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Measurement of Collins Asymmetries in inclusive production of pion pairs @ BaBar

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Outline

INTRODUCTION

- Theoretical framework
    - Collins fragmentation functions
    - Reference frames: RF12 and RF0
- 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

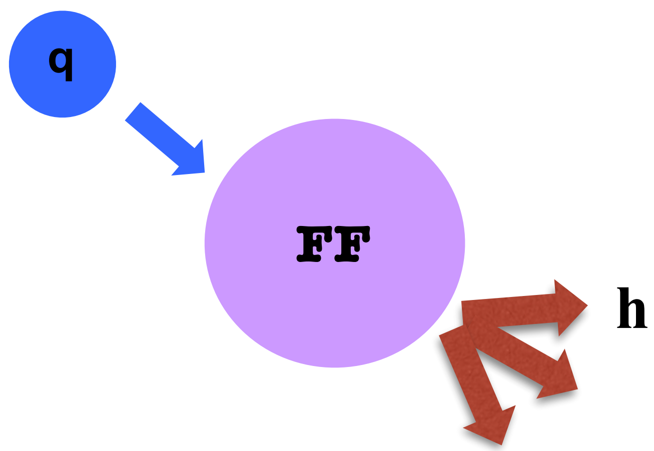
RESULTS

- Asymmetries *vs.* pion fractional energies, pion transverse momentum, analysis axis polar angle, and 4-D results

PLANS and **CONCLUSIONS**

Collins Fragmentation Function

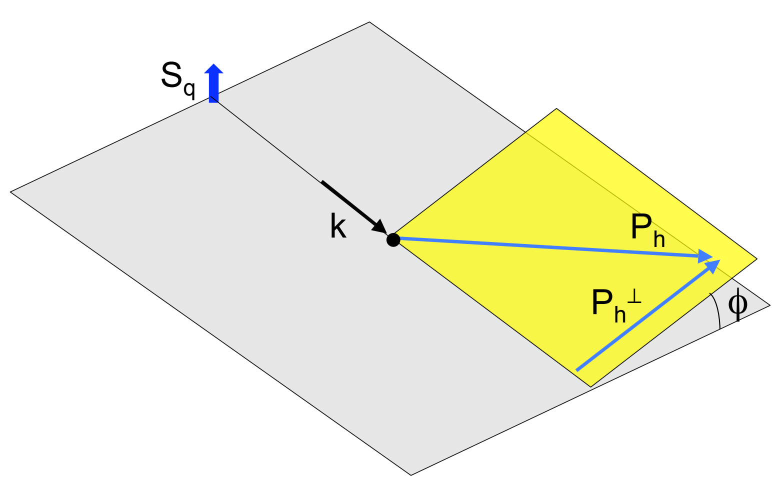
Fragmentation Functions (FFs) → dimensionless and universal functions
→ non-perturbative information
→ describe the final state particles in hard processes
→ dependence on $z=2E_h/\sqrt{s}$, $P_\perp$, and s_q



"Standard" unpolarized FF

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

Definition of the azimuthal angle ϕ in the case of a quark of momentum **k** and spin **S**$_q$ fragments into a spin-0 hadron of momentum **P**$_h$ with transverse component $P_h^\perp$ transverse to **k**



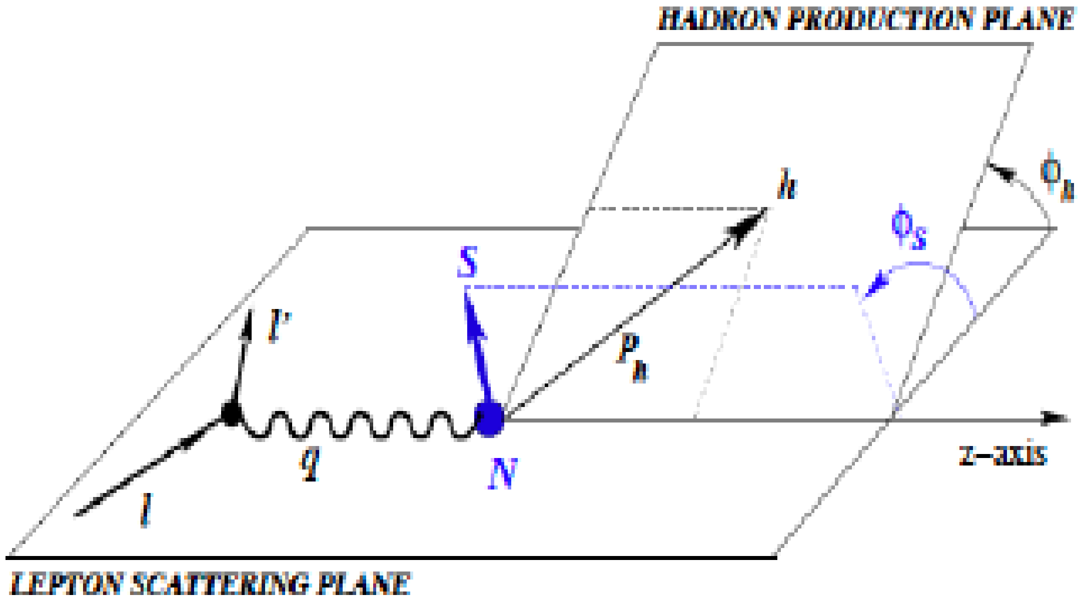
- could arise from a **spin-orbit** coupling
- leads to an azimuthal modulation of hadrons around the quark momentum **k** ==> **Collins asymmetry**

- $H_1^\perp$ 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)

Collins effect



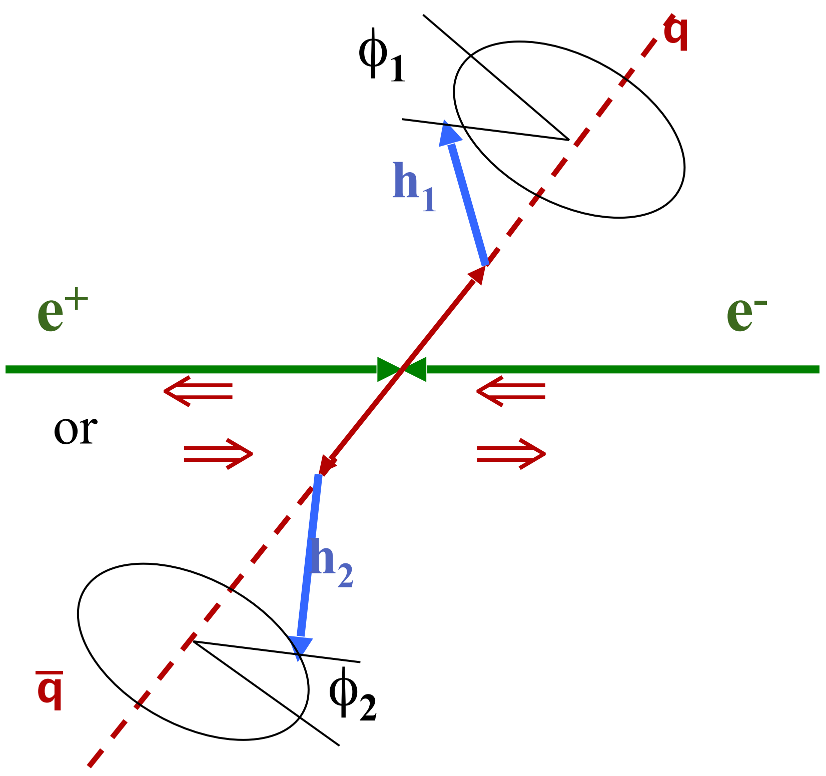
SIDIS

- First observed in Semi-Inclusive DIS (SIDIS)
  - unpolarized lepton beam (l) off transversely polarized target (N) (l**N**$\rightarrow l'\pi$**X**)
  - non-zero Collins effect
- $\sigma \propto \mathbf{\sin(\varphi_h + \varphi_s)\, h_1(x_B)} \otimes \mathbf{H_1^{\perp}(z_1)}$
  - two chiral-odd functions
  - azimuthal single spin asymmetry

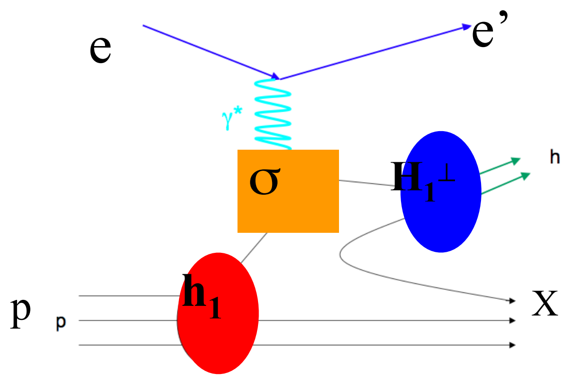
e^+e^- annihilation

- In a given event, the q and $\bar{q}$ spin directions are unknown, but they must be parallel, with a polarization component transverse to the q direction $\propto \sin^2\theta$
- exploit this correlation by using hadrons in opposite jets
- the observed asymmetry is proportional to the product of two Collins functions:

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



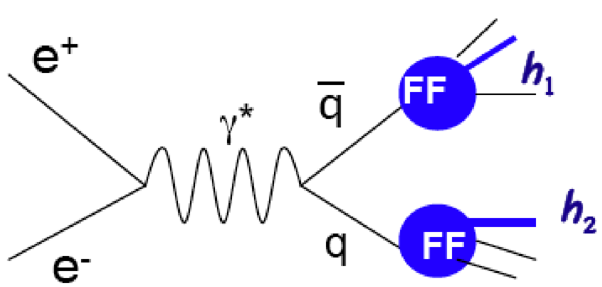
Extraction of Collins functions from data



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

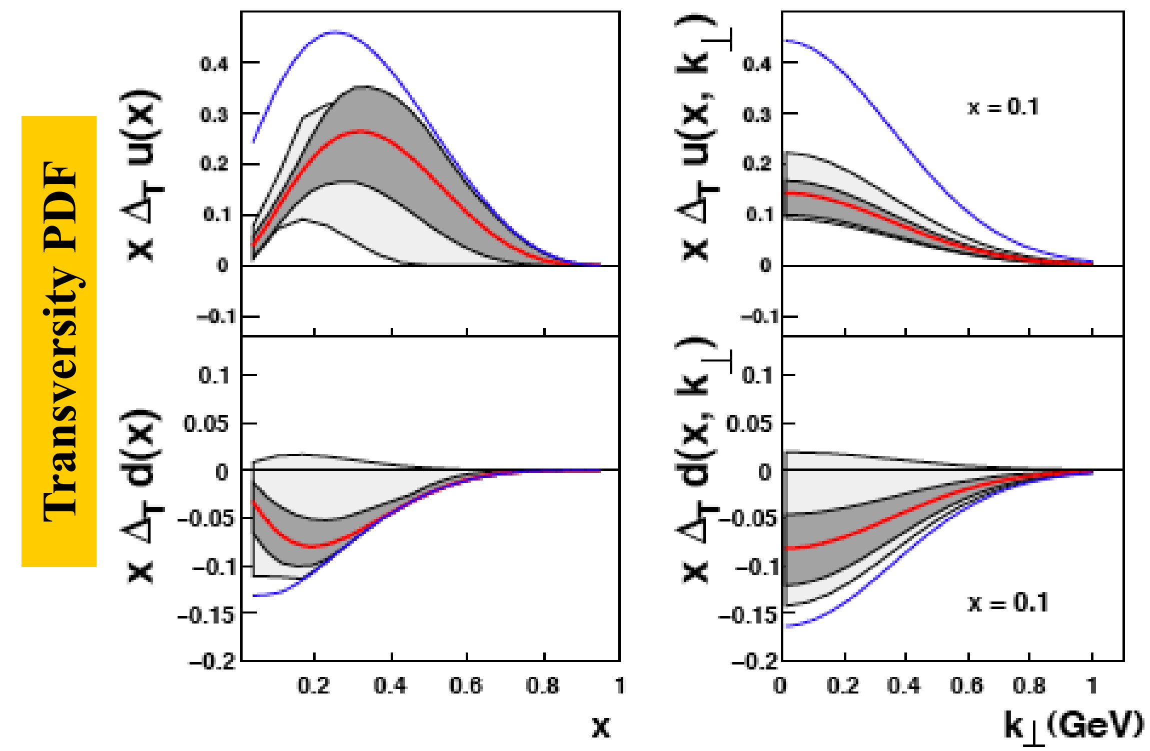
$A_T \propto h_1(x_B) \otimes H_1^{\perp}(z)$

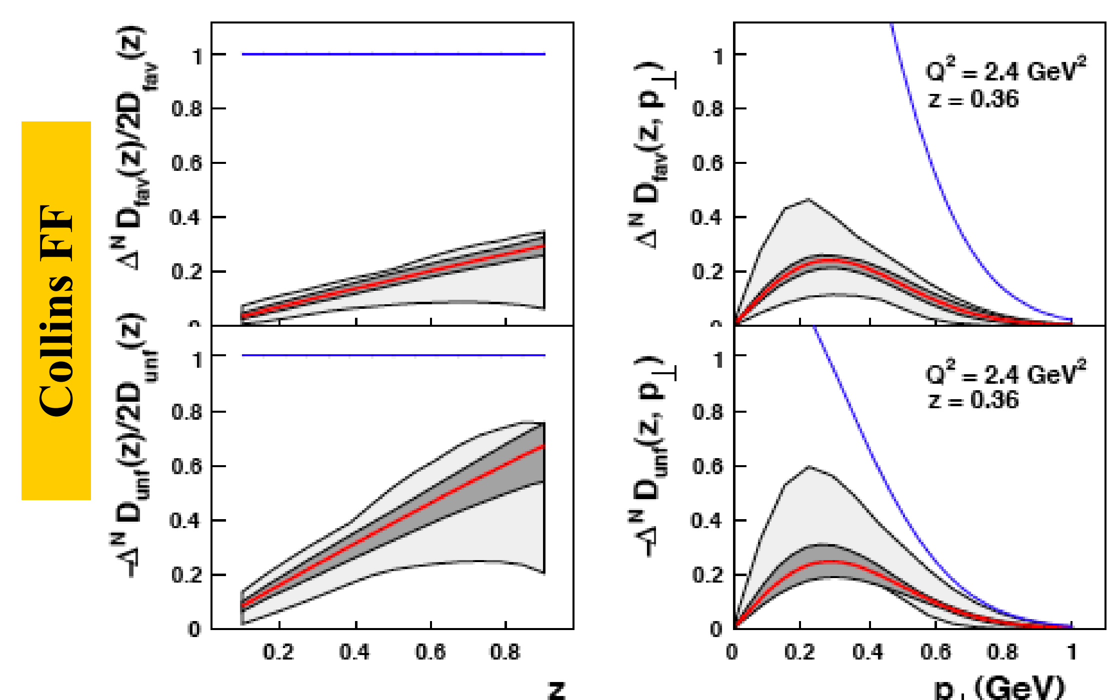
+



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

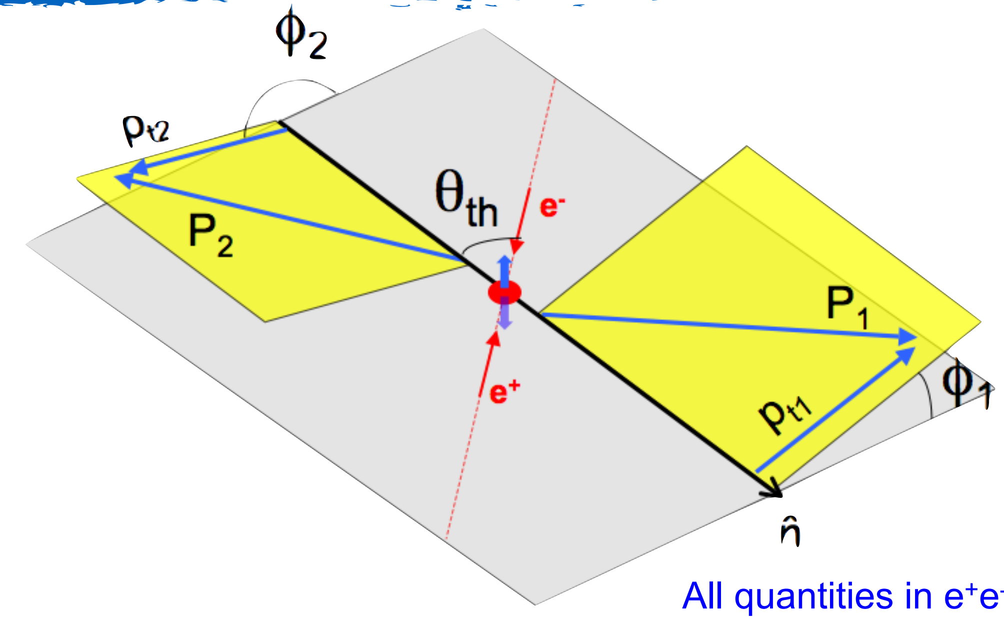
Improvements from BABAR studies:

- Different number of pion fractional energy intervals
- Asymmetry vs. p_t and 4-D analysis
- Measurement obtained with a different experimental setup

==> different systematics

Reference Frames

RF12 or Thrust RF



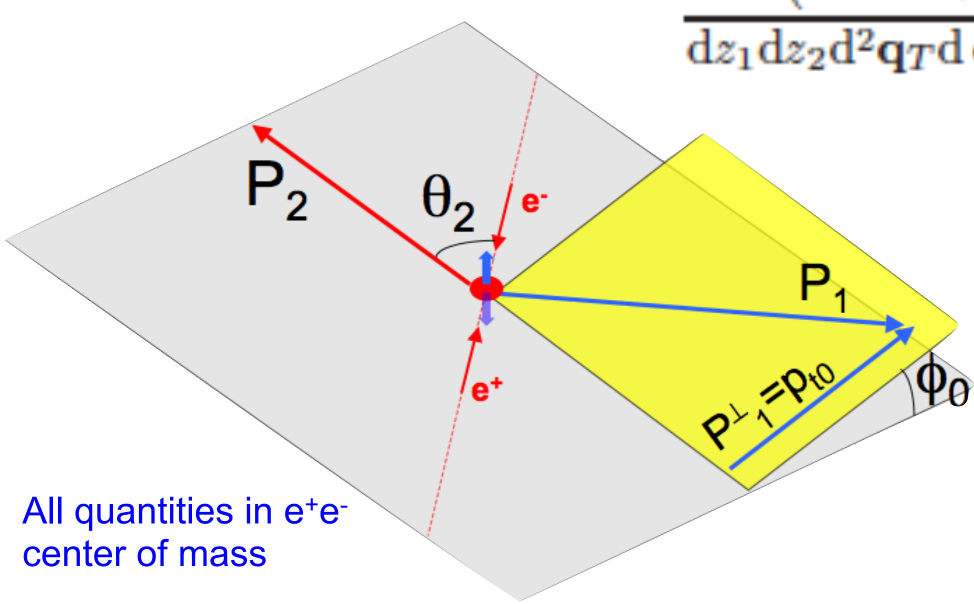
All quantities in e⁺e⁻ center of mass

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

$$\frac{\mathrm{d}\sigma(e^+e^- \to \pi_1\pi_2 X)}{\mathrm{d}z_1\mathrm{d}z_2\mathrm{d}\phi_1\mathrm{d}\phi_2\mathrm{d}\cos\theta_{th}} = \sum_{q,\bar{q}} \frac{3\alpha^2}{s}\frac{e_q^2}{4} z_1^2 z_2^2 \times$$
$$\left\{(1+\cos^2\theta_{th})\, D_1^{q,[0]}(z_1)\overline{D}_1^{q,[0]}(z_2) + \sin^2\theta_{th}\ \cos(\phi_1+\phi_2)\, H_1^{\perp q,[1]}(z_1)\overline{H}_1^{\perp q,[1]}(z_2)\right\}$$

RF0 or Second hadron frame

$$\frac{\mathrm{d}\sigma(e^+e^- \to \pi_1\pi_2 X)}{\mathrm{d}z_1\mathrm{d}z_2\mathrm{d}^2\mathbf{q}_T\mathrm{d}\cos(\theta_2)d\phi_0} = \frac{3\alpha^2}{s}\frac{z_1^2 z_2^2}{4} \times \left\{(1+\cos^2\theta_2)\,\mathcal{F}(D_1(z_1)\overline{D}_1(z_2)) + \sin^2\theta_2\ \cos(2\phi_0)\right.$$
$$\left.\times\mathcal{F}\left[(2\hat{\mathbf{h}}\cdot\mathbf{k}_T\,\hat{\mathbf{h}}\cdot\mathbf{p}_T - \mathbf{k}_T\cdot\mathbf{p}_T)\frac{H_1^\perp(z_1)\overline{H}_1^\perp(z_2)}{M_\pi^2}\right]\right\}$$



All quantities in e⁺e⁻ center of mass

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

[See NPB 806, 23 (2009)]

Collins effect in e^+e^- annihilation

Different combination of charged pions: $e^+e^- \rightarrow q\bar{q} \rightarrow \pi_1^{\pm}\pi_2^{\pm(\mp)} X$ (q=u, d, s)

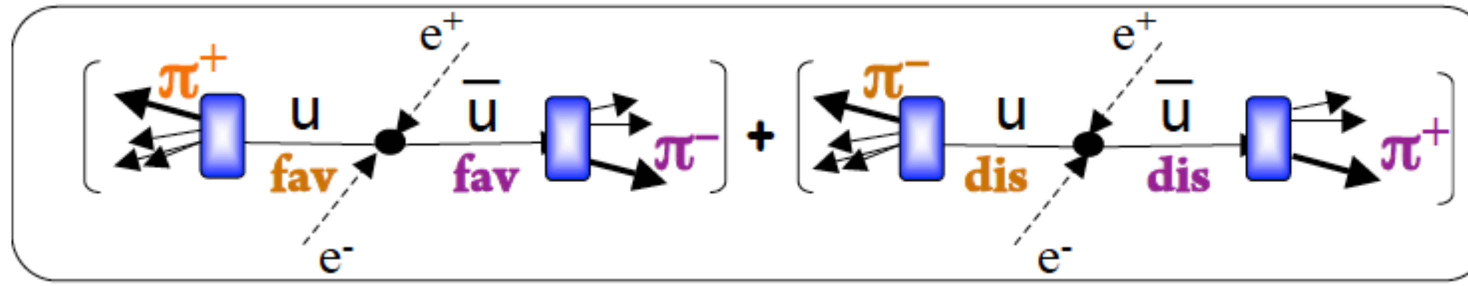
$\Rightarrow$ sensitivity to **favored** or **unfavored** FFs

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

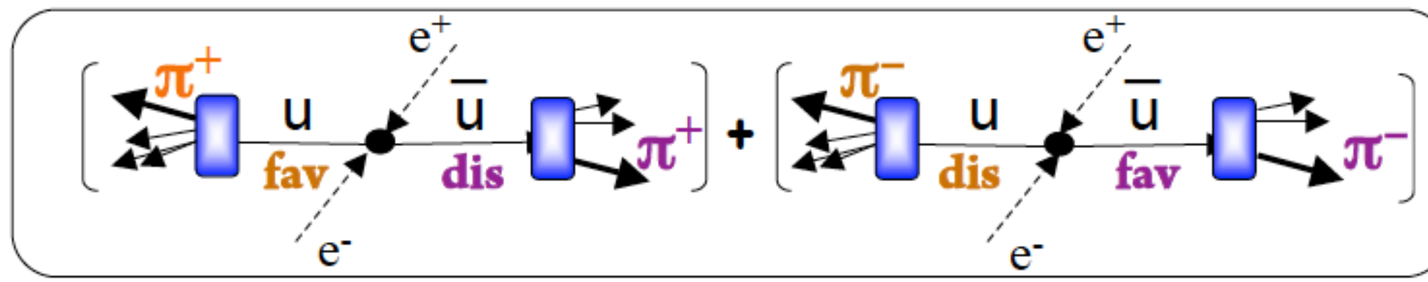
$$D^{\rm fav}(z) = D_u^{\pi^+}(z) = D_d^{\pi^-}(z)$$
$$\overline{D}^{\rm fav}(z) = D_{\bar{u}}^{\pi^-}(z) = D_{\bar{d}}^{\pi^+}(z)$$
$$D^{\rm dis}(z) = D_u^{\pi^-}(z) = D_d^{\pi^+}(z) = D_s^{\pi^{\pm}}(z)$$
$$D^{\rm dis}(z) = D_u^{\pi^-}(z) = D_d^{\pi^+}(z) = D_s^{\pi^{\pm}}(z)$$

Collins effect in e+e- annihilation

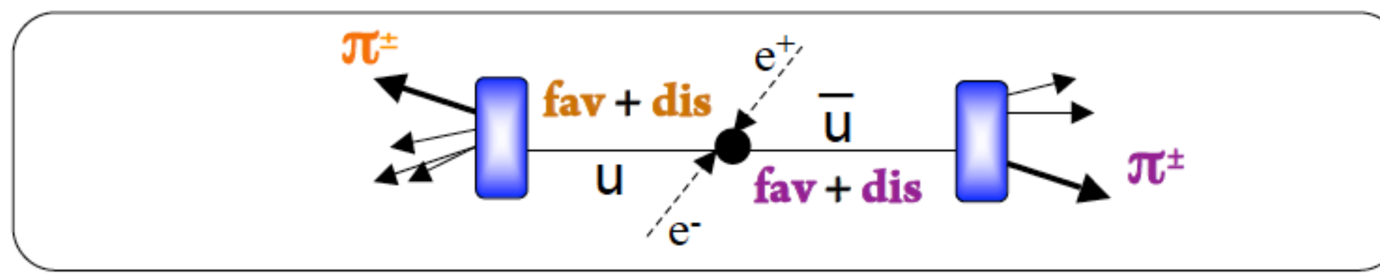
Unlike-sign pion pair = **U:**
$\pi^{\mp}\pi^{\pm}$: (fav x fav)+(dis x dis)



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)
$\pi=\pi^{\pm}$



The cross section can be written in terms of favored and disfavored fragmentation functions:

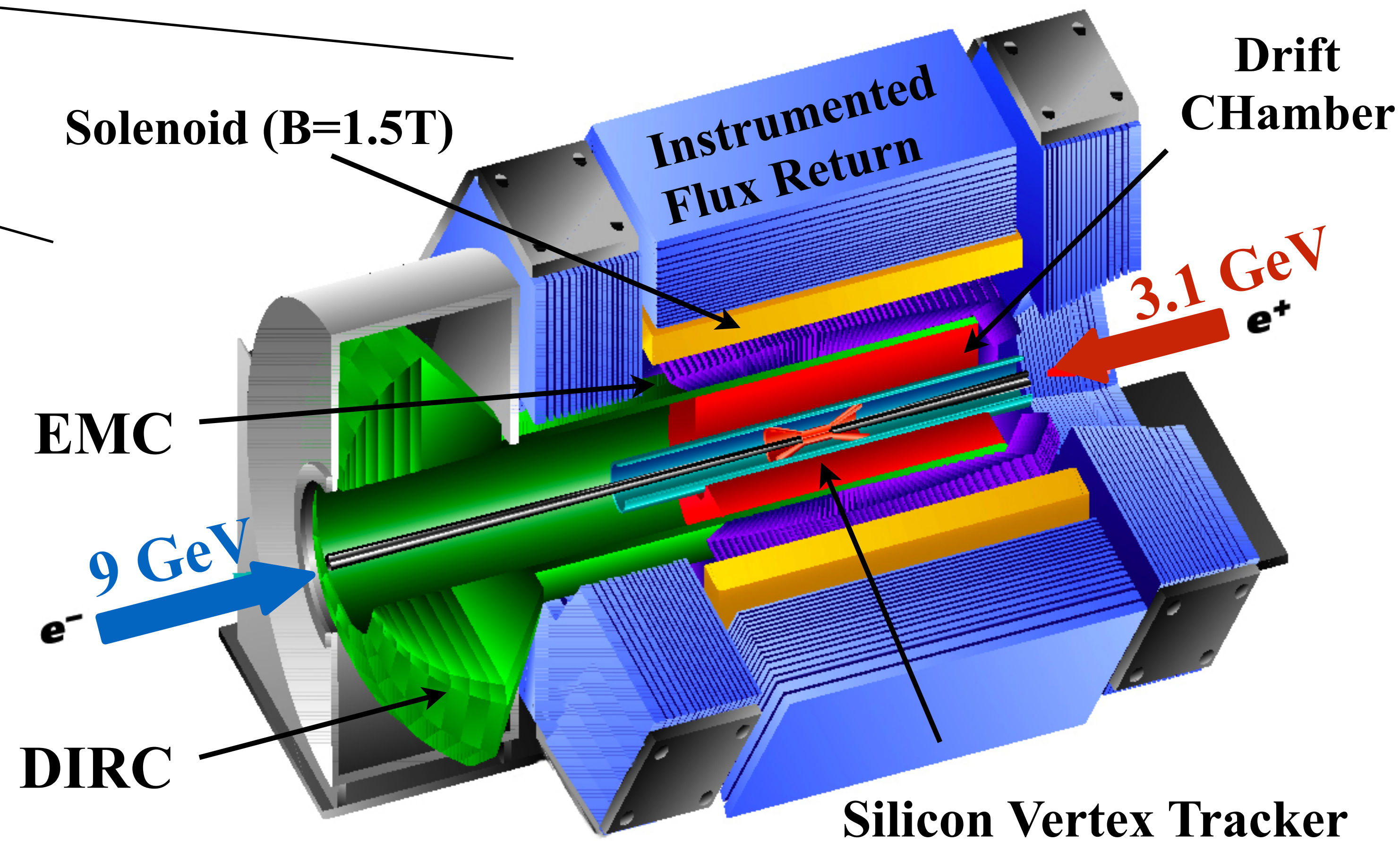
$$N^U(\phi) = \frac{d\sigma(e^+e^- \to \pi^{\pm}\pi^{\mp}X)}{d\Omega dz_1 dz_2} \propto \frac{5}{9}D^{\text{fav}}(z_1)\overline{D}^{\text{fav}}(z_2) + \frac{7}{9}D^{\text{dis}}(z_1)\overline{D}^{\text{dis}}(z_2)$$

$$N^L(\phi) = \frac{d\sigma(e^+e^- \to \pi^{\pm}\pi^{\pm}X)}{d\Omega dz_1 dz_2} \propto \frac{5}{9}D^{\text{fav}}(z_1)\overline{D}^{\text{dis}}(z_2) + \frac{5}{9}D^{\text{dis}}(z_1)\overline{D}^{\text{fav}}(z_2) + \frac{2}{9}D^{\text{dis}}(z_1)\overline{D}^{\text{dis}}(z_2)$$

$$N^C(\phi) = \frac{d\sigma(e^+e^- \to \pi\pi X)}{d\Omega dz_1 dz_2} = N^U(\phi) + N^L(\phi) \propto \frac{5}{9}[D^{\text{fav}}(z_1) + D^{\text{dis}}(z_1)][\overline{D}^{\text{fav}}(z_2) + \overline{D}^{\text{dis}}(z_2)] + \frac{4}{9}D^{\text{dis}}(z_1)\overline{D}^{\text{dis}}(z_2)$$

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: ***L*** **~ 468 fb^{-1}** used here



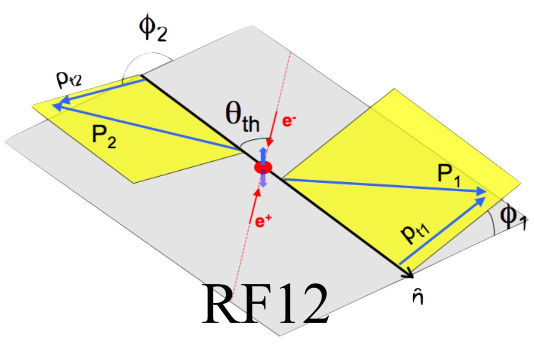
- Asymmetric detector
  - c.m. acceptance $-0.9<\cos\theta^*<0.85$ wrt e^- beam
- Excellent performance
  - good tracking, mass resolution
  - good γ, π^0 reconstruction
  - full e, μ, π, K, and p identification

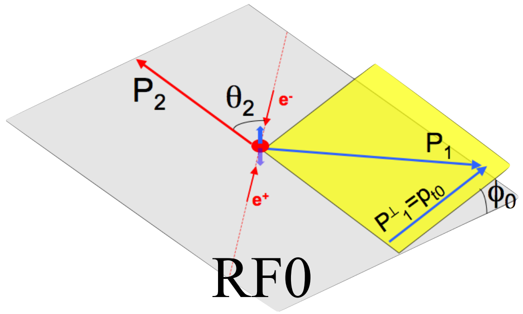
NIM A479,1 (2002),
update: NIM A729, 615 (2013)

Analysis strategy

1) **The analysis is performed using an integrated luminosity of $\mathcal{L}$~470 fb^{-1} of data collected at the Υ(4S) and off-resonance**
2) **We study the Collins asymmetry in two different reference frames: RF12 and RF0**
   (Nucl.Phys. B 806, 23 (2009), PRD 78, 032011 (2008))

- Selection of multi-hadronic events
- Selection of pions in opposite jets according to the thrust axis
  - the thrust axis in the $e^+ e^-$ center of mass frame is assumed to be the $q\bar{q}$ direction
  - thrust axis direction chosen at random to avoid forward/backward detector asymmetry effect
- Measurement of the azimuthal angles ϕ_i in both reference frames as a function of:
  - pion fractional energies (z_1,z_2) ==> (6x6) bins
  - pion transverse momenta: (p_{t1},p_{t2}) ==> (4x4) bins; p_{t0} ==> 9 bins
  - $\sin^2\theta_{(th,2)}/(1+\cos^2\theta_{(th,2)})$ ==> 15 bins
  - 4-D analysis ==> (z_1,z_2) x (p_{t1},p_{t2}) ==> (4x4) x (3x3)
- Fit to the azimuthal distributions
- Estimation and subtraction of backgrounds
- Study of the systematic effects





Event and track selection

EVENT SELECTION

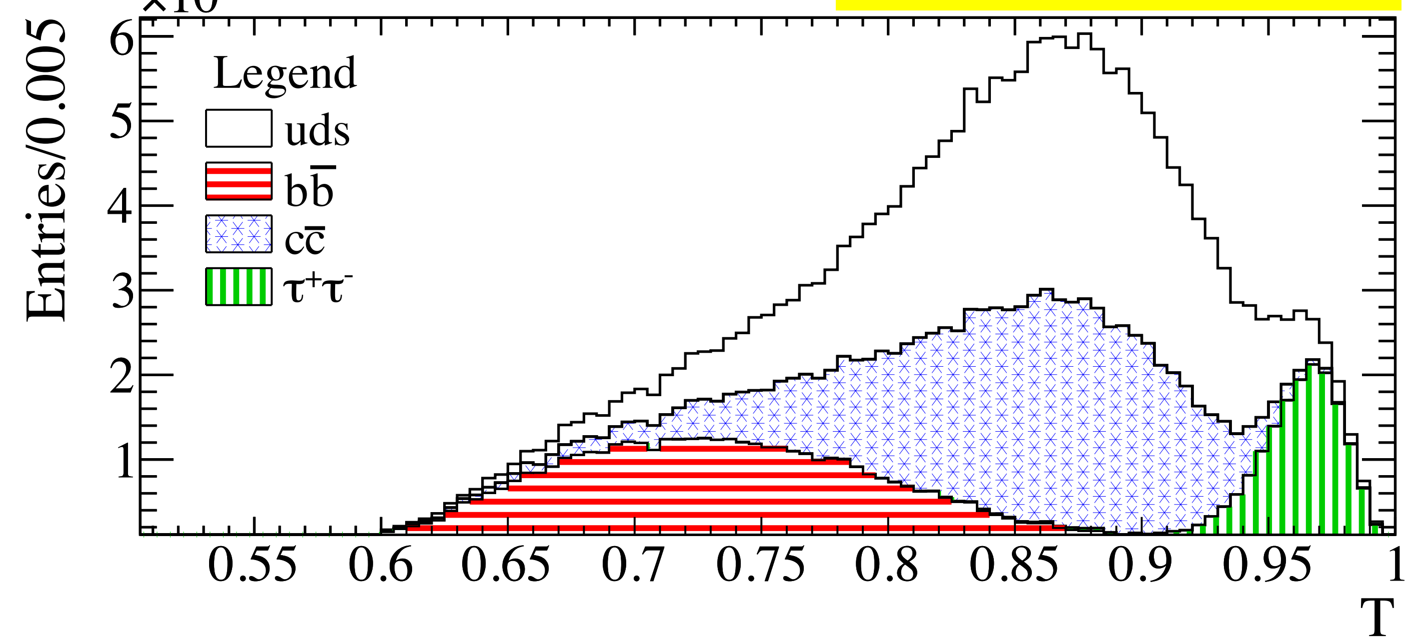
→ Number of charged tracks > 2

→ Visible energy: **E_{vis} > 7 GeV**

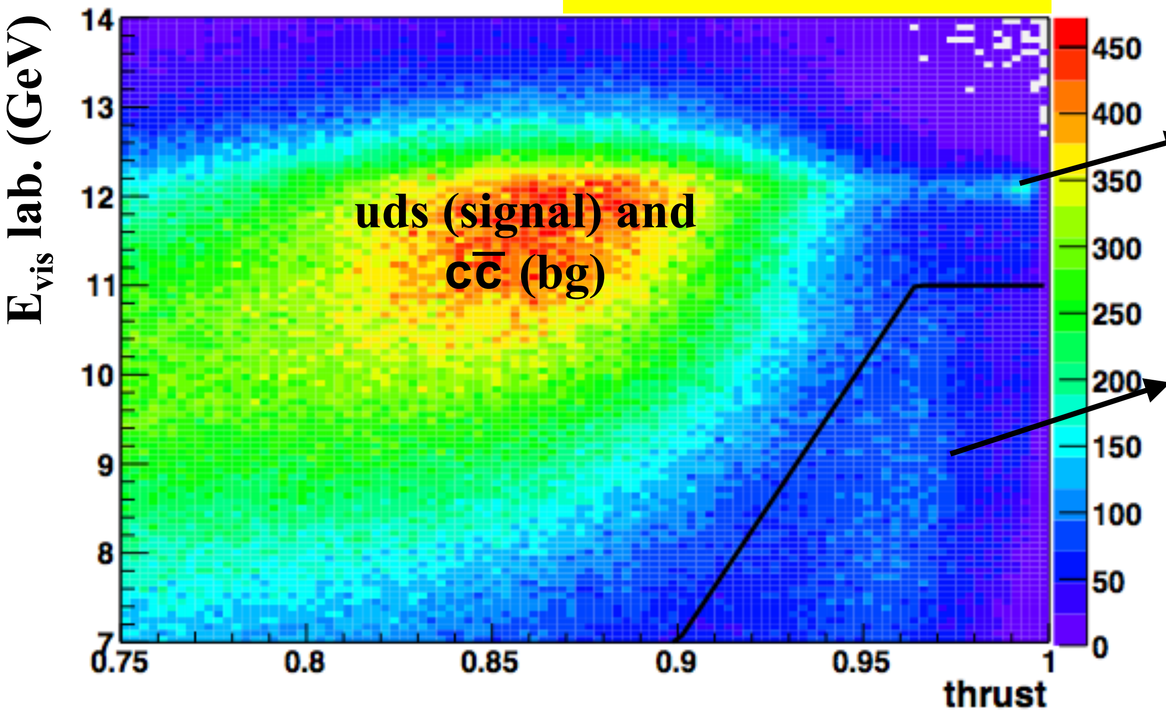
→Selection of two-jet topology events requiring **thrust>0.8**

→ 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

$\tau^+\tau^-$ 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°

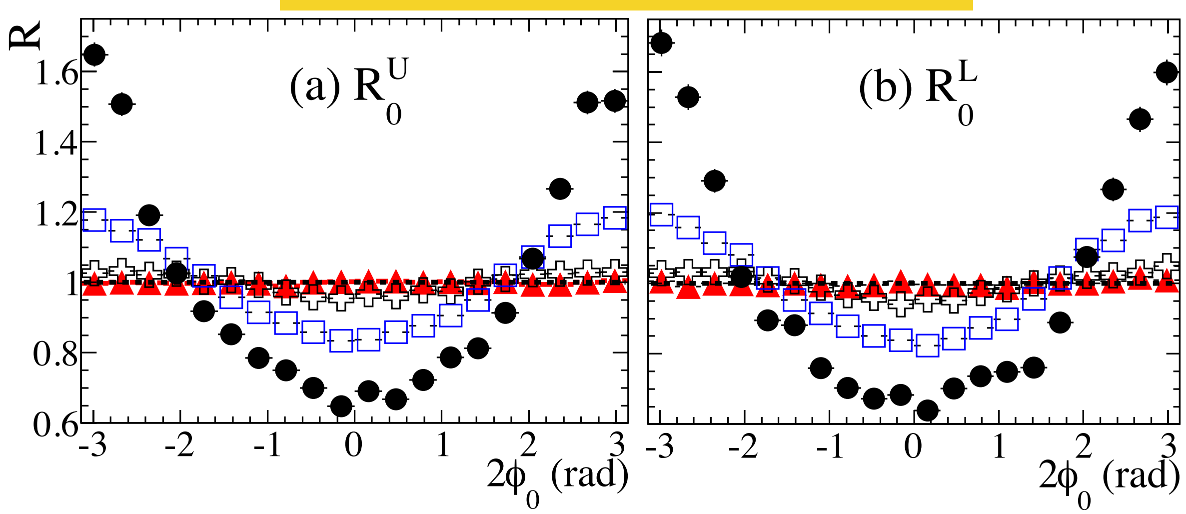
→ **Q_t<3.5 GeV**, where Q_t is the transverse momentum of the virtual photon in the pions c.m.

Raw asymmetry

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

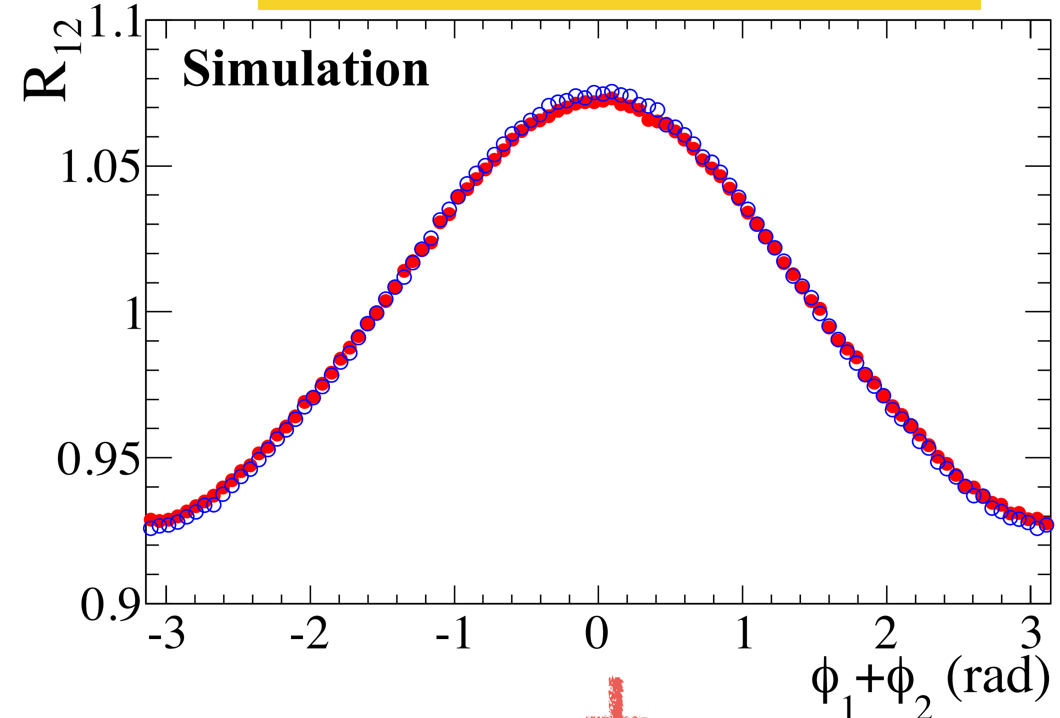
- **The MC generator (JETSET) does not include the Collins effect, but it shows a strong cosine modulation**
  - mostly due to acceptance of the detector
  - depends strongly on the thrust axis polar angle
  - but similar distribution for **U** and **L** pairs

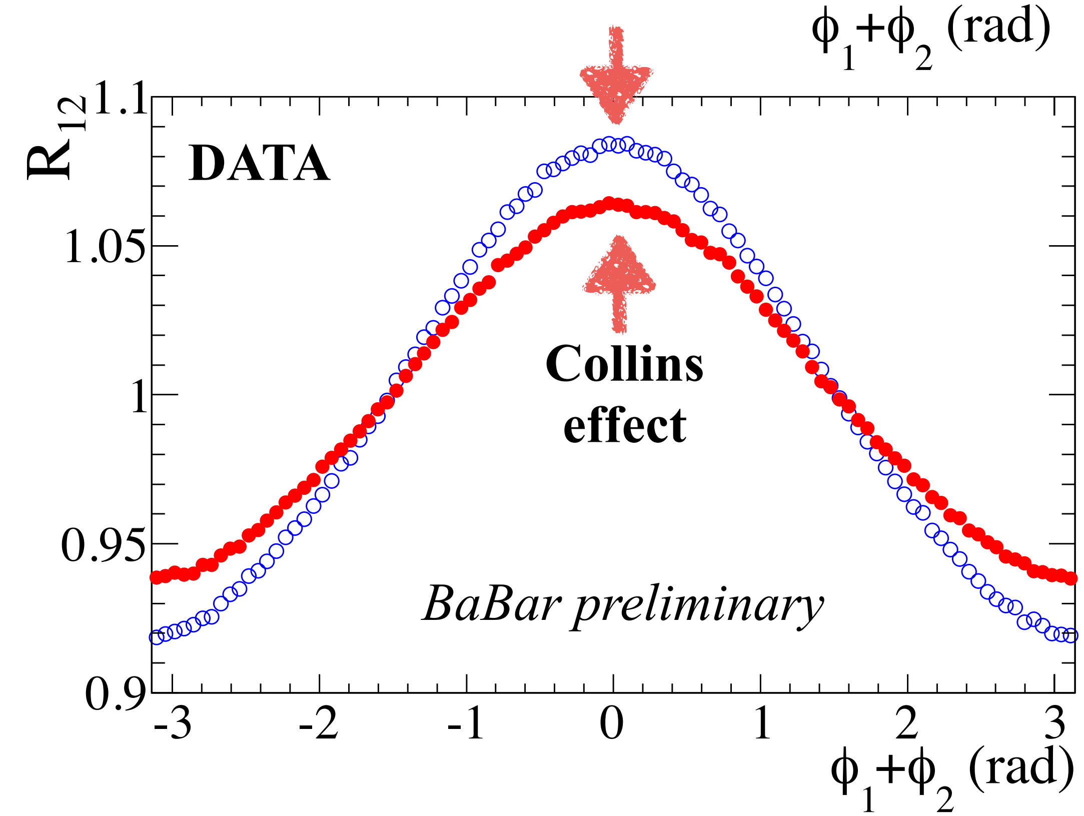
Normalized distribution in RF0



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

Normalized distribution in RF12

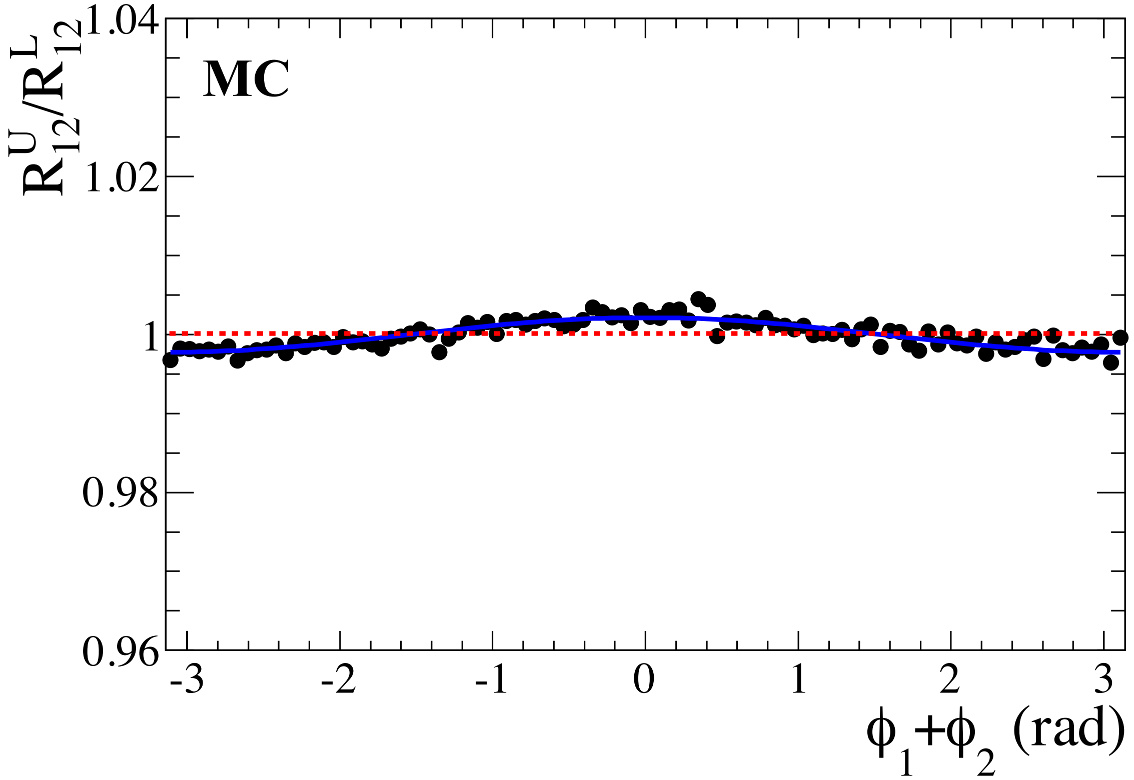


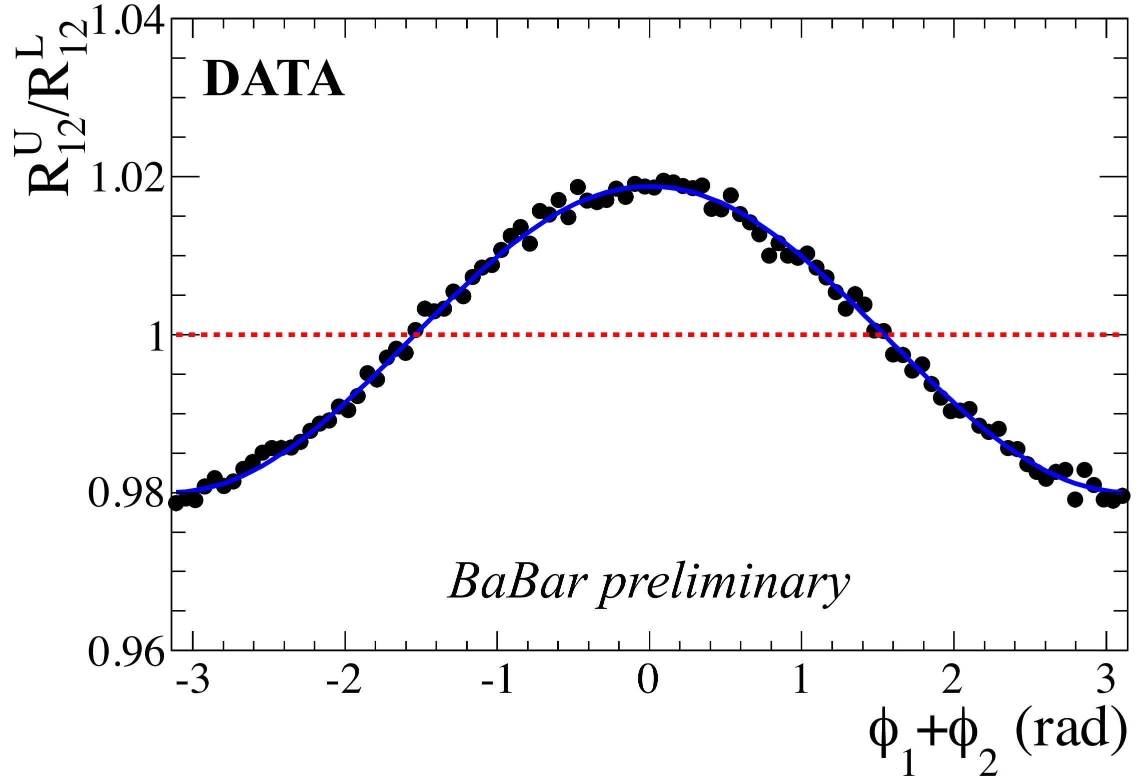


Double Ratio

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

- small deviation from zero still present (≪ asymmetry measured in data sample)





MC: small deviation from 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

Extraction of uds Collins asymmetry

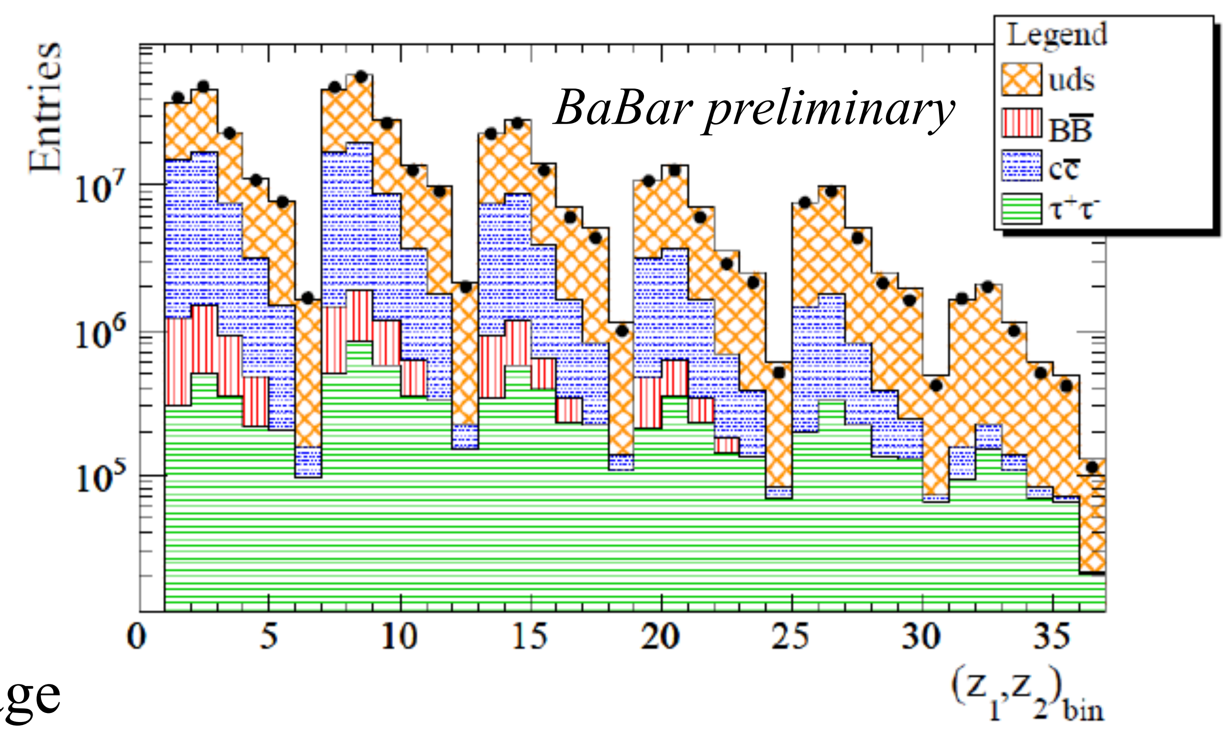
- In each bin, the data sample includes pairs from
  - signal uds events
  - $B\overline{B}$ events (small, mostly at low z)
  - $c\overline{c}$ events (important at low/medium z)
  - $\tau^+\tau^-$ events (important at high z)

Fraction of ππ due to the i[th] bkg process

True asymmetry

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

Bkg asymmetry

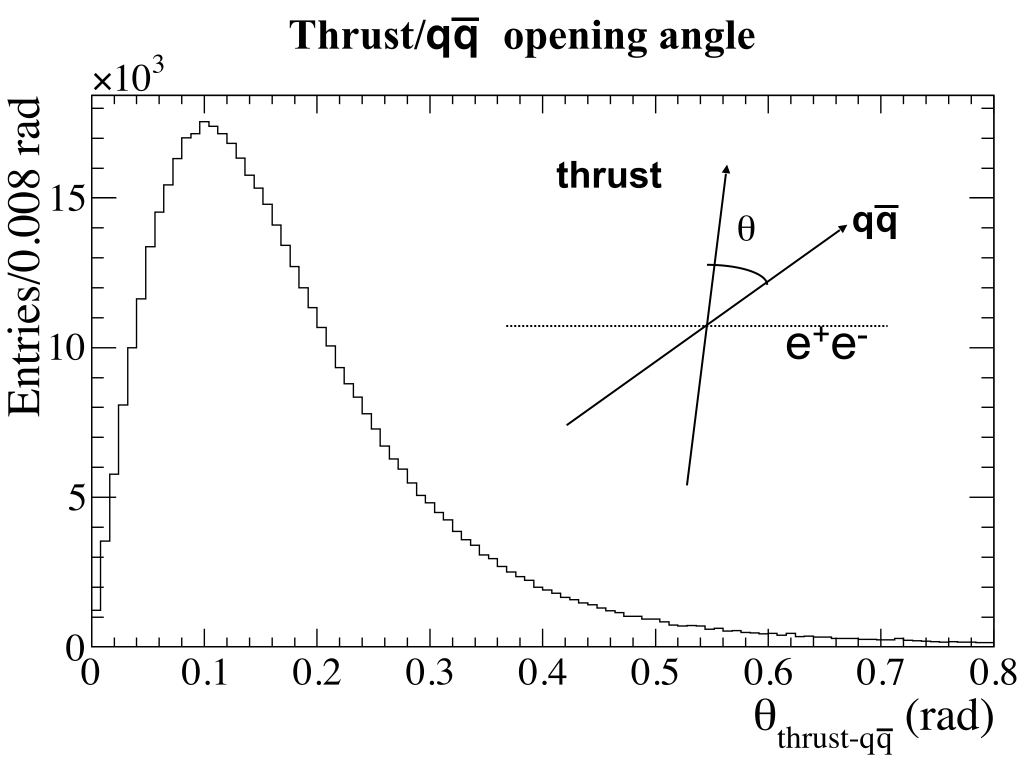


- We must calculate these quantities:
  - F_i using MC sample; we assign MC-data difference in each bin as systematic error
  - $A^{B\overline{B}}$ must be zero; we set $A^{B\overline{B}} = 0$
  - A^τ small in simulation; checked in data; we set $A^\tau = 0$

- **Charm** background contribution is about 30% on average
  - Both fragmentation processes and weak decays can introduce azimuthal asymmetries
  - We used a **$D^{*\pm}$-enhanced control sample** to estimate its effect

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

Asymmetry dilution



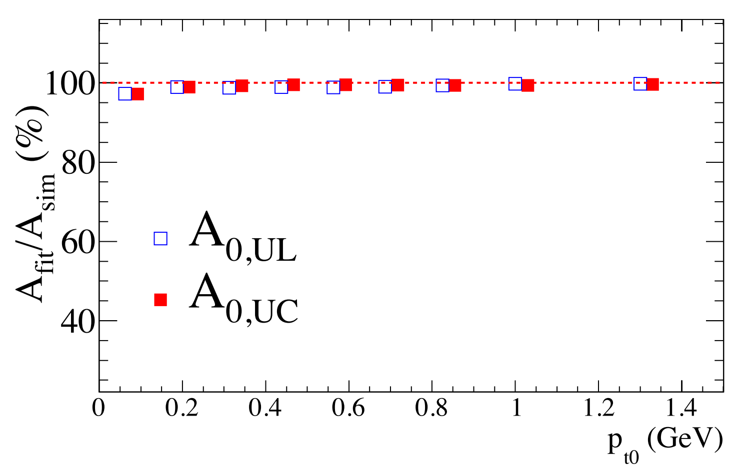
The experimental method assumes the thrust axis as $q\bar{q}$ direction: this is only a rough approximation

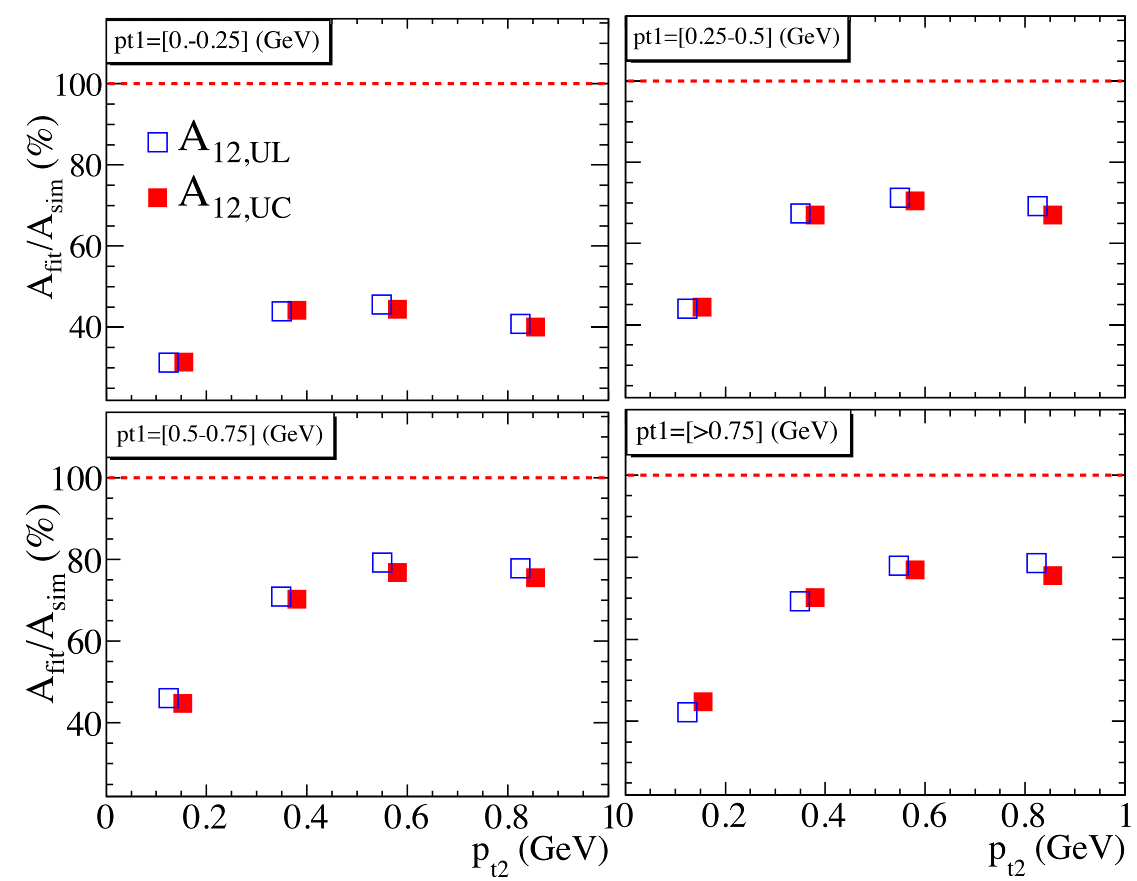
RF12: large smearing since the azimuthal angles φ_1 and φ_2 are calculated with respect to the thrust axis; additional dilution due to very energetic tracks close to the thrust axis.

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 $\mathbf{w^{UL(UC)}=1\pm a \bullet \cos(\phi_{gen12,0})}$ are applied to every selected pion pairs.

RF12: correction ranging between (1.3-2.3) as a function of z, and (1.3-3) as a function of p_t.
RF0: no correction needed.

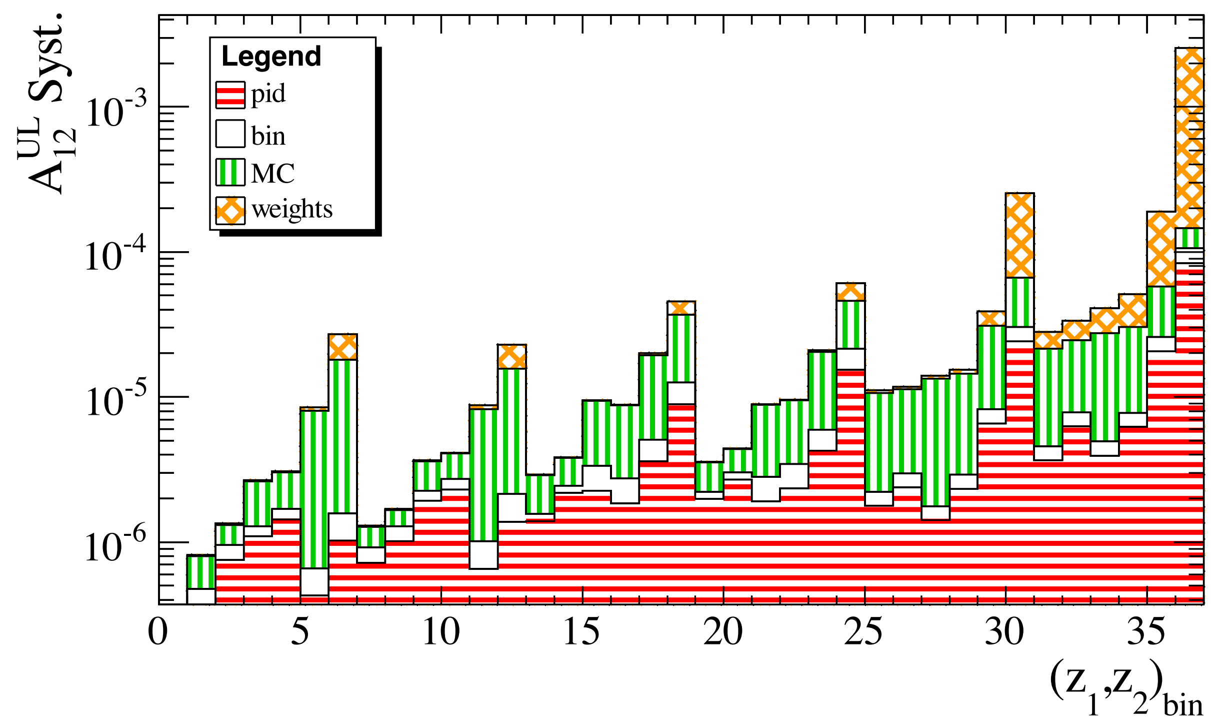




Corrections and Systematics summary

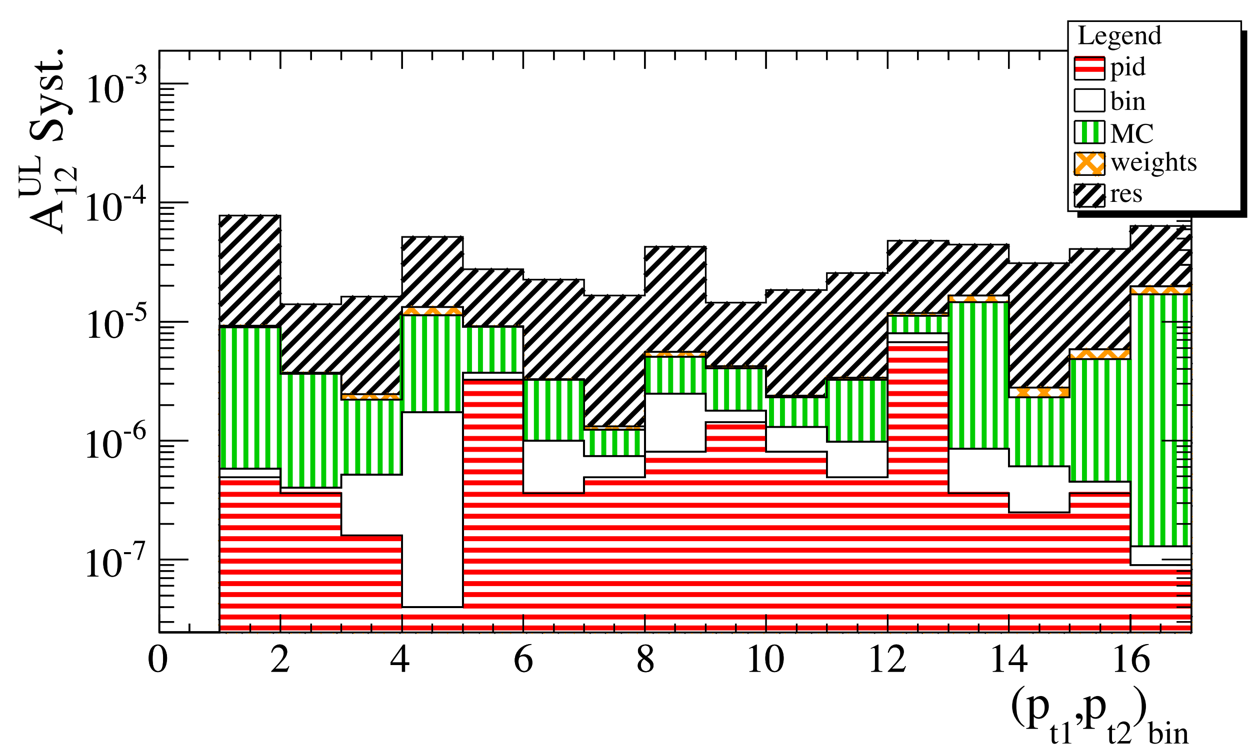
We correct the asymmetries for:

- **Background contributions**
- **MC bias**
- **Dilution effects** (RF12 only)



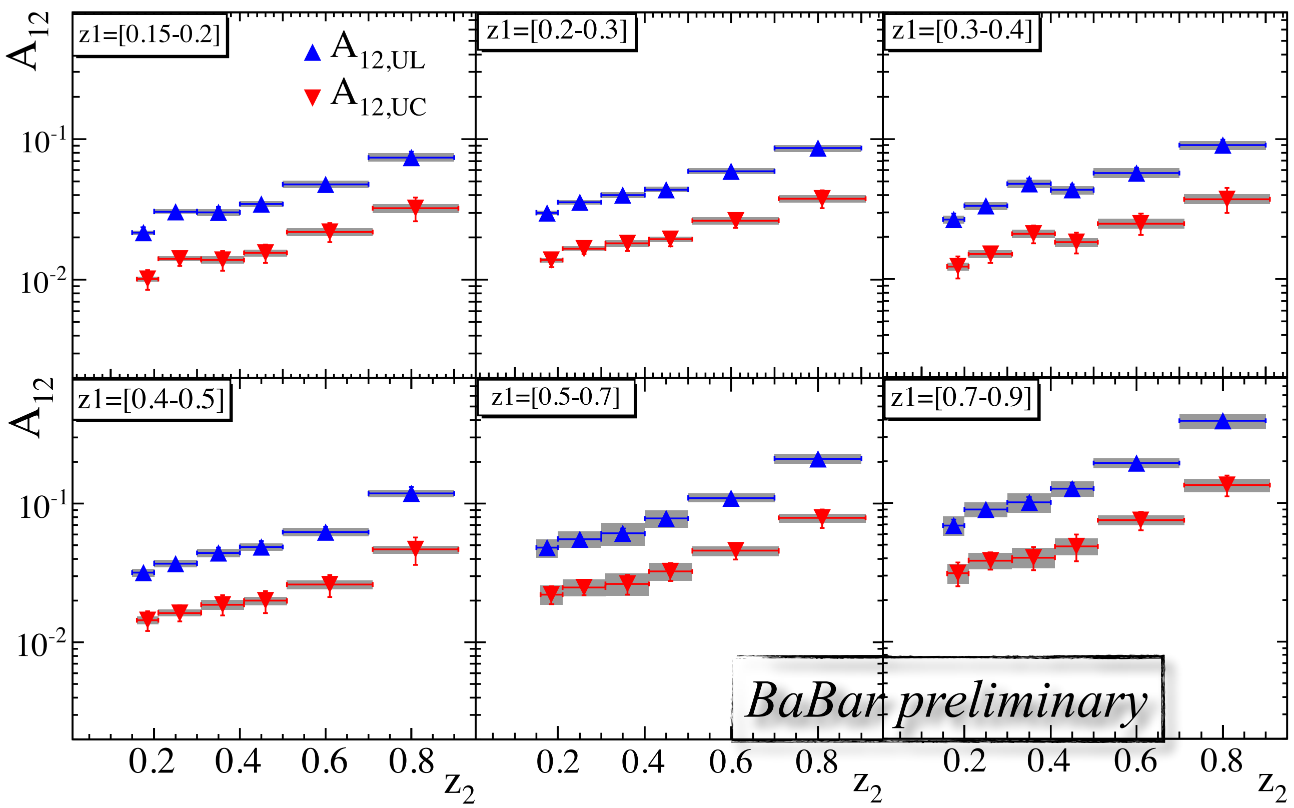
A large number of systematic checks were done. The main contributions come from:

- **Particle identification (PID)**: few percent change in the asymmetry by changing the PID cuts
- **Fit procedure:** different angular bin size leads to about 1% of deviation from standard bins
- **MC uncertainties:** we used different track selection requirements
- **Dilution method**
- Pion transverse **momentum resolution** (only for the asymmetry *vs.* (p_{t1},p_{t2})). The p_t resolution is about 100 MeV on average ==> 10% effect on asymmetries for all bins, except for the lowest energies (30%)

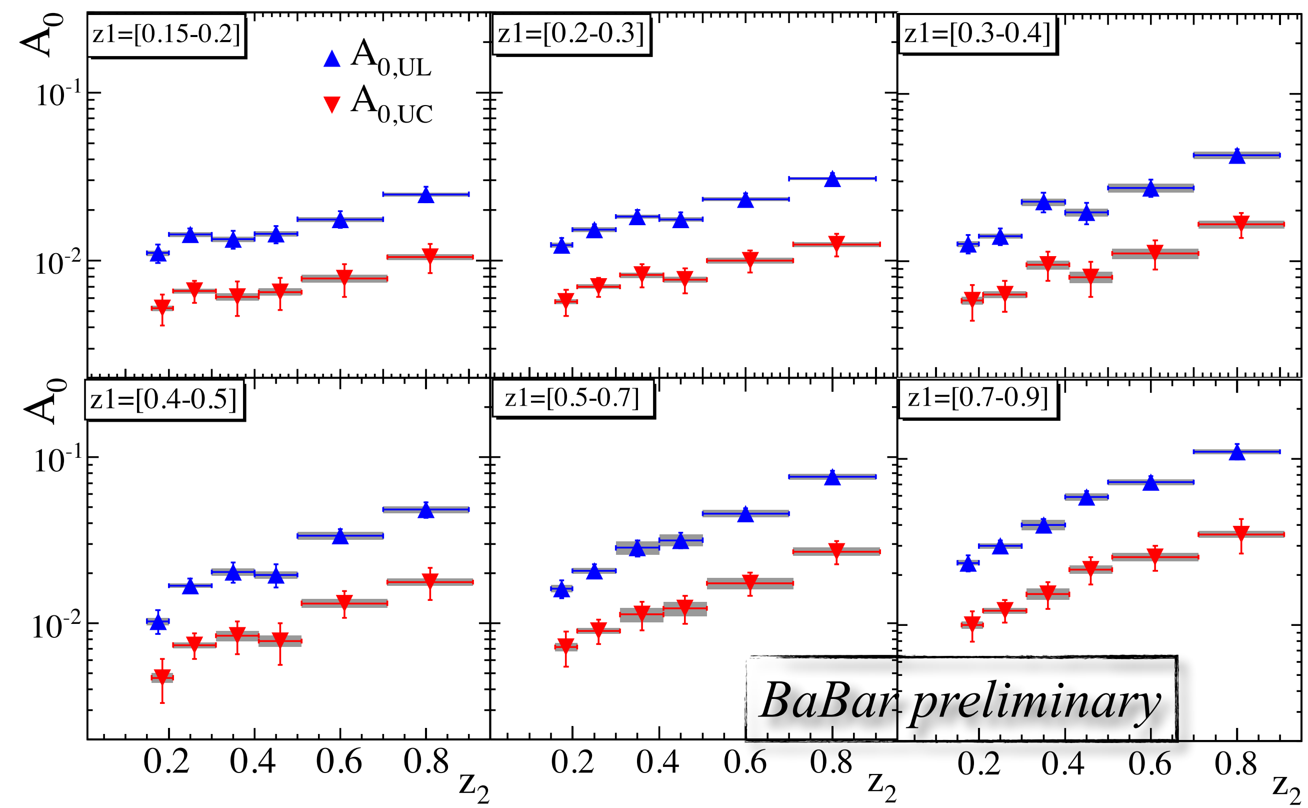


Results I: asymmetry *vs.* (z_1, z_2)

RF12



RF0



Statistical errors shown as bars; systematic errors shown as bands

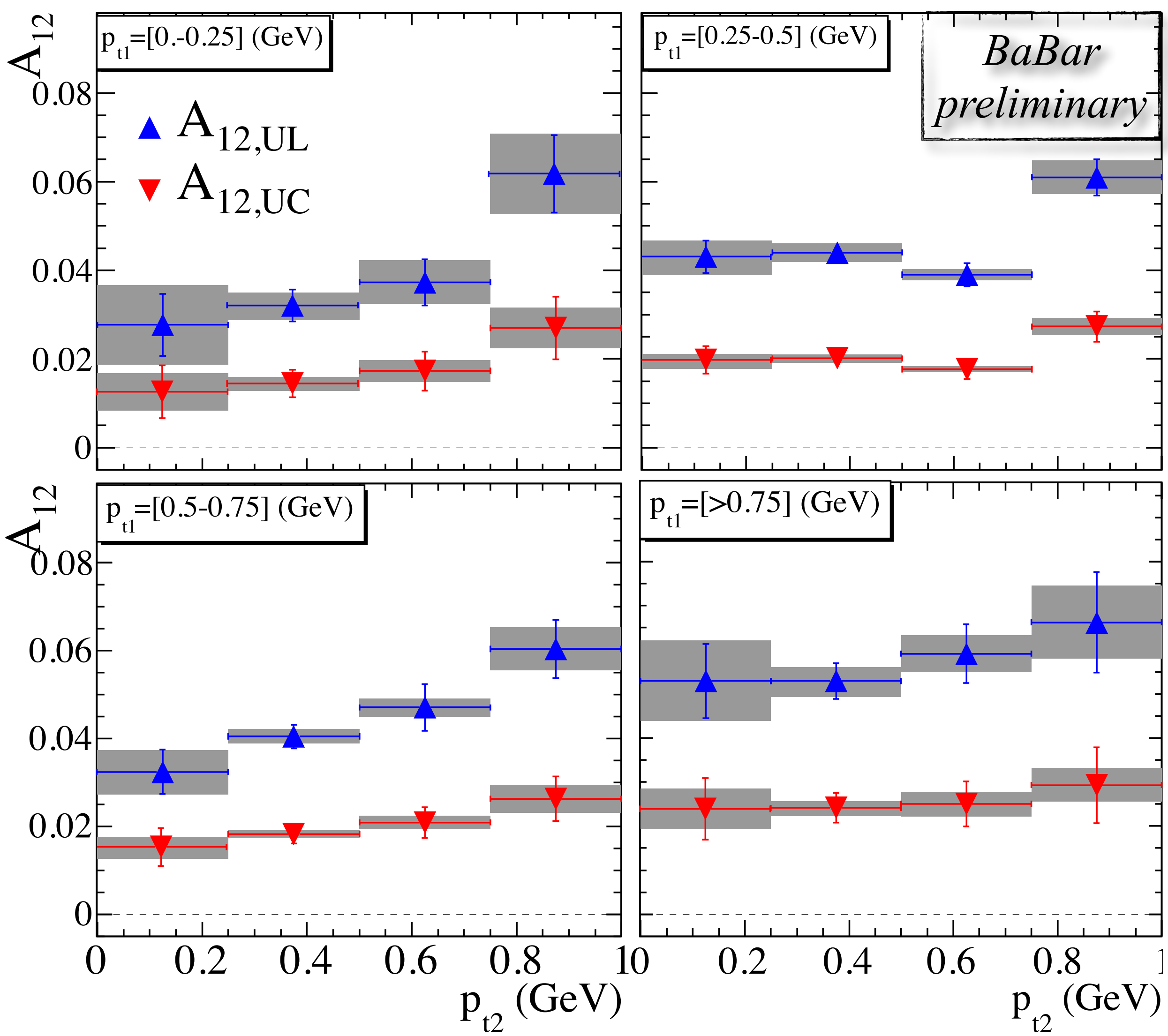
Significant nonzero A^{UL} and A^{UC} in all bins

- strong dependence on (z_1, z_2): 1-39% in RF12 and 1-11% in RF0
- $A^{UC} < A^{UL}$ as expected; complementary information about the favored and disfavored fragmentation processes (PRD 73, 094025 (2006))
- consistent with $z_1 \Leftrightarrow z_2$ symmetry

Results II: asymmetry *vs.* (p_{t1}, p_{t2})

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

RF12

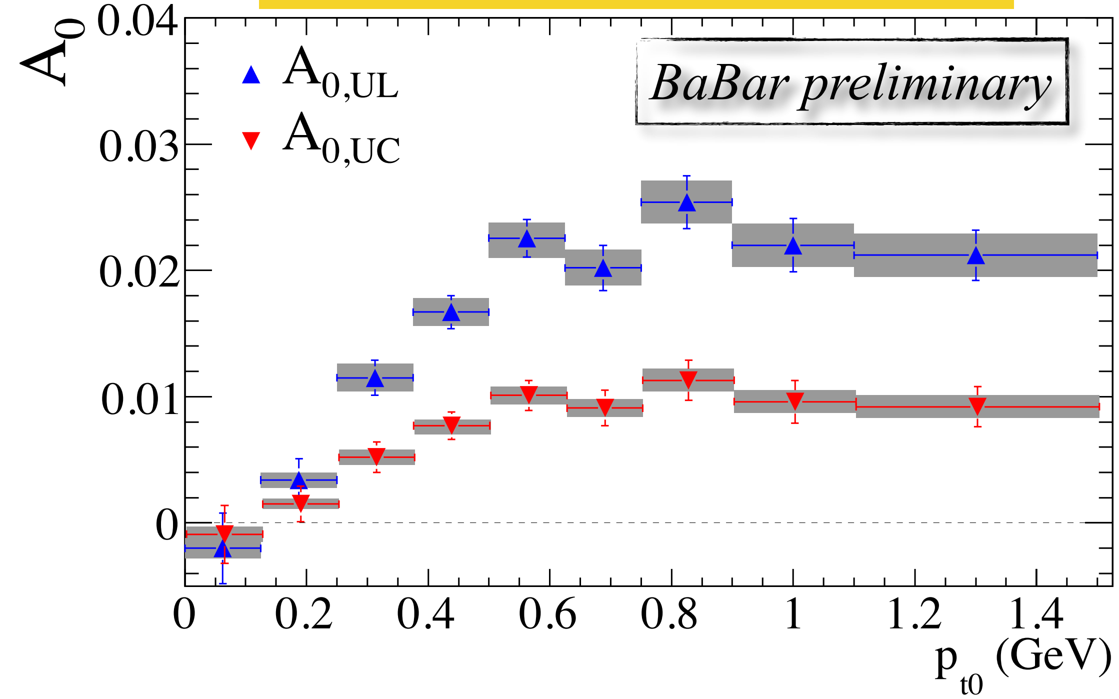


⇒ only modest dependence on (p_{t1}, p_{t2})

⇒ $A_0 < A_{12}$, but interesting structure in p_t

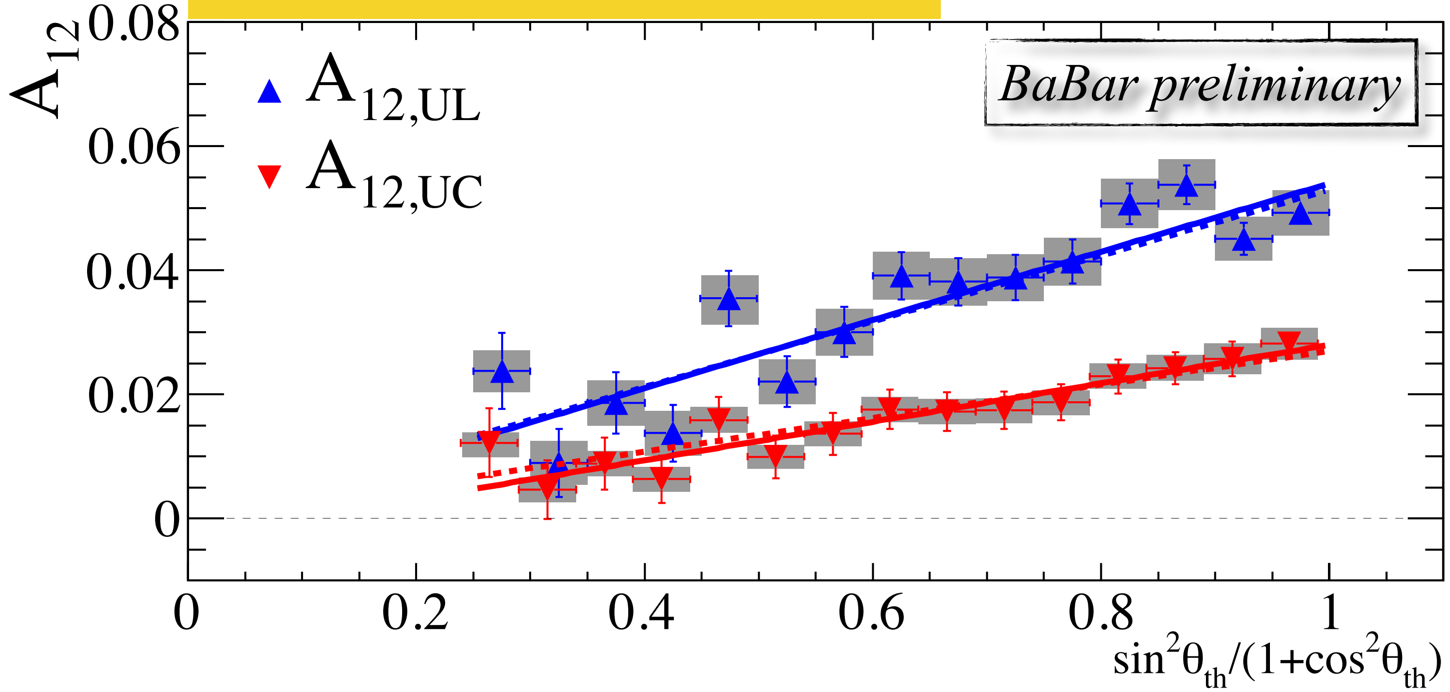
$\mathbf{A^{UC} < A^{UL}}$: complementary information on $H_1^{\perp,\,fav}$ and $H_1^{\perp,\,dis}$

RF0



Results III: asymmetry *vs.* polar angle

RF12

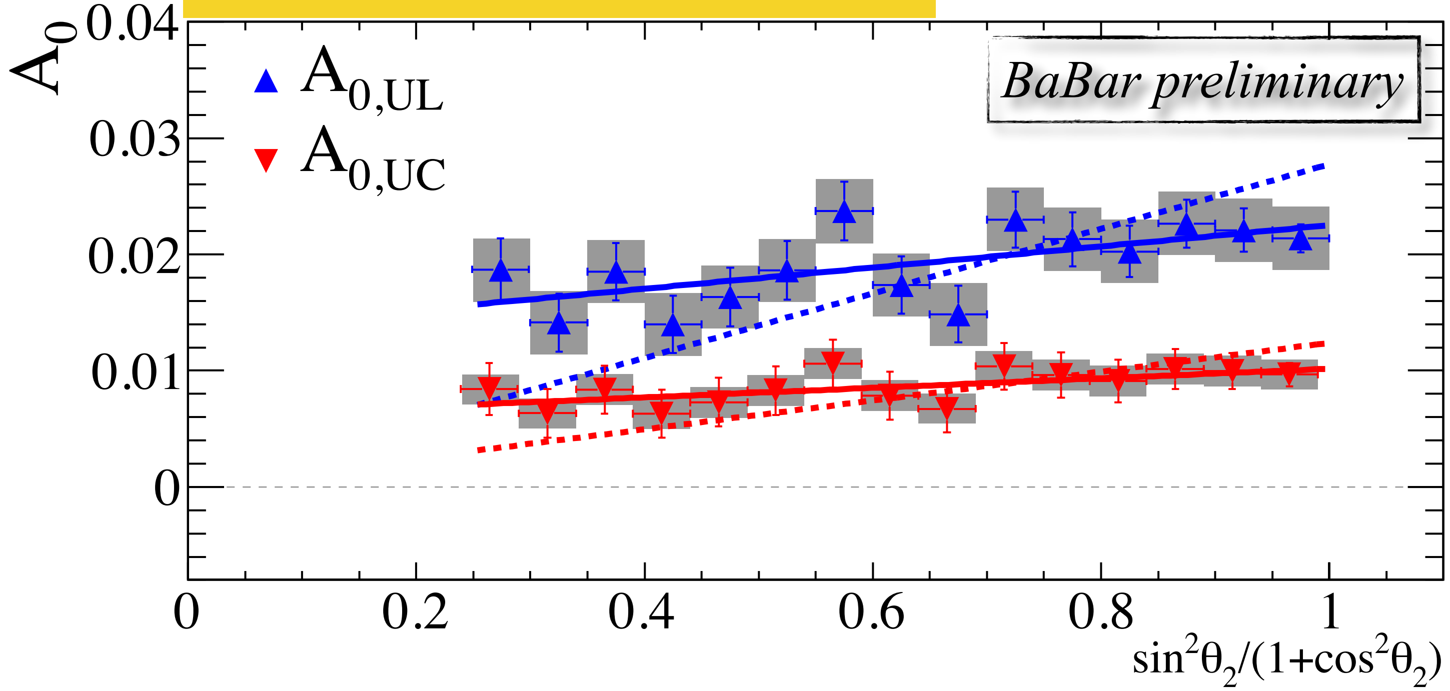


We study the angular dependence after integration over fraction energies and transverse momenta

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

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

RF0

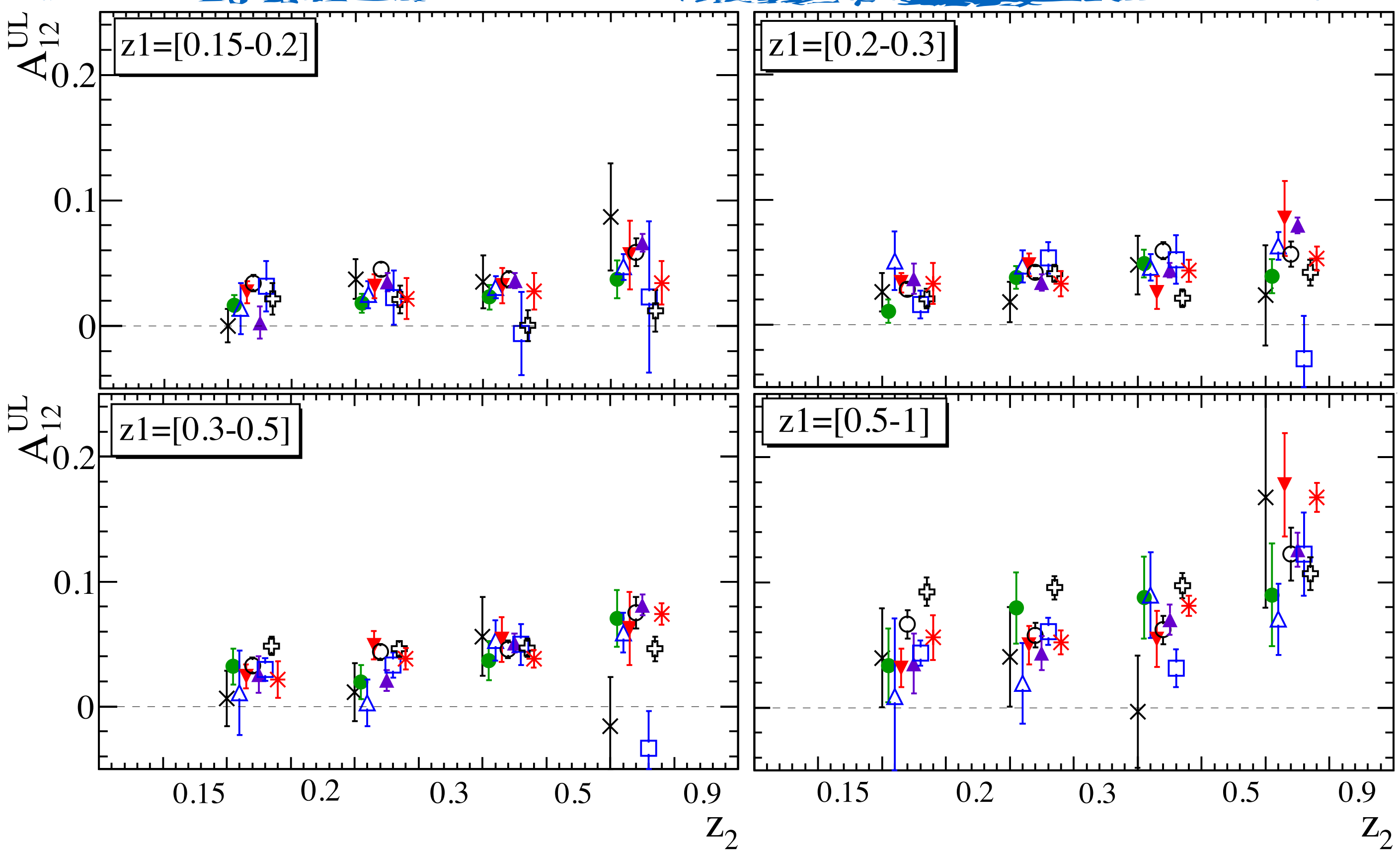


$$A_0 \propto \frac{\sin^2\theta_2}{1+\cos^2\theta_2} \cos(2\phi_0)\mathcal{F}\left[\frac{H_1^\perp(z_1)\bar{H}_1^\perp(z_2)}{D_1(z_1)\bar{D}_1(z_2)}\right]$$

==> The linear fit gives a non-zero constant parameter (consistent with Belle results)

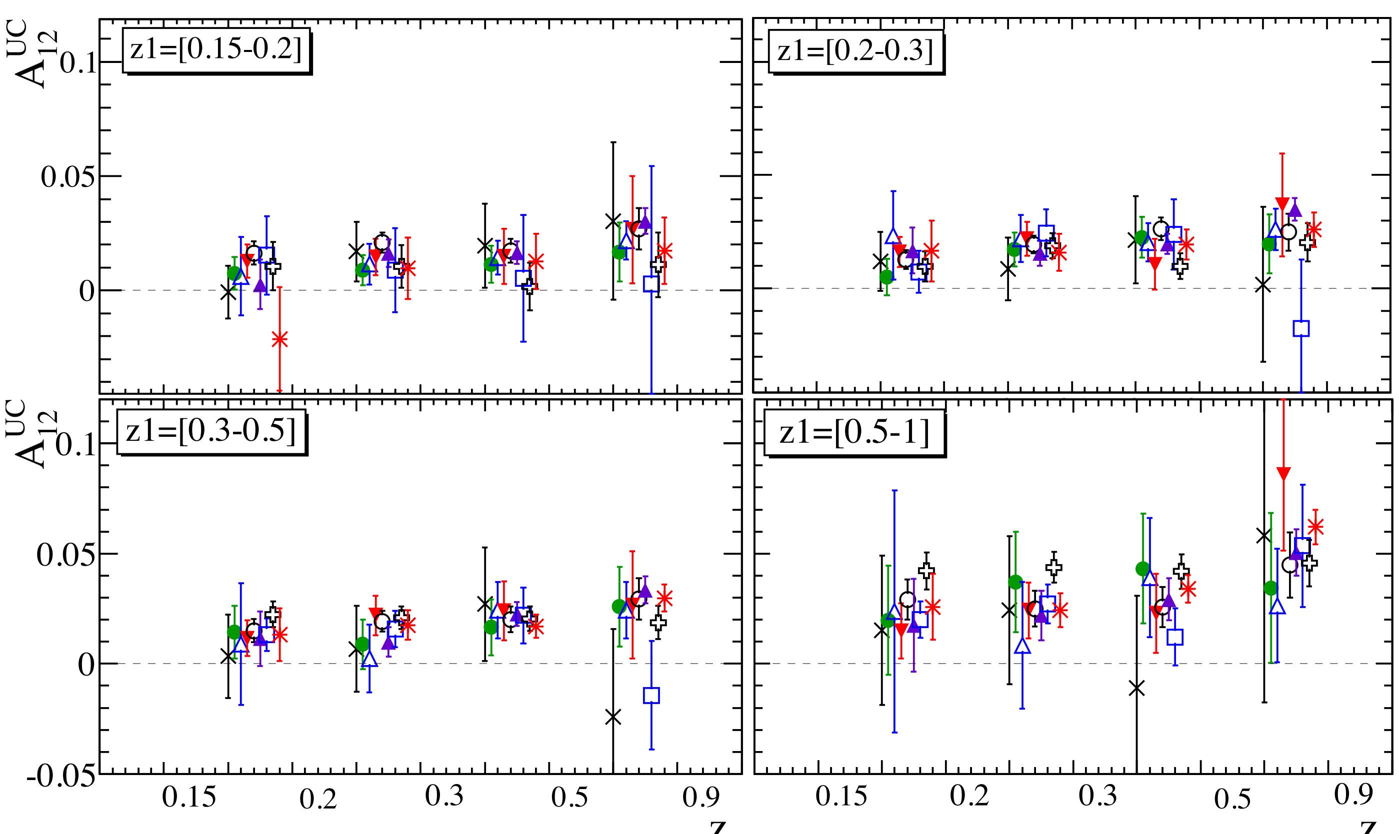
Lines: fit results with a linear functions
Dotted lines: fit results with a linear function crossing the origin

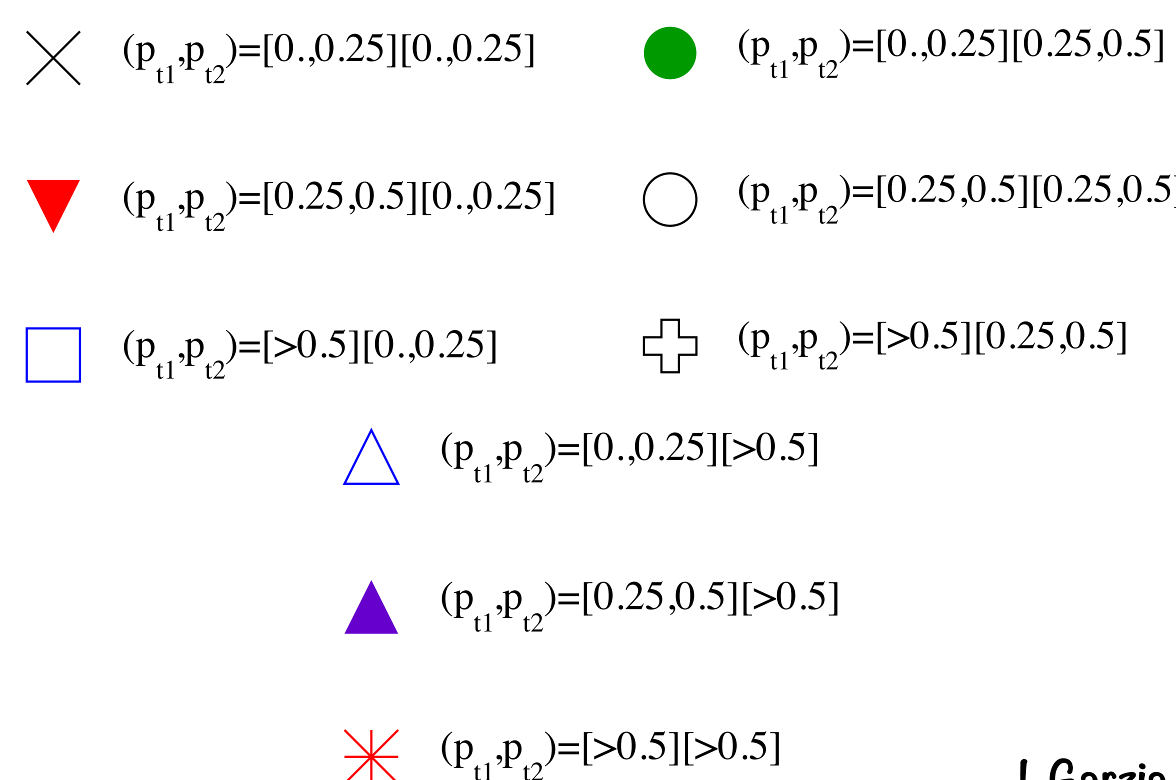
4-D: asymmetry *vs.* $(z_1,z_2)x(p_{t1},p_{t2})$



We study the asymmetries in the RF12 frame in a four-dimensional space: (z_1,z_2,p_{t1},p_{p2})

- We use 4 z_i and 3 p_t intervals
- Test to probe the factorization of the Collins fragmentation functions
- Powerful tools to access p_t - z correlation





I. Garzia

Summary

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

⇒ 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}
⇒ 4-D analysis	z_1, z_2, p_{t1}, p_{t2}	
⇒ 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 $Q^2 \sim 110$ $(GeV/c)^2$
- 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

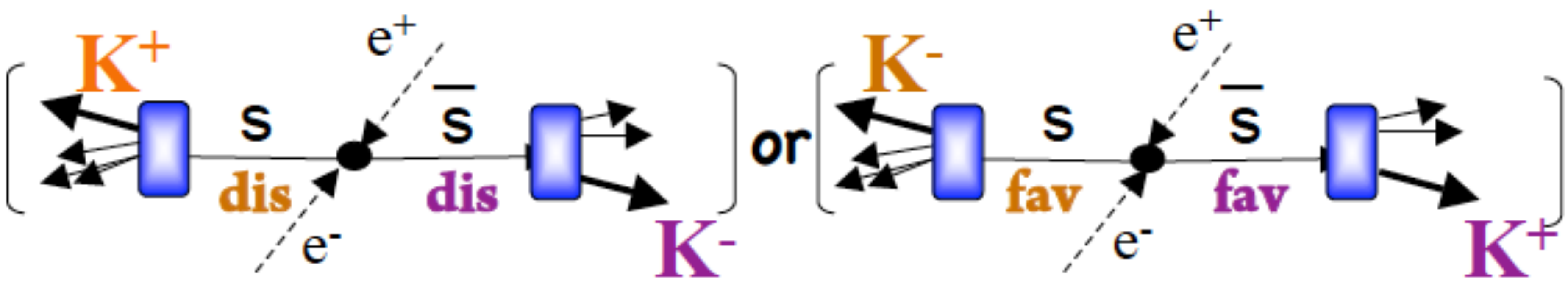
Paper submitted to PRD

PLANS

work in progress

WHAT NEXT? Collins effect for kaon pairs

Why kaon pairs? ➪Strange contribution to the Collins effect

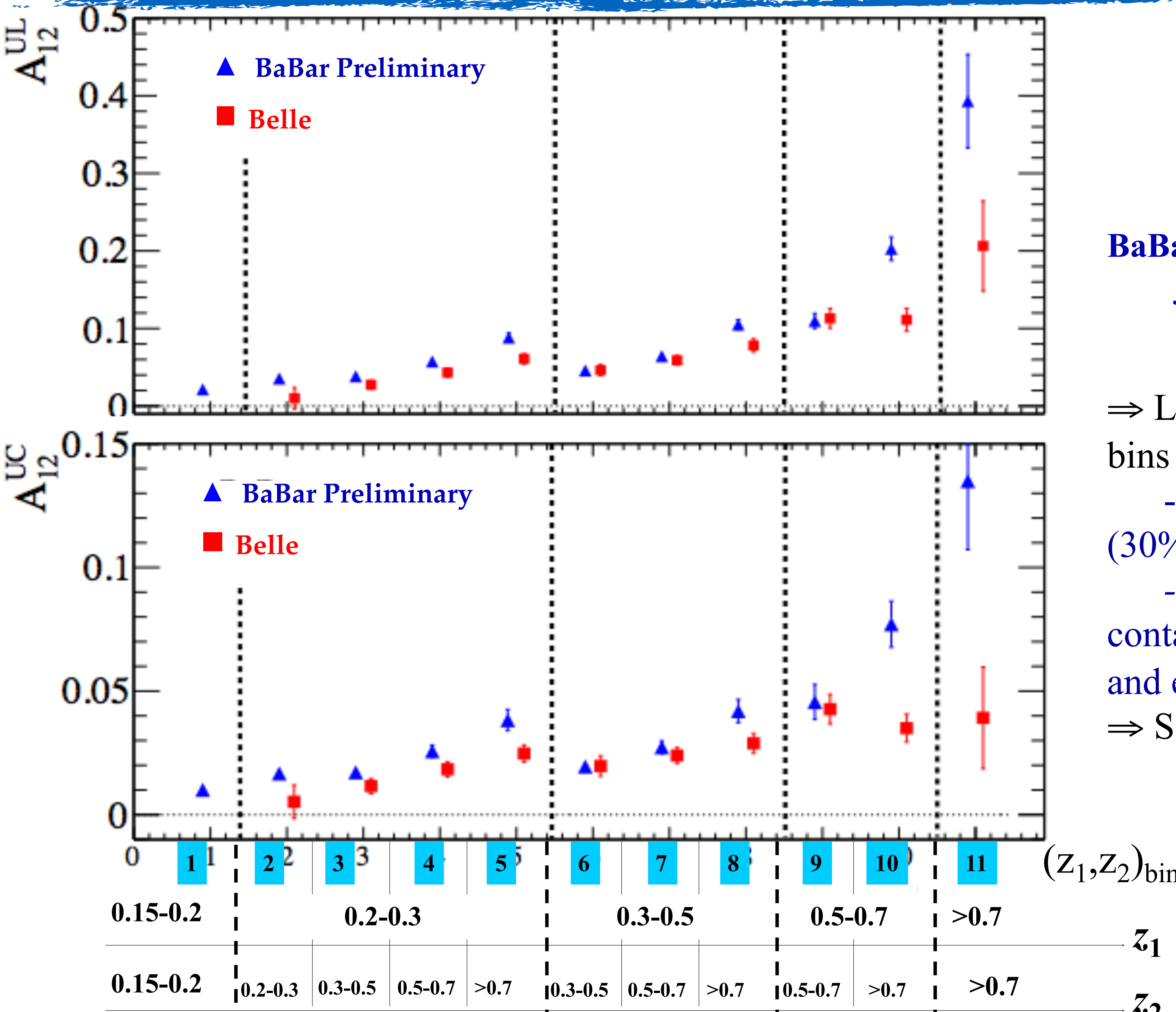


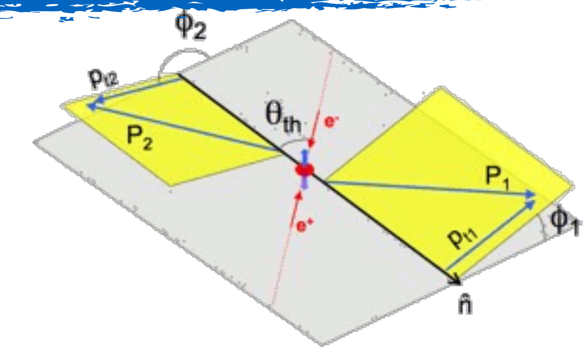
Results expected soon

Thanks for your attention

BK SLIDES

RF12: BaBar/Belle comparisons





BaBar (0.15<z<0.9) $\int\mathcal{L}$~468 fb^{-1}

Belle (0.2<z<1) $\int\mathcal{L}$~547 fb^{-1}

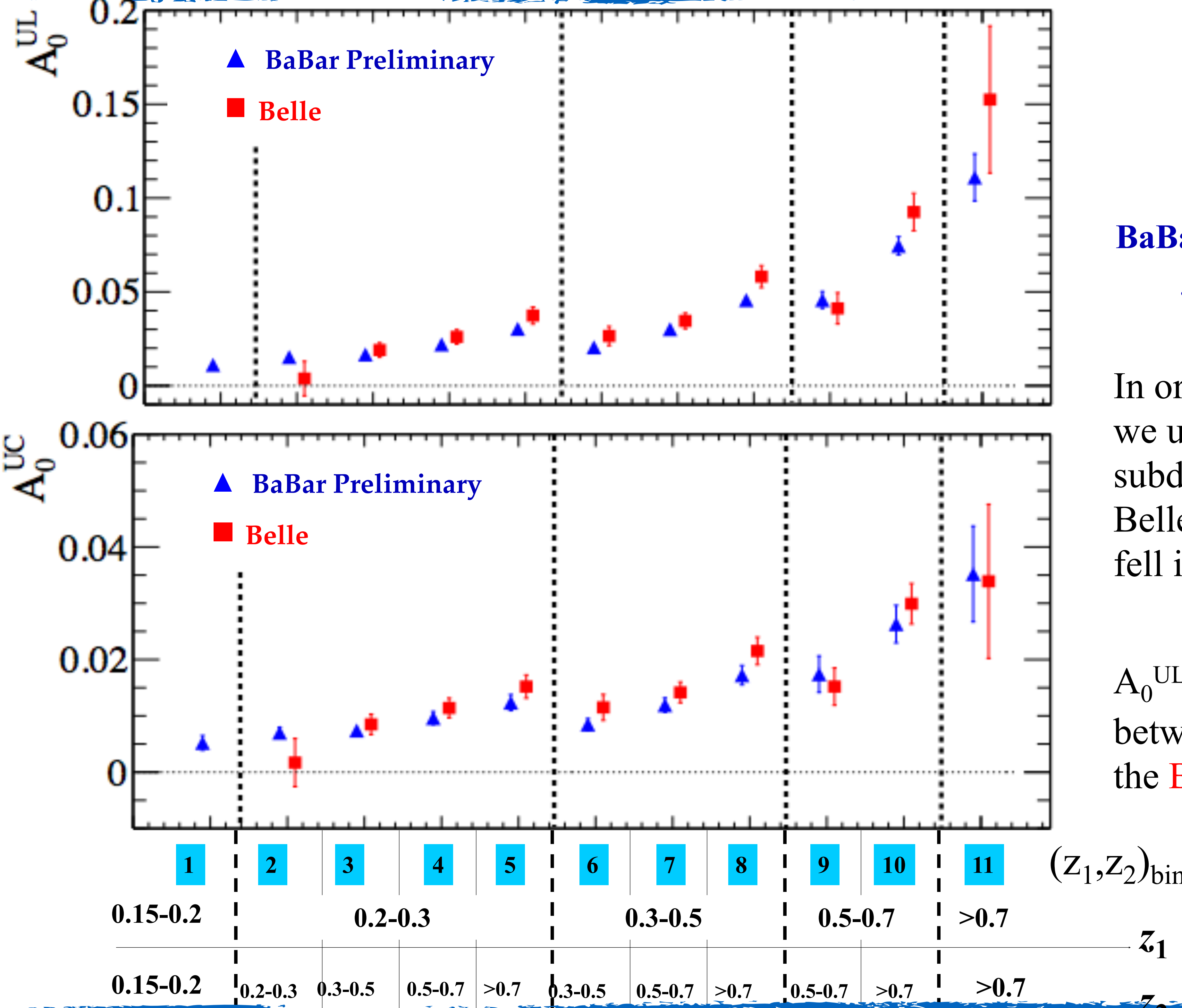
PRD 86, 039905(E) (2012)

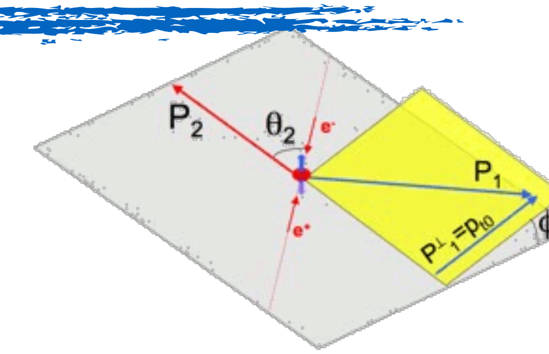
⇒ Large discrepancy in the last two bins of z:

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

⇒ Slightly higher at lower z

RF0: BaBar/Belle comparisons





BaBar (0.15<z<0.9) $\int\mathcal{L}$~468 fb^{-1}

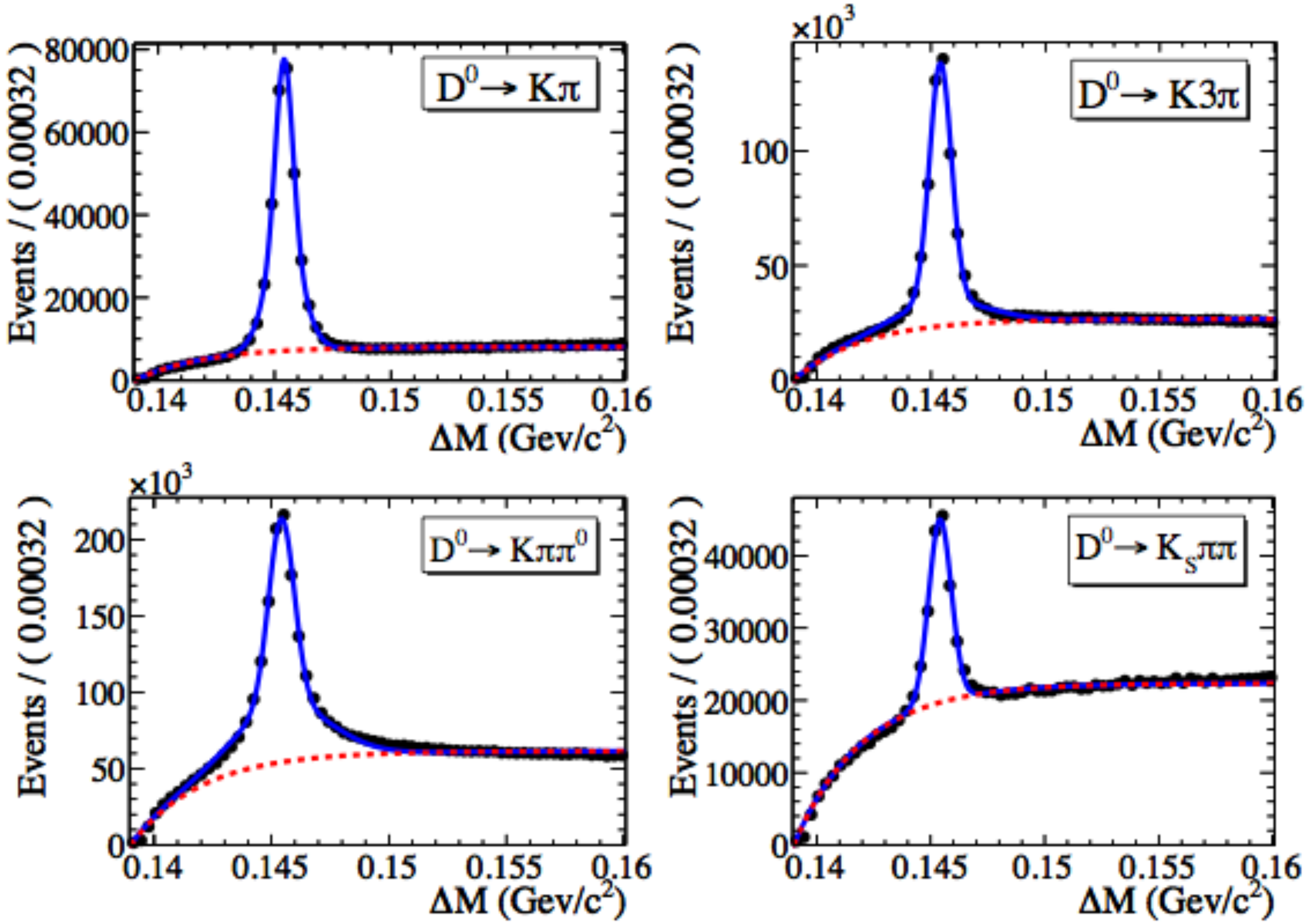
Belle (0.2<z<1) $\int\mathcal{L}$~547 fb^{-1}

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.

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