# Precision Measurements of Quark Fragmentation Functions in Belle

**International Workshop on**

**Structure and Spectroscopy**

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| | |
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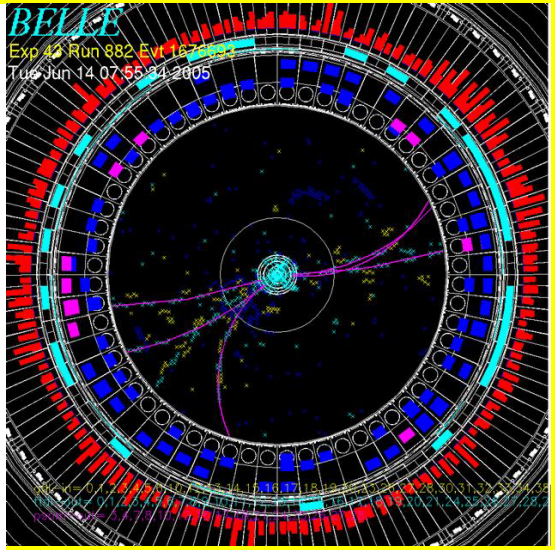
*for the Belle Collaboration*

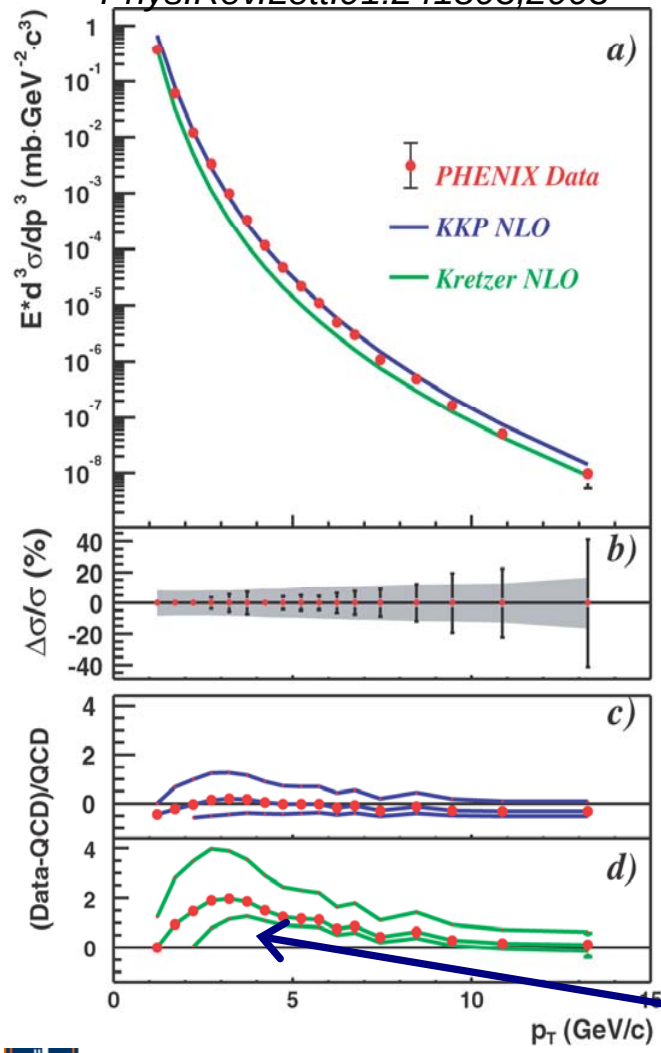
# ---------- Outline ----------

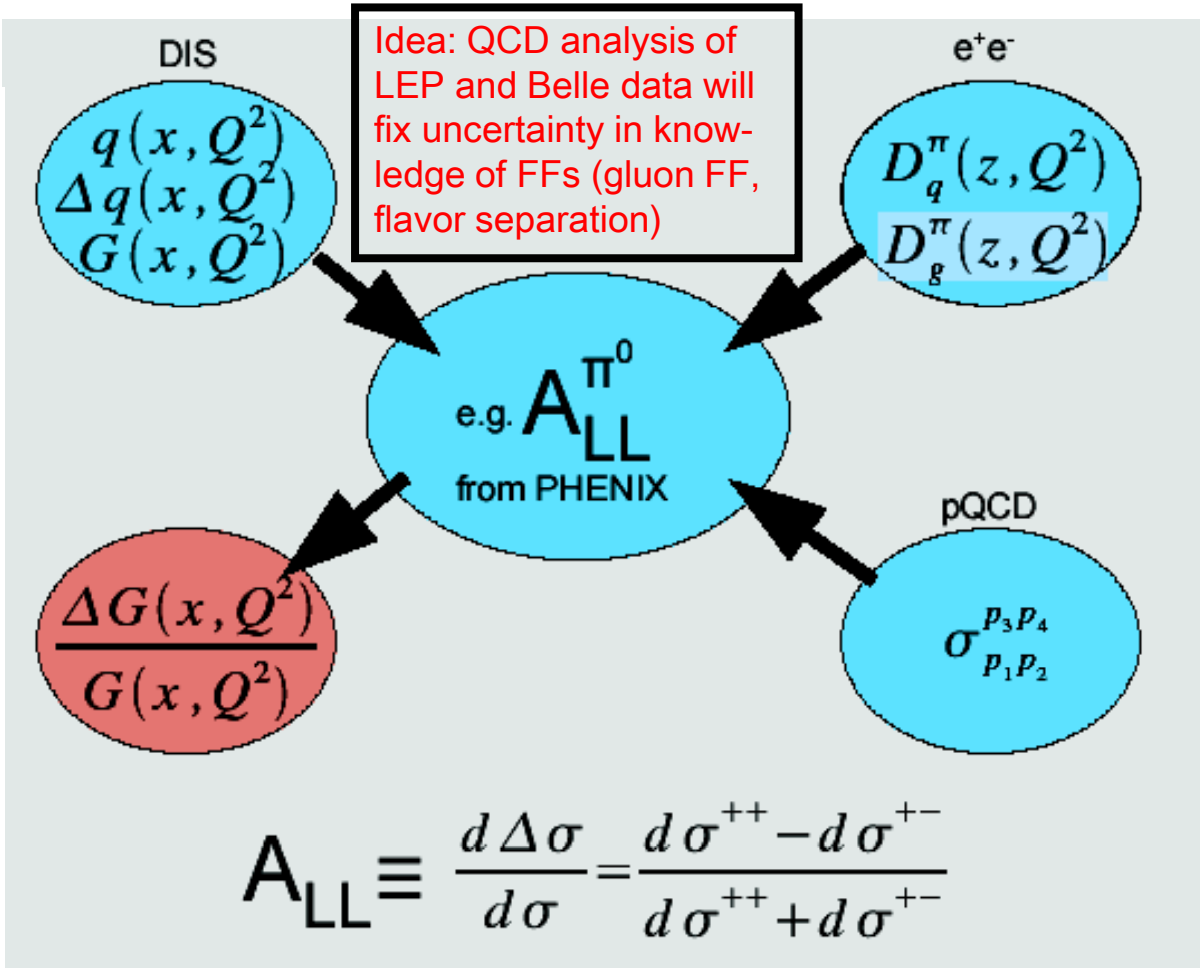
- Motivation
  - FFs for Measurements at RHIC and in SIDIS
- Collins Asymmetries in $e^+e^-$
  - LEP first work on Delphi data in the 90s:
  - *Efremov, Smirnova, Tkatchev and Bonivento, Matteuzzi, Kotzinian*
  - KEKB and Belle: B-Factory and Experiment
  - Data Analysis and Results
- QCD analysis

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

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

*Phys.Rev.Lett.91:241803,2003*

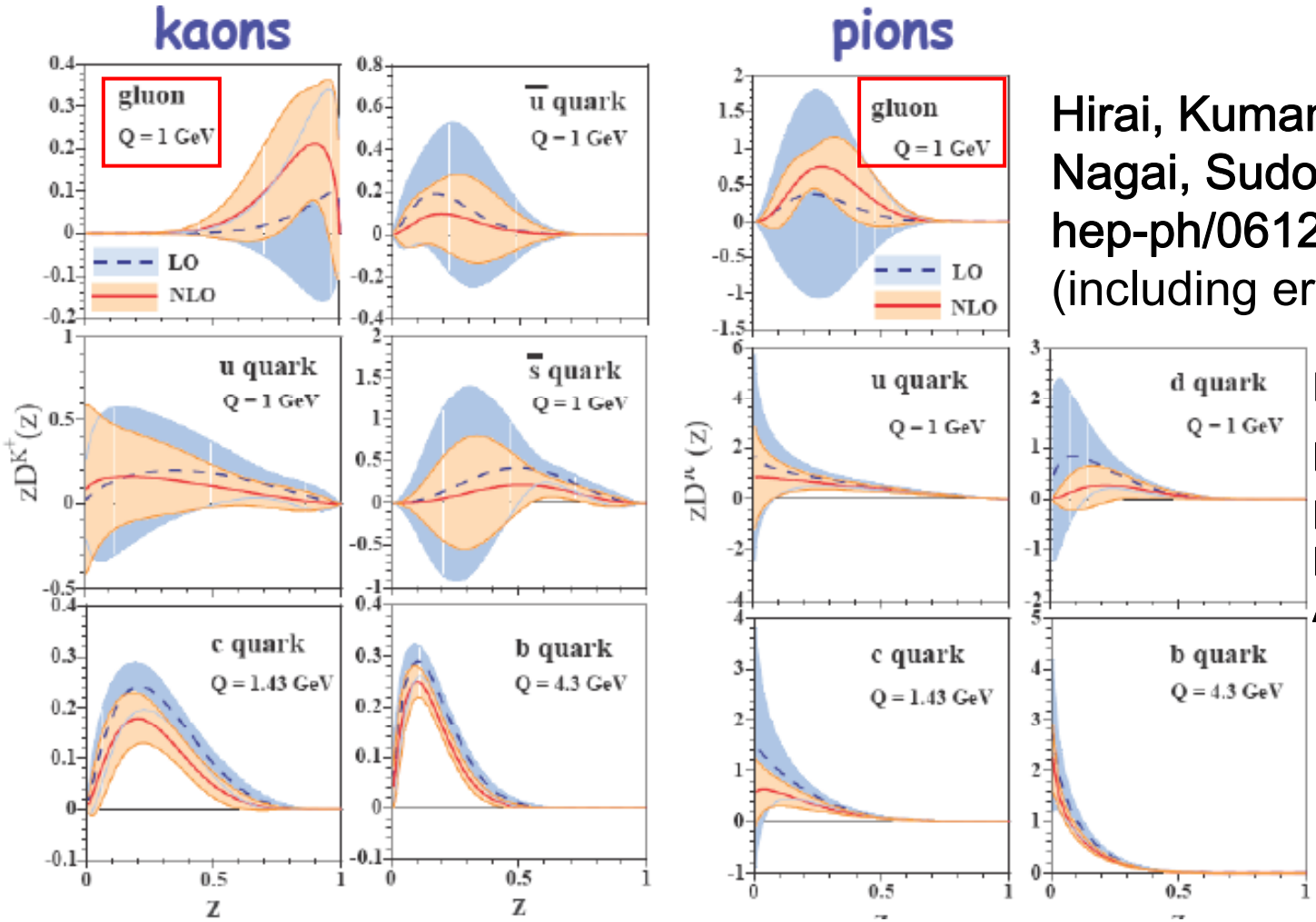



Idea: QCD analysis of LEP and Belle data will fix uncertainty in know-ledge of FFs (gluon FF, flavor separation)

**Deviation connected to uncertainties in FFs → gluon FF!**

# 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

# questions to ask (III)

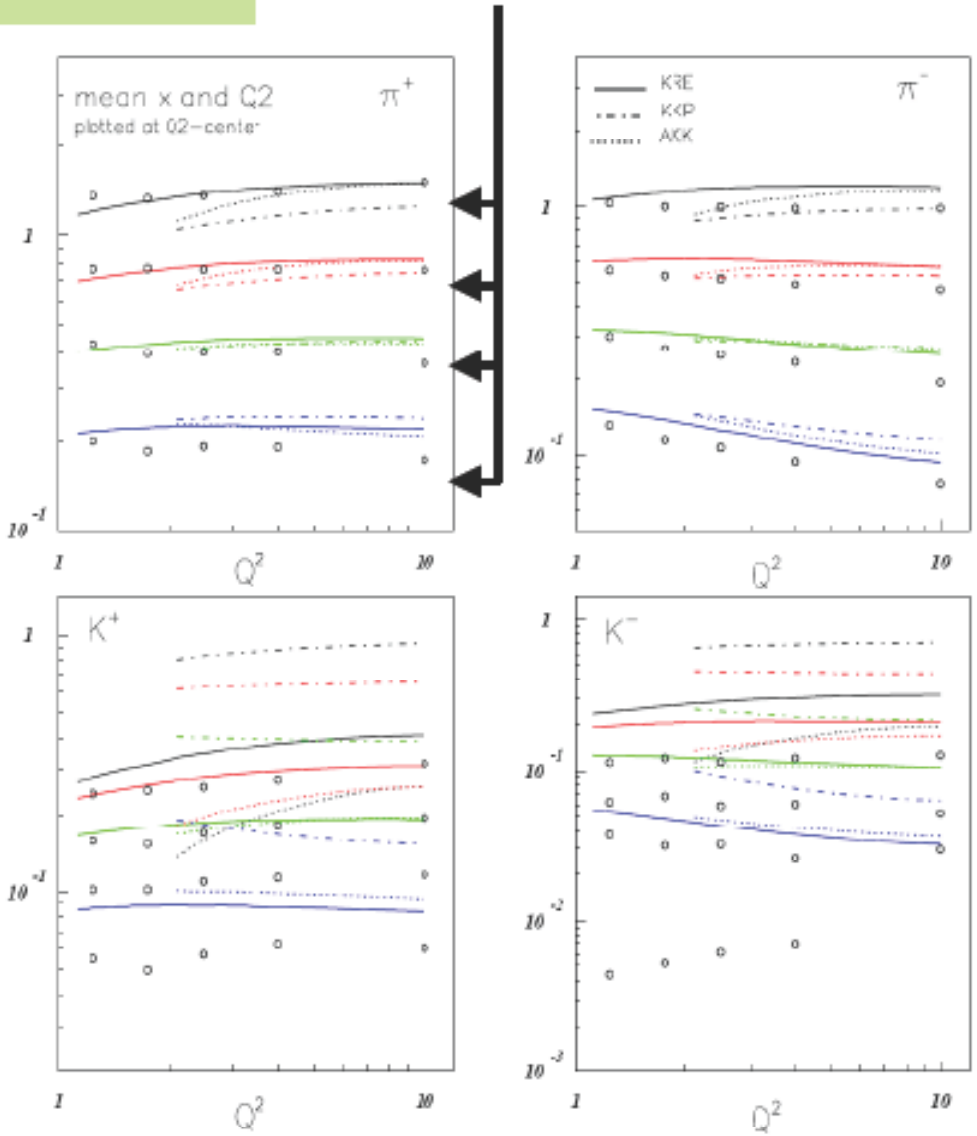
**From Marco Stratmann**
**Seminar at RIKEN, Feb 2007**

at similar scales and momentum fractions z, all current frag. fcts. (Kretzer, KKP, AKK) fail for semi-incl. DIS $ep \to \pi^{\pm}, K^{\pm} X$ (multiplicities)

**key question:**

**Is it possible to arrive at a *unified* description of $e^+e^-$, ep, and pp data in terms of a *universal set* of fragmentation functions?**

different bins in z



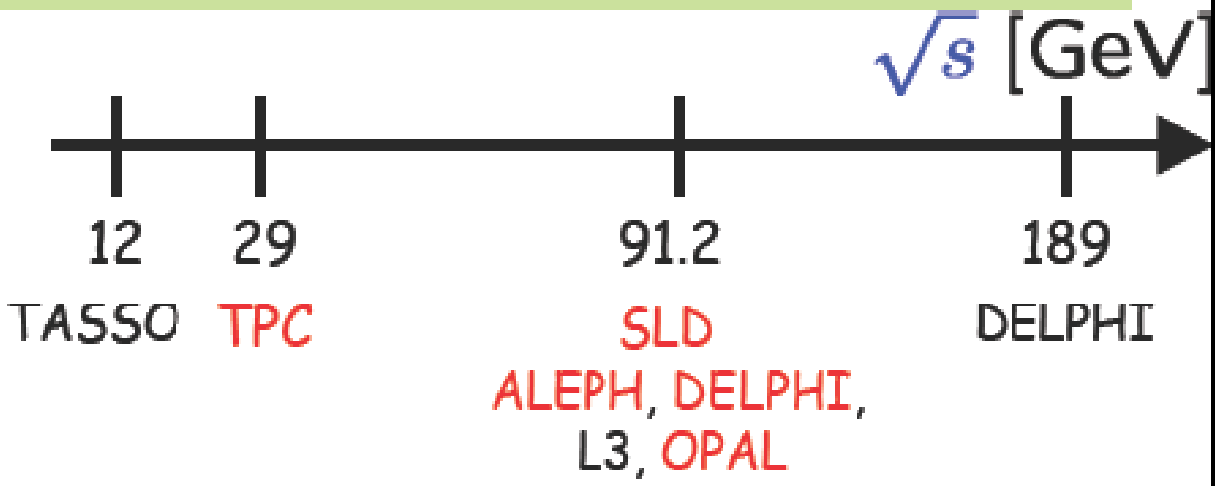

[data taken from A. Hillenbrand's (HERMES) thesis]

# $e^+e^-$ annihilation: what is measured

Durham reaction database:
durpdg.dur.ac.uk/hepdata

**DESY**
CELLO, JADE, TASSO
**SLAC**
HRS, MARK-II, SLD, TPC
**KEK**
AMY, TOPAZ
**CERN**
ALEPH, DELPHI, L3, OPAL

$\pi^{\pm}$, $K^{\pm}$,
p, $h^{\pm}$, ...




data on pions, kaons used in theoretical fits

**"limitations":**

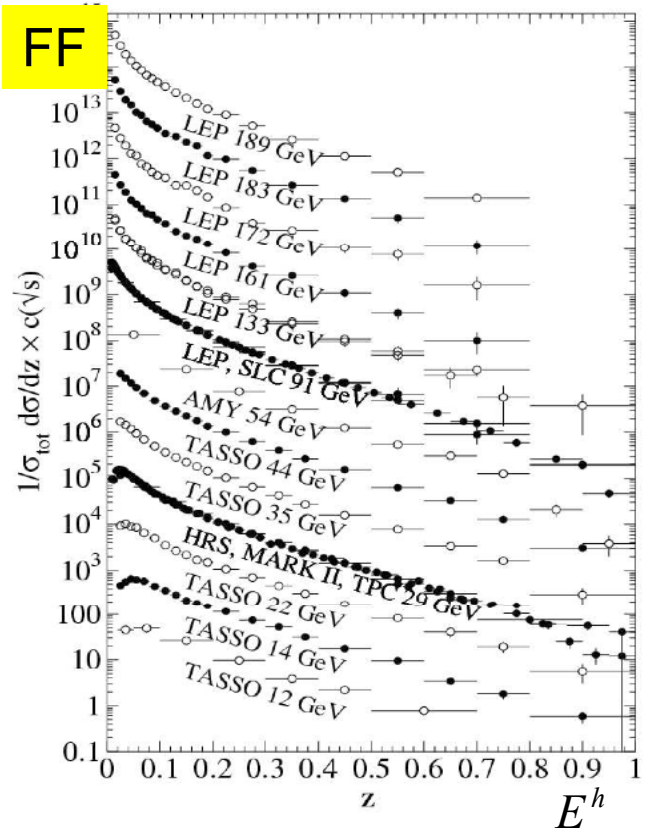
- overwhelming statistics on Z-resonance; only TPC data are of some use to study QCD scale evolution – the only handle on $D_{gluon}$

LEP/SLD data mainly constrain the total *singlet fragmentation* $D_{\Sigma}$ to $\pi^+ + \pi^-$, etc.
no valence/sea or flavor separation

From Marco Stratmann
Seminar at RIKEN, Feb 2007

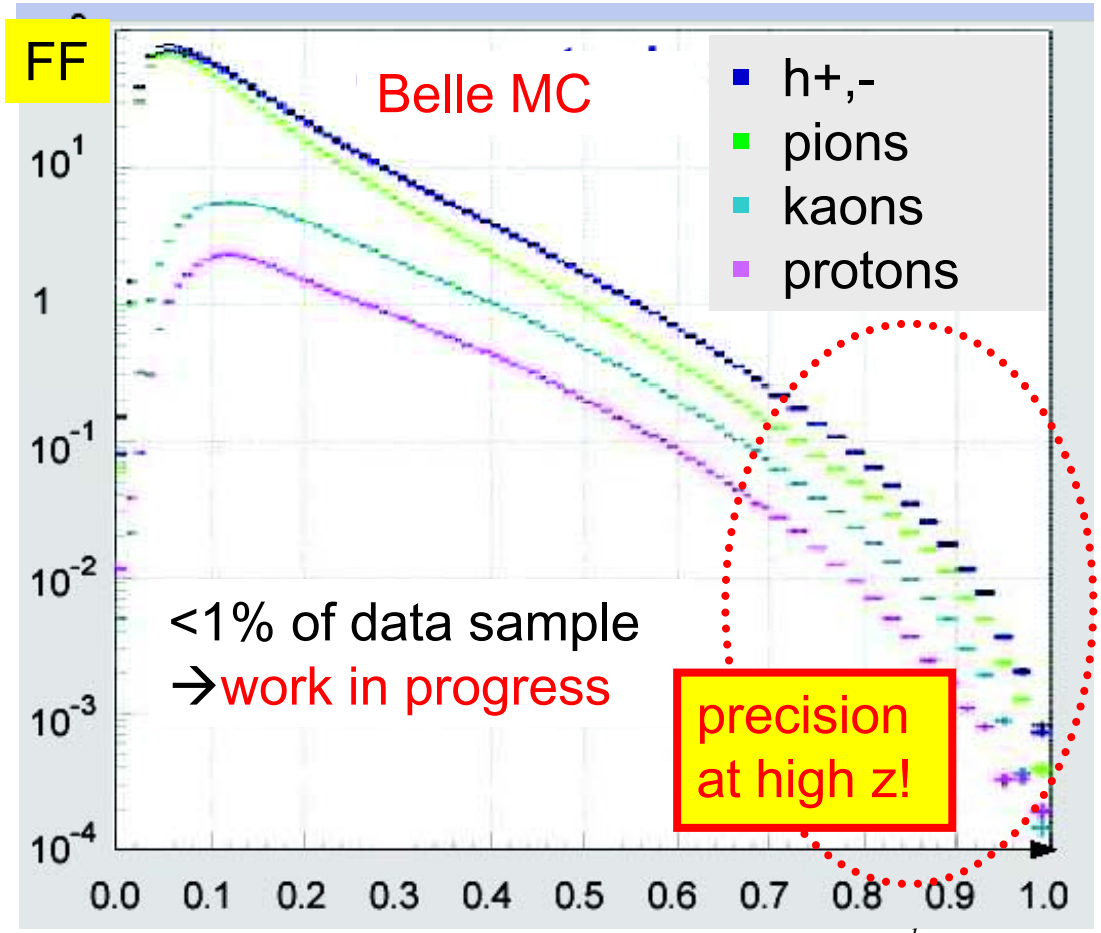
# pact on the Knowledge of FFs

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




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

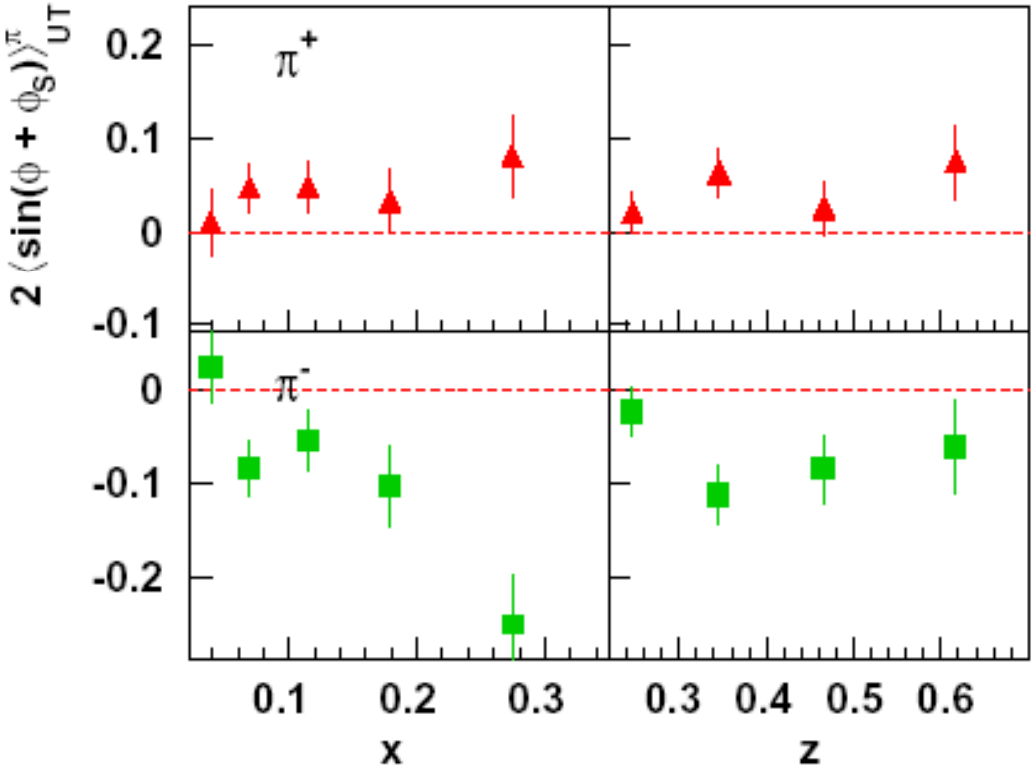
Belle: Charged $h^{+/-}$, pions, kaons, protons




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

# Motivation II Transversity Quark Distributions from Collins- and Interference-Fragmentation

**HERMES results for Collins Asymmetries**
**A. Airapetian, et al., Phys.Rev.Lett.94:012002,2005**




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

*~ Transversity x CFF*

*~ Transversity x IFF*

Collins- and IFF- asymmetries In e+e- are of the form

~ CFF x CFF

~ IFF x IFF

➔ global analysis

# Global Analysis: Extract Transversity Distributions

SIDIS $\Rightarrow$
transversity $\times$ Collins
transversity $\times$ IFF
HERMES, COMPASS, JLAB, EIC

Factorization
+
Universality ?!

$e^+e^-$ $\Rightarrow$ Collins FF
Interference FF
**Belle**

Transversity Tensor Charge

Theory

Bakker-Leader-Trueman sum rule

+

Lattice QCD: Tensor Charge

pp $\Rightarrow$ **RHIC**
$A_N$ for inclusive hadrons, Jets
$A_T$ in Jets: transversity $\times$ Collins
transversity $\times$ IFF
$A_{TT}$ Drell Yan:
transversity $\times$ transversity
BRAHMS, PHENIX, STAR, GSI

# Motivation III
## Lambda Fragmentation Functions ?

Pending detailed studies it appears possible to measure

Lambda-FF for longitudinal spin ➔ s(x) Q.H. Xu, et al. (pp)
J. Ellis, A. Kotzinian, D. Naumov,
M. Spaozhnikov (SIDIS)

Lambda-FF for transverse spin ➔ transversity Q.H. Xu et al. (pp)
M. Anselmino (SIDIS)

Lambda-c-FF for longitudinal spin ➔ $\Delta G$ , K. Sudoh (pp)

# Measurement of Collins Asymmetries

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

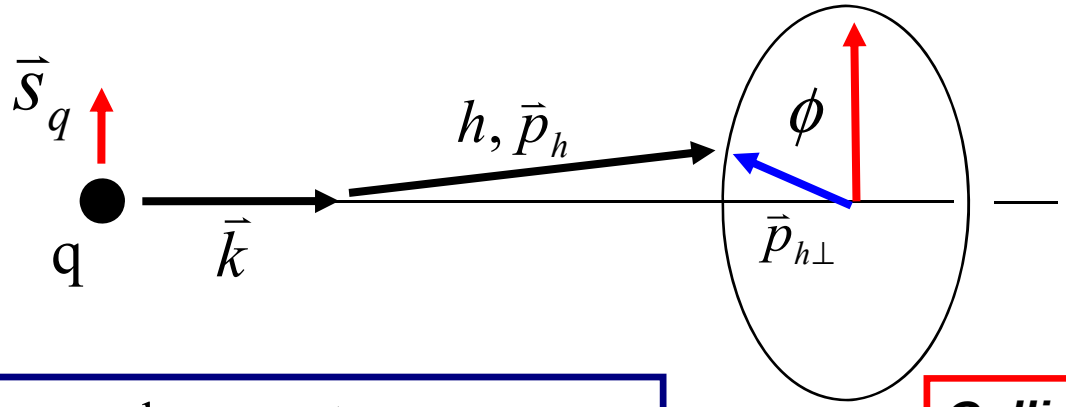
# Why is the Collins Fragmentation Function Interesting?

- 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

# 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 |
| $z_h = E_h / E_q$ | |
| $= 2\,E_h / \sqrt{s}$ | : 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, $q$:

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

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

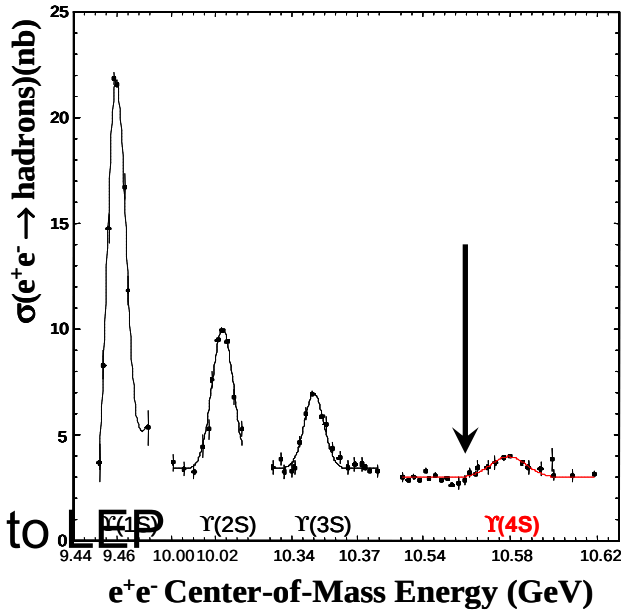
- Quark spin direction unknown: measurement of Collins function in one hemisphere is not possible *sin* $\varphi$ modulation will average out!

- 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.

- Fraction of sample with correlated quark- and anti-quark spin direction ~ $sin^2\theta$ (assuming negligible beam polarization)

# 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 ($Q^2 \sim 110\ GeV^2$)
  - 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)*



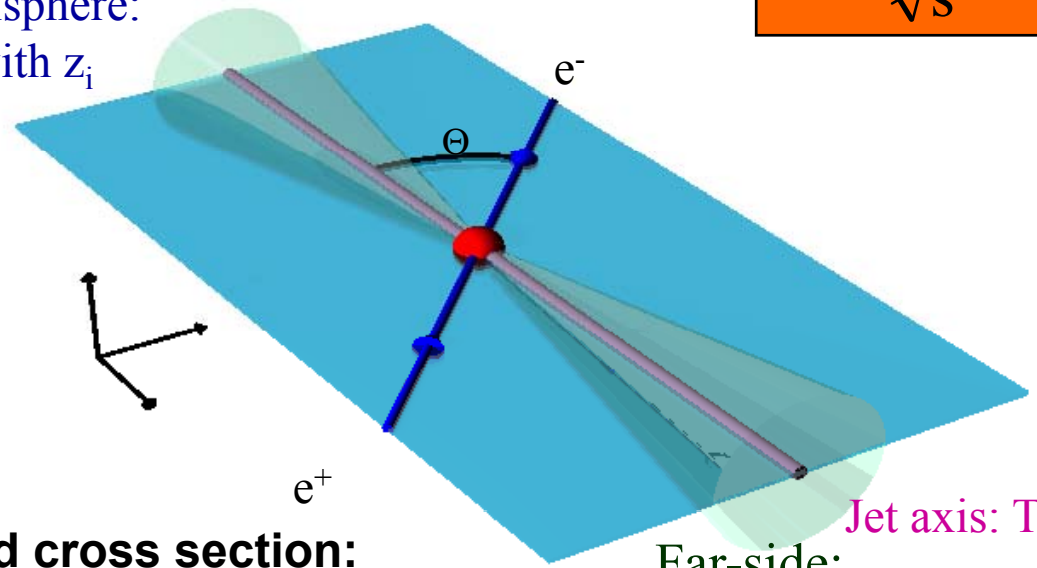

Total number of hadronic events ~ 1.5 x $10^9$

# Event Structure at Belle

$e^+e^-$ CMS frame:

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

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 $z_j$

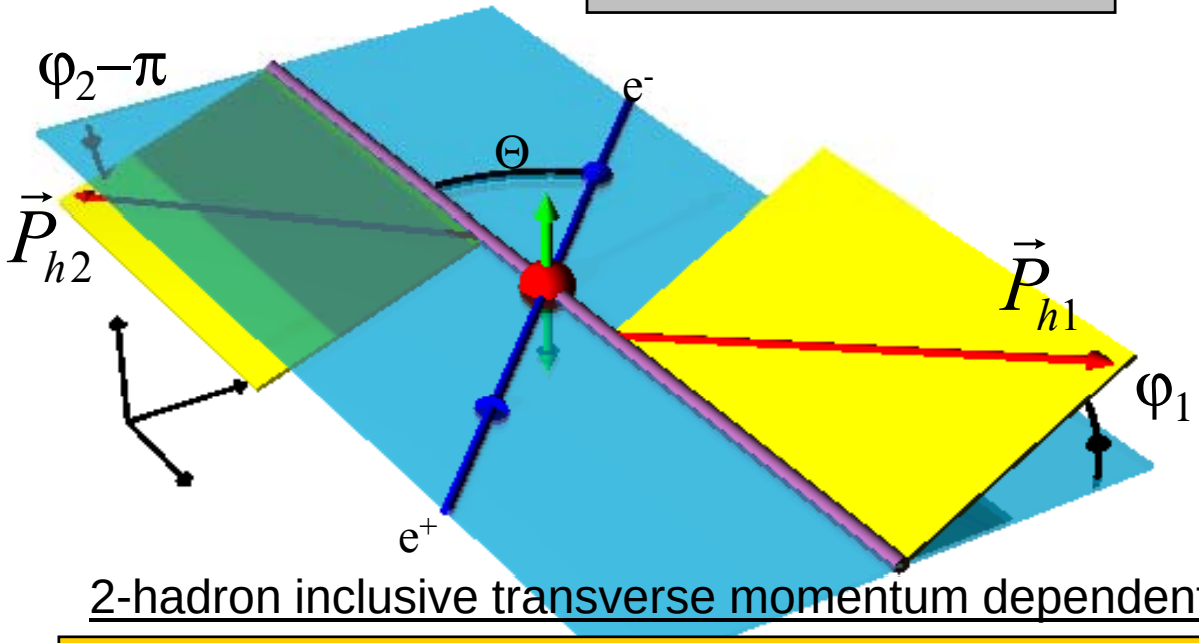
**Spin averaged cross section:**

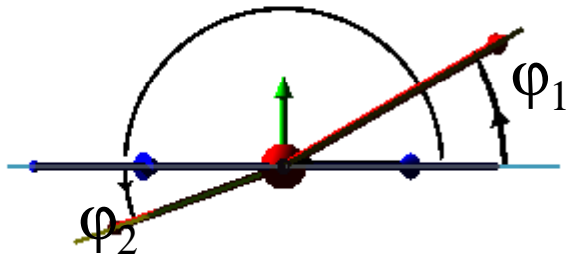
$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{d\Omega dz_1 dz_2} = \frac{3\alpha^2}{Q^2} A(y) \sum_{a,\bar{a}} e_a^2 D_1(z_1) \bar{D}_1(z_2)$$

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

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

$e^+e^-$ CMS frame:




2-hadron inclusive transverse momentum dependent cross section:

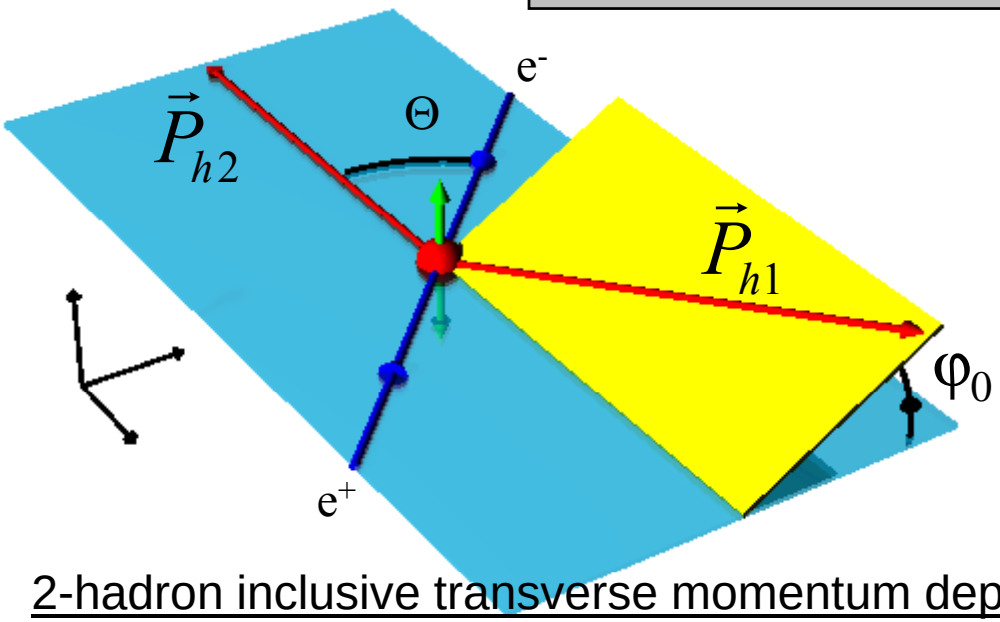
$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{d\Omega dz_1 dz_2 d^2\boldsymbol{q}_T} = \cdots B(y)\cos(\varphi_1+\varphi_2) H_1^{\perp[1]}(z_1)\overline{H}_1^{\perp[1]}(z_2)$$

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

Net anti-alignment of transverse quark spins

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

$e^+e^-$ CMS frame:




- Independent of thrust-axis
- Convolution integral $\mathcal{I}$ over transverse momenta involved

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

2-hadron inclusive transverse momentum dependent cross section:

$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{d\Omega dz_1 dz_2 d^2\boldsymbol{q}_T} = \cdots B(y)\cos(2\varphi_0)\mathcal{I}\left[\left(2\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T - \boldsymbol{k}_T\cdot\boldsymbol{p}_T\right)\frac{H_1^\perp \bar{H}_1^\perp}{M_1 M_2}\right]$$

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

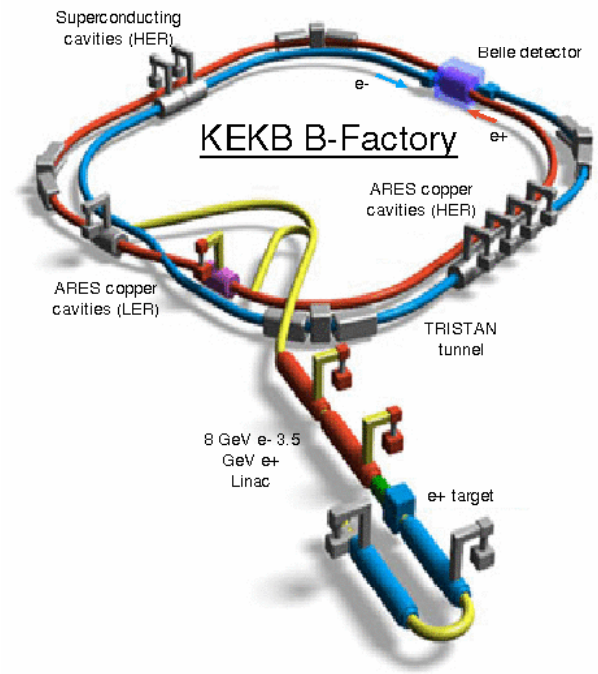
Net anti-alignment of transverse quark spins

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

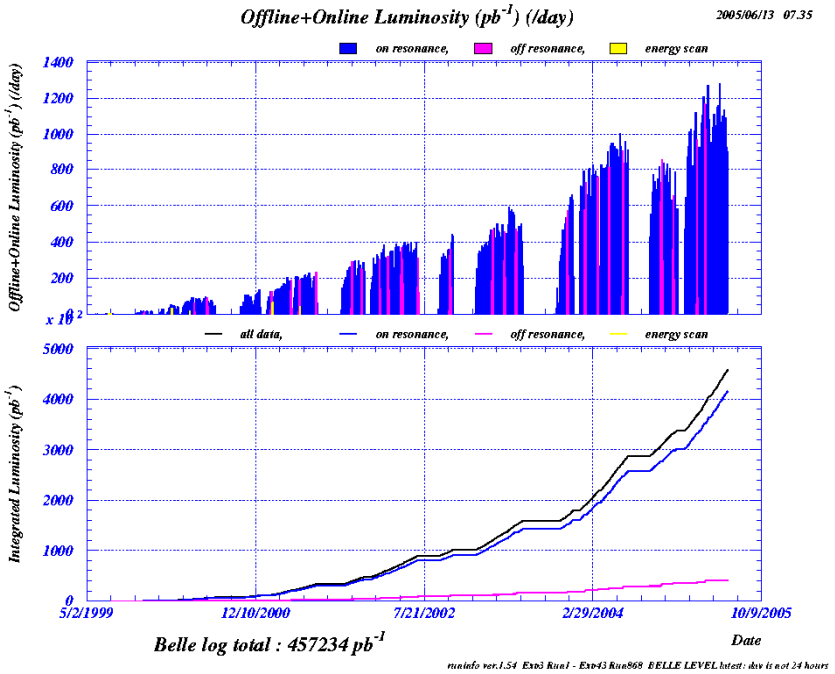
- KEKB
  - Asymmetric collider
  - 8GeV $e^-$ + 3.5GeV $e^+$
  - $\sqrt{s}$ = 10.58GeV ($\Upsilon(4S)$)
    $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
  - Off-resonance: 10.52 GeV
    $e^+e^- \rightarrow q\bar{q}$ (u,d,s,c)
  - Integrated Luminosity: > 600 $fb^{-1}$
    > 60$fb^{-1}$ => off-resonance

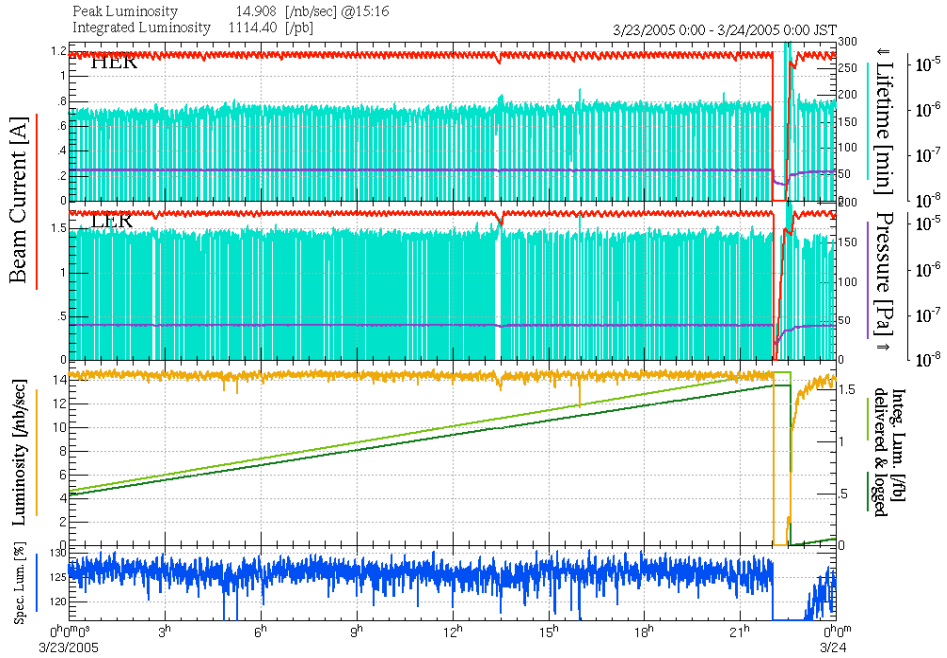

- Average Trigger rates:

| | |
|---|---|
| $\Upsilon(4S) \rightarrow BB$ | 11.5Hz |
| $q\bar{q}$ | 28 Hz |
| $\mu\mu + \tau\tau$ | 16 Hz |
| *Bhabha* | *4.4 Hz* |
| *$2\gamma$* | *35 Hz* |

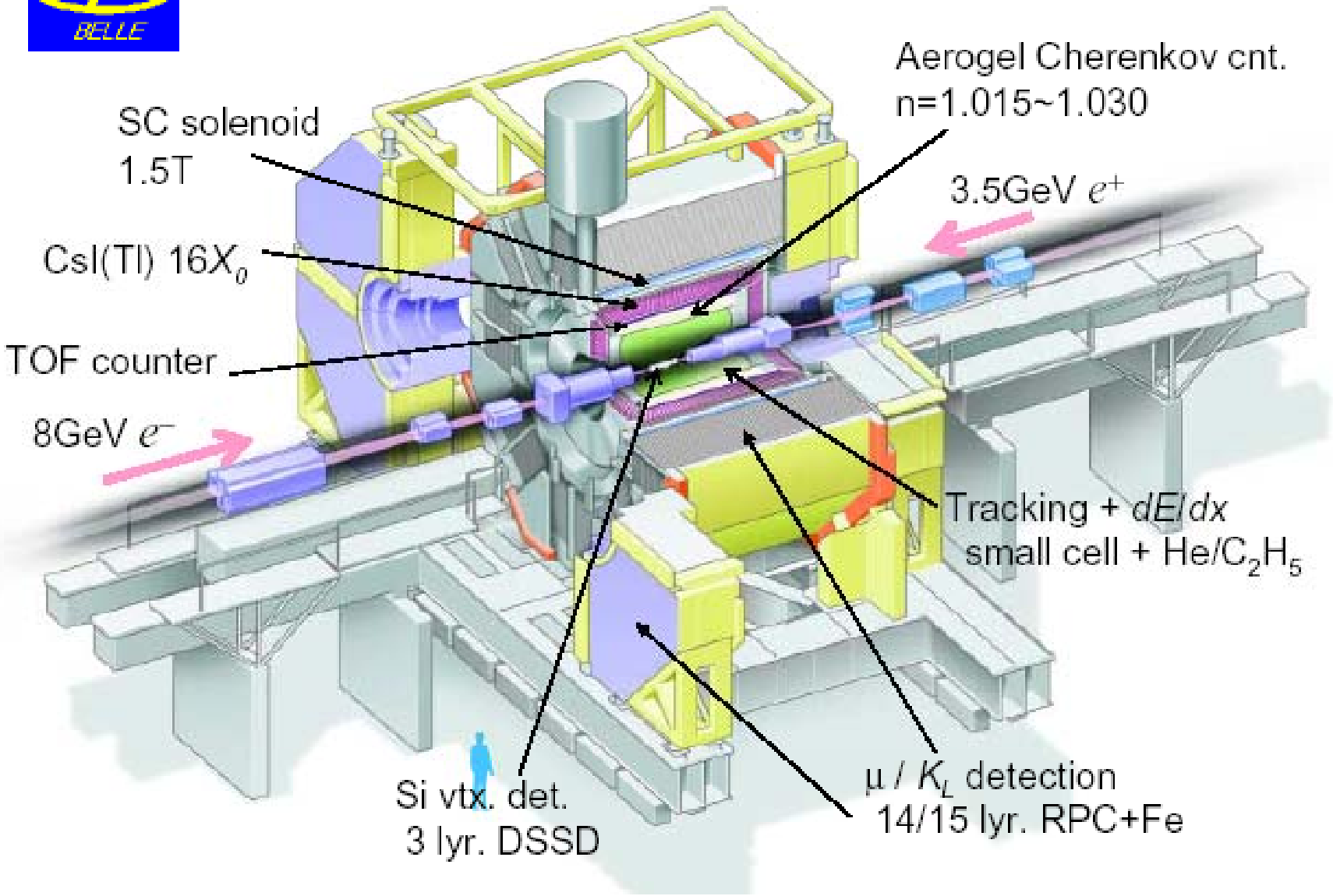



祝 ∫ℒ =400 fb-1 達成
APR-05-2005


Offline+Online Luminosity (pb-1) (/day)
2005/06/13 07.35
on resonance, off resonance, energy scan
Offline+Online Luminosity (pb-1) (/day)
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

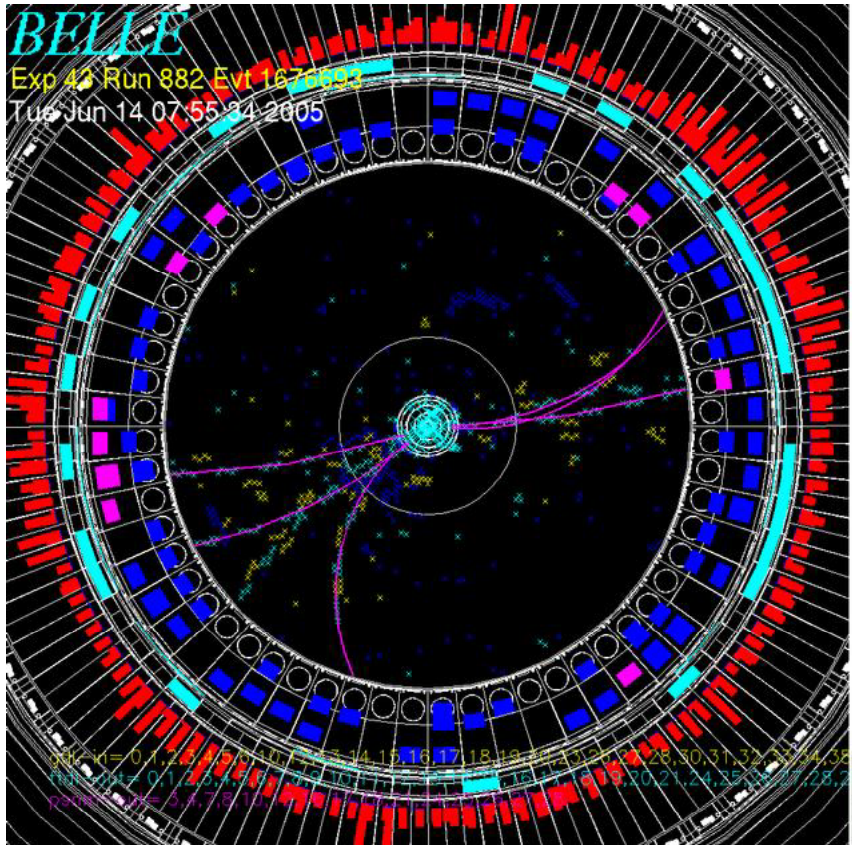

Peak Luminosity 14.908 [/nb/sec] @15:16
Integrated Luminosity 1114.40 [/pb]
3/23/2005 0:00 - 3/24/2005 0:00 JST
HER
LER
Beam Current [A]
Lifetime [min]
Pressure [Pa]
Luminosity [/nb/sec]
Integ. Lum. [/fb] delivered & logged
Spec. Lum. [%]
3/23/2005
3/24

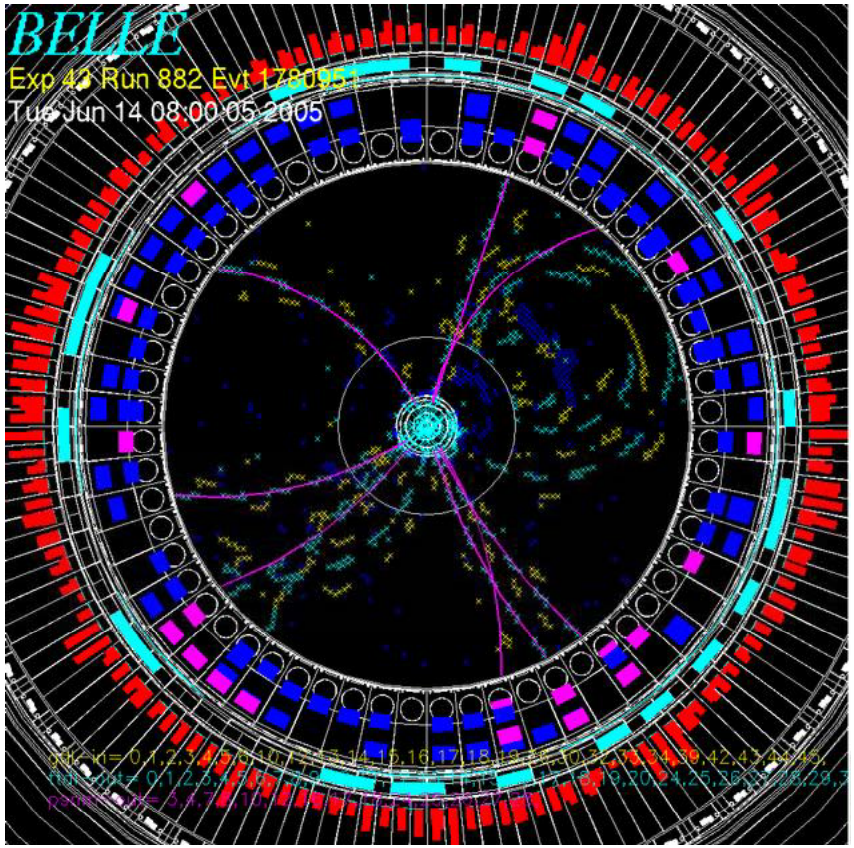
# Belle Detector




**Good tracking and particle identification!**

# Typical Hadronic Events at Belle




~ 1

$$thrust = \frac{\sum_{i=\text{particles}} \vec{p}_i \cdot \hat{n}}{\sum_i |\vec{p}_i|}$$

~ 0.5

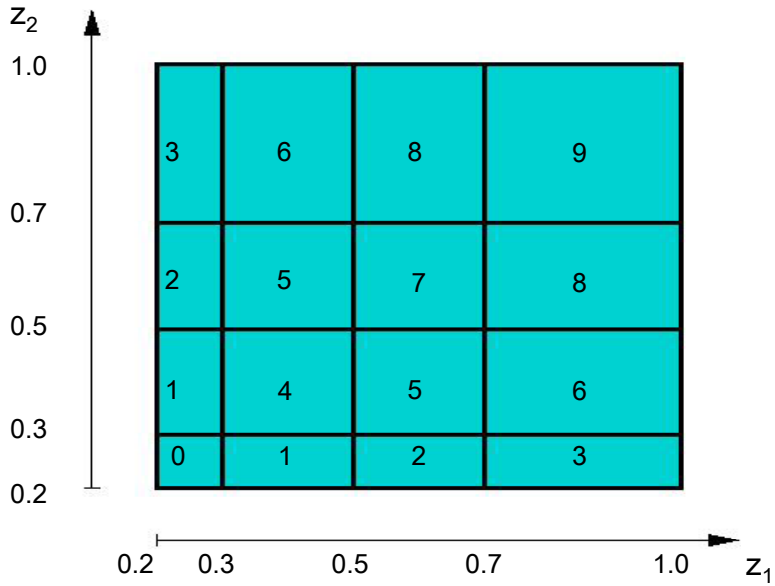
# Applied Cuts, Binning

- 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

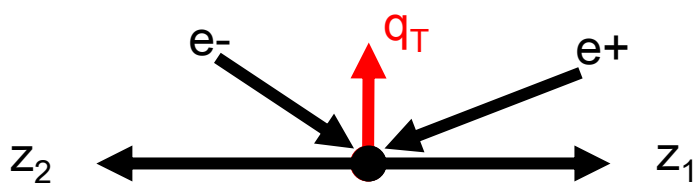


# Experimental Issues

- Cos2$\phi$ 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(2$\phi$)* asymmetries for jets or $\gamma\gamma$
- False asymmetries from weak decays ➔ Study effect in $\tau$ 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

# Gluon Emission

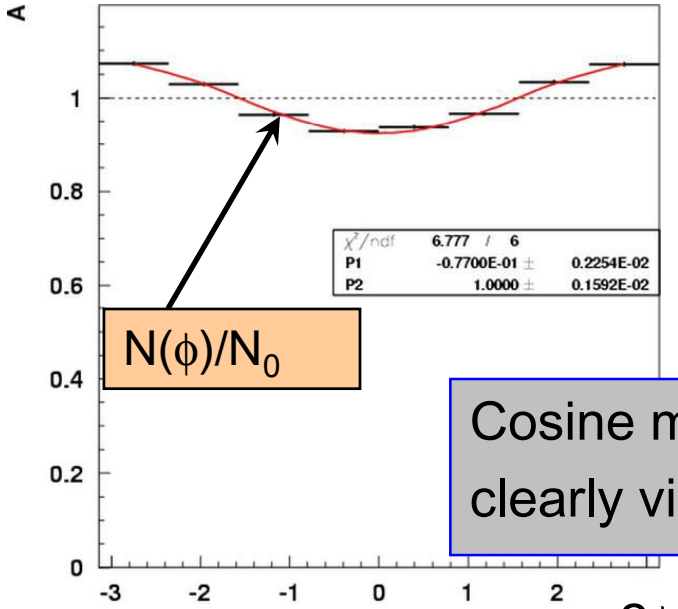
$$\frac{dN}{d\Omega dz_1 dz_2 dq_T} \propto \sum\left[\frac{q_T^2}{Q^2+q_T^2}\sin^2\theta\cos(2\phi_0)D_1(z_1)\overline{D}_1(z_2)\right]$$



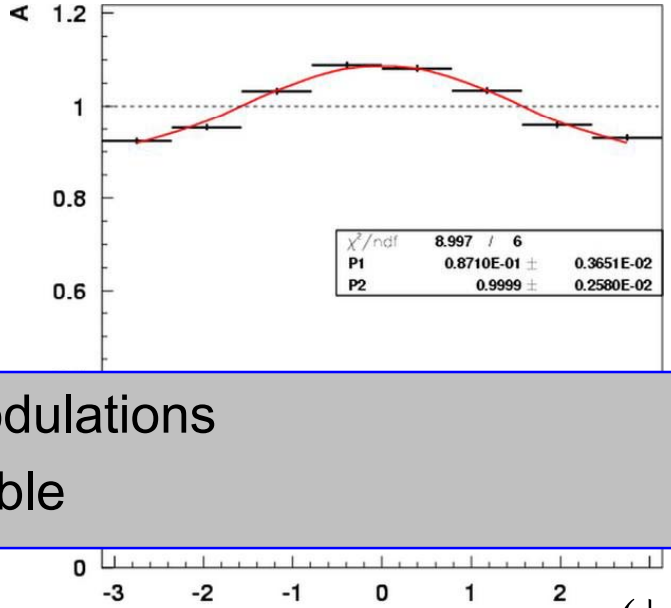

Frame:

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

# Examples of Fits to Azimuthal Asymmetries




$2\phi_0$




$(\phi_1+\phi_2)$

Cosine modulations clearly visible

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

$D_1$ : spin averaged fragmentation function,

$H_1$: Collins fragmentation function

No change in cosine moments when including sine and higher harmonics

# Methods to eliminate gluon contributions: Double ratios and subtractions

Double ratio method:

$$R := \frac{\frac{N^{Unlike}(\phi)}{N_0^{Unlike}}}{\frac{N^{Like}(\phi)}{N_0^{Like}}} \approx 1 + F\left(\frac{H_1^{\perp,fav}(z)}{D_1^{fav}(z)}, \frac{H_1^{\perp,unfav}(z)}{D_1^{unfav}(z)}\right) + \mathcal{O}\left(F(Q_T)^2)\right)$$

Pros: Acceptance cancels out

Cons: Works only if effects are small (both gluon radiation and signal)

Subtraction method:

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

Pros: Gluon radiation cancels out exactly

Cons: Acceptance effects remain

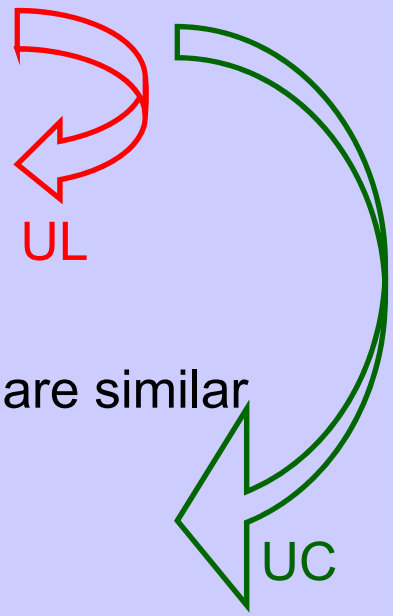
**2 methods give very small difference in the result**

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

# Other Favored/Unfavored Combinations →charged pions or $\pi^0$

Challenge: double ratios in PRL not very sensitive separate favored and disfavored Collins function ➔ Examine other combinations:

- 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)

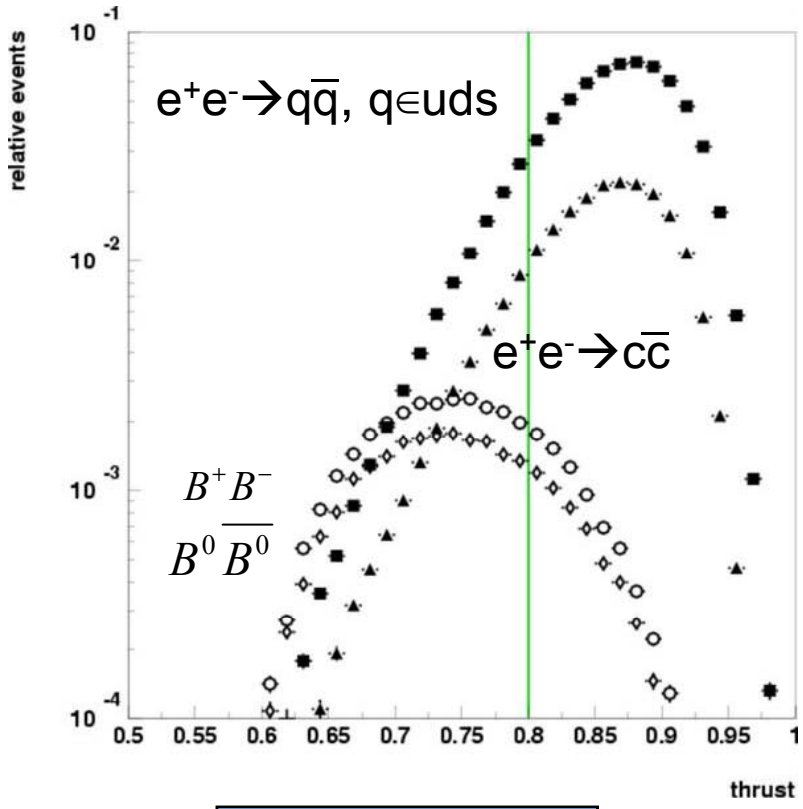



➔Build new double ratios:

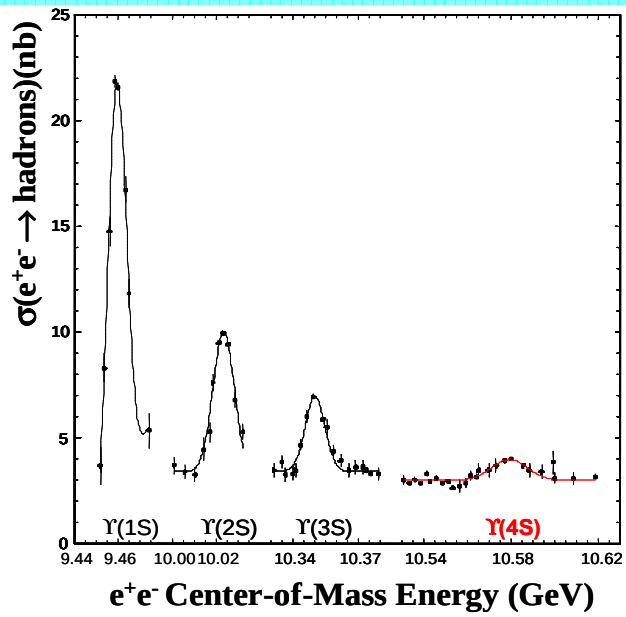
➔Unlike-sign/ charged $\pi\pi$ pairs (UC)

| | |
|---|---|
| Favored | = $u \rightarrow \pi^+, d \rightarrow \pi^-$,cc. |
| Unfavored | = $d \rightarrow \pi^+, u \rightarrow \pi^-$,cc. |

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



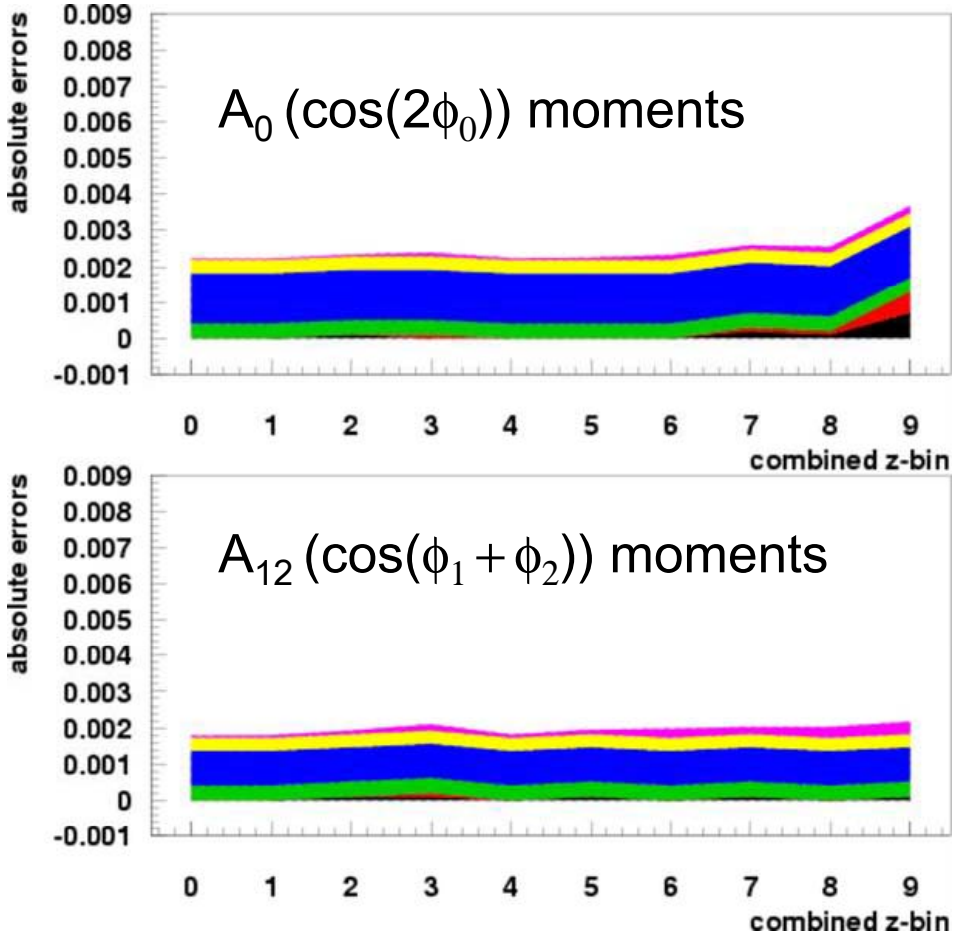

$$\text{thrust} = \frac{\sum_i |p_i \cdot \hat{n}|}{\sum_i |p_i|}$$




- 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

# Improved Systematic Errors (UC)

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

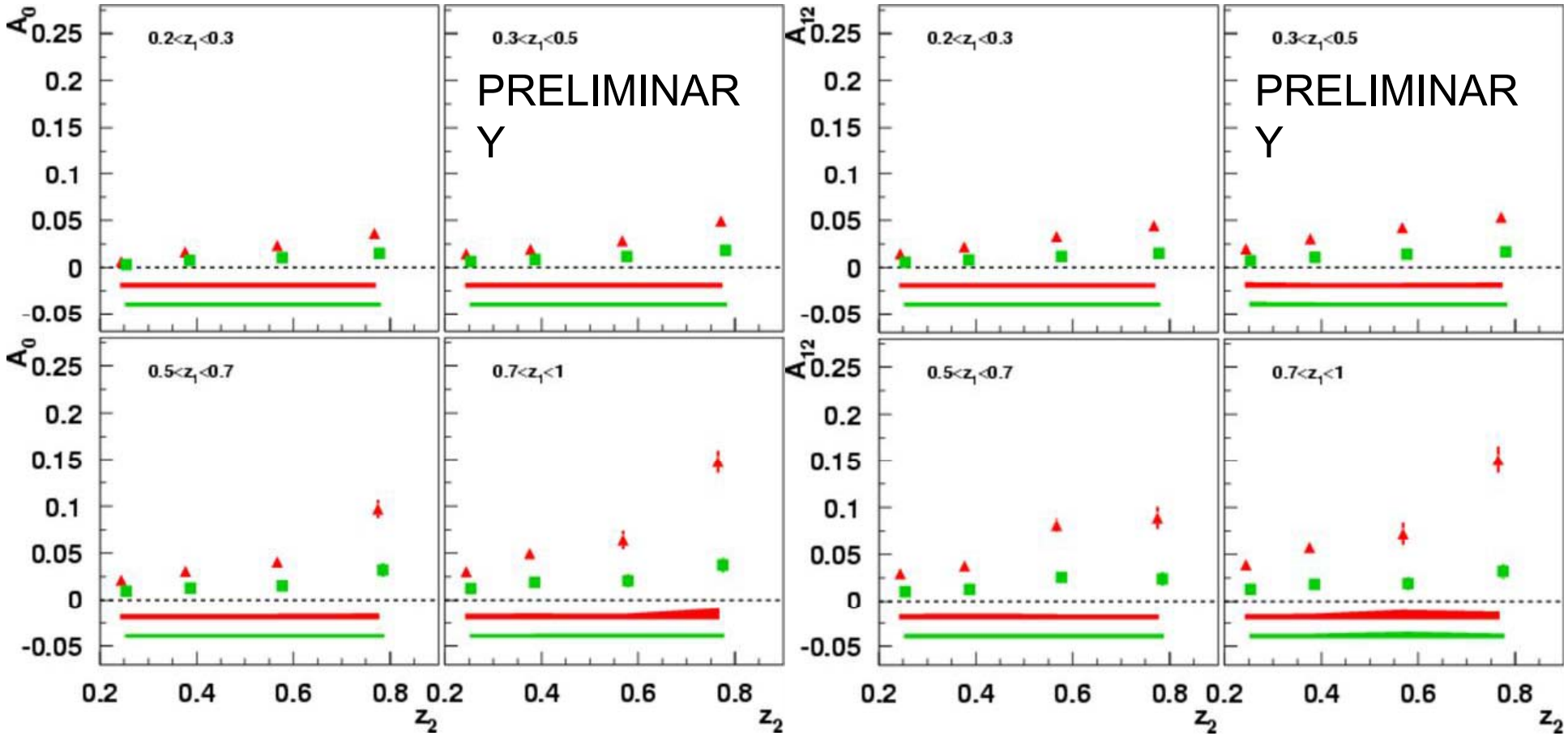



Reweighting asymmetries:
→underestimation of cos($\phi_1$+$\phi_2$) asymmetries →rescaled by 1.21
Correlation studies:
→statistical errrors rescaled by 1.02 (UL) and 0.55 (UC)
Beam polarization studies
→consistent with zero

# Collins Asymmetries I: 4x4 $z_1$, $z_2$ binning

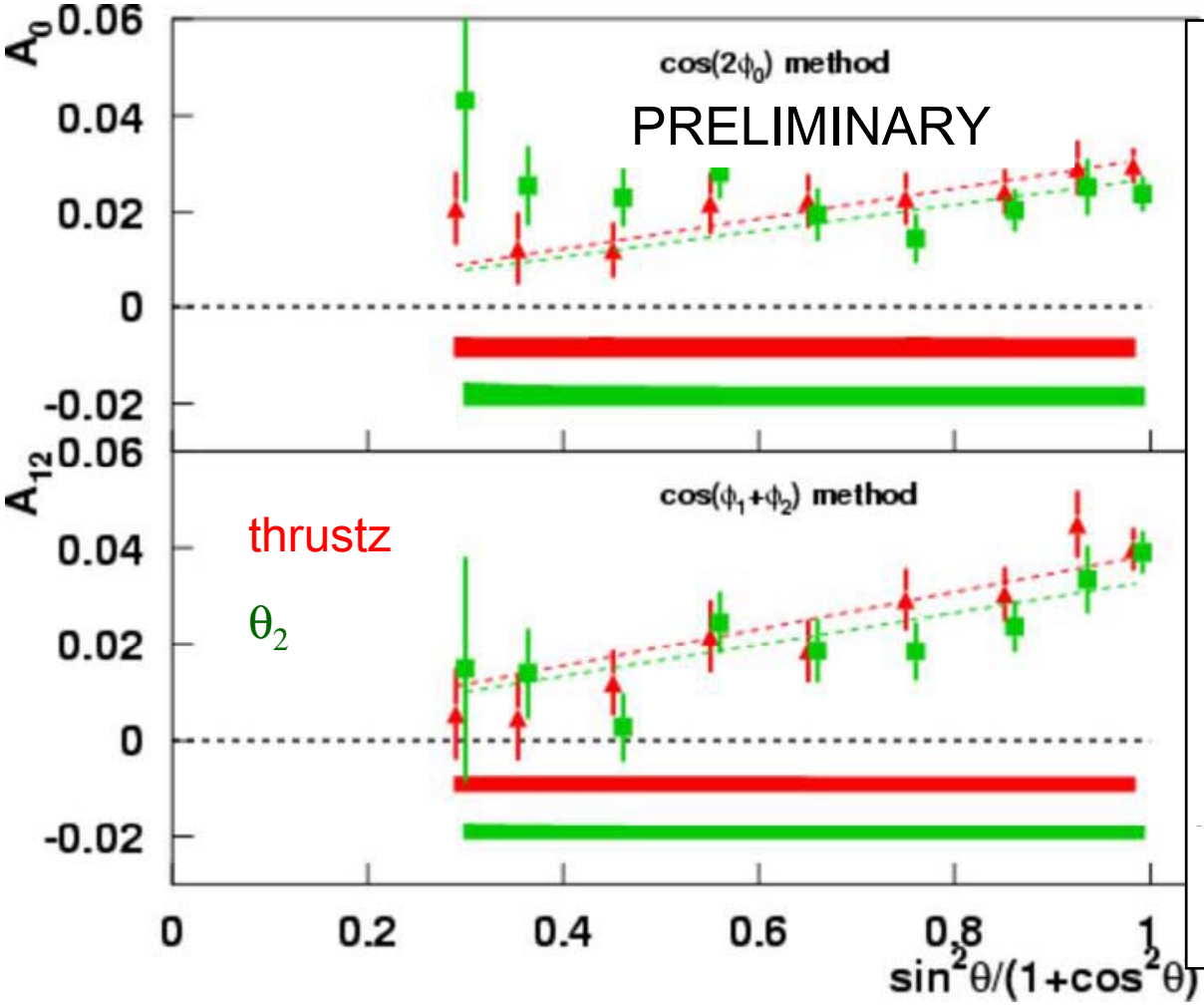
$A_0$ ($\cos(2\phi_0)$) moments

$A_{12}$ ($\cos(\phi_1+\phi_2)$) moments



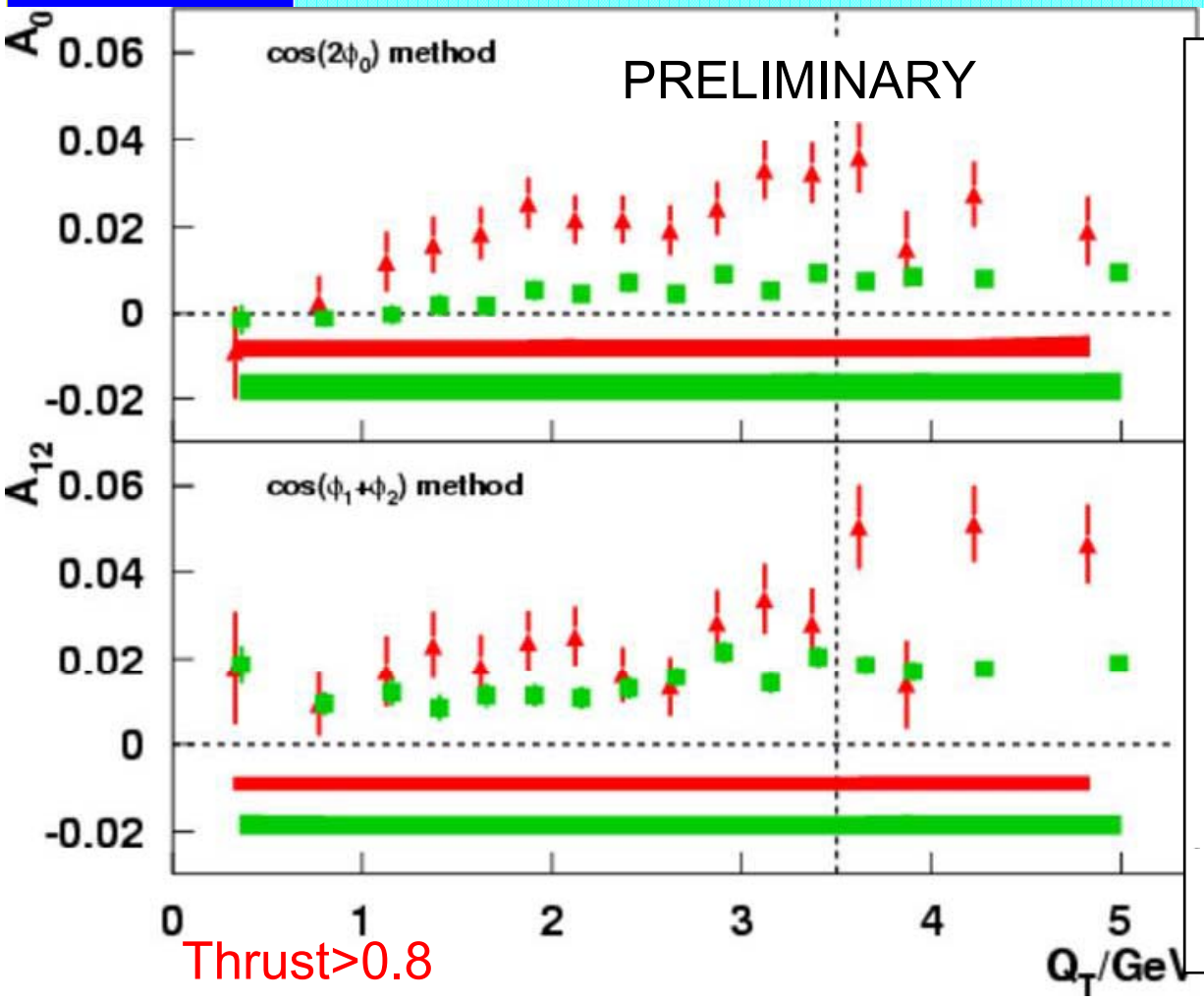

- 547 $fb^{-1}$ charm corrected data sample,
- UL and UC double ratios

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




- Nonzero quark polarization ~ $\sin^2\theta$
- Unpolarized denominator ~ $1+\cos^2\theta$
- 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)

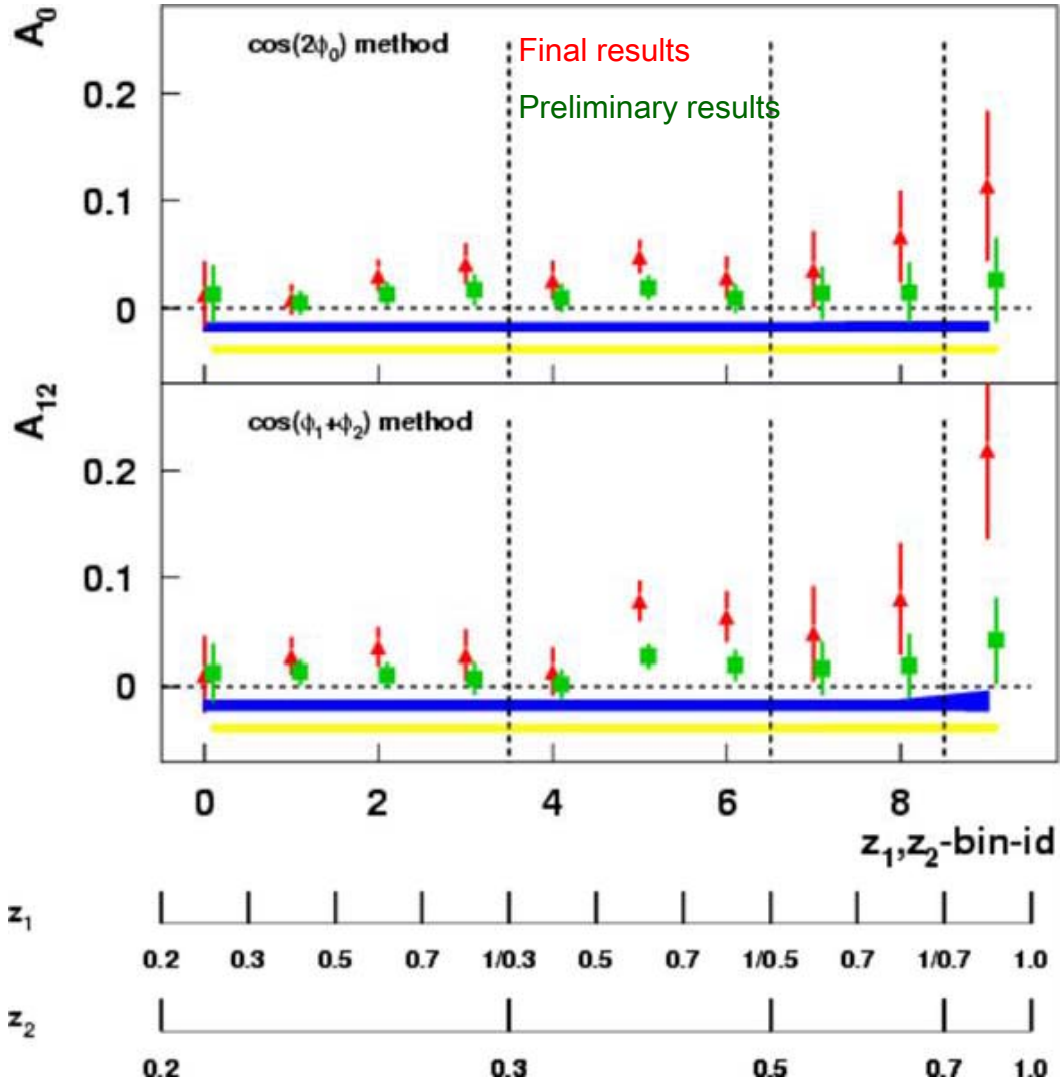
- Reduced asymmetries in low thrust sample
- At low thrust significant B contribution
  (for t<0.8 ~20 % B
  for t>0.8 < 1 % B)
- $A_{12}$ thrust axis dependent
- High $Q_T$ (>3.5 GeV) asymmetries from beam related BG
- UC plots similar

# Final Charm Corrected Results for $e^+ e^- \rightarrow \pi \pi X$ (29fb$^{-1}$ of Continuum Data)

Phys.Rev.Lett.96:232002,2006

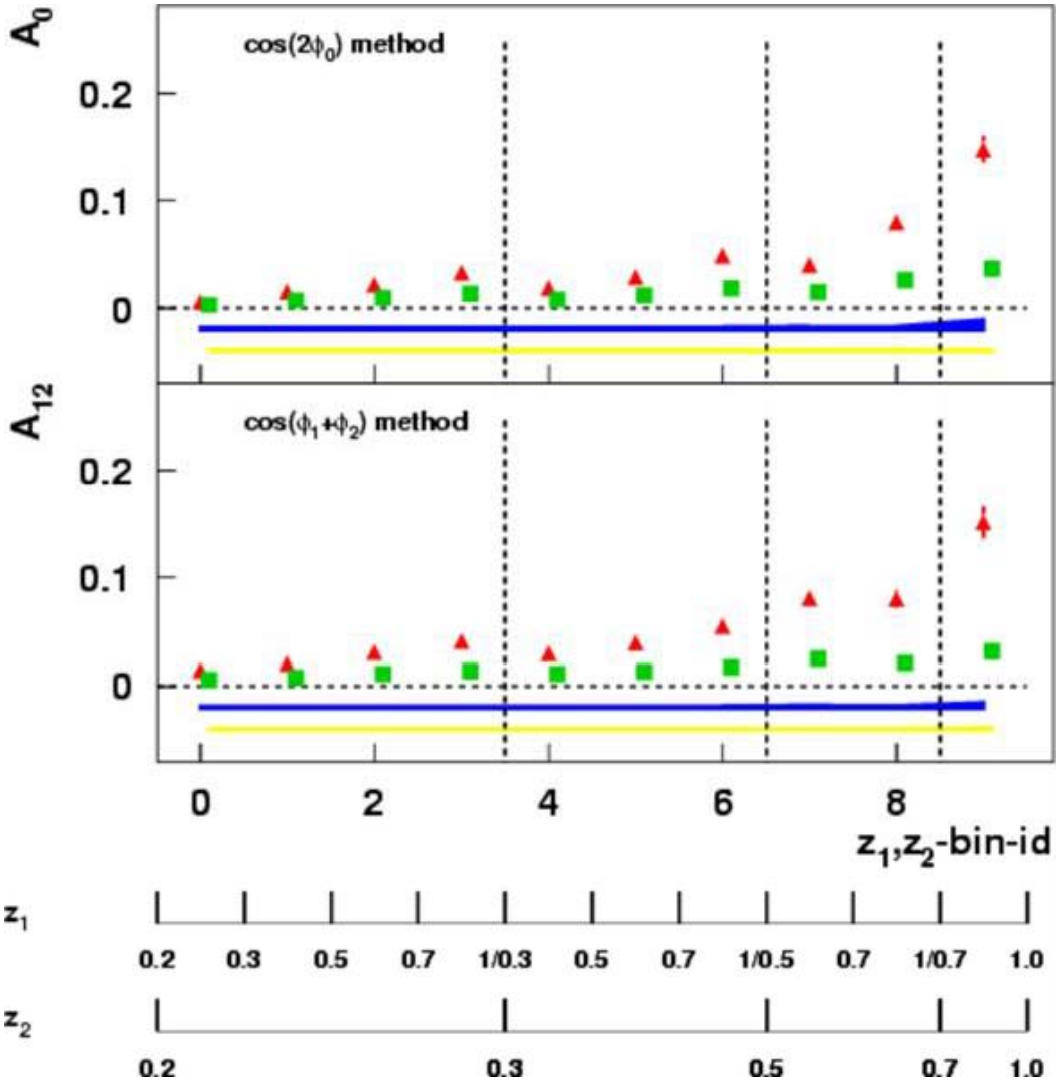
- Significant non-zero asymmetries
- Rising behavior vs. z
- UL/C asymmetries about 40-50% of UL/L asymmetries
- First direct measurements of the Collins function
- UL/L data published

| Integrated results: | |
|---|---|
| $A_0$(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 $fb^{-1}$)

- 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)% |

# 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

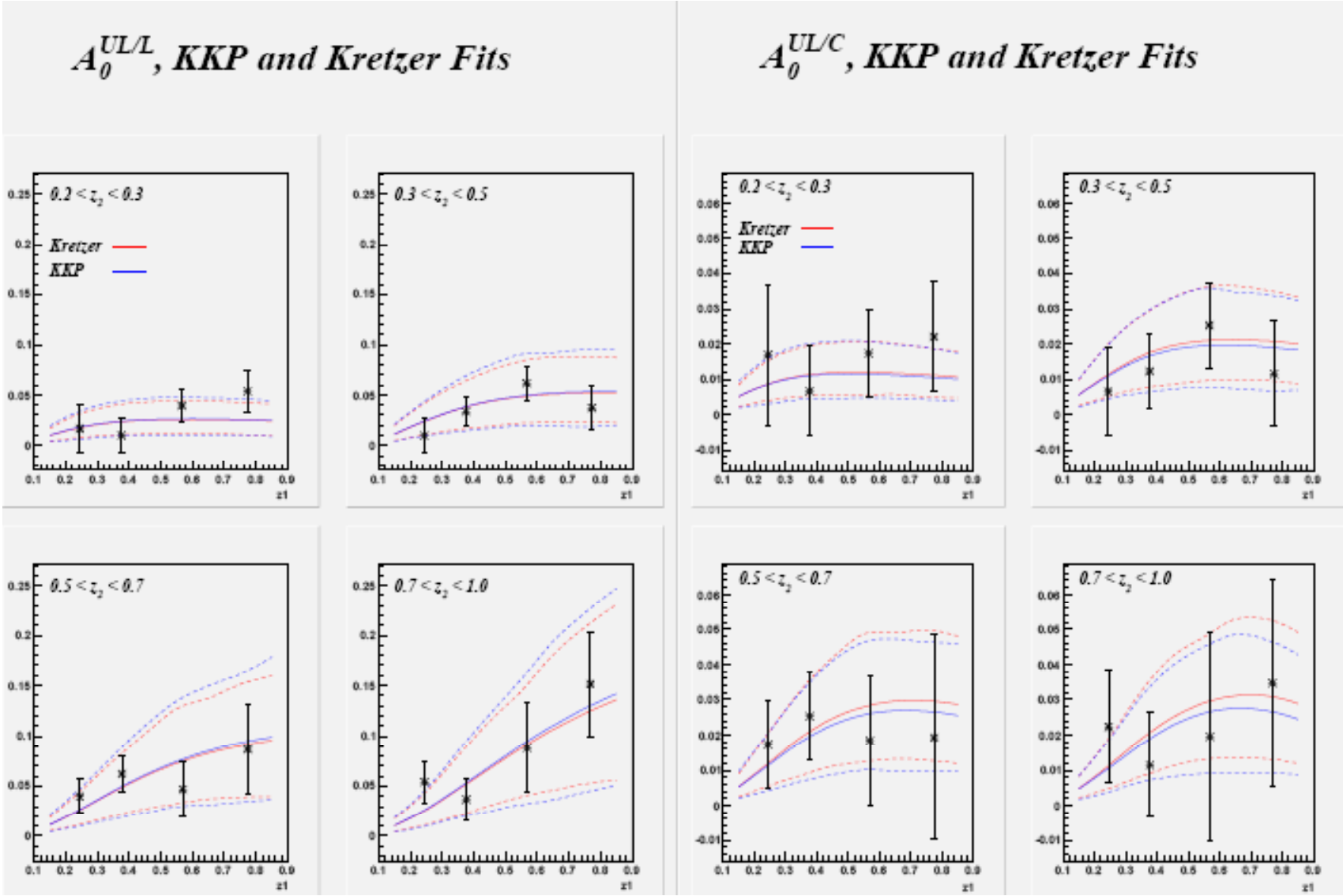
Kretzer FFs (also KKP)

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

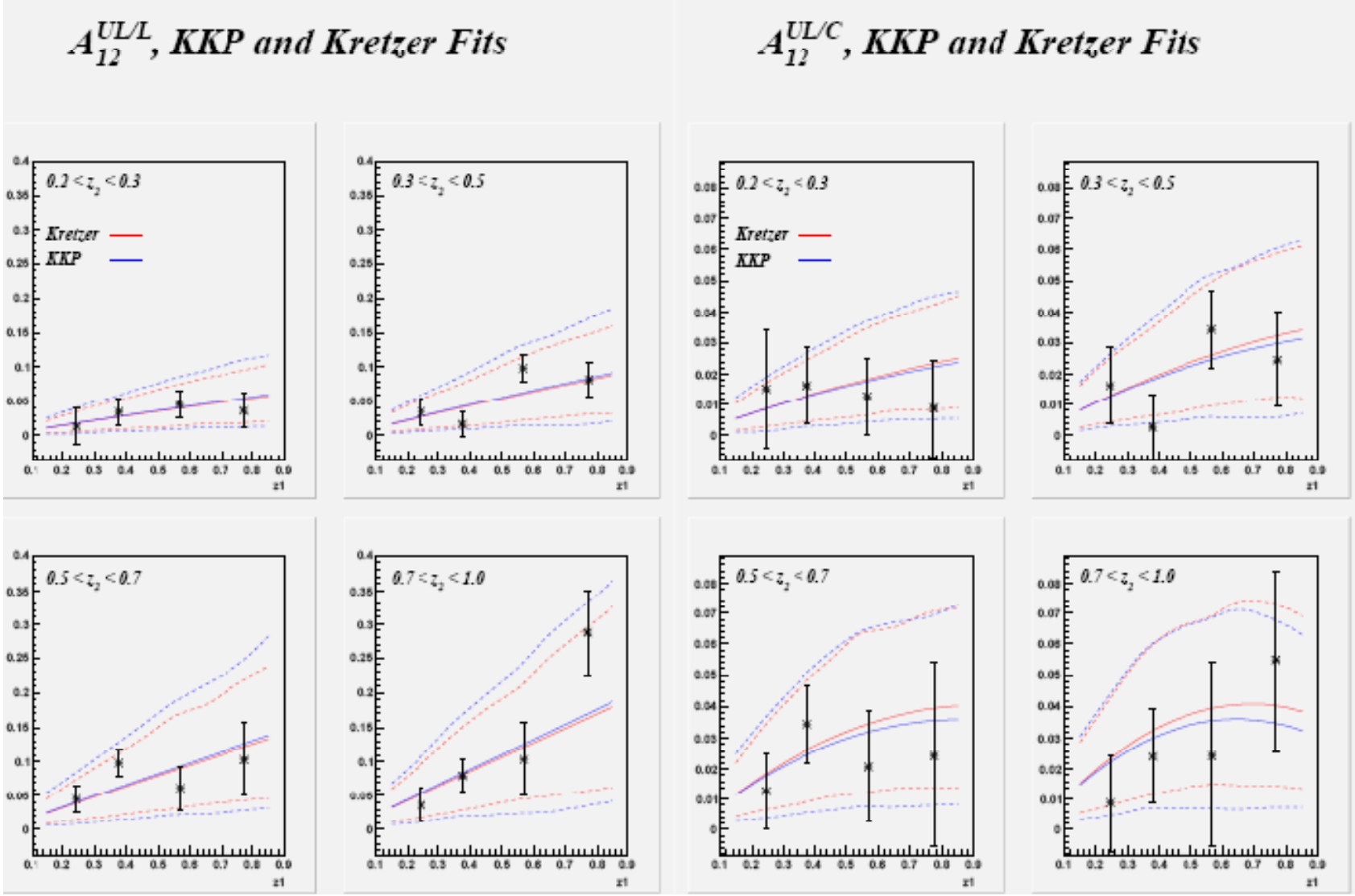
Experimental double ratio:

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

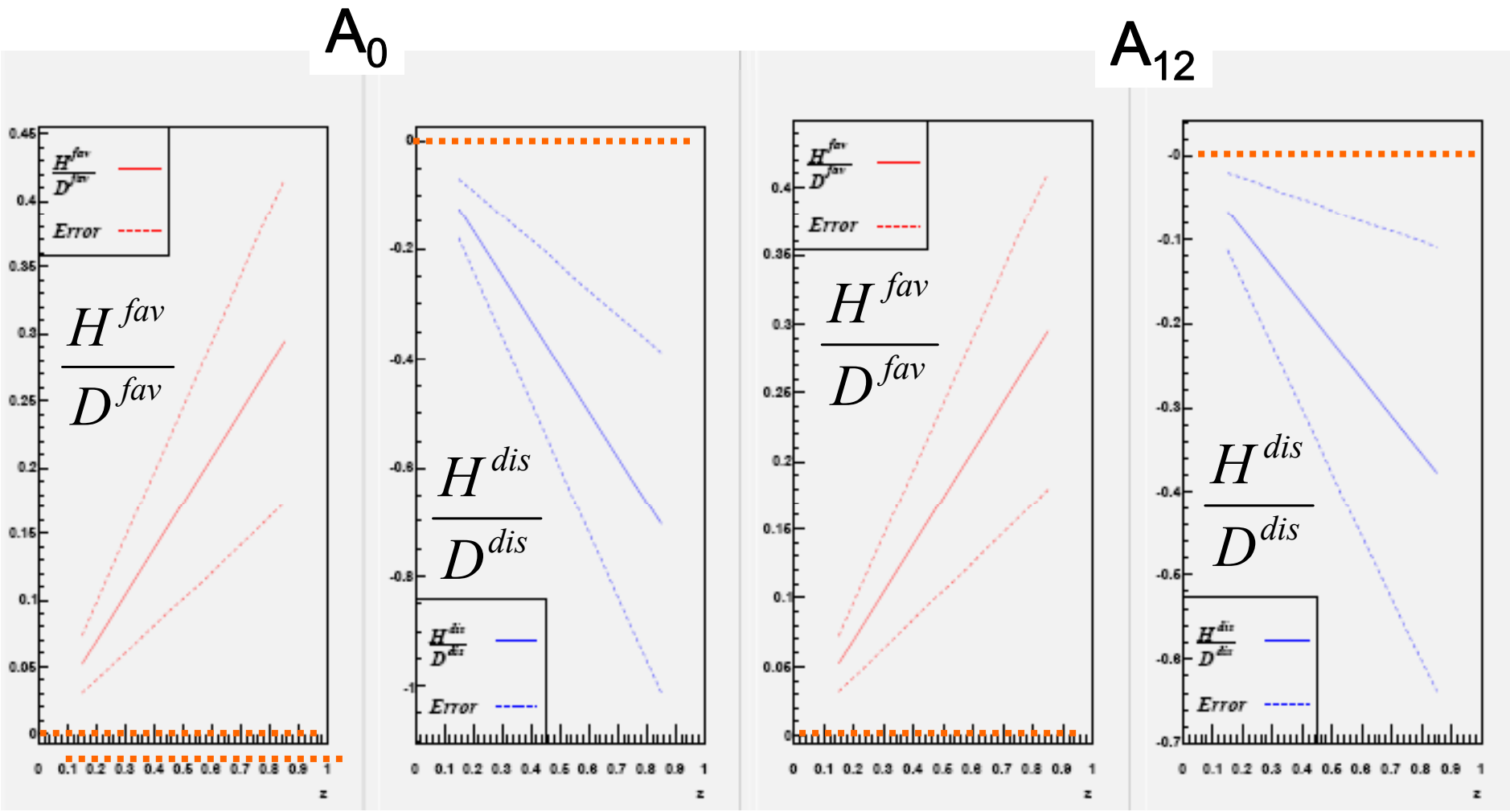
# Fits of the Belle Collins Asymmetries $A_0$ with $\int Ldt$ = 29 fb-1



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



# Results for the Collins FF




0 < z < 1

# 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.

- Fundamental interesting + important input for the transverse spin physics programs at RHIC, HERMES, COMPASS and JLab

Outlook:

- (Much) more spin dependent FFs:

  → interference fragmentation
  → Collins FF for VMs
  → Lambdas

- Precision measurement of spin averaged fragmentation functions as input to RHIC program to extract the gluon polarization through $A_{LL}$ measurements in inclusive hadron production