SLAC NATIONAL ACCELERATOR LABORATORY

Measurement of Collins Asymmetries in inclusive production of pion pairs in e^+e^- interactions at BaBar

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BABAR

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Outline

INTRODUCTION
- Theoretical framework
  - Collins Fragmentation Function in e^+e^- annihilation

ANALYSIS OVERVIEW
- Reference frames and analysis method
- Extraction of the asymmetry for light quarks
- Asymmetry corrections and studies of systematic uncertainties

RESULTS
- Asymmetries *vs.* fractional energies, pion transverse momentum, and analysis axis polar angle
- Comparison with Belle measurements

CONCLUSIONS

Collins Fragmentation Function in e^+e^- annihilation

Fragmentation Functions (FFs):
- dimensionless and universal functions
- describe hadrons *h* in a quark (or gluon) jet in terms of $z=p_h/k_q$, and $P_\perp$ of *h* with respect to the fragmenting quark direction.

For spinless hadron in a quark jet:

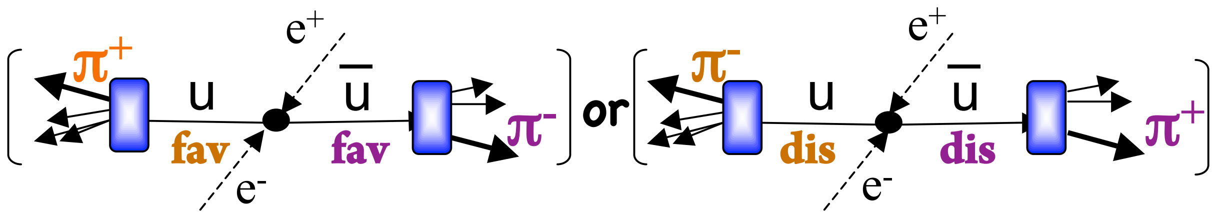
$$D_1^{q\uparrow}(z, \mathbf{P}_\perp; s_q) = D_1^q(z, P_\perp) + \frac{P_\perp}{zM_h} H_1^{\perp q}(z, P_\perp)\, \mathbf{s}_q \cdot (\mathbf{k}_q \times \mathbf{P}_\perp)$$

$H_1^\perp$: polarized FF or **Collins** FF
- transversely polarized quark → spinless hadron
- **chiral-odd** function

Collins effect (or Collins asymmetry): introduces an azimuthal modulation with respect to q spin direction
- should appear (mostly) in leading particles

In $e^+e^- \to q\bar{q}$, spins unknown but $s_q \parallel s_{\bar{q}}$
- correlation between two pions detected in opposite jet
- define **favored** ($u\to\pi^+$, $d\to\pi^-$) and **disfavored** ($d\to\pi^+$, $u\to\pi^-$) FFs, and consider the combination:

Unlike-sign pion pair = **U** ($\pi^\mp\pi^\pm$): (**fav x fav**)+(**dis x dis**)



Like-sign pion pair
$\pi^\pm\pi^\pm$ (**L**): (**fav x dis**)+(**dis x fav**)

Charged pion pair
$\pi\pi$ (**C**): (**fav + dis**)x(**fav + dis**)

Event and track selection

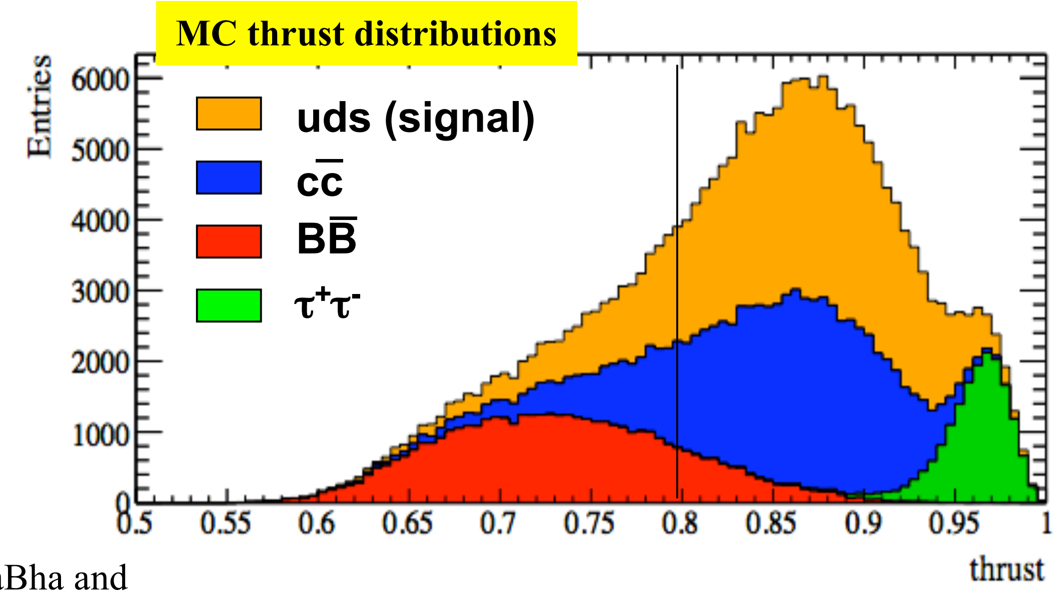
EVENT SELECTION:

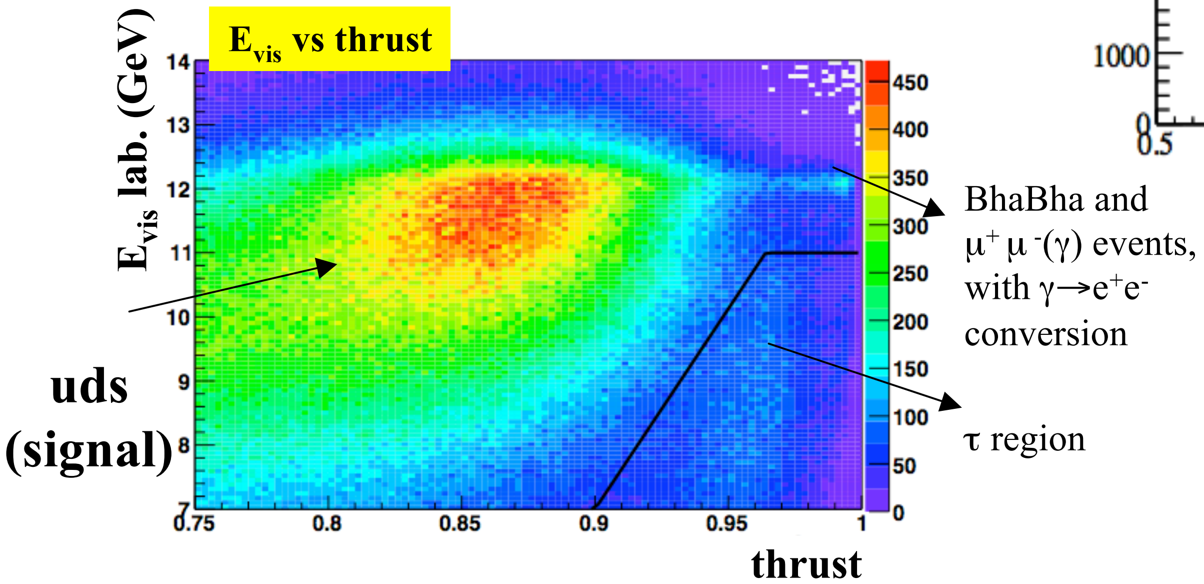
→ Number of charged tracks > 2

→ Visible energy: E_{vis} **> 7 GeV**

→ Selection of two-jet topology events requiring **thrust>0.8**

→ Events in the $\tau^+\tau^-$ region removed





TRACK SELECTION:

→ $\mu^\pm$ and $e^\pm$ veto, and pion ID required

→ Tracks in the detector acceptance region: $0.41<\theta_{lab}<2.54$ rad.

→ Pion fractional energies $\mathbf{0.15<z=2E_h/\sqrt{s}<0.9}$

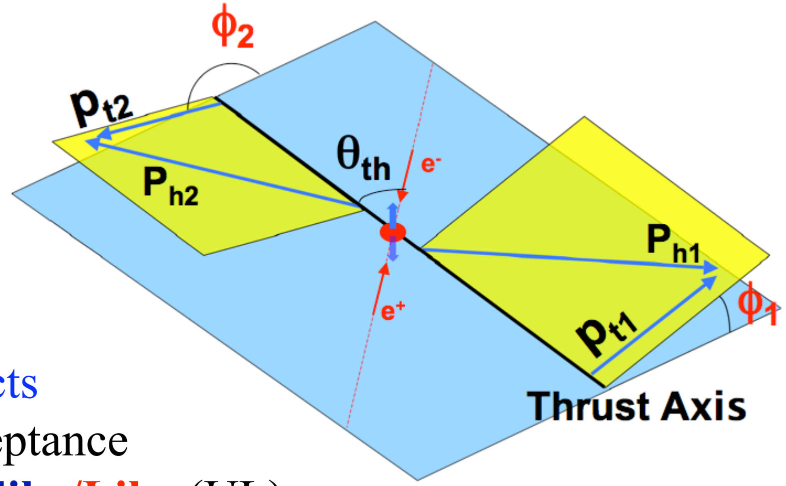
→ Opening angle ($\theta_{pi\text{-}thrust}$) of each pion with respect to the thrust axis < 45°

→ **Q_t<3.5 GeV** to reduce gluon radiation (where Q_t is the transverse momentum of the virtual photon in the pions center of mass frame)

RF12: Double ratio method

Two reference frames used in literature: Nucl.Phys. **B** 806,23 (2009)
PRD 78, 032011 (2008)

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



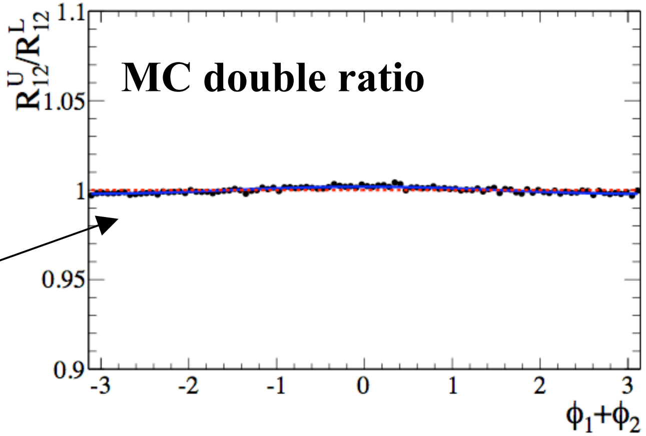
$\phi_{12}=\phi_1+\phi_2$ or Thrust RF (RF12)

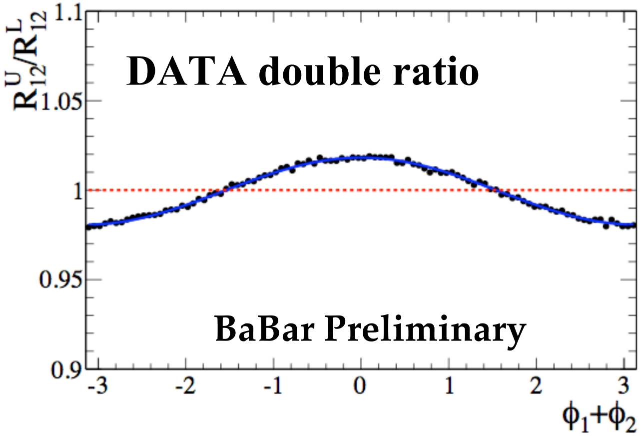
$$\sigma \sim 1 + \frac{\sin^2\theta_{th}}{1+\cos^2\theta_{th}} \cos(\phi_1+\phi_2) \frac{H_1^\perp(z_1)\bar{H}_1^\perp(z_2)}{D_1(z_1)\bar{D}_1(z_2)}$$

- The MC generator (JETSET) does not include the Collins effects
  - large modulation observed in MC sample due to detector acceptance
- Acceptance effects can be removed performing the ratio of **Unlike/Like** (UL) sign pion pairs (or **Unlike/Charged** (UC)):

$$\frac{R_\alpha^U}{R_\alpha^{L(C)}} = \frac{N^U(\phi_\alpha)/<N^U(\phi_\alpha)>}{N^{L(C)}(\phi_\alpha)/<N^{L(C)}(\phi_\alpha)>} \rightarrow B_\alpha^{UL(UC)} + A_\alpha^{UL,(UC)} \cdot \cos(\phi_\alpha) \quad (\alpha=12)$$

small deviation from zero
still present in MC sample
==> systematic errors



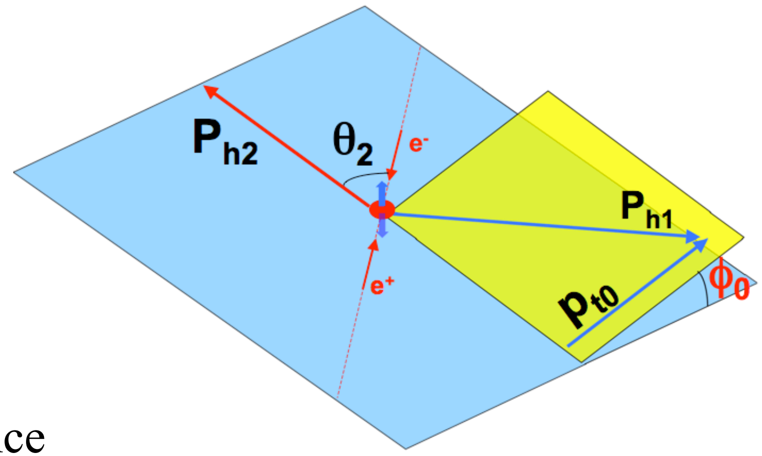


RF0: Double ratio method

$2\phi_0$ or Second hadron momentum RF (RF0)

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

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



- The MC generator (JETSET) does not include the Collins effects
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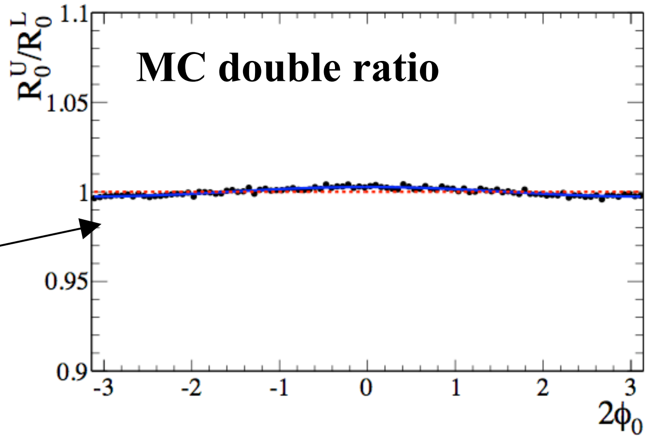
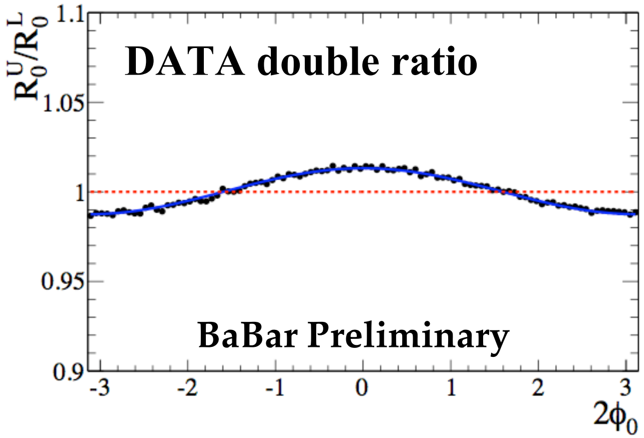
small deviation from zero still present in MC sample ==> systematic errors





Asymmetry corrections and systematic effects

==> We study the Collins asymmetry *vs.* pion fractional energies (z_1 and z_2), pion transverse momentum (p_{t1}, p_{t2}, and p_{t0}), polar angles θ_{th}, and θ_2

==> The asymmetry measurement is affected by a number of **systematic effects.** We study possible systematic contributions and correct the asymmetries independently **for each *z* and p_t bin**

The main corrections and contributions to systematic effects are:

• Background contamination from charm (~30%), bottom, and τ events which survives the selection;

- We use a **$D^{*\pm}$-enhanced control sample** to estimate this effect on a **bin-by-bin basis**:

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

F_i and f_i are estimated using MC control samples

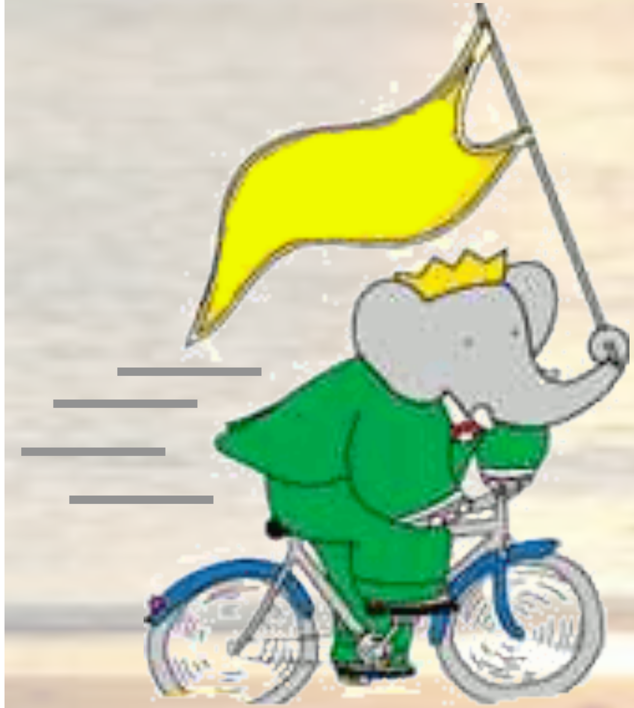
uds Collins asymmetry

• **A significant source of systematic error can arise from the fraction F_i (f_i) estimated using MC samples:** we assign the bin-by-bin discrepancies in the value of F_i (f_i) between MC and data as systematic uncertainties

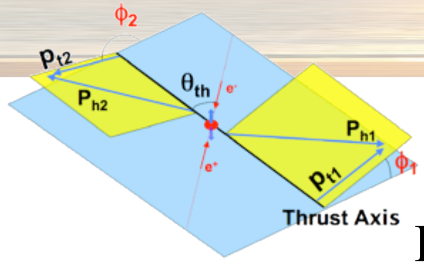
• **Asymmetry dilution due to the thrust axis approximation as the $q\bar{q}$ axis**. The statistical error of the correction is taken as systematic error

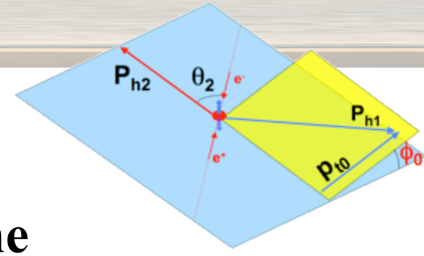
•**Asymmetries measured in the *uds* Monte Carlo:** we subtract the small asymmetry observed in the MC sample; we vary the track selection criteria in order to evaluate the systematic error

RESULTS

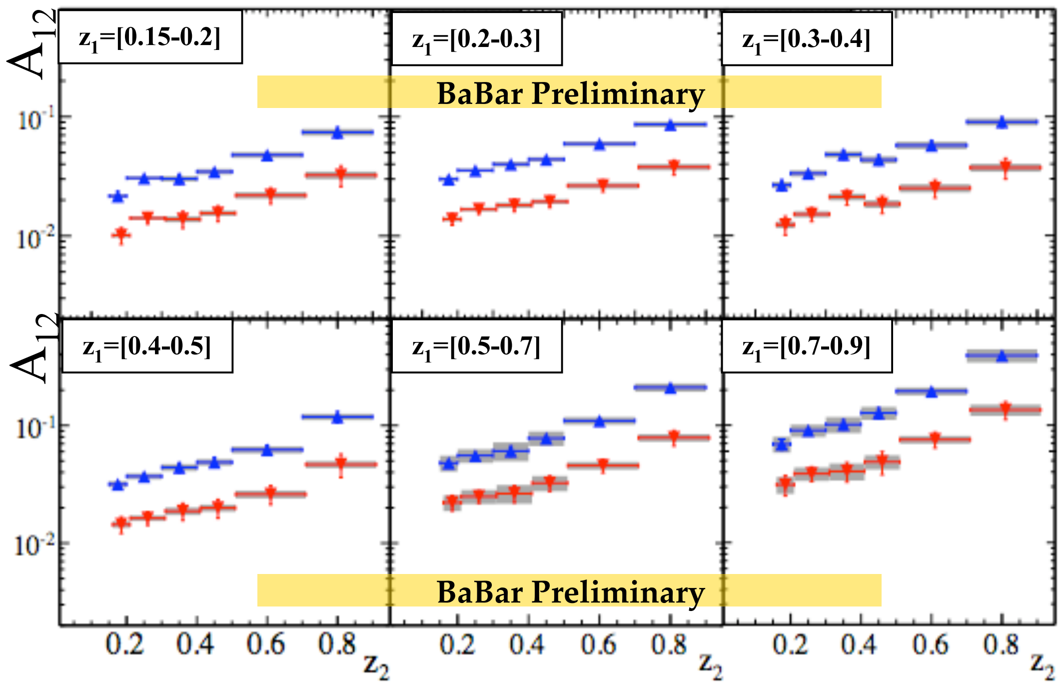


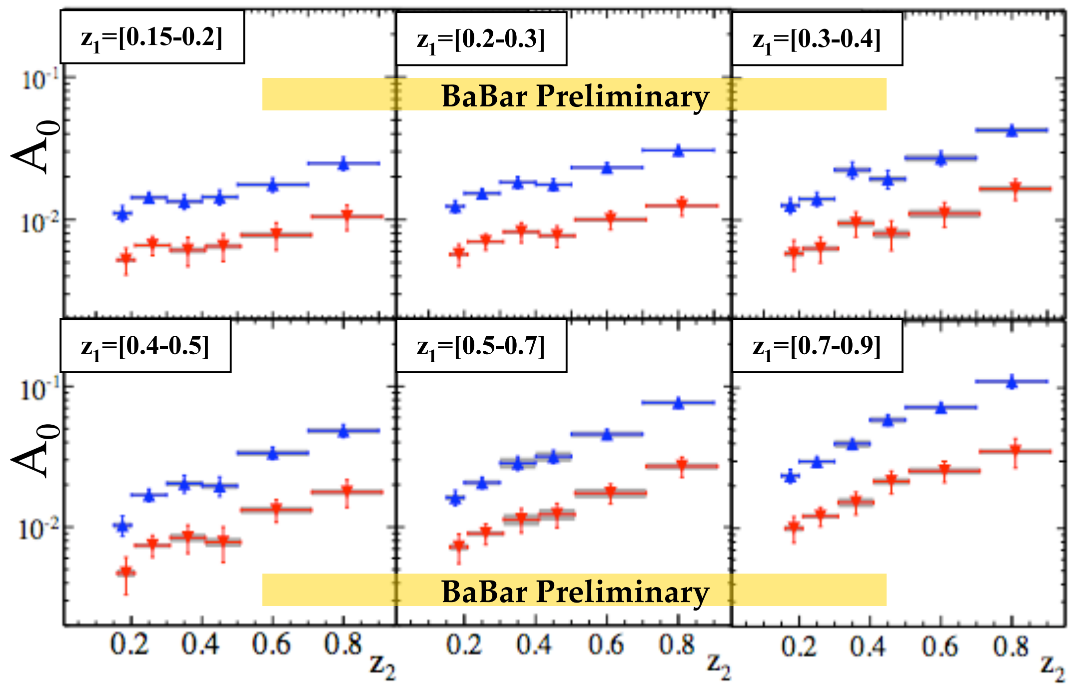
Collins asymmetry vs. z





RF12 frame | **RF0 frame**



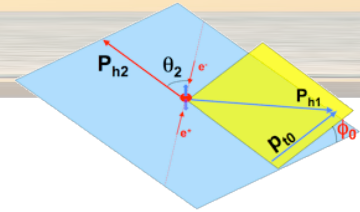


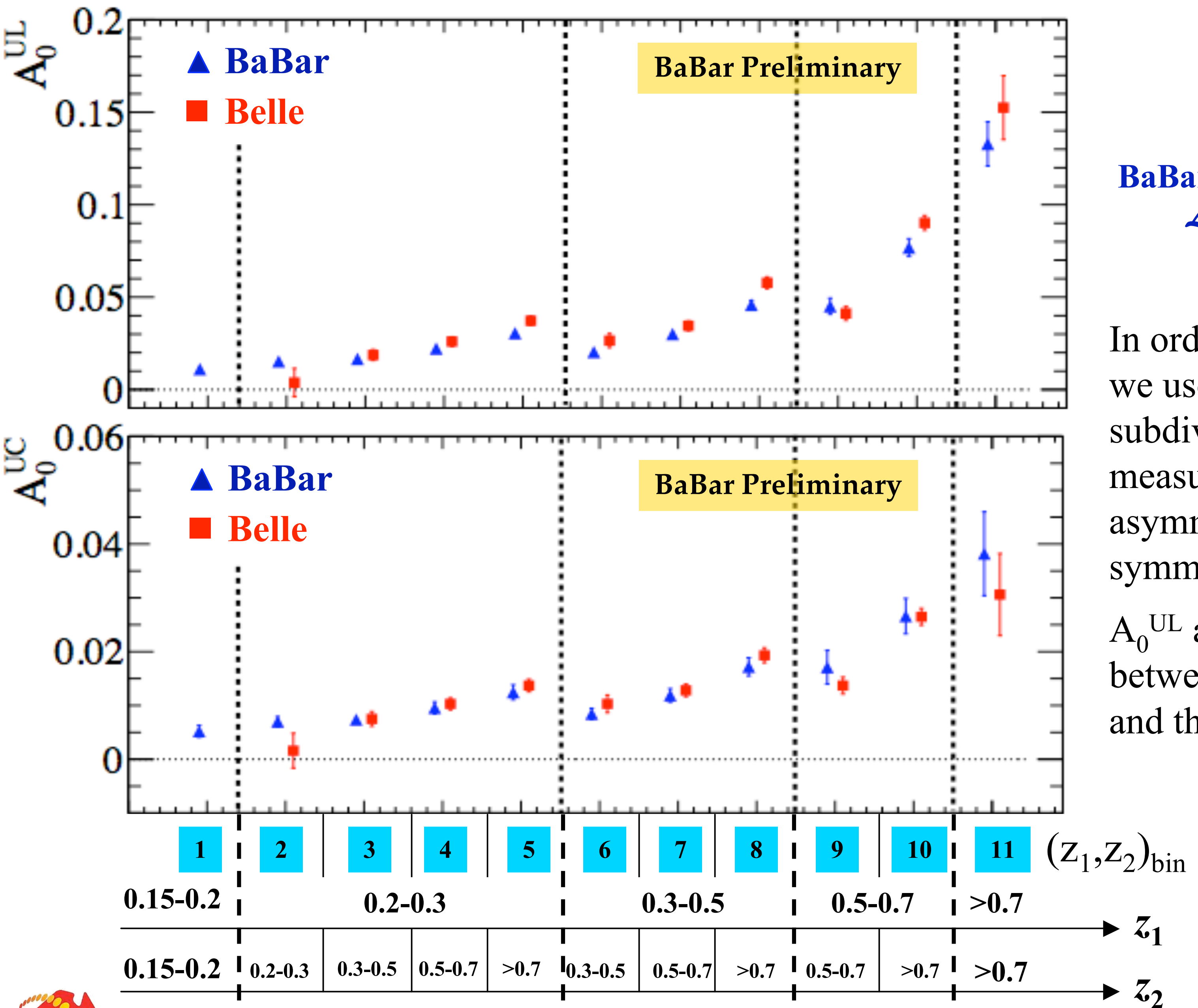
Systematic errors indicated by shaded bands

1) The asymmetry increases significantly with *z* (note log y-axis), as expected
(RF12: 1-39 %, RF0: 0.5-15 %)

2) UC (▼) double ratio significantly smaller than UL (▲) (PRD 73, 094025 (2006))

RFO: BaBar/Belle asymmetry comparisons





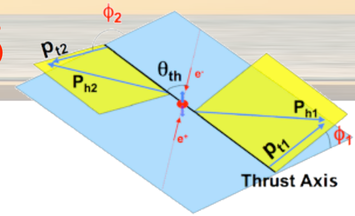
BaBar (0.15<*z*<0.9)
$\mathcal{L}$~470 fb^{-1}

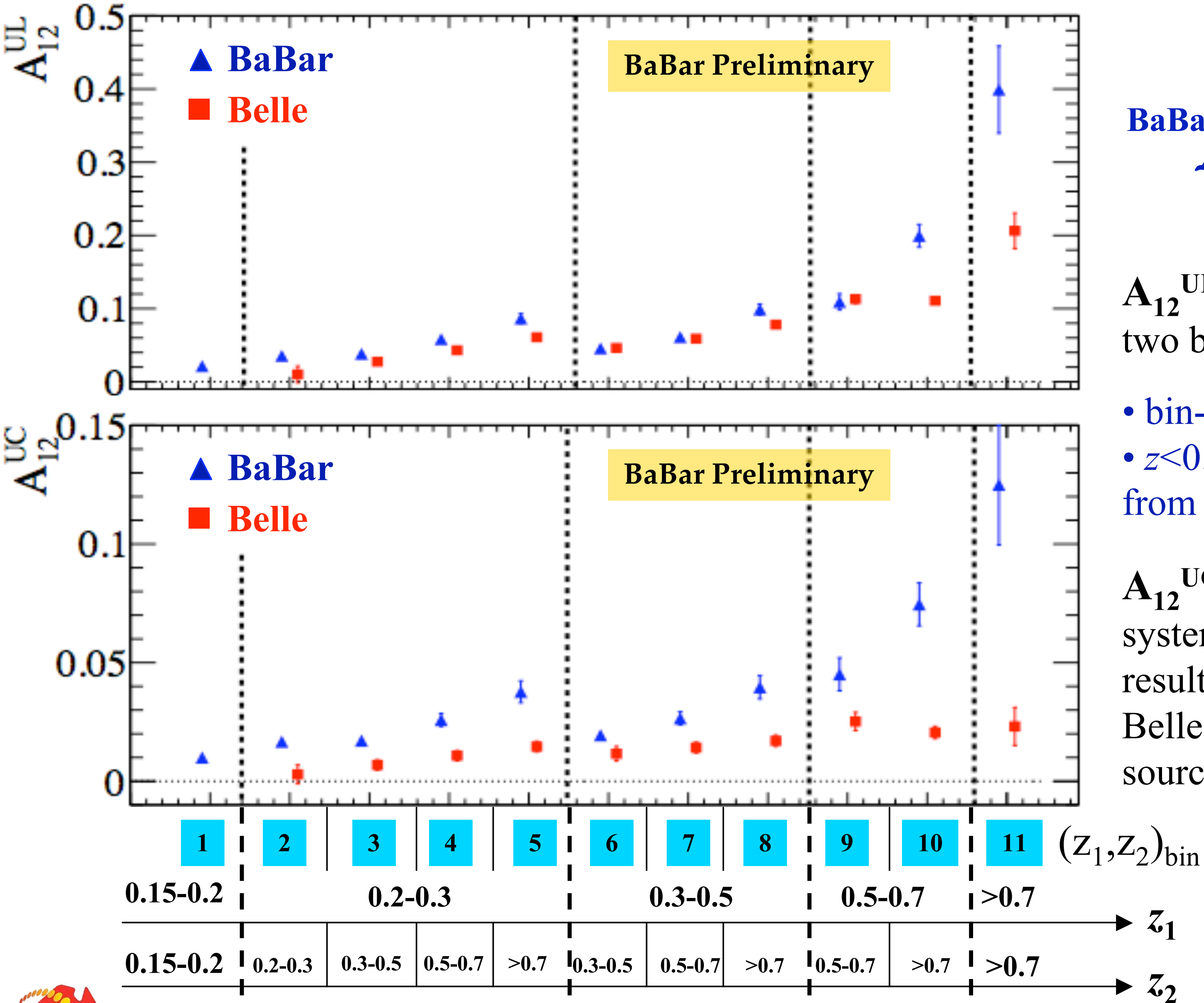
Belle (0.2<*z*<1)
$\mathcal{L}$~547 fb^{-1}
PRD 78, 032011 (2008)

In order to perform this comparison, we used 10 (+1) symmetrized *z*-bin subdivisions, averaging the measured Belle and BaBar asymmetries which fell in the same symmetric bins

A_0^{UL} and A_0^{UC} : good agreement between the BaBar asymmetries and the Belle results.

RF12: BaBar/Belle asymmetry comparisons





BaBar (0.15<z<0.9) **Belle (0.2<z<1)**

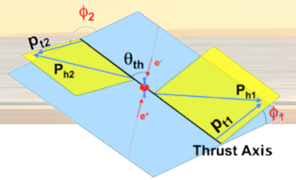
$\mathcal{L}$~470 fb^{-1} **$\mathcal{L}$~547 fb^{-1}**

PRD 78, 032011 (2008)

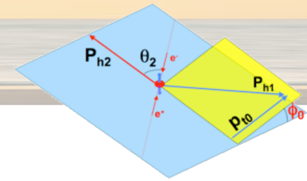
A_{12}^{UL}: large discrepancy in the last two bins of z

- bin-by-bin correction factors (30%)
- z<0.9 to remove the contamination from μμγ background events

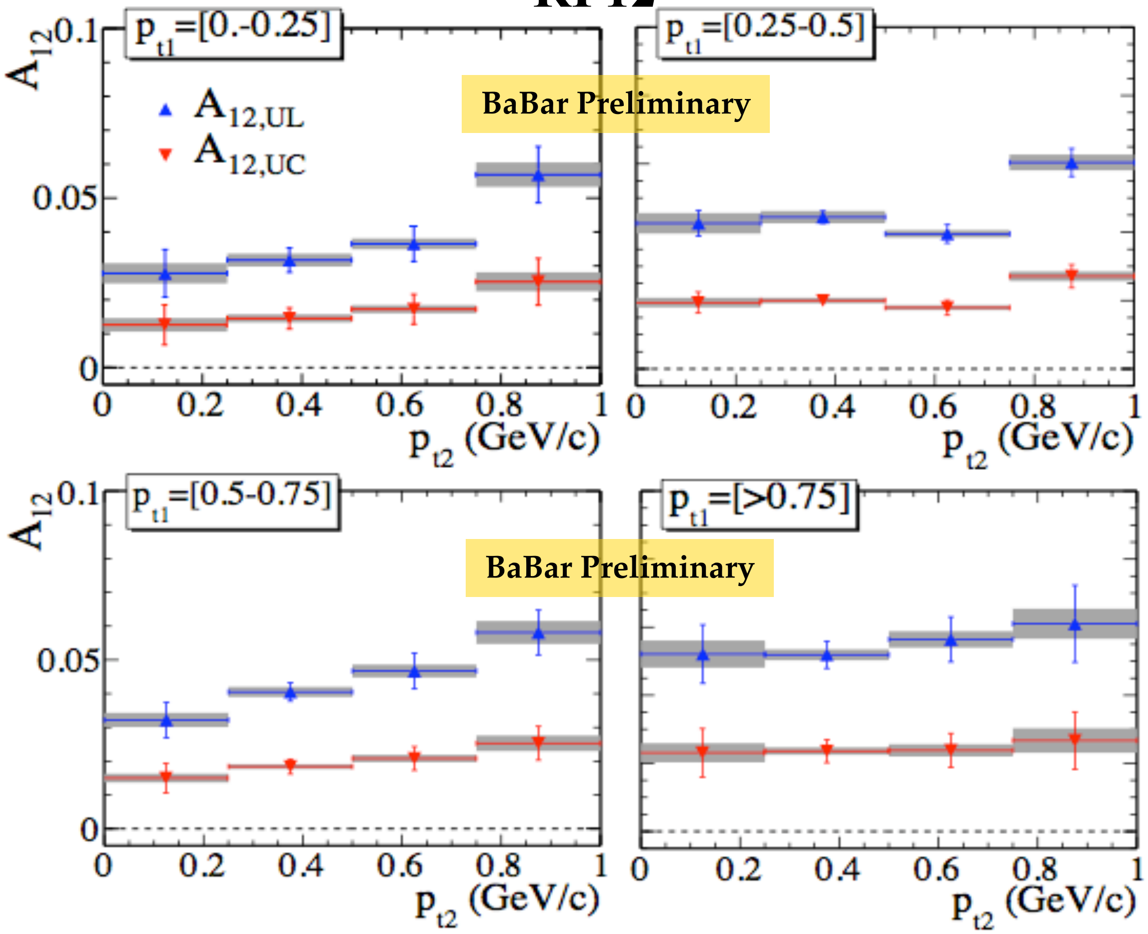
A_{12}^{UC}: BaBar asymmetry systematically above the Belle results for all z.
Belle analysts are investigating the source of discrepancies.



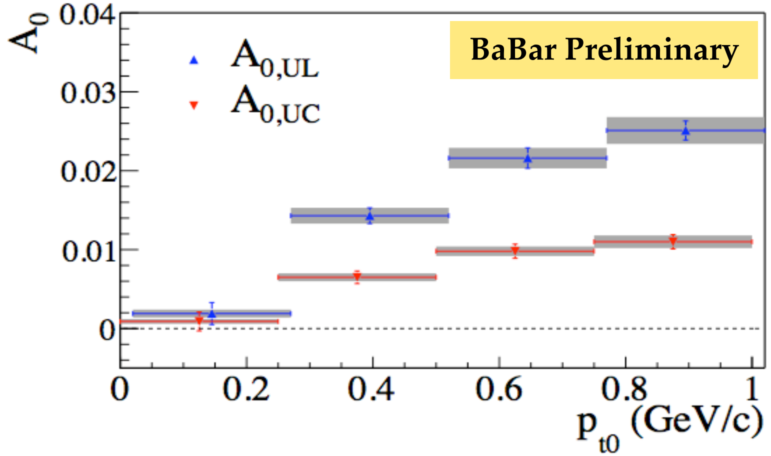
Collins asymmetry vs. p_t



RF12



RF0



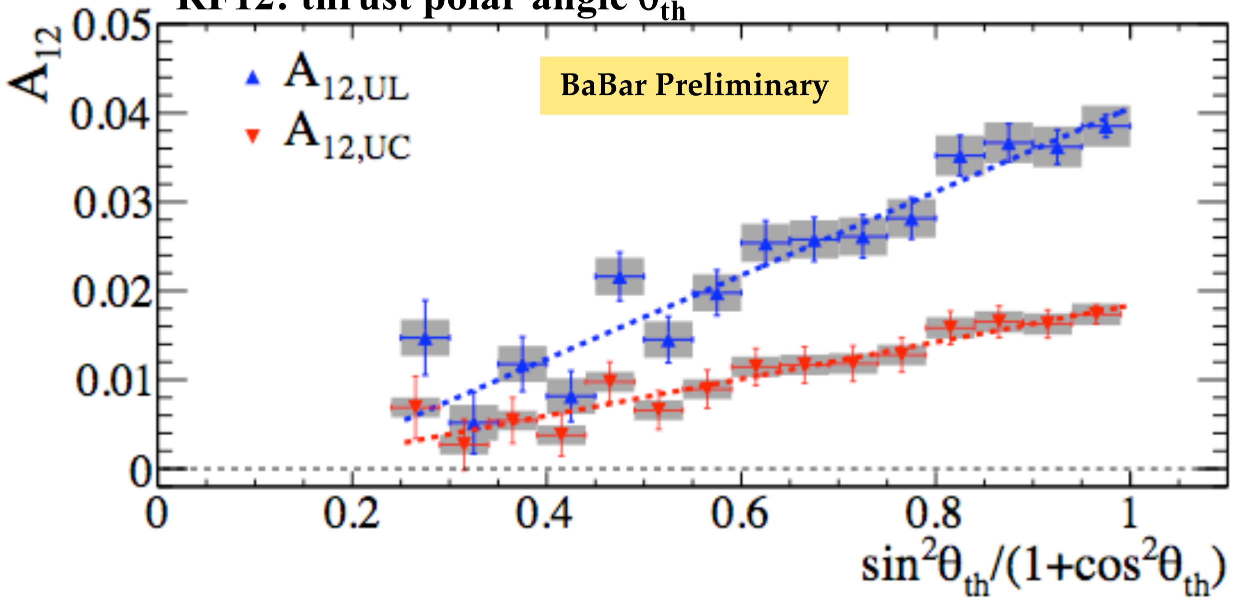
Systematic errors indicated by shaded bands

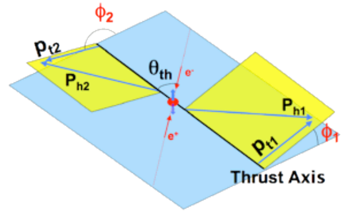
- **Collins asymmetries *vs.* p_t measured in e^+e^- annihilation at Q^2~110 $(GeV/c)^2$ (time-like region)**
- The asymmetries increase as a function of p_t; the increase is expected to continue up to a certain value of p_t, and to decrease there after

These measurements provide information about the evolution of the fragmentation functions (available only space-like measurements at lower Q^2 (PRD 75,054032 (2007), PRL 94, 012002 (2005), PLB 692, 240 (2010)).

Collins asymmetry vs. $\sin^2\theta/(1+\cos^2\theta)$

RF12: thrust polar angle θ_{th}

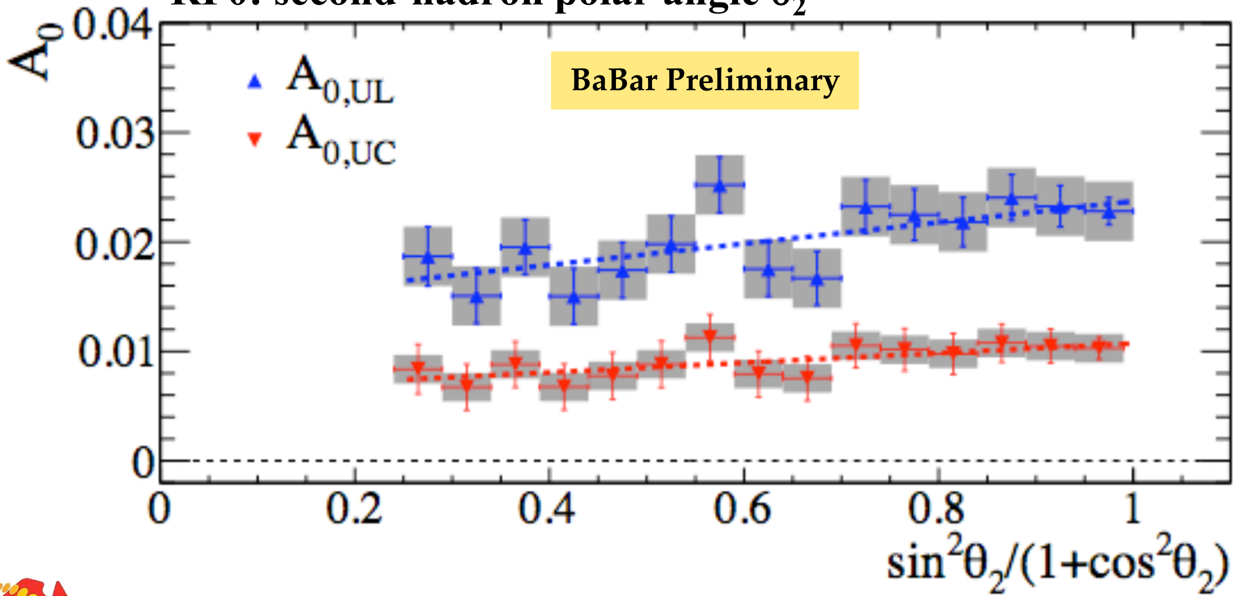


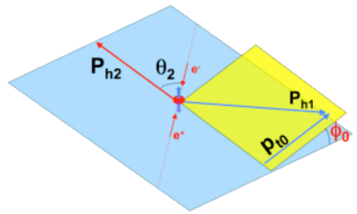


$$A_{12} \propto \frac{\sin^2\theta_{th}}{1+\cos^2\theta_{th}} \cos(\phi_1+\phi_2) \frac{H_1^\perp(z_1)\bar{H}_1^\perp(z_2)}{D_1(z_1)\bar{D}_1(z_2)}$$

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

RF0: second-hadron polar angle θ_2





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

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

Conclusions

We have measured Collins asymmetries for pion pairs in light quark (*uds*) jets from $e^+e^- \rightarrow q\bar{q}$ in two reference frames [A_{12} A_0]

as a function of: ⇒ **$\pi^\pm$ fractional energy z** [z_1, z_2 z_1, z_2]

⇒ **$\pi^\pm$ transverse momentum p_t** [p_{t1}, p_{t2} p_{t0}]

⇒ **quark polar angle** [θ_{th} θ_2]

➲ **A_{12} and A_0 increase with increasing z_1, z_2**
- consistent with theoretical expectations
- effect is stronger for leading particles

➲ **A_{12} (A_0) increases (strongly) with p_{t1}, p_{t2} (p_{t0}) for p_t between 0 to 1 GeV/c**
- first measurement in e^+e^- annihilation at $Q^2 \sim 110$ $(GeV/c)^2$
- important for understanding the evolution of the fragmentation function

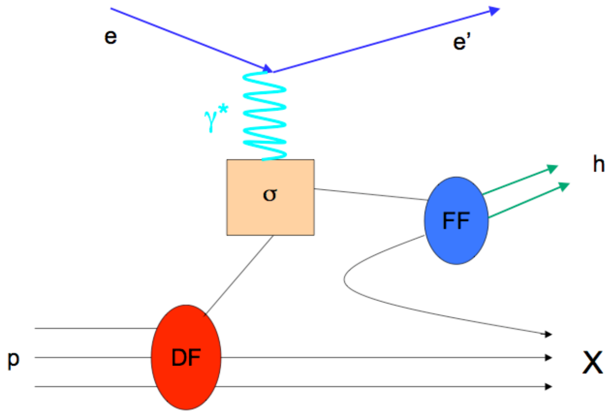
➲ **A_{12} is linear in $\sin^2\theta_{th}/(1+\cos^2\theta_{th})$, with zero intercept**
- consistent with the expectations

➲ **A_0 is linear in $\sin^2\theta_2/(1+\cos^2\theta_2)$, but intercept ≠ 0**
- θ_2 is a poor measure of quark direction

Thanks for your attention

BACKUP SLIDES

Global analysis: transversity and Collins FF extraction



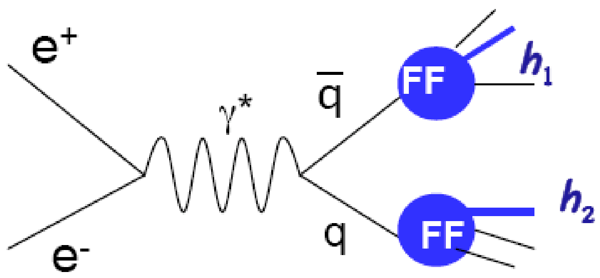
$$\sigma^{ep\to ehX} = \sum_q DF \times \sigma(eq \to eq) \times FF$$

Transversity function (h_1): describes the distribution of quark's transverse spin in a transversely polarized nucleon → remains the least known distribution due to its **chiral-odd nature**
==> Partial information from Semi-Inclusive Deep Inelastic Scattering (SIDIS), where it appears with another chiral-odd function:

$$A_T \propto h_1(x_B) \otimes H_1^{\perp}(z)$$

HERMES: PRL 94, 012002 (2005)
COMPASS: PRL 94, 202002 (2005)

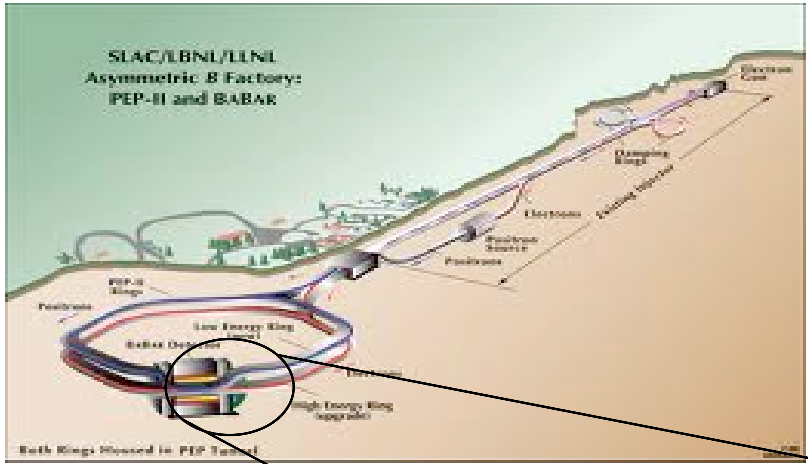
B-Factories e^+e^- → **direct evidence of non-zero Collins FF**: BELLE (PRL 96, 232002(2006), PRD 78, 032011(2008))



Collins effect:
The correlation between two hadrons detected in opposite jets results in an azimuthal asymmetry
$A \propto \cos(\phi_i)\ H_1^{\perp}(z_1) \otimes H_1^{\perp}(z_2)$ where $z_{1,2}=2E_h/\sqrt{s}$

SIDIS + e^+e^- : global analysis (HERMES & COMPASS & BELLE) ==> simultaneous determination of h_1 and $H_1^{\perp}$ (M. Anselmino et al., PRD 75, 054032 (2008))

PEP-II and the BaBar detector at SLAC

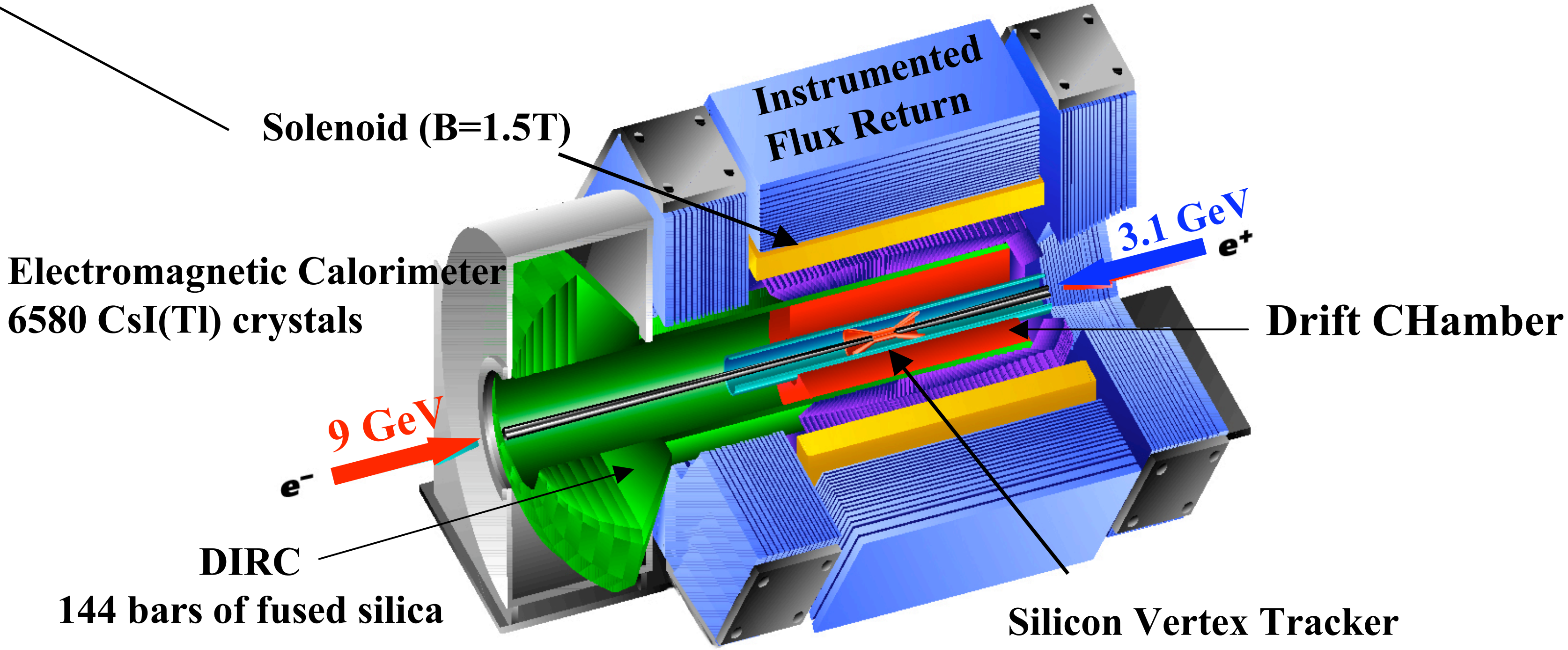


- Asymmetric e^+e^- collider operating at the $\Upsilon(4S)$ resonance ($\sqrt{s}$=10.58 GeV)
- High Energy Ring (**HER**): 9.0 GeV e^-
- Low Energy Ring (**LER**): 3.1 GeV e^+
- $\beta\gamma \approx 0.56$

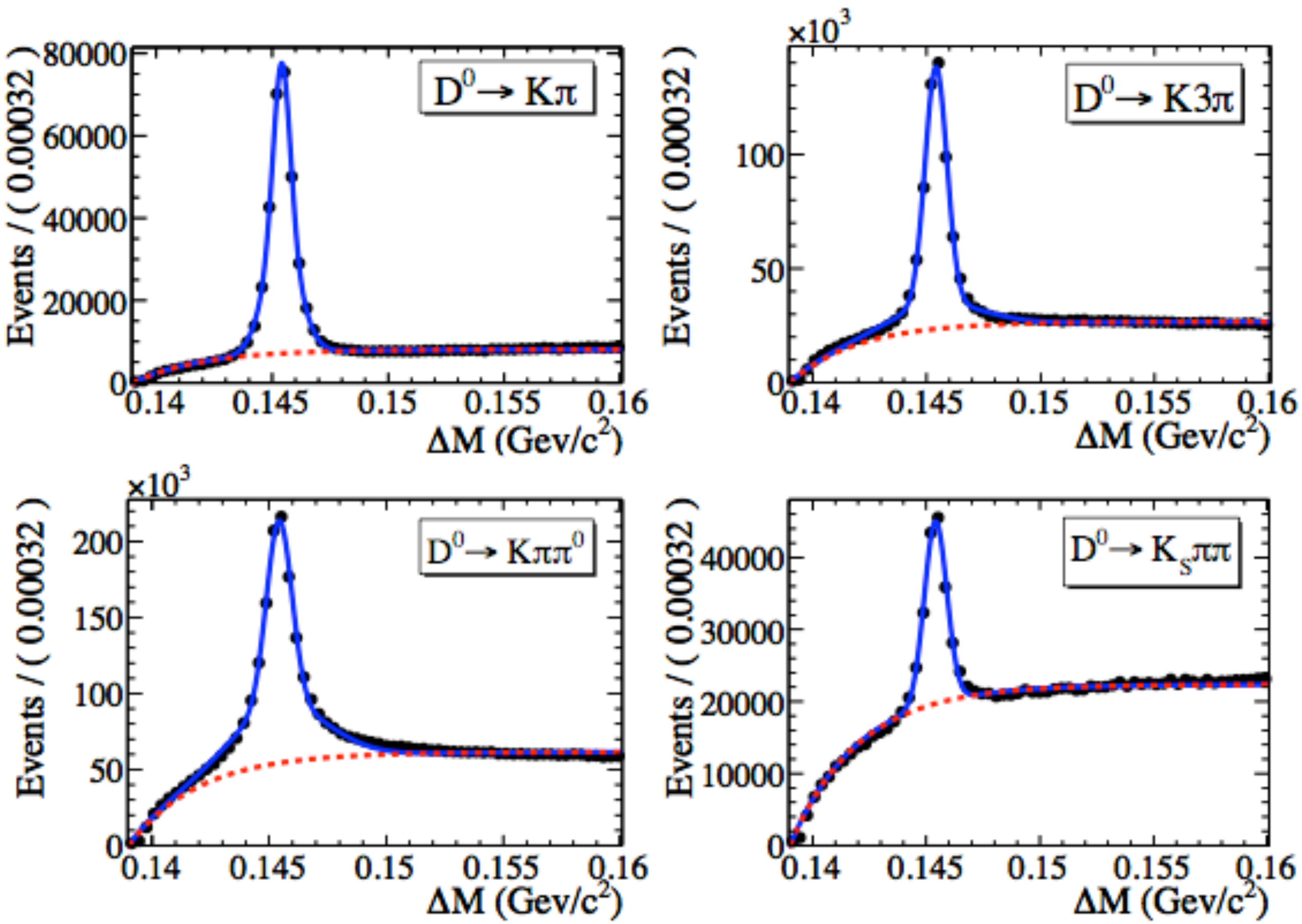
$\mathcal{L}$ **~ 430 fb^{-1}** : peak of the $\Upsilon(4S)$ resonance

$\mathcal{L}$ **~ 40 fb^{-1}** : 40 MeV below the $\Upsilon(4S)$ resonance

==> ~10^9 uds events



$D^{*\pm}$-enhanced control sample



$D^{*\pm} \rightarrow D^0\pi^{\pm}$, $D^0 \rightarrow K\pi$ (mode 1)

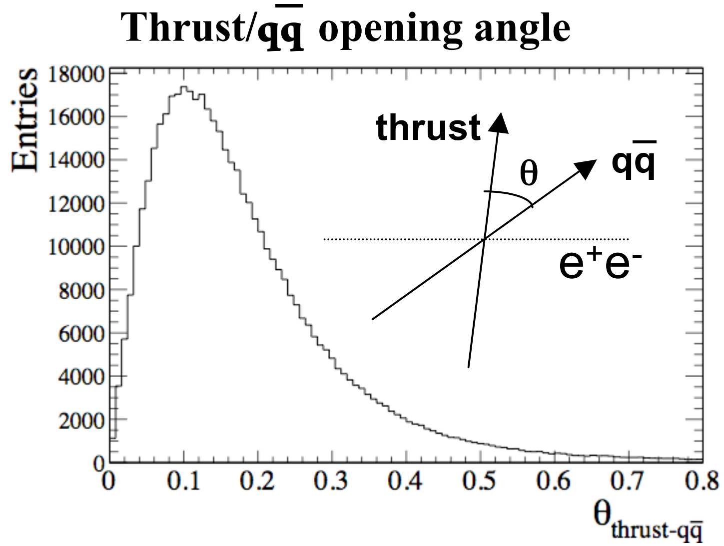
$D^0 \rightarrow K3\pi$ (mode 2)

$D^0 \rightarrow K\pi\pi^0$ (mode 3)

$D^0 \rightarrow K_S\pi\ \pi$ (mode 4)

$1.835 < M_{D0} < 1.895$ GeV/c^2
$0.1425 < \Delta M < 0.149$ GeV/c^2
($\Delta M = M_{D^*} - M_{D0}$)

Asymmetry dilution

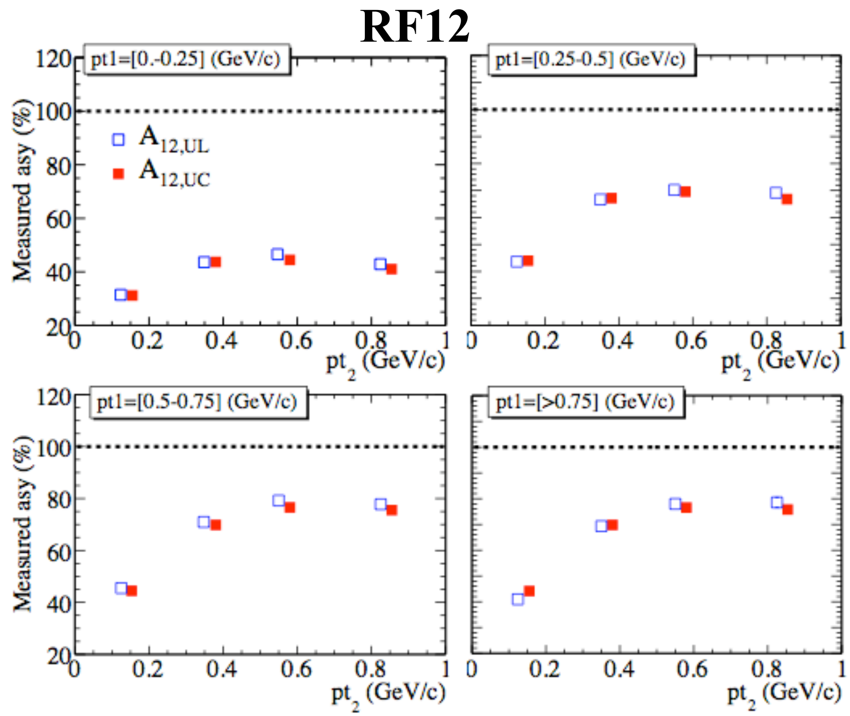


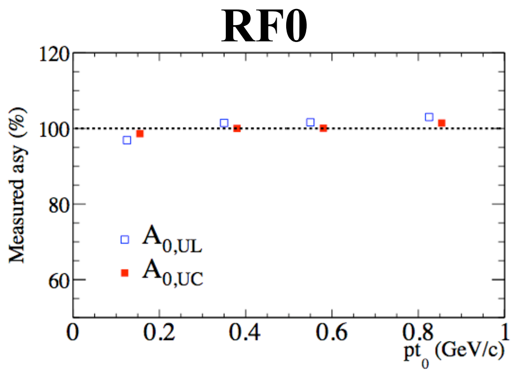
The experimental method assumes the thrust axis as $q\bar{q}$ direction: this is only a rough approximation

RF12: large smearing since the azimuthal angles ϕ_1 and ϕ_2 are calculated with respect to the thrust axis; additional dilution due to very energetic tracks close to the thrust axis.

RF0: the azimuthal angle ϕ_0 is calculated with respect to the second hadron momenta → small smearing due to PID and tracking resolution.

→We study the influence of the detector effects by correcting a posteriori the generated angular distribution: weights defined as $w^{UL(UC)}=1\pm a\cdot\cos(\phi_{gen12,0})$ are applied to every selected pion pairs.





RF12: correction performed for each bins of z and p_t: (1.3-2.3) as a function of z, and (1.3-3) as a function of p_t.
RF0:no correction needed.

Normalized distributions and Double Ratio

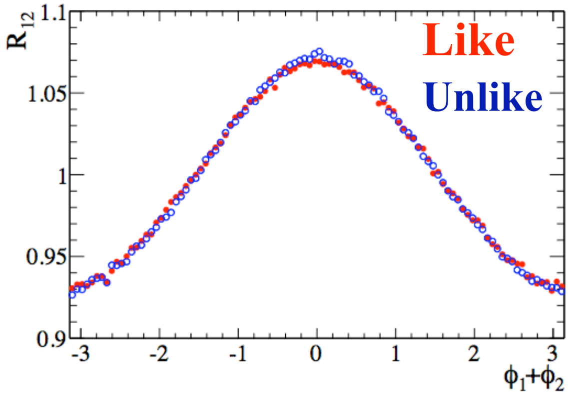
- Collins asymmetry
  - fit to the normalized azimuthal distribution

$$R_\alpha = \frac{N(\phi_\alpha)}{< N_\alpha >} = b_\alpha + a_\alpha \cdot \cos(\phi_\alpha) \quad \alpha\text{=12 or 0}$$

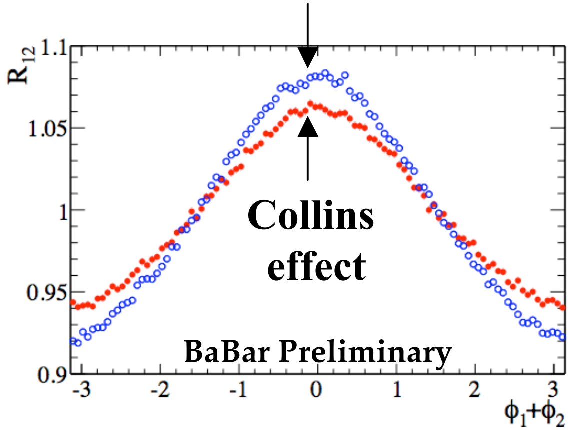
  - unpolarized distribution $<N_\alpha>$ is flat
  - Collins FF contained in the cosine moment *a*

- The MC generator (JETSET) does not include the Collins effects
  - observed modulation in MC sample produced by detector acceptances

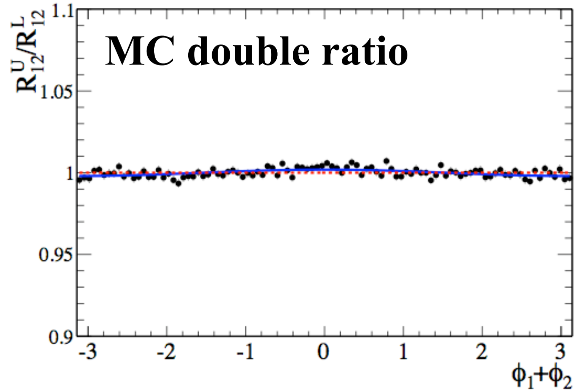
==> Acceptances effects can be removed performing the ratio of **Unlike/Like** (UL) sign pion pairs (or **Unlike/Charged** (UC))
- small deviation from zero still present in MC sample ==> systematic errors

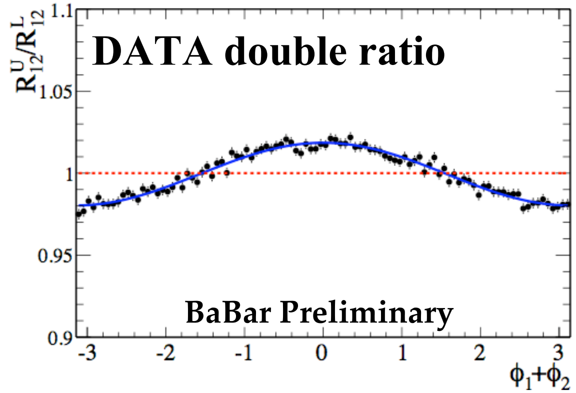


MC: Like and Unlike distributions are coincident



DATA: difference in the Like and Unlike distributions





$$\frac{R^U_\alpha}{R^{L(C)}_\alpha} = \frac{N^U(\phi_\alpha)/< N^U(\phi_\alpha) >}{N^{L(C)}(\phi_\alpha)/< N^{L(C)}(\phi_\alpha) >} \rightarrow B^{UL(UC)}_\alpha + A^{UL,(UC)}_\alpha \cdot \cos(\phi_\alpha)$$

A_α: contains only the Collins effect and higher order radiative effects