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CENTRO EUROPEO PER LA SCIENZA, L'ARTE E LA CULTURA

The Abdus Salam International Centre for Theoretical Physics

Collins fragmentation functions at BABAR and BESIII

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on behalf of BESIII and BaBar Collaborations

TMDe2015 - A PATH TOWARDS TMD EXTRACTION

2-4 SEPTEMBER 2015 TRIESTE - ITALY

Outline

- **Introduction**
  - The Collins effect
  - The BaBar and BESIII experiments
- **Collins asymmetries for ππ pairs**
  - BaBar results
  - BESIII preliminary results
- **BaBar preliminary results: Collins asymmetries for KK and Kπ hadron pairs**
- **Summary and conclusions**

Introduction: the Collins effect

Our understanding of the hadronic physics depends strongly on what we know about the parton distributions functions (PDFs) and **fragmentation functions** (FFs)

- Universal
- Non-perturbative objects

Transverse Momentum Dependent (TMD) FFs ⇒ to study the spin-dependent observables

- when only spinless hadrons (π, K) are considered, we have:

$q^{\uparrow} \rightarrow hX$:

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

Unpolarized FF

Collins FF [NP**B 396**, 161 (1993)]: chiral-odd function, related to the probability that a transversely polarized quark ($q^{\uparrow}$) fragments into a spinless hadron

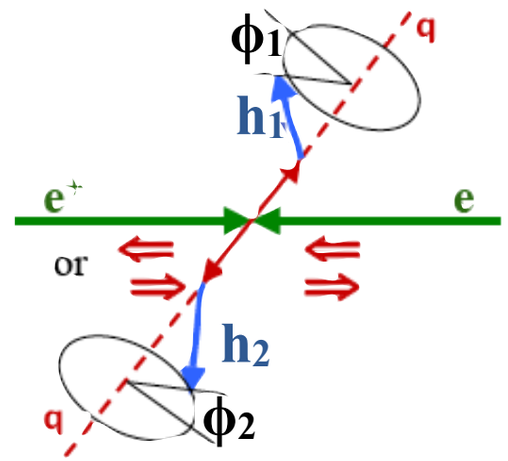
Physics motivation:

- e^+e^- annihilation experiments are the most clean environment to study fragmentation processes
- evolution of TMD objects
- Global analysis (PRD 78,032011 (2007); PRD 87,094019 (2013), PRD 91,014034 (2015)):
  - combines Semi Inclusive Deep Inelastic Scattering (SIDIS) and e^+e^- data
  - extraction of $H^{\perp}_1$ and transversity parton distributions h_1 for the "u" and "d" quarks

Collins effect in e^+e^- annihilation

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

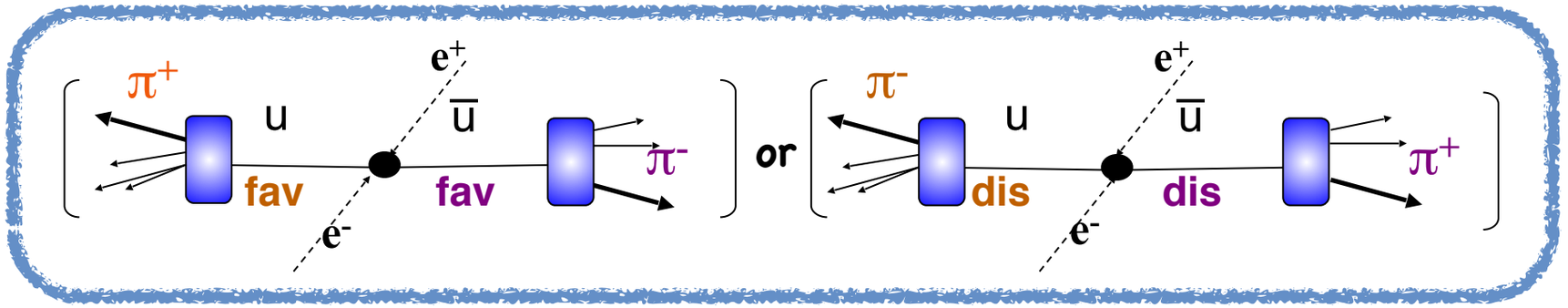


$$e^+e^-\to q\bar{q}\to h_1h_2X \ (q=u,d,s) \Rightarrow \sigma\propto \underbrace{\cos(\phi_1+\phi_2)}H_1^{\perp(h1)}\times H_1^{\perp(h_2)}$$

Azimuthal modulation wrt the quark spin direction:
Collins effect (or Collins asymmetry)

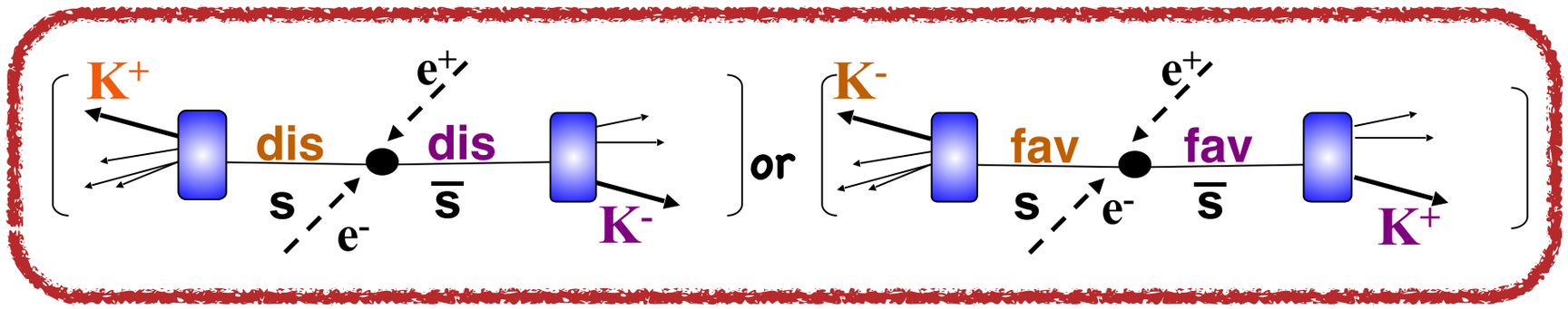
Example: Unlike ππ pairs (U)

Collins asymmetry for ππ



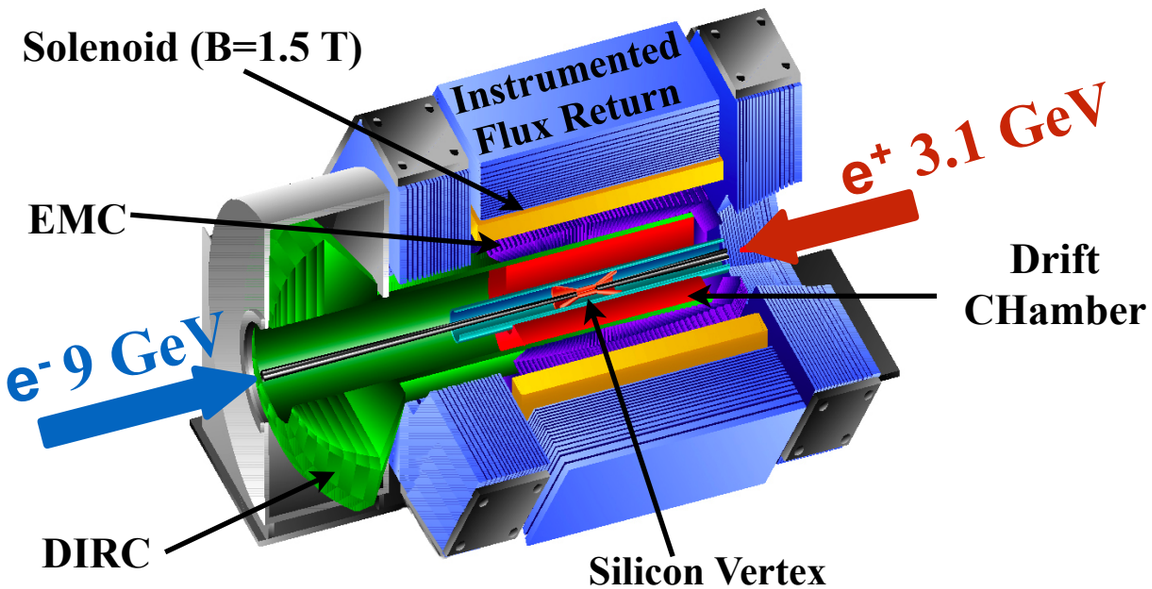
Example: Unlike KK pairs (U)

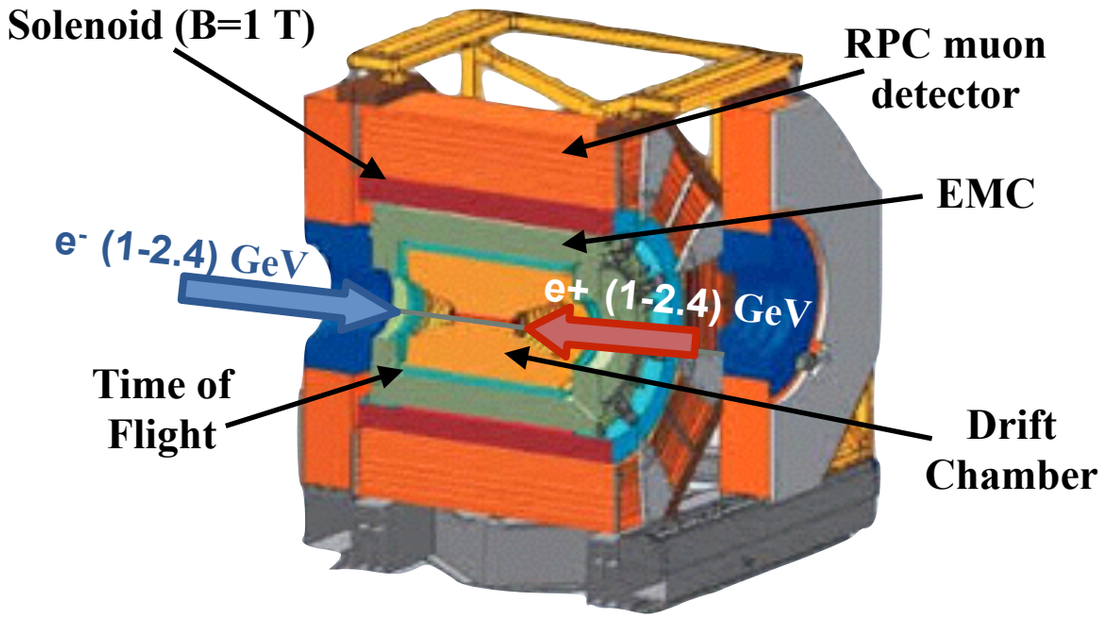
Collins asymmetry for KK:
Favored contribution to the fragmentation of the strange quark



Collins asymmetries for KK pairs not yet available: only BaBar preliminary resuls

The BaBar and BESIII detectors





- PEP-II storage ring
  - **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: $\mathcal{L} \sim$ **468 fb^{-1}** used here

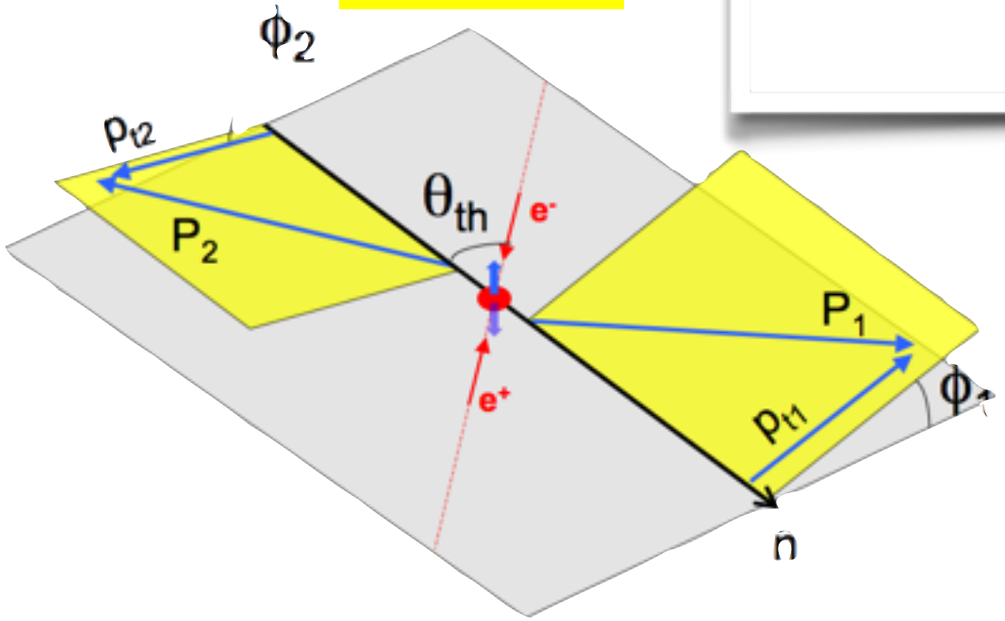
NIM **A479**, 1 (2002),
update: NIM **A729**, 615 (2013)

- Beijing Electron Positron Collider II (BEPCII)
  - **Symmetric** e^+e^- collider
  - Beam energy: 1-2.3 GeV
  - 2008: test run
  - 2009-today: BESIII physics runs
- Luminosity: $\mathcal{L} \sim$ **62 pb^{-1}** @ 3.65 GeV used here (below open charm threshold)

NIM **A614**, 345 (2010)

Reference frames

RF12

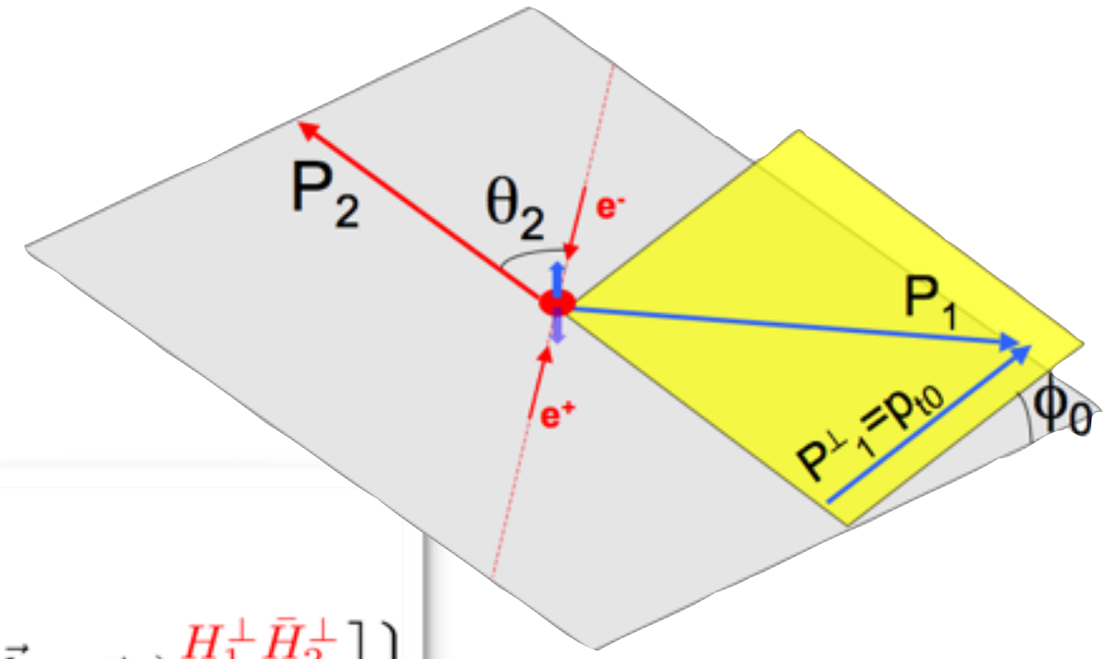


$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{d\Omega dz_1 dz_2 d\phi_1 d\phi_2} = \sum_{q,\bar{q}} \frac{3\alpha^2}{Q^2}\frac{e_q^2}{4} z_1^2 z_2^2 \Big[(1+cos^2\theta) D_1^{q,(0)}(z_1)\bar{D}_1^{q,(0)}(z_2) + \\ + sin^2(\theta) cos(\phi_1+\phi_2) H_1^{\perp,(1),q}(z_1)\bar{H}_1^{\perp,(1),q}(z_2)\Big]$$

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



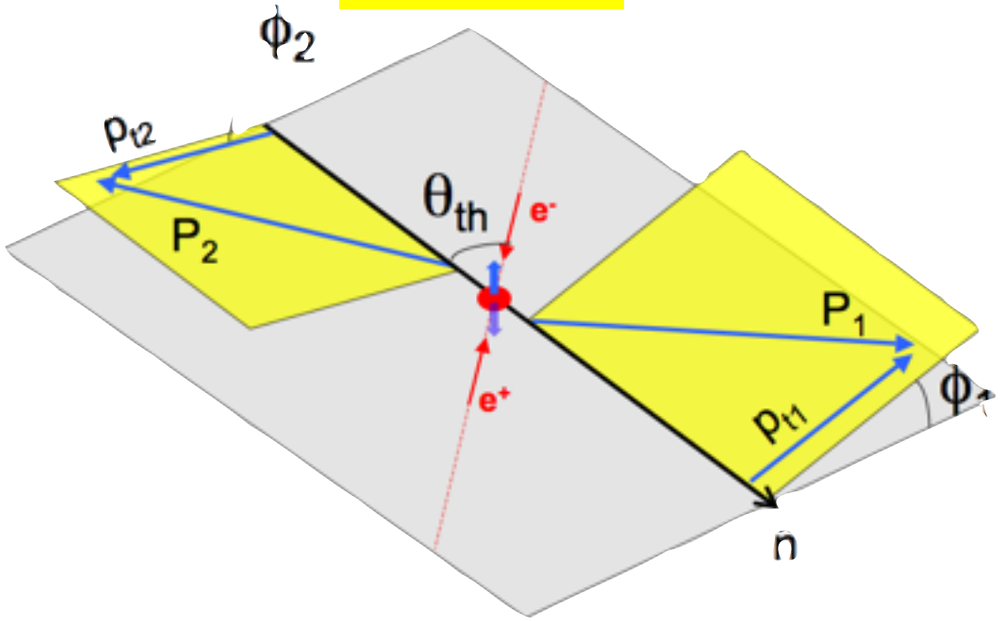
θ_2: angle between the e^+e^- axis and P_{h2};
φ_0: angle between the plane spanned by P_{h2} and the e^+e^- axis, and the direction of P_{h1} perpendicular to P_{h2}.

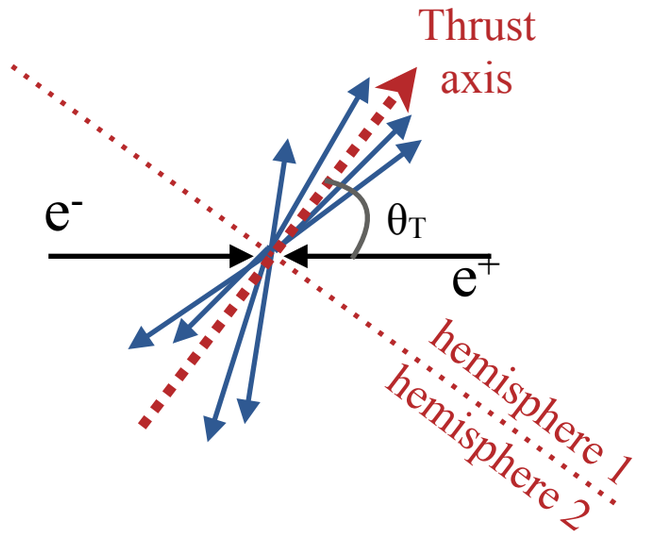
All quantities in e+e- center of mass

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

Reference frames

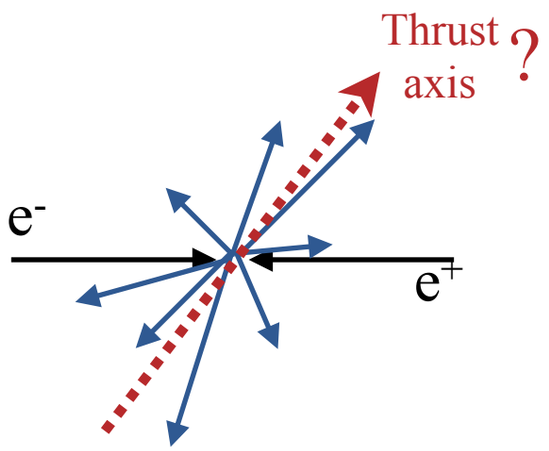
RF12



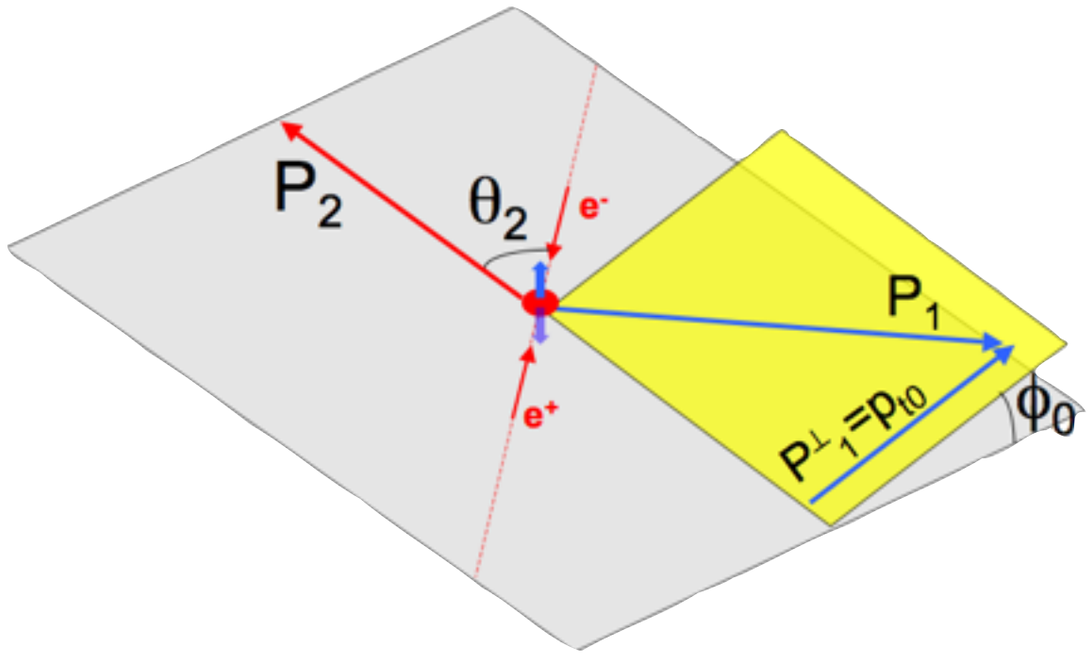


Jet-like events
- B factories (BaBar and Belle)
- No useful in BESIII

The only frame used in BESIII
- low center of mass energy: more spherical events
- Jet-like topology ensured by requiring $\theta_{h1h2}>120°$



RF0



Analysis Strategy

- Event and track selection
- Construction of spinless hadron pairs
  - KK, Kπ, ππ for BaBar
  - ππ for BESIII
- Measure of the azimuthal angles ϕ_1 and ϕ_2 in RF12 (BaBar), and ϕ_0 in RF0 (BaBar and BESIII)
- Construction of the normalized raw distributions for like (L), Unlike (U) and Charged (C=U+L) hadron pairs: $R^i=N^i(\phi)/<N>$
- Calculation of the ratios of normalized distributions: U/L and U/C
  - fit to these distributions with the function b+a·cos(x)
- Evaluation of background contributions and extraction of the Collins asymmetries

BaBar RESULTS (PRD90,052003):

- RF12 and RF0
- A^{UL} and A^{UC}
- (z_1,z_2) bins, where $z_{1,2}=2E_h/\sqrt{s}$, (p_{t1},p_{t2}) and p_0 bins, $\sin^2\theta/(1+\cos^2\theta)$, and 2D analysis: (z_1,z_2) vs. (p_{t1},p_{t2})
- **NEW PRELIMINARY (arXiv:1506.05864) KK and Kπ asymmetries vs. (z_1,z_2)**

BESIII PRELIMINARY RESULTS:

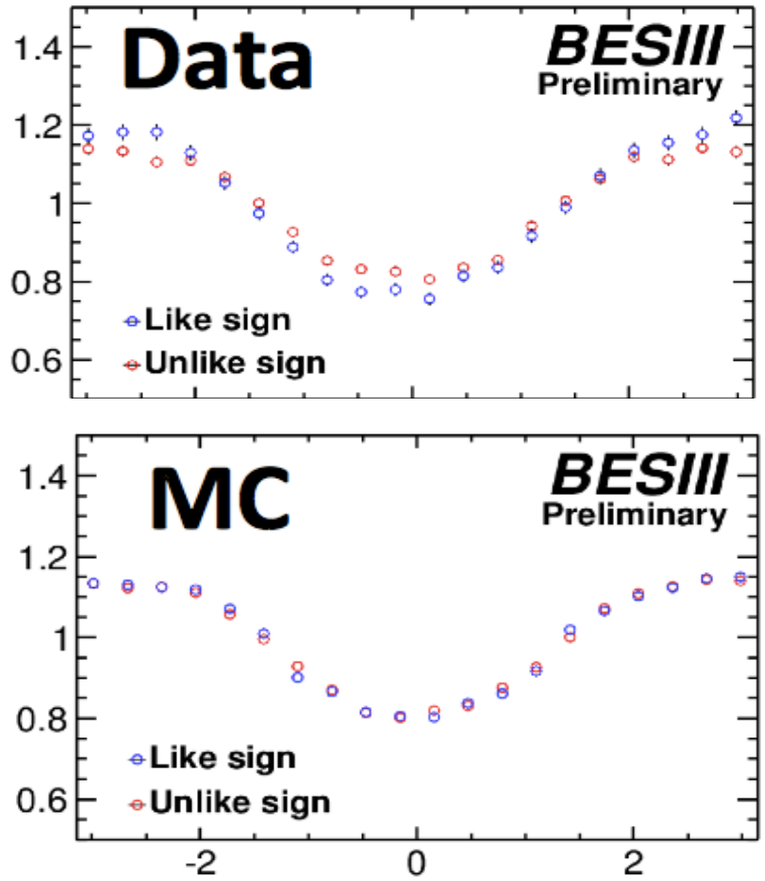
- **arXiv:1507.06824**
- RF0
- A^{UL} and A^{UC}
- (z_1,z_2) bins, where $z_{1,2}=2E_h/\sqrt{s}$, (p_{t1},p_{t2}) and p_0 bins, $\sin^2\theta/(1+\cos^2\theta)$

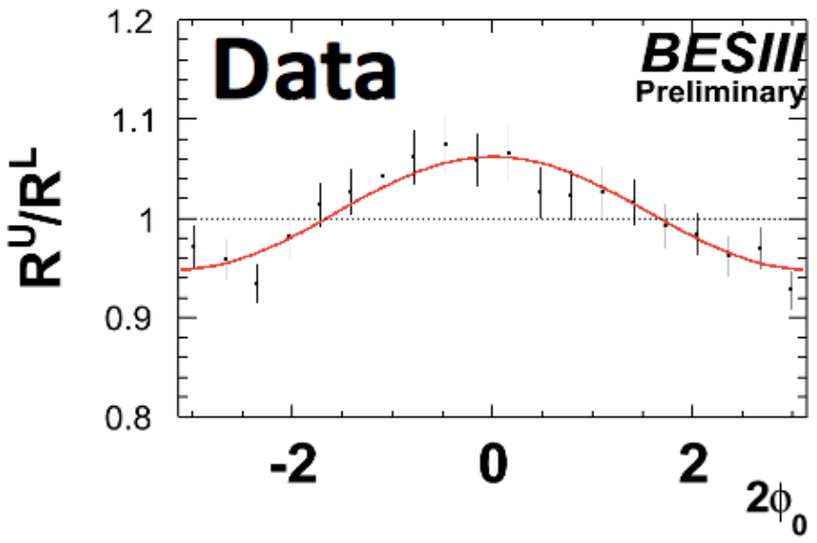
Measurement of Collins effect

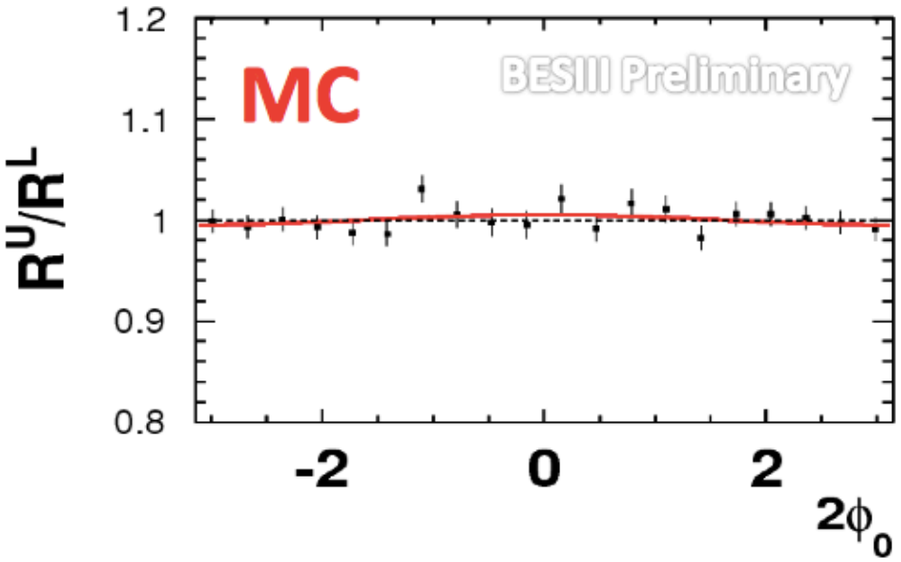
- Normalized azimuthal distribution for hadron pair with same charge (L), opposite charge (U), and the sum of the two samples (C)
- Collins effect is not simulated in uds-MC → strong azimuthal MC modulation principally due to the detector acceptance
- nonzero Collins effect in data sample → different combinations of fav and dis FF for L, U, and C

Double ratio of U/L and U/C normalized distributions: Collins effect measured by fitting the double ratio distributions with the function $B+A\cdot\cos(\phi_i)$

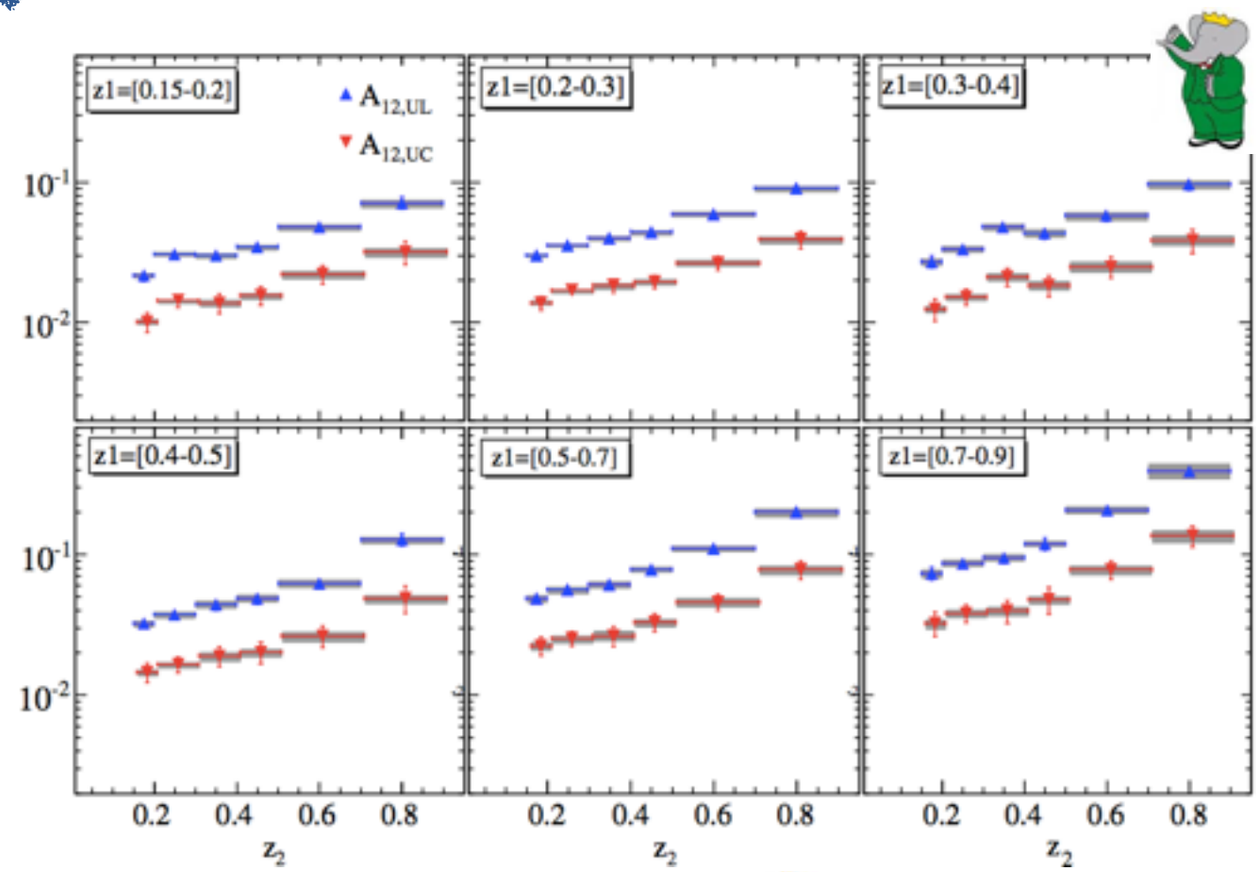
RF0: π π pairs





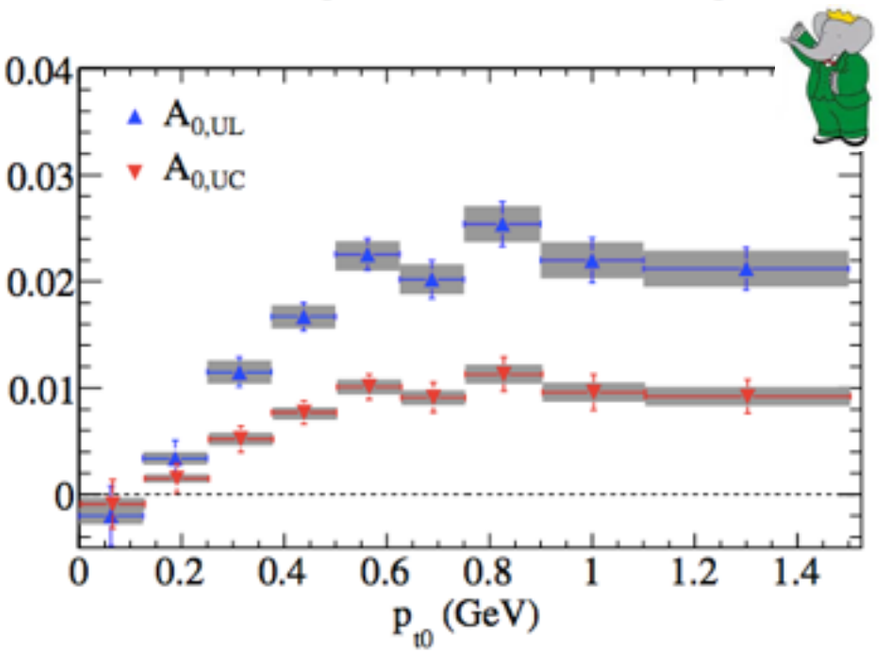


BaBar results for ππ pairs

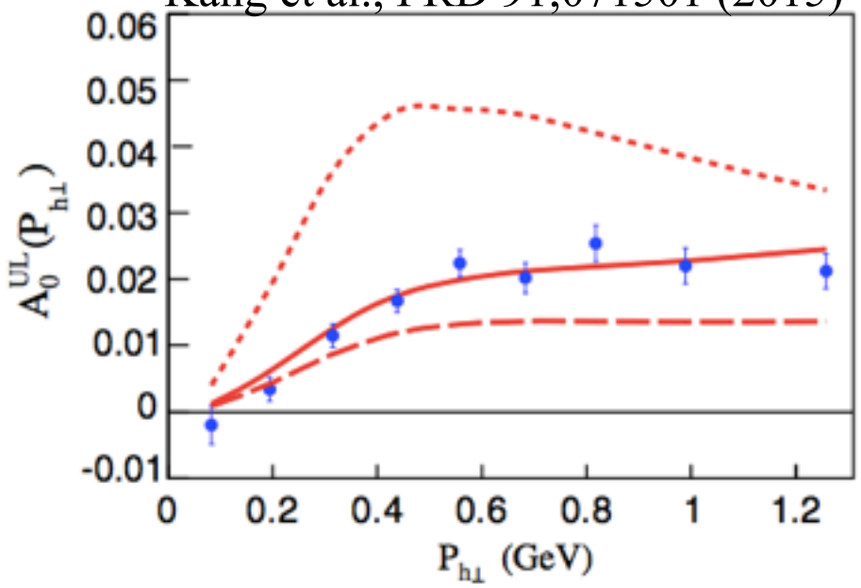


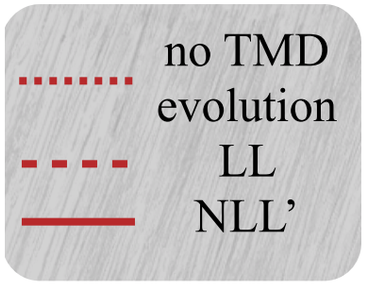
PRD 90,052003 (2014)

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

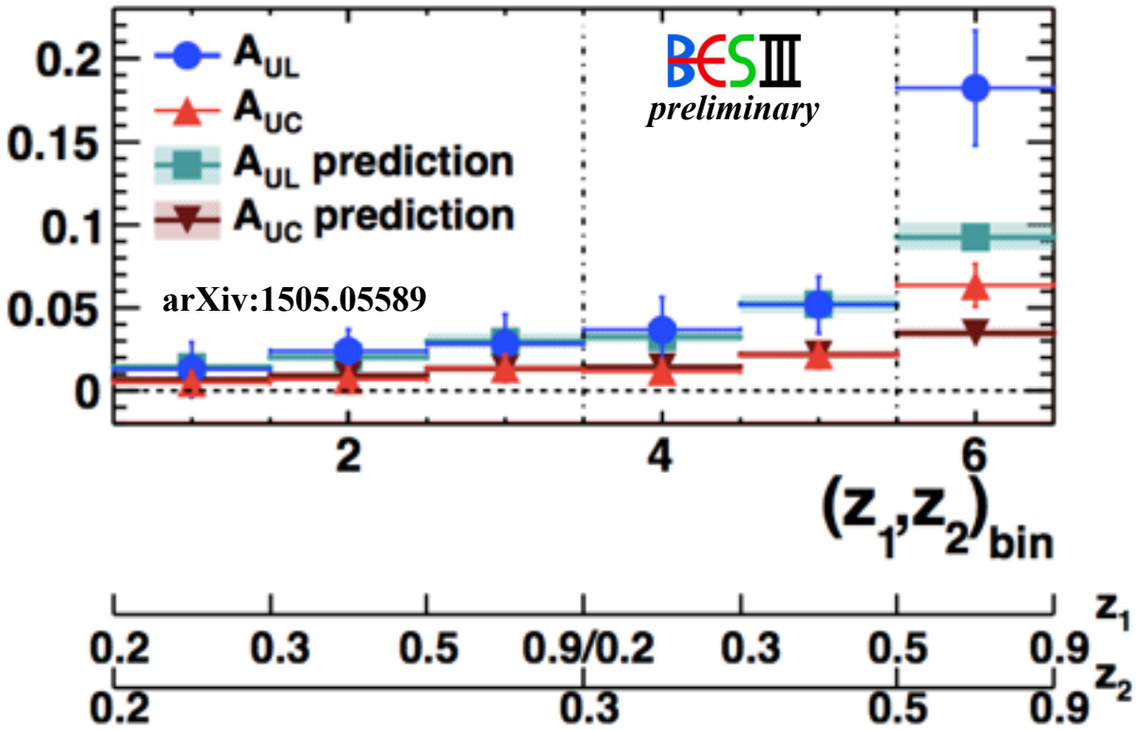


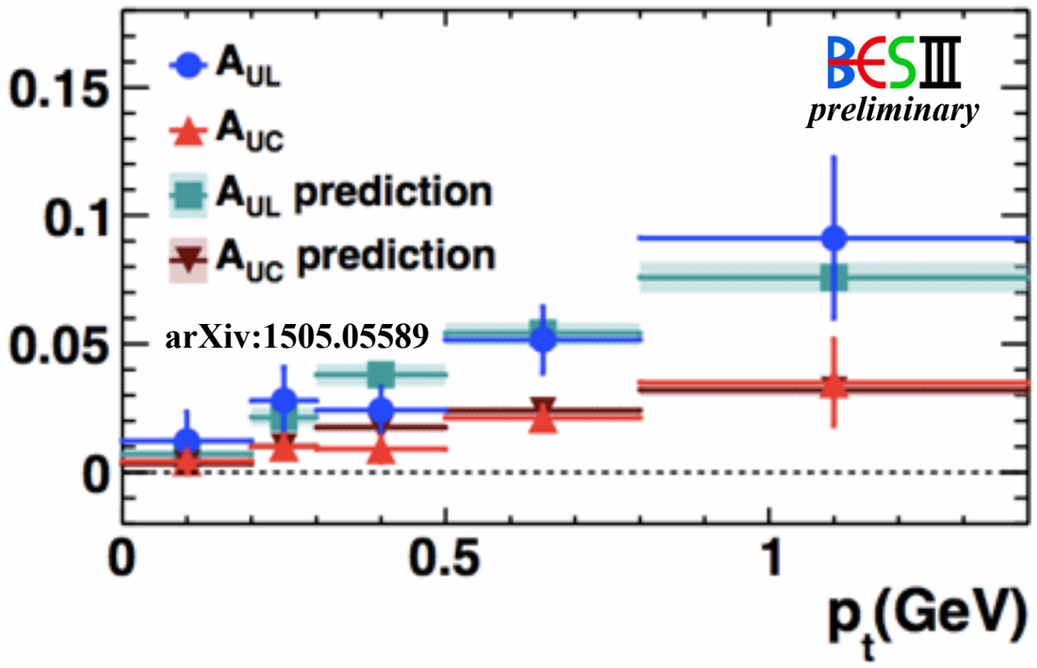
Kang et al., PRD 91,071501 (2015)

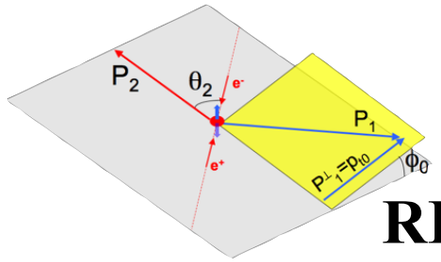




BESIII preliminary results





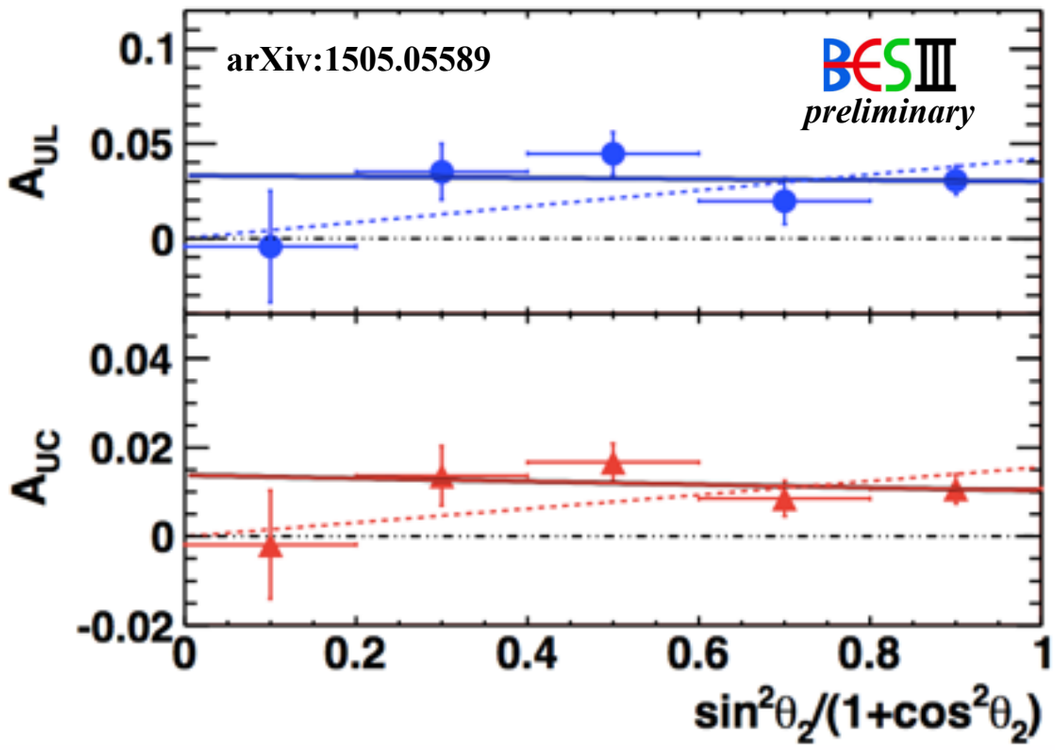


RF0 only

arXiv:1507.06824

Submitted on PRL

- Collins asymmetry measured as function of
  - 6 symmetric (z_1,z_2) bins
  - 5 bins of p_{t0}
  - asymmetry vs. $\sin^2\theta_2/(1+\cos^2\theta_2)$
  - comparison with prediction reported in arXiv: 1505.05589

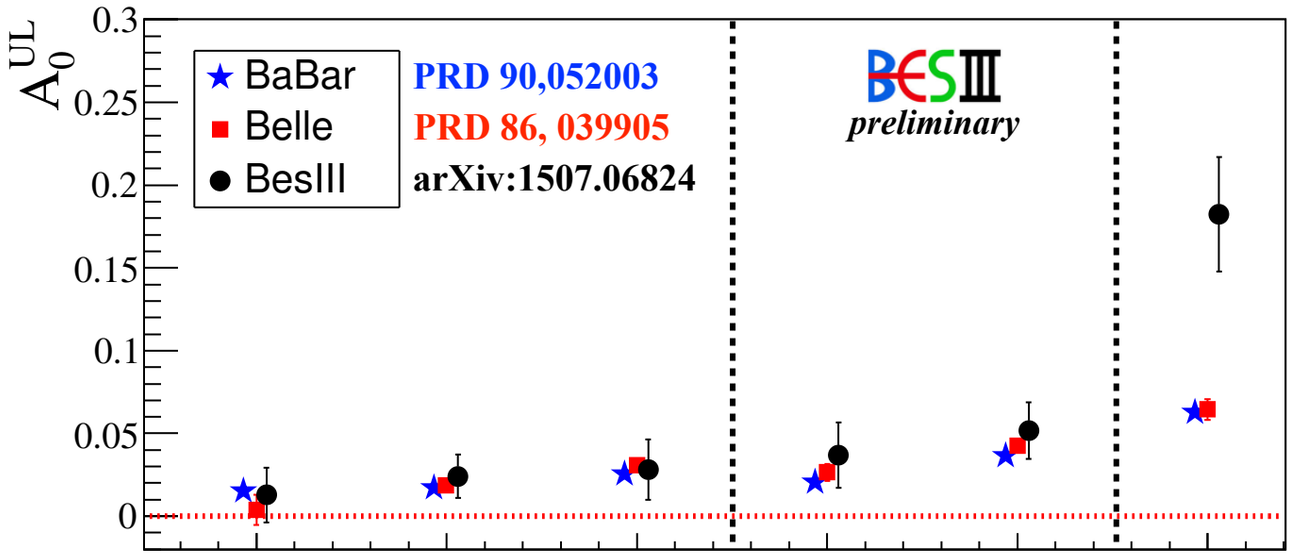


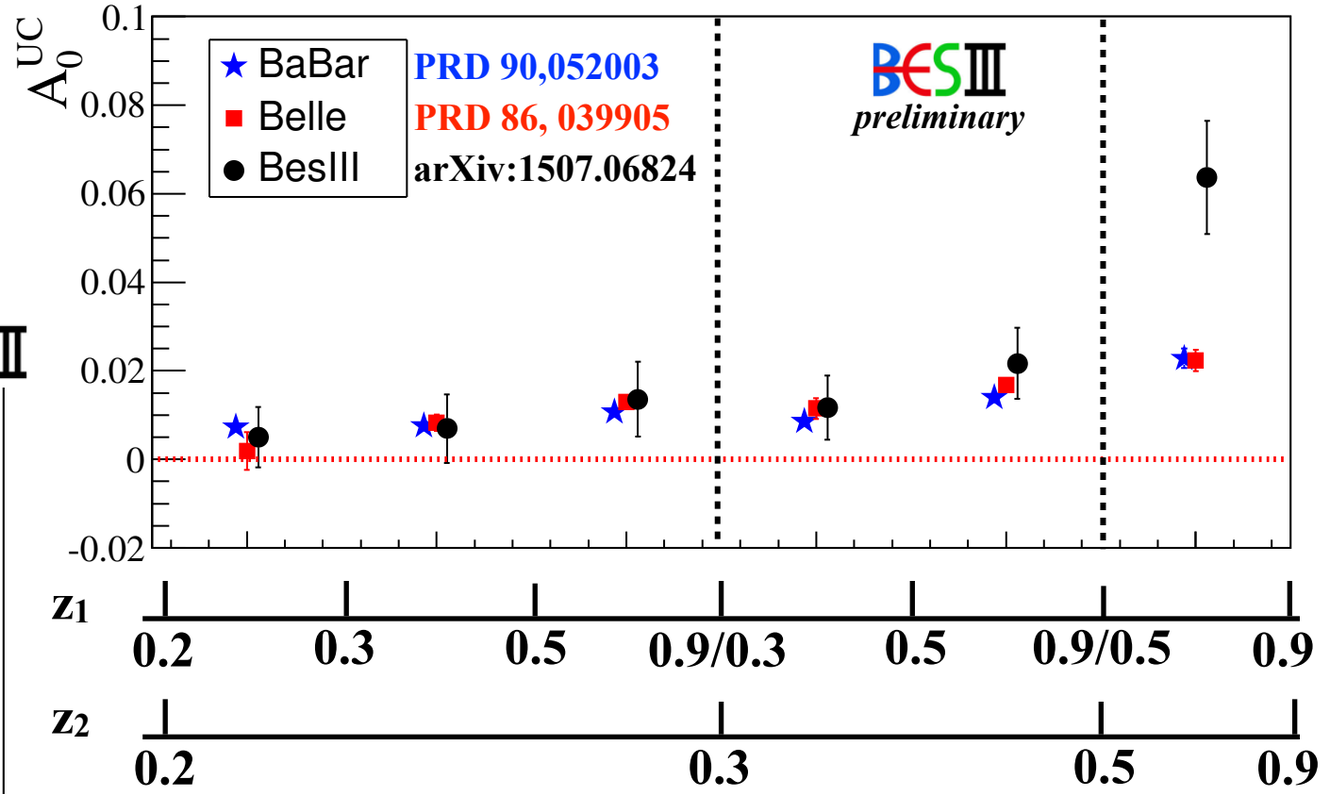
Asymmetries comparison in RF0

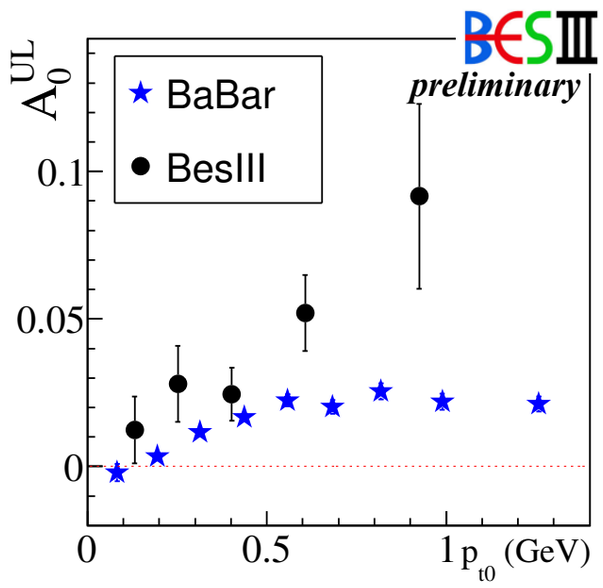
Comparison between different results obtained at different Q^2:

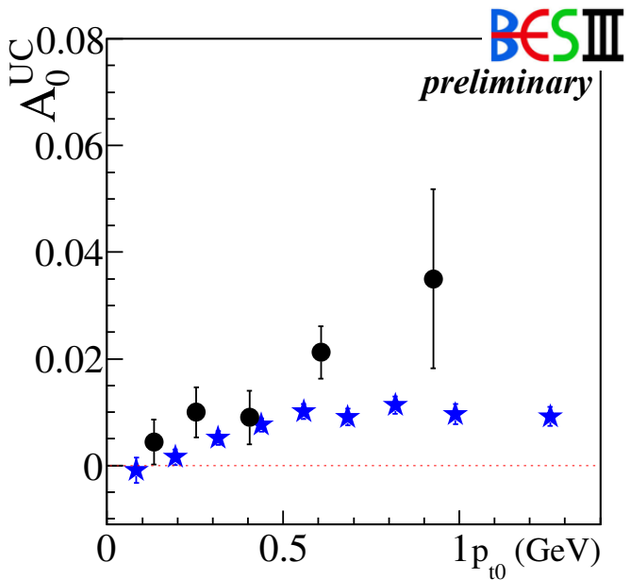
- **BaBar and Belle @ $Q^2 \sim 110$ GeV^2**
- **BESIII @ $Q^2 \sim 13$ GeV^2**

- 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 set for low z
- BESIII larger asymmetries in the last z-bins: consistent with the prediction reported in *arXiv:1505.05589*









arXiv:1506.05864
Submitted on PRL

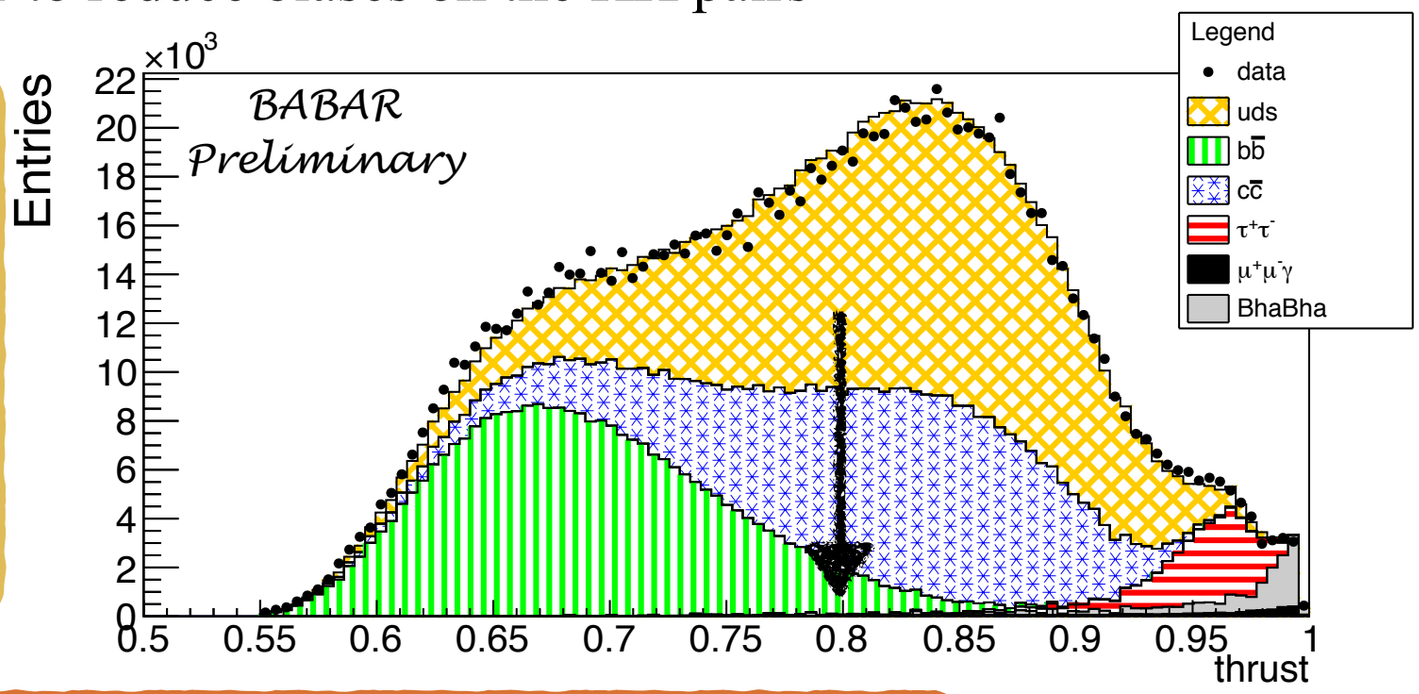
New BaBar Preliminary Result: Collins asymmetries for KK and Kπ hadron pairs

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

Extraction of KK, Kπ and ππ asymmetries

GOAL: 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

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

1. **Background sources:**
   - mainly from **$e^+e^- \to c\bar{c}$ 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^* ($\xi_{hh}^{(hh)c\bar{c}-D^*}$)

Simultaneous extraction of asymmetry

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

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

= Collins asymmetries for light hadrons

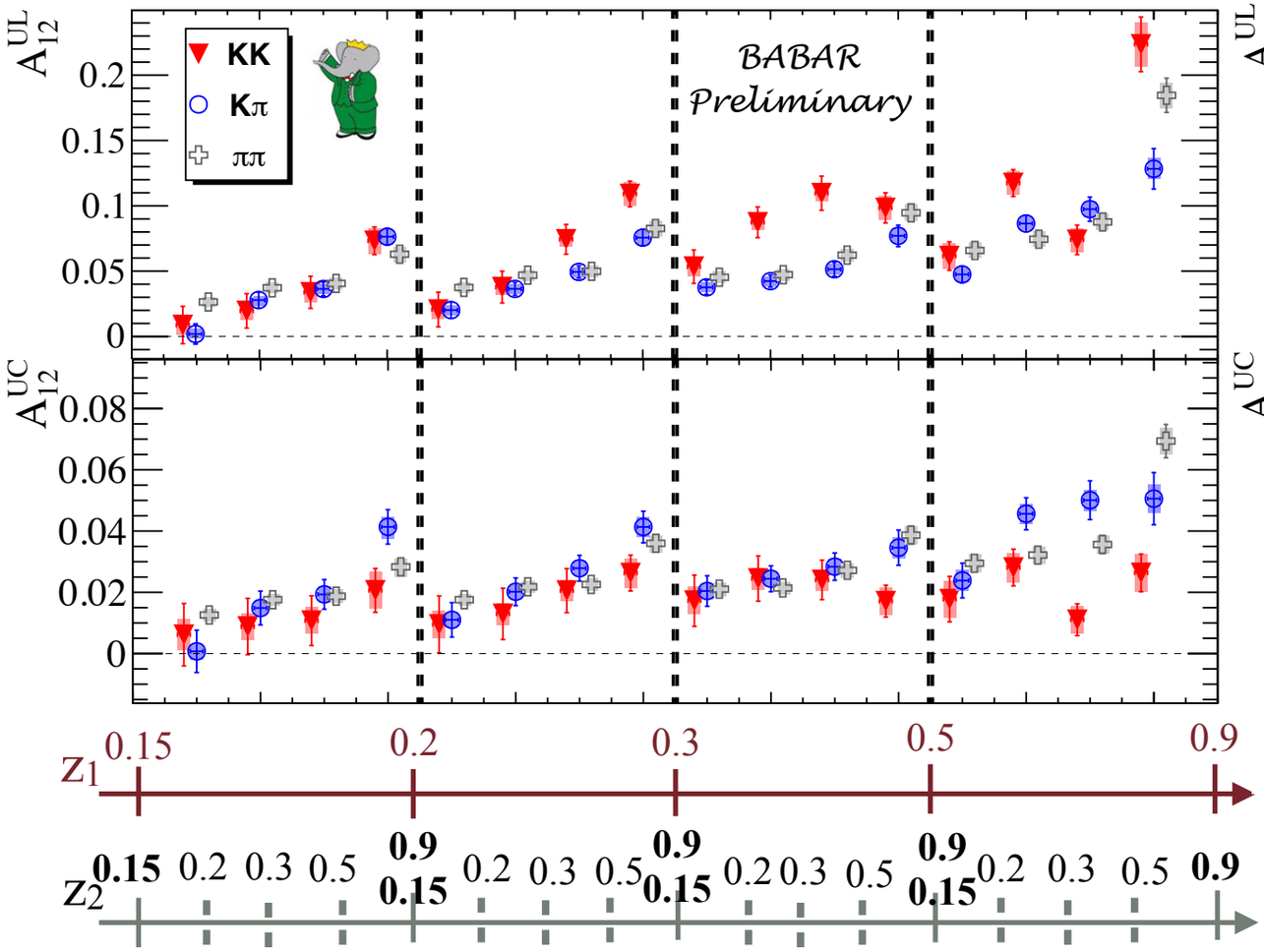
Results: RF12

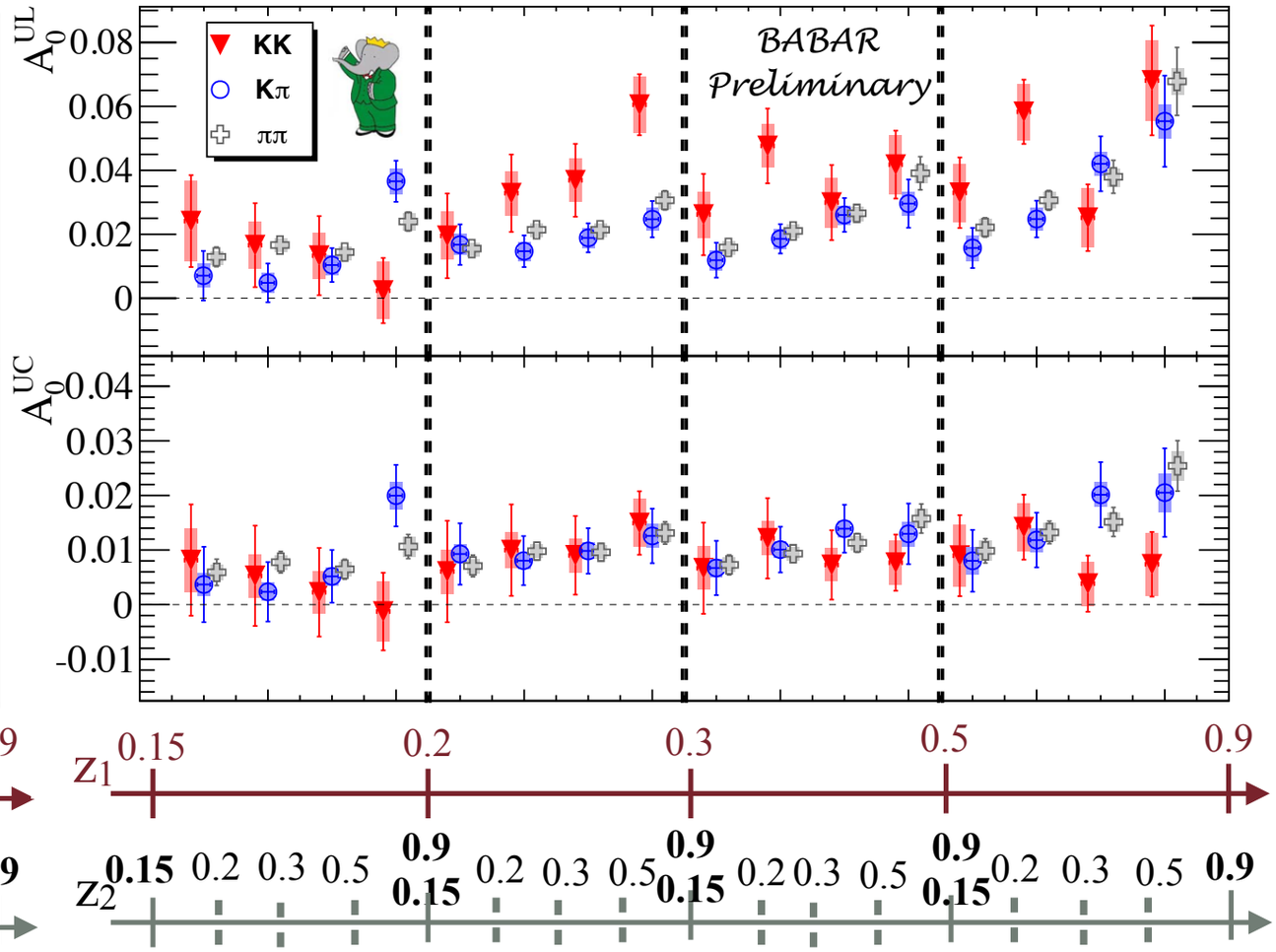
Simultaneous measurement of KK, Kπ and ππ Collins asymmetries

- all corrections are applied

arXiv:1506.05864

Submitted on PRL





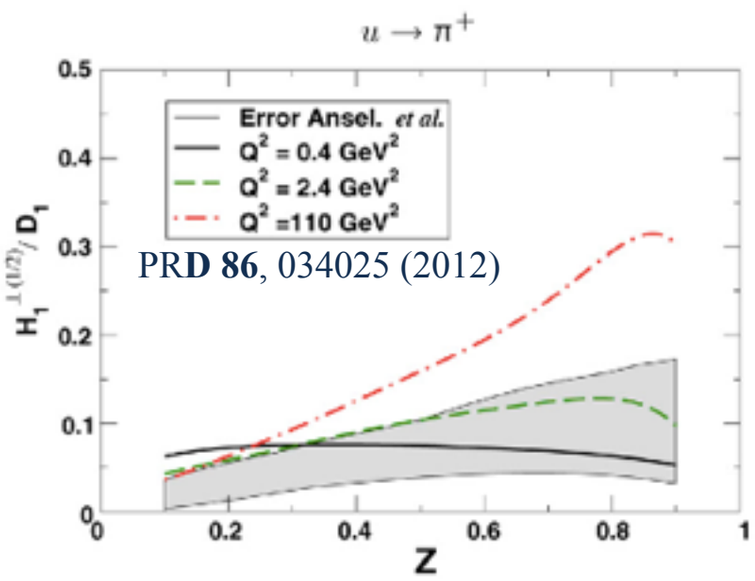
- Rising of the asymmetry as a function of *z* (more pronounced for U/L)
- A^{UL} KK asymmetry slightly higher than pion asymmetry for high z
- KK asymmetry consistent with zero at lower z

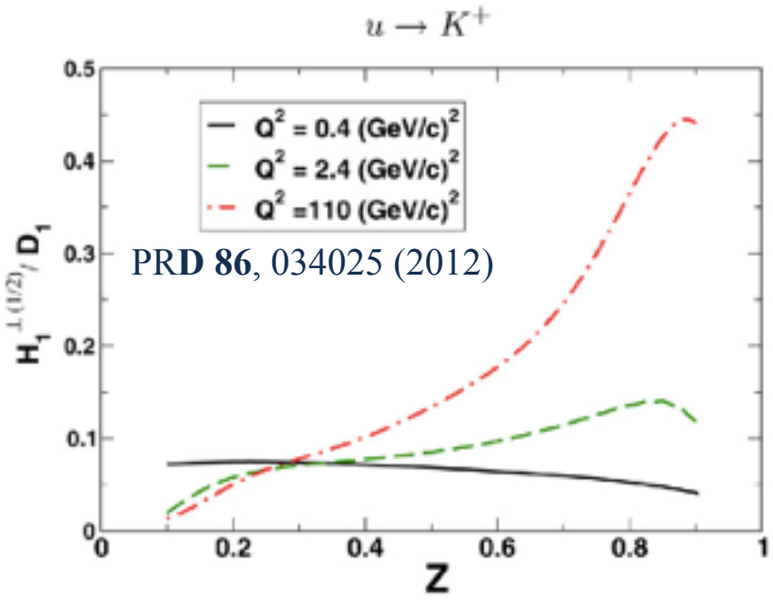
Note that A^{UL} and A^{UC} asymmetries are obtained using the same data sample, and are strongly correlated

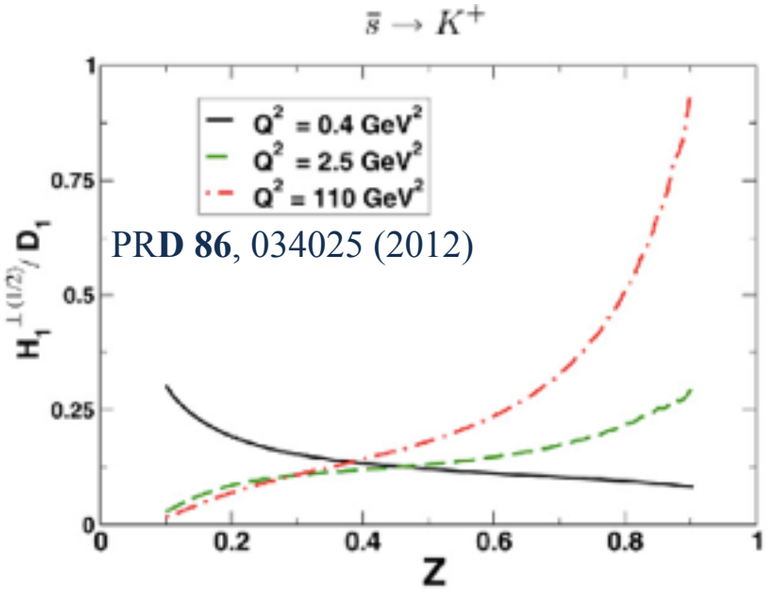
Conclusions

- Collins asymmetries for ππ pairs was deeply investigated:
  - BaBar and Belle @ Q^2~110 GeV^2 (PR**D90**,052003, PR**D86**,039905)
  - **BESIII preliminary results @ Q^2~13 GeV^2 allow to study the evolution of TMD objects**
  - Collins effect studied as a function of several kinematic variables

- BaBar preliminary results: simultaneous extraction of A_{KK}, $A_{K\pi}$, and $A_{\pi\pi}$ Collins asymmetries
  - 16 (z_1,z_2)-bins
  - Good agreement with previous BaBar results (PRD 90,052003 (2014))







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

Backup slides