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

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OUTLINE

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

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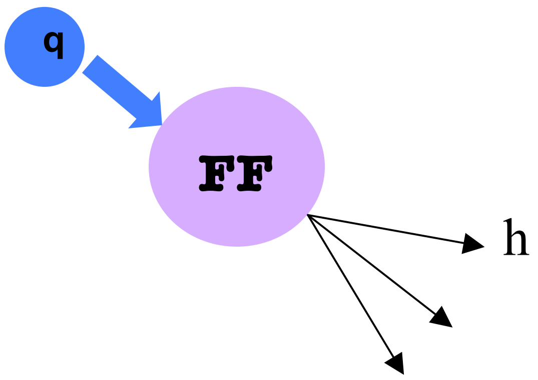
- Analysis method
- Extraction of the asymmetry for light quarks
- Asymmetry corrections and studies of systematic uncertainty

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

CONCLUSIONS

Collins Fragmentation Function

Fragmentation Functions (FFs) → 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



"Standard" unpolarized FF

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

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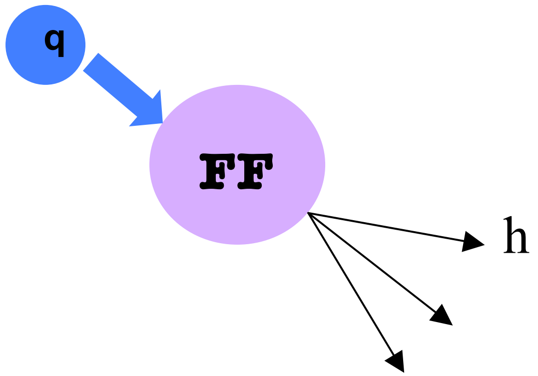

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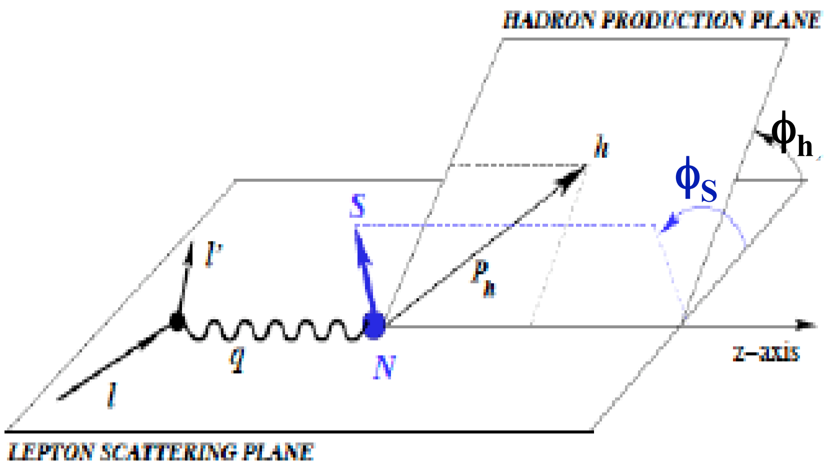
- could arise from a **spin-orbit** coupling
- leads to an asymmetry in the angular distribution of final state particles (**Collins effect**)

- **$H_1^\perp$** is the **polarized** fragmentation function or **Collins FF** → it describes the fragmentation of a **transversely polarized quark into a spinless (or unpolarized) hadron *h***
- J. C. Collins, 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)

Collins effect



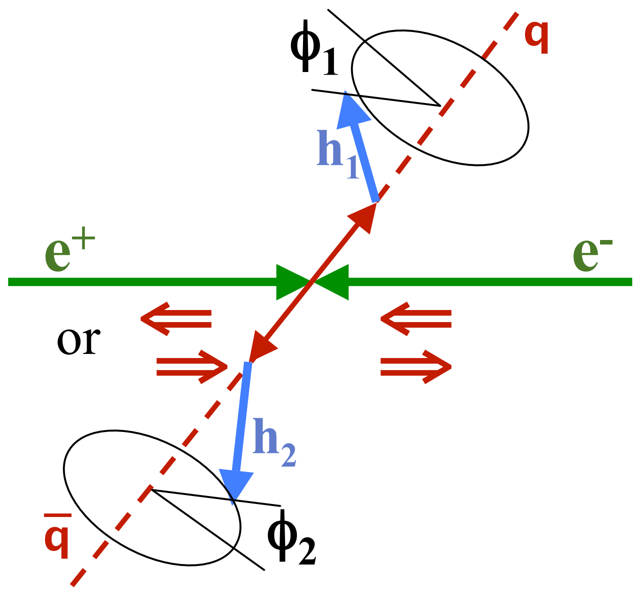
Semi-Inclusve DIS (SIDIS)

- Unpolarized lepton beam (l) off transversely polarized target (N) ($\ell N \rightarrow \ell' \pi X$)
  - non-zero Collins effects PRL 94,012002; NPB 765, 31
  - 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

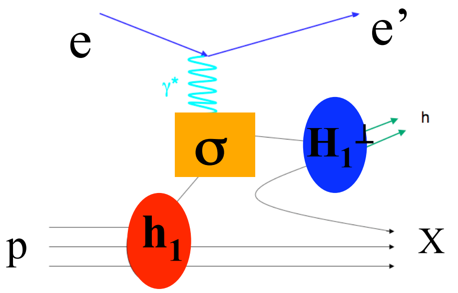
e^+e^- annihilation

- γ^* (spin-1) → 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 ($\sim\sin^2\theta$)
- exploit this correlation by using hadrons in opposite jets

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



Extraction of Collins FF from data



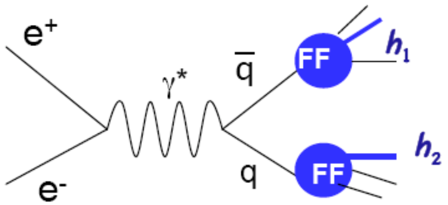
SIDIS

HERMES: PRL **94**, 012002 (2005)

COMPASS: NP **B765**, 31 (2007)

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

+



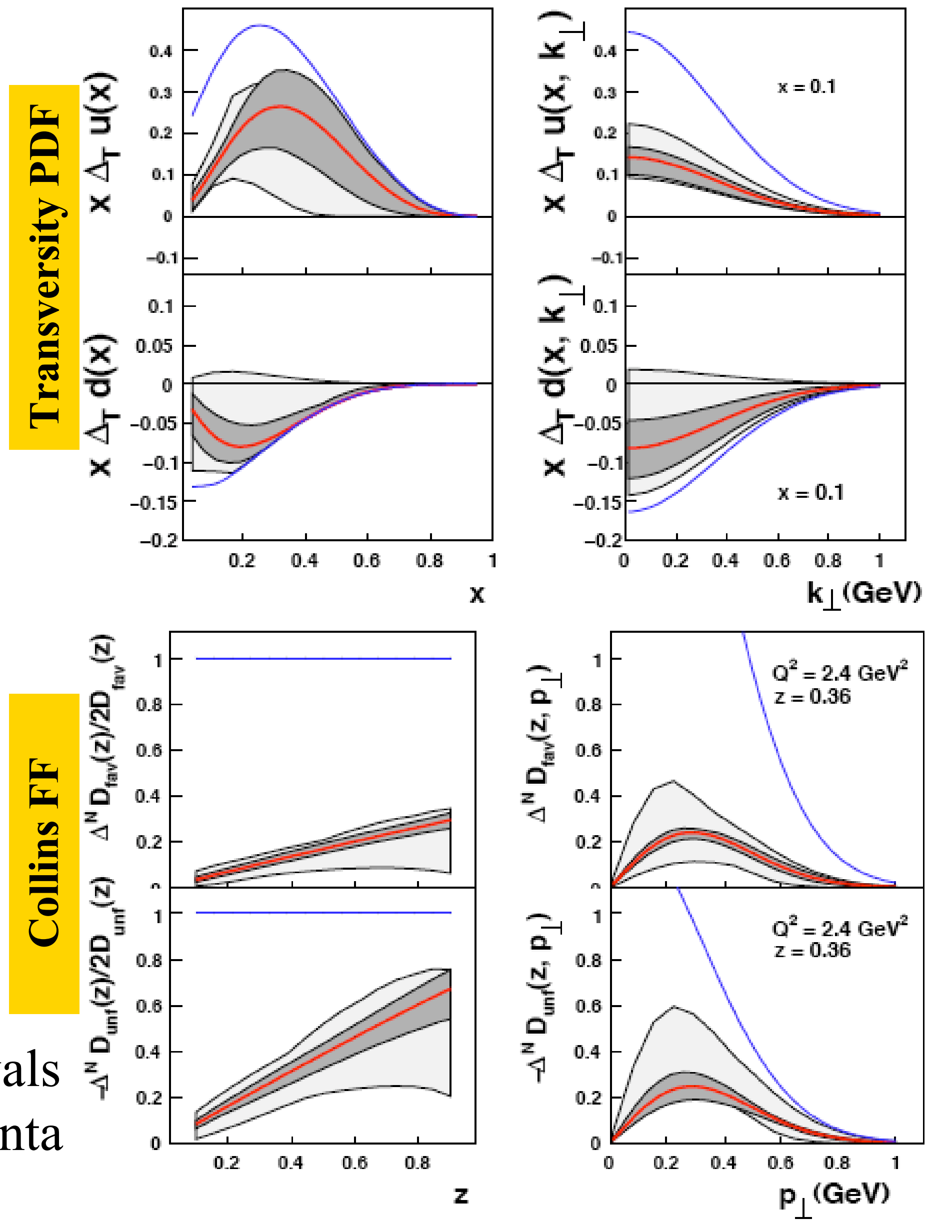
e^+e^- annihilation

BELLE: PRL 96, 232002, PRD 78, 03201, PRD 86,039905(E)

$$A \propto H_1^{\perp}(z_1) \otimes H_1^{\perp}(z_2)$$

<u>GLOBAL ANALYSIS</u>: simultaneous determination of $H_1^{\perp}$ and the transversity parton distribution function h_1

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



Improvements from BABAR studies:

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

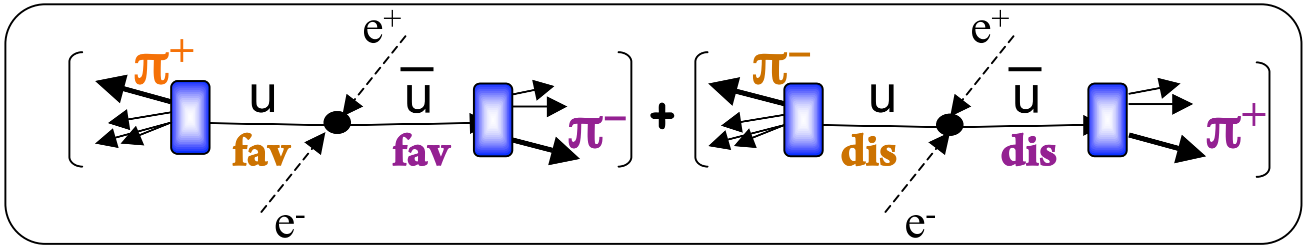
Collins effect in e^+e^- annihilation

$e^+e^- \to q\bar{q} \to \pi_1^{\pm}\pi_2^{\pm} X$ (q=u, d, s)

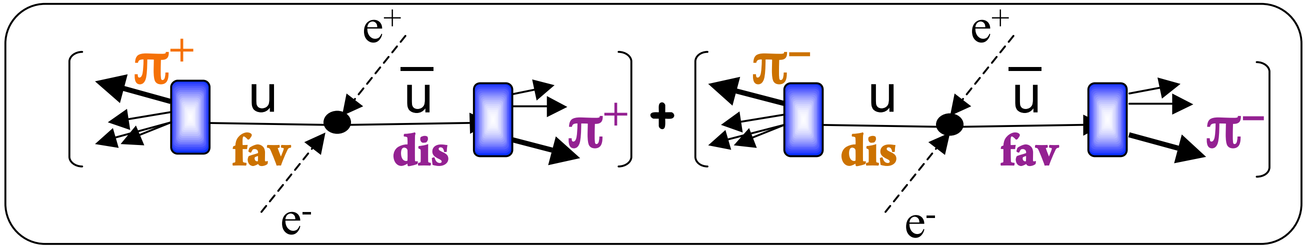
Different combination of charged pions ⇒ sensitivity to **favored** or **unfavored** FFs

- **favored** fragmentation process describes the fragmentation of a quark of flavor q into a hadron with a valence quark of the same flavor: i.e.: $u \to \pi^+$, $d \to \pi^-$
- **disfavored** for $d \to \pi^+$, $u \to \pi^-$, and $s \to \pi^{\pm}$

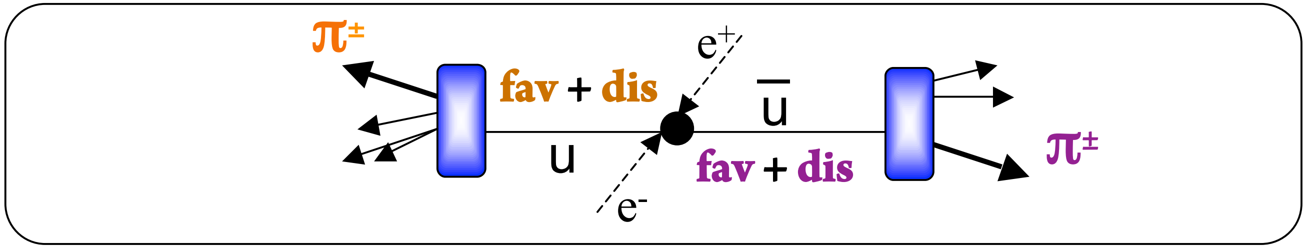
Unlike-sign pion pair = **U:**
$\pi^{\mp}\pi^{\pm}$: (**fav x fav**)+(**dis x dis**)



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)

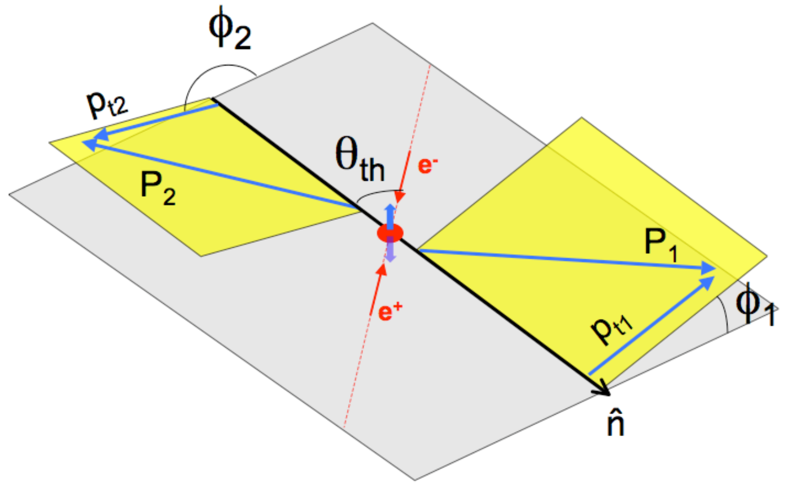
[See NPB 806, 23 (2009)]

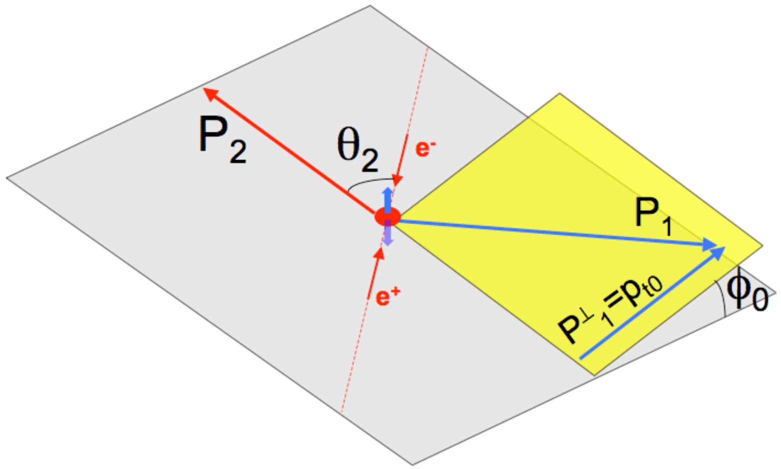
All quantities in e^+e^- center of mass

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,…

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





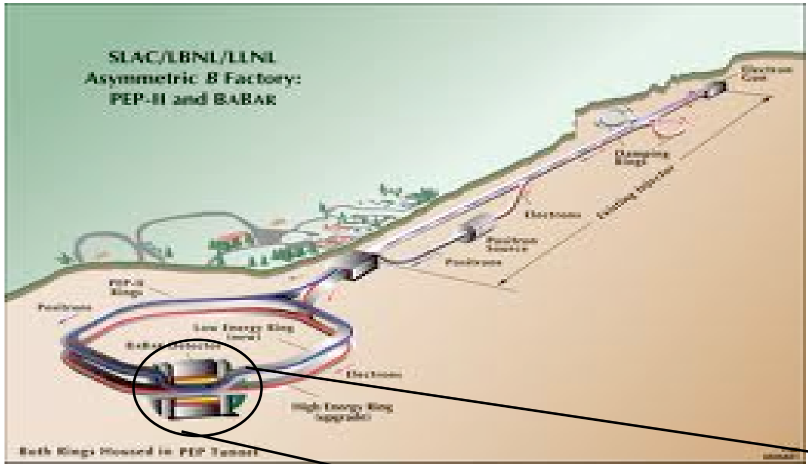
All quantities in e^+e^- center of mass

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

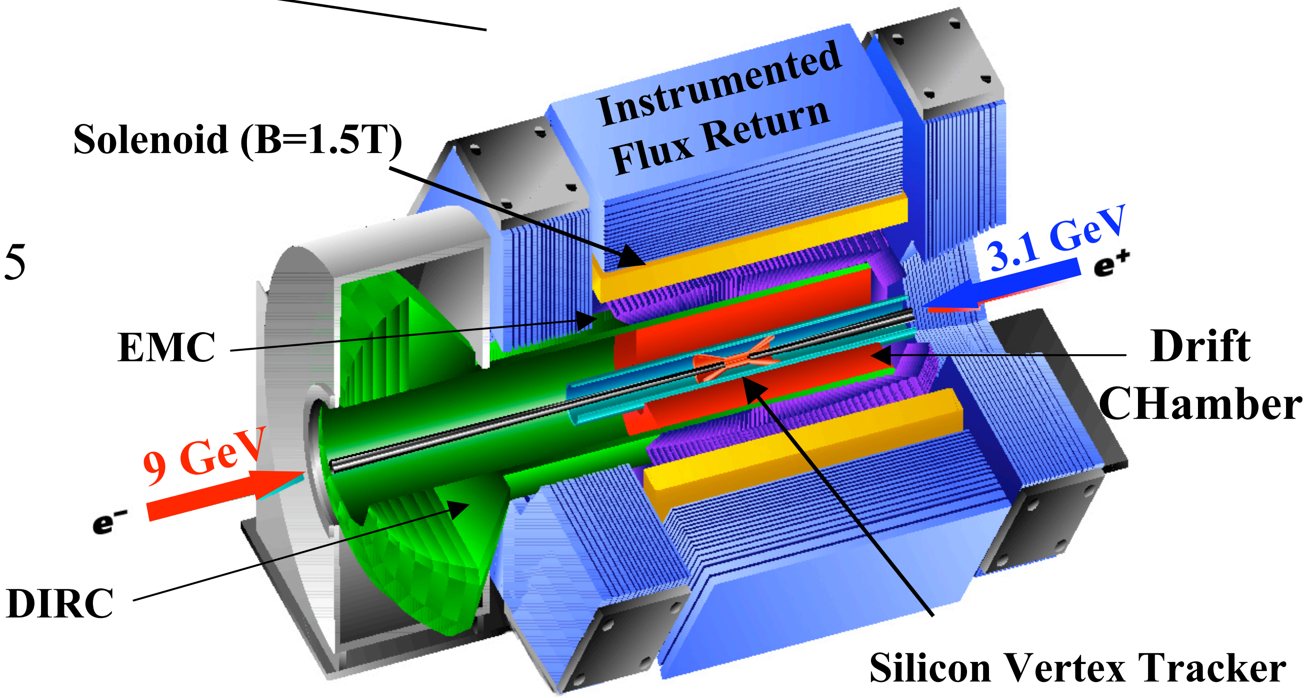
$$\sigma \sim 1 + \frac{\sin^2\theta_2}{1+\cos^2\theta_2} \cos(2\phi_0) \mathcal{F}\left[\frac{H_1^{\perp}(z_1)\bar{H}_1^{\perp}(z_2)}{D_1(z_1)\bar{D}_1(z_2)}\right]$$

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^+
  - c.m.-lab boost, $\beta\gamma \approx 0.56$
- High luminosity: **$\mathcal{L}$ ~ 468 fb^{-1}** used here

- Asymmetric detector
  - c.m. acceptance $-0.9<\cos\theta^*<0.85$ wrt e^- beam
- Excellent performance
  - good tracking, mass resolution
  - good γ, π^0 reconstruction
  - full e, μ, π, K, and p identification



Event and track selection

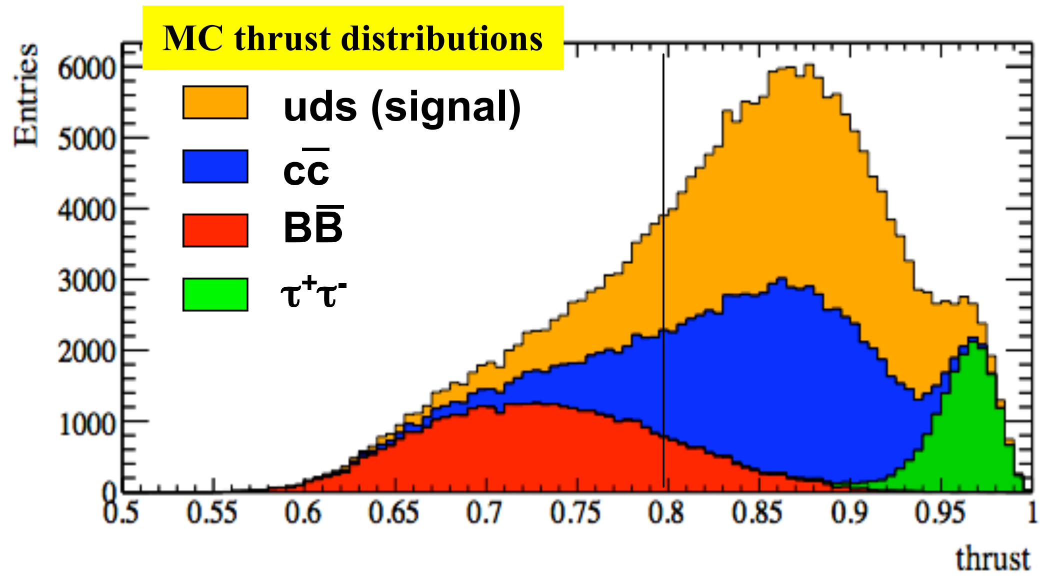
EVENT SELECTION

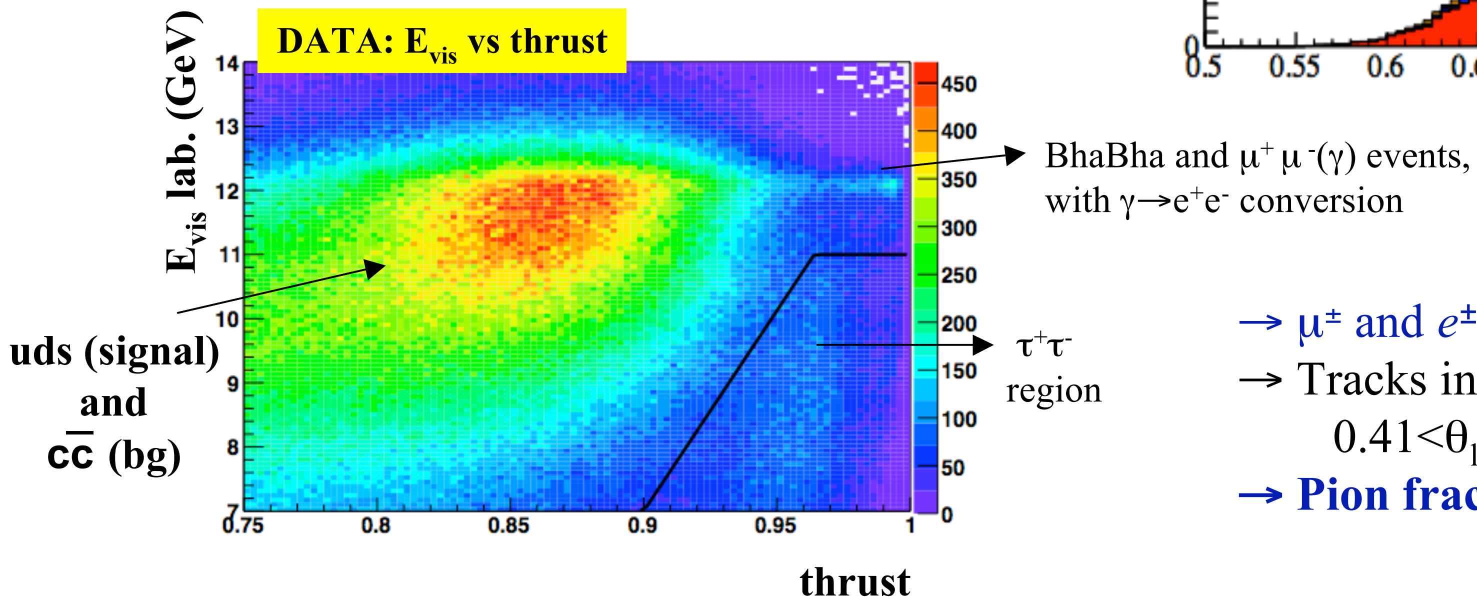
→ Number of charged tracks > 2

→ 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: $0.15<z=2E_h/\sqrt{s}<0.9$**

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

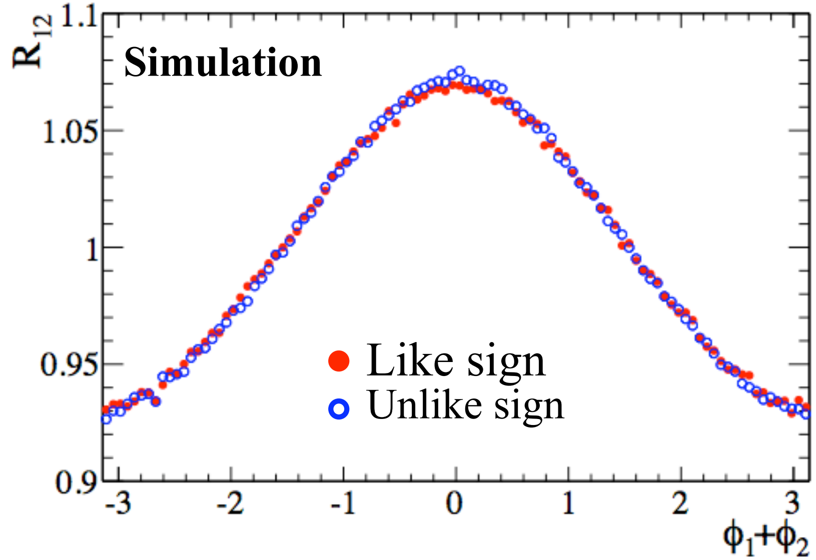
→ **Q_t<3.5 GeV**, where Q_t is the transverse momentum of the virtual photon in the pions CMS

Raw Asymmetries

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

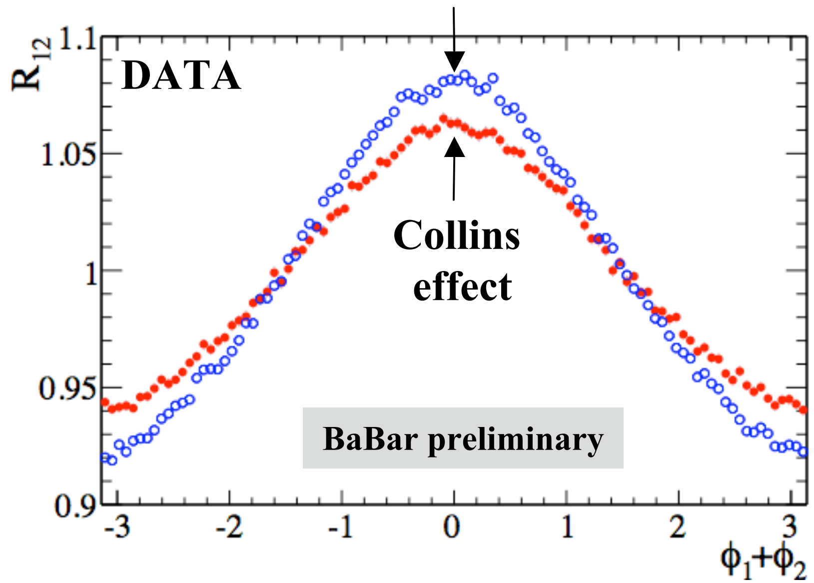
$$R_\alpha = \frac{N(\phi_\alpha)}{< N_\alpha >} = a + b \cdot cos(\phi_\alpha)$$

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



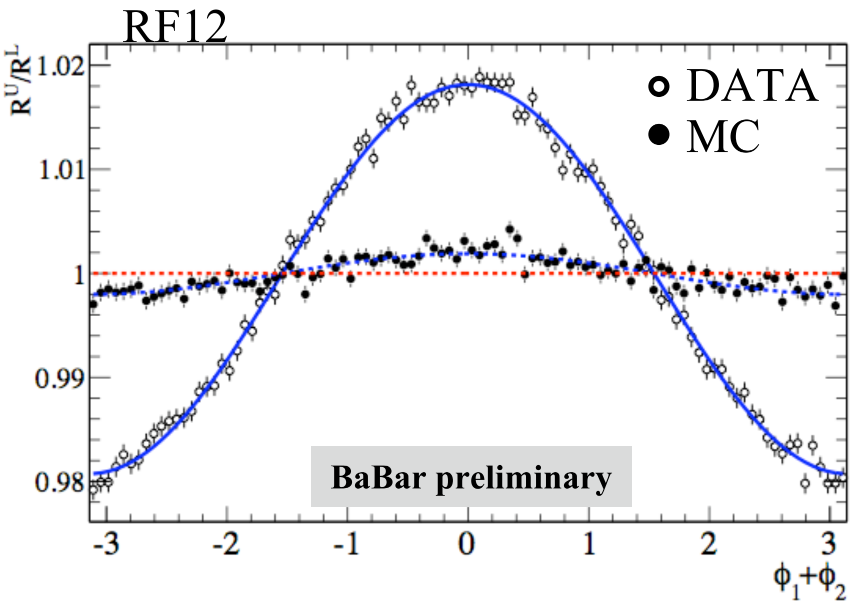
- **The MC generator (JETSET) does not include the Collins effect, but it shows a strong cosine modulation**
  - due to acceptance of the detector
  - depends strongly on the thrust axis polar angle
  - but similar distribution for **U** and **L** pairs

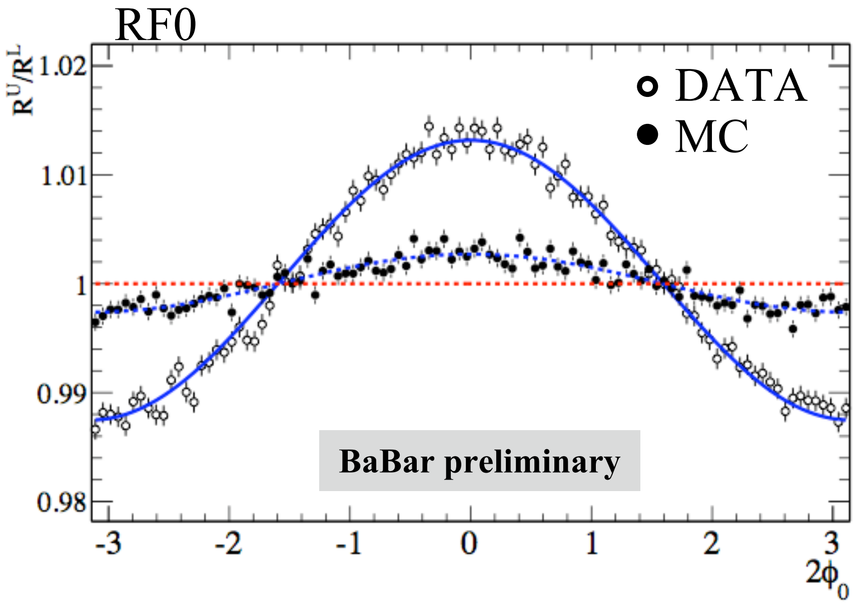
- **Data** shows a **large difference between U and L distributions,** that can be ascribed to the **Collins effect**



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

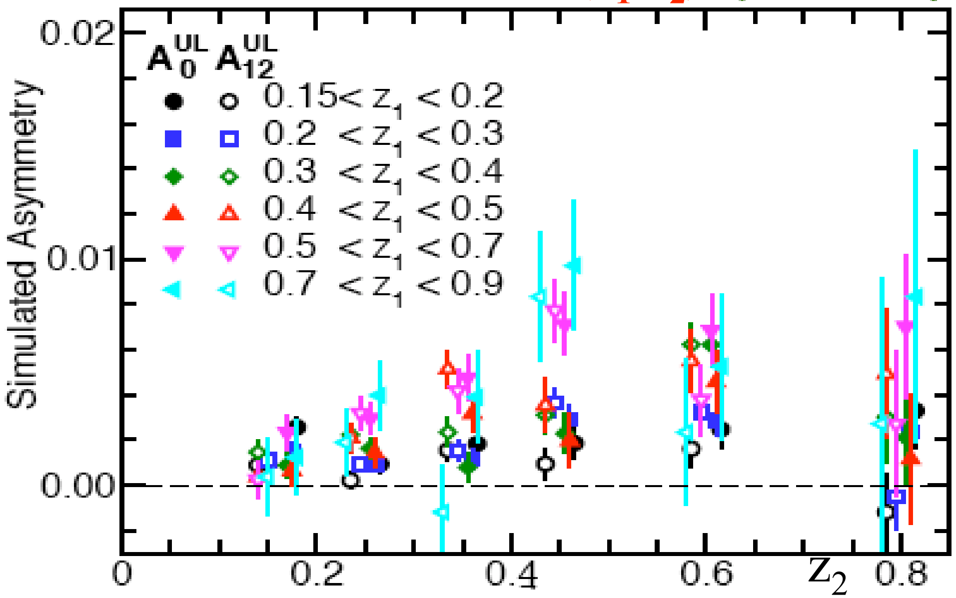
$$\frac{R^U_\alpha}{R^{L(C)}_\alpha} = \frac{N^U(\phi_\alpha)/ < N^U(\phi_\alpha) >}{N^{L(C)}(\phi_\alpha)/ < N^{L(C)}(\phi_\alpha) >} \to B^{UL(UC)}_\alpha + A^{UL,(UC)}_\alpha \cdot \cos(\phi_\alpha)$$

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

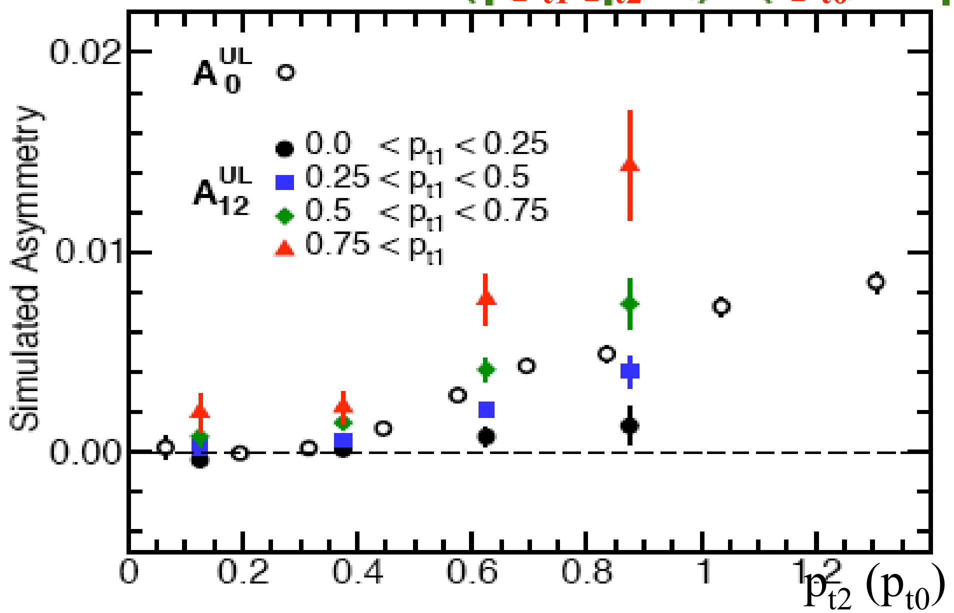
Asymmetry binning and corrections

- 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:

6x6 bins in (z_1,z_2)



4x4 bins in (p_{t1},p_{t2}) (9 in p_{t0})

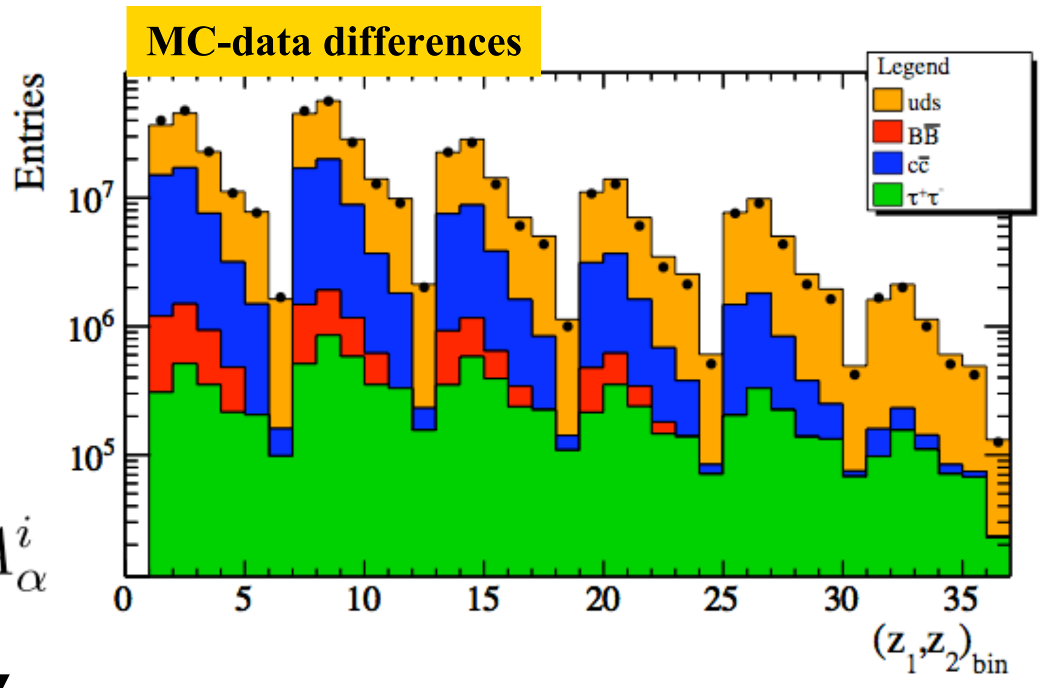


- Simulated asymmetries also depend on these quantities →must correct in each bin independently
  ⇒ Systematic on MC value evaluated by varying track selection/acceptance

- 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*, and between 1.3-3 as a function of p_t
  ⇒ No correction needed in the RF0 frame

Extraction of the 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:

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

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

True asymmetry

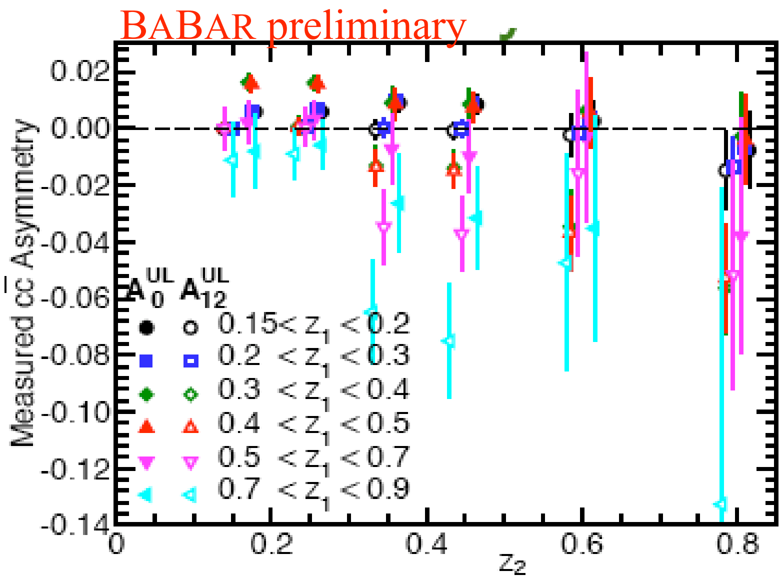
Asymmetry measured in the background data control sample

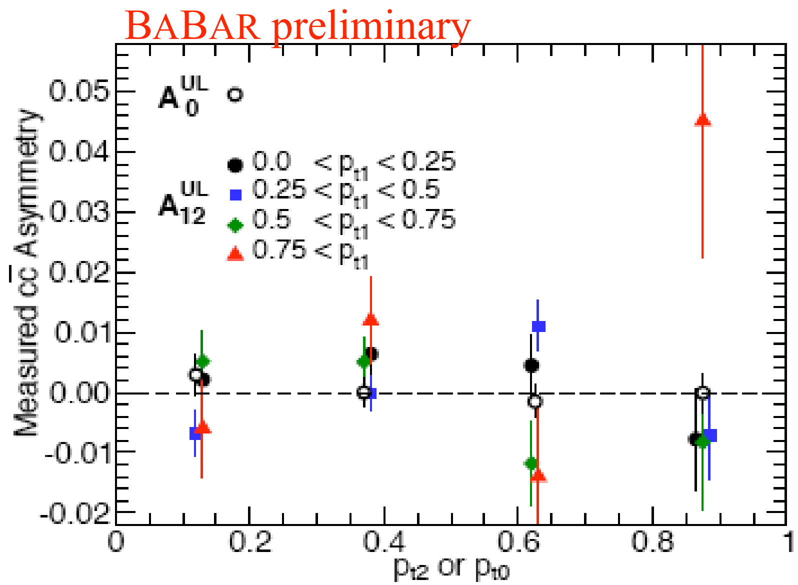
- We must calculate these quantities:
  - F_i using MC sample; we assign MC-data difference in each bin as systematic error
  - $A^{B\bar{B}}$ must be zero; we set $A^{B\bar{B}} = 0$
  - A^τ small in simulation; checked in data; we set $A^\tau = 0$

Extraction of the uds asymmetry

- 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**
  - 4 complementary decay modes $D^{*\pm}\rightarrow D^0\pi^\pm$, with $D^0\rightarrow K\pi, K3\pi, K\pi\pi^0, K_s\pi\pi$
  - mostly $c\bar{c}$ events, some $B\bar{B}$
- Again, f_i from MC, data-MC difference as systematic error

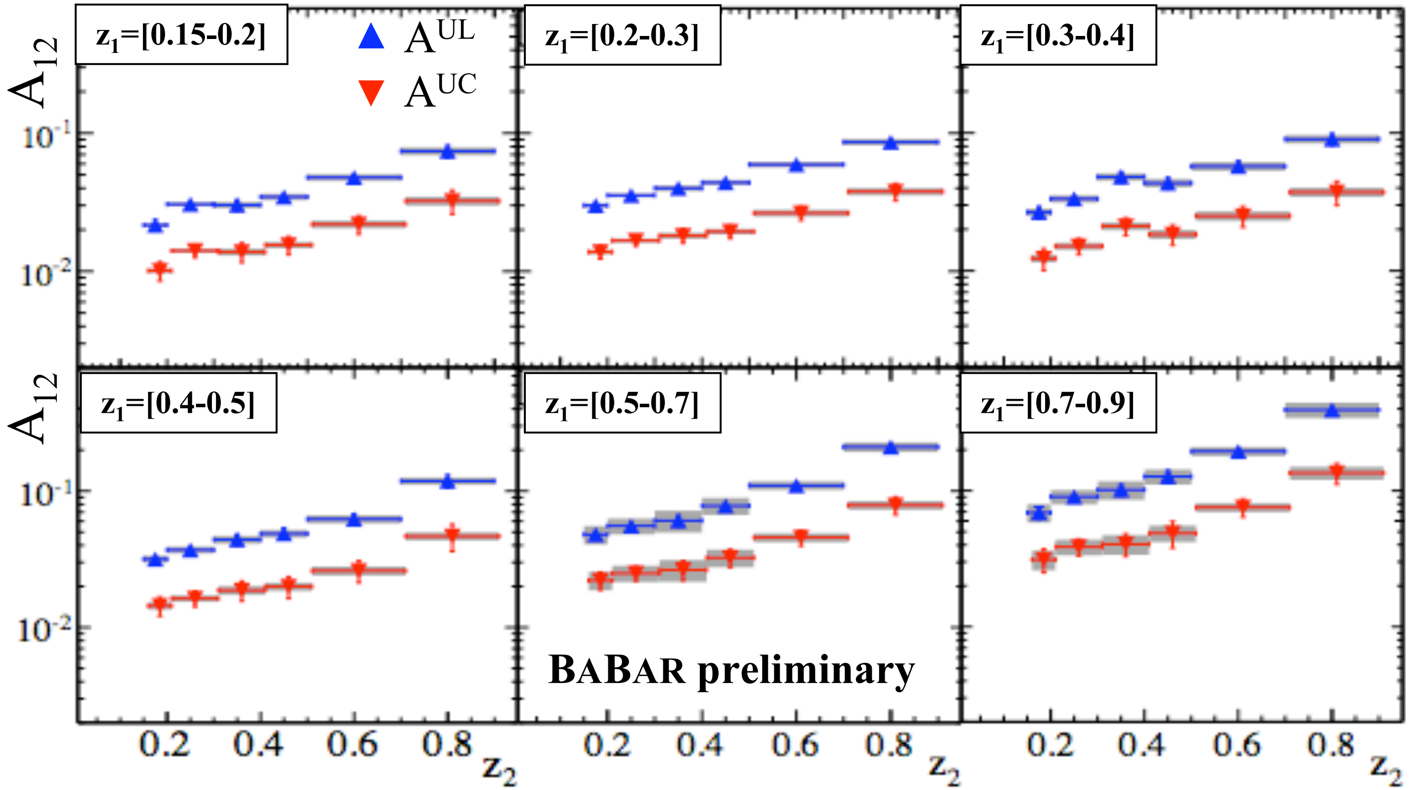
$$A_\alpha^{meas} = (1 - F_c - F_B - F_\tau)\cdot A_\alpha + F_c \cdot A_\alpha^{ch}$$
$$A_\alpha^{D^*} = f_c \cdot A_\alpha^{ch} + (1 - f_c - f_B)\cdot A_\alpha$$

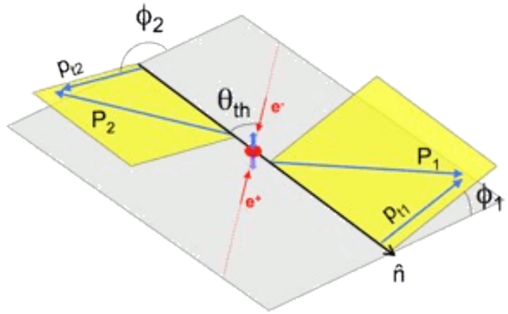




- the A^{ch} are very small (slightly negative?)

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





Systematic errors indicated by shaded bands

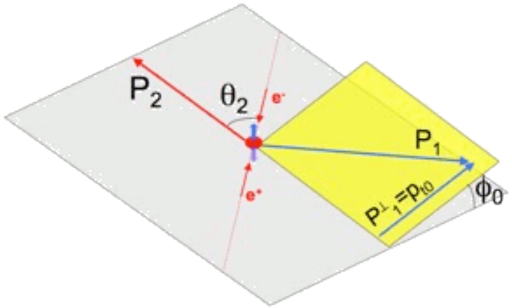
- **Very significant nonzero A^{UL} and A^{UC} in all bins**

  ⇒ strong dependence on (z_1,z_2), 1-39%

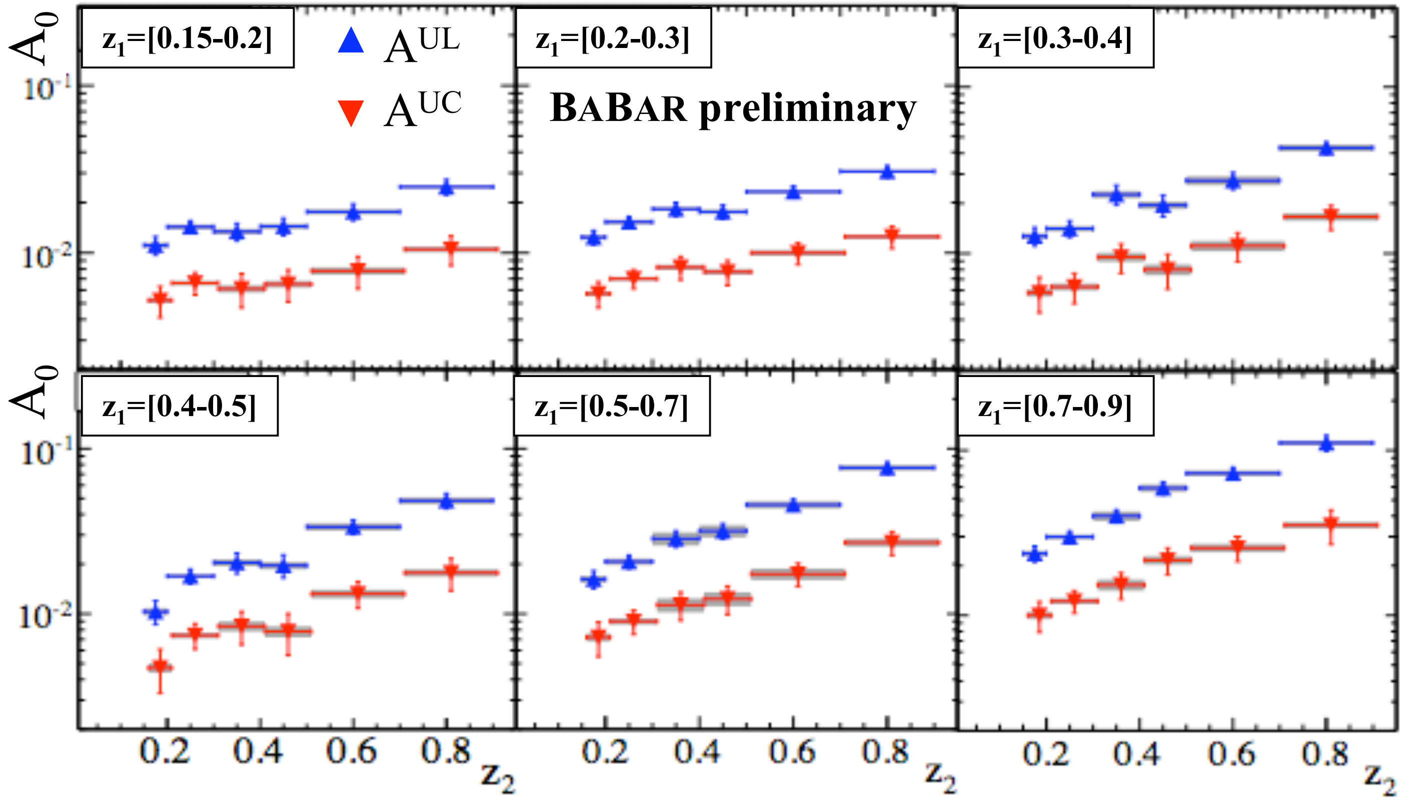
  ⇒ $A^{UC} < A^{UL}$ as expected; complementary information about the favored and disfavored fragmentation processes (PRD 73, 094025 (2006))

  ⇒ consistent with $z_1 \Leftrightarrow z_2$ symmetry

Results: A_0 vs. (z_1,z_2)

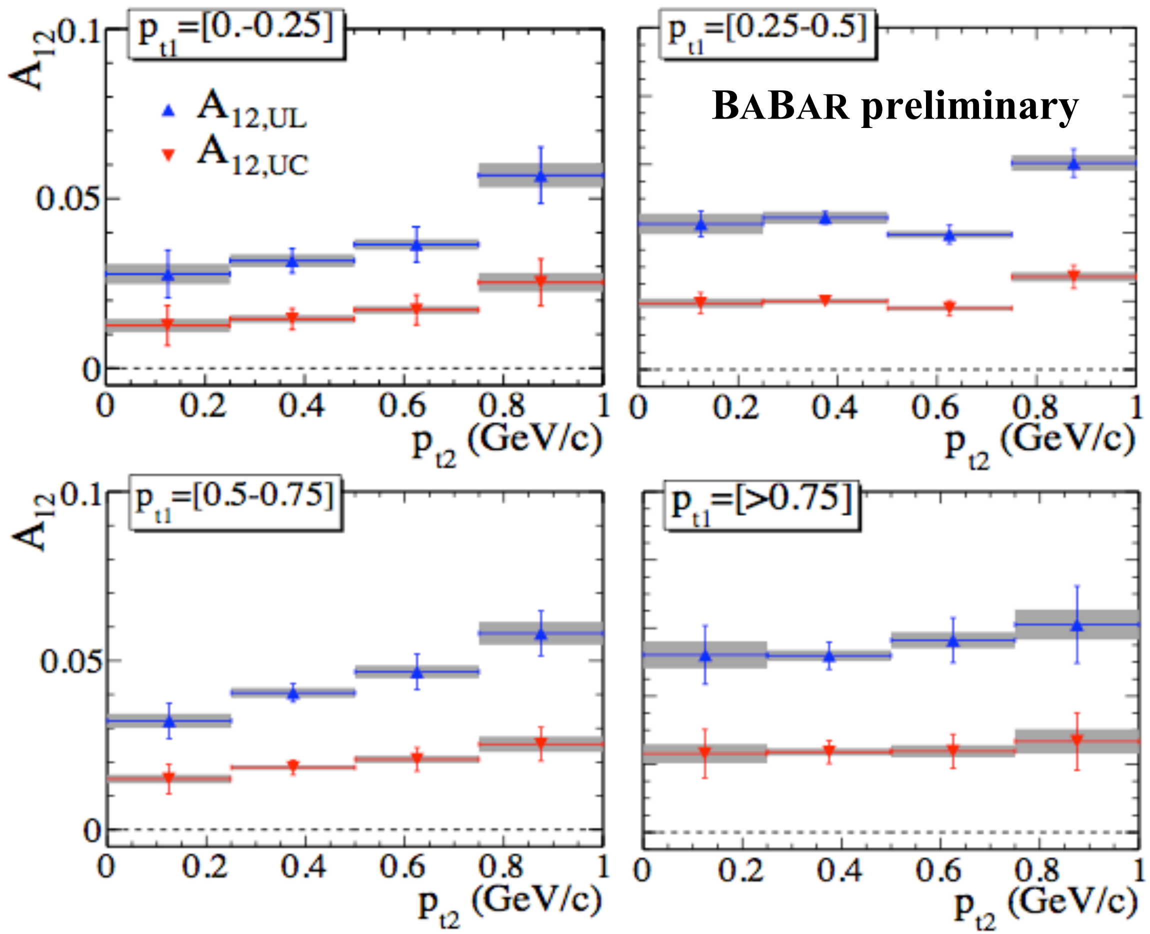


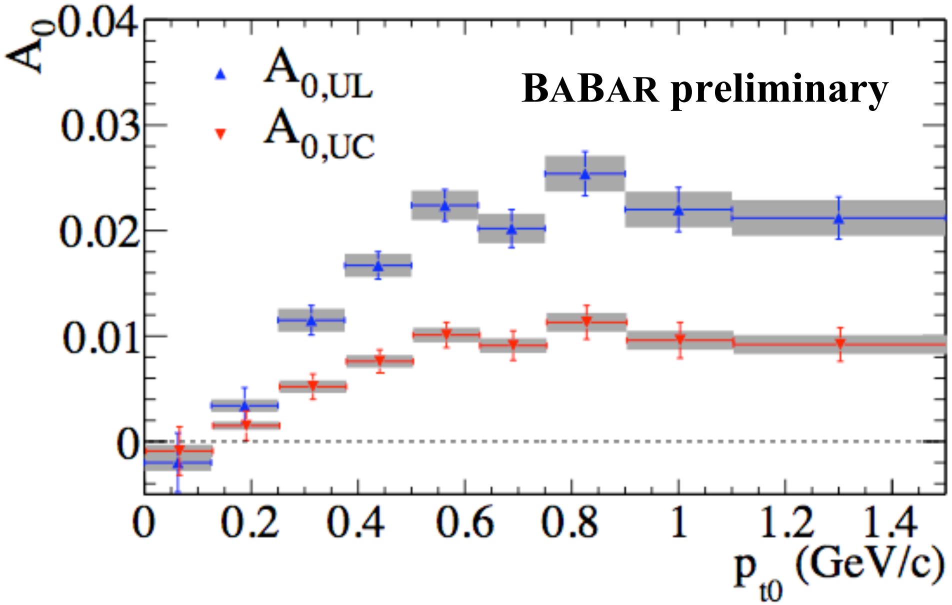
Systematic errors indicated by shaded bands



- **Very significant nonzero A^{UL} and A^{UC} in all bins**
  - ⇒ strong dependence on (z_1,z_2), 0.5-11%
  - ⇒ smaller than A_{12};
  - ⇒ $A^{UC} < A^{UL}$; complementary information on $H_1^{\perp,\,fav}$ and $H_1^{\perp,\,dis}$
  - ⇒ consistent with $z_1 \Leftrightarrow z_2$ symmetry

Results: A_{12} vs. (p_{t1},p_{t2}); A_0 vs. p_{t0}



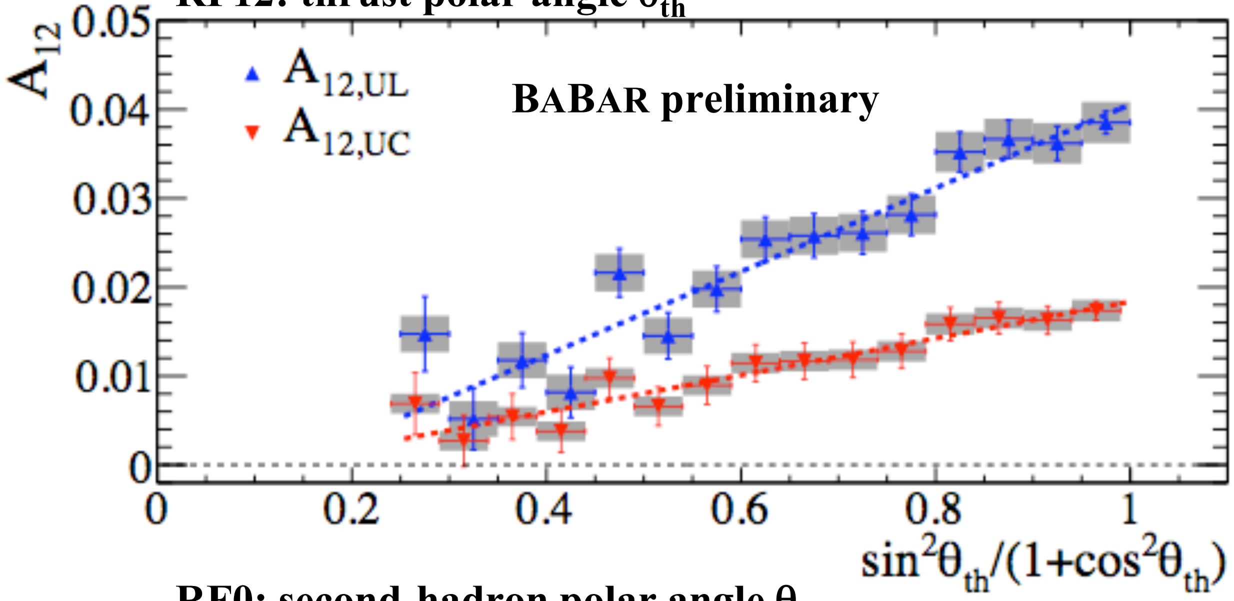


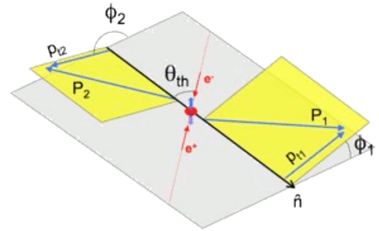
FIRST MEASUREMENT of Collins asymmetries *vs.* p_t in e^+e^- annihilation at Q^2~110 $(GeV/c)^2$ (time-like region)

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

Results: A_{12} vs. θ_{th}; A_0 vs. θ_2

RF12: thrust polar angle θ_{th}

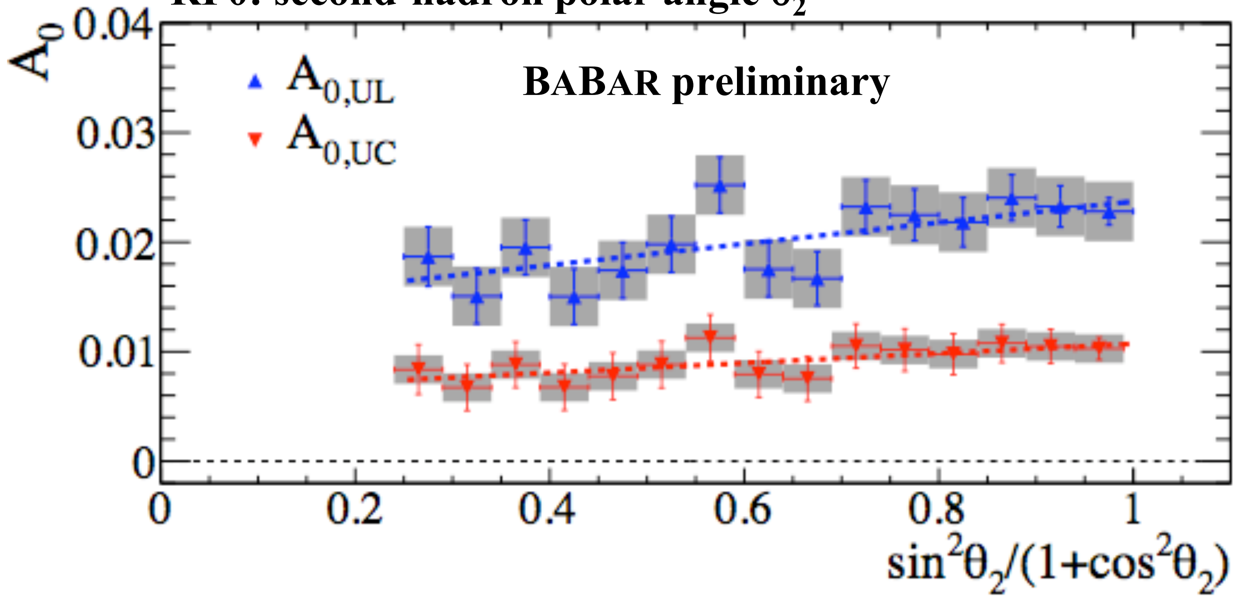


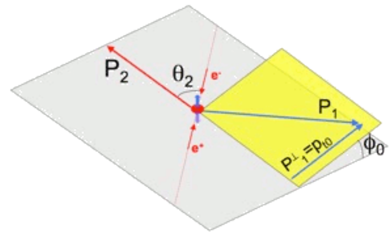


$$A_{12} \propto \frac{\sin^2\theta_{th}}{1+\cos^2\theta_{th}} \cos(\phi_1 + \phi_2) \frac{H_1^\perp(z_1)\bar{H}_1^\perp(z_2)}{D_1(z_1)\bar{D}_1(z_2)}$$

==> 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

BABAR has measured the Collins asymmetries for charged pion pairs in
$e^+e^-\to u\bar{u}, d\bar{d}, s\bar{s} \to \pi^\pm \pi^\pm X$

	RF12	RF0
⇒ in two distinct reference frames	RF12	RF0
⇒ vs. $\pi^\pm$ fractional energy z	z_1, z_2	z_1, z_2
⇒ vs. $\pi^\pm$ 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
- general agreement with Belle results (PRD 86, 039905(E) (2012))
- effect is stronger for leading particles

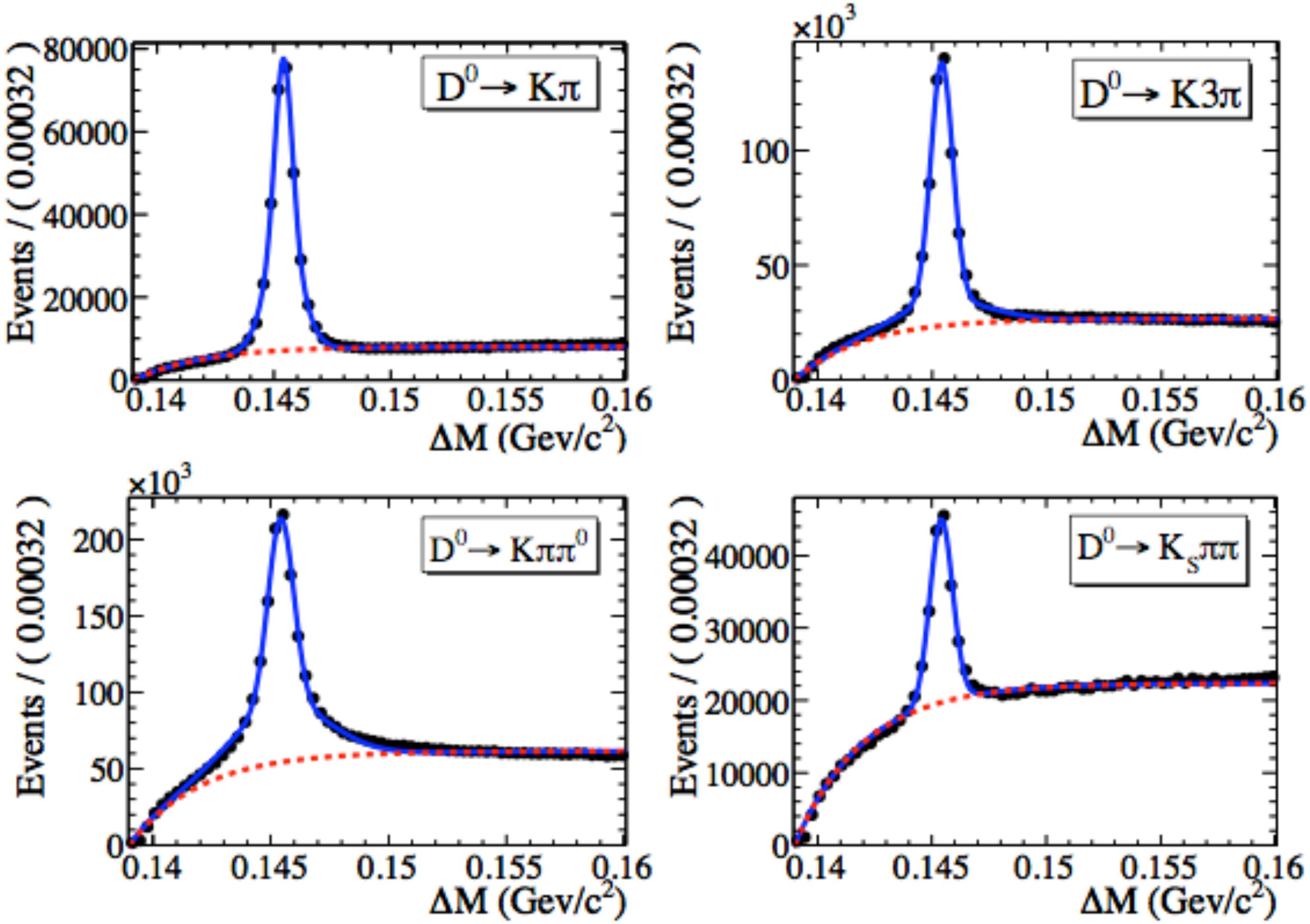
➲ **A_{12} (A_0) increases with p_{t1}, p_{t2} (p_{t0}) for p_t between 0 to 1 GeV/c**
- first measurement in e^+e^- annihilation at Q^2~110 $(GeV/c)^2$
- important for understanding the evolution of the fragmentation function

➲ **A_{12} (A_0) increases linearly with $\sin^2\theta/(1+\cos^2\theta)$**
- as (might be) expected

➲ **BABAR internal review in final stage for paper submission**

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)

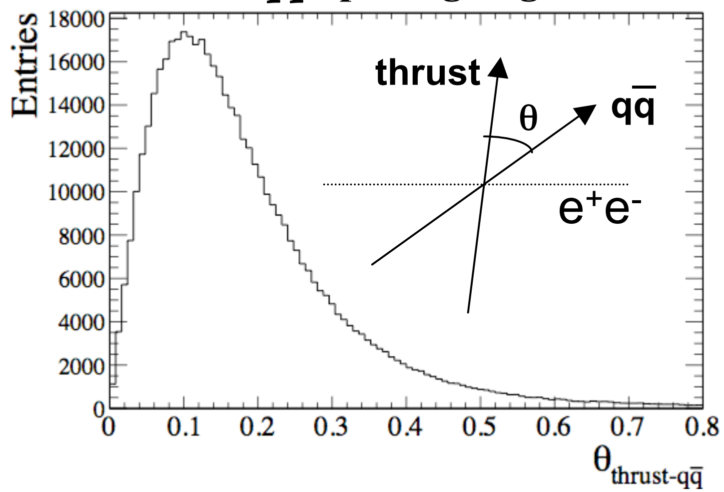
$1.835 < M_{D0} < 1.895$ GeV/c^2

$0.1425 < \Delta M < 0.149$ GeV/c^2

$(\Delta M = M_{D^*} - M_{D0})$

Asymmetry dilution

Thrust/$q\bar{q}$ opening angle



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

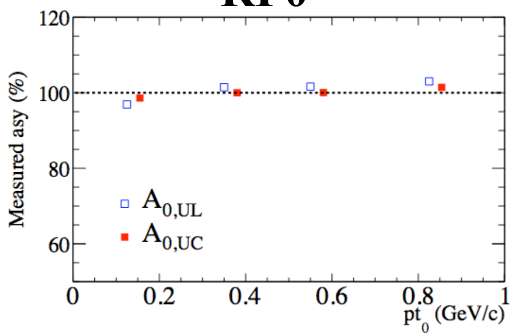
RF12: large smearing since the azimuthal angles ϕ_1 and ϕ_2 are calculated with respect to the thrust axis; additional dilution due to very energetic tracks close to the thrust axis.

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

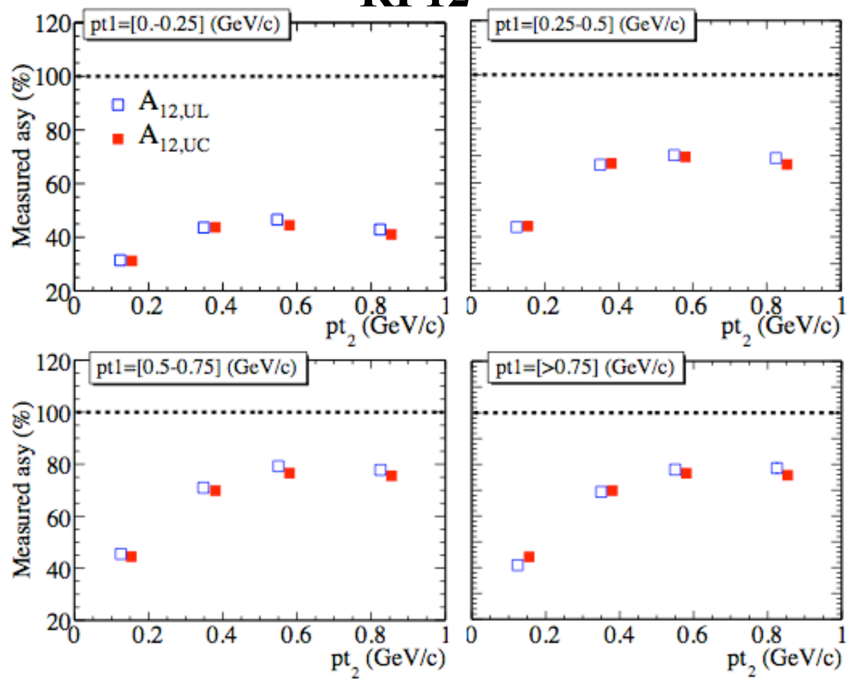
→We study the influence of the detector effects by correcting a posteriori the generated angular distribution: weights defined as $w^{UL(UC)}=1\pm a\bullet\cos(\phi_{gen12,0})$ are applied to every selected pion pairs.

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.

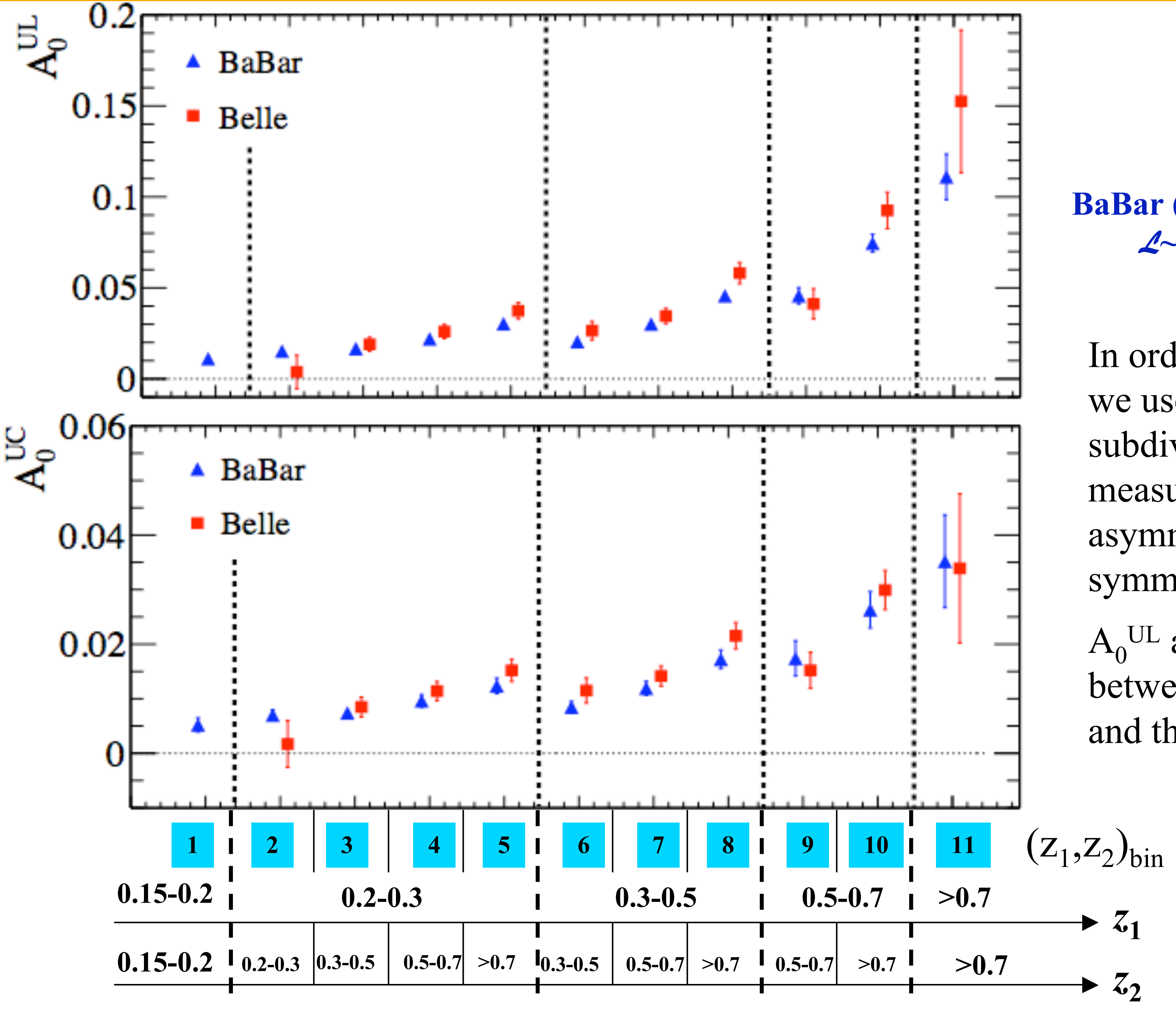
RF0

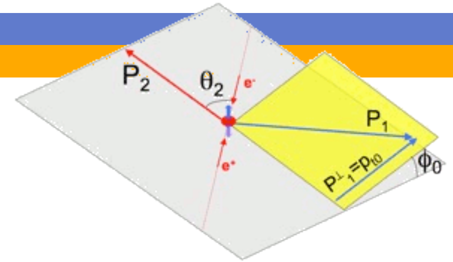


RF12



RFO:BaBar/Belle asymmetries comparisons





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

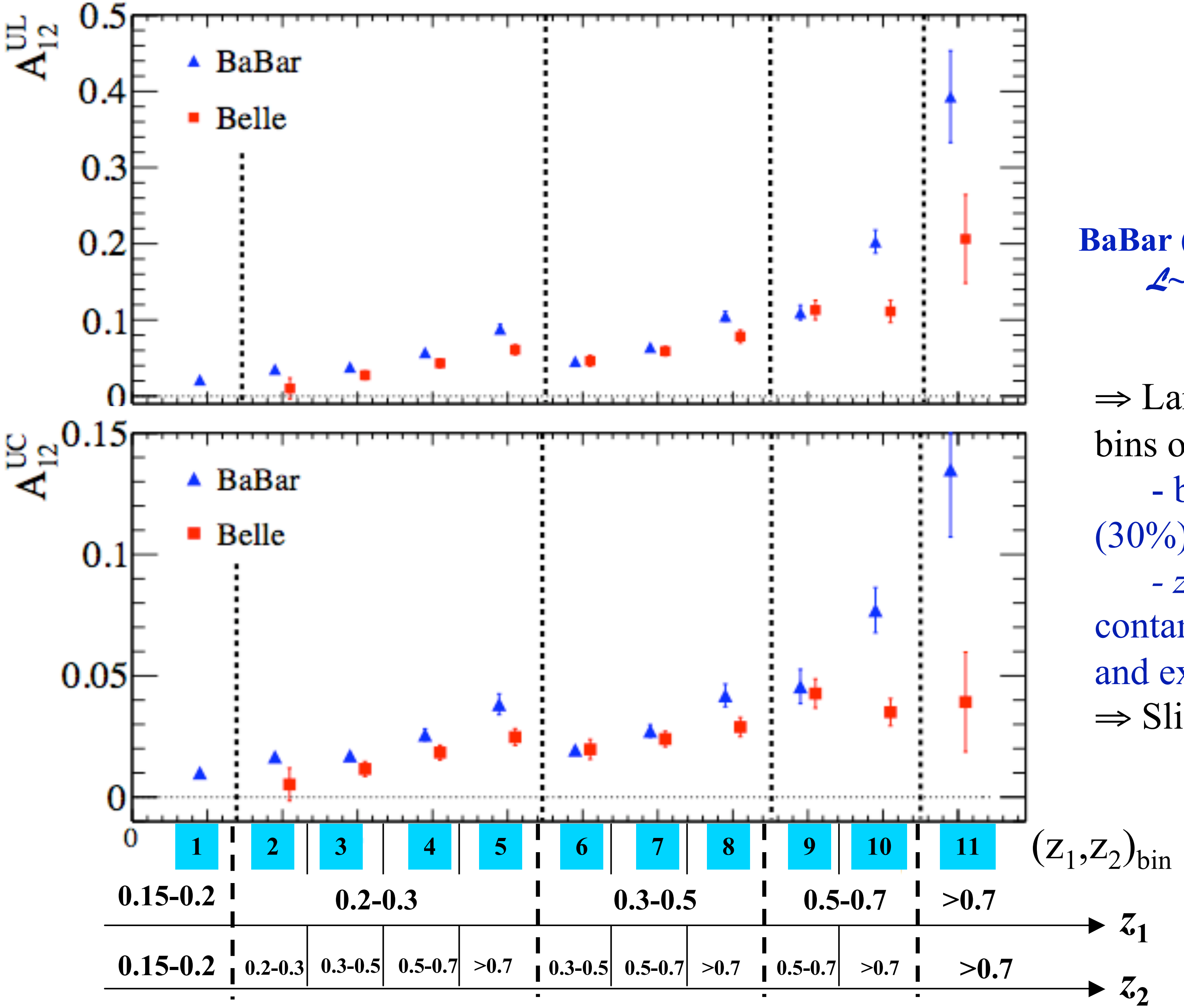
$\mathcal{L}$~470 fb^{-1} **$\mathcal{L}$~547 fb^{-1}**

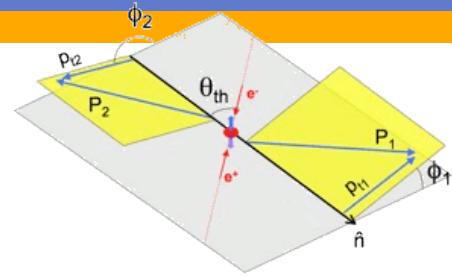
PRD 86, 039905(E) (2012)

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 comparisons





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⇒ 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

⇒ Slightly higher at lower z