

# Polarized Fragmentation Function

## Measurements at *BABAR*

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Meeting of the Division of Particles and Fields  
Of the American Physical Society  
University of Michigan, Ann Arbor, MI  
August 4-8, 2015



# Outline

## INTRODUCTION

- Theoretical framework
  - Collins effect in di-hadron correlations
  - Reference frames
- PEP-II and the BaBar detector at SLAC

## ANALYSIS OVERVIEW

- Analysis method
- Extraction of the asymmetry for light quarks
- Asymmetry corrections and studies of systematic uncertainty

## RESULTS

- Asymmetries vs. fractional energies, hadron transverse momentum, and analysis axis polar angle

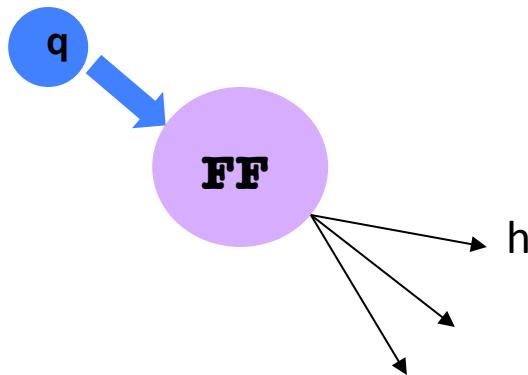
## CONCLUSIONS

Results reported in PRD90, 052003 (2014) and  
ArXiv:1506.05864 (Submitted to Phys. Rev. Lett.)

# Collins Fragmentation Function

## Fragmentation Functions (FFs)

- dimensionless and universal functions
- non-perturbative information
- describe the final state particles in hard processes
- dependence on  $z = 2E_h / \sqrt{s}$ ,  $P_\perp$ , and  $s_q$



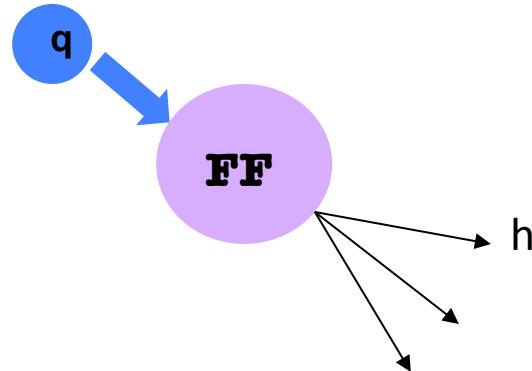
Unpolarized FF

$$D_1^{q\uparrow}(z, \mathbf{P}_\perp; s_q) = D_1^q(z, P_\perp) + \frac{P_\perp}{z M_h} H_1^{\perp q}(z, P_\perp) s_q \cdot (\mathbf{k}_q \times \mathbf{P}_\perp)$$

# Collins Fragmentation Function

## Fragmentation Functions (FFs)

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- ✓ non-perturbative information
- ✓ describe the final state particles in hard processes
- ✓ dependence on  $z = 2E_h / \sqrt{s}$ ,  $P_\perp$ , and  $s_q$



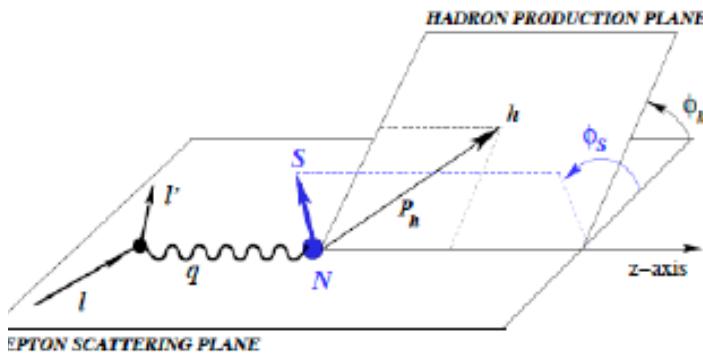
Unpolarized FF

$$D_1^{q\uparrow}(z, \mathbf{P}_\perp; s_q) = D_1^q(z, P_\perp) + \frac{P_\perp}{z M_h} H_1^{\perp q}(z, P_\perp) s_q \cdot (\mathbf{k}_q \times \mathbf{P}_\perp)$$

- Could arise from a spin-orbit coupling
- Leads to asymmetry in the angular distribution of final state particles (**Collins Effect**)

- $H_1^\perp$  is the **polarized** fragmentation function or **Collins FF**, describing the fragmentation of a **transversely polarized quark into a spinless (or unpolarized) hadron  $h$**
- J. C. Collins, Nucl.Phys. **B396**, 161 (1993)
- **Chiral-odd** function, ideal to access the chiral-odd parton distribution functions in Semi-Inclusive Deep Inelastic Scattering (SIDIS)

# Collins Effect



## SIDIS

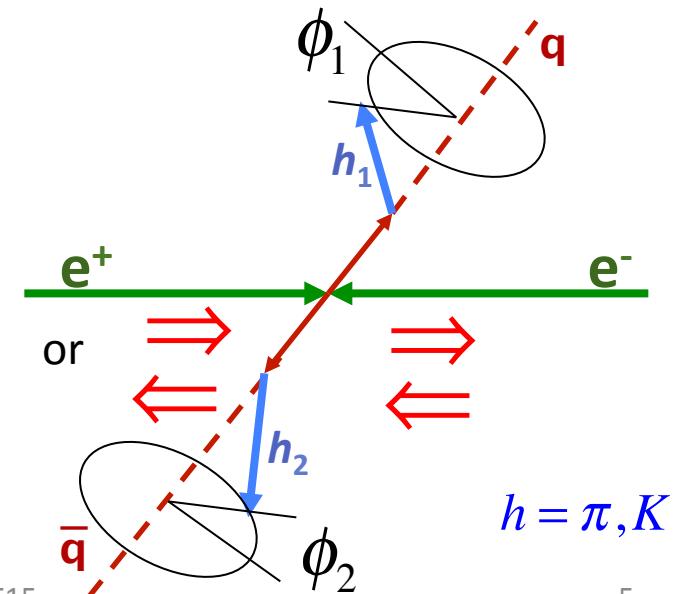
- Unpolarized lepton beam ( $l$ ) off transversely polarized target ( $N$ )  $lN \rightarrow l'\pi X$ 
  - non-zero Collins effects
  - spin direction known ( $S$ )
- $\sigma \propto \sin(\phi_h + \phi_s) h_1(x_B) \otimes H_1^\perp(z_1)$ 
  - two chiral-odd functions
  - azimuthal Single Spin Asymmetry

## $e^+e^-$ annihilation

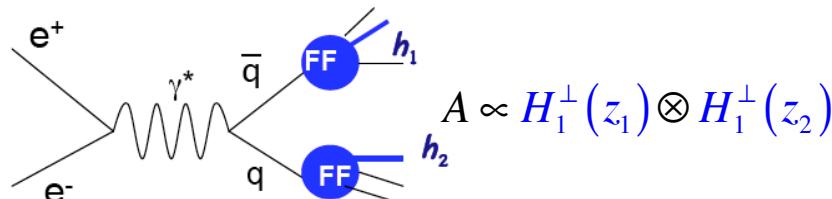
- $\gamma^*$  (spin-1) goes to spin-1/2  $q$  and  $\bar{q}$ 
  - in a given event, the spin directions are unknown, but they must be parallel
  - they have a polarization component transverse to the  $q$  direction
- exploit this correlation by using hadrons in opposite jets

$$e^+e^- \rightarrow q\bar{q} \rightarrow h_1 h_2 X \quad (q = u, d, s)$$

$$\sigma \propto \cos(\phi_i) H_1^\perp(z_1) \otimes H_1^\perp(z_2)$$



# Extracting Collins FF from data

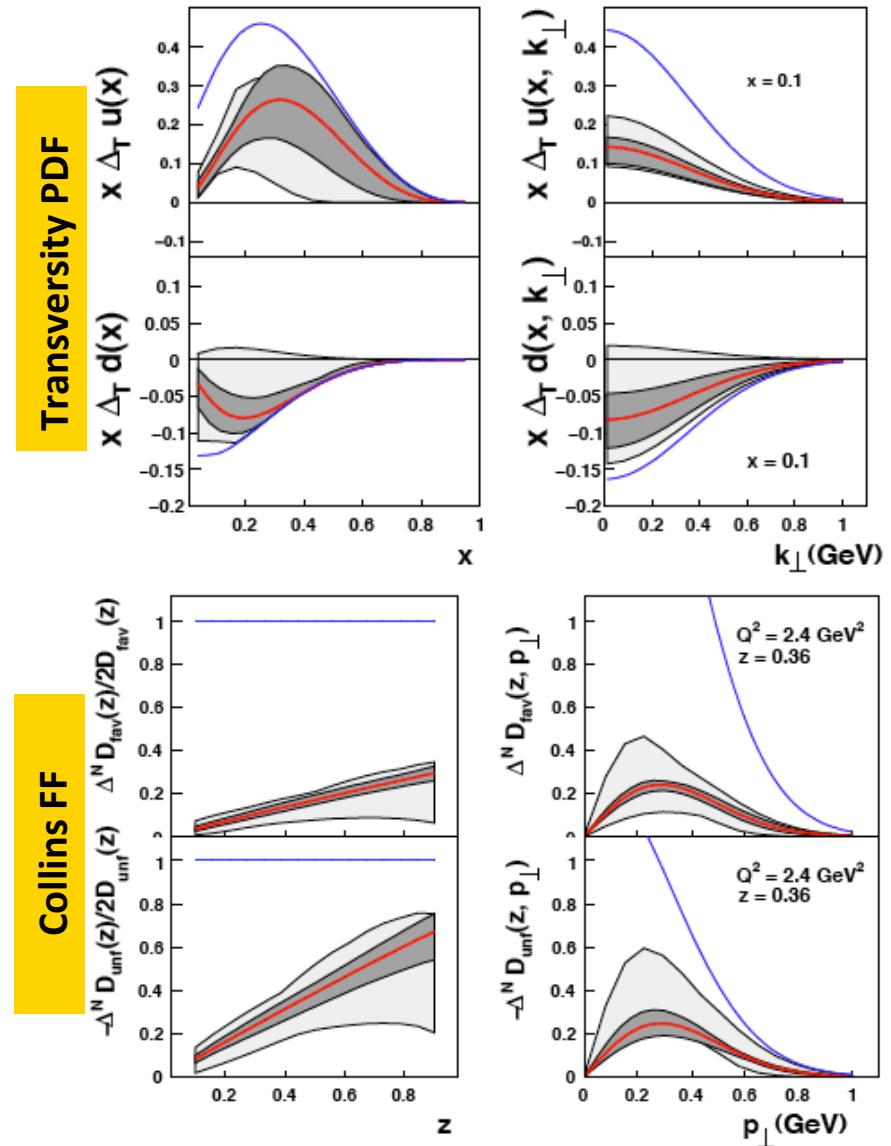


Perform a **Global Analysis**, simultaneously determining  $H_1^\perp$  and the transversity parton distribution function

*Anselmino et al., PRD 75, 054032, NP Proc.Suppl. 191, 98*

**BABAR** study offers:

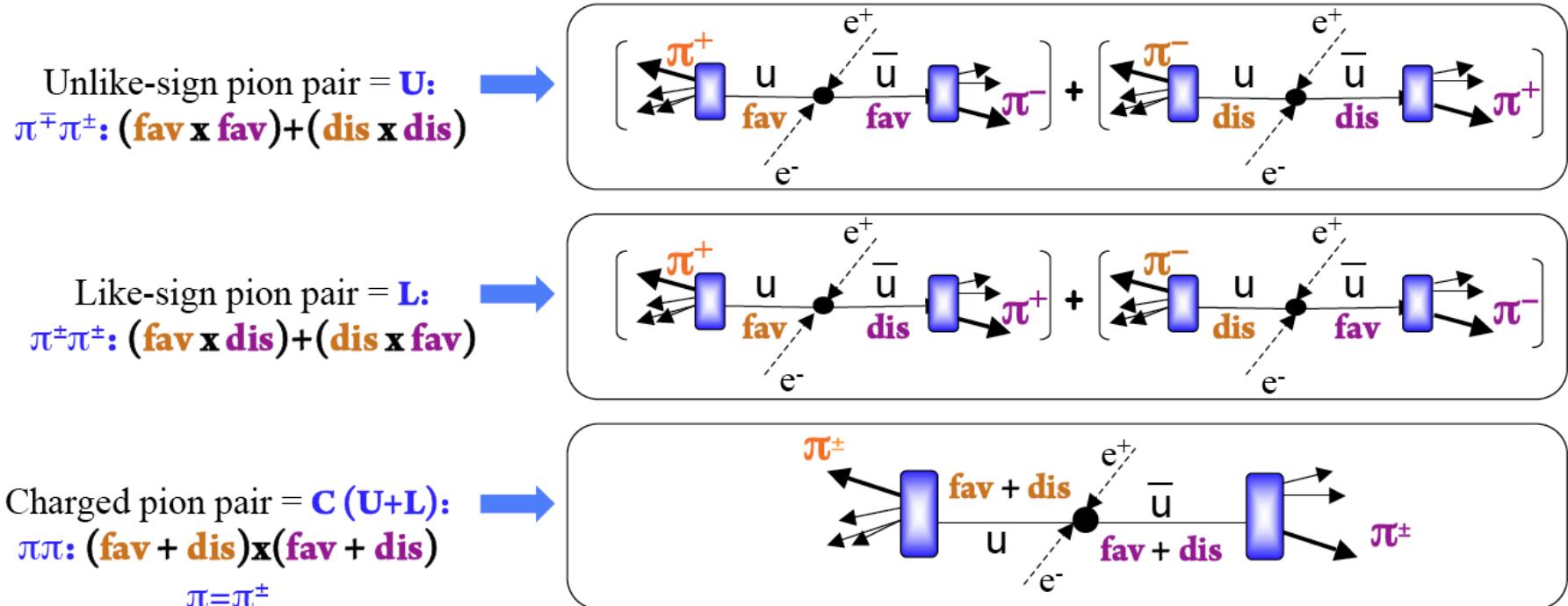
- Large number of energy intervals
- Asymmetry as a function of hadron transverse momentum



# Collins Effect in $e^+e^-$ Annihilation

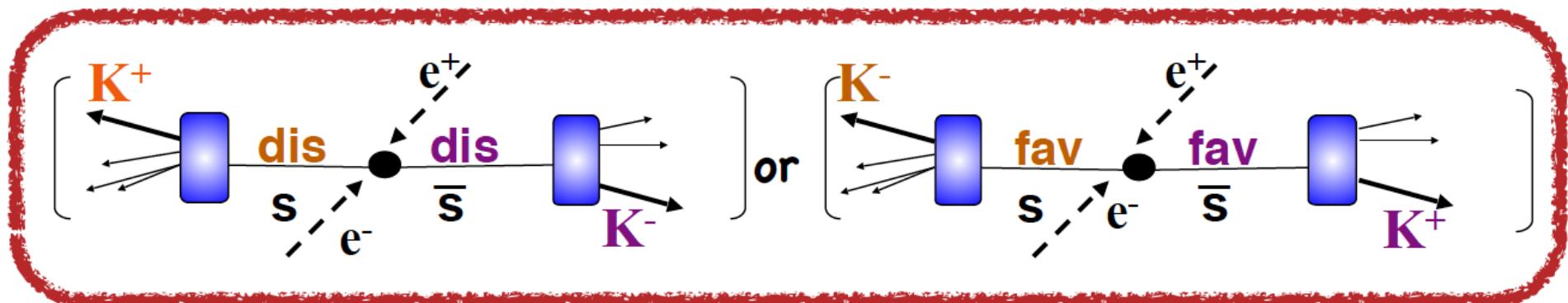
$$e^+e^- \rightarrow q\bar{q} \rightarrow h_1^\pm h_2^\pm X \quad (q=u,d,s \quad h=\pi,K)$$

- Experimentally, we see **Like (L)** or **Unlike (U)** sign pairs of charged hadrons
  - Can't unambiguously assign hadron to specific quark
- Introduce notion of **favored** and **disfavored** fragmentation functions
  - **Favored:** the parent quark matches a valence quark in the hadron
  - **Disfavored:** no such match  $u \rightarrow \pi^-, d \rightarrow \pi^+, s \rightarrow \pi^\pm$ , etc     $u \rightarrow \pi^+, d \rightarrow \pi^-, s \rightarrow K^\pm$ , etc



# Collins Effect with Kaons

- Collins effect not previously measured with Kaons
  - Provides direct access to the favored contribution to the Collins Fragmentation Function for the strange quark



# Analysis Reference Frame (RF)

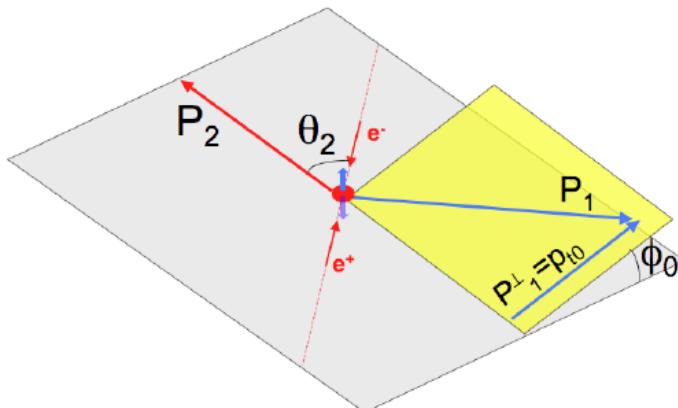
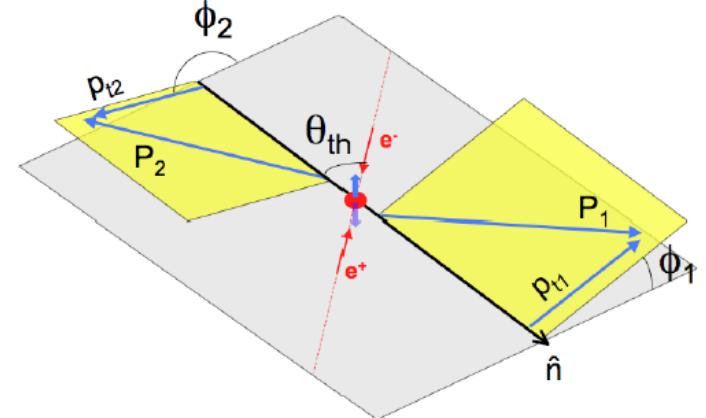
[See NPB 806, 23 (2009)]

## RF12 or Thrust RF

- **Thrust axis** to estimate the  $q\bar{q}$  direction
- $\phi_{1,2}$  defined using thrust-beam plane
- Modulation diluted by gluon radiation, detector acceptance,...

$$\sigma \sim 1 + \frac{\sin^2 \theta_{th}}{1 + \cos^2 \theta_{th}} \cos(\phi_1 + \phi_2) \frac{H_1^\perp(z_1) \bar{H}_1^\perp(z_2)}{D_1(z_1) \bar{D}_1(z_2)}$$

All quantities in  $e^+e^-$  center of mass



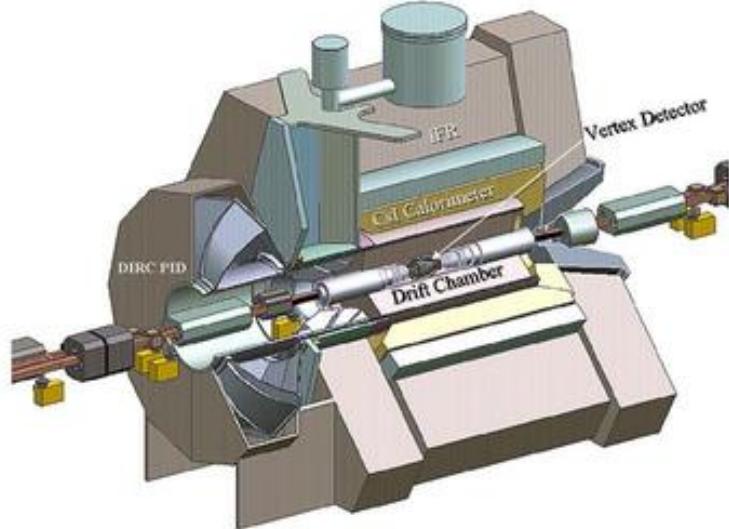
All quantities in  $e^+e^-$  center of mass

## RF0 or Second hadron momentum RF

- Alternatively, just use **one track** in a pair
- Very clean experimentally (no thrust axis), less theoretically
- Gives quark direction for higher pion momentum

$$\sigma \sim 1 + \frac{\sin^2 \theta_2}{1 + \cos^2 \theta_2} \cos(2\phi_0) \mathcal{F} \left[ \frac{H_1^\perp(z_1) \bar{H}_1^\perp(z_2)}{D_1(z_1) \bar{D}_1(z_2)} \right]$$

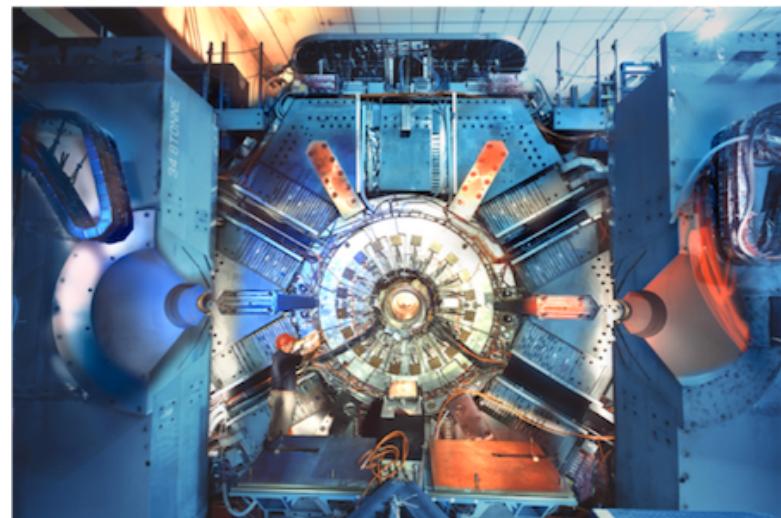
# The *BABAR* Experiment at SLAC



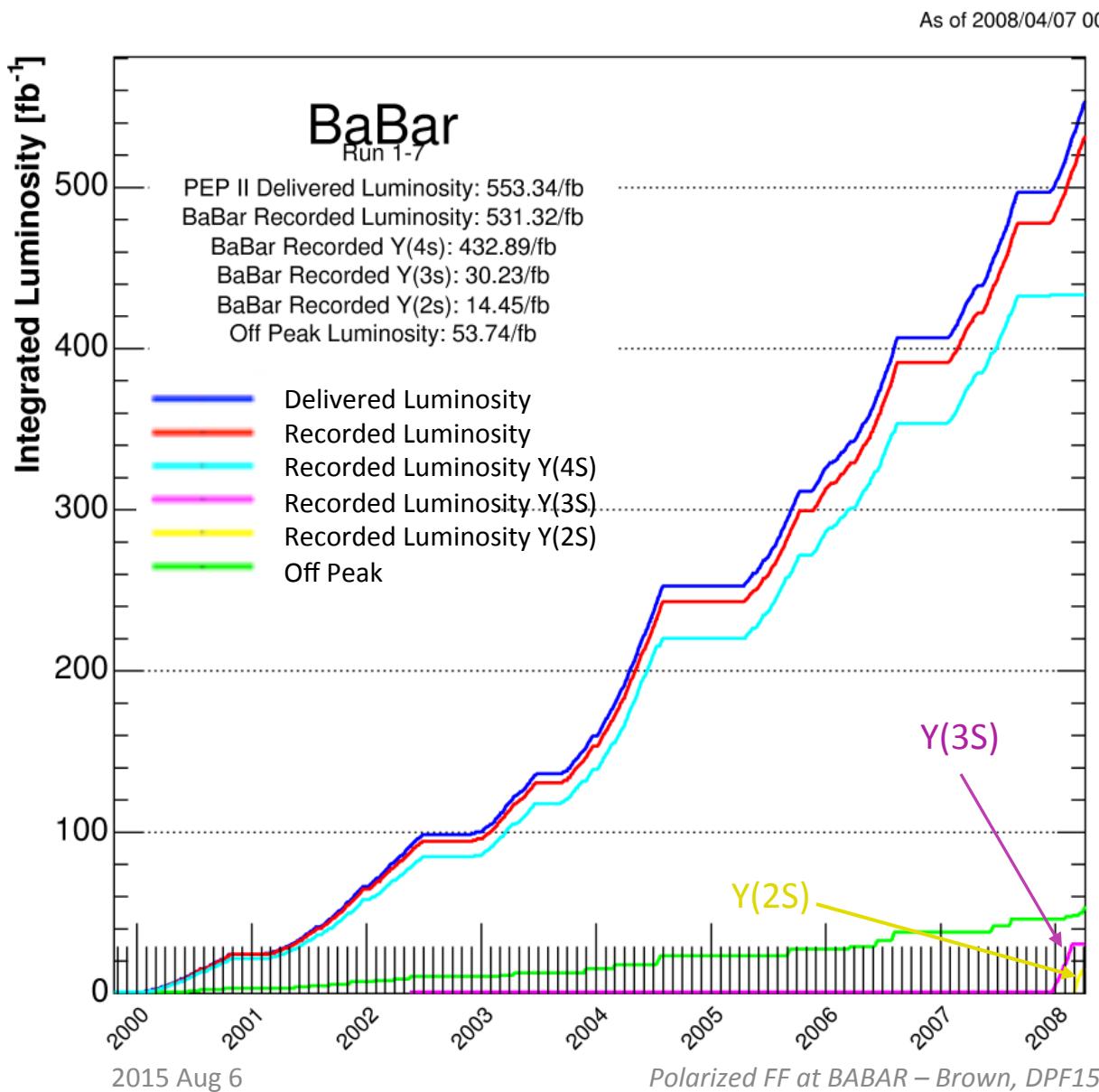
- Asymmetric-energy beams for boost
- Modern/state of the art detector
- 5 cylindrical subdetectors with a 40-layer drift chamber
- Excellent electromagnetic calorimetry
- Multiple measurements for particle identification
- Excellent momentum resolution

- Primarily designed for study of  $CP$ -violation in  $B$  meson decays
- Quality and general-purpose design make it suitable for a large variety of studies

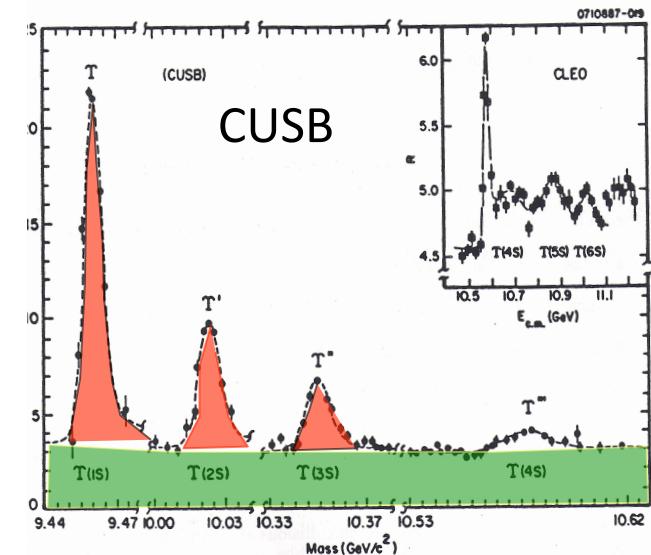
NIM A479,1 (2002),  
update: NIM A729, 615 (2013)



# The *BABAR* Running Era



7 Runs over the course of 9 years



This analysis uses  $468 \text{ fb}^{-1}$  of data

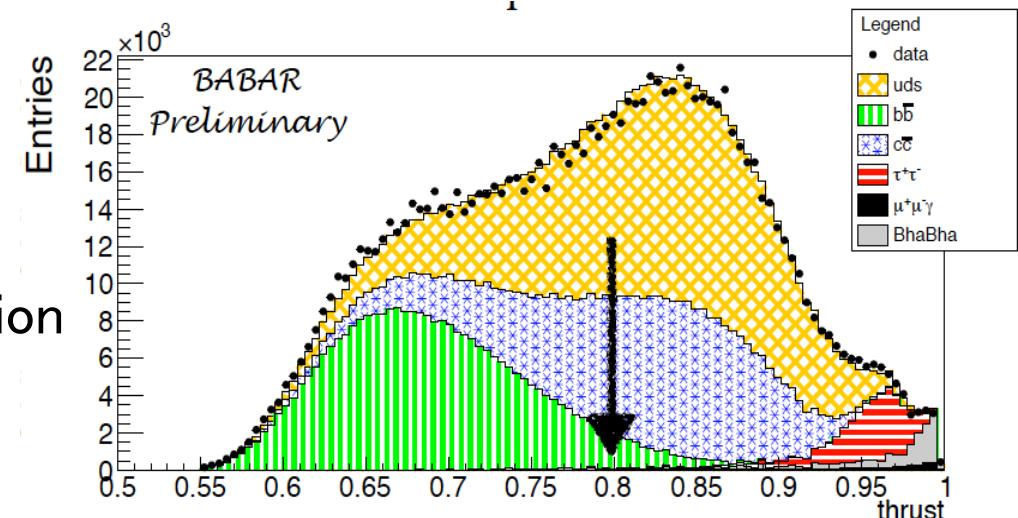
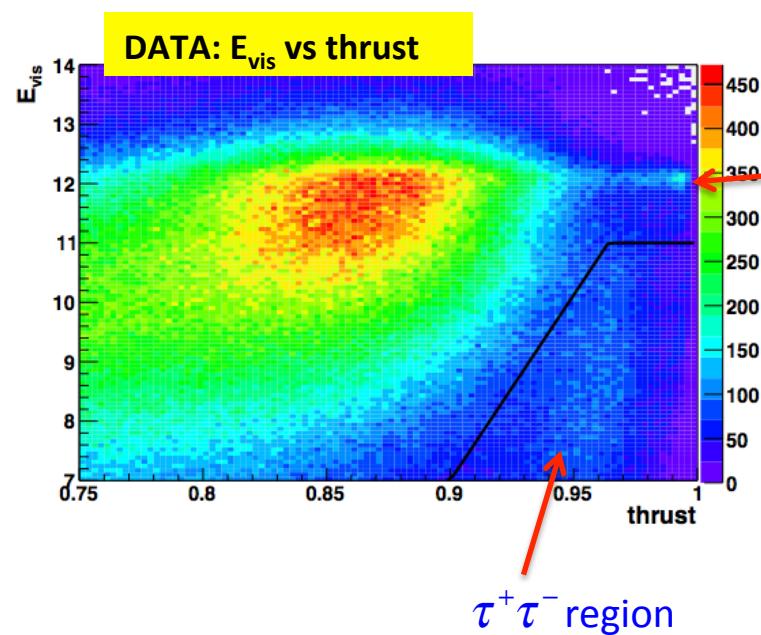
- First collisions with BaBar  
May 26, 1999
- Final data taken 12:43 p.m., April 7, 2008

# Analysis Strategy

- ❖ Goal: **simultaneous measurement of KK, K $\pi$ , and  $\pi\pi$  pairs**
  - ❖ Event and track selection
  - ❖ we identify the three sample of hadron pairs (KK, K $\pi$ ,  $\pi\pi$ ), and we divide the two hadrons in opposite jets using the thrust axis
  - ❖ we measure the azimuthal angles  $\phi_1$  and  $\phi_2$  in RF12, and  $\phi_0$  in RF0
  - ❖ we construct the normalized raw distributions for like (L), Unlike (U) and Charged (C=U+L) hadron pairs:  $R^i = N^i(\phi)/\langle N \rangle$
  - ❖ we calculate the ratios of normalized distributions: U/L and U/C and we fit these distributions
  - ❖ we extract the Collins asymmetries and we correct for the K/ $\pi$  misidentification, background contributions,...
  - ❖ we study systematic effects
- ❖ RESULTS: **4x4 ( $z_1, z_2$ ) bins, where  $z_{1,2} = 2E_h/\sqrt{s}$  is the hadron fractional energy**
  - ❖  $z_{1,2} = (0.15-0.2), (0.2-0.3), (0.3-0.5), (0.5-0.9)$
  - ❖ RF12 and RF0
  - ❖  $A^{UL}$  and  $A^{UC}$

# Event Selection

- Select Hadronic Events:
  - Number of charged tracks  $> 2$
  - Visible energy ( $E_{\text{vis}}$ )  $> 11 \text{ GeV}$
  - Veto events with  $\mu^\pm$  or  $e^\pm$
  - Remove events in the  $\tau^+\tau^-$  region



- Refine Event Selection
  - Select two-jet events by requiring  $\text{thrust} > 0.8$
  - Hadrons close to thrust axis:  $|\cos\theta_{\text{thrust}}| < 0.6$
  - Most energetic photon in event has  $E_\gamma < 2 \text{ GeV}$

## Particle Selection

- Select hadrons
  - Charged tracks well-identified via combined ionization and Cerenkov radiation measurements
  - Charged tracks in region of highest detector acceptance:  $0.41 < \theta_{lab} < 2.54$  rad
  - hadron fractional energies:  $0.15 < z = 2E_h / \sqrt{s} < 0.9$

Use particle ID tuned for high hadron efficiency across all lab momenta (typically 95+%)  
With minimal misidentification of electrons (< 2%) and muons (<4%)

# Raw Asymmetries

- **Collins asymmetry**

- consider all the **U** and **L** pion pairs
- make histograms of  $\phi_\alpha = \phi_1 + \phi_2$  or  $2\phi_0$  ( $\alpha=12,0$ )
- normalize by the average:

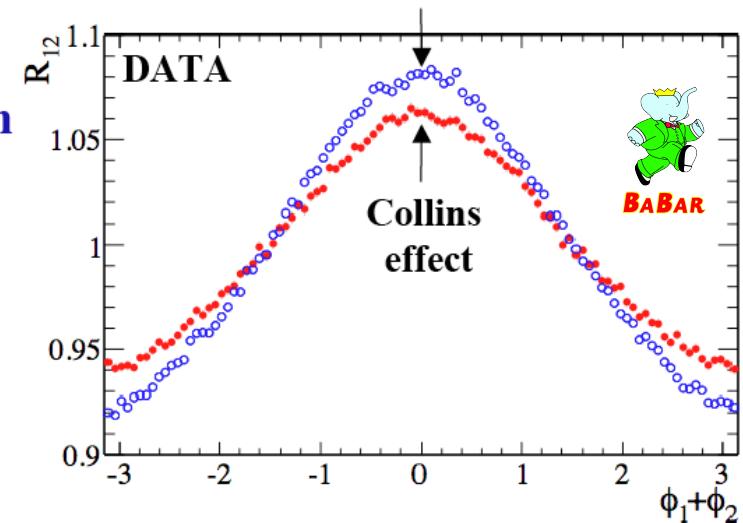
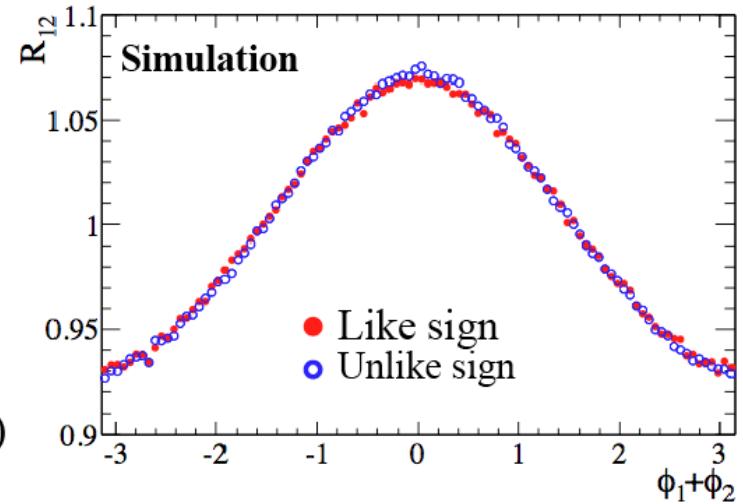
$$R_\alpha = \frac{N(\phi_\alpha)}{\langle N_\alpha \rangle} = a + b \cdot \cos(\phi_\alpha)$$

Proportional to the product (convolution) of the two Collins functions

- **The MC generator (JETSET) does not include the Collins effect, but it shows a strong cosine modulation**

- due to acceptance of the detector
- depends strongly on the thrust axis polar angle
- but similar distribution for **U** and **L** pairs

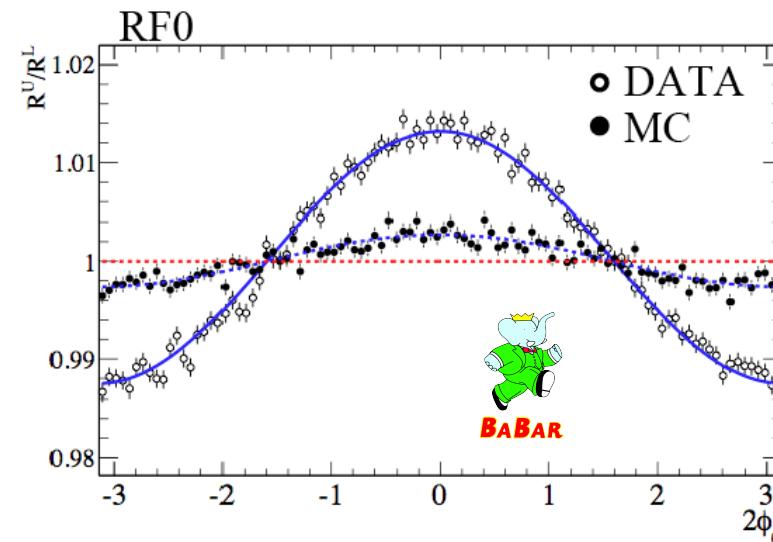
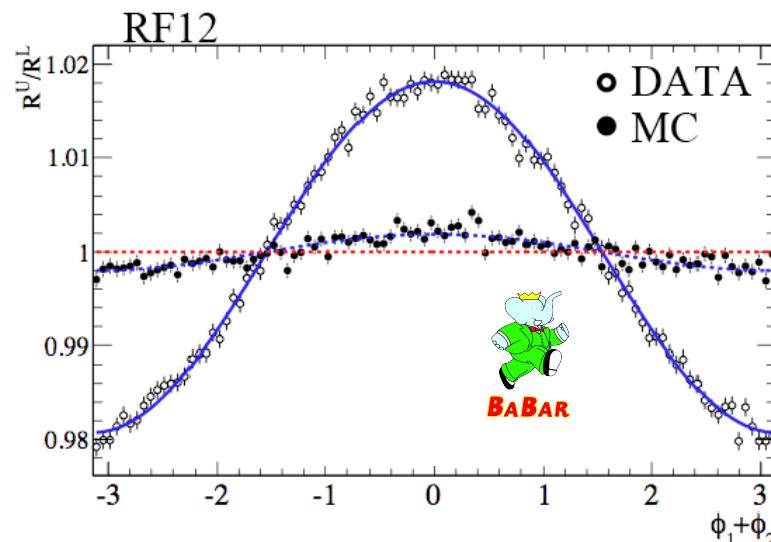
- **Data** shows a large difference between **U** and **L** distributions, that can be ascribed to the **Collins effect**



# Double Ratios

==> Acceptance effects can be reduced by performing the ratio of **Unlike/Like** sign pion pairs (or **Unlike/Charged**)

- small deviation from zero still present ( $\ll$  asymmetry measured in data sample)



**MC:** consistent with a flat distribution

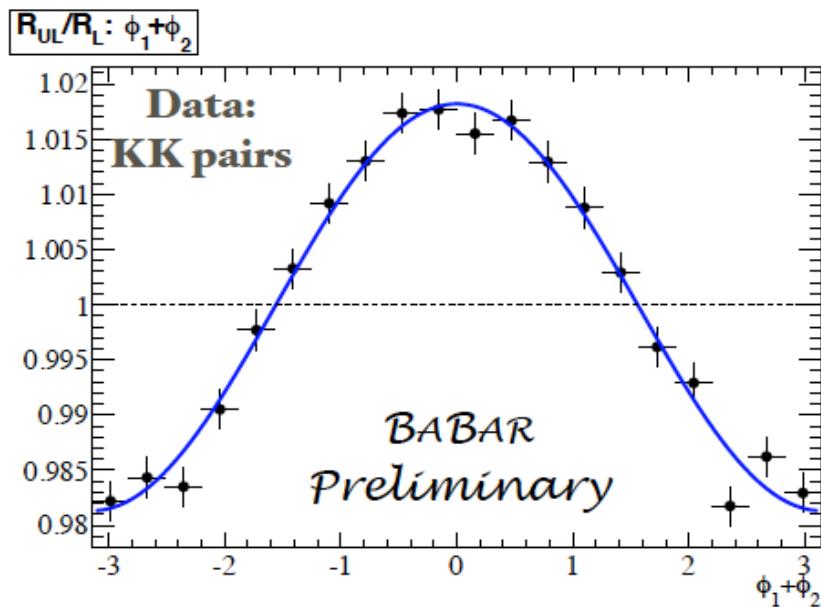
**DATA:** cosine modulation clearly visible

$$\frac{R_\alpha^U}{R_\alpha^{L(C)}} = \frac{N^U(\phi_\alpha) / \langle N^U(\phi_\alpha) \rangle}{N^{L(C)}(\phi_\alpha) / \langle N^{L(C)}(\phi_\alpha) \rangle} \rightarrow B_\alpha^{UL(UC)} + A_\alpha^{UL,(UC)} \cdot \cos(\phi_\alpha)$$

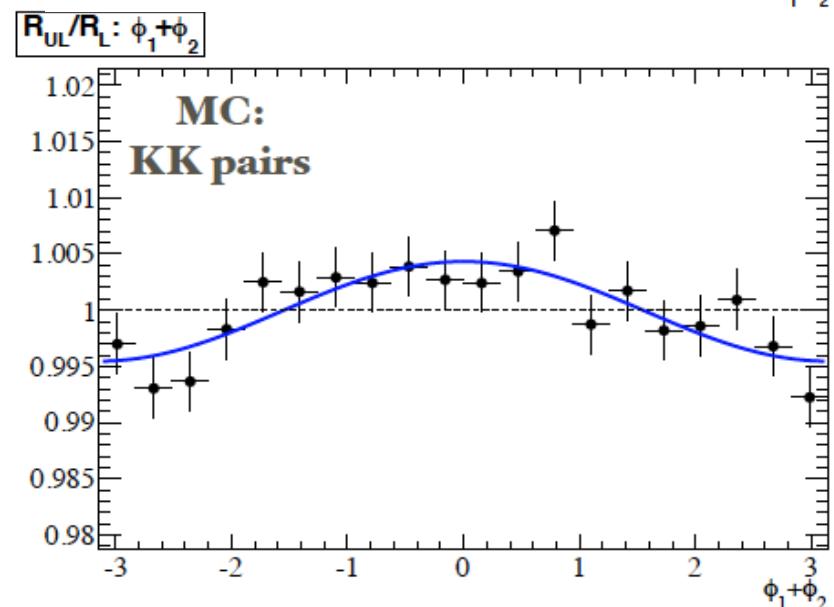
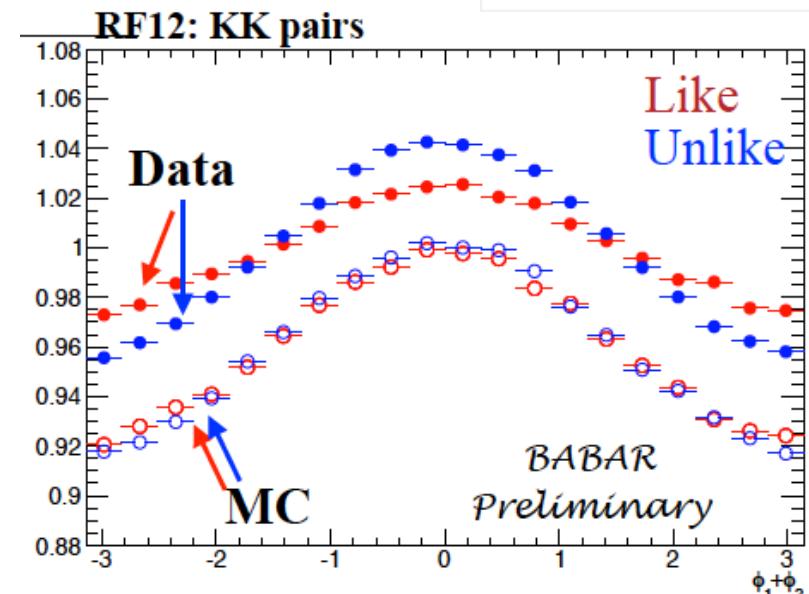
**A:** contains only the Collins effect and higher order radiative effects

# Raw and Ratio Data for KK

See the same trends in data for  $KK$  as for  $\pi\pi$  (both current and previous analyses)



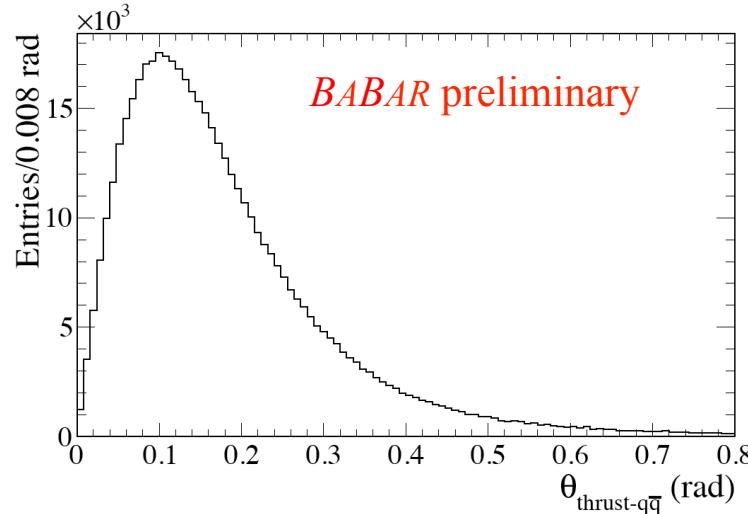
2015 Aug 6



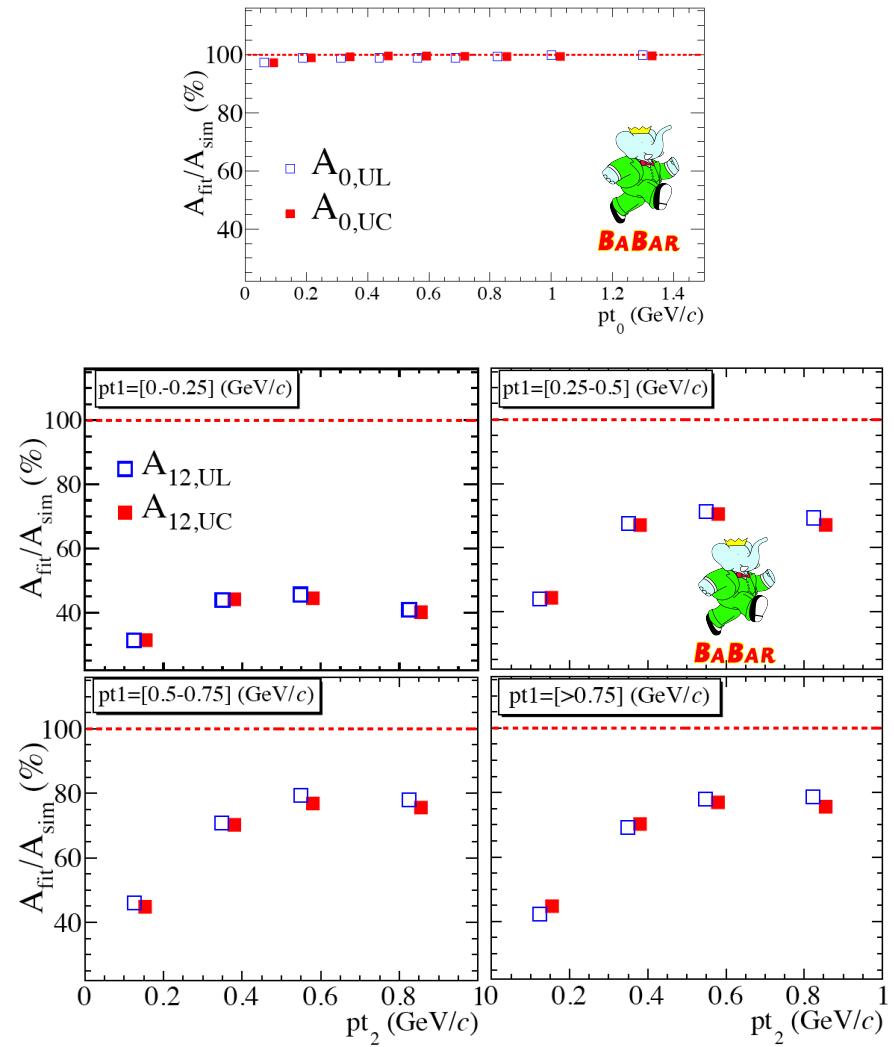
Polarized FF at BABAR – Brown, DPF15

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# Asymmetry dilution – thrust axis



Thrust axis reconstruction is not perfectly aligned with  $q\bar{q}$  axis.  
Introduces dilution of asymmetry in RF12. Correct through MC study.



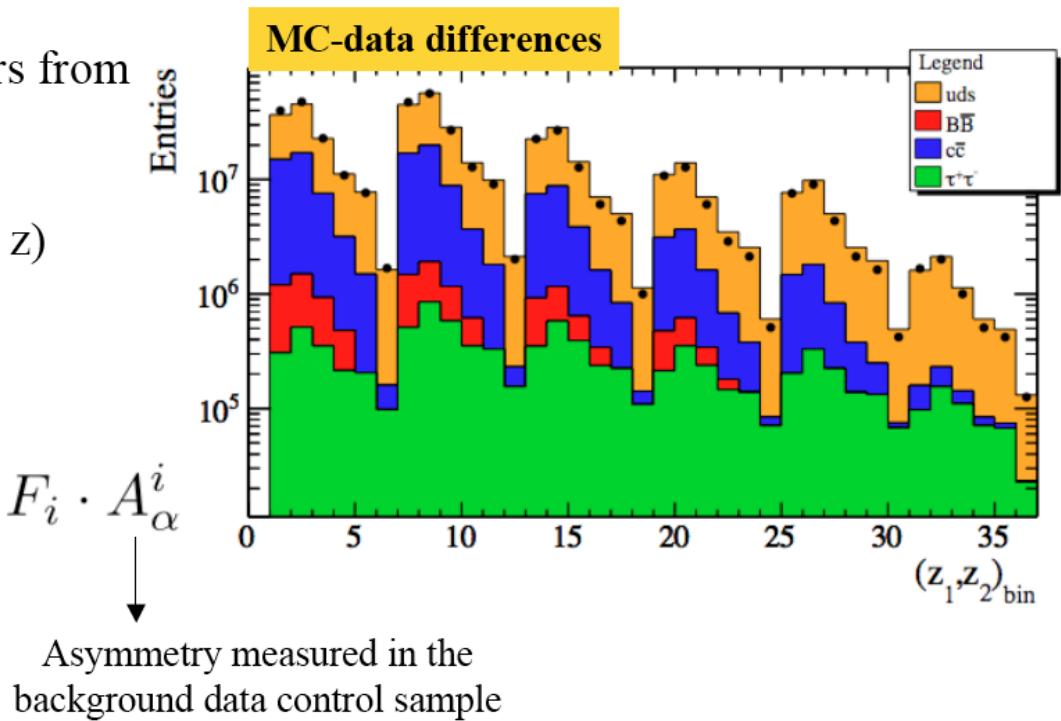
# Extracting uds asymmetry

- In each bin, the data sample includes pairs from
  - signal uds events
  - $B\bar{B}$  events (small, mostly at low z)
  - $c\bar{c}$  events (important at low/medium z)
  - $\tau^+\tau^-$  events (important at high z)
- We measure:

$$A_{\alpha}^{meas} = \left(1 - \sum_i F_i\right) \cdot A_{\alpha} + \sum_i F_i \cdot A_{\alpha}^i$$

↓  
**True  
asymmetry**

Fraction of pion pairs due to  
the  $i^{\text{th}}$  background process



Asymmetry measured in the  
background data control sample

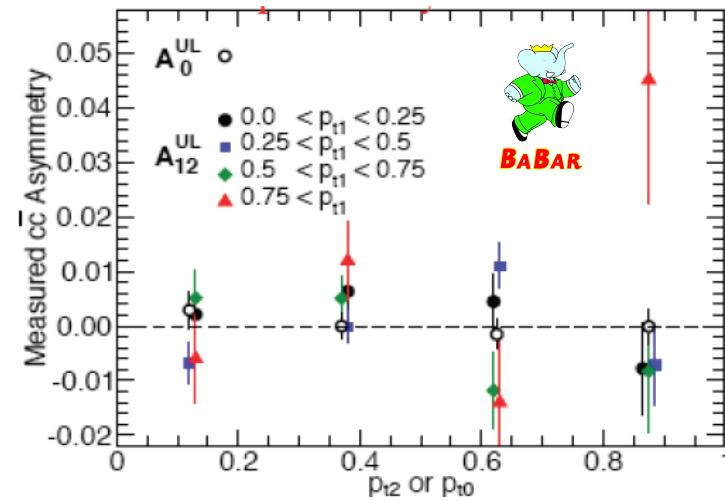
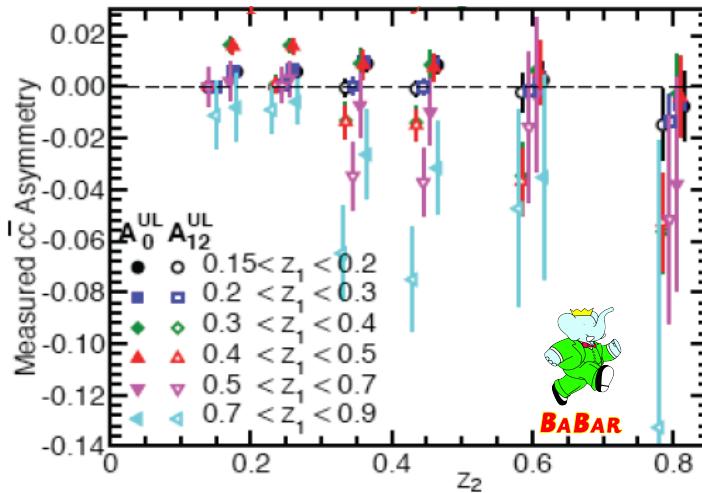
- We must calculate these quantities:
  - $F_i$  using MC sample; we assign MC-data difference in each bin as systematic error
  - $A^{B\bar{B}}$  must be zero; we set  $A^{B\bar{B}} = 0$
  - $A^{\tau}$  small in simulation; checked in data; we set  $A^{\tau} = 0$

## Extracting uds Asymmetry 2

- Charm background contribution is about 30% on average
  - Both fragmentation processes and weak decays can introduce azimuthal asymmetries
  - We used a **D<sup>\*±</sup>-enhanced control sample** to estimate its effect on a **bin-by-bin basis**
  - 4 complementary decay modes D<sup>\*±</sup>→D<sup>0</sup>π<sup>±</sup>, with D<sup>0</sup>→Kπ, K3π, Kππ<sup>0</sup>, K<sub>s</sub>ππ
  - mostly c̄c events, some B̄B̄
- Again, f<sub>i</sub> from MC, data-MC difference as systematic error

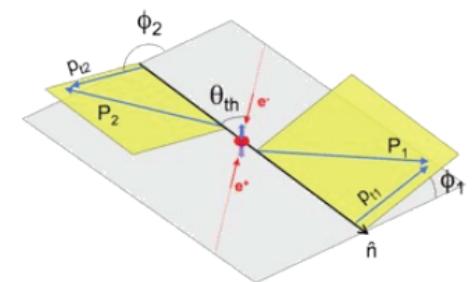
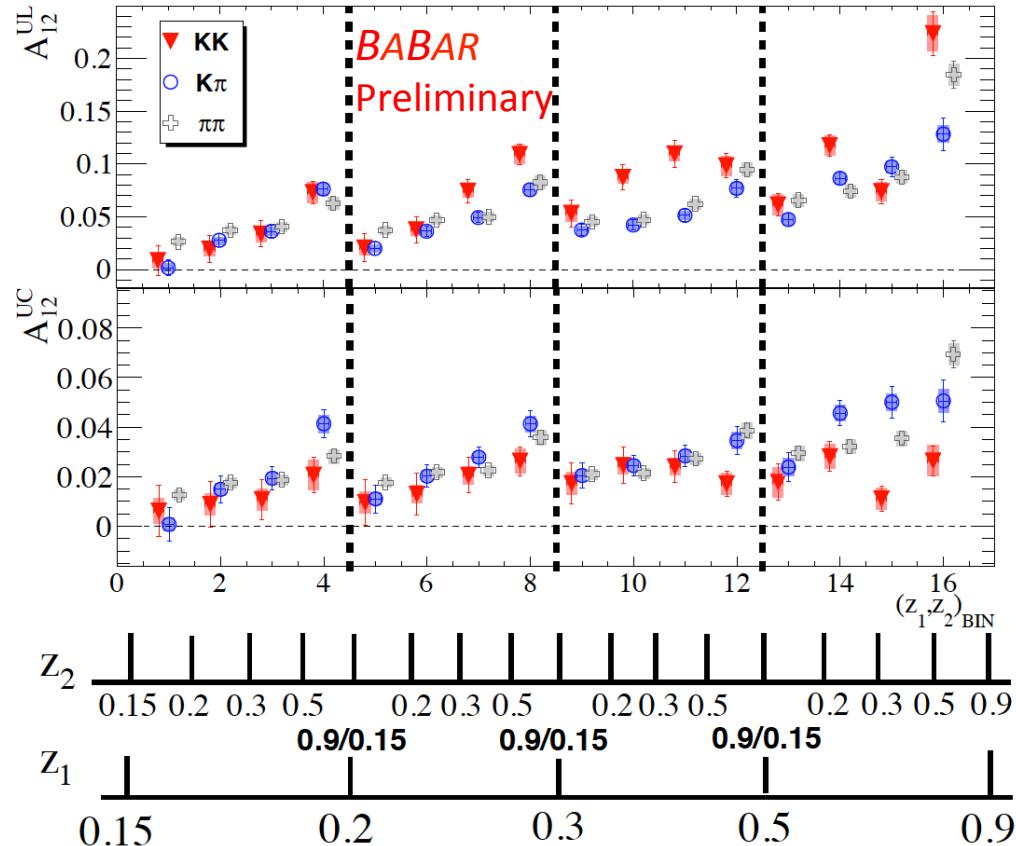
$$A_{\alpha}^{meas} = (1 - F_c - F_B - F_{\tau}) \cdot A_{\alpha} + F_c \cdot A_{\alpha}^{ch}$$

$$A_{\alpha}^{D^*} = f_c \cdot A_{\alpha}^{ch} + (1 - f_c - f_B) \cdot A_{\alpha}$$



- the  $A^{ch}$  are very small (slightly negative? )

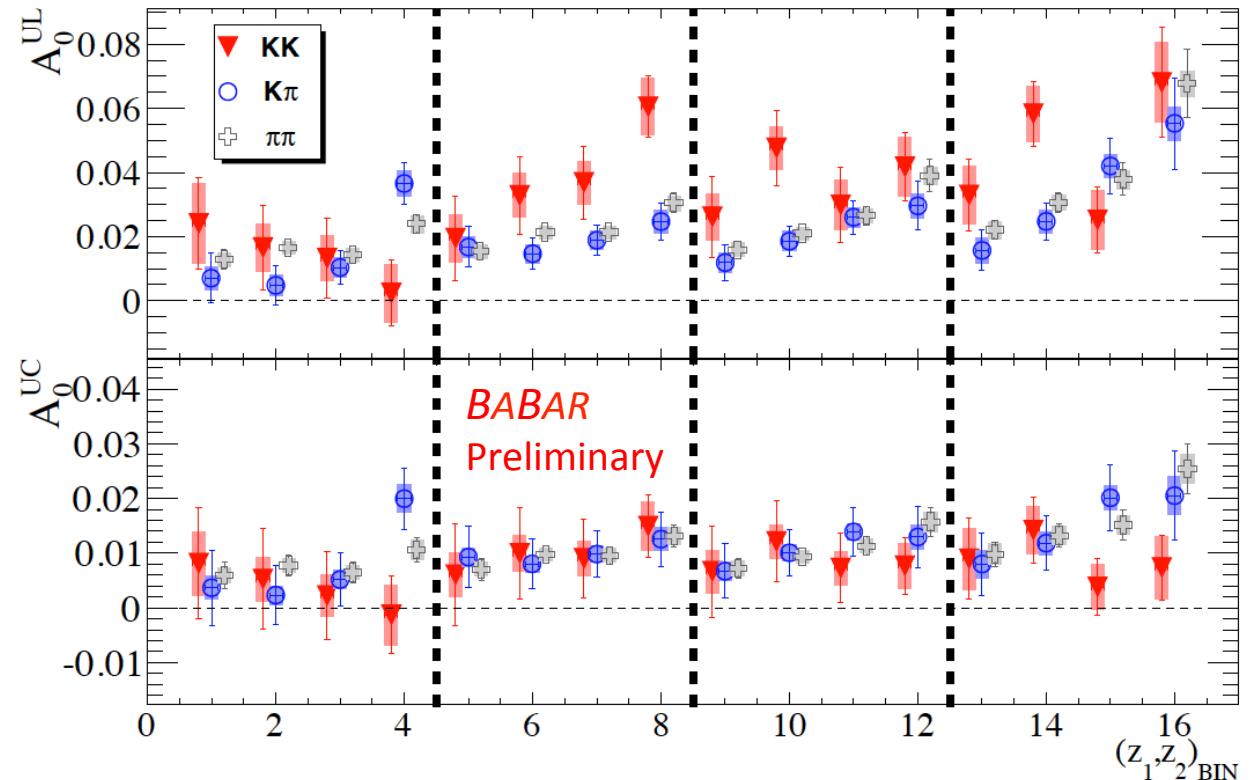
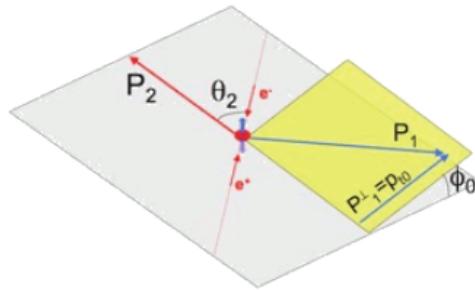
# Results: $A_{12}$ vs $(z_1, z_2)$



- **Very significant nonzero  $A^{UL}$  and  $A^{UC}$**

⇒ strong dependence on  $(z_1, z_2)$ ,  
⇒  $A^{UC} < A^{UL}$  as expected; complementary information about the favored and disfavored fragmentation processes (PRD 73, 094025 (2006))  
⇒ consistent with  $z_1 \Leftrightarrow z_2$  symmetry

# Results: $A_0$ vs $(z_1, z_2)$



- **Very significant nonzero  $A_0^{\text{UL}}$  and  $A_0^{\text{UC}}$** 
  - ⇒ strong dependence on  $(z_1, z_2)$ ,
  - ⇒ smaller than  $A_{12}$ ;
  - ⇒  $A_0^{\text{UC}} < A_0^{\text{UL}}$ ; complementary information on  $H_1^{\perp, \text{fav}}$  and  $H_1^{\perp, \text{dis}}$
  - ⇒ consistent with  $z_1 \Leftrightarrow z_2$  symmetry



# Summary & Conclusions



- *BABAR* continues producing interesting and competitive results.
- *BABAR* has measured Collins asymmetries for charged hadron pairs in two-jet events. Measurements are made in two different reference frames.
  - Asymmetries increase with increasing fractional energy for  $\pi\pi$  and  $K\pi$  but the same can not be concluded for  $KK$
  - Improves our understanding of quark fragmentation.
  - New results for  $\pi\pi$  in study including  $K$ 's consistent with previous study using only pions
  - Results consistent with theoretical predictions (**PLB659**, 234 (2009); **PRD86**, 034025 (2012))

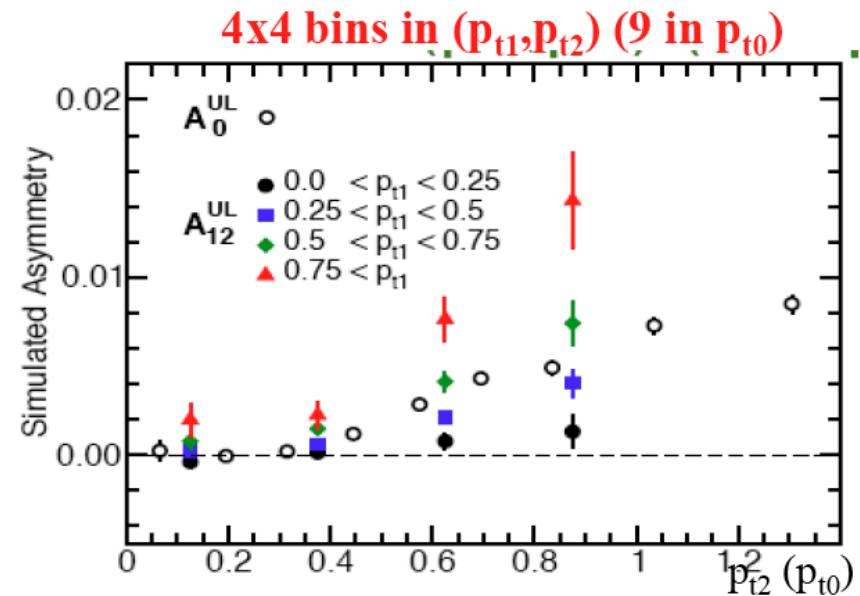
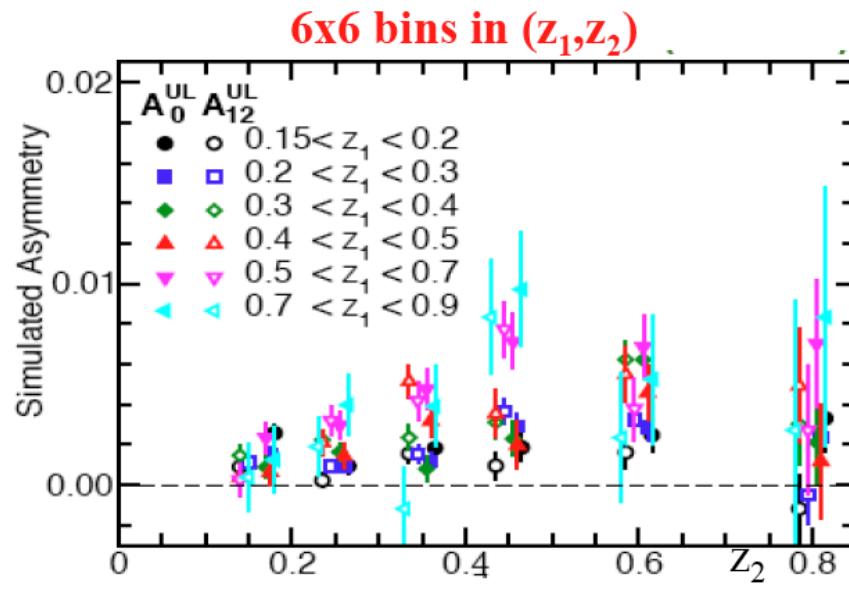
Results reported in **PRD90**, 052003 (2014) and  
**ArXiv:1506.05864** (Submitted to Phys. Rev. Lett.)

**Thank You!**

# Back Up Slides

# Asymmetry binning and corrections

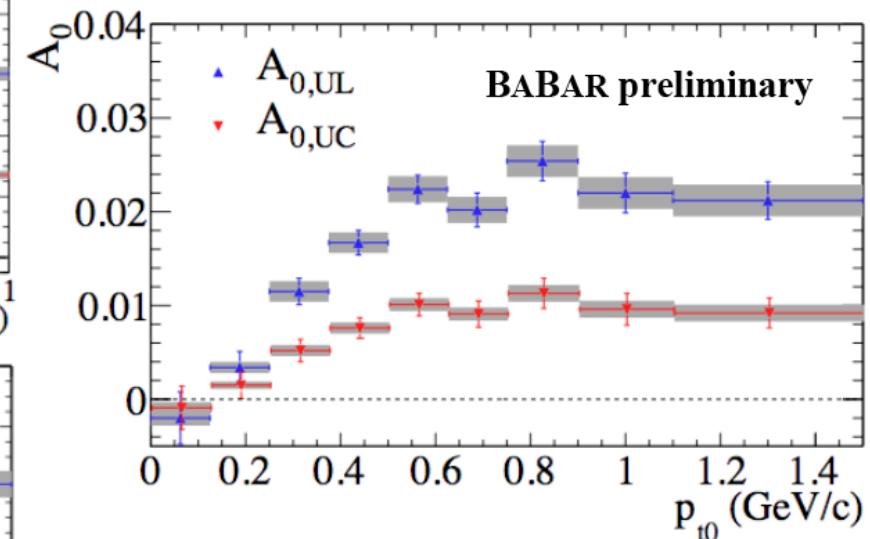
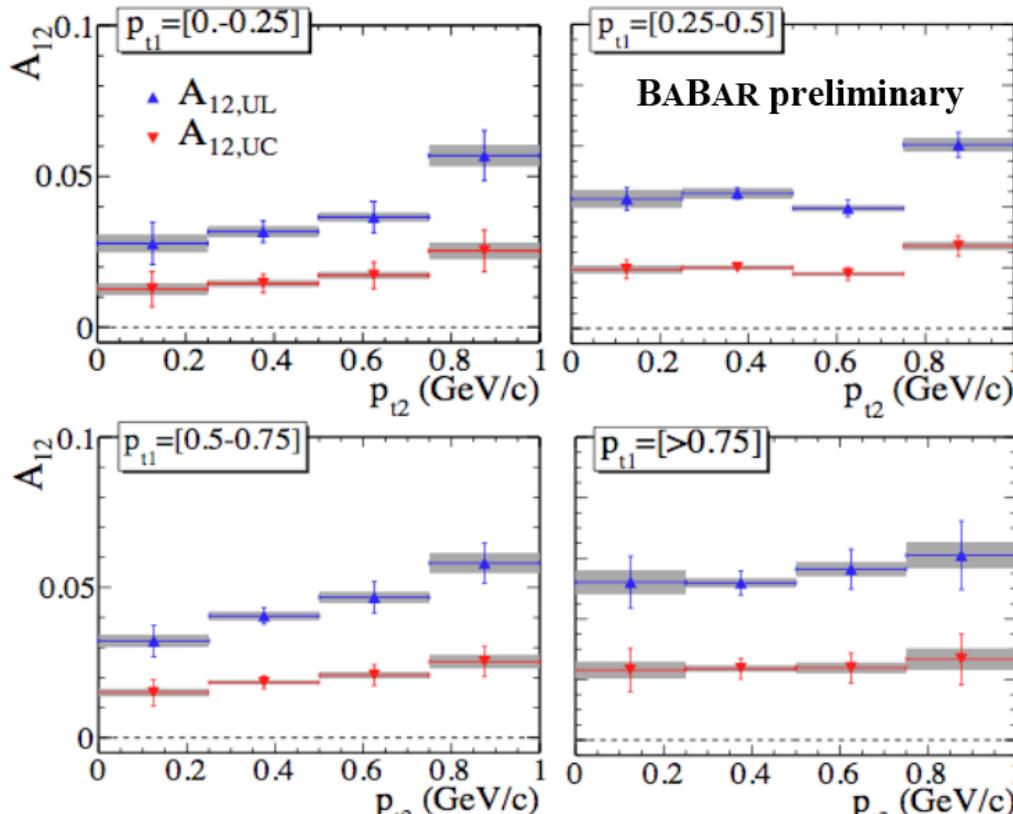
- The Collins effect is expected to depend on  $z_1$ ,  $z_2$ ,  $p_{t1}$ ,  $p_{t2}$  (or  $p_{t0}$ ), as well as  $\cos\theta_{th}$  (or  $\cos\theta_2$ )  
 ⇒ analyze in bins of these quantities:



After reconstruction, simulated data shows small asymmetry due to detector acceptance effects. Correct for this on a bin-by-bin basis

Systematic effect on MC value evaluated by varying track/event selections

# Asymmetries vs. transverse momenta

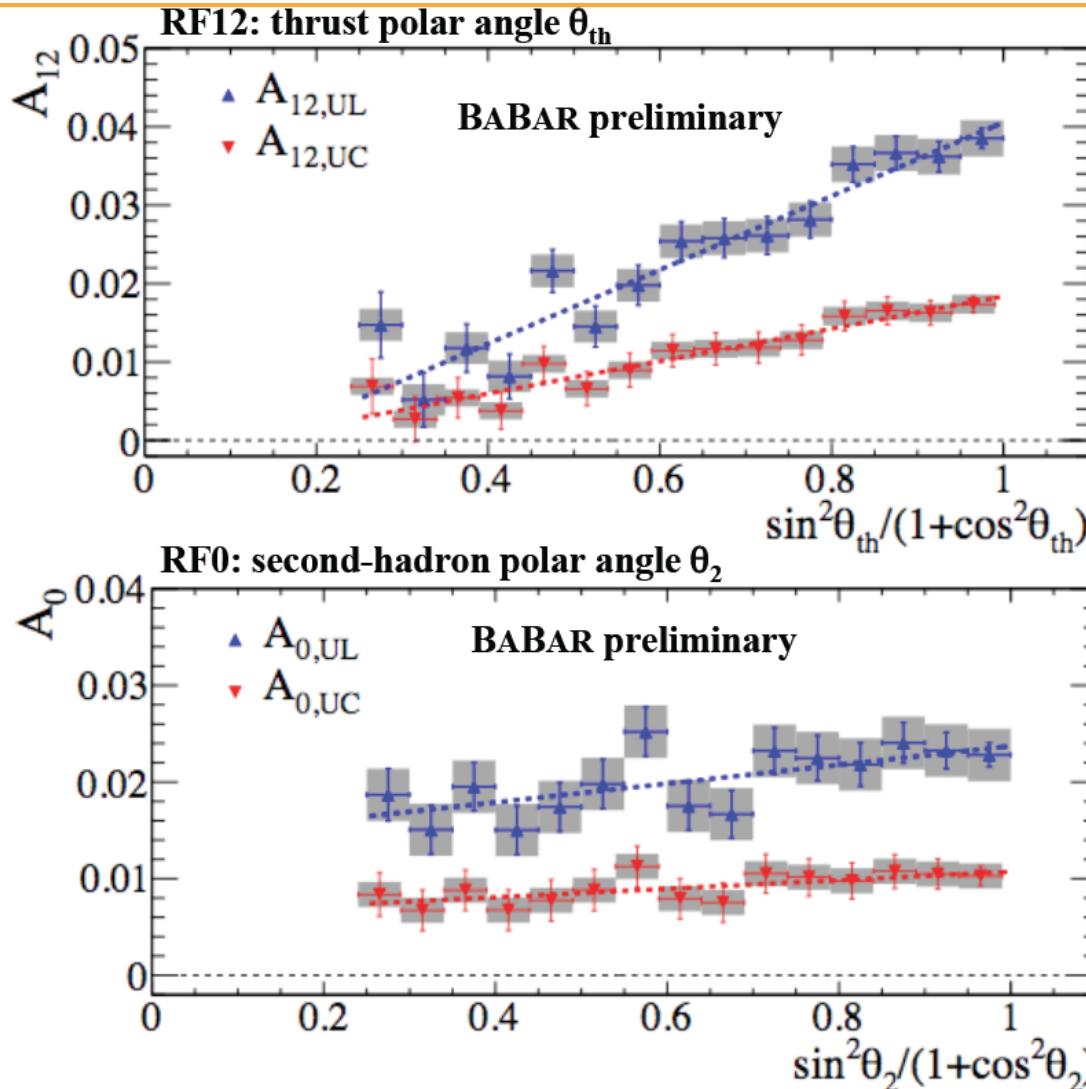


**FIRST MEASUREMENT of Collins asymmetries  $\text{vs. } p_t$  in  $e^+e^-$  annihilation at  $Q^2 \sim 110 \text{ (GeV/c)}^2$  (time-like region)**

- nonzero  $A^{\text{UL}}$  and  $A^{\text{UC}}$

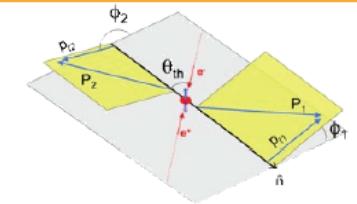
- ⇒ only modest dependence on  $(p_{t1}, p_{t2})$ ; disagreement with the expectation
- ⇒  $A^{\text{UC}} < A^{\text{UL}}$ ; complementary information on  $H_1^{\perp, \text{fav}}$  and  $H_1^{\perp, \text{dis}}$
- ⇒  $A_0 < A_{12}$ , but interesting structure in  $p_t$

## Results: Angular comparison



$$A_{12} \propto \frac{\sin^2 \theta_{th}}{1 + \cos^2 \theta_{th}} \cos(\phi_1 + \phi_2) \frac{H_1^\perp(z_1) \bar{H}_1^\perp(z_2)}{D_1(z_1) \bar{D}_1(z_2)}$$

==> Intercept consistent with zero, as expected (consistent with Belle results)



$$A_0 \propto \frac{\sin^2 \theta_2}{1 + \cos^2 \theta_2} \cos(2\phi_0) \mathcal{F} \left[ \frac{H_1^\perp(z_1) \bar{H}_1^\perp(z_2)}{D_1(z_1) \bar{D}_1(z_2)} \right]$$

==> The linear fit gives a non-zero constant parameter → the second hadron momentum provides a worse estimation of the  $q\bar{q}$  direction (consistent with Belle results)

