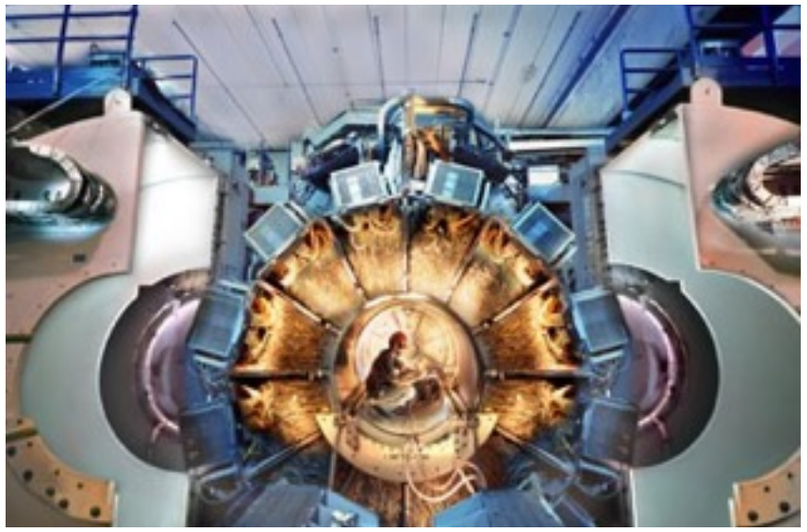
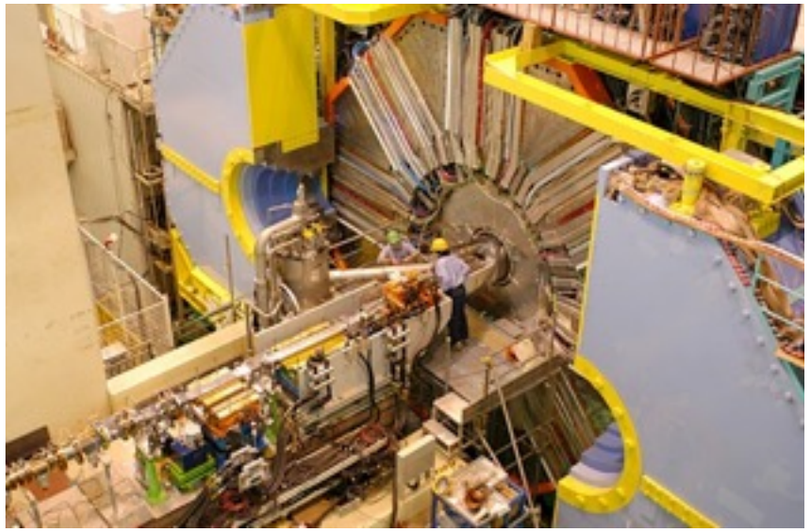
# EW and radiative penguin transitions from *B*-factories



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**BEAUTY 2016**

*Marseille, France, 02-06 Mai 2016*

# Outline

- **Physics motivations and experimental setups**
- **Angular analyses of $B \to K^* \ell^+ \ell^-$ decays:**
  - **PRD 93, 052015 (2016)**, arXiv:1508.07960 [hep-ex]
  - **Preliminary results**, arXiv:1604.04042 [hep-ex]
- **Searches for rare $b \to s\,\gamma(\ell\ell)$ processes:**
  - **Search for $B^0 \to \phi\,\gamma$ decays,** arXiv:1603.06546 [hep-ex]
  - **Search for $B^+ \to K^+ \tau^+ \tau^-$ decays,** preliminary results
- **Summary & conclusions**

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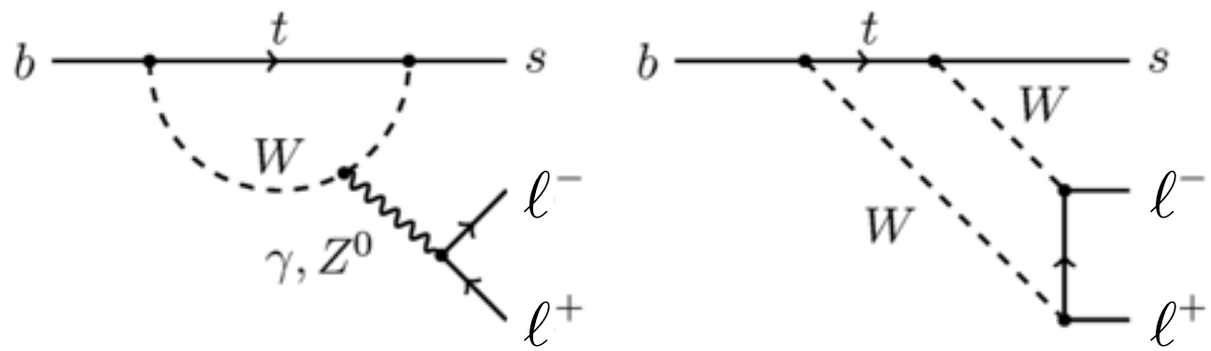
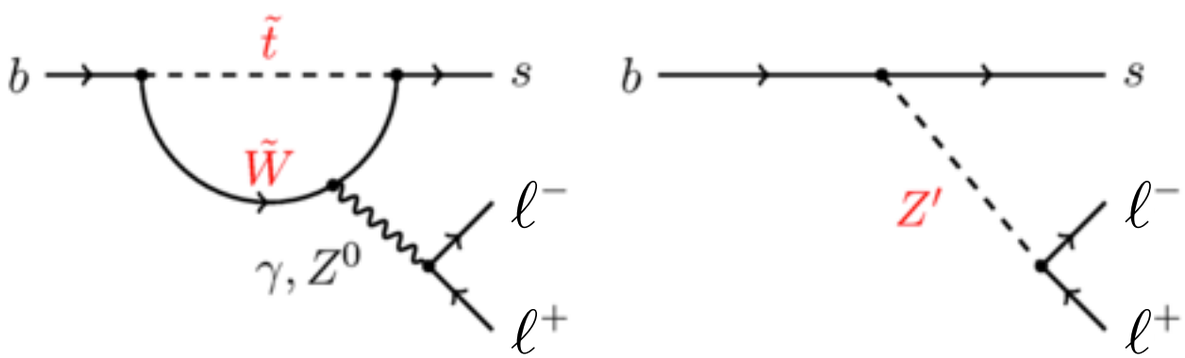
# Physics motivations and experimental setups

# Motivations

- **Since the early 70's we know that Flavour Changing Neutral Currents (FCNCs) are forbidden at tree level in the SM and only occur as loop-suppressed**




- **New heavy particles can contribute either at tree or loop-level**




- **Branching fractions or angular distributions can be altered**

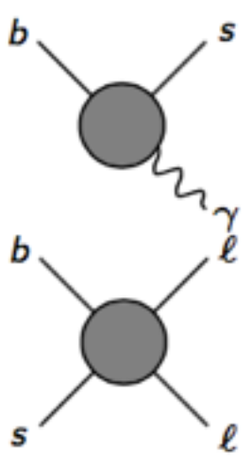
# Motivations

- **Model independent description in effective field theory**

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{tq}}^* \sum_i \underbrace{\mathcal{C}_i \mathcal{O}_i}_{\text{Left handed}} + \underbrace{\mathcal{C}_i' \mathcal{O}_i'}_{\text{Right handed, } \frac{m_s}{m_b} \text{ suppressed}} + \sum \frac{c}{\Lambda_{\text{NP}}^2} \mathcal{O}_{\text{NP}}$$

| | |
|---|---|
| $i = 1, 2$ | Tree |
| $i = 3 - 6, 8$ | Gluon penguin |
| $i = 7$ | Photon penguin |
| $i = 9, 10$ | EW penguin |
| $i = S, P$ | (Pseudo)scalar penguin |

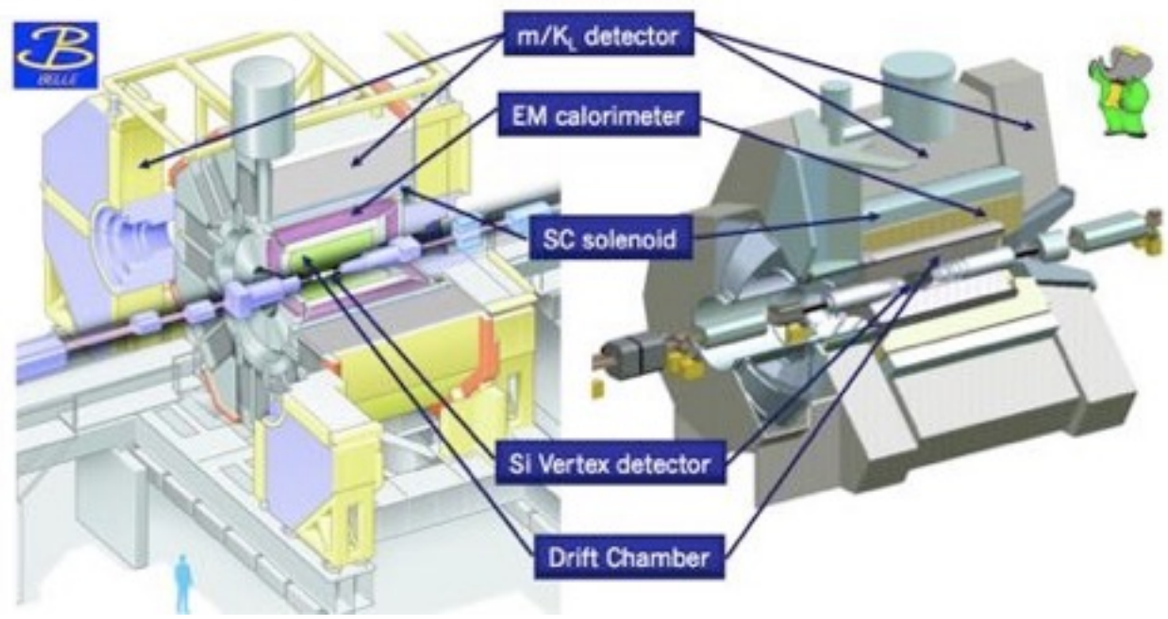
- **Wilson coefficients (WC) $C^{(\prime)}$ encode short-distance physics, $O^{(\prime)}$ corr. operators**

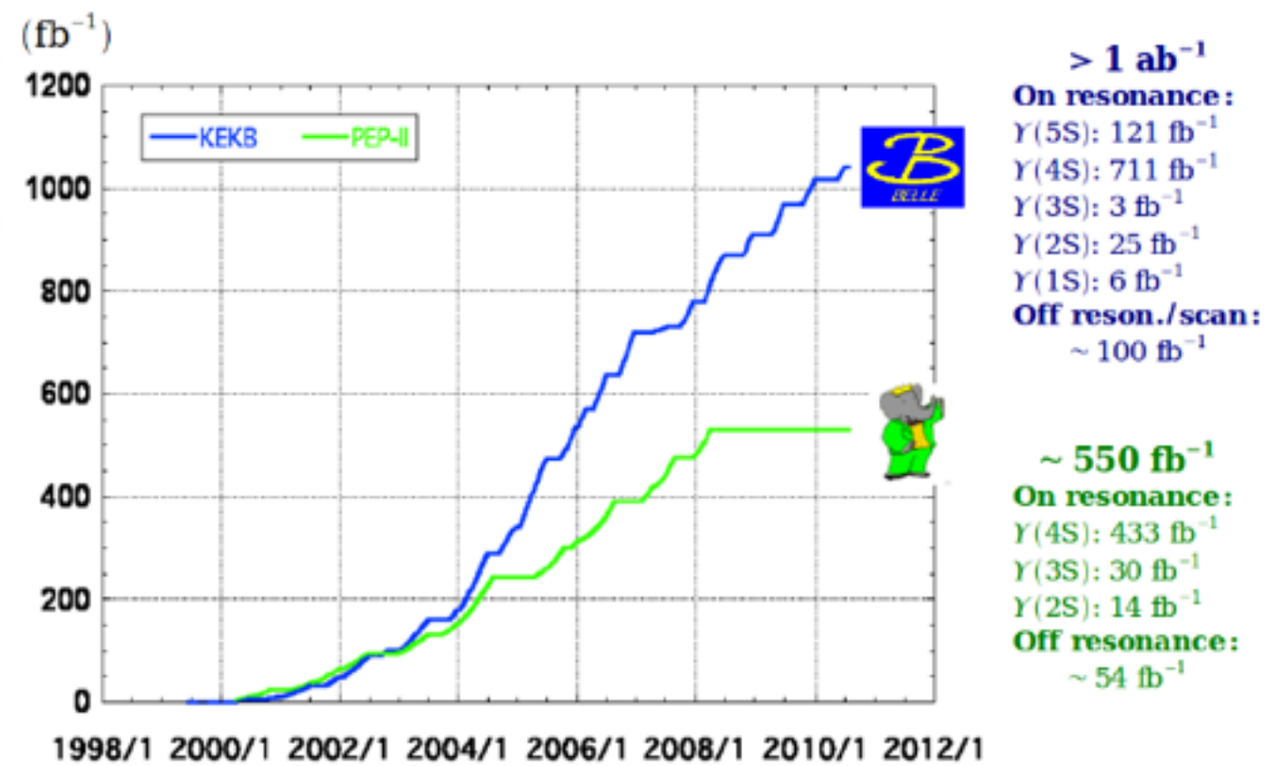


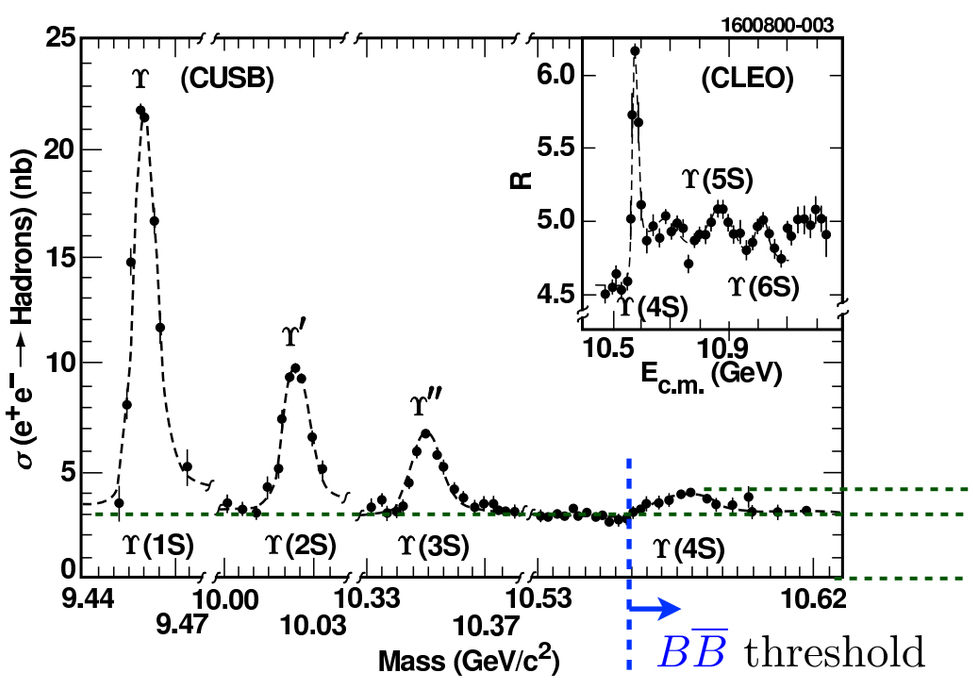

| | $b \to s\gamma$ | $b \to s\ell\ell$ |
|---|---|---|
| $\mathcal{O}_7^{(\prime)}$ photon penguin | ✓ | ✓ |
| $\mathcal{O}_9^{(\prime)}$ vector coupling | | ✓ |
| $\mathcal{O}_{10}^{(\prime)}$ axialvector coupling | | ✓ |

# Experimental setup

- **Extensive study of *B* mesons by the *B*-factories: 2000-2010**



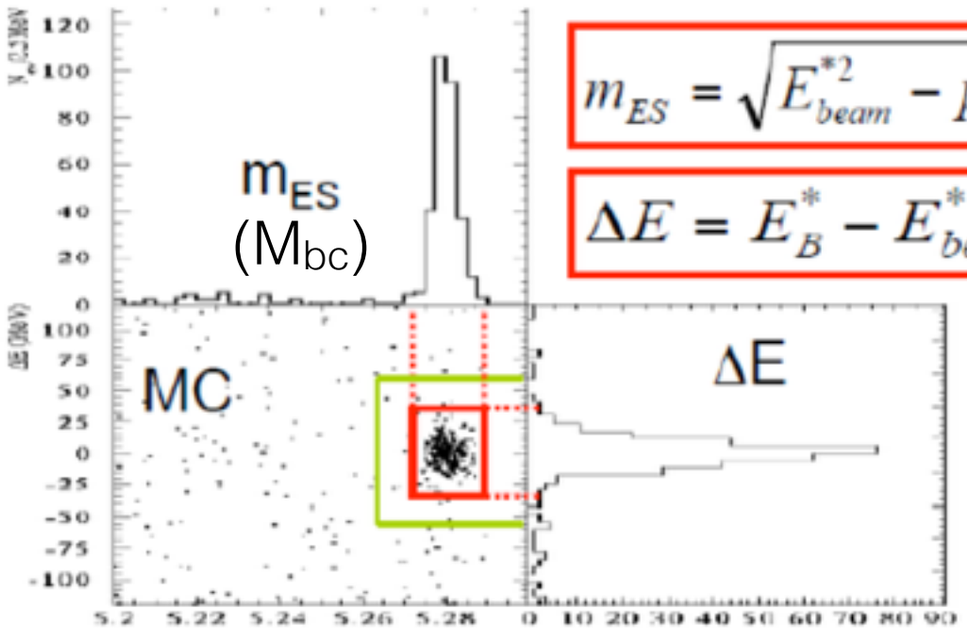




$$\frac{\sigma(b\bar{b})}{\sigma(\text{hadrons})} = 0.28$$

- **Mainly $B_u$ and $B_d$ produced (~770M + 470M $b\bar{b}$)**
- **Clean environment wrt hadronic machines**

# Common analysis techniques

## Kinematics of fully reconstructed B

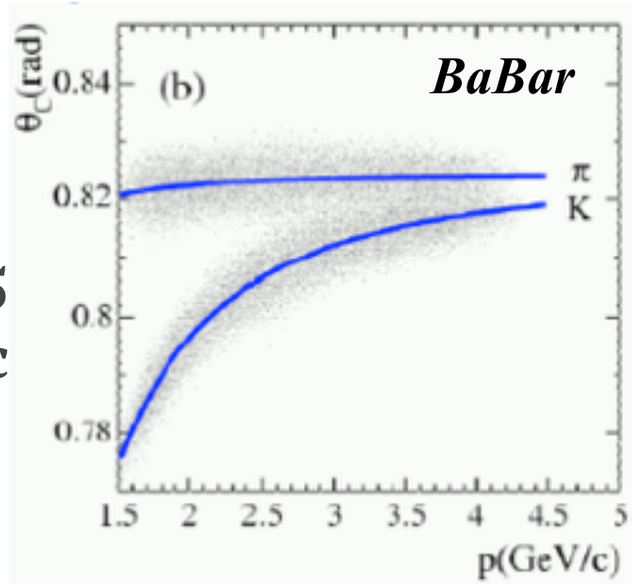



$$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$$

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

## K/π separation

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

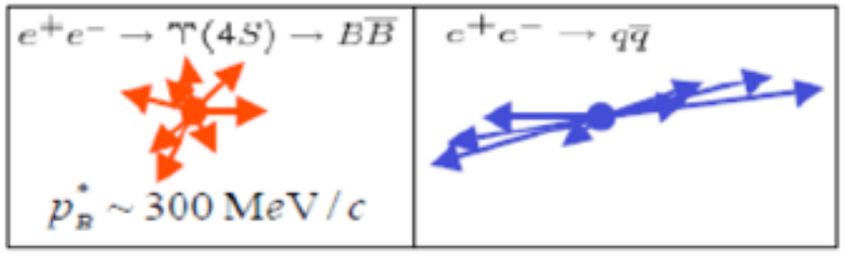



## Background discrimination

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

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

Topology:




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

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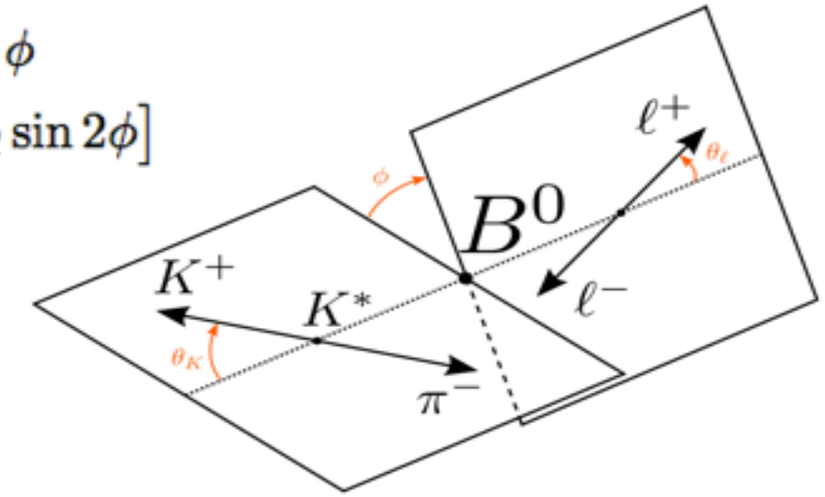
# Angular analyses of $B \to K^* \ell^+ \ell^-$ decays

# Angular analysis of $B \to K^* \ell^+ \ell^-$ decays

- **Decay fully described by three helicity angles $\Omega = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\ell\ell}$**

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$




Also for $B^+$ decays with $K^0_S$ or $\pi^0$

- Angular observables, $F_\mathrm{L}$, $A_\mathrm{FB}$, $S_i$ appearing in the full decay rate are combinations of $K^*$ amplitudes depending on WC $C_7^{(\prime)}$, $C_9^{(\prime)}$, $C_{10}^{(\prime)}$ and form factors (FF)
- Large part of theory uncertainty due to hadronic FF
- Introduced the $P_i^{(\prime)}$ observables, less dependent on FF:

$$P_2 = -\frac{2}{3}\frac{A_\mathrm{FB}}{(1-F_\mathrm{L})} \qquad P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}} \qquad P'_6 = \frac{S_7}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}$$

[*S. Descotes-Genon et al., JHEP, 05 (2013) 137*]

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# Angular analyses of $B \to K^* \ell^+ \ell^-$ decays

- **PRD 93, 052015 (2016)**
  **arXiv:1508.07960 [hep-ex]**
  **471 million $B\bar{B}$ pairs**

BABAR

NEW!

# Angular analysis of $B \to K^* \ell^+ \ell^-$ decays

PRD 93, 052015 (2016)

- **Analysis strategy:**
  - Very challenging: BF($B \to K^* \ell^+ \ell^-$) ~ $10^{-7}$
  - 5 exclusive final states:

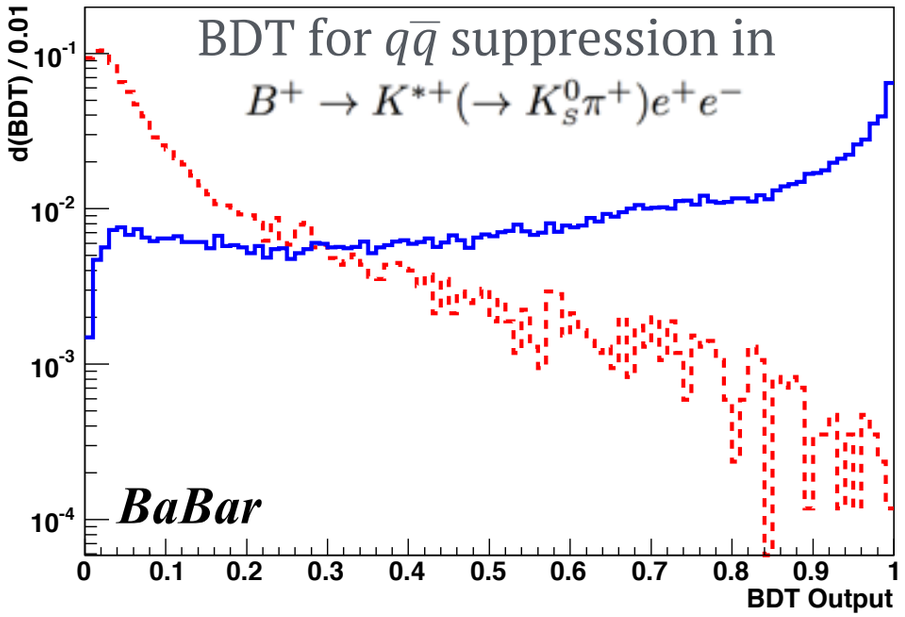
$$B^+ \to K^{*+}(\to K^+\pi^0)e^+e^-; \quad B^+ \to K^{*+}(\to K^0_S\pi^+)\mu^+\mu^-;$$

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

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

  - Analysis performed in 5+1 $q^2$ bins
  - Veto $J/\psi$ and $\psi(2S)$ and used as control samples
  - Build 8 separated Boosted Decision Trees (BDT) to suppress $B\bar{B}$ and $q\bar{q}$ backgrounds ($q\bar{q}$ BDT > 0.4)
  - Measures $F_L$, $A_{FB}$ and $P_2$ in each $q^2$ bin in a several stage LH fit (see next slides)
  - Ignore $m_{K\pi}$ S-wave component in the LH fit (negligible bias compared to other uncertainties)

| $q^2$ bin | $q^2$ min ($GeV^2/c^4$) | $q^2$ max ($GeV^2/c^4$) |
|---|---|---|
| $q_1^2$ | 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 |



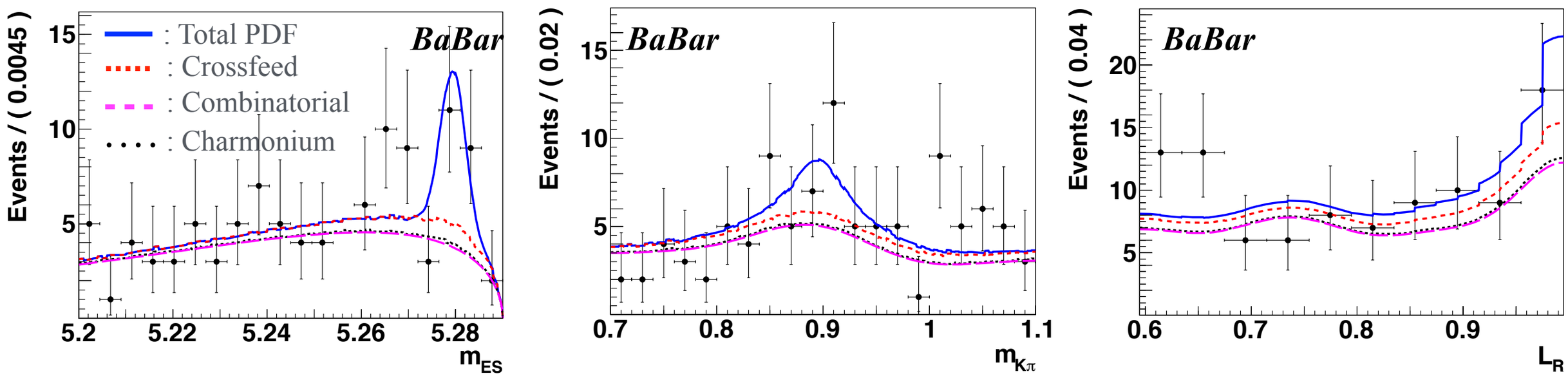
# Angular analysis of $B \to K^* \ell^+ \ell^-$ decays

PRD 93, 052015 (2016)

- **Fitting strategy:**
  - Include in the fit a likelihood ratio ($L_R$) built from $B\bar{B}$ BDTs
  - Measures $F_L$, $A_{FB}$ and $P_2$ in each $q^2$ bin in a several stage fit

    1. 3D fit to $m_{ES}$ (>5.20), $m_{K\pi}$ and $L_R$ $\Rightarrow$ PDF shapes and normalisations fixed for next steps

$$B^0 \to K^{*0}(\to K^+\pi^-)e^+e^- \text{ in } q_5^2$$




Overall fitted signal yields (statistical uncertainties only)

| Mode | $q_0^2$ | $q_1^2$ | $q_2^2$ | $q_3^2$ | $q_4^2$ | $q_5^2$ |
|---|---|---|---|---|---|---|
| $B \to K^* \ell^+ \ell^-$ | $40.8 \pm 8.4$ | $31.7 \pm 7.1$ | $11.9 \pm 5.5$ | $21.3 \pm 8.5$ | $31.9 \pm 9.2$ | $33.2 \pm 7.8$ |
| $B^+ \to K^{*+} \ell^+ \ell^-$ | $17.7 \pm 5.2$ | $8.7 \pm 4.1$ | $3.8 \pm 4.0$ | $7.7 \pm 5.6$ | $9.0 \pm 4.8$ | $9.4 \pm 4.2$ |
| $B^0 \to K^{*0} \ell^+ \ell^-$ | $23.1 \pm 6.6$ | $22.9 \pm 5.8$ | $8.1 \pm 3.8$ | $13.7 \pm 6.4$ | $22.8 \pm 7.8$ | $23.8 \pm 6.6$ |

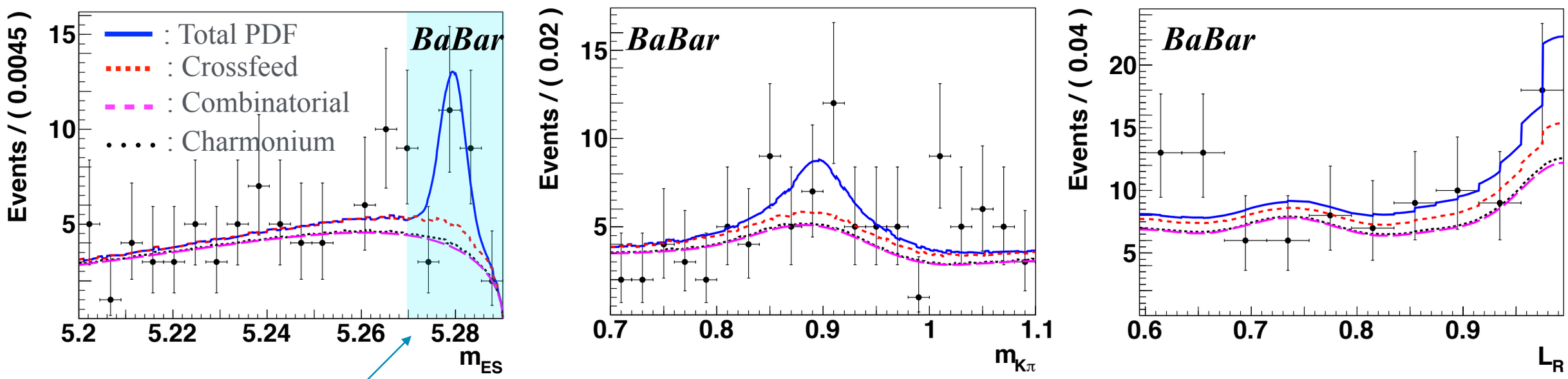
# Angular analysis of $B \to K^* \ell^+ \ell^-$ decays

PRD 93, 052015 (2016)

- **Fitting strategy:**
  - Include in the fit a likelihood ratio ($L_R$) built from $B\bar{B}$ BDTs
  - Measures $F_L$, $A_{FB}$ and $P_2$ in each $q^2$ bin in a several stage fit

    1. 3D fit to $m_{ES}$ (>5.20), $m_{K\pi}$ and $L_R$ $\Rightarrow$ PDF shapes and normalisations fixed for next steps

$$B^0 \to K^{*0}(\to K^+\pi^-)e^+e^- \text{ in } q_5^2$$




Angular fit region for next steps: $m_{ES}$ (>5.27)

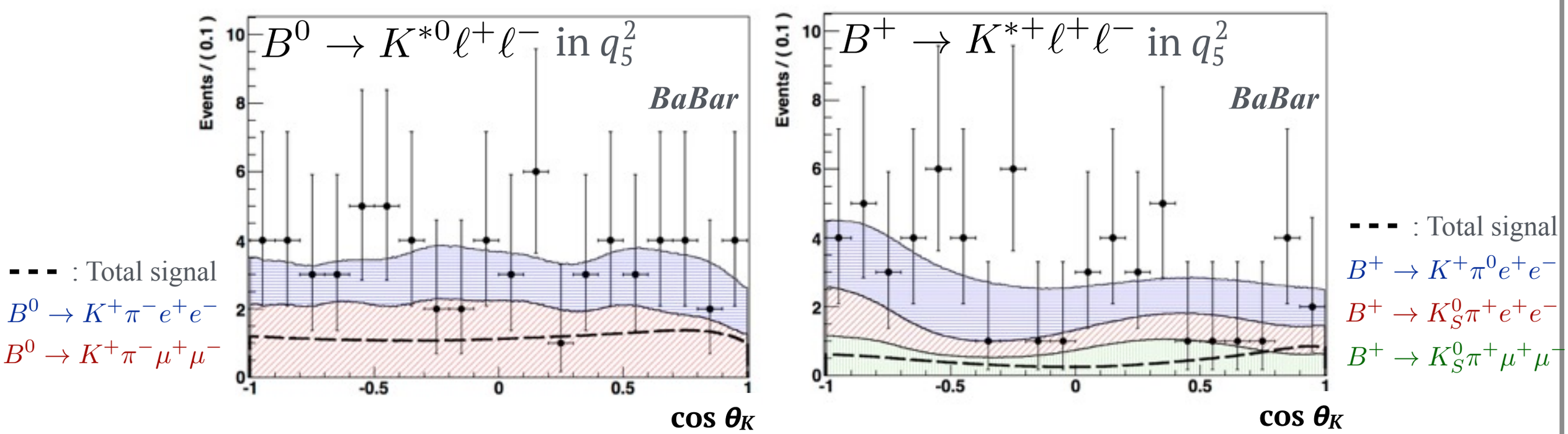
# Angular analysis of $B \to K^* \ell^+ \ell^-$ decays

PRD 93, 052015 (2016)

- **Fitting strategy:**
  - Include in the fit a likelihood ratio ($L_R$) built from $B\bar{B}$ BDTs
  - Measures $F_L$, $A_{FB}$ and $P_2$ in each $q^2$ bin in a several stage fit

    1. 3D fit to $m_{ES}$ (>5.20), $m_{K\pi}$ and $L_R \Rightarrow$ PDF shapes and normalisations fixed for next steps
    2. 4D fit to $m_{ES}$ (>5.27), $m_{K\pi}$, $L_R$ and $\cos\theta_K \Rightarrow$ measure $F_L$ as only free param.

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



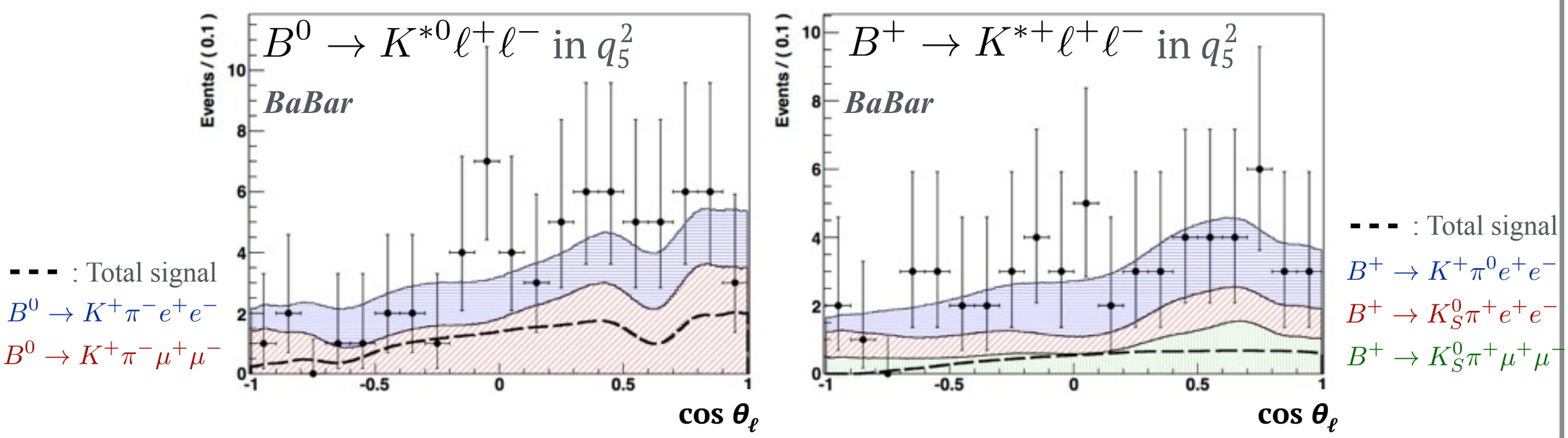
# Angular analysis of $B \to K^* \ell^+ \ell^-$ decays

PRD 93, 052015 (2016)

- **Fitting strategy:**
  - Include in the fit a likelihood ratio ($L_R$) built from $B\bar{B}$ BDTs
  - Measures $F_L$, $A_{FB}$ and $P_2$ in each $q^2$ bin in a several stage fit

1. 3D fit to $m_{ES}$ (>5.20), $m_{K\pi}$ and $L_R \Rightarrow$ PDF shapes and normalisations fixed for next steps
2. 4D fit to $m_{ES}$ (>5.27), $m_{K\pi}$, $L_R$ and $\cos\theta_K \Rightarrow$ measure $F_L$ as only free param.
3. 4D fit to $m_{ES}$ (>5.27), $m_{K\pi}$, $L_R$ and $\cos\theta_\ell \Rightarrow$ measure $A_{FB}$ as only free param. ($F_L$ from step 2)

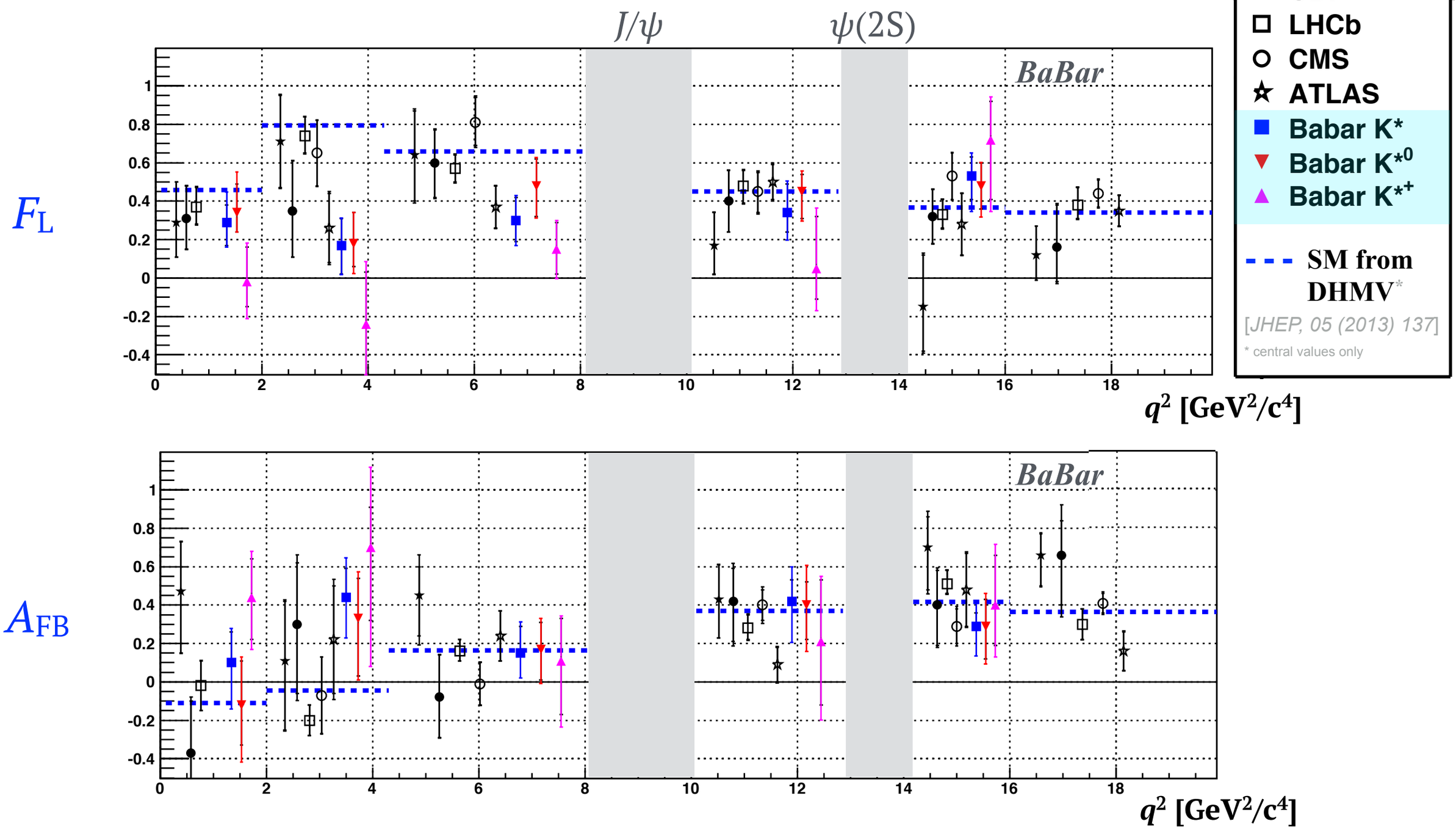
$$\frac{1}{\Gamma(q^2)}\frac{d\Gamma}{d(\cos\theta_\ell)} = \frac{3}{4}F_L(q^2)(1-\cos^2\theta_l)+\frac{3}{8}(1-F_L(q^2))(1+\cos^2\theta_l)+A_{FB}(q^2)\cos\theta_l$$



# Angular analysis of $B \to K^* \ell^+ \ell^-$ decays

PRD 93, 052015 (2016)

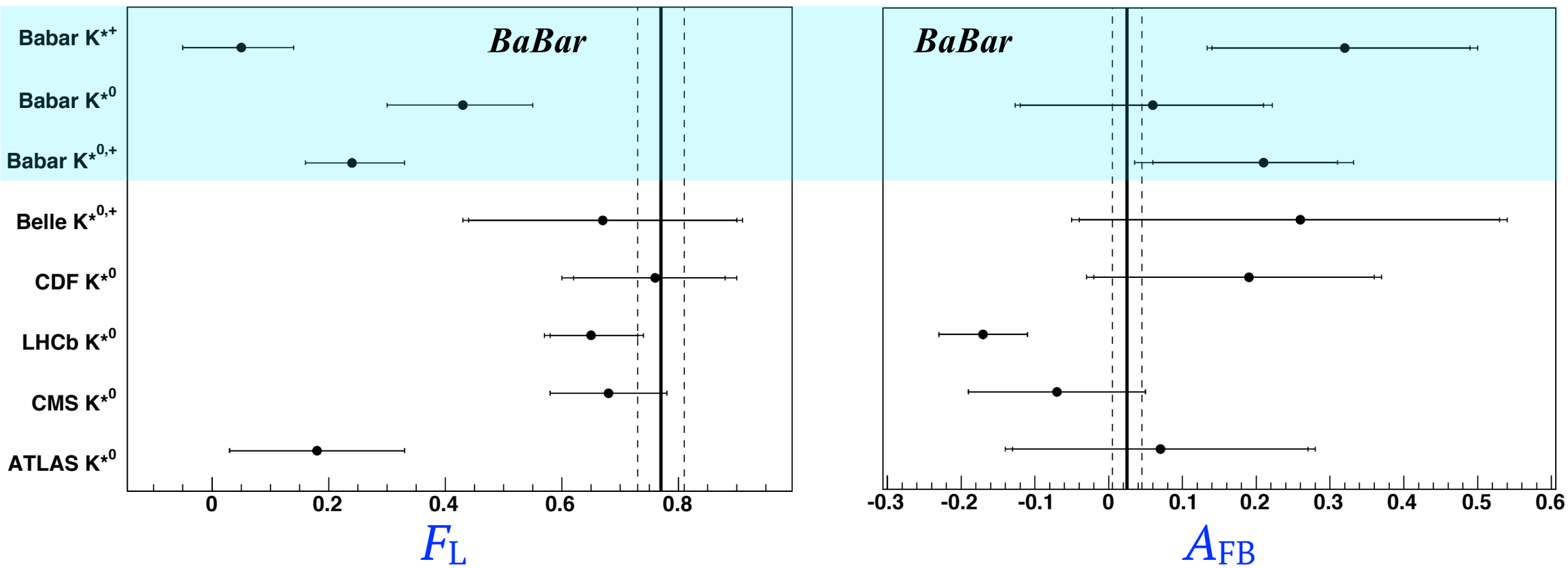
- **Angular fit results:** (numerical values in back up)



# Angular analysis of $B \to K^* \ell^+ \ell^-$ decays

PRD 93, 052015 (2016)

- **Angular fit results:** (numerical values in back up)
  - Results in the $q_0^2$ bin: [1, 6] GeV$^2$/c$^4$




  - **Tension appears in $F_L$ for the charged mode results (first measurement)** with both SM prediction and neutral mode result!
  - $A_{FB}$ in good agreement with previous results and SM predictions

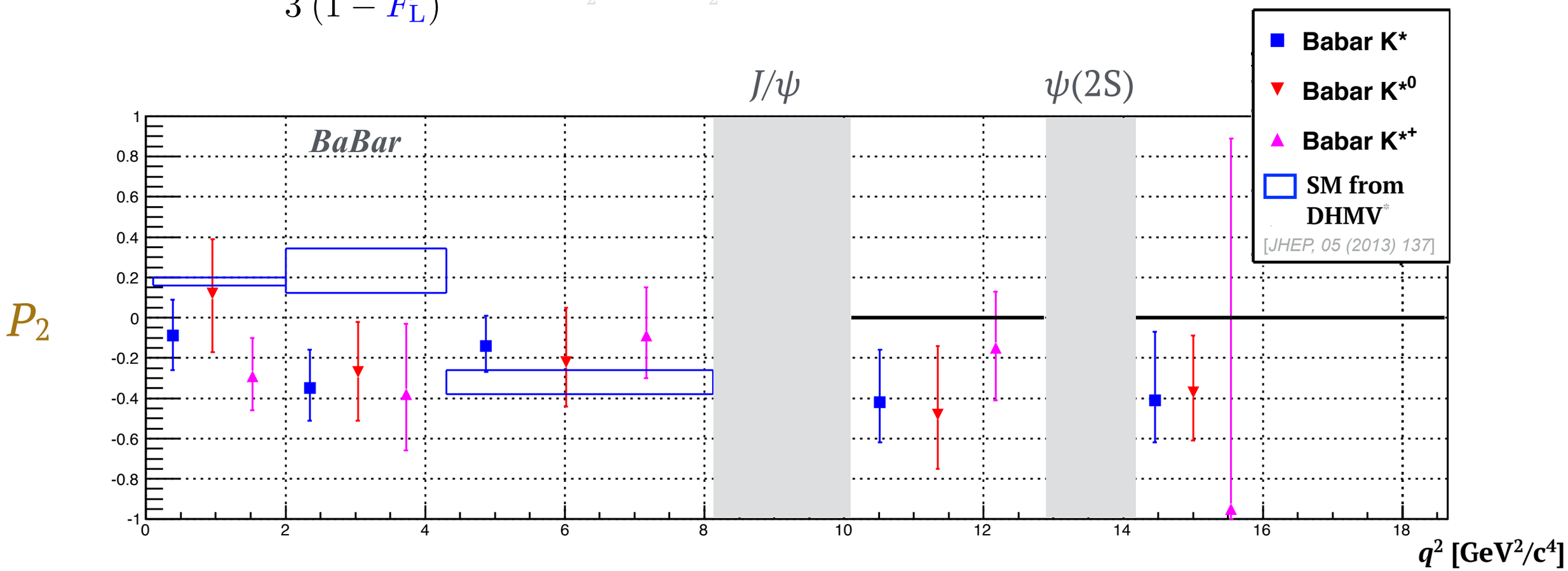
# Angular analysis of $B \to K^* \ell^+ \ell^-$ decays

PRD 93, 052015 (2016)

- **Angular fit results:** (numerical values in back up)

$$P_2 = -\frac{2}{3}\frac{A_{\rm FB}}{(1-F_{\rm L})}$$

$P_2^{\rm BaBar} = -P_2^{\rm LHCb}$




- **Global agreement with SM prediction with small tension in $q_2^2$**

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# Angular analyses of $B \to K^* \ell^+ \ell^-$ decays

- PRD 93, 052015 (2016)
  arXiv:1508.07960 [hep-ex]
- **Preliminary results**
  arXiv:1604.04042 [hep-ex]
  772 million $B\bar{B}$ pairs

BELLE

NEW!

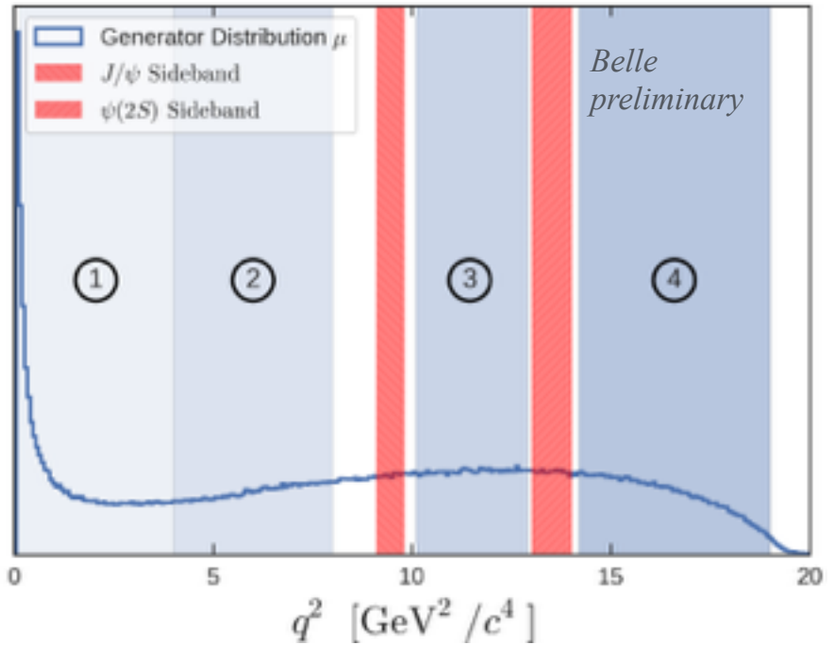
# Angular analysis of $B^0 \to K^{*0}\ell^+\ell^-$ decays

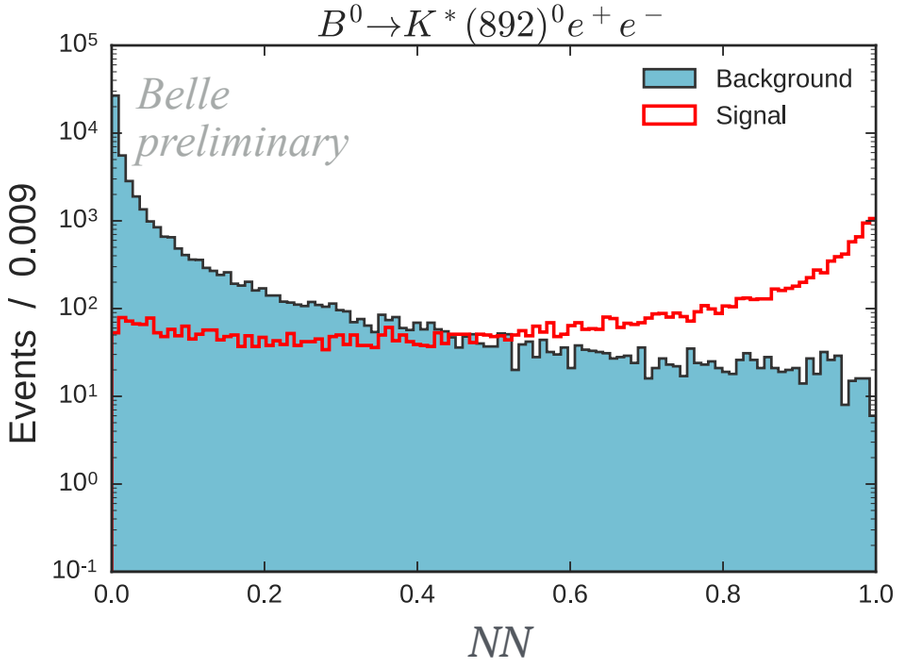
arXiv:1604.04042 [hep-ex]

- **Analysis strategy:**
  - Very challenging: BF($B \to K^*\ell^+\ell^-$) ~ $10^{-7}$
  - 2 exclusive final states:

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

    $B^0 \to K^{*0}(\to K^+\pi^-)e^+e^-.$
  - Analysis performed in 4+1 $q^2$ bins
  - Veto $J/\psi$ and $\psi(2S)$ and used as control samples
  - Build 2 separated NNs (one for each final state) to suppress $B\bar{B}$ and $q\bar{q}$ backgrounds
  - Adopted the folding method introduced by LHCb in 2013 [*Phys. Rev. Lett. 111, 191801 (2013)*]
  - Measures $F_L$, $S_3$ and $P'_{4,5,6,8}$ in each $q^2$ bin from a 3D angular fit (see next slides)



# Angular analysis of $B^0 \to K^{*0}\ell^+\ell^-$ decays

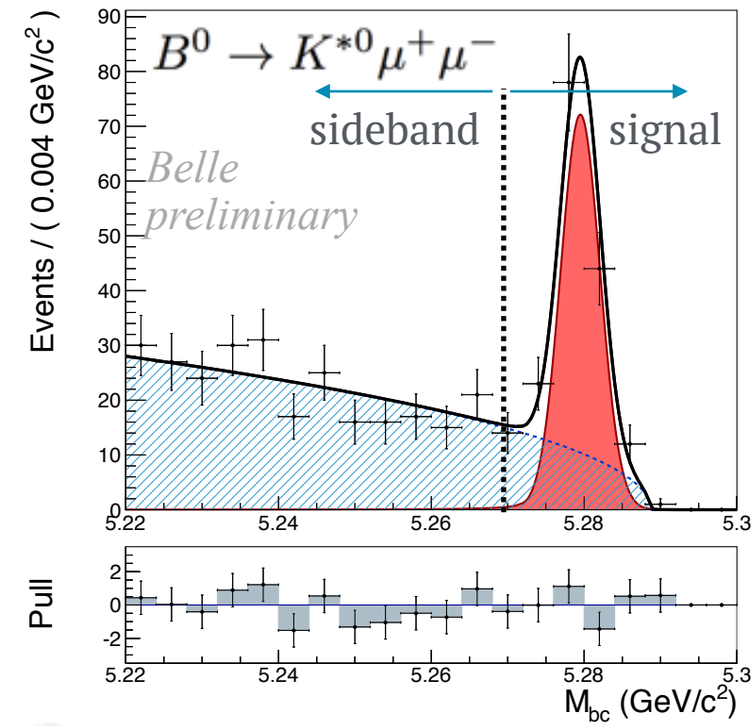
arXiv:1604.04042 [hep-ex]

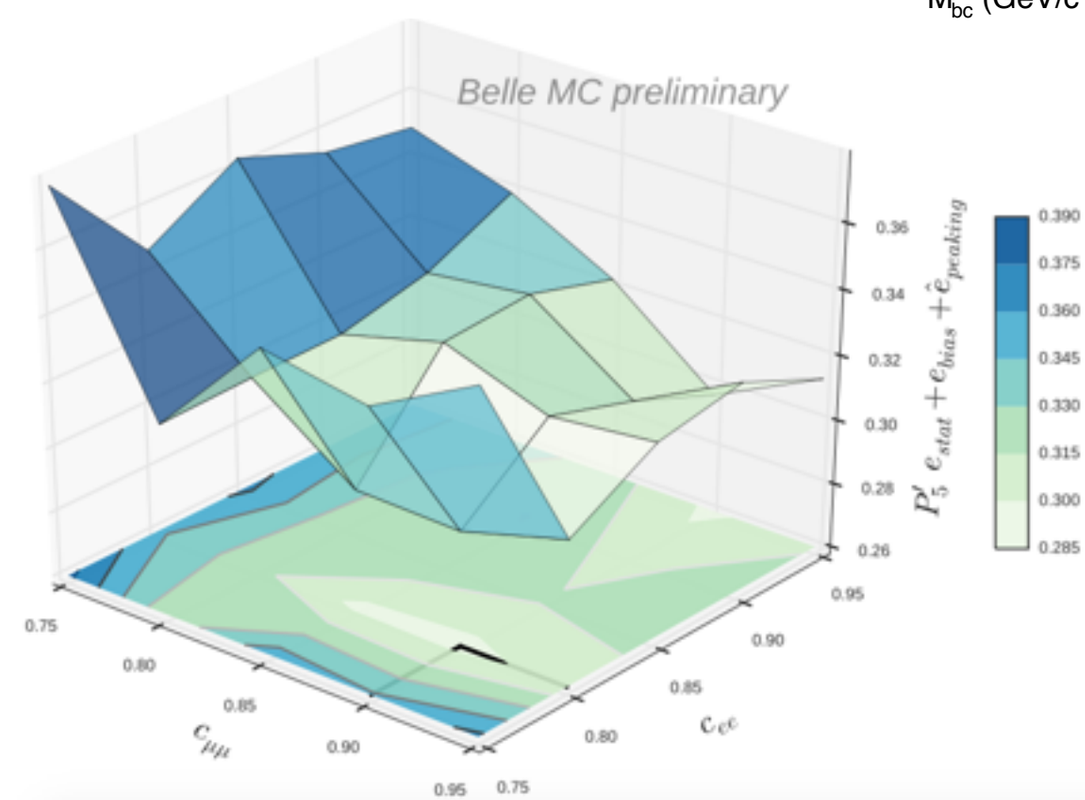
- **Fitting strategy:**
  - Signal identified from a fit to $M_{bc}$ (in the full range)

    $B^0 \to K^{*0}\mu^+\mu^- \Rightarrow$ 117.6 ± 12.4 signal candidates

    $B^0 \to K^{*0}e^+e^- \Rightarrow$ 69.4 ± 12.0 signal candidates

    $\Rightarrow$ signal to background ratio is determined
  - Use sideband ($M_{bc}$<5.27) to model background angular PDFs (histograms)
  - Acceptance and efficiency included as per-event weight in the fit (back-up)
  - Iterative procedure using toys with simulated events to optimize NNs as a function of $P_5'$ uncertainty in $q_2^2$
  - Thanks to folding method only 3 free parameters (instead of 8) in angular fit: independent measurements of $P'_{4,5,6,8}$ (details in back-up)



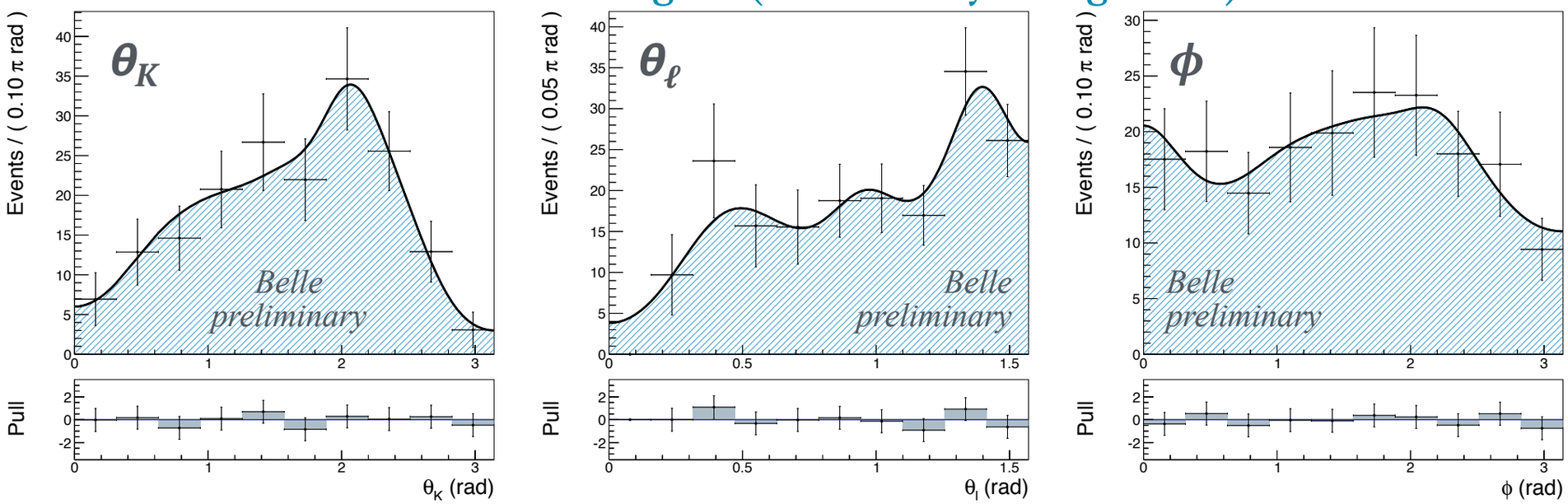



# Angular analysis of $B^0 \to K^{*0}\ell^+\ell^-$ decays

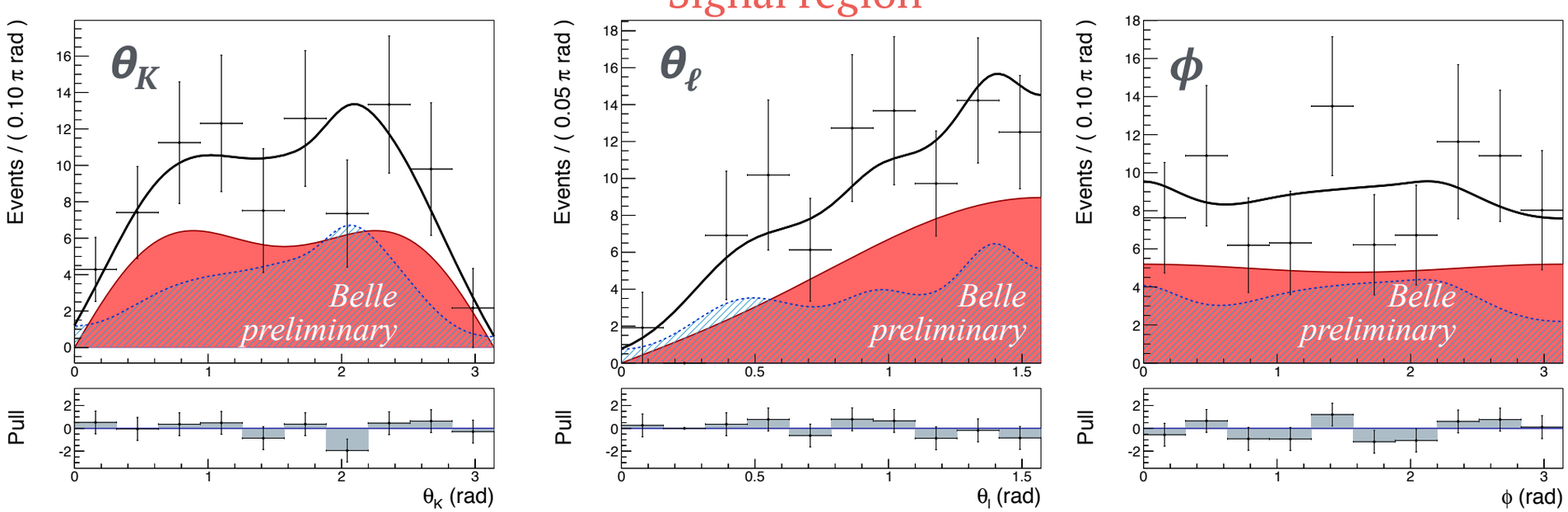
arXiv:1604.04042 [hep-ex]

- **Angular fit projections:** here $P_5'$ in $q_2^2$ as example

Sideband region (dominantly background)



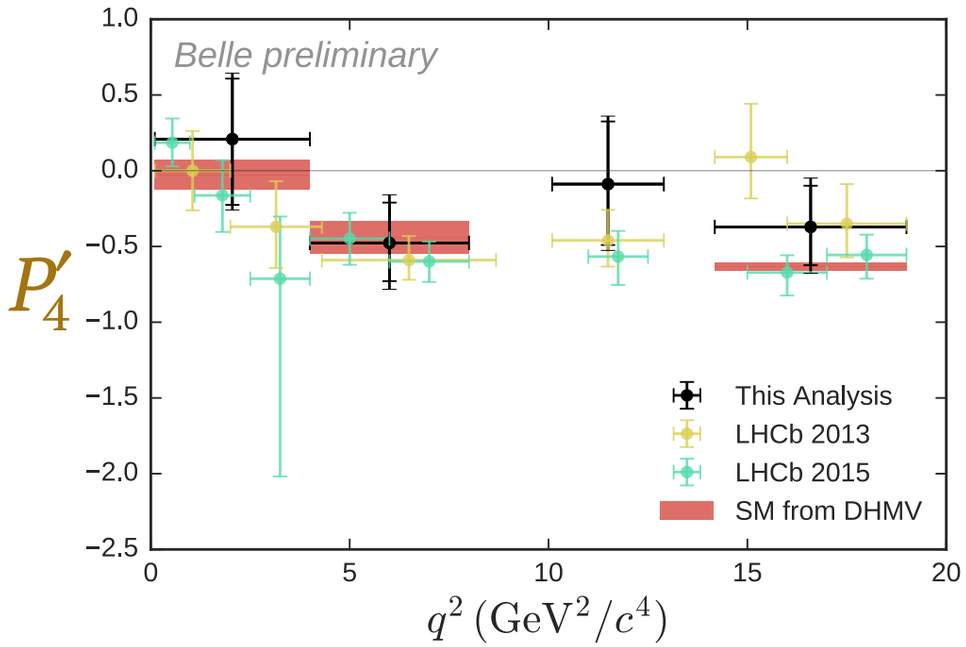

Signal region

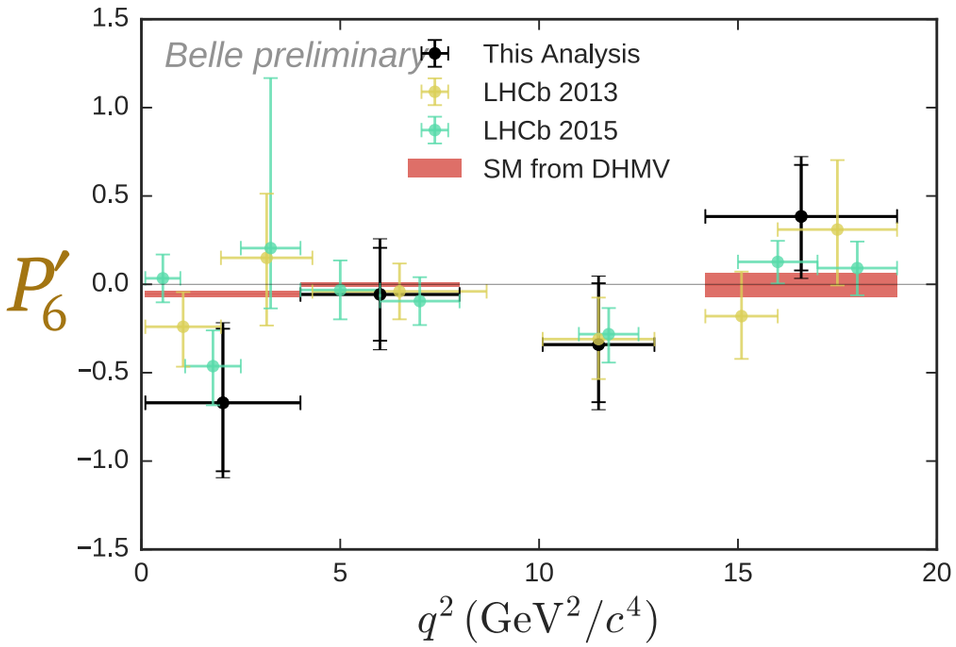


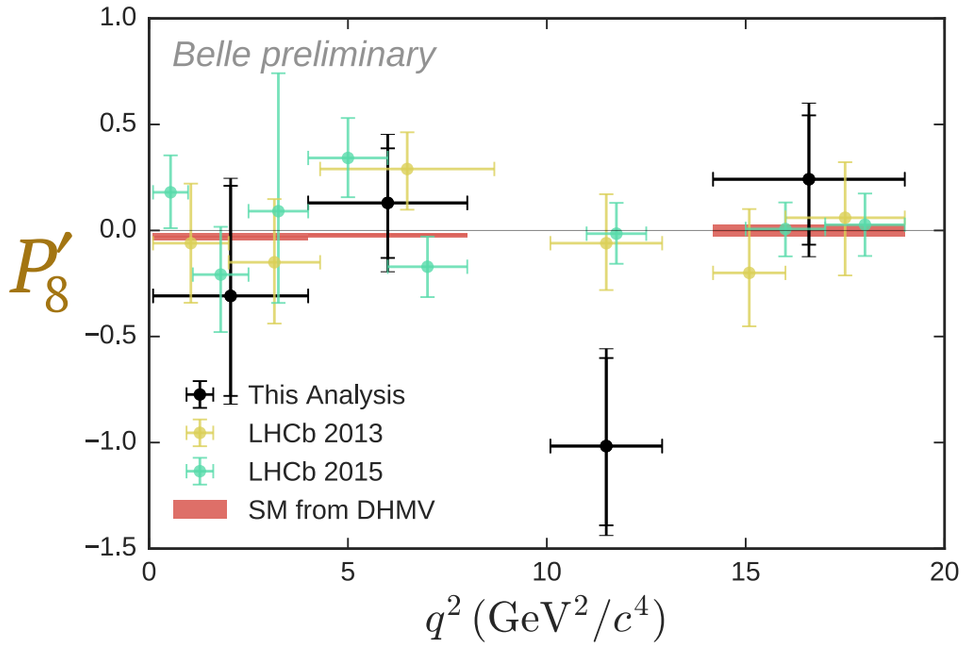
# Angular analysis of $B^0 \to K^{*0}\ell^+\ell^-$ decays

arXiv:1604.04042 [hep-ex]

- **Angular fit result:** (numerical values including $q_0^2$ in back up)



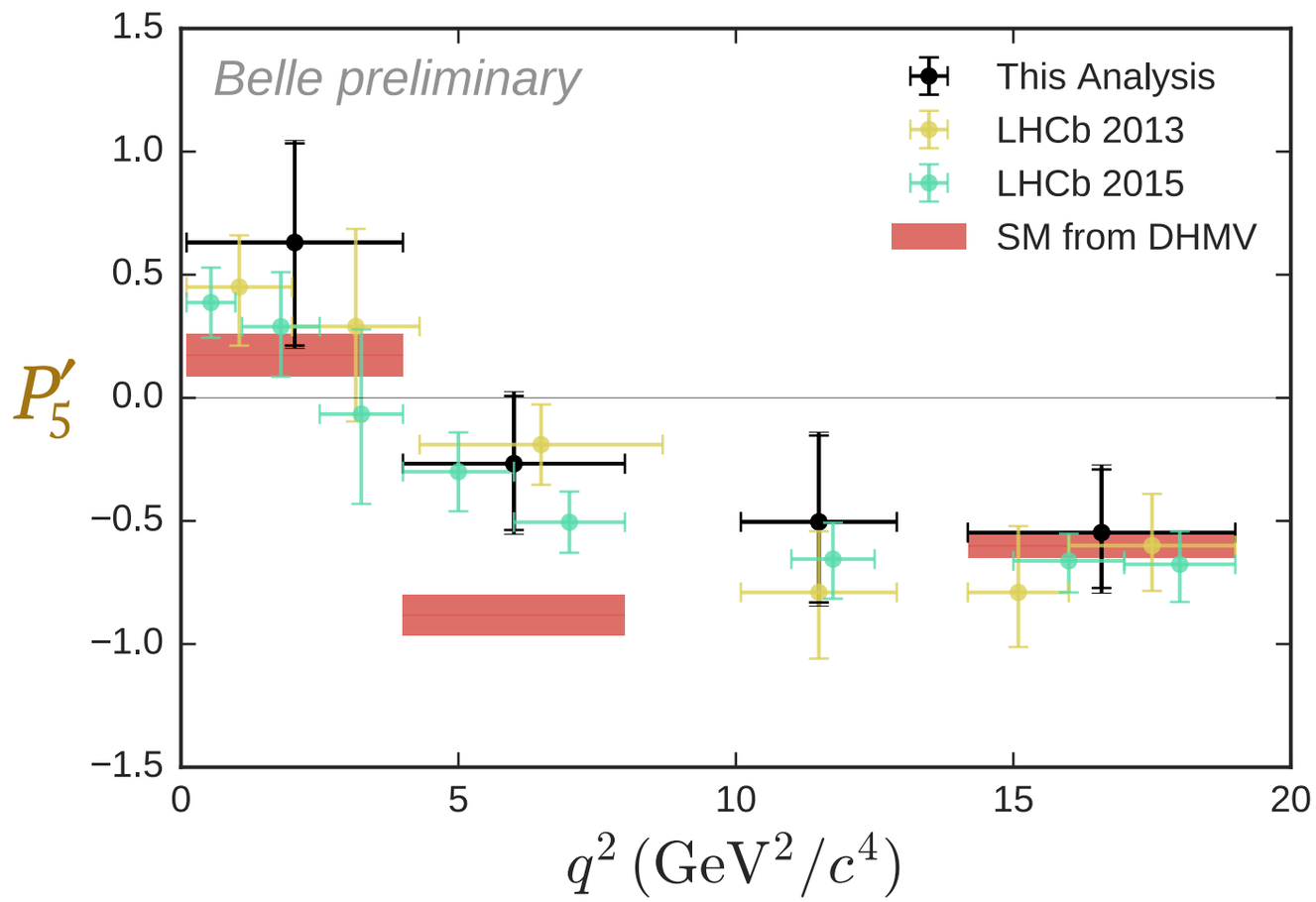



# Angular analysis of $B^0 \to K^{*0}\ell^+\ell^-$ decays

arXiv:1604.04042 [hep-ex]

- **Angular fit result:** (numerical values including $q_0^2$ in back up)




- **Good agreement between this measurements and LHCb previous results and compatible with SM prediction**
- **Confirmation of the tension (at the level of 2.1 $\sigma$) for $P_5'$ in the same direction and in the same $q^2$ region as LHCb!**

*Rear Window*, Alfred Hitchcock (1954)

# 3

# Searches for rare $b \to s\,\gamma(\ell\ell)$ processes

*Rear Window*, Alfred Hitchcock (1954)

3

# Searches for rare $b \to s\,\gamma(\ell\ell)$ processes

- **Search for $B^0 \to \phi\,\gamma$ decays**

  arXiv:1603.06546 [hep-ex]

  772 million $B\bar{B}$ pairs

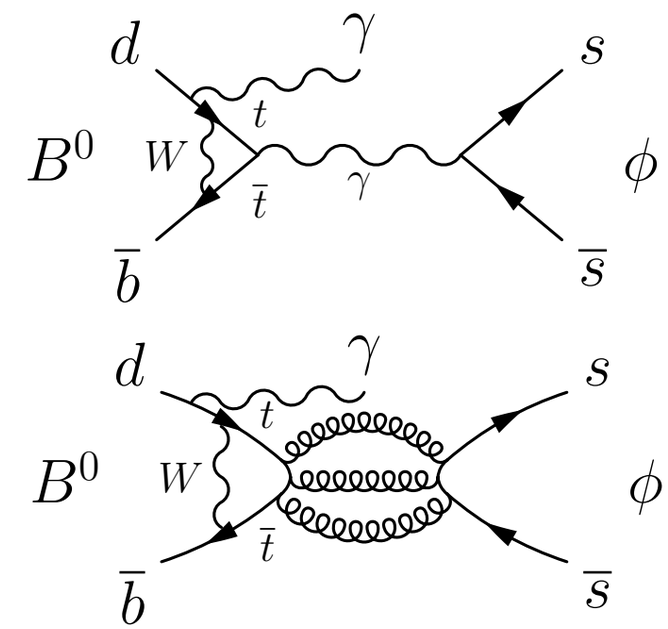
BELLE

NEW!

# Search for $B^0 \to \phi\,\gamma$ decays

arXiv:1603.06546 [hep-ex]

- **Analysis overview:**
  - Very rare decay: **BF($B^0 \to \phi\,\gamma$) ~ [$10^{-12}$, $10^{-11}$]**
  - Presence of new heavy particles such as charged Higgs or squarks could enhance the BF ∈ [$10^{-9}$ ; $10^{-8}$]
  - Current upper limit set by BaBar: BF($B^0 \to \phi\gamma$) < 8.5 × $10^{-7}$ (90% C.L.) [*PRD 72, 091103 (2005)*]




  - Require high energy photons: [2.0, 2.8] GeV/c in CM
  - Reject $\pi^0$ and $\eta$ using likelihoods based on the invariant mass
  - Background rejection from NN ($C'_{NN}$), with loose selection applied

  - Measures signal yield ($Y_{sig}$) from a 4D fit to $M_{bc}$, $\Delta E$, $C'_{NN}$ and $\cos\theta_\phi$

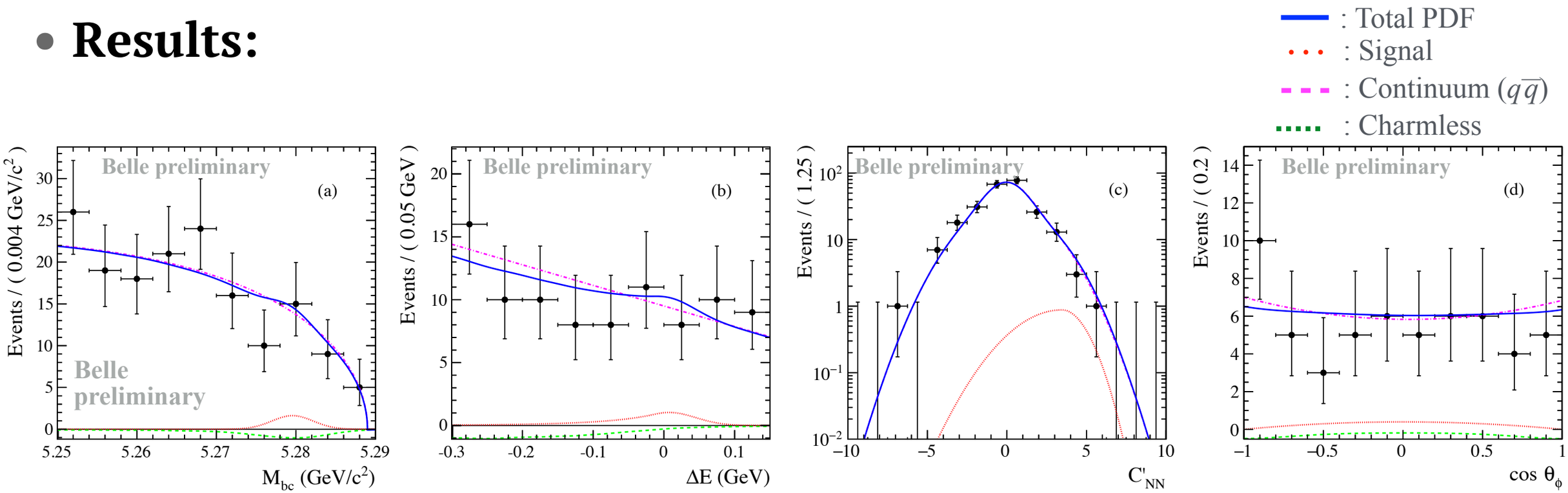
$$\mathcal{B}\left(B^0 \to \phi\gamma\right) = \frac{Y_{sig}}{N_{B\overline{B}} \cdot \varepsilon \cdot \mathcal{B}(\phi \to K^+K^-)}$$

(helicity angle $\theta_\phi$ is the angle between the $K^+$ momentum and the opposite of the B flight direction in the $\phi$ rest frame)

# Search for $B^0 \to \phi\,\gamma$ decays

arXiv:1603.06546 [hep-ex]

- **Results:**




- No significant signal found ⇒ placed an upper limit:

$$\mathrm{BF}(B^0 \to \phi\,\gamma) < 1.0 \times 10^{-7}\ (90\%\ \mathrm{C.L.})$$

- **Improves previous upper limit by one order of magnitude**

*Rear Window*, Alfred Hitchcock (1954)

3

# Searches for rare $b \to s\,\gamma(\ell\ell)$ processes

- Search for $B^0 \to \phi\,\gamma$ decays
  arXiv:1603.06546 [hep-ex]
  772 million $B\bar{B}$ pairs
- **Search for $B^+ \to K^+\tau^+\tau^-$ decays**
  preliminary results
  471 million $B\bar{B}$ pairs

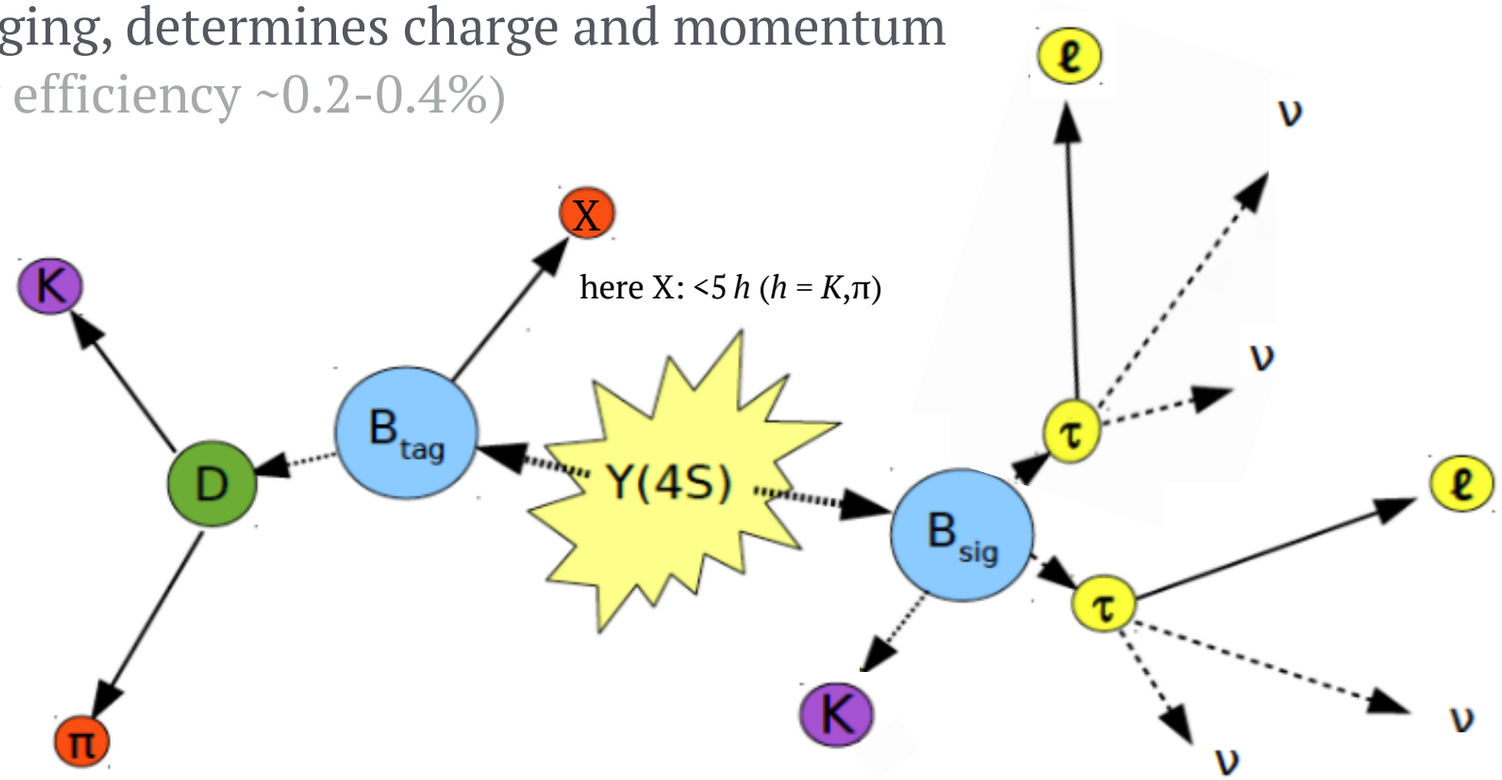
BABAR

NEW!

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

preliminary results

- **Analysis strategy:**
  - Rare decay: **BF($B^+ \to K^+\tau^+\tau^-$) ~ $10^{-7}$**, and experimentally **very challenging**
  - Presence of new heavy particles such as neutral Higgs with large coupling to third family could significantly alter the decay rate
  - Recent measurement of $R_K$ exhibit tensions with SM predictions $R_K \equiv \frac{\mathcal{B}(B \to K\mu\mu)}{\mathcal{B}(B \to Kee)}$
  - Use ***B* meson tagging technique** to handle weak signal signature:
    - Many neutrinos in the final state
    - Lack of kinematic constraints
    - Hadronic $B$ tagging, determines charge and momentum of signal $B$ (tag efficiency ~0.2-0.4%)



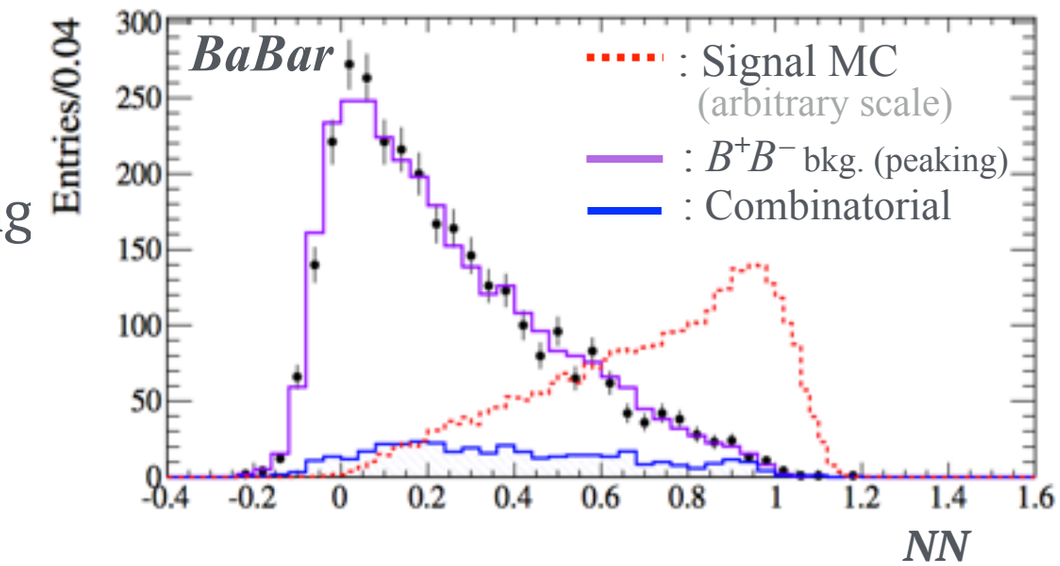
# Search for $B^+ \to K^+\tau^+\tau^-$ decays

preliminary results

- **Analysis strategy:**
  - Construct NN to suppress signal like topology $B^+ \to D^{(*)}\ell\bar{\nu}_\ell$ with $D^{(*)} \to K\ell\bar{\nu}_\ell$ events
  - Measure the branching fraction using a counting method:

$$\mathcal{B}_i = \frac{N^i_{\rm obs} - N^i_{\rm bkg}}{\epsilon^i_{\rm sig} N_{B\bar{B}}}$$

where $N^i_{\rm bkg}$ is obtained from MC




- **Results:**
  - No significant signal was found
  - Placed an upper limit:

| | $e^+e^-$ | $\mu^+\mu^-$ | $e^+\mu^-$ |
|---|---|---|---|
| $N^i_{\rm bkg}$ | 49.4±2.4±2.9 | 45.8±2.4 ±3.2 | 59.2±2.8 ±3.5 |
| $\epsilon^i_{\rm sig}(\times 10^{-5})$ | 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 ($\sigma$) | -0.6 | 0.9 | 3.7 |

**BF($B^+ \to K^+\tau^+\tau^-$) < 2.25 × $10^{-3}$ (90% C.L.)**

  - **First search for this challenging decay mode!**

*Calanque de Sugiton,* Marseille

# 4

# Summary and Conclusions

# Summary and conclusion

- ***B*-factories continue 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 in this talk are compatible with the SM predictions, with some tensions appearing in the angular analyses of $B \to K^* \ell^+ \ell^-$ decays:**
  - **Belle reports a 2.1 $\sigma$ deviation for $P_5'$ in $q_2^2$**
  - **BaBar measurement of $F_L$ for charged *B* decays**

- **Expect several new results in the coming years!**
  - **$B^+ \to K^{*+} \ell^+ \ell^-$ and $B^+ \to K^+ \tau^+ \tau^-$ at Belle**
  - **Belle II with 50 times more luminosity**

# Additional material

- **Angular analyses of $B \to K^* \ell^+ \ell^-$ decays:**
  - Go-To
  - Go-To
- **Searches for rare $b \to s\,\gamma(\ell\ell)$ processes:**
  - **Search for $B^0 \to \phi\,\gamma$ decays** Go-To
  - **Search for $B^+ \to K^+ \tau^+ \tau^-$ decays** Go-To

# Angular analysis of $B \to K^* \ell^+ \ell^-$ decays

PRD 93, 052015 (2016)

- **Numerical angular results:** (first stat. / second total syst.)

$F_L$

| | $B^+ \to K^{*+}\ell^+\ell^-$ | $B^0 \to K^{*0}\ell^+\ell^-$ | $B \to K^*\ell^+\ell^-$ |
|---|---|---|---|
| $q_0^2$ | $+0.05^{+0.09+0.02}_{-0.10-0.10}$ | $+0.43^{+0.12+0.02}_{-0.13-0.02}$ | $+0.24^{+0.09+0.02}_{-0.08-0.02}$ |
| $q_1^2$ | $-0.02^{+0.18+0.09}_{-0.13-0.14}$ | $+0.34^{+0.15+0.15}_{-0.10-0.02}$ | $+0.29^{+0.09+0.13}_{-0.12-0.05}$ |
| $q_2^2$ | $-0.24^{+0.27+0.18}_{-0.39-0.10}$ | $+0.18^{+0.16+0.02}_{-0.12-0.10}$ | $+0.17^{+0.14+0.02}_{-0.15-0.02}$ |
| $q_3^2$ | $+0.15^{+0.14+0.05}_{-0.13-0.08}$ | $+0.48^{+0.14+0.05}_{-0.16-0.05}$ | $+0.30^{+0.12+0.05}_{-0.11-0.07}$ |
| $q_4^2$ | $+0.05^{+0.27+0.16}_{-0.16-0.15}$ | $+0.45^{+0.09+0.06}_{-0.14-0.06}$ | $+0.34^{+0.15+0.07}_{-0.10-0.10}$ |
| $q_5^2$ | $+0.72^{+0.20+0.10}_{-0.31-0.21}$ | $+0.48^{+0.12+0.02}_{-0.12-0.11}$ | $+0.53^{+0.10+0.07}_{-0.12-0.14}$ |

$A_{FB}$

| | $B^+ \to K^{*+}\ell^+\ell^-$ | $B^0 \to K^{*0}\ell^+\ell^-$ | $B \to K^*\ell^+\ell^-$ |
|---|---|---|---|
| $q_0^2$ | $+0.32^{+0.18+0.08}_{-0.18-0.05}$ | $+0.06^{+0.15+0.06}_{-0.18-0.05}$ | $+0.21^{+0.10+0.07}_{-0.15-0.09}$ |
| $q_1^2$ | $+0.44^{+0.20+0.13}_{-0.22-0.16}$ | $-0.12^{+0.23+0.10}_{-0.21-0.21}$ | $+0.10^{+0.16+0.08}_{-0.15-0.19}$ |
| $q_2^2$ | $+0.70^{+0.21+0.36}_{-0.38-0.49}$ | $+0.33^{+0.21+0.12}_{-0.30-0.11}$ | $+0.44^{+0.15+0.14}_{-0.18-0.11}$ |
| $q_3^2$ | $+0.11^{+0.22+0.08}_{-0.28-0.20}$ | $+0.17^{+0.14+0.08}_{-0.16-0.08}$ | $+0.15^{+0.14+0.08}_{-0.12-0.05}$ |
| $q_4^2$ | $+0.21^{+0.32+0.11}_{-0.33-0.24}$ | $+0.40^{+0.12+0.17}_{-0.18-0.16}$ | $+0.42^{+0.11+0.14}_{-0.17-0.13}$ |
| $q_5^2$ | $+0.40^{+0.26+0.18}_{-0.21-0.17}$ | $+0.29^{+0.14+0.10}_{-0.17-0.10}$ | $+0.29^{+0.07+0.10}_{-0.10-0.12}$ |

# Angular analysis of $B \to K^* \ell^+ \ell^-$ decays

PRD 93, 052015 (2016)

- **Numerical angular results:** (total uncertainties)

$P_2$

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

# Angular analysis of $B \to K^* \ell^+ \ell^-$ decays

PRD 93, 052015 (2016)

- **Systematics on angular results:** from 3D fit

| | $F_L$ systematic | | | $\mathcal{A}_{FB}$ systematic | | |
|---|---|---|---|---|---|---|
| | $B^+ \to K^{*+}\ell^+\ell^-$ | $B^0 \to K^{*0}\ell^+\ell^-$ | $B \to K^*\ell^+\ell^-$ | $B^+ \to K^{*+}\ell^+\ell^-$ | $B^0 \to K^{*0}\ell^+\ell^-$ | $B \to K^*\ell^+\ell^-$ |
| $q_0^2$ | $+0.02\ -0.09$ | $+0.02\ -0.02$ | $+0.02\ -0.02$ | $+0.05\ -0.04$ | $+0.01\ -0.04$ | $+0.02\ -0.07$ |
| $q_1^2$ | $+0.09\ -0.13$ | $+0.02\ -0.02$ | $+0.02\ -0.05$ | $+0.12\ -0.08$ | $+0.07\ -0.02$ | $+0.07\ -0.08$ |
| $q_2^2$ | $+0.18\ -0.05$ | $+0.02\ -0.01$ | $+0.02\ -0.02$ | $+0.34\ -0.48$ | $-0.02\ -0.08$ | $+0.09\ -0.07$ |
| $q_3^2$ | $+0.05\ -0.07$ | $+0.02\ -0.02$ | $+0.05\ -0.06$ | $+0.02\ -0.19$ | $-0.02\ -0.04$ | $+0.01\ -0.02$ |
| $q_4^2$ | $+0.11\ -0.14$ | $+0.02\ -0.06$ | $+0.02\ -0.10$ | $+0.09\ -0.23$ | $+0.15\ -0.11$ | $+0.13\ -0.10$ |
| $q_5^2$ | $+0.02\ -0.19$ | $+0.02\ -0.10$ | $+0.02\ -0.14$ | $+0.16\ -0.09$ | $+0.05\ -0.02$ | $+0.08\ -0.02$ |

# Angular analysis of $B \to K^* \ell^+ \ell^-$ decays

PRD 93, 052015 (2016)

- **Systematics on angular results:** from combinatorial bkg. modeling

| | $F_L$ systematic | | | | | | $\mathcal{A}_{FB}$ systematic | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $B^+ \to K^{*+}\ell^+\ell^-$ | | $B^0 \to K^{*0}\ell^+\ell^-$ | | $B \to K^*\ell^+\ell^-$ | | $B^+ \to K^{*+}\ell^+\ell^-$ | | $B^0 \to K^{*0}\ell^+\ell^-$ | | $B \to K^*\ell^+\ell^-$ | |
| $q_0^2$ | — | −0.05 | — | — | — | — | +0.04 | — | — | — | — | −0.04 |
| $q_1^2$ | +0.02 | −0.02 | — | — | — | — | +0.05 | — | — | — | — | — |
| $q_2^2$ | — | −0.05 | — | — | — | — | — | −0.07 | — | −0.04 | — | — |
| $q_3^2$ | — | — | — | — | — | — | — | — | — | — | — | — |
| $q_4^2$ | +0.10 | — | — | — | — | — | — | −0.04 | — | — | — | — |
| $q_5^2$ | — | −0.10 | — | −0.05 | — | — | +0.04 | −0.08 | +0.04 | — | — | — |

# Angular analysis of $B \to K^* \ell^+ \ell^-$ decays

PRD 93, 052015 (2016)

- **Systematics on angular results:** from angular efficiencies

| | $F_L$ systematic | | | | | | $\mathcal{A}_{FB}$ systematic | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $B^+ \to K^{*+}\ell^+\ell^-$ | | $B^0 \to K^{*0}\ell^+\ell^-$ | | $B \to K^*\ell^+\ell^-$ | | $B^+ \to K^{*+}\ell^+\ell^-$ | | $B^0 \to K^{*0}\ell^+\ell^-$ | | $B \to K^*\ell^+\ell^-$ | |
| $q_0^2$ | — | $-0.02$ | — | — | — | — | $+0.04$ | — | $+0.04$ | — | $+0.05$ | — |
| $q_1^2$ | $+0.02$ | $-0.04$ | $+0.14$ | — | $+0.13$ | — | — | $-0.13$ | — | $-0.20$ | — | $-0.17$ |
| $q_2^2$ | — | $-0.07$ | — | $-0.10$ | — | $-0.02$ | $+0.12$ | — | $+0.09$ | — | $+0.07$ | — |
| $q_3^2$ | — | $-0.04$ | $+0.04$ | $-0.05$ | $+0.02$ | $-0.04$ | $+0.08$ | — | $+0.06$ | $-0.04$ | $+0.07$ | $-0.02$ |
| $q_4^2$ | $+0.07$ | $-0.05$ | $+0.06$ | — | $+0.07$ | — | $+0.06$ | — | — | $-0.09$ | $+0.02$ | $-0.06$ |
| $q_5^2$ | $+0.10$ | — | $+0.02$ | — | $+0.07$ | — | — | $-0.09$ | — | $-0.08$ | — | $-0.10$ |

# Angular analysis of $B \to K^* \ell^+ \ell^-$ decays

PRD 93, 052015 (2016)

- **Systematics on angular results:** $A_{\mathrm{FB}}$ from $F_{\mathrm{L}}$

| | $\mathcal{A}_{FB}$ systematic | | |
|---|---|---|---|
| | $B^+ \to K^{*+}\ell^+\ell^-$ | $B^0 \to K^{*0}\ell^+\ell^-$ | $B \to K^*\ell^+\ell^-$ |
| $q_0^2$ | $\pm 0.04$ | $\pm 0.04$ | $\pm 0.04$ |
| $q_1^2$ | $\pm 0.04$ | $\pm 0.07$ | $\pm 0.04$ |
| $q_2^2$ | $\pm 0.07$ | $\pm 0.07$ | $\pm 0.08$ |
| $q_3^2$ | $\pm 0.03$ | $\pm 0.06$ | $\pm 0.04$ |
| $q_4^2$ | $\pm 0.04$ | $\pm 0.07$ | $\pm 0.06$ |
| $q_5^2$ | $\pm 0.08$ | $\pm 0.07$ | $\pm 0.07$ |

# Angular analysis of $B \to K^* \ell^+ \ell^-$ decays

PRD 93, 052015 (2016)

- **Systematics on angular results:** total uncertainties

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

# Angular analysis of $B^0 \to K^{*0}\ell^+\ell^-$ decays

arXiv:1604.04042 [hep-ex]

- **Numerical angular results:**

| $q^2$ in GeV$^2/c^4$ | Observable | Measurement |
|---|---|---|
| $[0.10, 4.00]$ | $P_4'$ | $0.208^{+0.400}_{-0.434} \pm 0.070$ |
| | $P_5'$ | $0.631^{+0.403}_{-0.419} \pm 0.067$ |
| | $P_6'$ | $-0.670^{+0.419}_{-0.387} \pm 0.194$ |
| | $P_8'$ | $-0.309^{+0.519}_{-0.472} \pm 0.210$ |
| $[4.00, 8.00]$ | $P_4'$ | $-0.477^{+0.266}_{-0.252} \pm 0.070$ |
| | $P_5'$ | $-0.267^{+0.275}_{-0.269} \pm 0.049$ |
| | $P_6'$ | $-0.057^{+0.264}_{-0.262} \pm 0.189$ |
| | $P_8'$ | $0.130^{+0.257}_{-0.259} \pm 0.172$ |
| $[10.09, 12.90]$ | $P_4'$ | $-0.088^{+0.414}_{-0.402} \pm 0.114$ |
| | $P_5'$ | $-0.504^{+0.351}_{-0.327} \pm 0.057$ |
| | $P_6'$ | $-0.341^{+0.347}_{-0.326} \pm 0.222$ |
| | $P_8'$ | $-1.017^{+0.415}_{-0.374} \pm 0.207$ |
| $[14.18, 19.00]$ | $P_4'$ | $-0.371^{+0.272}_{-0.252} \pm 0.074$ |
| | $P_5'$ | $-0.547^{+0.257}_{-0.225} \pm 0.058$ |
| | $P_6'$ | $0.384^{+0.292}_{-0.306} \pm 0.236$ |
| | $P_8'$ | $0.242^{+0.301}_{-0.309} \pm 0.233$ |

| $q^2$ in GeV$^2/c^4$ | Observable | Measurement |
|---|---|---|
| $[1.00, 6.00]$ | $P_4'$ | $-0.095^{+0.302}_{-0.309} \pm 0.174$ |
| | $P_5'$ | $0.385^{+0.276}_{-0.285} \pm 0.099$ |
| | $P_6'$ | $-0.202^{+0.278}_{-0.270} \pm 0.172$ |
| | $P_8'$ | $0.440^{+0.311}_{-0.320} \pm 0.195$ |

# Angular analysis of $B^0 \to K^{*0}\ell^+\ell^-$ decays

arXiv:1604.04042 [hep-ex]

- **Systematics:** $P_4'$

| Bin | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Peaking Background | 0.0855 | 0.0646 | 0.0366 | 0.0457 | 0.0358 |
| Data/MC Difference | 0.0109 | 0.0088 | 0.0020 | 0.0003 | 0.0047 |
| Efficiency Correction | 0.1475 | 0.0241 | 0.0599 | 0.0877 | 0.0650 |
| Fit Bias | 0.0316 | 0.0114 | 0.0007 | 0.0558 | 0.0027 |
| Total | 0.1738 | 0.0704 | 0.0702 | 0.1135 | 0.0744 |

# Angular analysis of $B^0 \to K^{*0}\ell^+\ell^-$ decays

arXiv:1604.04042 [hep-ex]

- **Systematics:** $P_5'$

| Bin | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Peaking Background | 0.0901 | 0.0636 | 0.0078 | 0.0498 | 0.0131 |
| Data/MC Difference | 0.0112 | 0.0067 | 0.0208 | 0.0142 | 0.0029 |
| Efficiency Correction | 0.0397 | 0.0205 | 0.0098 | 0.0215 | 0.0327 |
| Fit Bias | 0.0031 | 0.0061 | 0.0430 | 0.0127 | 0.0460 |
| Total | 0.0992 | 0.0675 | 0.0494 | 0.0575 | 0.0580 |

# Angular analysis of $B^0 \to K^{*0}\ell^+\ell^-$ decays

arXiv:1604.04042 [hep-ex]

- **Systematics:** $P_6'$

| Bin | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Peaking Background | 0.0170 | 0.0513 | 0.0229 | 0.0215 | 0.0026 |
| Data/MC Difference | 0.1298 | 0.1378 | 0.1655 | 0.2201 | 0.2341 |
| Efficiency Correction | 0.0835 | 0.0432 | 0.0683 | 0.0218 | 0.0192 |
| Fit Bias | 0.0735 | 0.1189 | 0.0562 | 0.0027 | 0.0268 |
| Total | 0.1718 | 0.1939 | 0.1890 | 0.2222 | 0.2364 |

# Angular analysis of $B^0 \to K^{*0}\ell^+\ell^-$ decays

arXiv:1604.04042 [hep-ex]

- **Systematics:** $P_8'$

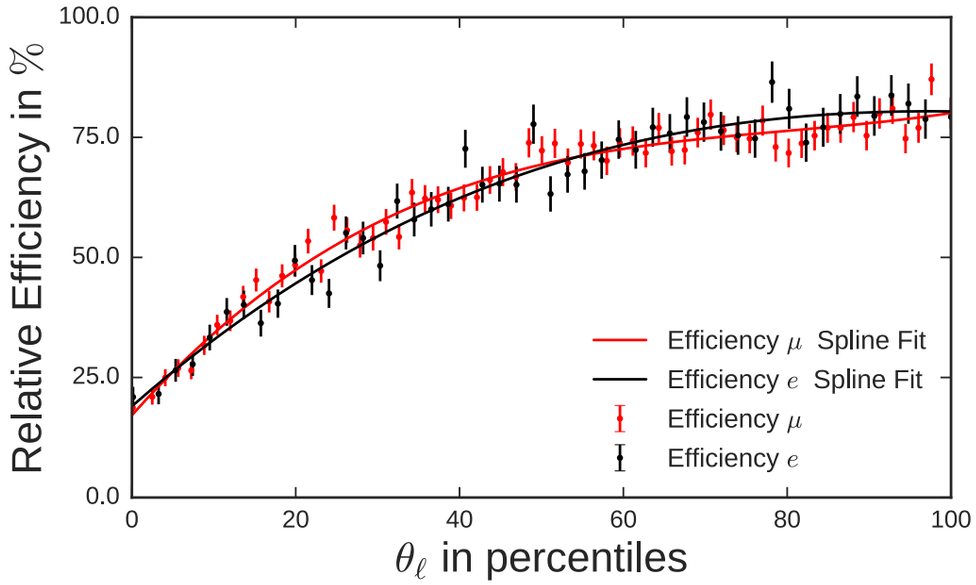
| Bin | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Peaking Background | 0.1242 | 0.0161 | 0.0395 | 0.0518 | 0.0255 |
| Data/MC Difference | 0.1433 | 0.1630 | 0.1531 | 0.1955 | 0.2316 |
| Efficiency Correction | 0.0319 | 0.0824 | 0.0359 | 0.0418 | 0.0099 |
| Fit Bias | 0.0337 | 0.1033 | 0.0579 | 0.0048 | 0.0047 |
| Total | 0.1952 | 0.2105 | 0.1722 | 0.2065 | 0.2332 |

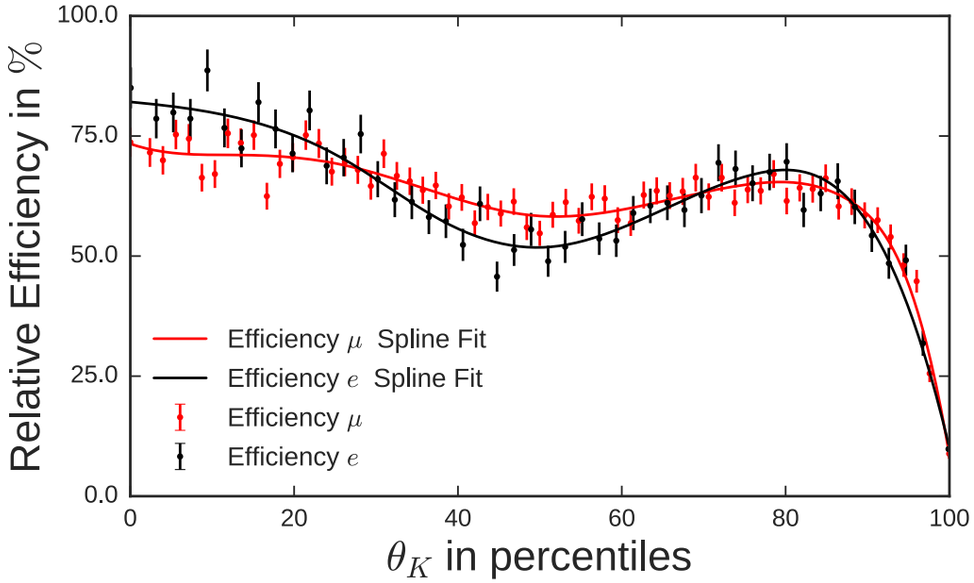
# Angular analysis of $B^0 \to K^{*0}\ell^+\ell^-$ decays

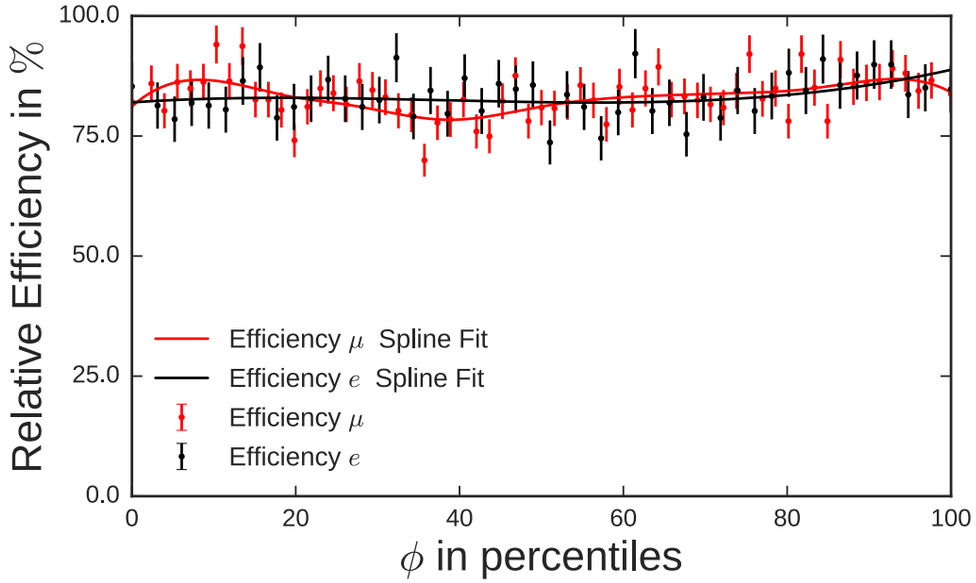
arXiv:1604.04042 [hep-ex]

- **Angular acceptance:**
  - Obtained from fully simulated MC
  - Assume no correlation between angular variables

$$f_{\rm eff}^{\rm bin}(\cos\theta_\ell, \cos\theta_K, \phi, q^2) = \epsilon(\cos\theta_\ell) \otimes \epsilon(\cos\theta_K) \otimes \epsilon(\phi) \otimes \epsilon(q^2)$$



# Angular analysis of $B^0 \to K^{*0}\ell^+\ell^-$ decays

arXiv:1604.04042 [hep-ex]

- **Folding method:**

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

- Redefinition of angles allow to reduce the number of parameters in the decay rate
- Four independent measurements (on the same data set) are performed with different foldings, each one allowing to measure a set of observables: $F_{\mathrm{L}}$, $S_3$ and another $S_i$ such as

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}} \qquad P'_6 = \frac{S_7}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}}$$

$$S_4, P'_4 \;:\; \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \phi \to \pi - \phi & \text{for } \theta_L > \pi/2 \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \pi/2, \end{cases}$$

$$S_5, P'_5 \;:\; \begin{cases} \phi \to -\phi & \text{for } \phi < 0 \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \pi/2, \end{cases}$$

$$S_7, P'_6 \;:\; \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \pi/2 \\ \phi \to -\pi - \phi & \text{for } \phi < -\pi/2 \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \pi/2, \end{cases}$$

$$S_8, P'_8 \;:\; \begin{cases} \phi \to \pi - \phi & \text{for } \phi > \pi/2 \\ \phi \to -\pi - \phi & \text{for } \phi < -\pi/2 \\ \theta_K \to \pi - \theta_K & \text{for } \theta_L > \pi/2 \\ \theta_L \to \pi - \theta_L & \text{for } \theta_L > \pi/2. \end{cases}$$

# Search for $B^0 \to \phi\,\gamma$ decays

arXiv:1603.06546 [hep-ex]

- **Systematics:**

| Source | Uncertainty (events) |
|---|---|
| PDF parameterization | $^{+1.21}_{-1.14}$ |
| Fit bias | $^{+0.00}_{-0.08}$ |
| $C_{\rm NN}$ selection efficiency | 0.03 |
| $C_{\rm NN}$ background sample | 0.02 |
| Tracking efficiency | 0.02 |
| PID efficiency | 0.05 |
| Photon reconstruction | 0.08 |
| MC statistics | 0.01 |
| $\mathcal{B}(\phi \to K^+K^-)$ | 0.03 |
| Number of $B\overline{B}$ events | 0.05 |
| Total | $^{+1.22}_{-1.15}$ |