Measurement of Collins Asymmetries in e^+e^- Annihilation at Belle

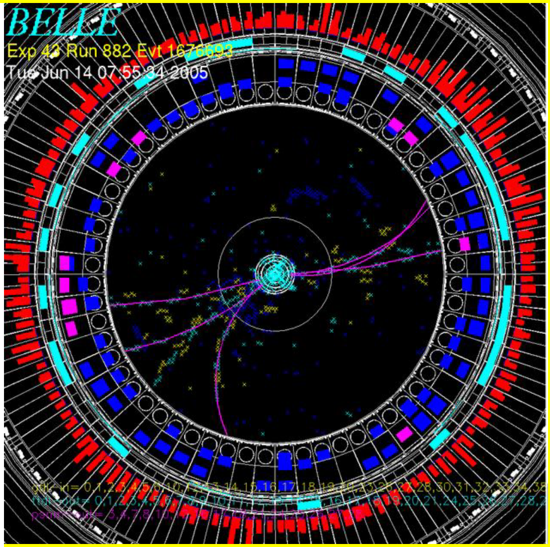
Workshop on Exclusive Reactions at

High Mon <a href="talks/ Sandorfi.pdf"> Transfer

May 24th , Thor n Laboratory

D. Gabbert	Illinois and RBRC
M. G.Perdekamp	Illinois and RBRC
K. Hasuko	RIKEN and RBRC
S. Lange	Frankfurt
M. Leitgab	Illinois
D. Mertens	Illinois
A. Ogawa	BNL and RBRC
R. Seidl	Illinois and RBRC
V. Siegle	RBRC

for the Belle Collaboration



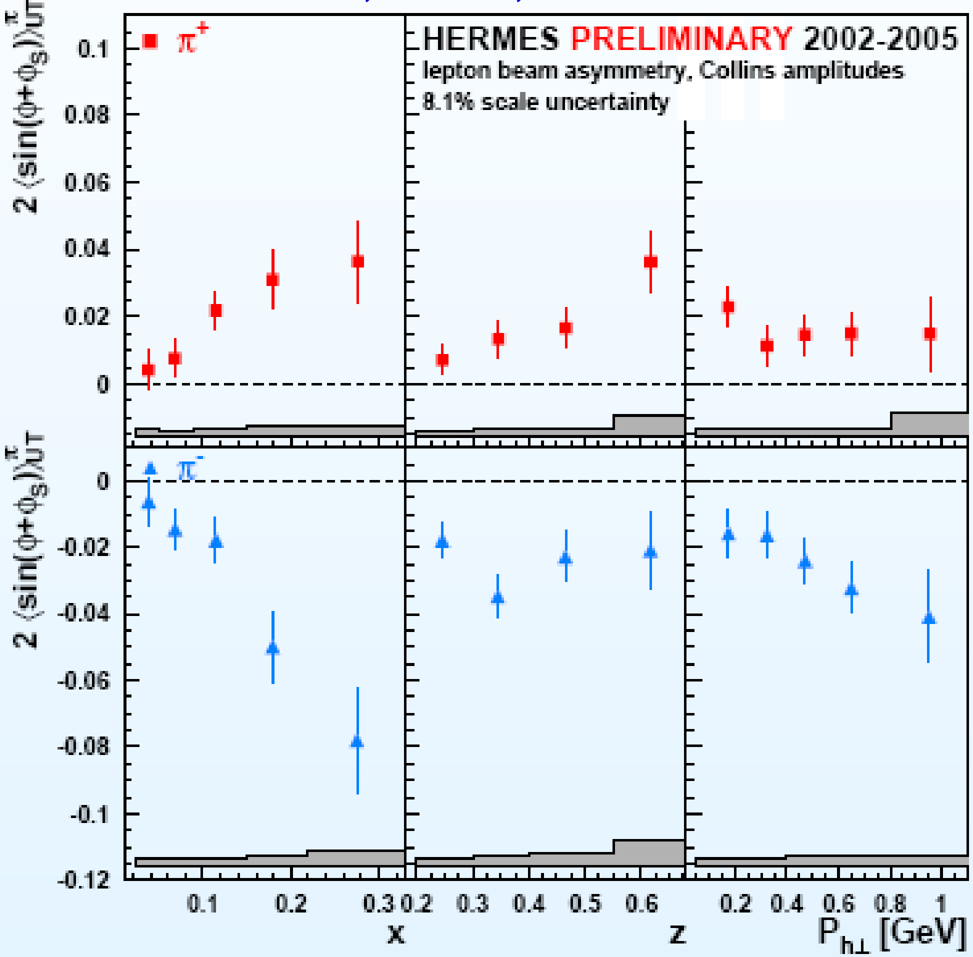
------------ Outline ------------

- Motivation
  - Collins FF for global QCD analysis of single transverse asymmetries in pp and SIDIS

- Collins Asymmetries from e^+e^-
  - LEP first work on Delphi data in the 90s:
    Efremov, Smirnova, Tkatchev and
    Bonivento, Matteuzzi, Kotzinian
  - Experimental technique
  - Results

Motivation Transversity Quark Distributions from Collins- and Interference-Fragmentation

New HERMES results for Collins Asymmetries
M. Diefenthaler, DIS 2007, Munich



Collins- and IFF- asymmetries in SIDIS and pp are of the form

~ Transversity (x) x CFF(z)

~ Transversity (x) x IFF(z)

Collins- and IFF- asymmetries in e^+e^- are of the form

~ $CFF(z_1)$ x $CFF(z_2)$

~ $IFF(z_1)$ x $IFF(z_2)$

➔ global QCD analysis

Global Analysis: Extract Transversity Distributions

SIDIS $\Rightarrow$

transversity $\times$ Collins

transversity $\times$ IFF

HERMES, COMPASS, JLAB, EIC

Factorization + Universality ?!

e^+e^- $\Rightarrow$ Collins x Collins

Interference FF x Interference FF

Belle

Transversity Tensor Charge

Theory

Lattice QCD: Tensor Charge

RHIC / GSI

pp $\Rightarrow$

A_N for inclusive hadrons, Jets

A_T in Jets: transversity $\times$ Collins

transversity $\times$ IFF

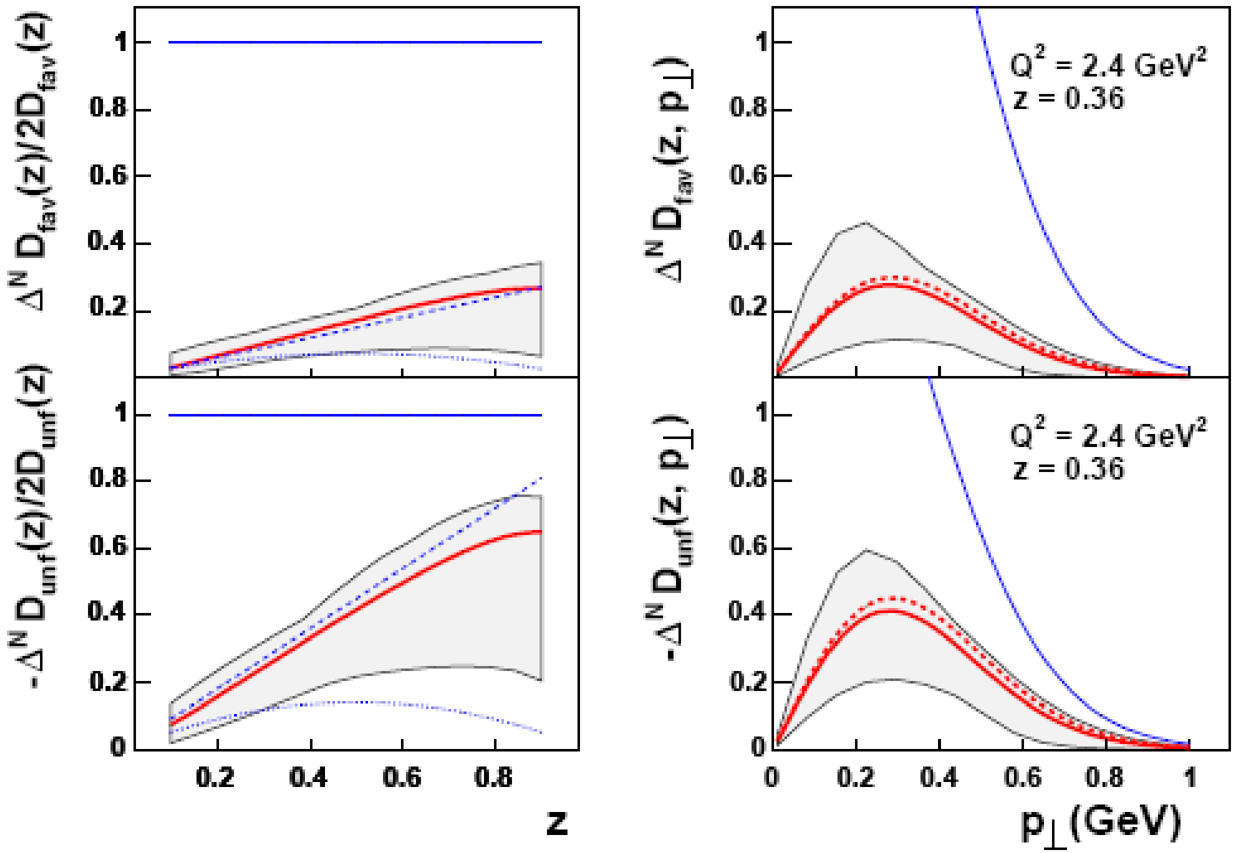
GSI

A_{TT} Drell Yan:

transversity $\times$ transversity

First QCD Analysis of SIDIS + e^+e^- !

Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Prokudin, Turk
Phys. Rev. D75:05032,2007



Fit includes:

HERMES SIDIS

+ COMPASS SIDIS

+ Belle e^+e^-

→ transversity dist.

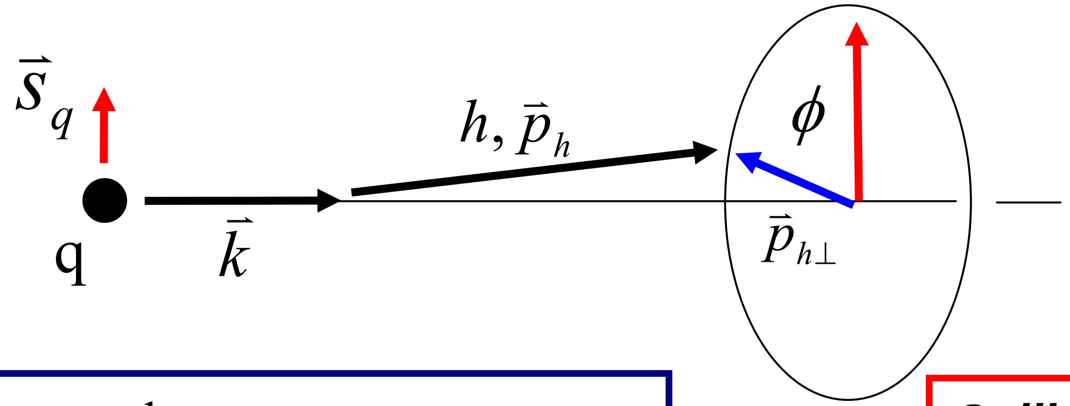
+ Collins FF

Measurement of Collins Asymmetries In e^+e^- at KEK B with the Belle

Phys.Rev.Lett.96:232002,2006
and update at Spin 2006 in Kyoto

Collins Effect in Quark Fragmentation

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



$\vec{k}$: quark momentum

$\vec{s}_q$: quark spin

$\vec{p}_h$: hadron momentum

$\vec{p}_{h\perp}$: transverse hadron momentum

$$z_h = E_h / E_q$$
$$= 2E_h/\sqrt{s}$$: relative hadron momentum

Collins Effect:
Fragmentation of a transversely polarized quark *q* into spin-less hadron *h* carries an azimuthal dependence:

$$\propto \left(\vec{k} \times \vec{p}_{h\perp}\right) \cdot \vec{s}_q$$
$$\propto \sin\phi$$

General Form of Fragmentation Functions

Number density for finding hadron *h* from a transversely polarized quark, *q*:

$$D_{q^\uparrow}^{h}(z,\vec{p}_{h\perp}) = \underbrace{D_1^{q,h}(z)}_{\text{unpolarized FF}} + \underbrace{H_1^{\perp q,h}(z,p_{h\perp}^2)}_{\text{Collins FF}} \frac{\left(\hat{k}\times\vec{p}_{h\perp}\right)\cdot\vec{s}_q}{zM_h}$$

unpolarized FF **Collins FF**

Collins FF in e^+e^- : Need Correlation between Hemispheres !

- Quark spin direction unknown: measurement of Collins function in one hemisphere is not possible $\sin\varphi$ modulation will average out.

- Correlation between two hemispheres with $\sin\varphi_i$ Collins single spin asymmetries results in $\cos(\varphi_1+\varphi_2)$ modulation of the observed di-hadron yield.

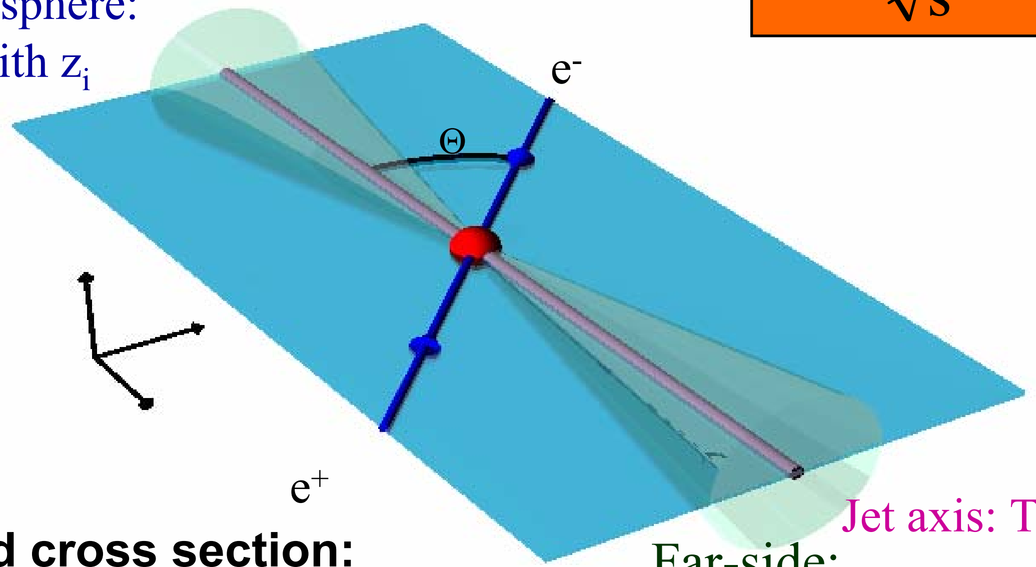
→ Measurement of azimuthal correlations for pion pairs around the jet axis in two-jet events!

Event Structure at Belle

e+e- CMS frame:

$$z = \frac{2E_h}{\sqrt{s}}, \quad \sqrt{s} = 10.52\,GeV$$

Near-side Hemisphere:
h_i, $i=1,N_n$ with z_i



$\langle N_{h+,-} \rangle = 6.4$

Jet axis: Thrust

Far-side:
h_j, $j=1,N_f$ with z_j

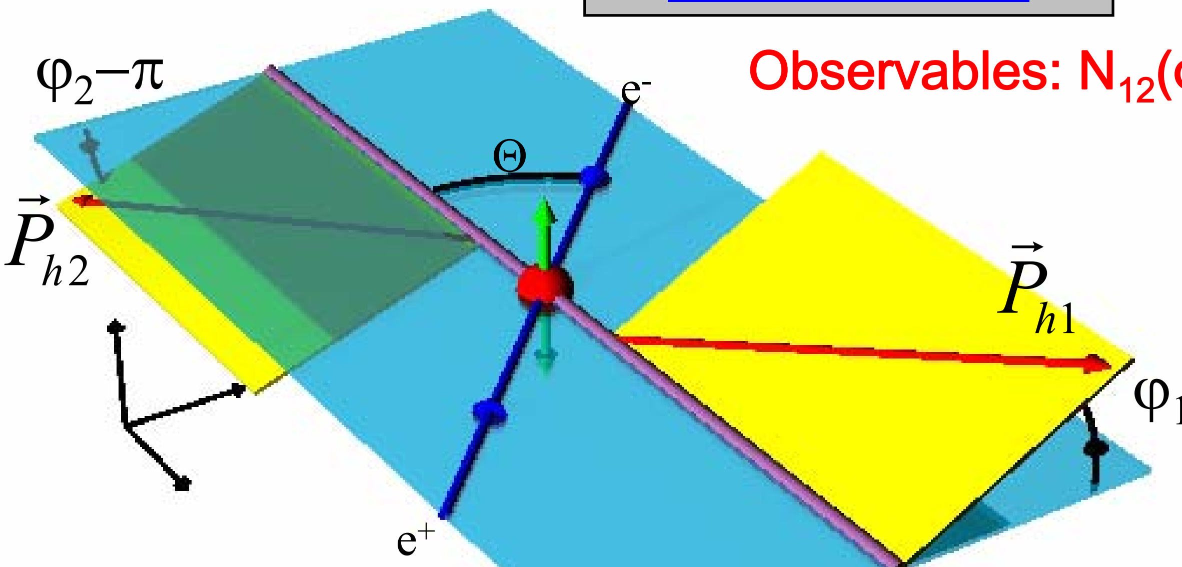
Spin averaged cross section:

$$\frac{d\sigma(e^+e^- \rightarrow h_1 h_2 X)}{d\Omega dz_1 dz_2} = \frac{3\alpha^2}{Q^2} A(y) \sum_{a,\bar{a}} e_a^2 D_1(z_1) \overline{D}_1(z_2)$$

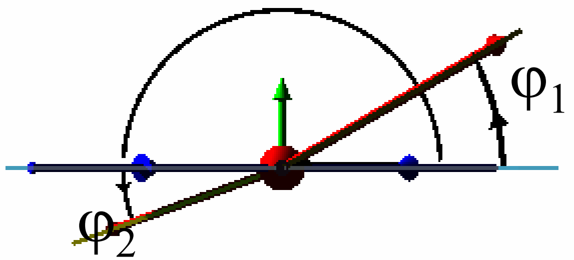
$$A(y) = \left(\frac{1}{2} - y + y^2\right) \overset{(cm)}{=} \frac{1}{4}\left(1 + cos^2\Theta\right)$$

Collins Fragmentation: Angles and Cross Section $\cos(\phi_1+\phi_2)$ Method

e+e- CMS frame:



Observables: $N_{12}(\varphi_1+\varphi_2)$, $A_{12}(z_1,z_2)$



2-hadron inclusive transverse momentum dependent cross section:

$$\frac{d\sigma(e^+e^-\to h_1h_2X)}{d\Omega\, dz_1 dz_2 d^2\mathbf{q}_T} = \cdots B(y)\cos(\varphi_1+\varphi_2)H_1^{\perp[1]}(z_1)\overline{H}_1^{\perp[1]}(z_2)$$

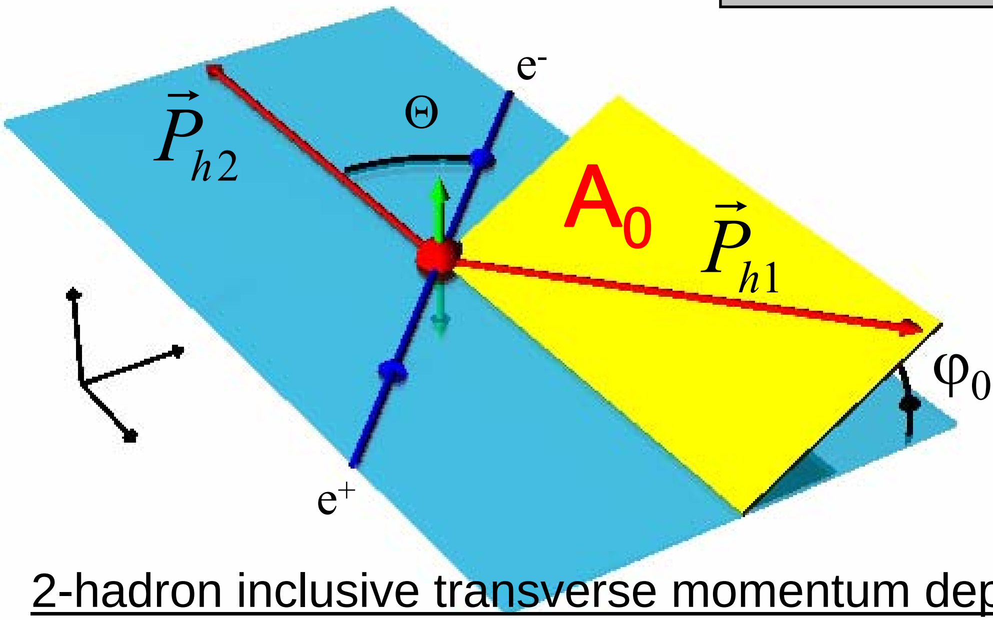
$$B(y)=y(1-y)\stackrel{cm}{=}\frac{1}{4}\sin^2\Theta$$

Net anti-alignment of transverse quark spins

Collins Fragmentation: Angles and Cross Section $\cos(2\phi_0)$ Method

Observables: $N_0(\varphi_0)$, $A_{12}(z_1,z_2)$

e^+e^- CMS frame:



- Independent of thrust-axis
- Convolution integral I over transverse momenta involved

[Boer,Jakob,Mulders: NPB504(1997)345]

2-hadron inclusive transverse momentum dependent cross section:

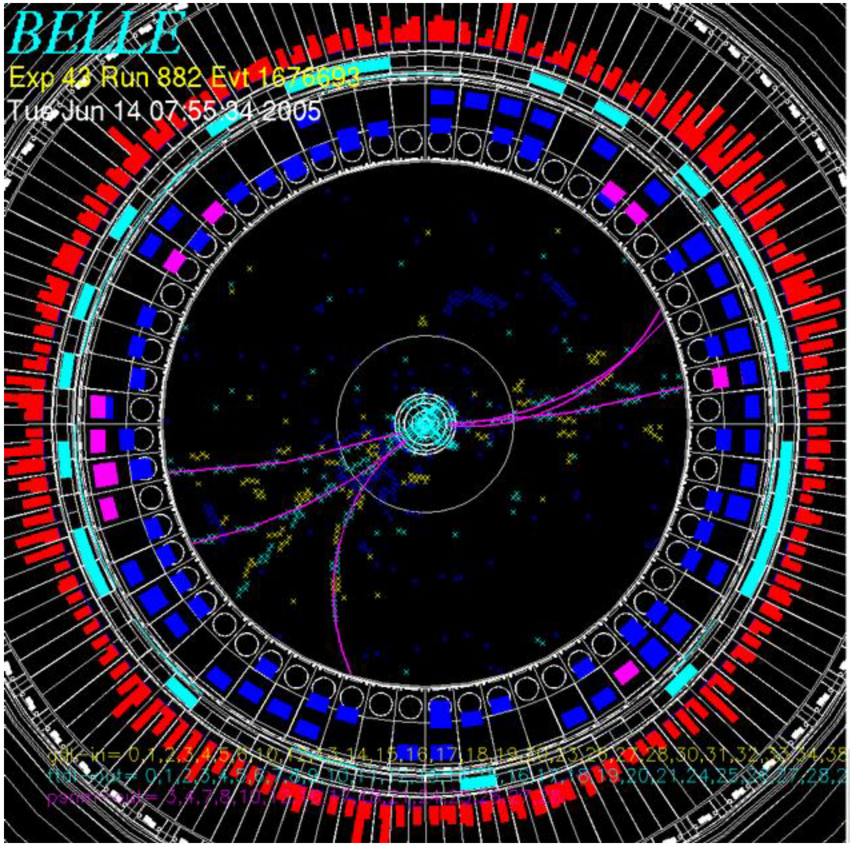
$$\frac{d\sigma(e^+e^- \to h_1h_2X)}{d\Omega dz_1 dz_2 d^2\boldsymbol{q}_T} = \cdots B(y)\cos(2\varphi_0) I\left[\left(2\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T - \boldsymbol{k}_T\cdot\boldsymbol{p}_T\right)\frac{H_1^\perp \overline{H}_1^\perp}{M_1M_2}\right]$$

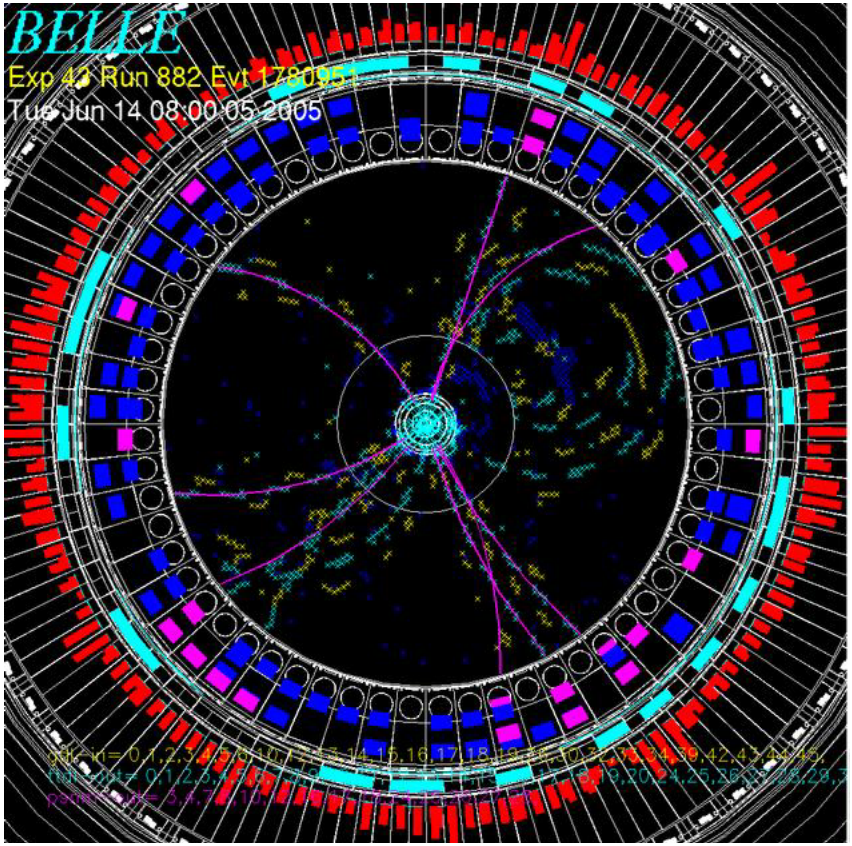
$$B(y) = y(1-y) \overset{cm}{=} \frac{1}{4}\sin^2\Theta$$

Net anti-alignment of transverse quark spins

Hadronic Events observed with Belle

➔ 1.5 x 10^9 hadronic events in analysis

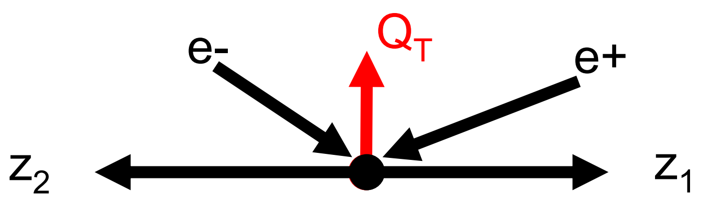




On resonance: 547fb^{-1} , $\sqrt{s}$=10.52 GeV *(published)*
Off resonance: 29fb^{-1} , $\sqrt{s}$=10.58 GeV *(preliminary)*

Gluon Emission

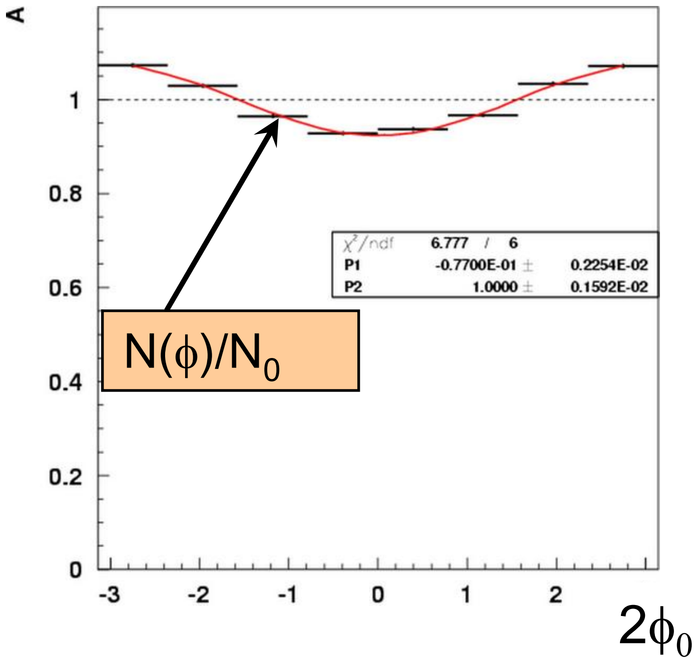
$$\frac{dN}{d\Omega dz_1 dz_2 dq_T} \propto \sum \left[\frac{q_T^2}{Q^2 + Q_T^2} \sin^2\theta \cos(2\phi_0) D_1(z_1) \overline{D}_1(z_2) \right]$$

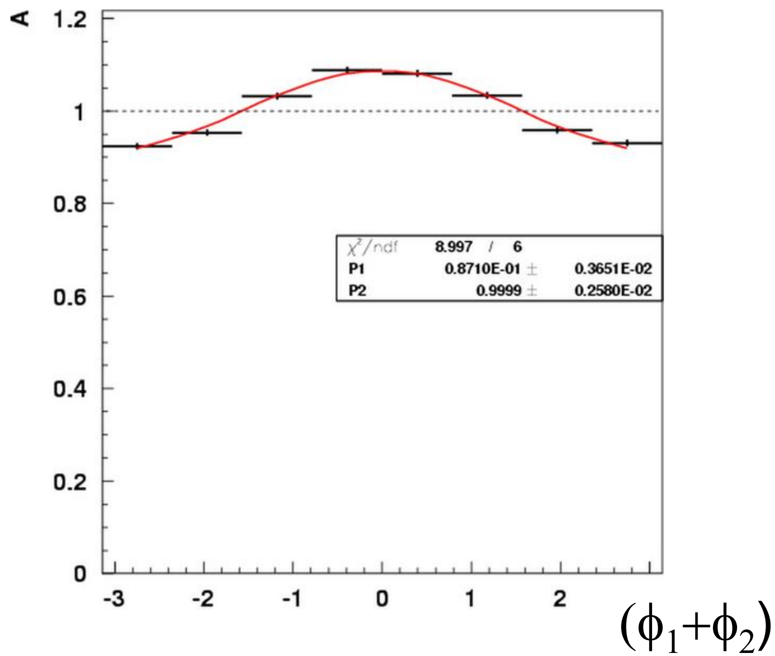


Frame:

$\vec{p}_1 = -\vec{p}_2$

Examples of Fits to Azimuthal Asymmetries





$$\frac{N(\phi)}{N_0} = \frac{aD_1\overline{D_1} + cos(2\phi)\left(bH_1\overline{H_1} + cD_1\overline{D_1}\right)}{aD_1\overline{D_1}} = P2 + P1\cos(2\phi)$$

D_1 : spin averaged fragmentation function,

H_1: Collins fragmentation function

Method to eliminate gluon contributions: Double ratios for unlike- and like sign pions

Double ratio method:

$$R := \frac{\frac{N^{Unlike}(\phi)}{N_0^{Unlike}}}{\frac{N^{Like}(\phi)}{N_0^{Like}}} \approx 1 + F\left(\frac{H_1^{\perp,fav}(z)}{D_1^{fav}(z)}, \frac{H_1^{\perp,unfav}(z)}{D_1^{unfav}(z)}\right)$$

$$+ \quad \mathcal{O}\left(F(Q_T)^2\right)$$

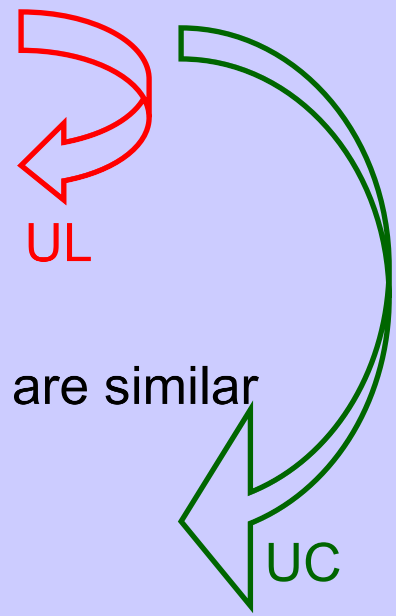
$$F \sim \frac{\sin^2(\theta)}{1+\cos^2(\theta)}\left[\frac{\sum_q e^2(H^{Fav}\cdot\overline{H}^{Fav} + H^{Unf}\cdot\overline{H}^{Unf})}{\sum_q e^2(D^{Fav}\cdot\overline{D}^{Fav} + D^{Unf}\cdot\overline{D}^{Unf})}\right]\cos(\phi_0)$$

← $A_0(z_1,z_2)$ →

Two Double Ratios

Double ratios unlike/like-sign not very sensitive in separating favored and disfavored Collins functions ➔ look at unlike-sign/charge-sum

- Unlike-sign pion pairs (U):
  (favored x favored + unfavored x unfavored)
- Like-sign pion pairs (L):
  (favored x unfavored + unfavored x favored)
- $\pi^{\pm}\pi^{0}$ pairs
  (favored + unfavored) x (favored + unfavored)
- A. Efremov et al. (**[hep-ph/0603054]**): charged $\pi\pi$ pairs are similar (and easier to handle) (C):
  (favored + unfavored) x (favored + unfavored)



Observables: $A_{12}(UL)$, $A_{12}(UC)$, $A_0(UL)$, $A_0(UC)$

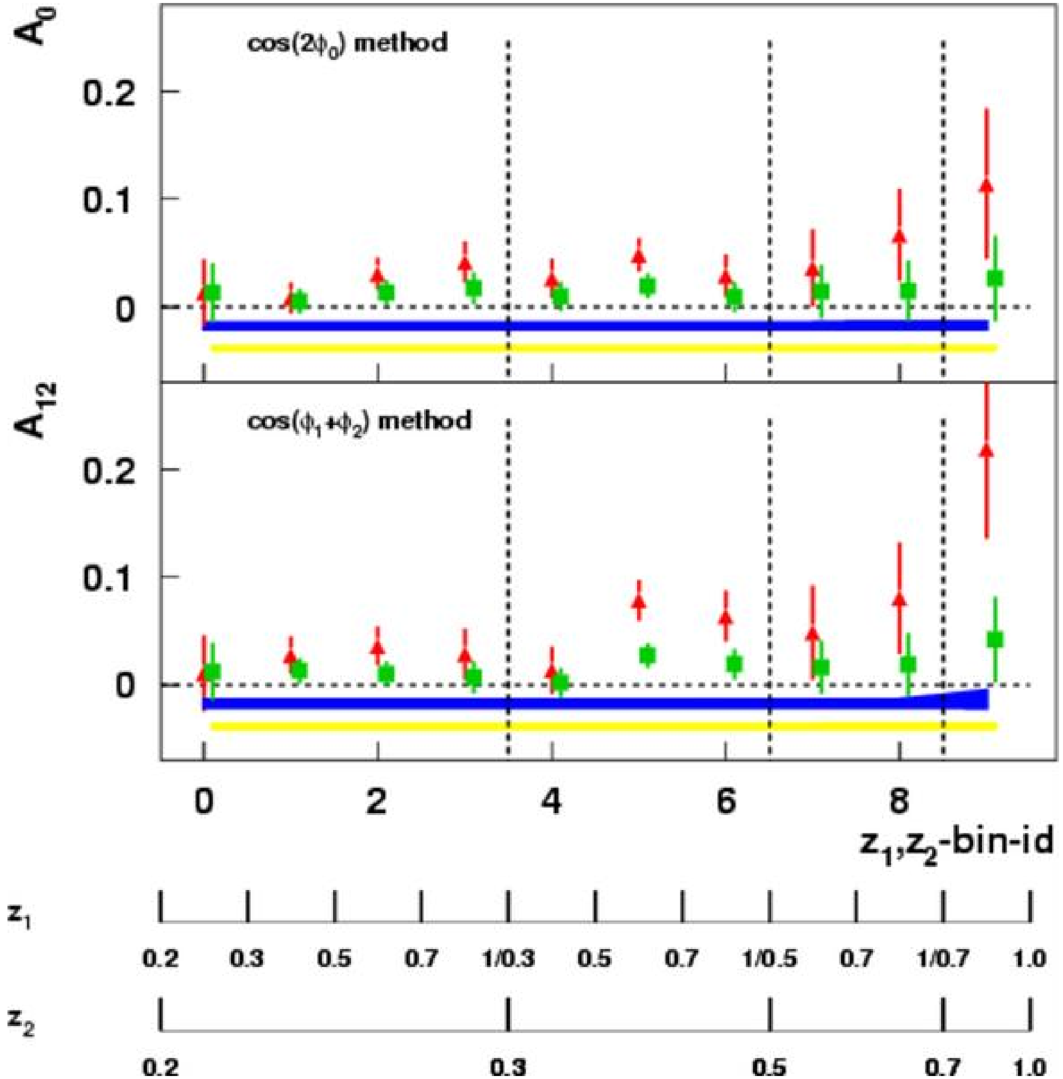
published and input to fit by Anselmino et al.

Final Charm Corrected Results for $e^+ e^- \rightarrow \pi \pi X$ ($29 fb^{-1}$, off-resonance Data)

Phys.Rev.Lett.96:232002,2006

- Significant non-zero asymmetries
- Rising behavior vs. z
- UL/C asymmetries about 40-50% of UL/L asymmetries
- First direct measurements of the Collins function
- UL/L data published

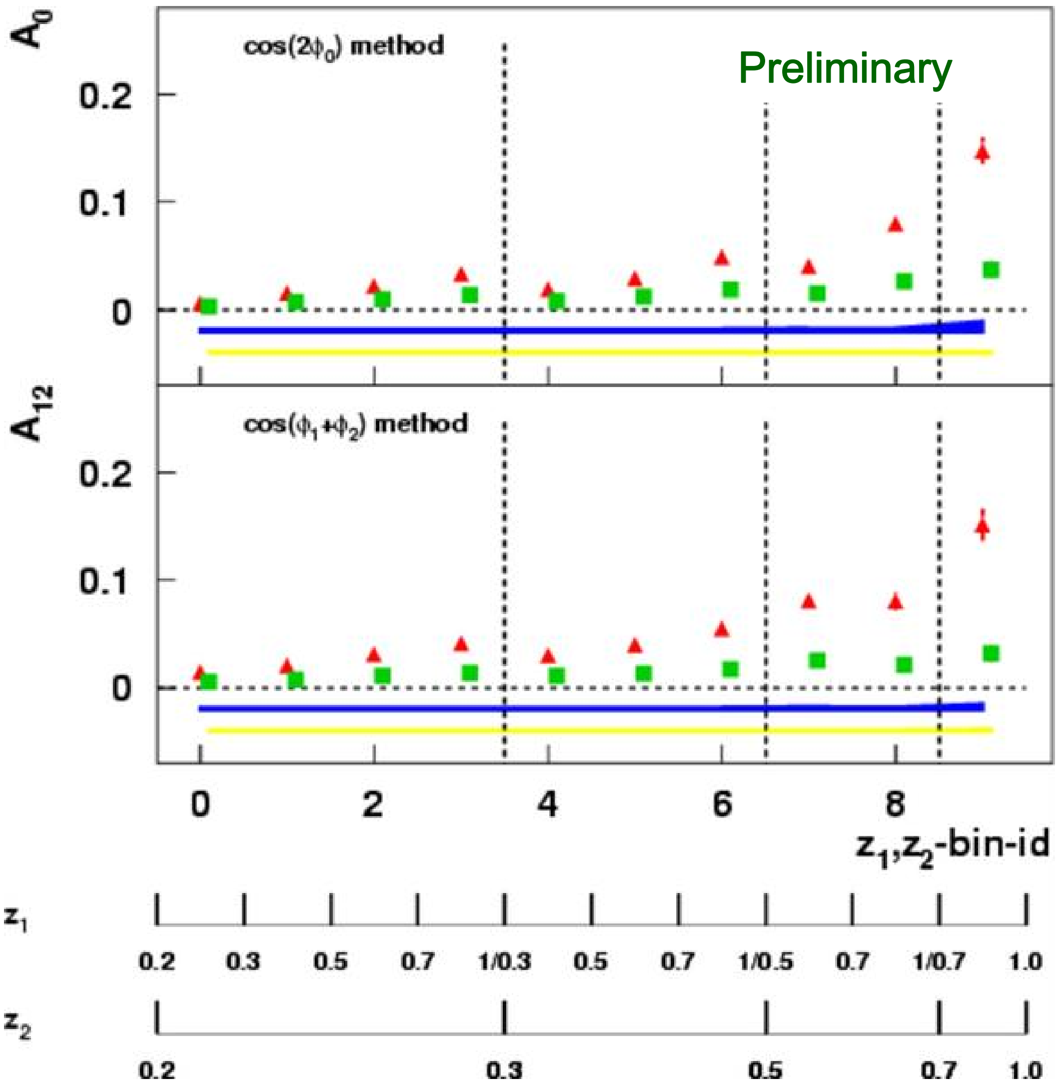
A_0(UL/L)	(3.06 ± 0.57 ± 0.55)%
A_{12}(UL/L)	(4.26 ± 0.68 ± 0.68)%
A_0(UL/C)	(1.27 ± 0.49 ± 0.35)%
A_{12}(UL/C)	(1.75 ± 0.59 ± 0.41)%



Preliminary Charm Corrected Results for $e^+ e^- \rightarrow \pi \pi X$ (547 fb^{-1}, on-resonance)

- Significance largely increased
- Behavior unchanged
- Reduced systematics
- Precise measurements of the Collins function

Integrated results:	
A_0(UL/L)	(2.67 ± 0.10 ± 0.26)%
A_{12}(UL/L)	(3.55 ± 0.08 ± 0.15)%
A_0(UL/C)	(1.11 ± 0.11 ± 0.22)%
A_{12}(UL/C)	(1.46 ± 0.09 ± 0.13)%



Summary and Outlook

Summary:

- Observation of large azimuthal asymmetries in light quark fragmentation. Updated statistics:

  $\int Ldt = 29\ fb^{-1} \rightarrow 547\ fb^{-1}$

- Double ratios reliably cancel contributions from detector acceptance and gluon radiation.

  important input for the transverse spin physics programs at RHIC, HERMES, COMPASS and JLab

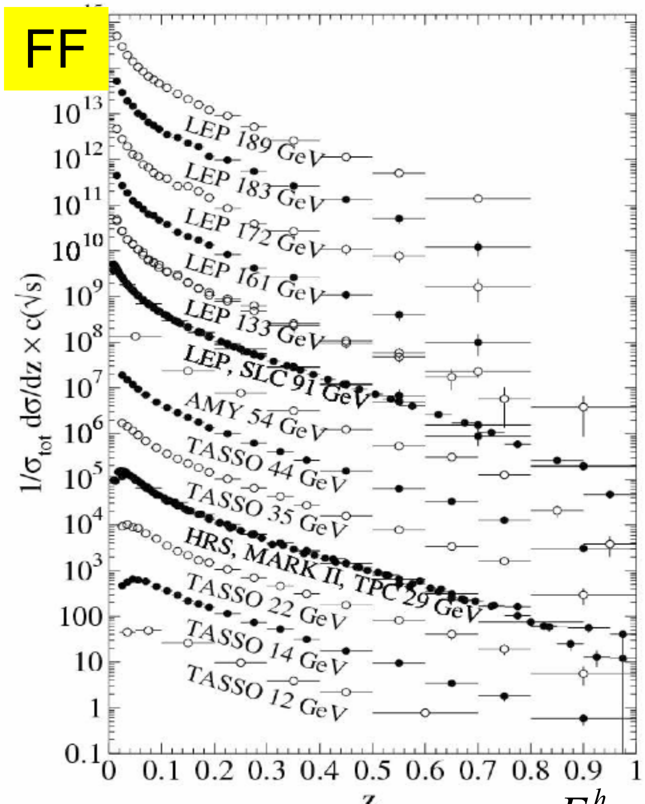
Outlook:

- Future spin dependent FFs:
  - → update Collins FF
  - → measure p_T dependence
  - → interference fragmentation
  - → Collins FF for VMs
  - → Lambdas

- Precision measurement of spin averaged fragmentation functions as input to RHIC program with inclusive hadrons and future precision measurements in SIDIS.

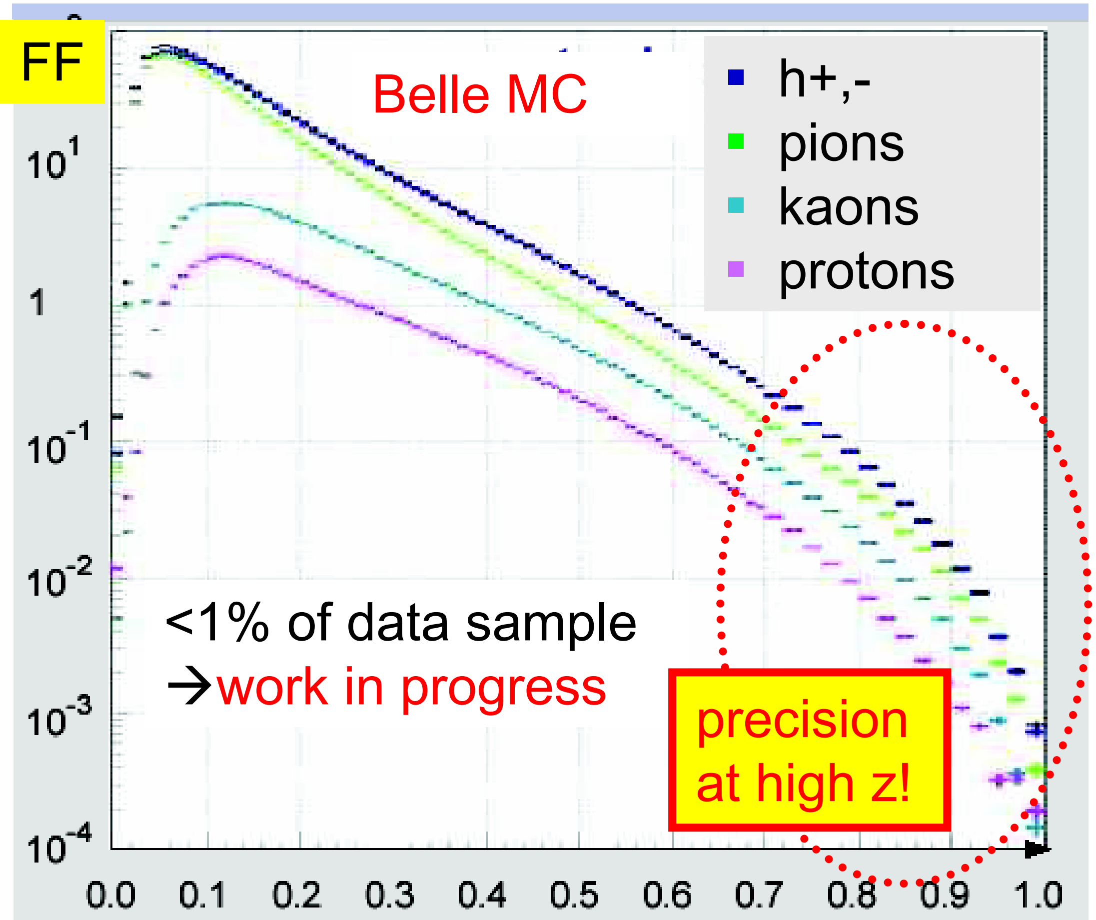
pact on the Knowledge of FFs

Input also for precision measurements of quark helicity distributions in SIDIS, in particular at a possible future electron-polarized proton collider.



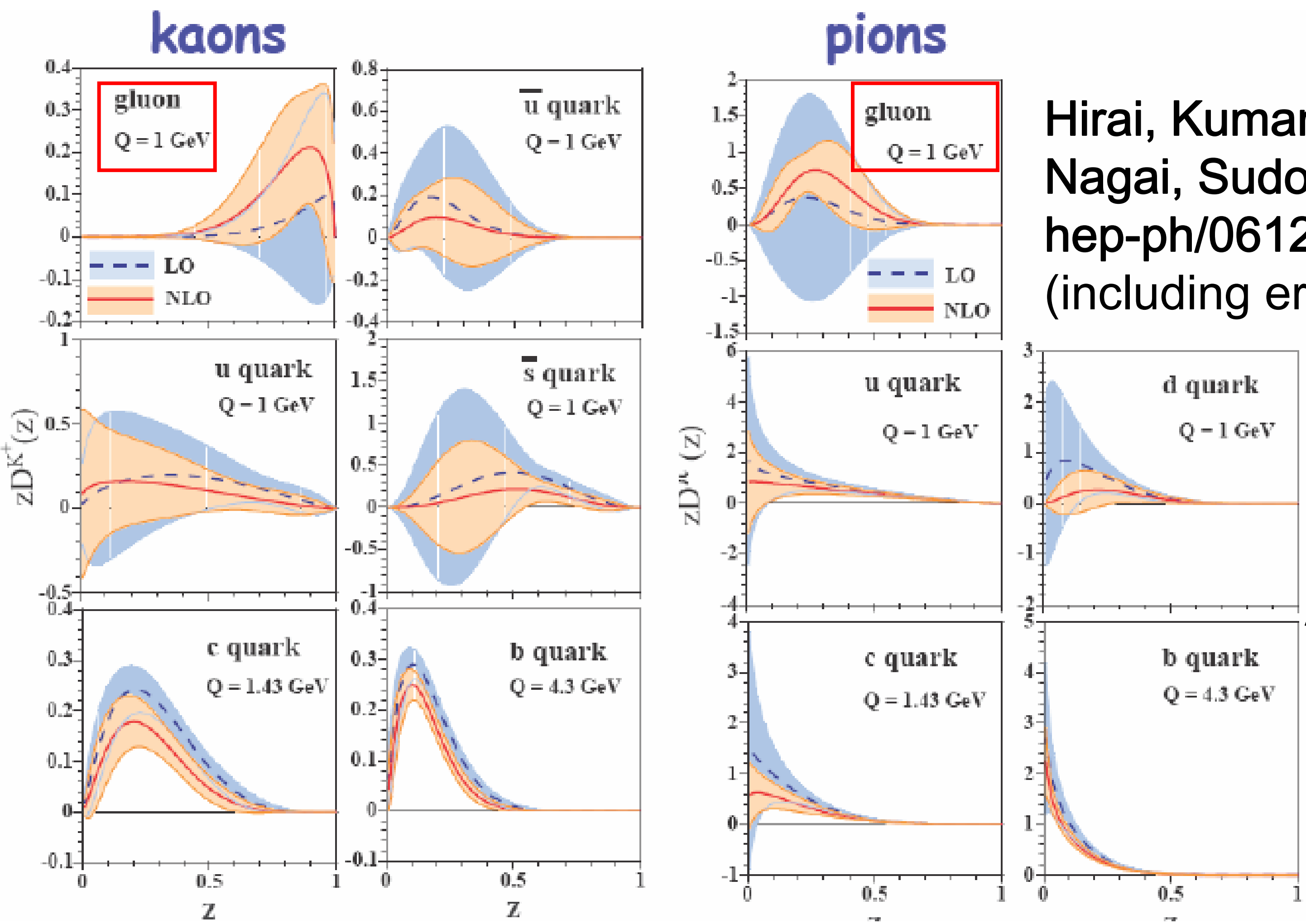
$$z = \frac{E^h}{\sqrt{s}/2}$$

Belle: Charged h+/-, pions, kaons, protons



$$z = \frac{E^h}{\sqrt{s}/2}$$

What is Known Experimentally ?



Hirai, Kumano, Nagai, Sudo
hep-ph/0612009
(including errors!)

Earlier work:

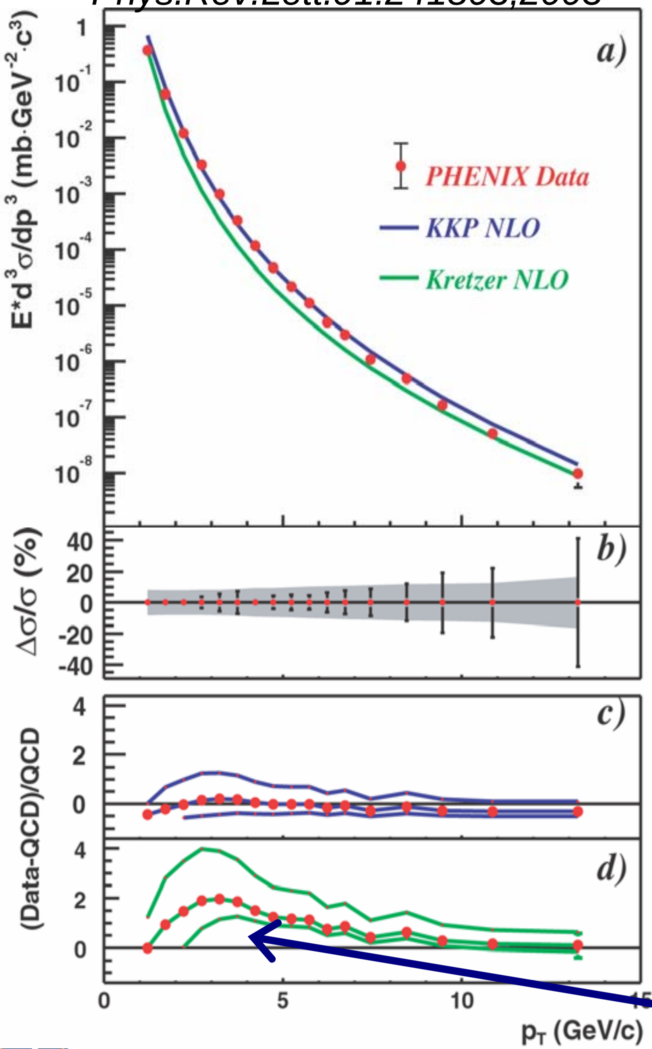
Kretzer

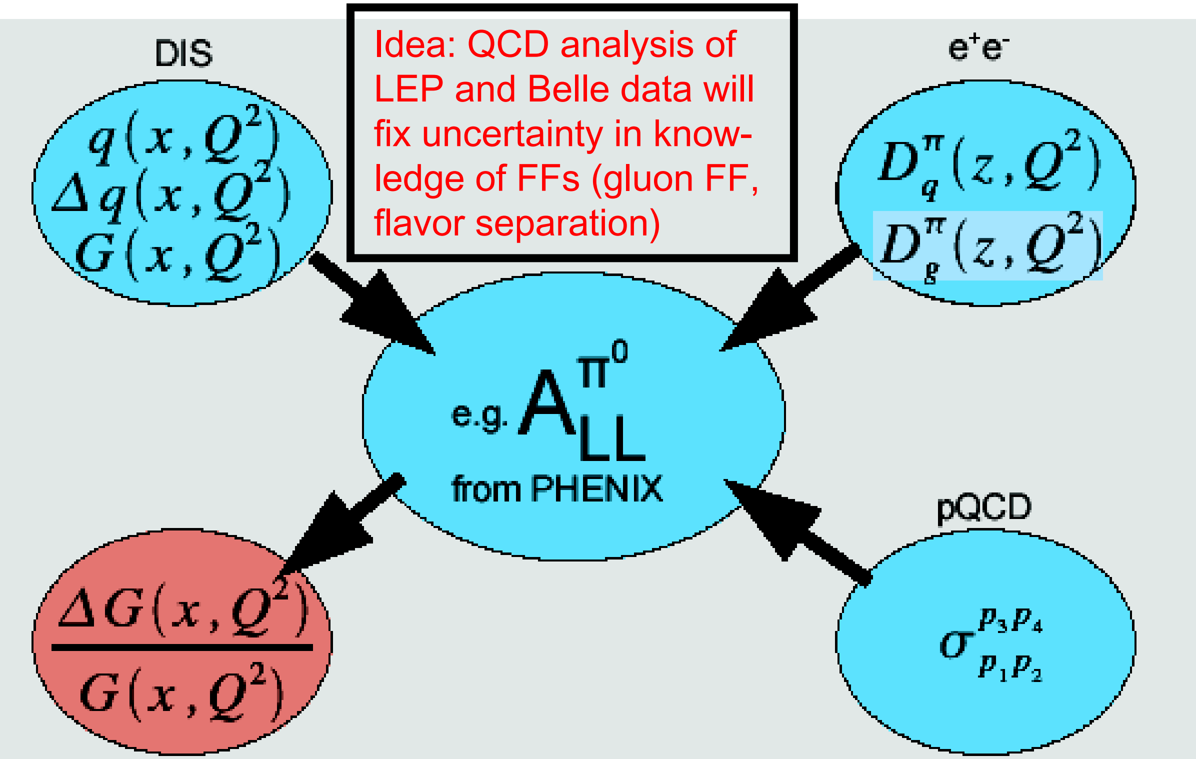
Binnewies, Potter, Albino
Kniehl, Kramer, Potter
Albino, Kniehl, Kramer

Motivation I ΔG from QCD Analysis of A_{LL} for inclusive hadrons: $\pi^{0,+,-}$, η, $K^{+,-}$

PHENIX π^0 cross section a $|\eta|<0.35$

Phys.Rev.Lett.91:241803,2003





$$A_{LL} \equiv \frac{d\Delta\sigma}{d\sigma} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}}$$

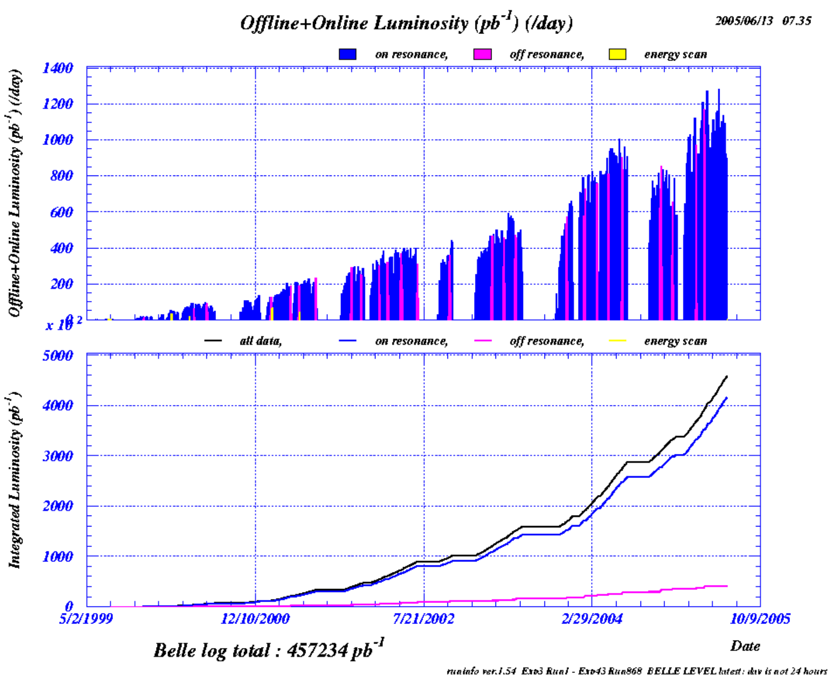
Deviation connected to uncertainties in FFs → gluon FF!

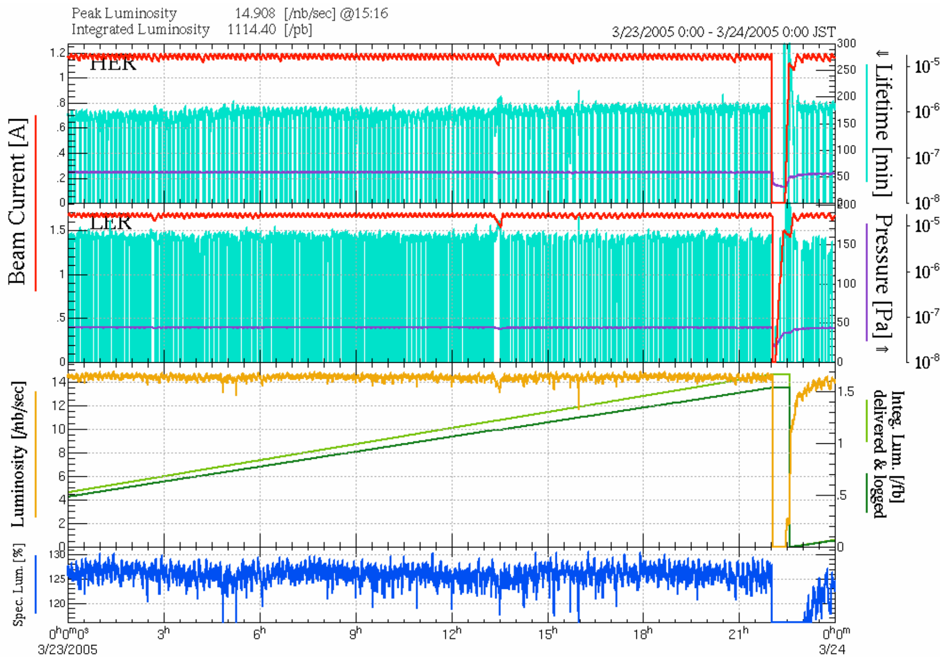
Why is the Collins Fragmentation Function Interesting?

- o Very basic QCD process: Fundamental test case for any approach to solve QCD at soft scales.
- o Tests of universality and factorization between e+e-, DIS and p-p collisions
- o Symmetry properties
- o Evolution is fundamental QCD prediction
- o Connection between microscopic and macroscopic observables:

➔ Probe/analyzer for transverse quark spin
critical input for transverse proton spin program at DESY, CERN, JLab and RHIC


祝 ∫L = 400 fb-1 達成
APR-05-2005

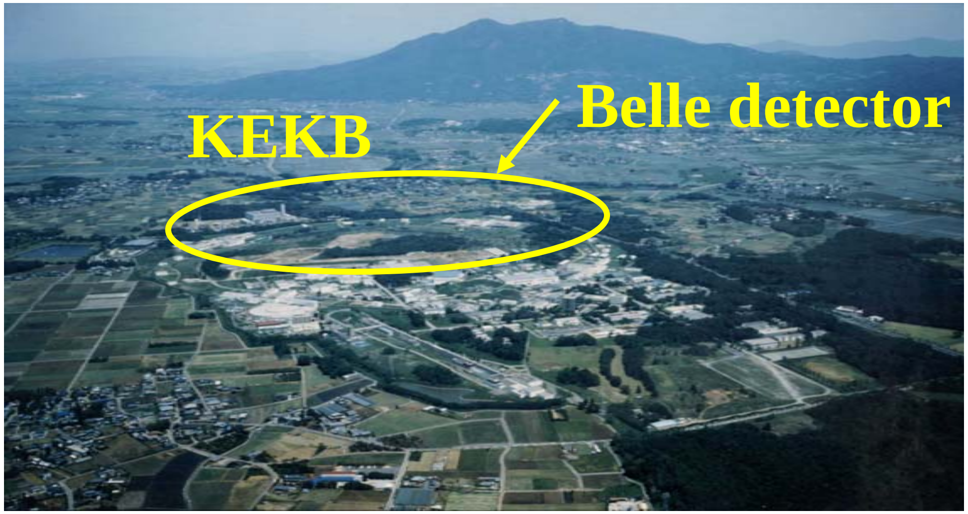

Offline+Online Luminosity (pb-1) (/day)
2005/06/13 07.35
on resonance, off resonance, energy scan
Offline+Online Luminosity (pb-1) (/day)
x 10^2
all data, on resonance, off resonance, energy scan
Integrated Luminosity (pb-1)
5/2/1999
12/10/2000
7/21/2002
2/29/2004
10/9/2005
Date
Belle log total : 457234 pb-1


Peak Luminosity 14.908 [/nb/sec] @15:16
Integrated Luminosity 1114.40 [/pb]
3/23/2005 0:00 - 3/24/2005 0:00 JST
HER
LER
Beam Current [A]
Lifetime [min]
Pressure [Pa]
Luminosity [/nb/sec]
Integ. Lum. [/fb] delivered & logged
Spec. Lum. [%]
3/23/2005
3/24

KEKB: L>1.6 x $10^{34}cm^{-2}s^{-1}$!!

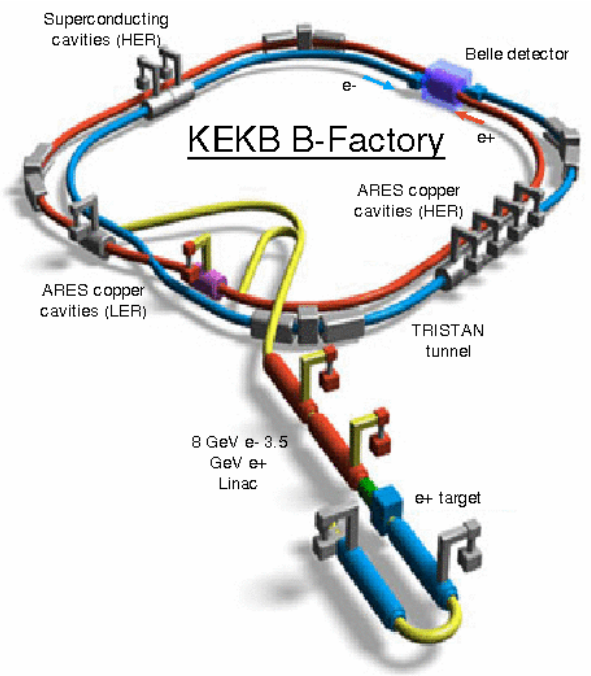
➔ 1.5 x 10^9 hadronic events in analysis

- KEKB
  - Asymmetric collider
  - 8GeV e^- + 3.5GeV e^+
  - $\sqrt{s}$ = 10.58GeV (Υ(4S))
    $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\,\bar{B}$
  - Off-resonance: 10.52 GeV
    $e^+e^- \rightarrow q\,\bar{q}$ (u,d,s,c)
  - Integrated Luminosity: > 600 fb^{-1}
    > 60fb^{-1} => off-resonance

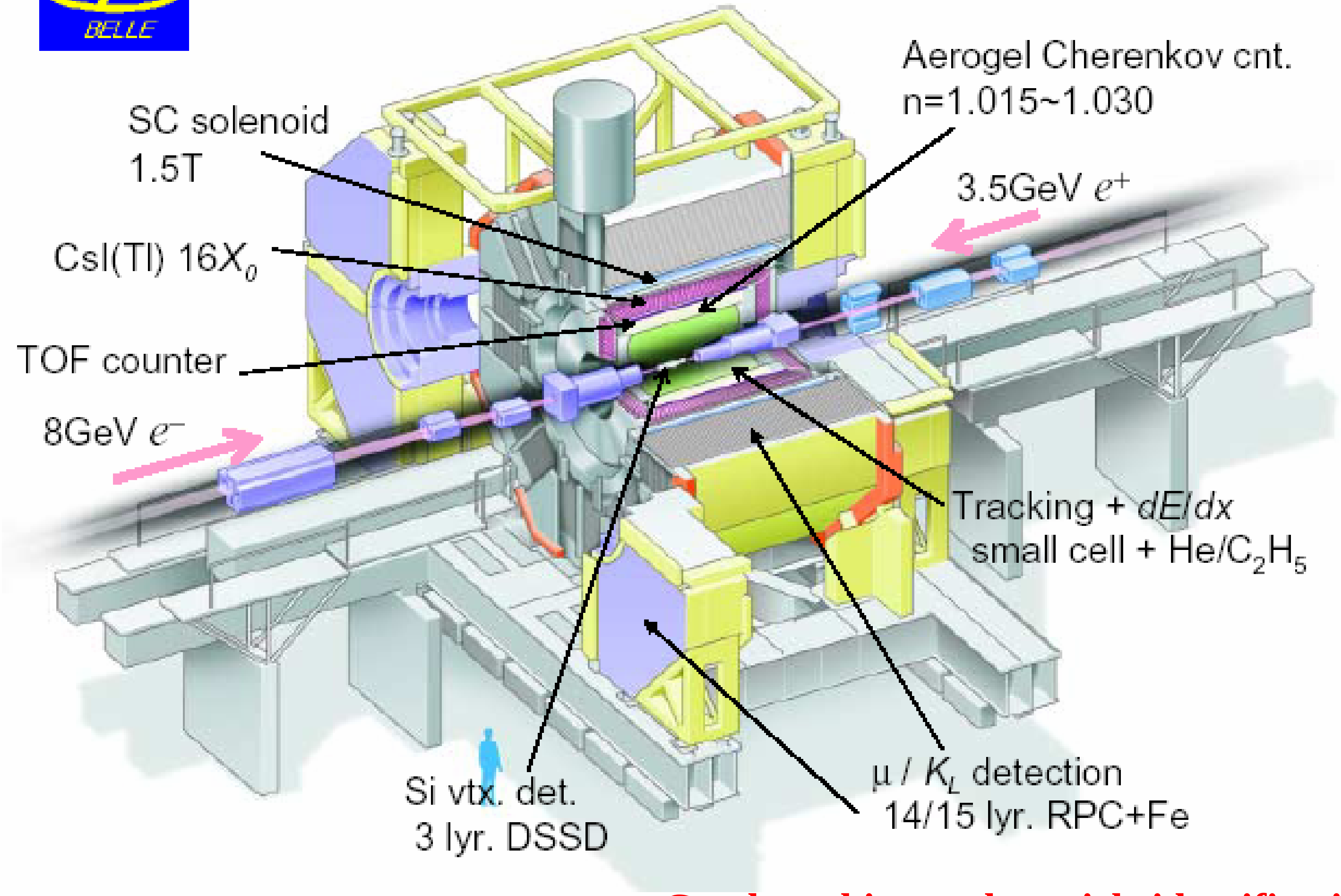


•Average Trigger rates:

$\Upsilon(4S) \rightarrow B\bar{B}$	11.5Hz
$q\,\bar{q}$	28 Hz
$\mu\mu + \tau\tau$	16 Hz
Bhabha	*4.4 Hz*
2γ	*35 Hz*



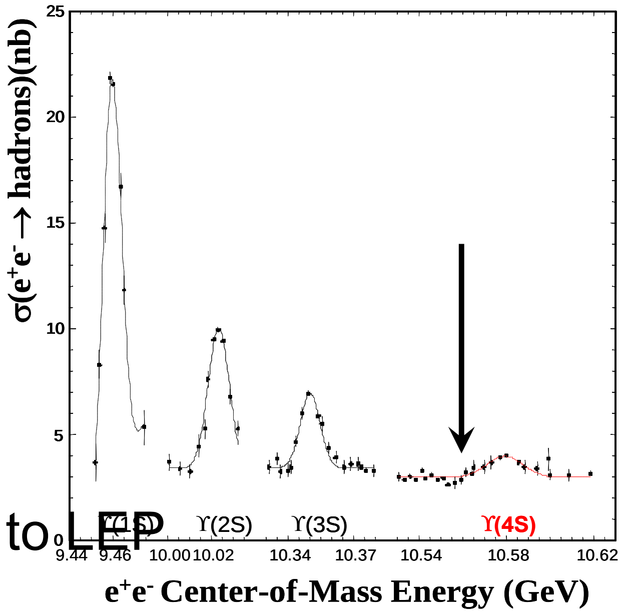
Belle Detector



Good tracking and particle identification!

Belle is Well Suited for FF Measurements:

- Good detector performance (acceptance, momentum resolution, pid)
- Jet production from light quarks
  → off-resonance (60 MeV below resonance)
  (~10% of all data)
- Intermediate Energy
  → Sufficiently high scale (Q^2 ~ *110 GeV²*)
  - can apply pQCD
  → Not too high energy ($Q^2 << M_Z^2$)
  -avoids complication from Z interference
- Sensitivity = $A^2 sqrt(N)$ ~ **x 25** *(100)* compared to LEP
  A_{Belle} / A_{LEP} ~ **x 2** (A scales as $ln\ Q^2$)
  $\int L_{Belle}\ dt / \int L_{LEP}\ dt$ ~ **x 46** *(600)*



Total number of hadronic events ~ 1.5 x 10^9

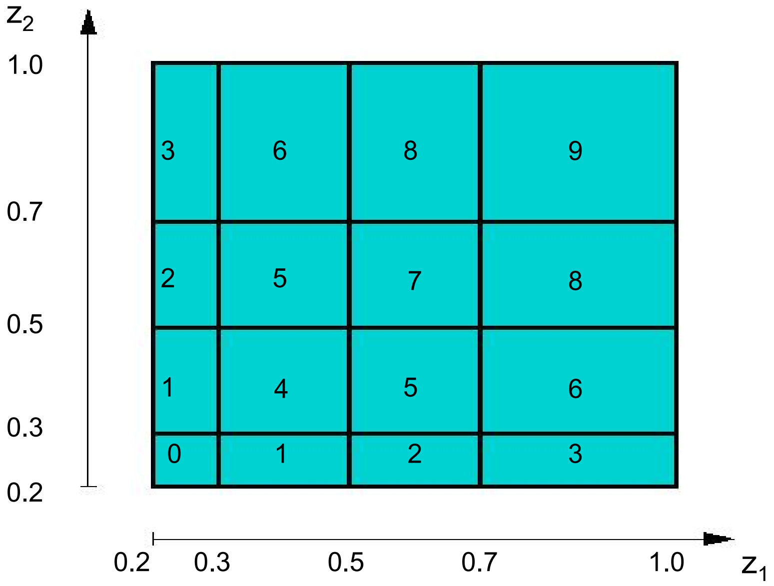
Applied Cuts, Binning

- Originally off_resonance data, now also on_resonance data (29.1 → 547 fb^{-1})
- Track selection:
  - pT > 0.1GeV
  - vertex cut: dr<2cm, |dz|<4cm
- Acceptance cut
  - $-0.6 < \cos\theta_i < 0.9$
- Event selection:
  - Ntrack ≥ 3
  - Thrust > 0.8
  - $Z_1, Z_2 > 0.2$

- Hemisphere cut

$$(P_{h2} \cdot \hat{n})\hat{n} \cdot (P_{h1} \cdot \hat{n})\hat{n} < 0$$

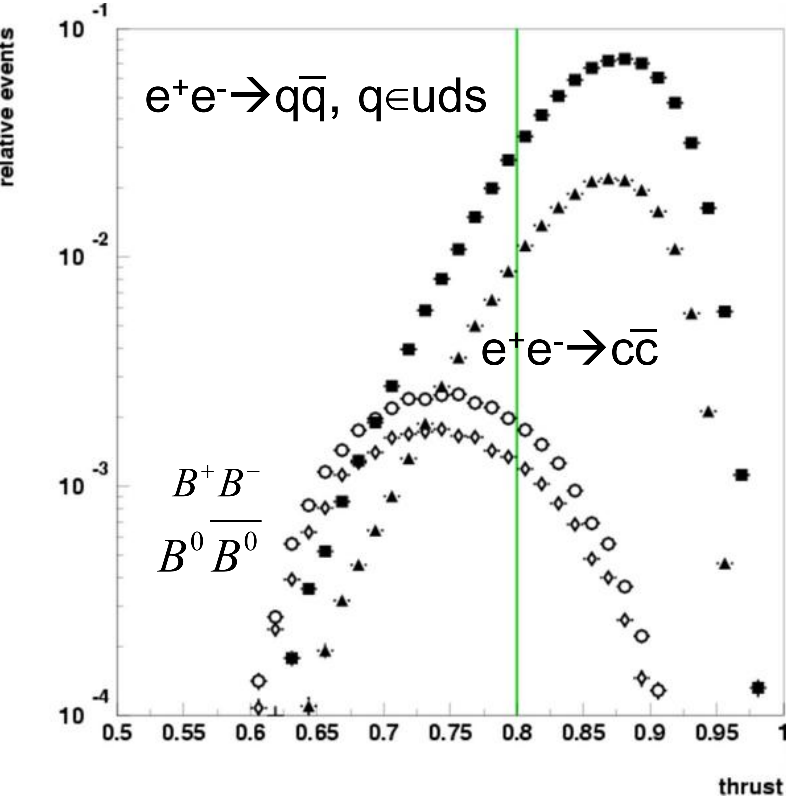
- $Q_T < 3.5$ GeV
- Pion PID selection



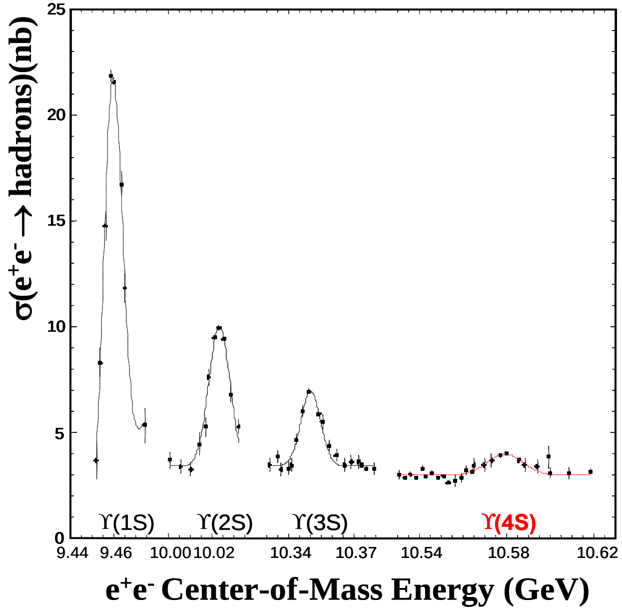
Experimental Issues

- Cos2ϕ moments have two contributions:
  - Collins → Can be isolated either by subtraction or double ratio method
  - Radiative effects → Cancels exactly in subtraction method, and in LO of double ratios
- Beam Polarization zero? → *cos(2ϕ)* asymmetries for jets or $\gamma\gamma$
- False asymmetries from weak decays → Study effect in τ decays, constrain through D tagging
- False asymmetries from misidentified hemispheres → Q_T or polar angle cut
- False asymmetries from acceptance → Cancels in double ratios, can be estimated in charge ratios, fiducial cuts
- Decaying particles → lower z cut

Why is it Possible to Include Data on Resonance? Different Thrust Distributions



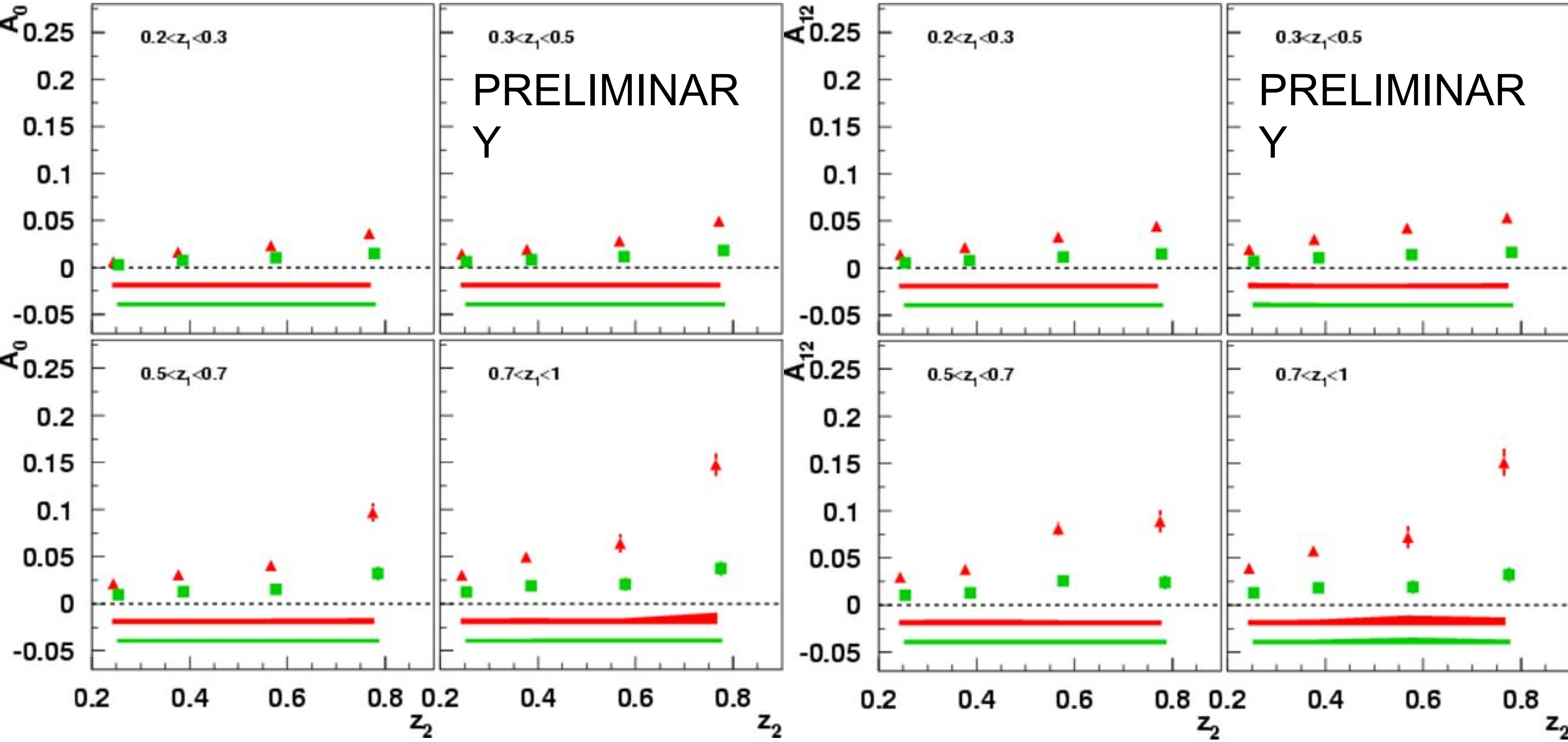
$$\text{thrust} = \frac{\sum_i |p_i \cdot \hat{n}|}{\sum_i |p_i|}$$



- small B contribution (<1%) in high thrust sample
- >75% of X-section continuum under ϒ (4S) resonance
- 29 fb^{-1} ➔ 547 fb^{-1}
- many systematic errors reduce with more statistics
- Charm-tagged Data sample also increases

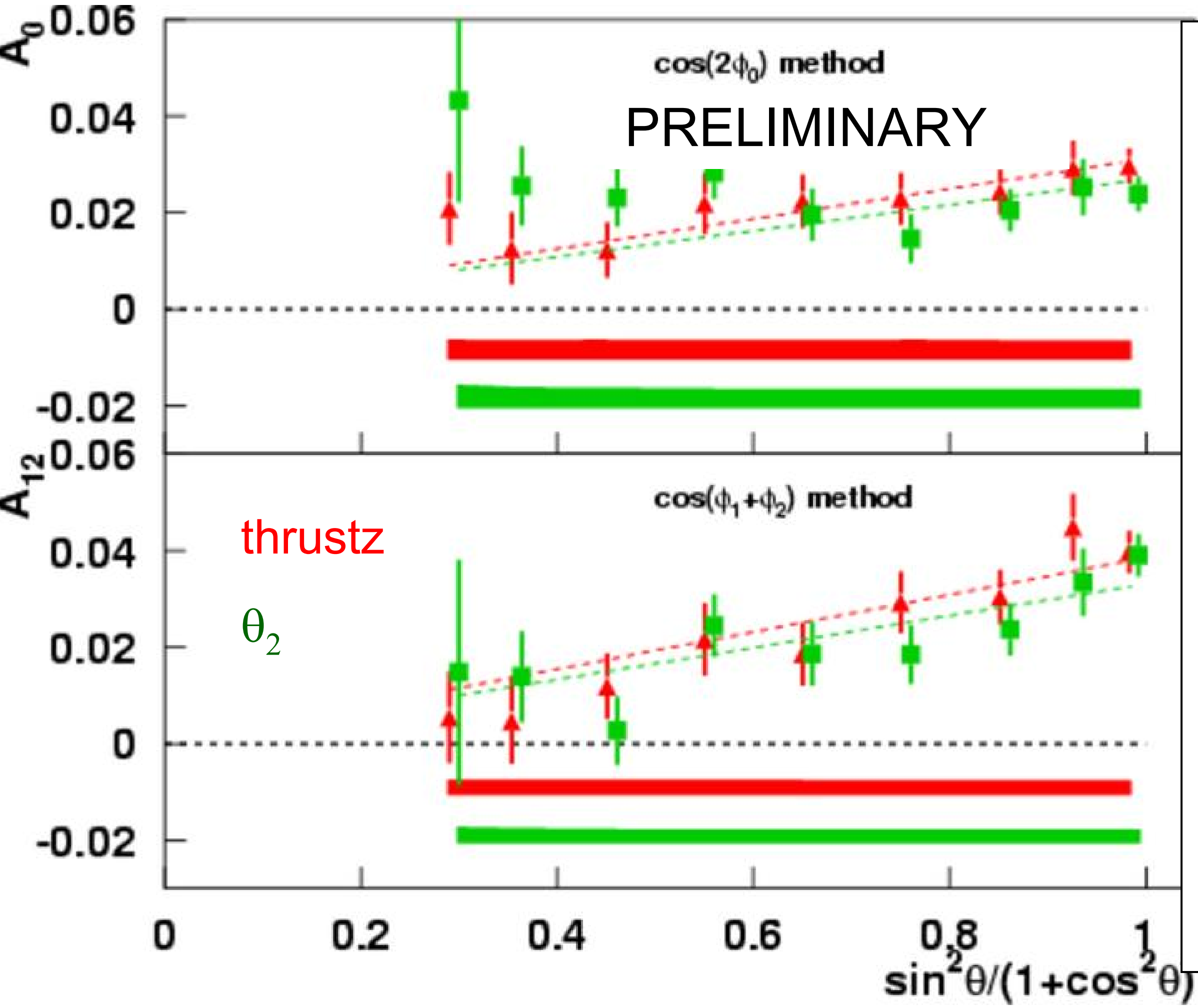
Collins Asymmetries I: 4x4 z_1, z_2 binning

A_0 ($\cos(2\phi_0)$) moments $\quad$ A_{12} ($\cos(\phi_1+\phi_2)$) moments



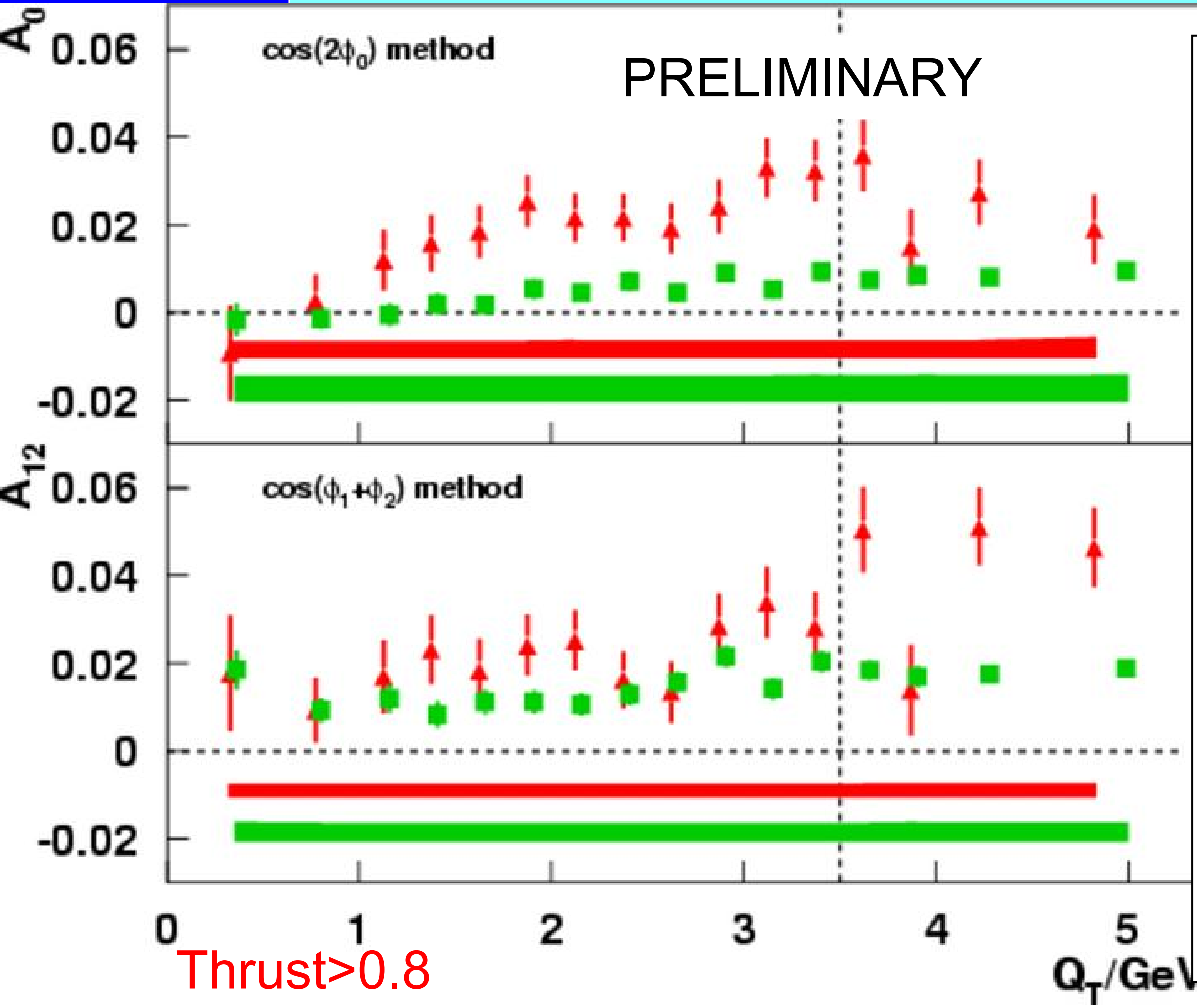
- 547 fb^{-1} charm corrected data sample,
- UL and UC double ratios

Collins Asymmetries II: $\sin^2\theta/(1+\cos^2\theta)$ Binning (UL)



- Nonzero quark polarization ~ $\sin^2\theta$
- Unpolarized de-nominator ~ $1+\cos^2\theta$
- Clear linear behavior seen when using either thrustz or 2nd hadron as polar angle
- Better agreement for thrust axis (~approximate quark axis)
- UC plots similar

Collins Asymmetries III: Q_T Binning (UL)



Thrust>0.8

Thrust<0.8 (not corrected for heavy quark contributions)

- Reduced asymmetries in low thrust sample
- At low thrust significant B contribution

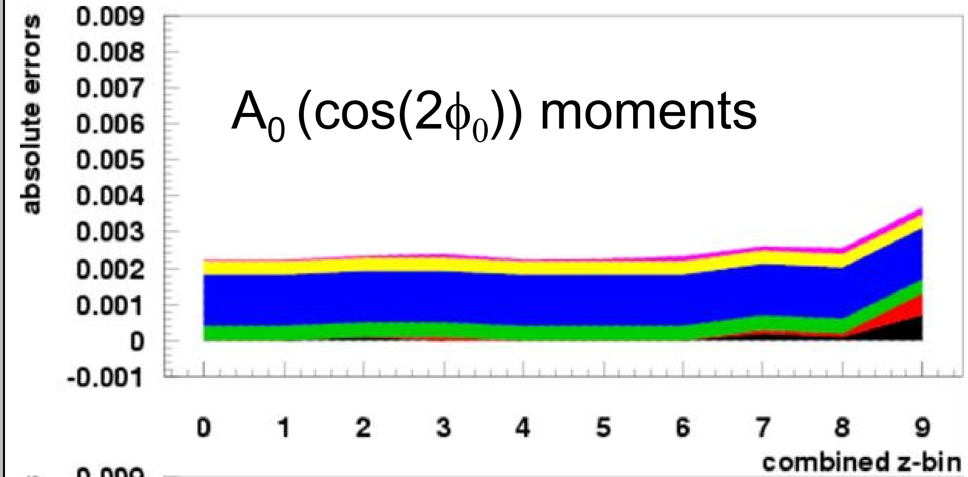
  (for t<0.8 ~20 % B

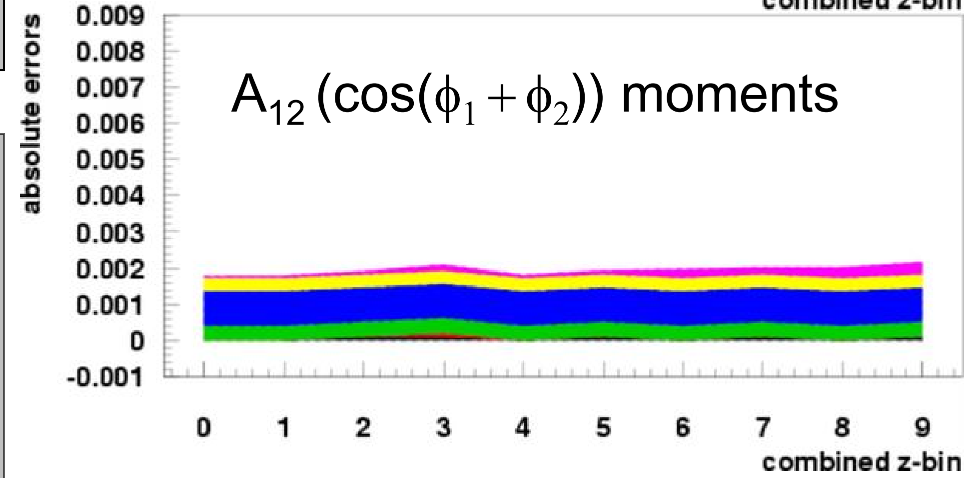
  for t>0.8 < 1 % B)
- A_{12} thrust axis dependent
- High Q_T (>3.5 GeV) asymmetries from beam related BG
- UC plots similar

Improved Systematic Errors (UC)

- Tau contributions
- PID systematics*
- MC double ratios
- Charged ratios ($\pi^+\pi^+ / \pi^-\pi^-$)
- Higher order terms
- Double ratio-subtraction method

Reweighting asymmetries:
→underestimation of $\cos(\phi_1+\phi_2)$ asymmetries →rescaled by 1.21
Correlation studies:
→statistical errrors rescaled by 1.02 (UL) and 0.55 (UC)
Beam polarization studies
→consistent with zero





Collins Asymmetry → Collins FF

QCD analysis:

(I) Efremov, Goeke, Schweitzer (Phys.Rev.D73:094025,2006): consistency between Belle, HERMES and COMPASS asymmetries.

(II) Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Prokudin and Tuerk (hep-ph/0701006) extract transversity distributions and the Collins FF (see tomorrow).

(III) UIUC fit to Belle data (work in progress):

$$H^{fav}(z) = a^{fav} \cdot z \cdot D^{fav}(z)$$
$$H^{dis}(z) = a^{dis} \cdot z \cdot D^{dis}(z)$$

Spin Averaged FF + Collins Asymmetry

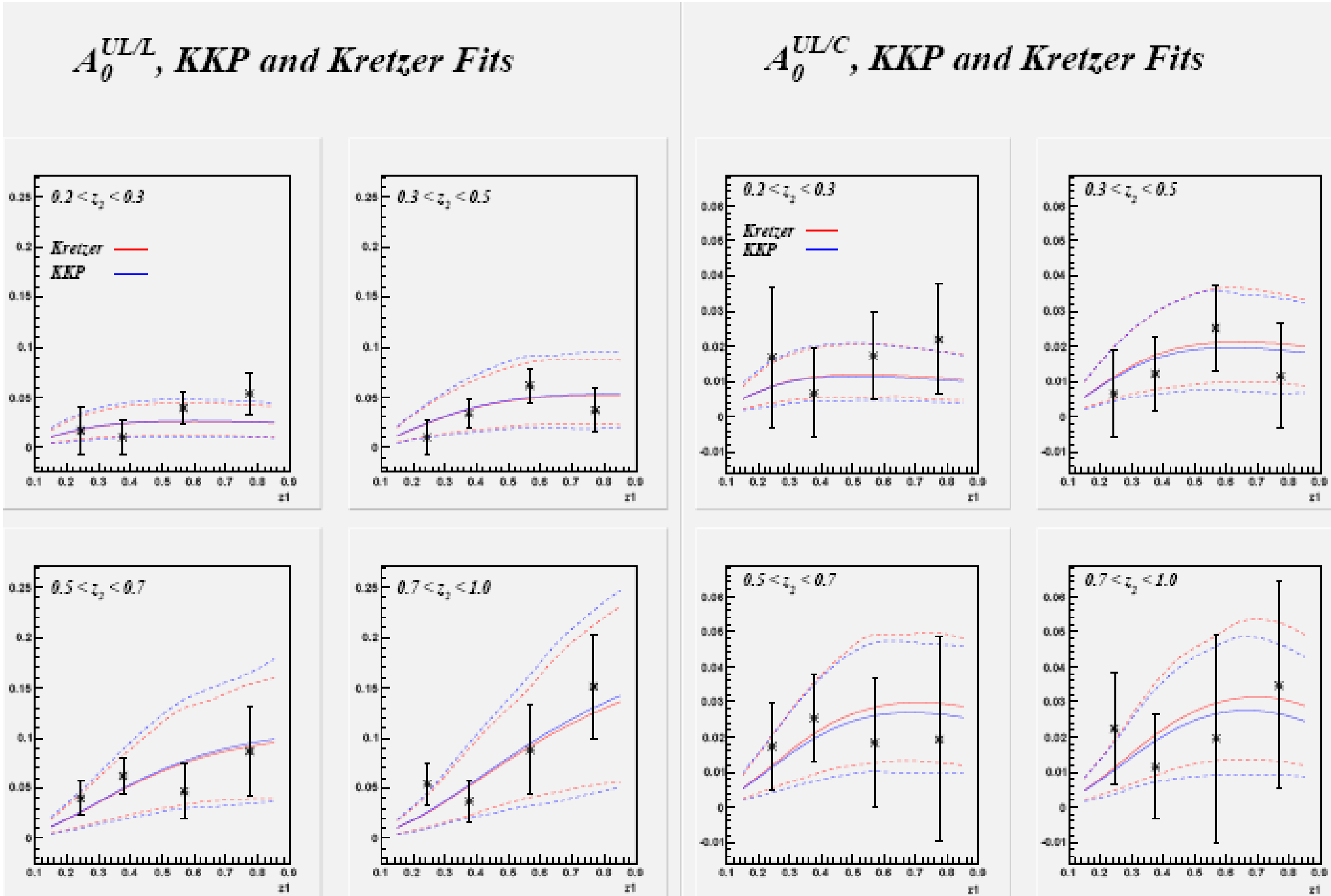
Kretzer FFs (also KKP)

$$D^{fav}(z) = \frac{1}{4}\left(D_{\bar{d}}^{\pi^+} + D_{u}^{\pi^+} + D_{d}^{\pi^-} + D_{\bar{u}}^{\pi^-}\right)$$
$$D^{dis}(z) = \frac{1}{4}\left(D_{d}^{\pi^+} + D_{\bar{u}}^{\pi^+} + D_{\bar{d}}^{\pi^-} + D_{u}^{\pi^-}\right)$$

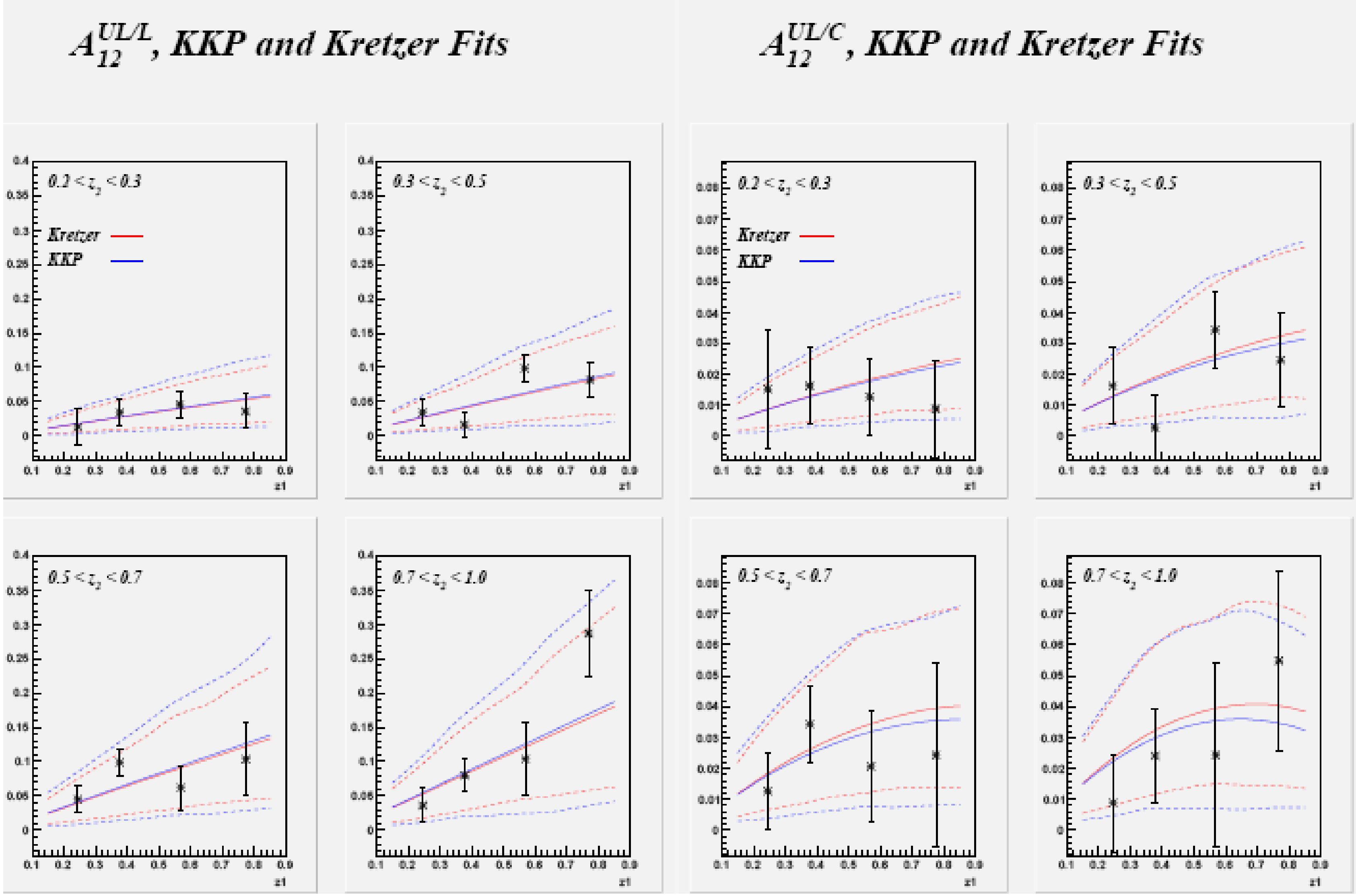
Experimental double ratio:

$$A_{12}^{UL/L}(z_1,z_2) = \frac{\sin^2\theta}{1+\cos^2\theta}\left(\frac{H_1^{fav}H_2^{fav} + H_1^{dis}H_2^{dis}}{D_1^{fav}D_2^{fav} + D_1^{dis}D_2^{dis}} - \frac{H_1^{fav}H_2^{dis} + H_1^{dis}H_2^{fav}}{D_1^{fav}D_2^{dis} + D_1^{dis}D_2^{fav}}\right)$$

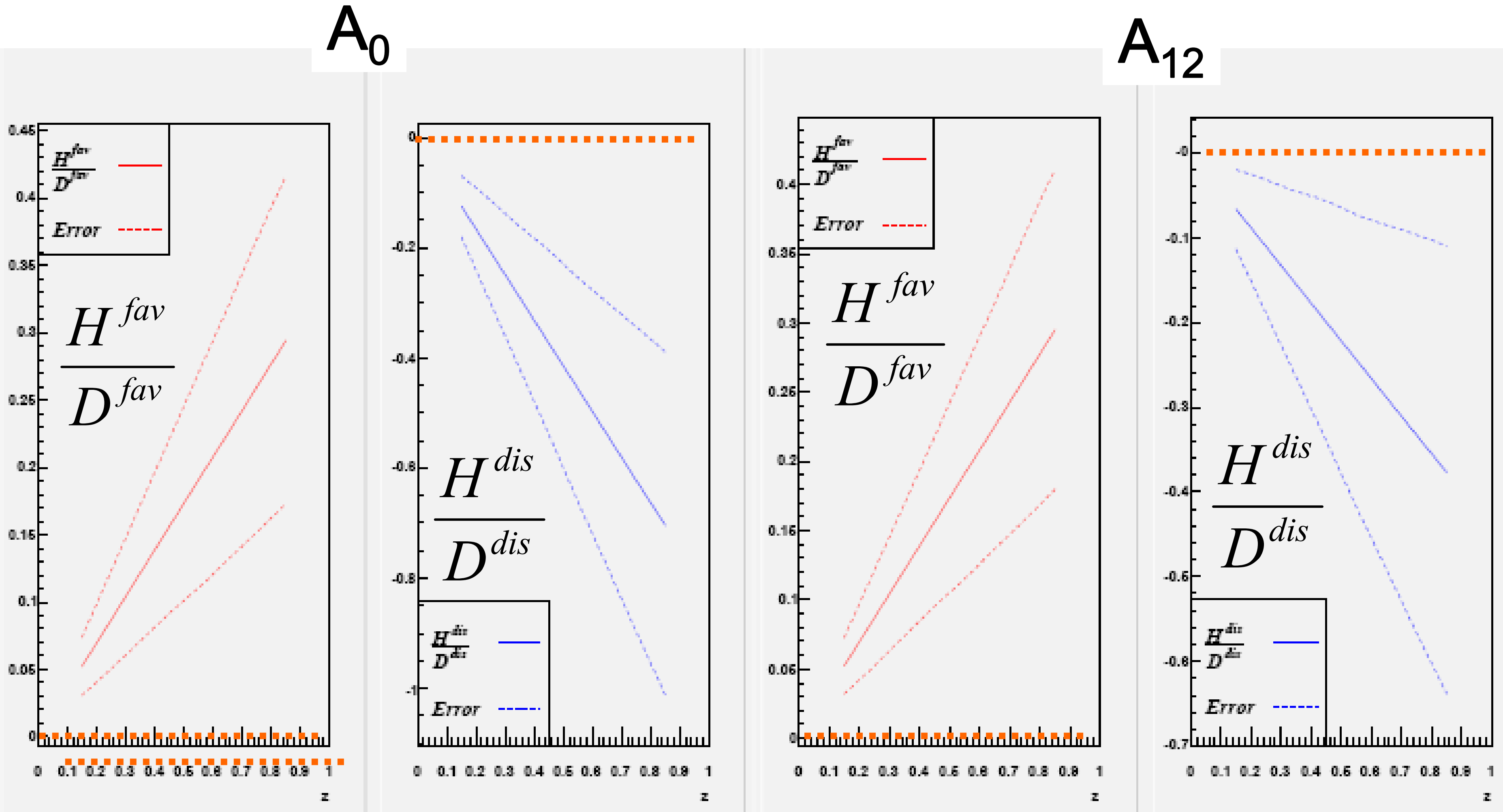
Fits of the Belle Collins Asymmetries A_0 with $\int Ldt$ = 29 fb-1



Fits of the Belle Collins Asymmetries A_{12} with $\int Ldt$ = 29 fb^{-1}



Results for the Collins FF



0 < z < 1