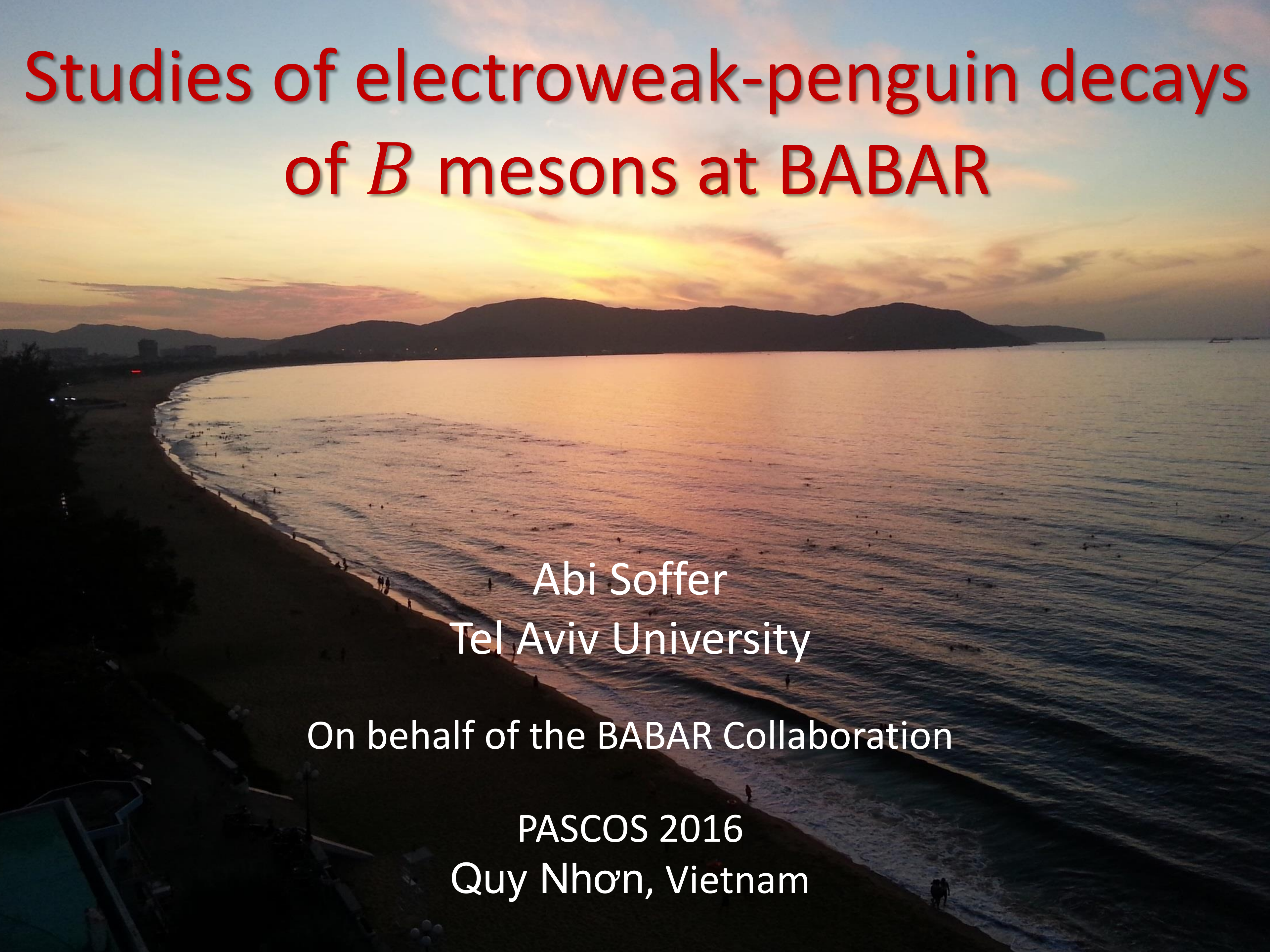

Studies of electroweak-penguin decays of B mesons at BABAR

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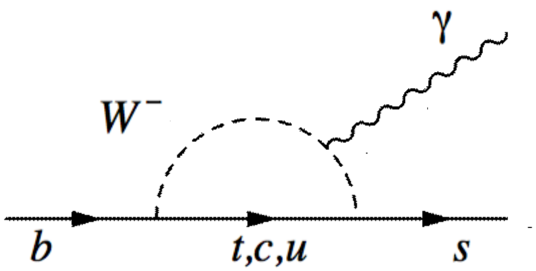
Tel Aviv University

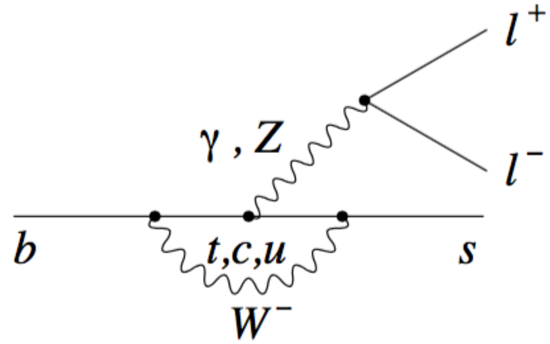
On behalf of the BABAR Collaboration

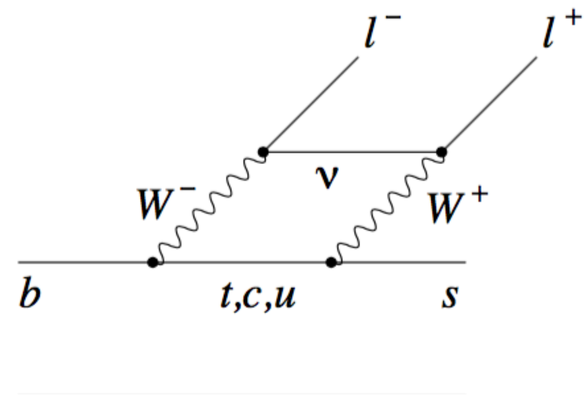
PASCOS 2016
Quy Nhơn, Vietnam

Electroweak penguins

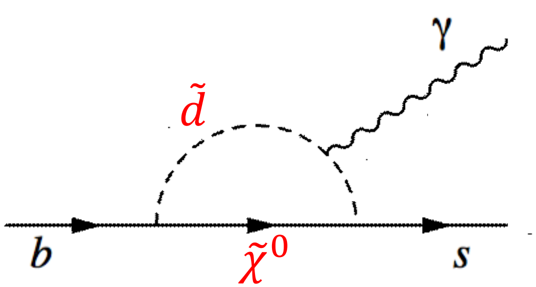
- Loop-level FCNC processes in the SM:

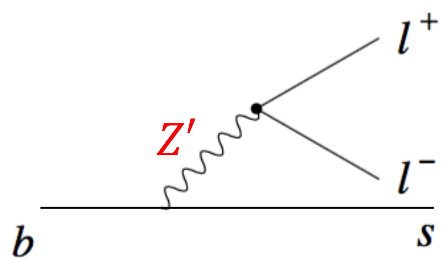


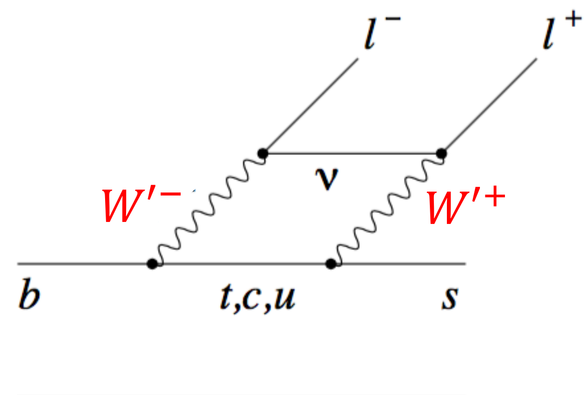




- Sensitive to new physics, e.g.,



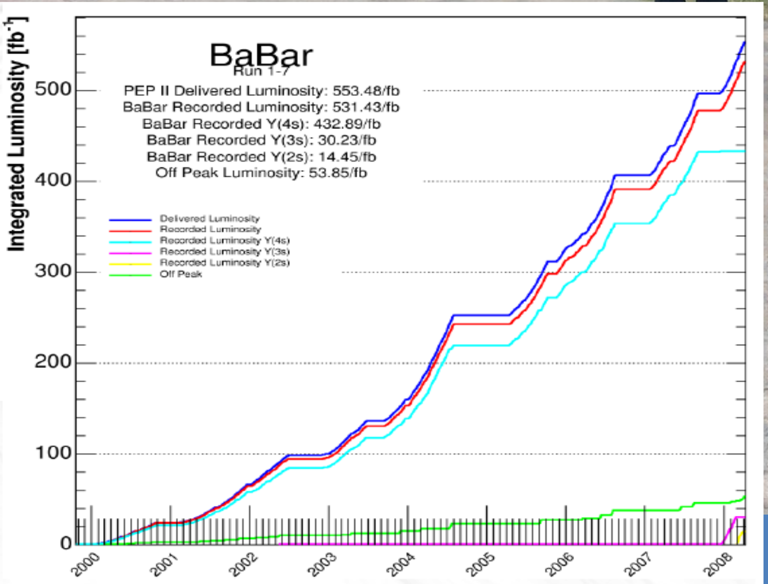




Outline

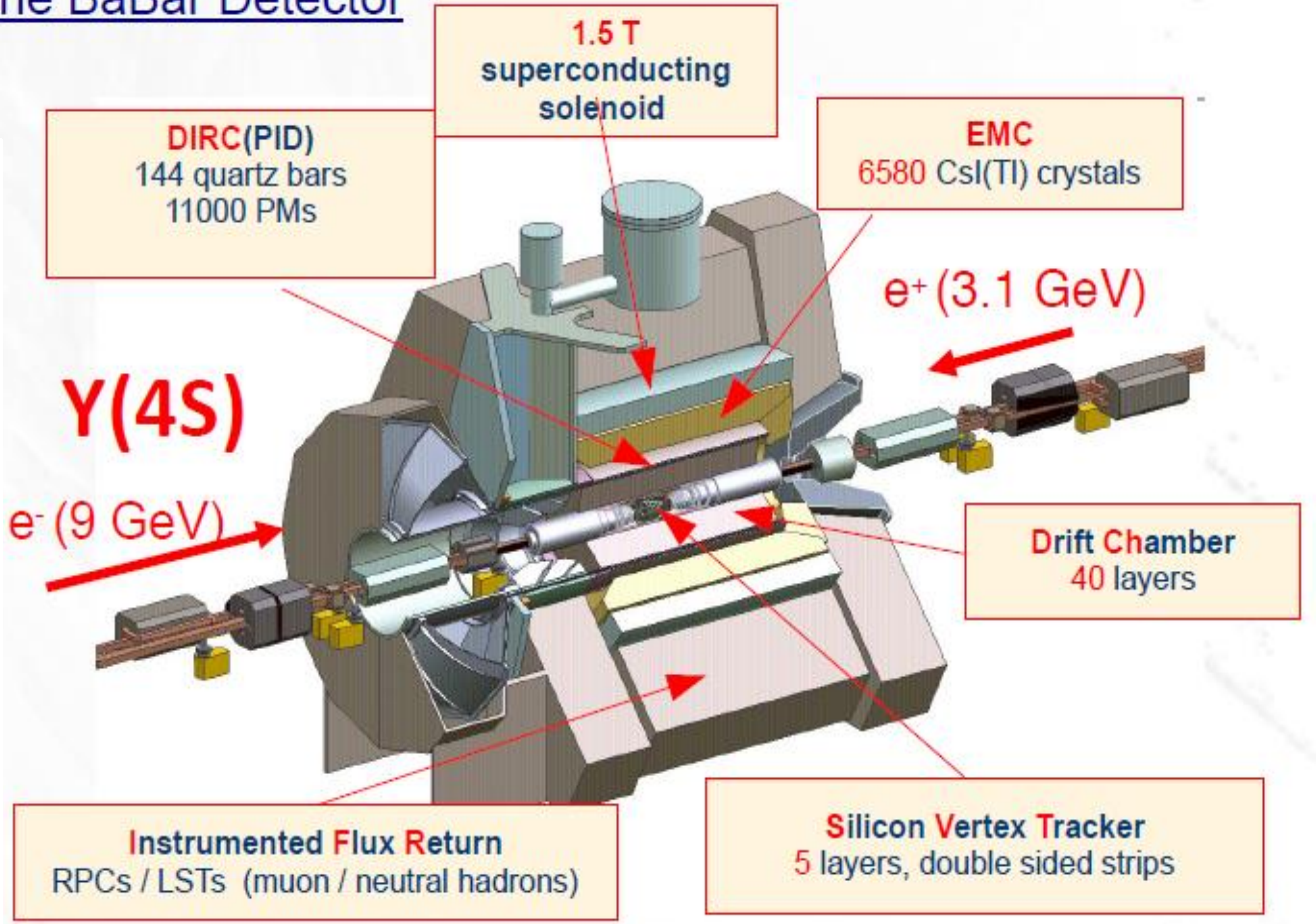
- Quick intro to BABAR
- New results:
  1. Time-dependent CP asymmetries in $B^0 \rightarrow K^0_s \pi^- \pi^+ \gamma$
     - PRD 93 052013 (2016)
  2. Angular asymmetries in the decays $B \rightarrow K(*) l^+ l^-$
     - PRD 93 052015 (2016)
  3. Search for $B^+ \rightarrow K^+ \tau^+ \tau^-$
     - arXiv:1605.09637

BABAR data



	Lumi	$B\bar{B}$ Events
$\Upsilon(4S)$	424 fb^{-1}	471×10^6
$\Upsilon(3S)$	28 fb^{-1}	121×10^6
$\Upsilon(2S)$	14 fb^{-1}	99×10^6
$\tau^+\tau^-$		$\sim 450\times10^6$

The BaBar Detector

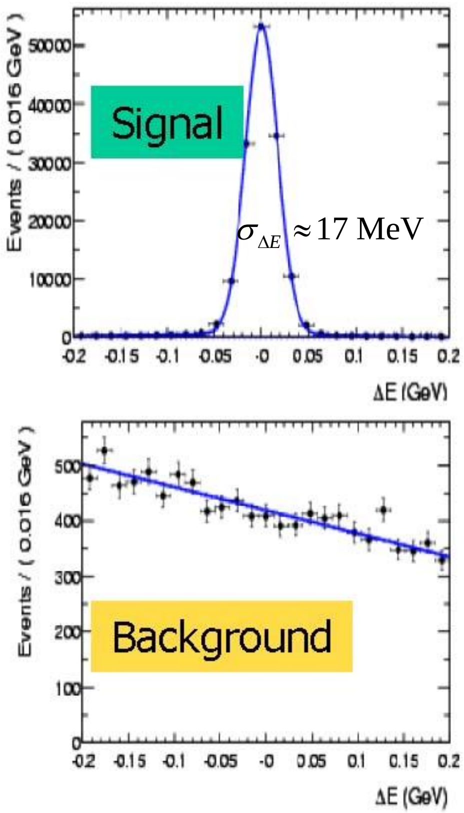


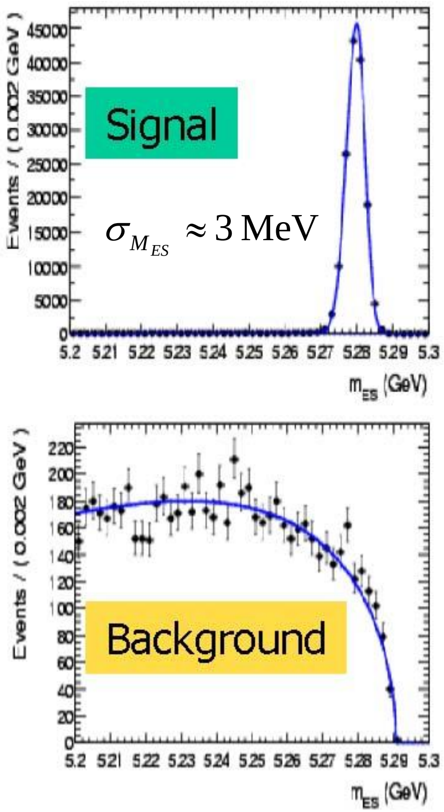
Reconstructing B mesons

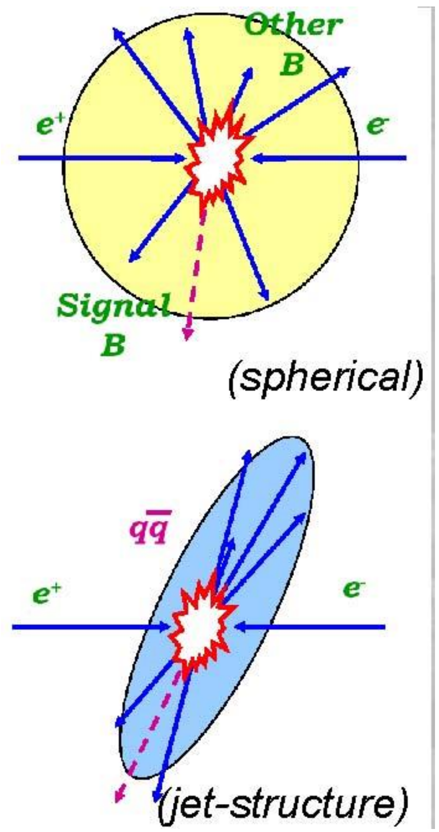
$$\Delta E = E_B^* - E_{beam}^*$$

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

Event "shape"





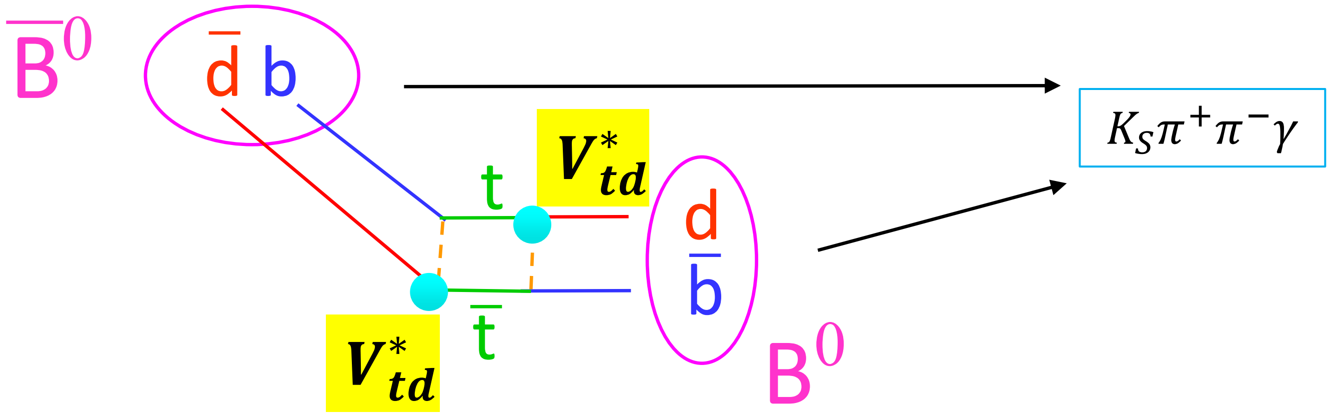


Plus: blinded analysis, multivariate discriminants, Maximum Likelihood (ML) fits

Time-dependent CP asymmetries in $B^0 \rightarrow K^0_s \pi^- \pi^+ \gamma$

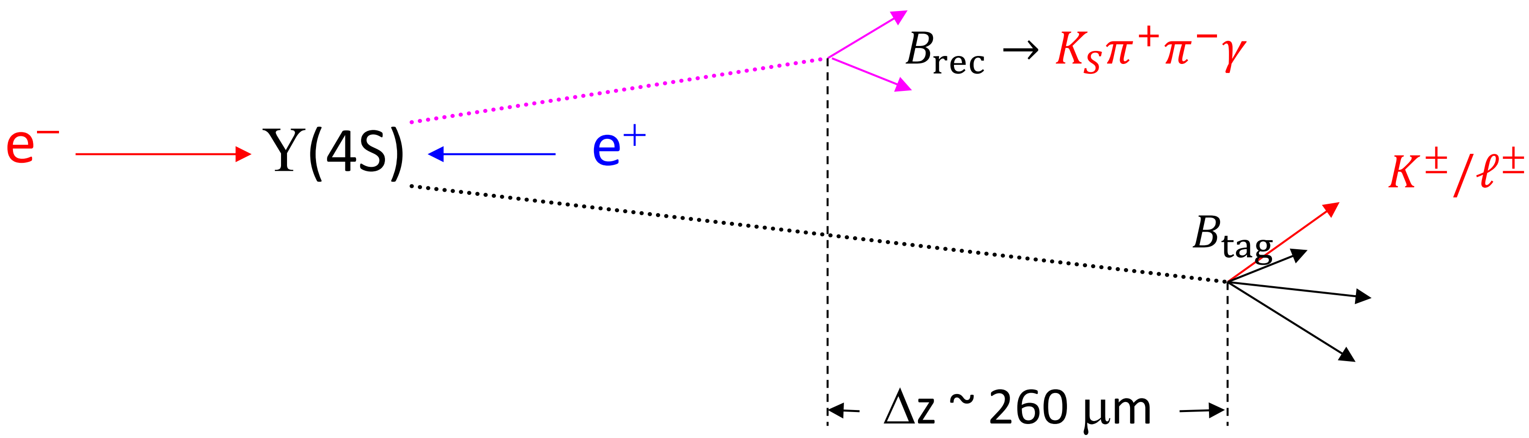
Time-dependent CP asymmetries in $B^0 \to K^0_s \pi^- \pi^+ \gamma$

- CP violation from interference between B-meson decay and $B^0 - \bar{B}^0$ mixing:

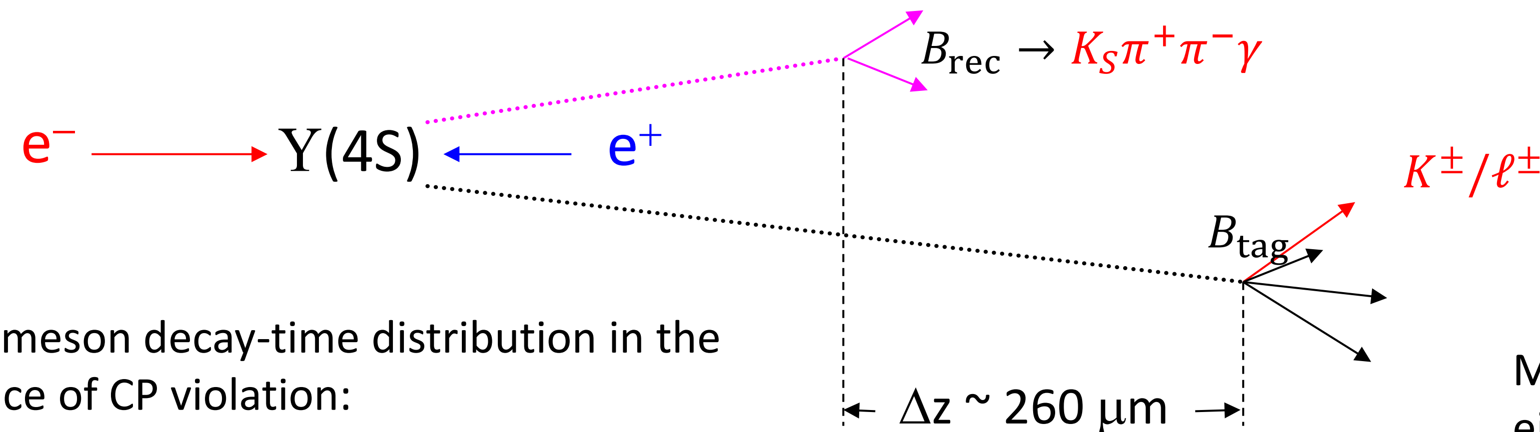


- Due to the V-A structure of the SM, the γ in $b \to s\gamma$ decays is predominantly left-handed (opposite helicity suppressed by $\sim m_s/m_b$).
- → dominant decays are $\bar{B}^0 \to X_S\, \gamma_L$, $B^0 \to X_S\, \gamma_R$.
- → $B^0 - \bar{B}^0$ interference is suppressed → CP violation is small.
- Models with large RH contributions (e.g., PRD 49, 5890 and 5894; PLB 333, 196) are allowed given the branching fractions, and could lead to large CPV.
- Related previous results found no evidence for CPV:
  - $B^0 \to K^0_s \rho^0 \gamma$ (Belle PRL101, 251601 (2008))
  - $B^0 \to K^0_s \pi^0 \gamma$ (BaBar PRD78, 071102 (2008); Belle PRD74, 111104 (2006))

$B^0 \rightarrow K^0_s \pi^- \pi^+ \gamma$ Analysis Method



$B^0 \to K^0_S \pi^- \pi^+ \gamma$ Analysis Method



The B-meson decay-time distribution in the presence of CP violation:

Mass-eigenstates mass diff.

$$\propto \exp\left(\frac{|\Delta t|}{\tau_{B^0}}\right)\left[1 + \frac{\Delta D}{2} + D q_{\rm tag}\{S \sin(\Delta t \Delta m) - C \cos(\Delta m \Delta t)\}\right] \otimes \text{Resolution } (\Delta t)$$

Mistag probabilities

$q_{\rm tag} = 1(-1)$ for $B_{\rm tag} = B^0(\bar{B}^0)$

CPV in interference (suppressed in SM)

CPV in decay (0 in SM for a CP-eigenstate final state)

- Primary goal: obtain $S_{K_S \rho \gamma}$ for the decay $B \to K_S \rho^0 \gamma$ with $\rho^0 \to \pi^+ \pi^-$

$B^0 \to K^0_s \pi^- \pi^+ \gamma$ Analysis Method

- Problem 1: background from $B^0 \to K^{*\pm}\pi^{\mp}\gamma$ "dilutes" $S_{K_S\rho\gamma}$ from $B^0 \to K^0_s\rho^0\gamma$
  – Need $K_S\pi^+\pi^-$ amplitude analysis to obtain dilution $D_{K_S\rho\gamma} \equiv \frac{S_{K_S\pi\pi\gamma}}{S_{K_S\rho\gamma}}$
- Problem 2: not enough $B^0 \to K^0_s\pi^-\pi^+\gamma$ for amplitude analysis
  – Perform amplitude analysis of $B^+ \to K^+\pi^-\pi^+\gamma$ to identify resonances and amplitudes.
  – Use isospin relations§ to relate $B^+ \to K^+\pi^-\pi^+\gamma$ amplitudes to $B^0 \to K^0_s\pi^-\pi^+\gamma$.
  – Calculate dilution factor from these amplitudes:

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

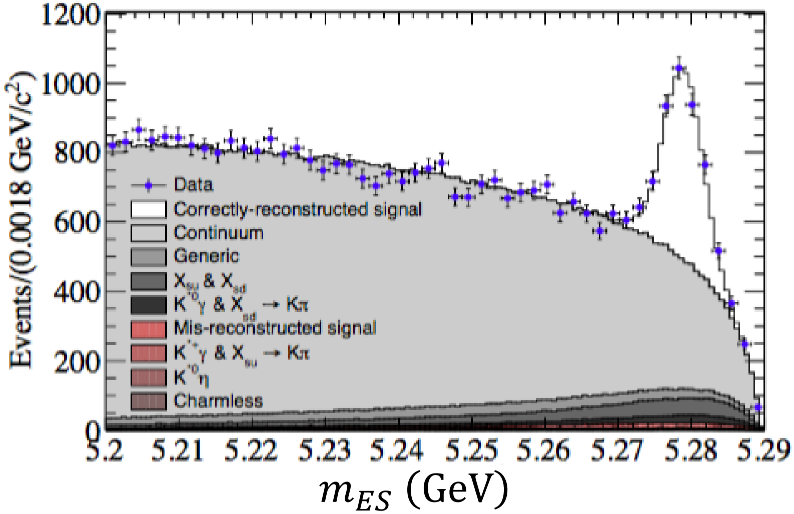
- Amplitude analysis performed over full Dalitz plane to identify resonances.
- Dilution extracted in optimized region $0.6 < m_{\pi\pi} < 0.9$ GeV, $m_{K\pi} < 0.845$ or $m_{K\pi} > 0.945$ GeV.

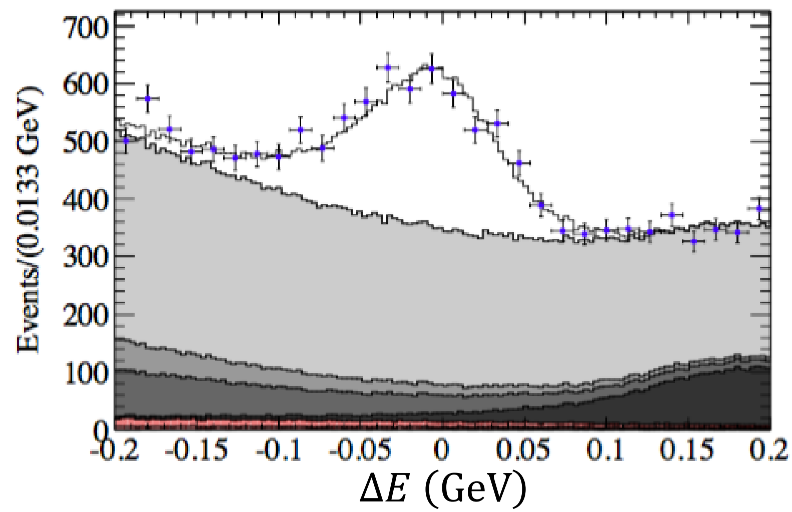
§= Hebinger, Kou and Yu, LAL-15-75

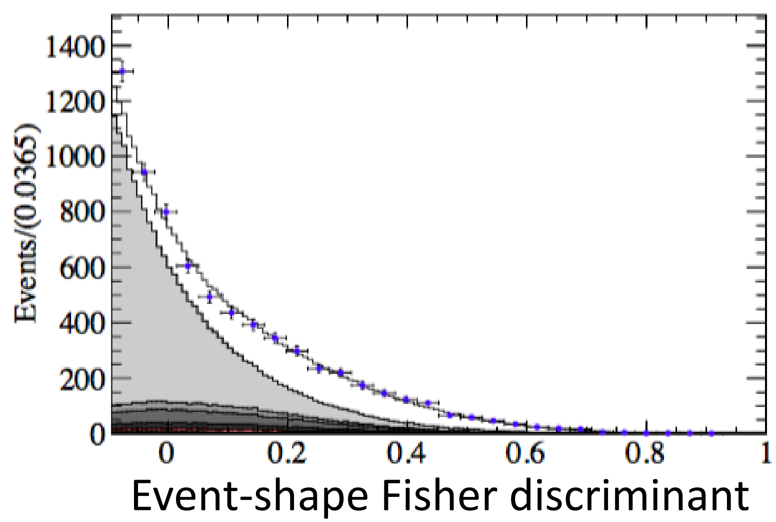
$B^+ \rightarrow K^+\pi^-\pi^+\gamma$ Results

PRD 93, 052013 (2016)

- B^+ yield extracted from ML fit to m_{ES}, ΔE, and event-shape Fisher discriminant.

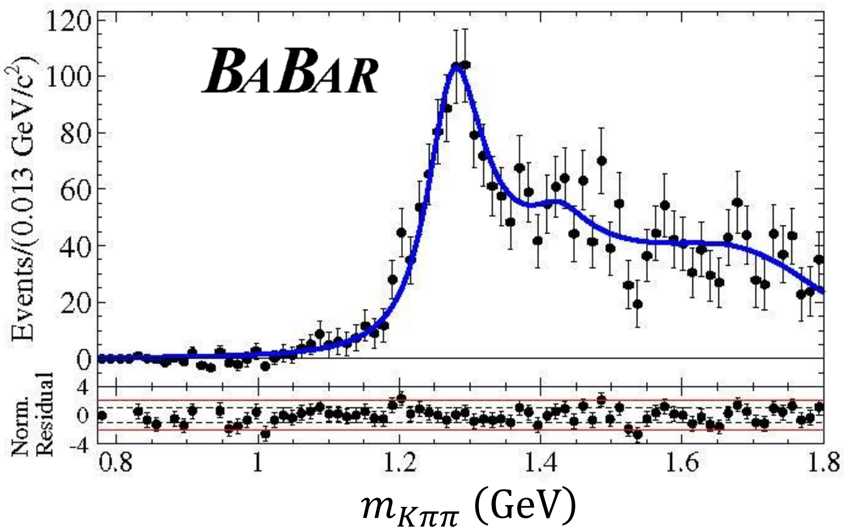




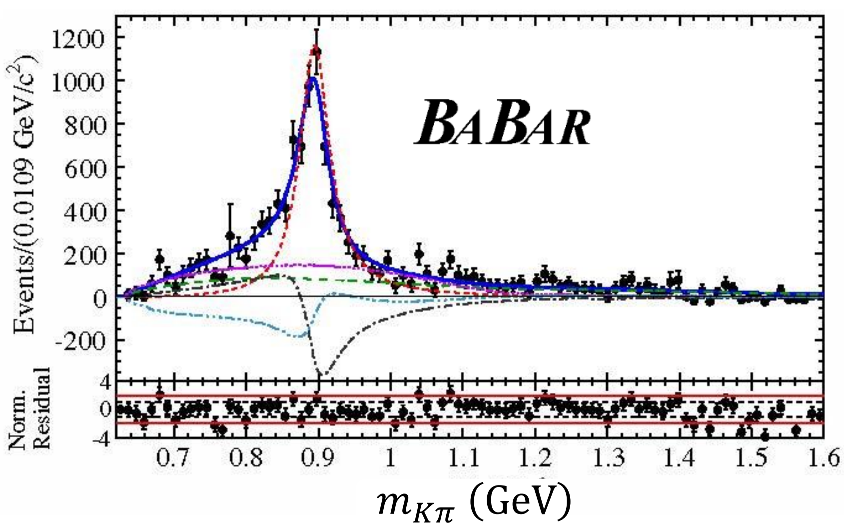


$B^+ \to K^+\pi^-\pi^+\gamma$ Amplitudes

PRD 93, 052013 (2016)



Mode	$B(B^+ \to \text{Mode})\times 10^{-6}$	Previous WAs
$B^+ \to K^+\pi^+\pi^-\gamma$	$24.5 \pm 0.9 \pm 1.2$	27.6 ± 2.2
$K_1(1270)^+\gamma$	$44.1^{+6.3+3.6}_{-4.4-3.6} \pm 4.6$	43 ± 13
$K_1(1400)^+\gamma$	$9.7^{+4.6+2.8}_{-2.9-2.3} \pm 0.6$	< 15
$K^*(1410)^+\gamma$	$27.1^{+5.5+5.2}_{-4.4-2.6} \pm 2.7$	n/a
$K_2^*(1430)^+\gamma$	$8.7^{+7.0+8.7}_{-5.3-10.4} \pm 0.4$	14 ± 4
$K^*(1680)^+\gamma$	$66.7^{+9.3+13.5}_{-7.8-10.0} \pm 5.4$	< 1900



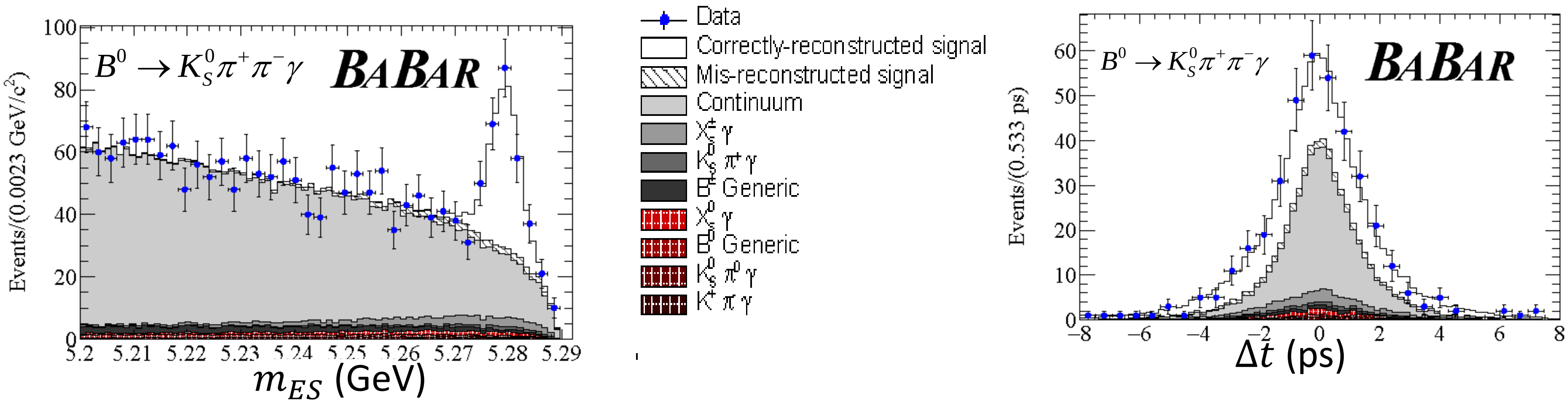
Mode	$B(B^+ \to \text{Mode})\times 10^{-6}$	Previous WAs
$K^*(892)^0\pi^+\gamma$	$23.4 \pm 0.9^{+0.8}_{-0.7}$	20^{+7}_{-6}
$K^+\rho(770)^0\gamma$	$8.2 \pm 0.4 \pm 0.8 \pm 0.02$	< 20
$(K\pi)^0_0\pi^+\gamma$ (NR)	$9.9 \pm 0.7^{+1.5}_{-1.9}$	< 9.2
$K_0^*(1430)^0\pi^+\gamma$	$1.32^{+0.09+0.20}_{-0.10-0.26} \pm 0.14$	n/a

Several amplitudes observed for first time

$B^0 \to K^0_s \pi^- \pi^+ \gamma$ Results

PRD 93, 052013 (2016)

B^0 yield and CP from time-dependent ML fit to (ΔE, m_{ES}, F, Δt, σ_t ; q_{tag},c).



$$B(B^0 \to K^0\pi^+\pi^-\gamma) = (24.0 \pm 2.4^{+1.7}_{-1.8}) \times 10^{-6}$$

$$S_{K_s^0\pi^+\pi^-\gamma} = +0.14 \pm 0.25 \pm 0.03 \qquad D_{K_s^0\rho^0\gamma} = -0.78^{+0.19}_{-0.17}$$

$$C_{K_s^0\pi^+\pi^-\gamma} = -0.39 \pm 0.20^{+0.03}_{-0.02} \qquad S_{K_s^0\rho^0\gamma} = -0.18 \pm 0.32^{+0.06}_{-0.05}$$

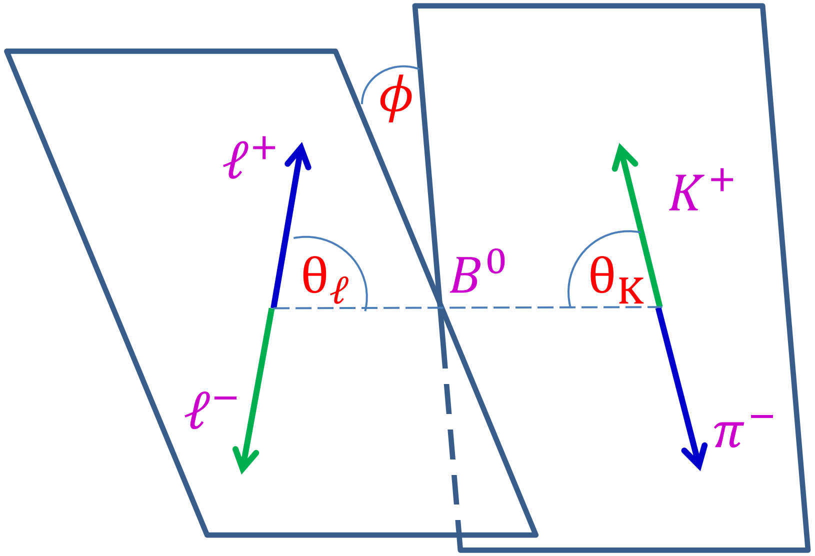
Results consistent with Belle [PRL 101, 251601 (2008)].
CP asymmetries consistent with zero and the SM.
Several new amplitudes observed.

Angular analysis of $B \rightarrow K^* l^+ l^-$

Angular analysis of B→K*l+l-

- Several marginal tensions with the SM recently observed in $B \to K^{(*)}\ell\ell$ observables (e.g., LHCb: PRL 111, 191801 (2013)), motivating further study.

- The B→K*l+l- angular distribution depends on:
  - θ_K: between K & B^0 in K* rest frame
  - θ_l: between $l^+(l^-)$ & $B(\bar{B})$ in l^+l^- rest frame
  - ϕ: between l^+l^- and $K\pi$ decay planes
- Not enough events for full angular analysis, so integrate over two angles at a time to find
  - Longitudinal-polarization fraction F_L
  - Lepton forward-backward asymmetry A_{FB}:



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

$$\frac{1}{\Gamma(q^2)}\frac{d\Gamma}{d(\cos\theta_l)} = \frac{3}{4}F_L(q^2)\sin^2\theta_l + \frac{3}{8}(1-F_L(q^2))(1+\cos^2\theta_l) + A_{FB}(q^2)\cos\theta_l$$

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

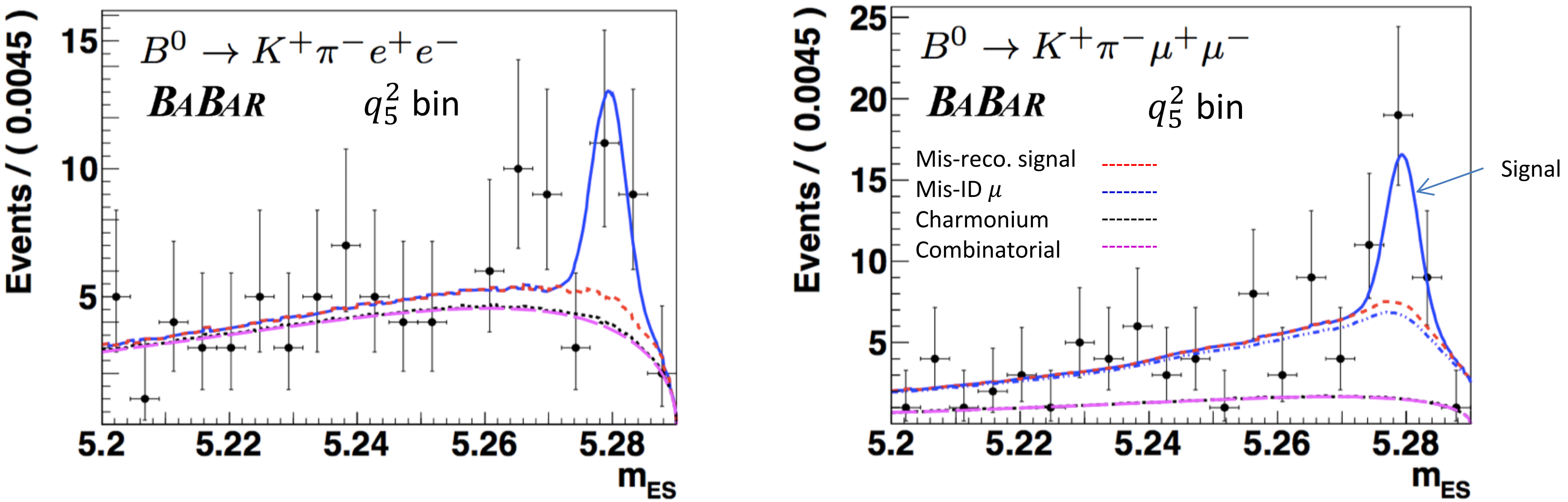
Angular analysis of $B \to K^* l^+ l^-$

- Perform the analysis in
  - 5 exclusive q^2 bins and one broad low- q^2 bin:
  - 5 decay channels:

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

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	$1.00 - 6.00$

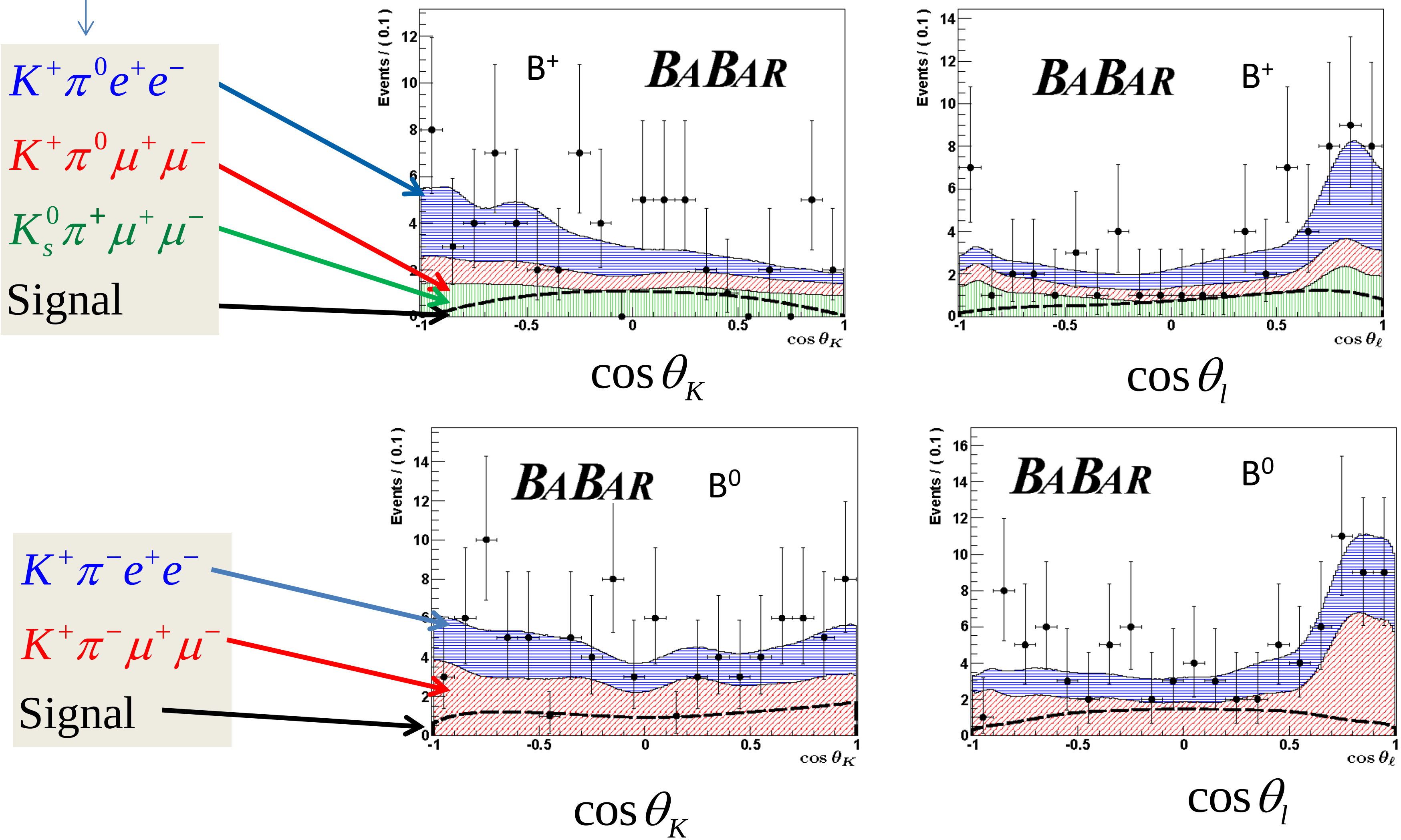
- Obtain signal yield from m_{ES} , $m(K\pi)$, Likelihood ratio. E.g., in the q_5^2 bin:



$B \to K^* l^+ l^-$ fits for bin q^2_0 $(1<q^2<6\ \mathrm{GeV}^2)$

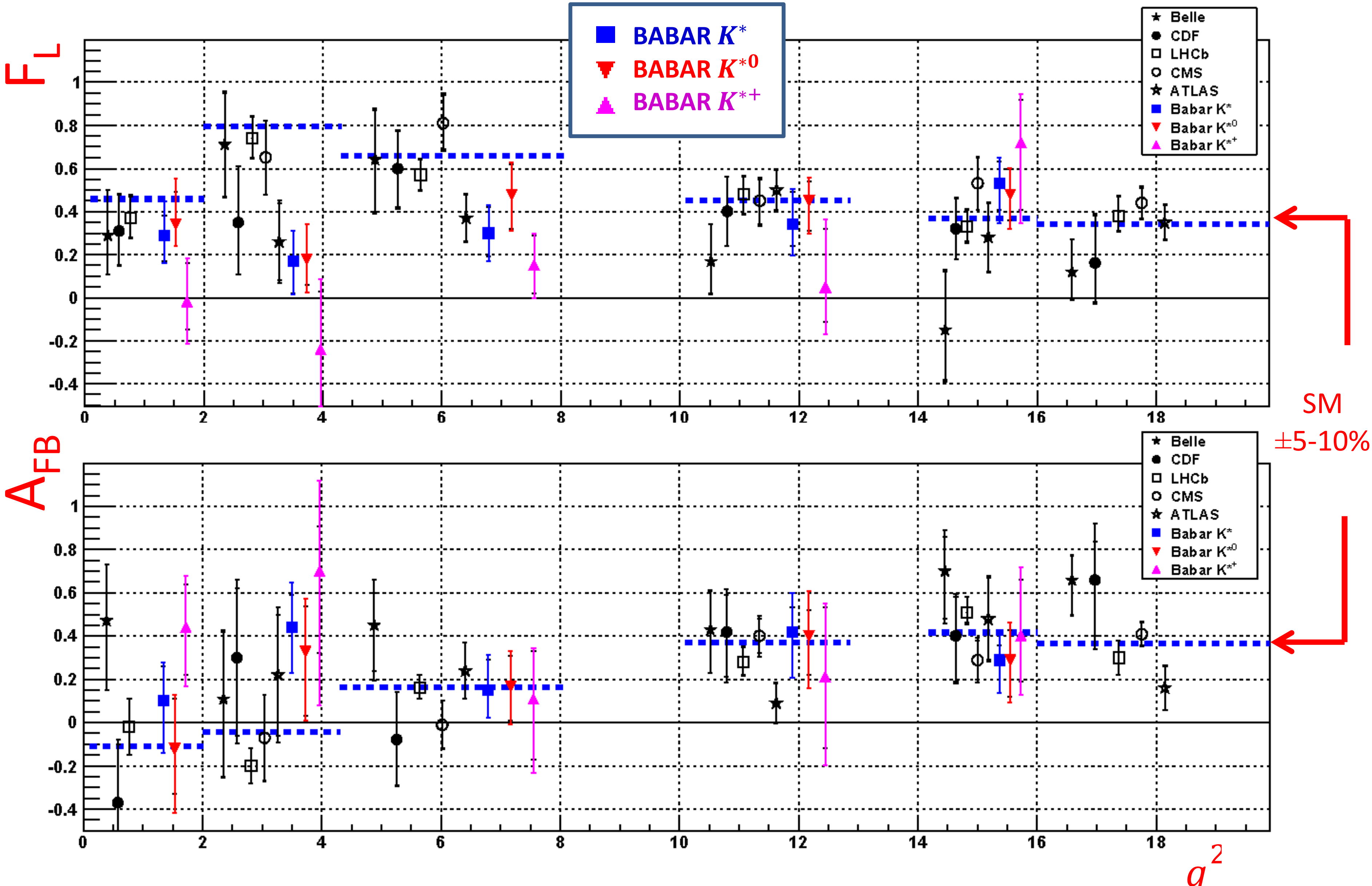
PRD 93, 052015 (2016)

Contributions of different channels to the final fit in bin



F_L and A_{FB} versus q^2 in $B \to K^* l^+ l^-$

PRD 93, 052015 (2016)

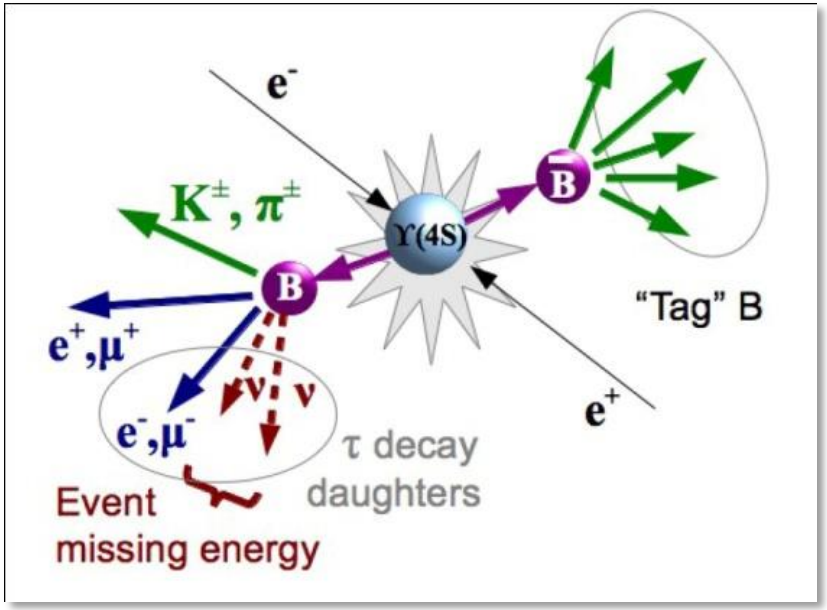


Search for $B^+ \rightarrow K^+\tau^+\tau^-$

Search for $B^+ \to K^+\tau^+\tau^-$: method

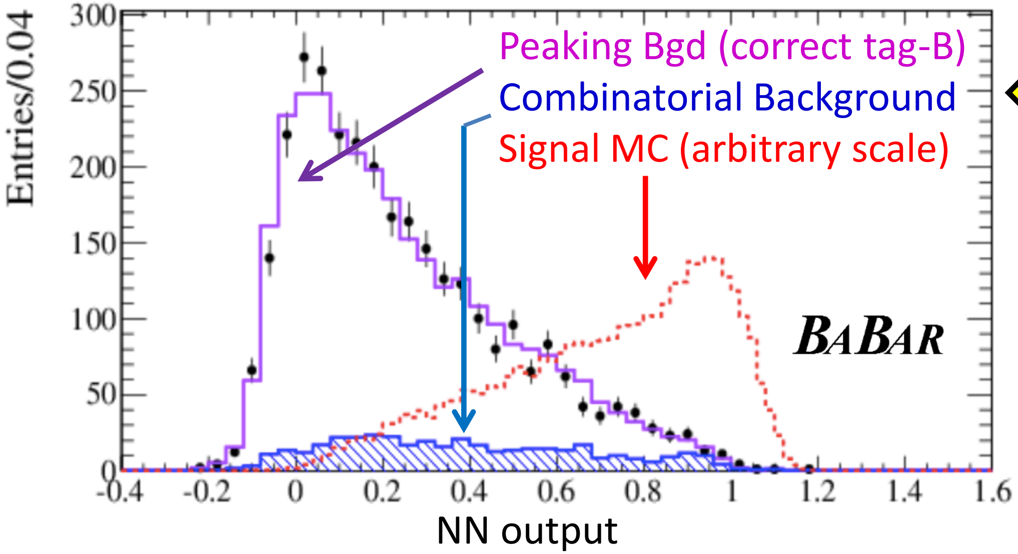
arXiv:1605.09637

- SM: BR$\sim 10^{-7}$. But new-physics fermion couplings might be nonuniversal.
- Important to check, note current 4.0σ discrepancy in $\bar{B} \to D^{(*)}\tau^+\nu$
- Reconstruct the decays $\tau^- \to e^-\nu_\tau\bar{\nu}_\mu$ and $\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu$.
- Multiple neutrinos – obtain kinematic constraint by fully reconstructing the other B meson in the event (B_{tag}) through its hadronic decays to
  - a charmed meson: $D^{(*)0}$, $D^{(*)\pm}$, $D_s^{*\pm}$, J/ψ
  - up to 5 additional pions + kaons
- B_{tag} selected with m_{ES} & ΔE cuts
- B_{tag} determines the signal-B kinematics: $p^\mu_{\text{sig}} = p^\mu_{e^+e^-} - p^\mu_{\text{tag}}$
- Require $m^2(\tau^+\tau^-) > 0.45\, m_B^2$
- 92% of background has correct tag-B.
- Background mostly $\bar{B} \to D^{(*)}\ell^+\nu$,
  $D \to \bar{K}\ell'^-\bar{\nu}$,
  which has the same final-state particles



Search for $B^+ \to K^+\tau^+\tau^-$: results

arXiv:1605.09637



Train an 8-variable neural-network to separate S-B. Optimal cuts on NN:

- > 0.70 for the ee & $\mu\mu$ modes
- > 0.75 for the $e\mu$ mode

Obtain background yield:

- Combinatorial: m_{ES} sideband
- Peaking: MC shape + tag-B yield, validated with $B^+ \to D^0\ell^+\nu$, $D^0 \to K^-\pi^+$ control sample

Expected and observed yields:

	e^+e^-	$\mu^+\mu^-$	$e^+\mu^- + e^-\mu^+$
N_{bkg}	$49.4 \pm 2.4 \pm 2.9$	$45.8 \pm 2.4 \pm 3.2$	$59.2 \pm 2.8 \pm 3.5$
ε_{sig} ($\times 10^{-5}$)	$1.1 \pm 0.2 \pm 0.1$	$1.3 \pm 0.2 \pm 0.1$	$2.1 \pm 0.2 \pm 0.2$
N_{obs}	45	39	92
Significance (σ)	-0.6	-0.9	3.7

$$\sigma = \frac{\text{observed} - \text{expected}}{\text{error}}$$

(Not interpreted as probability)

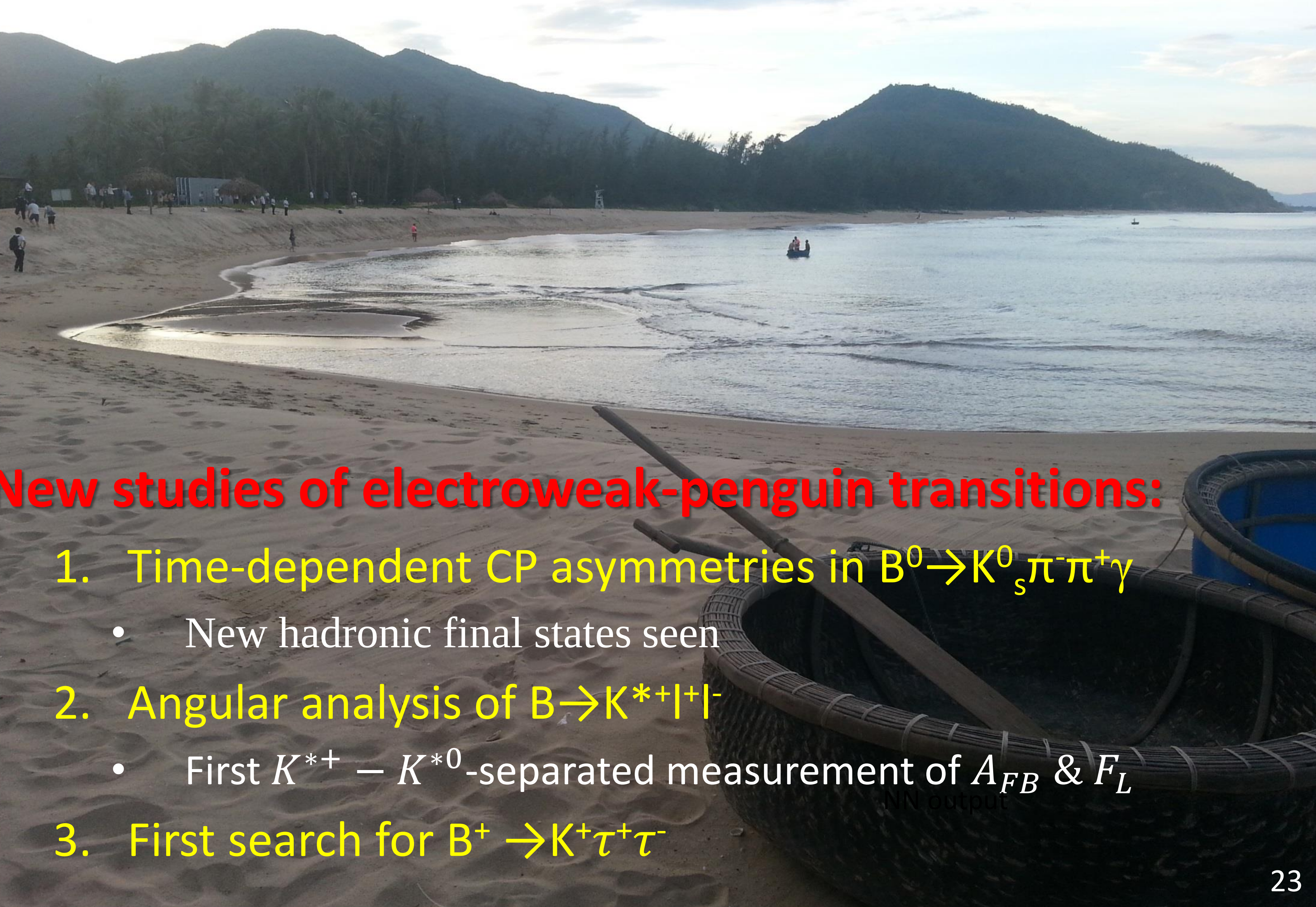
Scrutiny of the $e\mu$ events doesn't show a signal-like excess

Branching-fraction central value & upper limit:

$$B(B^+ \to K^+\tau^+\tau^-) = (1.31^{+0.66+0.35}_{-0.61-0.25}) \times 10^{-3}$$

$$B(B^+ \to K^+\tau^+\tau^-) < 2.25 \times 10^{-3} \text{ (90\% CL UL)}$$

Conclusion



New studies of electroweak-penguin transitions:

1. Time-dependent CP asymmetries in $B^0 \to K^0_s \pi^- \pi^+ \gamma$
   - New hadronic final states seen
2. Angular analysis of $B \to K^{*+} l^+ l^-$
   - First $K^{*+} - K^{*0}$-separated measurement of A_{FB} & F_L
3. First search for $B^+ \to K^+ \tau^+ \tau^-$

BACKUP SLIDES

Neural network variables in $B \to K\tau\tau$

1. The angle between the kaon and the oppositely charged lepton
2. The angle between the two leptons
3. The momentum of the lepton with charge opposite that of the K
4. The missing energy associated with the ττ pair

} ττ frame

5. The angle between the B candidate and the oppositely charged lepton
6. The angle between the K and the lower-momentum lepton

} CM frame

7. The invariant mass of the K+l− pair
8. Extra calorimeter energy in the event

} Lab frame