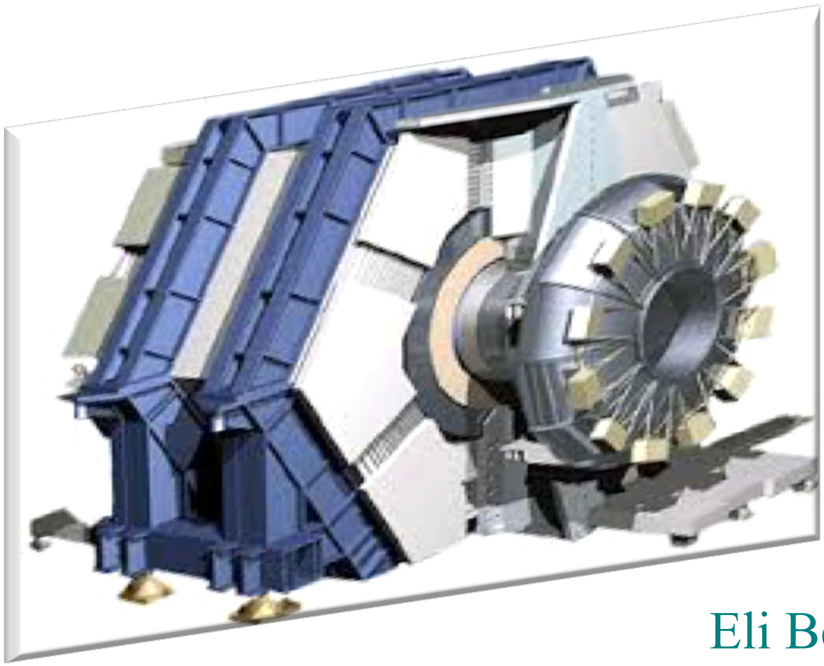
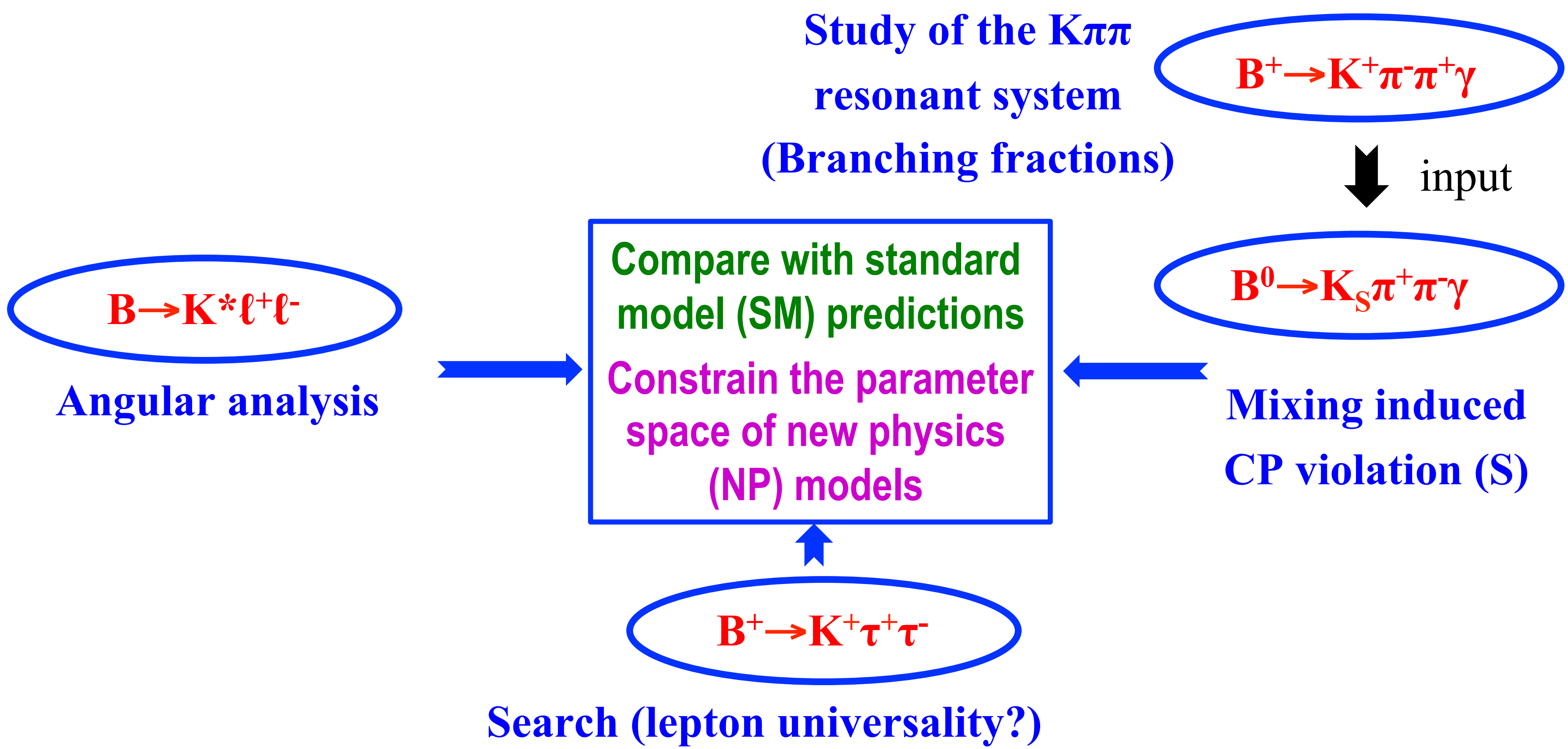
9th International Workshop on the CKM Unitarity Triangle
Mumbai, Nov. 28 – Dec. 2, 2016

Rare radiative and semileptonic $b \rightarrow sll$ decays at BaBar



Eli Ben-Haïm
LPNHE-IN2P3-
Université Pierre et Marie Curie (Paris)
On behalf of the *BABAR* collaboration

Introduction and overview

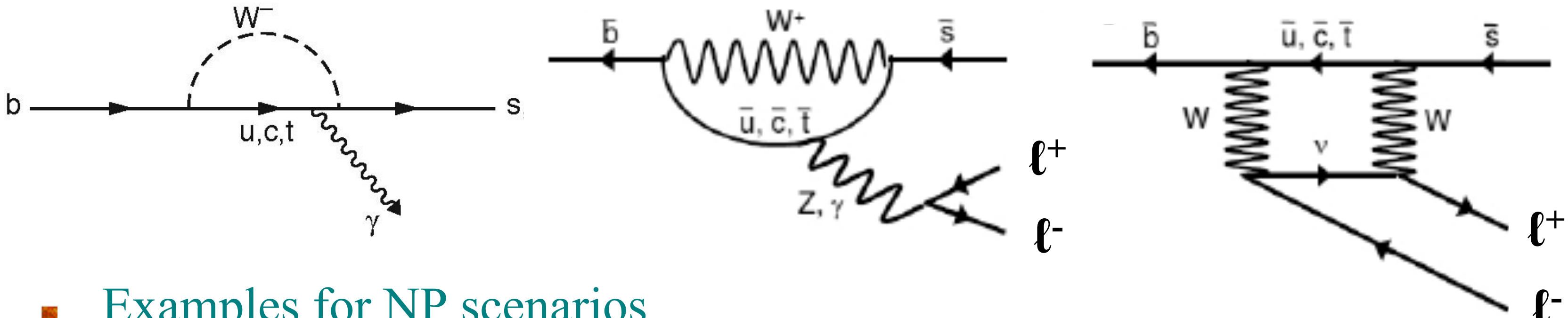


- Modes with branching fractions (BF) of ~ 10^{-5} to 10^{-7} in the standard model (SM)
- New physics (NP) could significantly alter BF, CP asymmetries or angular observables
- Challenge: small theoretical & experimental uncertainties for powerful comparison

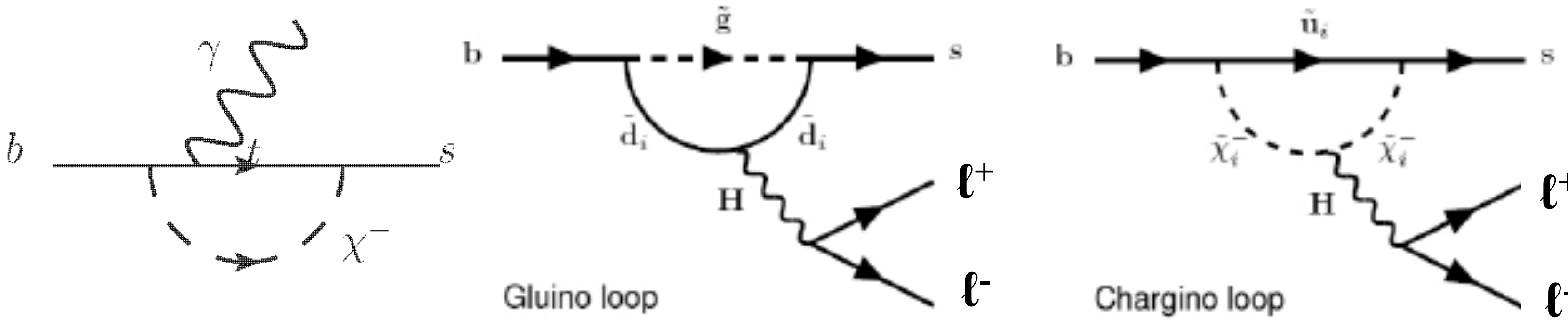
b→ s γ(ℓℓ): FCNC processes

They provide, at relatively low energy, probes to NP at large mass scales

- Within the SM, these processes proceed via loop/box diagrams like

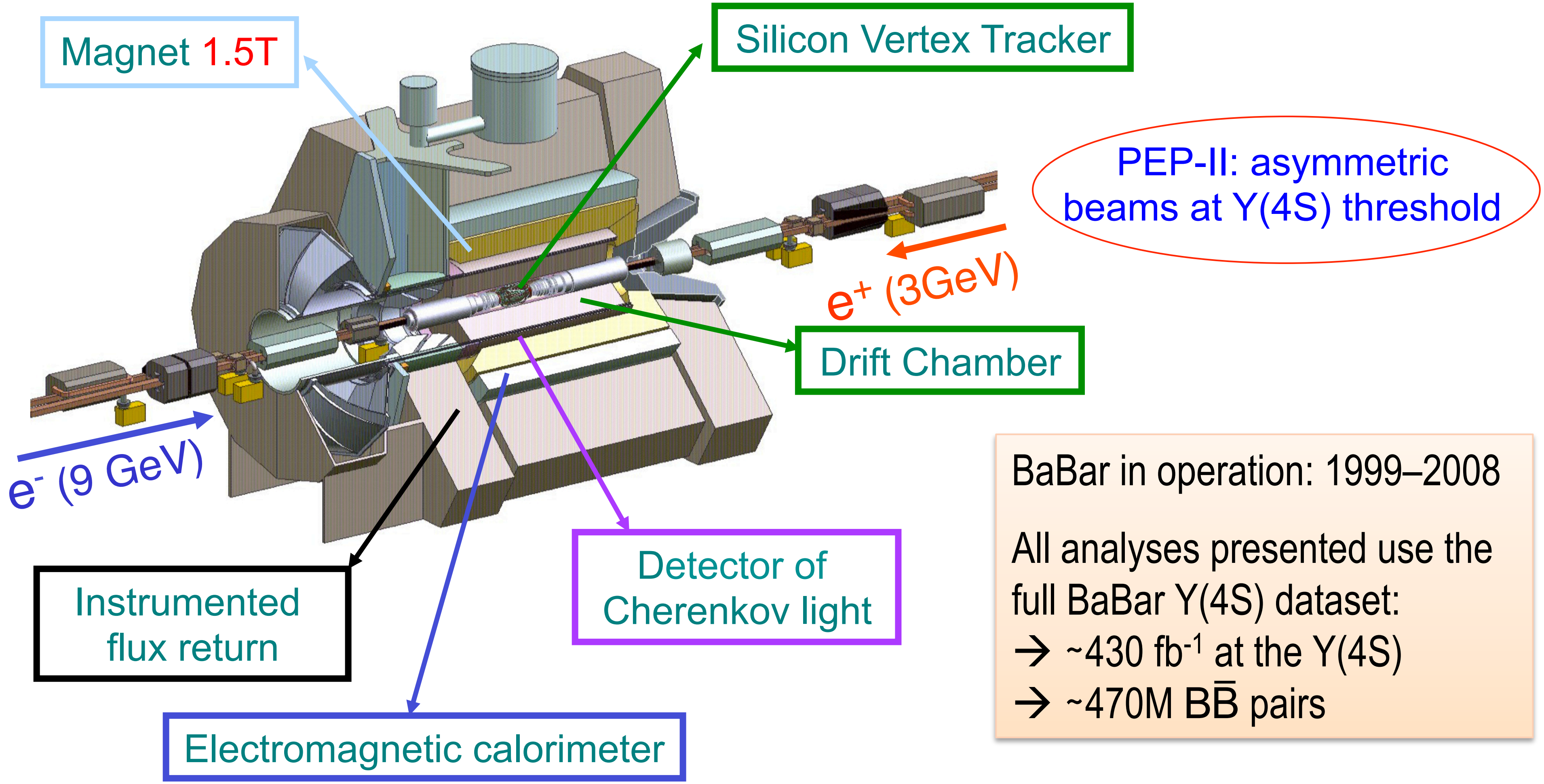


- Examples for NP scenarios



+ ?

The BaBar detector and dataset



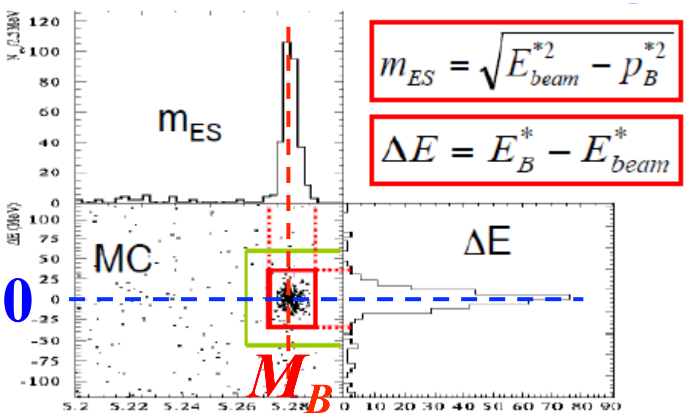
BaBar in operation: 1999–2008

All analyses presented use the full BaBar Y(4S) dataset:
→ ~430 fb^{-1} at the Y(4S)
→ ~470M $B\bar{B}$ pairs

BaBar is well suited for the measurements presented here : hermetic detector, clean environment, excellent PID, good K_S and π^0 reconstruction

Common analysis techniques

Kinematics of fully reconstructed B

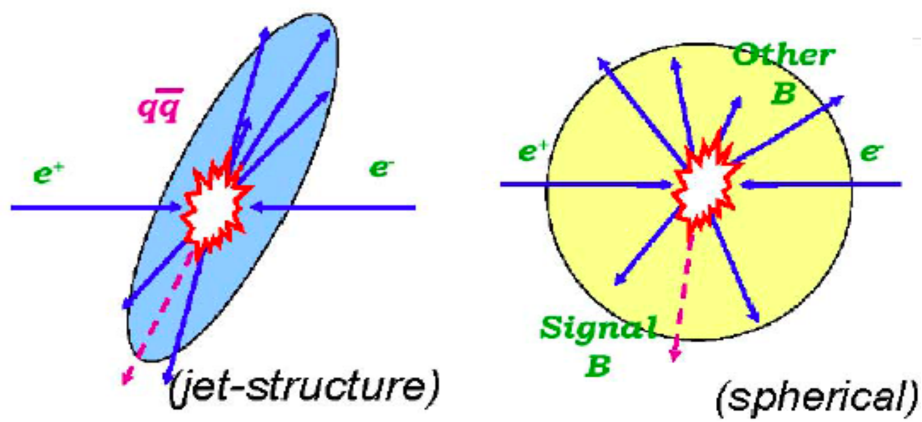


Background characterization:

→ Continuum: $e^+e^- \rightarrow q\bar{q}$ ($q = u,d,s,c$).

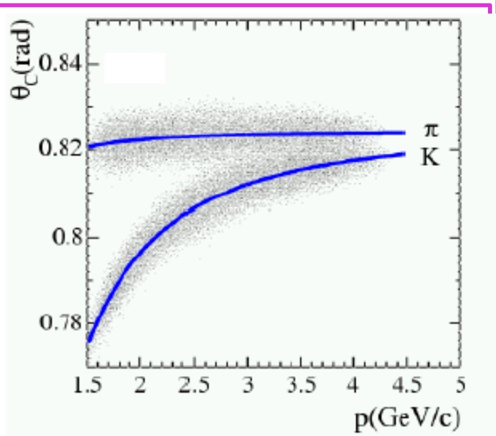
Suppression by multi-variable classifiers based on event-shape variables **(topology)**:

Fisher discriminant, Boosted Decision Trees (BDT)…



→ Background from B decays: classified by kinematic and topological properties

Good charged particle ID (in particular K/π) up to few GeV



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

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

- 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

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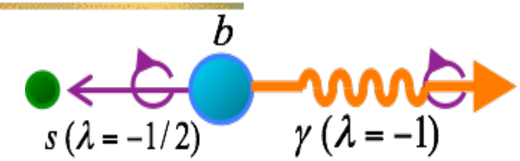
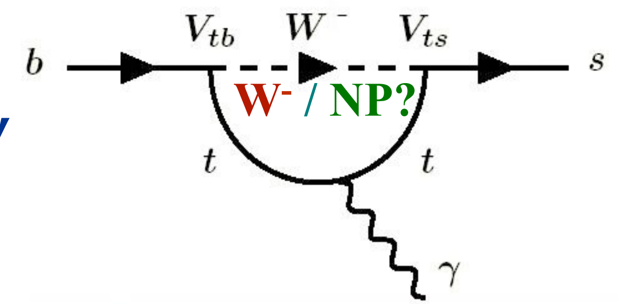
Fundamentals and motivations

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

- SM: left-handed quarks and right-handed antiquarks

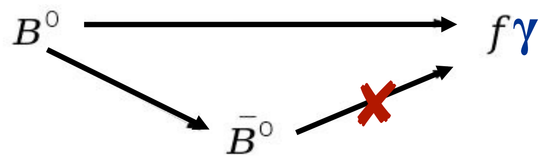


- NP particle may be present in the loop and enhance right-handed photons



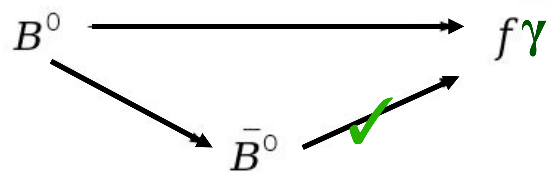
SM $\Rightarrow$ $b \to s\gamma_L$ or $\bar{b} \to \bar{s}\gamma_R$ $\Rightarrow$

CP asymmetry parameters ≈ 0



NP $\Rightarrow$ $b \to s\gamma_{L,R}$ or $\bar{b} \to \bar{s}\gamma_{R,L}$ $\Rightarrow$

CP asymmetry parameters ≠ 0



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

Observable

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

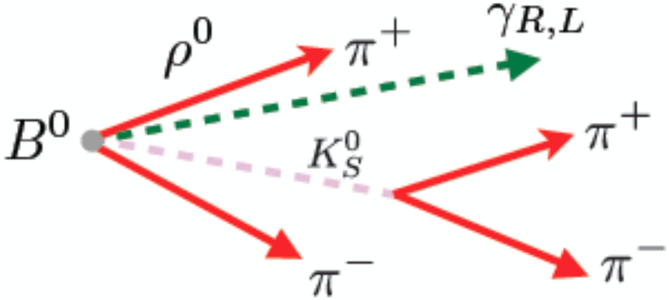
Objective: measurement of $\mathcal{S}$ in $B^0 \to K_S \rho \gamma$ decays
(probe for NP with right-handed currents)

- Measurements from both BaBar and Belle are available for $B^0 \to K_s\pi^0\gamma$

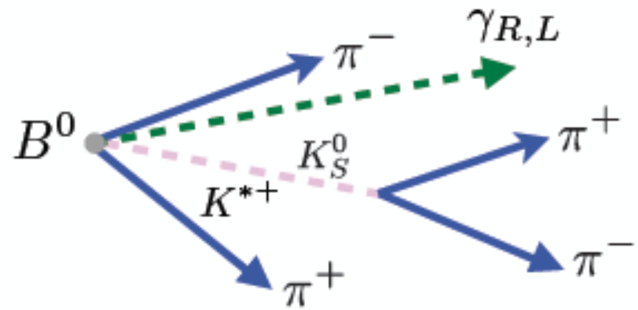
Strategy (I)

- Difficulty: irreducible contribution from non CP eigenstates

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



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



$\Rightarrow$ An amplitude analysis is necessary to extract a dilution factor:

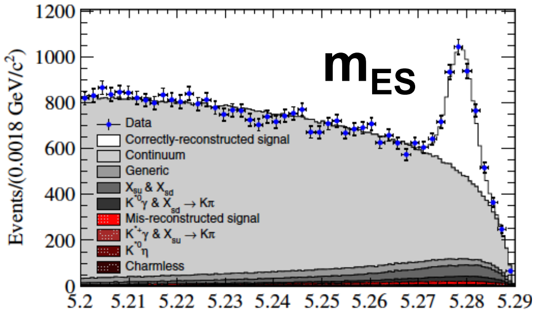
$$\mathcal{D}_{K_S^0 \rho\gamma} \equiv \frac{\mathcal{S}_{K_S^0 \pi^+\pi^-\gamma}}{\mathcal{S}_{K_S^0 \rho\gamma}}$$

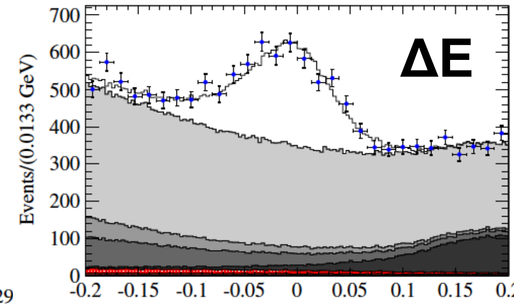
- As there are not enough $B^0 \to K_S\pi^+\pi^-\gamma$ signal events to perform this amplitude analysis, D is extracted from $B^+ \to K^+\pi^-\pi^+\gamma$ decays, assuming isospin symmetry.
- Further difficulty: due to the 4-body final state the kinematic boundaries of the $(K\pi$ - $\pi\pi)$ phase space vary event by event.

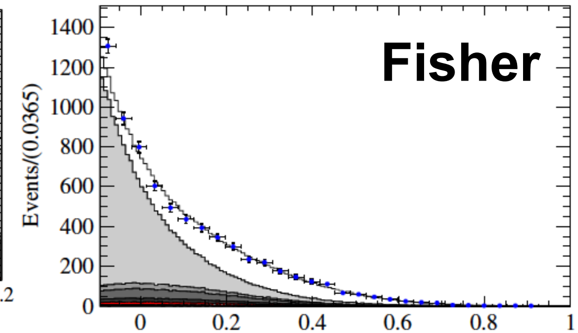
Strategy (II)

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

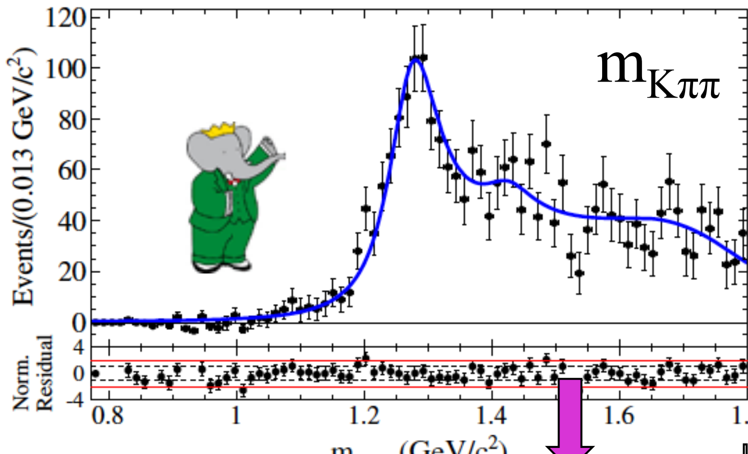
(1) Maximum likelihood fit

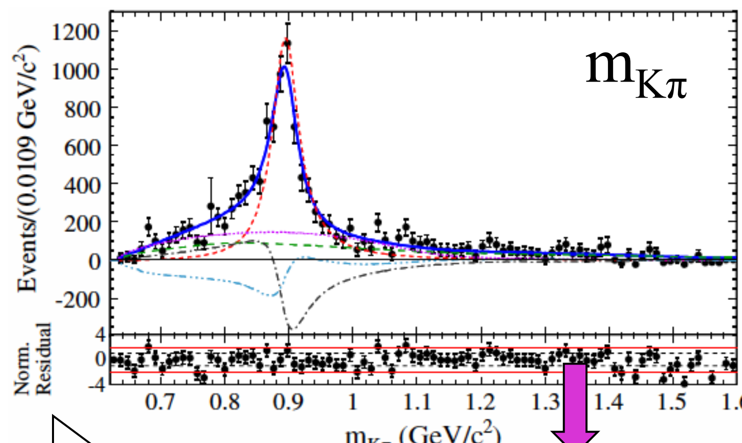






(2) Extraction of signal $m_{K\pi\pi}$ & $m_{K\pi}$ spectra





(3) Fit of $m_{K\pi\pi}$, $m_{K\pi}$ (projection) to **extract amplitudes**

$A(K_{res} \to K\pi\pi)$

(input)

A(K*), A(ρ)…

Amplitudes ➔ dilution factor and branching fractions

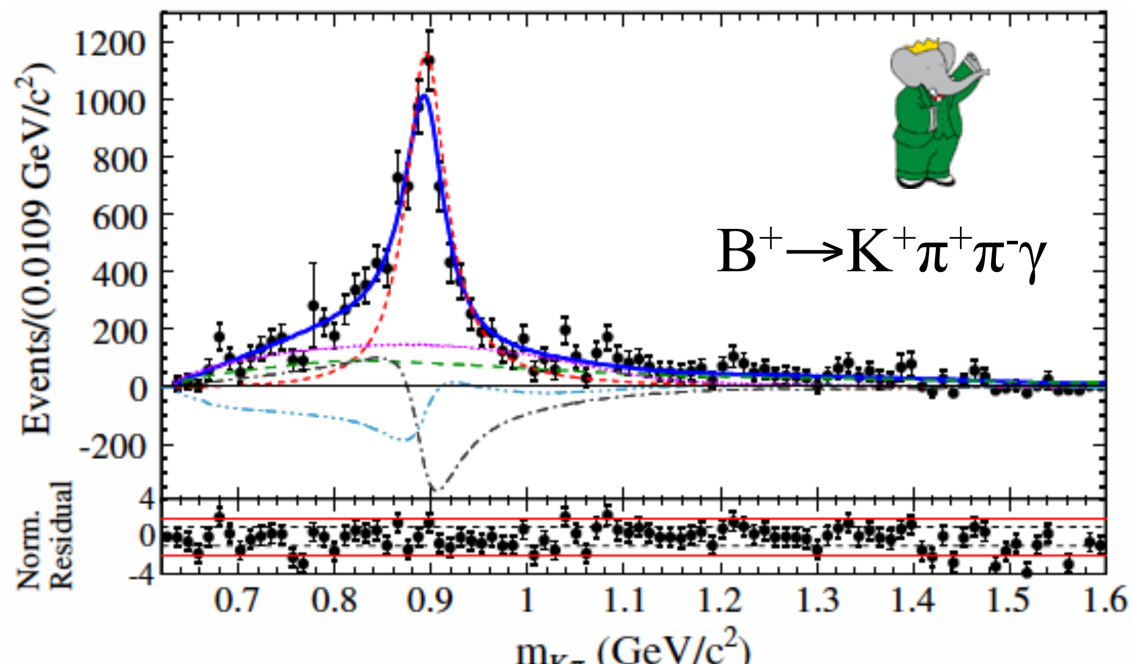
The dilution factor

- From the fit to the $\mathbf{m_{K\pi}}$ spectrum in the (charged) mode $\mathbf{B^+ \to K^+\pi^-\pi^+\gamma}$

$$\mathcal{D}_{K_S^0\rho\gamma} = \frac{\int \left[|A_{\rho K_S^0}|^2 - |A_{K^{*+}\pi^-}|^2 - |A_{(K\pi)_0^{*+}\pi^-}|^2 + 2\Re(A^*_{\rho K_S^0} A_{K^{*+}\pi^-}) + 2\Re(A^*_{\rho K_S^0} A_{(K\pi)_0^{*+}\pi^-})\right] dm^2}{\int \left[|A_{\rho K_S^0}|^2 + |A_{K^{*+}\pi^-}|^2 + |A_{(K\pi)_0^{*+}\pi^-}|^2 + 2\Re(A^*_{\rho K_S^0} A_{K^{*+}\pi^-}) + 2\Re(A^*_{\rho K_S^0} A_{(K\pi)_0^{*+}\pi^-})\right] dm^2}$$

(isospin symmetry)

[Hebinger, Kou and Yu, LAL-15-75]



$$D_{K_s^0\rho^0\gamma} = -0.78^{+0.19}_{-0.17}$$

Results (BF in $B^+ \to K^+\pi^-\pi^+\gamma$)

Measured in $m(K\pi\pi) < 1.8$ GeV

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

Mode	$\mathcal{B}(B^+ \to \text{Mode}) \times \mathcal{B}(K_{res} \to K^+\pi^+\pi^-) \times 10^{-6}$	$\mathcal{B}(B^+ \to \text{Mode}) \times 10^{-6}$	Previous world average (PDG) ($\times 10^{-6}$)
$B^+ \to K^+\pi^+\pi^-\gamma$	$\cdots$	$24.5 \pm 0.9 \pm 1.2$	27.6 ± 2.2
$K_1(1270)^+\gamma$	$14.5^{+2.1+1.2}_{-1.4-1.2}$	$44.1^{+6.3+3.6}_{-4.4-3.6} \pm 4.6$	43 ± 13
$K_1(1400)^+\gamma$	$4.1^{+1.9+1.2}_{-1.2-1.0}$	$9.7^{+4.6+2.8}_{-2.9-2.3} \pm 0.6$	<15 at 90% C.L.
$K^*(1410)^+\gamma$	$11.0^{+2.2+2.1}_{-2.0-1.1}$	$27.1^{+5.4+5.2}_{-4.8-2.6} \pm 2.7$	n/a
$K_2^*(1430)^+\gamma$	$1.2^{+1.0+1.2}_{-0.7-1.5}$	$8.7^{+7.0+8.7}_{-5.3-10.4} \pm 0.4$	14 ± 4
$K^*(1680)^+\gamma$	$15.9^{+2.2+3.2}_{-1.9-2.4}$	$66.7^{+9.3+13.3}_{-7.8-10.0} \pm 5.4$	<1900 at 90% C.L.

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

Mode	$\mathcal{B}(B^+ \to \text{Mode}) \times \mathcal{B}(R \to h\pi) \times 10^{-6}$	$\mathcal{B}(B^+ \to \text{Mode}) \times 10^{-6}$	Previous world average (PDG) ($\times 10^{-6}$)
$K^*(892)^0\pi^+\gamma$	$15.6 \pm 0.6 \pm 0.5$	$23.4 \pm 0.9^{+0.8}_{-0.7}$	20^{+7}_{-6}
$K^+\rho(770)^0\gamma$	$8.1 \pm 0.4^{+0.8}_{-0.7}$	$8.2 \pm 0.4 \pm 0.8 \pm 0.02$	<20 at 90% C.L.
$(K\pi)^{*0}_0\pi^+\gamma$	$10.3^{+0.7+1.5}_{-0.8-2.0}$	$\cdots$	n/a
$(K\pi)^0_0\pi^+\gamma$ (NR)	$\cdots$	$9.9 \pm 0.7^{+1.5}_{-1.9}$	<9.2 at 90% C.L.
$K_0^*(1430)^0\pi^+\gamma$	$0.82 \pm 0.06^{+0.12}_{-0.16}$	$1.32^{+0.09+0.20}_{-0.10-0.26} \pm 0.14$	n/a

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

Results (BF in $B^+ \to K^+\pi^-\pi^+\gamma$)

Measured in $m(K\pi\pi) < 1.8$ GeV

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

Mode	$\mathcal{B}(B^+ \to \text{Mode})\times \mathcal{B}(K_{\text{res}} \to K^+\pi^+\pi^-) \times 10^{-6}$	$\mathcal{B}(B^+ \to \text{Mode}) \times 10^{-6}$	Previous world average (PDG) ($\times 10^{-6}$)
$B^+ \to K^+\pi^+\pi^-\gamma$	...	$24.5 \pm 0.9 \pm 1.2$	27.6 ± 2.2
$K_1(1270)^+\gamma$	$14.5^{+2.1+1.2}_{-1.4-1.2}$	$44.1^{+6.3+3.6}_{-4.4-3.6} \pm 4.6$	43 ± 13
$K_1(1400)^+\gamma$	$4.1^{+1.9+1.2}_{-1.2-1.0}$	$9.7^{+4.6+2.8}_{-2.9-2.3} \pm 0.6$	<15 at 90% C.L.
$K^*(1410)^+\gamma$	$11.0^{+2.2+2.1}$	$27.1^{+5.4+5.2} \pm 2.7$	n/a
$K_2^*(1430)^+\gamma$			14 ± 4
$K^*(1680)^+\gamma$			<1900 at 90% C.L.

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

Resonances

Mode	$\mathcal{B}(B^+ \to \text{Mode})\times \mathcal{B}(R \to h\pi) \times 10^{-6}$	$\mathcal{B}(B^+ \to \text{Mode}) \times 10^{-6}$	Previous world average (PDG) ($\times 10^{-6}$)
$K^*(892)^0\pi^+\gamma$	$15.6 \pm 0.6 \pm 0.5$	$23.4 \pm 0.9^{+0.8}_{-0.7}$	20^{+7}_{-6}
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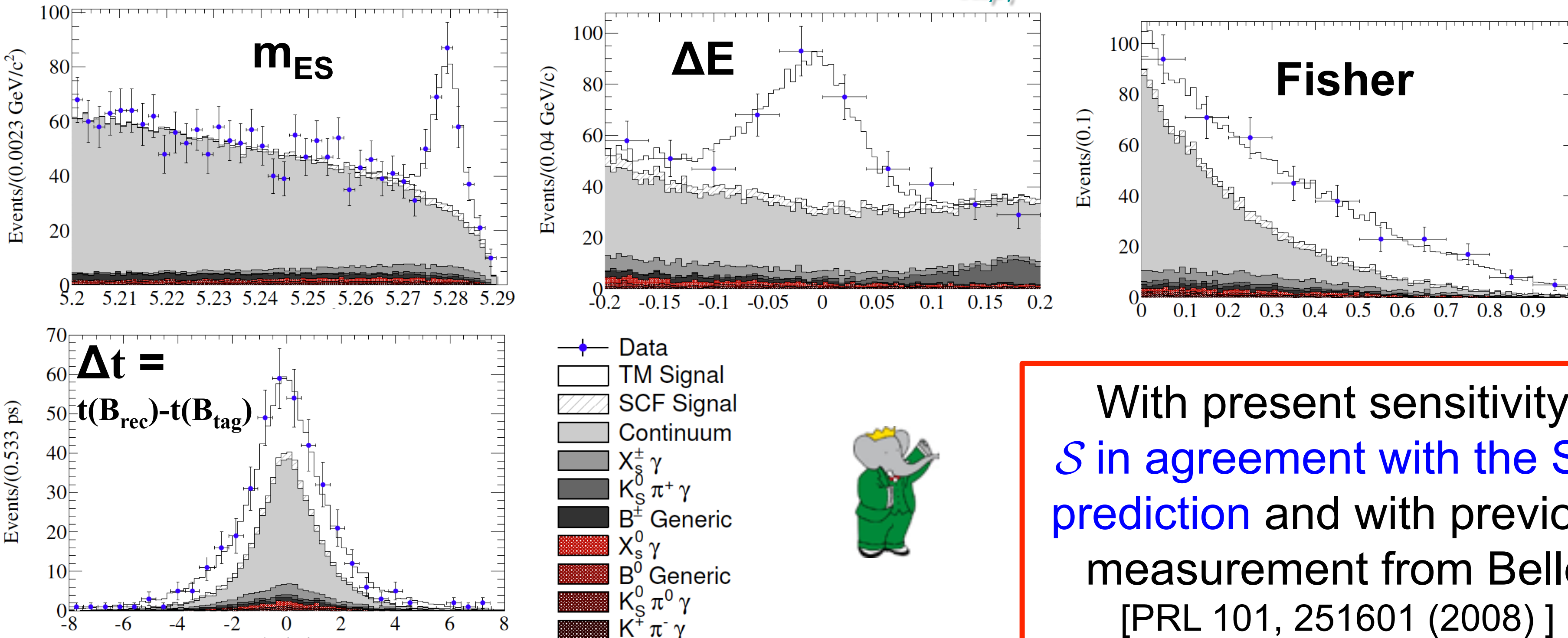
$(K\pi)_0^{*0}\pi^+\gamma$	$10.3^{+0.7+1.5}_{-0.8-2.0}$	...	n/a
$(K\pi)_0^0\pi^+\gamma$ (NR)	...	$9.9 \pm 0.7^{+1.5}_{-1.9}$	<9.2 at 90% C.L.
$K_0^*(1430)^0\pi^+\gamma$	$0.82 \pm 0.06^{+0.12}_{-0.16}$	$1.32^{+0.09+0.20}_{-0.10-0.26} \pm 0.14$	n/a

Results ($\mathcal{S}$)

- From the time-dependent analysis of the (neutral) decay mode **$B^0 \to K_S\pi^-\pi^+\gamma$**
- Performed in phase space region optimizing $\mathcal{S}_{Ks\rho\gamma}$



With present sensitivity, $\mathcal{S}$ in agreement with the SM prediction and with previous measurement from Belle [PRL 101, 251601 (2008)]

$$\mathcal{S}_{K_S^0\pi^+\pi^-\gamma} = 0.14 \pm 0.25 \pm 0.03 \qquad \mathcal{C}_{K_S^0\pi^+\pi^-\gamma} = -0.39 \pm 0.20^{+0.03}_{-0.02}$$

$$\mathcal{S}_{K_S^0\rho\gamma} = \frac{\mathcal{S}_{K_S^0\pi^+\pi^-\gamma}}{\mathcal{D}_{K_S^0\rho\gamma}} = -0.18 \pm 0.32^{+0.06}_{-0.05}$$

$$\mathcal{S}_{K_S^0\rho^0\gamma} \overset{SM}{\sim} 0.02$$

Stay tuned…

- Recent theoretical developments result in a different expression of the dilution factor
- A paper with a new computation will be shortly submitted to the arXiv
- $\mathcal{S}_{K_S\rho\gamma}$ will be re-extracted from the BaBar measurements presented here.
- Possibly, another BaBar time-dependent analysis could be performed in a different part of phase-space to minimize the uncertainty on $\mathcal{S}_{K_S\rho\gamma}$.

The time-dependent *CP* asymmetry in $B^0 \to K_{\rm res}\gamma \to K^0_S\pi^+\pi^-\gamma$ decays

[a]S. Akar, [b]E. Ben-Haim, [c]J. Hebinger, [c]E. Kou and [d]F.-S. Yu

[a]*University of Cincinnati, Cincinnati, OH, United States*

[b]*Laboratoire de Physique Nucléaire et des Hautes Énergies, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France*

[c]*Laboratoire de l'Accélérateur Linéaire, Univ. Paris-Sud, CNRS/IN2P3 (UMR 8607), Université Paris-Saclay, 91898 Orsay Cédex, France*

[d] *Lanzhou University - Department of Physics, Lanzhou 730000, Gansu, China*

Abstract

The time-dependent *CP* asymmetry in $B^0 \to \rho^0 K^0_S\gamma \to K^0_S\pi^+\pi^-\gamma$ has been measured recently by the *BABAR* and Belle collaborations. This measurement is sensitive to the photon polarization in the quark level process $b \to s\gamma$. While this polarization is predominantly left handed in the standard model, it could be modified by the existence of new physics contributions that may possess different *CP* properties. In this paper, we derive the *CP* violation formulae for $B^0 \to K^0_S\pi^+\pi^-\gamma$ including the most dominant intermediate states. We also discuss the future prospects of this measurement at LHCb and Belle II.

$B \to K^{*}\ell^{+}\ell^{-}$

- Measurement of angular asymmetries in the decays $B \to K^{*}\ell^{+}\ell^{-}$

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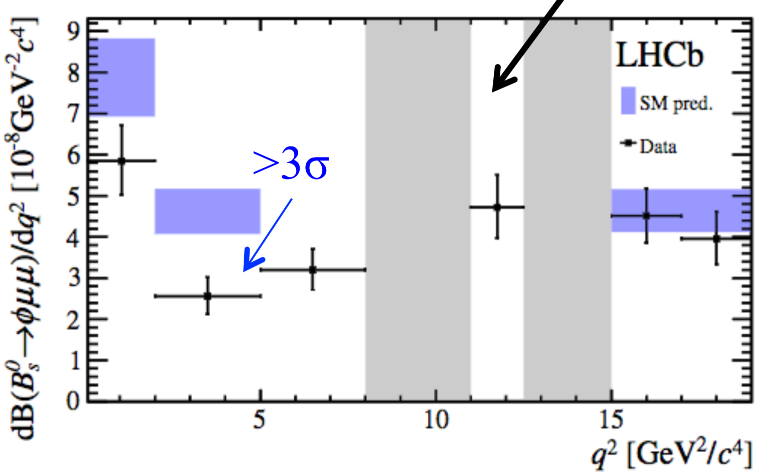
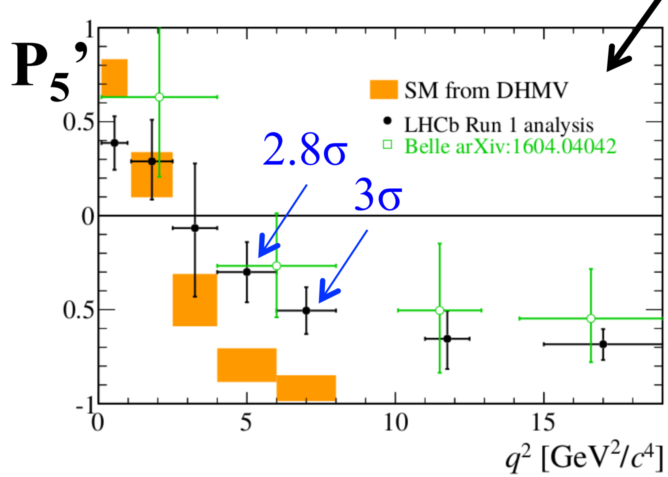
Fundamentals and motivations

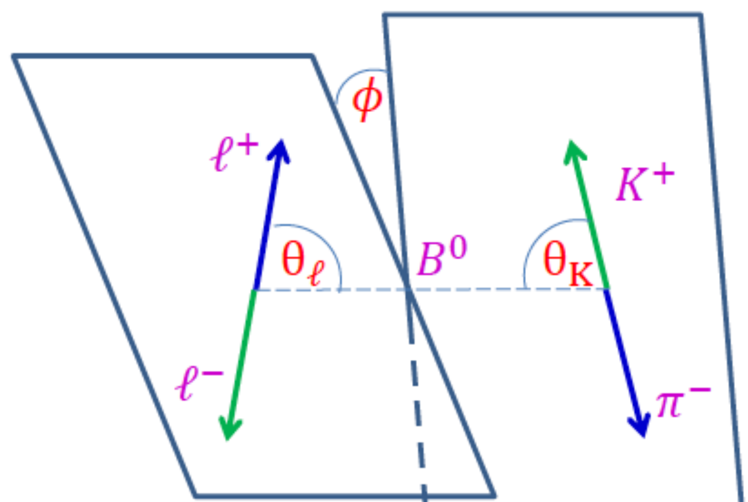
- Possible hints of physics beyond SM seen in angular analyses of $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 1602 (2016) 104 (LHCb), arXiv:1604.04042 (Belle)] and in partial BFs of $B_s \to \phi\ell^+\ell^-$ [JHEP 1509 (2015) 179 (LHCb)]





Motivates investigating similar modes

- $B \to K^*\ell^+\ell^-$ angular distribution depends on:
  - θ_K: between K & B^0 in the K* rest frame
  - θ_ℓ: between ℓ^+& B^0 in the $\ell^+\ell^-$rest frame
  - Φ: Between $\ell^+\ell^-$ and K* decay plane



Strategy (I)

$B \to K^* \ell^+ \ell^-$

- The sample size does not allow performing a full angular analysis
  ➔ determine from the **$\cos\theta_K$** and **$\cos\theta_\ell$** distributions:
  - Longitudinal K^* polarization F_L
  - Forward-backward asymmetry A_{FB}

$$\frac{1}{\Gamma(q^2)}\frac{\mathrm{d}\Gamma}{\mathrm{d}(\cos\theta_K)} = \frac{3}{2}F_L(q^2)\cos^2\theta_K + \frac{3}{4}(1-F_L(q^2))(1-\cos^2\theta_K)$$

$$\frac{1}{\Gamma(q^2)}\frac{\mathrm{d}\Gamma}{\mathrm{d}(\cos\theta_\ell)} = \frac{3}{4}F_L(q^2)(1-\cos^2\theta_l) + \frac{3}{8}(1-F_L(q^2))(1+\cos^2\theta_l) + \mathcal{A}_{FB}(q^2)\cos\theta_l\,.$$

- The analysis is done
  - Combining 5 decay channels
  - In 5 exclusive q^2 bins and one broad low-q^2

première

$$B^+ \to K^{*+}(\to K^0_S\pi^+)\mu^+\mu^-$$

$$B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-;$$

première

$$B^+ \to K^{*+}(\to K^+\pi^0)e^+e^-$$

$$B^+ \to K^{*+}(\to K^0_S\pi^+)e^+e^-$$

$$B^0 \to K^{*0}(\to K^+\pi^-)e^+e^-.$$

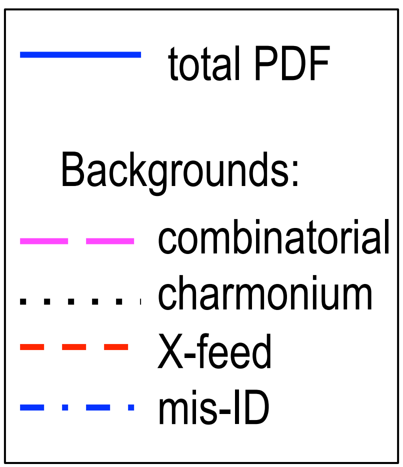
q^2 bin	Range (GeV^2/c^4)
q_1^2	0.10 – 2.00
q_2^2	2.00 – 4.30
q_3^2	4.30 – 8.12
q_4^2	10.11 – 12.89
q_5^2	$14.21-(m_B-m_{K^*})^2$
q_0^2	1.00 – 6.00

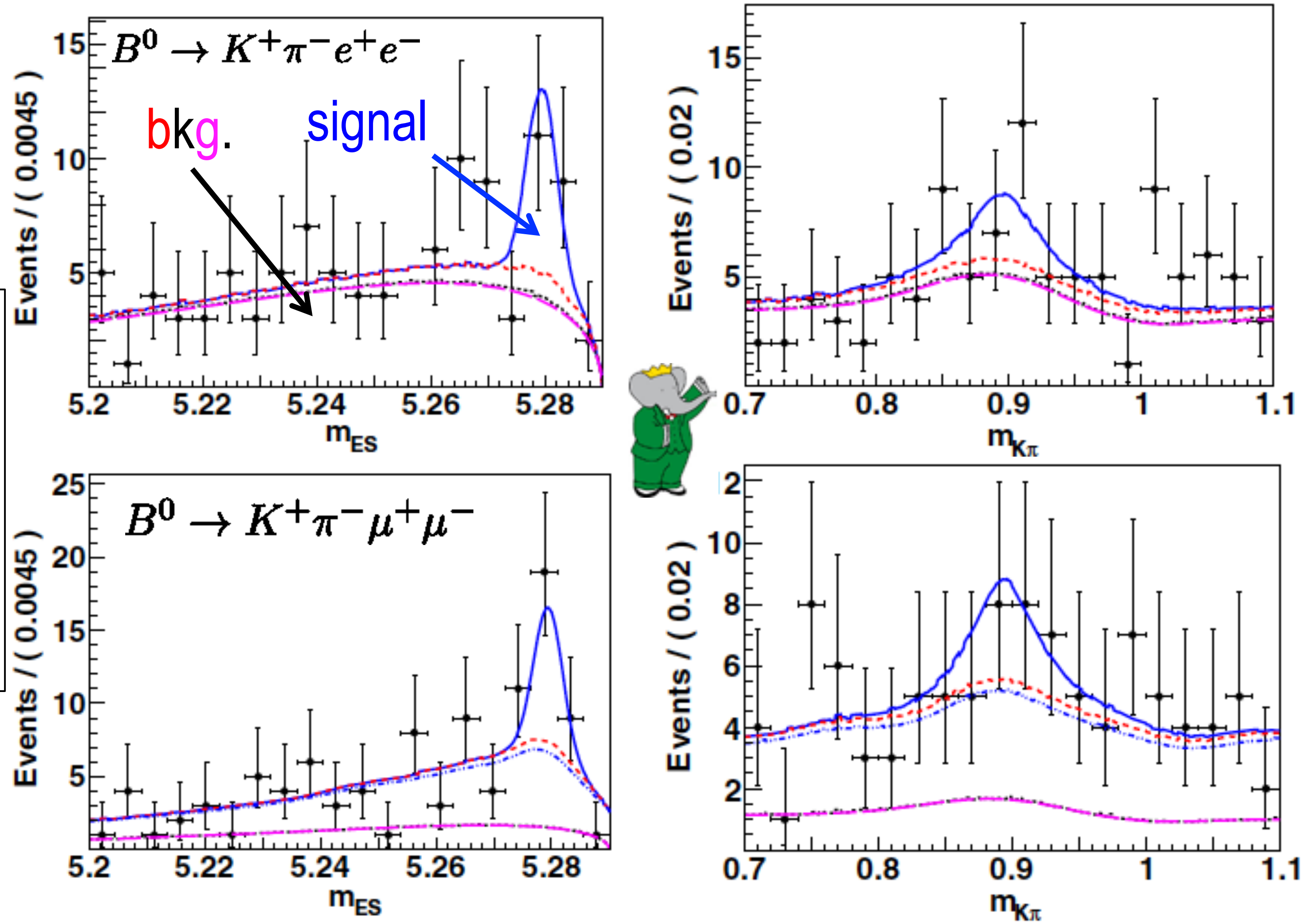
$$q^2 \equiv m(\ell^+\ell^-)^2$$

Strategy (II)

- Signal yield obtained from $\mathbf{m_{ES}}$, $\mathbf{m_{K\pi}}$ and a **Likelihood ratio** based on a BDT

bin
q^2_5
(example)





Angular fits

for bin q^2_0 ($1<q^2<6$ GeV^2)

(Shaded distributions include signal and background)

B^+

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

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

$K_s^0\pi^+\mu^+\mu^-$

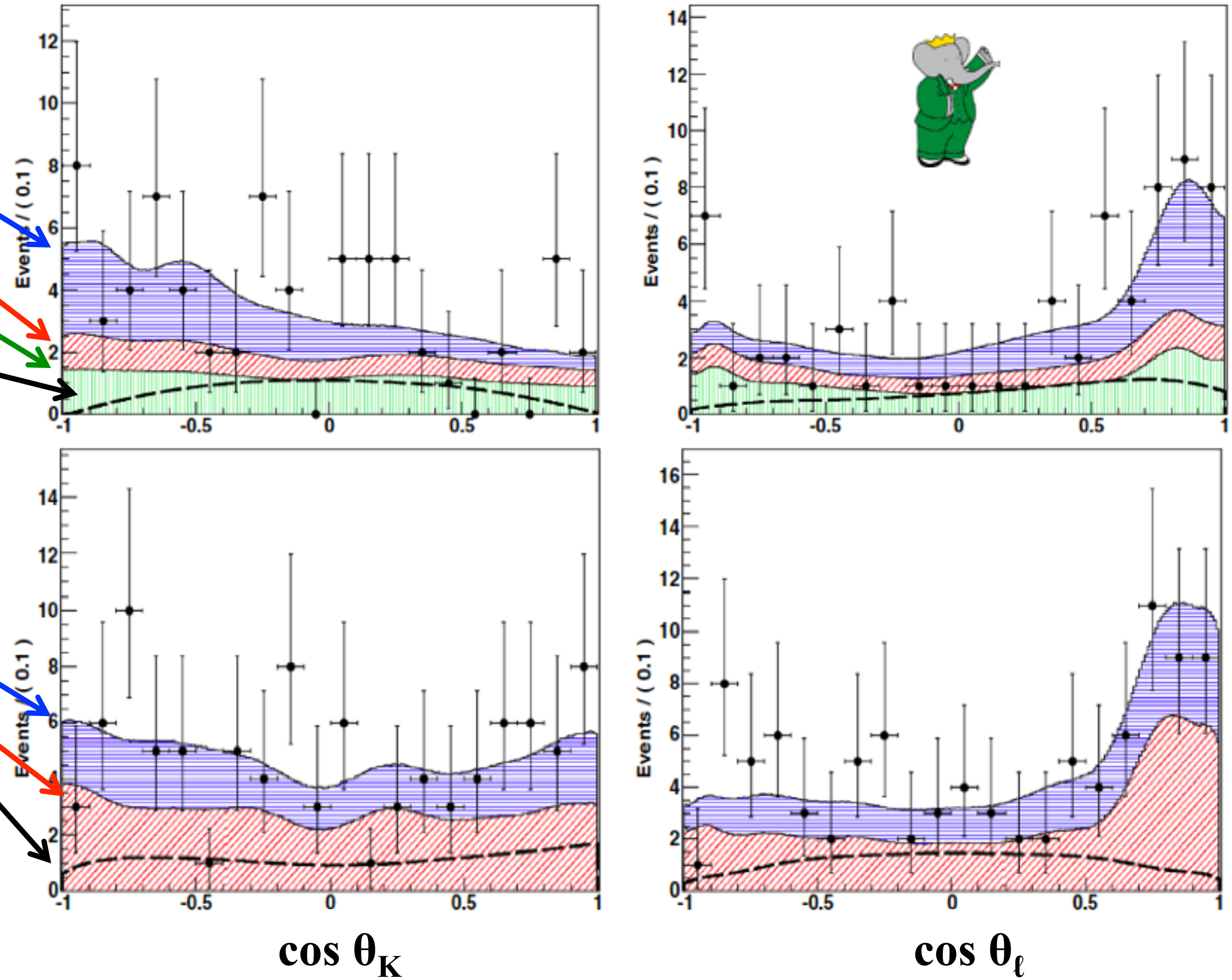
Signal (total)

B^0

$K^+\pi^-e^+e^-$

$K^+\pi^-\mu^+\mu^-$

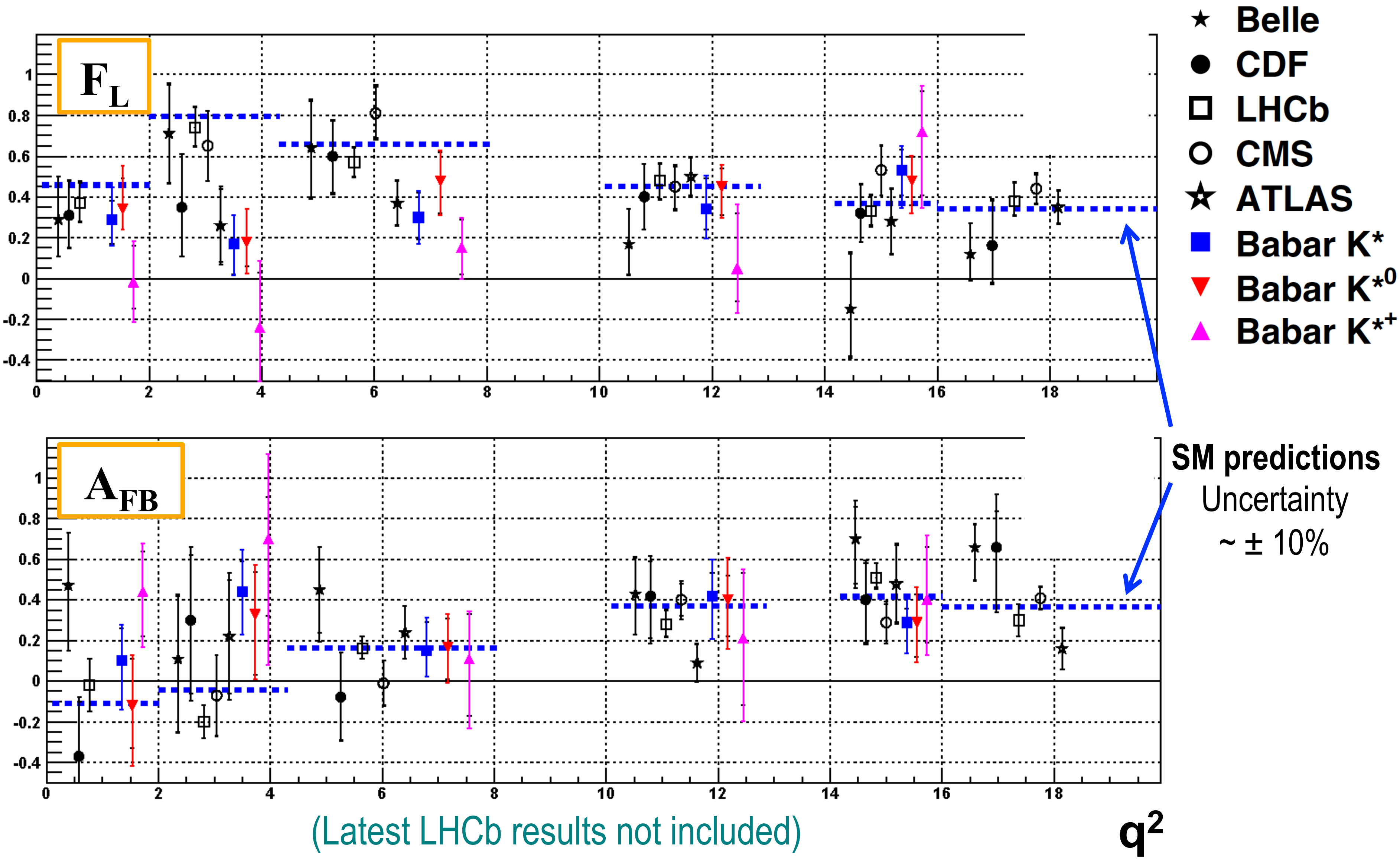
Signal (total)



Results

F_L and A_{FB} versus q^2

$B \to K^*\ell^+\ell^-$

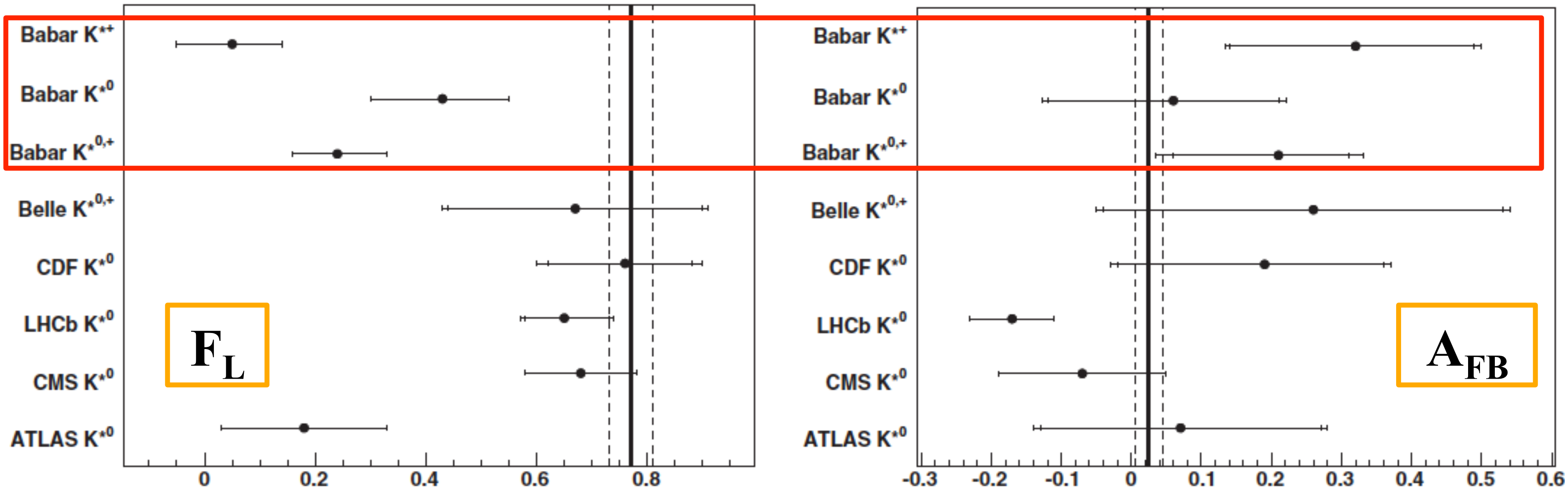


(Latest LHCb results not included)

Results

F_L and A_{FB} for q^2_0 ($1<q^2<6$ GeV^2)

$B \rightarrow K^* \ell^+ \ell^-$



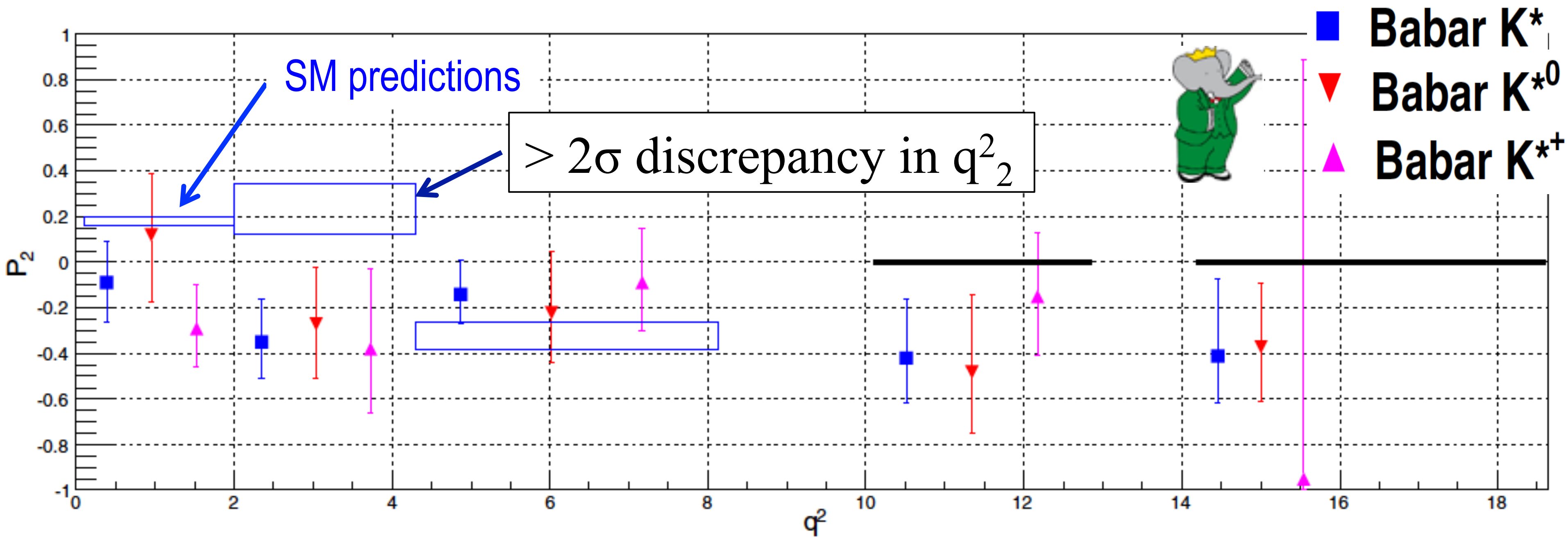
- In the low q^2 region theoretical uncertainties (e.g. charmonia) are smaller
- BaBar F_L is lower than SM prediction (>3σ)
- BaBar A_{FB} agrees with SM and other experiments

Results

The observable P_2 versus q^2

$$P_2 = -\frac{2}{3}\frac{A_{FB}}{(1-F_L)}$$

(has smaller theoretical uncertainties)



$P_2(1 < q^2 < 6\ \mathrm{GeV}^2) = 0.11 \pm 0.10$

$B^+ \rightarrow K^+\tau^+\tau^-$

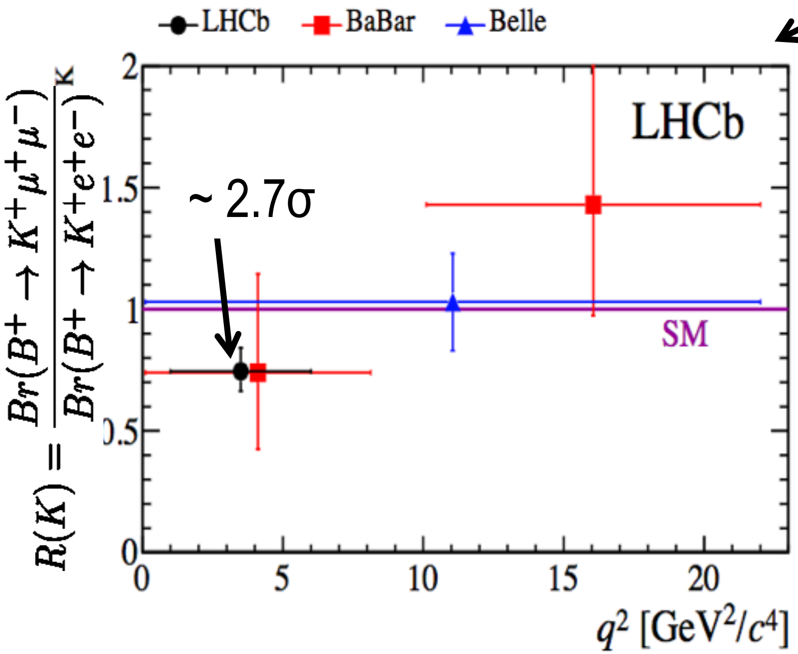
- Search for $B^+ \rightarrow K^+\tau^+\tau^-$ at the BaBar experiment

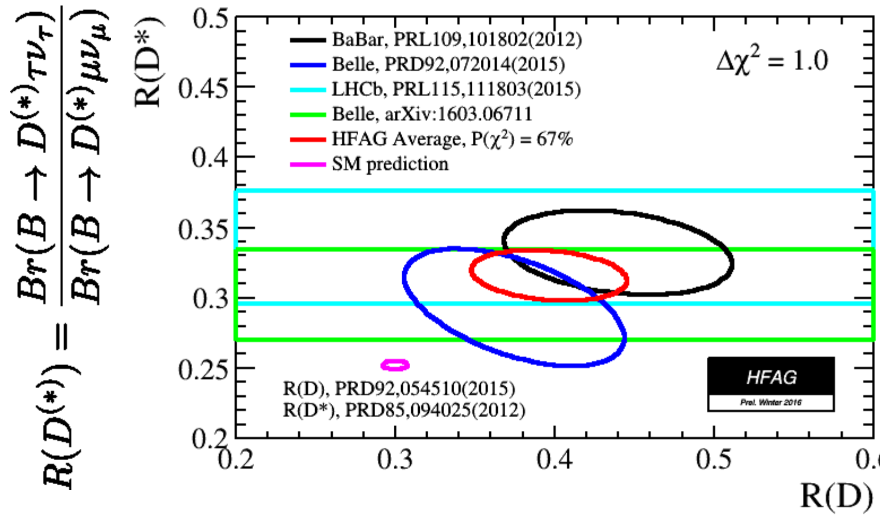
    arXiv: 1605.09637 (accepted for publication in PRL)

Fundamentals and Motivation

$B^+ \to K^+\tau^+\tau^-$

- Hints of lepton universality violation in R(K) and R(D$^{(*)}$) → NP with Higgs bosons?





- Clearly motivates search for $B^+ \to K^+\tau^+\tau^-$ (BR~10^{-7} in SM)

- τ reconstructed in leptonic modes: $\tau^- \to e^-\nu_\tau\bar{\nu}_\mu$ $\quad\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu$
- Final state with missing energy… extremely challenging

Strategy

- Kinematic constraints from fully reconstructing the second "Tag" B through its hadronic decays ($\varepsilon \sim 0.3$ %)

$B_{tag} \to S\ X$

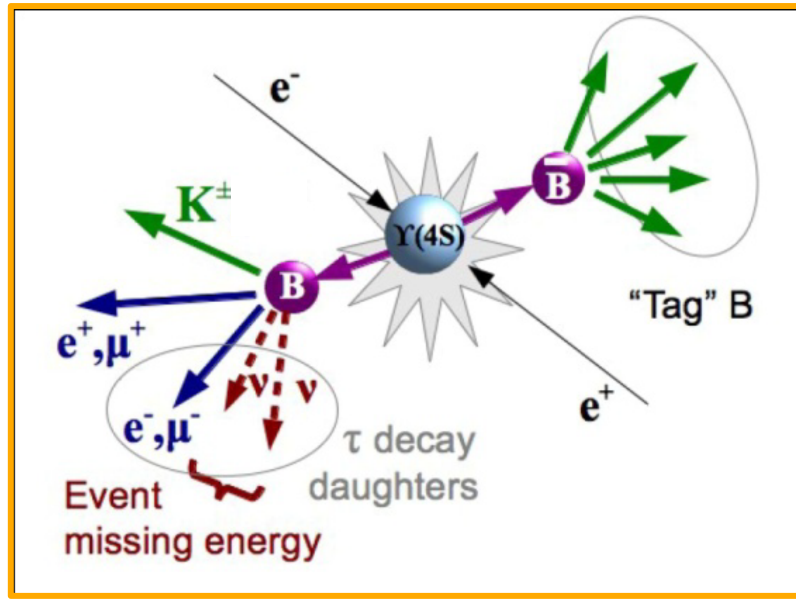
$D^{(*)0}$, $D^{(*)\pm}$, D_s^*, J/ψ → S   <= 5 K and π → X

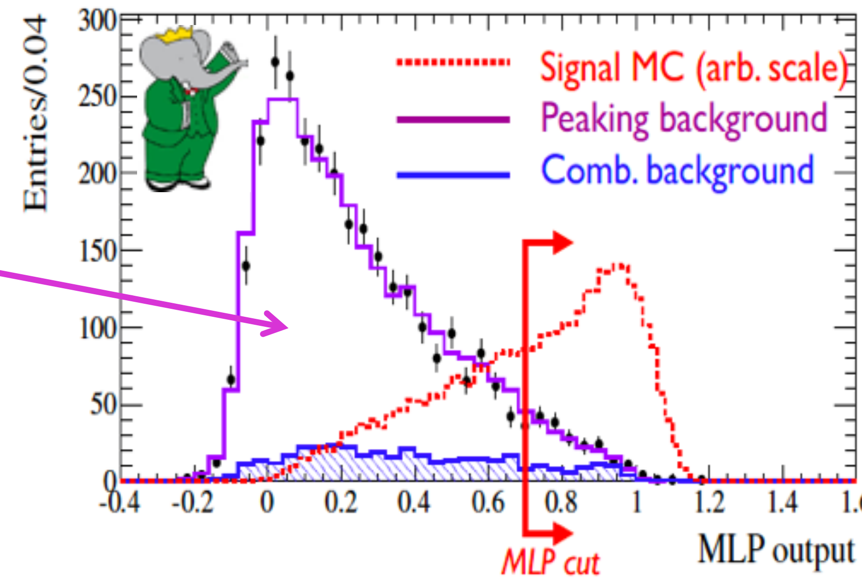
- m_{ES} and ΔE requirements on B_{tag}
- Signal B event selection (e.g.):
  - Significant missing energy
  - Constraints on $q^2(\tau^+\tau^-)$

$$q^2 = (\tilde{p}_{e^+e^-} - \tilde{p}_{tag} - \tilde{p}_K)^2$$

- 92% of the background has correct B_{tag} (peaking), mostly $\bar{B} \to D^{(*)}(\to \bar{K}\,\ell'^-\bar{\nu})\ell^+\nu$ with the same final state

  ➔ Train 8-variable NN (Multi Layer Perceptron) to optimally subtract this background by applying a cut.





Results

$B^+ \to K^+\tau^+\tau^-$

- Compare observed number of candidates after MLP cut with expected background yields:
  - Combinatorial: m_{ES} sideband data ($5.20 < m_{ES} < 5.26$ GeV/c^2)
  - Peaking: MC shape + B_{tag} yield, validated with $B^+ \to D^0(\to K^-\pi^+)\ell^+\nu$ control sample

	e^+e^-	$\mu^+\mu^-$	$e^+\mu^-$
$N^i_{\rm bkg}$	49.4±2.4±2.9	45.8±2.4 ±3.2	59.2±2.8 ±3.5
$\epsilon^i_{\rm sig}(\times10^{-5})$	1.1 ±0.2±0.1	1.3±0.2±0.1	2.1±0.2±0.2
$N^i_{\rm obs}$	45	39	92
Significance (σ)	-0.6	-0.9	3.7

- No excess → set upper limit

$$B(B^+ \to K^+\tau^+\tau^-) = (1.31^{+0.66+0.35}_{-0.61-0.25})\times10^{-3}$$

$$B(B^+ \to K^+\tau^+\tau^-) < 2.25\times10^{-3} \text{(90\% CL UL)}$$

- Sensitivity far from SM expectation, but probes phase space of some NP models

Summary and Conclusions

- BaBar continues to produce exciting physics results, adding more information and using more sophisticated analysis techniques to probe new physics effects in radiative and $b \rightarrow sll$ decays
- Few hints of tensions with the SM predictions in $B \rightarrow K^* \ell^+ \ell^-$ modes. Other measurements shown agree with the SM predictions. All measurements provide constraints in the parameter space of NP.
- Larger samples are needed to tell whether or not there could be indications for NP. The analyses shown here have interesting perspectives with more data and more modes (Belle II and LHCb)

Due for first physics at 2017-2018

Already results from Run-II
Upgrade planned for 2019

Extras

Effective Hamiltonian

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_i [\ \underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu) O_i'(\mu)}_{\substack{\text{right-handed part} \\ \text{suppressed in SM}}}\ ]$$

$i = 1,2$	Tree
$i = 3-6,8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9,10$	Electroweak penguin
$i = S$	Higgs (scalar) penguin
$i = P$	Pseudoscalar penguin

$M_{K\pi\pi}$ fit model

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

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

J^P	K_{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

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

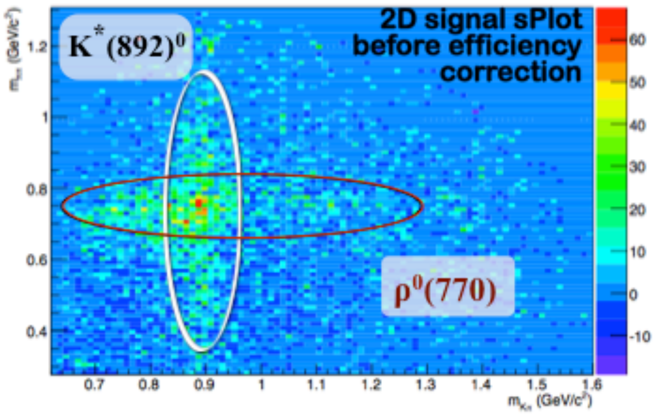
$$|A(m;c_j)|^2 = \left.\sum_J \left|\sum_j c_j \,\mathrm{BW}_j^J(m)\right|^2\right|_{m=m_{K\pi\pi}}$$

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

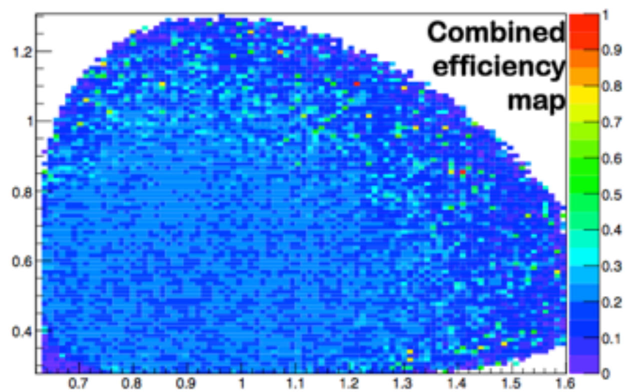
- **Fit to $K\pi\pi$ invariant mass sPlot (binned) distribution**
  - 8 fitted parameters:
    - ➜ 4 magnitudes, 2 relative phases
    - ➜ 2 widths ($K_1(1270)$ and $K^*(1680)$)
  - Due to the integration over the angular variables, only resonances with same J^P interfere
  - Randomized initial parameter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

Efficiency Correction of $M_{K\pi}$

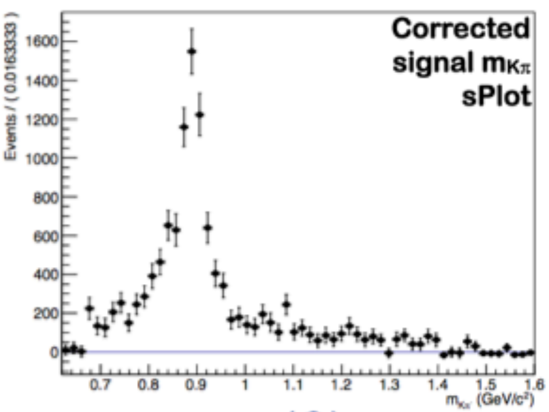
- Need to correct the 2-dimensional $m_{K\pi}$-$m_{\pi\pi}$ signal sPlot **(A)**
- Built $m_{K\pi}$-$m_{\pi\pi}$ efficiency maps for each $K_{res} \to K\pi\pi$
- Checked that efficiency maps were not correlated to m_{Kpipi}
- Combine them using weights extracted from data **(B)**
- Used projection on $m_{K\pi}$ for the fit **(C)**



(A)



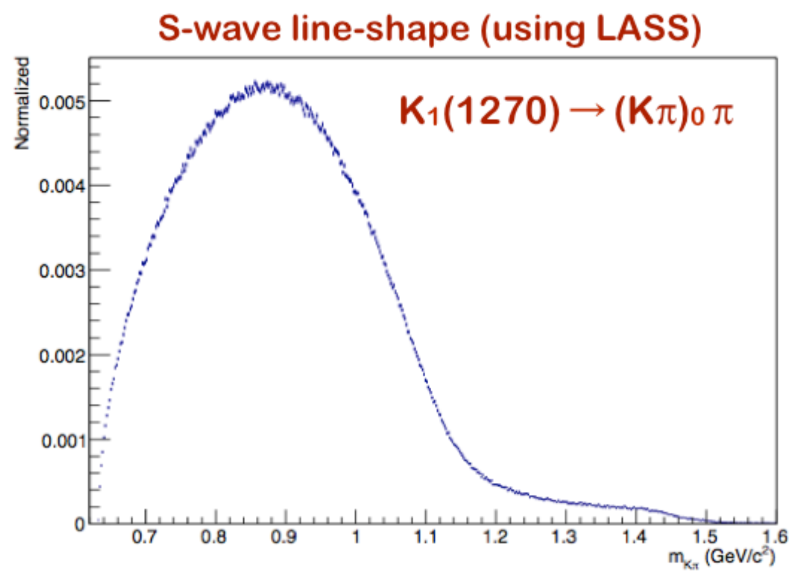
(B)

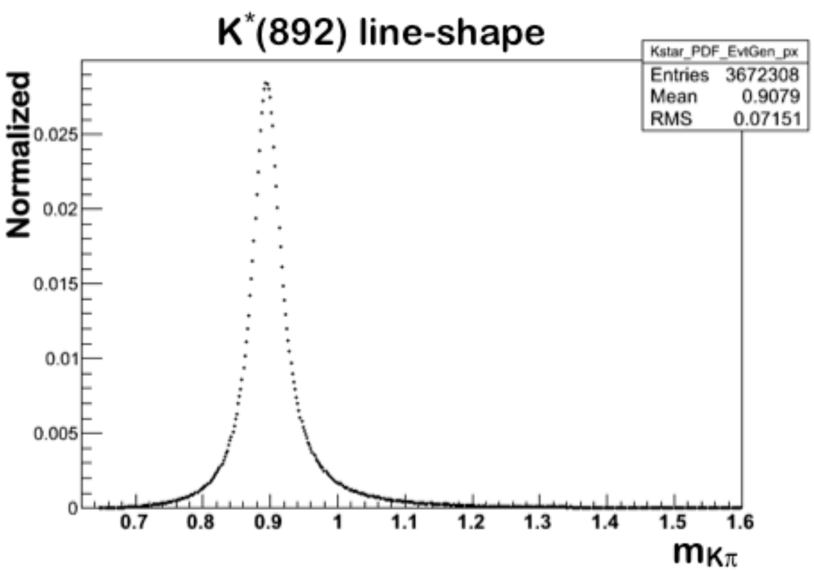


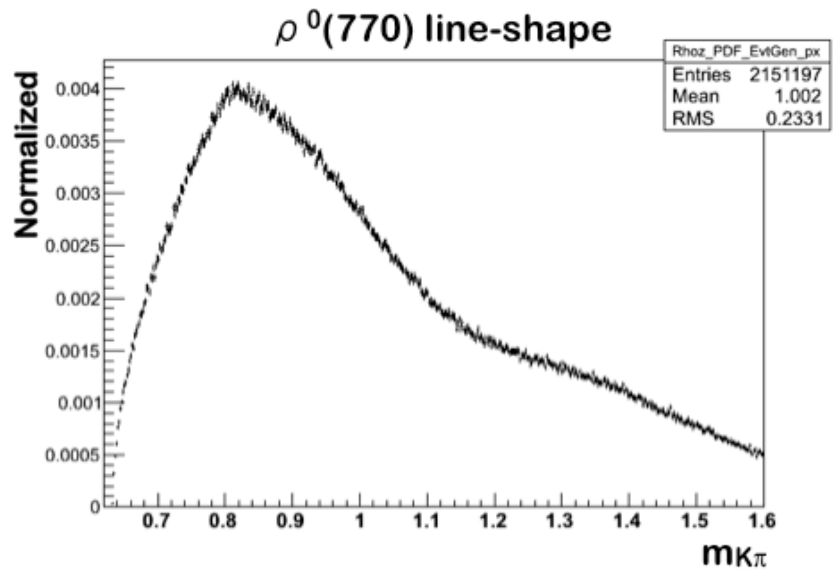
(C)

Lineshapes in $M_{K\pi}$ fit

- Based on generator level MC, with input from $M_{K\pi\pi}$ fit
- Takes into account large distortions due to phase space







$M_{K\pi}$ fit model (I)

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

Total PDF:

- Coherent sum of K*(892), ρ^0(770) and Kπ S-wave component:

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

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

- 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:

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

$M_{K\pi}$ fit model (II)

Interference:

- Interference terms:

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

Term describing interference between the $K^*(892)$ and $\rho^0(770)$ amplitudes

Term describing interference between the $\rho^0(770)$ and $(K\pi)$ S-wave amplitudes

Interference vanishes between the S-wave and the $K^*(892)$

Time dependent CP parameters (I)

- **Measured the time-dependent CP asymmetry parameters in the decay $B^0 \to K_S\pi^-\pi^+\gamma$ 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)

$$\mathcal{S}_{K_S^0\pi^+\pi^-\gamma} = 0.14 \pm 0.25 \pm 0.03$$

$$\mathcal{C}_{K_S^0\pi^+\pi^-\gamma} = -0.39 \pm 0.20^{+0.03}_{-0.02}$$

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

$$\mathcal{C}^{\mathrm{Belle}}_{K_S^0\pi^+\pi^-\gamma} = -0.05 \pm 0.18(\mathrm{stat.}) \pm 0.06(\mathrm{syst.})$$

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

Time dependent CP parameters (II)

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

- The mixing induced CP violation parameter for $B^0 \to K_S \rho^0 \gamma$ decays:

$$\mathcal{S}_{K_S^0\rho\gamma} = \frac{\mathcal{S}_{K_S^0\pi^+\pi^-\gamma}}{\mathcal{D}_{K_S^0\rho\gamma}} = -0.18 \pm 0.32^{+0.06}_{-0.05}$$

- 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