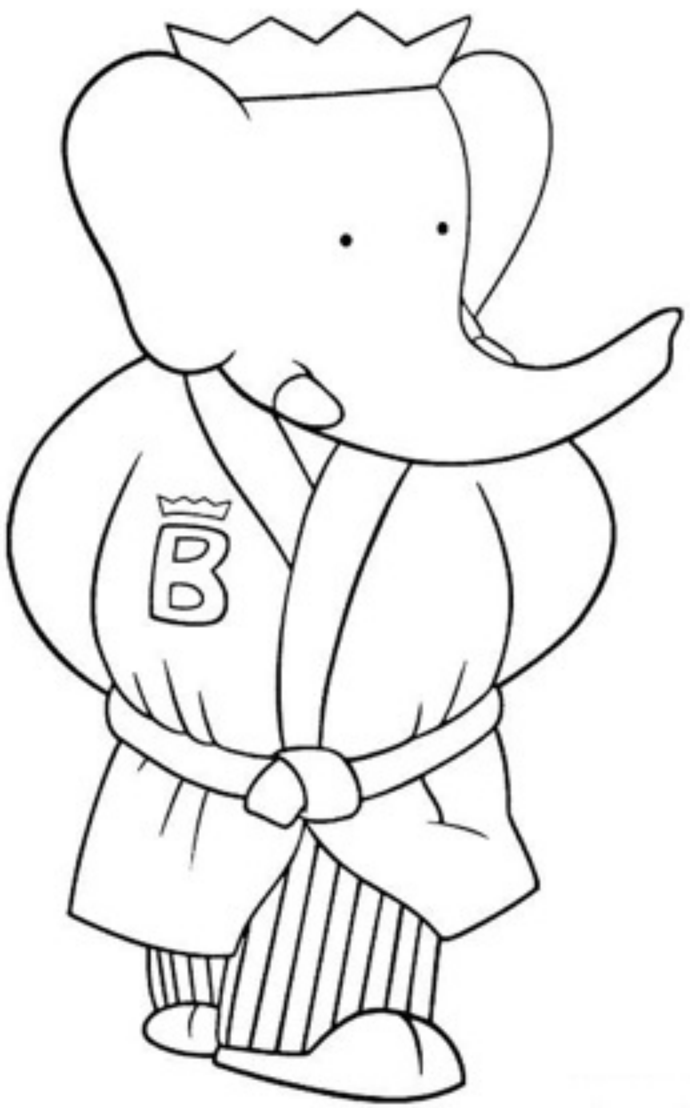
Penguin and rare decays in BaBar



BEACH 2014

XI International Conference on Hyperons, Charm and Beauty Hadrons

University of Birmingham, UK
21-26 July 2014

Simon Akar

on behalf of the *BABAR* collaboration

cnrs IN2P3 Les deux infinis

OUTLINE

Full dataset:

$\int \mathscr{L}\, dt \sim 433\ \mathrm{fb}^{-1}$ @$\Upsilon(4S)$

$470 \times 10^6\ B\bar{B}$

$B \to X_S\gamma$

A_{CP} & ΔA_{CP}

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

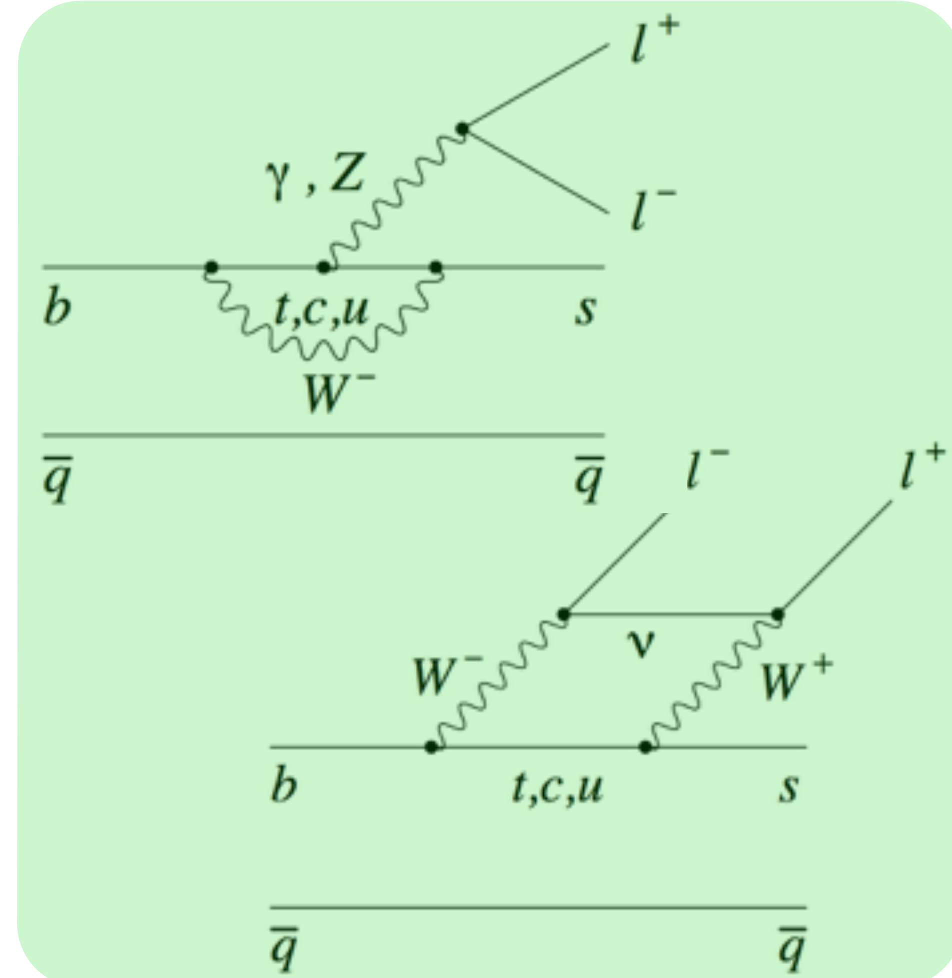
SEMI-INCLUSIVE RATE & A_{CP}

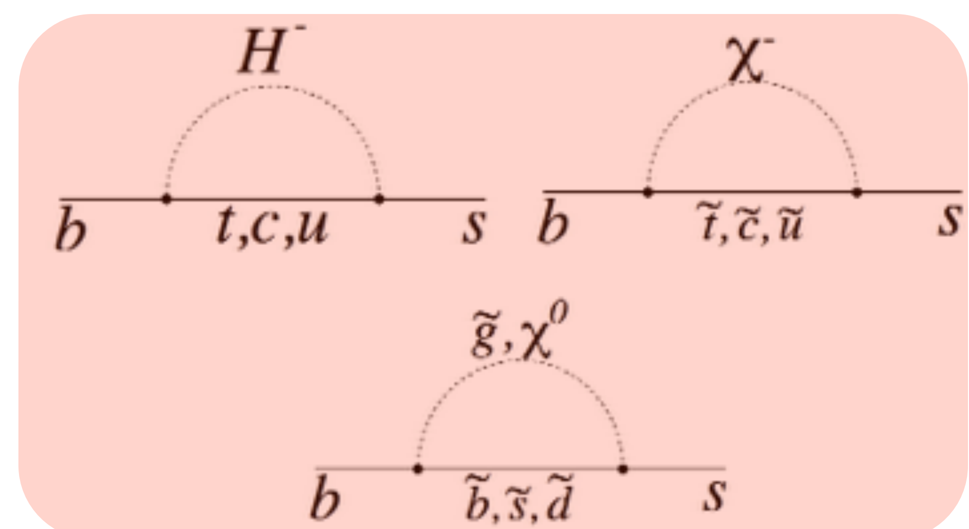
$B \to K\pi^-\pi^+\gamma$

PHOTON POLARISATION

MOTIVATIONS

- In Standard Model (SM):
  - FCNC are forbidden at tree level
  - leading decay amplitude occurs at higher order: loop / box diagram
- Small branching fractions O(10^{-6}):
  - large data samples of the B-factories ~430(*BABAR*) / ~710(Belle) fb^{-1} at $\Upsilon(4S)$ allow to study such processes
- New Physics (NP) contributions:
  - other virtual particle in the loop
- NP probes:
  - Altered branching fractions,
  - CP asymmetry (A_{CP}),
  - Lepton number violation (LNV),
  - Isospin asymmetry (A_I),
  - Forward-Backward asymmetry (A_{FB})...





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$B \rightarrow X_S\gamma$

Measurement of direct CP asymmetries in $B \rightarrow X_s\gamma$ decays using sum of exclusive decays

Paper to be submitted to Phys. Rev. D
arXiv:1406.0534

$B \to X_s\gamma$
Analysis Goal

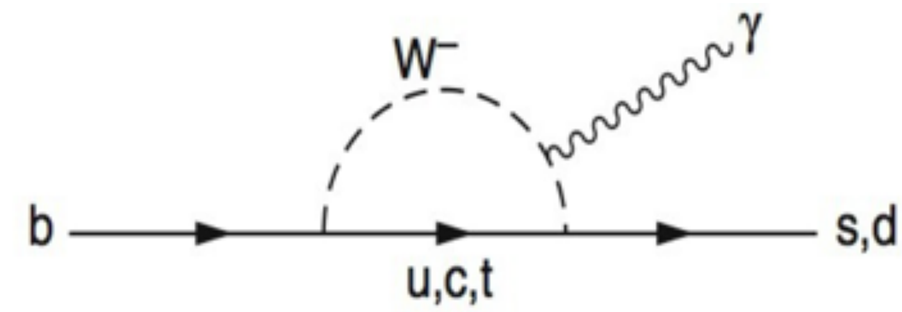
arXiv:1406.0534

- **Measure the direct A_{CP} to probe NP:**
  - **Expected small in the SM due to left-handed nature of interaction:**

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

    [Benzke et al, PRL 106, 141801 (2011)]
  - **NP may enhance A_{CP} up to 15%**

    [Nucl. Phys. B 704 56, PRL 73 2809, PRD 60 014003]



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

- **New observable: isospin difference of A_{CP}**

  $$\Delta A_{CP} = A_{CP}(B^{\pm}) - A_{CP}(B^0/\bar{B}^0)$$

  - **Used to access directly Wilson coefficients**

    $$\Delta A_{CP} \propto \mathrm{Im}\left(\frac{C_{8g}}{C_{7\gamma}}\right)$$

  - **In SM, Wilson coefficients are real: $\Delta A_{CP} = 0$**
  - **Since C_7 is constrained by BF measurements, gives first experimental information on C_8**

$$H_{Eff} \propto \sum_{i=1}^{10} C_i O_i$$

Effective hamiltonian: factorizes short distance perturbative from long distance non-perturbative effects

$B \to X_S\gamma$
EVENT RECONSTRUCTION

- Measurement performed using a sum of 38 reconstructed modes:
  - 16 self-tagging modes for A_{CP} measurement →
- K, π using charged PID, π/η→γγ
- Selection criteria:
  - $1.6 < E\gamma^* < 3.0$ GeV
  - $0.6 < m_{Xs} < 2.0$ GeV
  - $|\Delta E| > 0.15$ GeV
- Use of two multi-variate classifiers:
  - reduce continuum background
  - select the best candidate

$B^{\pm}$ decays

$K_S^0\ \pi^+\ \gamma$

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

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

$K_S^0\ \pi^+\ \pi^0\ \gamma$

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

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

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

$K_S^0\ \pi^+\ \pi^0\ \pi^0\ \gamma$

$K^+\ \eta\ \gamma$

$K^+\ K^-\ K^+\ \gamma$

$B^0/\bar{B}^0$ decays

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

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

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

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

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

$K^+\ K^-\ K^-$

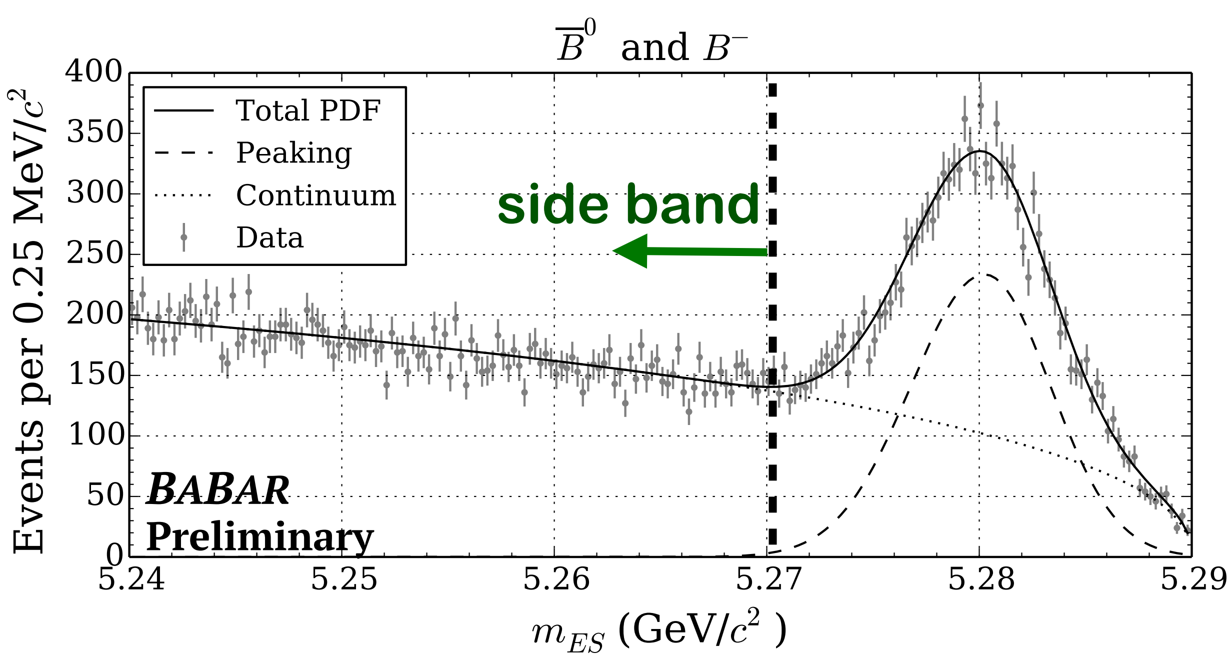
$B \to X_S \gamma$

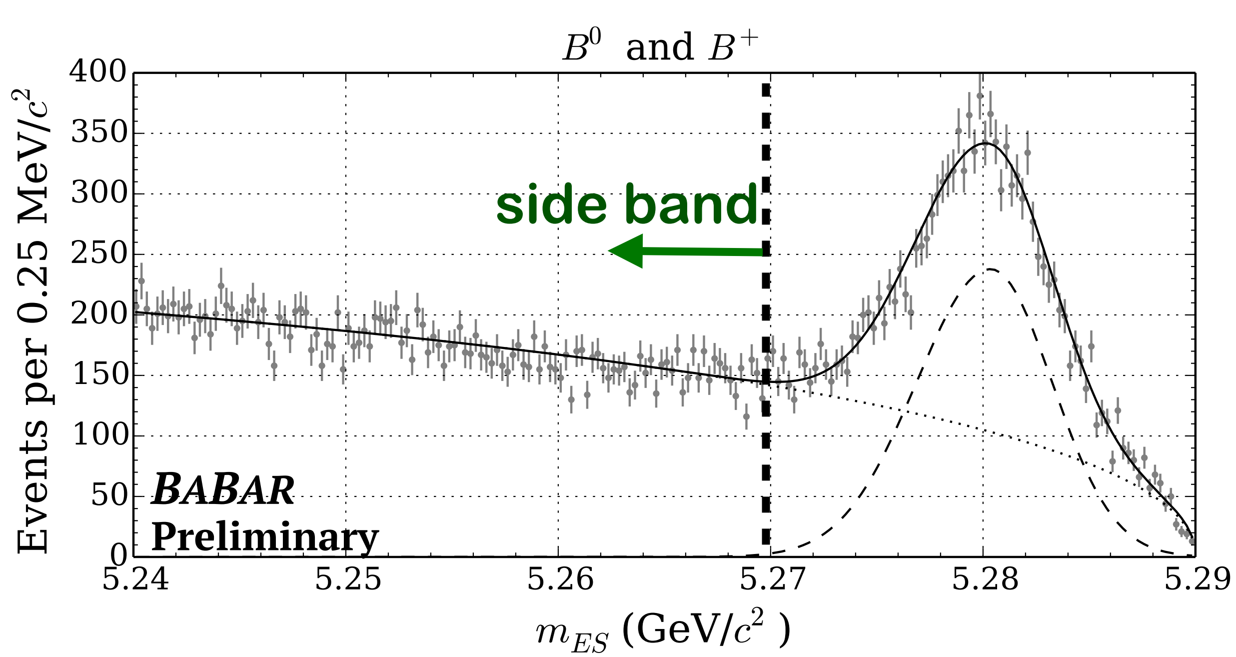
A_{CP} EXTRACTION PROCEDURE

- Fitting simultaneously charged and neutral samples on the m_{ES} variable

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

- A_{peak}: - from raw fitted yields
- A_{det}:
  - due to difference in K^+ and K^- efficiencies ($\sigma_{K^-} > \sigma_{K^+}$ in the detector material)
  - extracted from m_{ES} side band: $A_{\text{det}} = (-1.4 \pm 0.7)\%$
- A_D:
  - possible asymmetry in peaking background and wrongly reconstructed $B \to X_s\gamma$
  - Accounted for as systematic uncertainty: $\delta A_{CP} = 0.9\%$





$B \to X_S \gamma$ Results

- **CP asymmetry for all B mesons:**

$$A_{CP} = +(1.7 \pm 1.9 \pm 1.0)\%$$

- **Isospin difference of A_{CP}:**

$$\Delta A_{CP} = +(5.0 \pm 3.9 \pm 1.5)\%$$

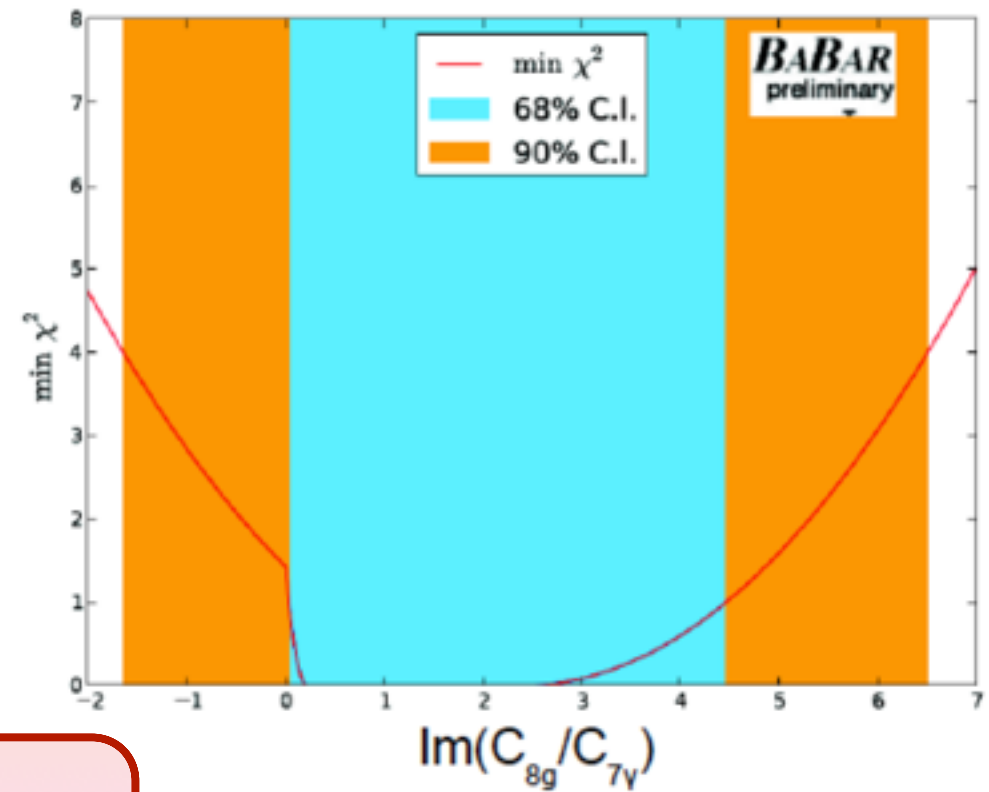
- **Constraints on Wilson coefficients:**

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

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

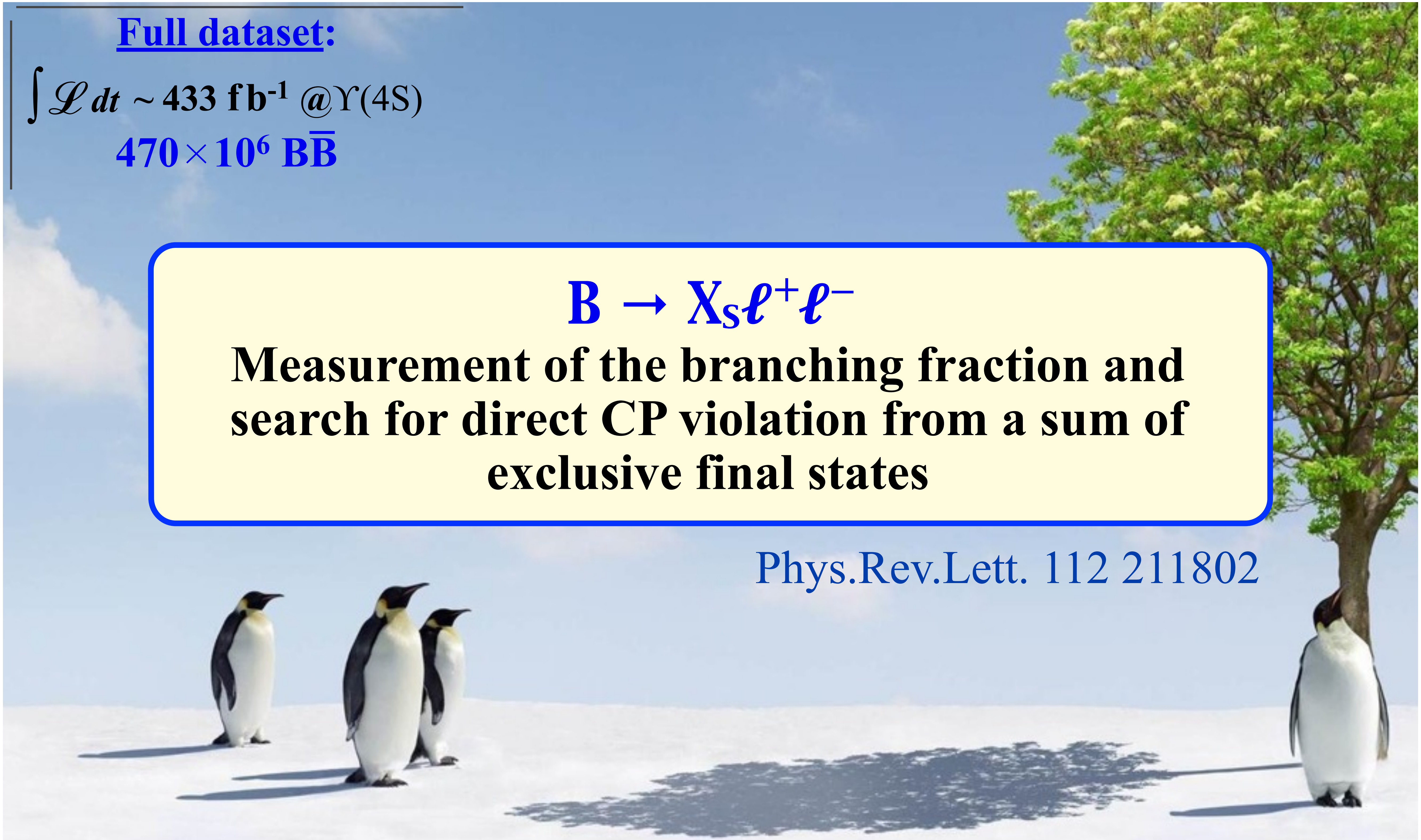
B Sample	A_{CP}
All B	$+(1.73 \pm 1.93 \pm 1.02)\%$
Charged B	$+(4.23 \pm 2.93 \pm 0.95)\%$
Neutral B	$-(0.74 \pm 2.57 \pm 1.10)\%$

Systematics from background dilution and detector asymmetry



- **In agreement with the SM prediction**
- **First measurement of ΔA_{CP} → constraint on poorly known Wilson coefficient C_8**

OUTLINE



Full dataset:

$\int \mathscr{L}\,dt \sim 433\ \mathrm{fb}^{-1}$ @$\Upsilon(4S)$

$470 \times 10^{6}\ B\bar{B}$

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

Measurement of the branching fraction and search for direct CP violation from a sum of exclusive final states

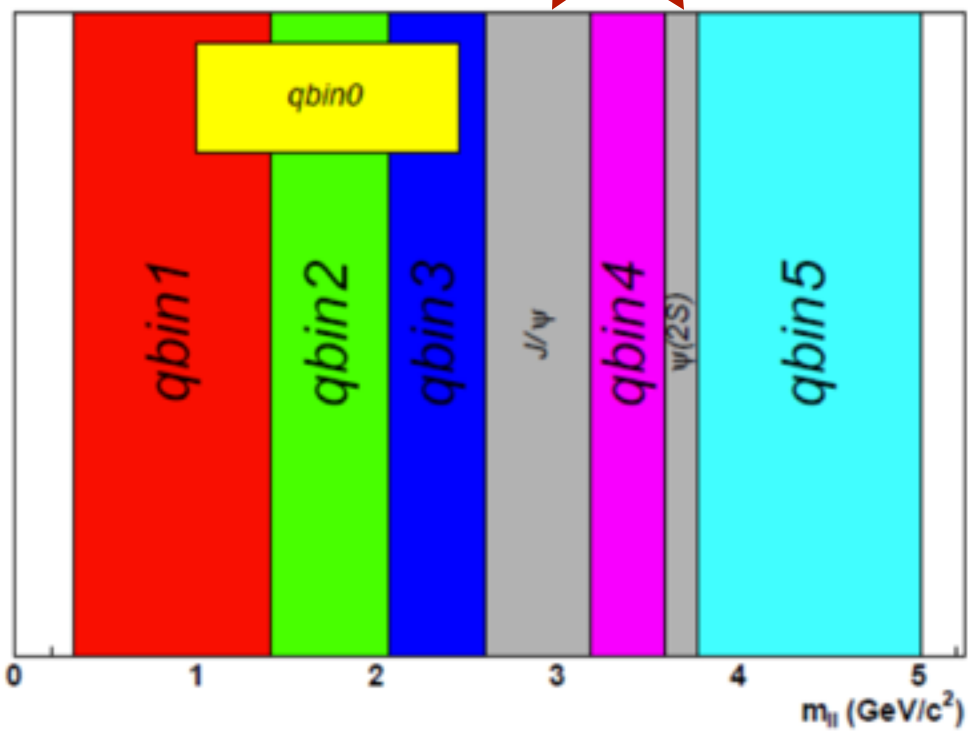
Phys.Rev.Lett. 112 211802

$B \to X_S \ell^+ \ell^-$
ANALYSIS STRATEGY (1/2)

- Lepton pair (e^+e^- or $\mu^+\mu^-$) in final state offers more observables than $B \to X_s\gamma$
- Sum of exclusive states:
  - only method used currently to study $b \to s\ell\ell$
  - MC to estimate the missing modes
- Branching fraction and A_{CP} extraction:
  - observables vary with q^2 (= $m^2_{\ell\ell}$) and m_{Xs}
  - measure partial BF in bins of q^2 and m_{Xs}
- J/ψ and ψ(2S) with same final states:
  - vetoed and taken as control sample

q^2 bin	$m^2_{\ell\ell}$ (GeV^2/c^4)	$m_{\ell\ell}$ (GeV/c^2)
0	1.0 – 6.0	1.00 – 2.45
1	0.1 – 2.0	0.32 – 1.41
2	2.0 – 4.3	1.41 – 2.07
3	4.3 – 8.1	2.07 – 2.60
4	10.1 – 12.9	3.18 – 3.59
5	$14.2 - (M_B - M_K^*)^2$	$3.77 - (M_B - M_K^*)$

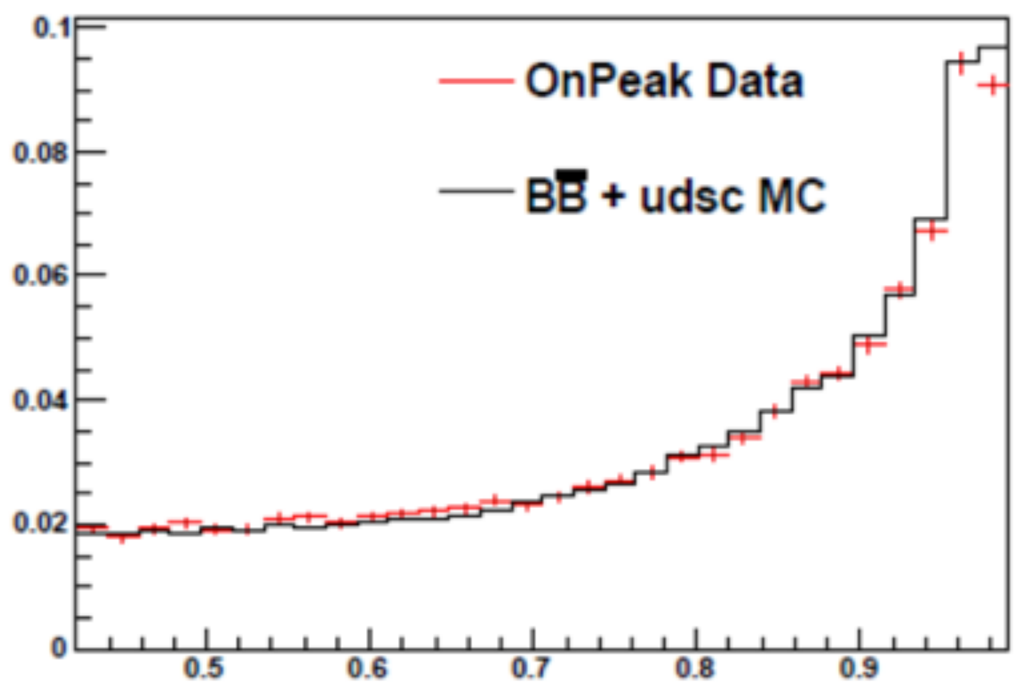
J/ψ and ψ(2S) vetoes



$B \to X_S \ell^+ \ell^-$
Analysis Strategy (2/2)

- **Study of 20 exclusive final states:**
  - m_{X_S} < 1.8 GeV/c²
  - represents ~70% of inclusive rate
  - only self-tagging modes* for A_{CP}
- **Signal yields extraction:**
  - 2D MLF to m_{ES} and a likelihood ratio (LHR)
  - m_{ES} > 5.225 GeV
  - $-0.1(-0.05) < \Delta E < 0.05$ for $X_s e^+e^-(X_s\mu^+\mu^-)$

Likelihood ratio on J/ψ sample



0 π

- $B^0 \to K_S \mu^+\mu^-$
- *$B^+ \to K^+ \mu^+\mu^-$
- $B^0 \to K_S e^+e^-$
- *$B^+ \to K^+ e^+e^-$

1 π

- $B^0 \to K_S$ pi0 $\mu^+\mu^-$
- *$B^+ \to K^+ \pi^0 \mu^+\mu^-$
- *$B^+ \to K_S \pi^+ \mu^+\mu^-$
- *$B^0 \to K^+ \pi^- \mu^+\mu^-$
- $B^0 \to K_S \pi^0 e^+e^-$
- *$B^+ \to K^+ \pi^0 e^+e^-$
- *$B^+ \to K_S \pi^+ e^+e^-$
- *$B^0 \to K^+ \pi^- e^+e^-$

2 π

- *$B^+ \to K_S \pi^+ \pi^0 \mu^+\mu^-$
- *$B^0 \to K^+ \pi^- \pi^0 \mu^+\mu^-$
- $B^0 \to K_S \pi^+ \pi^- \mu^+\mu^-$
- *$B^+ \to K^+ \pi^- \pi^- \mu^+\mu^-$
- *$B^+ \to K_S \pi^+ \pi^0 e^+e^-$
- *$B^0 \to K^+ \pi^- \pi^0 e^+e^-$
- $B^0 \to K_S \pi^+ \pi^- e^+e^-$
- *$B^+ \to K^+ \pi^+ \pi^- e^+e^-$

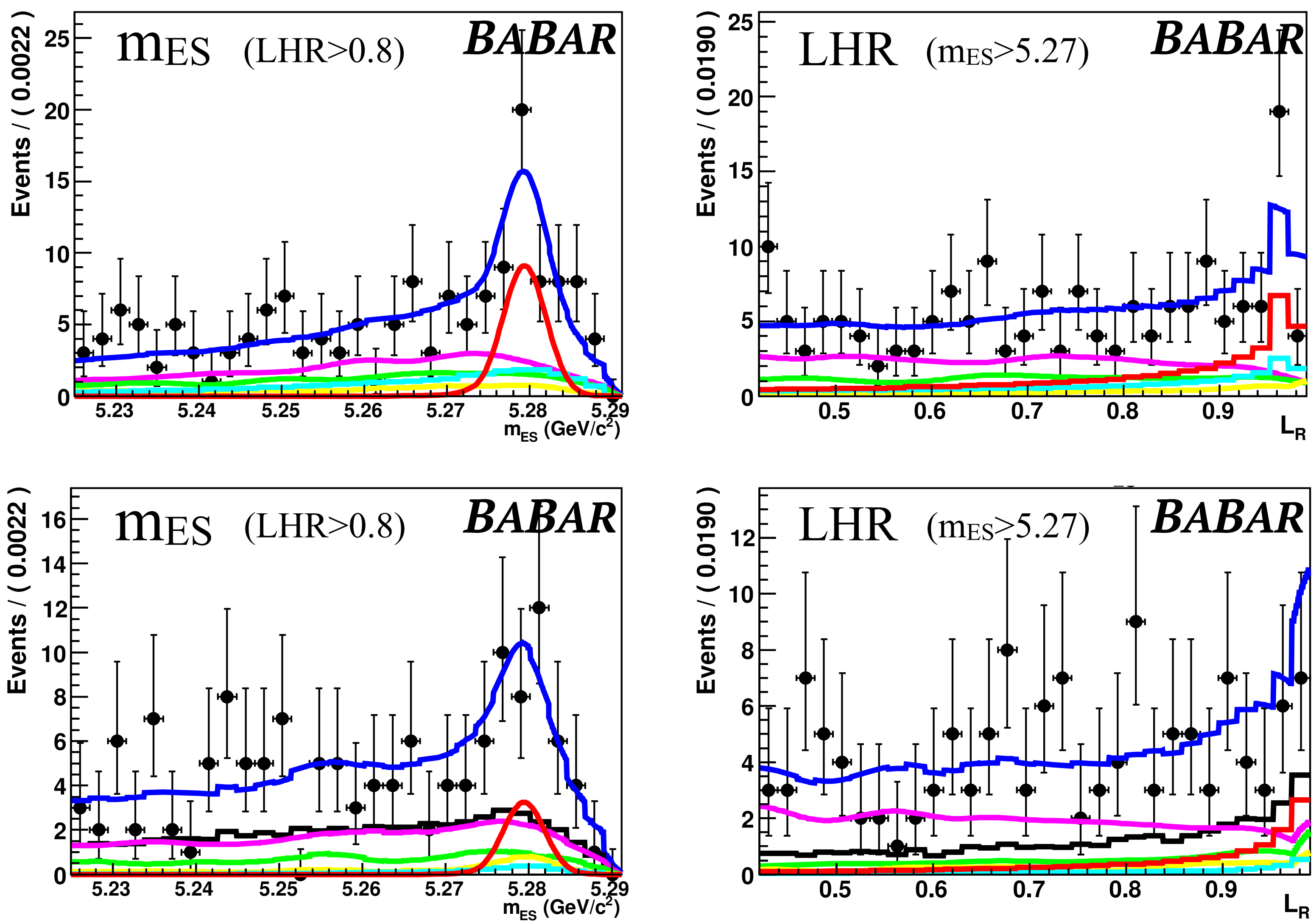
Phys.Rev.Lett. 112 211802

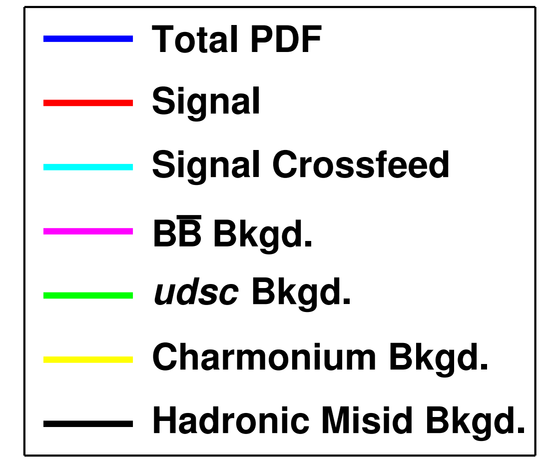
$B \to X_S \ell^+ \ell^-$
RESULTS (1/3)

- **Fit projection examples:**

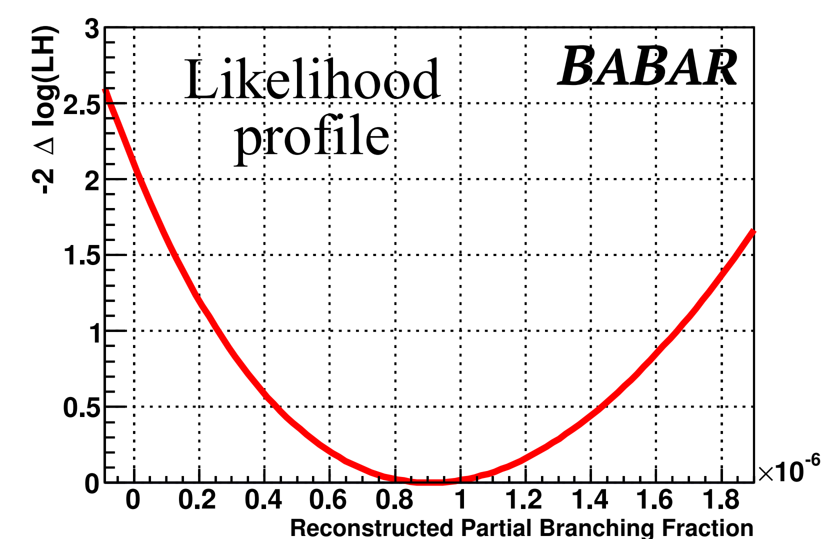
$X_s e^+ e^-$ q_5^2 bin

$X_s \mu^+ \mu^-$ q_1^2 bin





3 bkg. for e^+e^- modes
+ 1 for $\mu^+\mu^-$ modes



- **Partial branching fractions:**
  - extracted from likelihood profile

$B \to X_S \ell^+ \ell^-$ Results (2/3)

Phys.Rev.Lett. 112 211802

- **Branching fractions** (most precise SM calculations done for two q^2 regions, our q^2_0 and q^2_5):

SM prediction ($\times 10^{-6}$)		this measurement ($\times 10^{-6}$)
[Nucl.Phys.B 802, 40 (2008)]	$1.0 < q^2 < 6.0$ GeV^2	
$\mathcal{B}(B \to X_s \mu^+ \mu^-) = (1.59 \pm 0.11)$	$X_s \mu^+ \mu^-$	$0.66^{+0.82}_{-0.76}{}^{+0.30}_{-0.24} \pm 0.07$
$\mathcal{B}(B \to X_s e^+ e^-) = (1.64 \pm 0.11)$	$X_s e^+ e^-$	$1.93^{+0.47}_{-0.45}{}^{+0.21}_{-0.16} \pm 0.18$
	$X_s \ell^+ \ell^-$	$1.60^{+0.41}_{-0.39}{}^{+0.17}_{-0.13} \pm 0.18$
[Nucl.Phys.B 802, 40 (2008)]	$q^2 > 14.2$ GeV^2	
$\mathcal{B}(B \to X_s \mu^+ \mu^-)_{\text{high}} = (0.25^{+0.07}_{-0.06})$	$X_s \mu^+ \mu^-$	$0.60^{+0.31}_{-0.29}{}^{+0.05}_{-0.04} \pm 0.00$
	$X_s e^+ e^-$	$0.56^{+0.19}_{-0.18}{}^{+0.03}_{-0.03} \pm 0.00$
	$X_s \ell^+ \ell^-$	$0.57^{+0.16}_{-0.15}{}^{+0.03}_{-0.02} \pm 0.00$

- **CP asymmetry** (value for the entire region $q^2 > 0.1$):

$$A_{CP} = \frac{\Gamma_{\bar{B}} - \Gamma_B}{\Gamma_{\bar{B}} + \Gamma_B} = 0.04 \pm 0.11 \pm 0.01$$

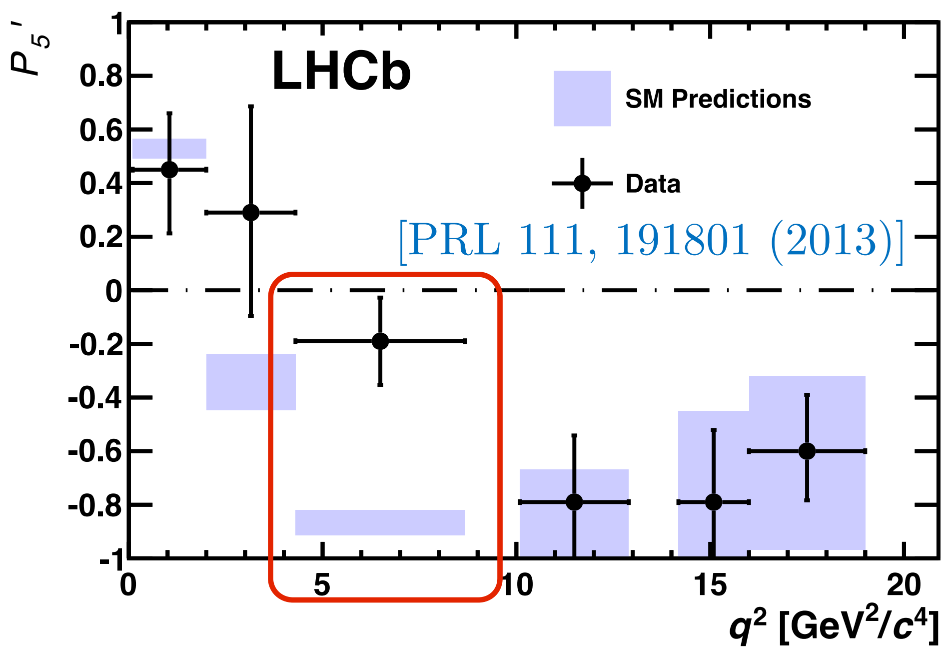
$$A_{CP}^{SM} = 0.0019^{+0.0017}_{-0.0019}$$

[PRD 54, 882 (1996), Eur. Phys. J C 8, 619 (1999)]

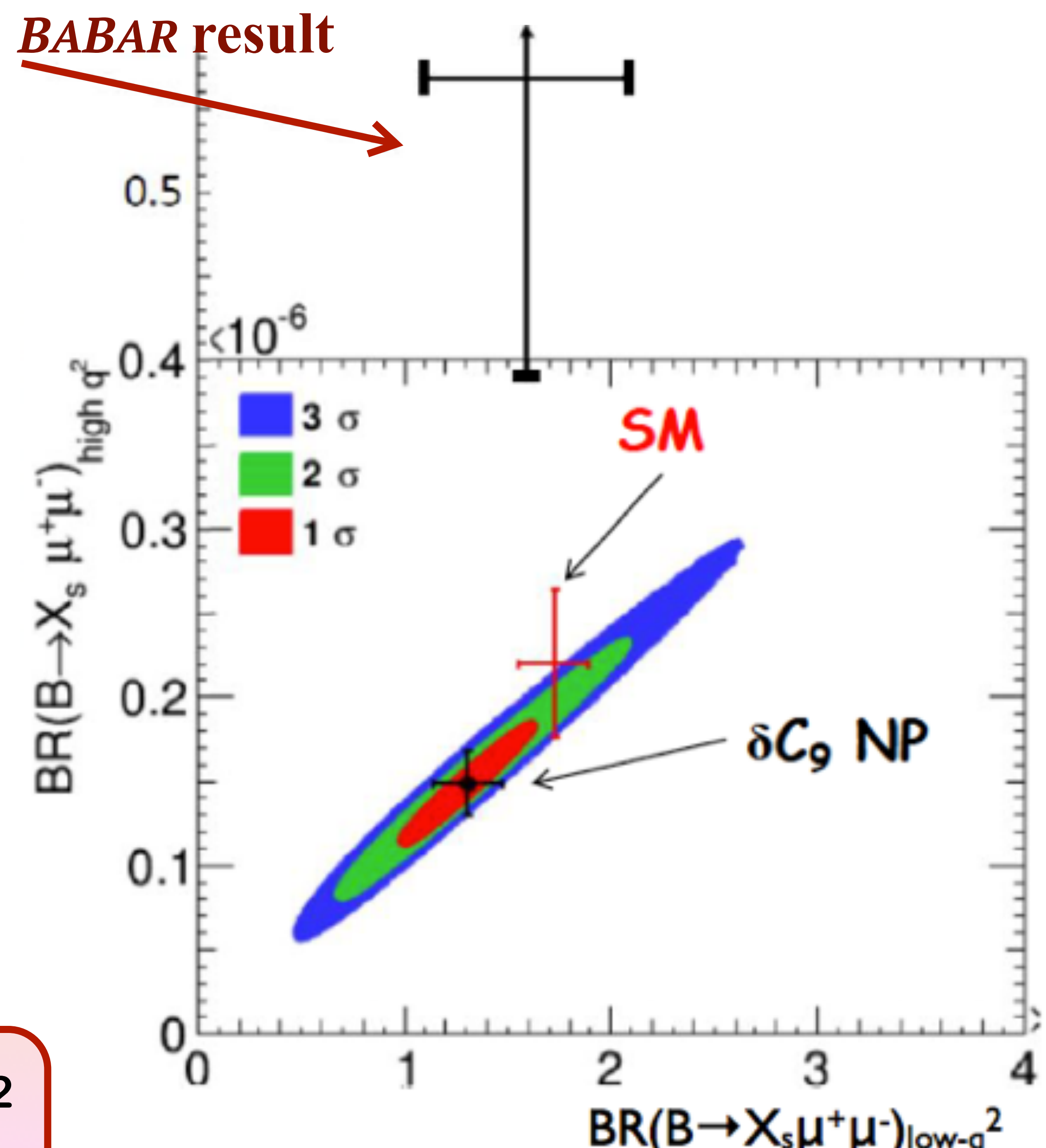
All the results are consistent with SM expectations (within 2σ)

$B \to X_S \ell^+ \ell^-$
RESULTS (3/3)

- **LHCb anomaly in B→K*μμ:**
  - Global fits to recent $b \to s\ell\ell$ and $b \to s\gamma$ data favor decreased value of C9.



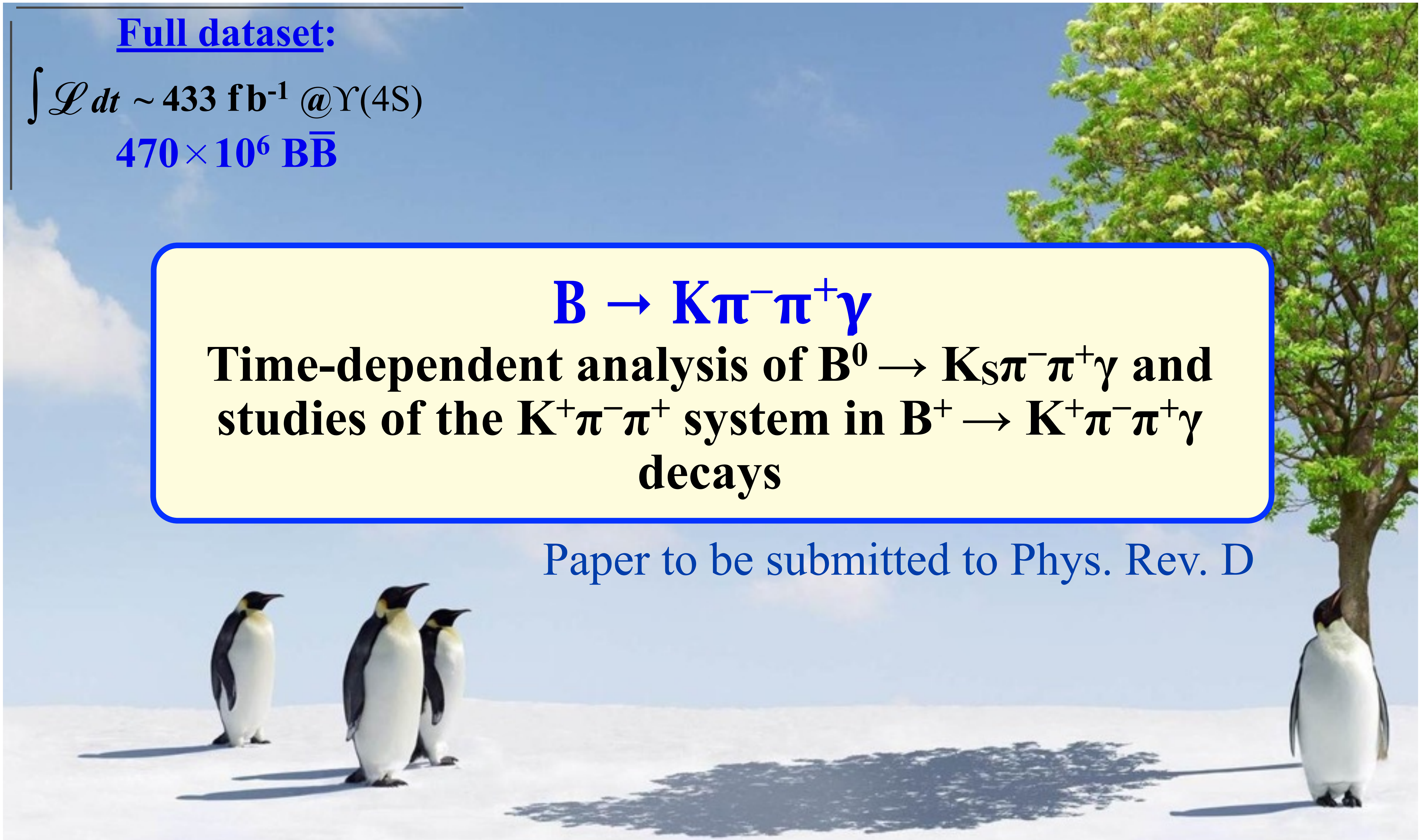
  - Indication of NP?
  - This leads to a reduced value of inclusive BF($B \to X_s \ell^+ \ell^-$)



T. Hurth and F. Mahmoudi, arXiv:1312.5267
based on model independent fit from
S. Descotes-Genon et al., Phys. Rev. D88 (2013) 074002

BABAR measurement of BF at high-q^2 does not support this hypothesis

OUTLINE



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

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

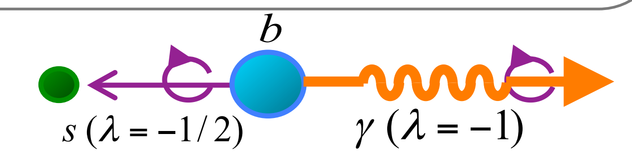
Paper to be submitted to Phys. Rev. D

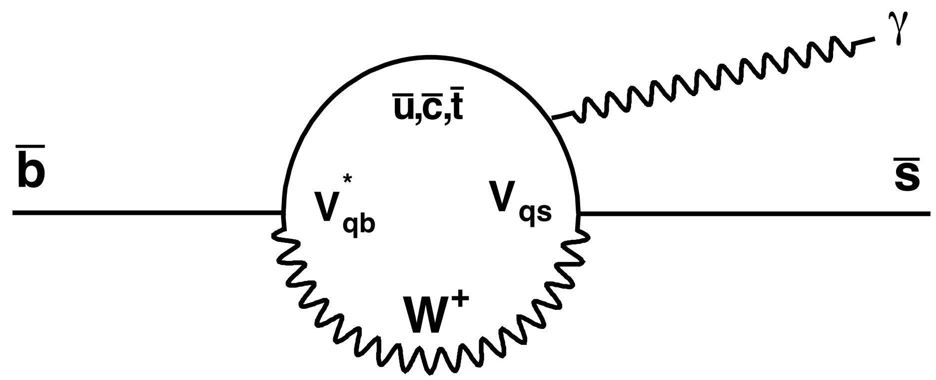
$B \to K\pi^-\pi^+\gamma$
The Photon Polarization

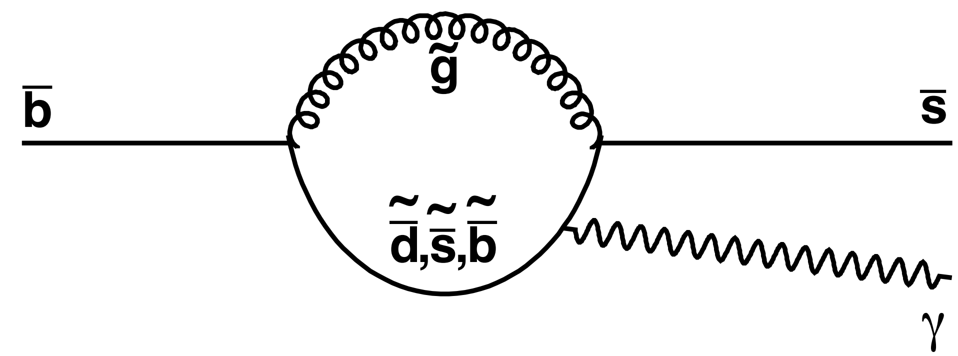
- **Radiative decays $b \to s\gamma$ (FCNC):**

  In SM interaction between left-handed quarks or right-handed antiquarks

Helicity: spin projection on the momentum of a particle $\lambda = \frac{\vec{S}\cdot\vec{p}}{|\vec{p}|}$







<u>In the SM</u> : predominance of left-handed photons

<u>Contribution of NP particles</u> : enhancement of the right-handed photons contribution

- **Several experimental methods to probe the photon polarization:**
  - **Measurement of CP asymmetry parameters in radiative decay modes:**

$B^0 \to K_S \rho^0 \gamma$

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

Observable

$$\mathcal{S}_{f_{CP}} \overset{SM}{\propto} \frac{m_s}{m_b} \simeq 0.02$$

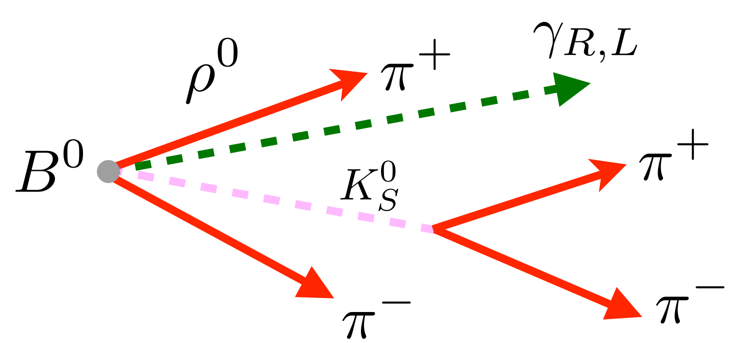
$B \to K\pi^-\pi^+\gamma$

ANALYSIS STRATEGY (1/2)

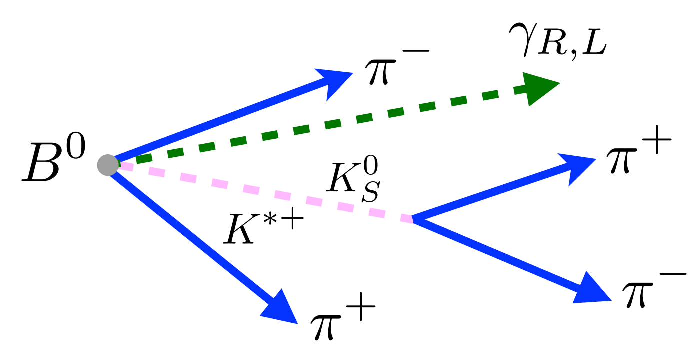
Goal : Extract the parameter $S_{K_S\rho\gamma}$ in $B^0 \to K_S\,\rho^0\,\gamma$ decays

- **Time dependent analysis** of $B^0 \to K_S\,\pi^-\pi^+\gamma$ decays:
  - Difficulties:
    - rare decay $\to BR(B^0 \to K_S\,\pi^-\pi^+\gamma) = (9.8 \pm 1.1) \times 10^{-6}$
    - irreducible contribution from non CP eigenstates diluting the value of $S_{K_S\rho\gamma}$

$B^0 \to K_S\,\rho^0(\to\pi^-\pi^+)\,\gamma$:



$B^0 \to K^{*\pm}(\to K_S\,\pi^\pm)\,\pi^\mp\,\gamma$:



    - measure an effective value of S: $S_{K_S\pi\pi\gamma}$
    - the value of $S_{K_S\rho\gamma}$ is diluted by a factor $\mathcal{D}_{K_S\rho\gamma}$ such as:

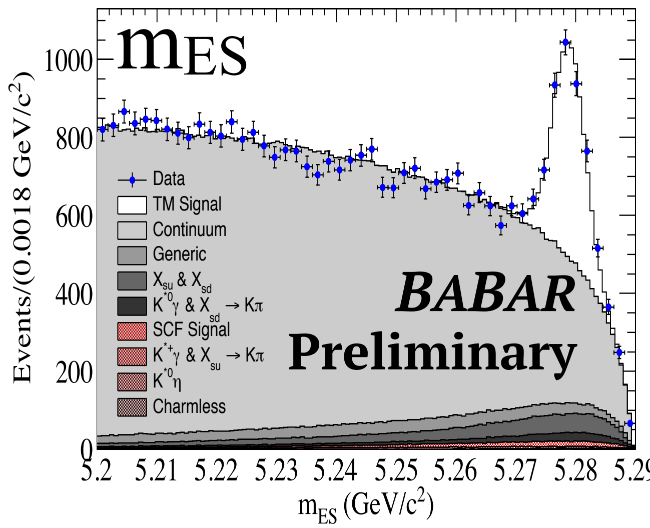
$$\mathcal{D}_{K_S^0\rho\gamma} \equiv \frac{\mathcal{S}_{K_S^0\pi^+\pi^-\gamma}}{\mathcal{S}_{K_S^0\rho\gamma}}$$

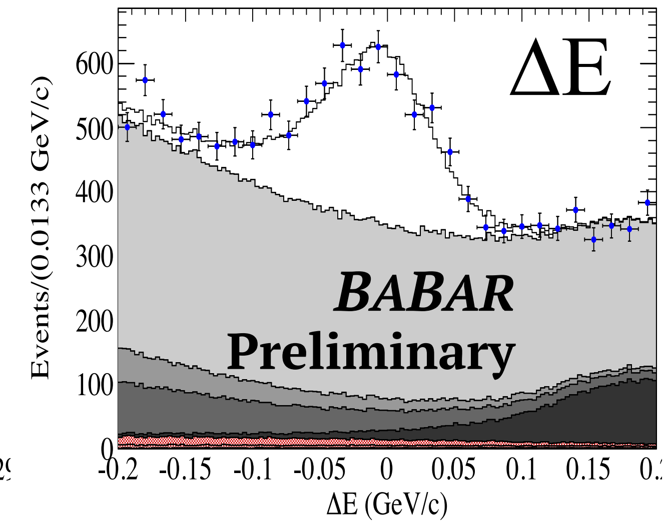
- $\mathcal{D}_{K_S\rho\gamma}$ is extracted from an amplitude analysis of $B^+ \to K^+\pi^-\pi^+\gamma$ decays using the hypothesis of isospin conservation

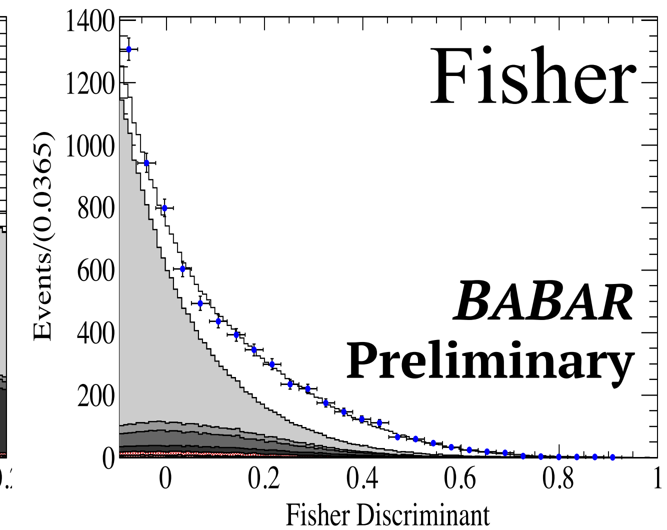
$B \rightarrow K\pi^-\pi^+\gamma$
ANALYSIS STRATEGY (2/2)

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

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

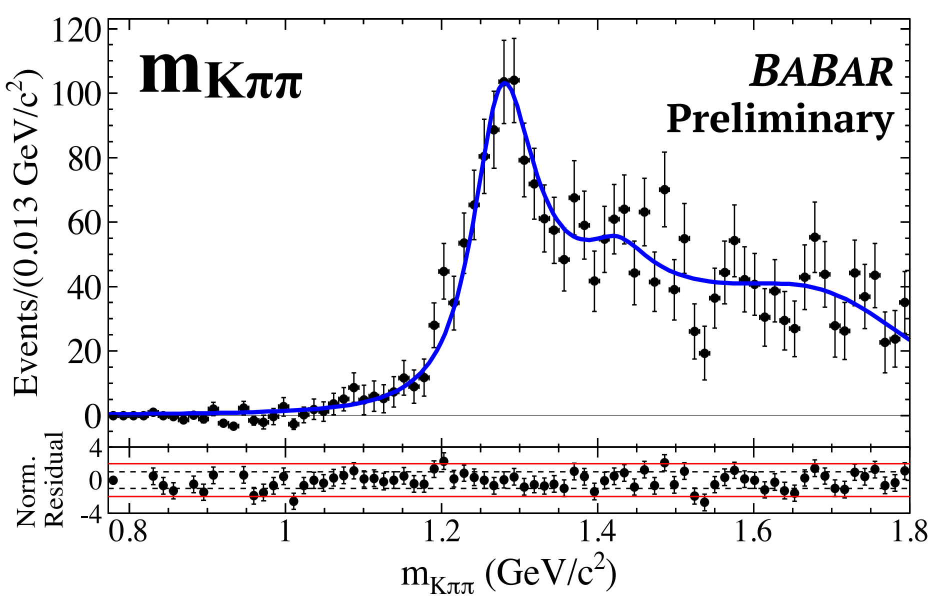




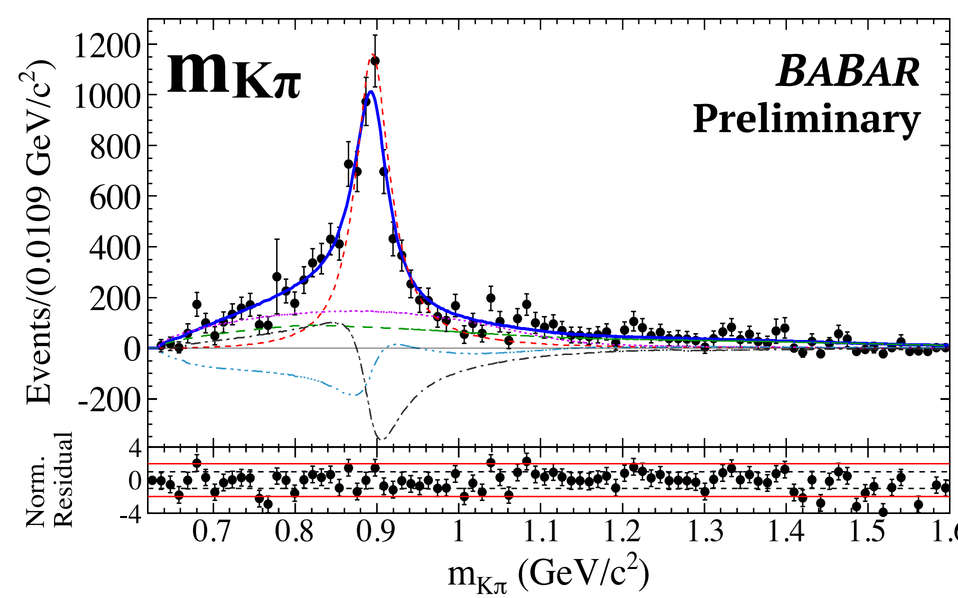


(2) Fit to $m_{K\pi\pi}$ spectrum to determine K_{res} amplitudes and BFs

(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

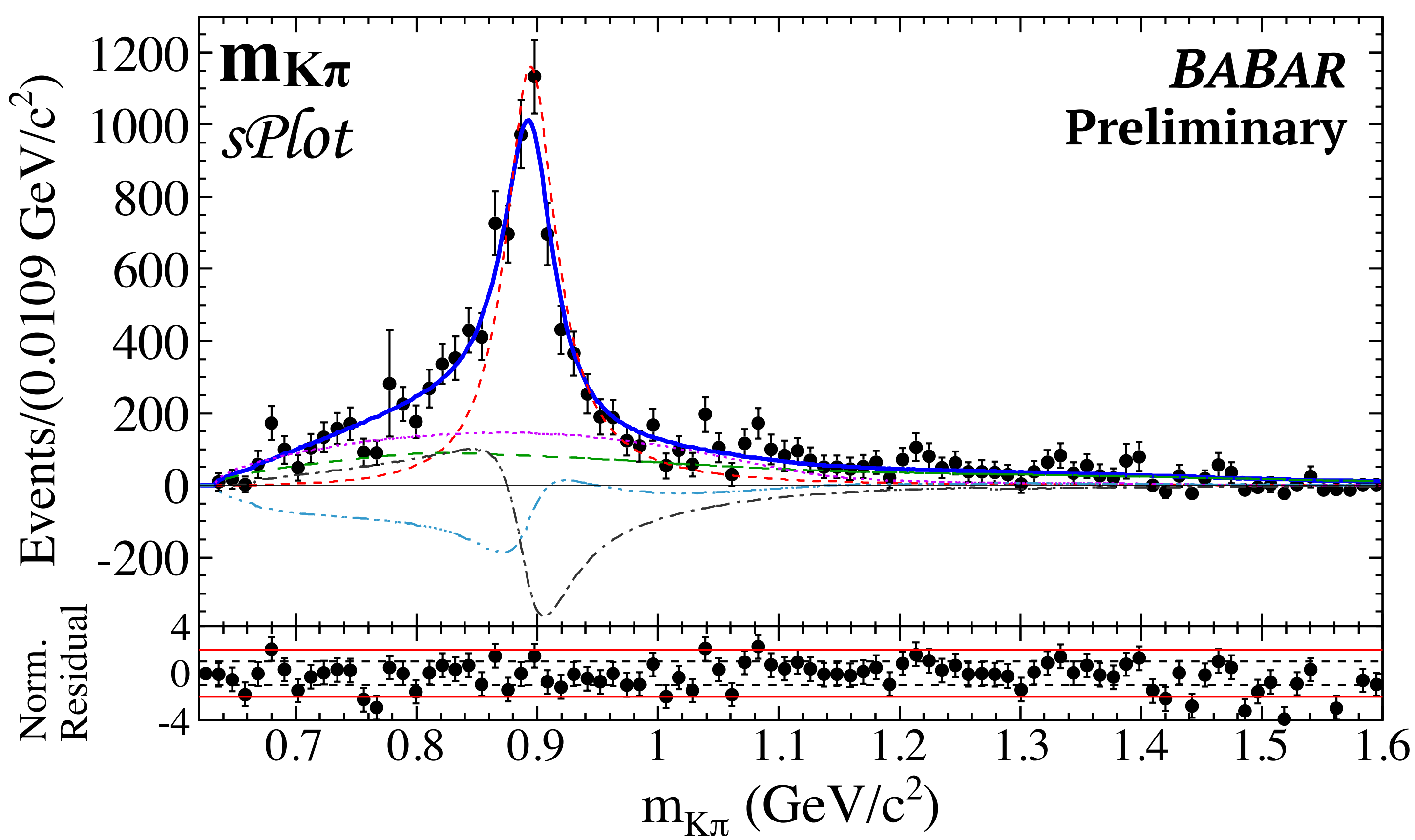


$B^+ \to K^+\pi^-\pi^+\gamma$
THE DILUTION FACTOR

- $\mathcal{D}_{K_S\rho\gamma}$ is determined from the charged decay mode $B^+ \to K^+\pi^-\pi^+\gamma$:
  - $\mathcal{D}_{K_S\rho\gamma}$ is extracted from a fit to the $m_{K\pi}$ spectrum

$$\mathcal{D}_{K^0_S\rho\gamma} = \frac{\int \left[|A_\rho|^2 + \Re(A^*_\rho A_{K^{*+}}) + \Re(A^*_\rho A_{K^{*-}}) + \Re(A^*_{K^{*+}} A_{K^{*-}}) + \Re(A^*_{(K\pi)^+} A_{(K\pi)^-}) \right]}{\int \left[|A_\rho|^2 + \Re(A^*_\rho A_{K^{*+}}) + \Re(A^*_\rho A_{K^{*-}}) + \frac{|A_{K^{*+}}|^2 + |A_{K^{*-}}|^2}{2} + \frac{|A_{(K\pi)^+}|^2 + |A_{(K\pi)^-}|^2}{2} \right]}$$

$\propto \mathrm{FF}_\rho$; $\propto \mathrm{FF}^{\mathrm{interf.}}_{K^*-\rho}$; $\propto \mathrm{FF}_{K^*}$; $\propto \mathrm{FF}_{(K\pi)_0}$



: PDF Total

: $K^*(892)$

: $\rho^0(770)$

: $(K\pi)$ S-wave

: $K^*(892) - \rho^0(770)$ interference

: $\rho^0(770) - (K\pi)_0$ interference

$$\mathcal{D}_{K^0_S\rho\gamma} = 0.549^{+0.096}_{-0.094}$$

$B^+ \to K^+\pi^-\pi^+\gamma$
Branching fractions

BABAR **preliminary**

$K_{res} \to K^+\pi^-\pi^+$

Mode	$\mathcal{B}(B^+ \to \text{Mode})\times \mathcal{B}(K_{res} \to K^+\pi^+\pi^-) \times 10^{-6}$	$\mathcal{B}(B^+ \to \text{Mode}) \times 10^{-6}$	PDG values $(\times 10^{-6})$
Inclusive $B^+ \to K^+\pi^+\pi^-\gamma$	$\cdots$	$27.21 \pm 1.01^{+1.14}_{-1.25}$	27.6 ± 2.2
$K_1(1270)^+\gamma$	$14.47^{+1.97+1.14}_{-1.30-1.23}$	$44.04^{+6.00+3.48}_{-3.97-3.73} \pm 4.58$	43 ± 13
$K_1(1400)^+\gamma$	$4.07^{+1.92+1.29}_{-1.21-0.76}$	$9.65^{+4.55+3.05}_{-2.86-1.80} \pm 0.61$	< 15 CL= 90%
$K^*(1410)^+\gamma$	$9.71^{+2.13+2.42}_{-1.87-0.68}$	$23.83^{+5.23+5.94}_{-4.59-1.43} \pm 2.38$	$\emptyset$
$K_2^*(1430)^+\gamma$	$1.45^{+1.21+0.87}_{-0.97-1.38}$	$10.41^{+8.68+6.34}_{-6.95-9.88} \pm 0.54$	14 ± 4
$K^*(1680)^+\gamma$	$17.03^{+1.71+3.49}_{-1.35-2.99}$	$71.67^{+7.18+14.70}_{-5.67-12.58} \pm 5.83$	< 1900 CL= 90%

Resonances in the $K^+\pi^-\pi^+$ system

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 $B^+ \to K^+\pi^+\pi^-\gamma$	$\cdots$	$27.21 \pm 1.01^{+1.14}_{-1.25}$	27.6 ± 2.2
$K^{*0}(892)\pi^+\gamma$	$17.31^{+0.94+1.19}_{-0.89-1.12}$	$25.96^{+1.42+1.79}_{-1.34-1.68}$	20^{+7}_{-6}
$K^+\rho(770)^0\gamma$	$9.12^{+0.75+1.30}_{-0.69-1.31}$	$9.21^{+0.76+1.31}_{-0.70-1.32} \pm 0.02$	< 20 CL= 90%
$(K\pi)^{*0}_0\pi^+\gamma$	$11.32^{+1.48+2.00}_{-1.54-2.60}$	$\cdots$	$\emptyset$
$(K\pi)^0_0\pi^+\gamma$ (NR)	$\cdots$	$10.81^{+1.42+1.91}_{-1.47-2.48}$	< 9.2 CL= 90%
$K_0^*(1430)^0\pi^+\gamma$	$0.51 \pm 0.07^{+0.09}_{-0.12}$	$0.82 \pm 0.11^{+0.15}_{-0.19} \pm 0.08$	$\emptyset$

$B^+ \to K^+\pi^-\pi^+\gamma$
Branching fractions

BABAR **preliminary**

$K_{res} \to K^+\pi^-\pi^+$

Mode	$\mathcal{B}(B^+ \to \text{Mode}) \times \mathcal{B}(K_{res} \to K^+\pi^+\pi^-) \times 10^{-6}$	$\mathcal{B}(B^+ \to \text{Mode}) \times 10^{-6}$	PDG values ($\times 10^{-6}$)
Inclusive $B^+ \to K^+\pi^+\pi^-\gamma$	...	$27.21 \pm 1.01^{+1.14}_{-1.25}$	27.6 ± 2.2
$K_1(1270)^+\gamma$	$14.47^{+1.97+1.14}_{-1.30-1.23}$	$44.04^{+6.00+3.48}_{-3.97-3.73} \pm 4.58$	43 ± 13
$K_1(1400)^+\gamma$	$4.07^{+1.92+1.29}_{-1.21-0.76}$	$9.65^{+4.55+3.05}_{-2.86-1.80} \pm 0.61$	< 15 CL$= 90\%$
$K^*(1410)^+\gamma$	$9.71^{+2.13+2.42}_{-1.87-0.68}$	$23.83^{+5.23+5.94}_{-4.59-1.43} \pm 2.38$	$\emptyset$
[illegible]	[illegible]	[illegible]	14 ± 4
[illegible]	[illegible]	[illegible]	< 1900 CL$= 90\%$

Several of these measurements are the world best (or done for the first time)

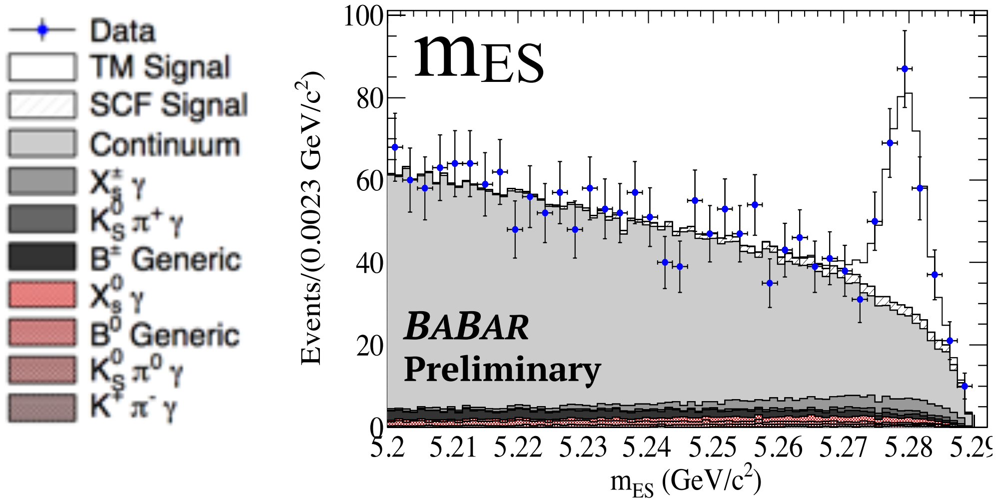
Resonances in the $K^+\pi^-\pi^+$ system

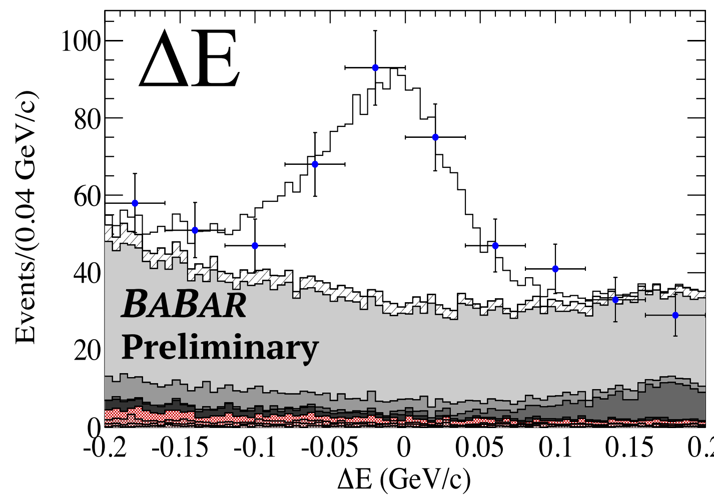
[illegible]	[illegible]	[illegible]	PDG values ($\times 10^{-6}$)
Inclusive $B^+ \to K^+\pi^+\pi^-\gamma$	...	$27.21 \pm 1.01^{+1.14}_{-1.25}$	27.6 ± 2.2
$K^{*0}(892)\pi^+\gamma$	$17.31^{+0.94+1.19}_{-0.89-1.12}$	$25.96^{+1.42+1.79}_{-1.34-1.68}$	20^{+7}_{-6}
$K^+\rho(770)^0\gamma$	$9.12^{+0.75+1.30}_{-0.69-1.31}$	$9.21^{+0.76+1.31}_{-0.70-1.32} \pm 0.02$	< 20 CL$= 90\%$
$(K\pi)^{*0}_0\pi^+\gamma$	$11.32^{+1.48+2.00}_{-1.54-2.60}$	...	$\emptyset$
$(K\pi)^0_0\pi^+\gamma$ (NR)	...	$10.81^{+1.42+1.91}_{-1.47-2.48}$	< 9.2 CL$= 90\%$
$K^*_0(1430)^0\pi^+\gamma$	$0.51 \pm 0.07^{+0.09}_{-0.12}$	$0.82 \pm 0.11^{+0.15}_{-0.19} \pm 0.08$	$\emptyset$

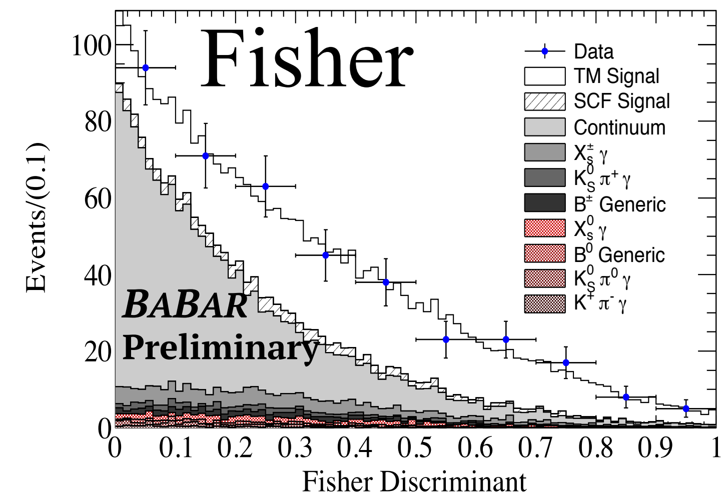
$B^0 \rightarrow K_S\pi^-\pi^+\gamma$

RESULTS ($S_{K_S\rho\gamma}$)

- **Measurement of the "effective" CP asymmetry parameters:**
  - **Extracted directly from a 4D ML fit to four discriminating variables on the neutral decay mode $B^0 \rightarrow K_S\,\pi^-\pi^+\gamma$:**







$$\mathcal{S}_{K^0_S\pi^+\pi^-\gamma} = 0.137 \pm 0.249(\text{stat.})^{+0.042}_{-0.033}(\text{syst.})$$

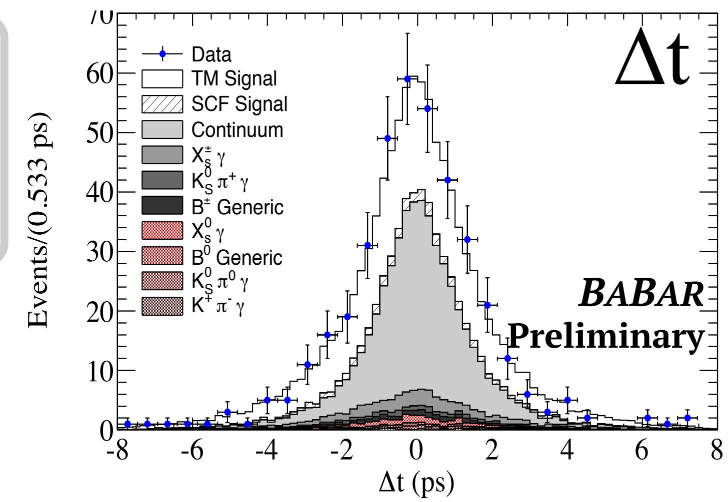
$$\mathcal{C}_{K^0_S\pi^+\pi^-\gamma} = -0.390 \pm 0.204(\text{stat.})^{+0.045}_{-0.050}(\text{syst.})$$

+

$$\mathcal{D}_{K^0_S\rho\gamma} = 0.549^{+0.096}_{-0.094}$$

↳

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



- **In agreement with the SM prediction**
- **With the current sensitivity, does not allow constrain out NP models**

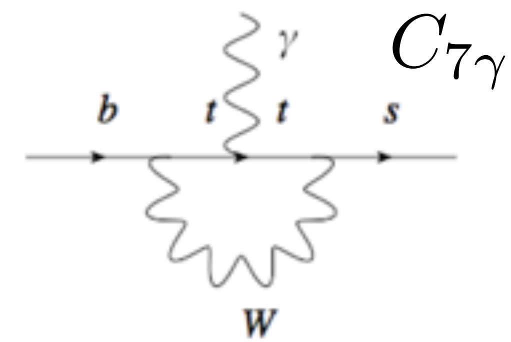
Summary & Conclusions

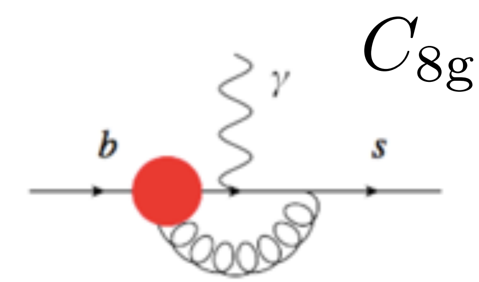
- *BABAR* continues to produce exciting physics results, adding more information and using more sophisticated analysis techniques to improve the precision of measurements in radiative-penguin B decays
- All measurements presented here agree with the standard model predictions
- Larger samples are needed to tell whether or not there could be indications for NP. The analyses shown here have interesting prospectives with more data (Belle II and LHCb)

Back-Up

$B \to X_s\gamma$

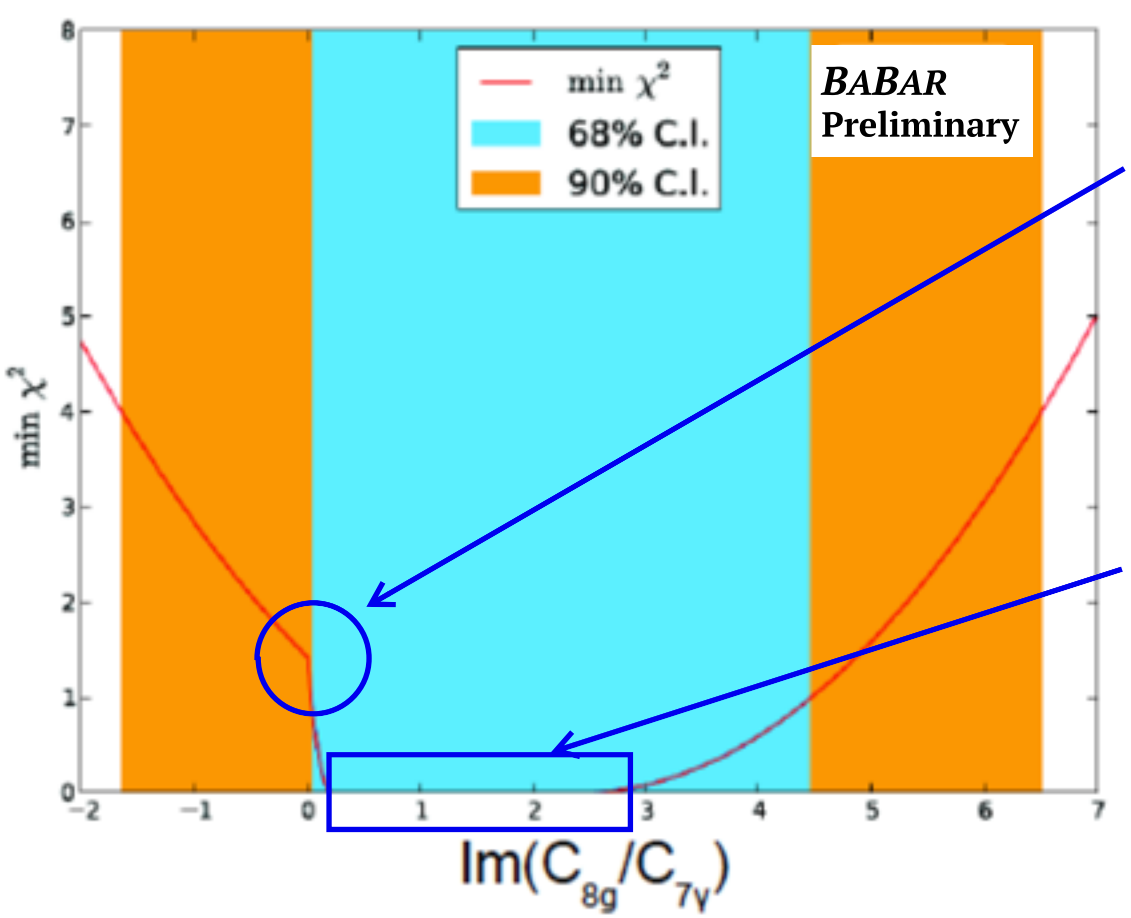
The CP isospin asymmetry depends on interference between electromagnetic dipole ($C_{7\gamma}$) and chromo-magnetic dipole (C_{8g}) transitions via an interference amplitude



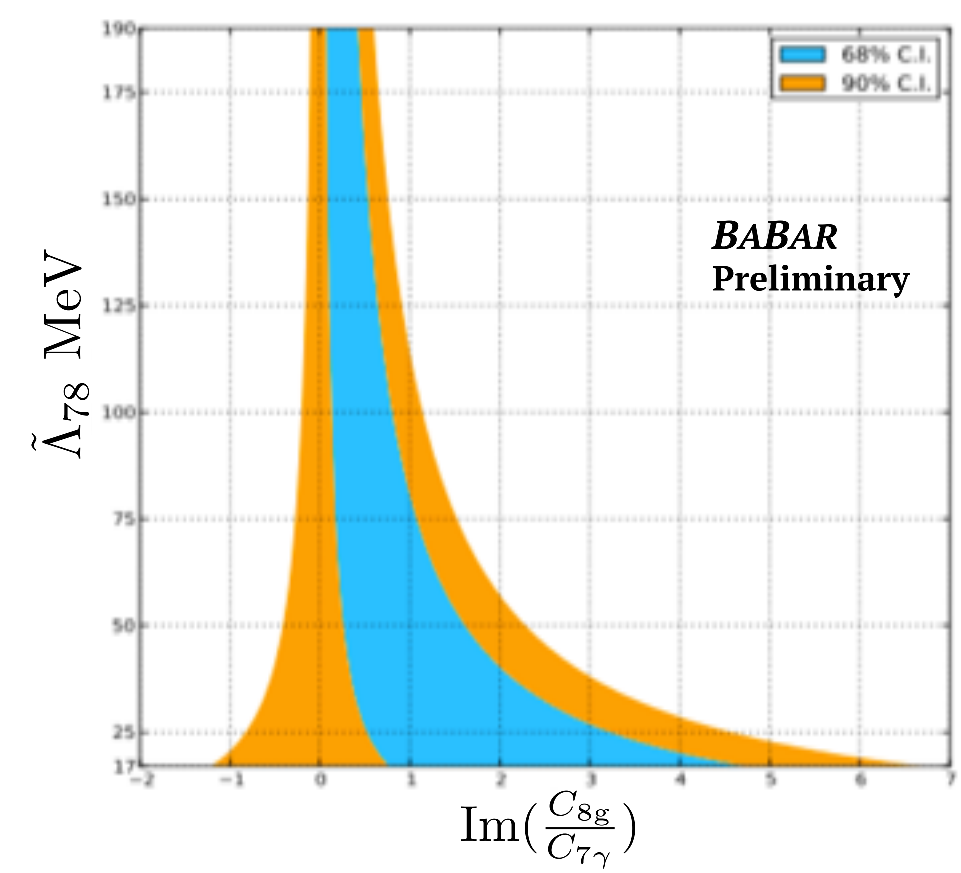


$$\Delta A_{CP}^{X_s\gamma} \simeq 0.12 \times \frac{\tilde{\Lambda}_{78}}{100\mathrm{MeV}} \mathrm{Im}\left(\frac{C_{8g}}{C_{7\gamma}}\right)$$

$$\tilde{\Lambda}_{78} \in [17\mathrm{MeV}, 190\mathrm{MeV}]$$

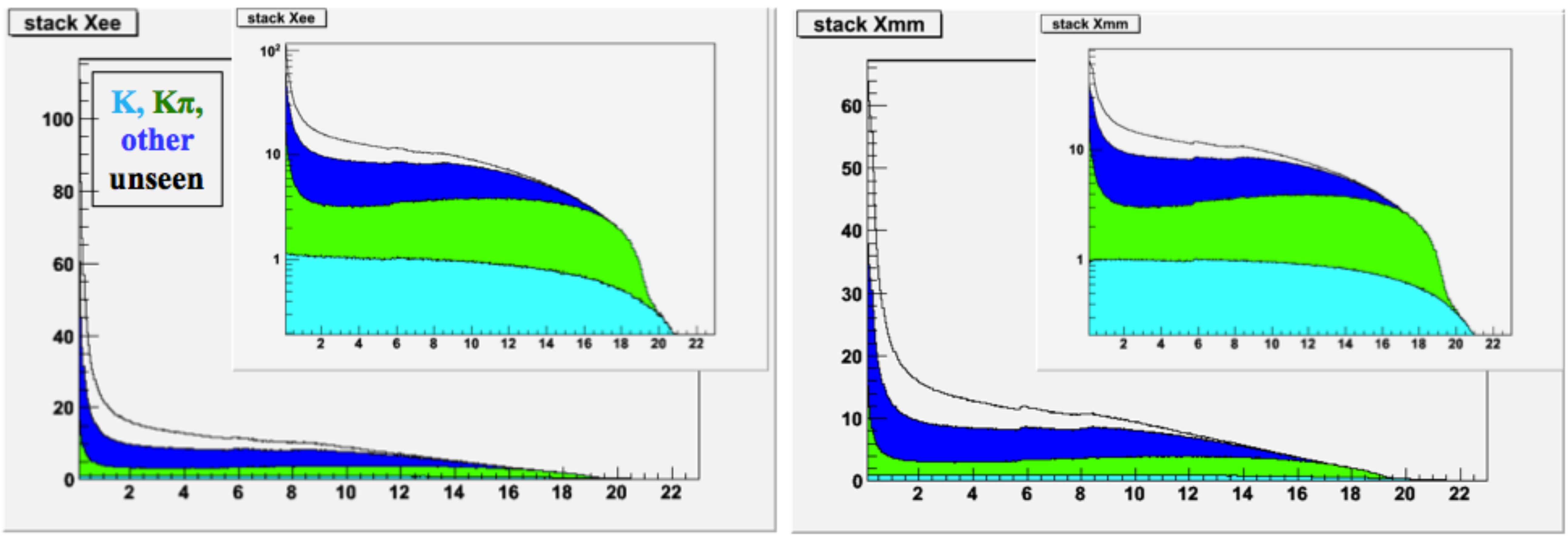


- Discontinuity due to different Λ_{78} values for $\mathrm{Im}(C_{8g}/C_{7\gamma})<0$ or >0
- Flat plateau: $\Delta A_{Exp}=\Delta A_{Th}$



$B \rightarrow X_S \ell^+ \ell^-$
MISSING MODES

- **Extrapolation to fully inclusive rate:**
  - A scaling factor derived from the ratio of unseen to seen events in simulated $B \rightarrow X_S \ell^+ \ell^-$ signal events is used to scale the measured BF into the total BF



$B \to X_S \ell^+ \ell^-$
SYSTEMATICS

- **Systematics are grouped into three categories:**
  - Possible biases arising from uncertainties in the fit model pdf parameterizations and normalizations, affecting the fitted raw signal yields;
  - Systematics affecting the calculation of un-extrapolated branching fractions, e.g. BB counting, reconstruction efficiencies, etc.;
  - Systematics associated with the unseen scaling factor derived from the underlying event generator model are characterized using:
    - 20 a priori generator-level variations in b-quark mass and Fermi motion parameter, and hadronization of the X_s system by JETSET; and
    - a posteriori variations of ±50% in the π^0, π^+ and kaon multiplicities from the nominal generator model.

The Dilution Factor
Analytical Expression

- **Defined as the ratio:**

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

- **CP asymmetry when considering all the resonances** ρ^0, $K^{*\pm}$ or $(K\pi)^{\pm}$ S-wave **in the total amplitude:**

$$\mathcal{A}_{CP}^{K^0_S\pi^+\pi^-\gamma}(t) = \mathcal{C}_{K^0_S\pi^+\pi^-\gamma}\cos(\Delta \mathrm{M}t) + \mathcal{S}_{K^0_S\pi^+\pi^-\gamma}\sin(\Delta \mathrm{M}t)$$

- **CP asymmetry when considering only the ρ⁰ resonance in the total amplitude:**

$$\mathcal{A}_{CP}^{K^0_S\rho\gamma}(t) = \mathcal{C}_{K^0_S\rho\gamma}\cos(\Delta \mathrm{M}t) + \mathcal{S}_{K^0_S\rho\gamma}\sin(\Delta \mathrm{M}t)$$

The Dilution Factor
Analytical Expression

- **In terms of amplitudes:**

$$B^0(t) \to H_{\rm res} P_{\rm scal}\gamma \qquad H_{\rm res} = \rho^0,\ K^{*\pm} \text{ or } (K\pi)^{\pm} \text{ S-wave };\quad P_{\rm scal} = K^0_S \text{ or } \pi^{\pm}$$

$$\begin{aligned}
A_R^{H_{\rm res}}(B^0 \to H_{\rm res}P_{\rm scal}\gamma_L) &= \xi_1 A_{H_{\rm res}} \sin\psi e^{-i\phi_R^{H_{\rm res}}} e^{i\delta^{H_{\rm res}}} \\
A_L^{H_{\rm res}}(B^0 \to H_{\rm res}P_{\rm scal}\gamma_R) &= \xi_2 A_{H_{\rm res}} \cos\psi e^{-i\phi_L^{H_{\rm res}}} e^{i\delta^{H_{\rm res}}} \\
\overline{A}_L^{H_{\rm res}}(\overline{B}^0 \to H_{\rm res}P_{\rm scal}\gamma_L) &= \xi_3 A_{H_{\rm res}} \cos\psi e^{i\phi_L^{H_{\rm res}}} e^{i\delta^{H_{\rm res}}} \\
\overline{A}_R^{H_{\rm res}}(\overline{B}^0 \to H_{\rm res}P_{\rm scal}\gamma_R) &= \xi_4 A_{H_{\rm res}} \sin\psi e^{i\phi_R^{H_{\rm res}}} e^{i\delta^{H_{\rm res}}}
\end{aligned}$$

$$\begin{aligned}
\tan\psi &= C'_{7_\gamma}/C_{7_\gamma} \\
\phi_{L/R}^{H_{\rm res}} &\Rightarrow CP\text{-odd weak phases} \\
\delta^{H_{\rm res}} &\Rightarrow CP\text{-even strong phases} \\
\xi_i &\equiv CP(H_{\rm res}P_{\rm scal}) = \pm 1 \\
(\xi_1,\xi_2,\xi_3,\xi_4) &= (+,-,+,-) \text{ for } \rho \text{ and } K^{*\pm} \\
(\xi_1,\xi_2,\xi_3,\xi_4) &= (+,+,+,+) \text{ for } (K\pi)^{\pm} \text{ S-wave}
\end{aligned}$$

$$\mathcal{A}_{CP}(t) = \frac{\Gamma_{\overline{B}^0}(t) - \Gamma_{B^0}(t)}{\Gamma_{\overline{B}^0}(t) + \Gamma_{B^0}(t)} \equiv \mathcal{C}\cos(\Delta {\rm M} t) + \mathcal{S}\sin(\Delta {\rm M} t)$$

$$\begin{aligned}
\Gamma_{B^0}(t) &= |\mathcal{M}_L(t)|^2 + |\mathcal{M}_R(t)|^2 \\
\Gamma_{\overline{B}^0}(t) &= |\overline{\mathcal{M}}_L(t)|^2 + |\overline{\mathcal{M}}_R(t)|^2
\end{aligned}$$

$$\begin{aligned}
\mathcal{M}_L(t) &= \sum_{H_{\rm res}} \left(A_L^{H_{\rm res}} {\rm f}_+(t) + \overline{A}_L^{H_{\rm res}} \frac{q}{p} {\rm f}_-(t) \right) ; \quad \overline{\mathcal{M}}_L(t) = \sum_{H_{\rm res}} \left(\overline{A}_L^{H_{\rm res}} {\rm f}_+(t) + A_L^{H_{\rm res}} \frac{q}{p} {\rm f}_-(t) \right) \\
\mathcal{M}_R(t) &= \sum_{H_{\rm res}} \left(A_R^{H_{\rm res}} {\rm f}_+(t) + \overline{A}_R^{H_{\rm res}} \frac{q}{p} {\rm f}_-(t) \right) ; \quad \overline{\mathcal{M}}_R(t) = \sum_{H_{\rm res}} \left(\overline{A}_R^{H_{\rm res}} {\rm f}_+(t) + A_R^{H_{\rm res}} \frac{q}{p} {\rm f}_-(t) \right)
\end{aligned}$$

$${\rm f}_{\pm}(t) \equiv \frac{1}{2}\left(e^{-i{\rm M}_L t} e^{-\frac{1}{2}\Gamma_L t} \pm e^{-i{\rm M}_H t} e^{-\frac{1}{2}\Gamma_H t} \right) \qquad \frac{q}{p} = e^{-i2\beta}$$

The Dilution Factor
Analytical Expression

- In terms of amplitudes, the dilution factor can be expressed as:

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

$$= \frac{\int \left[|A_\rho|^2 + \Re\left(A^*_\rho A_{K^{*+}}\right) + \Re\left(A^*_\rho A_{K^{*-}}\right) + \Re\left(A^*_{K^{*+}} A_{K^{*-}}\right) + \Re\left(A^*_{(K\pi)^+} A_{(K\pi)^-}\right)\right]}{\int \left[|A_\rho|^2 + \Re\left(A^*_\rho A_{K^{*+}}\right) + \Re\left(A^*_\rho A_{K^{*-}}\right) + \frac{|A_{K^{*+}}|^2 + |A_{K^{*-}}|^2}{2} + \frac{|A_{(K\pi)^+}|^2 + |A_{(K\pi)^-}|^2}{2}\right]}$$

Integration performed over phase-space region

The amplitudes entering in the dilution factor expression are extracted from a fit to the $m_{K\pi}$ spectrum

FIT TO THE K$\pi\pi$ SPECTRUM: FIT MODEL

- **Model:**
  - Five resonances modeled by BW (mean and width fixed to PDG values):

J^P	$K_{\rm res}$	Mass m_j^0 (MeV/c^2)	Width Γ_j^0 (MeV/c^2)
1^+	$K_1(1270)$	1272 ± 7	90 ± 20
	$K_1(1400)$	1403 ± 7	174 ± 13
1^-	$K^*(1410)$	1414 ± 15	232 ± 21
	$K^*(1680)$	1717 ± 27	322 ± 110
2^+	$K_2^*(1430)$	1425.6 ± 1.5	98.5 ± 2.7

$$\mathrm{BW}_j^J(m) = \left.\frac{1}{(m_j^0)^2 - m^2 - i m_j^0 \Gamma_j^0}\right|_{m=m_{K\pi\pi}}$$

$$|A(m;c_j)|^2 = \sum_J \left|\sum_j c_j\, \mathrm{BW}_j^J(m)\right|^2 \Bigg|_{m=m_{K\pi\pi}}$$

$$c_j = \alpha_j\, e^{i\phi_j}$$

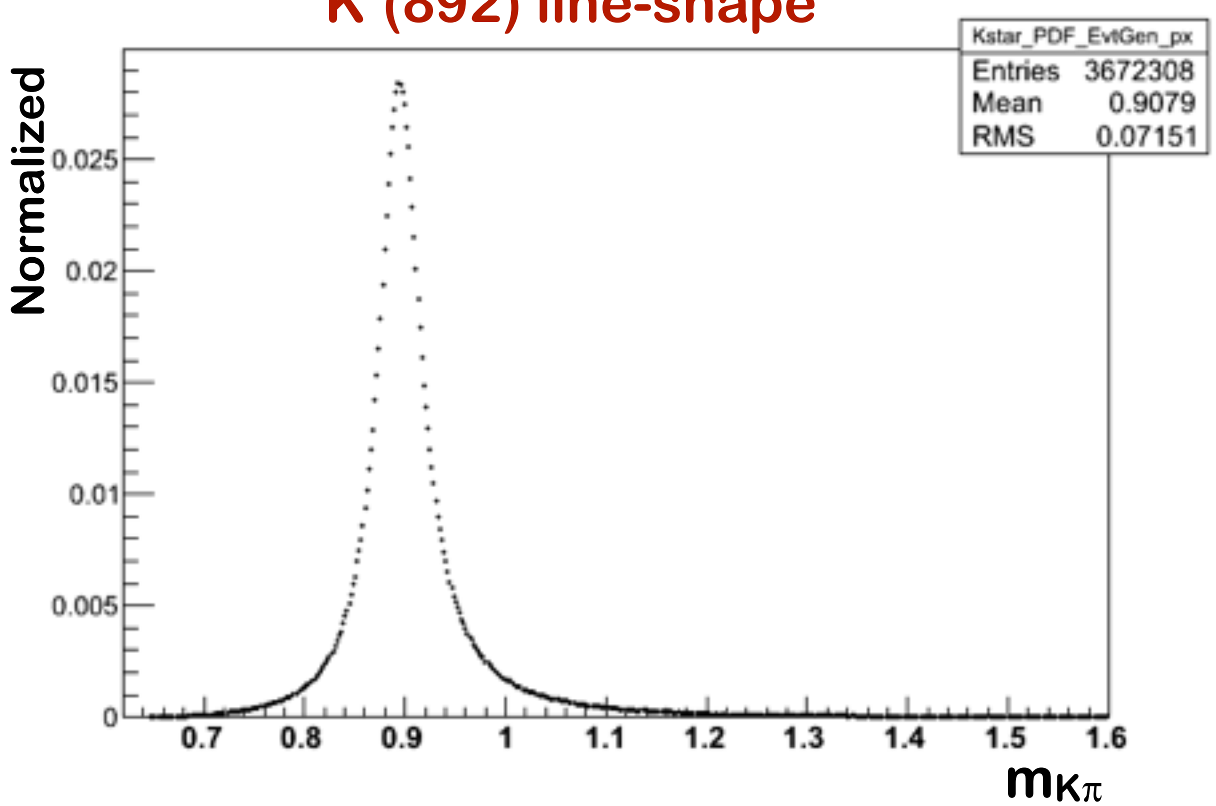
- **Fit to K$\pi\pi$ invariant mass sPlot (binned) distribution**
  - 8 fitted parameters:
    - ➜ 4 magnitudes, 2 relative phases
    - ➜ 2 widths ($K_1(1270)$ and $K^*(1680)$)
  - Due to the integration over the angular variables, only resonances with same J^P interfere
  - Randomized initial parameter values
- **Fit fractions computed from magnitudes and phases**

$M_{K\pi}$ Spectrum Fit
Model (1)

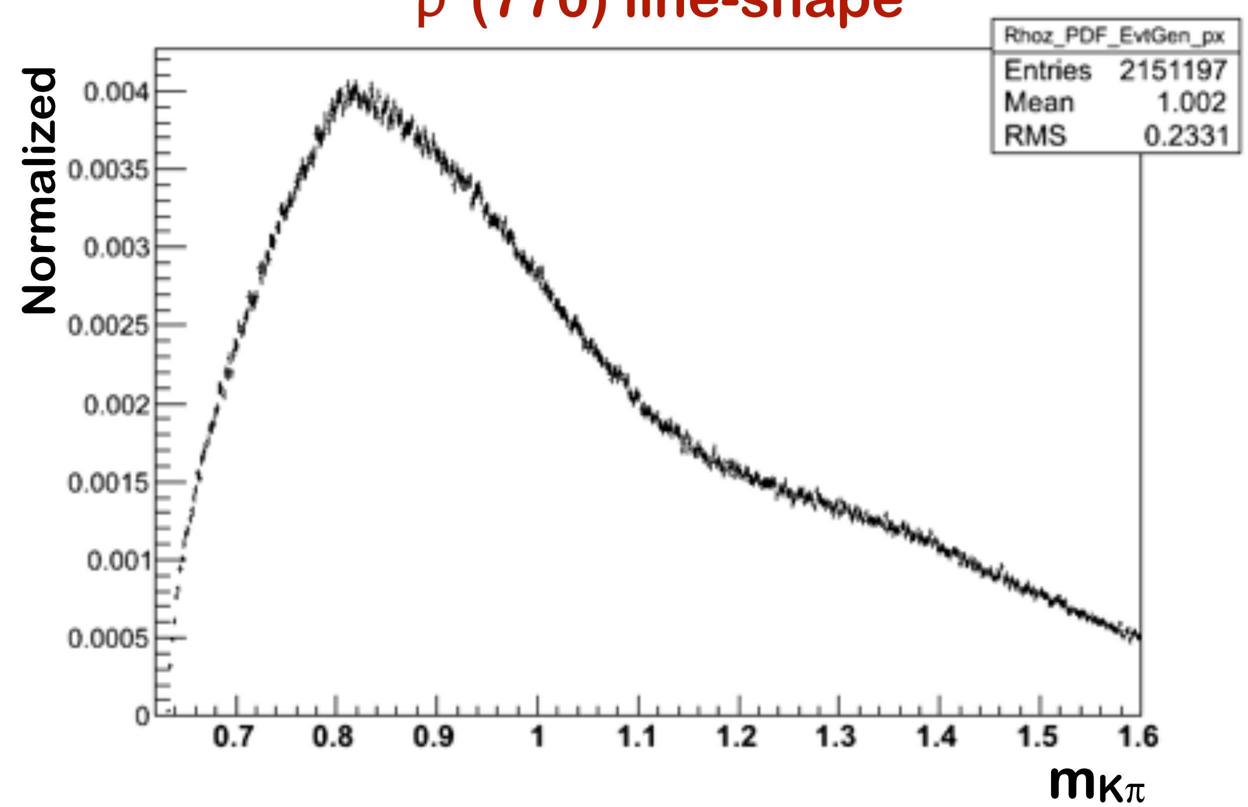
Line-shapes:

- Line-shapes significantly distorted due to phase-space effects
- Extracted from MC distributions at generator level using EvtGen:
  - Take phase-space corrections into account
  - To be used to fit efficiency-corrected TM signal sPlot
- Used fit based BR of the different $B \to K_{res}\,\gamma$

$K^*(892)$ line-shape



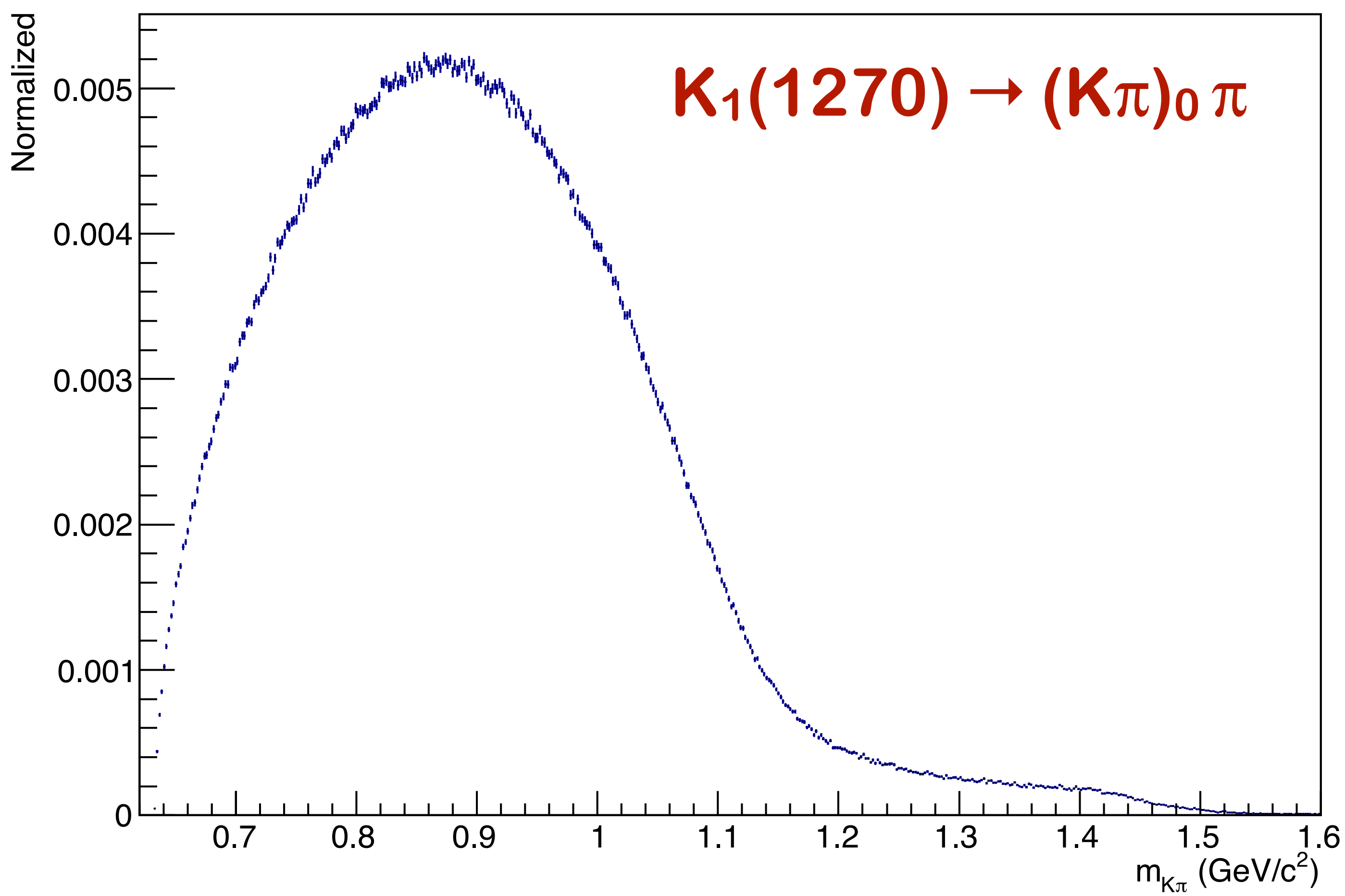
$\rho^0(770)$ line-shape



Line-shapes:

- **Line-shapes significantly distorted due to phase-space effects**
- **Extracted from MC distributions at generator level using EvtGen:**
  - **Take phase-space corrections into account**
  - **To be used to fit efficiency-corrected TM signal sPlot**

S-wave line-shape (using LASS)



$M_{K\pi}$ Spectrum Fit
Model (3)

Total PDF:

Parameters in the fit:
2 fixed as reference - 4 free

- Coherent sum of $K^*(892)$, $\rho^0(770)$ and $K\pi$ S-wave component:

$$|A(m_{K\pi};c_j)|^2 = \left| \int_{m_{\pi\pi}^{min}}^{m_{\pi\pi}^{max}} \left(\sum_j c_j \sqrt{\mathrm{H}_{\mathrm{R}_j}(m_{K\pi}, m_{\pi\pi})}\, e^{i\Phi_{\mathrm{R}_j}(m)} \right) dm_{\pi\pi} \right|^2 , \quad c_j = \alpha_j\, e^{i\phi_j}$$

$$= |c_{K^*}|^2 \mathcal{H}_{K^*} + |c_{\rho^0}|^2 \mathcal{H}_{\rho^0} + |c_{(K\pi)_0}|^2 \mathcal{H}_{(K\pi)_0} + I$$

Interference term described in next slide

- Invariant-mass-dependent magnitude defined as the projection of two-dimensional histograms:

$$\mathcal{H}_{R_j}(m_{K\pi}) = \int_{m_{\pi\pi}^{min}}^{m_{\pi\pi}^{max}} H_{R_j}(m_{K\pi}, m_{\pi\pi})\, dm_{\pi\pi}.$$

- The invariant-mass-dependent phase is taken from the analytical expression of the corresponding line shape:

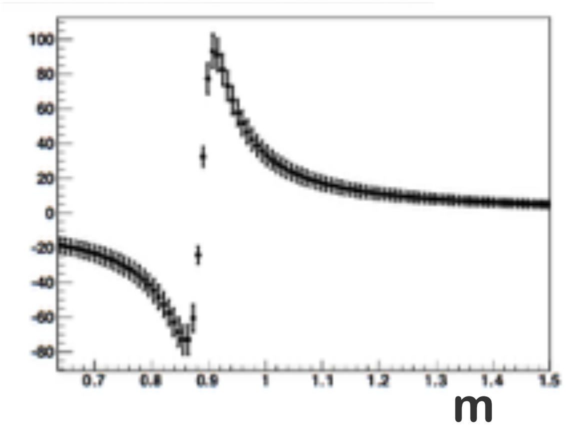
$$\Phi_{\mathrm{R}_j}(m) = \arccos\left(\frac{\Re[\mathrm{R}_j(m)]}{|\mathrm{R}_j(m)|}\right) \Leftrightarrow \begin{cases} m = m_{K\pi} \Rightarrow & \mathrm{R}_j(m_{K\pi}) \text{ is taken as RBW for } K^{*0}(892) \text{ and as LASS for S-wave ,} \\ m = m_{\pi\pi} \Rightarrow & \mathrm{R}_j(m_{\pi\pi}) \text{ is taken as a GS line shape for } \rho^0(770)\text{ ,} \end{cases}$$

$M_{K\pi}$ SPECTRUM FIT
MODEL (4)

Interference:

Illustration:

RBW+GS interf. (ϕ_{ρ^0}= π/2)



- **Interference terms:**

$$
\begin{aligned}
I(m_{K\pi}; c_{\rho^0}, c_{(K\pi)_0}) \;=\; & 2\alpha_{\rho^0}\left[\cos(\phi_{\rho^0}-\Phi_{\rm RBW})\int_{m_{\pi\pi}^{min}}^{m_{\pi\pi}^{max}} \sqrt{{\rm H}_{\rho^0}{\rm H}_{K^*}}\cos(\Phi_{\rm GS})\,dm_{\pi\pi}\right. \\
& \left. -\sin(\phi_{\rho^0}-\Phi_{\rm RBW})\int_{m_{\pi\pi}^{min}}^{m_{\pi\pi}^{max}} \sqrt{{\rm H}_{\rho^0}{\rm H}_{K^*}}\sin(\Phi_{\rm GS})\,dm_{\pi\pi}\right] \\
& +2\alpha_{\rho^0}\alpha_{(K\pi)_0}\left[\cos(\phi_{\rho^0}-\phi_{(K\pi)_0}-\Phi_{\rm LASS})\int_{m_{\pi\pi}^{min}}^{m_{\pi\pi}^{max}} \sqrt{{\rm H}_{\rho^0}{\rm H}_{(K\pi)_0}}\cos(\Phi_{\rm GS})\,dm_{\pi\pi}\right. \\
& \left. -\sin(\phi_{\rho^0}-\phi_{(K\pi)_0}-\Phi_{\rm LASS})\int_{m_{\pi\pi}^{min}}^{m_{\pi\pi}^{max}} \sqrt{{\rm H}_{\rho^0}{\rm H}_{(K\pi)_0}}\sin(\Phi_{\rm GS})\,dm_{\pi\pi}\right] .
\end{aligned}
$$

Term describing interference between the K*(892) and ρ^0(770) amplitudes

Term describing interference between the ρ^0(770) and (Kπ) S-wave amplitudes

The interference between the K*(892) and (Kπ) S-wave amplitudes vanishes due to the integration over the $m_{\pi\pi}$ dimension

RESULTS

- **$B^0 \rightarrow K_S\pi^-\pi^+\gamma$ TDCP analysis:**
  - **Measured the time-dependent CP asymmetry parameters in the decay $B^0 \rightarrow K_S\pi^-\pi^+\gamma$ with the full BaBar dataset**

(with $m_{K\pi\pi} < 1.8$ GeV/c², $0.6 < m_{\pi\pi} < 0.9$ GeV/c², $m_{K\pi} < 0.845$ GeV/c² and $m_{K\pi} > 0.945$ GeV/c²)

$$\mathcal{S}_{K_S^0\pi^+\pi^-\gamma} = 0.137 \pm 0.249(\text{stat.})^{+0.042}_{-0.033}(\text{syst.})$$
$$\mathcal{C}_{K_S^0\pi^+\pi^-\gamma} = -0.390 \pm 0.204(\text{stat.})^{+0.045}_{-0.050}(\text{syst.})$$

$$\mathcal{S}^{\text{Belle}}_{K_S^0\pi^+\pi^-\gamma} = 0.09 \pm 0.27(\text{stat.})^{+0.04}_{-0.07}(\text{syst.})$$
$$\mathcal{C}^{\text{Belle}}_{K_S^0\pi^+\pi^-\gamma} = -0.05 \pm 0.18(\text{stat.}) \pm 0.06(\text{syst.})$$

Comparable error on the effective CP asymmetry parameters compared to Belle's results (with ~1.4 times less events in the present analysis)

RESULTS

- $B^0 \to K_S\pi^-\pi^+\gamma$ **TDCP analysis:**
  - **The mixing induced CP violation parameter for $B^0 \to K_S\rho^0\gamma$ decays:**

$$\mathcal{S}_{K_S^0\rho\gamma} = \frac{\mathcal{S}_{K_S^0\pi^+\pi^-\gamma}}{\mathcal{D}_{K_S^0\rho\gamma}} = 0.249 \pm 0.455^{+0.076}_{-0.060}$$

Paper in prep.

  - **Compared with other CPV measurements in radiative decays:**

$$\mathcal{S}^{\text{Belle}}_{K_S^0\rho\gamma} = 0.11 \pm 0.33^{+0.05}_{-0.09}$$

PhysRevLett.101.251601

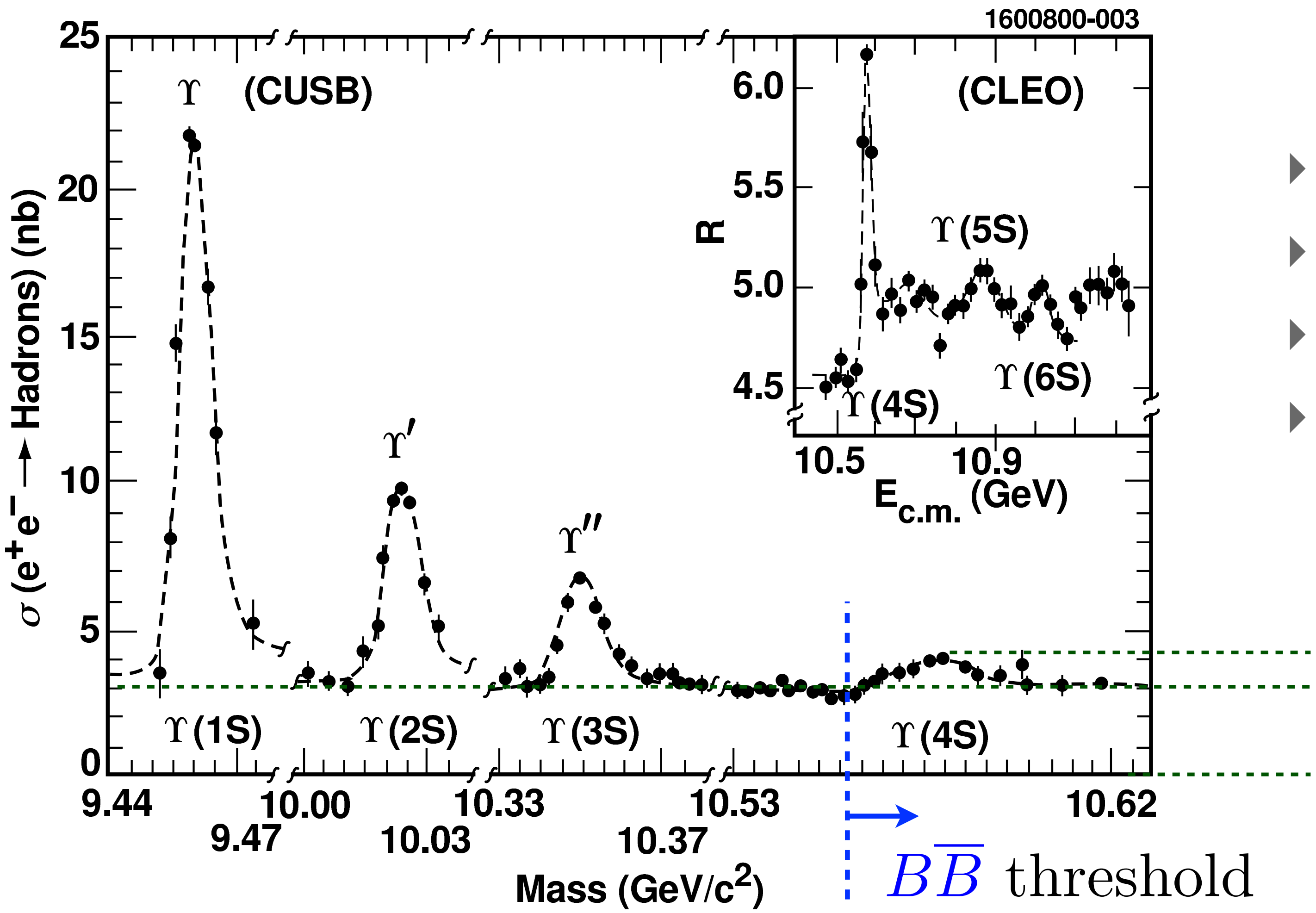
$$\mathcal{S}^{\text{BABAR}}_{K_S^0\pi^0\gamma} = -0.78 \pm 0.59 \pm 0.09$$

PhysRevD.78.071102

$$\mathcal{S}^{\text{Belle}}_{K_S^0\pi^0\gamma} = -0.10 \pm 0.31 \pm 0.07$$

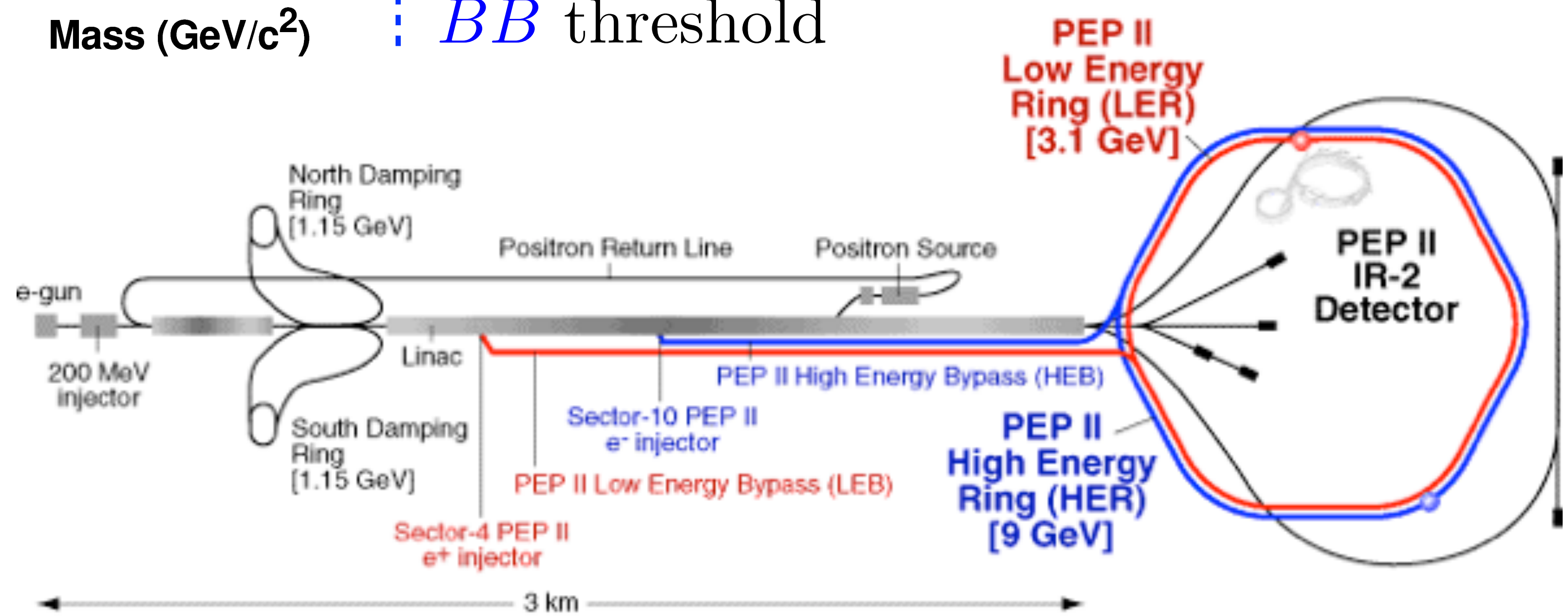
PhysRevD.74.111104

An asymmetric e^+e^- accelerator: PEP-II



- Babar at SLAC
- Running with PEP-II accelerator
- Clean environment
- Data taking stopped in 2008

$$\frac{\sigma(b\bar{b})}{\sigma(\text{hadrons})} = 0.28$$



The Babar detector and the data sample

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$; $B^0\bar{B}^0$ (coherent state) or B^+B^-

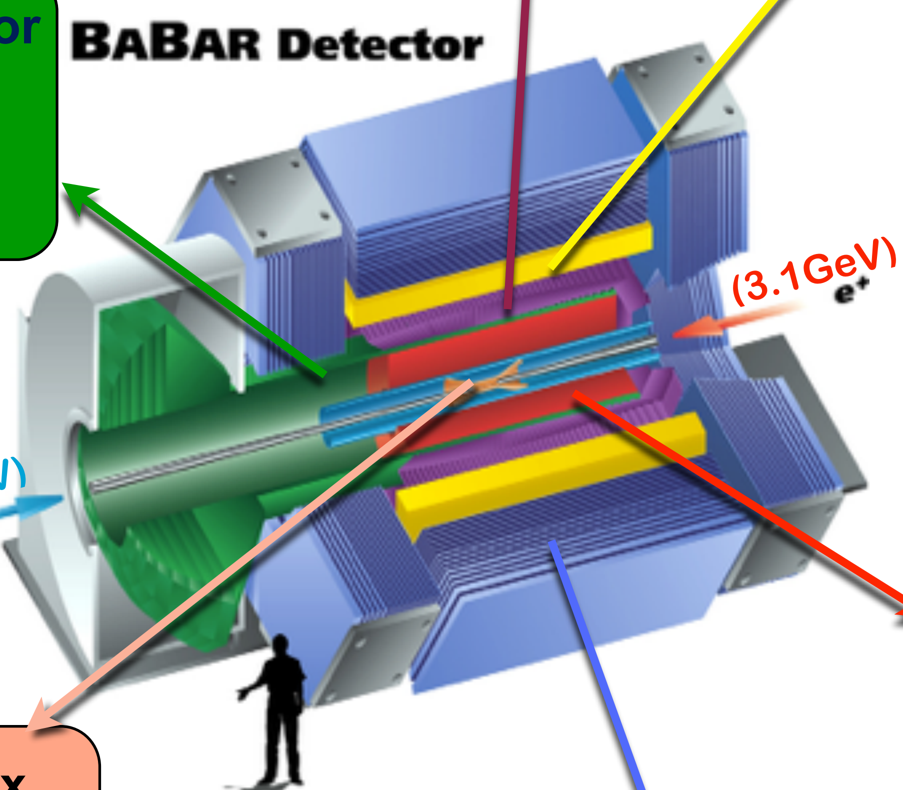
Electromagnetic calorimeter (EMC): 6580 CsI(Tl) crystals

Identification of charged particles
Separation K/π>2.5σ up to 4 GeV/c

1.5T solenoid

Cherenkov detector (DIRC): 144 quartz bars ; 11000 PMS

Identification of charged particles
Separation K/π>2.5σ up to 4 GeV/c



Drift Chamber: 40 stereo layers

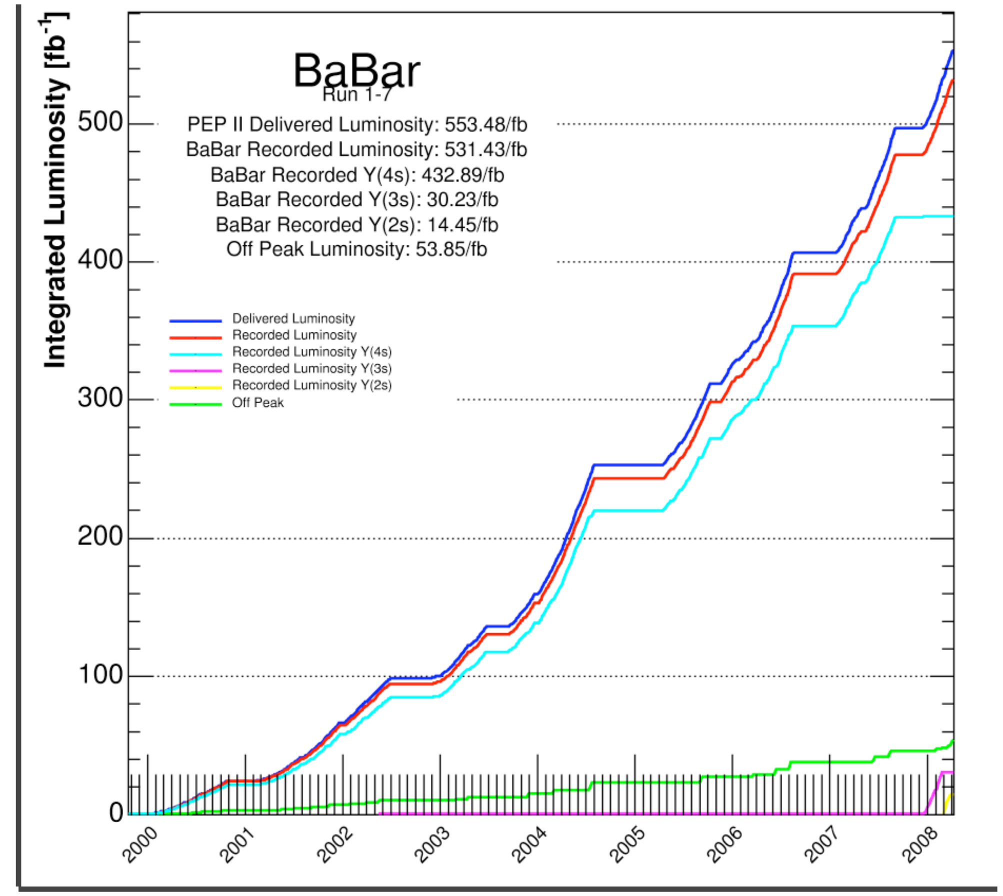
Reconstruction of deviated charged particles tracks: momentum and angles

Silicon Vertex Tracker (SVT): 5 layers

Reconstruction of decay vertex and tracks close to the IP

Instrumented Flux Return (IFR)

Muon identification



Full dataset:

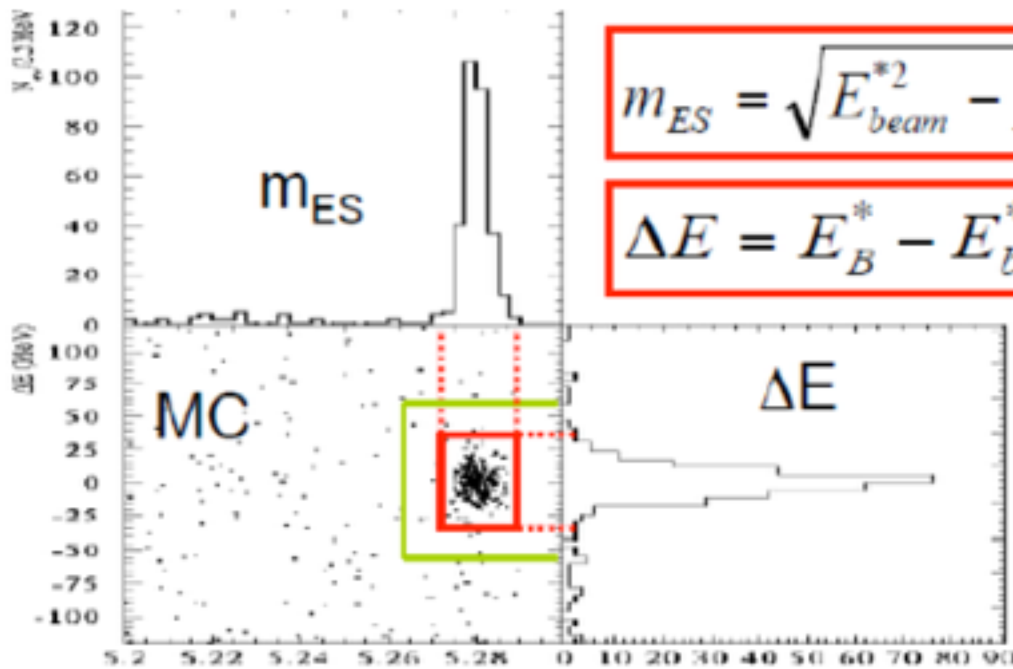
$\int \mathcal{L}dt \sim 433\ \mathrm{fb}^{-1}\ @\Upsilon(4S)$

$470 \times 10^6\ B\bar{B}$

$\int \mathcal{L}dt \sim 550\ \mathrm{fb}^{-1}$ total
(Off resonance, $\Upsilon(nS)$)

Common analysis techniques

Kinematics of fully reconstructed B



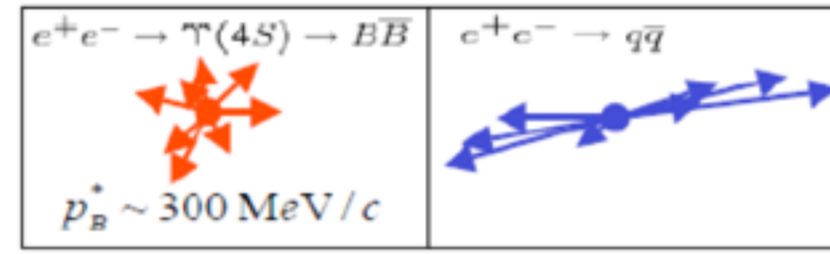
$$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$$

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

Background discrimination

Suppression by **multi-variable classifiers** based on **event-shape variables**:

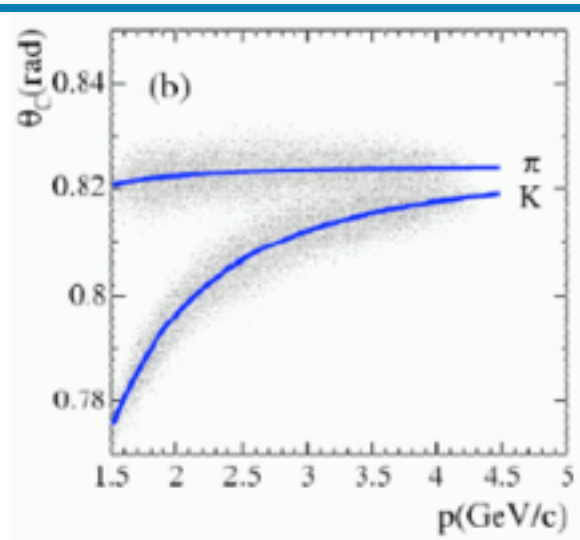
Topology:



Strongly discriminate continuum events ($e^+e^- \to q\bar{q}$ (q = u,d,s,c)

K/π separation

Very good **particle ID** between 1.5 and 4 GeV/c



Tagging parameters

$\beta\gamma \sim 0.56$ (BABAR)

$\Delta z = \beta\gamma c\Delta\tau$

$< \Delta z > \sim 250\mu m$

Variables are often combined in a **likelihood function**, used in a **maximum likelihood fit** for signal/background separation and to measure parameters of interest

Flavor tagging in BaBar

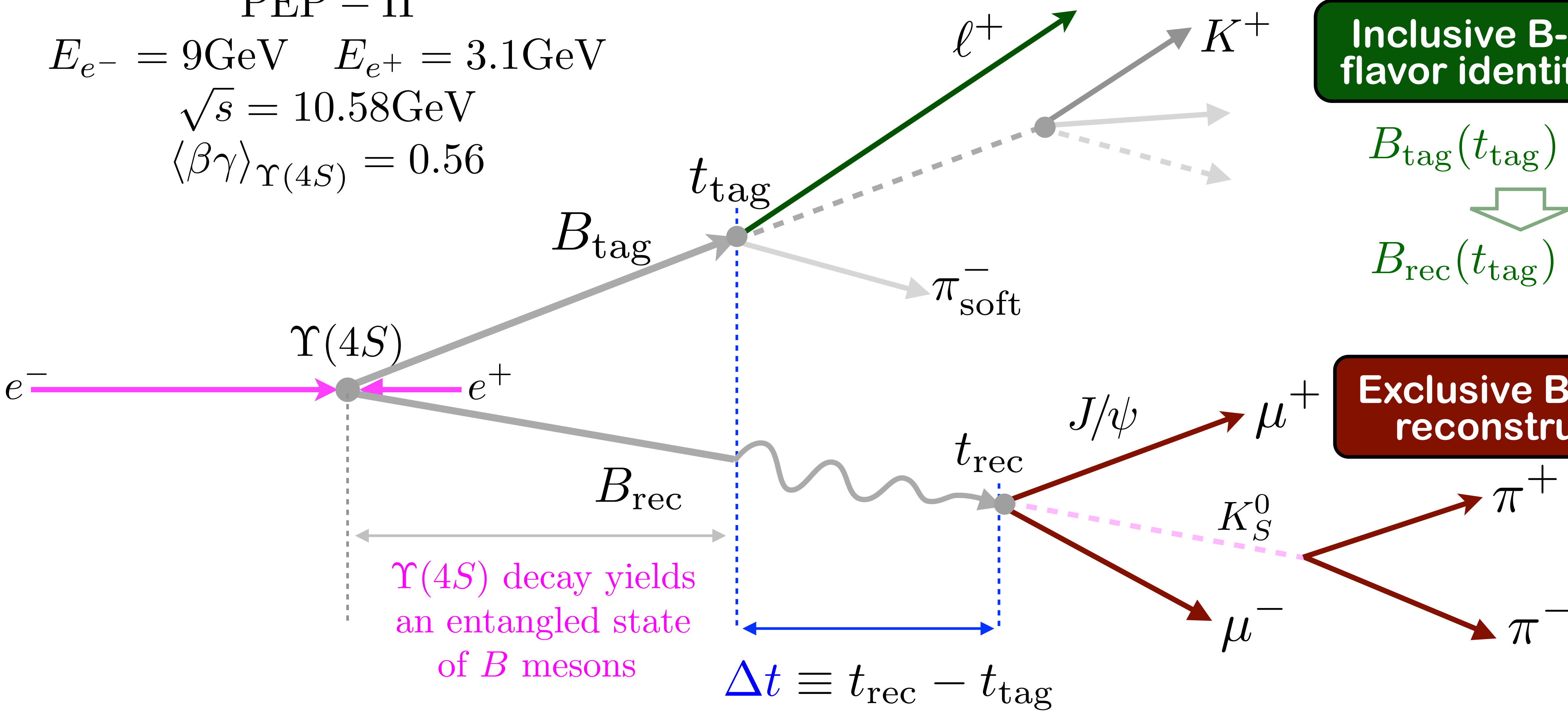
- **Flavor tagging:** **the "golden channel" $B^0 \to J/\psi\, K^0_S$ as an exemple**

PEP – II

$E_{e^-} = 9\text{GeV} \quad E_{e^+} = 3.1\text{GeV}$

$\sqrt{s} = 10.58\text{GeV}$

$\langle\beta\gamma\rangle_{\Upsilon(4S)} = 0.56$



Inclusive B-meson flavor identification

$B_{\text{tag}}(t_{\text{tag}}) = B^0$

$B_{\text{rec}}(t_{\text{tag}}) = \overline{B}^0$

Exclusive B-meson reconstruction

$$\Delta t \approx \frac{\Delta z}{\beta\gamma c} \qquad \langle\Delta z\rangle_{B\overline{B}} = 257\mu\text{m}$$

Good vertexing required for time difference determination