Recent Searches for Beyond-SM Effects at BABAR

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on behalf of the BABAR collaboration

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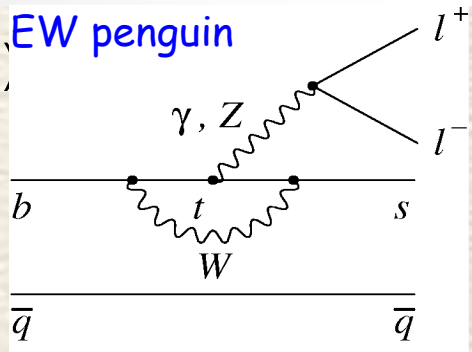
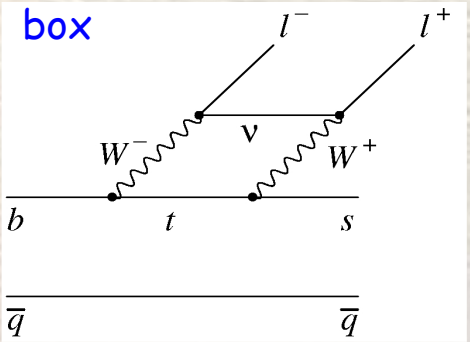
Outline

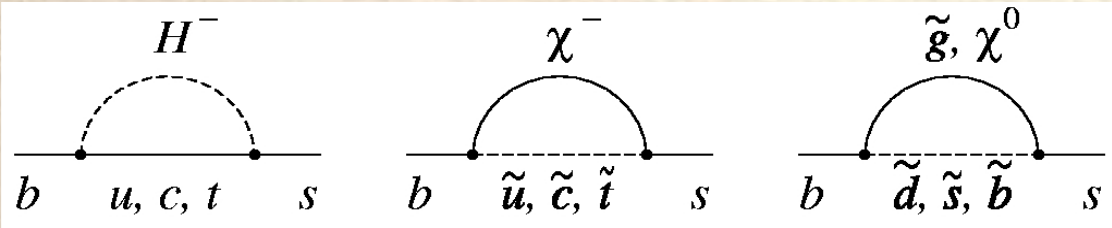
- Introdcution
- Angular asymmetries in $B \to K^* \ell^+ \ell^-$
- Search for $B^+ \to K^+ \tau^+ \tau^-$
- Conclusion

Introduction

- $B \to K^* \ell^+ \ell^-$ and $B^+ \to K^+ \tau^+ \tau^-$ are flavor-changing neutral current (FCNC) decays that are forbidden in the SM at tree level ($\ell^\pm = e^\pm$ or $\mu^\pm$)
- They proceed at higher orders via penguin loops & box diagrams
- New physics (NP) adds new loops with new particles
  ➔ modifies SM predictions

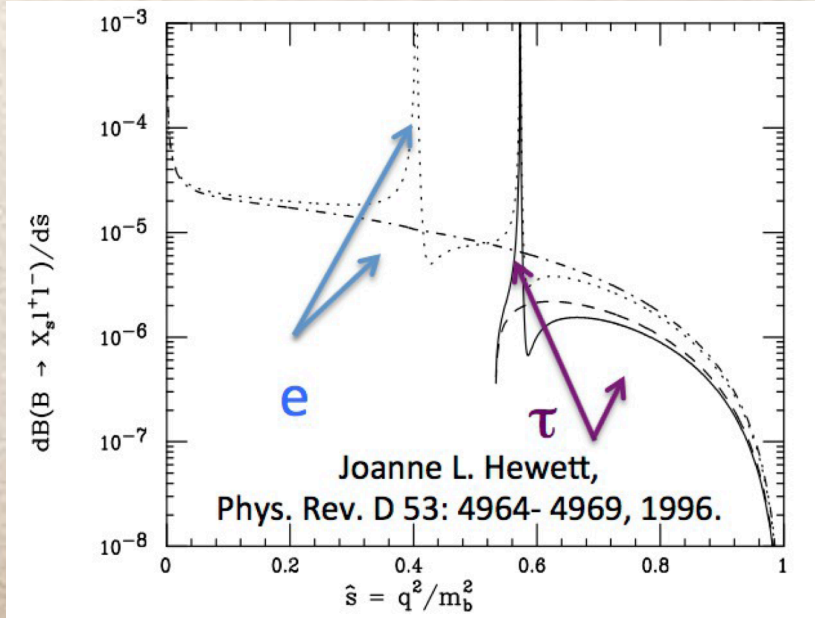






➔ probes new physics at ~few TeV scale

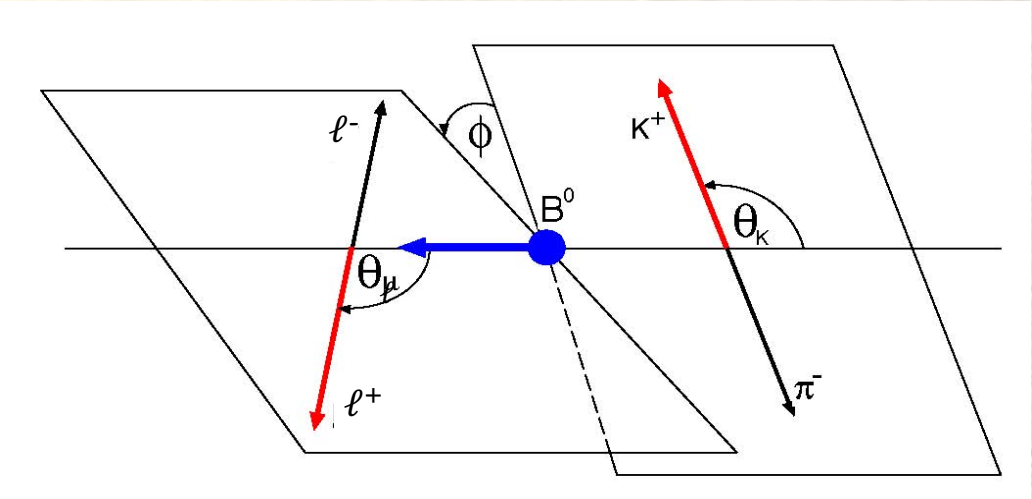
- Angular observables bear high sensitivity to NP
- $B^+ \to K^+ \tau^+ \tau^-$ is highly suppressed in the SM and the τ may couple stronger to NP than light ℓ



Angular Asymmetries in the Decays $B \to K^* \ell^+ \ell^-$

Angular Distributions in $B \to K^* \ell^+ \ell^-$

- The $B \to K^* \ell^+ \ell^-$ angular distribution depends on three angles, θ_K, θ_ℓ, ϕ
- θ_K is angle between K & B in K^* rest frame
- θ_ℓ is angle between ℓ^+ (ℓ^-) & $B(\bar{B})$ in $\ell^+\ell^-$ rest frame
- ϕ is the angle between the di-lepton and $K\pi$ decay planes

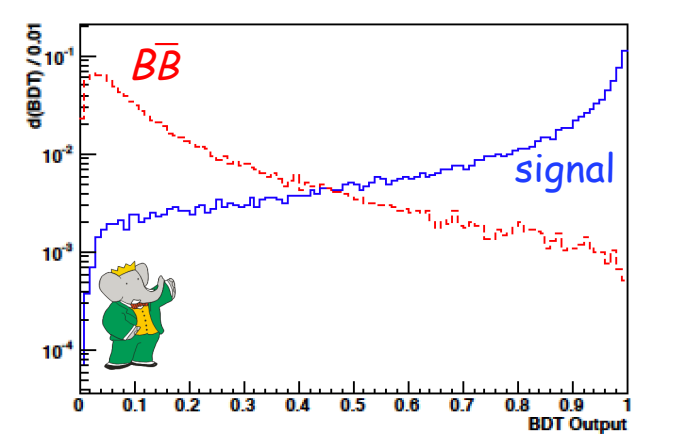


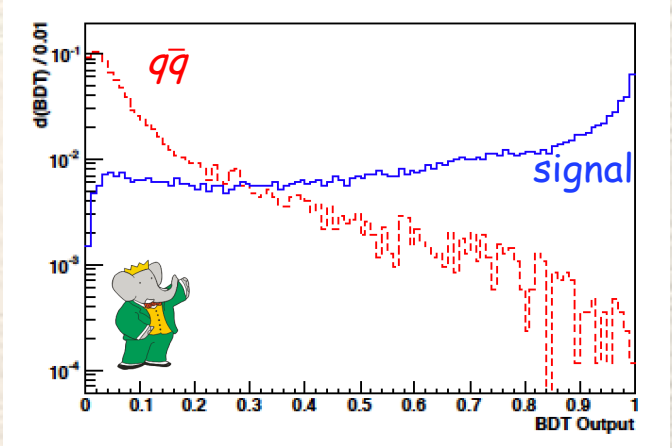
- The full angular distribution involves 11 coefficients that can be determined from angular fits for each $q^2 = m^2_{\ell\ell}$ bin ➔ for *CP*-averaged rates get 8 independent coefficients
- Use 1-d projections due to limited-statistics samples
- $W(\cos\theta_K) = \frac{3}{2}\mathcal{F}_L(q^2)\cos^2\theta_K + \frac{3}{4}(1-\mathcal{F}_L(q^2))\sin^2\theta_K$ — $\mathcal{F}_L(q^2)$: K^* longitudinal polarization
- $W(\cos\theta_\ell) = \frac{3}{4}\mathcal{F}_L(q^2)\sin^2\theta_\ell + \frac{3}{8}(1-\mathcal{F}_L(q^2))(1+\cos^2\theta_\ell) + \mathcal{A}_{FB}(q^2)\cos\theta_\ell$ — $\mathcal{A}_{FB}(q^2)$: lepton forward-backward asymmetry
- Fit angular distributions in 5 bins of q^2 & q^2_0=1-6 GeV^2 to extract $\mathcal{F}_L(q^2)$ and $\mathcal{A}_{FB}(q^2)$
- Determine also $P_2(q^2)$=(-2/3)$*$ $\mathcal{A}_{FB}(q^2)$/(1- $\mathcal{F}_L(q^2)$) that has smaller theory uncertainty

Analysis Methodology

- Use full BABAR data of 471×10^6 $B\bar{B}$ events

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





- Reconstruct 5 final states:
  - $B^+\to K^{*+}(\to K^0_S\pi^+)\mu^+\mu^-$
  - $B^0\to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$
  - $B^+ \to K^{*+}(\to K^0_S\pi^+)e^+e^-$
  - $B^+ \to K^{*+}(\to K^+\pi^0)e^+e^-$
  - $B^0 \to K^{*0}(\to K^+\pi^-)e^+e^-$

- Use kinematic variables:
  - $m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_B}$ and $\Delta E = E^*_B - E^*_{beam}$

- Use 8 bagged decision trees with 10 input variables to separate signal from $B\bar{B}$ and $q\bar{q}$ backgrounds for low/high q^2 and $e^+e^-/\mu^+\mu^-$ separately

q^2 bin	q^2 min (GeV^2/c^4)	q^2 max (GeV^2/c^4)
q^2_1	0.10	2.00
q^2_2	2.00	4.30
q^2_3	4.30	8.12
q^2_4	10.11	12.89
q^2_5	14.21	$(m_B - m_{K^*})^2$
q^2_0	1.00	6.00

- Combine $B\bar{B}$ BDT outputs into likelihood ratios: $L_R = \frac{P_{sig}}{P_{sig} + P_{bkg}}$ ➔ require L_R >0.6

- Initially, perform 3-d unbinned maximum-likelihood fit to m_{ES}, $m_{K\pi}$, L_R in each q^2 bin for each signal mode separately requiring m_{ES} > 5.2 GeV
  ➔ fix normalizations and pdfs for m_{ES}, $m_{K\pi}$, L_R

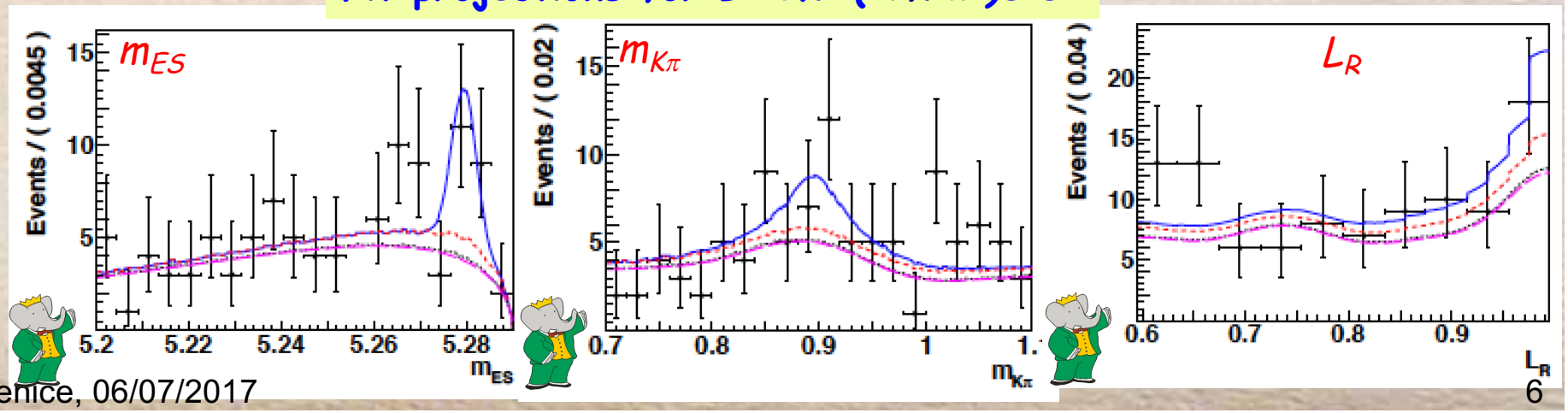
BABAR: PRD 93, no 5, 052015 (2016)

Determination of Angular Observables

- In each q^2 bin for each signal mode separately define normalizations and pdfs for m_{ES}, $m_{K\pi}$, L_R in angular-fit signal region ($m_{ES} > 5.27$ GeV) using results from prior fits
- Add $\cos\theta_K$ as 4th variable in likelihood function with $\mathcal{F}_L(q^2)$ as only free parameter keeping all other parameters fixed
- Add $\cos\theta_\ell$ as 4th variable in likelihood function with $\mathcal{A}_{FB}(q^2)$ as only free parameter keeping all other parameters and $\mathcal{F}_L(q^2)$ fixed
- Determine each angular result subsequently by direct construction and examination of –log(L) curves from scan across entire $\mathcal{F}_L(q^2)$ and $\mathcal{A}_{FB}(q^2)$ parameter space
- Use signal classes: correctly reconstructed, mis-reconstructed (cross feed) events
  Use background classes: combinatorial, leakage from J/ψ, ψ(2S) region (vetoed), hadrons misidentified as muons

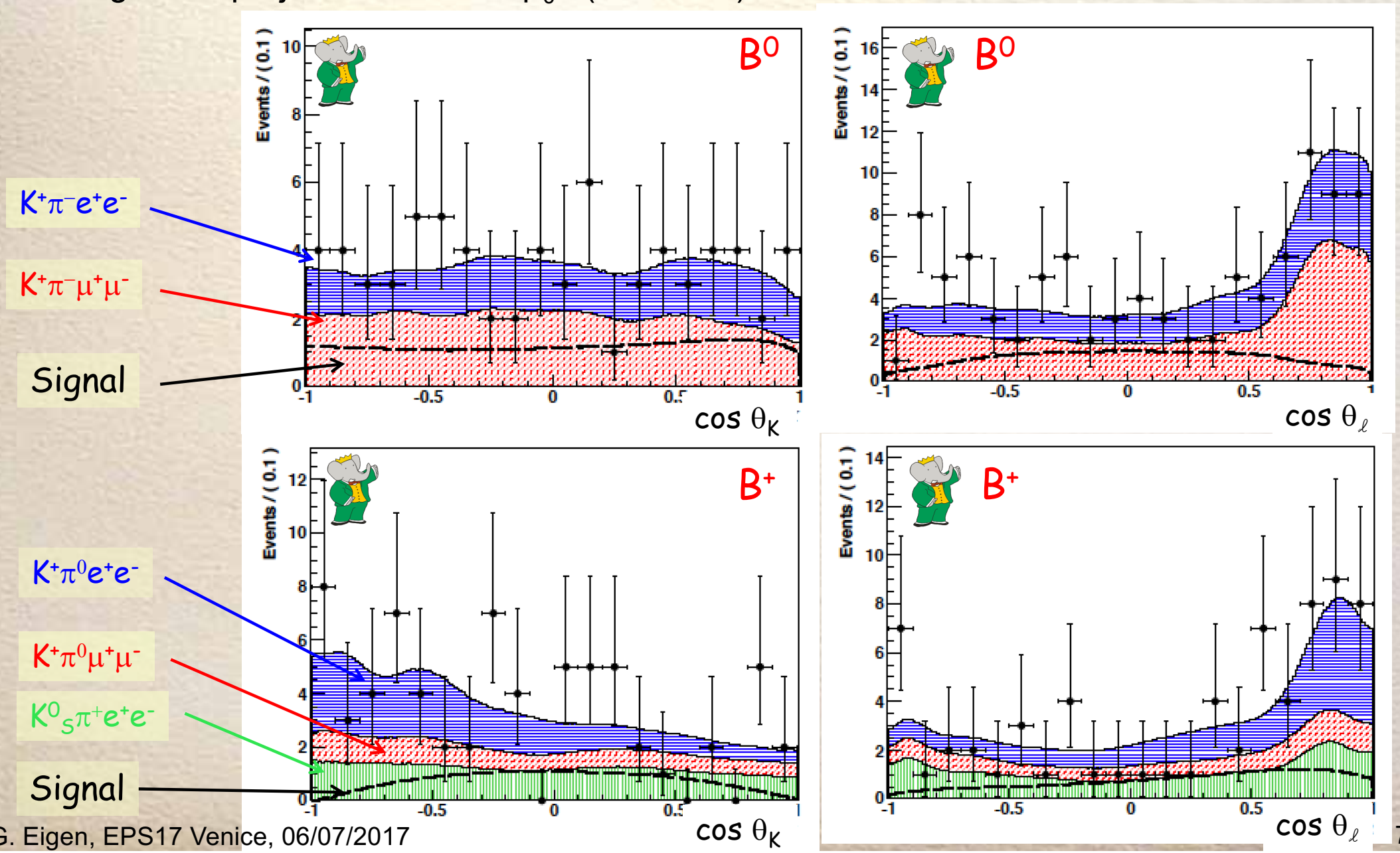
Fit projections for $B^0 \to K^{*0}(\to K^+\pi^-)e^+e^-$

--- combinatorial
..... cross feed
..... charmonium
—— total pdf



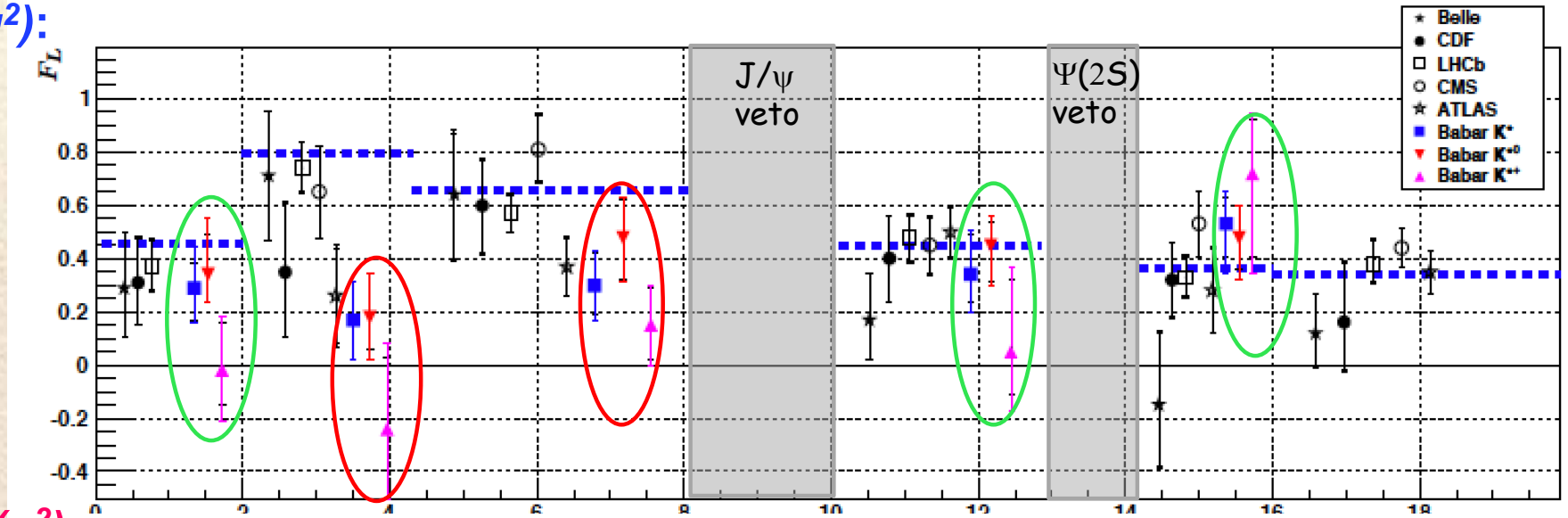
$B \to K^* \ell^+ \ell^-$ Angular Fit Projections

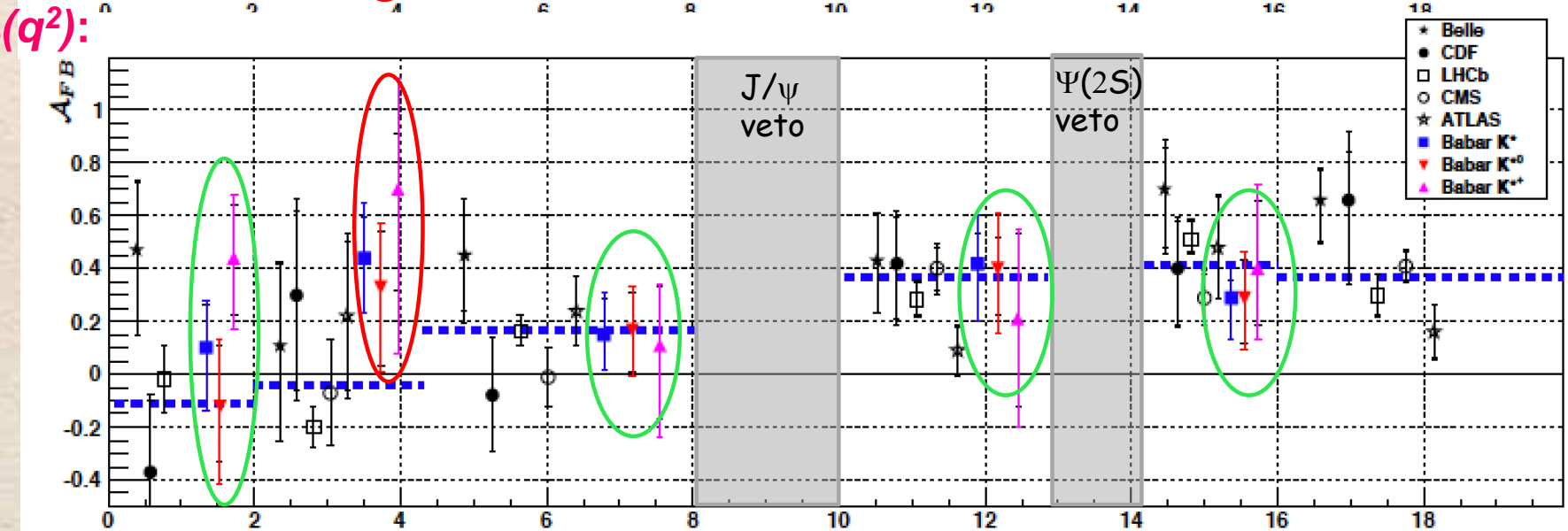
- Angular fit projections for bin q^2_0 (1-6 GeV^2)



$\mathcal{F}_L(q^2)$ and $\mathcal{A}_{FB}(q^2)$ Measurements

- BABAR $\mathcal{F}_L(q^2)$: for q^2_2 & q^2_3 see 3σ & 2σ deviations from the SM; values are lower for $B^+ \to K^{*+}\ell^+\ell^-$ than for $B^0 \to K^{*0}\ell^+\ell^-$
- BABAR $\mathcal{A}_{FB}(q^2)$: agrees well with the SM except for q^2_2 bin that shows >2σ deviation; values for $B^+ \to K^{*+}\ell^+\ell^-$ agree with those of $B^0 \to K^{*0}\ell^+\ell^-$

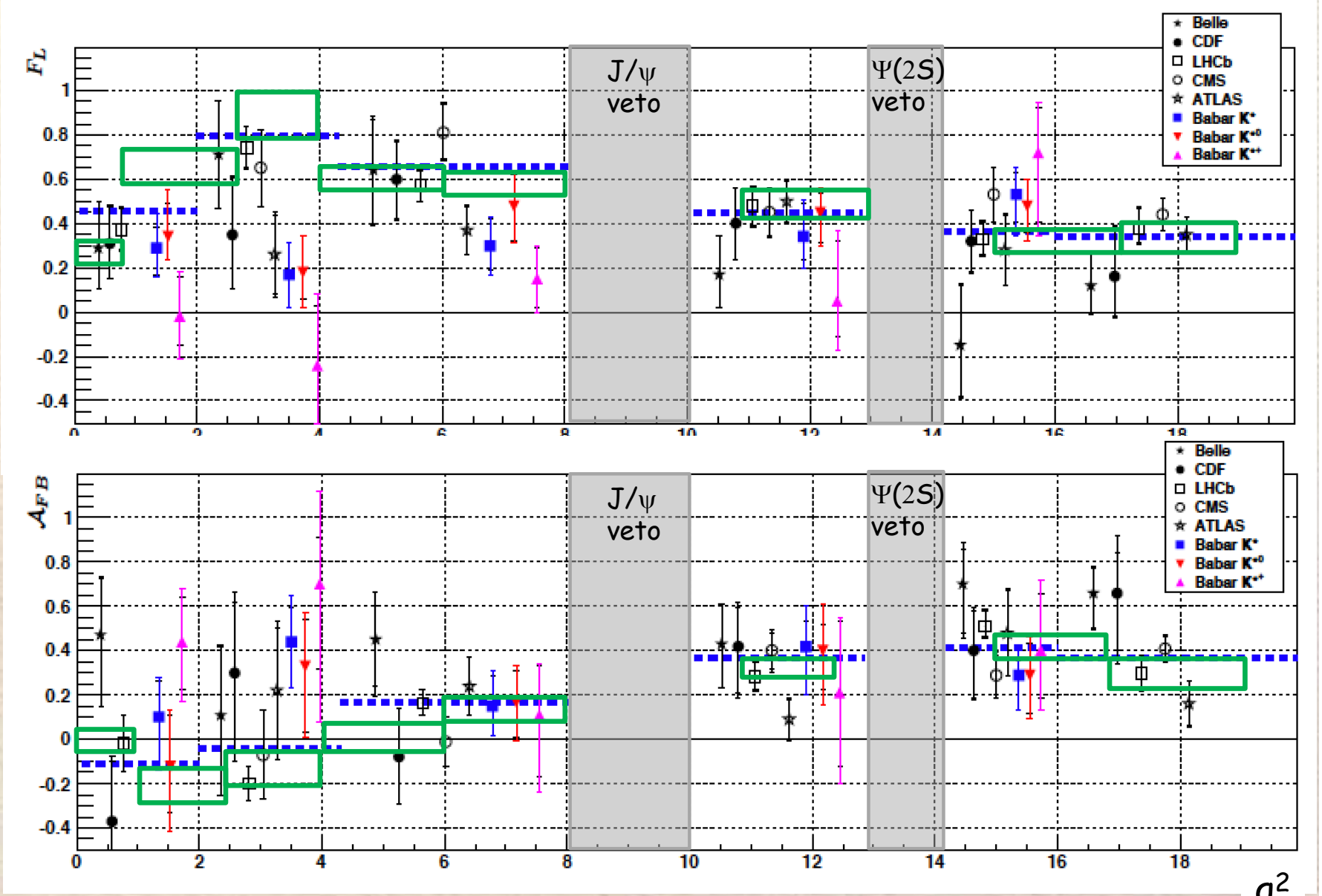




Belle: PRL 103, 171801 (2012) CDF: PRL 108, 081807 (2012) LHCb: JHEP1308, 131 (2013) CMS: PLB 727, 77 (2013) ATLAS: ATLAS-CONF 2013-038 (2013) BABAR: PRD 93, no 5, 052015 (2016)

$\mathcal{F}_L(q^2)$ and $\mathcal{A}_{FB}(q^2)$ Measurements

- $\mathcal{F}_L(q^2)$: new LHCb results are consistent with those of the SM
- $\mathcal{A}_{FB}(q^2)$: new LHCb results are in good agreement with the SM predictions

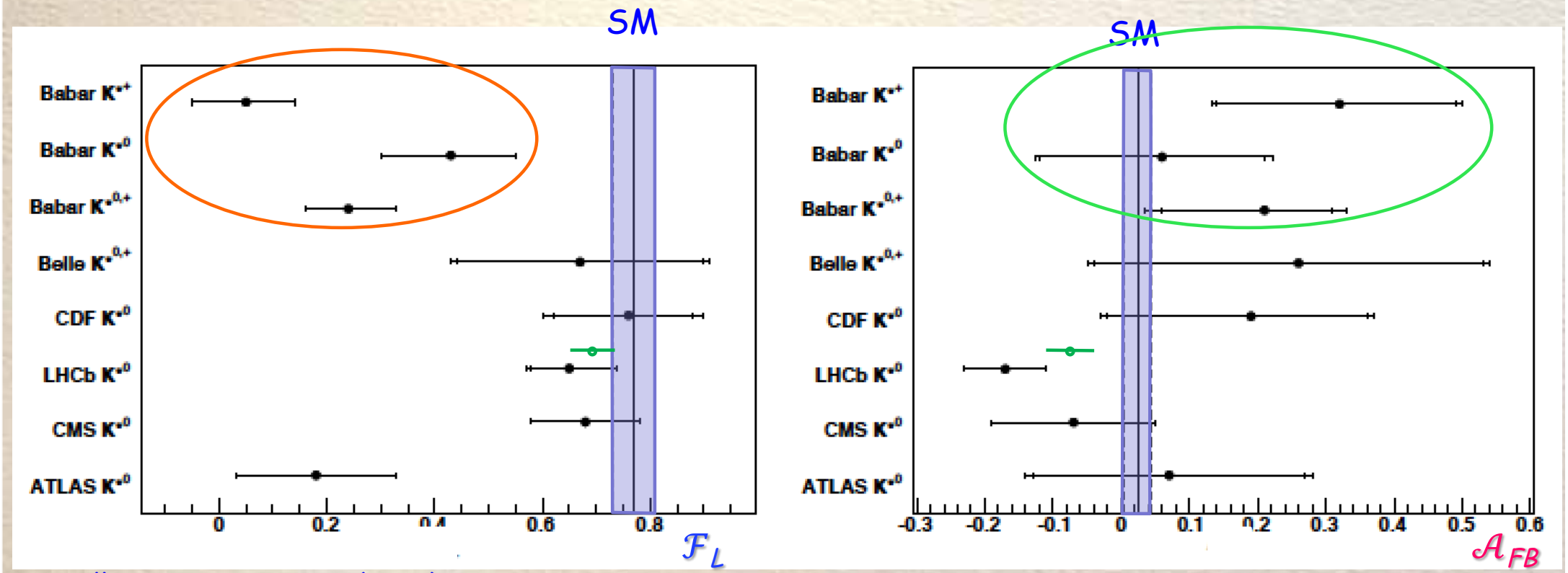


Belle: PRL 103, 171801 (2012)
CDF: PRL 108, 081807 (2012)
LHCb: JHEP1308, 131 (2013)
LHCb: JHEP1612, 065 (2016)
CMS: PLB 727, 77 (2013)
ATLAS: ATLAS-CONF 2013-038 (2013)
BABAR: PRD 93, no 5, 052015 (2016)

Comparison of $\mathcal{F}_L$ and $\mathcal{A}_{FB}$ for Bin q^2_0

- In bin q^2_0, BABAR results for $\mathcal{F}_L$ are substantially lower than the SM prediction
  ➔ deviation is > 3σ

- BABAR results for $\mathcal{A}_{FB}$ agree with the SM prediction, as do those of other experiments



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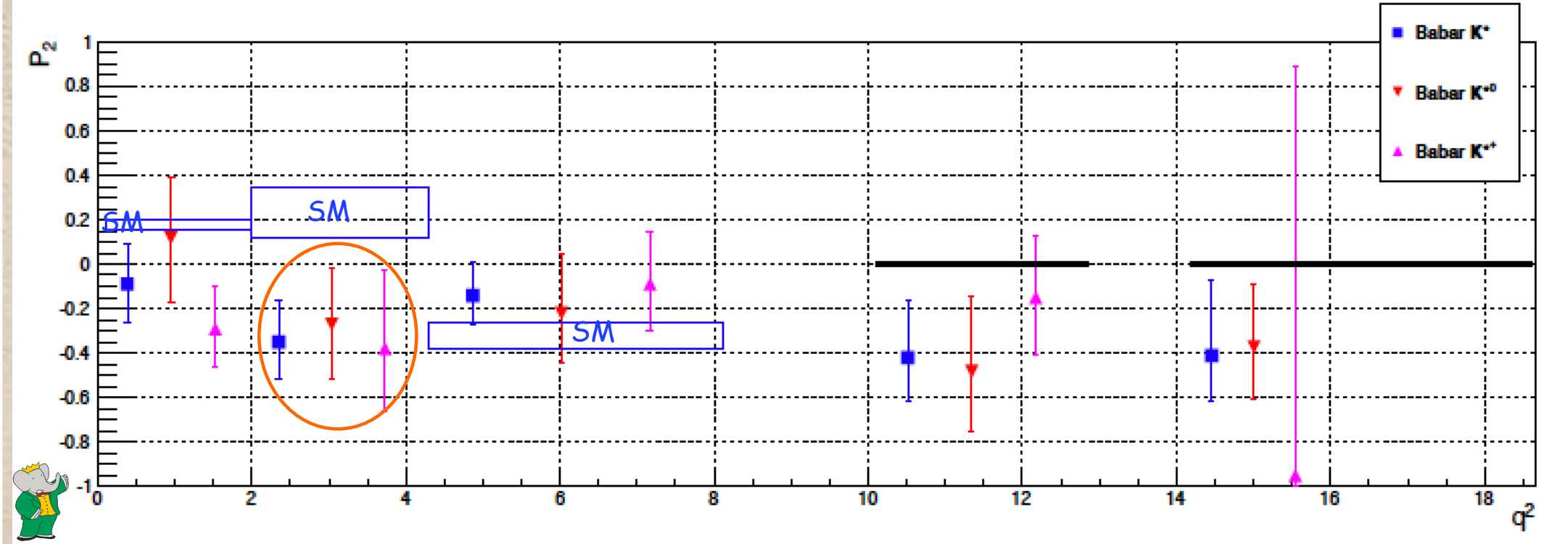
Results for P_2

- Extract P_2 from the angular fit results
- In bin q^2_2, see >2σ discrepancy with the SM prediction
- In bin q^2_0, P_2=0.11±0.10

$$P_2\left(q^2\right) = -\frac{2}{3}\frac{\mathcal{A}_{FB}}{1-\mathcal{F}_L}$$

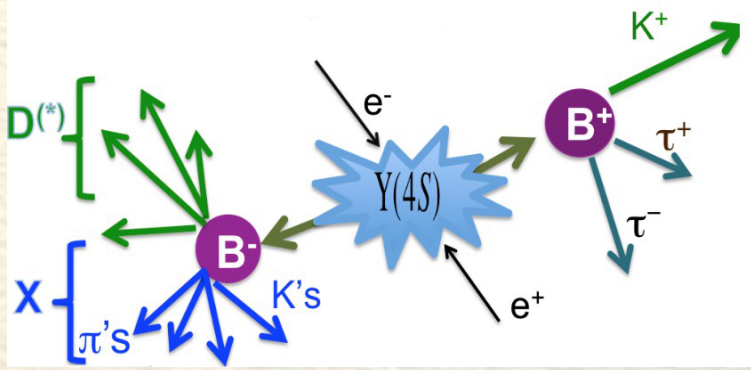


BABAR: PRD 93, no 5, 052015 (2016)

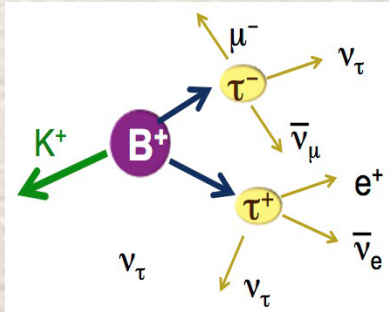
Search for $B^+ \to K^+ \tau^+ \tau^-$

Analysis Methodology

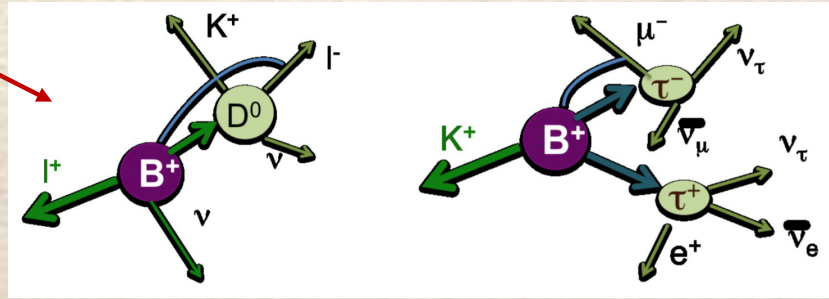
- Use the full BABAR data set of 471×10^6 $B\bar{B}$ events
- Tag one B meson via full hadronic reconstruction and look for $B^+\to K^+\tau^+\tau^-$ in the recoil



- Hadronic $B_{tag} \to X_c X$ reconstruction:
  $X_c = D^{(*)0}\pi$, $D^{(*)\pm}$, $D_s^{(*)}$, J/ψ & X=combination of 5π and/or K
- Use purely leptonic decays of both τ's



- Main background:
  $B \to D^{(*)} l\nu$ +tracks from B_{tag}



- B_{signal} selection:
  - Exactly 3 tracks with correct PID
  - $m_{ES}>5.27$ GeV^2
  - $|\Delta E|<0.12$ GeV
  - $E_{sig}^{miss}>0$ GeV
  - Reduce continuum background with Multi-Layer Perceptron NN using 6 event shape variables inserted into likelihood ratio

$$\mathcal{L} = \frac{P_B}{P_B + P_q} > 0.5$$

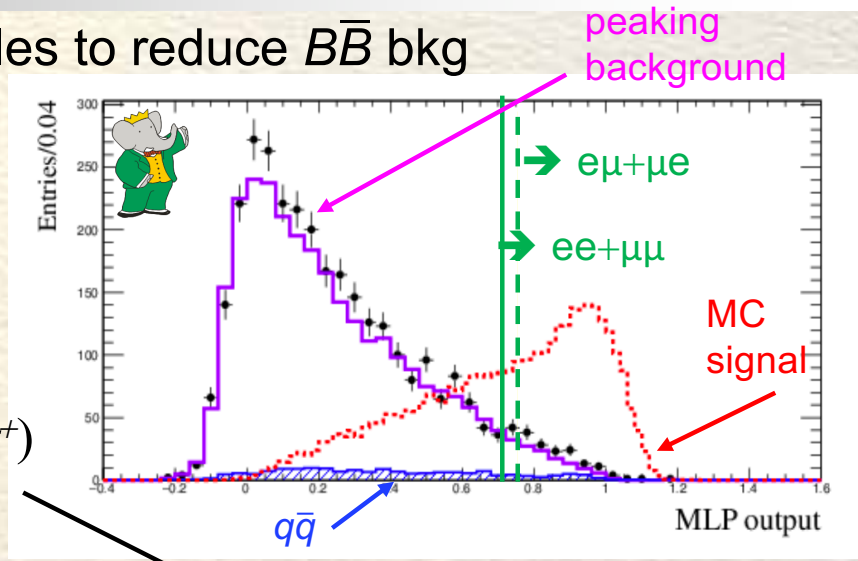
$P_B=\Pi_i P_B(x_i)$: probability for $B\bar{B}$
$P_q=\Pi_i P_q(x_i)$: probability for $q\bar{q}$

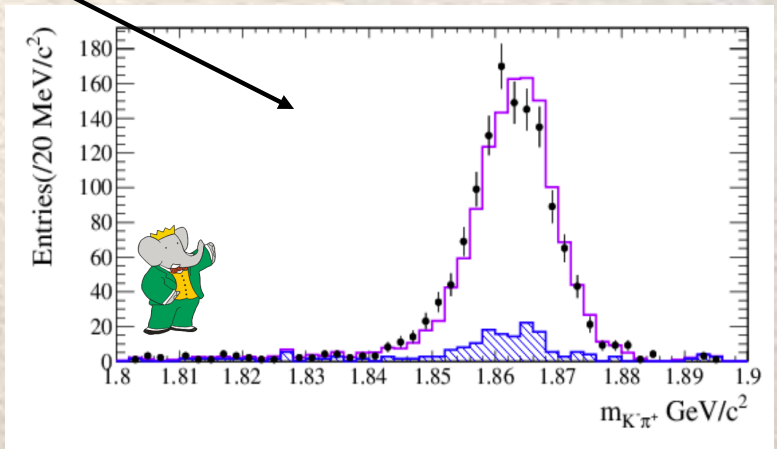
- Removes 75% of $q\bar{q}$ background while retaining 80% of $B\bar{B}$ (signal+background) events

Final Selection and Results

- Define another MLP NN using 8 event shape variables to reduce $B\bar{B}$ bkg
- Select MLP > 0.7 (0.75) for e^+e^-, $\mu^+\mu^-$ ($e\mu$)
- Remaining peaking backgrounds: 84% (correct B-tag, m_{ES} peaks at right mass)
- Cross check of B_{tag} signal with $B^+ \to D^0 \ell^+ \nu_\ell$ ($D^0 \to K^-\pi^+$) before MLP output requirement ➔ good agreement
- Systematic uncertainties:
  - PID: e^+e^-: 5%, $\mu^+\mu^-$: 7%, $e\mu$: 5%
  - π^0 veto: 3%
  - MLP NN: 2.6%
  - B_{tag}: efficiency 1.2%, background estimate 1.6%
  - Theory~3%
- Observed yield: 176±13 events
- Set branching fraction upper limit

$$\mathcal{B}\left(B^+ \to K^+\tau^+\tau^-\right) = 2.25\times10^{-3} \text{ @90\% CL}$$





	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

Conclusions

- We measured the angular distributions of $B^+ \to K^{*+} \ell^+ \ell^-$ and $B^0 \to K^{*0} \ell^+ \ell^-$ extracting $\mathcal{F}_L(q^2)$, $\mathcal{A}_{FB}(q^2)$ and P_2 in five disjoint bins of q^2 and $q^2{}_0$
  - $\mathcal{F}_L(q^2)$ for K^{*+} shows larger deviations from the SM prediction than that for K^{*0}
  - For K^* combination, $\mathcal{F}_L(q^2)$ deviates from the SM prediction in bins $q^2{}_2$ ($\geq 3\sigma$) and $q^2{}_3$ ($\geq 2\sigma$)
  - For K^* combination, $\mathcal{A}_{FB}(q^2)$ deviates from the SM prediction in bin $q^2{}_2$ ($\geq 2\sigma$)
  - For K^* combination, P_2 deviates from the SM prediction in bin $q^2{}_2$ ($\geq 2\sigma$)

- World averages for $\mathcal{F}_L(q^2)$ and $\mathcal{A}_{FB}(q^2)$ do not show large deviations from the SM predictions

- We searched for $B^+ \to K^+ \tau^+ \tau^-$ and set a branching fraction upper limit of

$$\mathcal{B}\left(B^+ \to K^+ \tau^+ \tau^-\right) = 2.25 \times 10^{-3} \text{ @90\% CL}$$

Backup Slides

Systematic Errors for $B \to K^* \ell^+ \ell^-$

	F_L systematic			$\mathcal{A}_{FB}$ systematic		
	$B^+ \to K^{*+}\ell^+\ell^-$	$B^0 \to K^{*0}\ell^+\ell^-$	$B \to K^*\ell^+\ell^-$	$B^+ \to K^{*+}\ell^+\ell^-$	$B^0 \to K^{*0}\ell^+\ell^-$	$B \to K^*\ell^+\ell^-$
q_0^2	$+0.02\ -0.10$	$+0.02\ -0.02$	$+0.02\ -0.02$	$+0.08\ -0.05$	$+0.06\ -0.05$	$+0.07\ -0.09$
q_1^2	$+0.09\ -0.14$	$+0.15\ -0.02$	$+0.13\ -0.05$	$+0.13\ -0.16$	$+0.10\ -0.21$	$+0.08\ -0.19$
q_2^2	$+0.18\ -0.10$	$+0.02\ -0.10$	$+0.02\ -0.02$	$+0.36\ -0.49$	$+0.12\ -0.11$	$+0.14\ -0.11$
q_3^2	$+0.05\ -0.08$	$+0.05\ -0.05$	$+0.05\ -0.07$	$+0.08\ -0.20$	$+0.08\ -0.08$	$+0.08\ -0.05$
q_4^2	$+0.16\ -0.15$	$+0.06\ -0.06$	$+0.07\ -0.10$	$+0.11\ -0.24$	$+0.17\ -0.16$	$+0.14\ -0.13$
q_5^2	$+0.10\ -0.21$	$+0.02\ -0.11$	$+0.07\ -0.14$	$+0.18\ -0.17$	$+0.10\ -0.10$	$+0.10\ -0.12$

	$B^+ \to K^{*+}\ell^+\ell^-$	$B^0 \to K^{*0}\ell^+\ell^-$	$B \to K^*\ell^+\ell^-$
q_0^2	$-0.22^{+0.14}_{-0.13}$	$-0.07^{+0.20}_{-0.21}$	$-0.18^{+0.13}_{-0.13}$
q_1^2	$-0.29^{+0.19}_{-0.17}$	$+0.12^{+0.27}_{-0.29}$	$-0.09^{+0.18}_{-0.17}$
q_2^2	$-0.38^{+0.35}_{-0.28}$	$-0.27^{+0.25}_{-0.24}$	$-0.35^{+0.19}_{-0.16}$
q_3^2	$-0.09^{+0.24}_{-0.21}$	$-0.22^{+0.27}_{-0.22}$	$-0.14^{+0.15}_{-0.13}$
q_4^2	$-0.15^{+0.28}_{-0.26}$	$-0.48^{+0.34}_{-0.27}$	$-0.42^{+0.26}_{-0.20}$
q_5^2	$-0.95^{+1.84}_{-0.96}$	$-0.37^{+0.28}_{-0.24}$	$-0.41^{+0.34}_{-0.21}$