Measurements of Collins Asymmetries in e^+e^- annihilations at BABAR

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on behalf of the BABAR Collaboration

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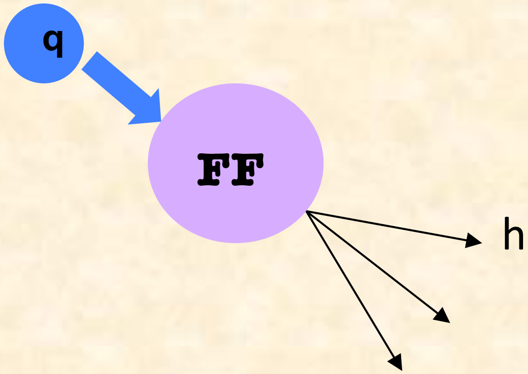
Collins Fragmentation Function

Fragmentation Functions (FFs)

- ☑ dimensionless and universal functions
- ☑ non-perturbative information
- ☑ describe the final state particles in hard processes
- ☑ dependence on

$$z = 2E_h/\sqrt{s}, \quad P_\perp, \text{ and } s_q$$



Unpolarized FF

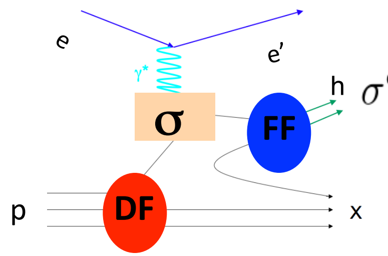
$$D_h^{q\uparrow}(z, \mathbf{P}_\perp; s_q) = D_1^q(z, P_\perp) + \frac{H_1^{\perp q}(z, P_\perp)\, s_q \cdot (\mathbf{k}_q \times \mathbf{P}_\perp)}{z M_h}$$

- Could arise from a spin-orbit coupling
- Leads to a modulation in the angular distribution of final state particles (Collins Effect or Collins asymmetry)

- $H_1^\perp$ is the **polarized** fragmentation function or **Collins FF**, describing the fragmentation of a **transversely polarized quark into a spinless (or unpolarized) hadron *h***
- J. C. Collins, Nucl.Phys. **B 396**, 161 (1993)
- **Chiral-odd** function, ideal to access the chiral-odd parton distribution functions in Semi-Inclusive Deep Inelastic Scattering (SIDIS)

Use Collins FF to extract Transversity

SIDIS: Semi Inclusive Deep Inelastic Scattering



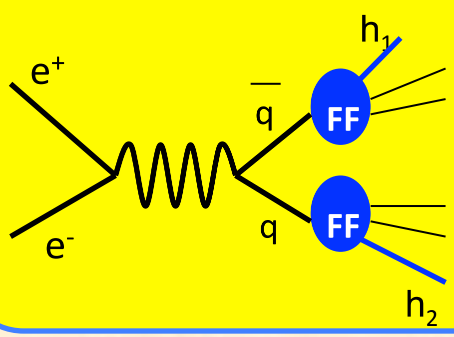
Factorization theorem:

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

$$\sigma \propto \sin(\phi_h + \phi_s) h_1(x_B) \otimes H_1^\perp(z_1)$$

Transversity function

Global analysis of **SIDIS (HERMES & COMPASS)** **and** **e+e- (BELLE, *BABAR,BESIII*)** data
==> simultaneous determination of Transversity(h_1) and Collins functions (CFF).



$$e^+e^- \to q\bar{q} \to h_1 h_2 X \quad (q = u,d,s)$$

$$\sigma \propto \cos(\phi_i) H_1^\perp(z_1) \otimes H_1^\perp(z_2)$$

SIDIS

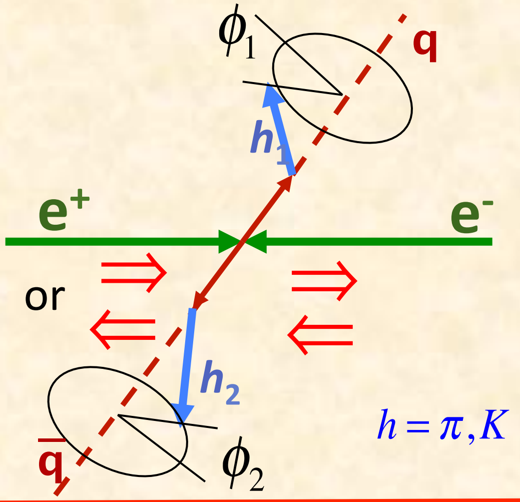
- Unpolarized lepton beam off transversely polarized nucleon target
  - non-zero Collins effects
  - spin direction known
  - two chiral-odd functions

  Transversity PDF & Collins FF

e^+e^- annihilation

- γ^* (spin-1) goes to spin-1/2 q and $\bar{q}$
  - **Two Collins functions contribute to the cross section**

Collins effect in di-hadron correlations



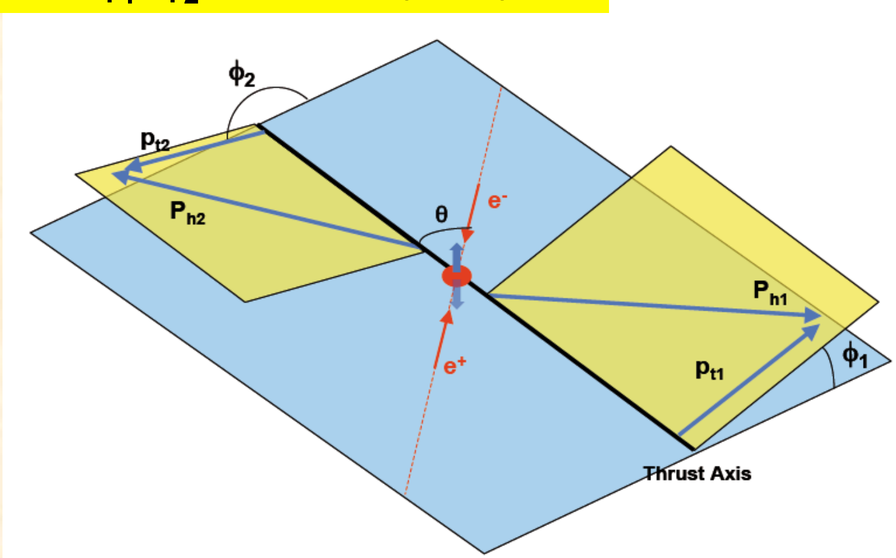
$e^+e^- \rightarrow h_1h_2X$ ($h_i = \pi, K$ spinless hadrons)

- quark spin direction unknown
  - ⇒ single-spin asymmetry vanishes
- They have a polarization component transverse to the quark direction
  - ⇒ Charged hadrons detected in opposite jets, correlated to the original quark-antiquark pair:

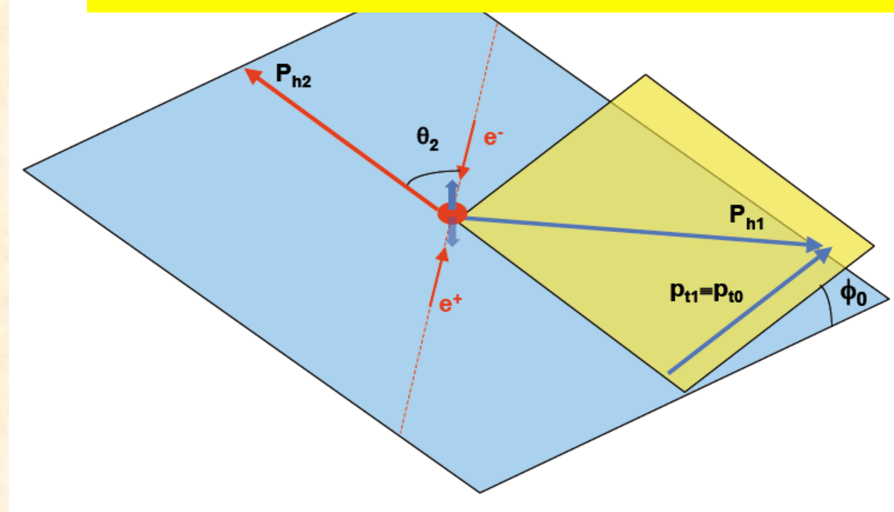
measure cosine modulation of the observed di-hadron yield

Reference frames

$\phi_1+\phi_2$ Thrust RF (RF12)



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



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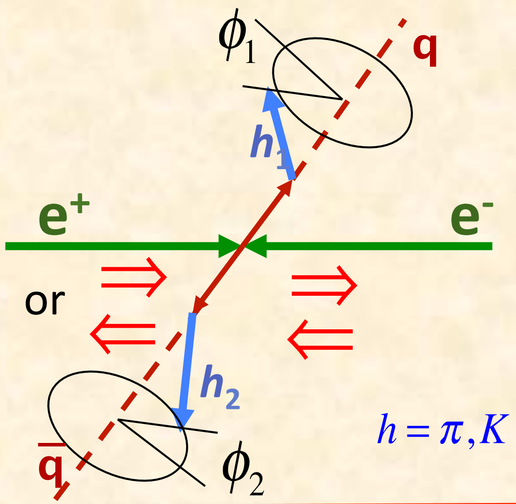

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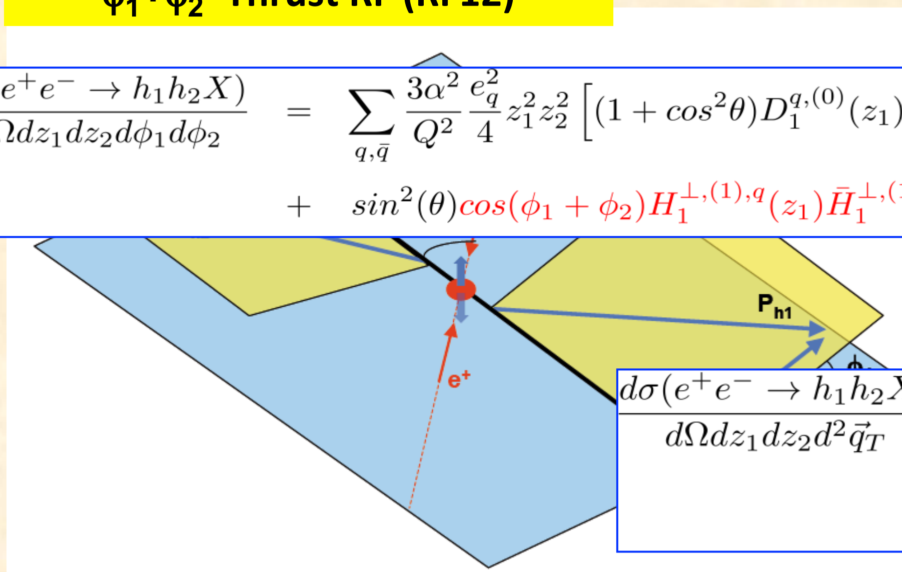
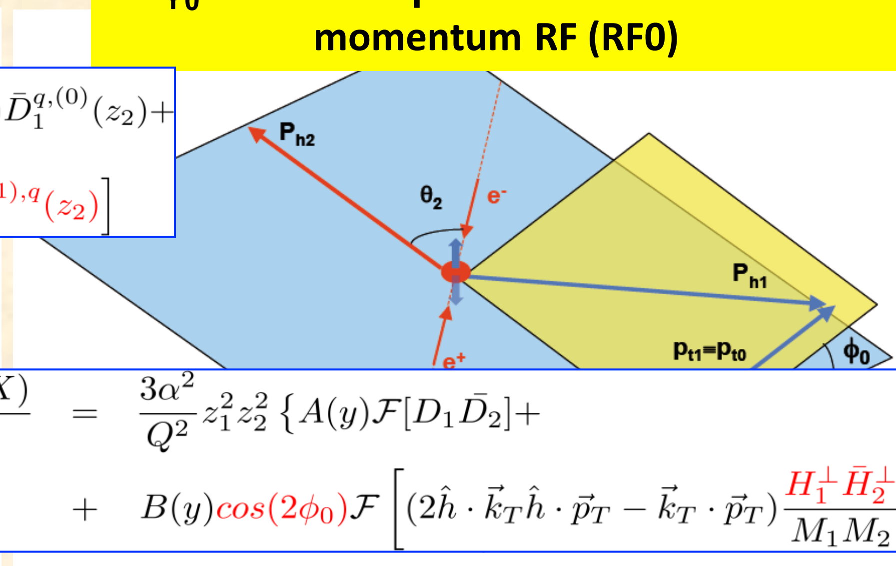


$$\frac{d\sigma(e^+e^- \to h_1h_2X)}{d\Omega dz_1dz_2d\phi_1d\phi_2} = \sum_{q,\bar{q}} \frac{3\alpha^2}{Q^2}\frac{e_q^2}{4} z_1^2 z_2^2 \Big[(1+cos^2\theta)D_1^{q,(0)}(z_1)\bar{D}_1^{q,(0)}(z_2) + + sin^2(\theta) cos(\phi_1+\phi_2) H_1^{\perp,(1),q}(z_1)\bar{H}_1^{\perp,(1),q}(z_2)\Big]$$



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

Collins effect in di-hadron correlation

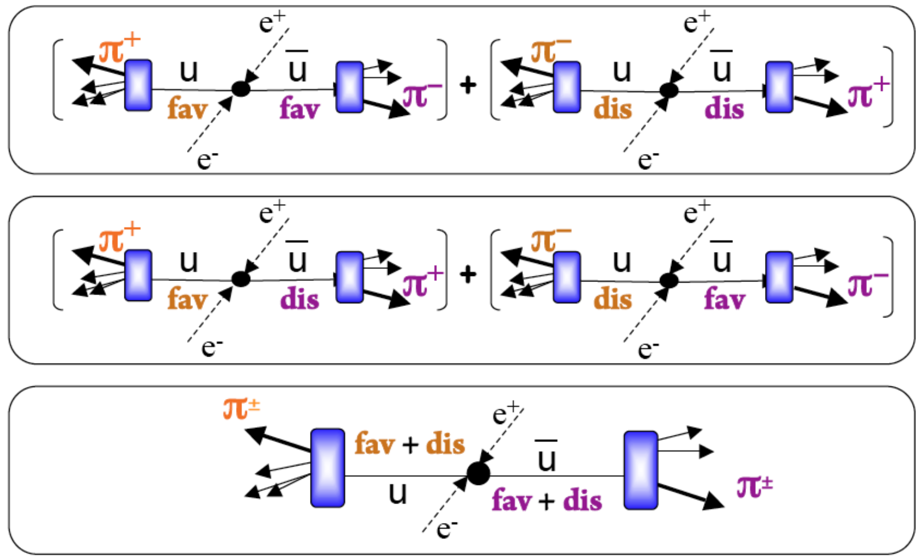
Detection of hadron pairs with same or opposite charge sensitive to different combination of **favored** and **disfavored** FFs

- **favored FF:** one of the parent quarks matches a valence quark in the hadron,
  - i.e.: $u \to \pi^+, d \to \pi^-, s \to K^-, \ldots$
- **disfavored FF:** no such match, *i.e.* $d \to \pi^+, u \to \pi^-, s \to K^-, s \to \pi^{\pm}, \ldots$

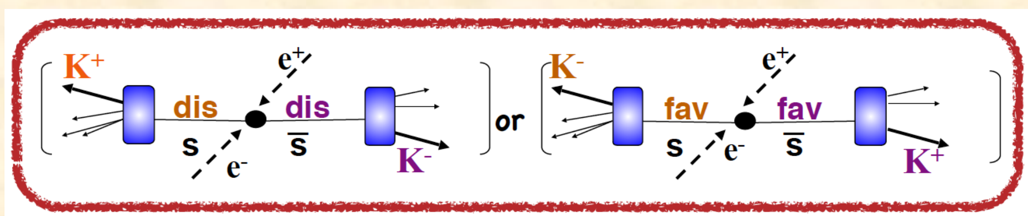
Unlike-sign pion pair = **U:**
$\pi^{\mp}\pi^{\pm}$: (fav x fav)+(dis x dis)

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

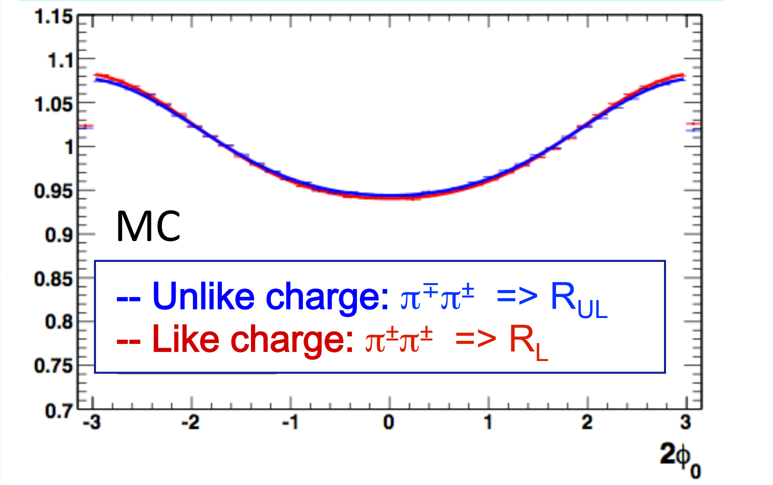


Similarly for Unlike-sign Kaon pairs:

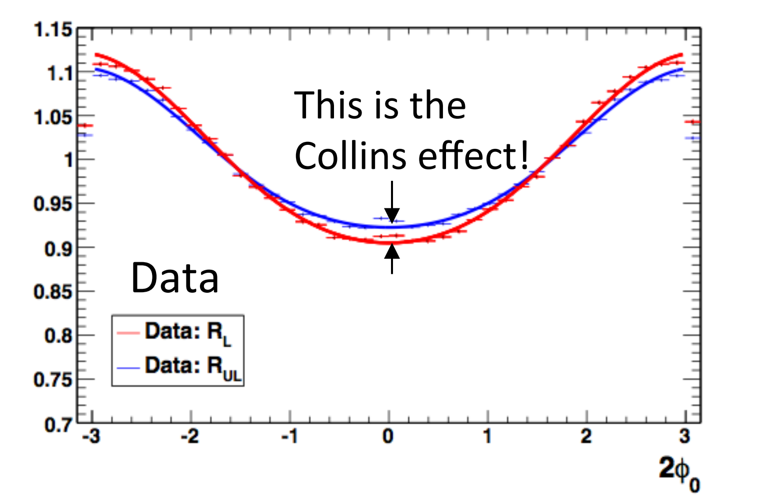


Extraction of asymmetry parameters from data

$N^{(U,L)}(\phi)/<N^{(U,L)}(\phi)>$ in MC sample



$N^{(U,L)}(\phi)/<N^{(U,L)}(\phi)>$ in data sample



- **Collins Asymmetries**
  - extracted from fit to the **normalized azimuthal** distribution

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

  - unpolarized contribution is flat
  - Collins FF contained in the cosine moment b
- The MC generator does not include polarized FF as the Collins FF
  - observed modulation in MC sample produced by detector acceptance
  - correction of these effects with MC would bring to too large systematic uncertainties
- Collins effect not sensitive to electric charge
  - U and L distribution coincident in MC
  - slightly different in data due different contribution of favored and unfavored FF

Double Ratios

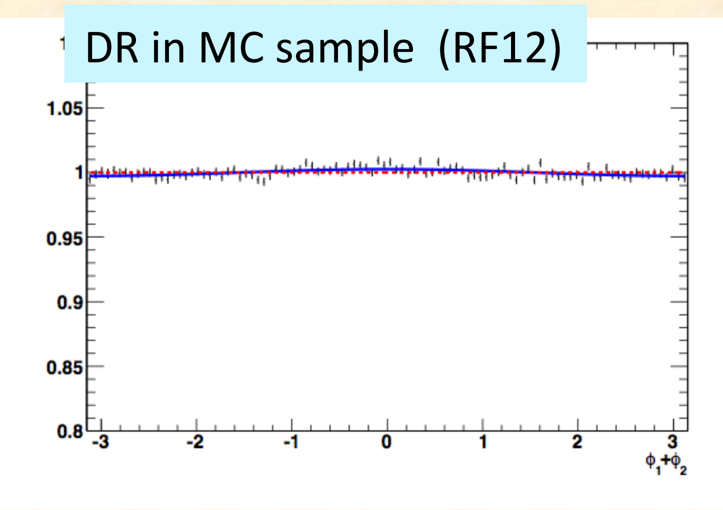
- **<u>Double Ratio (DR)</u>** <u>of Unlike sign over Like sign pion pairs</u>**:**

➲ **eliminate the acceptance effects and the first order radiative effects**

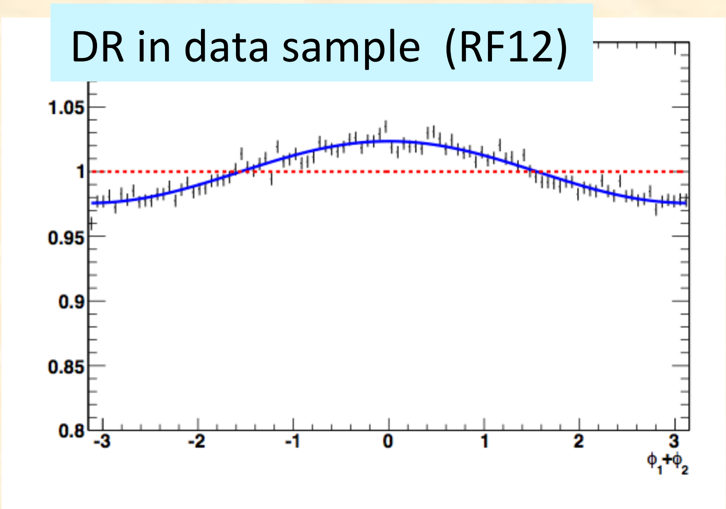
  - acceptances and radiative contributions do not depend on the charge combination of the pion pair;
  - approximation holds for small asymmetries.

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

Contains only the Collins effects and higher order radiative effects



MC: small deviation from zero
==> assigned as a systematic error

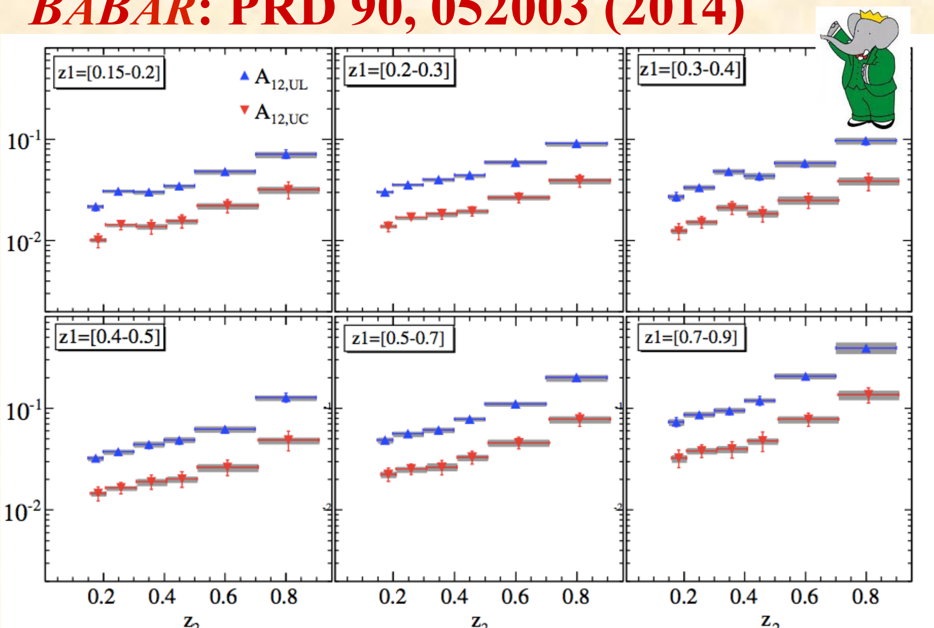


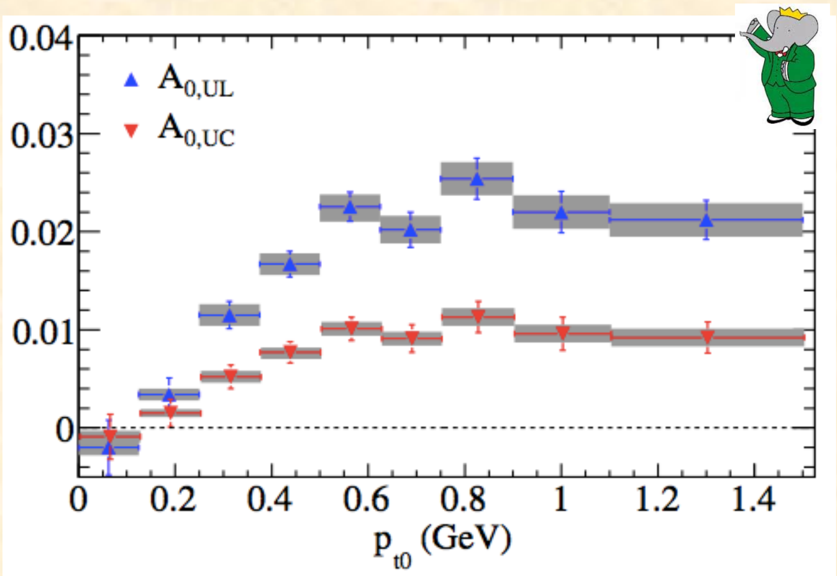
Uncorrected Asymmetry

Collins asymmetries in pion pair production

Measurement of Collins asymmetries from double ratios in $e^+e^- \rightarrow \pi^+\pi^- X$ have been performed by Belle (PRD78,032011, Erratum PRD 86, 039905) and *BABAR* at Q^2~110 GeV^2, and by BESIII (PRL 116, 042001) at Q^2~13 GeV^2

***BABAR*: PRD 90, 052003 (2014)**



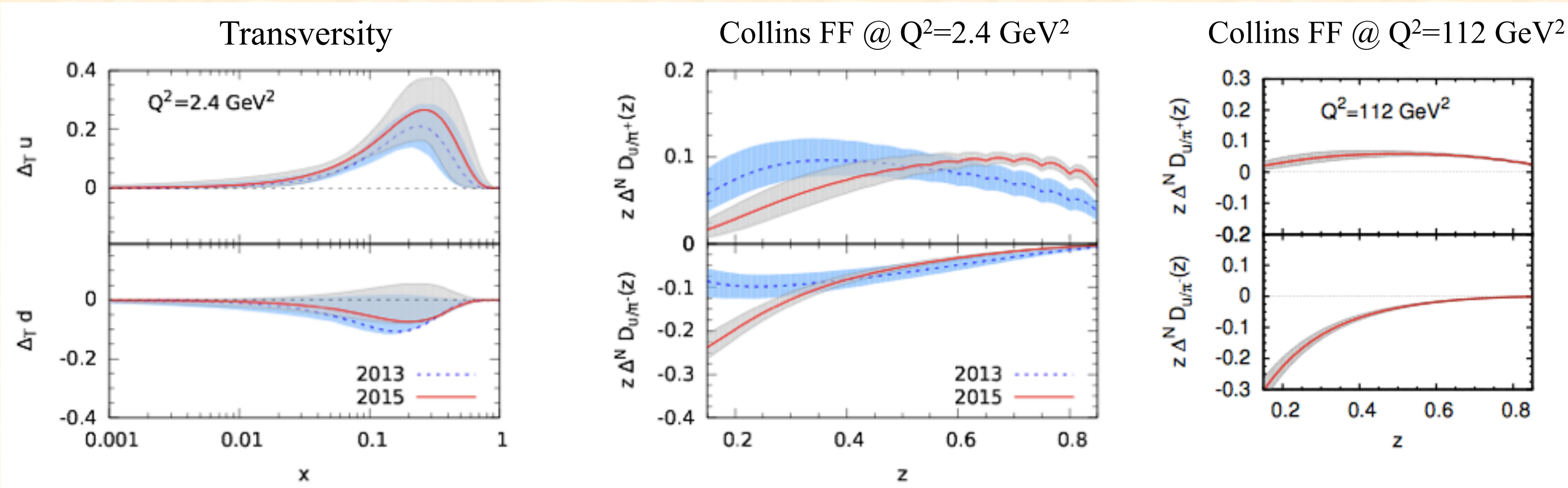


- Collins asymmetry measured as function of:
  - 6×6 bins of pion fractional energy
  - 4×4 bins of (p_{t1}, p_{t2}) in RF12
  - 9 bins of p_{t0} in RF0
  - asymmetry measured also *vs.* $\sin^2\theta_{th}/(1+\cos^2\theta_{th})$ and $\sin^2\theta_2/(1+\cos^2\theta_2)$

BABAR $\pi\pi$ results and global fits

Extraction of the Transversity PDF and Collins FF combining SIDIS and e^+e^- data

***Anselmino et al*: arXiv:1510.05389**



Comparison between old fit (no BABAR data available) with new fit

- Fit uncertainties significantly reduced in the new analysis
- Good consistency for the transversity function
- The differences seen for the Collins FF are mainly due to the different parametrization used:
    - old fit: *fav.* and *dis.* FFs have the same dependency on z, and could differ only for a renormalization constant
    - new fit: the *fav.* and *dis.* FFs are left uncorrelated

Collins asymmetries in KK and $K\pi$ pairs

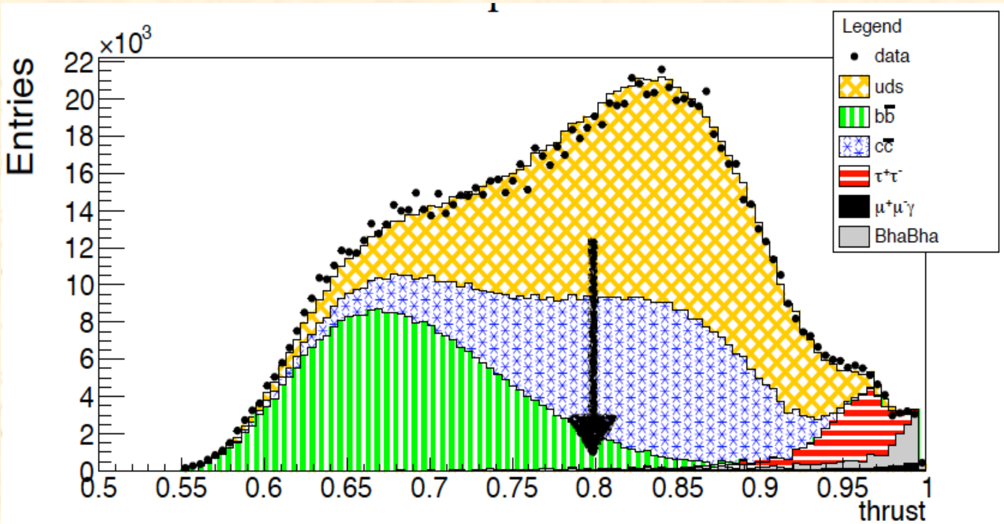
BABAR: PRD 92, 111101(R) (2015)

- Goal: *Simultaneous* measurement of Collins Asymmetry for charged hadron pairs: KK, $K\pi$, and $\pi\pi$
- Analysis strategy:
  - Perform event and particle selections
  - Separate into $\pi\pi$, KK and $K\pi$ candidate sets and subdivide into Like and Unlike charge
    - Charged data set is the combination of U and L.
  - Measure azimuthal angle distributions for each set in both reference frames
    - Take the ratios of Unlike to Like and Unlike to Charged normalized distributions
    - Extract Collins Asymmetry from each set, as a function of fractional energies

Event and track selection

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; direction chosen random

TRACK SELECTION

- Electrons and muons veto
- K and π in the Cherenkov det. acceptance region
- K/π fractional energy z: $0.15 < z < 0.9$
- Opening angle between the hadron and 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

Extraction of the asymmetries

- Simultaneous extraction of the asymmetries corrected for background contamination and K/π misidentification in each fractional energy interval

1. **Background sources:**

- Mainly **$e^+e^- \to c\bar{c}$ events**; smaller contribution from $B\bar{B}$, $\tau^+\tau^-$ (assume $A_{BB} \sim A_\tau \sim 0$)
- Select D^*-enhanced MC and data control samples to estimate the charm contribution
- Fit independently DRs of the three selected samples KK, Kπ, ππ in both the full sample and the D^*-enhanced sample ➔ obtain 6 measured asymmetries $A^{meas}_{hh'}$ and $A^{D^*}_{hh'}$ ($h,h'=\pi,K$)

- Determine from MC simulation the fractions of hadron pairs coming from signal (*uds*) and background events ($c\bar{c}$, $B\bar{B}$, $\tau^+\tau^-$)

2. **K/π misidentification:**

- Evaluate from MC the fraction that a given hadron pair is reconstructed as KK, Kπ, or ππ pair in each data sample

3. **A system of 6 equations with 6 unknown parameters (asymmetries for signal and charm background)**

- **Solve the system of equations to extract all asymmetry parameters**

Extraction of the asymmetries

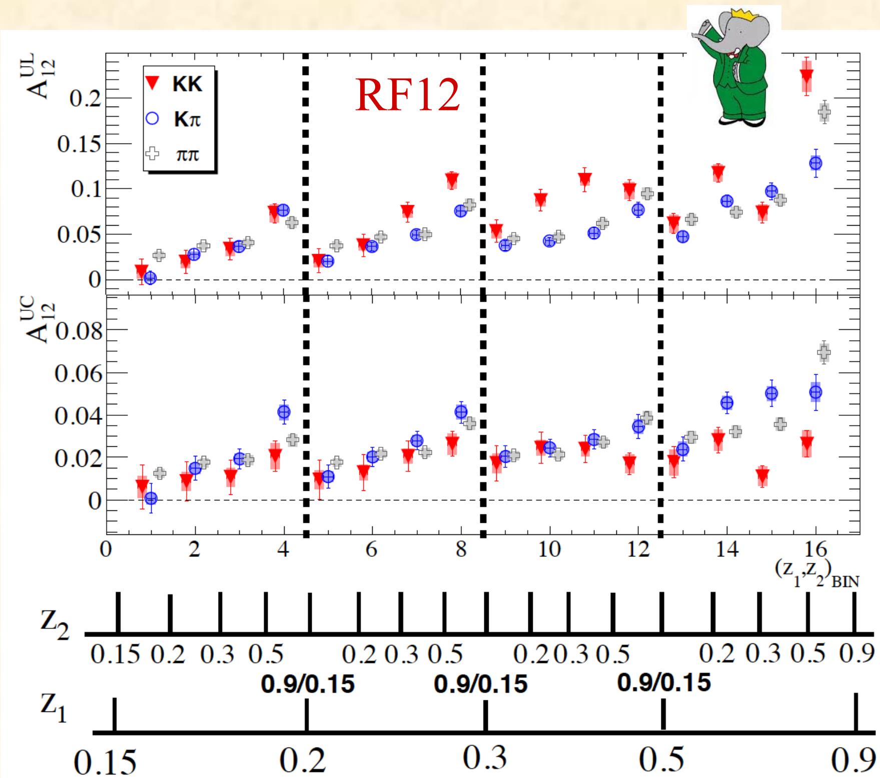
$$
\begin{aligned}
A_{KK}^{meas} = \; & F_{uds}^{KK} \cdot (\xi_{KK}^{(KK)} A_{KK} + \xi_{K\pi}^{(KK)} A_{K\pi} + \xi_{\pi\pi}^{(KK)} A_{\pi\pi}) + \\
& F_{c\bar{c}}^{KK} \cdot (\xi_{KK}^{(KK)c\bar{c}} A_{KK}^{ch} + \xi_{K\pi}^{(KK)c\bar{c}} A_{K\pi}^{ch} + \xi_{\pi\pi}^{(KK)c\bar{c}} A_{\pi\pi}^{ch})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

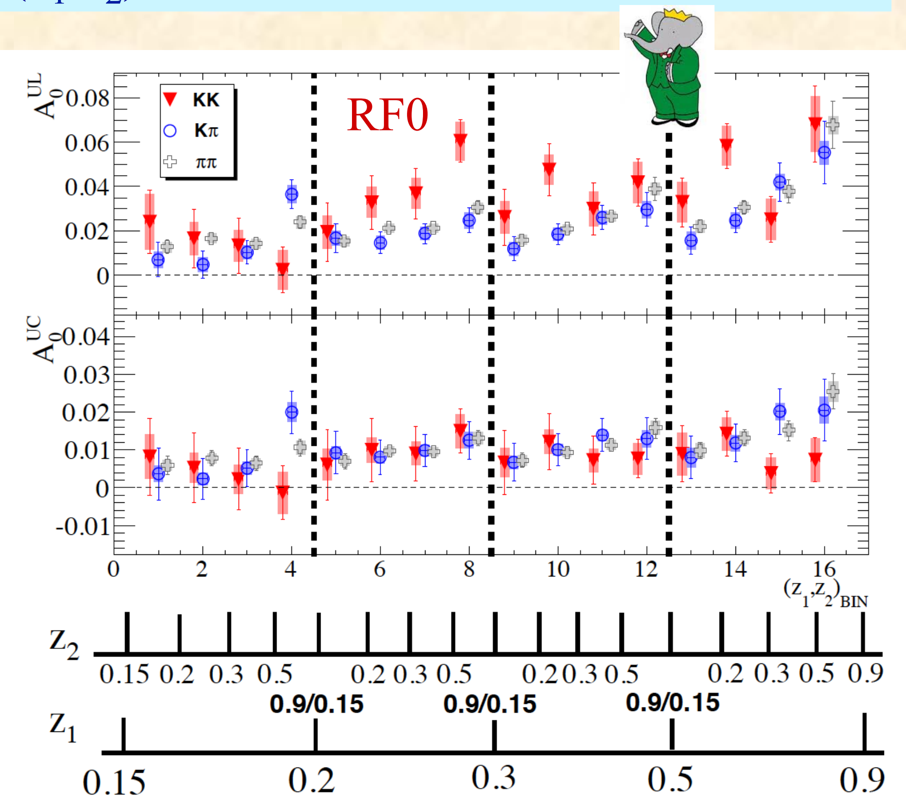
○ = Collins asymmetries for light hadrons

Results

PRD 92, 111101(R) (2015)

Measured Collins asymmetries reported in (z_1,z_2) bins





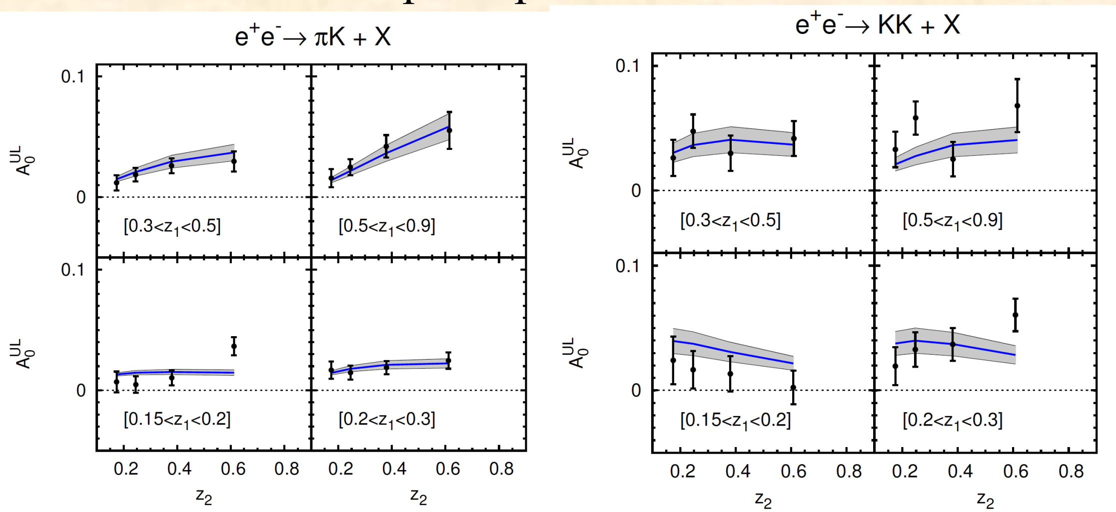
- Asymmetry rises as a function of z: more pronounced for U/L
- A^{UL} KK asymmetry slightly higher than pion asymmetry for high z
- KK asymmetry consistent with zero at lower z
- ππ results consistent with previous BABAR analysis

A^{UL} and A^{UC} asymmetries strongly correlated as they are obtained from the same data sample

Extraction of the Collins FF from BABAR kaon data

Anselmino et *al.*, arXiv:1512.02252

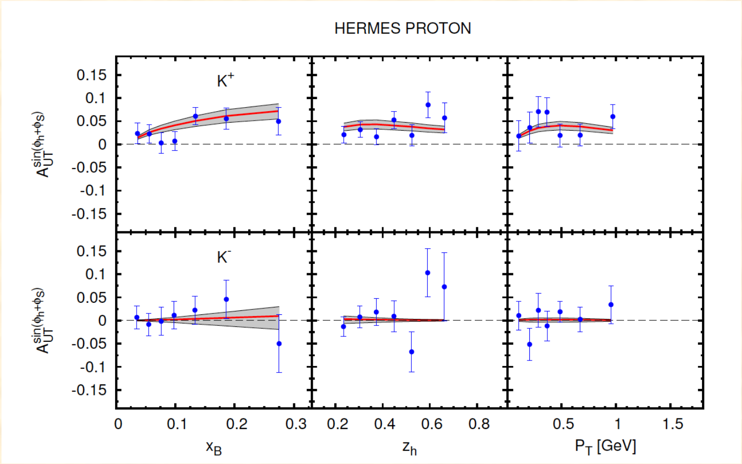
Fitted function superimposed to BABAR data

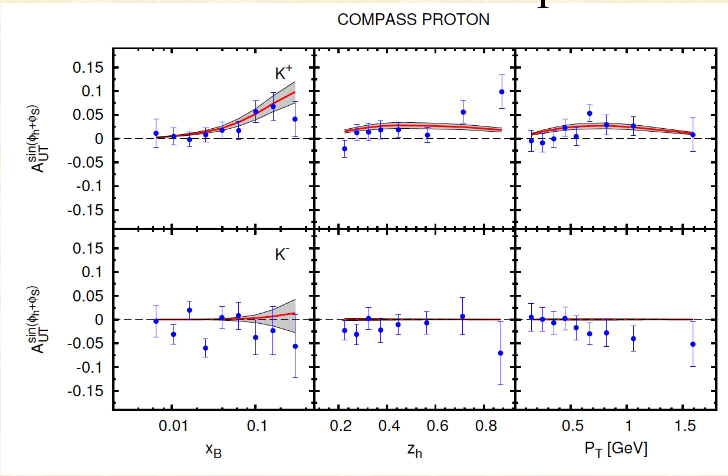


- It uses the pion fav. and disfav. Collins FF extracted in **arXiv: 1510.05389**,
- It assumes a simplified parametrization for the corresponding kaon Collins FFs.

Test universality of Collins FF:

Calculate SIDIS single spin asymmetries from the fitted function and compare with data





Conclusions and perspectives

- *BABAR* is continuing the program of studying fragmentation processes, making use of the ~500 fb^{-1} of e^+e^- collisions at ~10.6 GeV
- Collins asymmetries measured for charged hadron pairs in two-jet events. Measurements are made in two different reference frames.
  - Precise measurement of pion-pair asymmetries in fine bins of fractional energies and transverse momenta ⟹ **PRD 90, 052003 (2014)**
  - Simultaneous measurement of asymmetries for ππ, πK, and KK pairs as a function of fractional energies ⟹ **PRD 92, 111101(R) (2015)**
    - First information on kaon Collins FF in e^+e^- data
    - Results consistent with theoretical predictions (*e.g.* PL **B 659**, 234 (2009))

- Global analyses of e^+e^- (*BABAR*+Belle) and SIDIS asymmetries for pions allow extraction of the transversity PDF and the pion Collins FFs.
- πK and KK pairs results used to extract kaon Collins FF
  - consistency with HERMES and COMPASS data on kaons indicate the validity of universality of the Collins FF

- New results expected "soon".

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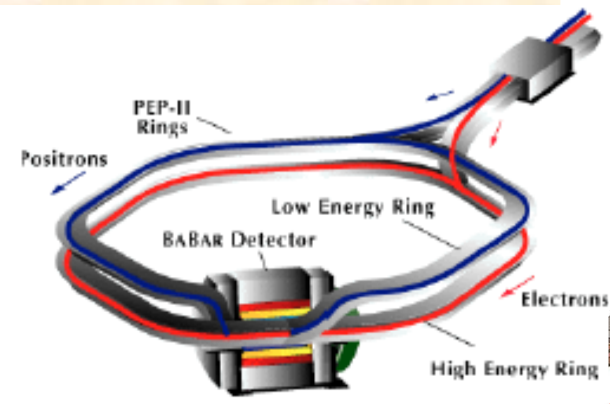
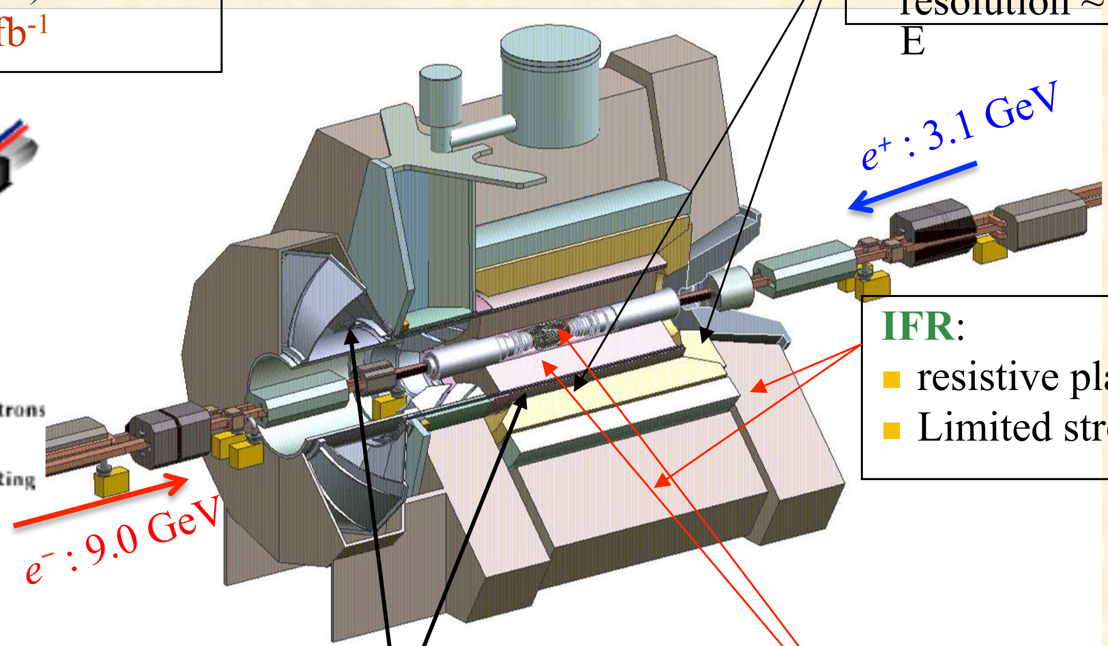
THANK YOU!

BACKUP SLIDES

PEPII and the *BABAR* detector

- **PEP-II** is an asymmetric e^+e^- collider operating at CM energy of Y(4S).
- Integrated luminosity = 531 fb^{-1}





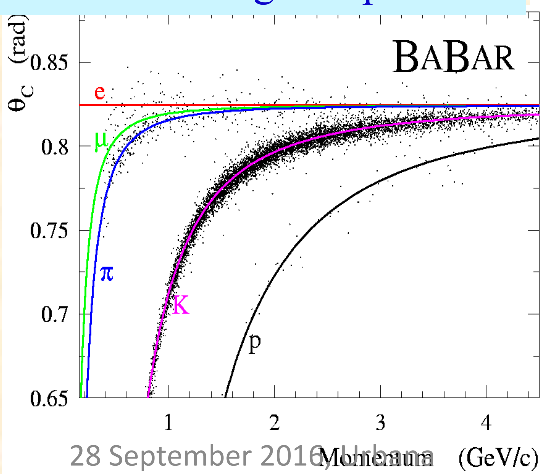
EMC:
- 6580 CsI(Tl) crystals, resolution ~1-2 % high E

IFR:
- resistive plate chambers
- Limited streamer tubes

BaBar DIRC
- particle ID up to 4-5 GeV/c

BaBar SVT and DCH
- precision vertexing and tracking

Cherenkov angle *vs* p



The Collins Fragmentation Function

J.C. Collins
Nucl.Phys.B396,161 (1993)

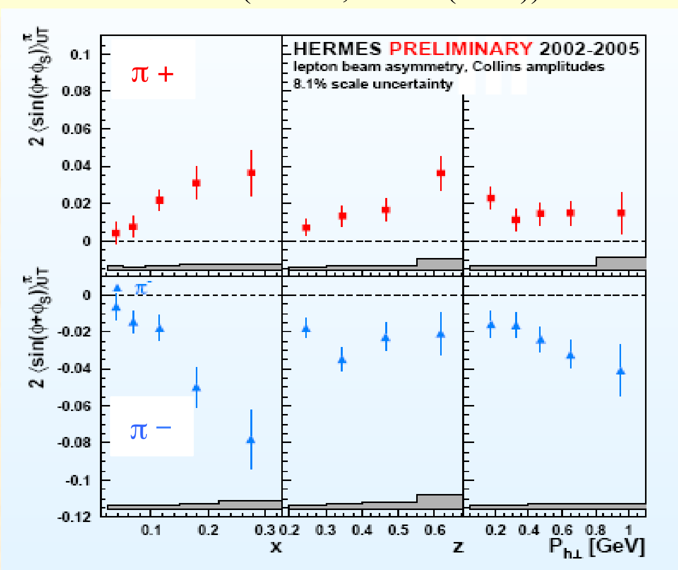
- Spin-dependent chiral-odd Fragmentation Function (FF)
- It is related to the probability that a transversely polarized quark will fragment into a spinless hadron

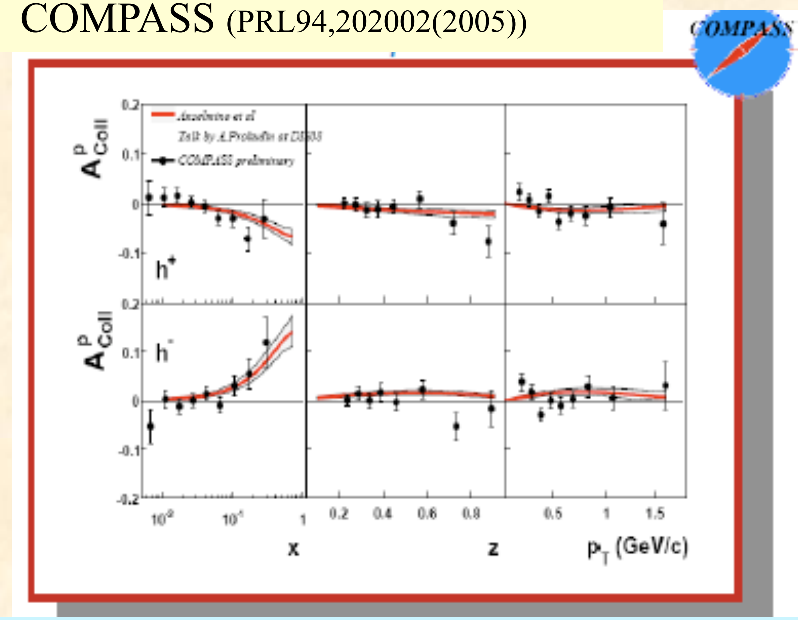
number density function:

$$D_{hq\uparrow} = D_1^q(z, P_{h\perp}^2) + H_1^{\perp q}(z, P_{h\perp}^2)\frac{\hat{k}\times\vec{P}_{h\perp}\cdot\vec{S}_q}{zM_h}$$

unpolarized FF CollinsFF

First experimental evidence of non zero Collins FF for pions came from SIDIS experiments:
HERMES (PRL94,012002(2005)) COMPASS (PRL94,202002(2005))





e^+e^- annihilations :
- not conclusive studies at LEP : DELPHI (Nucl.Phys.B79,554-556 (1999))
- **direct evidence of non-zero Collins FF** at KEKB: Belle (PRL96,232002(2006), PRD78,032011(2008))

BABAR $\pi\pi$ results compared to Belle and BESIII

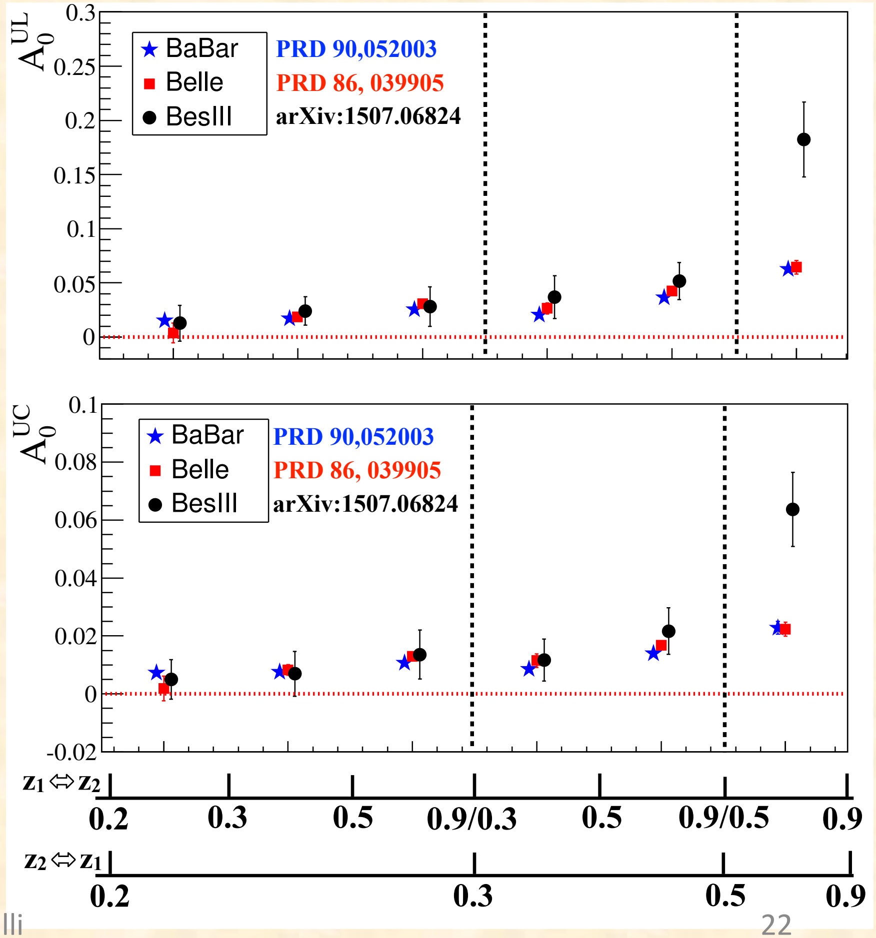
Extraction of the Transversity PDF and Collins FF combining SIDIS and e^+e^- data

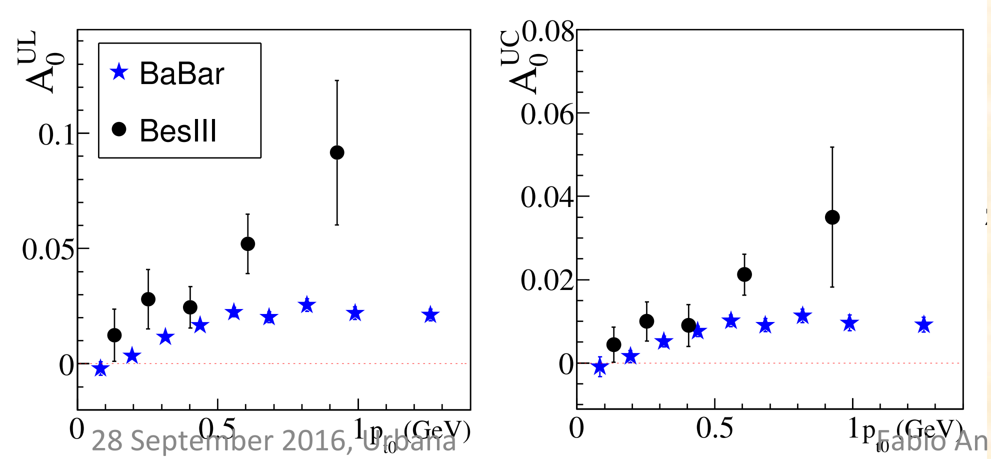
Comparison between different results obtained at different Q^2:

- **BaBar and Belle @ $Q^2 \sim 110$ GeV^2**
- **BESIII @ $Q^2 \sim 13$ GeV^2**

- BaBar and Belle results that fall in the larger BESIII z-bins are averaged taking into account the statistical and systematic uncertainties
- Good agreement between different data sets for low z
- BESIII larger asymmetries in the last z-bins: consistent with the prediction reported in *arXiv:1505.05589*
- Some tensions between BaBar and Belle for high z in the thrust frame (no BESIII data available)

Belle: PRD78, 032011 (2008)
(Erratum: PRD 86, 039905)
BESIII: PRL 116, 042001 (2016)





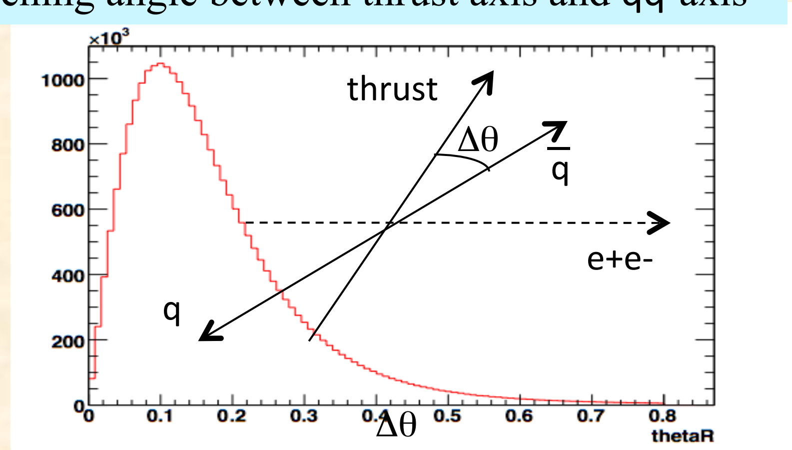
Extraction of the asymmetries

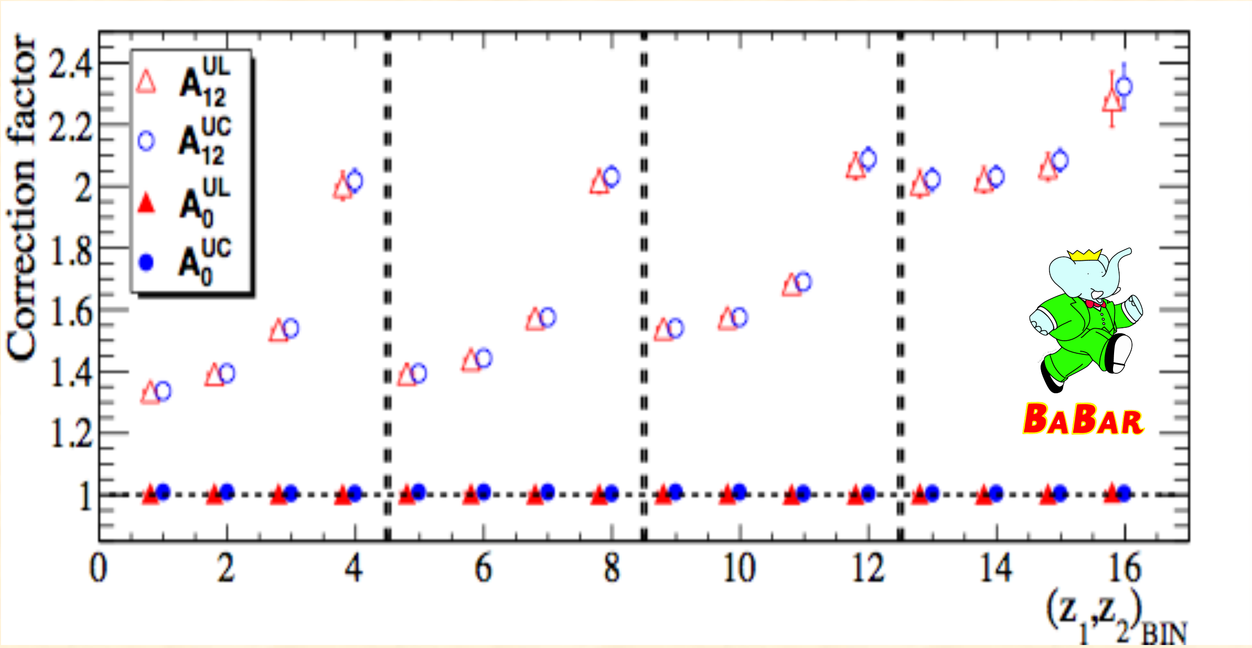
- The experimental method assumes the thrust axis as $q\bar{q}$ direction
- **This is only a rough approximation**

Introduces dilution of asymmetry in RF12.
Correct through MC study

No dilution effect in RF0

Opening angle between thrust axis and $q\bar{q}$ axis





Extraction of the asymmetries

- Simultaneous extraction of the asymmetries corrected for background (mainly charmed hadron decays, but also BB and τ+τ−) and K/π misidentification in each fractional energy interval
- Fit independently the double ratio distributions of the three selected samples KK, Kπ, ππ

$$A_{KK}^{\rm meas} = F_{uds} \cdot A_{KK}^{Collins} + \sum_i F_i^{KK} \cdot A_{KK}^i$$

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)
- construct a D^*-enhanced MC and data control samples to estimate the charm contribution

$D^{*\pm} \rightarrow D^0\pi^\pm$, $D^0 \rightarrow K\pi$, $D^0 \rightarrow K3\pi$, $D^0 \rightarrow K\pi\pi^0$, $D^0 \rightarrow K_S\pi\pi$

- The fractions ($F(f)_{\rm sig/bkg}^{hh}$) of hadron pairs coming from signal (uds) and background events ($c\bar{c}$, $B\bar{B}$, $\tau^+\tau^-$) are obtained from MC simulation

$$\begin{cases} A_{KK}^{\rm meas} = F_{uds}^{KK} \cdot A_{KK}^{Collins} + F_{c\bar{c}}^{KK} \cdot A_{KK}^{charm} \\ A_{KK}^{D^*} = f_{uds}^{KK} \cdot A_{KK}^{Collins} + f_{c\bar{c}}^{KK} \cdot A_{KK}^{charm} \end{cases}$$

Extraction of the asymmetries

- Simultaneous extraction of the asymmetries corrected for background (mainly charmed hadron decays, but also BB and $\tau^+\tau^-$) and K/π misidentification in each fractional energy interval
- Fit independently the double ratio distributions of the three selected samples KK, Kπ, ππ

$$A_{KK}^{\text{meas}} = F_{uds} \cdot A_{KK}^{Collins} + \sum_i F_i^{KK} \cdot A_{KK}^i$$

2. K/π misidentification:

- Evaluate from MC the fraction ($\xi_{hh}^{(hh)}$) that a given hadron pair is reconstructed as KK, Kπ, or ππ pair

$$A_{KK}^{\text{meas}} = F_{uds} \cdot \left(\sum_{nm} \xi_{nm}^{(KK)} \cdot A_{nm}^{Collins} \right) + F_{c\bar{c}}^{KK} \cdot \left(\sum_{nm} \xi_{nm}^{(KK)} \cdot A_{nm}^{charm} \right)$$

$\xi_{hh}^{(hh)}$ ← reconstructed hadron pairs

↘ generated hadron pairs

3. Solve the system of equations to extract all asymmetry parameters

Extraction of the asymmetries

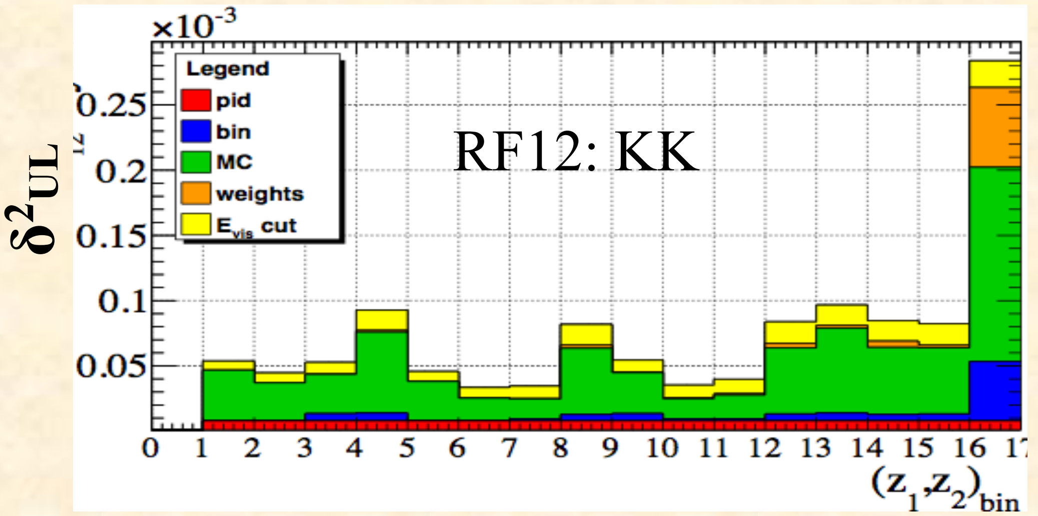
$$
\begin{aligned}
A^{meas}_{KK} = \; & F^{KK}_{uds} \cdot (\xi^{(KK)}_{KK} A_{KK} + \xi^{(KK)}_{K\pi} A_{K\pi} + \xi^{(KK)}_{\pi\pi} A_{\pi\pi}) + \\
& F^{KK}_{c\bar{c}} \cdot (\xi^{(KK)c\bar{c}}_{KK} A^{ch}_{KK} + \xi^{(KK)c\bar{c}}_{K\pi} A^{ch}_{K\pi} + \xi^{(KK)c\bar{c}}_{\pi\pi} A^{ch}_{\pi\pi})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

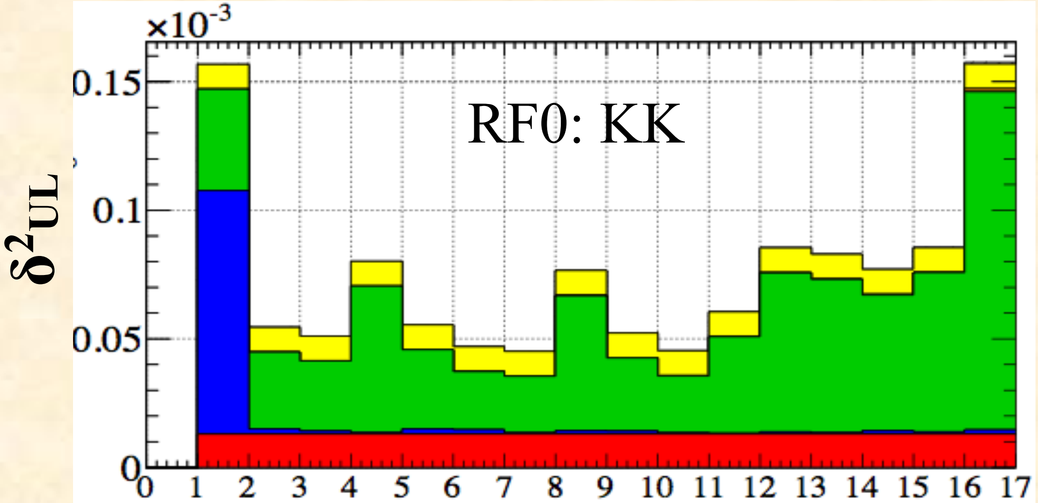
○ = Collins asymmetries for light hadrons

Systematic uncertainties

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





Sum in quadrature of systematic uncertainties (absolute values)

Additional checks show negligible effects, such as:

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