Collins asymmetries in inclusive charged KK and Kπ pairs at BABAR

I. GARZIA - INFN SEZIONE DI FERRARA, F. ANULLI - INFN SEZIONE DI ROMA

on behalf of the BABAR Collaboration

Collins effect in e^+e^- annihilation

Our understanding of the hadronic physics depends strongly on what we know about the **FRAGMENTATION FUNCTIONS** (FFs)

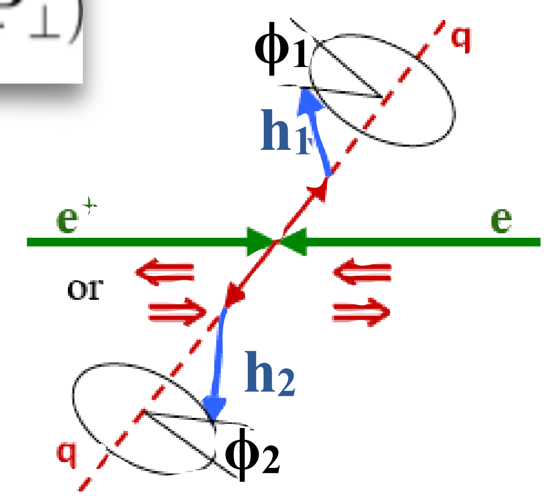
- Universal and non-perturbative objects describing the final-state hadron distributions
- **Transverse Momentum Dependent (TMD)** FFs ⇒ spin-dependent observables

When only spin-zero hadrons (π, K) are considered in the final state, we have:

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

Unpolarized FF

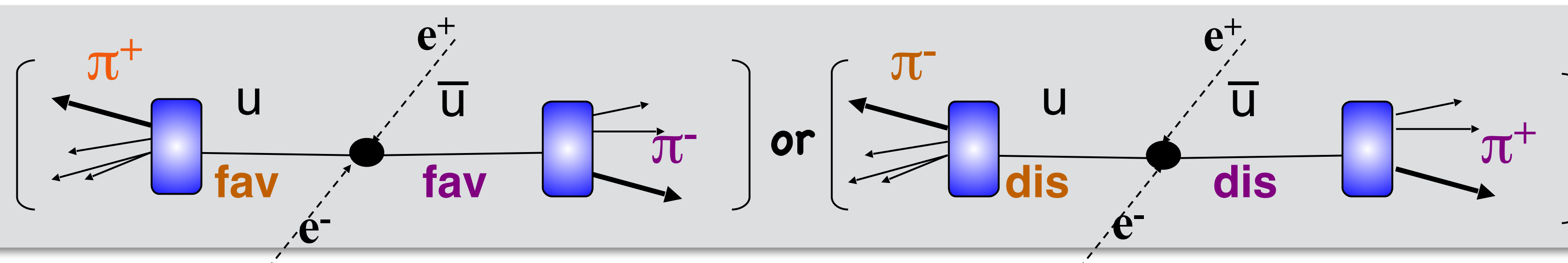
Collins FF [NP**B 396**, 161 (1993)]



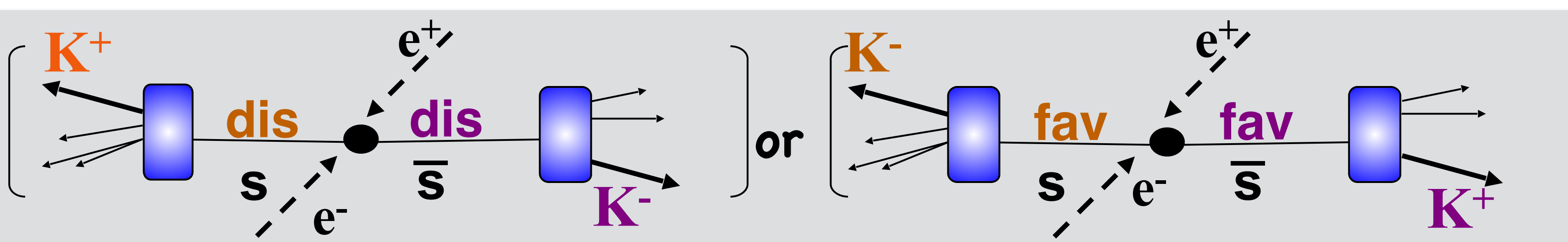
In $e^+e^- \to q\bar{q}$, spins unknown, but $s_q \parallel s_{\bar{q}}$ whit transverse spin component ~ $\sin^2\theta$

- exploit this correlation by using hadrons in opposite jets
- define **favored** ($u \to \pi^+$, $d \to \pi^-$) and **disfavored** ($d \to \pi^+$, $u \to \pi^-$, $s(\bar{s}) \to \pi^\pm$) FFs

Example: Unlike (U) ππ pairs
PRD 90,052003 (2014)



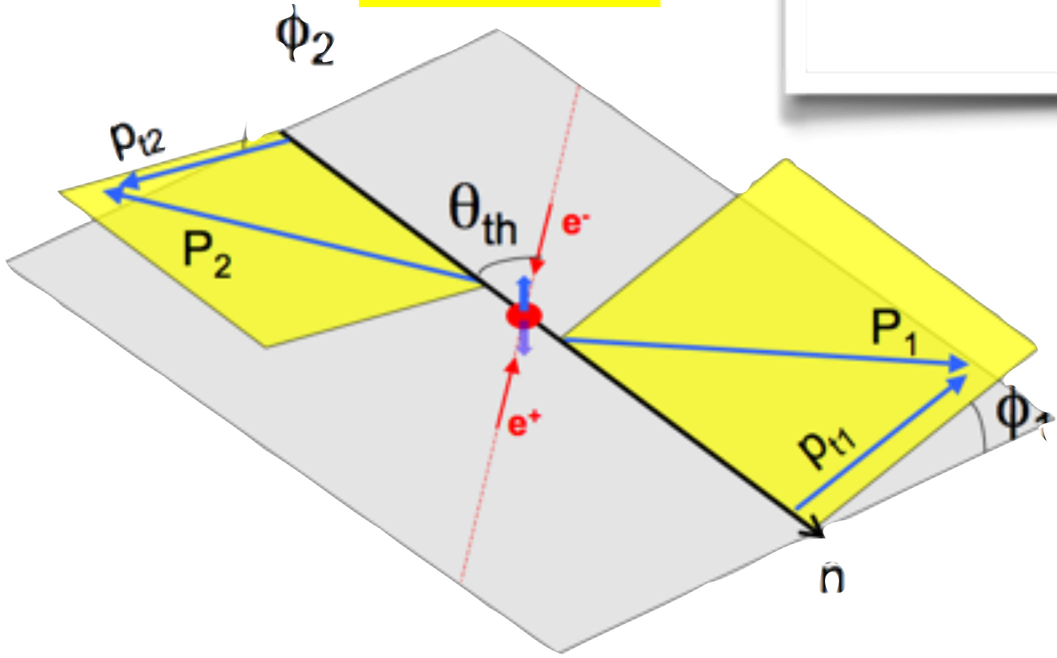
Example: Unlike (U) KK pairs
BaBar preliminary



$$e^+e^- \to q\bar{q} \to h_1 h_2 X \;\; (q=u,d,s) \;\; \Rightarrow \sigma \propto \cos(\phi_{h1h2}) H_1^{\perp(h1)} \times H_1^{\perp(h_2)}$$

Reference frames

RF12



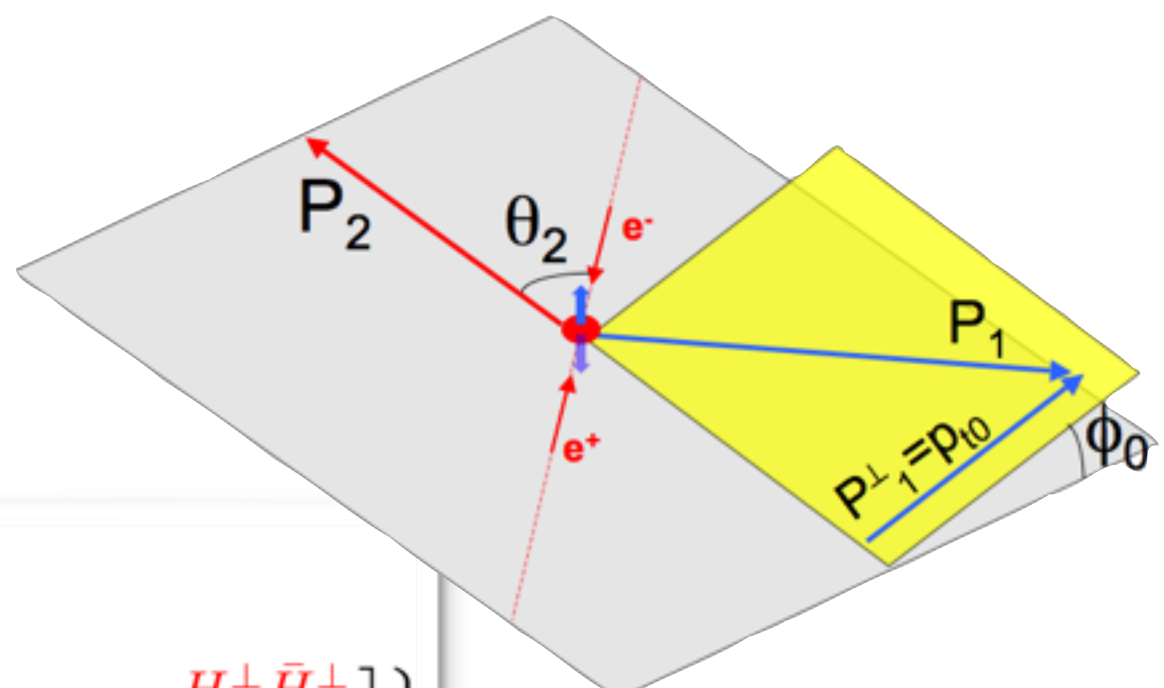
$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{d\Omega dz_1 dz_2 d\phi_1 d\phi_2} = \sum_{q,\bar{q}} \frac{3\alpha^2}{Q^2}\frac{e_q^2}{4} z_1^2 z_2^2 \left[(1+cos^2\theta) D_1^{q,(0)}(z_1)\bar{D}_1^{q,(0)}(z_2) + \right.$$
$$\left. + \quad sin^2(\theta) cos(\phi_1+\phi_2) H_1^{\perp,(1),q}(z_1)\bar{H}_1^{\perp,(1),q}(z_2)\right]$$

All quantities in e+e- center of mass

θ: angle between the e^+e^- axis and the thrust axis;
$\varphi_{1,2}$: azimuthal angles between $P_{h1(h2)}$ and the scattering plane

RF0

θ_2: angle between the e^+e^- axis and P_{h2};
φ_0: angle between the plane spanned by P_{h2} and the e^+e^- axis, and the direction of P_{h1} perpendicular to P_{h2}.



All quantities in e+e- center of mass

$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{d\Omega dz_1 dz_2 d^2\vec{q}_T} = \frac{3\alpha^2}{Q^2} z_1^2 z_2^2 \left\{A(y)\mathcal{F}[D_1\bar{D}_2] + \right.$$
$$\left. + \quad B(y) cos(2\phi_0) \mathcal{F}\left[(2\hat{h}\cdot\vec{k}_T \hat{h}\cdot\vec{p}_T - \vec{k}_T\cdot\vec{p}_T)\frac{H_1^\perp \bar{H}_2^\perp}{M_1 M_2}\right]\right\}$$

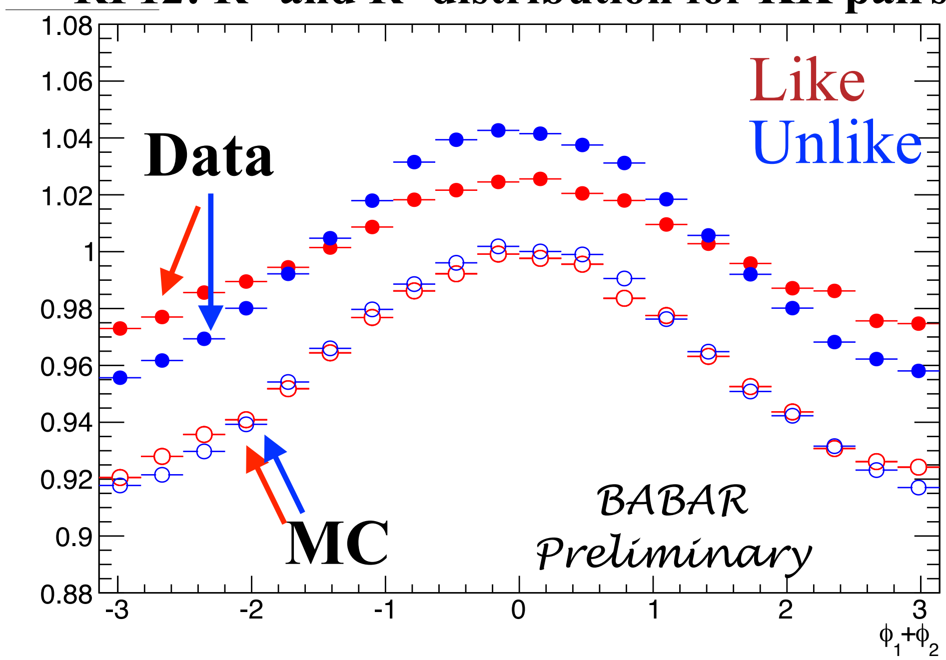
Analysis strategy: double ratios

Goal: **simultaneous measurement of KK, Kπ**, and **ππ** pairs

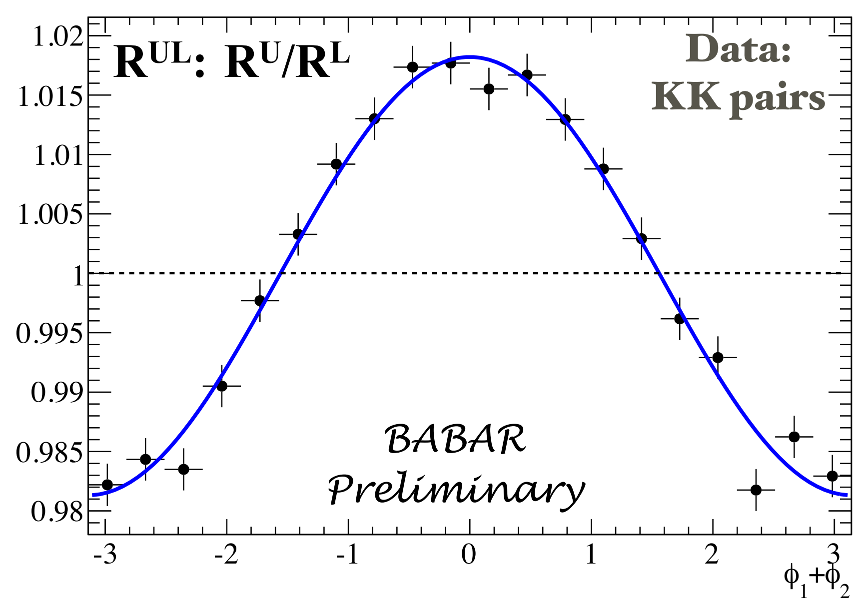
1. We measure the azimuthal angles ϕ_1 and ϕ_2 in RF12, and ϕ_0 in RF0
2. We construct the normalized distributions for like (L), Unlike (U) and Charged (C=U+L) hadron pairs: $R^i=N^i(\phi)/\langle N\rangle$

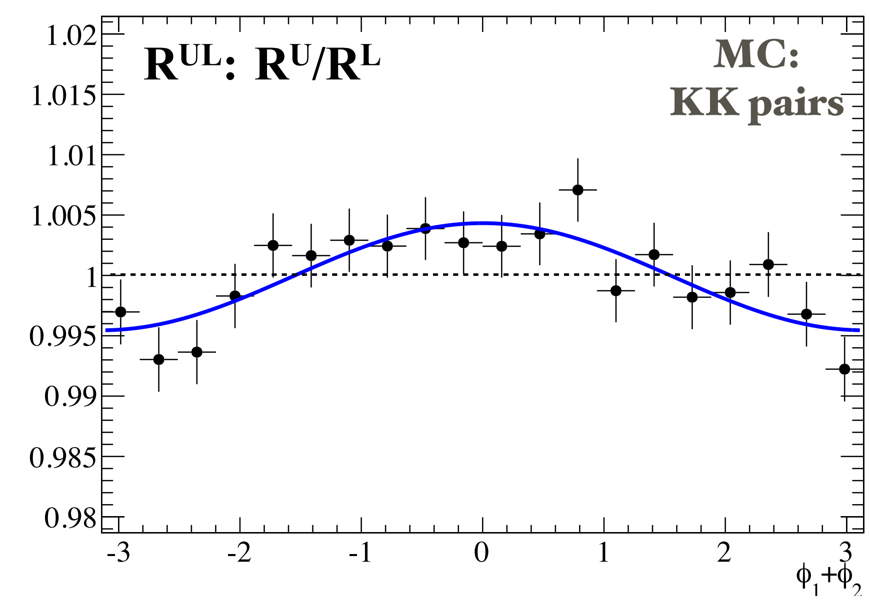
   - The Collins effect is not simulated in MC → strong azimuthal MC modulation principally due to the detector acceptance
   - Collins effect in data → different combinations of fav and dis FFs for L, U, and C

RF12: R^U and R^L distribution for KK pairs



3. We calculate the ratios of normalized distributions: U/L and U/C and we fit these distributions $(B+A\cdot\cos(\phi_i))$
   - detector effects cancel out





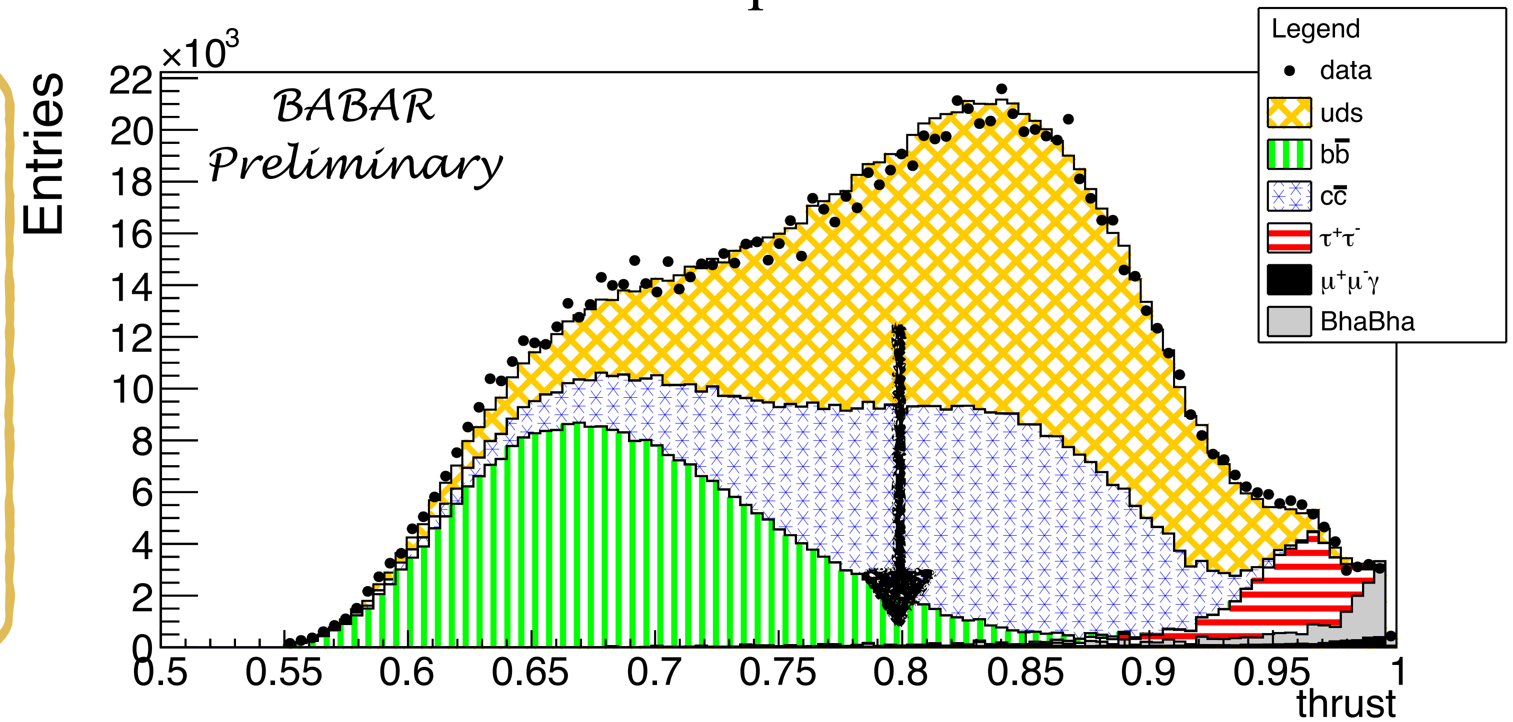
4. We extract the Collins asymmetries, we correct for the K/π misidentification and background contributions, and we study systematic uncertainties
5. RESULTS: **4x4 (z_1,z_2) bins, where $z_{1,2}=2E_h/\sqrt{s}$ is the hadron fractional energy**
   - **$z_{1,2}$ = (0.15-0.2), (0.2-0.3), (0.3-0.5), (0.5-0.9)**

Event and track selection

More stringent cuts optimized in order to reduce biases on the KK pairs

EVENT SELECTION

- Number of charged tracks > 2
- Selection of two jets topology: thrust > 0.8
- **$|\cos\theta_{thrust}|<0.6$**
- **Visible energy $E_{vis} > 11$ GeV**
- **Most energetic photon $E_\gamma < 2$ GeV**



Thrust axis: charged tracks + neutral candidates; thrust axis direction chosen random

TRACK SELECTION

- Electrons and muons veto
- K and π in the DIRC acceptance region
- K/π fractional energy z: $0.15 < z < 0.9$
- Opening angle $\theta_{h\text{-}thrust}$ of hadron 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 two hadrons center-of-mass energy

Measurement of Collins asymmetries

Simultaneous extraction of the asymmetries corrected for backgrounds and K/π misidentification for each interval of fractional energy

- 3 samples: KK, Kπ, ππ
- we fit independently the double ratio distributions of the three samples

$$\begin{aligned}
A_{KK}^{meas} = \quad & F_{uds}^{KK} \cdot (\xi_{KK}^{(KK)} A_{KK} + \xi_{K\pi}^{(KK)} A_{K\pi} + \xi_{\pi\pi}^{(KK)} A_{\pi\pi}) + \\
& F_{c\bar{c}}^{KK} \cdot (\xi_{KK}^{(KK)c\bar{c}} A_{KK}^{ch} + \xi_{K\pi}^{(KK)c\bar{c}} A_{K\pi}^{ch} + \xi_{\pi\pi}^{(KK)c\bar{c}} A_{\pi\pi}^{ch}) \\
A_{KK}^{D^*} = \quad & f_{uds}^{KK} \cdot (\xi_{KK}^{(KK)D^*} A_{KK} + \xi_{K\pi}^{(KK)D^*} A_{K\pi} + \xi_{\pi\pi}^{(KK)D^*} A_{\pi\pi}) + \\
& f_{c\bar{c}}^{KK} \cdot (\xi_{KK}^{(KK)c\bar{c}-D^*} A_{KK}^{ch} + \xi_{K\pi}^{(KK)c\bar{c}-D^*} A_{K\pi}^{ch} + \xi_{\pi\pi}^{(KK)c\bar{c}-D^*} A_{\pi\pi}^{ch})
\end{aligned}$$

1. **Background sources:**
   - mainly from **$e^+e^- \rightarrow c\bar{c}$ events** (more than 30%); smaller contribution from $B\bar{B}$, $\tau^+\tau^-$ (A_{bb}~A_τ~ 0)
     - we construct a D^*-enhanced MC and data control samples
     - we calculate from MC the fraction ($F(f)_{sig/bkg}^{hh}$) of hadron pairs coming from signal (uds) and background events ($c\bar{c}$, $B\bar{B}$, $\tau^+\tau^-$)
2. **K/π misidentification:**
   - we evaluate from MC the fraction ($\xi_{hh}^{(hh)}$) that a given hadron pair is reconstructed as KK, Kπ, or ππ pair
   - fractions evaluated in all samples used in the analysis: uds ($\xi_{hh}^{(hh)}$), D^*-uds ($\xi_{hh}^{(hh)D^*}$), $c\bar{c}$ ($\xi_{hh}^{(hh)c\bar{c}}$), $c\bar{c}$-D^* ($\xi_{hh}^{(hh)c\bar{c}-D^*}$)

Measurement of Collins asymmetries

Simultaneous extraction of the asymmetries corrected for backgrounds and K/π misidentification for each interval of fractional energy

- 3 samples: KK, Kπ, ππ
- we fit independently the double ratio distributions of the three samples

$$
\begin{aligned}
A_{KK}^{meas} = \quad & F_{uds}^{KK} \cdot (\xi_{KK}^{(KK)} A_{KK} + \xi_{K\pi}^{(KK)} A_{K\pi} + \xi_{\pi\pi}^{(KK)} A_{\pi\pi}) + \\
& F_{c\bar{c}}^{KK} \cdot (\xi_{KK}^{(KK)c\bar{c}} A_{KK}^{ch} + \xi_{K\pi}^{(KK)c\bar{c}} A_{K\pi}^{ch} + \xi_{\pi\pi}^{(KK)c\bar{c}} A_{\pi\pi}^{ch}) \\
A_{KK}^{D^*} = \quad & f_{uds}^{KK} \cdot (\xi_{KK}^{(KK)D^*} A_{KK} + \xi_{K\pi}^{(KK)D^*} A_{K\pi} + \xi_{\pi\pi}^{(KK)D^*} A_{\pi\pi}) + \\
& f_{c\bar{c}}^{KK} \cdot (\xi_{KK}^{(KK)c\bar{c}-D^*} A_{KK}^{ch} + \xi_{K\pi}^{(KK)c\bar{c}-D^*} A_{K\pi}^{ch} + \xi_{\pi\pi}^{(KK)c\bar{c}-D^*} A_{\pi\pi}^{ch})
\end{aligned}
$$

1. **Background sources:**
   - mainly from **$e^+e^- \rightarrow c\bar{c}$ events** (more than 30%); smaller contribution from $B\bar{B}$, $\tau^+\tau^-$ ($A_{bb} \sim A_\tau \sim 0$)
     - we construct a D^*-enhanced MC and data control samples
     - we calculate from MC the fraction ($F(f)_{sig/bkg}^{hh}$) of hadron pairs coming from signal (uds) and background events ($c\bar{c}$, $B\bar{B}$, $\tau^+\tau^-$)
2. **K/π misidentification:**
   - we evaluate from MC the fraction ($\xi_{hh}^{(hh)}$) that a given hadron pair is reconstructed as KK, Kπ, or ππ pair
   - fractions evaluated in all samples used in the analysis: uds ($\xi_{hh}^{(hh)}$), D^*-uds ($\xi_{hh}^{(hh)D^*}$), $c\bar{c}$ ($\xi_{hh}^{(hh)c\bar{c}}$), $c\bar{c}$-D^* ($\xi_{hh}^{(hh)c\bar{c}\text{-}D^*}$)

Measurement of Collins asymmetries: system of equations

Three samples (KK, Kπ, ππ) + background + K/π misidentification ⇒ **system of six equations and six unknown parameters**

$$
\begin{aligned}
A^{meas}_{KK} = \; & F^{KK}_{uds} \cdot (\xi^{(KK)}_{KK} A_{KK} + \xi^{(KK)}_{K\pi} A_{K\pi} + \xi^{(KK)}_{\pi\pi} A_{\pi\pi}) + \\
& F^{KK}_{c\bar{c}} \cdot (\xi^{(KK)c\bar{c}}_{KK} A^{ch}_{KK} + \xi^{(KK)c\bar{c}}_{K\pi} A^{ch}_{K\pi} + \xi^{(KK)c\bar{c}}_{\pi\pi} A^{ch}_{\pi\pi}) \\
A^{meas}_{K\pi} = \; & F^{K\pi}_{uds} \cdot (\xi^{(K\pi)}_{KK} A_{KK} + \xi^{(K\pi)}_{K\pi} A_{K\pi} + \xi^{(K\pi)}_{\pi\pi} A_{\pi\pi}) + \\
& F^{K\pi}_{c\bar{c}} \cdot (\xi^{(K\pi)c\bar{c}}_{KK} A^{ch}_{KK} + \xi^{(K\pi)c\bar{c}}_{K\pi} A^{ch}_{K\pi} + \xi^{(K\pi)c\bar{c}}_{\pi\pi} A^{ch}_{\pi\pi}) \\
A^{meas}_{\pi\pi} = \; & F^{\pi\pi}_{uds} \cdot (\xi^{(\pi\pi)}_{KK} A_{KK} + \xi^{(\pi\pi)}_{K\pi} A_{K\pi} + \xi^{(\pi\pi)}_{\pi\pi} A_{\pi\pi}) + \\
& F^{\pi\pi}_{c\bar{c}} \cdot (\xi^{(\pi\pi)c\bar{c}}_{KK} A^{ch}_{KK} + \xi^{(\pi\pi)c\bar{c}}_{K\pi} A^{ch}_{K\pi} + \xi^{(\pi\pi)c\bar{c}}_{\pi\pi} A^{ch}_{\pi\pi}) \\
A^{D^*}_{KK} = \; & f^{KK}_{uds} \cdot (\xi^{(KK)D^*}_{KK} A_{KK} + \xi^{(KK)D^*}_{K\pi} A_{K\pi} + \xi^{(KK)D^*}_{\pi\pi} A_{\pi\pi}) + \\
& f^{KK}_{c\bar{c}} \cdot (\xi^{(KK)c\bar{c}-D^*}_{KK} A^{ch}_{KK} + \xi^{(KK)c\bar{c}-D^*}_{K\pi} A^{ch}_{K\pi} + \xi^{(KK)c\bar{c}-D^*}_{\pi\pi} A^{ch}_{\pi\pi}) \\
A^{D^*}_{K\pi} = \; & f^{K\pi}_{uds} \cdot (\xi^{(K\pi)D^*}_{KK} A_{KK} + \xi^{(K\pi)D^*}_{K\pi} A_{K\pi} + \xi^{(K\pi)D^*}_{\pi\pi} A_{\pi\pi}) + \\
& f^{K\pi}_{c\bar{c}} \cdot (\xi^{(K\pi)c\bar{c}-D^*}_{KK} A^{ch}_{KK} + \xi^{(K\pi)c\bar{c}-D^*}_{K\pi} A^{ch}_{K\pi} + \chi^{(K\pi)c\bar{c}-D^*}_{\pi\pi} A^{ch}_{\pi\pi}) \\
A^{D^*}_{\pi\pi} = \; & f^{\pi\pi}_{uds} \cdot (\xi^{(\pi\pi)D^*}_{KK} A_{KK} + \xi^{(\pi\pi)D^*}_{K\pi} A_{K\pi} + \xi^{(\pi\pi)D^*}_{\pi\pi} A_{\pi\pi}) + \\
& f^{\pi\pi}_{c\bar{c}} \cdot (\xi^{(\pi\pi)c\bar{c}-D^*}_{KK} A^{ch}_{KK} + \xi^{(\pi\pi)c\bar{c}-D^*}_{K\pi} A^{ch}_{K\pi} + \xi^{(\pi\pi)c\bar{c}-D^*}_{\pi\pi} A^{ch}_{\pi\pi})
\end{aligned}
$$

= Collins asymmetries for light hadrons

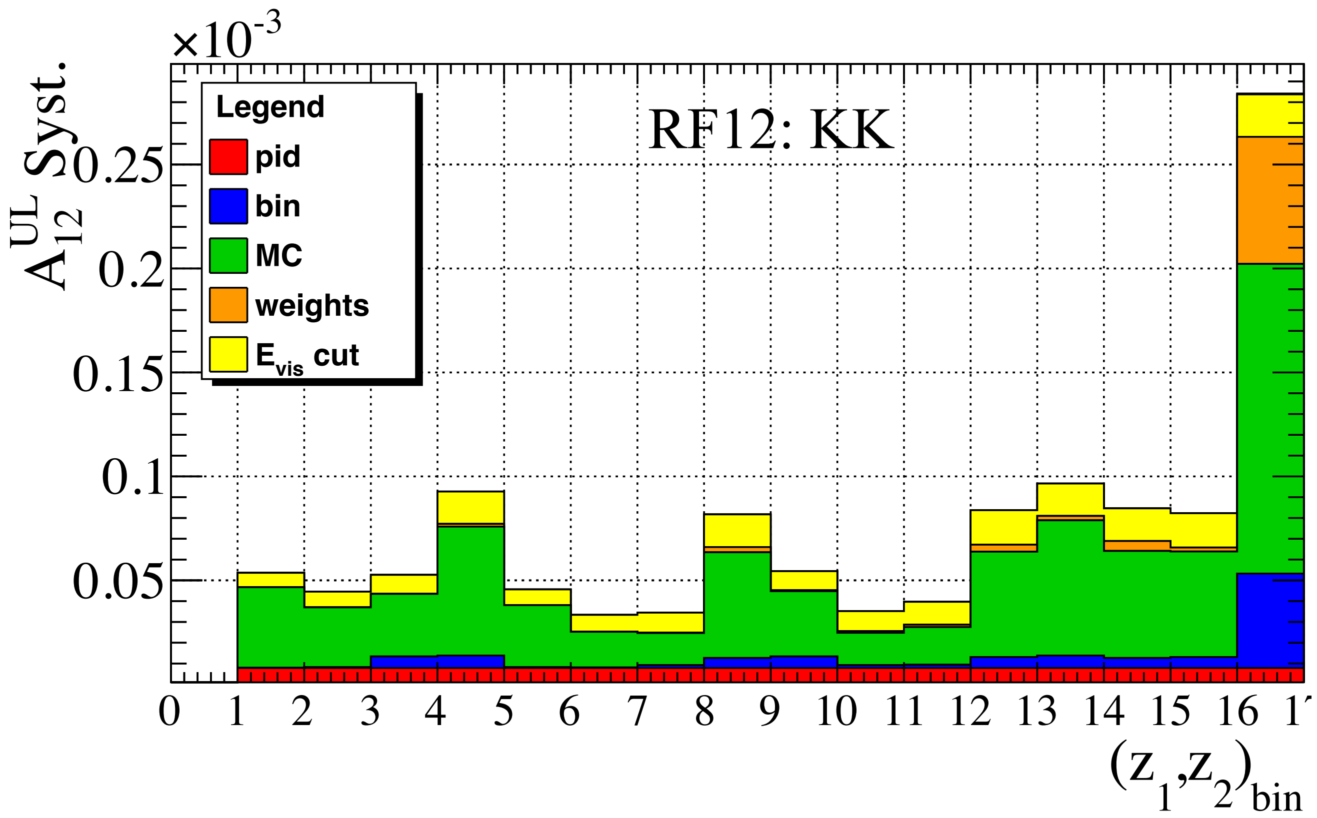
Asymmetry corrections and systematic studies

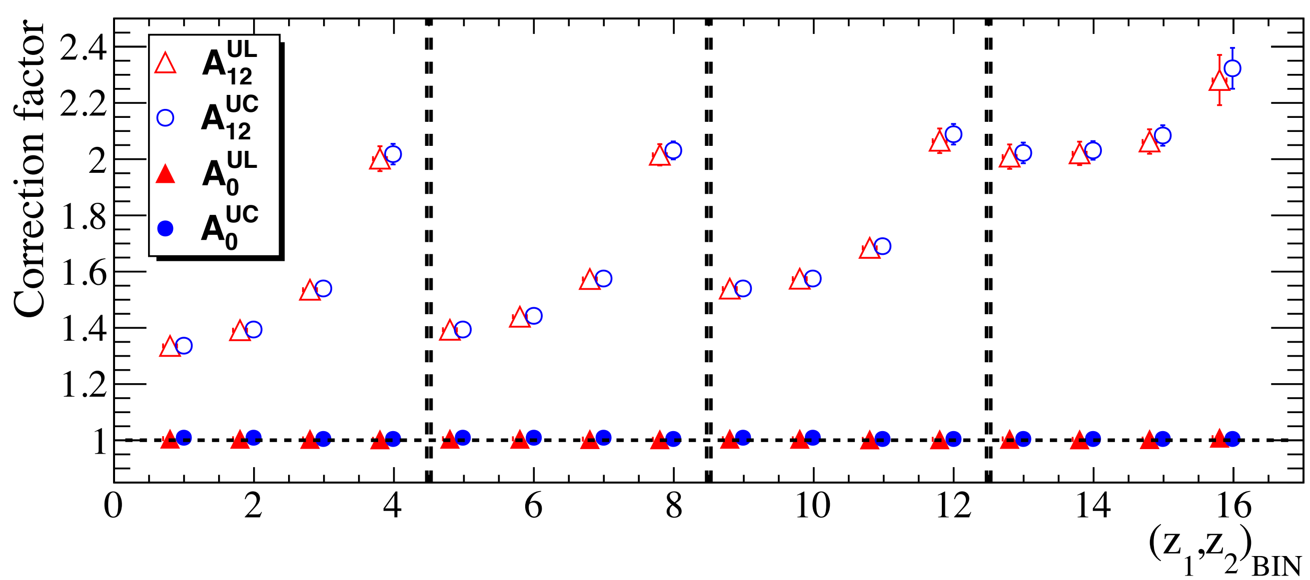
A large number of systematic checks were done.
The main contributions come from:

- MC uncertainties
- Particle identification (PID)
- Fit procedure
- Dilution method
- E_{vis} cut

Negligible contributions from

- Beam polarization studies
- Consistency between different data taking period
- Possible coupling between Collins and detector effect





- RF12: strong dilution observed ⇒ correction ranges between 1.3 to 2.3 for increasing z
- RF0: no correction needed

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

- RF12: the azimuthal angles are calculated respect to the thrust axis → large smearing;
- RF0: no thrust axis needed → smearing due only to PID and tracking resolution.

⇒ Using the MC sample,we introduce in the simulation several values of asymmetries, and we study the differences between the simulated and the reconstructed ones

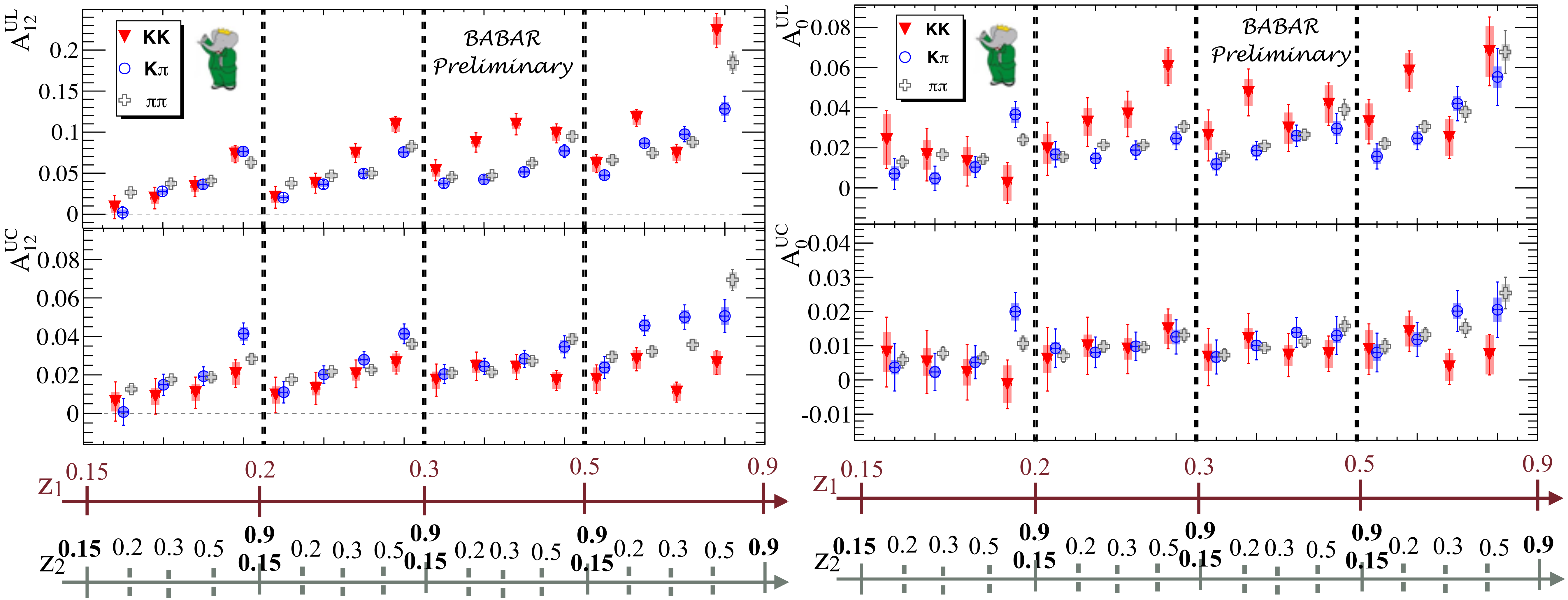
Same corrections applied for the three hadron pair combinations

Results

Simultaneous measurement of KK, Kπ and $\pi\pi$ Collins asymmetries

arXiv:1506.05864

- all corrections are applied
- statistical and systematic uncertainties represented by error bars and bands, respectively



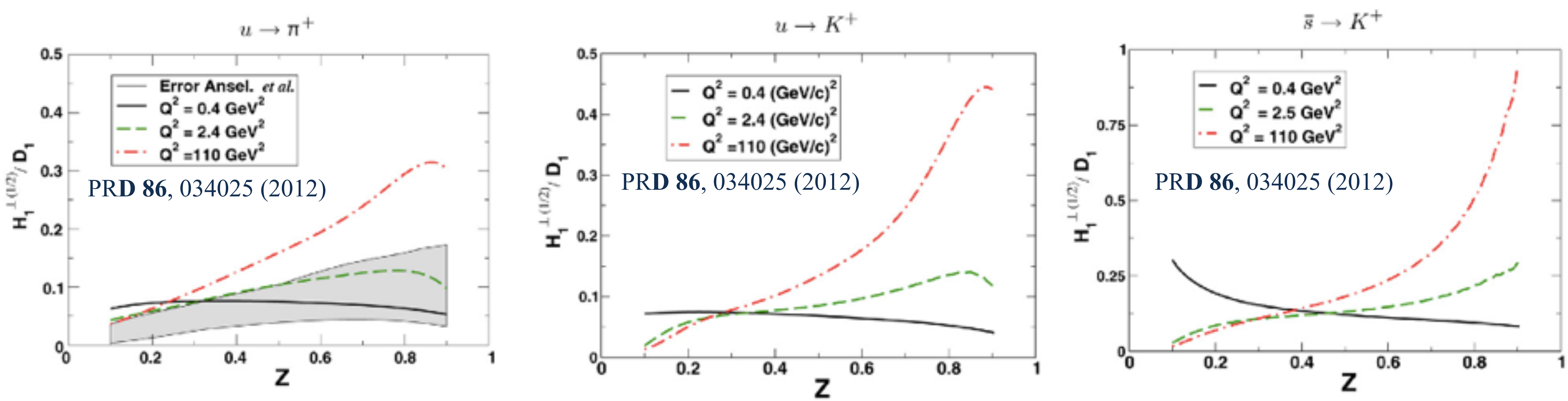
- Rising of the asymmetry as a function of *z* (more pronounced for U/L)
- A^{UL} KK asymmetry slightly higher than pion asymmetry for high z
- KK asymmetry consistent with zero at lower z

✔ **RESULTS SUBMITTED FOR PUBLICATION**

Note that A^{UL} and A^{UC} asymmetries are obtained using the same data sample, and are strongly correlated

Summary and conclusions

- Simultaneous extraction of A_{KK}, $A_{K\pi}$, and $A_{\pi\pi}$ Collins asymmetry
  - **arXiv:1506.05864**
  - Two reference frames: RF12 and RF0
  - 16 (z_1,z_2)-bins
  - Good agreement with previous BaBar results (PRD 90,052009 (2014))



- Agreement with theoretical prediction !? [*PL **B659**, 234 (2008); PRD **86**, 034025 (2012)*]
  - A^{UL} asymmetry for KK are slightly **larger** than $\pi\pi$
  - A^{UC} asymmetry for KK are slightly **lower** than $\pi\pi$

Backup slides

PEP-II and the BaBar detector

• 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, $\beta\gamma \approx 0.56$

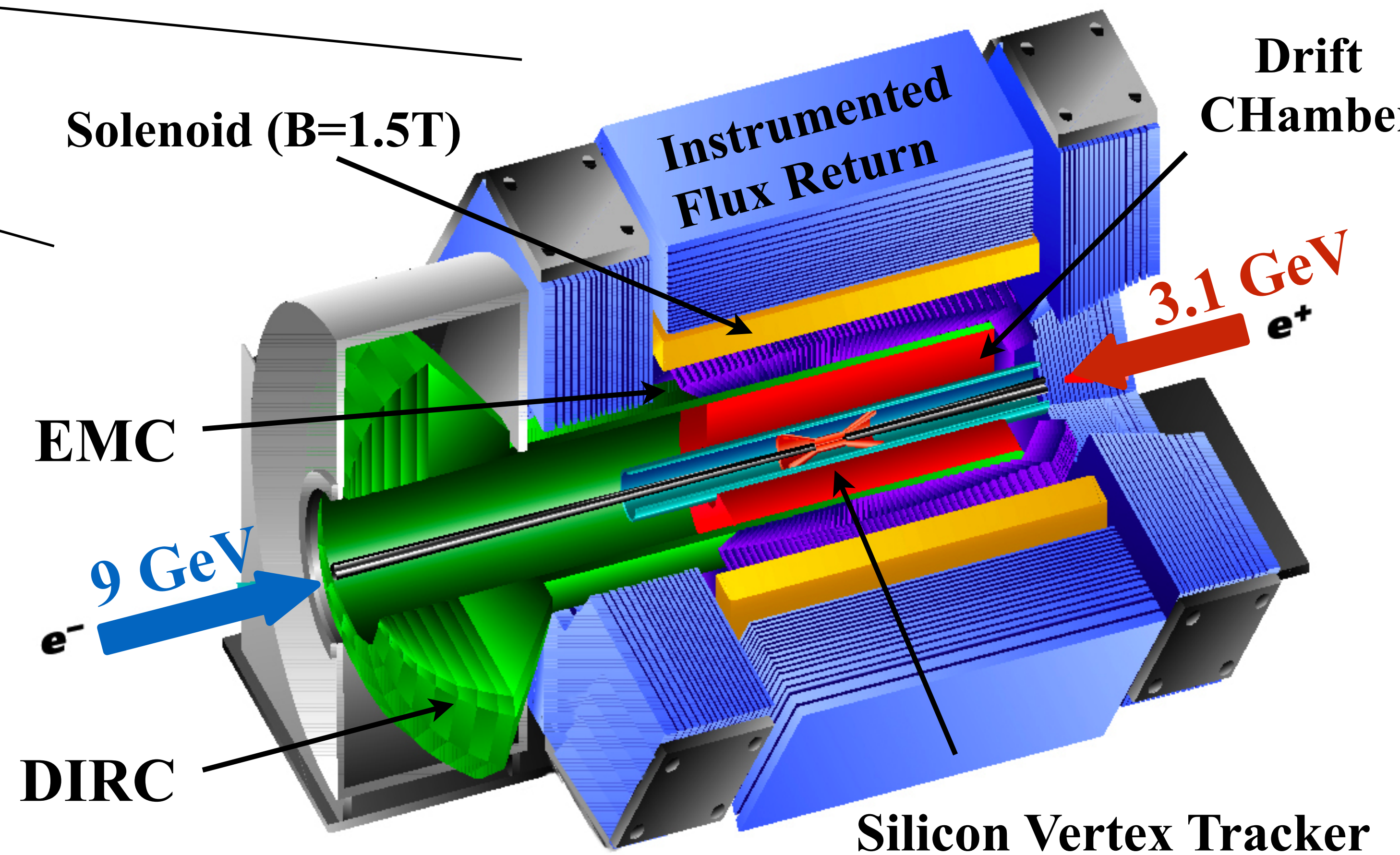
• High luminosity: $\mathcal{L}$ ~ **468 fb^{-1}** used here

• 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



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

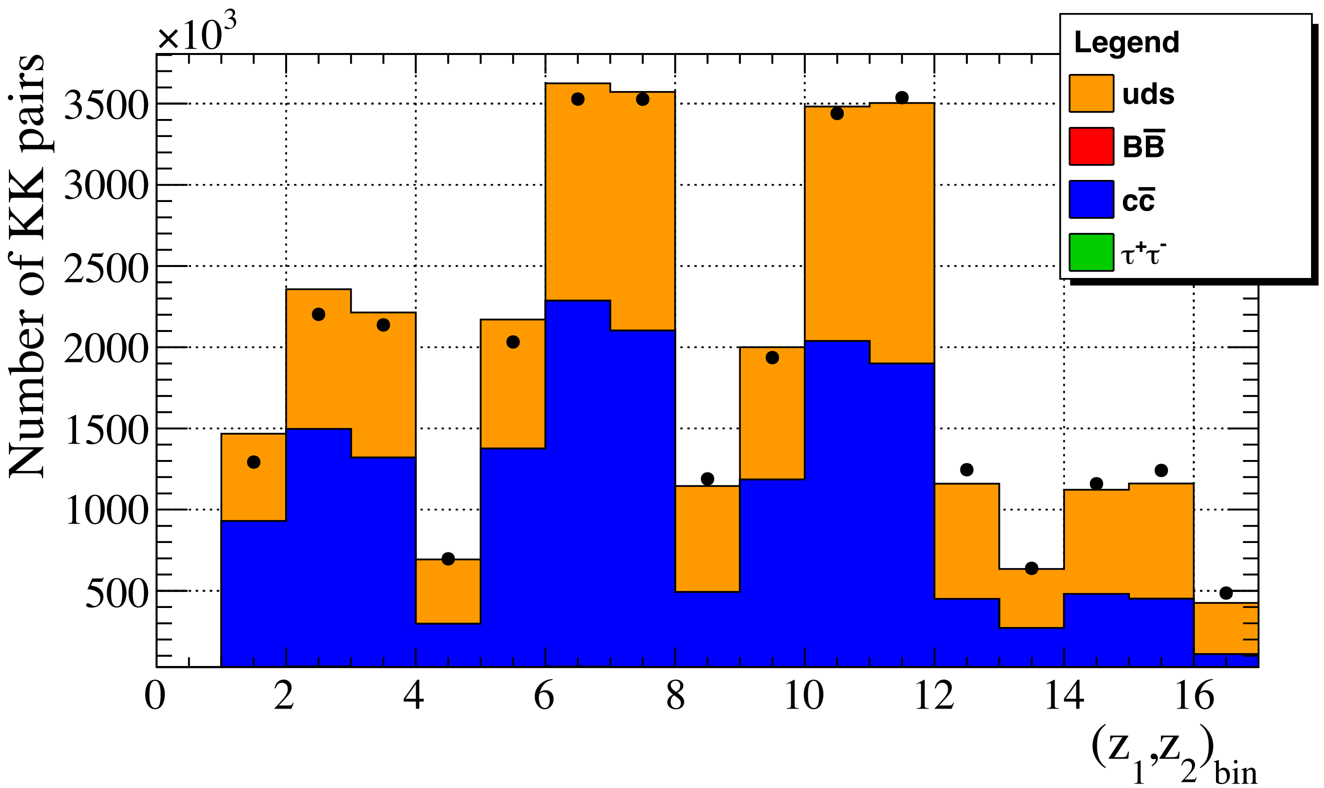
Fraction of hadron pairs

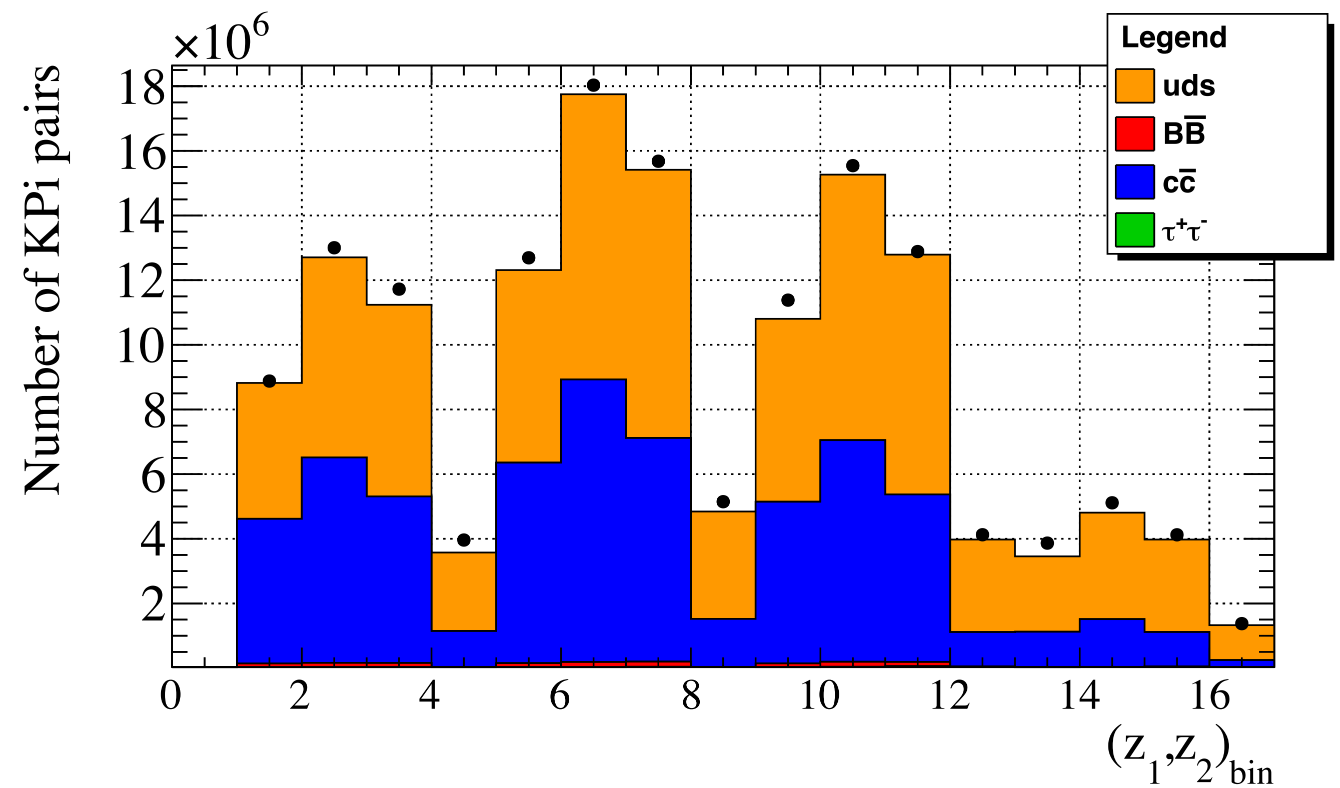
From MC samples, we calculate the number of hadron pairs (KK, K**π** and **ππ**) coming from light quarks and background events:

$$F_i = \frac{N_i^{(MC)}}{N_{data}}$$

We then calculate the corrected fractions in order to take into account the condition that their sum is equal to 1:

$$F_i^{corr} = F_i + \frac{(1 - \sum_{j=uds}^{cc,bb,\tau} F_j) * \sigma_i^2}{\sum_{j=uds}^{cc,bb,\tau} \sigma_j^2}$$

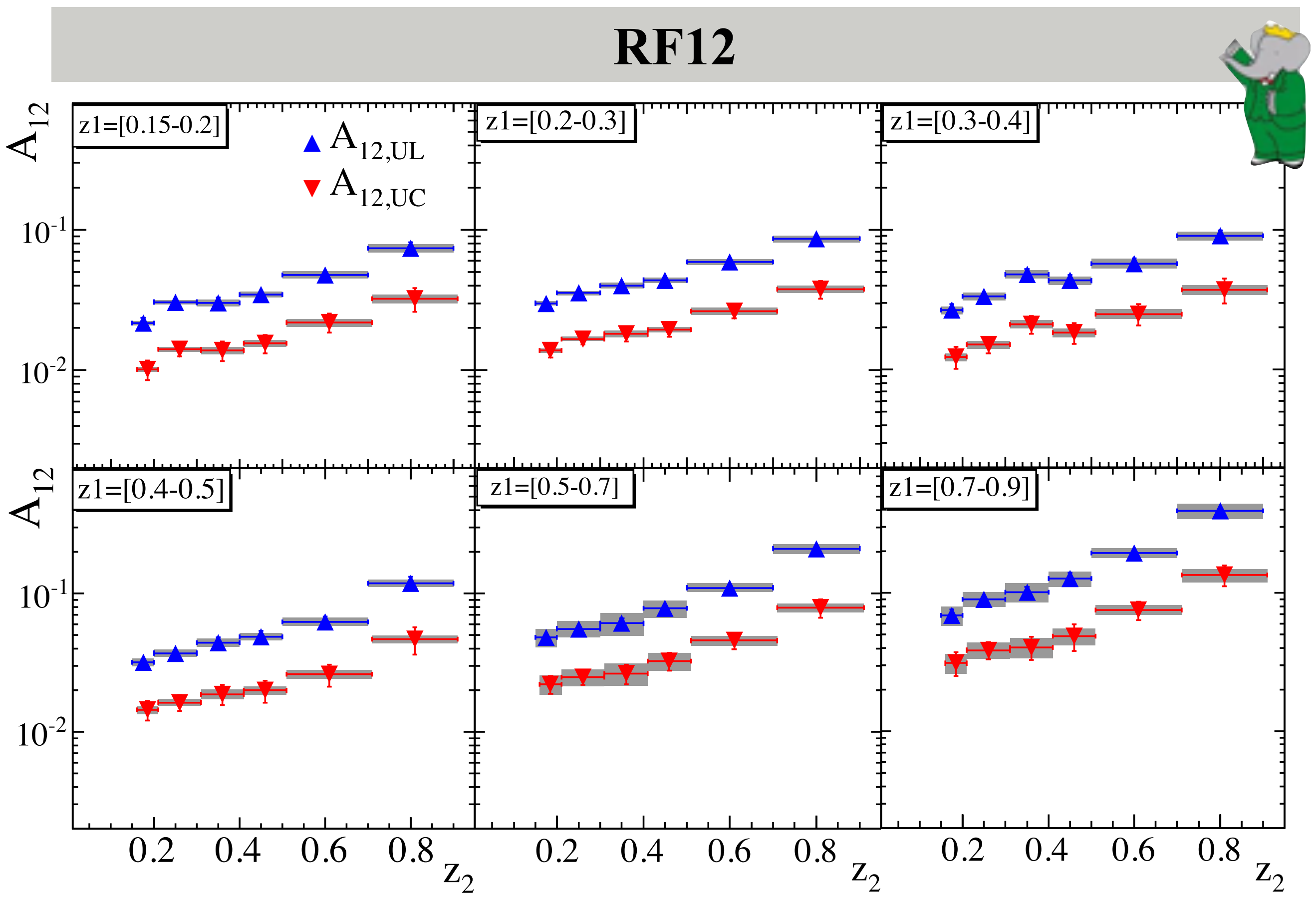


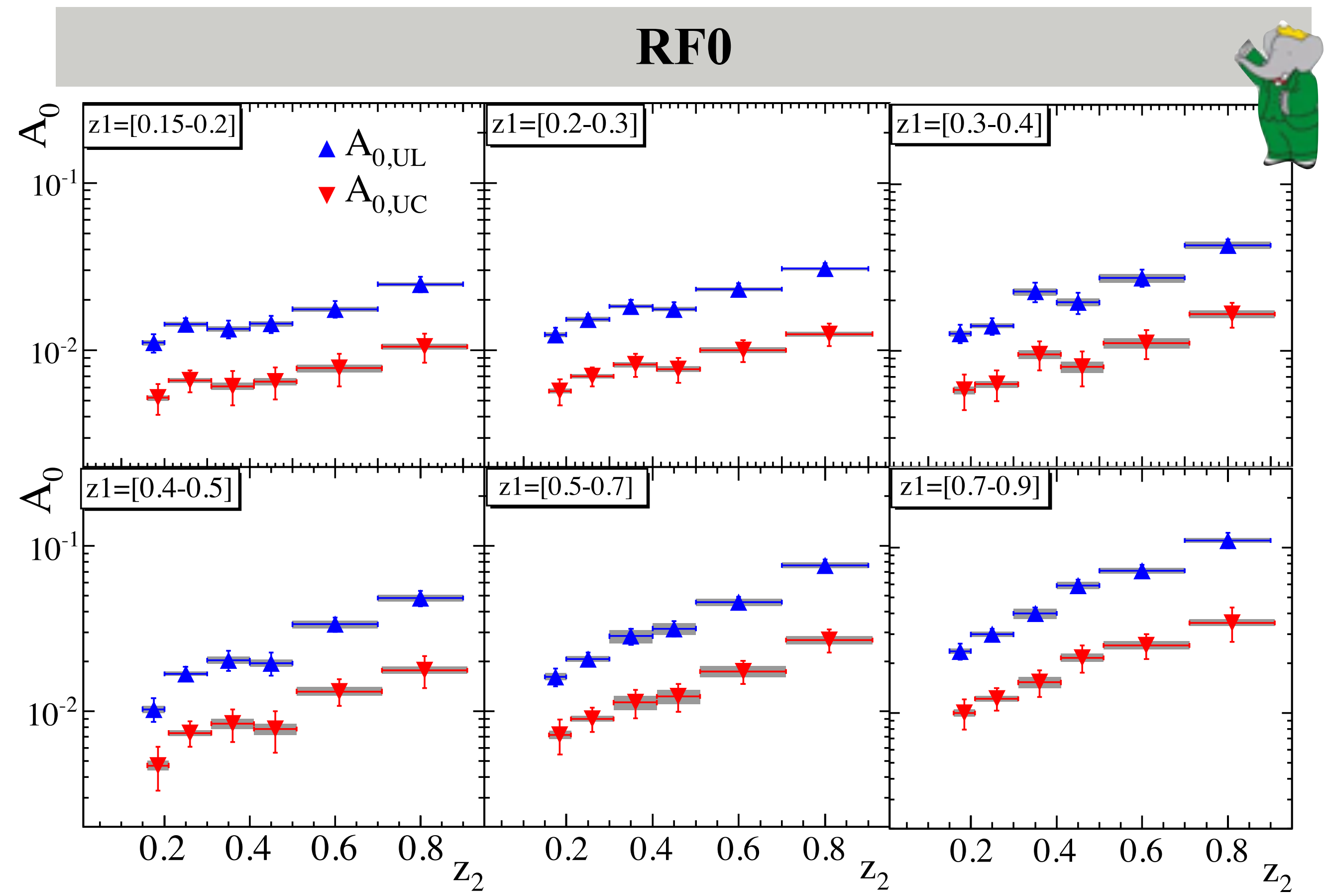


Similar distribution for D*-enhanced and ππ samples

ππ Collins effect: asymmetries vs. (z_1,z_2)

PRD 90,052003 (2014)





Statistical errors shown as bars; systematic errors shown as bands

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

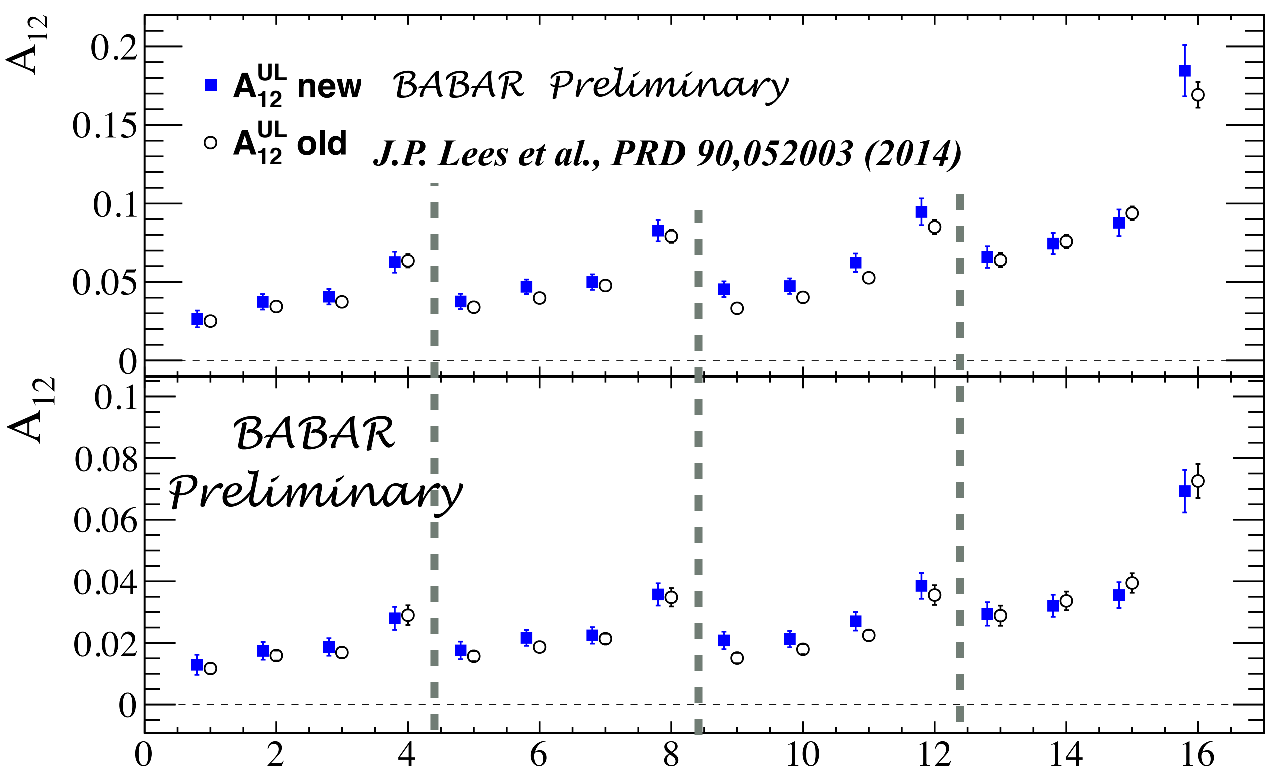
- strong dependence on (z_1,z_2): 1-39% in RF12 and 1-11% in RF0
- $A^{UC} < A^{UL}$ as expected; complementary information about the favored and disfavored fragmentation processes (PRD 73, 094025 (2006))
- consistent with $z_1 \Leftrightarrow z_2$ symmetry

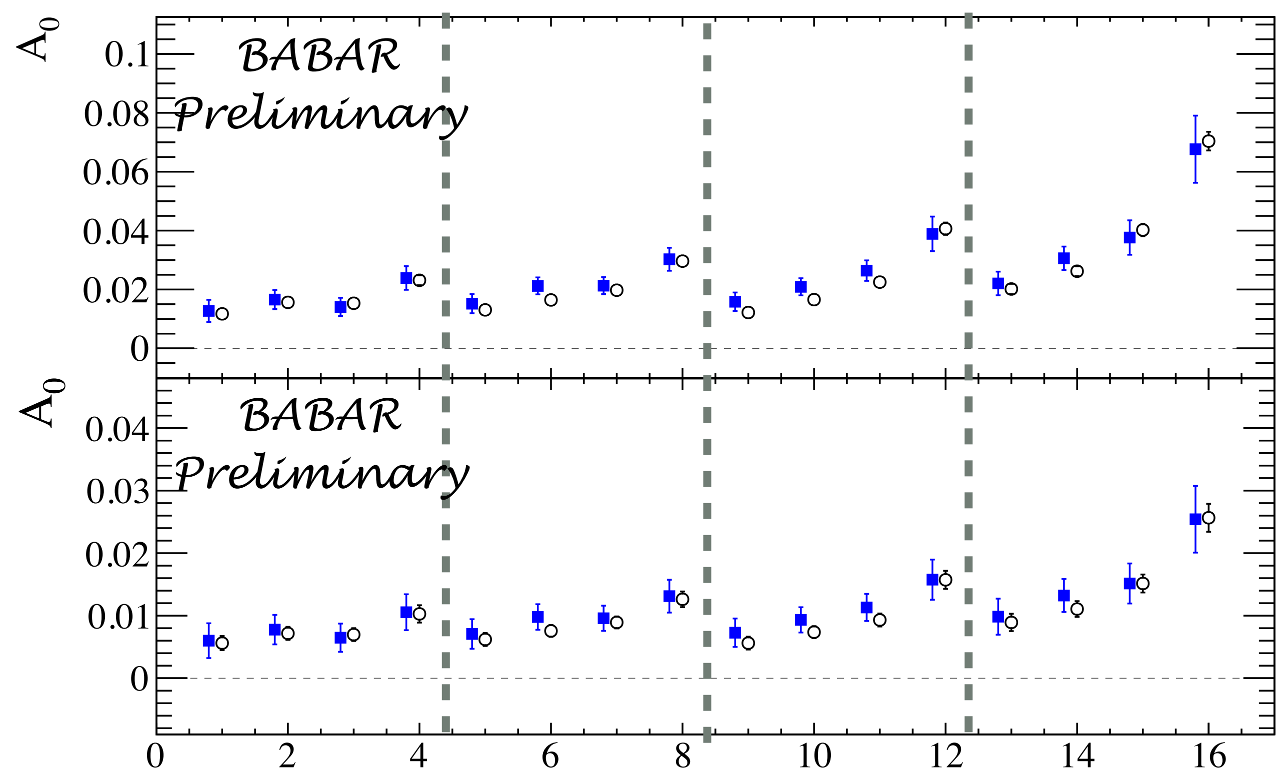
ππ consistency check

Comparison of the $\pi\pi$ asymmetries with those measured in the previous BaBar analysis:
PRD 90, 052003 (2014)

- Different kinematic regions: asymmetries rescaled for $<\sin^2\theta>/<1+\cos^2\theta>$
- Average values of the data in the new (z_1,z_2) intervals

$$\frac{R^{UL}}{R^L} = 1 + \cos(\phi_1+\phi_2)\cdot A_{12}^{UL} = 1+\cos(\phi_1+\phi_2)\cdot \frac{\langle \sin^2\theta_{th}\rangle}{\langle 1+\cos^2\theta_{th}\rangle}\cdot\frac{H_1^{\perp}(z)\overline{H}_1^{\perp}(z)}{D_1(z)\overline{D}_1(z)}$$





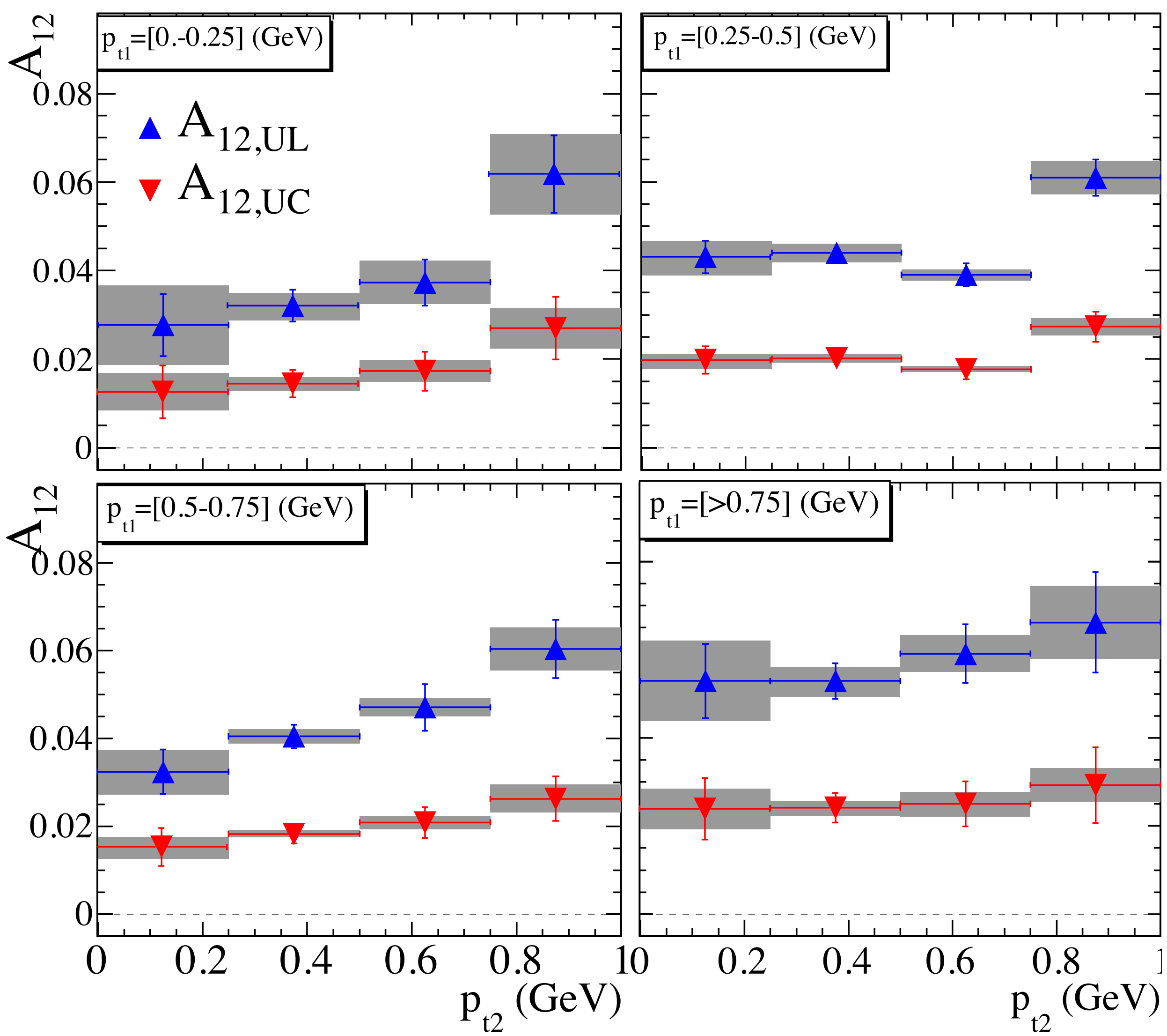
- New and previous results are in good agreement each other
  - we averaged those values falling in the new interval
- Cross check ⇒ make us confident about the goodness of the simultaneous extraction of KK, Kπ and $\pi\pi$

$\pi\pi$ Collins effect: asymmetries vs. (p_{t1},p_{t2}) and p_{t0}

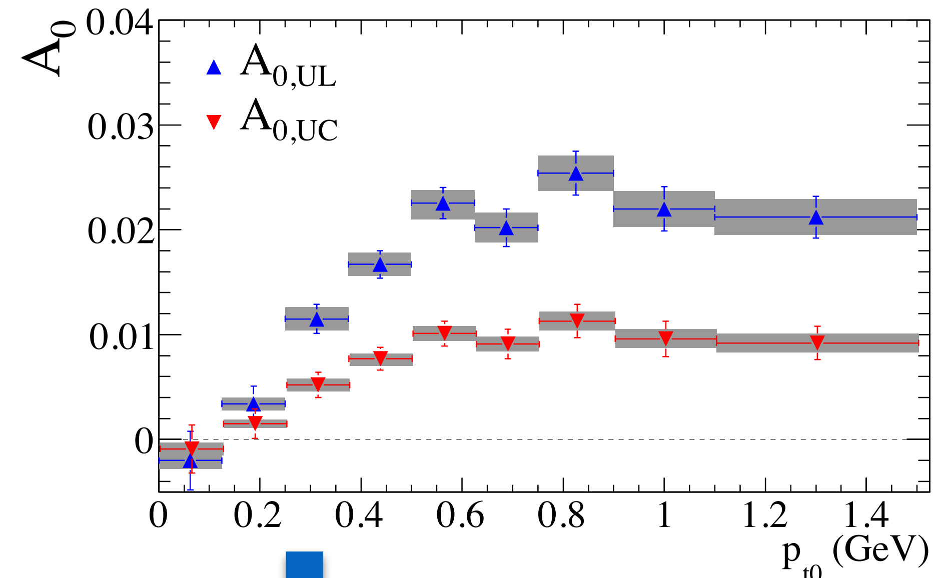
PRD 90,052003 (2014)

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

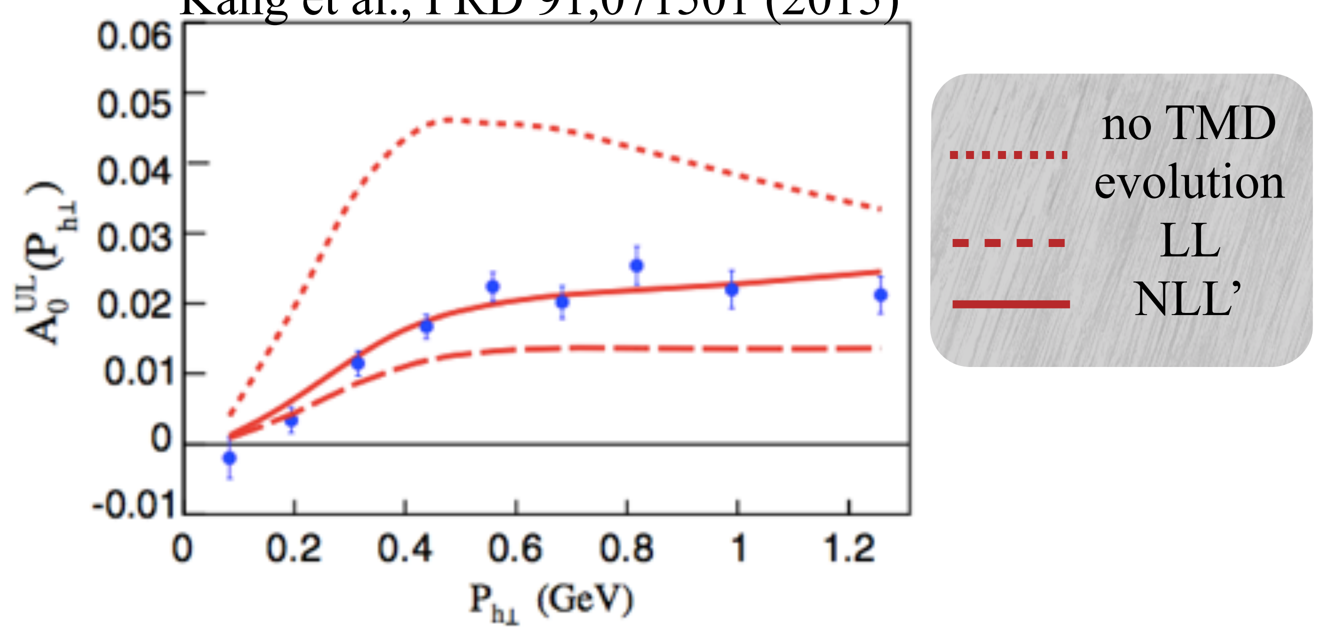
RF12



RF0

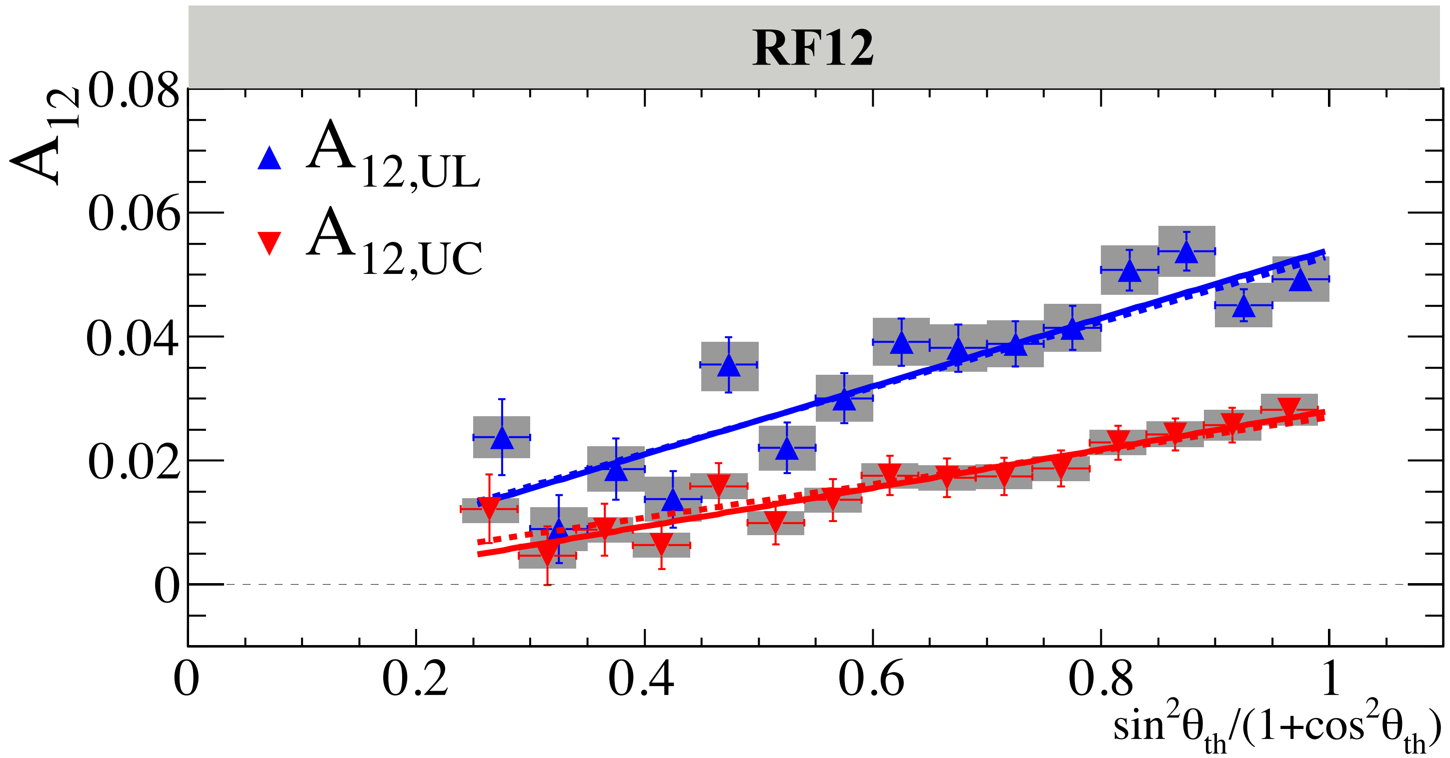


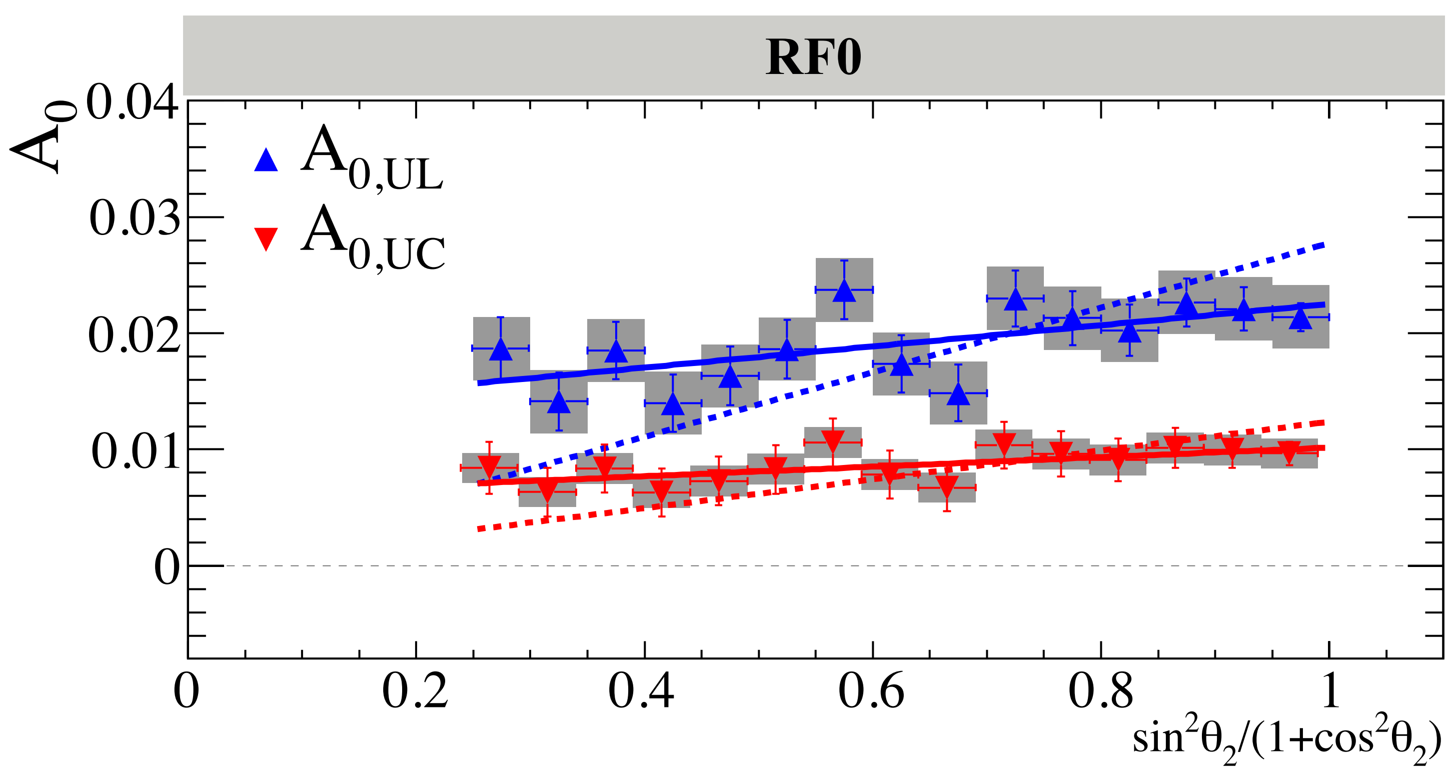
Kang et al., PRD 91,071501 (2015)



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

ππ Collins effect: asymmetries vs. polar angles





PRD 90,052003 (2014)

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)

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

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

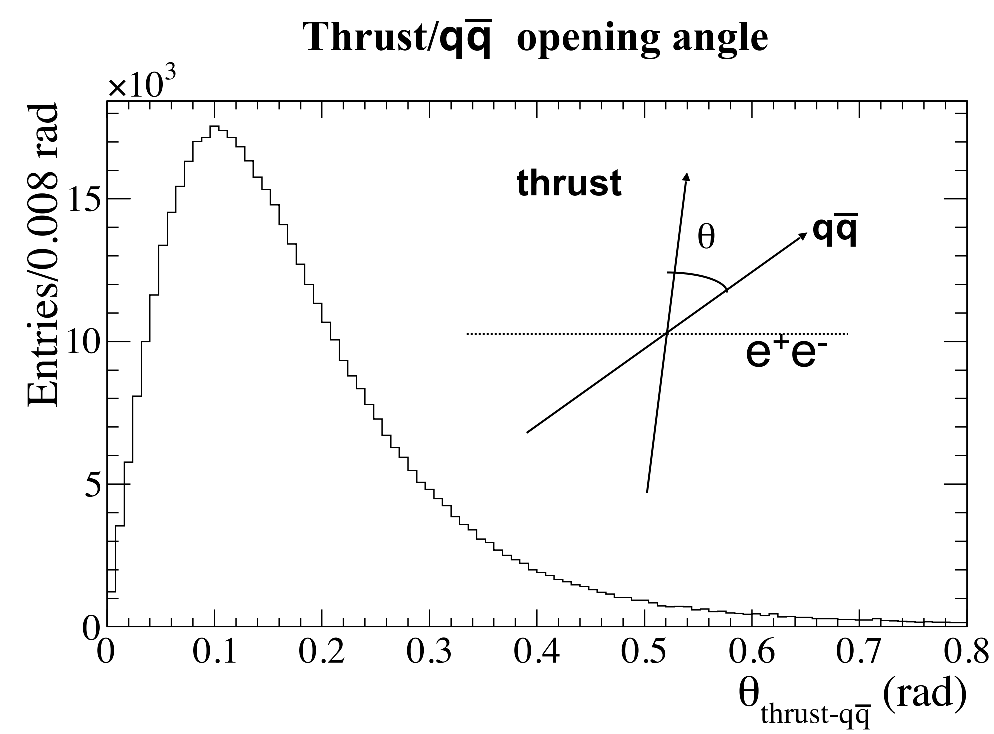
Lines: fit results with a linear functions
Dotted lines: fit results with a linear function crossing the origin

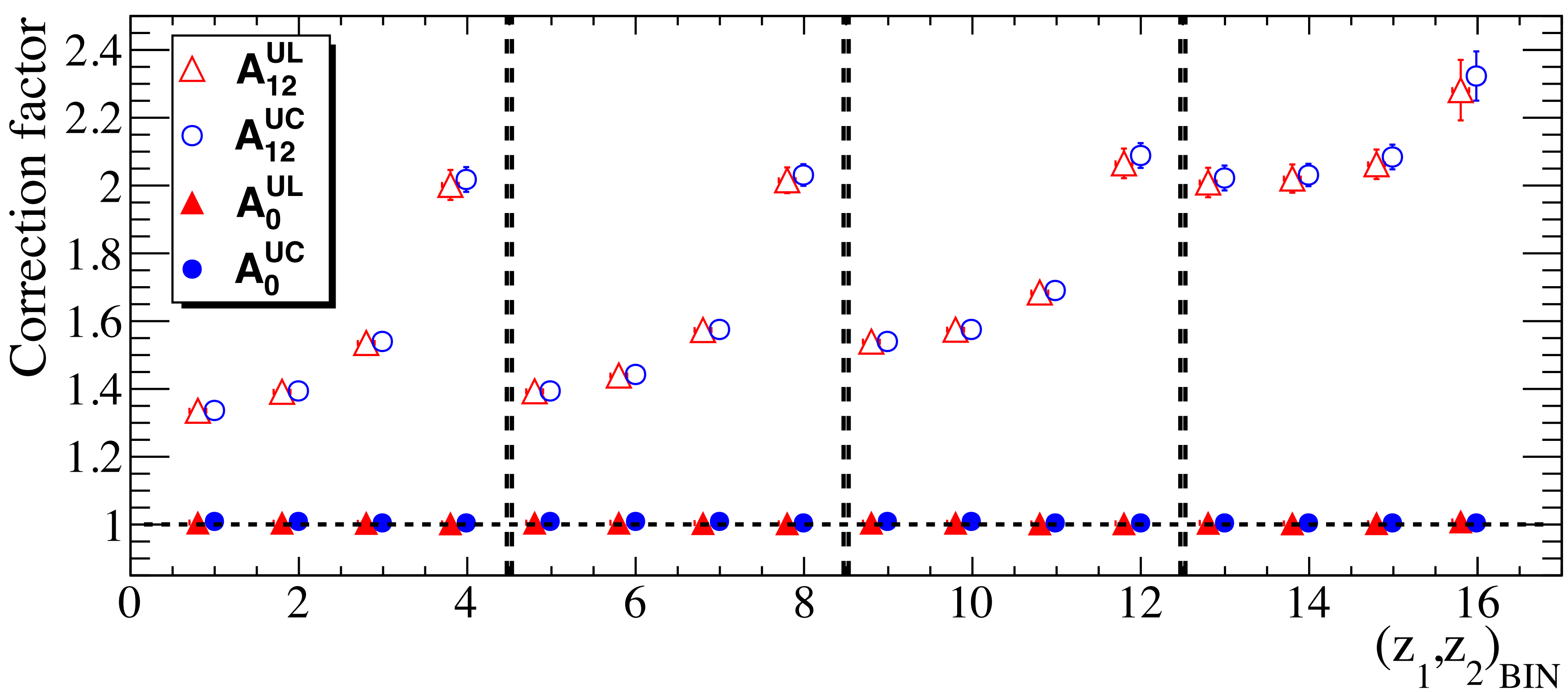
Corrections and systematic studies

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

- RF12: the azimuthal angles are calculated respect to the thrust axis → large smearing;
- RF0: no thrust axis needed → smearing due only to PID and tracking resolution.

⇒ Using the MC sample,we introduce in the simulation several values of asymmetries, and we study the differences between the simulated and the reconstructed ones





- RF12: strong dilution observed ⇒ correction ranges between 1.3 to 2.3 for increasing z
- RF0: no dilution observed ⇒ no correction needed

Same corrections applied for the three hadron pair combinations