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

Isabella Garzia
On behalf of the BaBar Collaboration
INFN-Sezione di Ferrara
University of Ferrara

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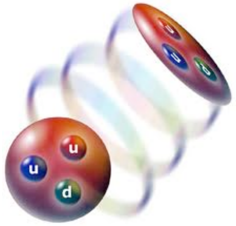


OUTLINE

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

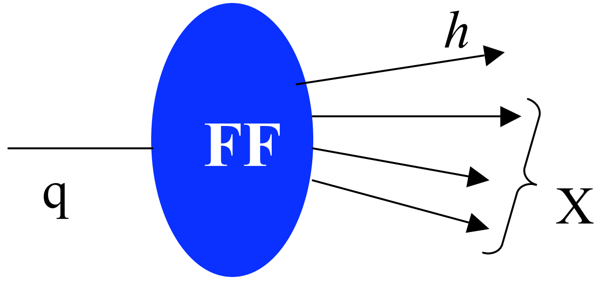
ANALYSIS OVERVIEW
- Analysis method
- Extraction of the asymmetry for light quarks
- Asymmetry corrections and studies of systematic uncertainty

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

CONCLUSIONS

Collins Fragmentation Function

Fragmentation Functions (FFs) are dimensionless functions that describe the final state particles in hard processes. For spinless hadrons production (π or K) in e^+e^- interaction, the process is described by two FFs:



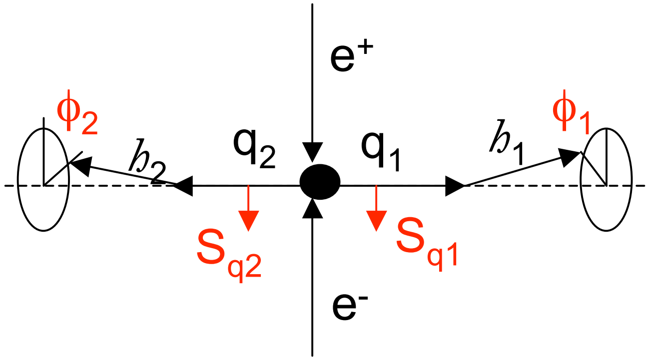
$$D_1^{q\uparrow}(z, \mathbf{P}_\perp; s_q) = \underset{\downarrow}{D_1^q(z, P_\perp)} + \frac{P_\perp}{zM_h} \boxed{H_1^{\perp q}(z, P_\perp)\, \mathbf{s}_q \cdot (\mathbf{k}_q \times \mathbf{P}_\perp)}$$

Unpolarized FF

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

⇒ The second term originates from a **spin-orbit correlation** in the fragmentation process → asymmetry in the angular distribution of final state particles (**Collins effect**)

e^+e^- annihilation: Collins effect in di-hadron correlation



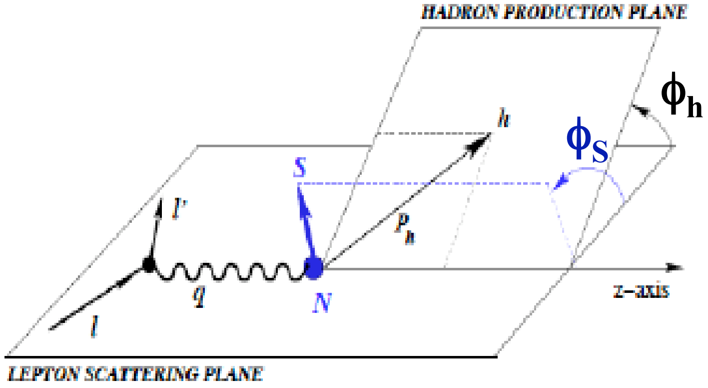
In $e^+e^-\rightarrow q\bar{q}$, spins direction unknown but $s_q \parallel s_{\bar{q}}$

- correlation between two pions detected in opposite jet:

$$e^+e^-\rightarrow q\bar{q}\rightarrow \pi_1\pi_2 X \ \ (q=u,\, d,\, s) \Longrightarrow \sigma\propto\cos(\phi_i) H_1^{\perp}(z_1)\otimes H_1^{\perp}(z_2),$$

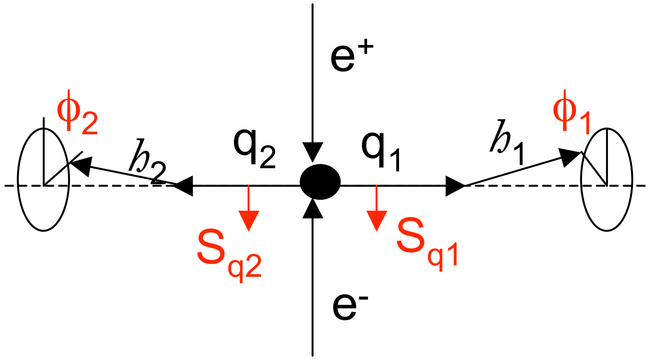
where $z_{1,2}=2E_h/\sqrt{s}$

Comparison with SIDIS experiment:



- Unpolarized lepton beam (l) off transversely polarized target (N)
  - spin direction knows (S)
- $\ell N\rightarrow \ell' \pi X \Longrightarrow \sigma\propto\sin(\phi_h+\phi_s)\, h_1(x_B)\otimes H_1^{\perp}(z_1)$
  - Two chiral-odd functions
  - Flavor tagging
  - Collins effect gives rise to azimuthal Single Spin Asymmetry

e^+e^- annihilation: Collins effect in di-hadron correlation



In $e^+e^- \to q\bar{q}$, spins direction unknown but $s_q \parallel s_{\bar{q}}$

- correlation between two pions detected in opposite jet:

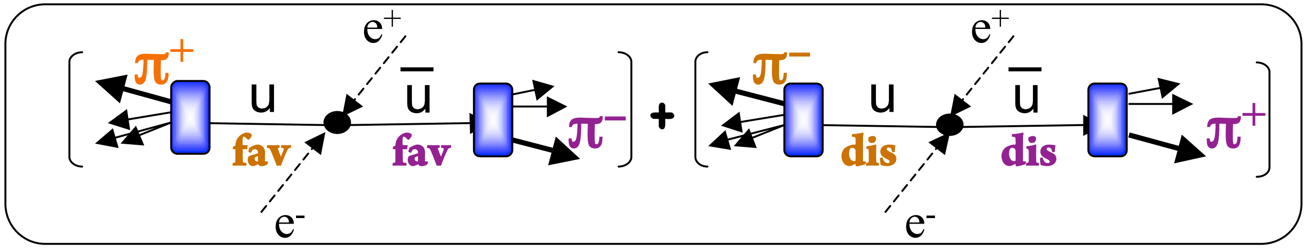
$e^+e^- \to q\bar{q} \to \pi_1\pi_2X$ **(q=u, d, s) ==>** $\sigma \propto \cos(\phi_i) H_1^\perp(z_1) \otimes H_1^\perp(z_2)$,

where $z_{1,2}=2E_h/\sqrt{s}$

- define **favored** (u→π^+, d→π^-) and **disfavored** (d→π^+, u→π^-) FFs, and consider the combination:

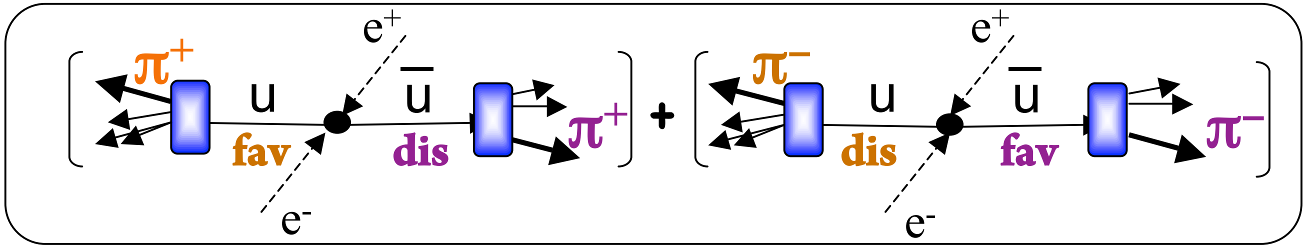
Unlike-sign pion pair = **U:**

$\pi^\mp\pi^\pm$: **(fav x fav)+(dis x dis)**



Like-sign pion pair = **L:**

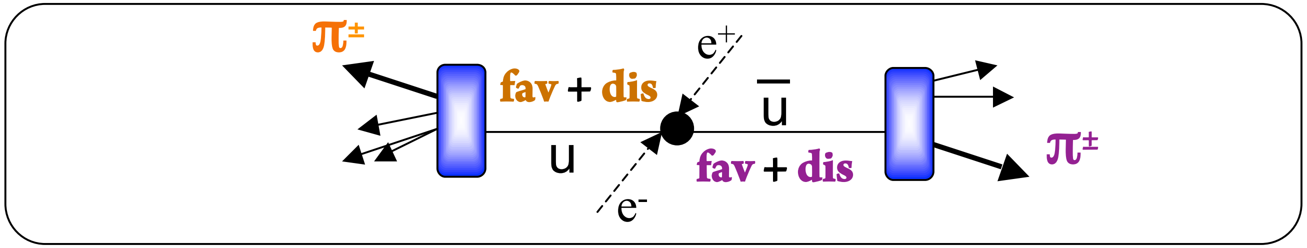
$\pi^\pm\pi^\pm$: **(fav x dis)+(dis x fav)**



Charged pion pair = **C (U+L):**

$\pi\pi$: **(fav + dis)x(fav + dis)**

$\pi=\pi^\pm$



Analysis Reference Rrame (RF)

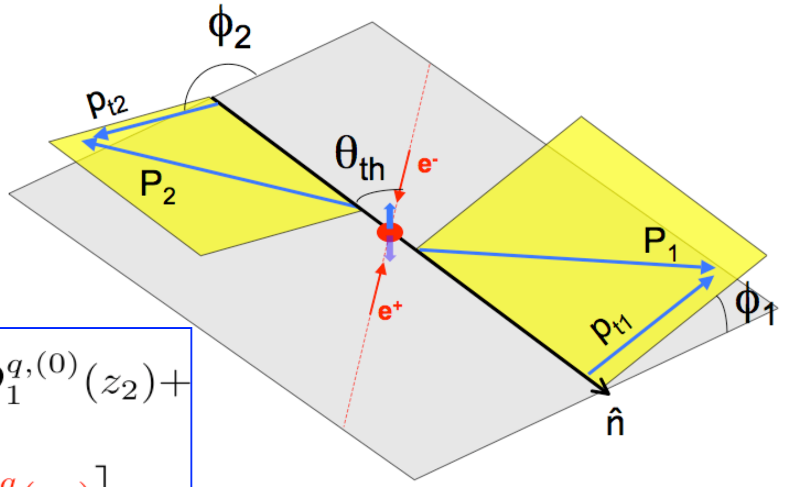
Two reference frames in literature:
Nucl. Phys. B 806, 23 (2009), PRD 78, 032011 (2008)

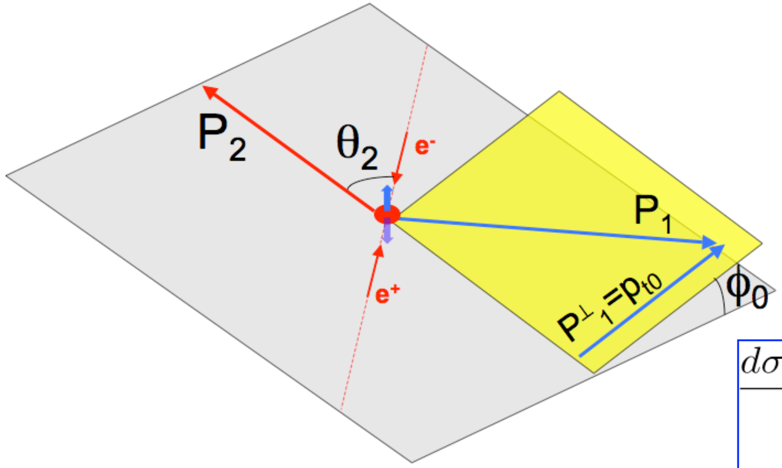
RF12 or Thrust RF

θ_{th}: angle between the e$^+$e$^-$ axis and the thrust axis;
$\phi_{1,2}$: azimuthal angles between $\boldsymbol{p}_{t1(t2)}$ and the scattering plane:

$$\frac{d\sigma(e^+e^- \to h_1h_2X)}{d\Omega dz_1dz_2d\phi_1d\phi_2} = \sum_{q,\bar{q}} \frac{3\alpha^2}{Q^2}\frac{e_q^2}{4}z_1^2z_2^2\left[(1+cos^2\theta)D_1^{q,(0)}(z_1)\bar{D}_1^{q,(0)}(z_2)+ \right. \\ \left. + \quad sin^2(\theta)cos(\phi_1+\phi_2)H_1^{\perp,(1),q}(z_1)\bar{H}_1^{\perp,(1),q}(z_2)\right]$$

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





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

RF0 or Second hadron momentum RF

θ_2: angle between the e$^+$e$^-$ axis and $\boldsymbol{P}_{h2}$;
ϕ_0: azimuthal angle between the plane spanned by $\boldsymbol{P}_{h2}$ and the e$^+$e$^-$ axis, and the direction of $\boldsymbol{P}_{h1}$ perpendicular to $\boldsymbol{P}_{h2}$:

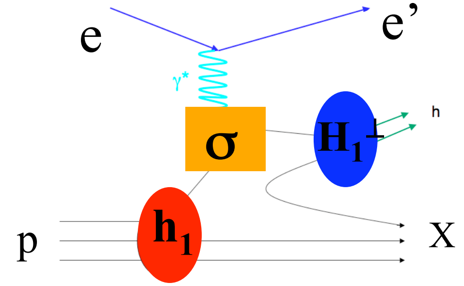
$$\frac{d\sigma(e^+e^- \to h_1h_2X)}{d\Omega dz_1dz_2d^2\vec{q}_T} = \frac{3\alpha^2}{Q^2}z_1^2z_2^2\left\{A(y)\mathcal{F}[D_1\bar{D}_2]+ \right. \\ \left. + \quad B(y)cos(2\phi_0)\mathcal{F}\left[(2\hat{h}\cdot\vec{k}_T\hat{h}\cdot\vec{p}_T-\vec{k}_T\cdot\vec{p}_T)\frac{H_1^\perp\bar{H}_2^\perp}{M_1M_2}\right]\right\}$$

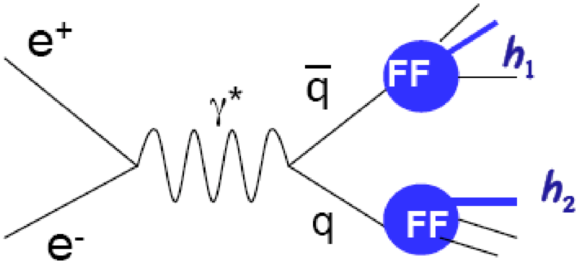
Extraction of Collins FF from data

First observation of non-zero Collins effects from SIDIS (HERMES and COMPASS Collaboration):

HERMES: PRL **94**, 012002 (2005)
COMPASS: NP **B765**, 31 (2007)

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





B-Factories e^+e^- → direct evidence of non-zero Collins FF

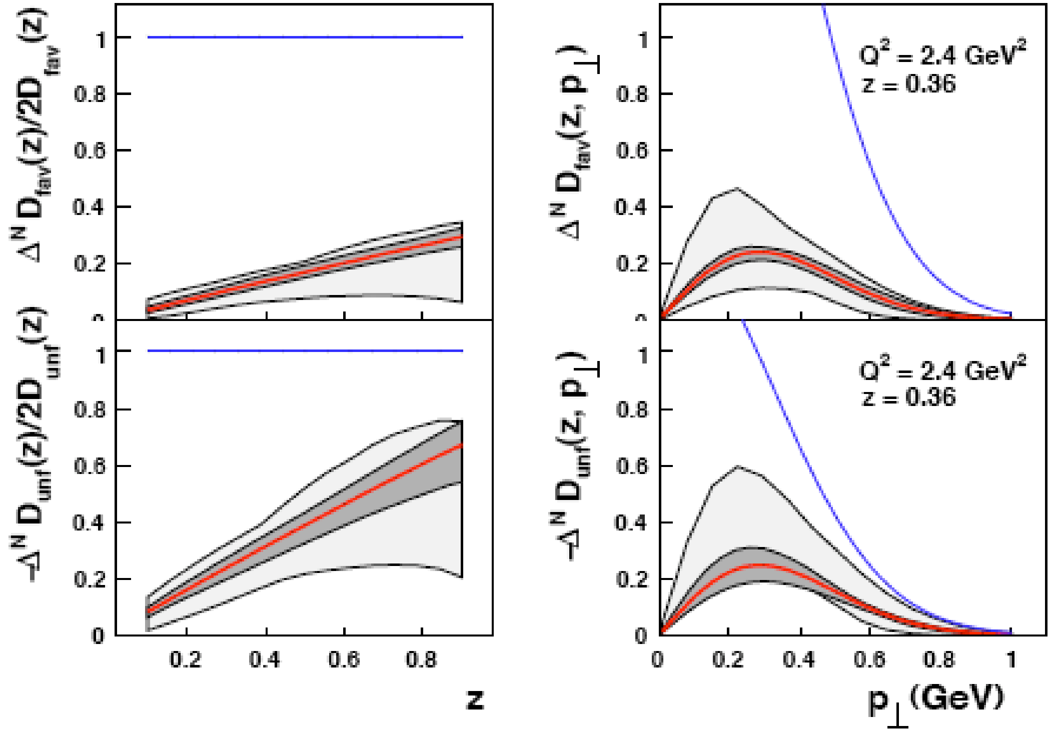
- BELLE: PRL 96, 232002(2006), PRD 78, 032011(2008)
- BaBar preliminary: arXiv:1201.4678 (procceding for Transversity-2011 workshop)

$A \propto H_1^{\perp}(z_1) \otimes H_1^{\perp}(z_2)$ where $z_{1,2}=2E_h/\sqrt{s}$

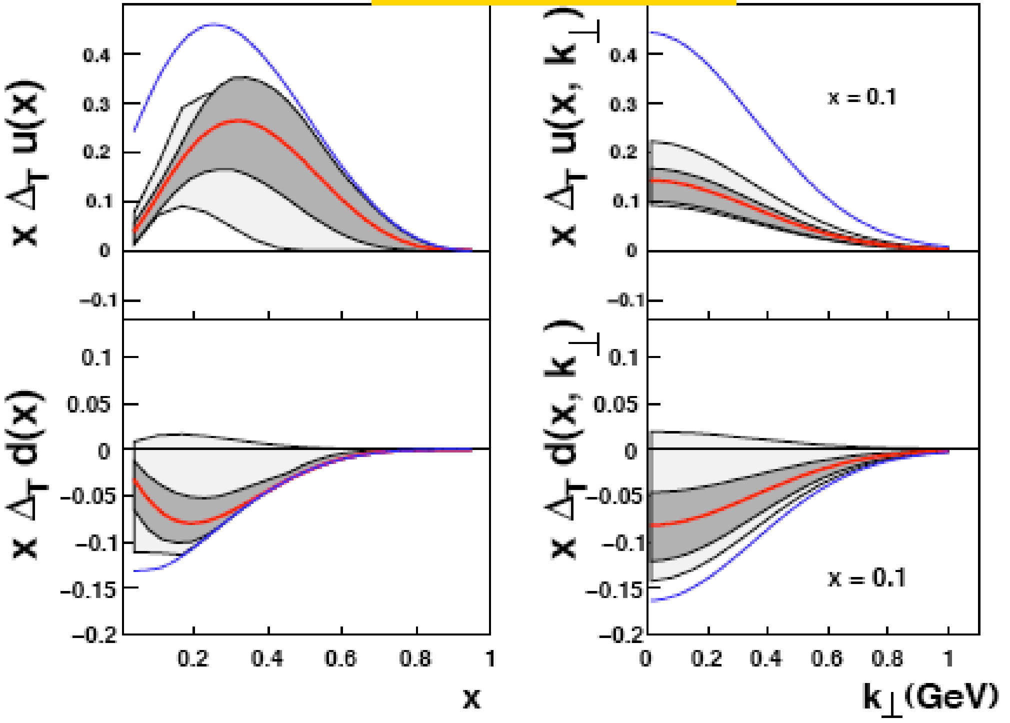
GLOBAL ANALYSIS: SIDIS + e^+e^- (HERMES, COMPASS, BELLE) ==> simultaneous determination of $H_1^{\perp}$ and the transversity parton distribution function h_1 [PRD **75**, 054032 (2008)].

Extraction of Collins FF from data

Collins FF



Transversity PDF

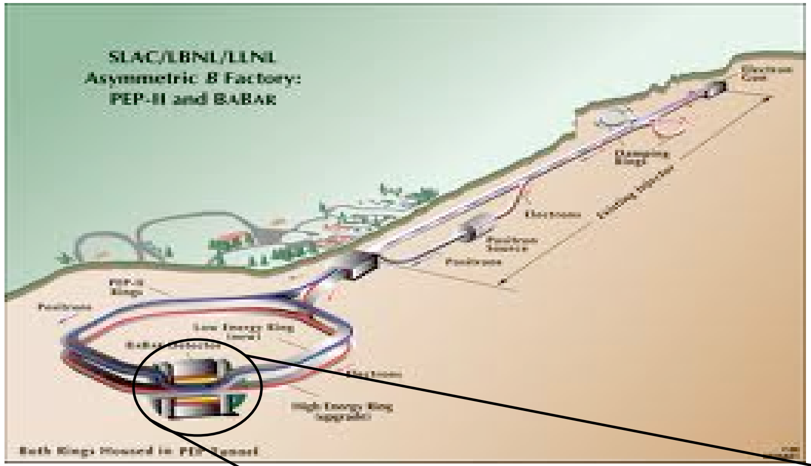


Anselmino et al., Phys. Rev. D 75, 054032 (2006)
Nucl.Phys.Proc.Suppl. 191, 98 (2009)

Improvements from BaBar studies:

- Increase in the number of pion fractional energies intervals
- Collins asymmetry behavior vs. pion transverse momenta

PEP-II and the BaBar detector at SLAC

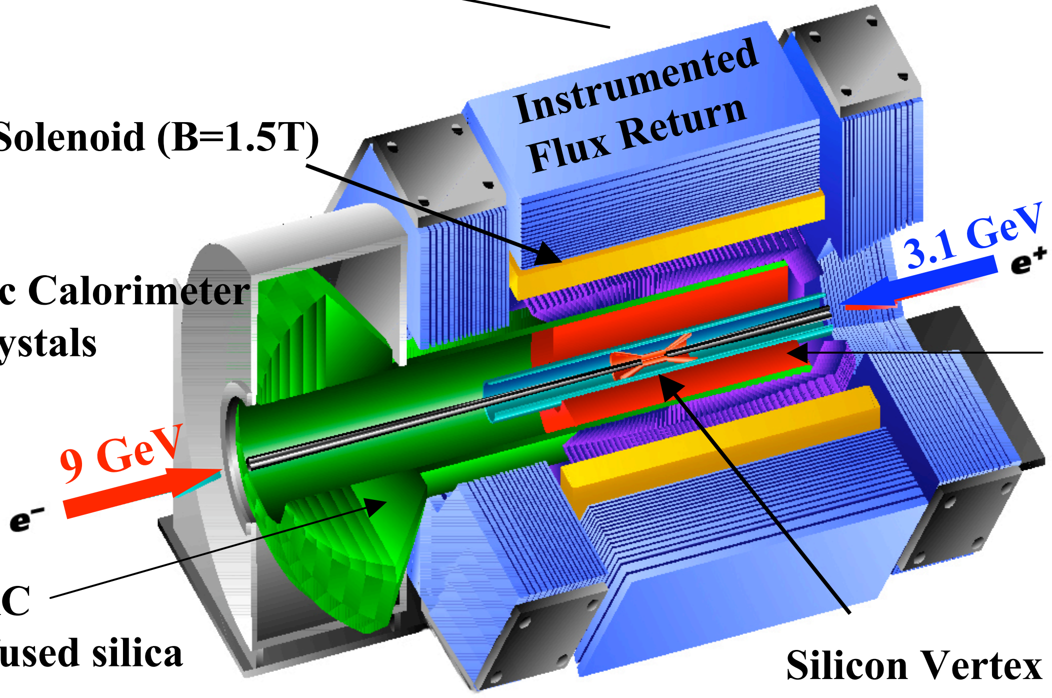


- Asymmetric e^+e^- collider operating at the $\Upsilon(4S)$ resonance ($\sqrt{s}=10.58$ GeV)
- High Energy Ring (**HER**): 9.0 GeV e^-
- Low Energy Ring (**LER**): 3.1 GeV e^+
- $\beta\gamma \approx 0.56$

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

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

==> $\sim 10^9$ uds events



Solenoid (B=1.5T)

Electromagnetic Calorimeter
6580 CsI(Tl) crystals

Drift CHamber

DIRC
144 bars of fused silica

Silicon Vertex Tracker

Event and track selection

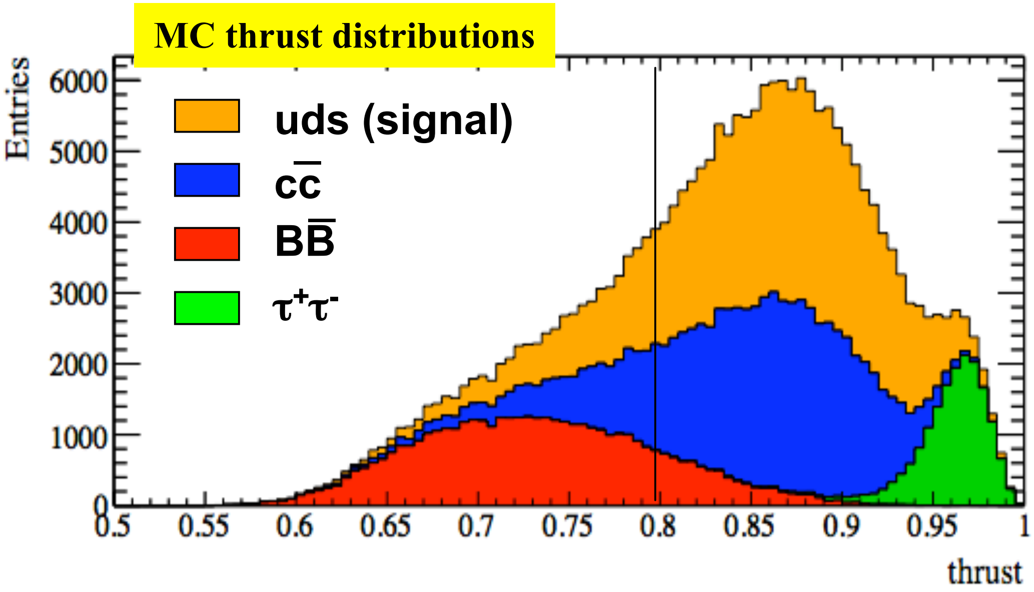
EVENT SELECTION

→ Number of charged tracks > 2

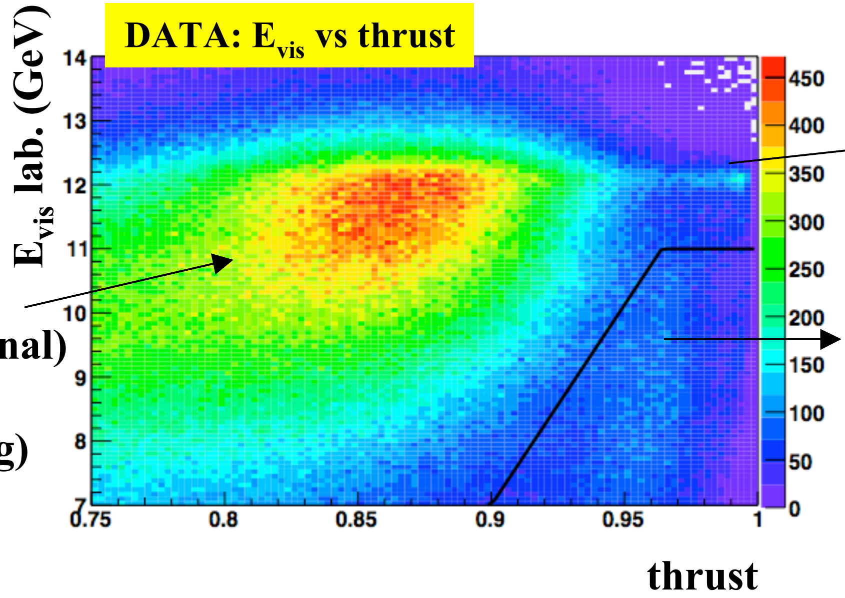
→ Visible energy: **E_{vis} > 7 GeV**

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

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



MC thrust distributions



DATA: E_{vis} vs thrust

BhaBha and $\mu^+\mu^-(\gamma)$ events, with $\gamma \to e^+e^-$ conversion

uds (signal) and $c\bar{c}$ (bg)

$\tau^+\tau^-$ region

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

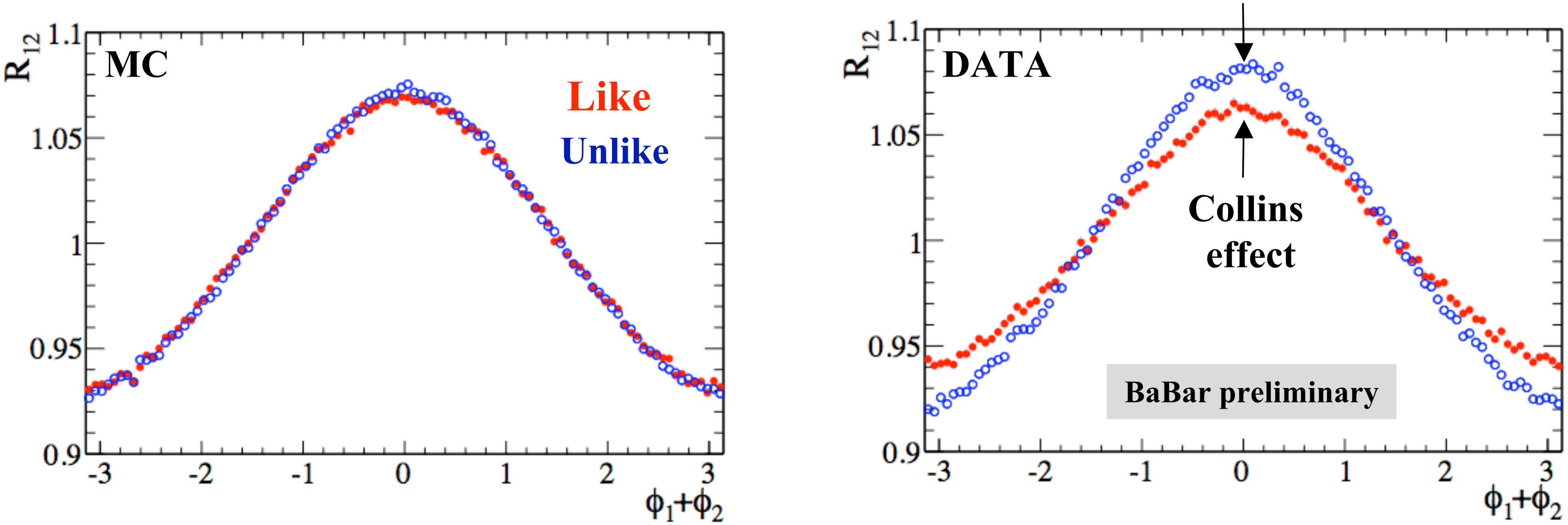
→ Pion fractional energies **$0.15<z=2E_h/\sqrt{s}<0.9$**

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

→ **Q_t<3.5 GeV**, where Q_t is the transverse momentum of the virtual photon in the pions CMS

Raw Asymmetries

- Collins asymmetry
  - fit to the normalized azimuthal distribution: $R_\alpha = \frac{N(\phi_\alpha)}{< N_\alpha >} = a + b \cdot cos(\phi_\alpha)$ (α=12 or 0)
  - Unpolarized distribution $<N_\alpha>$ is flat
  - Collins FF contained in the cosine moment *b*



MC: Like and Unlike reconstructed distributions are coincident

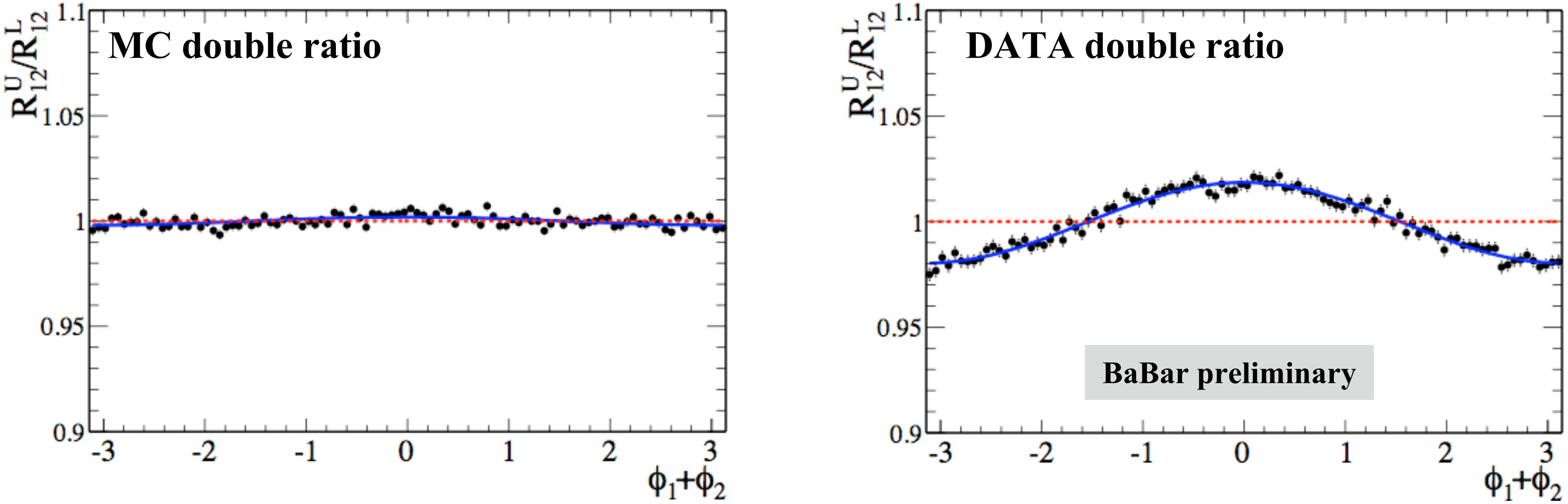
DATA: difference in the Like and Unlike distributions

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

Double ratio methods

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

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



MC: consistent with a flat distribution

DATA: cosine modulation clearly visible

$$\frac{R^U_\alpha}{R^L_\alpha} = \frac{N^U(\phi_\alpha)/<N^U(\phi_\alpha)>}{N^L(\phi_\alpha)<N^L(\phi_\alpha)>} \rightarrow P_0 + P_1 \cdot \cos(\phi_\alpha)$$

P_1: contains only the Collins effect and higher order radiative effects

Asymmetry corrections and systematic effects

We study the Collins asymmetry in
- RF12 (thrust RF): 6x6 $z_{1,2}$ bins and 4x4 $p_{t1,t2}$ bins
- RF0 (second hadron RF): 6x6 $z_{1,2}$ bins and 4 p_{t0} bins (with $\mathrm{p}_{\mathrm{t1,t2,t0}}$ defined in slide 6)

The asymmetry measurement is affected by a number of **systematic effects**
==> we correct the asymmetries and assign a systematic error independently **for each *z* and p_t bin**

The main contributions to systematic effects are:
- **Asymmetry dilution due to the thrust axis approximation**. The corrections in the RF12 frame range between:
  - ⇒ 1.3-2.3 as a function of *z*
  - ⇒ 1.3-3 as a function of p_t
  - ⇒ No correction needed in the RF0 frame

  The statistical error of the correction is taken as systematic errors
- **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

Extraction of the uds asymmetry

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

Fraction of pion pairs due to the ith background process

True asymmetry

Asymmetry measured in the background data control sample

⇒ $B\bar{B}$ background: small $F_{B\bar{B}}$ ⇒$A_{bottom}=0$

⇒ $\tau^+\tau^-$ background: $F_{\tau+\tau-}$ is small at lower fractional energies, and A_τ consistent with zero

⇒ Charm background contribution is about 30% on average

- Both fragmentation processes and weak decays can introduce azimuthal asymmetries ==> we used a **D*±-enhanced control sample** to estimate its effect on a **bin-by-bin basis**

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

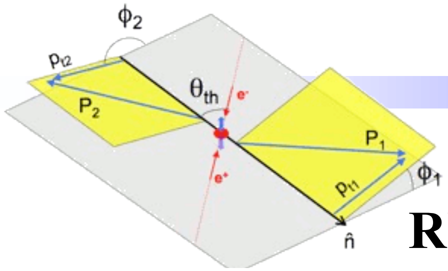
$$A_\alpha^{D^*} = f_c\cdot A_\alpha^{ch} + (1-f_c-f_b)\cdot \underline{A_\alpha}\ ,$$

A significant source of systematic error can arise from the fraction F, estimated using MC samples.

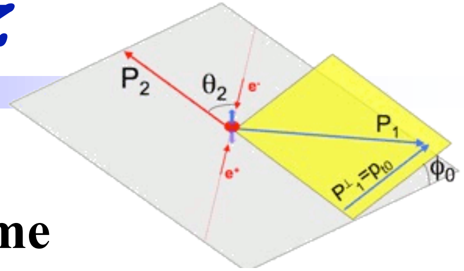
→ We assign the bin-by-bin discrepancies between MC and data as systematic uncertainties

RESULTS

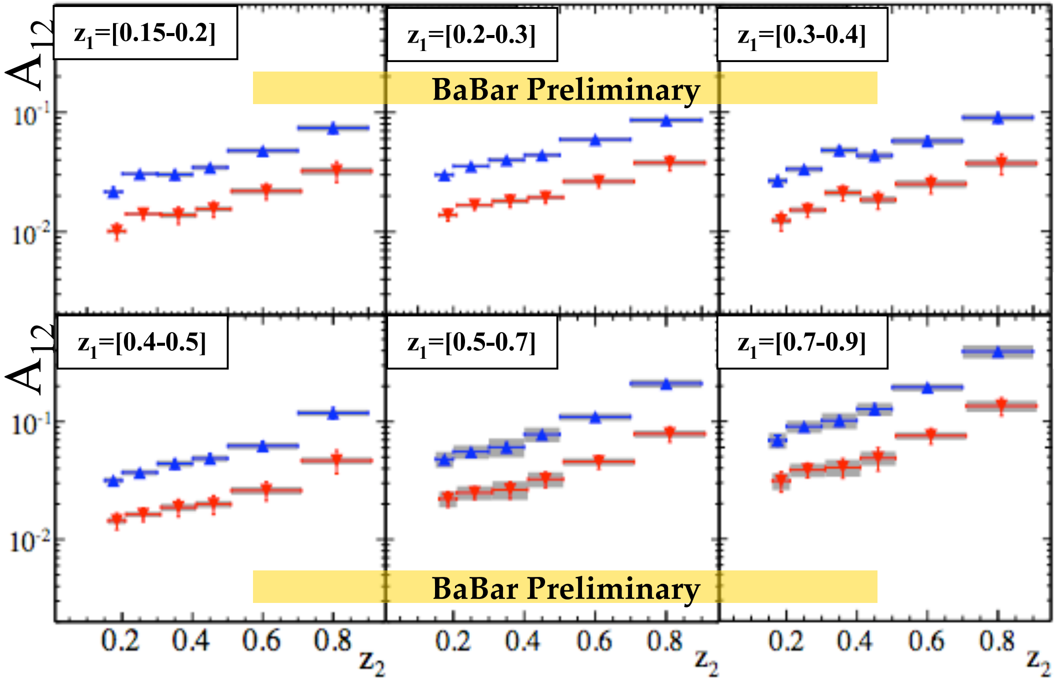
Collins asymmetry vs. z

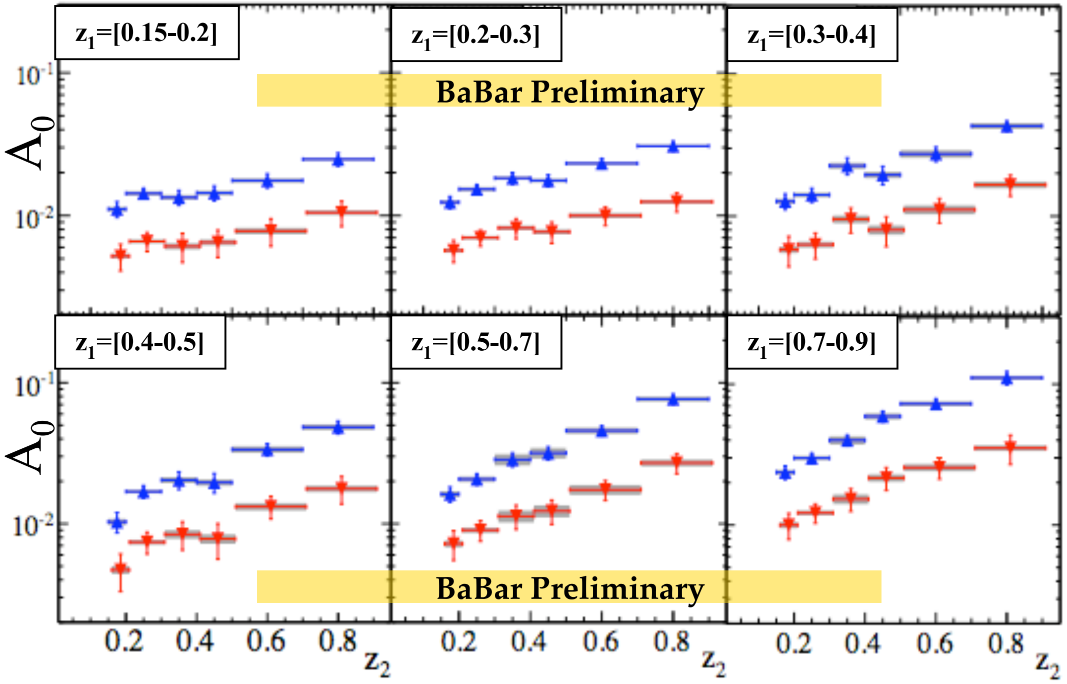


RF12 frame



RF0 frame



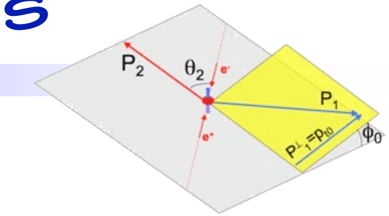


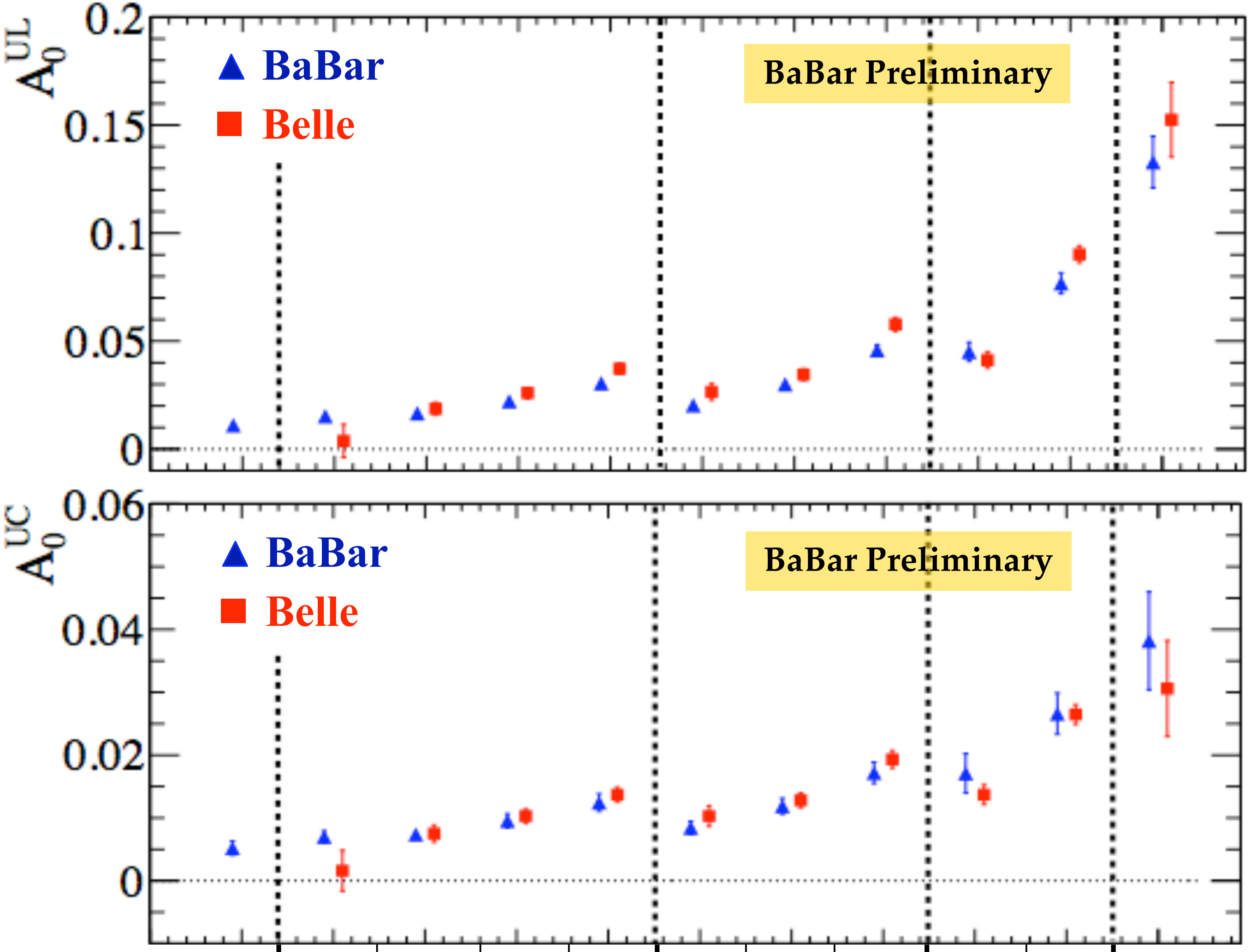
Systematic errors indicated by shaded bands

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 (▲)**
- different combination of $H_1^{\perp fav}$ and $H_1^{\perp dis}$ ==> information about the magnitude and sign (PRD 73, 094025 (2006))

RFO:BaBar/Belle asymmetries comparisons





1	2	3	4	5	6	7	8	9	10	11	$(z_1,z_2)_{bin}$
0.15-0.2	0.2-0.3				0.3-0.5			0.5-0.7		>0.7	z_1
0.15-0.2	0.2-0.3	0.3-0.5	0.5-0.7	>0.7	0.3-0.5	0.5-0.7	>0.7	0.5-0.7	>0.7	>0.7	z_2

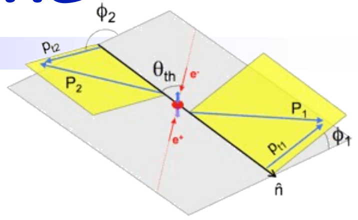
BaBar ($0.15<z<0.9$)
$\mathcal{L}$~470 fb^{-1}

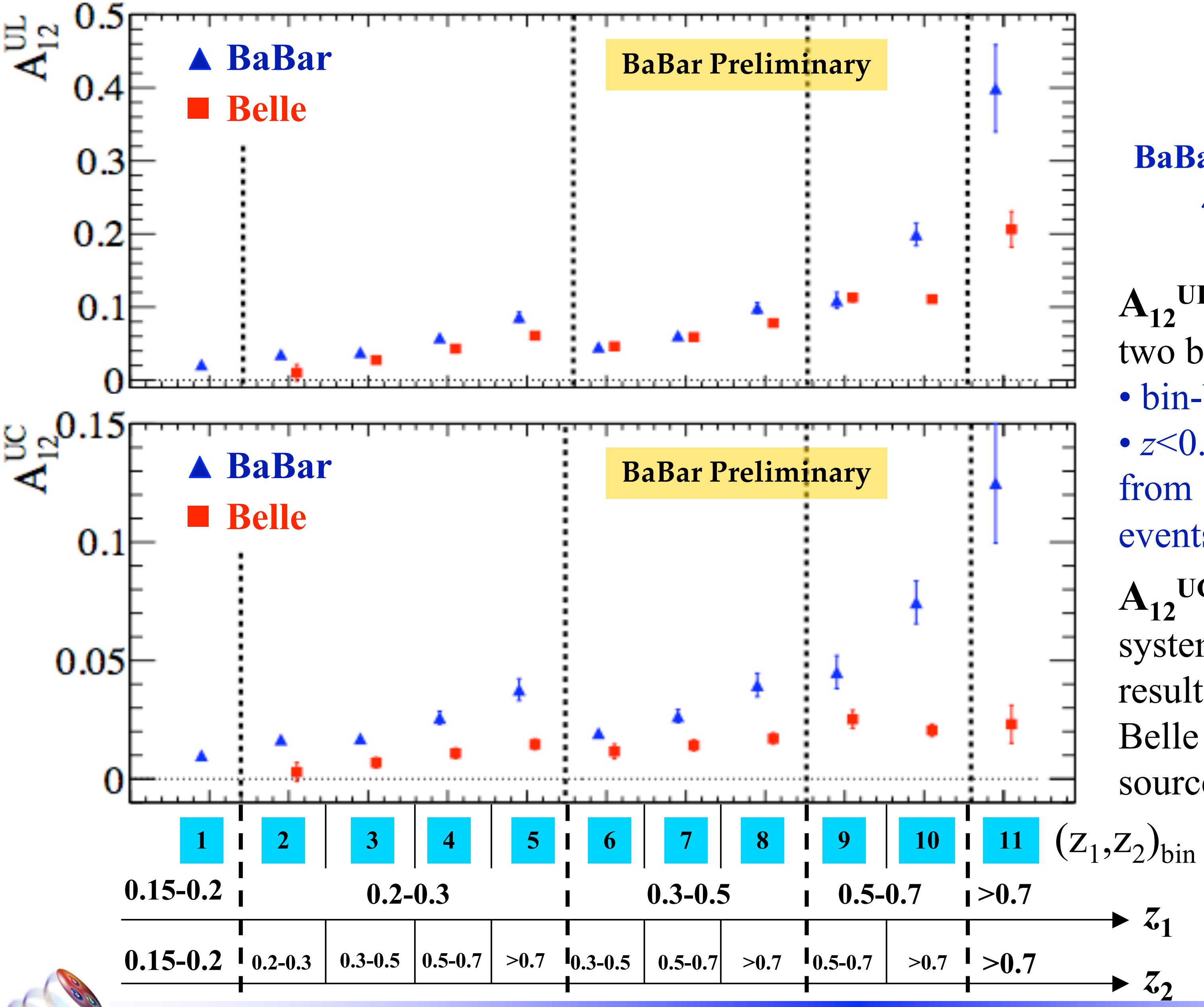
Belle ($0.2<z<1$)
$\mathcal{L}$~547 fb^{-1}
PRD 78, 032011 (2008)

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 asymmetries 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)

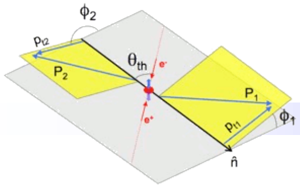
A_{12}^{UL}: large discrepancy in the last two bins of z

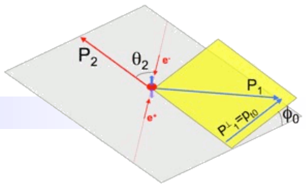
- bin-by-bin correction factors (30%)
- z<0.9 to remove the contamination from μμγ background and exclusive events

A_{12}^{UC}: BaBar asymmetry systematically above the Belle results for all z.

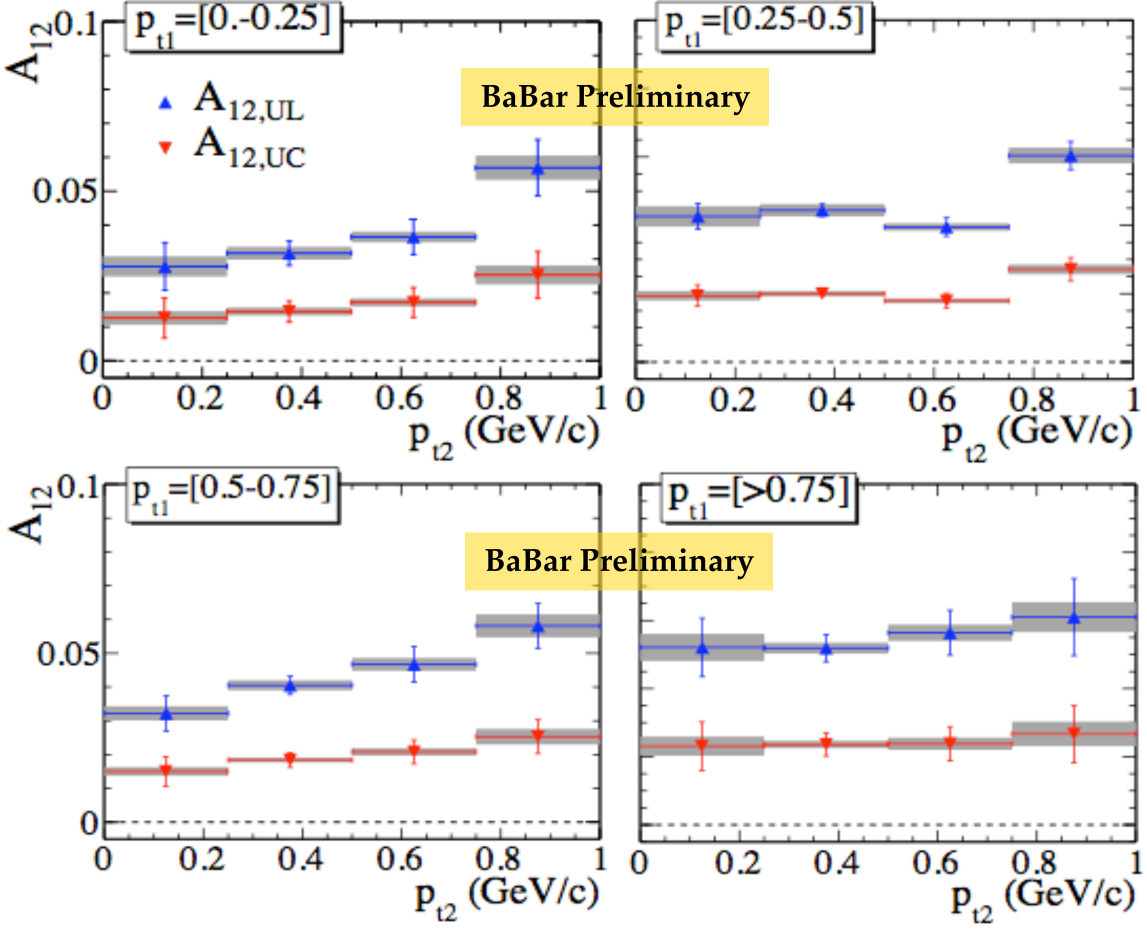
Belle analysts are investigating the source of discrepancies.

Collins asymmetry *vs.* p_t

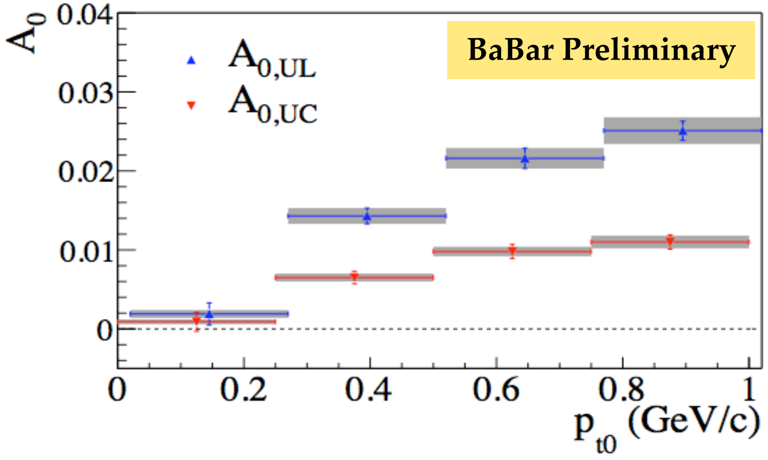




RF12



RF0

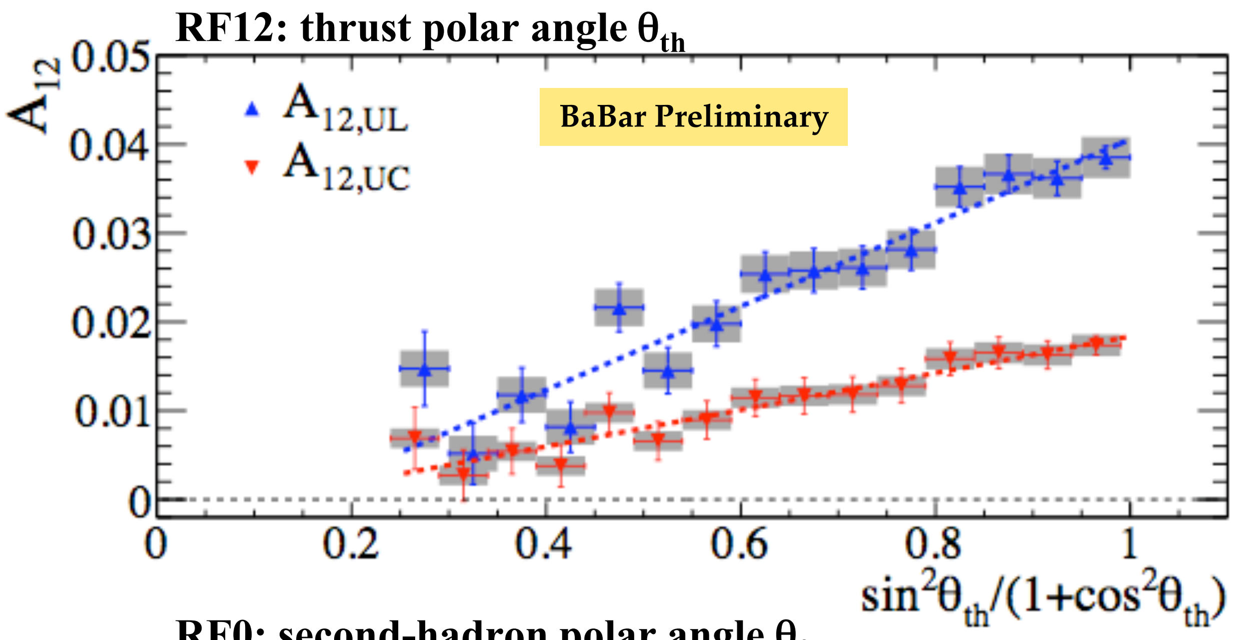


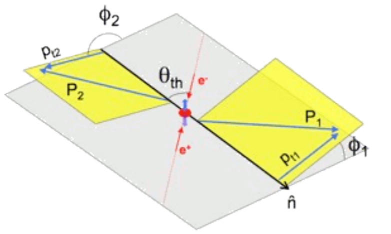
Systematic errors indicated by shaded bands

- **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

The combination of these measurements with those from SIDIS (space-like region) at lower Q^2 (~2.4 (GeV/c)^2) [PRD 75,054032 (2007), PRL 94, 012002 (2005), PLB 692, 240 (2010)] **provides information about the evolution of the fragmentation functions**

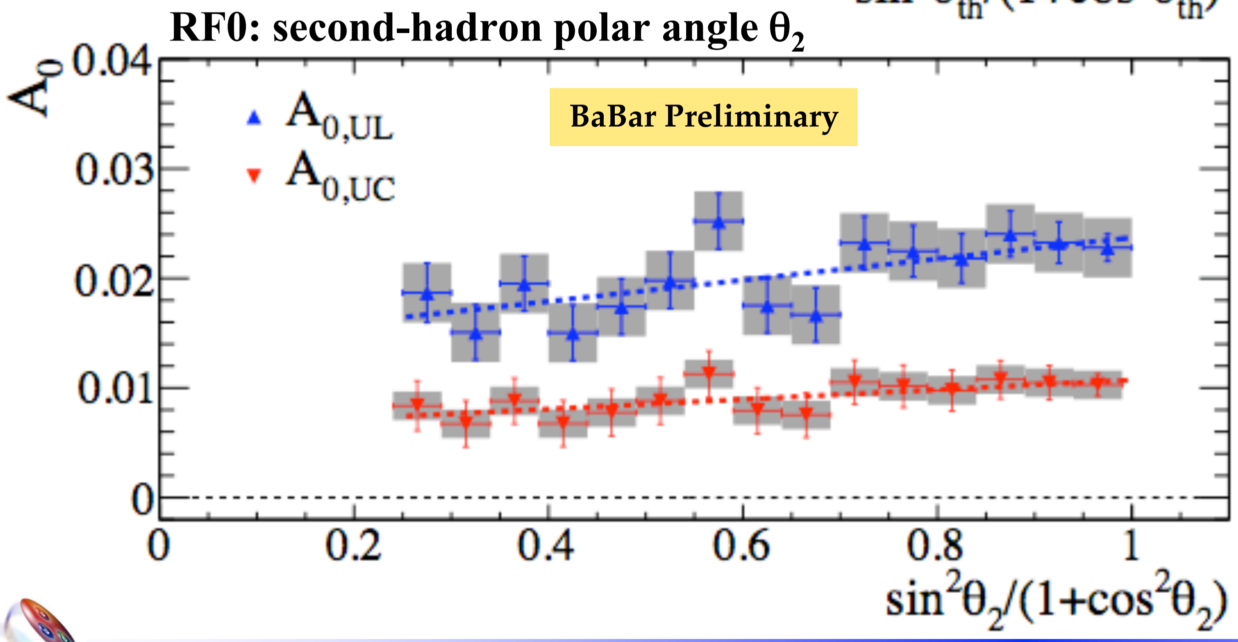
Collins asymmetry *vs.* $\sin^2\theta/(1+\cos^2\theta)$

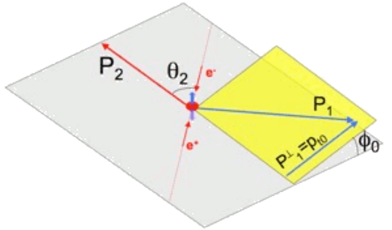

RF12: thrust polar angle θ_{th}



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

==> 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 worse estimation 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 $[\ A_{12} \quad A_0\ ]$
as a function of: $\Rightarrow$ **$\pi^\pm$ fractional energy *z*** $[\ z_1, z_2 \quad z_1, z_2\ ]$
$\Rightarrow$ **$\pi^\pm$ transverse momentum p_t** $[\ p_{t1}, p_{t2} \quad p_{t0}\ ]$
$\Rightarrow$ **quark polar angle** $[\ \theta_{th} \quad \theta_2\ ]$

➲ **A_{12} and A_0 increase with increasing z_1, z_2**

- consistent with theoretical expectations
- general agreement with Belle results (PRD 78, 032011 (2008)), with some discrepancies in the RF12
- effect is stronger for leading particles

➲ **A_{12} (A_0) increases with p_{t1}, p_{t2} (p_{t0}) for p_t between 0 to 1 GeV/c**

- first measurement in e^+e^- annihilation at $Q^2 \sim 110\ (\mathrm{GeV}/c)^2$
- 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**

➲ **A_0 is linear in $\sin^2\theta_2/(1+\cos^2\theta_2)$, but intercept $\neq 0$**

Perspectives and Plans

- PRD draft under review of the Collaboration

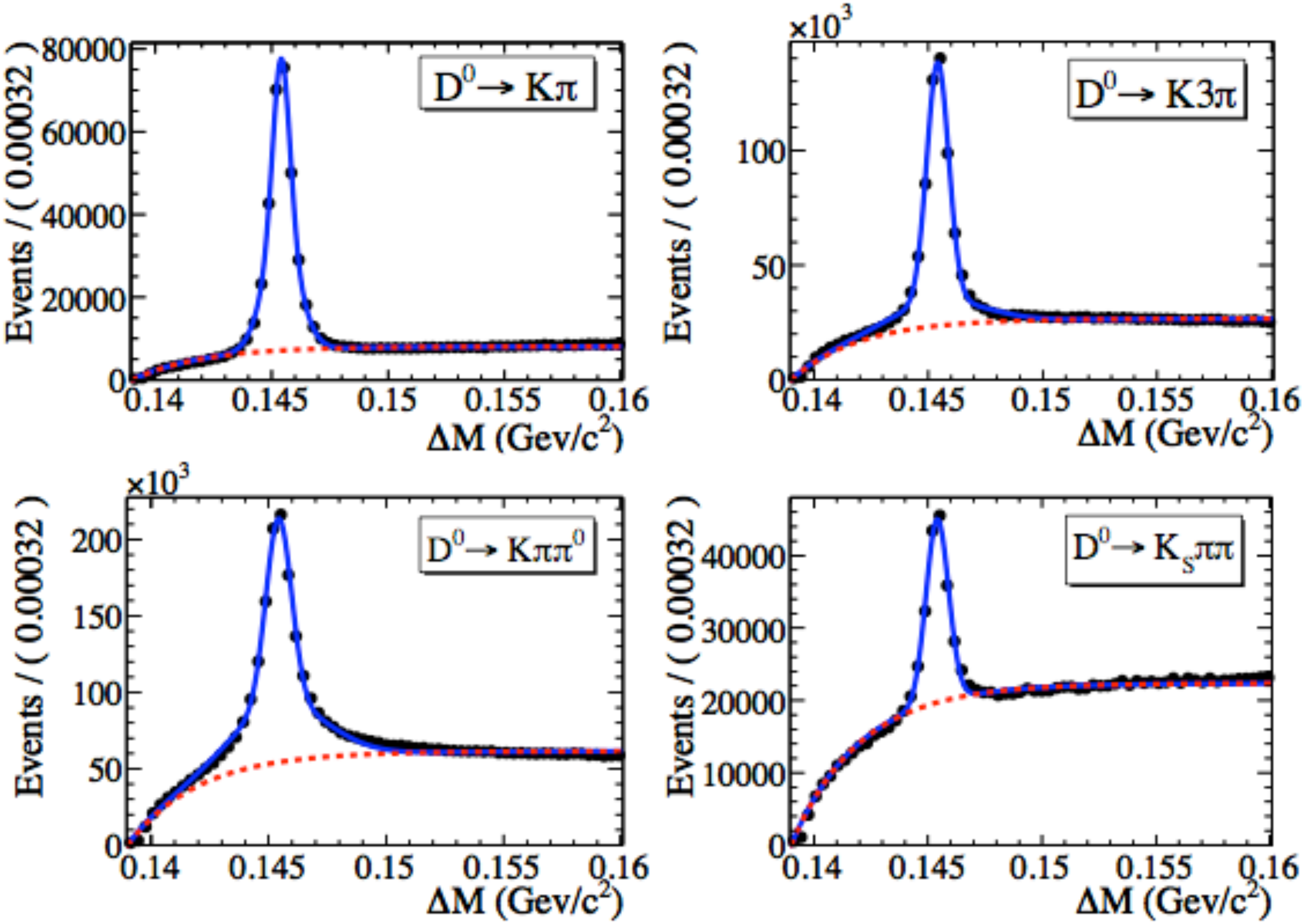
This study is the first step of a program of measuring polarized fragmentation function in e^+e^- annihilation at BaBar:
- study of the Collin asymmetries for the kaon system
- study of interference fragmentation function

Stay Tuned

Thanks for your attention

BACKUP SLIDES

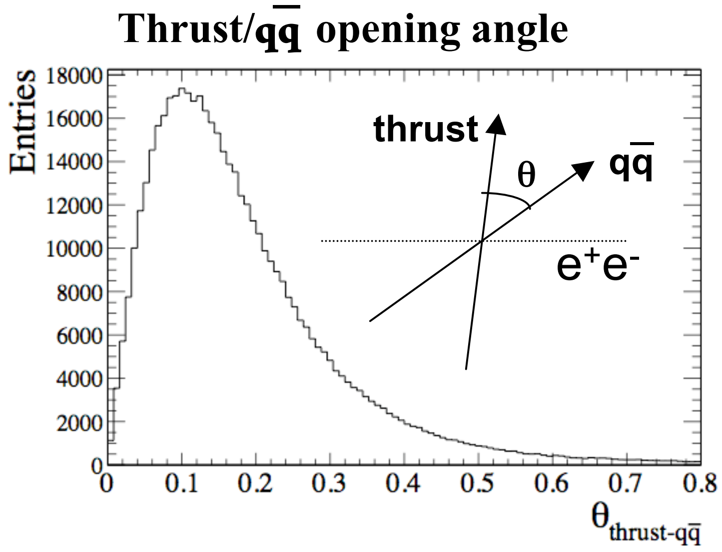
$D^{*\pm}$-enhanced control sample



$D^{*\pm} \to D^0\pi^\pm$, $D^0 \to K\pi$ (mode 1)
$D^0 \to K3\pi$ (mode 2)
$D^0 \to K\pi\pi^0$ (mode 3)
$D^0 \to K_S\pi\ \pi$ (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 $\mathbf{q\bar{q}}$ direction**:** this is only a rough approximation

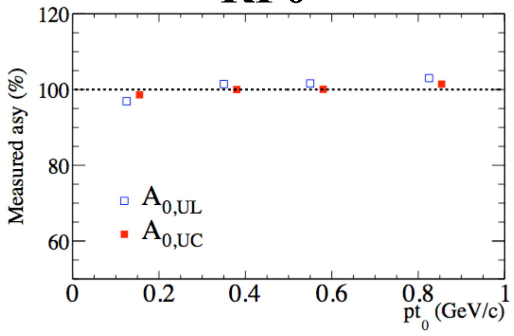
RF12: large smearing since the azimuthal angles ϕ_1 and ϕ_2 are calculated with respect to the thrust axis; additional dilution due to very energetic tracks close to the thrust axis.

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 $\mathbf{w^{UL(UC)}=1\pm a\bullet\cos(\phi_{gen12,0})}$ 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.

RF0



RF12