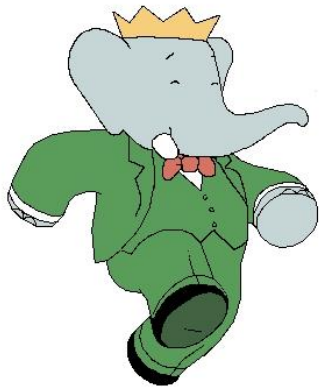
Recent studies of B-meson decays with the BaBar detector



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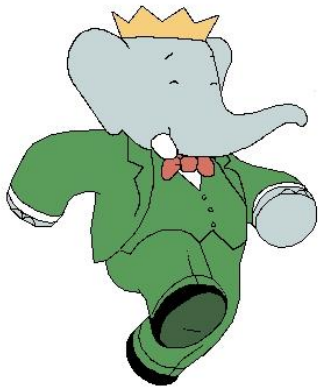
Brookhaven Forum 2015



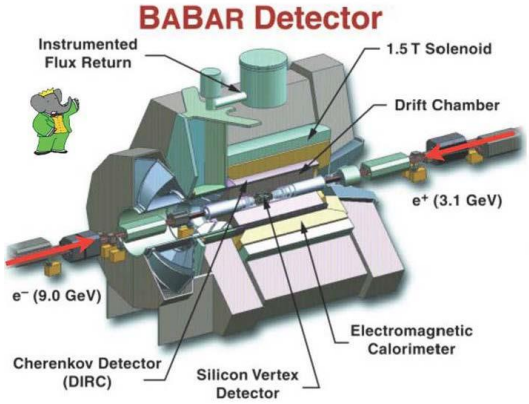
Outline

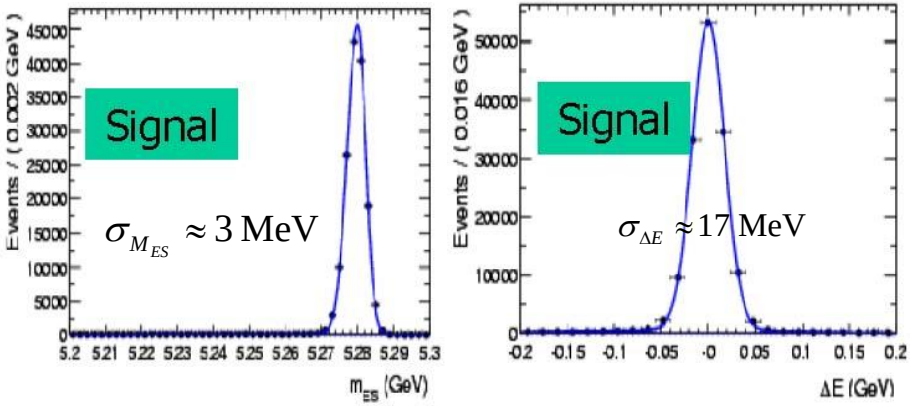
1. Time-dependent CP asymmetries in $B^0 \to K^0_s \pi^- \pi^+ \gamma$
   - To be submitted to PRD
2. Angular asymmetries in the decays $B \to K^* l^+ l^-$
   - arXiv:1508.07960, submitted to PRD
3. Lepton Universality in $B \to K l^+ l^-$
   - To be submitted to PRD
4. Observation of $\bar{B} \to D^{(*)} \pi^+ \pi^- l^- \bar{\nu}$
   - arXiv:1507.08303, submitted to PRL
5. V_{ub} from inclusive $B \to X_u e \nu$
   - To be submitted to PRD

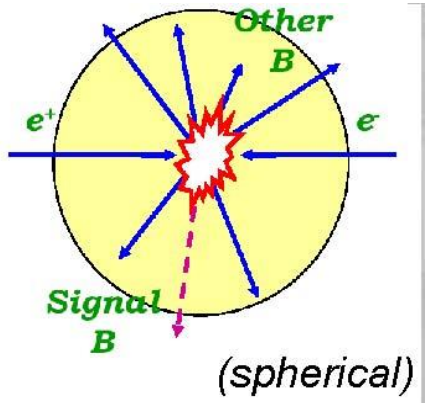
BaBar and PEP-II : $e^+e^- \rightarrow \Upsilon(nS)$

$$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}} \qquad \Delta E = E_B^* - E_{beam}^*$$

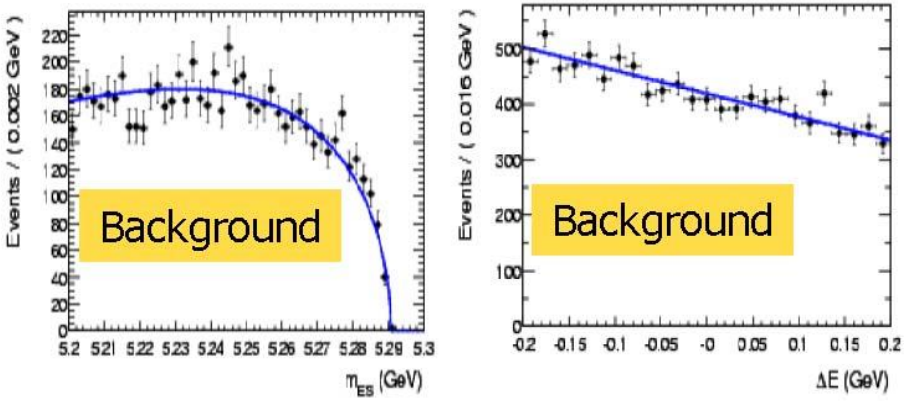
Event Topology

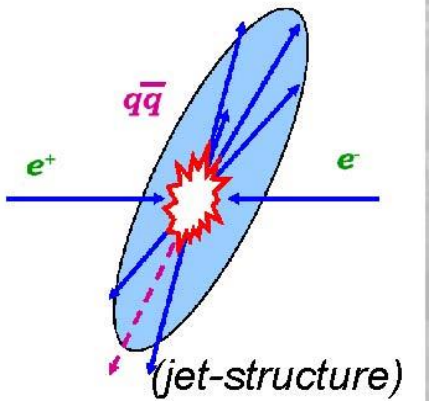






	Lumi	B$\bar{\text{B}}$ Events
$\Upsilon(4S)$	424 fb^{-1}	471×10^6
$\Upsilon(3S)$	28 fb^{-1}	121×10^6
$\Upsilon(2S)$	14 fb^{-1}	99×10^6
$\tau^+\tau^-$		$\sim 450\times10^6$

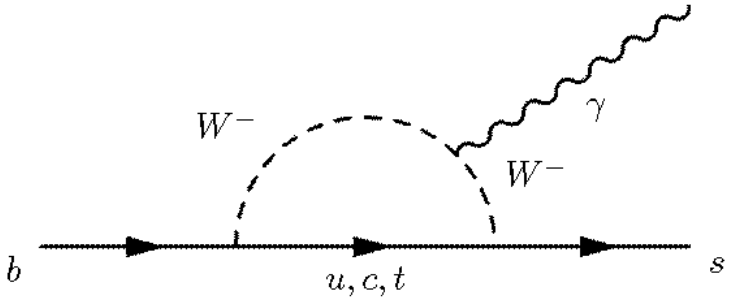




Plus: blinded analysis, multivariate discriminants, Maximum Likelihood (ML) fits

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

- The V-A structure of the Standard Model (SM) weak interactions yields predominantly left-handed γ in $b \to s\gamma$ decays ($B \to s\gamma_{RH}$, $\bar{B} \to \bar{s}\gamma_{LH}$).
- Implies mixing-induced CP asymmetry in $B \to f_{CP}\gamma$ is small in the SM.
- New Physics (NP) processes with an opposite-helicity γ may alter the SM prediction without contradicting branching fraction predictions
  - $B(B \to X_s\gamma) = (3.40 \pm 0.21) \times 10^{-4}$ (experiment)
  - $B(B \to X_s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$ (SM prediction)
- Some models have a right-handed process comparable in magnitude to left-handed processes e.g. PRD49, 5890 (1994); PRL B333, 196 (1994); PRD 49, 5894 (1994)

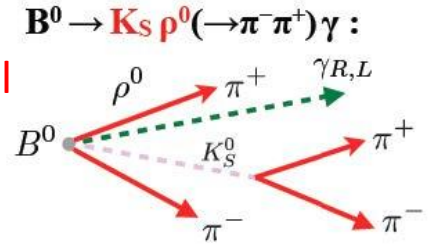


- Some previous results:
  - $B^0 \to K^0_S \rho^0 \gamma$ (Belle PRL101, 251601 (2008)), $B^0 \to K^0_S \pi^0 \gamma$ (BaBar PRD78, 071102 (2008); Belle PRD74, 111104 (2006): no evidence for NP, CP compatible with SM.
  - $B^+ \to K^+ \pi^- \pi^+ \gamma$: non-zero value ($5.2\sigma$) of photon polarisation (LHCb PRL 112, 161801 (2014))

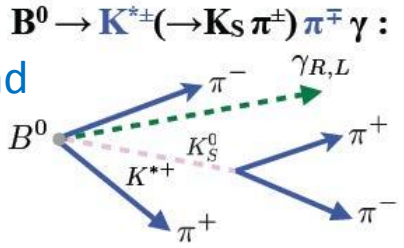
$B^0 \to K^0_S \pi^- \pi^+ \gamma$ Analysis Method

- Time-dependent mixing-induced CP asymmetry parameters $S_{K0s\rho\gamma}$ and $C_{K0s\rho\gamma}$ in $B^0 \to K^0_S \rho^0 \gamma$
- Problem 1: background from $B^0 \to K^{*\pm}\pi^{\mp}\gamma$ dilutes $S_{K0s\rho\gamma}$ from $B^0 \to K^0_S \rho^0 \gamma$

signal



background



- Problem 2: not enough $B^0 \to K^0_S \rho^0 \gamma$ for amplitude analysis
  - Use $B^+ \to K^+\pi^-\pi^+\gamma$ and relate to $B^0 \to K^0_S \pi^-\pi^+\gamma$ via isospin (LAL-15-75)
  - Assume same resonances in both modes
  - Measure: $S_{K0s\pi\pi\gamma}$ and $C_{K0s\pi\pi\gamma}$ in $B^0 \to K^0_S \pi^-\pi^+\gamma$
  - Need amplitude analysis to determine dilution factor $D_{K0s\rho\gamma}$

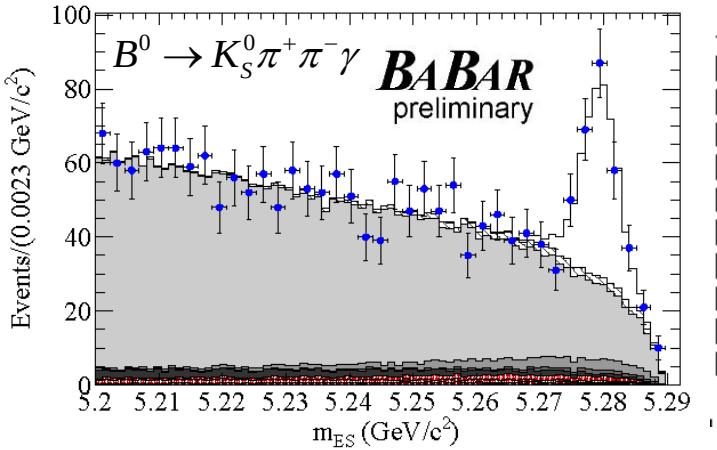
$$\mathcal{D}_{K^0_S\rho\gamma} \equiv \frac{\mathcal{S}_{K^0_S\pi^+\pi^-\gamma}}{\mathcal{S}_{K^0_S\rho\gamma}} = \frac{\int \left[\left|A_{\rho K^0_S}\right|^2 - \left|A_{K^{*+}\pi^-}\right|^2 - \left|A_{(K\pi)^+_0\pi^-}\right|^2 + 2\Re\left(A^*_{\rho K^0_S} A_{K^{*+}\pi^-}\right) + 2\Re\left(A^*_{\rho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

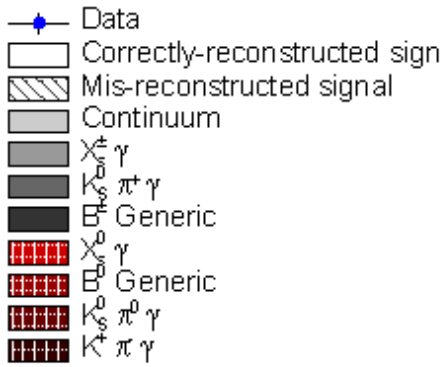
- Use ML fit to proper time distribution of $B^0 \to K^0_S \rho^0 \gamma$ to extract $C_{K0s\rho\gamma}$ and diluted $S_{K0s\rho\gamma}$:

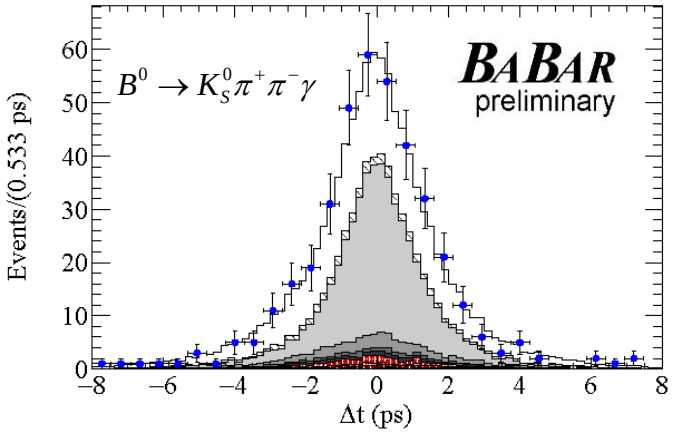
$$\mathcal{P}^i_{sig}(\Delta t, \sigma_\Delta; q_{tag}, c) = \frac{w^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}} \left[1 + q_{tag} \left(\frac{\Delta D_c}{2} + \langle D \rangle_c (\mathcal{S}\sin(\Delta m_d \Delta t) - \mathcal{C}\sin(\Delta m_d \Delta t)) \right) \right] \otimes \mathcal{R}^c_{sig}(\Delta t, \sigma_{\Delta_t})$$

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

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







Results consistent with Belle [PRL 101, 251601 (2008)]
CP asymmetries consistent with zero and SM.

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

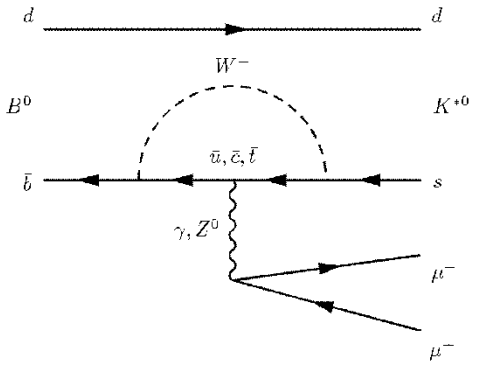
$$S_{K^0_s \pi^+ \pi^- \gamma} = +0.14 \pm 0.25^{+0.04}_{-0.03}$$

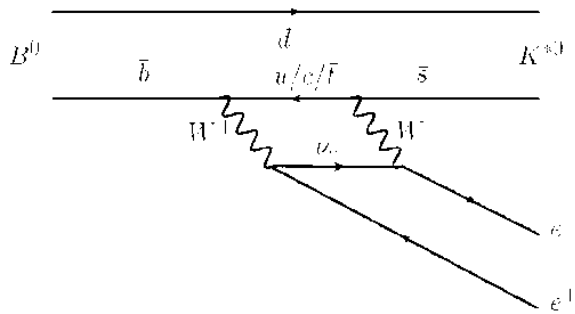
$$C_{K^0_s \pi^+ \pi^- \gamma} = -0.39 \pm 0.20 \pm 0.05$$

$$D_{K^0_s \rho^0 \gamma} = -0.79^{+0.18}_{-0.17}$$

$$S_{K^0_s \rho^0 \gamma} = -0.17 \pm 0.32^{+0.07}_{-0.06}$$

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





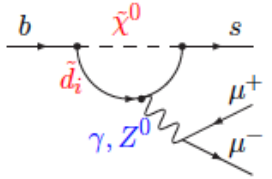
Effective Hamiltonian can be expressed via Operator Product Expansion (OPE) in terms of operators O and calculable Wilson coefficients C.

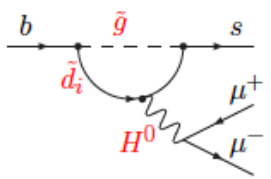
$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tq}^* V_{tb} \sum_{i=1} C_i^{(\prime)}(\mu) O_i^{(\prime)}(\mu) + \sum_i \frac{C_i^{NP}}{\Lambda^2} O_i^{NP}$$

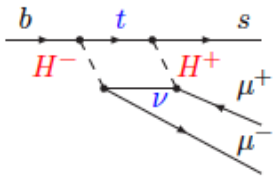
$i = 1,2$	Tree
$i = 3-6,8$	Gluon Penguin
$i = 7$	Photon Penguin
$i = 9$	EW Penguin (axial)
$i = 10$	EW Penguin (vector)
$i = S$	Scalar Penguin
$i = P$	Pseudoscalar Penguin

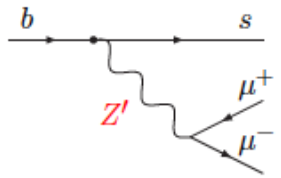
New Physics (NP) can enter via new particles in loops

- Potentially modifies magnitude and phase of SM C_i
- Probes new couplings and NP at a scale ~few TeV.
- Angular distributions as a function of q^2 sensitive to NP



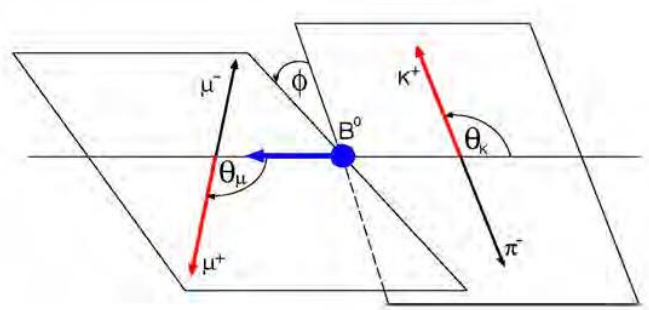






Angular analysis of the decays $B \to K^* l^+ l^-$

- Extract yield with ML to (m_{ES}, ΔE, BDT probability)
- The $B \to K^* l^+ l^-$ 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 the di-lepton and $K\pi$ planes



- Not enough events for full angular analysis, so integrate over two angles to find longitudinal polarisation F_L and lepton forward-backward asymmetry, A_{FB}:

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

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

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

- Perform F_L, A_{FB} fit in 6 q^2 bins with 5 final states

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

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

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

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	$1.00-6.00$

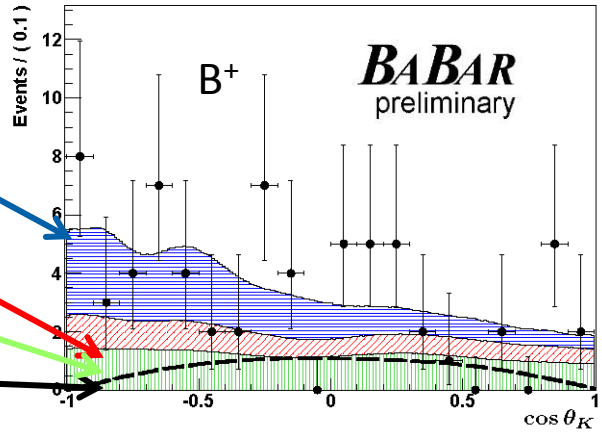
$B \to K^* l^+ l^-$ results for bin q^2_0 $1<q^2<6$ GeV^2

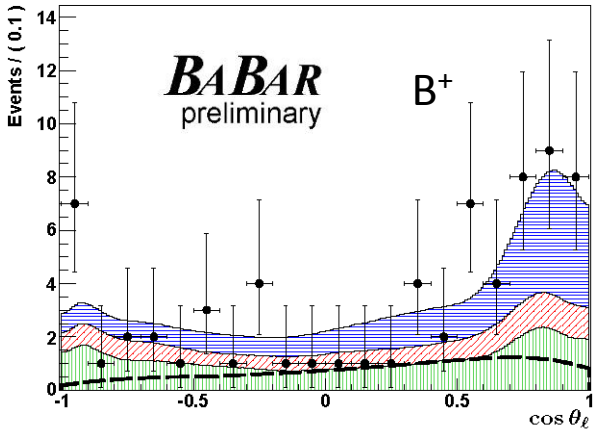
$K^+\pi^0 e^+ e^-$

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

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

Signal

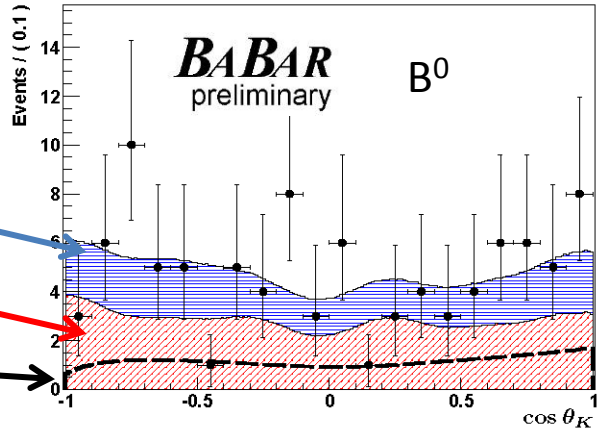


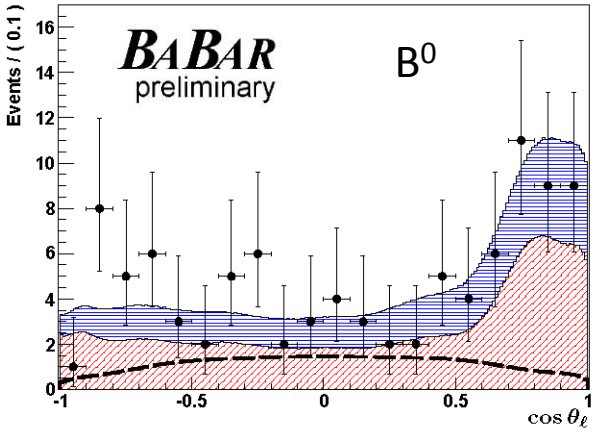


$K^+\pi^- e^+ e^-$

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

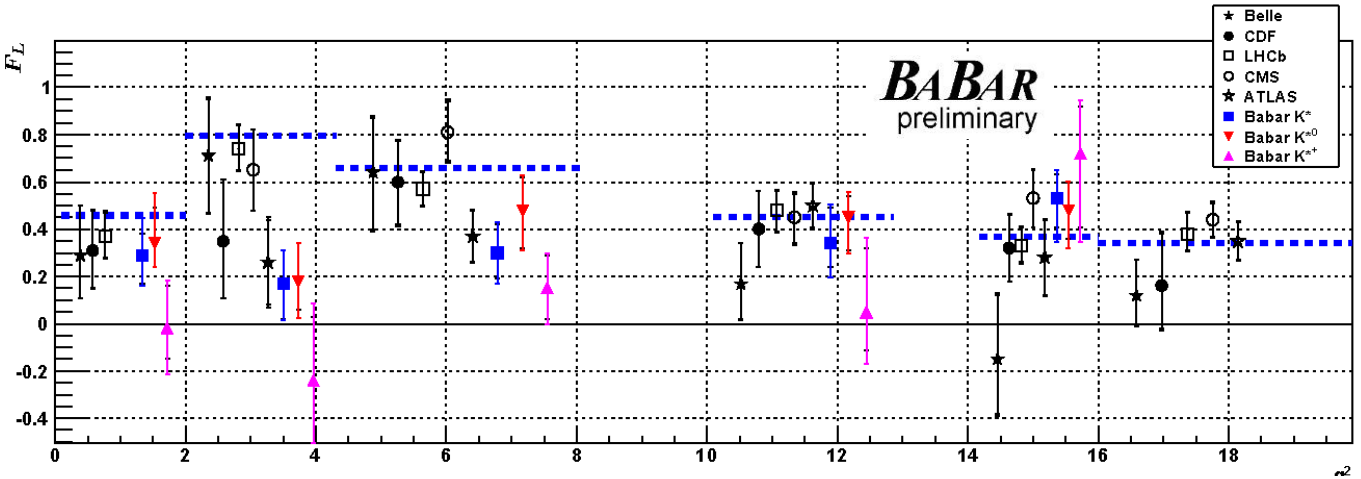
Signal



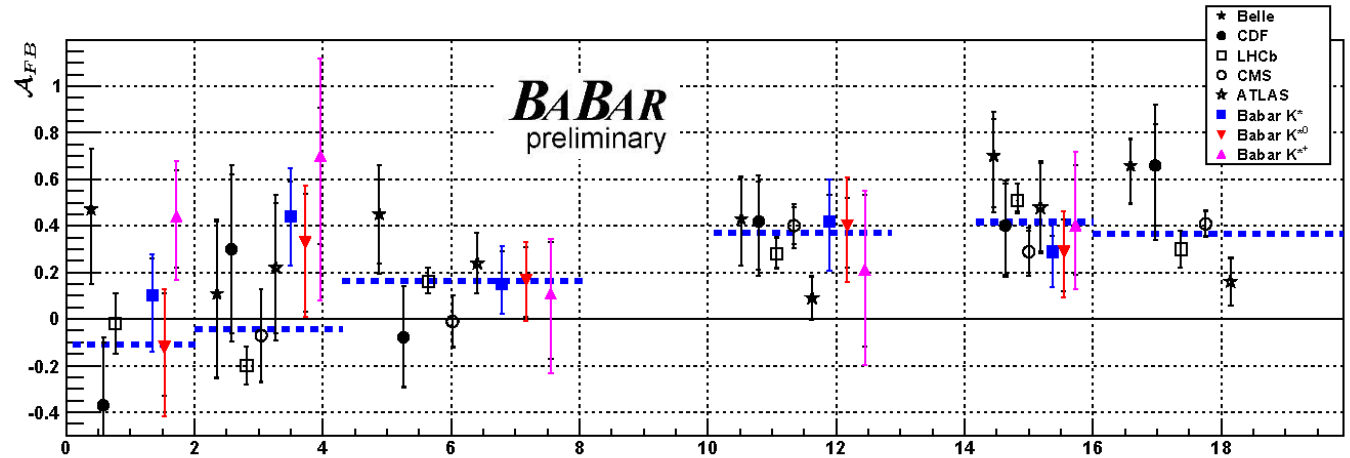


F_L and A_{FB} versus q^2

F_L



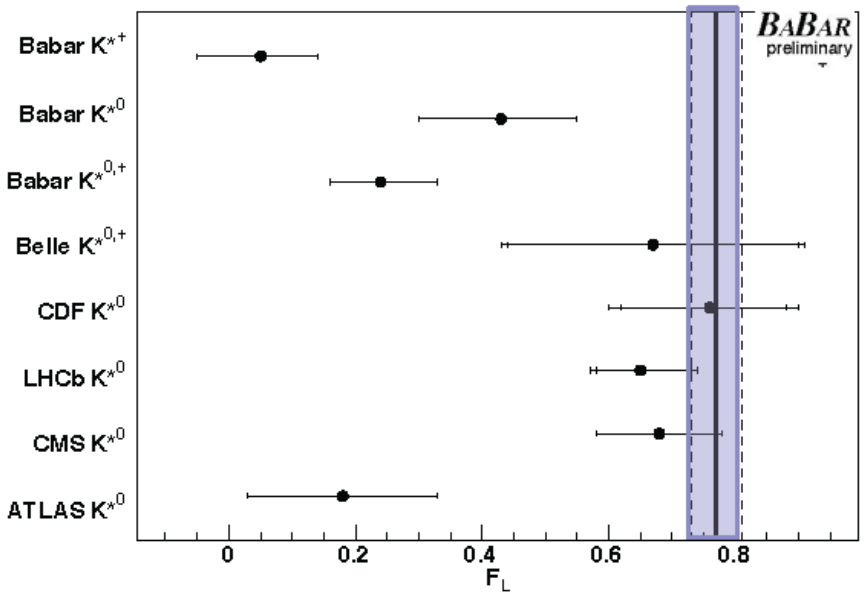
A_{FB}

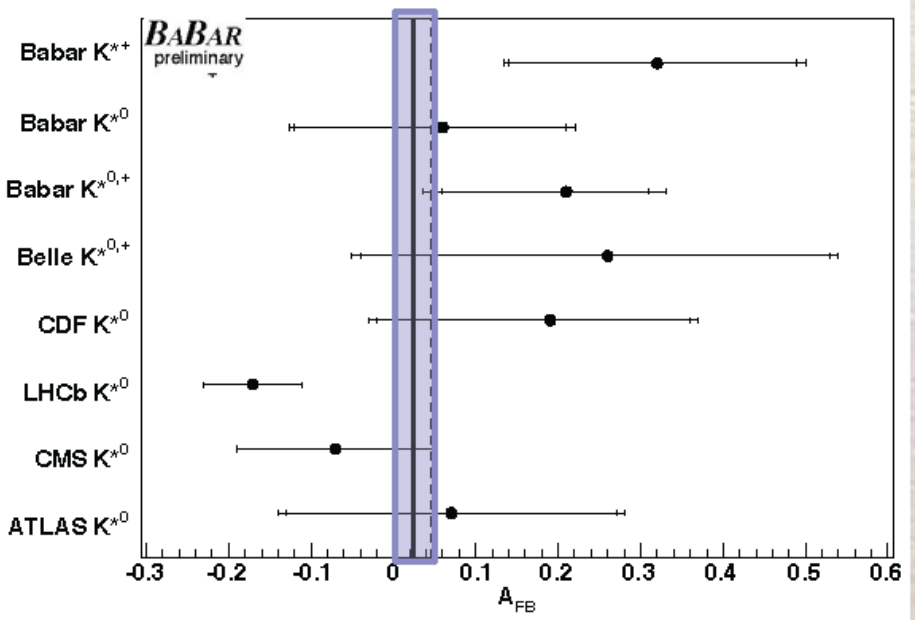


- F_L : BaBar $B^+ \rightarrow K^{*+}l^+l^-$ lower than BaBar $B^0 \rightarrow K^{*0}l^+l^-$
- F_L : BaBar $B \rightarrow Kl^+l^-$ agrees with SM except q^2_2 (>3σ) and q^2_3 (>2σ)
- A_{FB} : BaBar $B^+ \rightarrow K^{*+}l^+l^-$ agrees with BaBar $B^0 \rightarrow K^{*0}l^+l^-$
- A_{FB} : BaBar $B \rightarrow Kl^+l^-$ agrees with SM except q^2_2 (>2σ). Other bins agree with SM and other experiments.

F_L and A_{FB} between $1.0<q^2<6.0$ GeV^2

- $1.0<q^2<6.0$ GeV^2 region less susceptible to theoretical uncertainties e.g. charmonia.
- BaBar F_L lower than SM prediction (>3σ)
- BaBar A_{FB} agrees with SM and experiments.

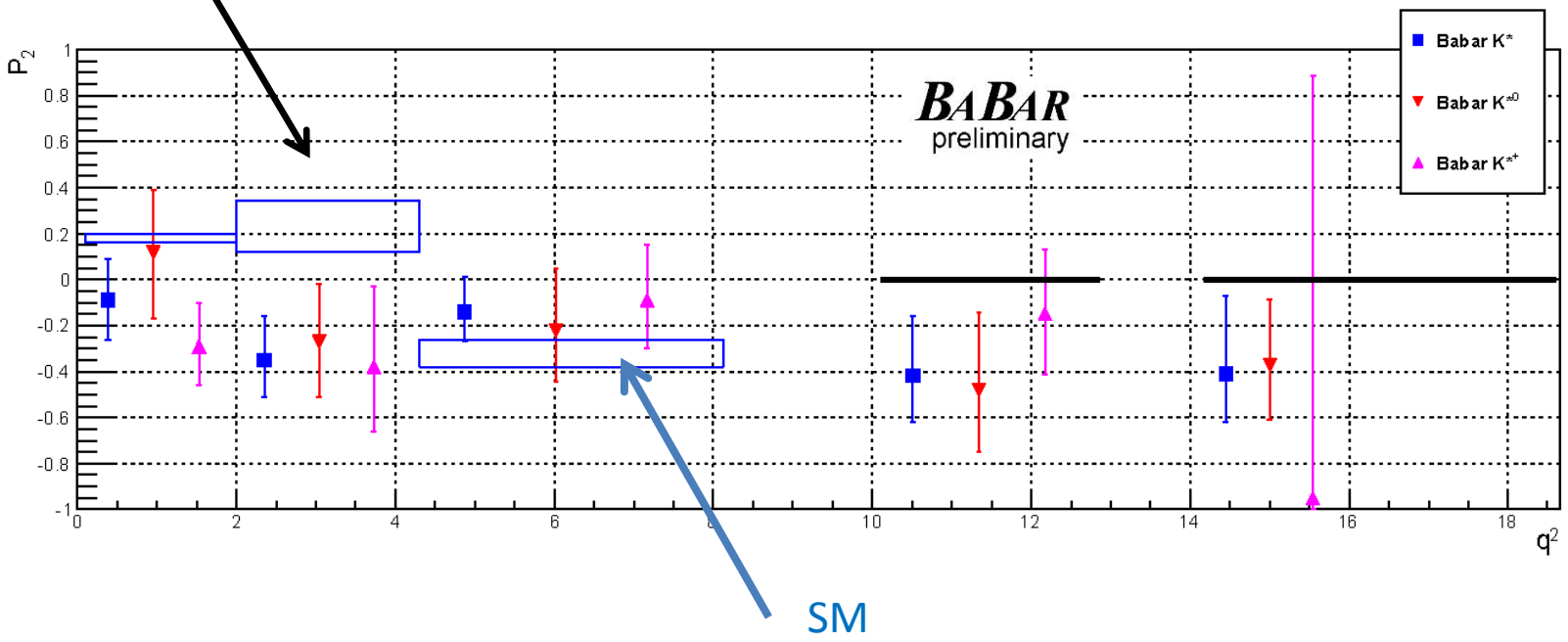




Belle: PRL 103, 171801 (2012); LHCb: JHEP 08 (2013) 131; ATLAS: ATLAS-CONF 2013-038 (2013); CDF: PRL 108, 081808 (2012); CMS: PLB 727, 77 (2013)

Results for P_2

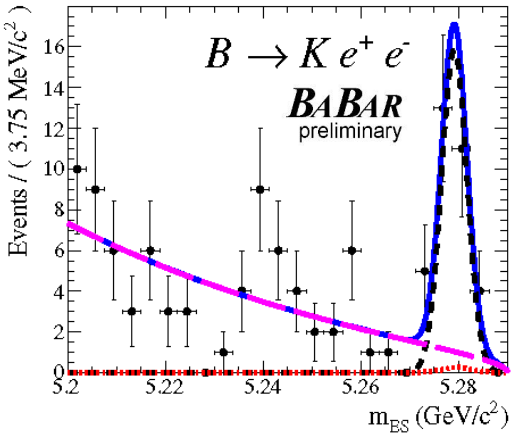
- Between $1.0<q^2<6.0$ GeV^2 : $P_2 = 0.11 \pm 0.10$
- In q^2_2, see $>2\sigma$ discrepancy with the SM

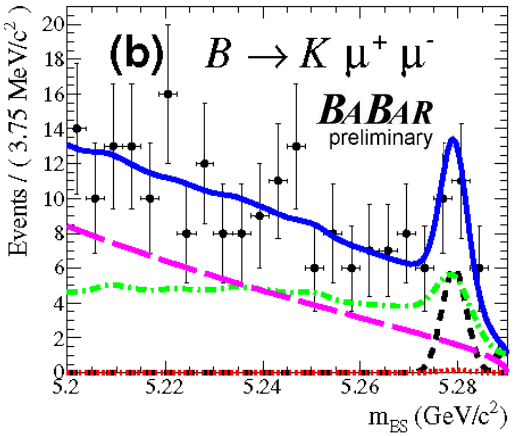


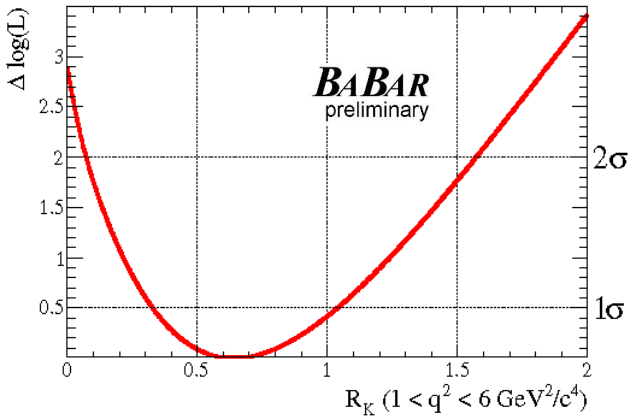
Lepton Universality in $B \to K l^+ l^-$

- Very similar selection and data as previous topic.
- Use $1.0<q^2<6.0$ GeV^2 region where theory uncertainties are lowest.
- SM prediction $R_K \approx 1.0 \pm (0.001\text{-}0.01)$

$$R_K = \frac{B(B \to K \mu^+ \mu^-)}{B(B \to K e^+ e^-)}$$







$$R_K = 0.64^{+0.39}_{-0.30} \pm 0.06 \text{ [this result]}$$

$$R_K = 0.74^{+0.40}_{-0.31} \pm 0.06 \text{ [BaBar PRD86, 032012 (2012)]}$$

$$R_K = 0.75^{+0.090}_{-0.074} \pm 0.036 \text{ [LHCb PRL113, 151601 (2014)]}$$

Consistent with previous BaBar result, SM and LHCb

Observation of $\bar{B} \to D^{(*)} \pi^+ \pi^- l^- \bar{\nu}$

As in $|V_{ub}|$, inclusive ($\bar{B} \to (X_c) l^- \bar{\nu}$) and exclusive measurements ($\bar{B} \to D^{(*)} l^- \bar{\nu}$) of $|V_{cb}|$ differ (by ~3σ).

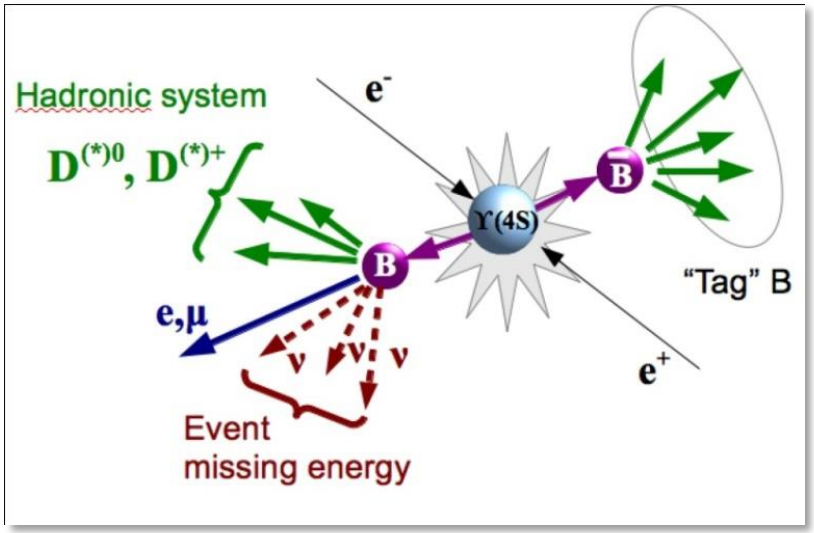
The measured exclusive rate for semi-leptonic B decays of $\bar{B} \to D^{(*)} l^- \bar{\nu}$, $\bar{B} \to D^{(*)} l^- \bar{\nu}$, and $\bar{B} \to D^{(*)} l^- \bar{\nu}$ only account for (85±2)% of the inclusive rate for semi-leptonic B decays to charm.

A possible background to $\bar{B} \to D^{(*)} \tau^- \bar{\nu}$ decay rates. The ratio $R(D^{(*)})$ of $\bar{B} \to D^{(*)} \tau^- \bar{\nu}$ to $\bar{B} \to D^{(*)} \mu^- \bar{\nu}$ rates has been measured to differ from SM by ~3.4σ by 3 different experiments (BaBar, Belle, LHCb).

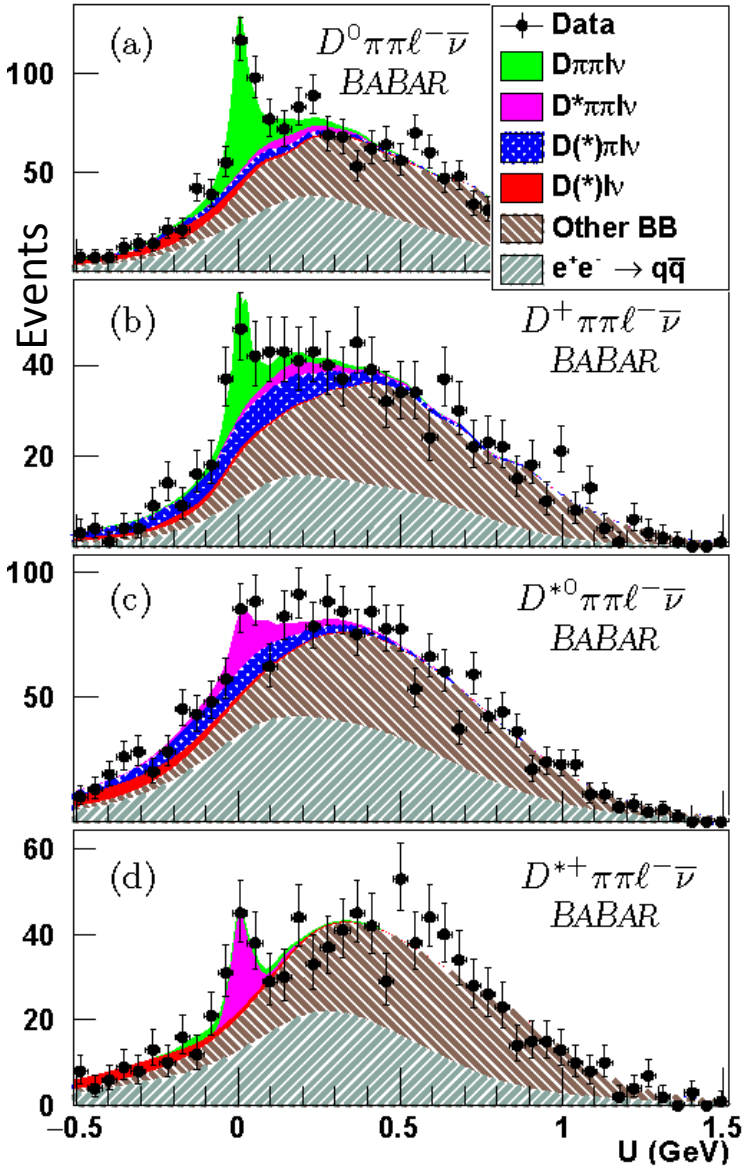
$\bar{B} \to D^{(*)} \tau^- \bar{\nu}$: PRD88, 072012 (2013); arXiv:1507.03233; PRL 114, 111803 (2015)

Fully reconstruct hadronic decay of one B-meson ("recoil method").

Use discriminant $U = E_{miss} - |p_{miss}|c$. For events with one missing ν, U peaks at 0 with width 0.1 GeV.



Observation of $\bar{B} \to D^{(*)} \pi^+ \pi^- l^- \bar{\nu}$



Channel	$R^{(*)}_{\pi^+\pi^-} \times 10^3$	$\mathcal{B} \times 10^5$
$D^0\pi^+\pi^-\ell^-\bar{\nu}$	$71 \pm 13 \pm 8$	$161 \pm 30 \pm 18 \pm 8$
$D^+\pi^+\pi^-\ell^-\bar{\nu}$	$58 \pm 18 \pm 12$	$127 \pm 39 \pm 26 \pm 7$
$D^{*0}\pi^+\pi^-\ell^-\bar{\nu}$	$14 \pm 7 \pm 4$	$80 \pm 40 \pm 23 \pm 3$
$D^{*+}\pi^+\pi^-\ell^-\bar{\nu}$	$28 \pm 8 \pm 6$	$138 \pm 39 \pm 30 \pm 3$
$D\pi^+\pi^-\ell^-\bar{\nu}$	$67 \pm 10 \pm 8$	$152 \pm 23 \pm 18 \pm 7$
$D^*\pi^+\pi^-\ell^-\bar{\nu}$	$19 \pm 5 \pm 4$	$108 \pm 28 \pm 23 \pm 4$

$$R_{\pi^+\pi^-} = \frac{B(\bar{B} \to D\pi^+\pi^- l^-\bar{\nu})}{B(\bar{B} \to Dl^-\bar{\nu})} = 0.067 \pm 0.01 \pm 0.008$$

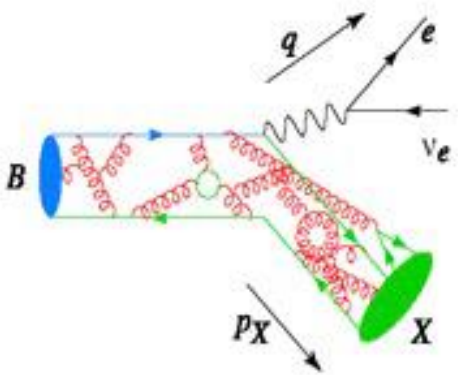
$$R^*_{\pi^+\pi^-} = \frac{B(\bar{B} \to D^*\pi^+\pi^- l^-\bar{\nu})}{B(\bar{B} \to D^* l^-\bar{\nu})} = 0.019 \pm 0.005 \pm 0.004$$

First observation of $\bar{B} \to D^0\pi^+\pi^- l^-\nu$

First evidence for $\bar{B} \to D^{(*)+}\pi^+\pi^- l^-\nu$

Accounts for (25-50)% of difference in inclusive and exclusive decay rates

V_{ub} from inclusive B $\rightarrow X_u e\nu$



- $|V_{ub}|/|V_{cb}|$ defines length of side opposite angle β in Unitarity Triangle. V_{ub} less precisely known than V_{cb}.
- Long-term discrepancy between $|V_{ub}|$ from inclusive ($B\rightarrow X_u l\nu$) and exclusive ($B\rightarrow(\pi,\rho,\omega,\ldots)l\nu$) measurements.

$$|V_{ub}|^{incl}_{DGE} = (4.52 \pm 0.16^{+0.15}_{-0.16}) \times 10^{-3}$$
$$|V_{ub}|^{excl} = (3.41 \pm 0.06^{+0.37}_{-0.32}) \times 10^{-3}$$

- $B\rightarrow X_u l\nu$ rate 50 times smaller than $B\rightarrow X_c l\nu$
- Electron momentum P_e kinematic endpoints
  - 2.6 GeV $B\rightarrow X_u e\nu$
  - 2.3 GeV $B\rightarrow X_c e\nu$

Most information on V_{ub} comes from P_e>2.3 GeV

- We use four models to relate dN/dP_e to $|V_{ub}|$

DeFazio & Neubert (DN) – E_e and E_γ spectrum in $B \rightarrow X_s\gamma$

Bosch, Lange, Neubert & Paz (BLNP) – improved DN

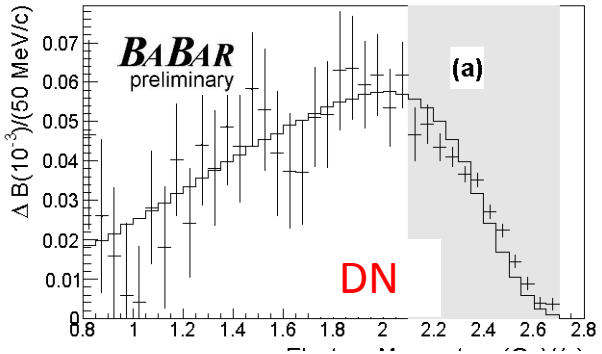
Gambino, Giordano, Ossola & Uraltsev (GGOU) – kinetic scheme

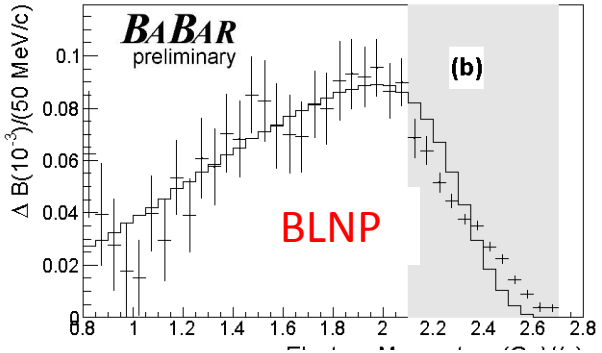
Anderson & Gardi (DGE) – Sudakov resummation

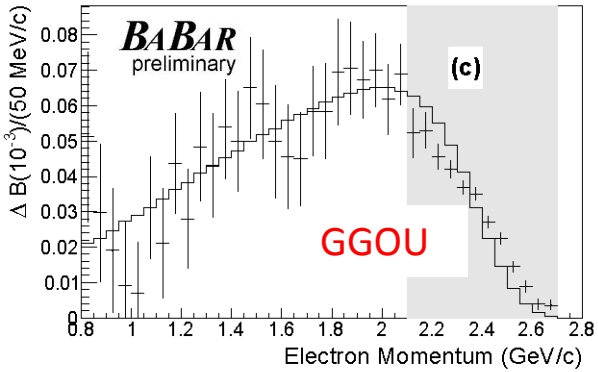
DN: JHEP 9906, 017 (1999); BLNP: PRD 72, 073006 (2005); GGOU: JHEP 10,058 (2007); DGE: JHEP 0601, 097 (2006)

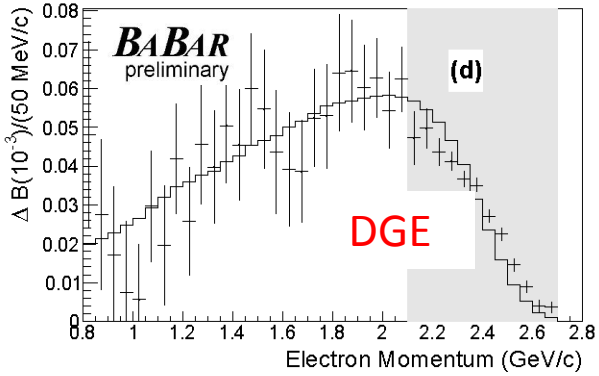
Comparison of models

- Binned Fit in CM momentum region $0.8 < P_e < 3.5$ GeV
- Use MC distributions for background for secondary e, mis-identified events, charm, τ, γ, etc… Normalizations allowed to float.









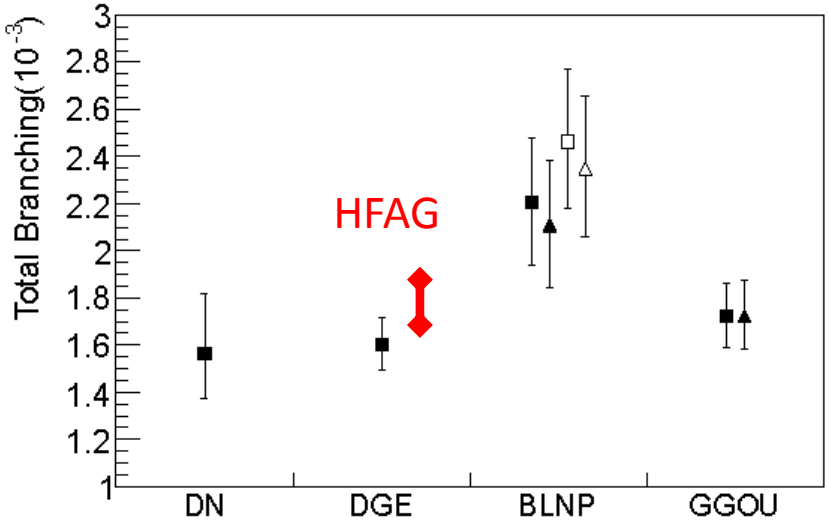
- Below 2.1 GeV, good agreement. Above 2.1GeV, shapes differ from data
- DN and DGE show best agreement

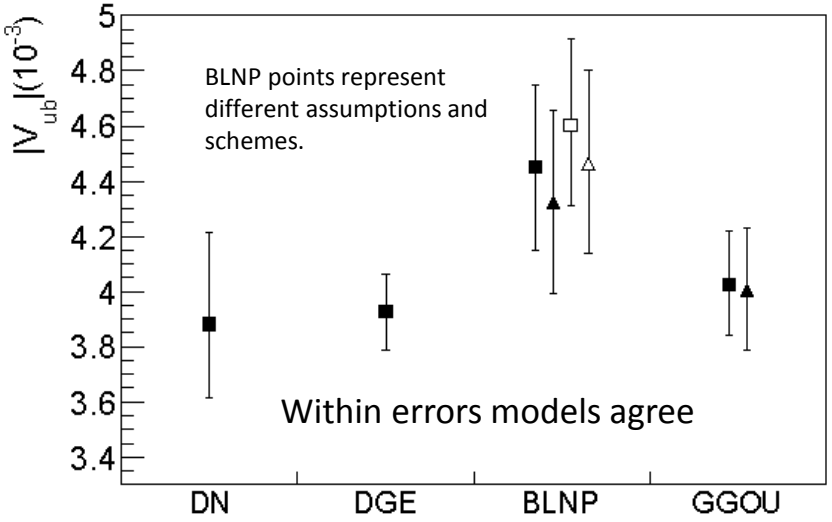
Total BF and V_{ub} for 4 models

$\|V_{ub}\| \times 10^3$	model
$3.881 \pm 0.113_{stat+syst} \, ^{+0.287}_{-0.212\ SF} \pm 0.120_{theory}$	DN
$3.926 \pm 0.111_{stat+syst} \, ^{+0.083}_{-0.079\ theory}$	DGE
m_c constraint fit of SF parameters with $\mu_i = 1.5GeV$	
$4.452 \pm 0.128_{stat+syst} \, ^{+0.200}_{-0.192\ SF} \, ^{+0.177}_{-0.191\ theory}$	BLNP
$4.026 \pm 0.110_{stat+syst} \, ^{+0.159}_{-0.149\ SF} \, ^{+0.003}_{-0.013\ theory}$	GGOU
$X_s\gamma$ constraint fit of SF parameters with $\mu_i = 1.5GeV$	
$4.321 \pm 0.123_{stat+syst} \, ^{+0.261}_{-0.241\ SF} \, ^{+0.172}_{-0.186\ theory}$	BLNP
$4.003 \pm 0.108_{stat+syst} \, ^{+0.197}_{-0.184\ SF} \, ^{+0.009}_{-0.014\ theory}$	GGOU
m_c constraint fit of SF parameters with $\mu_i = 2.0GeV$	
$4.604 \pm 0.130_{stat+syst} \, ^{+0.229}_{-0.206\ SF} \, ^{+0.163}_{-0.164\ theory}$	BLNP
$X_s\gamma$ constraint fit of SF parameters with $\mu_i = 2.0GeV$	
$4.462 \pm 0.127_{stat+syst} \, ^{+0.273}_{-0.251\ SF} \, ^{+0.158}_{-0.159\ theory}$	BLNP

- $|V_{ub}|$ from all models agree within errors
- Most precise model is DGE
- For DN, BLNP and GGOU limited by theory uncertainties
- HFAG BF average (BaBar+Belle) (P_e > 1GeV):

$$B(B \to X_u l\nu) = 1.80 \pm 0.13 \pm 0.14$$





Conclusion

- Presented recent preliminary results from BaBar:
  1. Time-dependent CP asymmetries in $B^0 \to K^0_s \pi^- \pi^+ \gamma$
  2. Angular asymmetries in the decays $B \to K^* l^+ l^-$
  3. Lepton Flavour Ratio in $B \to K\, l^+\, l^-$
  4. Observation of $\overline{B} \to D^{(*)}\, \pi^+ \pi^- l^- \bar{\nu}$
  5. V_{ub} from inclusive $B \to X_u e \nu$
- Only a subset of recent BaBar results.
- Results in process of being submitted to journals.