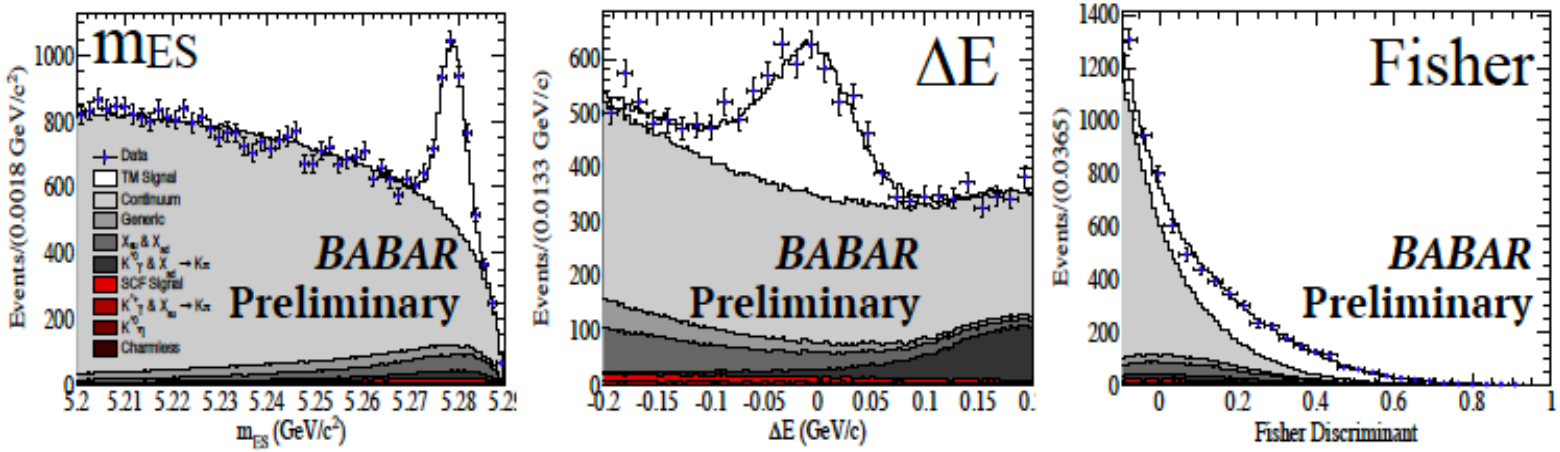
$$\mathcal{D}_{K^0_S\rho\gamma} = \frac{\mathcal{S}_{K^0_S\pi^+\pi^-\gamma}}{\mathcal{S}_{K^0_S\rho\gamma}}$$

- Dilution is extracted from the amplitudes of the intermediate resonances from $B^+ \to K^+\pi^-\pi^+\gamma$ assuming the Isospin Symmetry

$B \to K_s \pi\pi\gamma$ (3/5)

Three stages of the $B^+ \to K^+ \pi^- \pi^+ \gamma$ analysis:

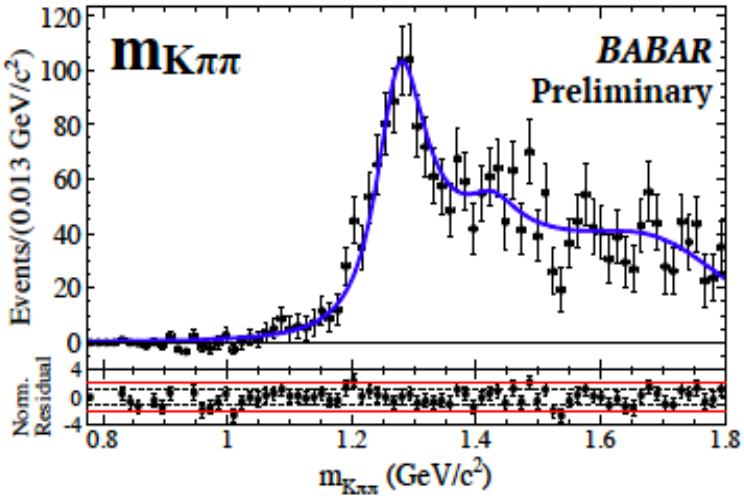
(1) 3D ML fit to extract $m_{K\pi\pi}$ and $m_{K\pi}$ signal spectra



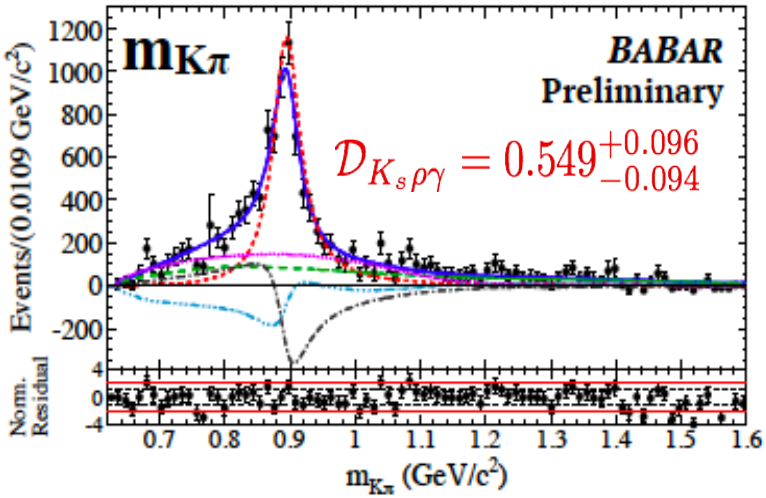
(2) Fit to $m_{K\pi\pi}$ spectrum to determine K_{res} amplitudes and BFs

(3) Fit to $m_{K\pi}$ spectrum to determine amplitudes of $K^*(892)$, $\rho^0(770)$,...

dilution factor calculation



K_{res} BFs used as input



$B \to K_s \pi\pi\gamma$ (4/5)

Resonances in the $K\pi\pi$ system

Several BF: measured:
- many are the world best
- some are measured for the first time

BRs of various resonances Decaing to $K\pi\pi$ system from m(Kpp)

Mode	$\mathcal{B}(B^+ \to \text{Mode}) \times \mathcal{B}(R \to hh) \times 10^{-6}$	$\mathcal{B}(B^+ \to \text{Mode}) \times 10^{-6}$	PDG values ($\times 10^{-6}$)
Inclusive $B^+ \to K^+\pi^+\pi^-\gamma$	...	$27.2 \pm 1.0^{+1.1}_{-1.3}$	27.6 ± 2.2
$K^{*0}(892)\pi^+\gamma$	$17.3 \pm 0.9^{+1.2}_{-1.1}$	$26.0^{+1.4}_{-1.3} \pm 1.8$	20^{+7}_{-6}
$K^+\rho(770)^0\gamma$	$9.1^{+0.8}_{-0.7} \pm 1.3$	$9.2^{+0.8}_{-0.7} \pm 1.3 \pm 0.02$	< 20 CL= 90%
$(K\pi)^{*0}_0\pi^+\gamma$	$11.3 \pm 1.5^{+2.0}_{-2.6}$	...	$\emptyset$
$(K\pi)^0_0\pi^+\gamma$ (NR)	...	$10.8^{+1.4+1.9}_{-1.5-2.5}$	< 9.2 CL= 90%
$K^*_0(1430)^0\pi^+\gamma$	$0.51 \pm 0.07^{+0.09}_{-0.12}$	$0.82 \pm 0.11^{+0.15}_{-0.19} \pm 0.08$	$\emptyset$

Mode	$\mathcal{B}(B^+ \to \text{Mode}) \times \mathcal{B}(K_{\text{res}} \to K^+\pi^+\pi^-) \times 10^{-6}$	$\mathcal{B}(B^+ \to \text{Mode}) \times 10^{-6}$	PDG values ($\times 10^{-6}$)
Inclusive $B^+ \to K^+\pi^+\pi^-\gamma$	...	$27.2 \pm 1.0^{+1.1}_{-1.3}$	27.6 ± 2.2
$K_1(1270)^+\gamma$	$14.5^{+2.0+1.1}_{-1.3-1.2}$	$44.0^{+6.0+3.5}_{-4.0-3.7} \pm 4.6$	43 ± 13
$K_1(1400)^+\gamma$	$4.1^{+1.9+1.3}_{-1.2-0.8}$	$9.7^{+4.6+3.1}_{-2.9-1.8} \pm 0.6$	< 15 CL= 90%
$K^*(1410)^+\gamma$	$9.7^{+2.1+2.4}_{-1.9-0.7}$	$23.8^{+5.2+5.9}_{-4.6-1.4} \pm 2.4$	$\emptyset$
$K^*_2(1430)^+\gamma$	$1.5^{+1.2+0.9}_{-1.0-1.4}$	$10.4^{+8.7+6.3}_{-7.0-9.9} \pm 0.5$	14 ± 4
$K^*(1680)^+\gamma$	$17.0^{+1.7+3.5}_{-1.4-3.0}$	$71.7^{+7.2+15}_{-5.7-13} \pm 5.8$	< 1900 CL= 90%

$B \to K_s \pi\pi\gamma$ (5/5)

- Time-dependent analysis of $B^0 \to K_s \pi\pi\gamma$ decays
- 4D ML fit to four discriminating variables

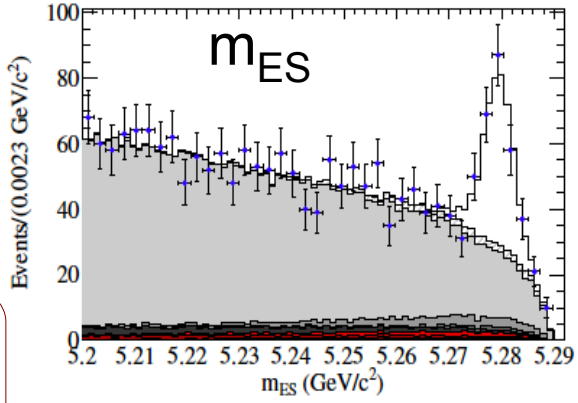
$$N_{signal} = 254 \pm 24^{+13}_{-16}$$

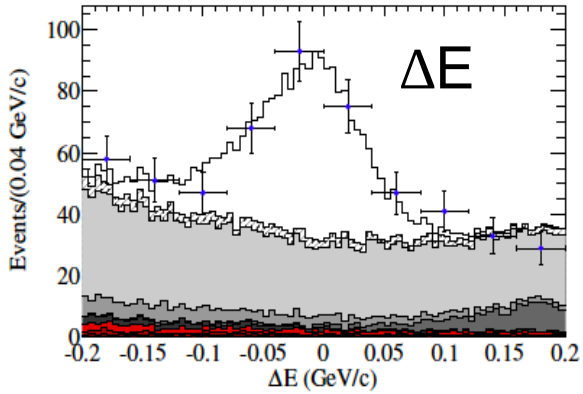
$$\mathcal{B}(B^0 \to K^0\pi^+\pi^-\gamma) = (23.9 \pm 2.4^{+1.6}_{-1.9}) \times 10^{-6}$$

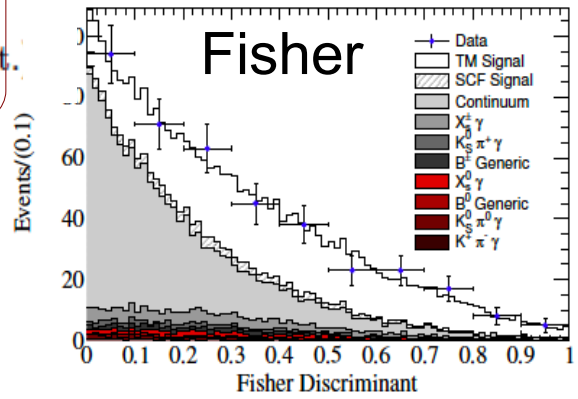
$$\mathcal{S}_{K^0_S\pi^+\pi^-\gamma} = 0.14 \pm 0.25(\text{stat.})^{+0.04}_{-0.03}(\text{syst.})$$

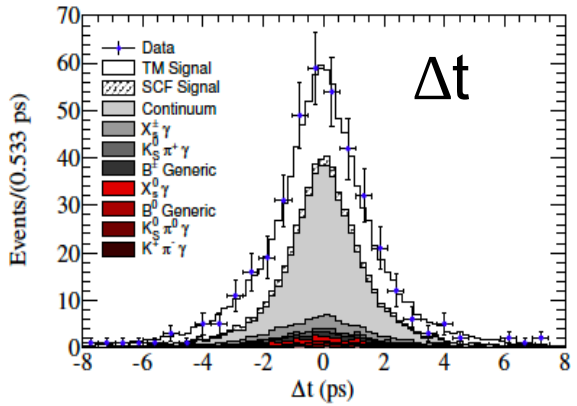
$$\mathcal{C}_{K^0_S\pi^+\pi^-\gamma} = -0.39 \pm 0.20(\text{stat.}) \pm 0.05(\text{syst.})$$

$$\mathcal{S}_{K^0_S\rho\gamma} = 0.249 \pm 0.455^{+0.076}_{-0.060}$$









- In agreement with SM prediction
- The current sensitivity does not allow to constrain NP models

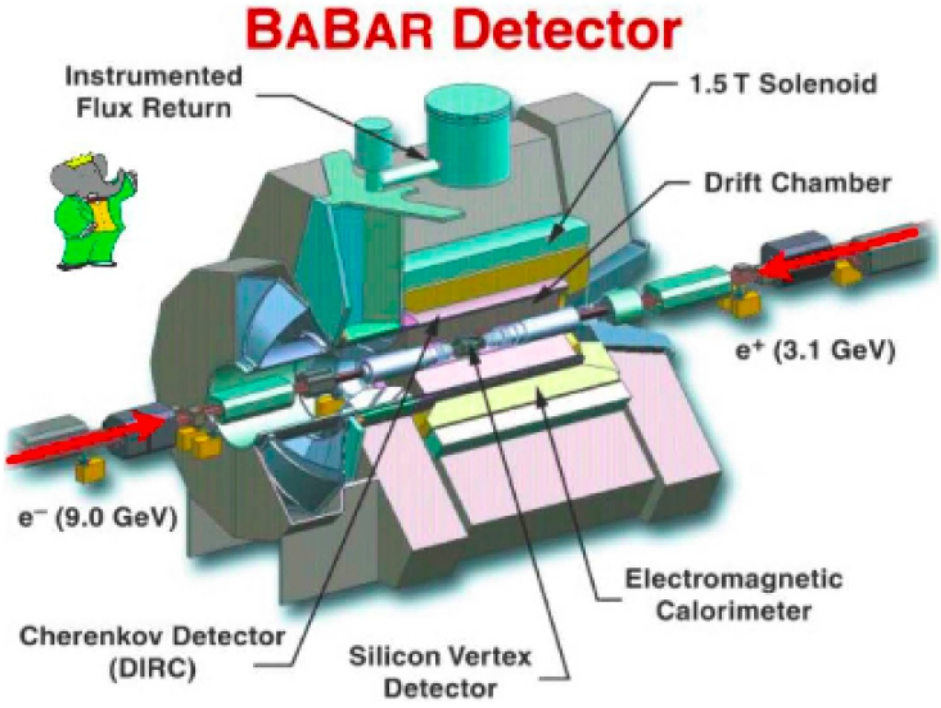
Conclusions

- BaBar still produces exciting physics results using new analysis techniques to access new interesting observables
  - $B \to X_s \ell^+ \ell^-$ from a sum of exclusive final decays
  - $B \to X_s \gamma$ search for CP viol. and first measurement of ΔA_{CP}
  - TD analysis of $B^0 \to K_s \pi\pi\gamma$ and study of $B^+ \to K\pi\pi\gamma$ decay
- No evidence of New Physics so far!
- Larger statistics are needed to tell wether or not there are indications of NP in these decays
- Search for indirect signal of NP is continuing with much high statistical samples @LHC (LHCb, CMS, ATLAS) and in near future at Belle-II

Backup slides

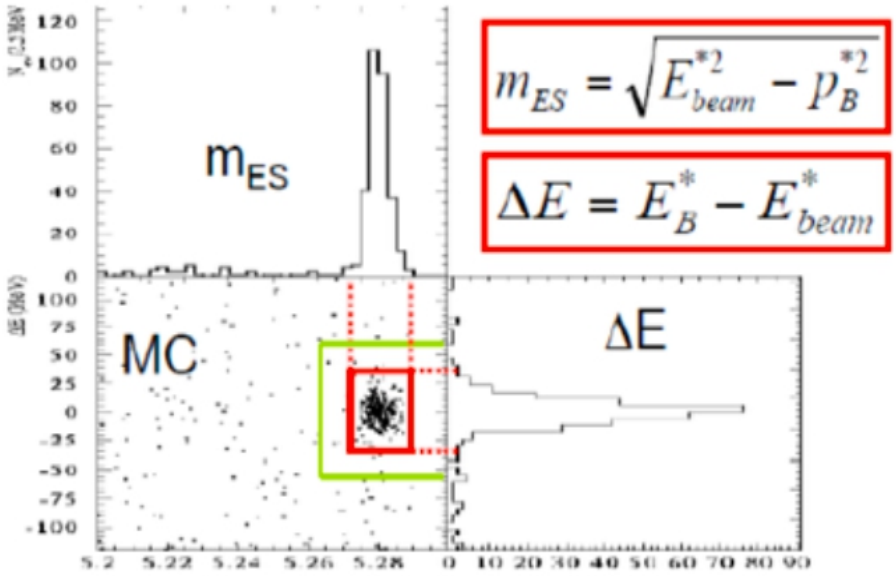
BaBar in a nutshell

- Operation: 05/1999-04/2008 (BaBar, **PEP-II**)
- e^+e^- machines run at Y(4S) resonance:
  - Y(4S) decays only in $B^0\underline{B}^0$ and B^+B^- (very clean environment)
  - Cross section is relatively high: 1.06nb
  - Backgrounds from $e^+e^- \rightarrow q\underline{q}$ (~3 nb)



~470 x 10^6 BB pairs

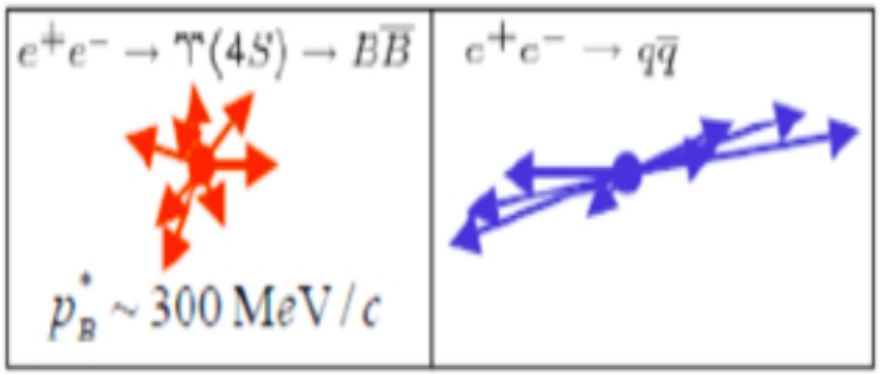
Kinematics of fully reconstructed B



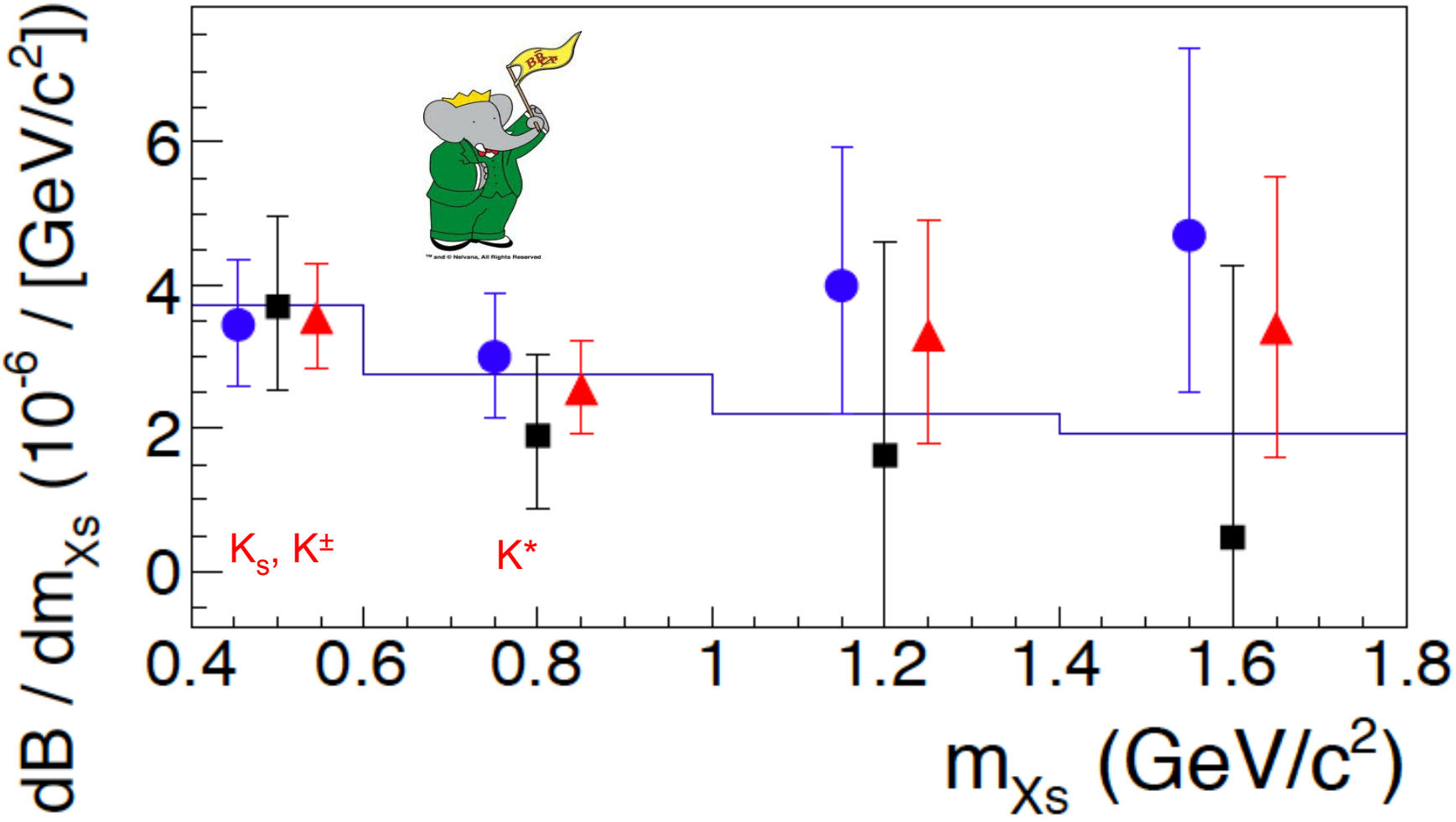
$$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_B}$$

$$\Delta E = E^*_B - E^*_{beam}$$

Backrground discrimination



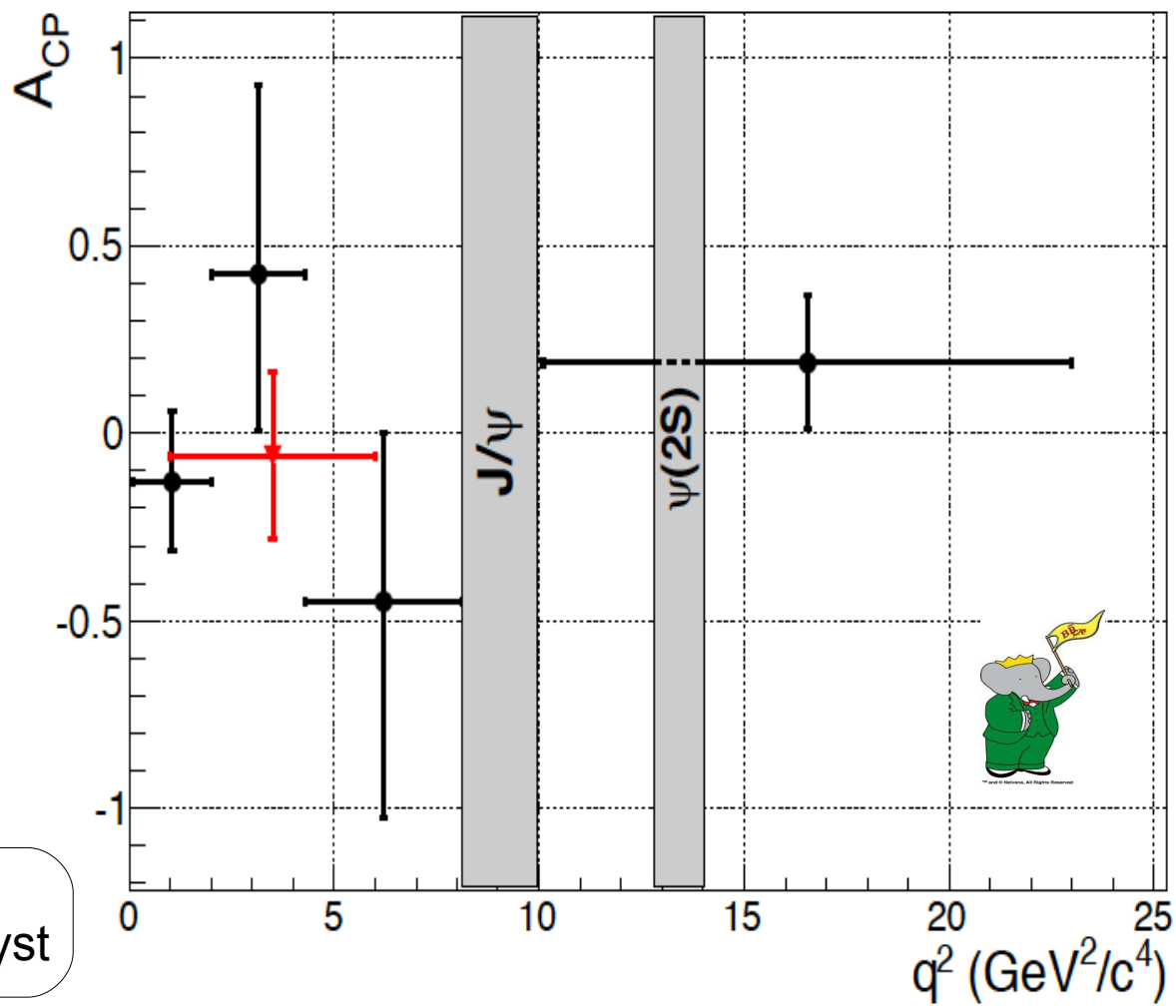
$B \to X_s \ell^+ \ell^-$ partial BF .vs. Mx



$B \to X_s \ell^+ \ell^-$ CP violation

$$A_{CP} = \frac{BF(B) - BF(\overline{B})}{BF(B) + BF(\overline{B})}$$

- Sample divided according to lepton kind and B flavor
  - Inferred from K/π charges
- No model-dependent extrapolation of signal rates performed



$A_{CP} = 0.04 \pm 0.11_{stat} \pm 0.01_{syst}$

- In agreement with SM predictions

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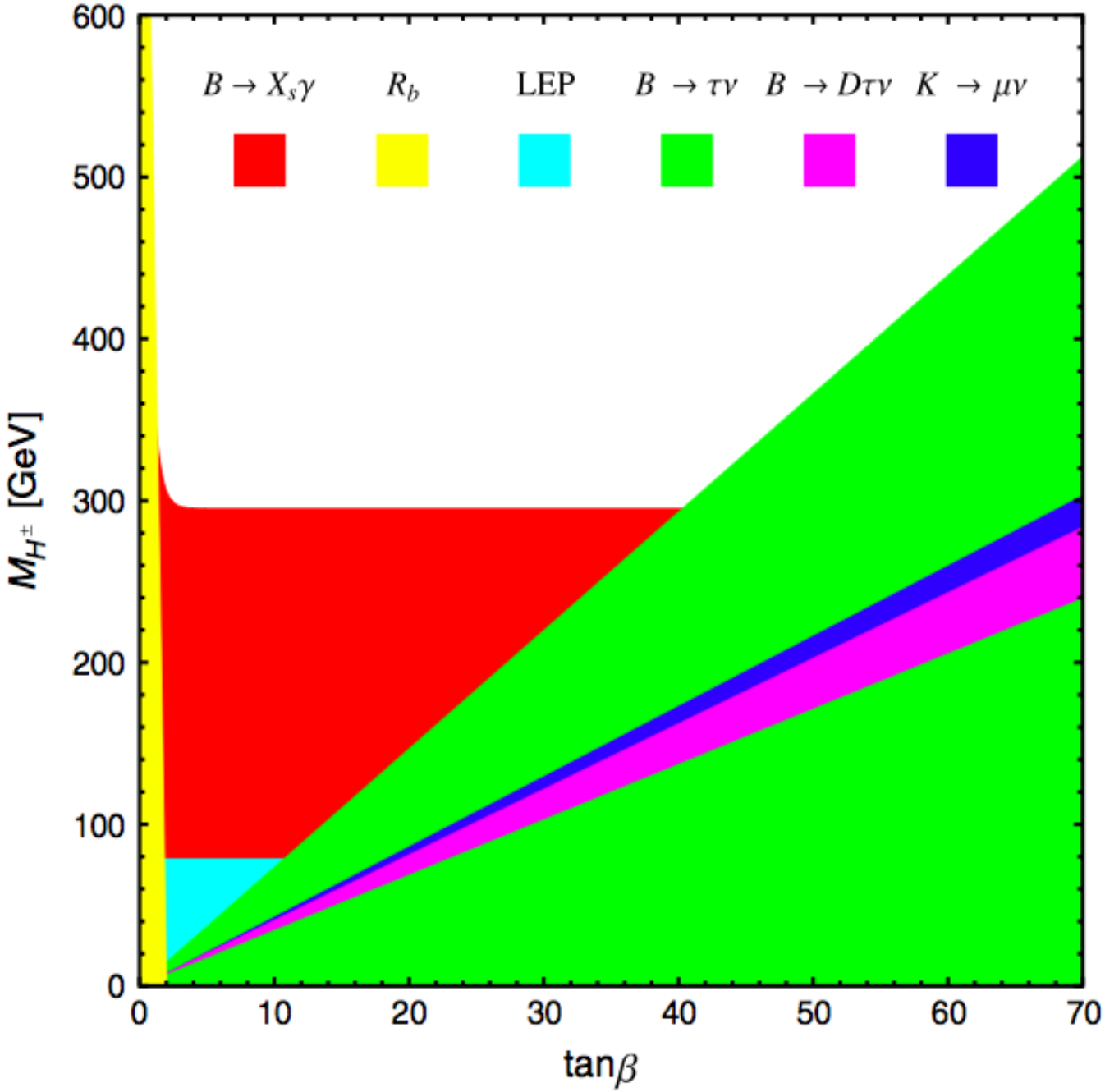

U. Haisch, arXiv:0805.2141