Collins Fragmentation Function at BESIII

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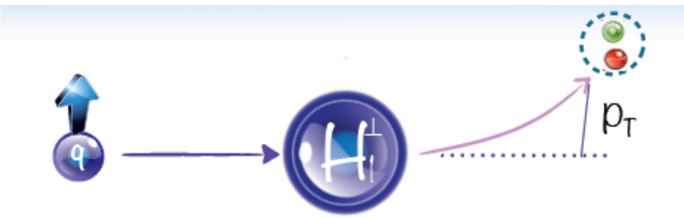
Outline

- Introduction
  - Collins Fragmentation Function
  - BEPCII and BESIII
- Collins asymmetries measurement at BESIII
  - Reference frame
  - Event selection; analysis procedure
  - Results of Collins asymmetries
  - Comparison with results from *B* factories
- Outlook and summary

Collins Fragmentation Function (FF)



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

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

D_1: the unpolarized FF

H_1: Collins FF

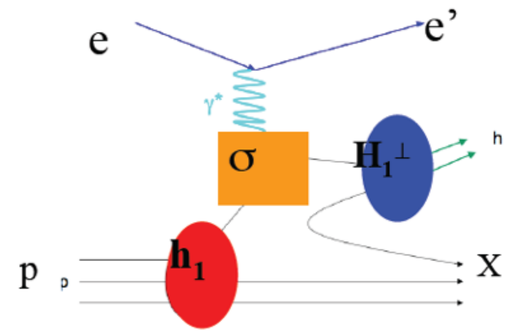
→ describes the fragmentation of a transversely polarized quark into a spinless hadron *h*.

→ depends on $z = 2E_h/\sqrt{s}$, $\mathbf{P}_{h\perp}$

→leads to an azimuthal modulation of hadrons around the quark momentum.

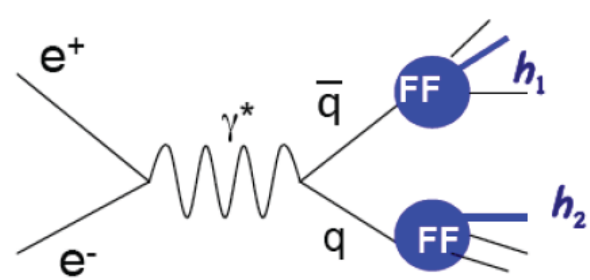
SIDIS

Transversity ⊗ Collins FF



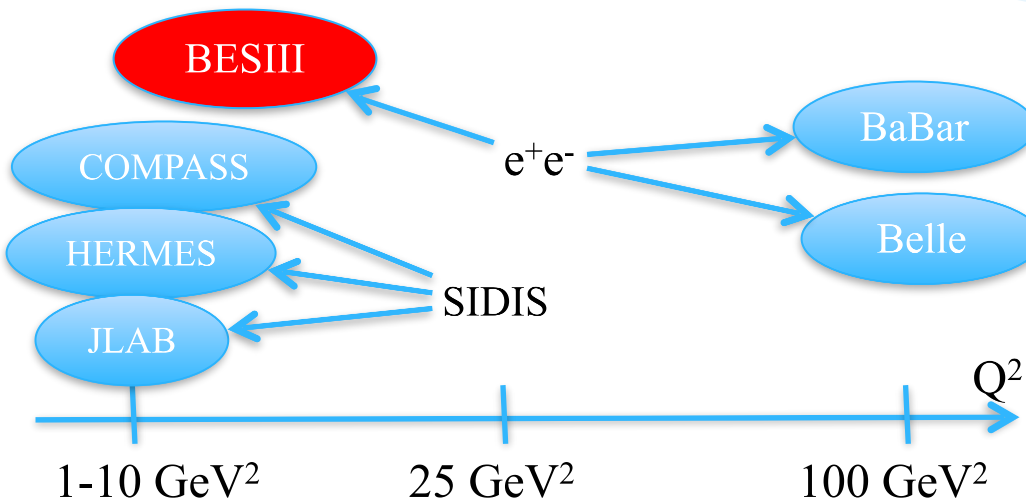
e+ e-

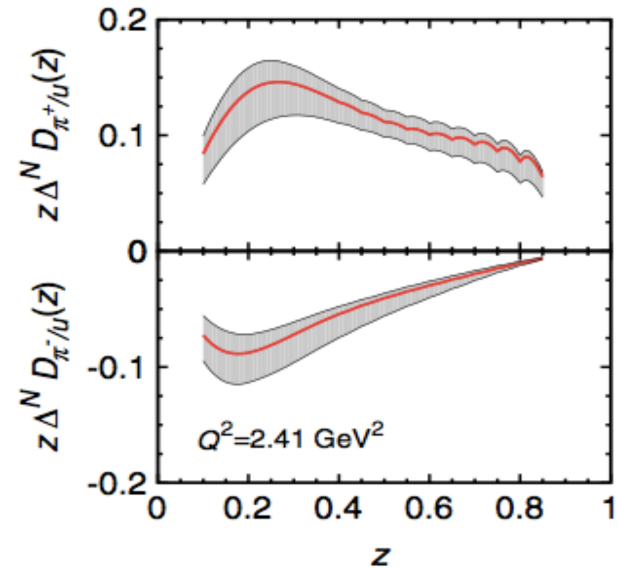
Collins FF ⊗ Collins FF



Collins FF: global analysis

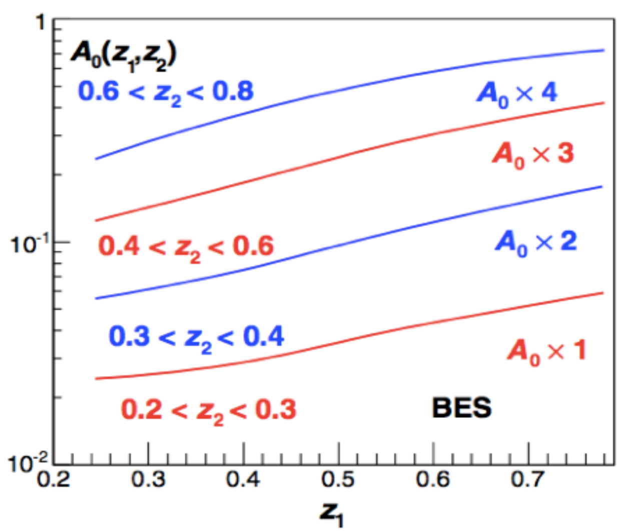
M. Anselmino *et al.*, PRD 87, 094019 (201





Data from HERMES, COMPASS and BELLE

P. Sum and F. Yuan, PRD 88, 034016 (2013)



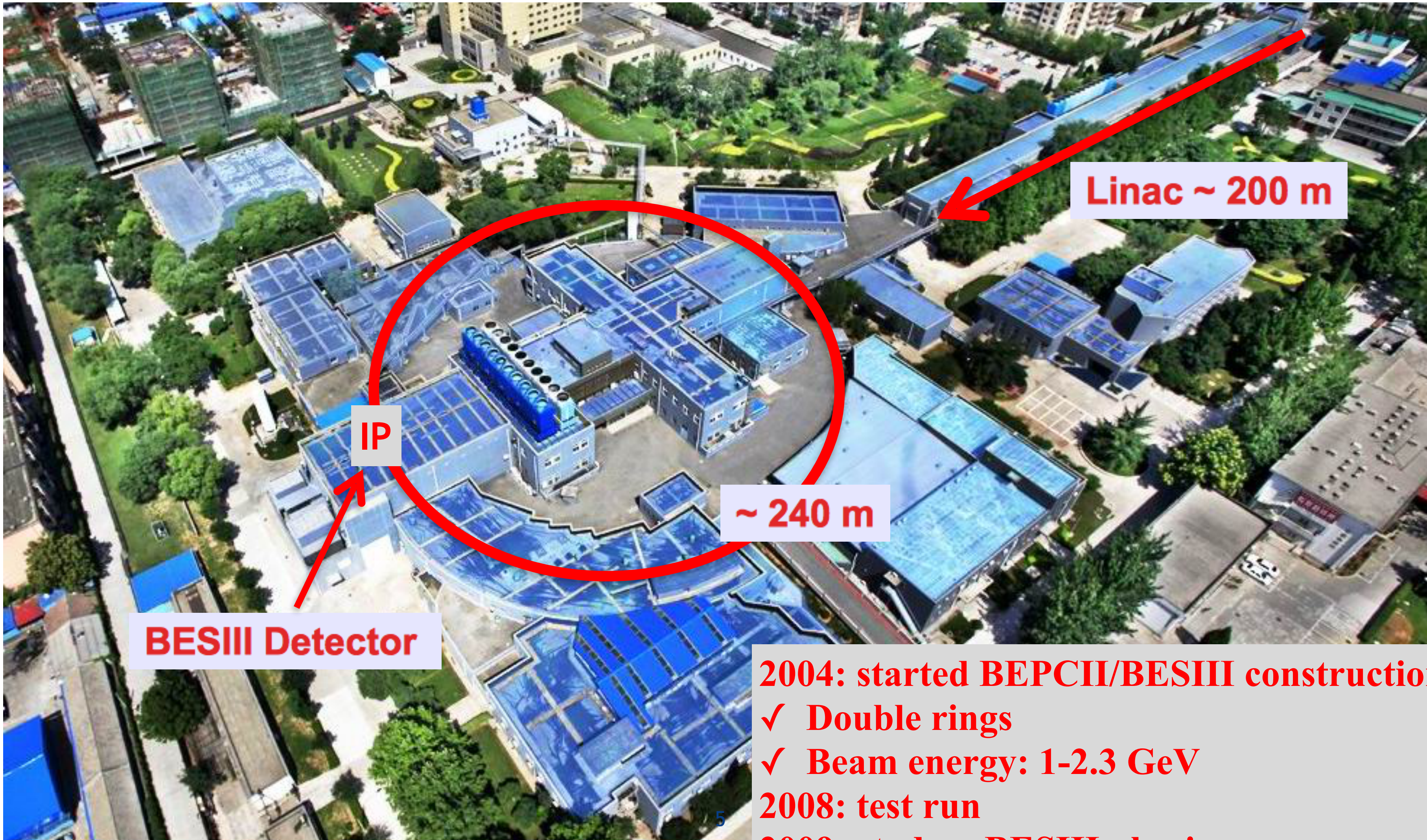
The Q^2 evolution of TMD FFs need to be understood

- BEPCII: similar Q^2 of SIDIS
- e^+e^- annihilation process at different energy with respect to B factories
- Prediction for BESIII in PRD 88, 034016

Beijing Electron Positron Collider II

- e+e- symmetric collider, unpolarized beams

✓ Designed luminosity: 1×10^{33} $cm^{-2}s^{-1}$, achieved on Apr. 6, 2016 @1.89GeV !!



2004: started BEPCII/BESIII construction

✓ Double rings

✓ Beam energy: 1-2.3 GeV

2008: test run

2009 – today: BESIII physics runs

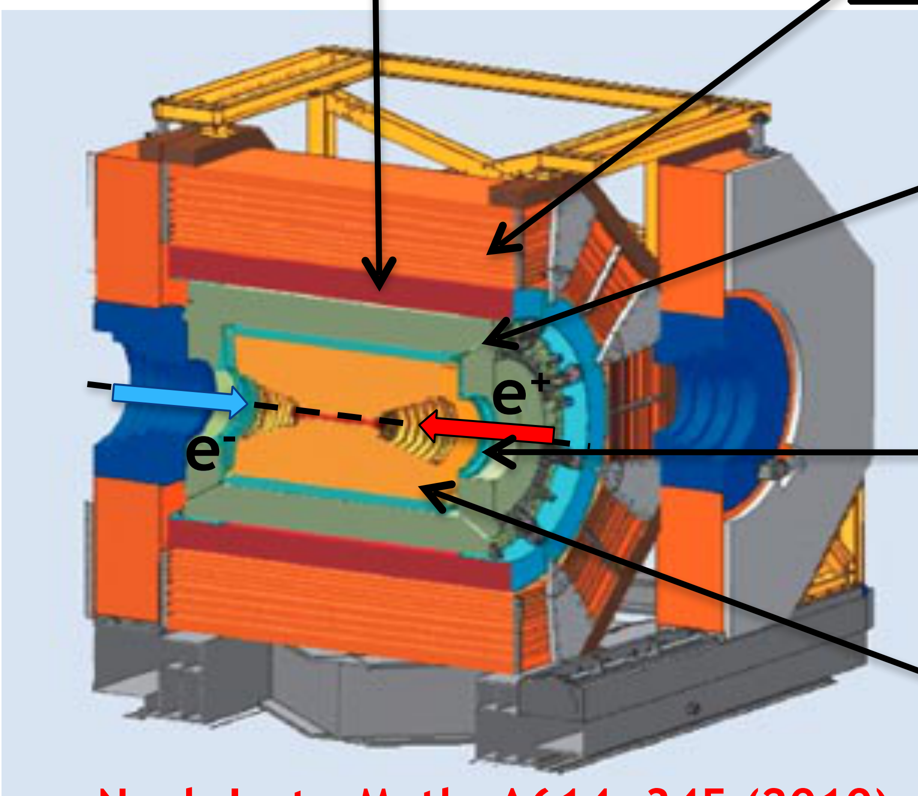
The BESIII detector

Large acceptance: 93% *4π

Superconducting solenoid (1T)

RPC Muon Detector
8 layers (end caps) + 9 layers (barrel)
$\Delta\Omega/4\pi = 93\%$

Electromagnetic CsI(Tl) Calorimeter
$\sigma_E/E < 2.5\%$ @ 1 GeV (barrel)
$\sigma_E/E < 5\%$ @ 1 GeV (end caps)
$\sigma_{xy} = (6\ \text{mm})/E^{1/2}$ @ 1 GeV

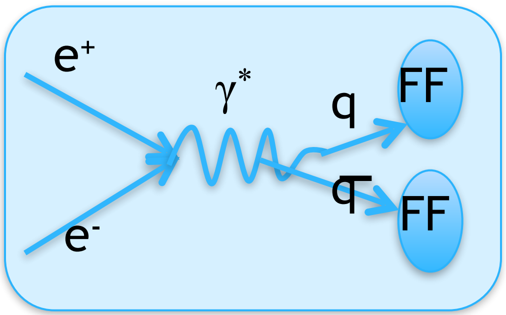


Time of Flight
$\sigma_t = 90$ ps (barrel)
$\sigma_t = 120$ ps (end caps)

Drift Chamber
$\sigma_{r\phi} = 130\ \mu m$ (single wire)
$\sigma_{pt}/p_t = 0.5\ \%$ @ 1 GeV

Nucl. Instr. Meth. A614, 345 (2010)

Collins Fragmentation Functions at BESIII



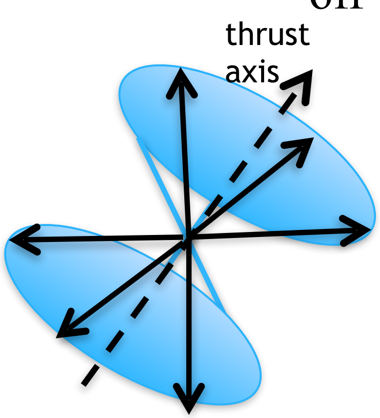
Collins FF ⊗ Collins FF

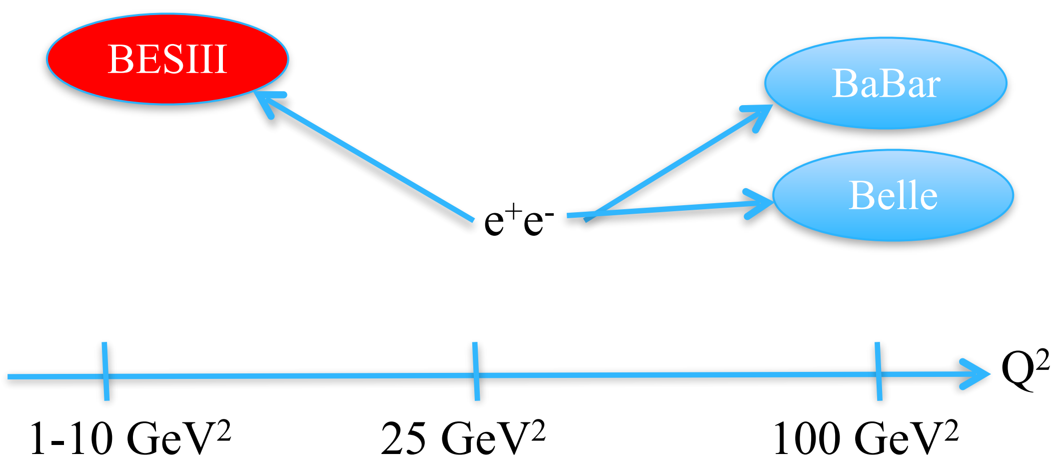
Unpolarized FF — Collins FF

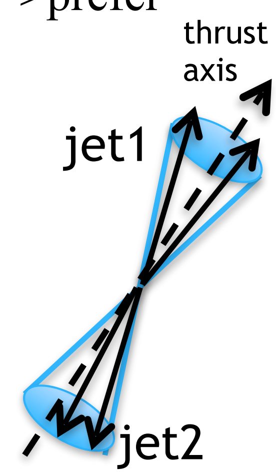
$$D_{hq^{\uparrow}}(z, P_{h\perp}) = D_1^q(z, P_{h\perp}^2) + H_1^{\perp q}(z, P_{h\perp}^2)\frac{(\hat{\mathbf{k}} \times \mathbf{P}_{h\perp}) \cdot \mathbf{S}_q}{z M_h}$$

J. Collins, Nucl. Phys. B936, 161 (1993)

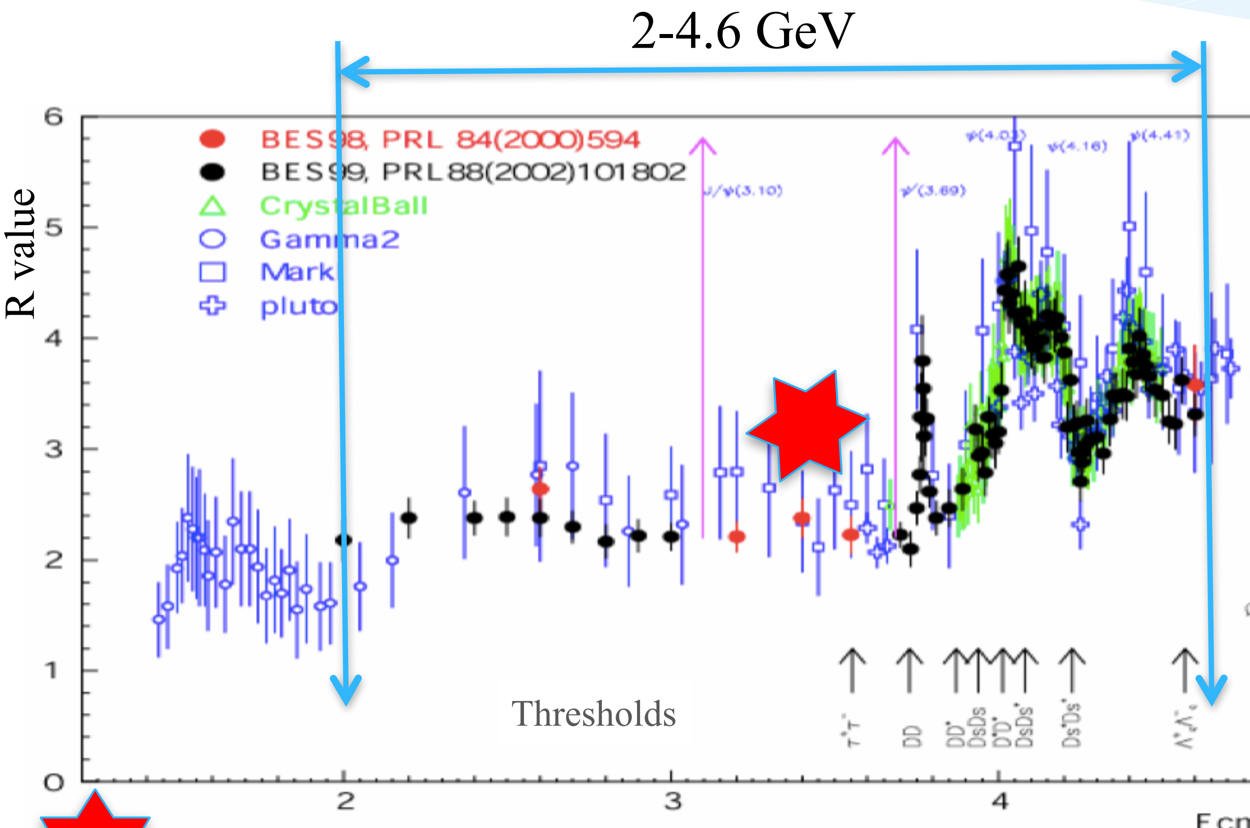
- jet structure at BESIII (low energy) is not clear —> can not reconstruct thrust axis correctly
- difficult to suppress backgrounds with on-resonance datasets —>prefer off-resonance data, in continuum region







Data Sample



- ✓ 1.3×10^{9} J/ψ
- ✓ 0.5×10^{9} ψ'
- ✓ 2.9 fb^{-1} @ ψ(3770)
- ✓ 1.9 fb^{-1} @ Y(4260), 4.23 GeV and 4.26 GeV
- ✓ R scan, 104 energy points between 3.85 and 4.59 GeV
- ✓ around the threshold of Lambda charm
- ✓ …

62 pb^{-1} @ 3.65 GeV
Continuum region
Below open-charm threshold

For Collins study, we also tried datasets @open-charm region; but too much bkg.

Reference Frame

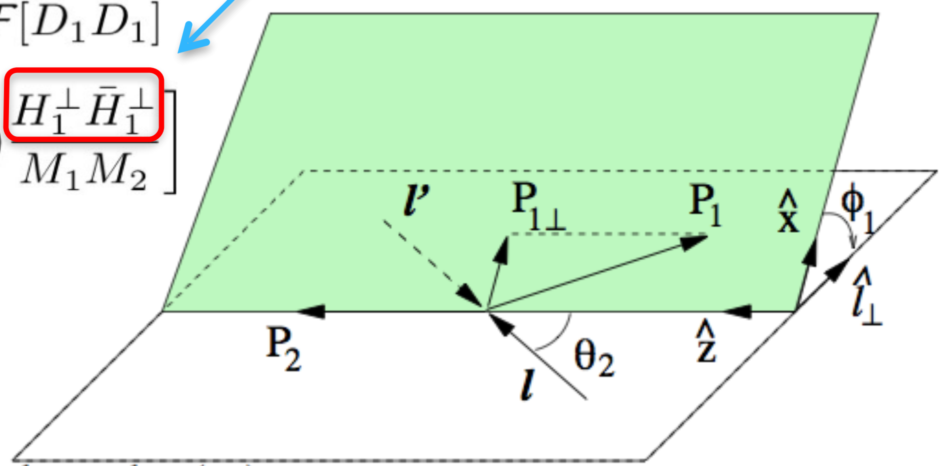
Two Collins FFs

$$\frac{d\sigma(e^+e^- \to \pi_1\pi_2 X)}{dz_1 dz_2 d\Omega d^2\mathbf{q}_T} \sim \frac{3\alpha^2}{Q^2} z_1^2 z_2^2 \{(1+\cos^2\theta_2)\mathcal{F}[D_1\bar{D}_1]$$

$$+ \sin^2\theta_2 \cos(2\phi) \mathcal{F}\left[(2\hat{\mathbf{h}}\cdot\mathbf{k_T}\hat{\mathbf{h}}\cdot\mathbf{p_T} - \mathbf{k_T}\cdot\mathbf{p_T})\frac{H_1^\perp \bar{H}_1^\perp}{M_1 M_2}\right]$$

$$\mathcal{F}[D\bar{D}] \equiv \sum_a e_a^2 \int d^2\mathbf{k}_T d^2\mathbf{p}_T \delta^2(\mathbf{k}_T + \mathbf{p}_T - \mathbf{q}_T)$$

$$D^a(z_1, z_1^2\mathbf{k}_T^2)\bar{D}^a(z_2, z_2^2\mathbf{p}_T^2)$$



D. Boer, Nucl. Phys. B806, 23 (2009)

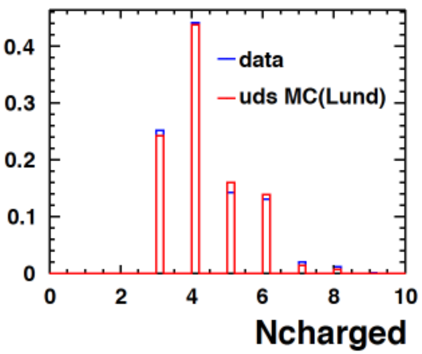
Event Selection

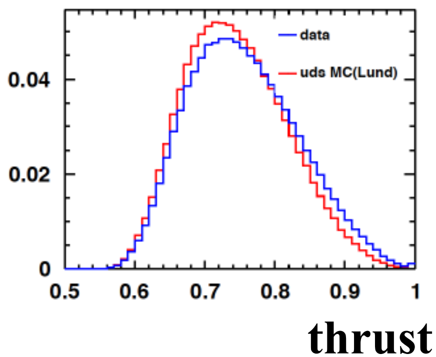
- Number of hadrons >3
- Number of charged pions ≥ 2
- Number of e^- = 0 to suppress BhaBha
- Total visible energy of the event $E_{vis} > 1.5$ GeV

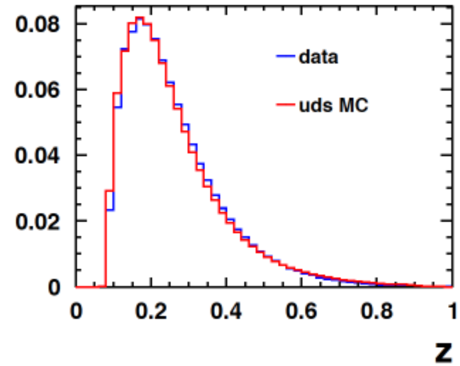
Pion selection:

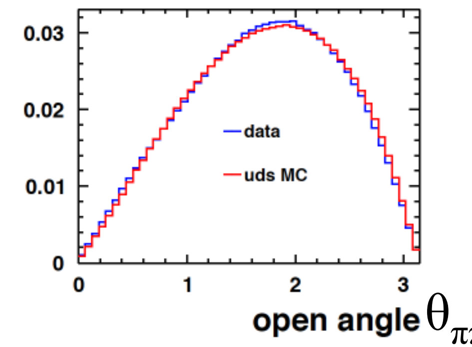
- Fractional energy $0.2 < z = 2E_h/\sqrt{s} < 0.9$
- Open angle between pion pair $\theta_{\pi\pi}$ >120 deg to select back-to-back pion pairs

Check on MC simulation

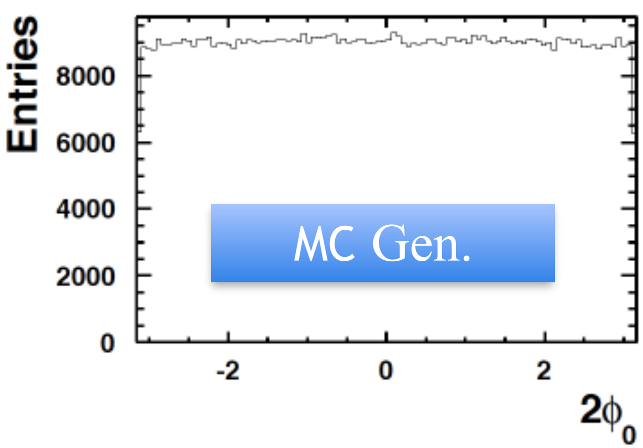


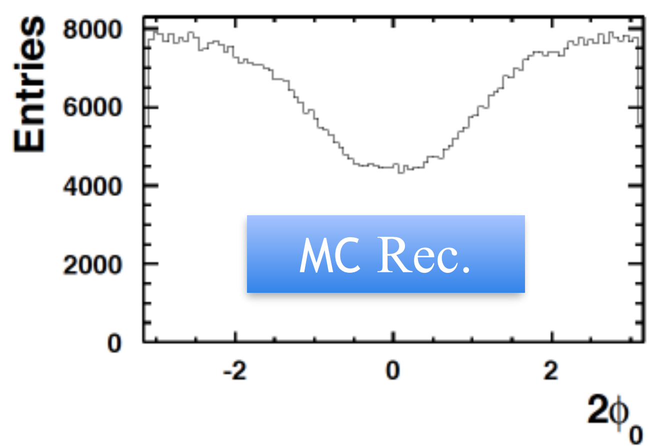






- MC can describe real data well basicallv.





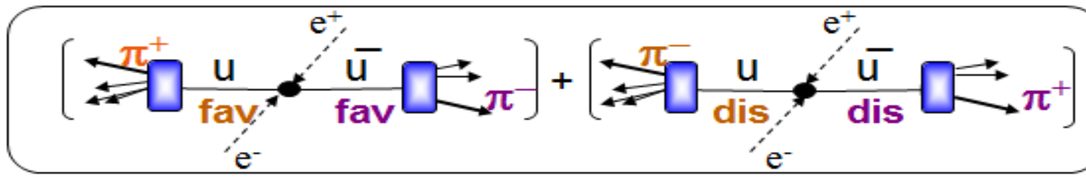
- MC simulation does not include Collins effect
- Detections effects/limit acceptance could induce false asymmetries.

Product of Two Collins FFs

- **Favored** fragmentation process describes the fragmentation of a quark of flavor q into a hadron with a valence quark of the same flavor: i.e.: u→π+, d→π-
- **Disfavored** for d→π^+, u→π^-

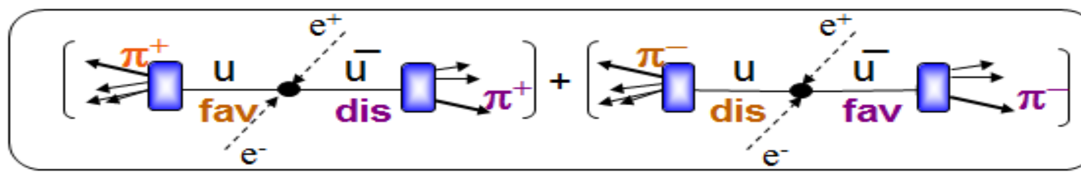
Unlike-sign pairs= **U:**

$\pi^{\mp}\pi^{\pm}$: (fav x fav)+(dis x dis)



Like-sign pairs = **L:**

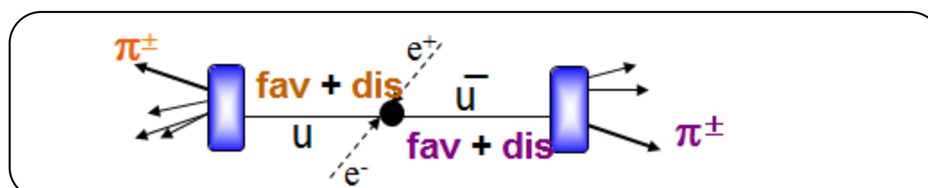
$\pi^{\pm}\pi^{\pm}$: (fav x dis)+(dis x fav)



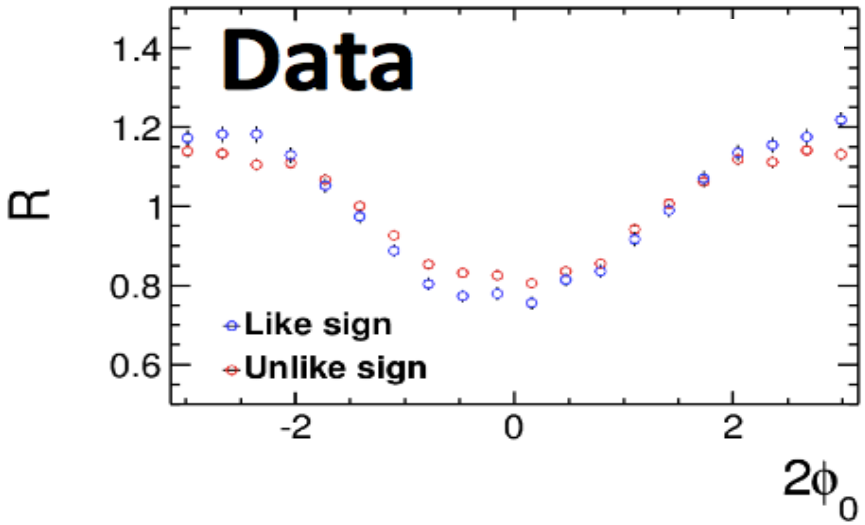
All charged pairs= C (U+L):

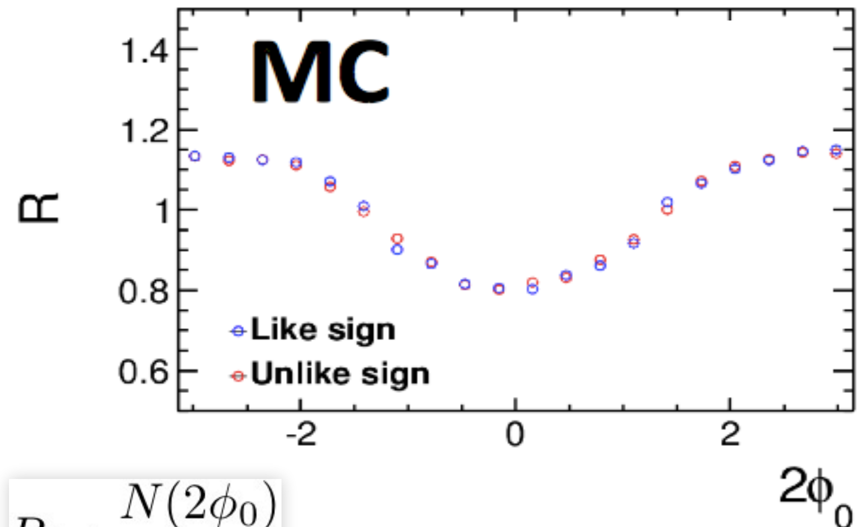
$\pi\pi$: (fav + dis)x(fav + dis)

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



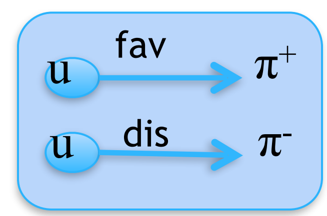
$2\Phi_0$ Distribution





Normalized ratio of raw asymmetries: $R = \frac{N(2\phi_0)}{\langle N_0 \rangle}$

- **U**nlike (**U**: $\pi^\pm\pi^\mp$), **L**ike (**L**: $\pi^\pm\pi^\pm$), **C**harged (**C**: $\pi^\pm\pi^\mp + \pi^\pm\pi^\pm$)
- Different combinations of favored and disfavored FFs

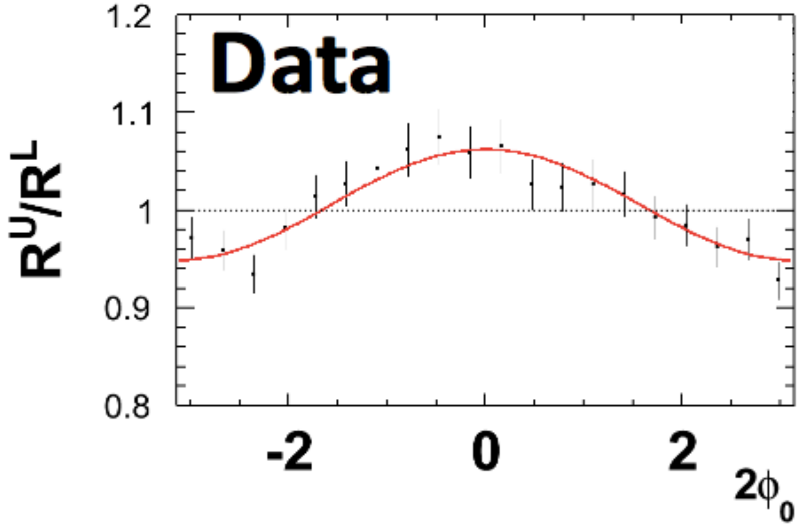


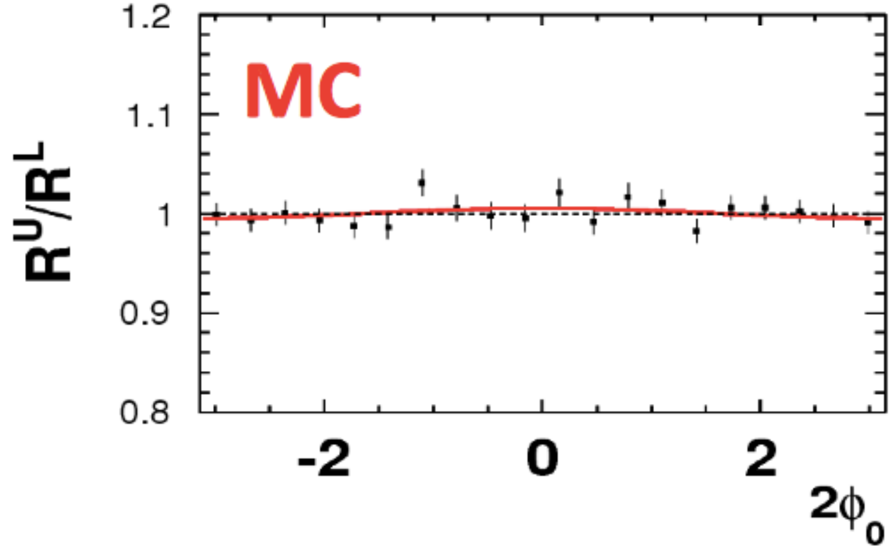
MC simulation does not include Collins effect

➢ Large detector effects: limited acceptance and non-uniform efficiency

➢ The differences between U, L, and/or C distributions in the data sample are due to the Collins effect

Double Ratio





Double Ratio: R^U/R^L and R^U/R^C

- Acceptance and efficiency effects reduce to a negligible level
  - MC asymmetry consistent with zero
- We fit the double ratio with a cosine function in order to extract the Collins asymmetry:

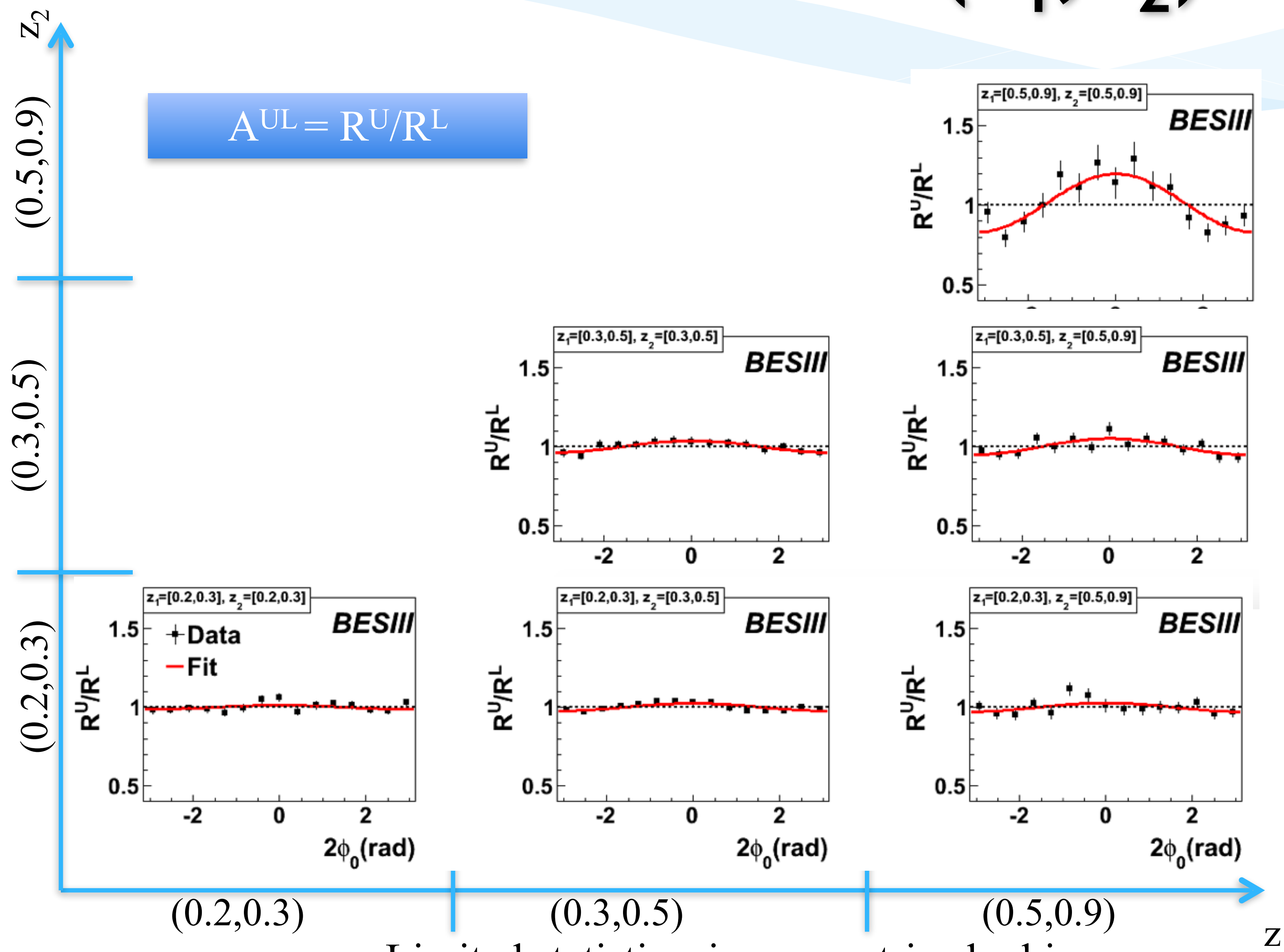
$$\frac{R^U}{R^{L(C)}} = 1 + \cos(2\phi_0) \cdot \frac{\sin^2\theta_2}{1+\cos^2\theta_2} \frac{\mathcal{F}(H_1^\perp(z_1)\bar{H}_1^\perp(z_2)/M_1M_2)}{D_1(z_1)\bar{D}_1(z_2)} =$$

$$= 1 + \cos(2\phi_0) \cdot A^{UL(UC)}$$

Depends on the pion pair fractional energy (z_1, z_2)

Double Ratio vs. (z_1,z_2)

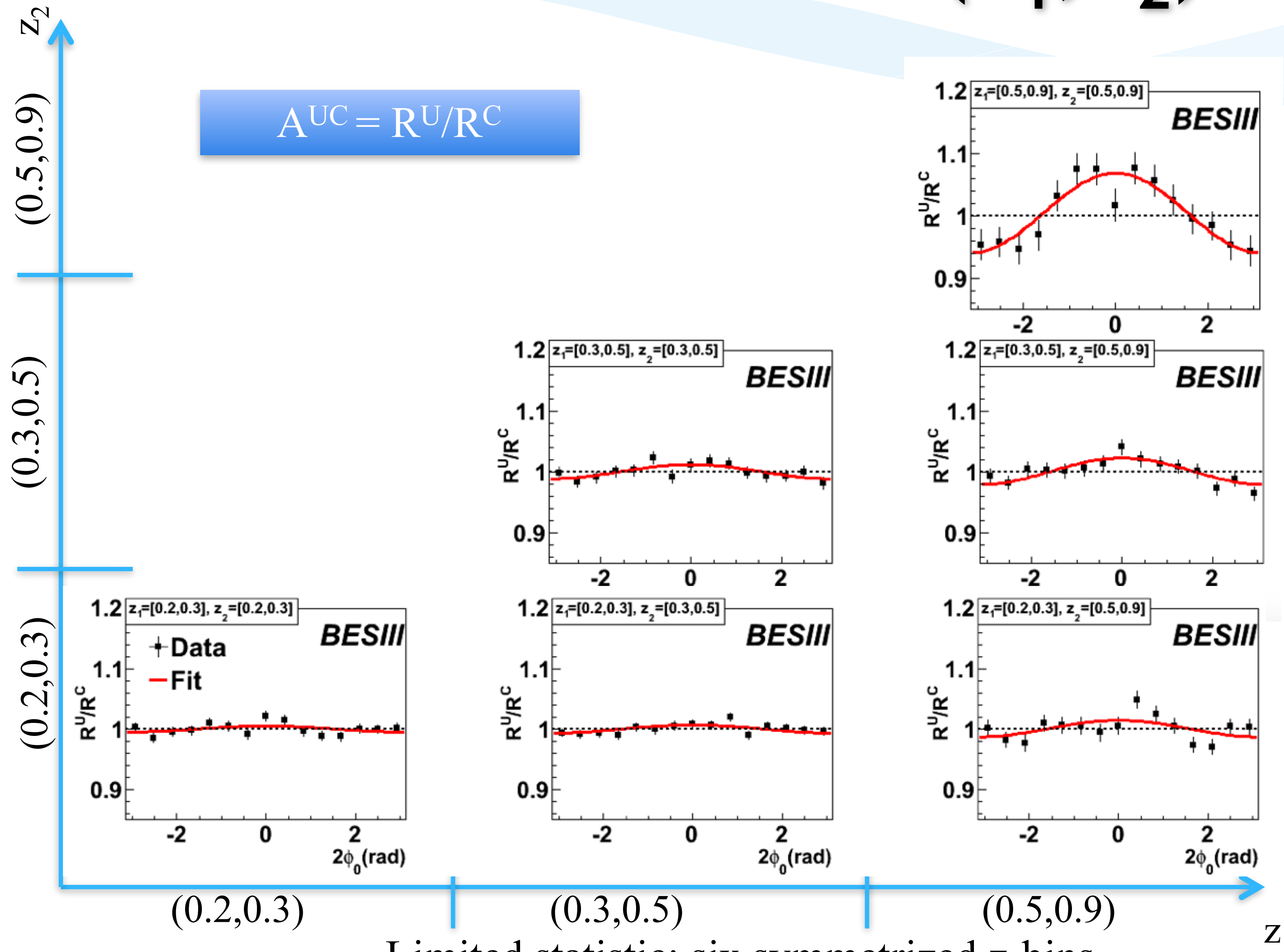
$A^{UL} = R^U/R^L$



Limited statistic; six symmetrized z-bins

Double Ratio vs. (z_1,z_2)

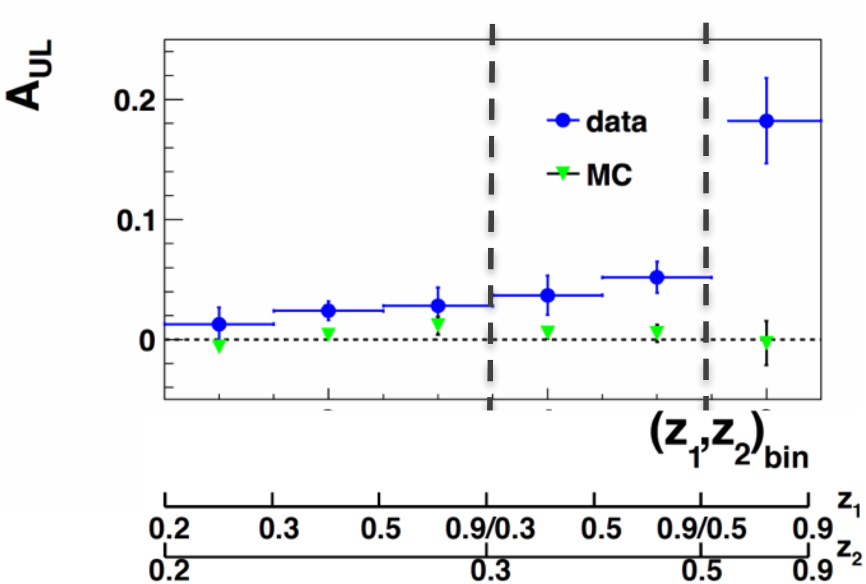
$A^{UC} = R^U/R^C$



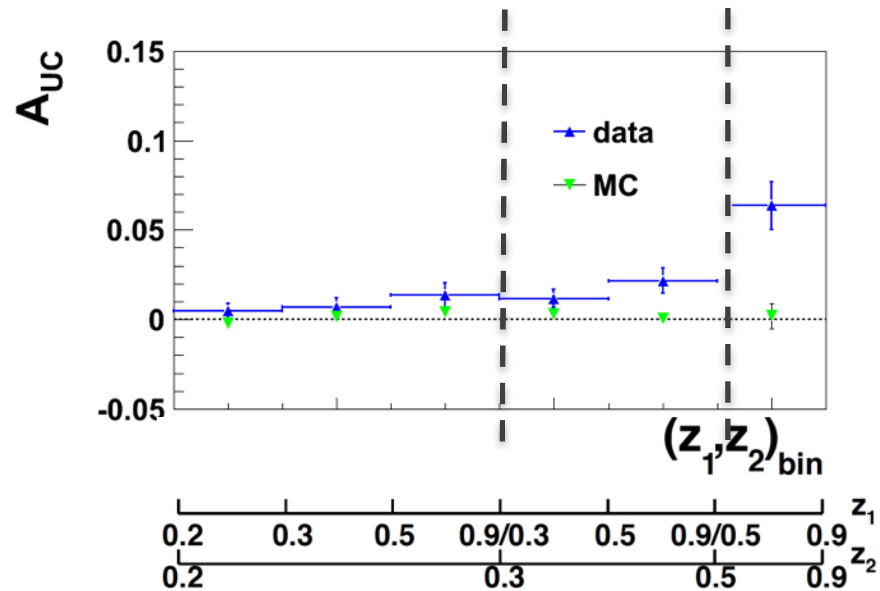
Limited statistic; six symmetrized z-bins

Double Ratio in Data/MC

$A^{UL} = R^U/R^L$



$A^{UC} = R^U/R^C$



Non zero A^{UL} and A^{UC} asymmetries in data

- Asymmetry measured in the MC sample consistent with zero in each bin of z: detector effects cancel with the double ratio

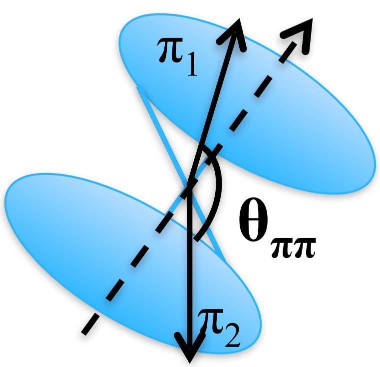
Background Contribution

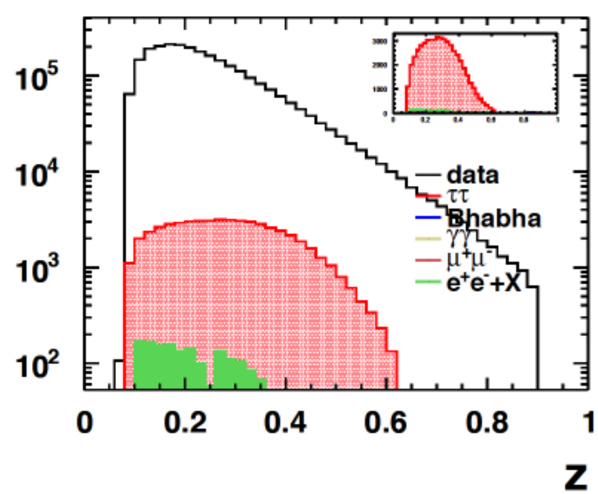
Possible background contamination at the center-of-mass energy of 3.65 GeV

- No charm contribution: below the $D\overline{D}$ threshold
- BhaBha, $\mu^+\mu^-$, $\gamma\gamma$: negligible contribution
- $\tau^+\tau^-$ ~ 2%
- Other sources: negligible effects

$\sqrt{s}$ = 3.65 GeV ➔ we cannot use the thrust axis to identify two jets

- $\theta_{\pi\pi}$ >120 deg kinematic selection to select back-to-back pions





Systematics(1)

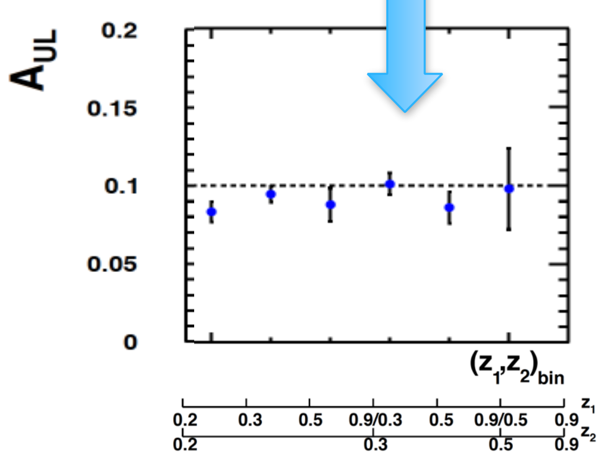
- ✓ We check the contamination from k-pi pairs, based on MC, the rate is not high
- ✓ Unfold the asymmetries from

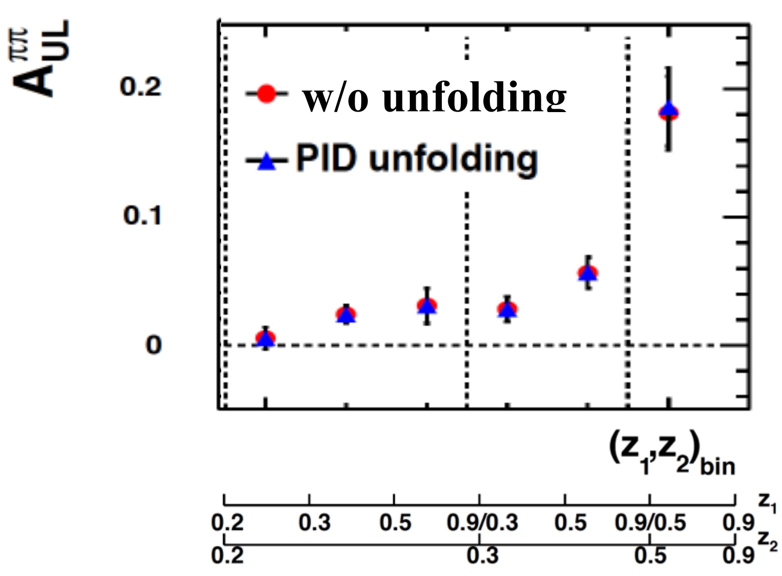
$$A^{\pi\pi}_{mea.} = (1 - f_{K\pi})A^{\pi\pi}_{ture} + f_{K\pi}A^{K\pi}_{ture},$$

$$A^{K\pi}_{mea.} = (1 - f_{\pi\pi})A^{K\pi}_{ture} + f_{\pi\pi}A^{\pi\pi}_{ture}.$$

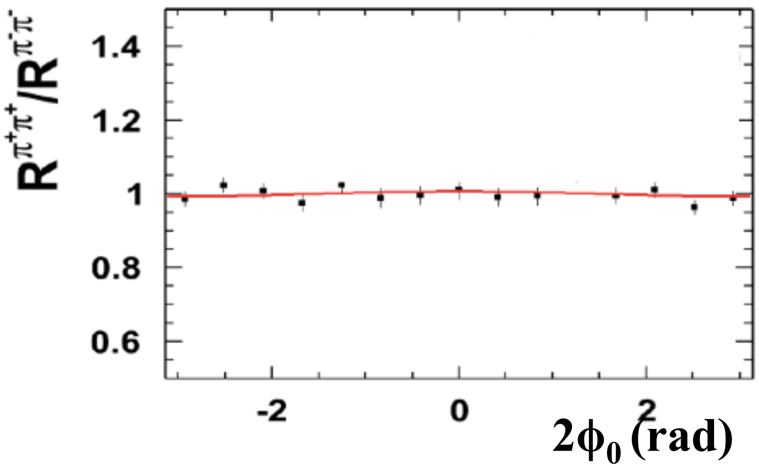
Bin id	1	2	3	4	5	6
$\pi - K$ fraction(%)	0.1	0.6	3.5	0.8	3.4	4.2

- ✓ Input asymmetries into MC using weighted method, ~10% A_{UL}
- ✓ reconstructed value can be consistent with input
- ✓ underestimate of the asymmetries due to smearing/resolution effect were included in the systematics

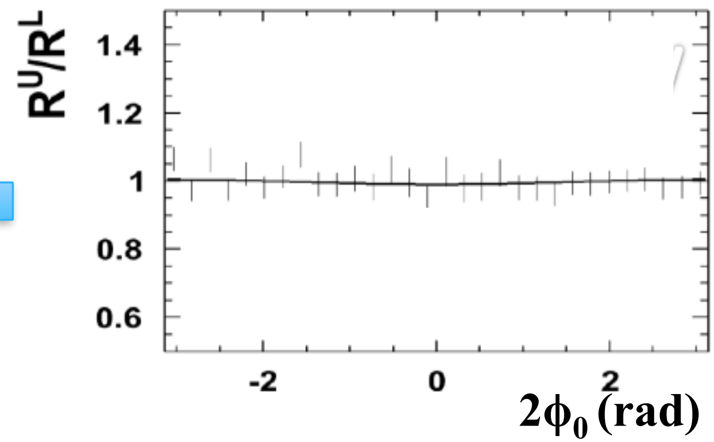




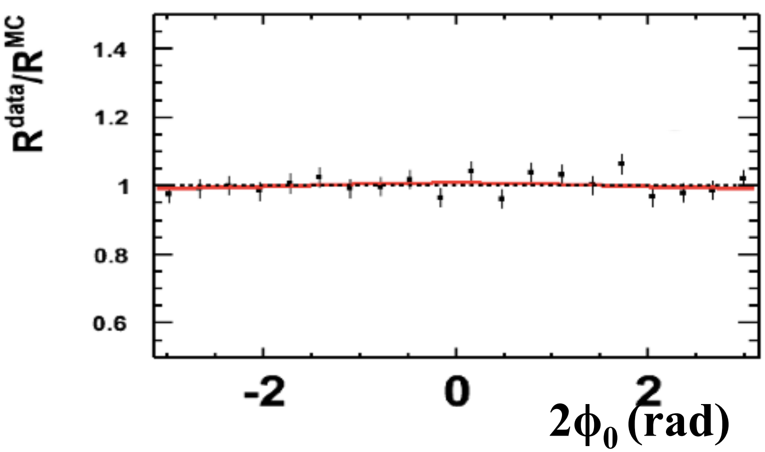
Systematics(2)—zero test



- ✓ We check the charge dependence of the detector response by studying the double ratio of $\pi^+\pi^+/\pi^-\pi^-$
- ✓ Asymmetry consistent with zero



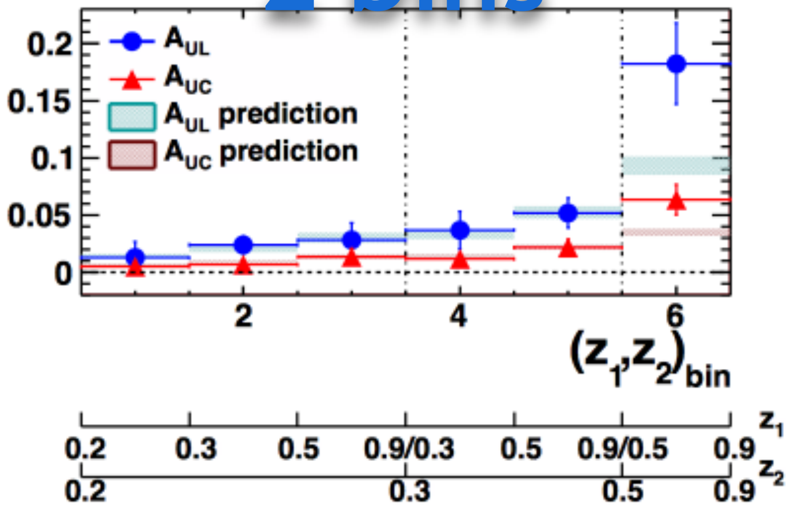
- ✓ Mixed events: we combine two pions coming from different events
- ✓ Asymmetry consistent with zero



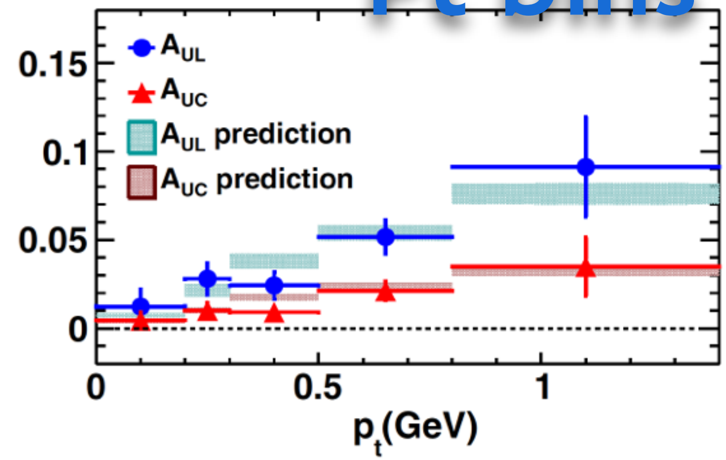
- ✓ Single spin asymmetry should be consistent with zero for unpolarized beams

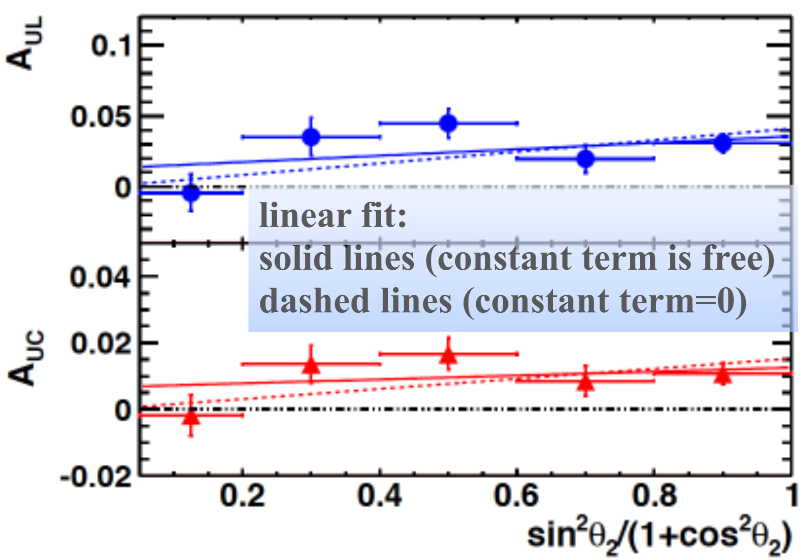
Results of Collins asymmetry

z bins



Pt bins





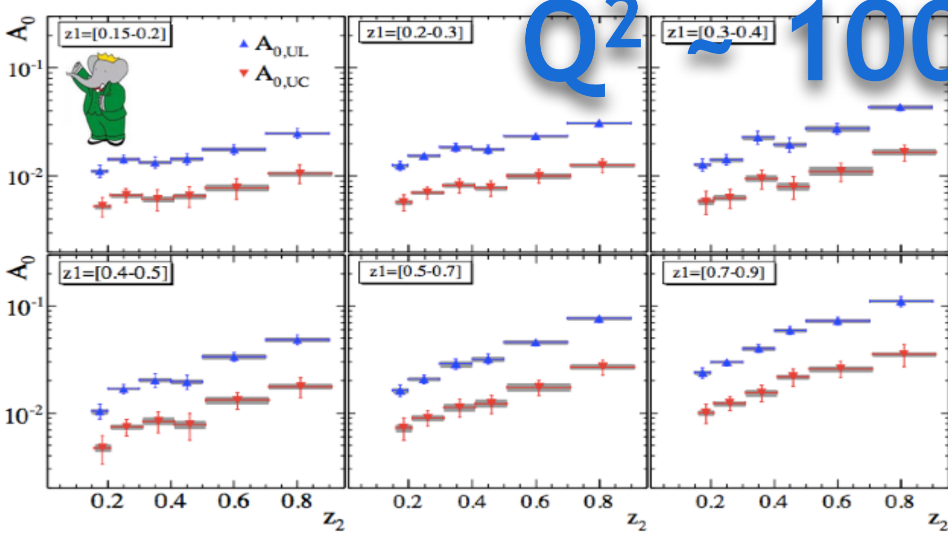
- ➢ Clear nonzero Collins asymmetries, increase with higher fraction energy, pt
- ➢ The expected behavior of the Collins asymmetries as a function of $\sin^2\theta_2/(1+\cos^2\theta_2)$ is linear and vanish at $\theta_2=0$
- ➢ comparable with predictions from authors of PRD 93, 014009, who provided the predictions using BESIII kinematics (z,pt)

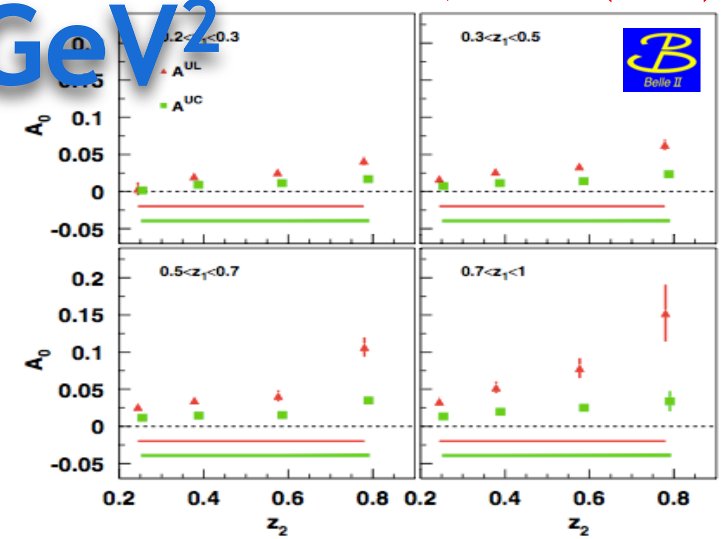
Collins asymmetry in different Q^2

J.P. Lees *et al*. (BaBar Collaboration), PRD 90, 052003 (2014)

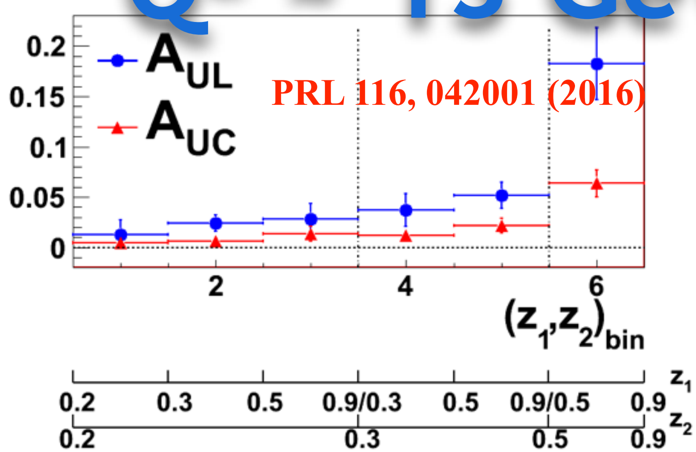
R. Seidl *et al*. (Belle Collaboration), PRD 86, 039905(2012)

$Q^2 \sim 100\ GeV^2$





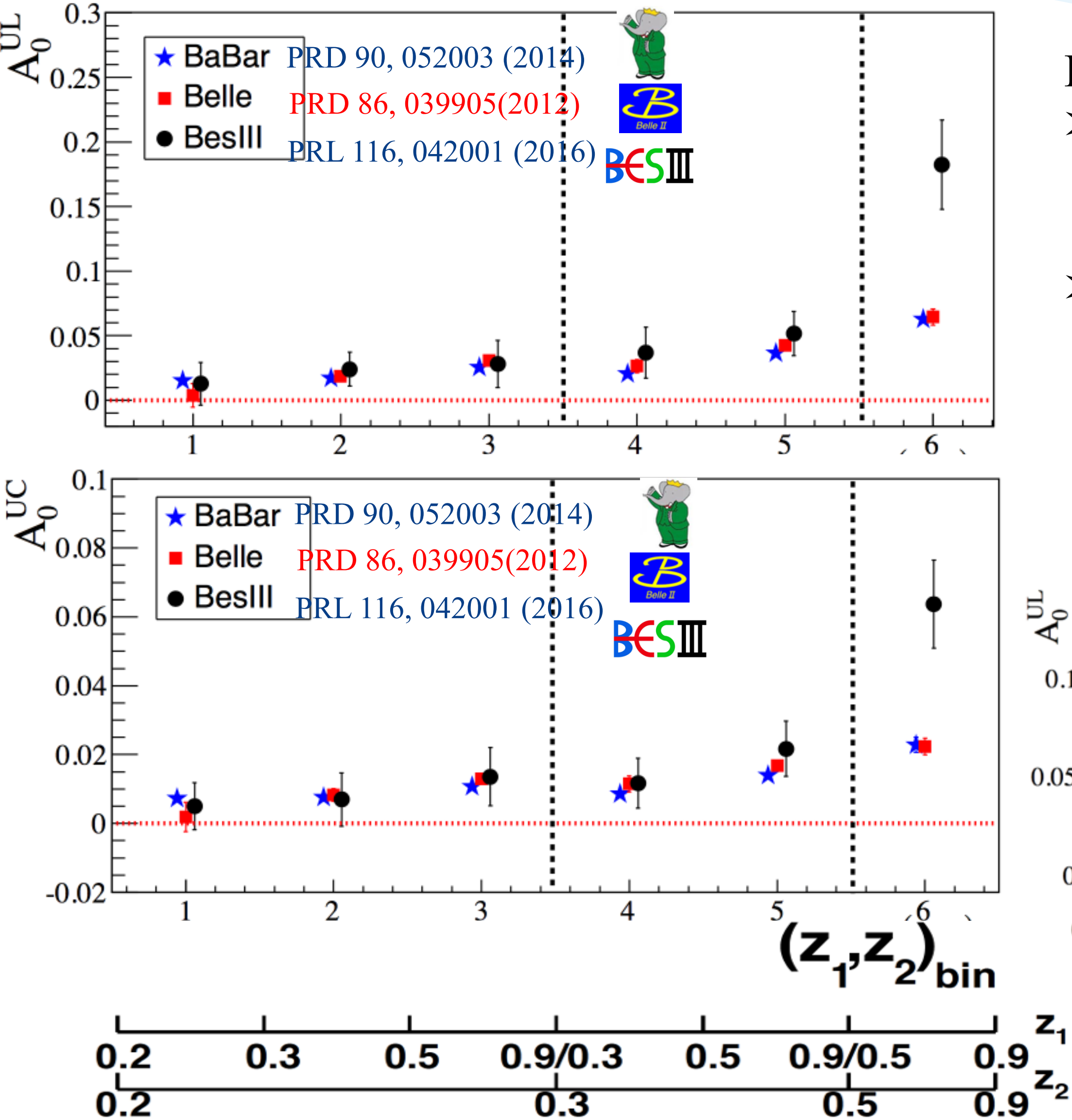
$Q^2 \sim 13\ GeV^2$



PRL 116, 042001 (2016)

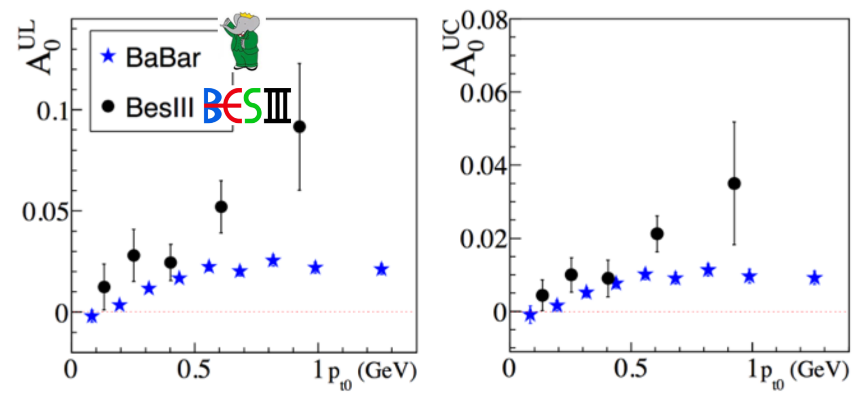
- ✓ Different (z_1,z_2) bins: we average those results from B factories that fall in larger BESIII intervals, next slide

Collins asymmetry in different Q^2



BESIII results

- ➢ the measured Collins asymmetry is larger than those measured at higher Q^2 experiments
- ➢ this behavior is qualitatively in agreement with prediction reported in the PRD 88, 034016 (2013) , PRD 93, 014009



Outlook

- More data set at BESIII?
  - Data above the charm threshold, background is an issue, thrust value is not powerful to suppress backgrounds.
  - BESIII plan to take more data @ 3.65GeV.
- Kπ , KK pairs
  - statistics is much lower.
  - contamination rate from $\pi\pi$ is high, for Kπ , 0.1%-35% in z[0.2-0.9].
    - inclusive pion production is much more than kaon,
    - K/π PID capacity at BESIII is limited at 1.0GeV (z~0.6).
- Involve neutral π^0, Ks, study on $\pi^0+\pi+X$, K +Ks + X
  - π^0 suffers from backgrounds.
  - Ks can help to suppress backgrounds, but K case may not be so inclusive.
- Inclusive $\Lambda/\bar{\Lambda}$, study on the polarization of $\Lambda/\bar{\Lambda}$ @4.26GeV.

Summary

We measure the Collins asymmetry using the BESIII data at the center-of-mass energy of 3.65 GeV

- clear nonzero asymmetry;
- larger than that measured at BaBar (PRD90,052003) and Belle (PRD86,039905);
- we study on z-dependence behavior, the p_t behavior and asymmetry as a function of $\sin^2\theta/(1+\cos^2\theta)$.
- comparable to theoretical predictions

Outlook

- Data above the charm threshold might be explored
- BESIII plans to take more data @ 3.65 GeV, can improve the precision
- More FFs explore at BESIII: $\pi^0\pi$; $K\pi$; KK; KsK; $\Lambda / \bar{\Lambda}$ …, but might be more difficult than pion-pion case.

THANK YOU!

BACK UP

The BESIII Collaboration

Europe
13 institutions:

Bochum University,Budker Instituteof Nuclear Physics,Ferrara University,GSI Darmstadt, Helmholtz Institute Mainz,INFN, Laboratori Nazionali di Frascati, Johannes Gutenberg University of Mainz, Joint Institute for Nuclear Research (JINR), KVI/University of Groningen,Turkish Accelerator Center Particle Factory Group (TAC-PF),Universitaet Giessen, University of Turin,Uppsala University

China
30 institutions:

Beihang University, China Center of Advanced Science and Technology, Guangxi Normal University, Guangxi University, Hangzhou Normal University, Henan Normal University, Henan University of Science and Technology, Huazhong Normal University, Huangshan College, Hunan University, Institute of High Energy Physics, Lanzhou University, Liaoning University, Nanjing Normal University, Nanjing University, Nankai University, Peking University, Shanxi University, Sichuan University, Shandong University, Shanghai Jiaotong Univeristy, Soochow University, Sun Yat-sen University, Tsinghua University, University of Chinese Academy of Sciences, University of Science and Technology of China, University of South China, Wuhan University, Zhejiang University, Zhengzhou University

USA
5 institutions:

Carnegie Mellon University,Indiana University, University of Hawaii, University of Minnesota, University of Rochester

OTHER IN ASIA
4 institutions:

COMSATS Institute of Information Technology (CIIT), Tokyo University,Seoul National University, University of the Punjab

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