

Measurement of Collins Asymmetry at **BESIII**

Xiao-Rui Lyu (吕晓睿)

(E-mail: xiaorui@ucas.ac.cn)

University of Chinese Academy of Sciences (UCAS), Beijing

(On Behalf of the BESIII collaboration)

DSPIN2015, DUBNA

Outline

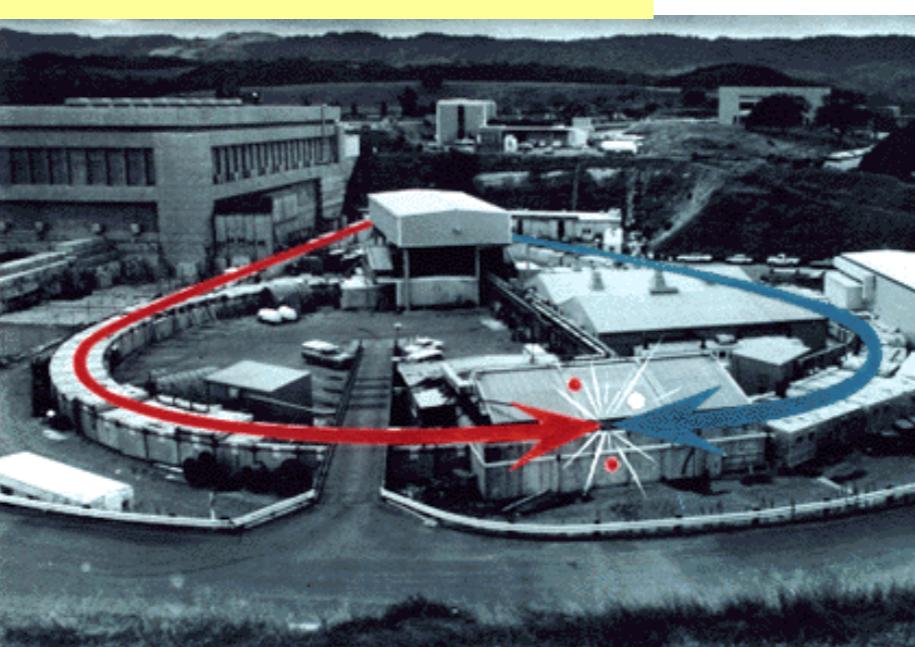
- BEPCII/BESIII
- Physics at BESIII
- Collins effect measurement
- Summary&Outlook

Charm from dedicated colliders

ADONE, FRASCATI '69-'93



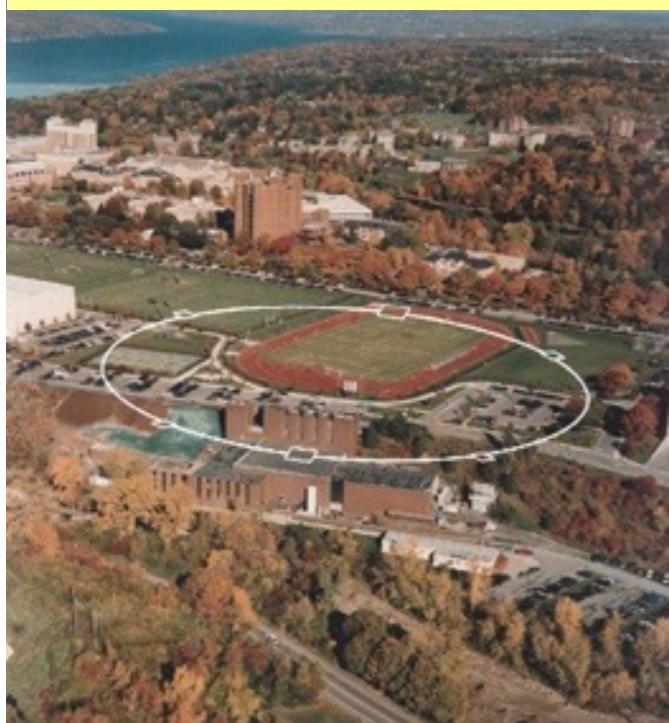
SPEAR, SLAC, '72-'90
 $6 \times 10^{29} \text{ cm}^{-2} \cdot \text{s}^{-1}$



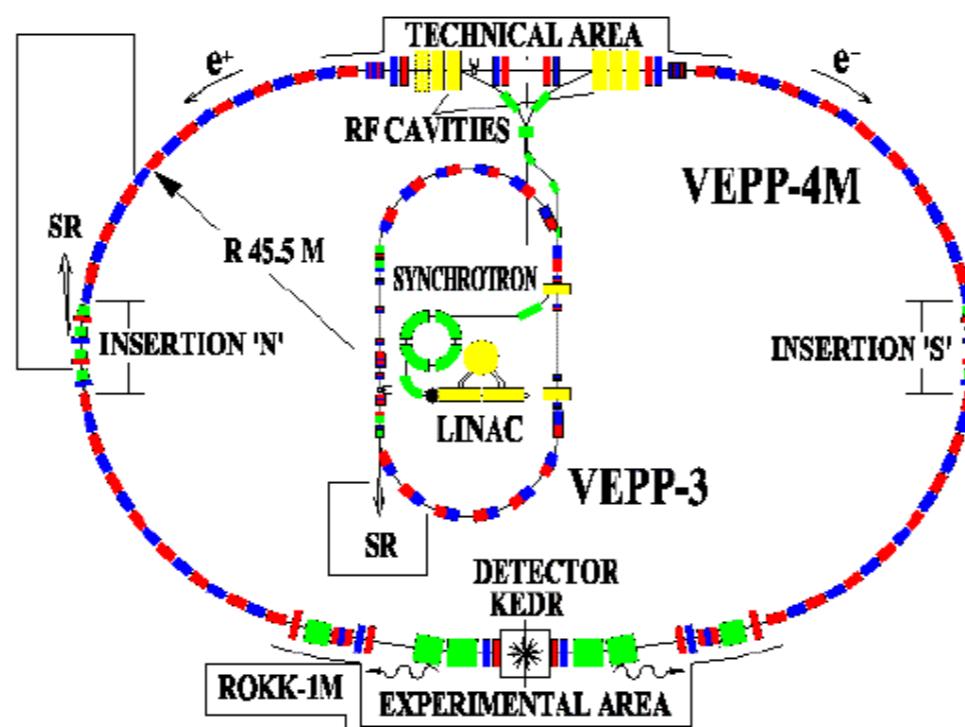
BEPC, IHEP, '90-'04
 $5 \times 10^{30} \text{ cm}^{-2} \cdot \text{s}^{-1}$



CESRc, Cornell, '04-'08
 $7 \times 10^{31} \text{ cm}^{-2} \cdot \text{s}^{-1}$



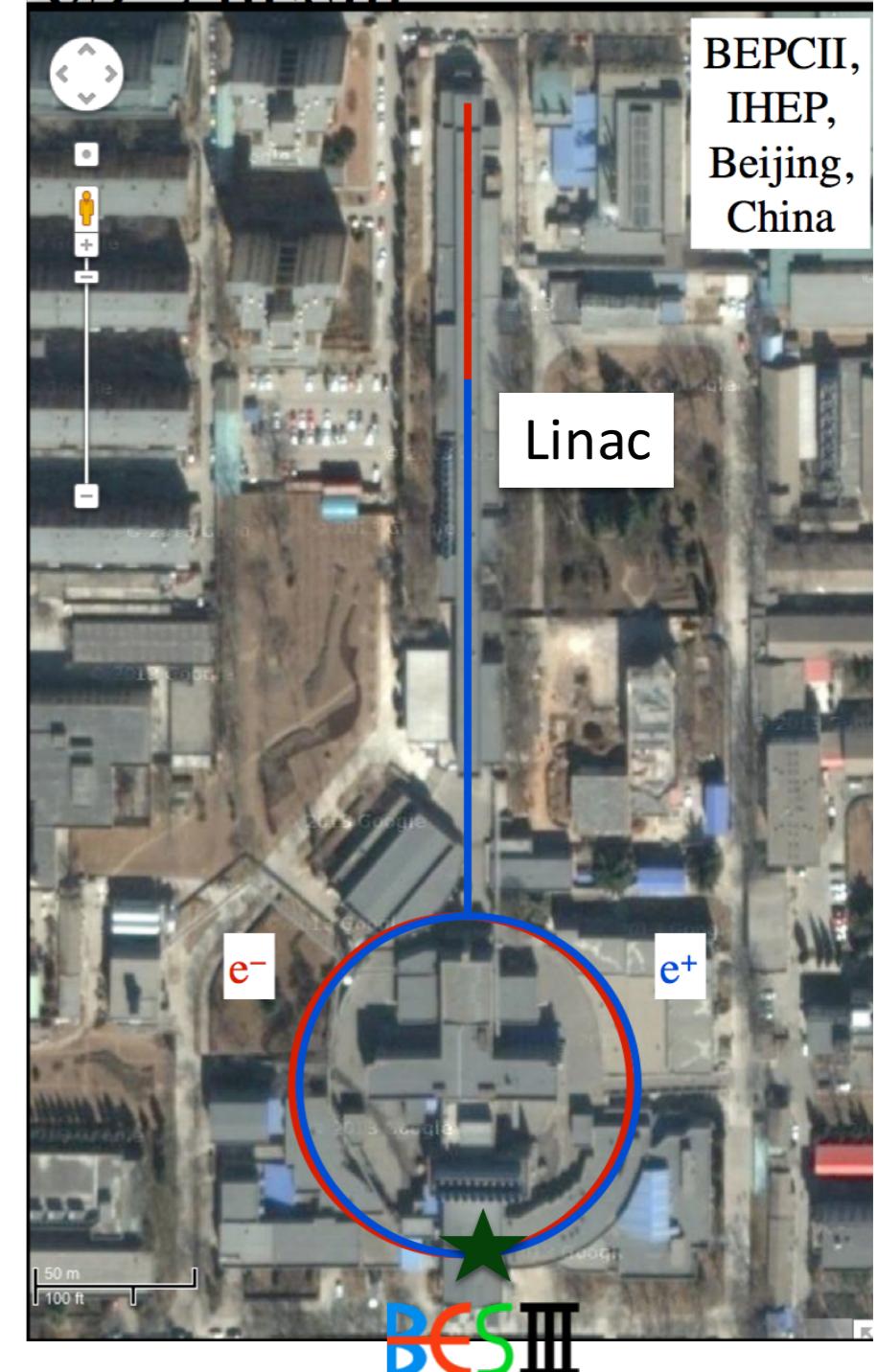
VEPP-4M, Novosibirsk, '02-'12
 $1 \times 10^{30} \text{ cm}^{-2} \cdot \text{s}^{-1}$



BEPCII, IHEP, '08-'20(?)
 $1 \times 10^{33} \text{ cm}^{-2} \cdot \text{s}^{-1}$

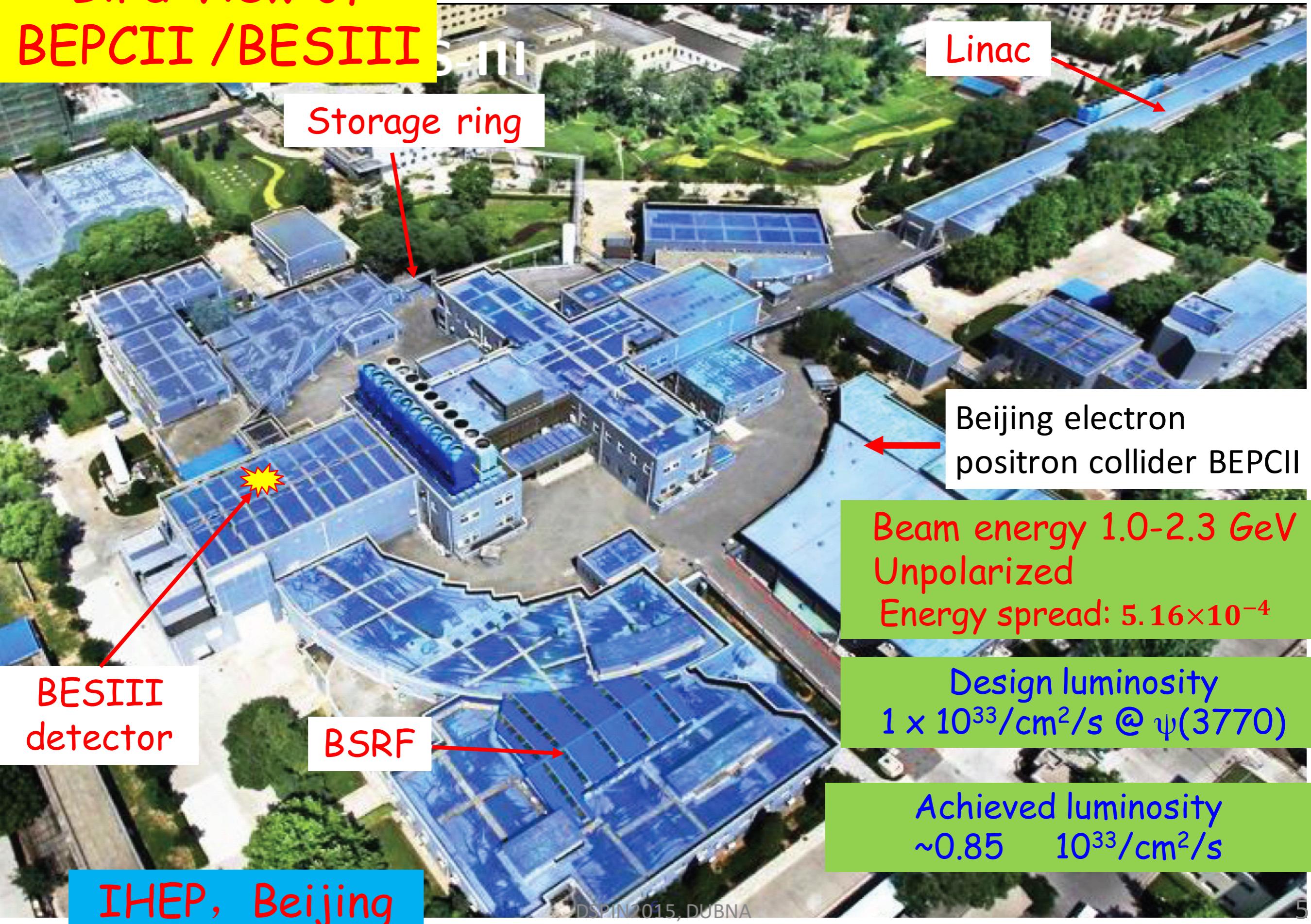


Beijing Electron Positron Collider-II (BEPCII)



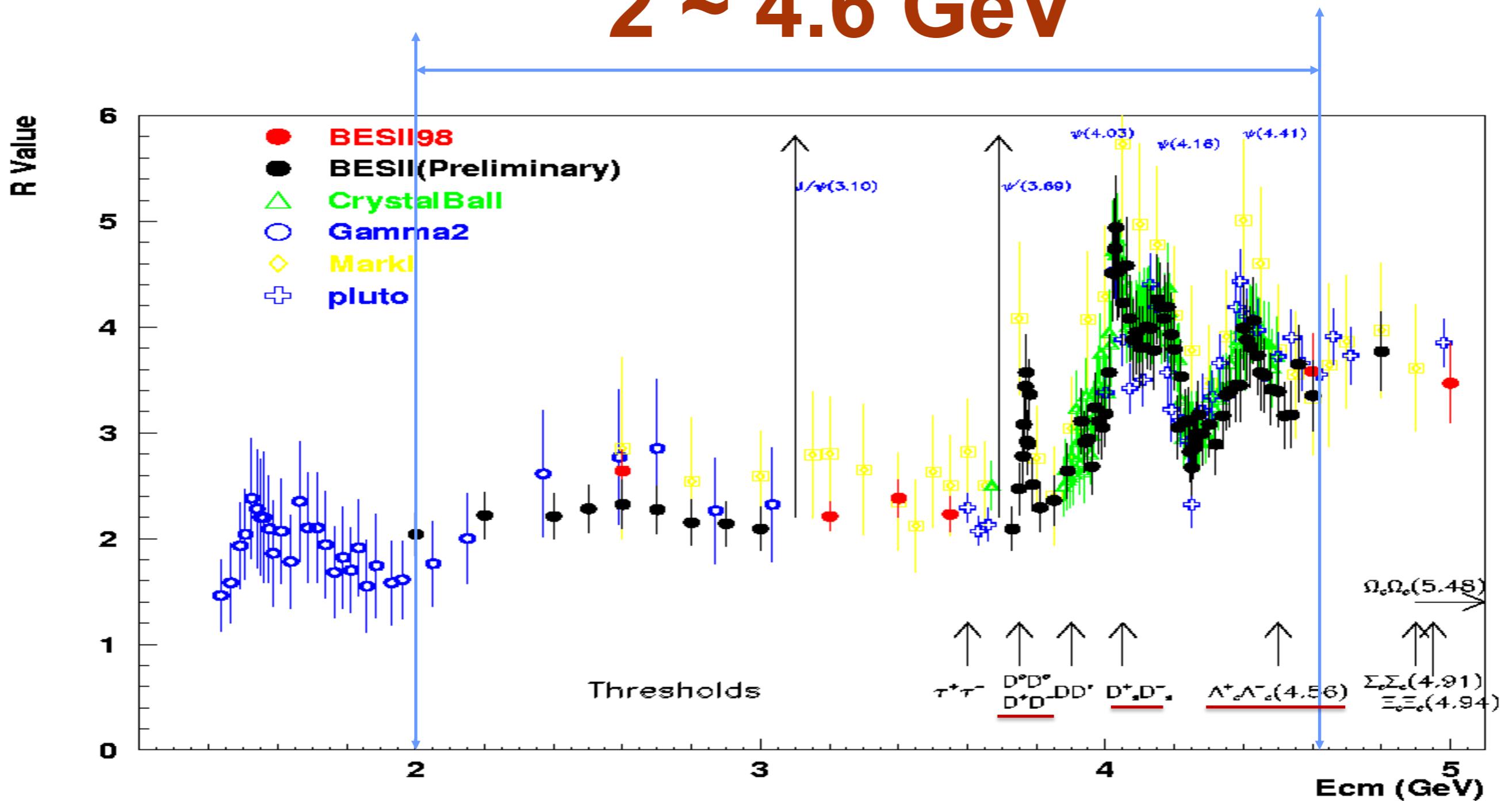
- **2004: started BEPCII/BESIII construction**
- **2008: test run**
- **2009 - now: BESIII physics run**
 - ~60% Physics run
 - ~30% Synchrotron radiation run

Bird View of BEPCII /BESIII



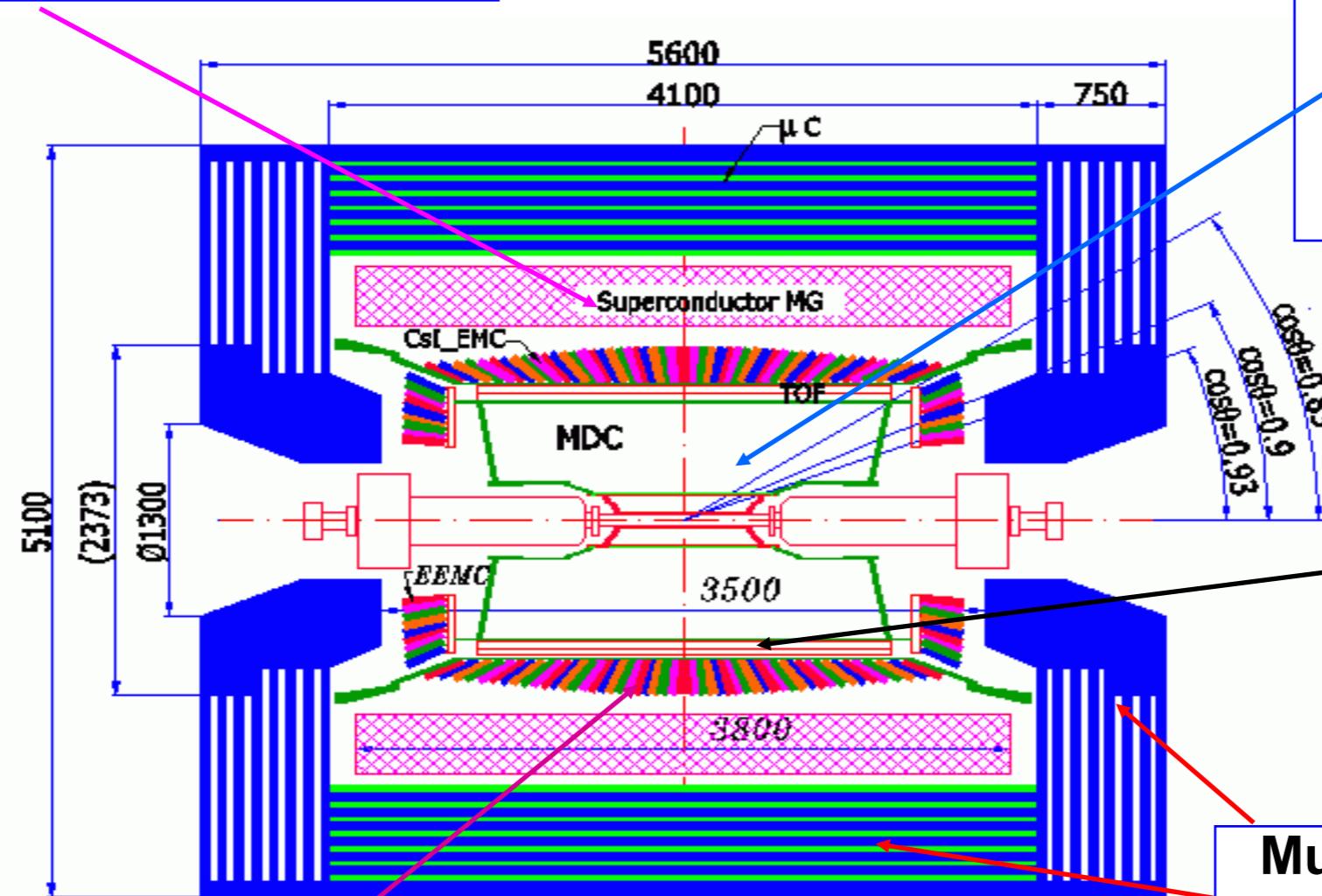
Energies of the BEPCII Collider

2 ~ 4.6 GeV



The BESIII Detector

Magnet: 1 T Super conducting



MDC: small cell & He gas
 $\sigma_{xy} = 130 \mu\text{m}$
 $s_p/p = 0.5\% @ 1\text{GeV}$
 $dE/dx = 6\%$

TOF:
 $\sigma_T = 90 \text{ ps Barrel}$
 110 ps Endcap

Muon ID: 8~9 layer RPC
 $\sigma_{R\Phi} = 1.4 \text{ cm} \sim 1.7 \text{ cm}$

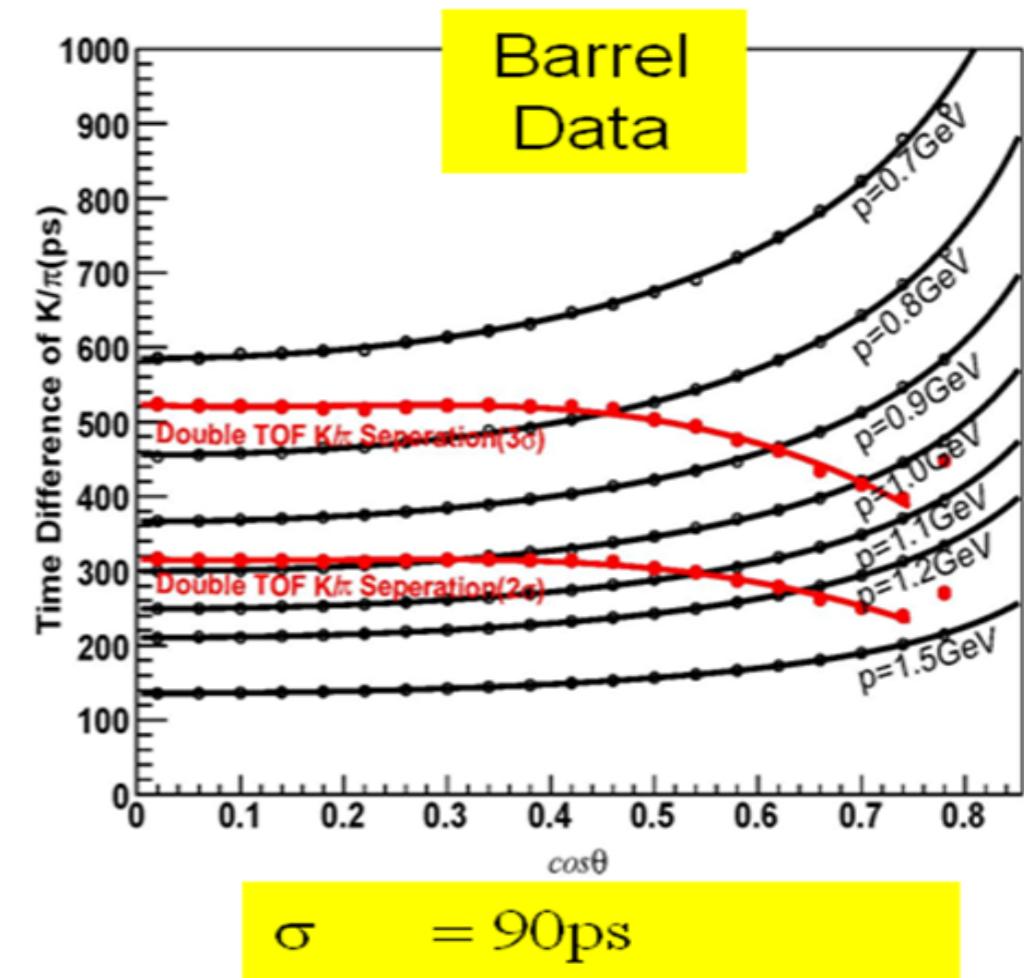
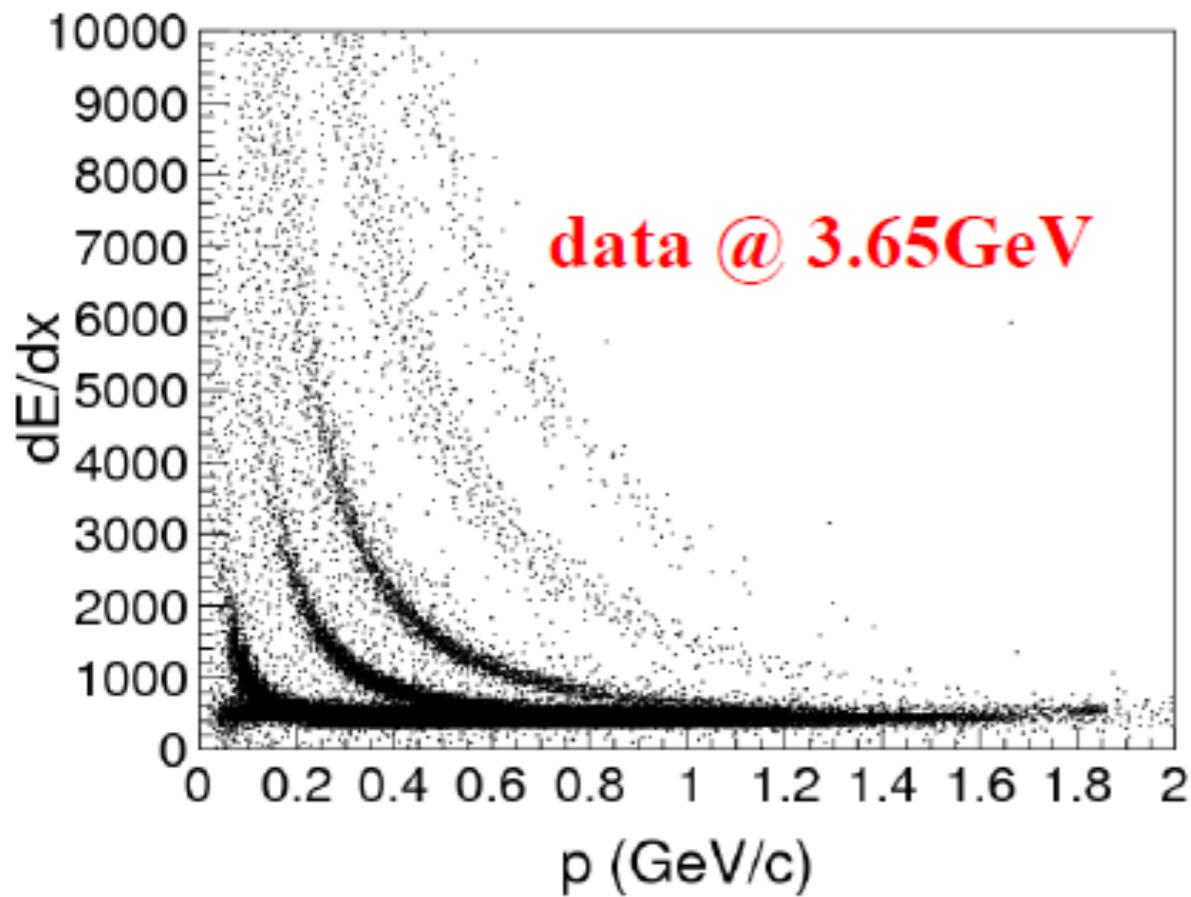
EMCAL: CsI crystal
 $\Delta E/E = 2.5\% @ 1\text{ GeV}$
 $\sigma_{\phi,z} = 0.5 \sim 0.7 \text{ cm}/\sqrt{E}$

Data Acquisition:
Event rate = 3 kHz
Throughput $\sim 50 \text{ MB/s}$

Trigger: Tracks & Showers
Pipelined; Latency = 6.4 μs

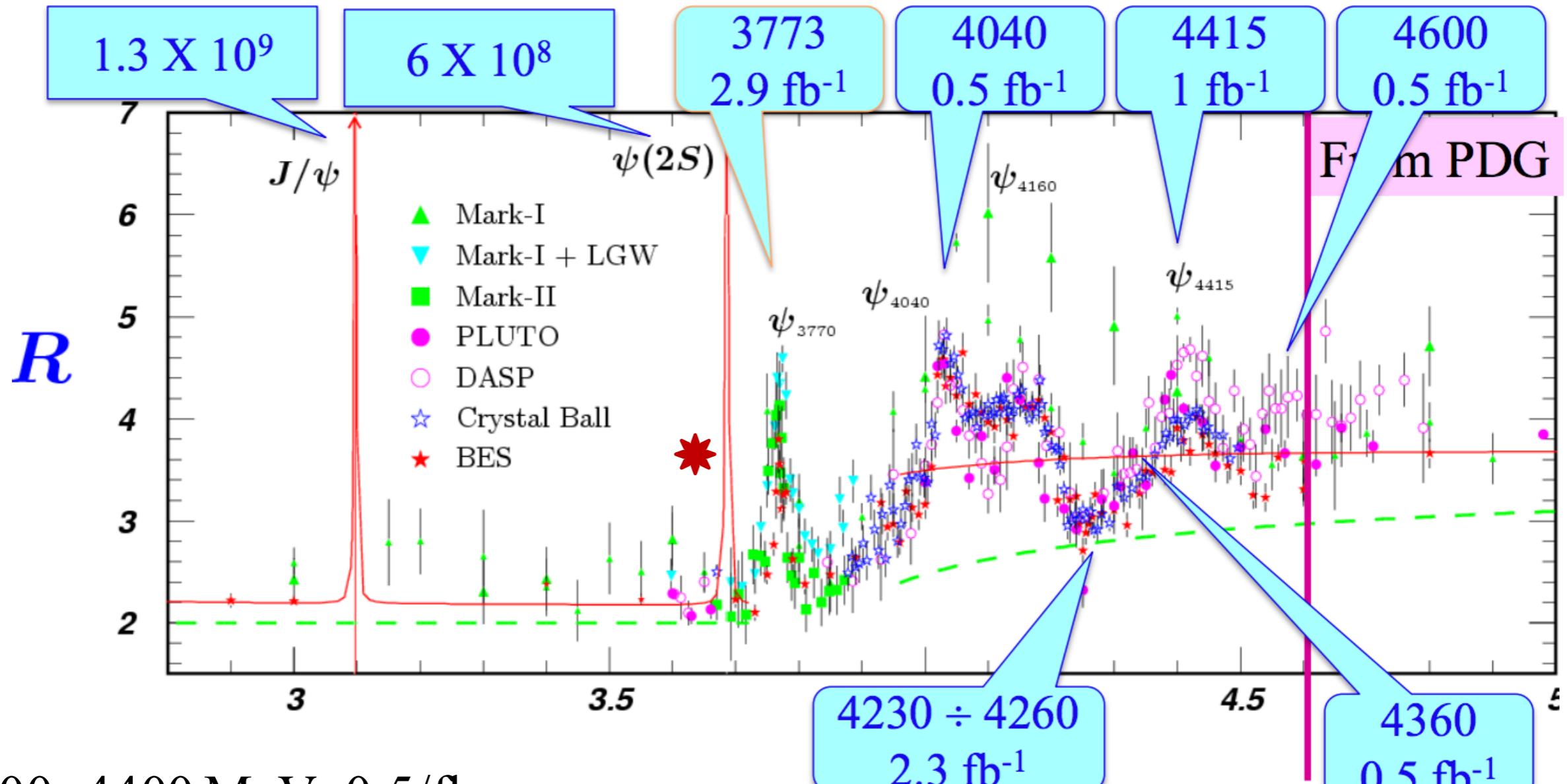
The new BESIII detector is hermetic for neutral and charged particle with excellent resolution, PID, and large coverage.

Particle ID Capacity



- dE/dx & TOF for PID
- Work well on $K/\pi < 1.0\text{GeV}$

BESIII data samples



- 4100~4400 MeV: 0.5/fb coarse scan
- 3850~4590 MeV: 0.5/fb fine scan
- In 2015, we finished energy scan at 2000~3000 MeV
- In 2016, we will take 3/fb Ds data about 4.17GeV (for Ds study) and 360/pb@3.51GeV (for Collins FF analysis)

Machine luminosity is optimal near ψ'' peak

The BESIII Collaboration

<http://bes3.ihep.ac.cn>

Political Map of the World, June 1999

USA (5)
Univ. of Hawaii
Carnegie Mellon Univ.
Univ. of Minnesota
Univ. of Rochester
Univ. of Indiana

Europe (13)
Germany: Univ. of Bochum,
Univ. of Giessen, GSI
Univ. of Johannes Gutenberg
Helmholtz Ins. In Mainz
Russia: JINR Dubna; BINP Novosibirsk
Italy: Univ. of Torino, Frascati, Ferrara U.
Netherland: KVI/Univ. of Groningen
Turkey: Turkey Accelerator Center

Mongolia (1)
Institute of phys. & Tech.
Korea (1)
Seoul Nat. Univ.

Pakistan (2)
Univ. of Punjab
COMSAT CIIT

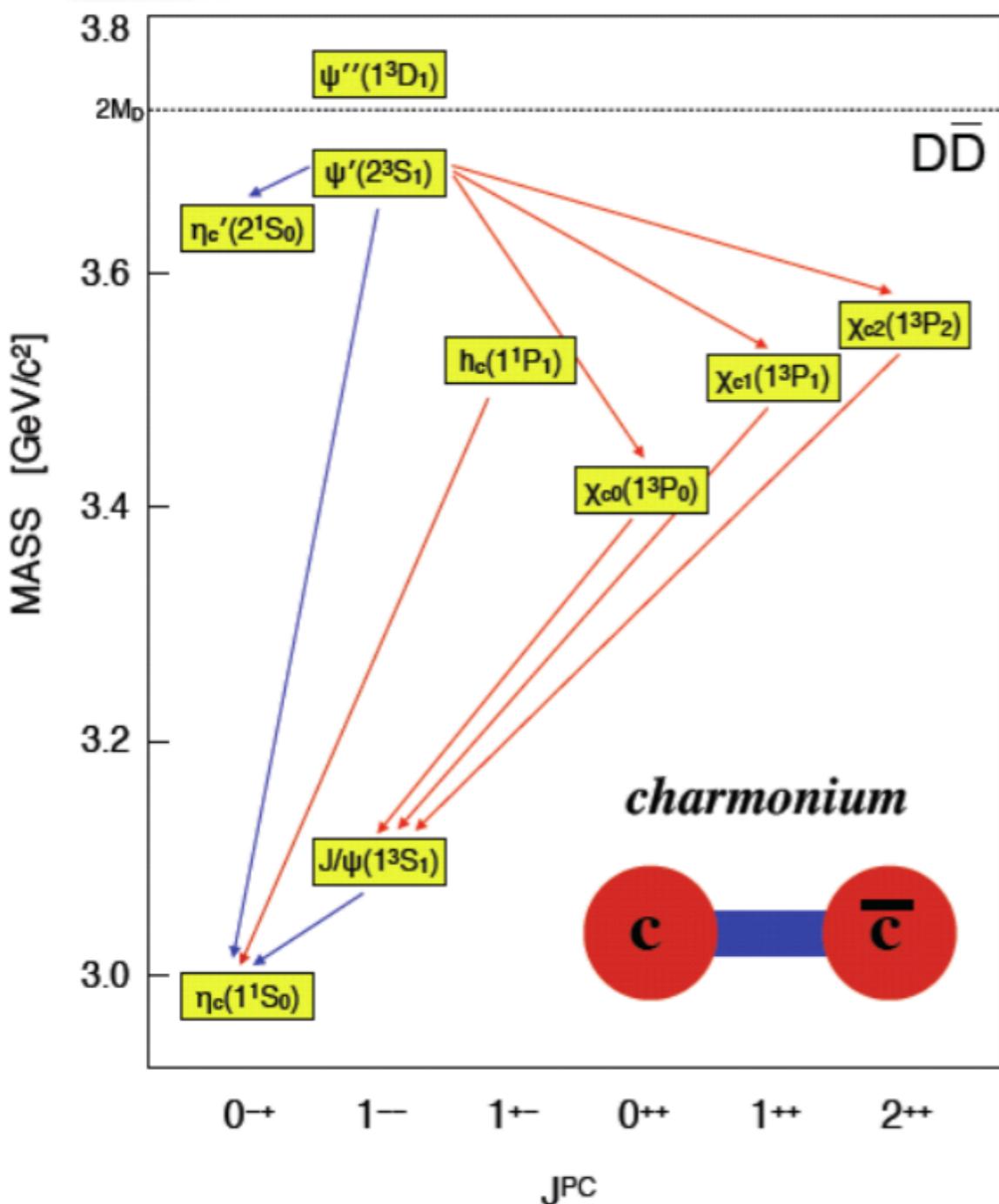
China(32)
IHEP, CCAST, [UCAS](#), Shandong Univ.,
Univ. of Sci. and Tech. of China
Zhejiang Univ., Huangshan Coll.
Huazhong Normal Univ., Wuhan Univ.
Zhengzhou Univ., Henan Normal Univ.
Peking Univ., Tsinghua Univ.,
Zhongshan Univ., Nankai Univ., Beihang Univ.
Shanxi Univ., Sichuan Univ., Univ. of South China
Hunan Univ., Liaoning Univ.
Nanjing Univ., Nanjing Normal Univ.
Guangxi Normal Univ., Guangxi Univ.
Suzhou Univ., Hangzhou Normal Univ.
Lanzhou Univ., Henan Sci. and Tech. Univ.
Univ. of Sci. & Tech. Liaoning

Japan (1)
Tokyo Univ.

~400 physicists

55 institutions from 12 countries

BESIII – physics using “charm”



Charmonium physics:

- Spectroscopy
- transitions and decays

Light hadron physics:

- meson & baryon spectroscopy
- glueball & hybrid
- two-photon physics
- e.m. form factors of nucleon

Charm physics:

- (semi)leptonic + hadronic decays
- decay constant, form factors
- CKM matrix: V_{cd} , V_{cs}
- D^0 - $D^0\bar{\text{bar}}$ mixing and CP violation
- rare/forbidden decays

Tau physics:

- Tau decays near threshold
- tau mass scan

...and many more.

... and more

- Form factor
 - ✓ An important observable of hadron structure
 - ✓ To access time-like form factor through (ISR) electron-position annihilation process.
 - To test the analyticity of G_E and G_M
 - Near threshold measurement of proton and neutron
 - Unique hyperon data: Λ , Λ_c
 - ✓ To extract Space-Like transition form factor using $\gamma\gamma^*\rightarrow P$
- Fragmentation functions (FF) → unpolarized FF
 - Single hadron inclusive production
 - ✓ Constrain FF at low energy scale and high z: $K^{\pm/0}/\pi^{\pm/0}+X$
 - ✓ New data for inclusive η/ϕ production...
 - Two hadron inclusive production
→ correlation of two FF
 - ✓ To probe spin-dependent FF, eg, Collins FF

Collins Fragmentation Function(FF)



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

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

D_1 : the unpolarized FF

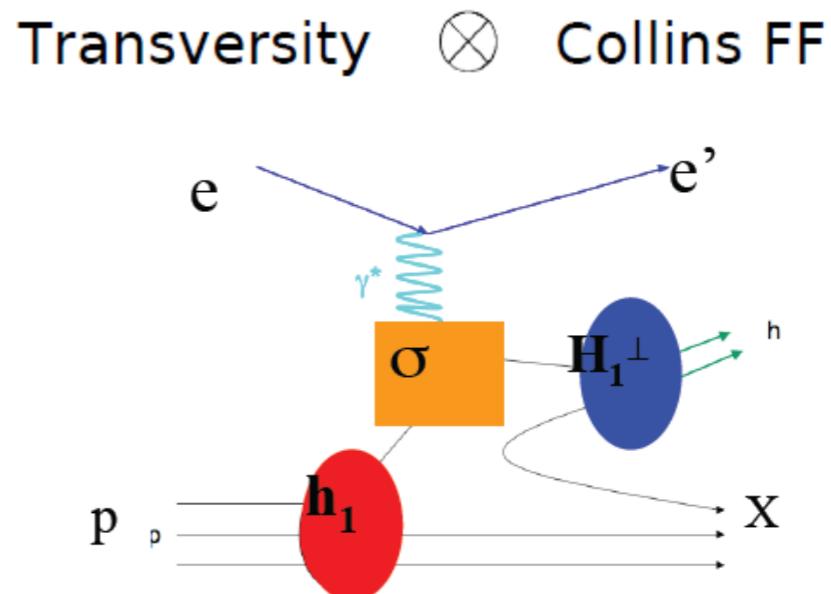
H_1 : Collins FF

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

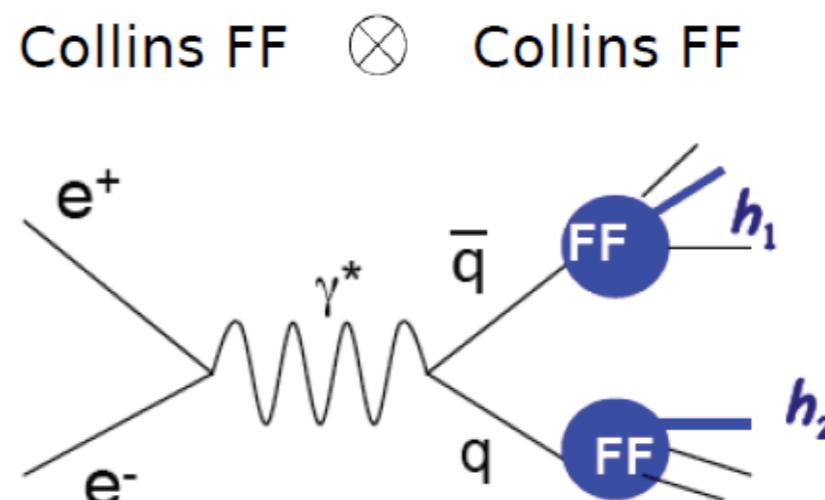
→ depends on $z = 2E_h/\sqrt{s}$, $\mathbf{P}_{h\perp}$

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

SIDIS



e+ e-

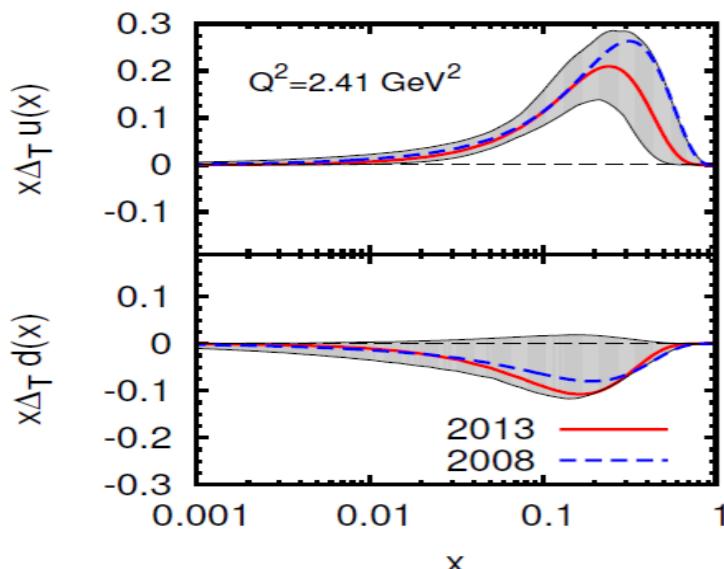


Global Analysis on Collins FF

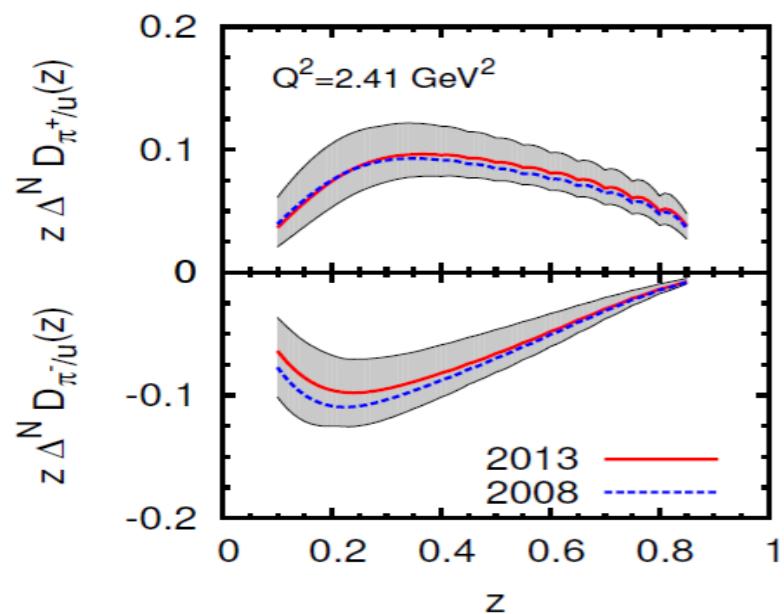
Anselmino et al., PRD 87, 094019 (2013)

Using data from HERMES, COMPASS, Belle

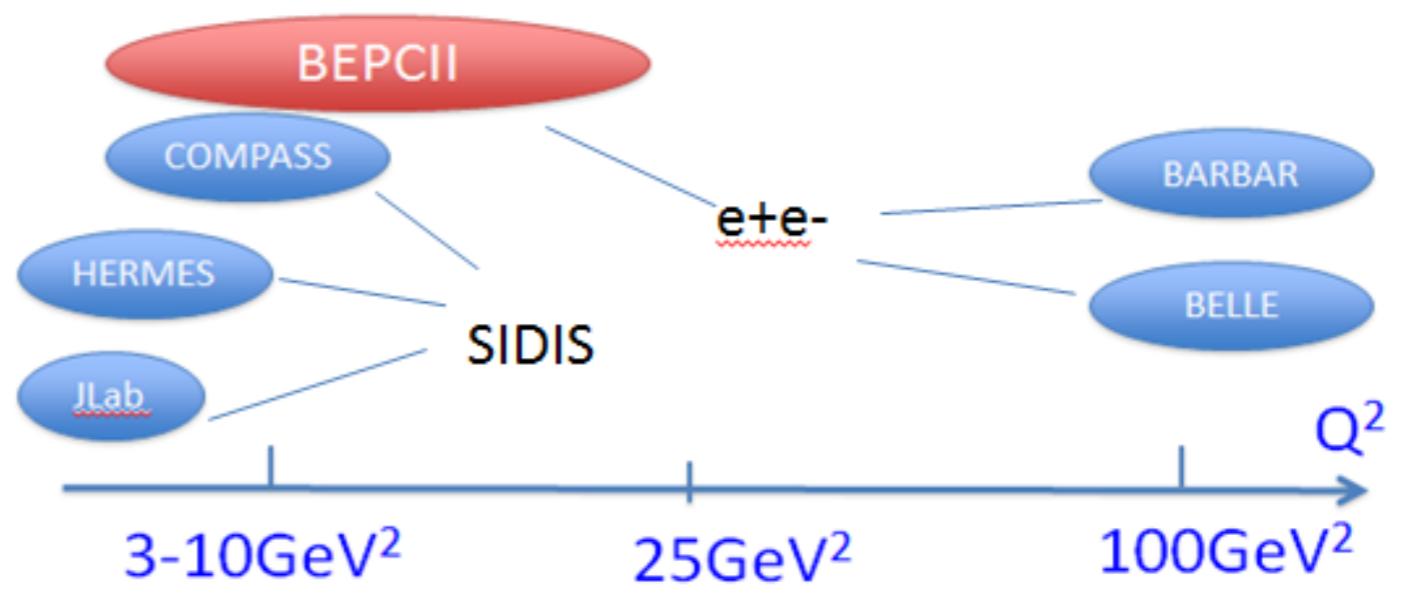
Transversity



Collins pion FF

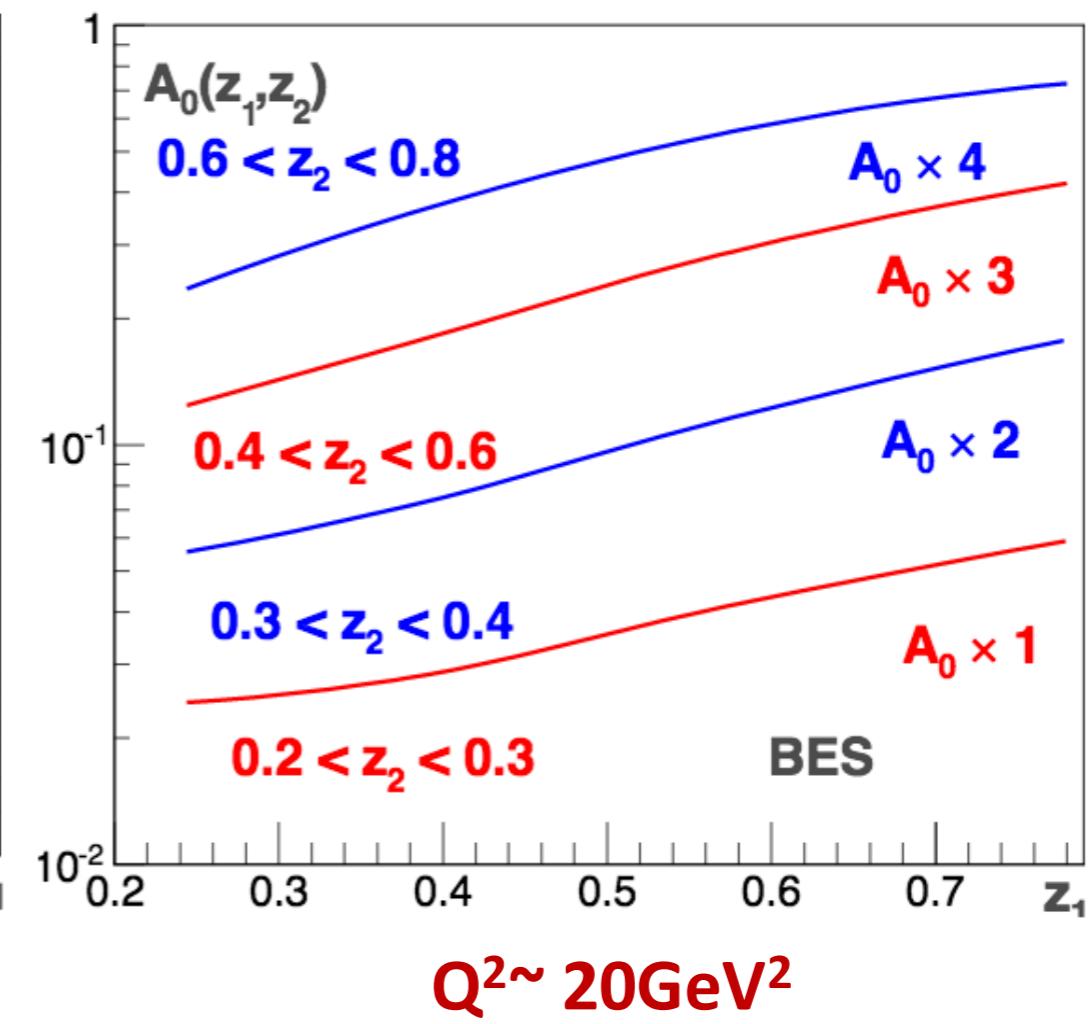
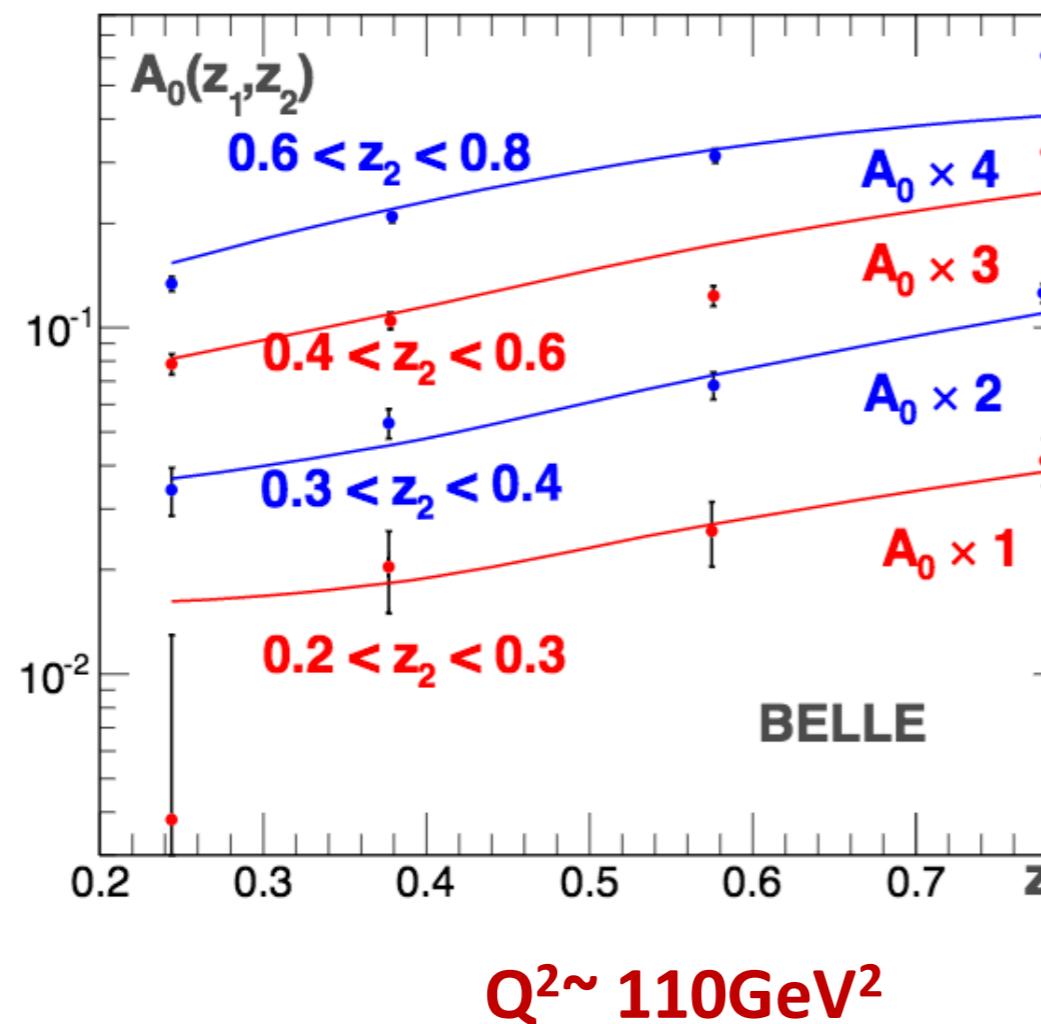


- The Q^2 evolution of Collins FFs was assumed following the extrapolation in the unpolarized FF, and this has not been validated.
- Low Q^2 data from e^+e^- collider is useful.
- BEPCII
 - Similar Q^2 coverage with SIDIS



Predicted Collins Asymmetries

P. Sun and F. Yuan, Phys. Rev. D 88, 034016 (2013).

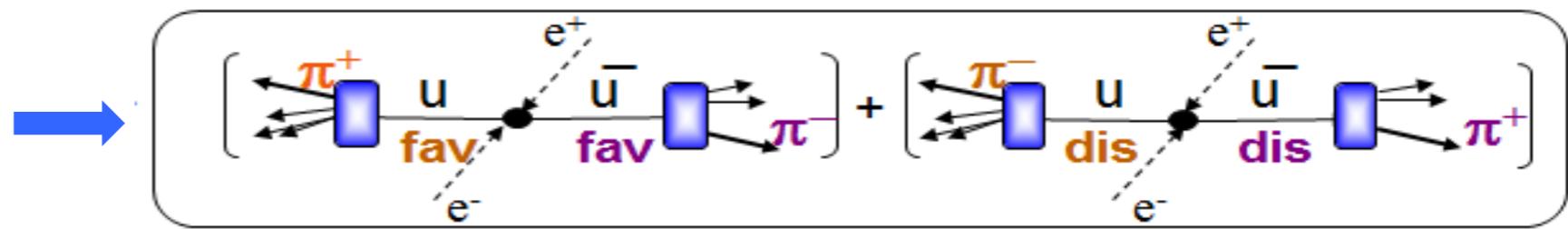


- Collins asymmetry is predicted larger at lower Q^2 region!
- Asymmetries increase as z grows

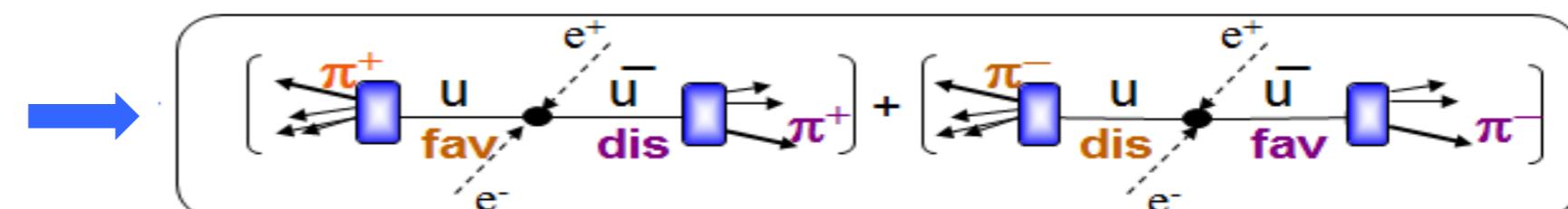
Product of Two Collins FFs

- **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.: $u \rightarrow \pi^+$, $d \rightarrow \pi^-$
- **Disfavored** for $d \rightarrow \pi^+$, $u \rightarrow \pi^-$

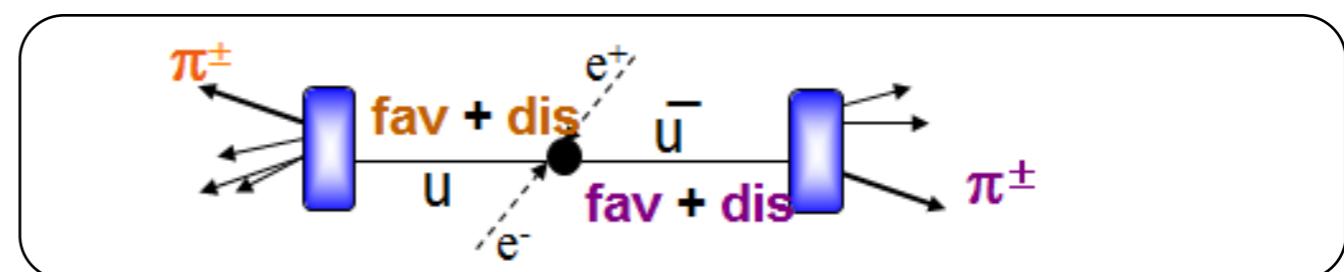
Unlike-sign pairs = U:
 $\pi^\mp\pi^\pm: (\text{fav} \times \text{fav}) + (\text{dis} \times \text{dis})$



Like-sign pairs = L:
 $\pi^\pm\pi^\pm: (\text{fav} \times \text{dis}) + (\text{dis} \times \text{fav})$



All charged pairs = C (U+L):
 $\pi\pi: (\text{fav} + \text{dis}) \times (\text{fav} + \text{dis})$
 $\pi = \pi^\pm$



- All charged pion pairs are divided into:
 - **Unlike-sign pairs ($\pi^+\pi^-$)**
 - **Like-sign pairs ($\pi^+\pi^+$ and $\pi^-\pi^-$)**
 - **All Charged pairs ($\pi\pi$)**

Data Sample and Event Selection

arXiv:1507.06824



$\sim 62 \text{ pb}^{-1}$ @3.65GeV

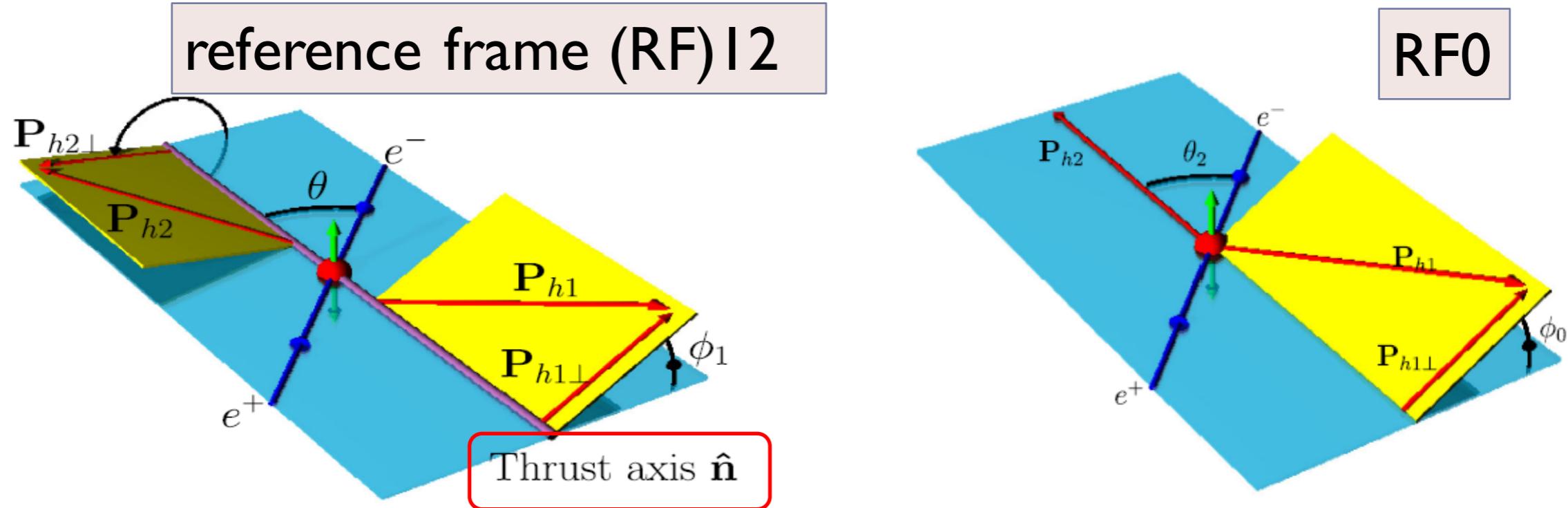
- continuum region in-between J/psi and psi(2S) peaks
- fewer charm backgrounds!

- ◆ # of charged tracks ≥ 3
- ◆ # of charged pion ≥ 2
- ◆ No electron to suppress Bhabha
- ◆ The total visible energy $> 1.5 \text{ GeV}$.

to suppress resonance decays to dipions, we require the charged π

- ◆ $0.2 < z = 2E_h/\sqrt{s} < 0.9$
- ◆ open angle $> 120^\circ$ to select back-to-back pion-pair.

Double Collins Asymmetries (DCA)

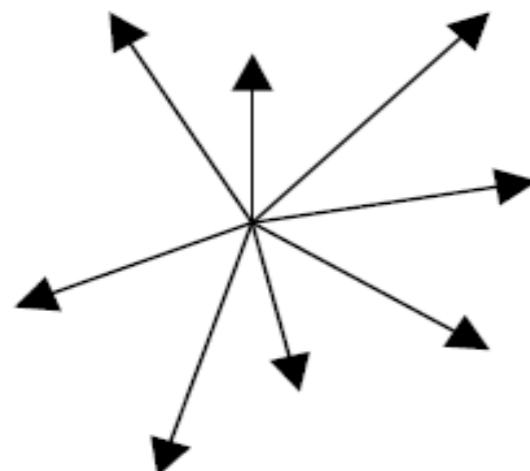


- ▶ The spin correlation of hadron fragmented from quark and anti-quark in opposite hemisphere follows a $\cos(\phi_1 + \phi_2)$ modulation in RF12 or a $\cos(2\phi_0)$ modulation in RF0
 - DCA were observed in both definitions by Belle and BaBar

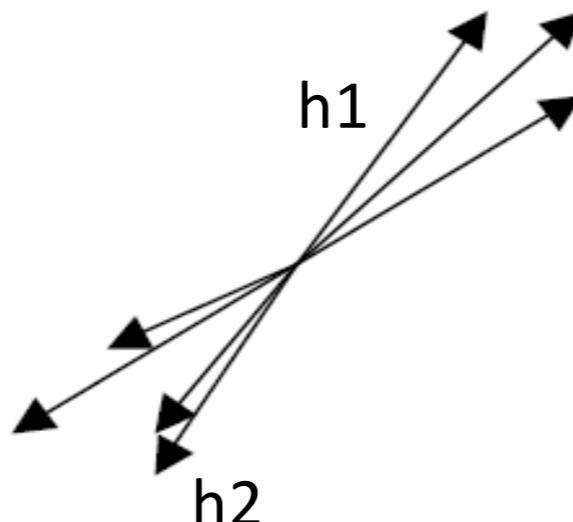
Belle Collaboration: Phys. Rev. Lett. 96, 232002 (2006); Phys. Rev. D 78, 032011 (2008); Phys. Rev. D 86, 039905(E) (2012).

BaBar Collaboration: Phys. Rev. D 90, 052003 (2014)

Difficulties---event shape is not jetty



BEPCII energy

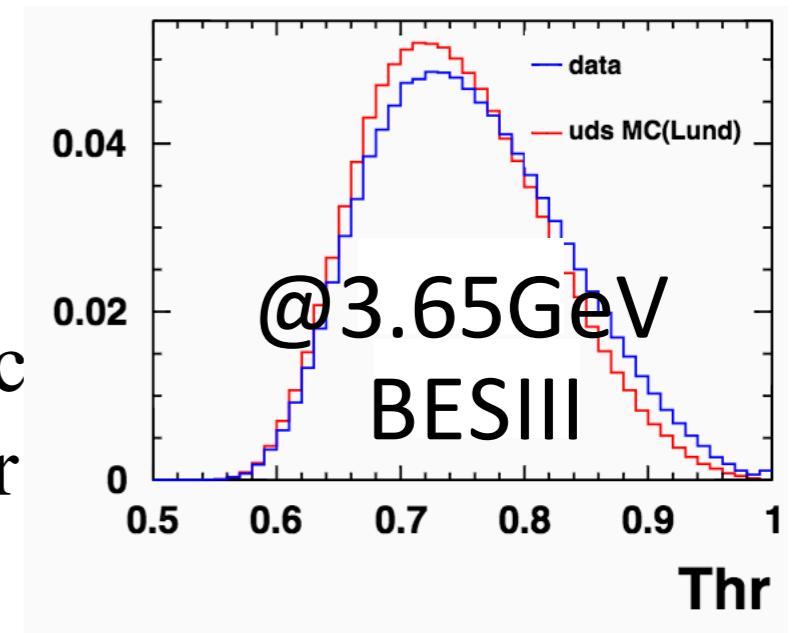


Belle/Babar

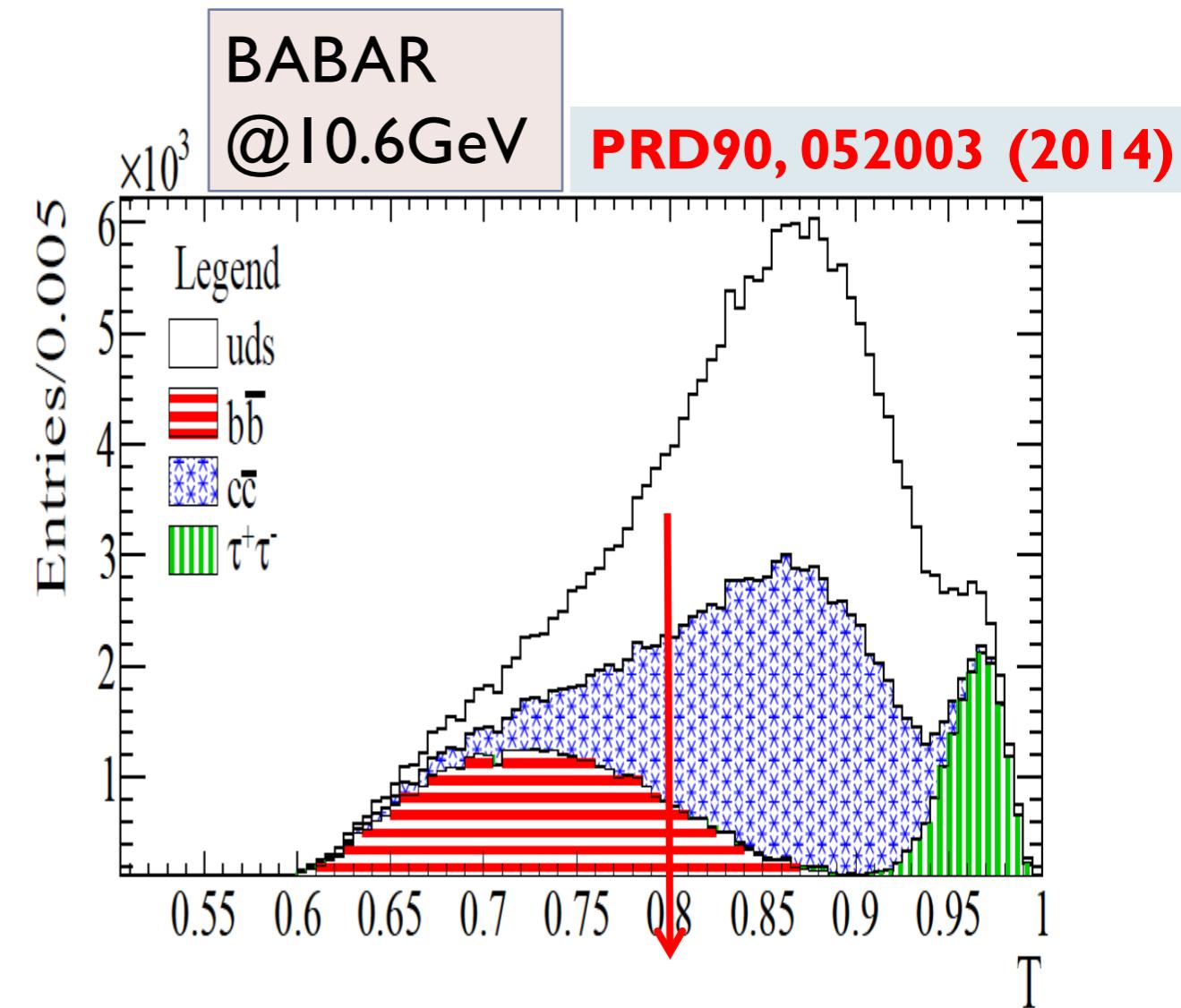
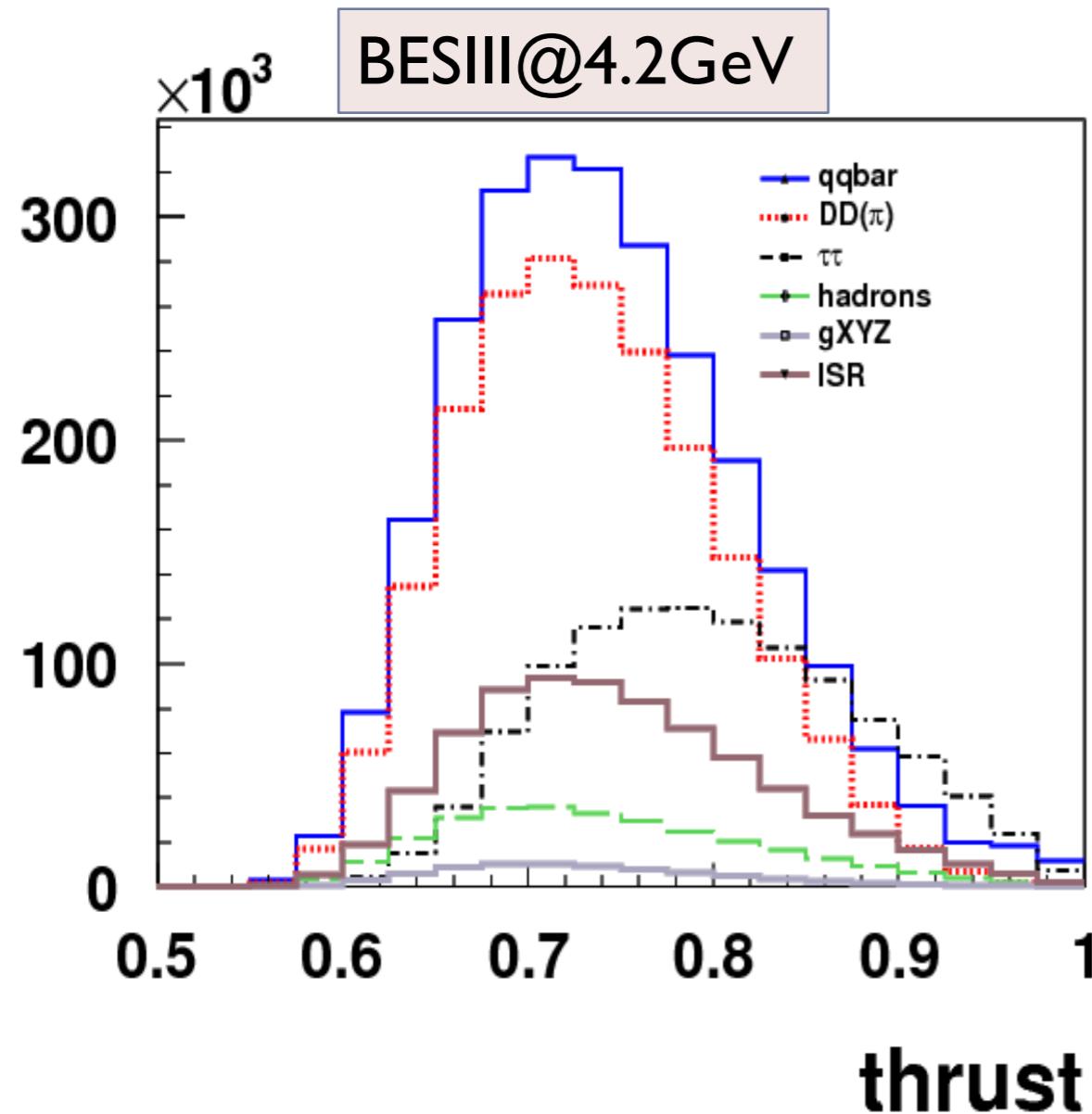
$$e^+e^- \rightarrow q\bar{q} \rightarrow h_1 h_2 X$$

$$T = \frac{\max_h \sum |\mathbf{P}_h^{\text{CMS}} \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h^{\text{CMS}}|},$$

- ✓ In B factories, the thrust axis is used as a approximation of the $q\bar{q}$ axis
 - not needed in RF0, hence RF0 is adopted
- ✓ At BESIII, $q\bar{q}$ events shape are more isotropic
- ✓ Very different situation compared to Belle/BaBar



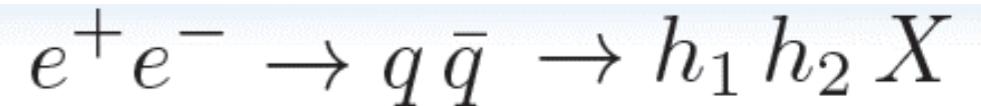
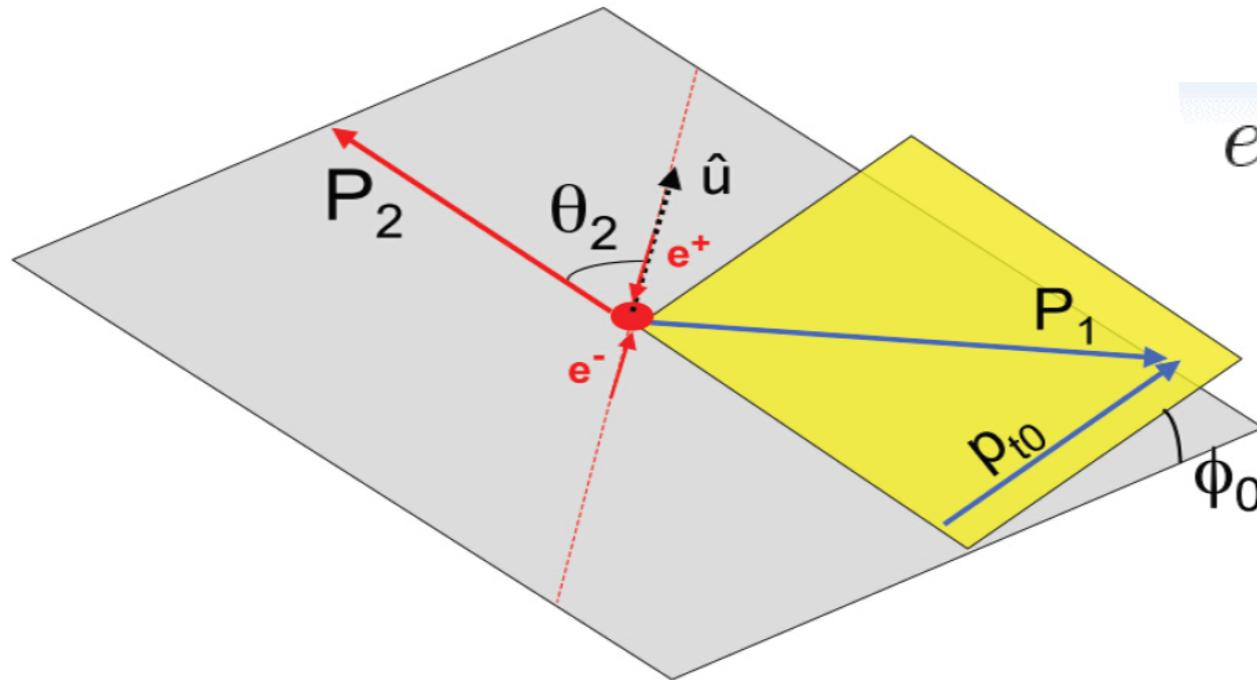
Difficulties at higher energy



- ✓ Thrust value is used to suppress backgrounds at Belle/BaBar.
- ✓ However, it is not a good cut criterion at BESIII

The Reference Frame

D. Boer Nucl.Phys.B806:23,2009



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

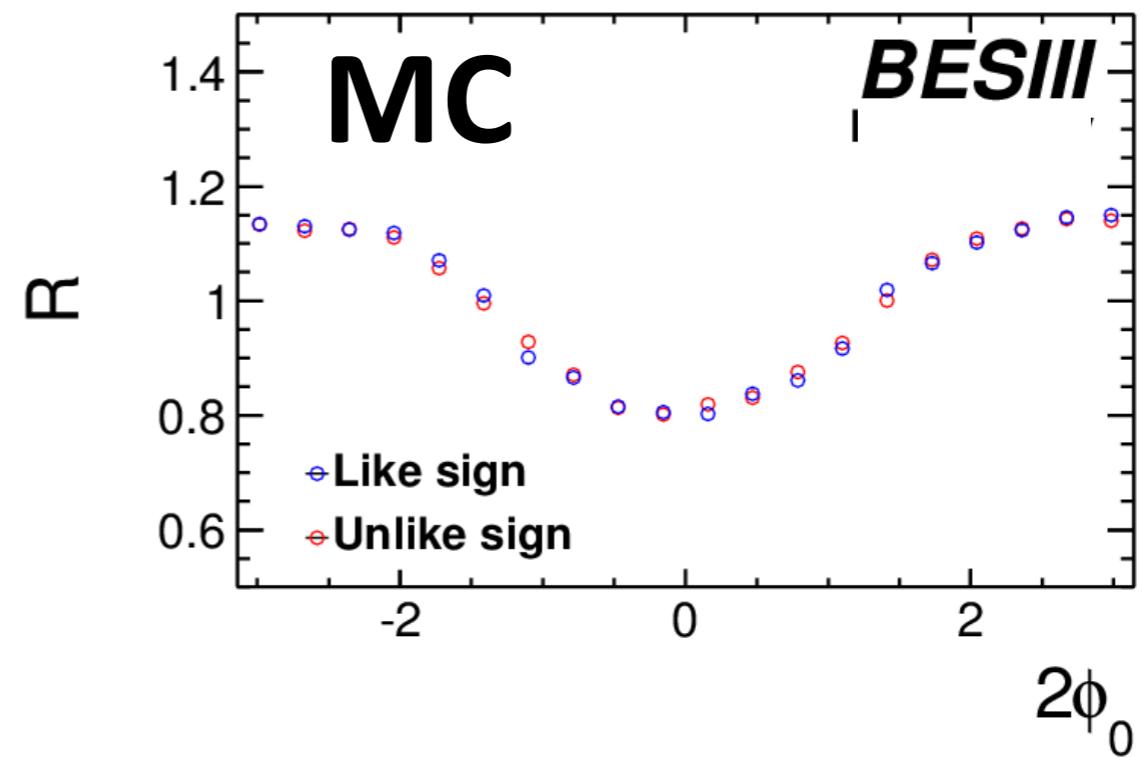
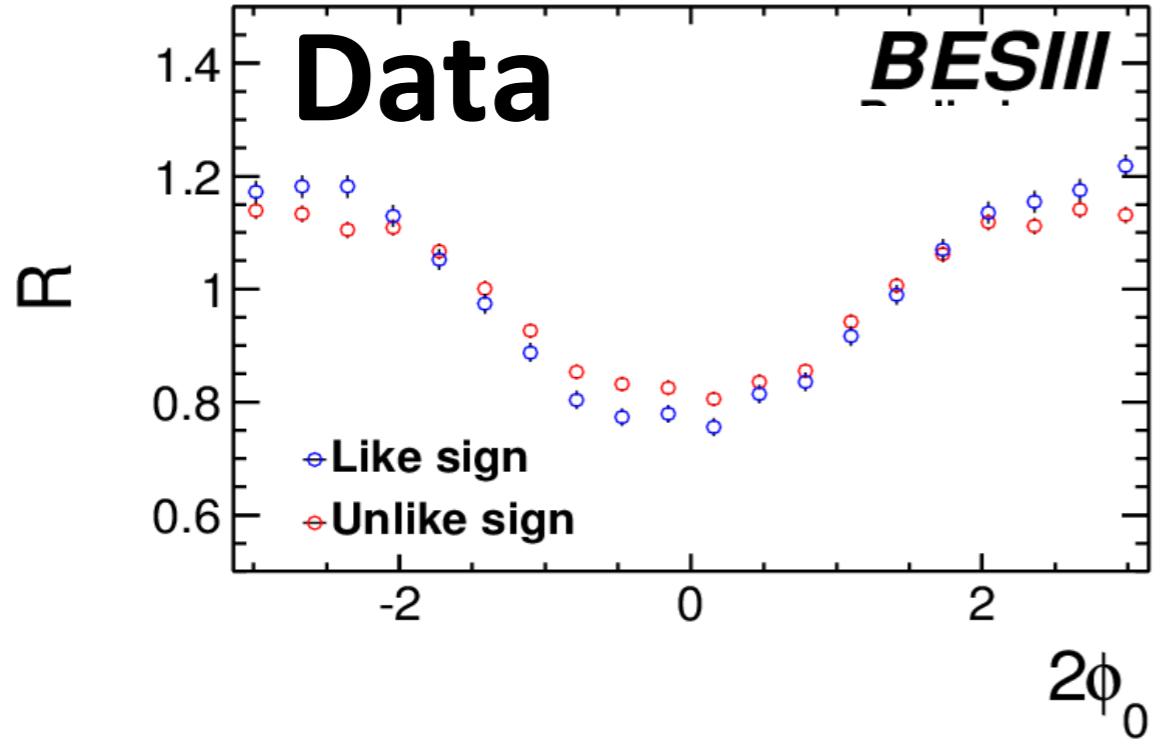
$$\mathcal{F}[X] = \sum_{q\bar{q}} \int [2\hat{h} \cdot k_{T1} \hat{h} \cdot k_{T2} - k_{T1} \cdot k_{T2}]$$

$$d^2 k_{T1} d^2 k_{T2} \delta^2(k_{T1} + k_{T2} - q_T) X$$

$$k_{Ti} = z_i p_{Ti}$$

- Collins effect: cosine modulation.

$2\phi_0$ Raw Distribution

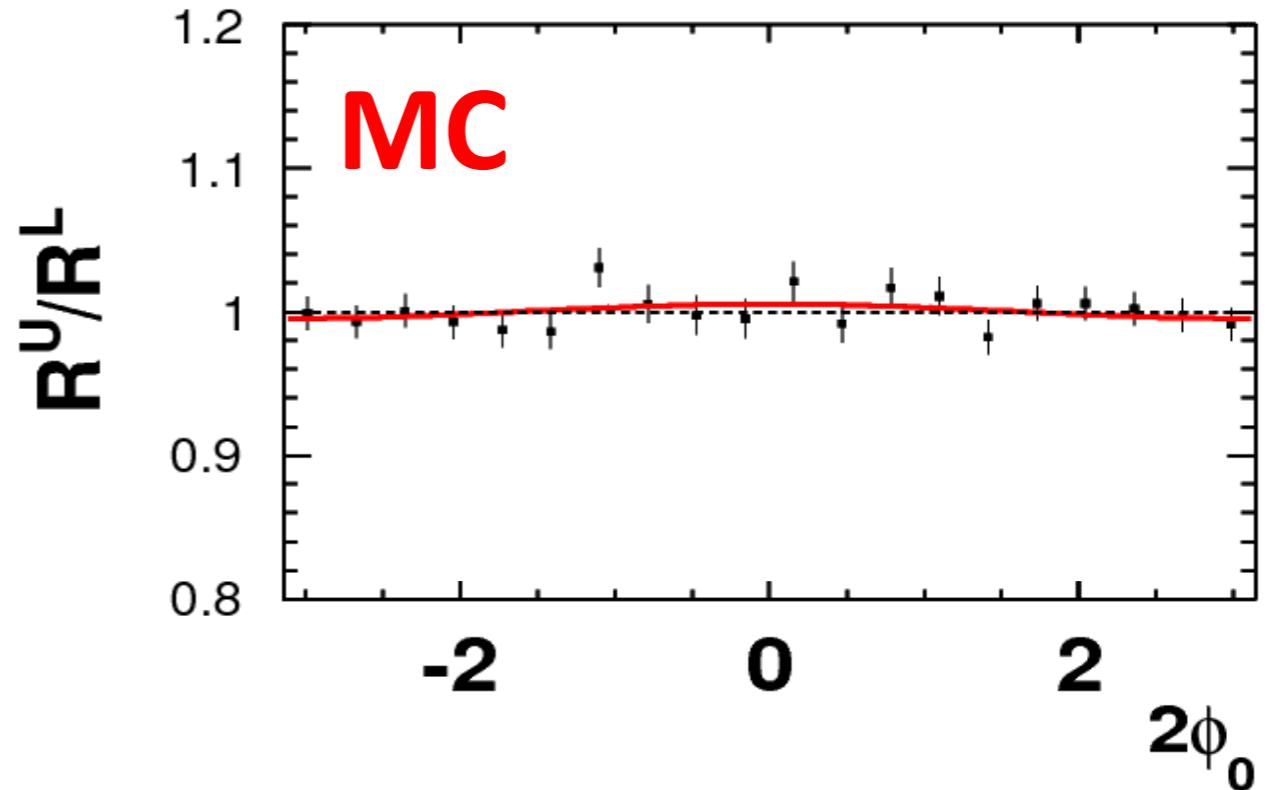
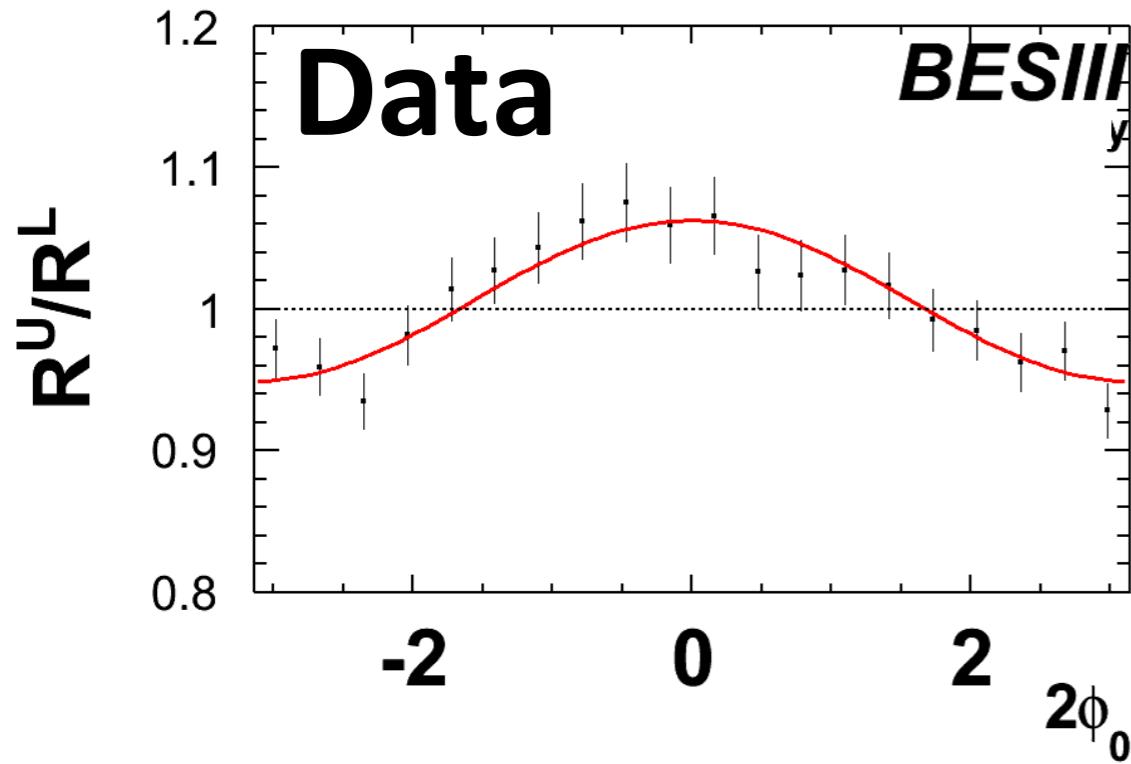


- The normalized ratio

$$R := \frac{N(2\phi_0)}{\langle N_0 \rangle}$$

- For **Charged**, **Unlike-sign** and **Like-sign** pairs, we have R^U , R^C , R^L
- Raw $2\phi_0$ distributions are subjected to the limited **acceptance** and non-uniform **efficiencies** of the detector!
- The MC simulation does not include the Collins effect.
- Small deviations in **Like** and **Unlike** in data indicate asymmetries.

Double Ratio (DR)



- Acceptance effects and radiation effects can be reduced by performing the ratio of Unlike/Like sign pion pairs (R^U/R^L) or Unlike/Charged pairs (R^U/R^C)

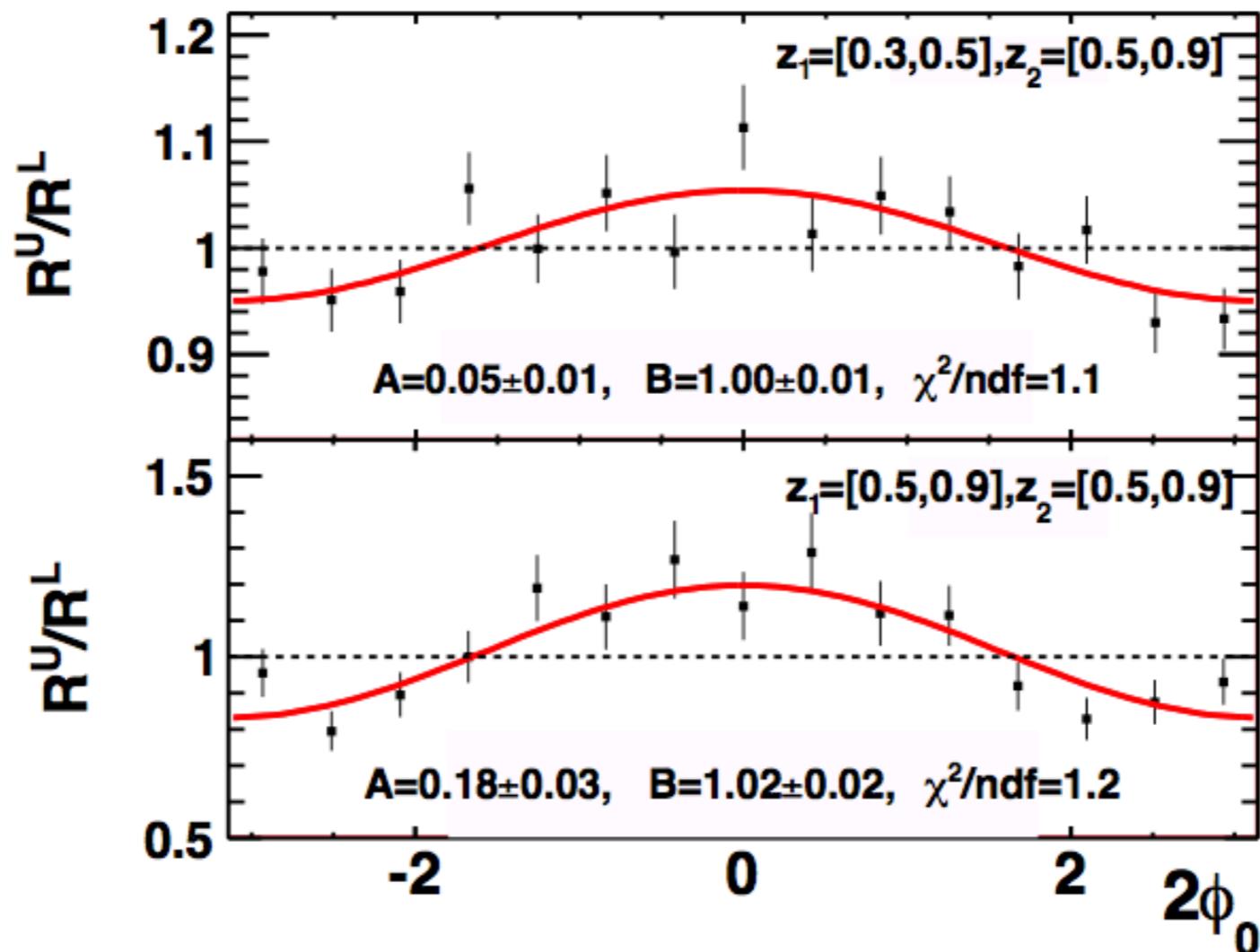
$$\frac{R^U}{R^L} \simeq 1 + \frac{\sin^2 \theta}{1 + \cos^2 \theta} \boxed{\cos(2\phi_0)(G^U - G^L)}$$

$$\frac{R^U}{R^C} \simeq 1 + \frac{\sin^2 \theta}{1 + \cos^2 \theta} \boxed{\cos 2\phi_0(G^U - G^C)}$$

- DRs are fitted by $\frac{R^U}{R^{L(C)}} = a \cos(2\phi_0) + b,$

- $A_{UL(C)} = \frac{a}{b}$ represents the asymmetries of interest.

Fit to DR in Different z Bins

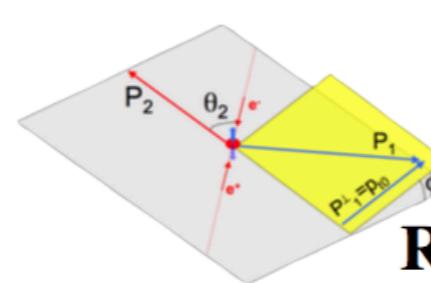
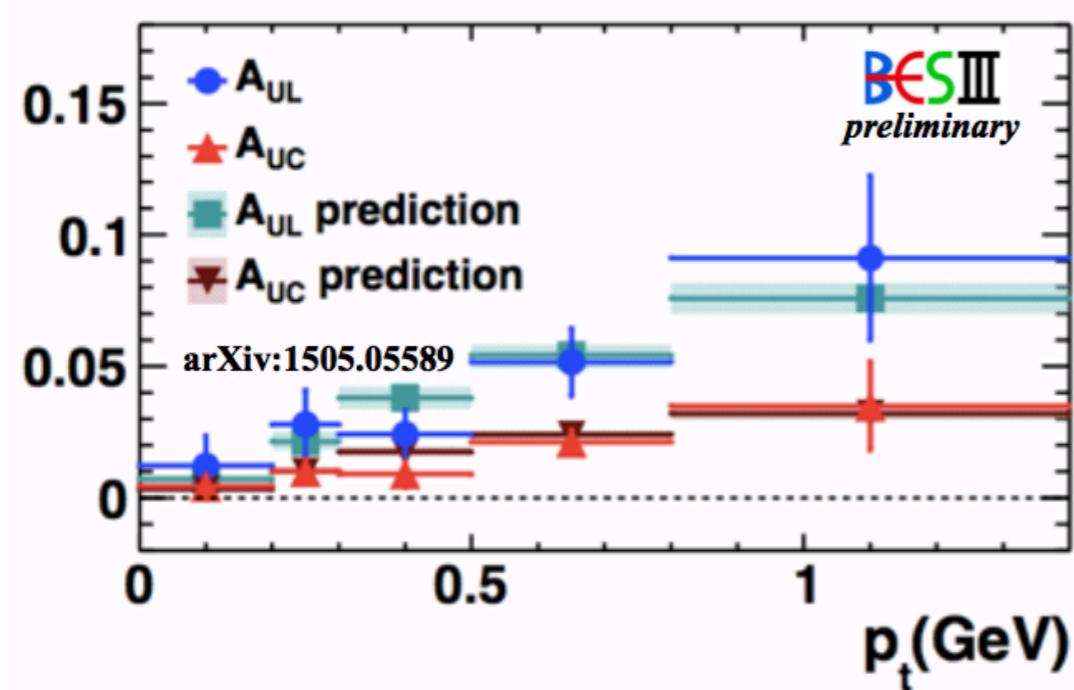
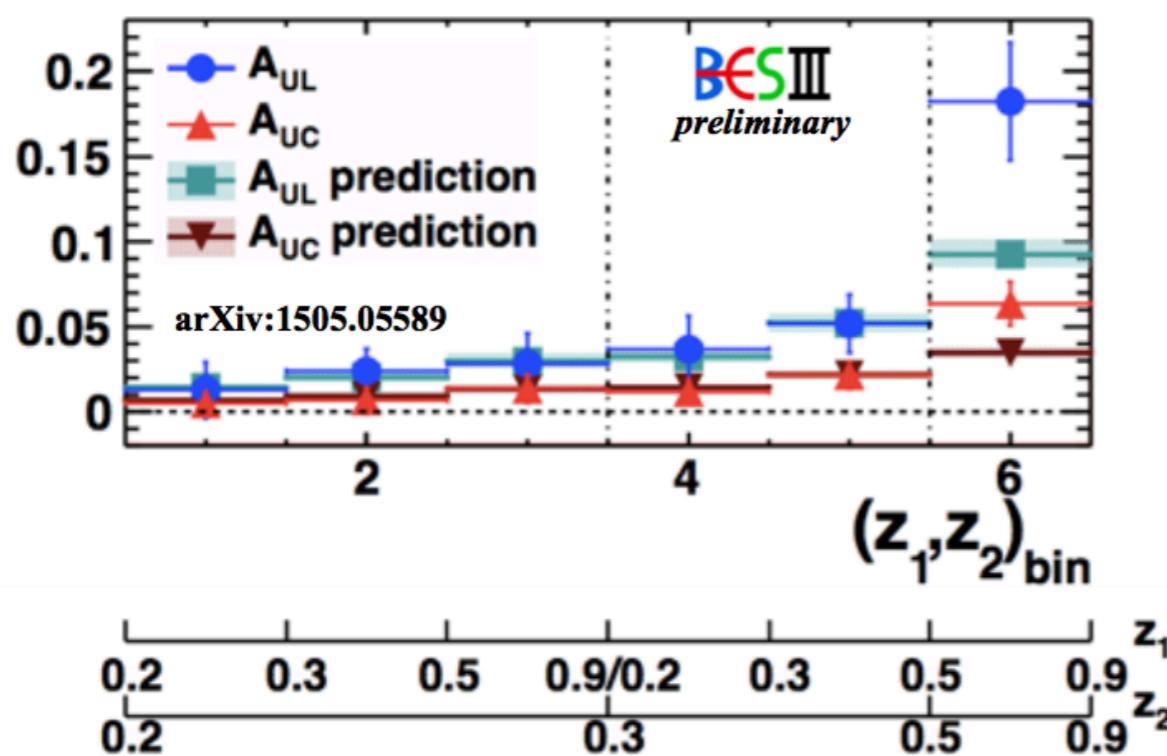


$$\frac{R^U}{R^{L(C)}} = A \cos(2\phi_0) + B,$$

Other considerations and checks

- Misidentification of K and π : unfolding the measurement of $A^{\pi\pi}$ and $A^{K\pi}$
- Gluon radiation effect: subtracting normalized yields $R^U - R^{L(C)}$
- Higher harmonic terms: including in the fit function
- Possible charge-dependent acceptance effects: studying double ratio of positively over negatively charged pion pairs
- Beam polarization: studying the angular distribution of $e^+e^- \rightarrow \mu^+\mu^-$
- Several zero asymmetry tests

Measurement of the Asymmetries

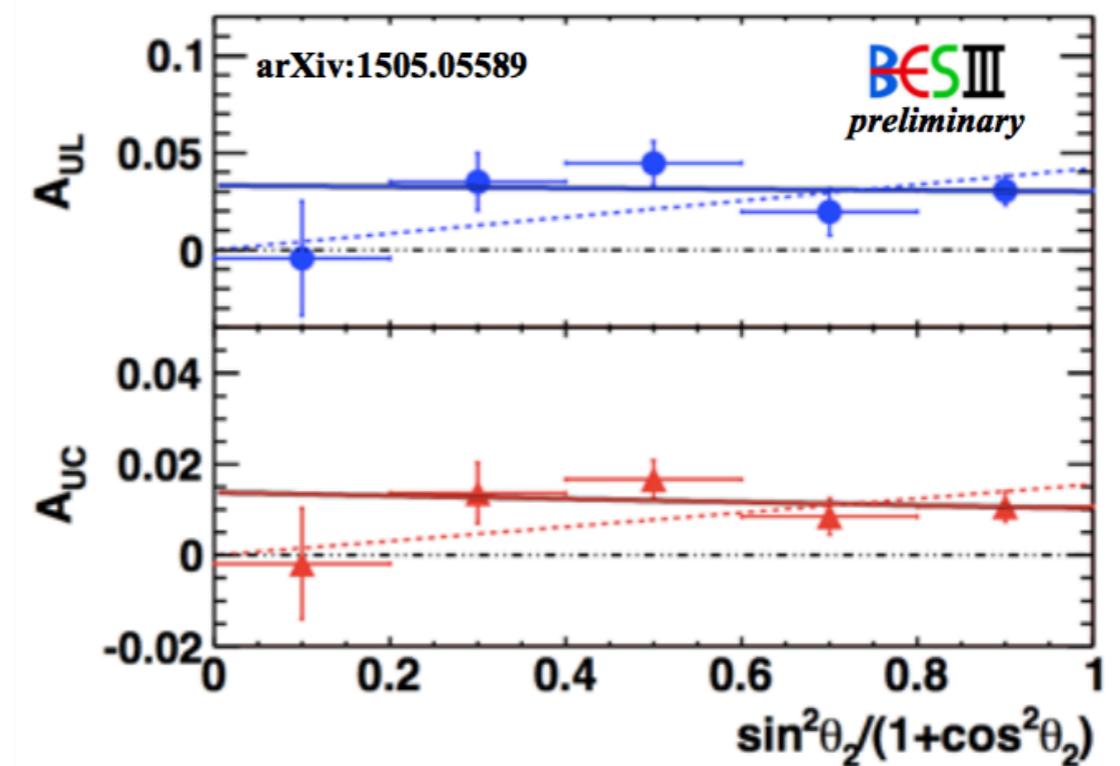


arXiv:1507.06824

Submitted on PRL

RF0 only

- 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

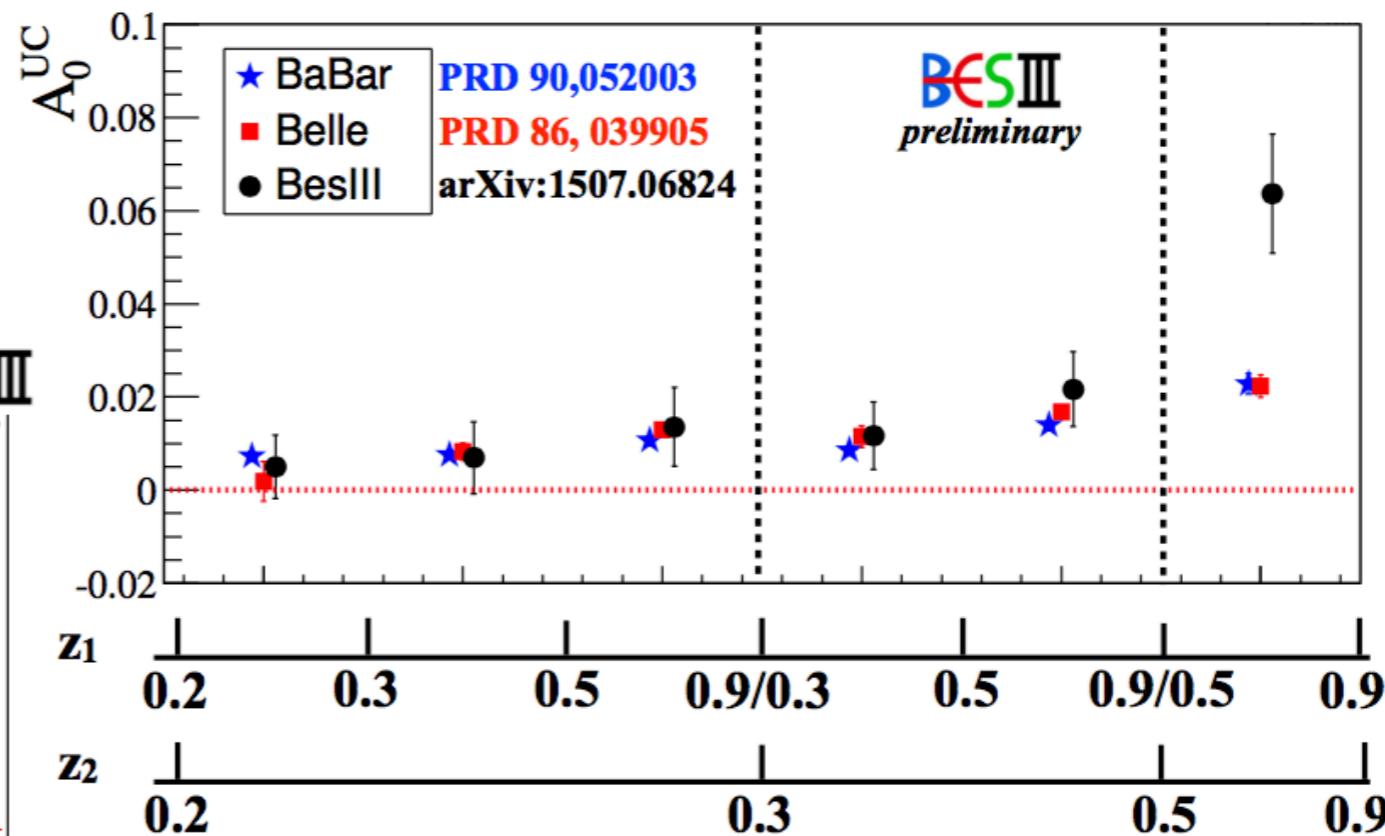
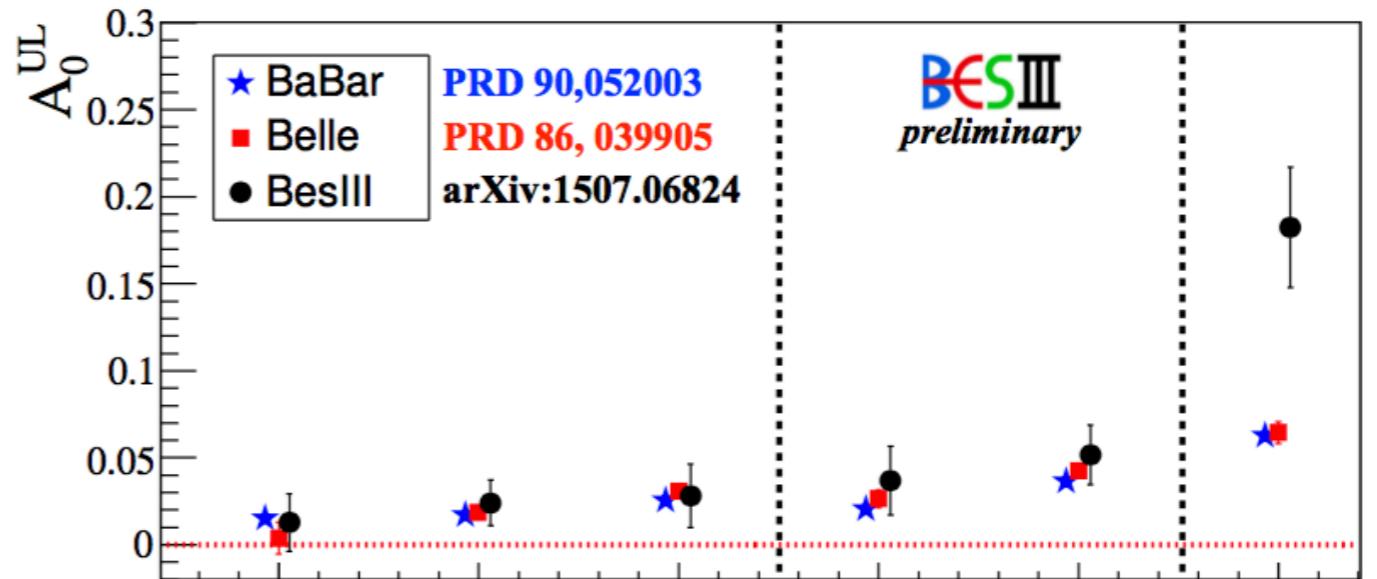
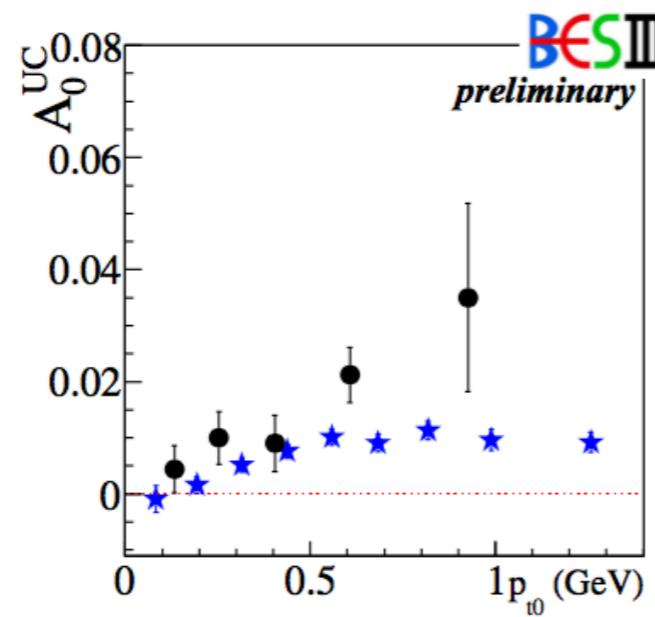
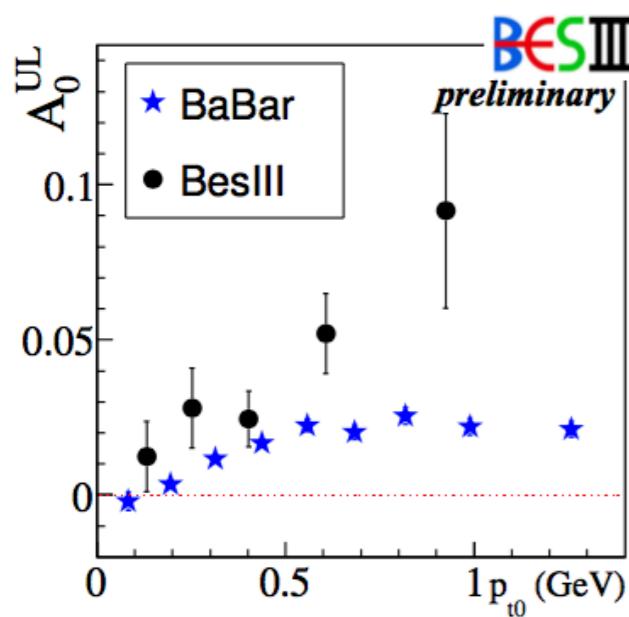


Comparisons of Asymmetries

Comparison between different results obtained at different Q^2 :

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

- 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*



Summary and Outlook

- **Collins effects measurement is implemented using BESIII data @3.65GeV.**
 - Nonzero Collins asymmetries were observed.
 - First measurement at medium energy, which is closer to SIDIS experiments
 - It allows to study the evolution of TMD objects
 - Collins effect studied as a function of several kinematic variables
- **Outlook**
 - Simultaneous measurement of KK, K π and $\pi\pi$ Collins asymmetries
 - Including π^0 in final states
 - Potential of data above charm threshold can be explored.
 - BESIII will take $\sim 360/\text{pb}$ data $\sqrt{s} = 3.51\text{GeV}$, which will improve precision of this measurement.

Backup

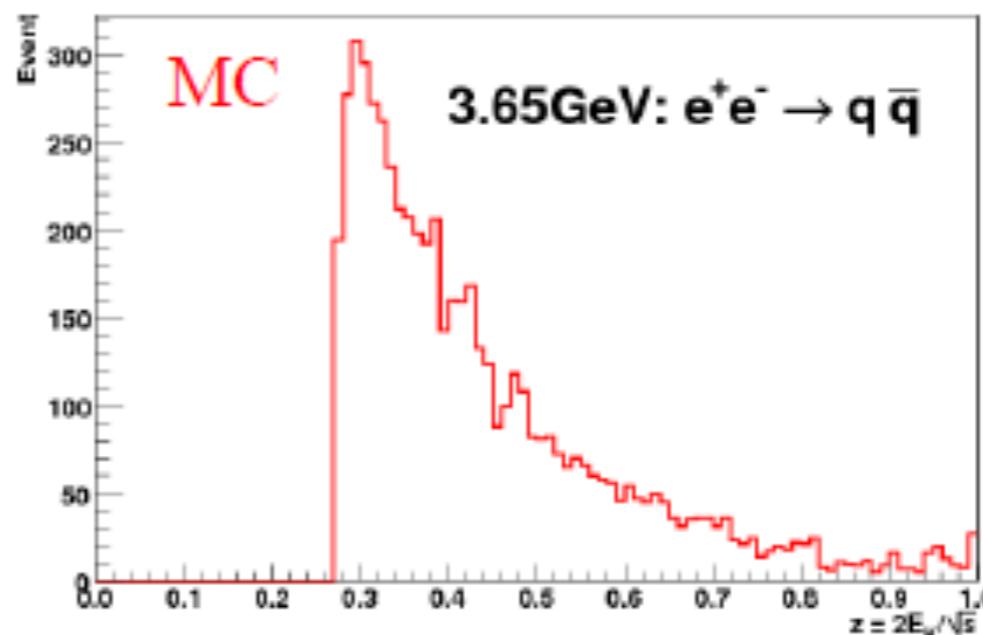
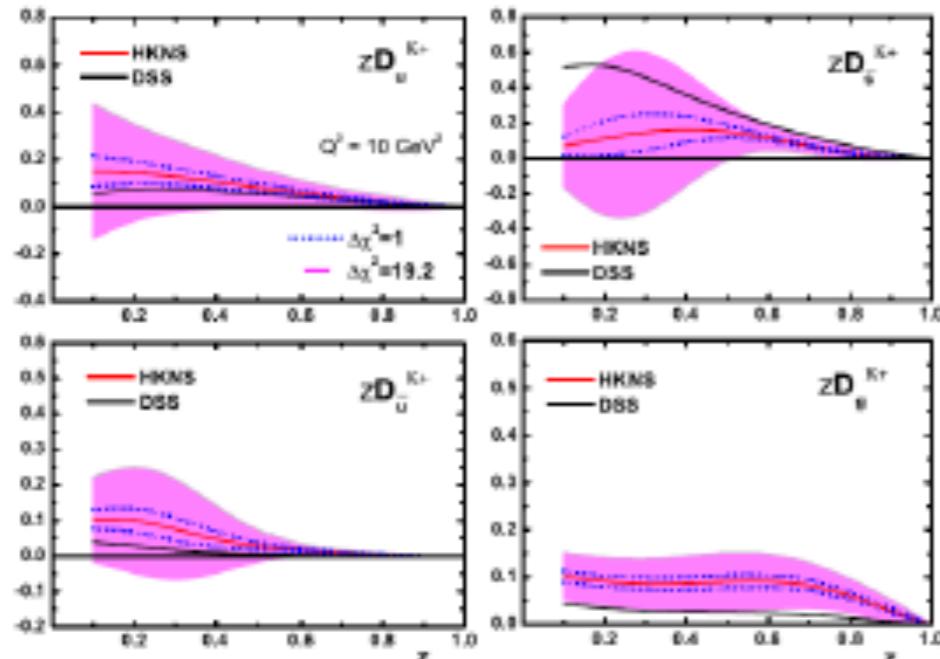
New scan in 2 – 3.1 GeV

- 2014.12.30-2015.5.1;
- From **high** to **low**;
- Added 2.05 GeV;
- **20 energy points**, total online luminosity **525 pb⁻¹**;
- Allows for form factor measurements, threshold studies, ...

E_{cm} (GeV)	E_{th} (GeV)	L_{Needed} (pb ⁻¹)	t_{beam} (days)	Purpose
2.0		≥ 8.95	14.6	Nucleon FFs
2.1		10.8	14.8	Nucleon FFs
2.15		2.7	2.29	$Y(2175)$
2.175		10(+)	8.5	$Y(2175)$
2.2		13	11	Nucleon FFs, $Y(2175)$
2.2324	2.2314	11	4	Hyp threshold ($\Lambda\Lambda$)
2.3094	2.3084	20	16	Nucleon & Hyp FFs Hyp Threshold ($\Sigma^0\bar{\Lambda}$)
2.3864	2.3853	20	8.7	Hyp Threshold ($\Sigma^0\bar{\Sigma}^0$) Hyp FFs
2.3960	2.3949	≥ 64	27.8	Nucleon & Hyp FFs Hyp Threshold ($\Sigma^-\bar{\Sigma}^+$)
2.5		0.4895	8h	R scan
2.6444	2.6434	65	18	Nucleon & Hyp FFs Hyp Threshold ($\Xi^-\bar{\Xi}^+$)
2.7		0.5542	4.2h	R scan
2.8		0.6136	4h	R scan
2.9		100	18.5	Nucleon & Hyp FFs
2.95		15	2.8	$m_{p\bar{p}}$ step
2.981		15	2.8	η_c , $m_{p\bar{p}}$ step
3.0		15	2.8	$m_{p\bar{p}}$ step
3.02		15	2.8	$m_{p\bar{p}}$ step
3.08		120	13.2	Nucleon FFs (+30 pb ⁻¹)

Fragmentation function

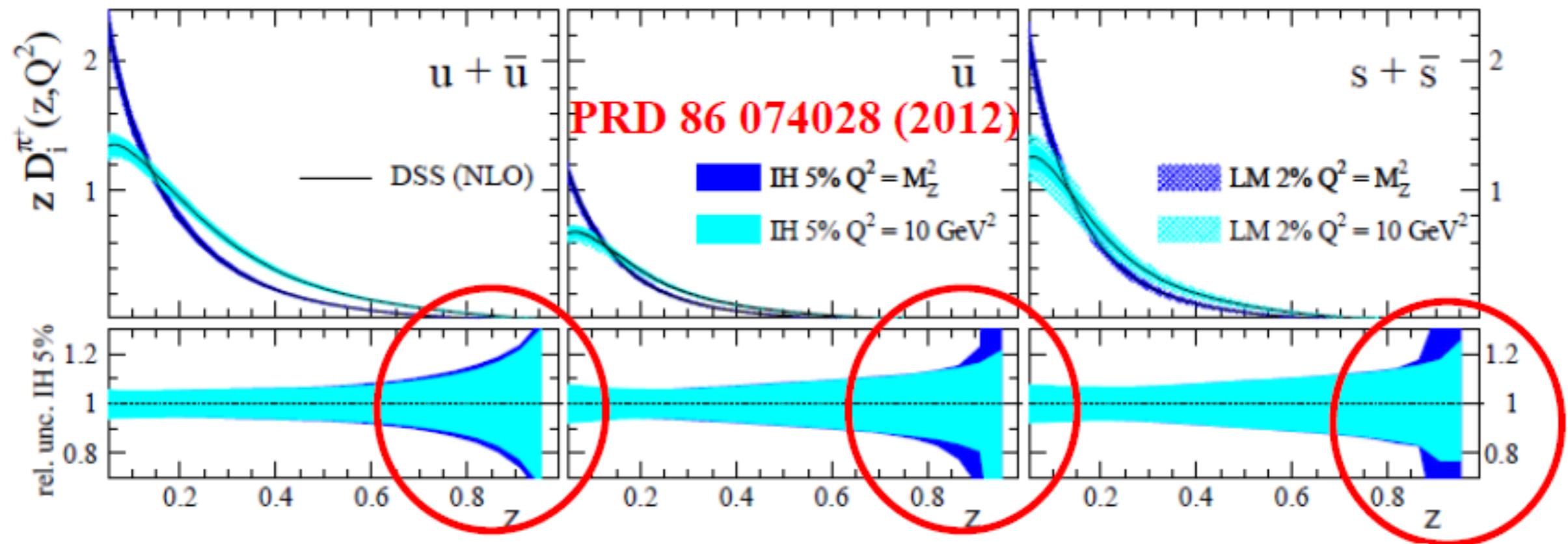
- e^+e^- cms $< 10.0\text{GeV}$ data for fitting: NOT USE
 - Accuracy is low and number of data points are small
 - DASP: π^\pm @ 3.6GeV; average stat. uncertainty 18% } About 30
 - DASP: k^\pm @ 3.6GeV; average stat. uncertainty 55% } years ago



- $D_s^{K^+}$: large difference between HKNS and DSS around $[0.15, 0.45]$ at $Q^2 = 10\text{GeV}^2$
- $D_s^{K^+}$: large uncertainty around $[0.15, 0.45]$ at $Q^2 = 10\text{GeV}^2$
- BESIII MC data: most of events have z around $[0.28, 0.60]$
- Could BESIII data improve FFs theory uncertainty ?

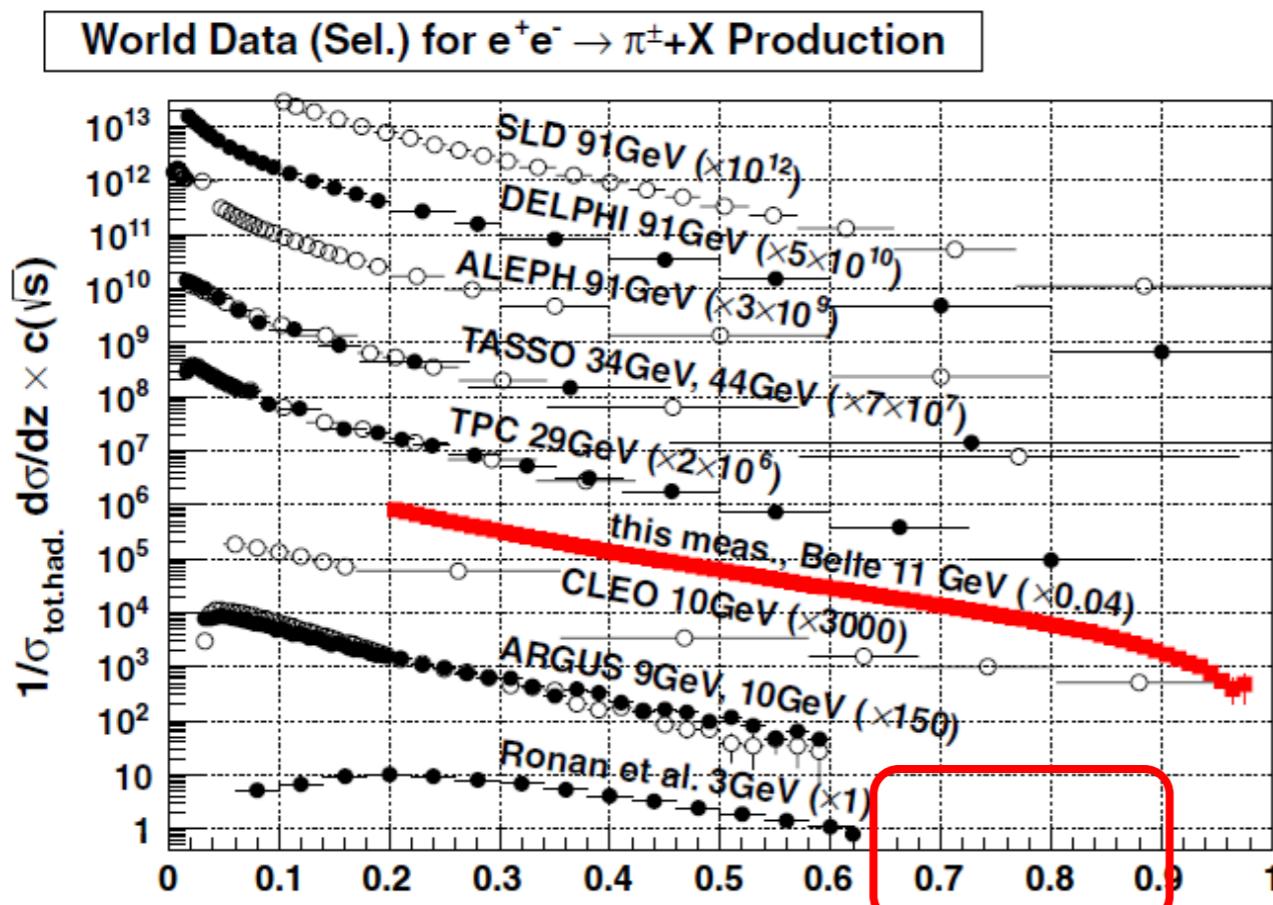
$$e^+ e^- \rightarrow \pi + X$$

- Theory predictions at high z : with large uncertainty



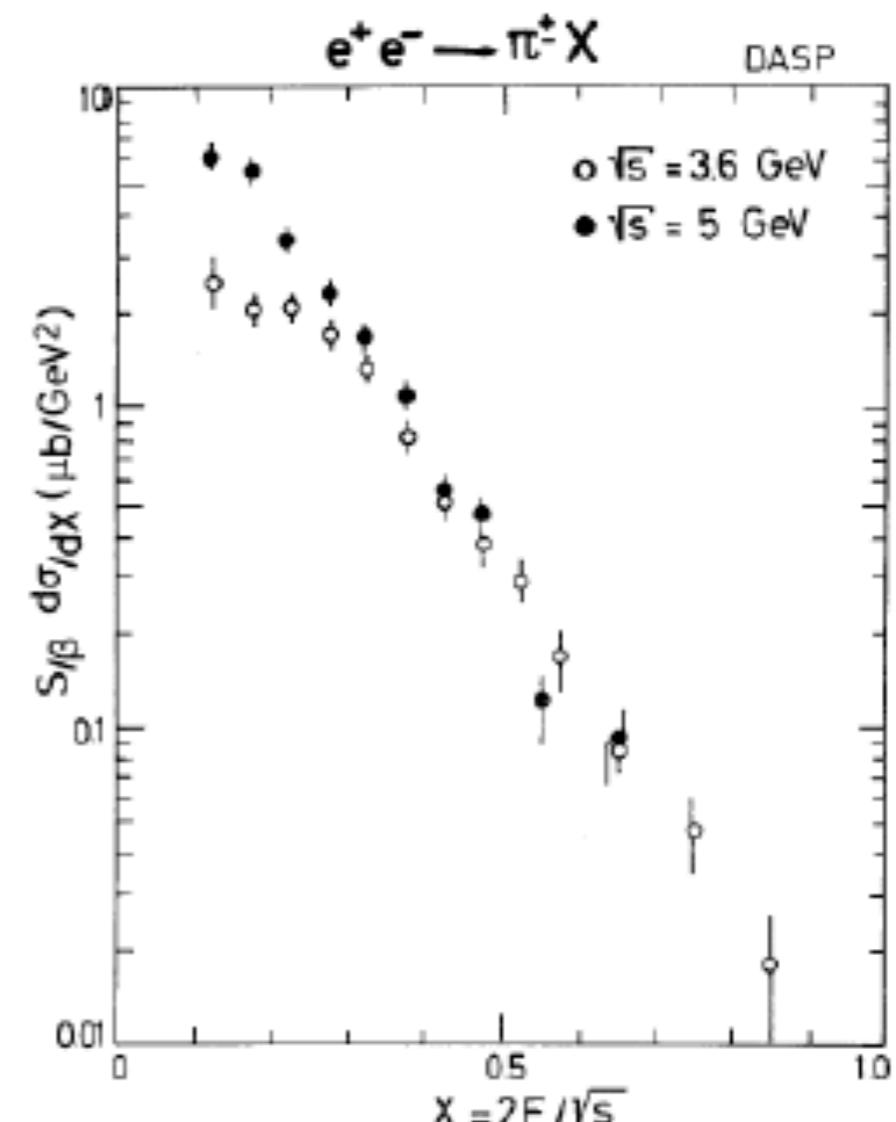
- BESIII data could provide:
 - Data at low energy scale
 - At high z
 - Constrain fragmentation function at low energy scale and high z

$e^+e^- \rightarrow \pi + X$



PRL 111 062002 (2013)

- Lack of data at **low energy scale**
 - BESIII energy: [2, 4.6] GeV
 - Poor precision
- Lack data at **high $z=2E_{\text{hadron}}/\sqrt{s}$**

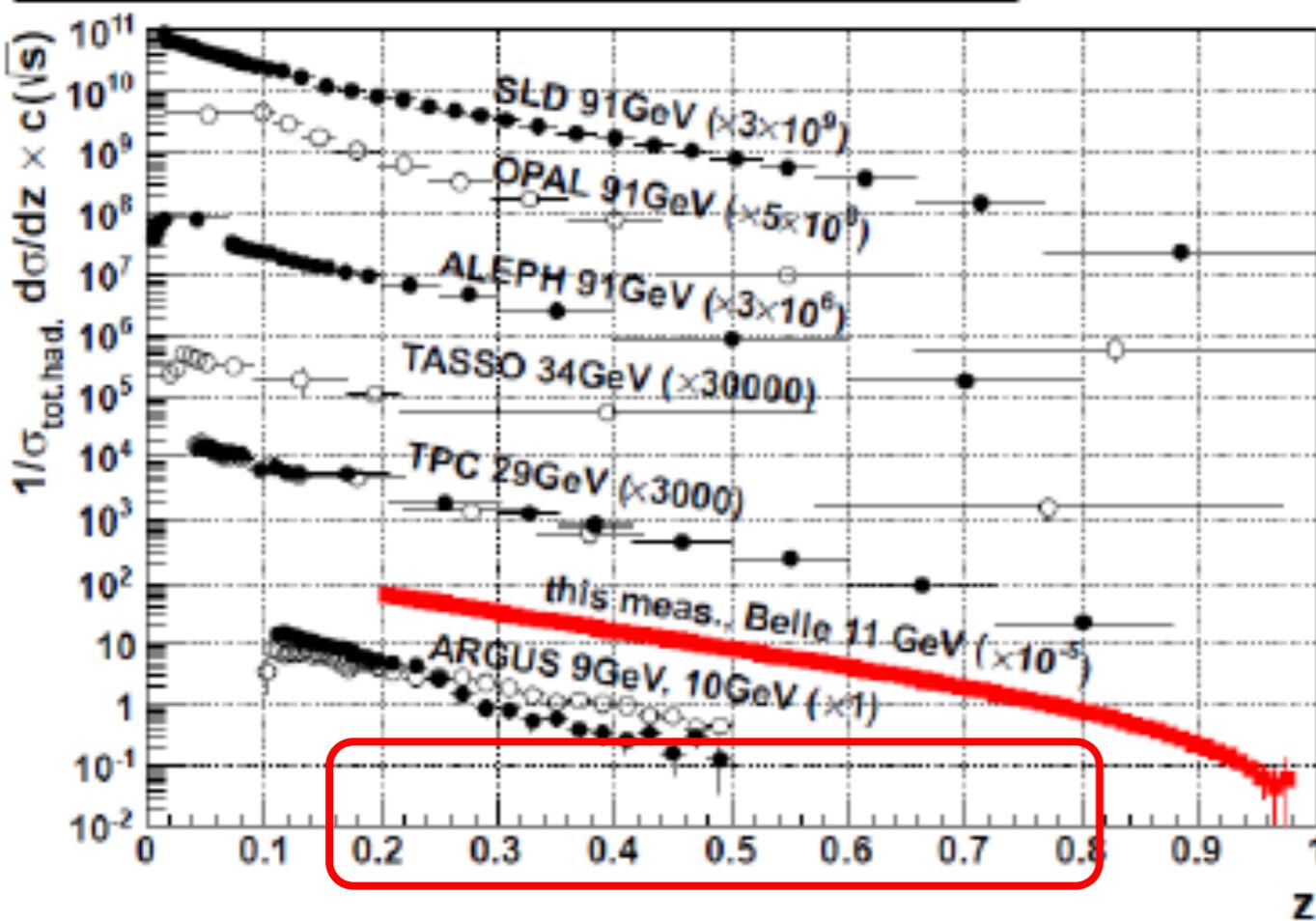


NPB 148 189 (1979)

- DASP: about 35 years ago
- Stat. uncertainty: 18%

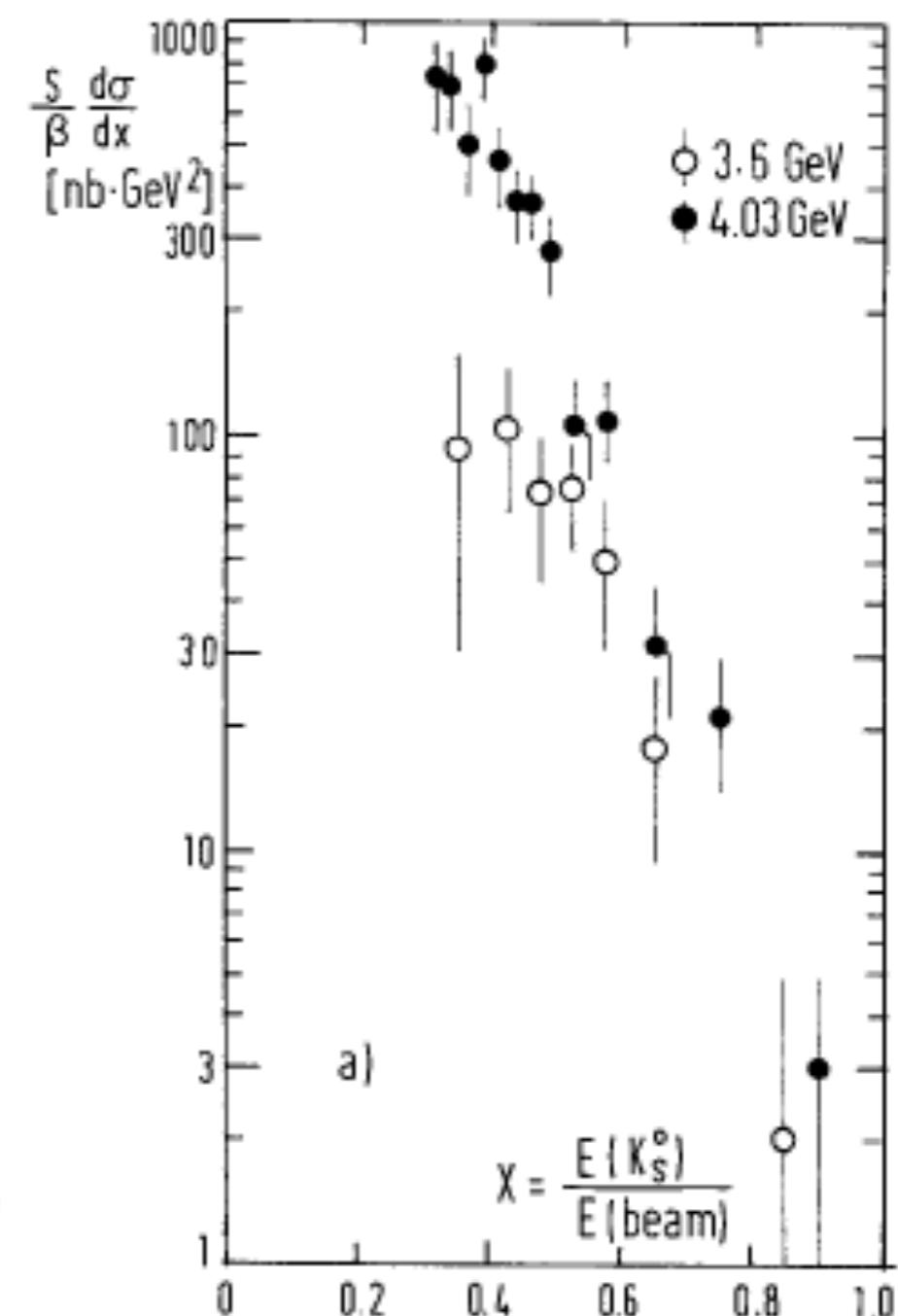
$e^+e^- \rightarrow K + X$

World Data (Sel.) for $e^+e^- \rightarrow K^+X$ Production



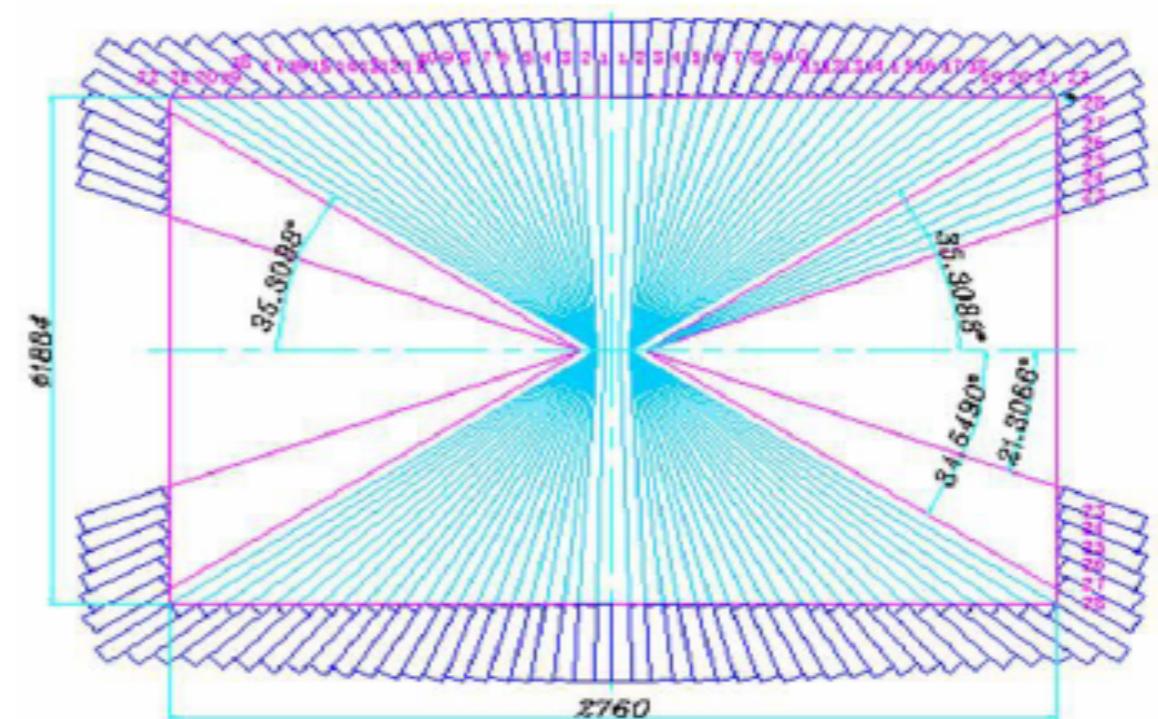
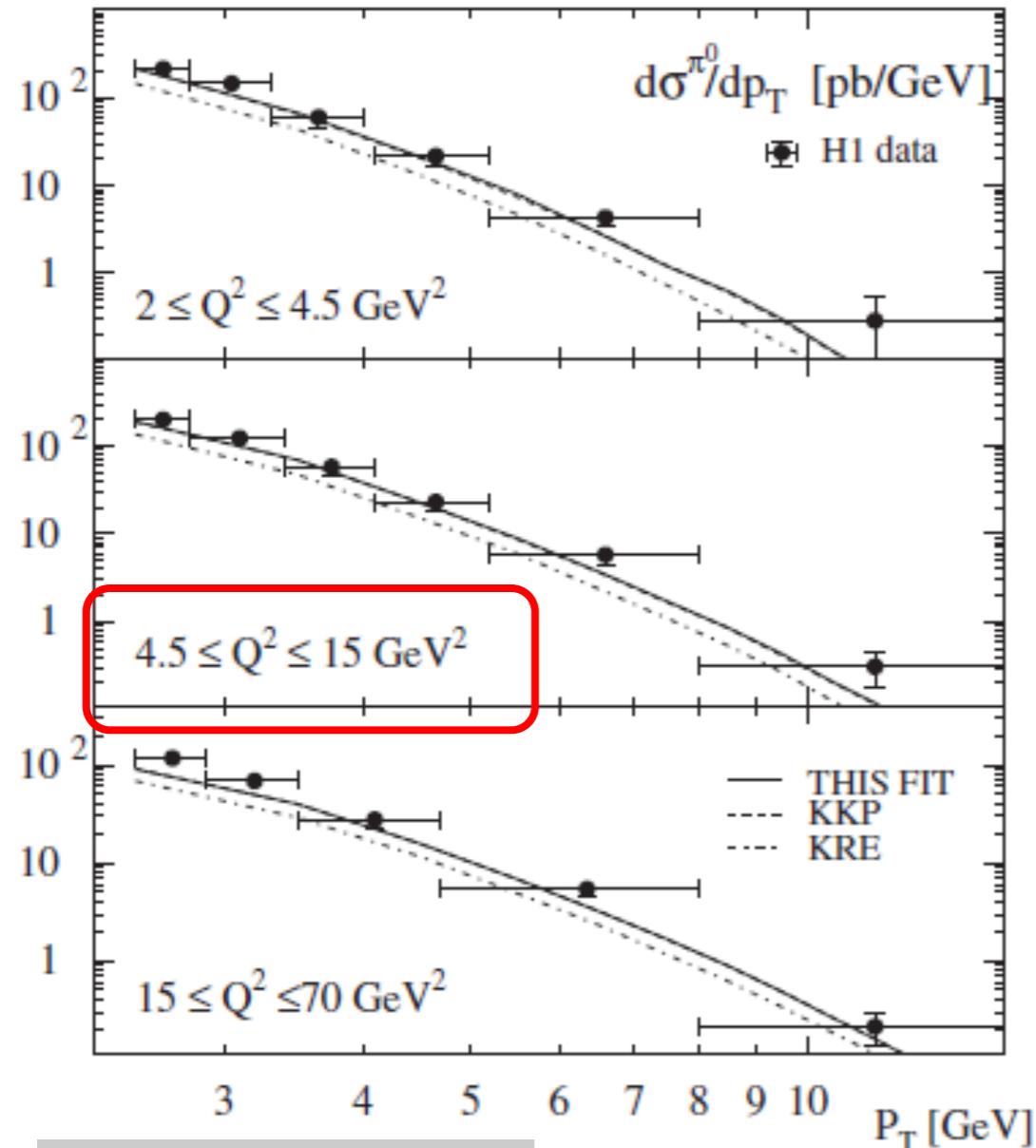
PRL 111 062002 (2013)

- Lack of data at **low energy scale**
- PLUTO: about 35 years ago
 - Stat. uncertainty: 41%



PLB 67 367 (1977)

$e^+e^- \rightarrow \pi^0 + X$



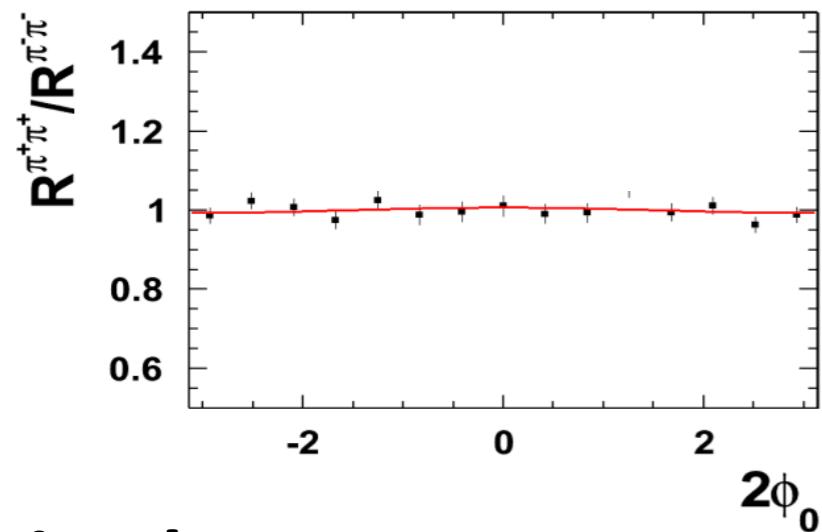
Resolution	Energy	Position
Barrel	2.5%@1GeV	6mm@1GeV
Endcap	5.0%@1GeV	9mm@1GeV

- $\pi^0 \rightarrow 2\gamma$ with EMC
- $e^+e^- \rightarrow \pi^0 + X$ @BESIII

- DSS FFs could describe H1 ep neutral pion's data
- π^0 do not need PID

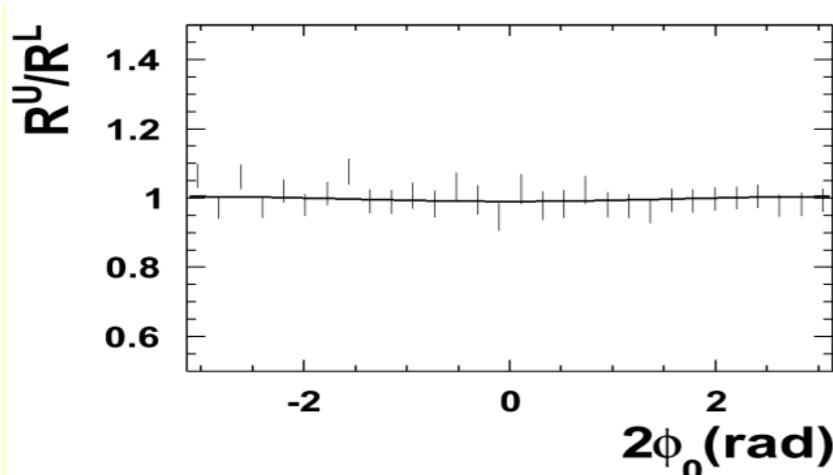
Zero Test in Data

- Check efficiency differences of π^+ and π^- , make sure DR can cancel detection effects.

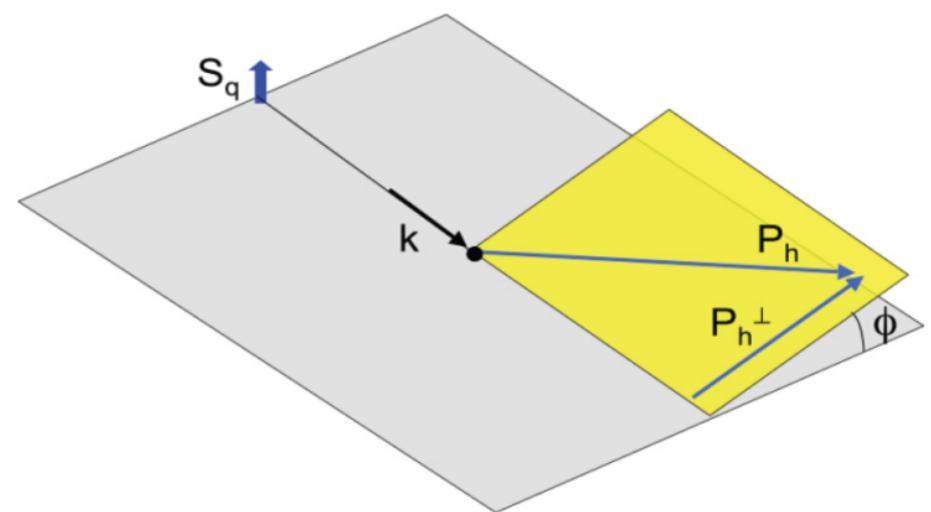


- Mixed events

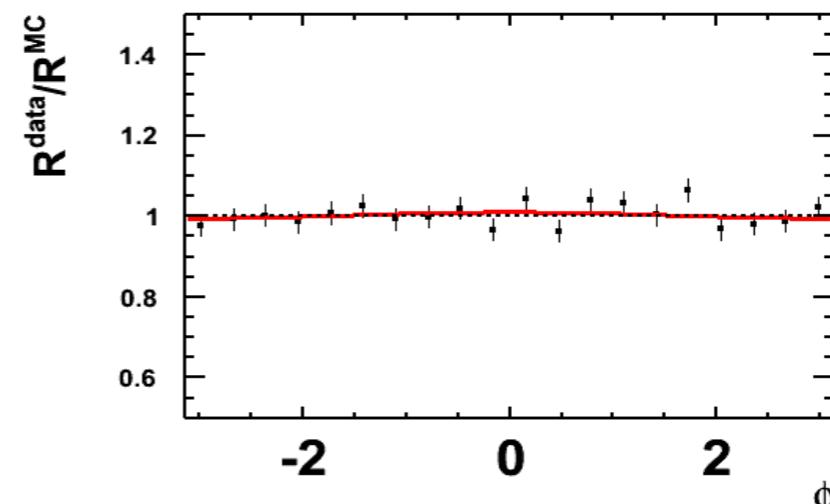
- Combine two π from different events in data. Zero asymmetry is expected.



- Single hadron asymmetry



- Thrust axis is assumed as the direction of the initial quark
- With **unpolarized beam**, no azimuthal angle dependence is expected. To cancel efficiencies, $R^{\text{data}}/R^{\text{MC}}$ was used.

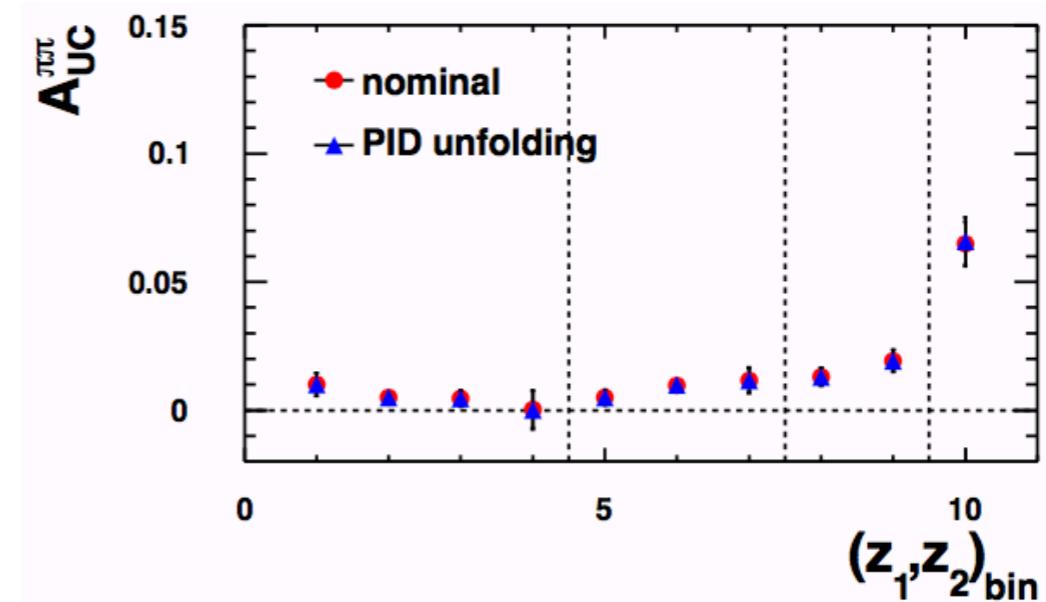
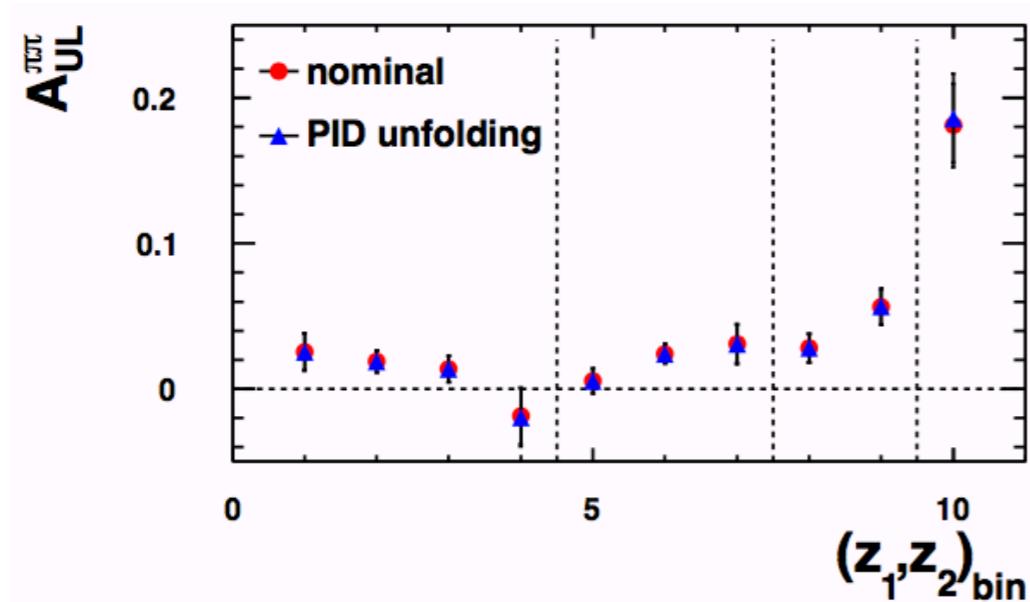


Particle mis-identification

- PID mis-ID rate ranges from 0.05% to 4.2% for different bins
- Unfold the measured $K\pi$ and $\pi\pi$ asymmetries
- Correction factors are obtained based on MC

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

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

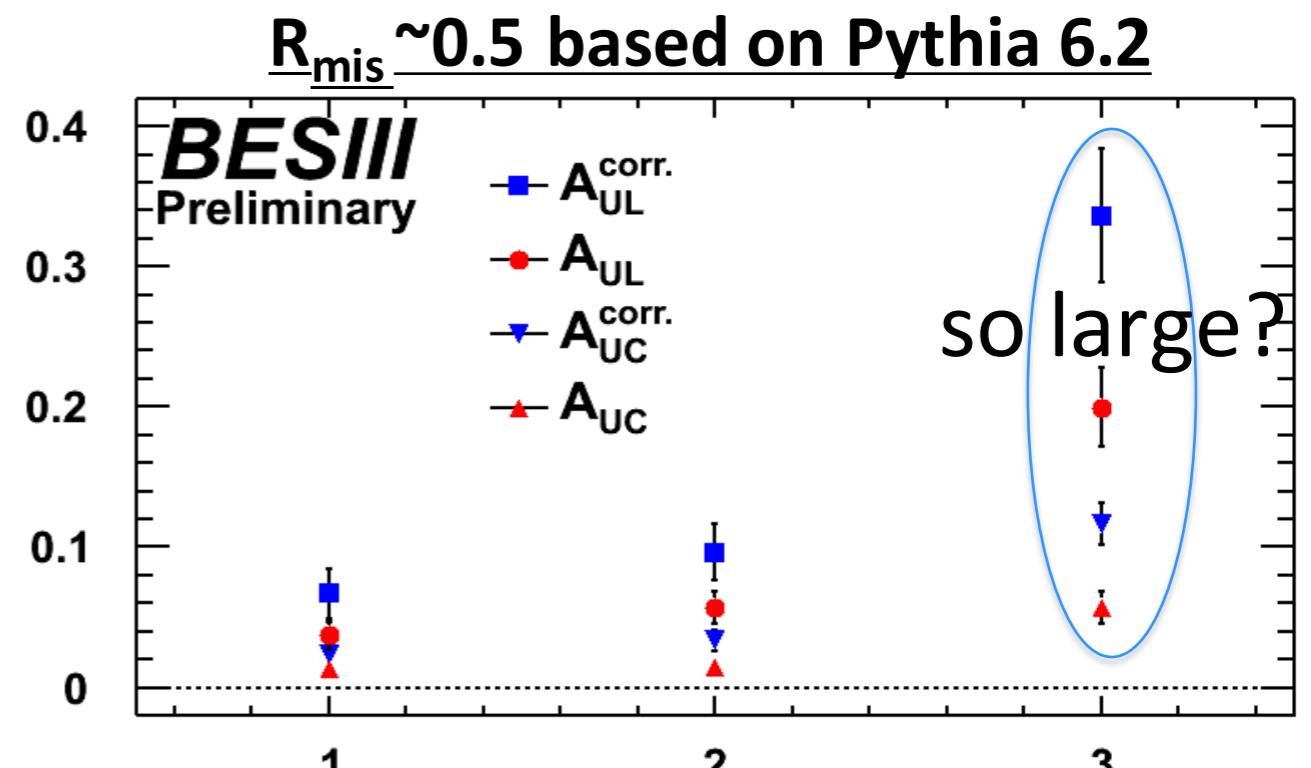


Almost no changes before and after unfolding

Hadron Mis-combination

- The open angle cut $>120^\circ$ is supposed to guarantee that the two hadrons are from two different quarks, esp., at high z region
- Mis-combination problem: **without identifying jets**, pions from the same quark fragmentation may be combined. This dilutes the asymmetries of interest.
- We could estimate the combined rate R_{mis} only **relying on MC models, eg, Pythia 6.2.**

- However, no credible assignment of quark in MC
- Theoretical treatment can cover this inclusiveness and describe experimental data without correction.

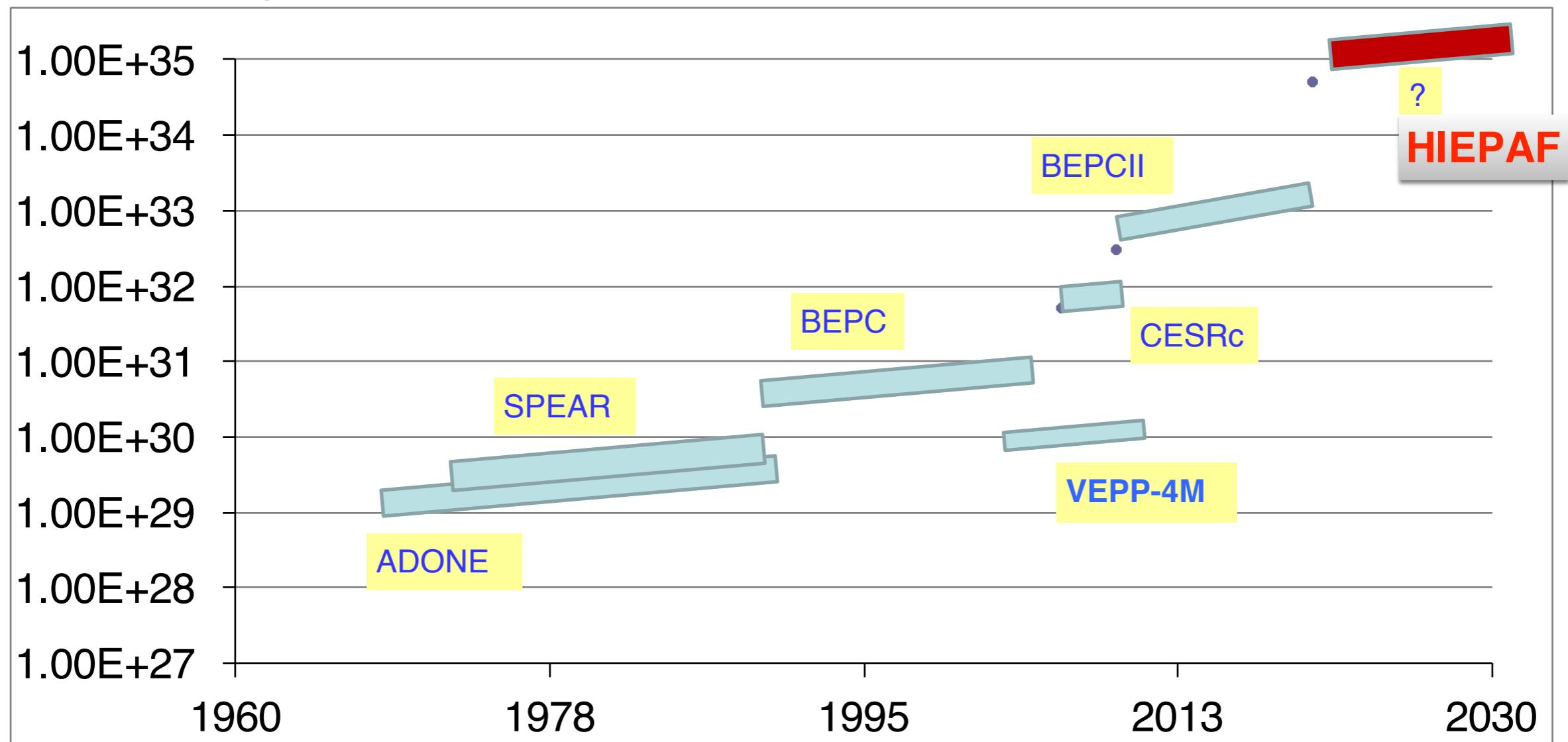


$$A^{\text{corr.}} = \frac{A^{\text{mea.}}}{(1 - R_{\text{mis}})}$$

(z_1, z_2) bin

HIEPAF

Luminosity($\text{cm}^{-2}\text{s}^{-1}$)



Thank you!
謝謝！