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

AGS&RHIC Users' Meeting

June 19th , Brookhaven National Laboratory

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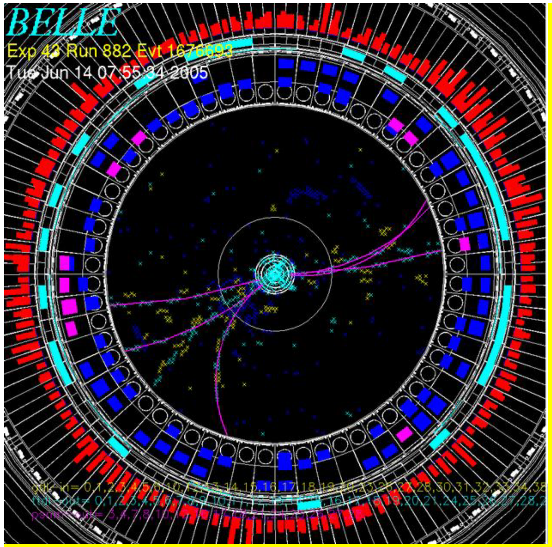


------------ Outline ------------

- 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

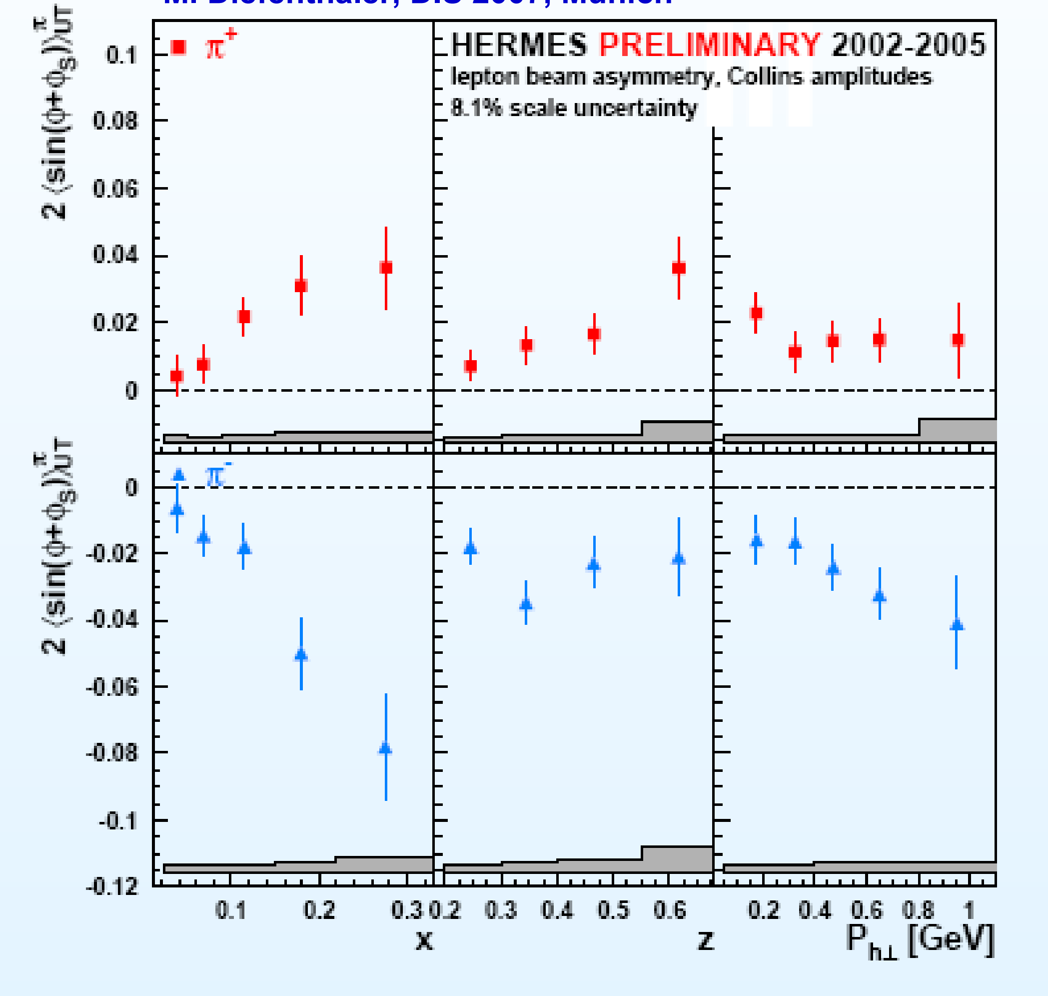
Why is the Collins Fragmentation Function Interesting?

- 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

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

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

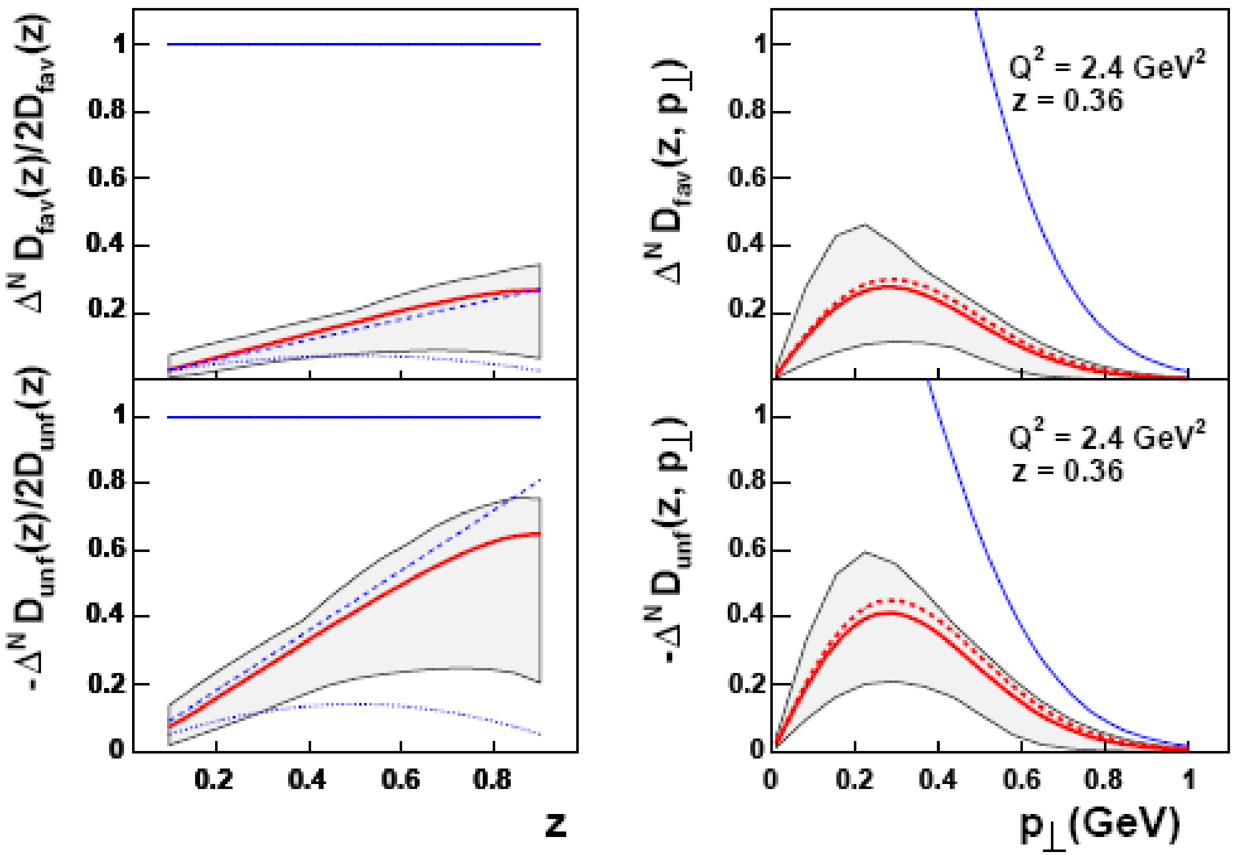
Transversity Tensor Charge

Theory

Lattice QCD: Tensor Charge

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^-

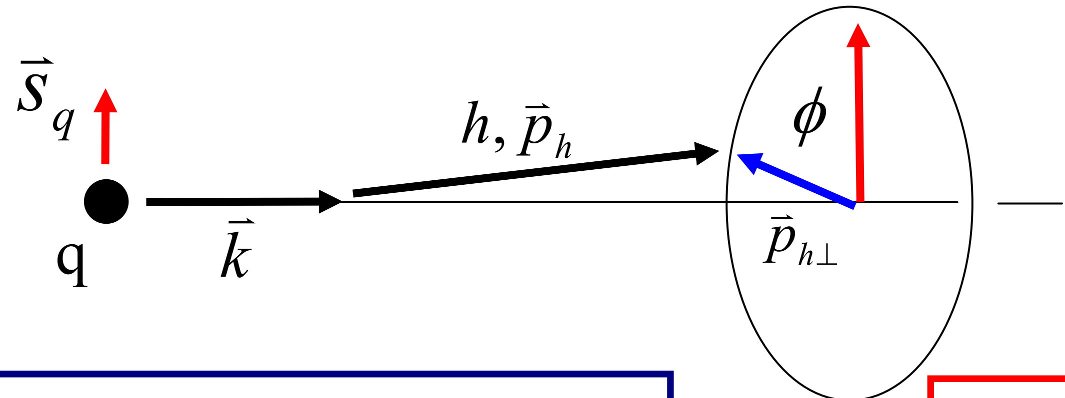
→ transversity dist.
+ Collins FF

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:

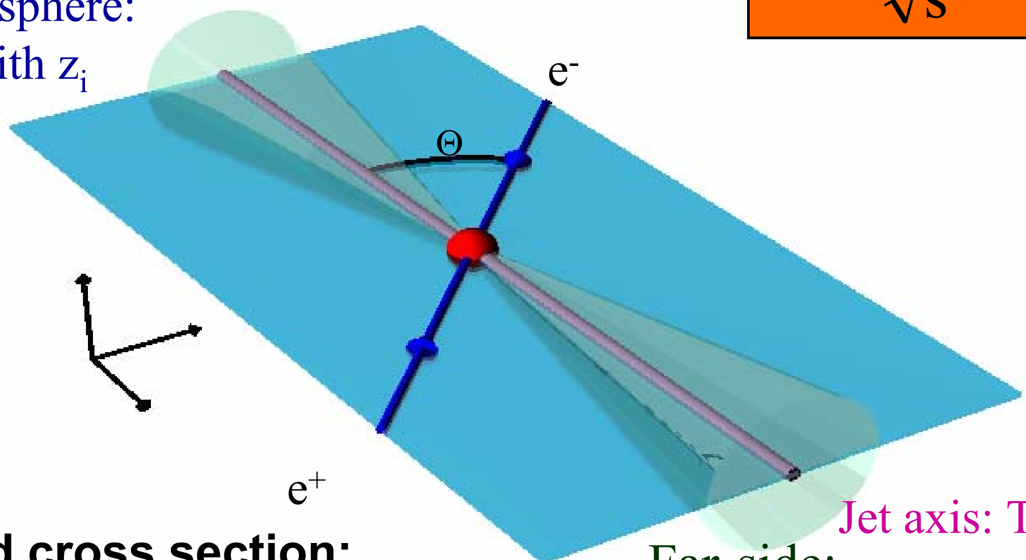
$$D_{q^\uparrow}^{h}(z,\vec{p}_{h\perp}) = \underbrace{D_1^{q,h}(z)}_{\text{unpolarized FF}} + \underbrace{H_1^{\perp q,h}(z,p_{h\perp}^2)}_{\text{Collins FF}} \frac{\left(\hat{k}\times\vec{p}_{h\perp}\right)\cdot\vec{s}_q}{zM_h}$$

Event Structure at Belle

e+e- CMS frame:

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

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



$<N_{h+,-}> = 6.4$

Jet axis: Thrust

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

Spin averaged cross section:

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

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

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

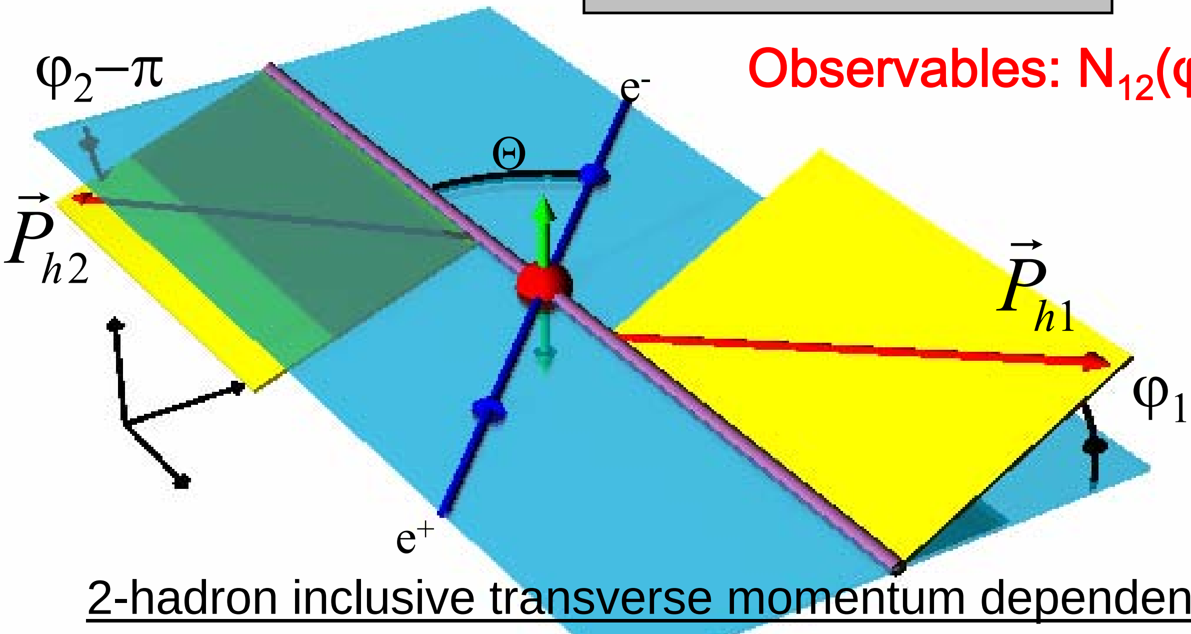
- Quark spin direction unknown: measurement of Collins function in one hemisphere is not possible $\sin \varphi$ modulation will average out.

- 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.

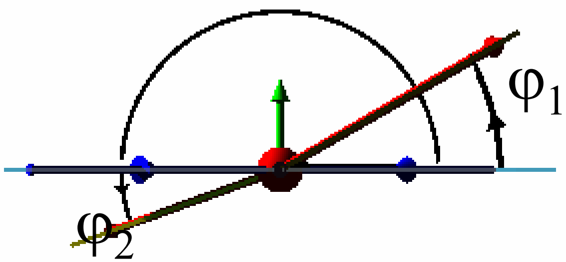
Measurement of azimuthal correlations for pion pairs around the jet axis in two-jet events!

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:

$$\frac{d\sigma(e^+e^-\rightarrow h_1h_2X)}{d\Omega dz_1dz_2d^2\boldsymbol{q}_T} = \cdots B(y)\cos(\varphi_1+\varphi_2)H_1^{\perp[1]}(z_1)\overline{H}_1^{\perp[1]}(z_2)$$

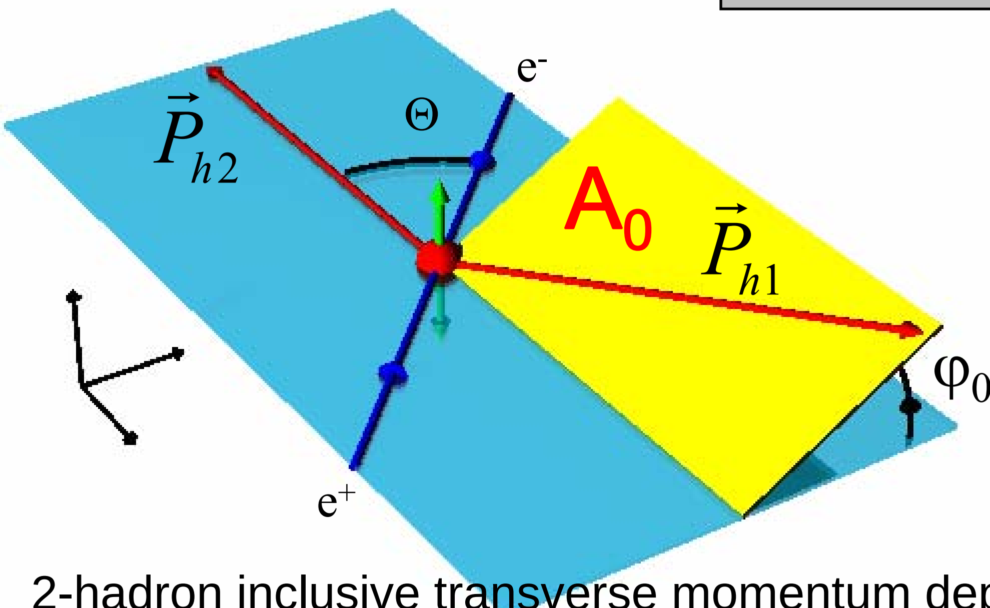
$$B(y) = y(1-y) \overset{cm}{=} \frac{1}{4}\sin^2\Theta$$

Net anti-alignment of transverse quark spins

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

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:

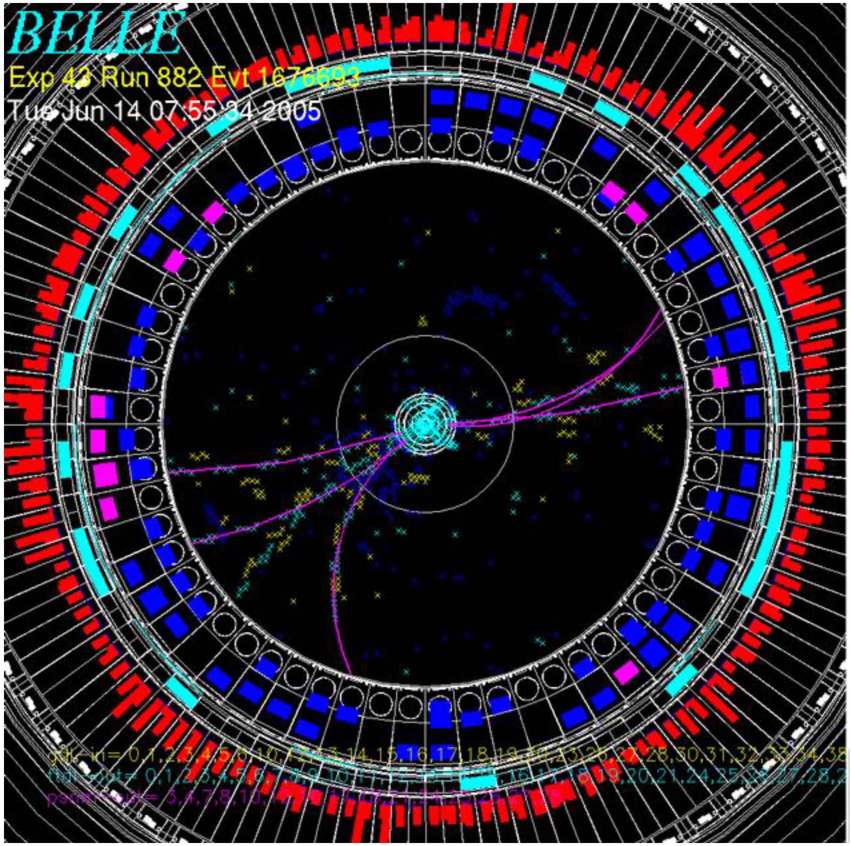
$$\frac{d\sigma(e^+e^- \to h_1h_2X)}{d\Omega dz_1 dz_2 d^2\boldsymbol{q}_T} = \cdots B(y)\cos(2\varphi_0) I\left[\left(2\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T - \boldsymbol{k}_T\cdot\boldsymbol{p}_T\right)\frac{H_1^\perp\overline{H}_1^\perp}{M_1M_2}\right]$$

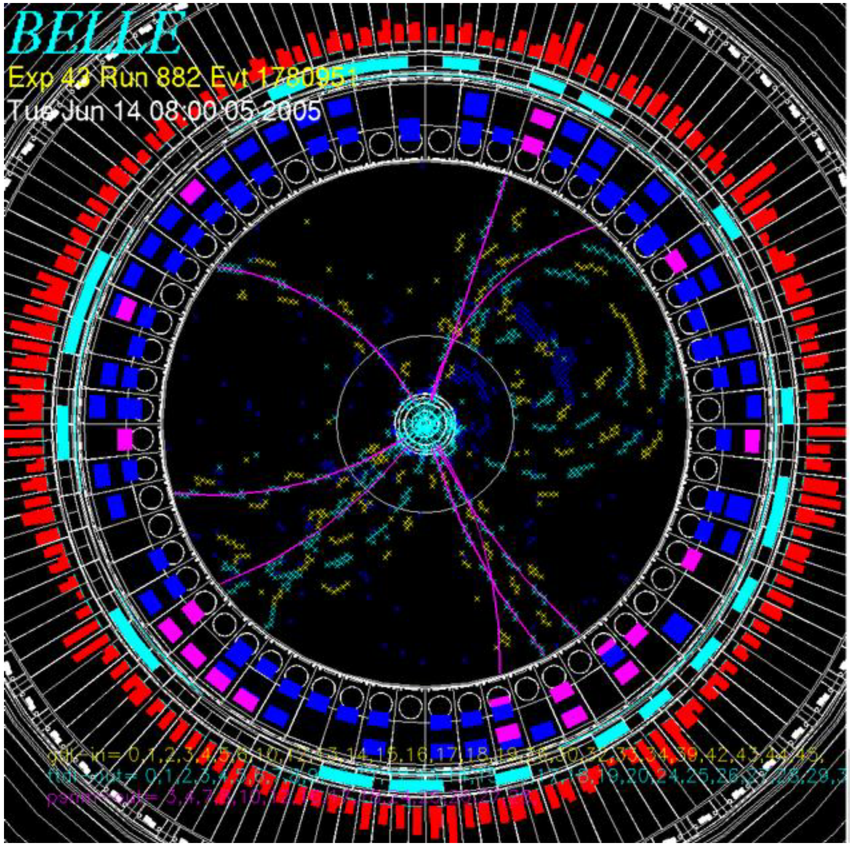
$$B(y) = y(1-y) \overset{cm}{=} \frac{1}{4}\sin^2\Theta$$

Net anti-alignment of transverse quark spins

Hadronic Events observed with Belle

➔ 1.5 x 10^9 hadronic events in analysis

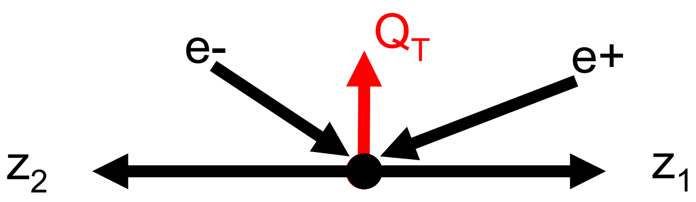




On resonance: $547 fb^{-1}$, $\sqrt{s}$=10.52 GeV *(published)*
Off resonance: $29 fb^{-1}$, $\sqrt{s}$=10.58 GeV *(preliminary)*

Gluon Emission

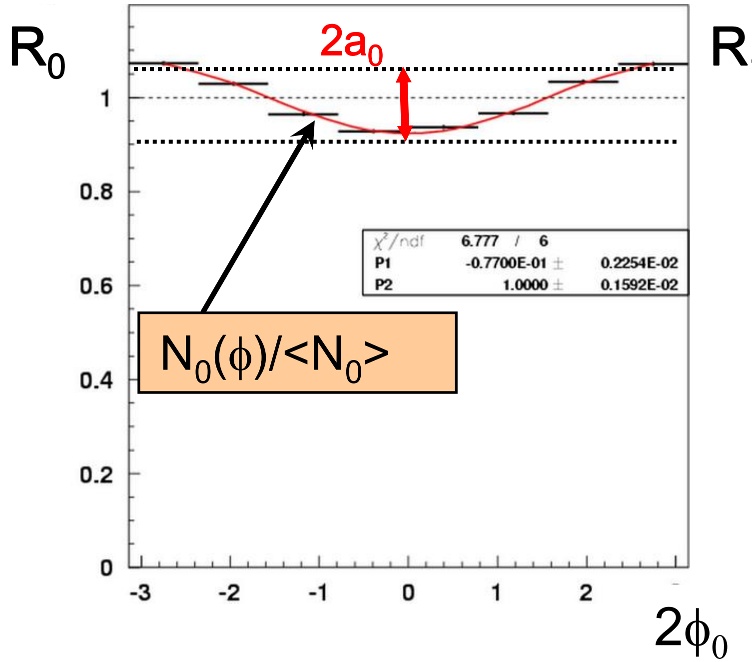
$$\frac{dN}{d\Omega dz_1 dz_2 dq_T} \propto \sum \left[\frac{q_T^2}{Q^2 + Q_T^2} \sin^2\theta \cos(2\phi_0) D_1(z_1) \overline{D}_1(z_2) \right]$$

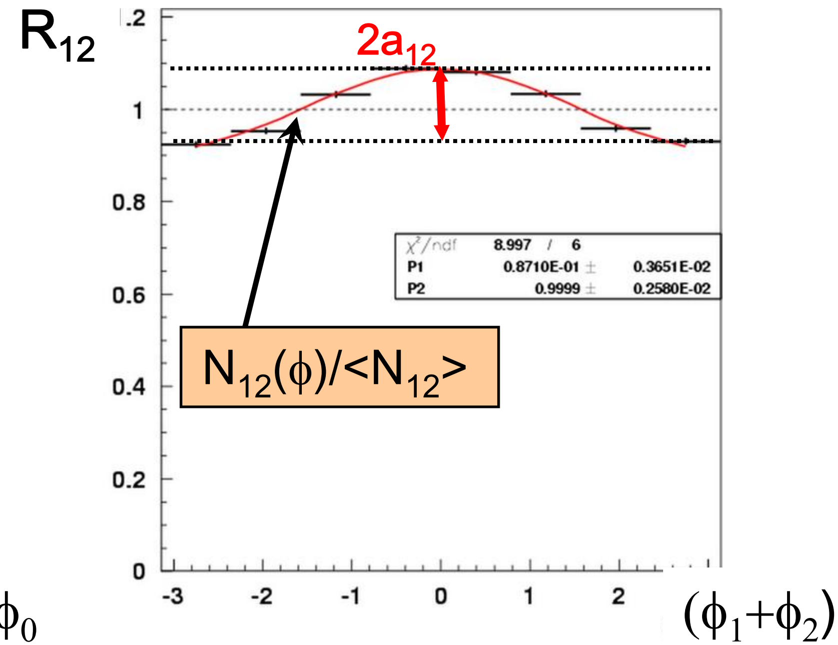


Frame:

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

Examples of Fits to Azimuthal Asymmetries





$$R_0 = \frac{N_0(\phi_0)}{\langle N_0 \rangle} \propto \frac{aD_1\overline{D}_1 + \cos(\phi_0)\left[bH_1\overline{H}_1 + cD_1\overline{D}_1\right]}{aD_1\overline{D}_1} = b_0 + a_0\cos(\phi_0)$$

D_1 : spin averaged fragmentation function,

H_1: Collins fragmentation function

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

Form double ratios for unlike and like-sign pion pairs:

$$R = \frac{R_{12}^{UnLike-sign}}{R_{12}^{Like-sign}} = \frac{N_{12}^{UL}(\phi_1+\phi_2)}{\langle N_{12}\rangle} \Big/ \frac{N_{12}^{L}(\phi_1+\phi_2)}{\langle N_{12}\rangle}$$

$$\approx 1 + \frac{1}{4}\cos(\phi_1+\phi_2)\,\boxed{A_{12}^{UL/L}(z_1,z_2)}$$

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

(I) radiative effects are charge independent and cancel.

(II) R^{UL} and R^{L} depend depend on H^{fav} and H^{dis} differently.

➔ A_{12} retains sensitivity for the Collins effect!

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)

UL

UC

Observables:

A_{12}(UL), A_{12}(UC)
A_0(UL) , A_0(UC)

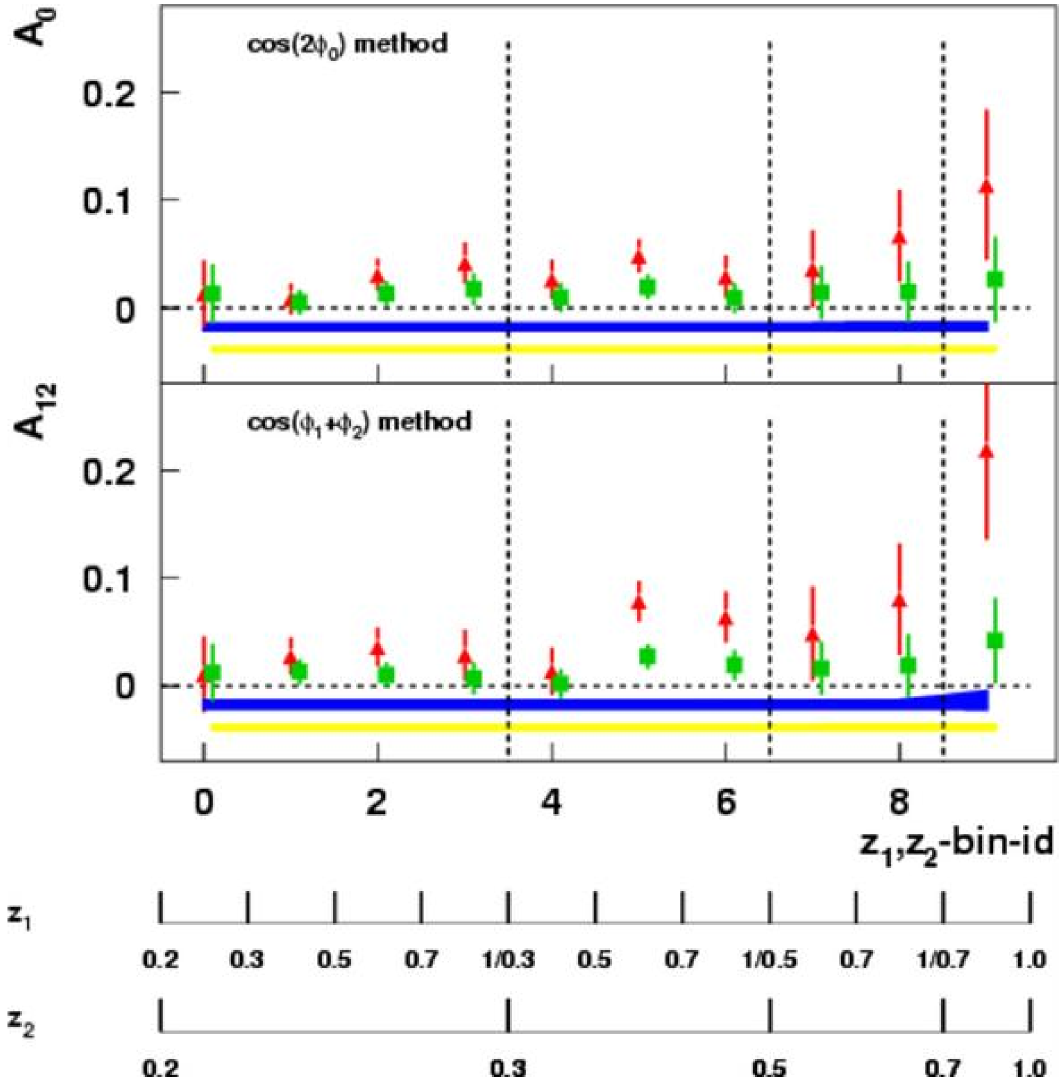
published and input to fit by Anselmino et al.

Final Charm Corrected Results for $e^+ e^- \rightarrow \pi \pi X$ (29fb^{-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

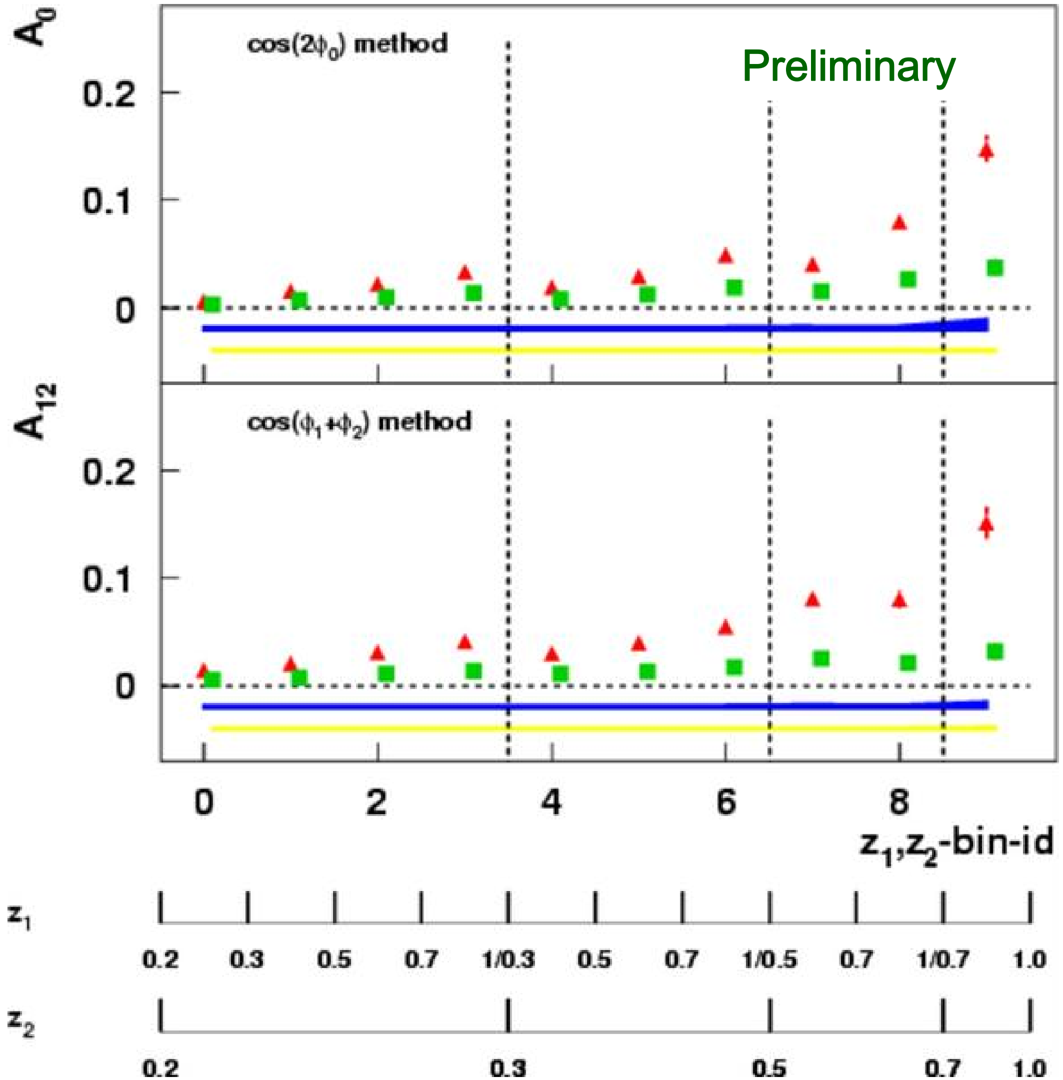
A_0(UL/L)	$(3.06 \pm 0.57 \pm 0.55)\%$
A_{12}(UL/L)	$(4.26 \pm 0.68 \pm 0.68)\%$
A_0(UL/C)	$(1.27 \pm 0.49 \pm 0.35)\%$
A_{12}(UL/C)	$(1.75 \pm 0.59 \pm 0.41)\%$



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 & Outlook

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

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

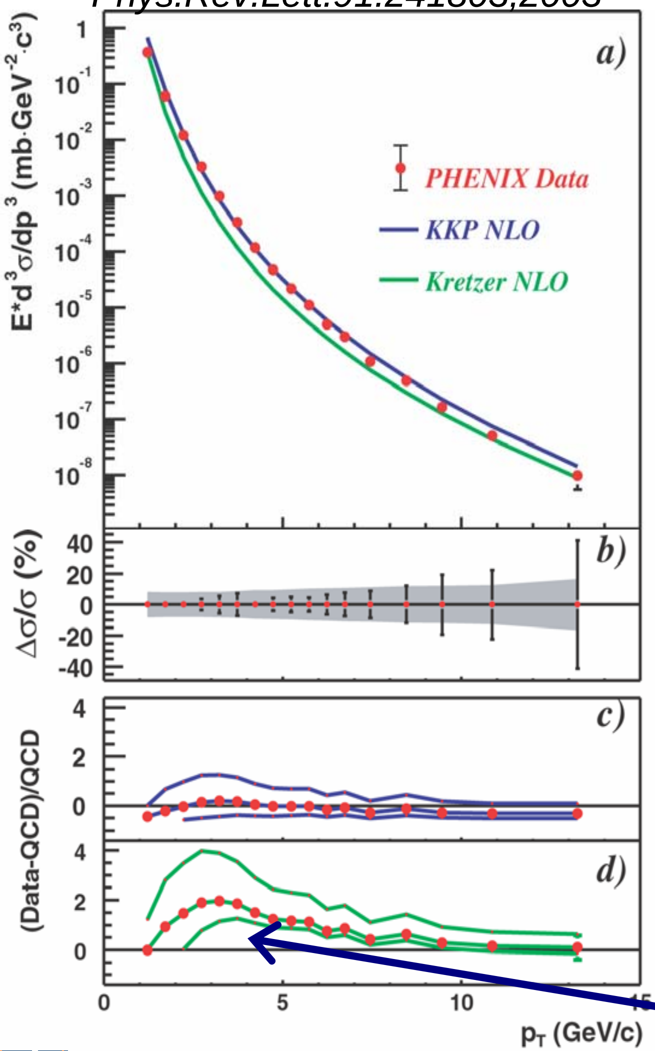
- Double ratios reliably cancel contributions from detector acceptance and gluon radiation.
- Important input for the transverse spin physics programs at RHIC, HERMES, COMPASS and JLab.
- Fundamental test case for QCD at soft scales!

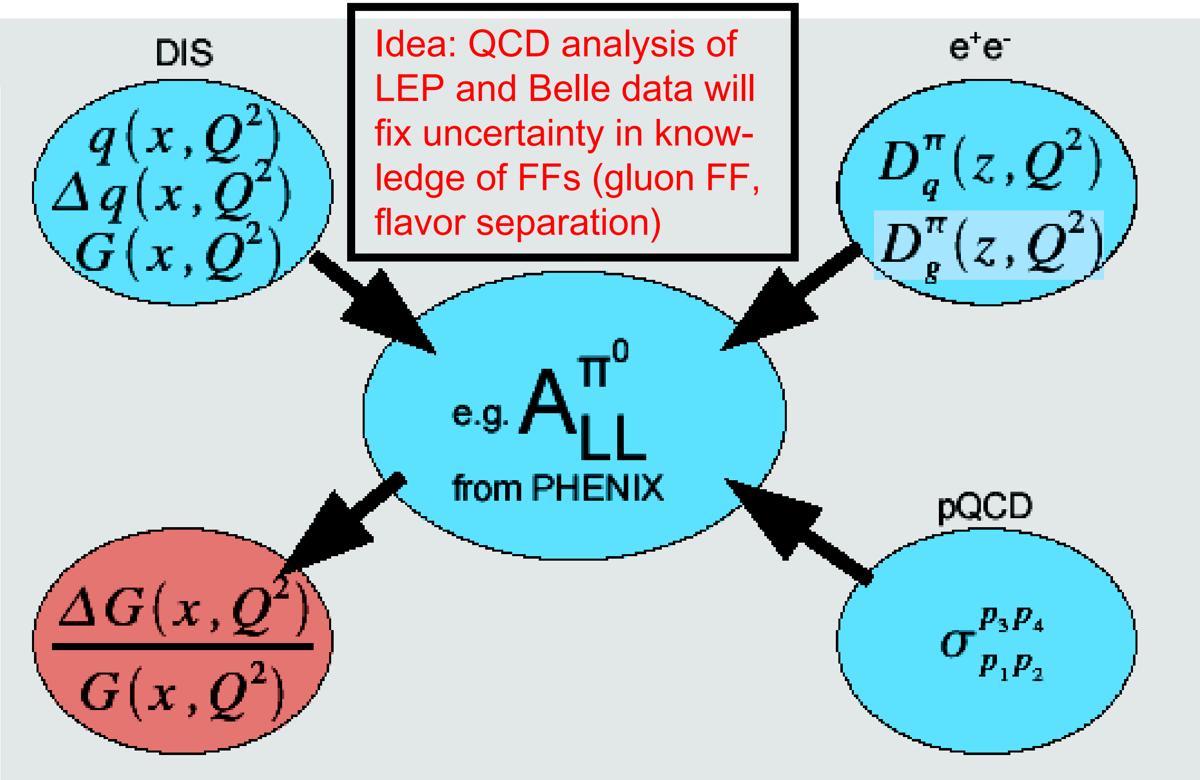
- Future spin dependent FFs:
  - → update Collins FF
  - → measure p_T dependence
  - → interference fragmentation
  - → Collins FF for VMs
  - → Lambdas
- Precision measurement of spin averaged fragmentation functions as input to RHIC program with inclusive hadrons and future precision measurements in SIDIS.

Motivation 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

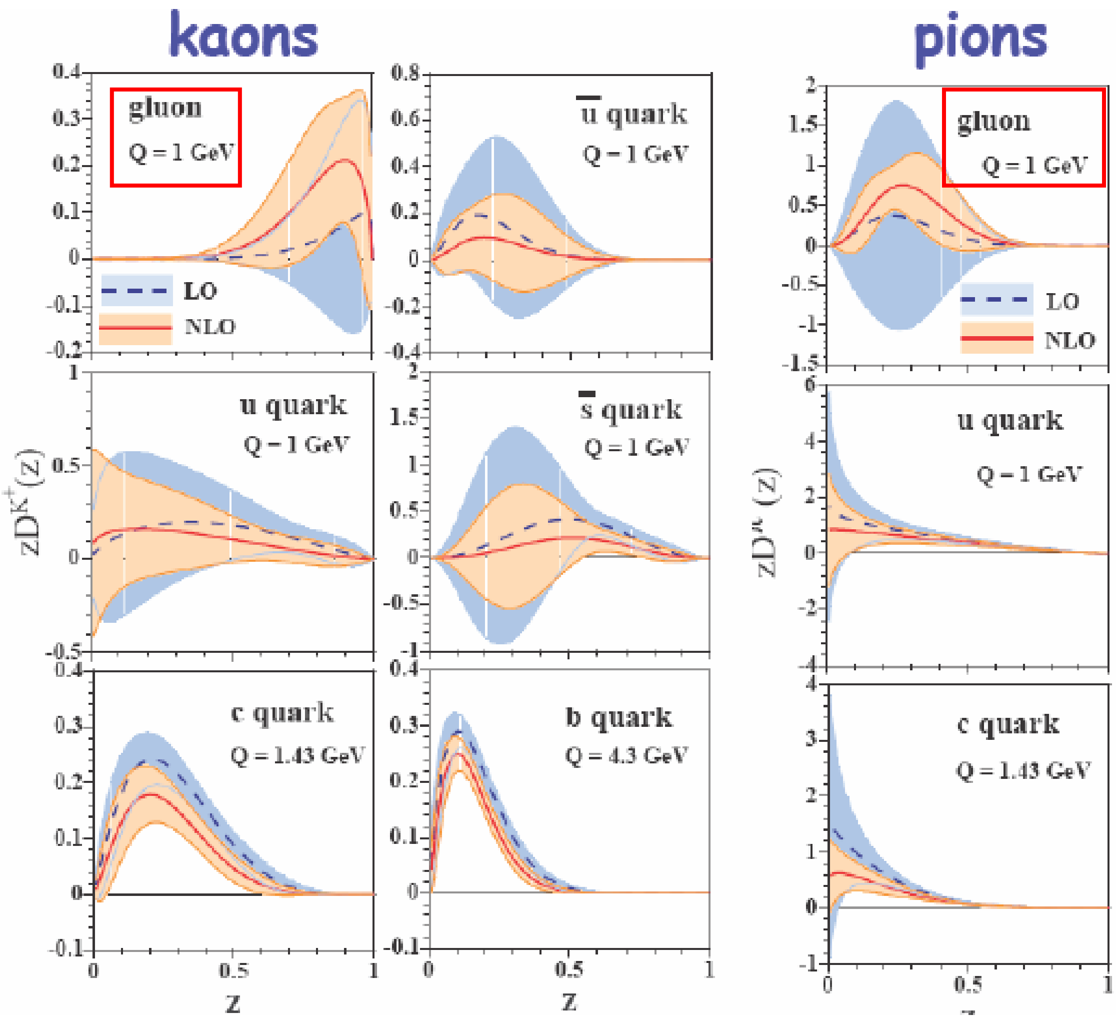




$$A_{LL} \equiv \frac{d\Delta\sigma}{d\sigma} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}}$$

Deviation connected to uncertainties in FFs → gluon FF!

What is Known Experimentally in e^+e^- ?



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

Earlier work:

Kretzer

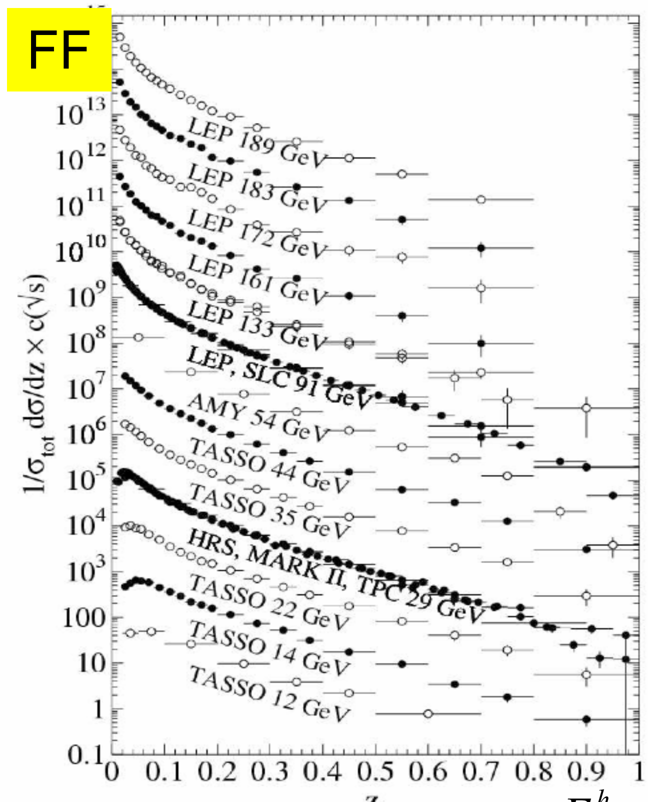
Binnewies, Potter, Albino
Kniehl, Kramer, Potter
Albino, Kniehl, Kramer

Most recent work:

De Florian, Sassot, Stratmann

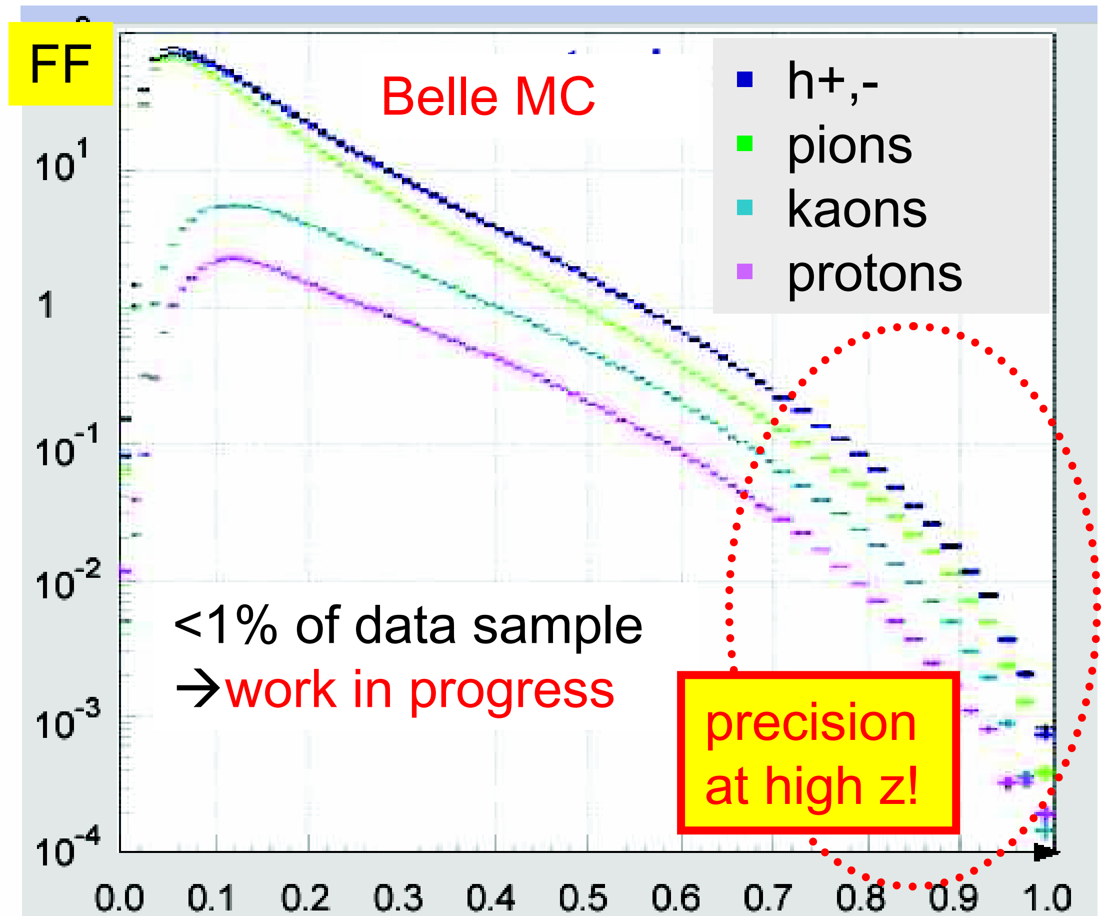
pact on the Knowledge of FFs

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



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

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- o Evolution is fundamental QCD prediction
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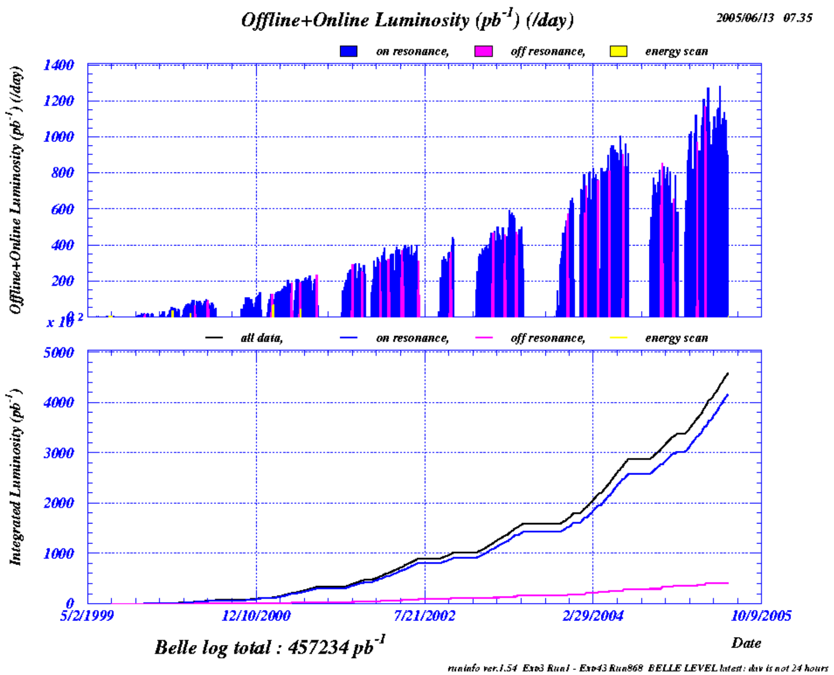
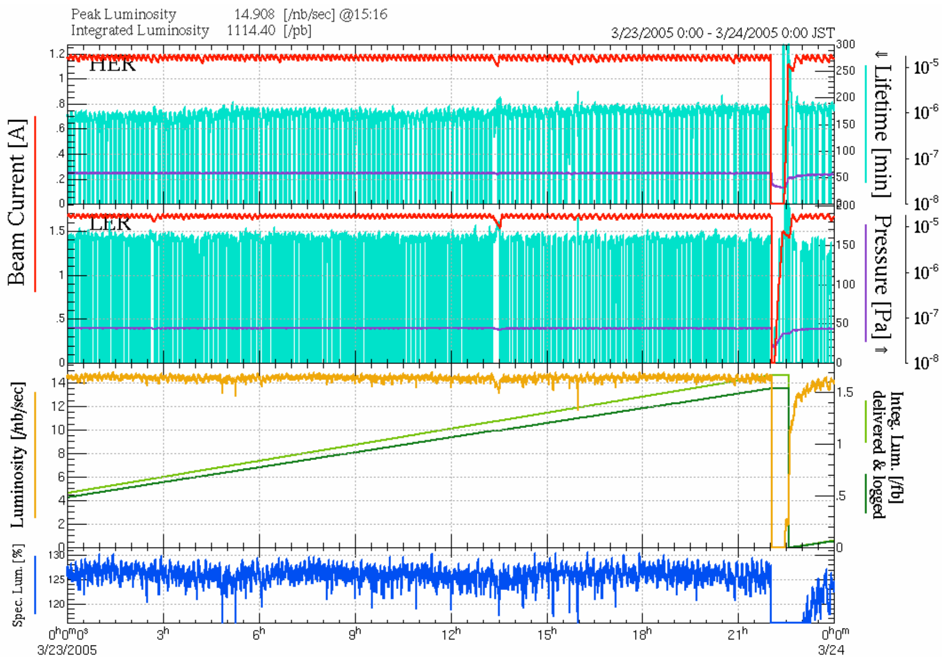
祝 ∫ℒ = 400 fb⁻¹ 達成
APR-05-2005


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

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

→ 1.5×10^9 hadronic events in analysis

- KEKB
  - Asymmetric collider
  - 8GeV e^- + 3.5GeV e^+
  - $\sqrt{s}$ = 10.58GeV ($\Upsilon(4S)$)

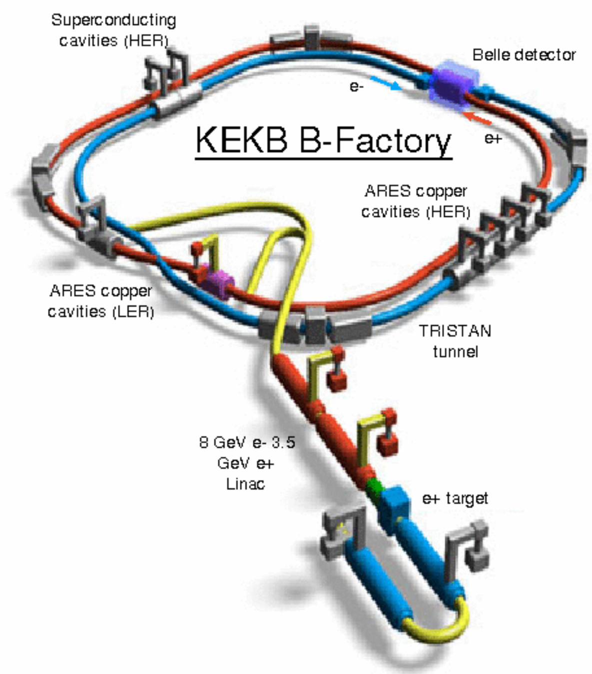
    $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
  - Off-resonance: 10.52 GeV

    $e^+e^- \to q\bar{q}$ (u,d,s,c)
  - Integrated Luminosity: > 600 fb^{-1}

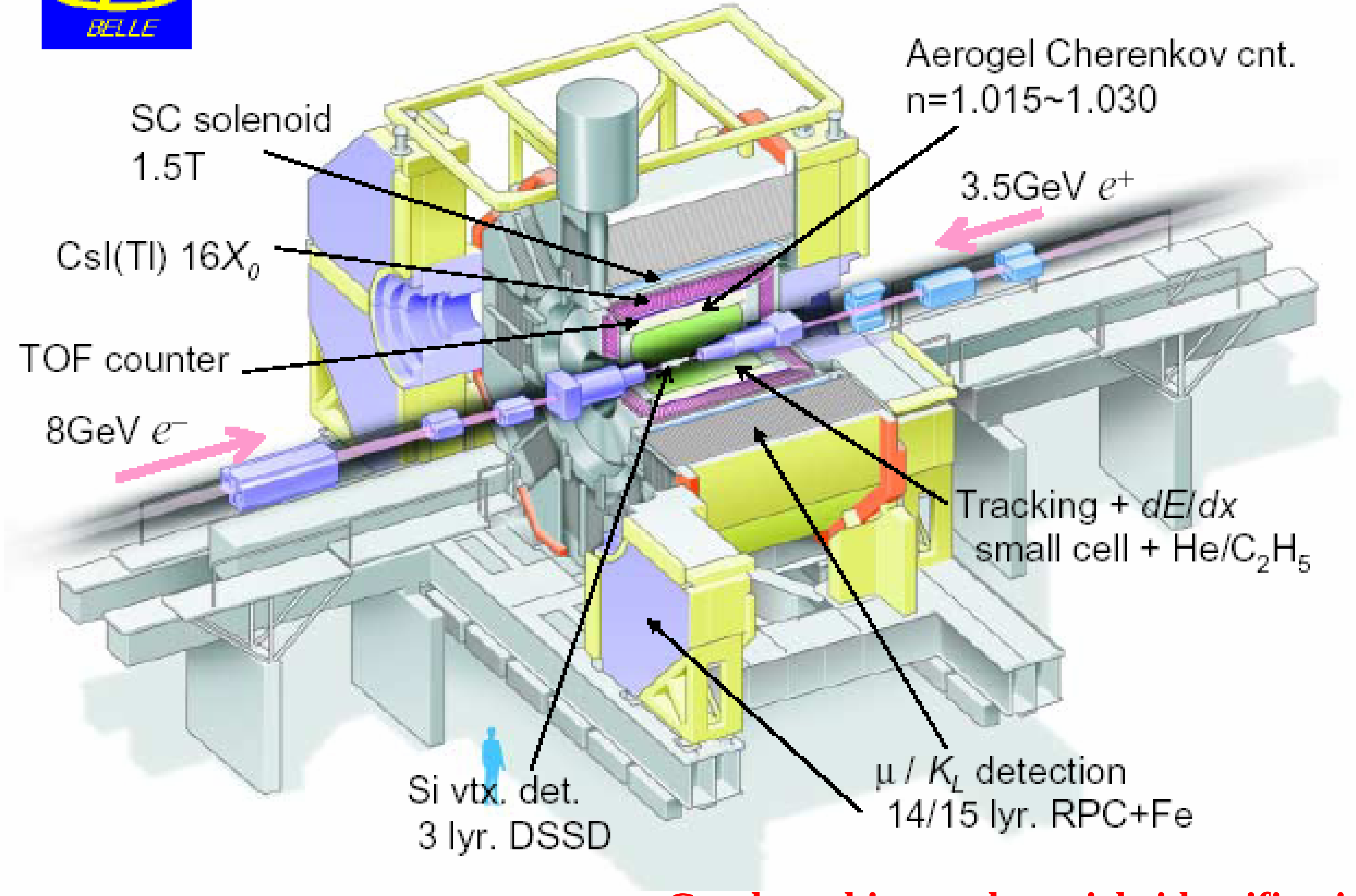
    > 60fb^{-1} => off-resonance

•Average Trigger rates:

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



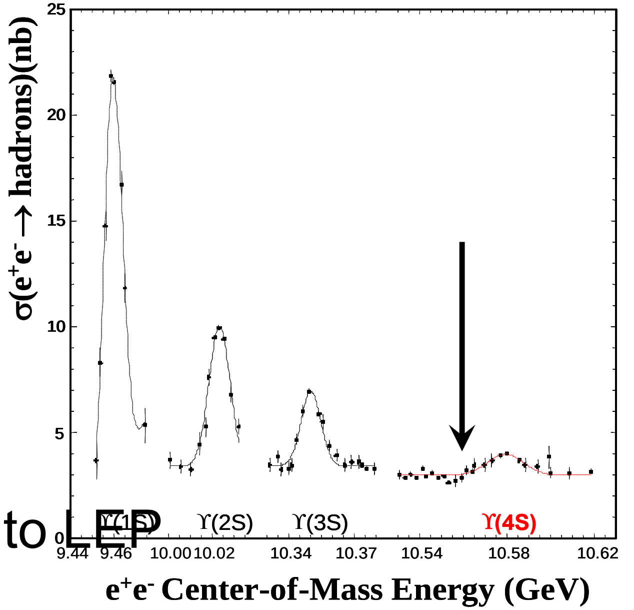
Belle Detector



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

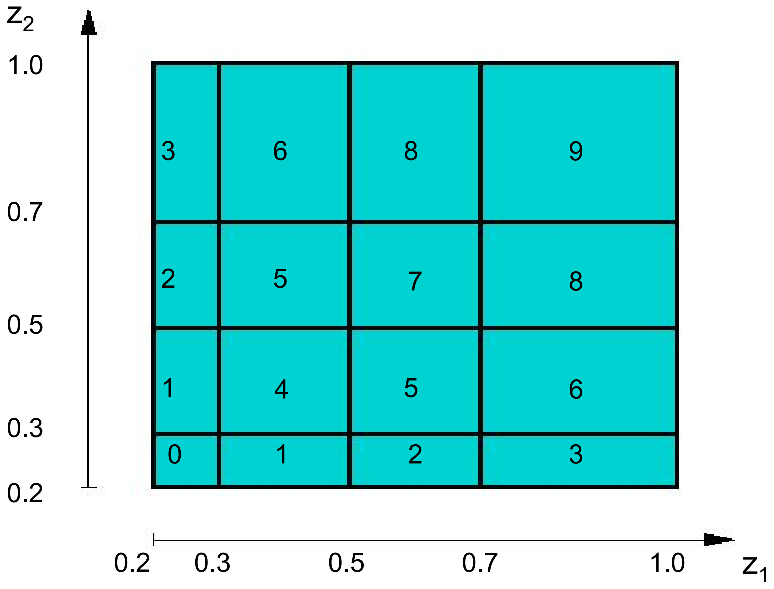


Total number of hadronic events ~ 1.5 x 10^9

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
  - $Z_1, Z_2 > 0.2$

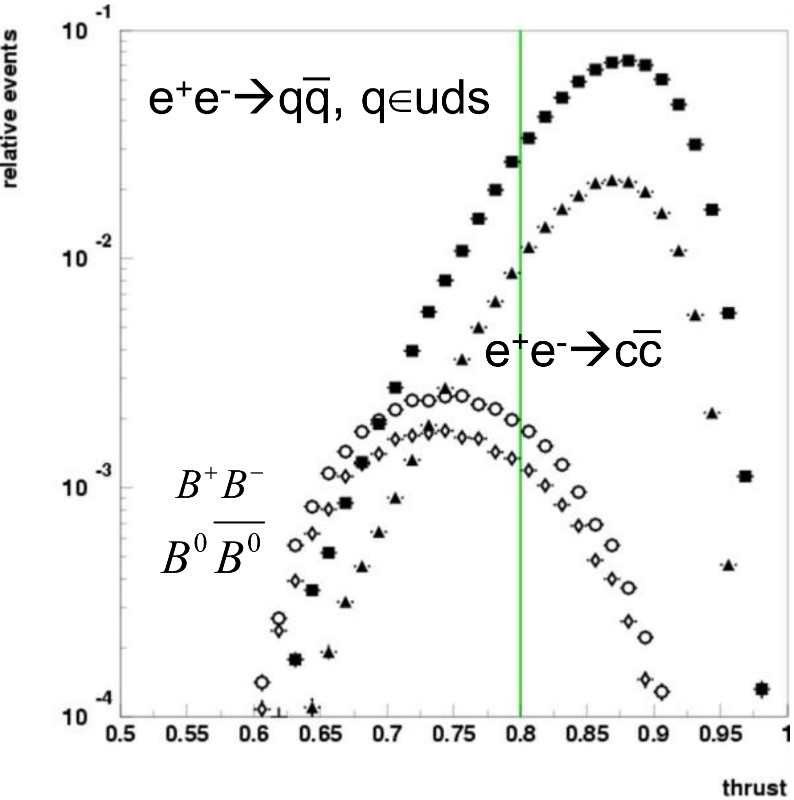
- Hemisphere cut $\boxed{(P_{h2} \cdot \hat{n})\hat{n} \cdot (P_{h1} \cdot \hat{n})\hat{n} < 0}$
- $Q_T < 3.5$ GeV
- Pion PID selection

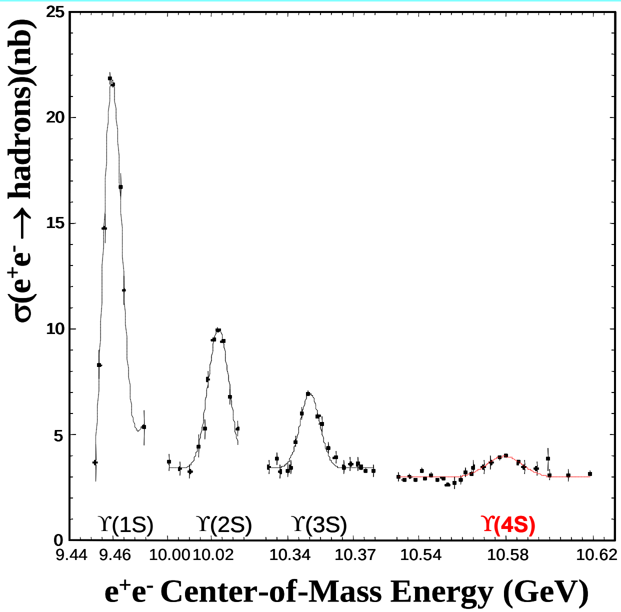


Experimental Issues

- 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? → *$\cos(2\phi)$* 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



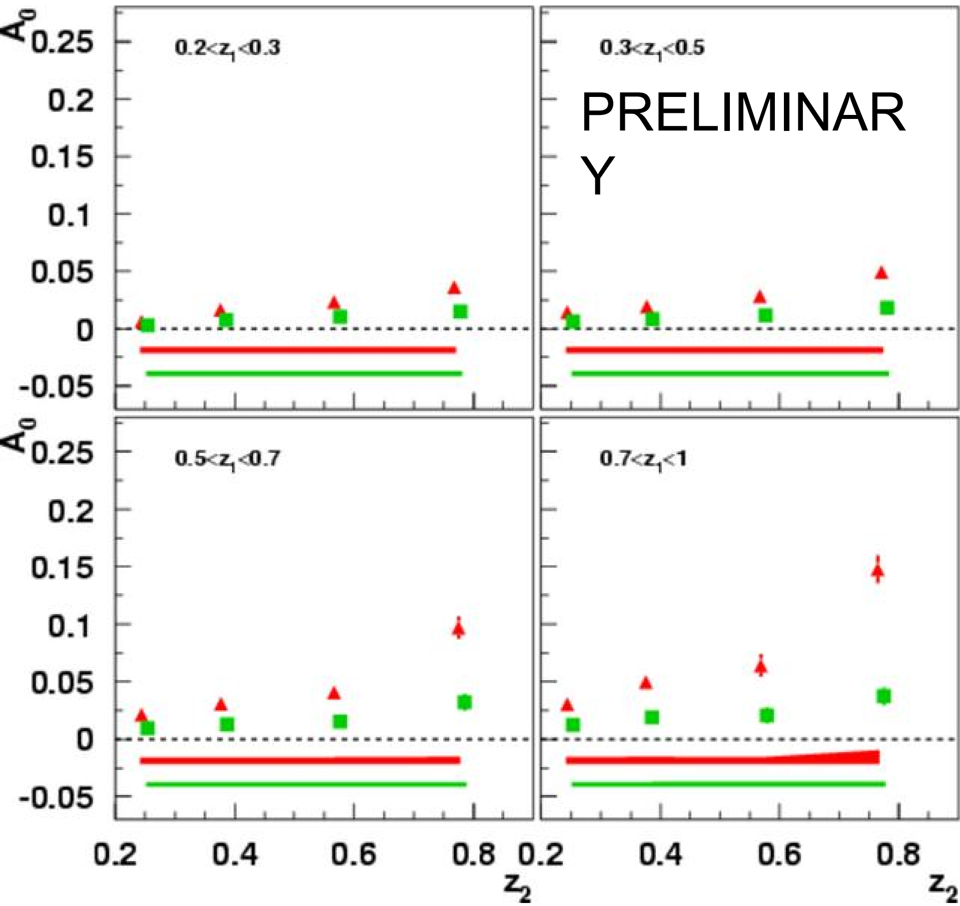


$$\text{thrust} = \frac{\sum_i |p_i \cdot \hat{n}|}{\sum_i |p_i|}$$

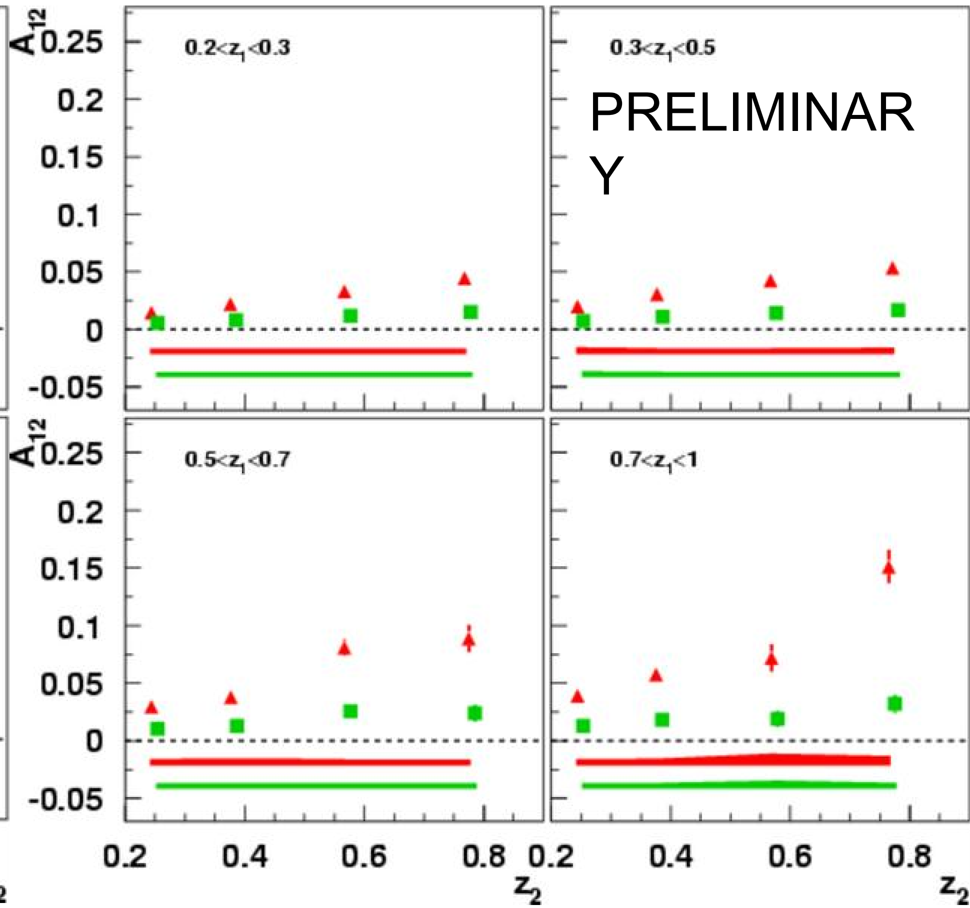
- small B contribution (<1%) in high thrust sample
- >75% of X-section continuum under Υ (4S) resonance
- 29 fb^{-1} ➔ 547 fb^{-1}
- many systematic errors reduce with more statistics
- Charm-tagged Data sample also increases

Collins Asymmetries I: 4x4 z_1, z_2 binning

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

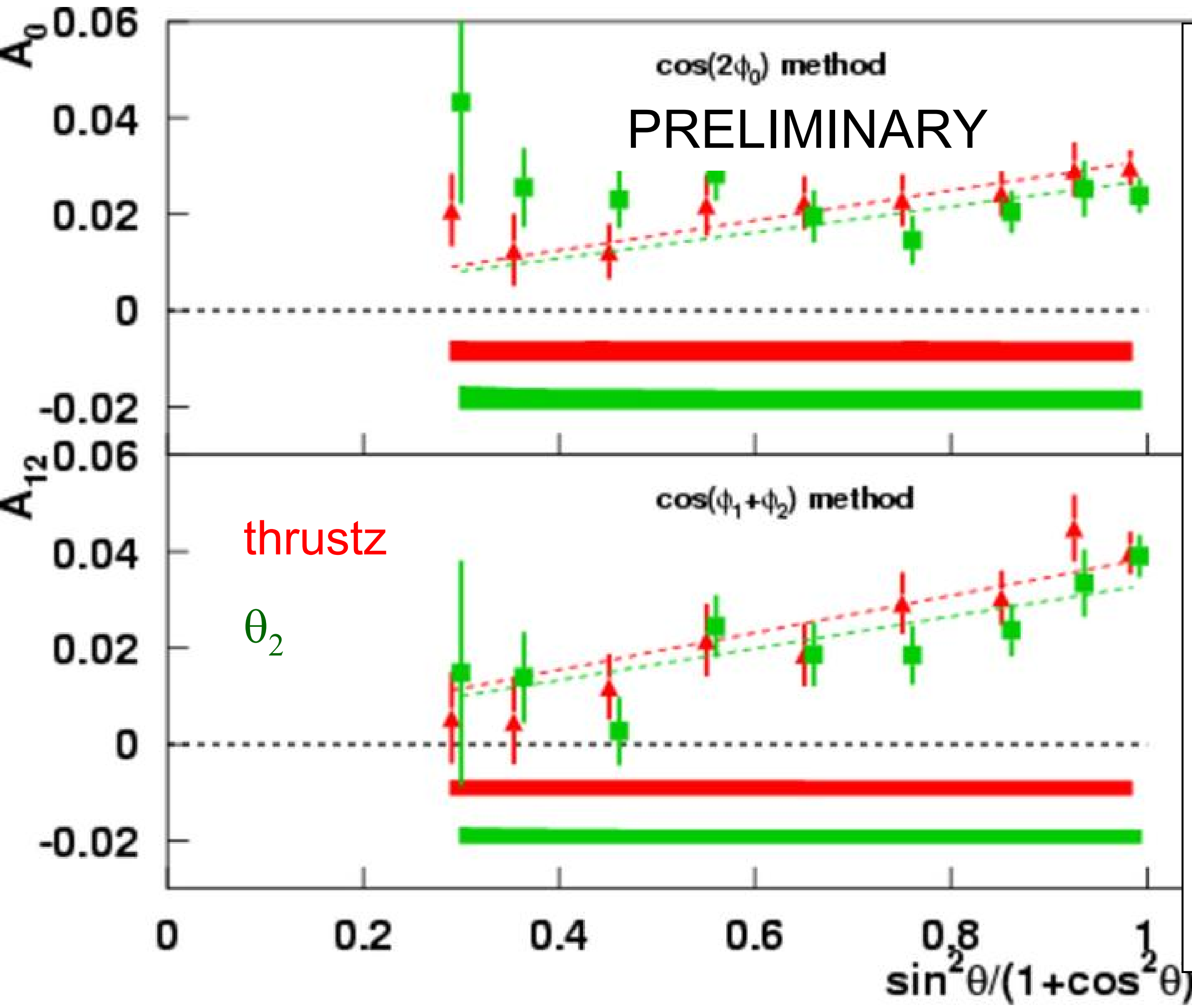


A_{12} ($\cos(\phi_1+\phi_2)$) moments



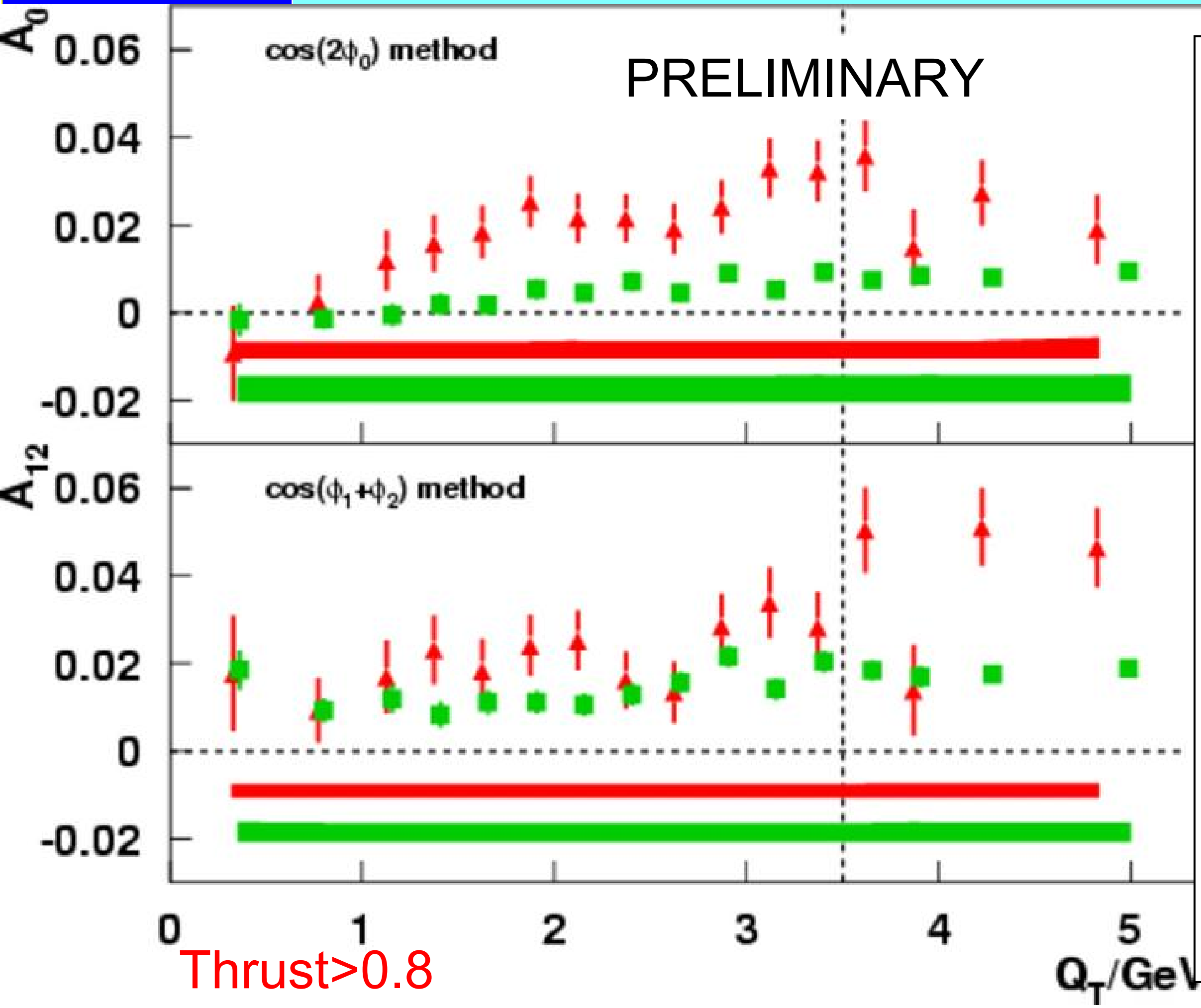
- 547 fb^{-1} charm corrected data sample,
- UL and UC double ratios

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)

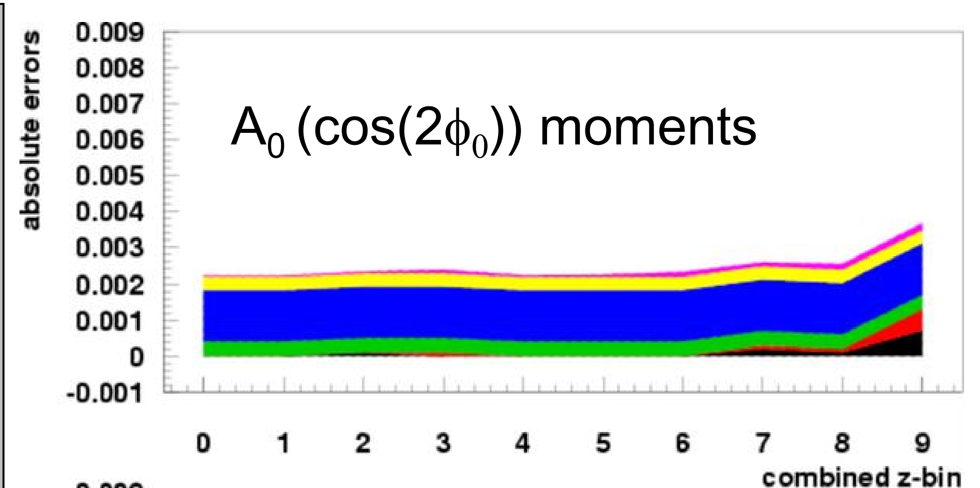
- Reduced asymmetries in low thrust sample
- At low thrust significant B contribution

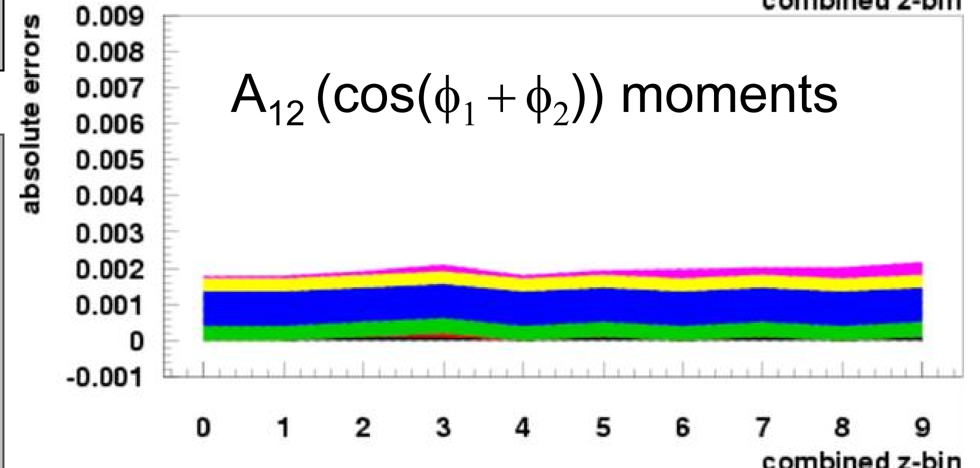
  (for t<0.8 ~20 % B

  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