Chiral-odd fragmentation functions at Belle

(see hep-ex/0507063 for details, submitted to PRL)

Compass Seminar

March 20th, CERN

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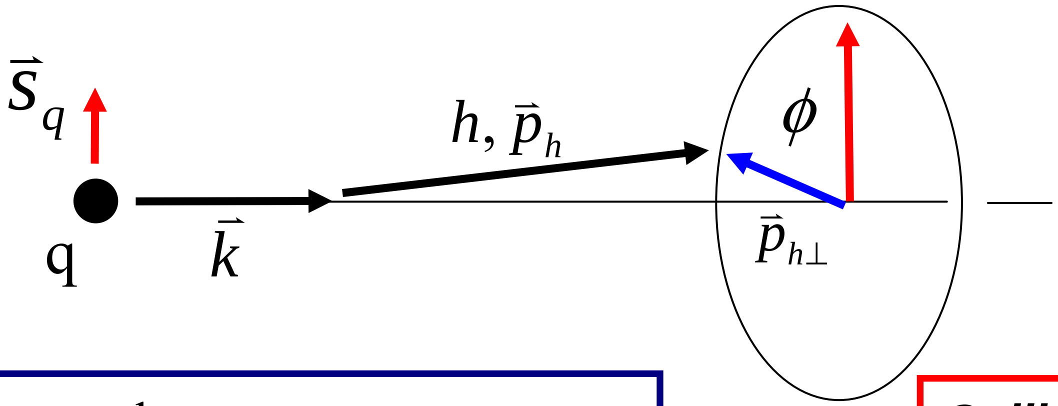
Collins Effect in Quark Fragmentation

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

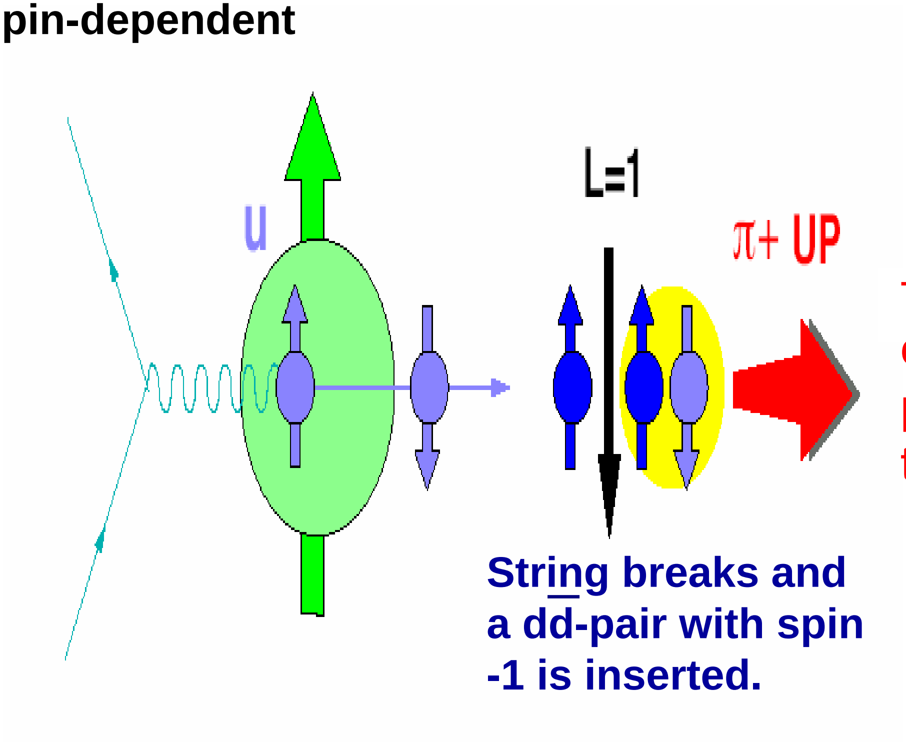
Collins Effect:
Fragmentation of a transversely polarized quark *q* into spin-less hadron *h* carries an azimuthal dependence:

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

$$\propto \sin\phi$$

The Collins Effect in the Artru Fragmentation Model

A simple model to illustrate that spin-orbital angular momentum coupling can lead to left right asymmetries in spin-dependent fragmentation:



String breaks and a dd-pair with spin -1 is inserted.

π^+ picks up L=1 to compensate for the pair S=1 and is emitted to the right.

Motivation: Global Transversity Analysis

SIDIS experiments (HERMES and COMPASS) measure δq(x) together with either Collins Fragmentation function $H_1^{\perp}(z)$ or Interference Fragmentation function

RHIC measures the same combinations of quark Distribution (DF) and Fragmentation Functions (FF) plus unpolarized DF q(x)

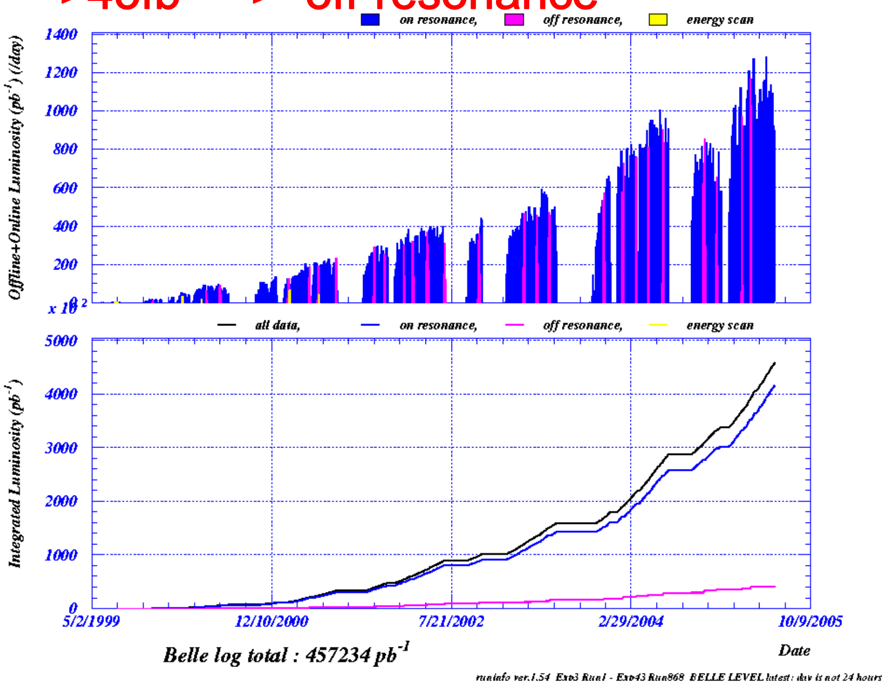
There are always 2 unknown functions involved which cannot be measured independently

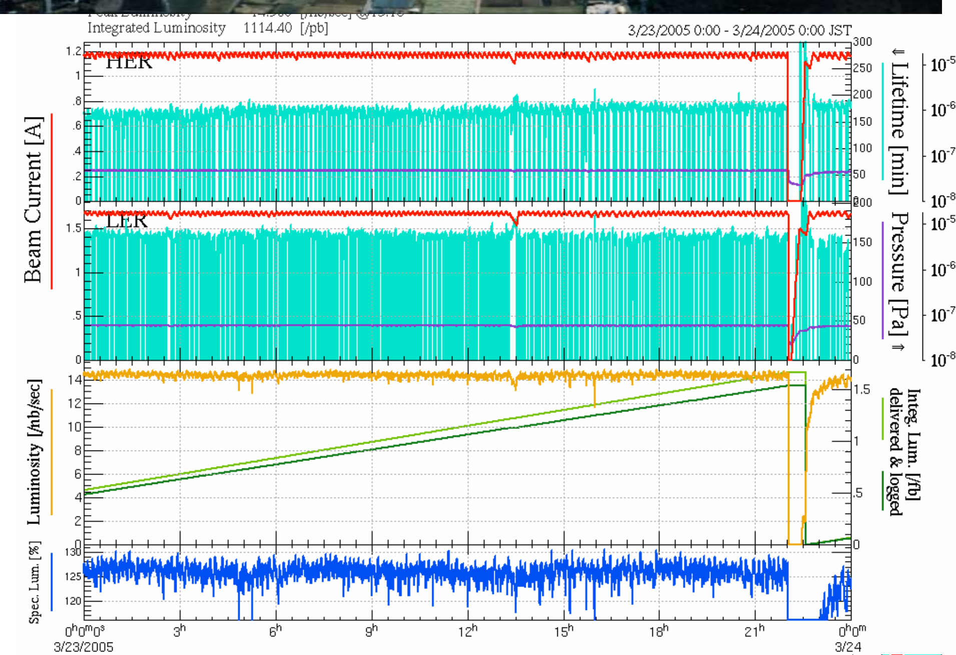
Universality appears to be proven in LO by Collins and Metz: [**PRL93:(2004)252001**]

The Spin dependent Fragmentation function analysis yields information on the Collins and the Interference Fragmentation function !

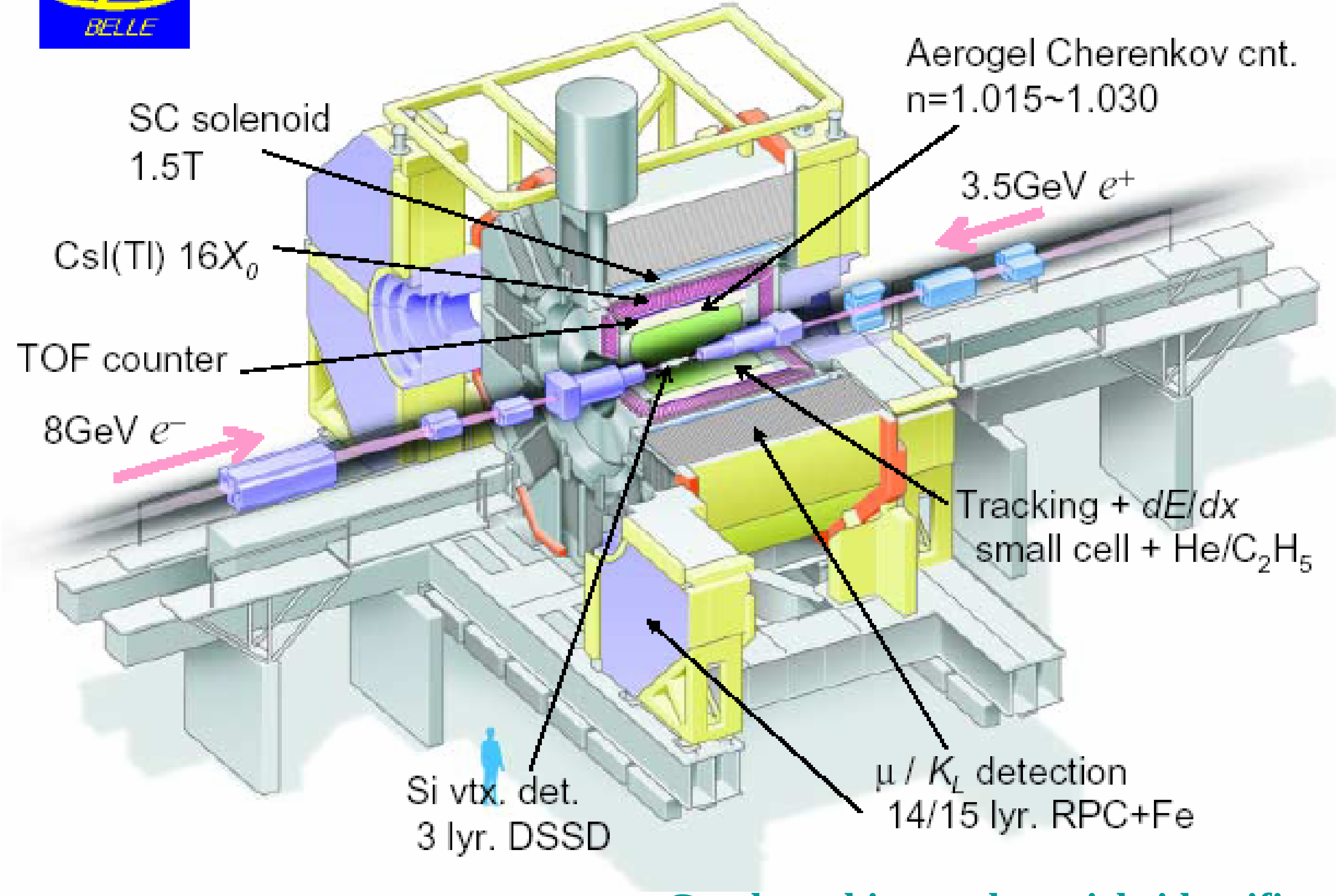
KEKB: L>1.5x10^{34}cm^{-2}s^{-1} !!

- Asymmetric collider
- 8GeV e$^-$ + 3.5GeV e$^+$
- $\sqrt{s}$ = 10.58GeV (Υ(4S))
- e$^+$e$^-$→Υ(4S)→B $\bar{B}$
- Off-resonance: 10.52 GeV
- e$^+$e$^-$→q $\bar{q}$ (u,d,s,c)
- Integrated Luminosity: >500 fb^{-1}
- >45fb^{-1} => off-resonance





Belle Detector

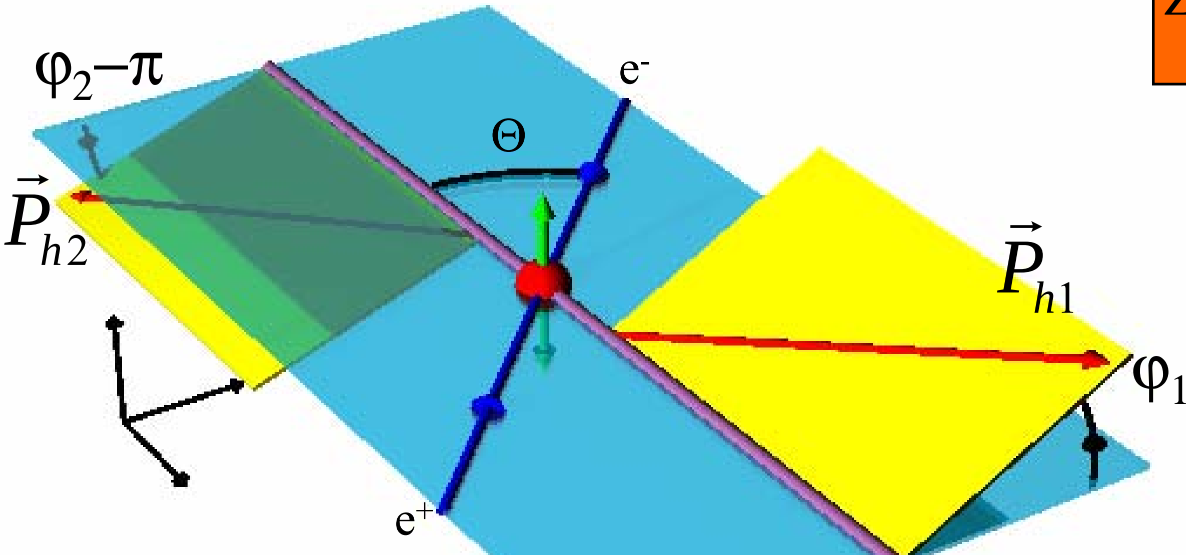


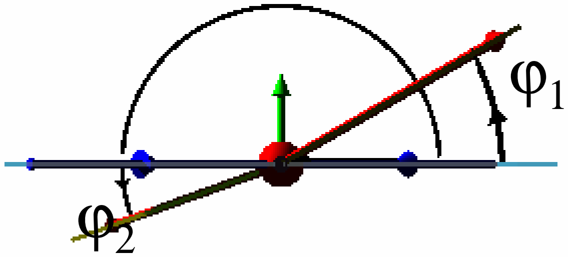
Good tracking and particle identification!

Collins fragmentation in e^+e^-: Angles and Cross section $\cos(\phi_1+\phi_2)$ method

e^+e^- CMS frame:

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





[D.Boer: PhD thesis(1998)]

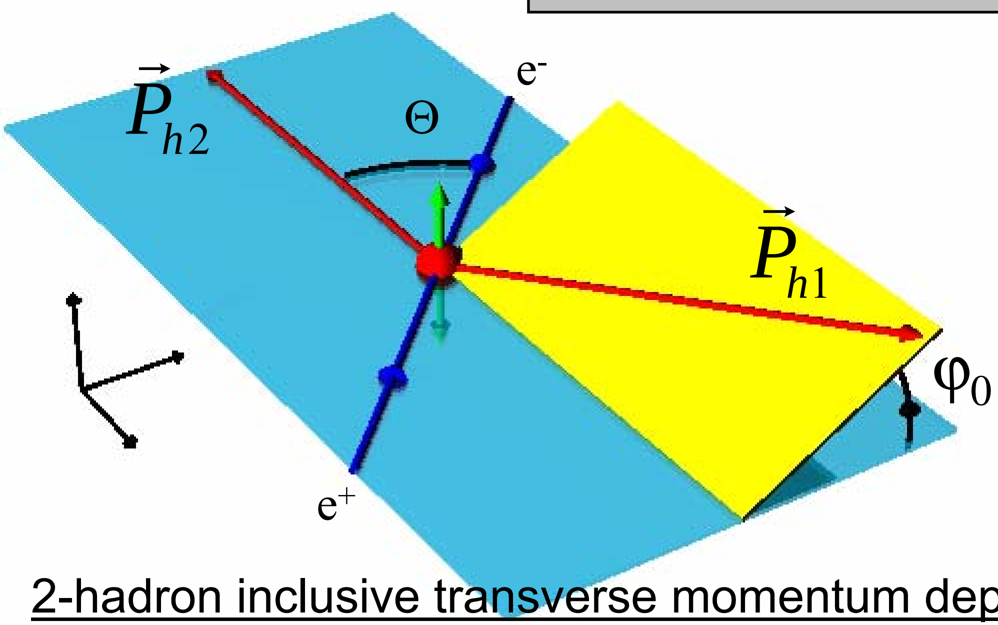
2-hadron inclusive transverse momentum dependent cross section:

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

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

Net (anti-)alignment of transverse quark spins

Collins fragmentation in e^+e^- : Angles and Cross section $\cos(2\phi_0)$ method



- 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:

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

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

Net (anti-)alignment of transverse quark spins

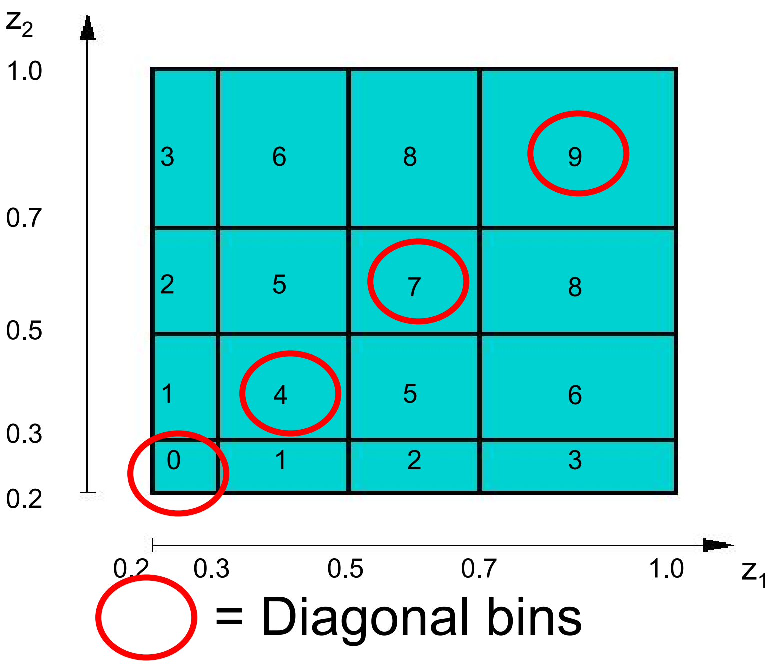
Applied cuts, binning

- Off-resonance data
  - 60 MeV below Υ(S) resonance
  - 29.1 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
  - $Z_1, Z_2 > 0.2$

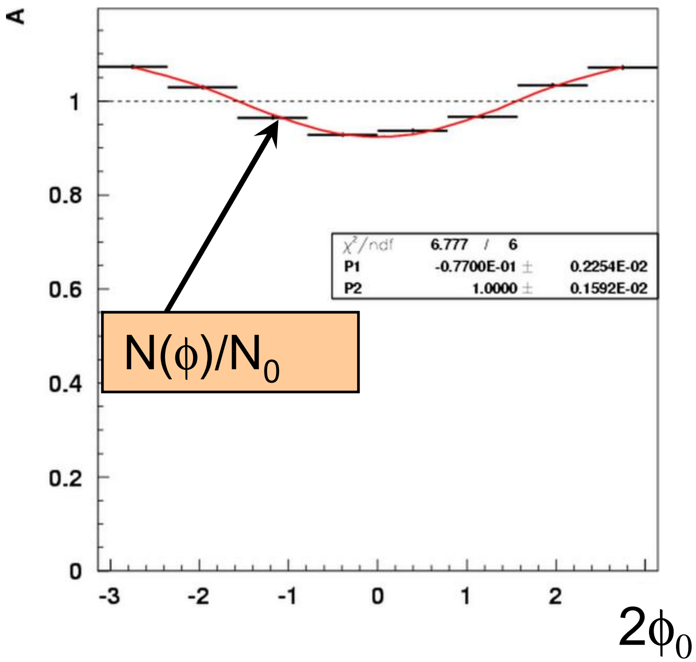
- Hemisphere cut

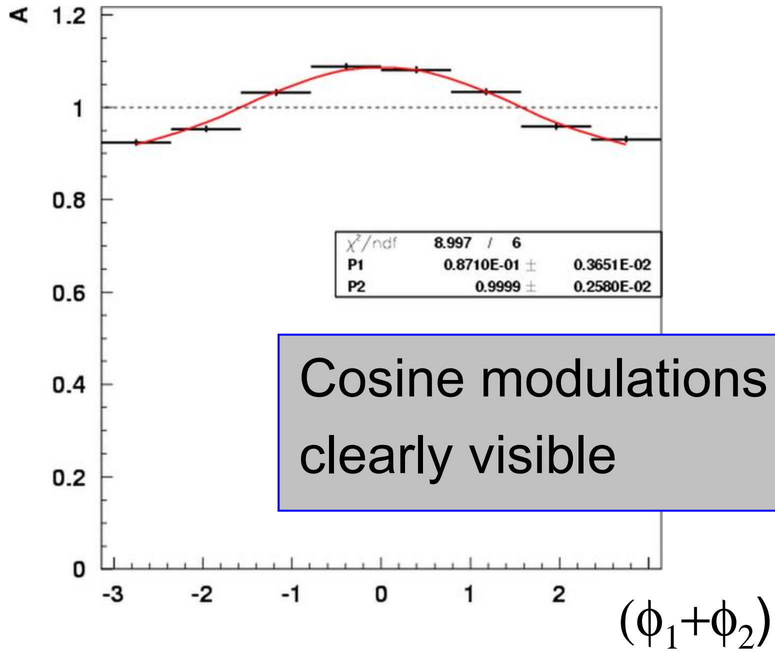
$$(P_{h2} \cdot \hat{n})\hat{n} \cdot (P_{h1} \cdot \hat{n})\hat{n} < 0$$

- Q_T < 3.5 GeV



Examples of fits to azimuthal asymmetries





Cosine modulations clearly visible

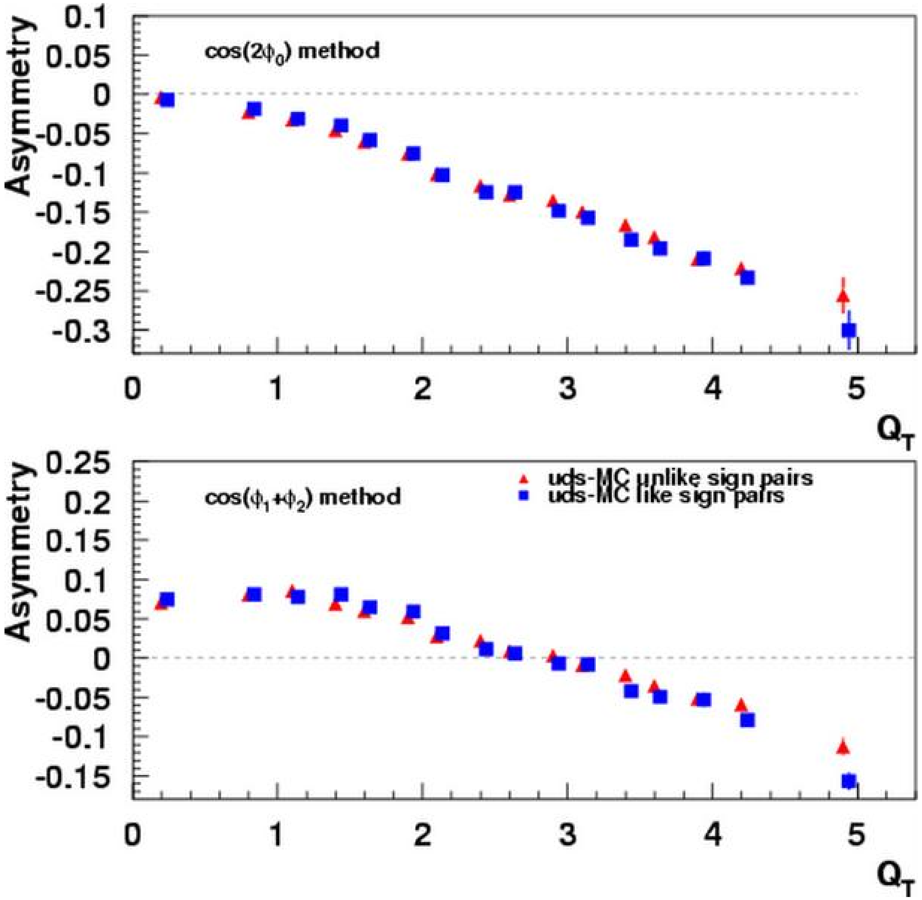
$$\frac{N(\phi)}{N_0} = \frac{aD_1\overline{D_1} + cos(2\phi)\left(bH_1\overline{H_1} + cD_1\overline{D_1}\right)}{aD_1\overline{D_1}} = P2 + P1\cos(2\phi)$$

D_1 : spin averaged fragmentation function,

H_1: Collins fragmentation function

No change in cosine moments when including sine and higher harmonics (even though double ratios will contain them)

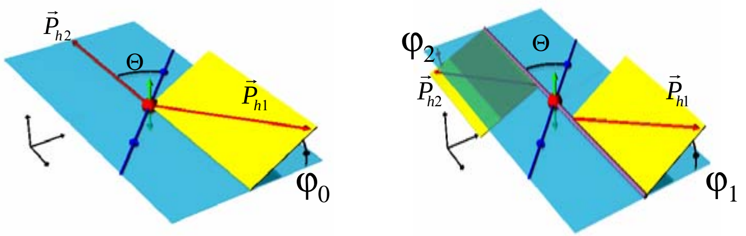
Raw asymmetries vs Q_T



- Q_T describes transverse momentum of virtual photon in $\pi\pi$ CMS system
- Significant nonzero Asymmetries visible in MC (w/o Collins)
- Acceptance, radiative and momentum correlation effects similar for like and unlike sign pairs

$$\frac{dN}{d\Omega} \propto \sin^2\theta \cos(2\phi_0)\frac{Q_T^2}{Q^2+Q_T^2}$$

- uds MC ($\pi\pi$) Unlike sign pairs
- uds MC ($\pi\pi$) Like sign pairs



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:

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

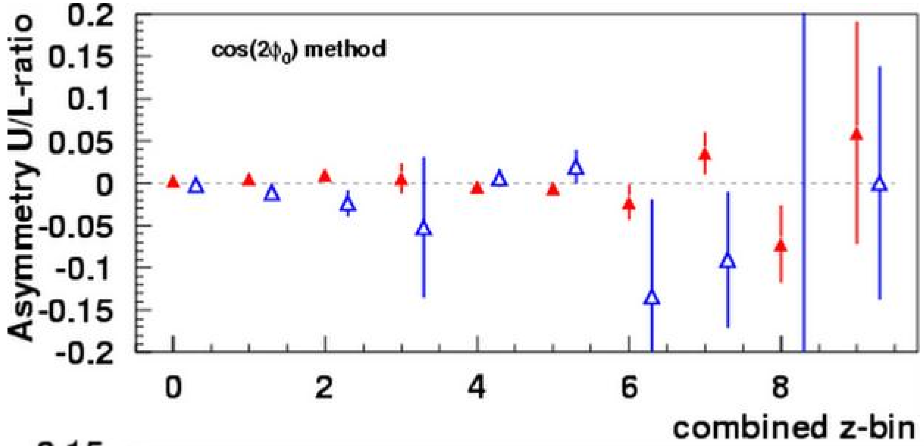
Pros: Gluon radiation cancels out exactly

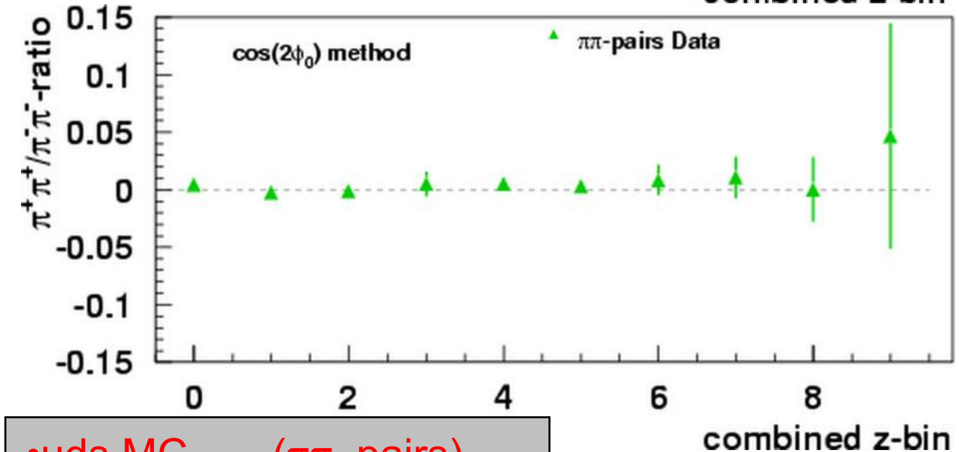
Cons: Acceptance effects remain

2 methods give very small difference in the result

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

Testing the double ratios with MC





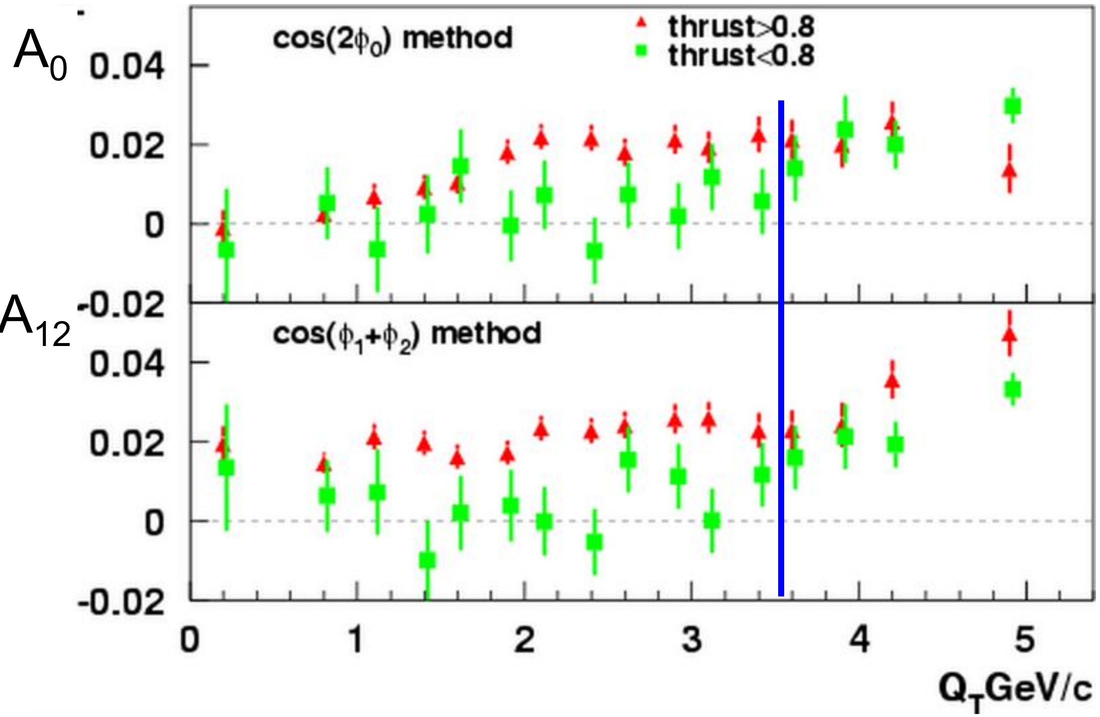
- Asymmetries do cancel out for MC
- Double ratios of $\pi^+\pi^+/\pi^-\pi^-$ compatible with zero
- Mixed events also show zero result
- Asymmetry reconstruction works well for τ MC (weak decays)
- Single hemisphere analysis yields zero

➔Double ratios are safe to use

- •uds MC (ππ–pairs)
- •charm MC (ππ–pairs)
- •Data ($\pi^+\pi^+/\pi^-\pi^-$)

	ππ uds	ππ charm	ππ mixed	kk mixed
constant	0.26%±0.19%	-0.45%±0.33%	0.06%±0.09%	0.01%±0.16%
reduced χ^2	1.17	1.35	1.14	1.2

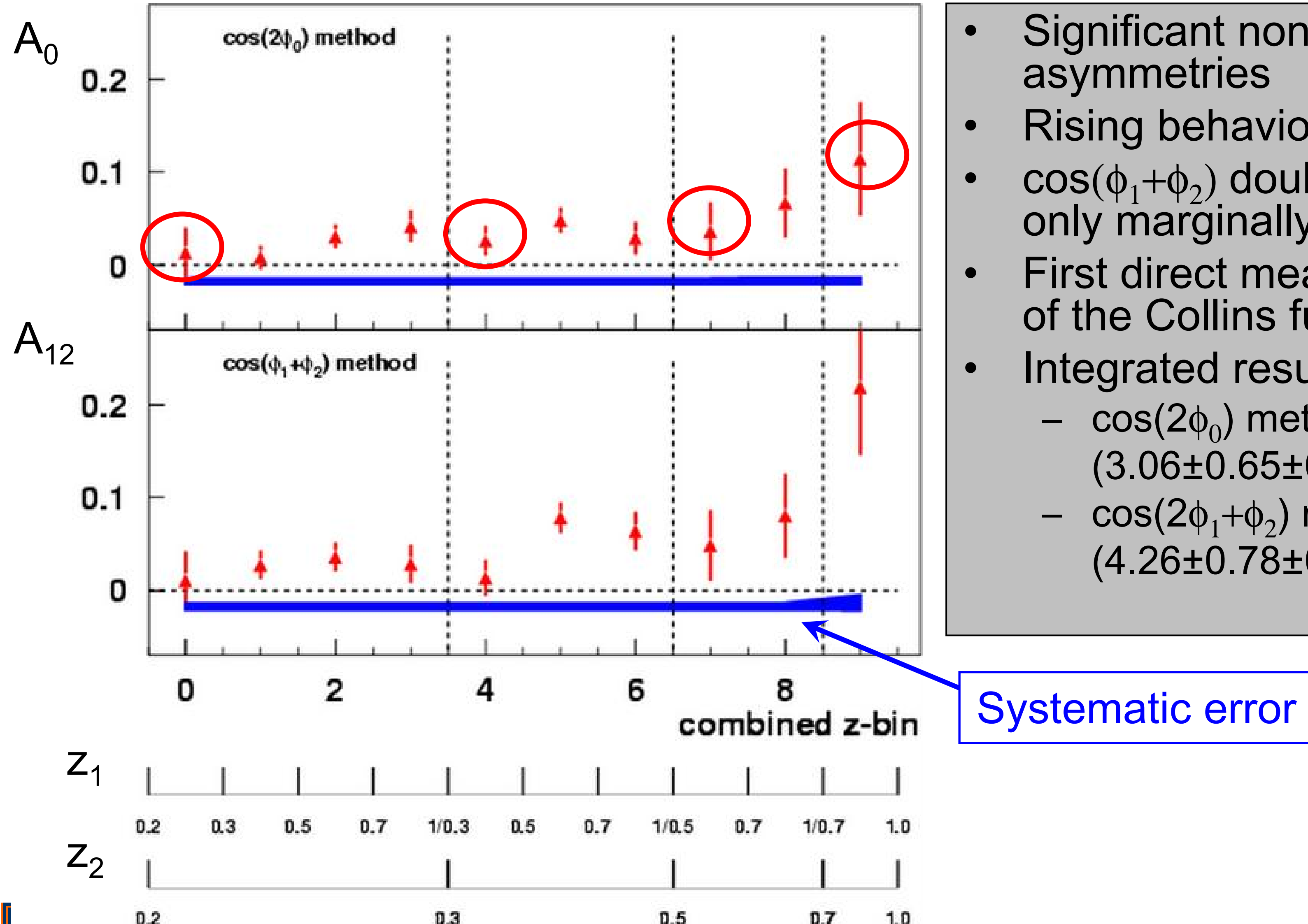
Small double ratios in low thrust data sample



- Low thrust contains radiative effects
- Collins effect vanishes

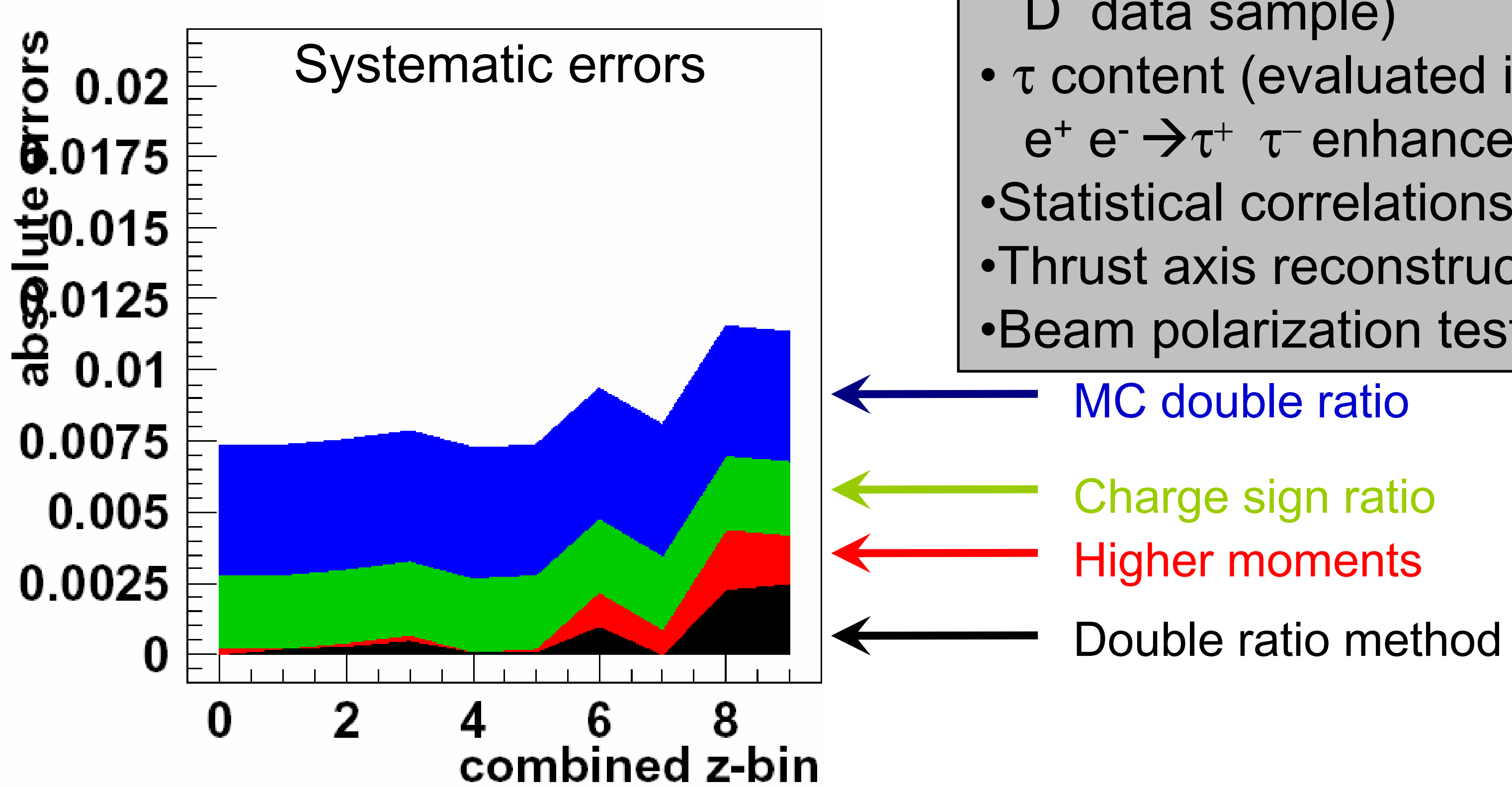
➔Strong experimental indication that double ratio method works

Results for $e^+ e^- \rightarrow \pi \pi X$ for $29 fb^{-1}$



- Significant non-zero asymmetries
- Rising behavior vs. z
- $\cos(\phi_1+\phi_2)$ double ratios only marginally larger
- First direct measurement of the Collins function
- Integrated results:
  - $\cos(2\phi_0)$ method $(3.06\pm0.65\pm0.55)\%$
  - $\cos(2\phi_1+\phi_2)$ method $(4.26\pm0.78\pm0.68)\%$

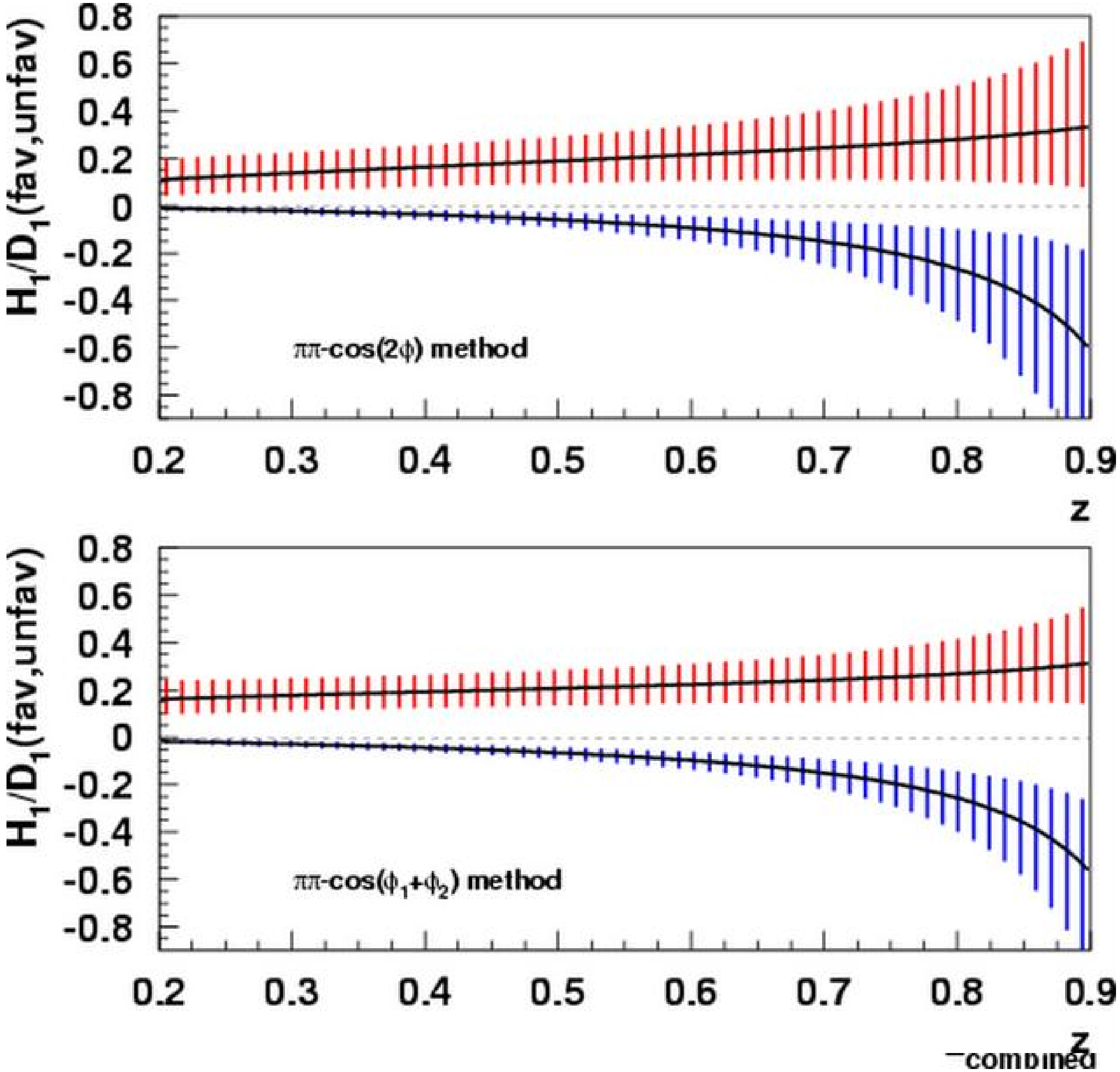
Contributions to systematic errors



Other uncertainties:

- smearing (reweighted MC)
- PID (variation of PID cuts)
- charm contribution (corrected by D^* data sample)
- τ content (evaluated in $e^+ e^- \rightarrow \tau^+ \tau^-$ enhanced sample)
- Statistical correlations
- Thrust axis reconstruction
- Beam polarization tested

An experimentalist's interpretation: fitting parameterizations of the Collins function(s)



- Take unpolarized parameterizations (Kretzer at Q^2=2.5GeV^2)
- Assume
$$H_1^{\perp,fav} = a\ z^b\ (1-z)^c$$
(PDF-like behavior)
- Assume
$$H_1^{\perp,unfav} / H_1^{\perp,fav} = -0.1$$
- Little sensitivity to to favored/disfavored Collins ratio

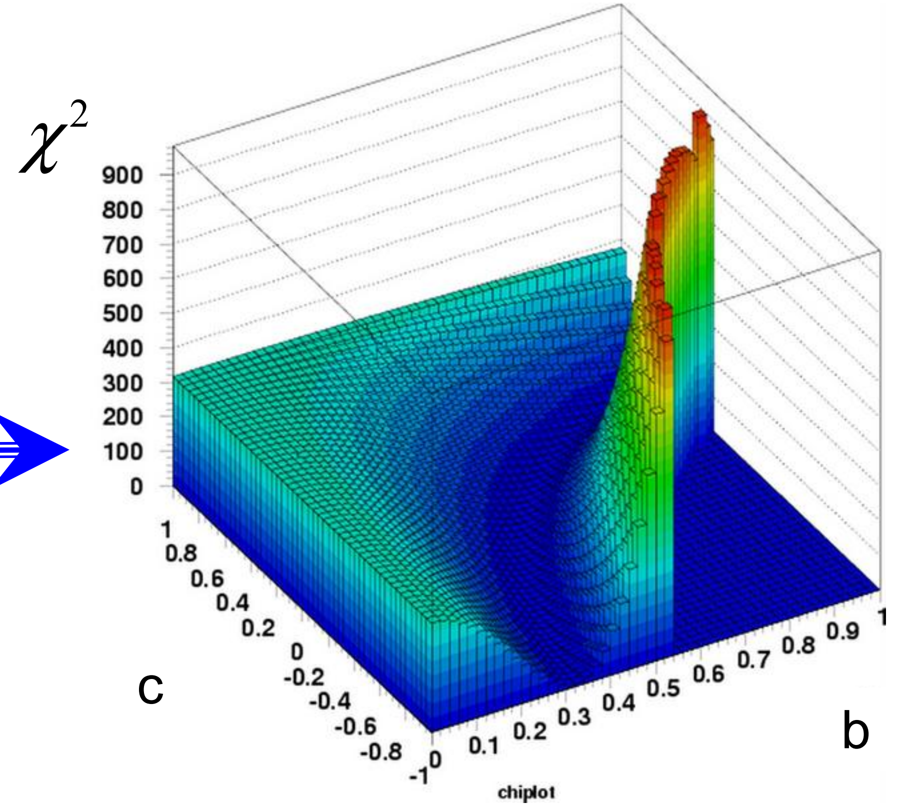
Favored/Disfavored contribution →Sensitivity

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

Take simple parameterization to test sensitivity on favored to disfavored Ratio

$$H_1^{\perp,fav} = bzD_1^{fav}$$

$$H_1^{\perp,unf} = c\cdot bzD_1^{unf}$$



Other Favored/Unfavored Combinations →π^0

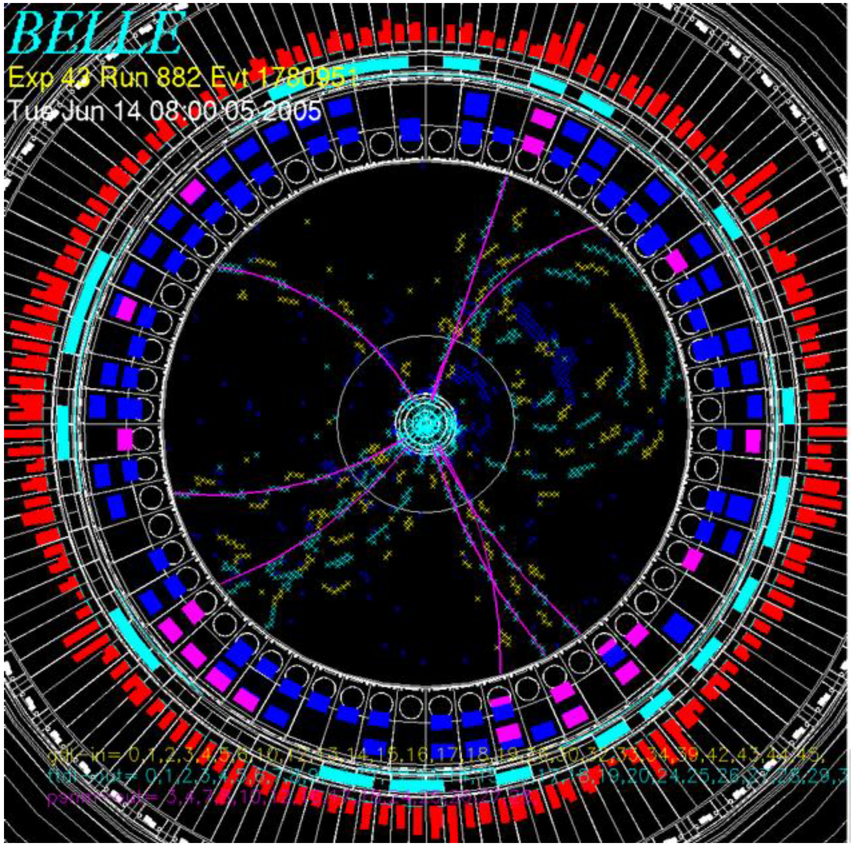
Problem: current double ratios not very sensitive to favored to disfavored Collins function ratio → Examine other combinations:

- Unlike-sign pion pairs:
  (favored x favored +unfavored x unfavored)
- Like-sign pion pairs:
  (favored x unfavored +unfavored x favored)
- $\pi^{\pm}\pi^0$ pairs
  (favored + unfavored) x (favored + unfavored)
- P.Schweitzer([hep-ph/0603054]): charged $\pi\pi$ pairs are similar (and are easier to handle):
  (favored + unfavored) x (favored + unfavored)

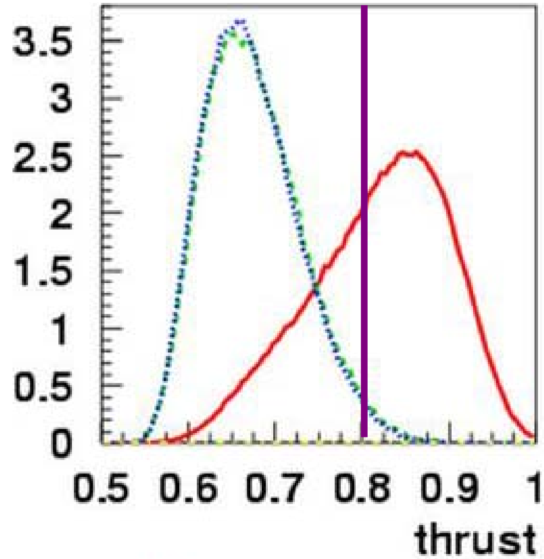
→ Build new double ratios

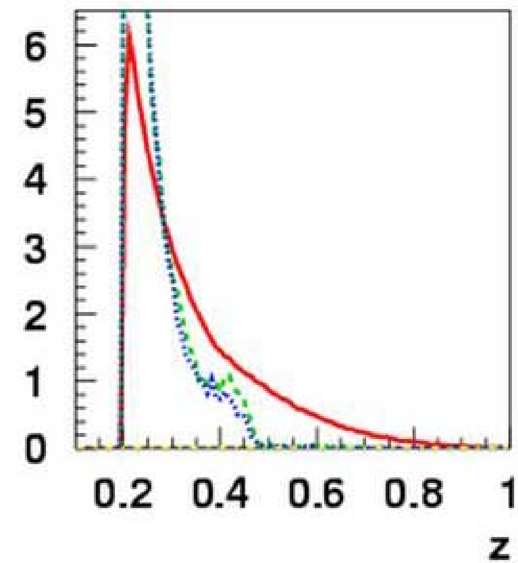
Favored	= u→π^+,d→π^-,cc.
Unfavored	= d→π^+,u→π^+,cc.

Why is it possible to include on_resonance data? Different Thrust distributions



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

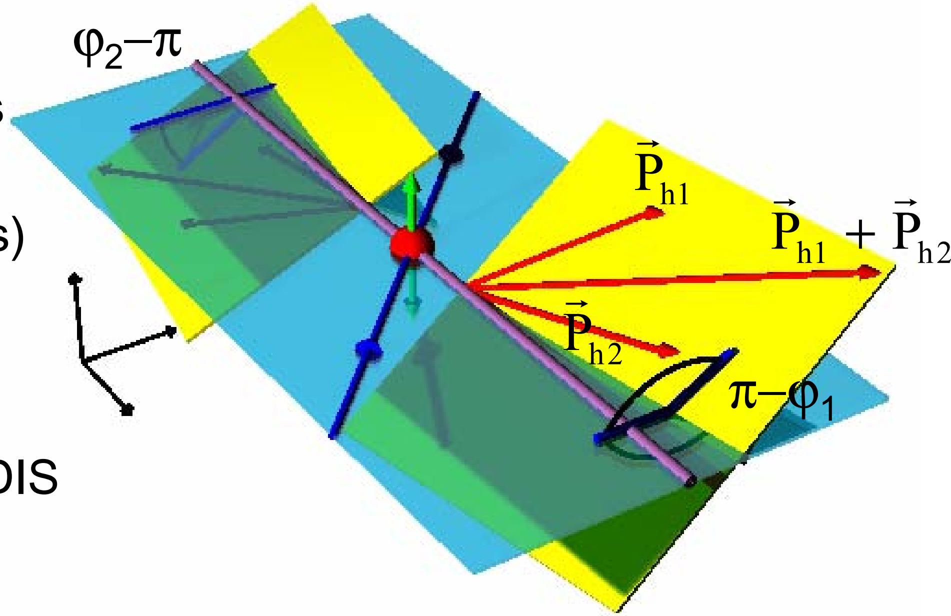




- $e^+ e^- \rightarrow q \bar{q}$ (q in uds) MC
- Υ(4S) → $B^+ B^-$ MC
- Υ(4S) → $B^0 \bar{B}^0$ MC

Interference Fragmentation – thrust method

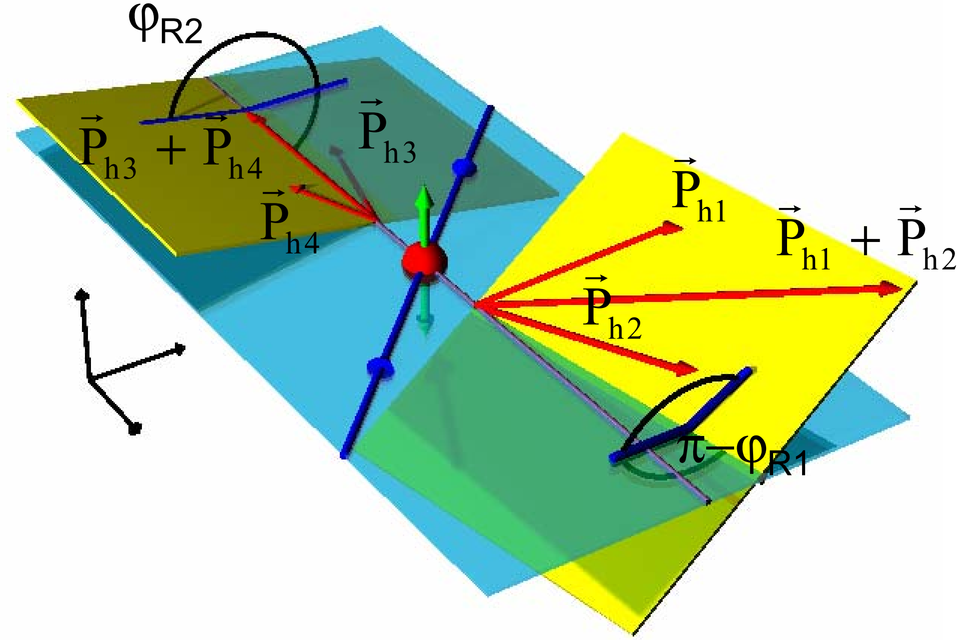
- $e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^-\pi^+)_{jet2}X$
- Stay in the mass region around ρ-mass
- Find pion pairs in opposite hemispheres
- Observe angles $\varphi_1+\varphi_2$ between the event-plane (beam, jet-axis) and the two two-pion planes.
- Transverse momentum is integrated (universal function, evolution easy → directly applicable to semi-inclusive DIS and pp)
- Theoretical guidance by papers of Boer,Jakob,Radici and Artru,Collins



$$A \propto H_1^{\angle}(z_1, m_1)\overline{H}_1^{\angle}(z_2, m_2)\cos(\varphi_1 + \varphi_2)$$

Interference Fragmentation – " ϕ_0 " method

- Similar to previous method
- Observe angles $\varphi_{1R}+\varphi_{2R}$ between the event-plane (beam, two-pion-axis) and the two two-pion planes.
- Theoretical guidance by Boer,Jakob,Radici



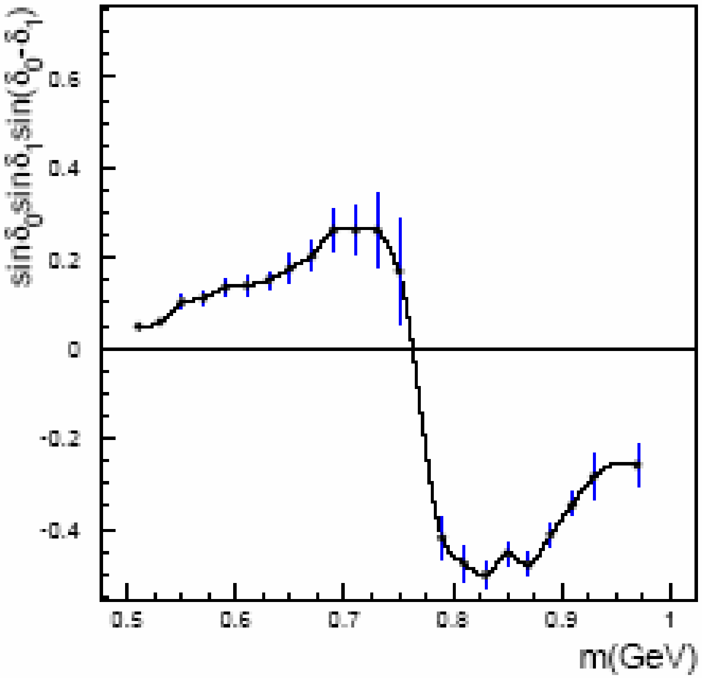
$$A \propto H_1^{\angle}(z_1, m_1)\overline{H}_1^{\angle}(z_2, m_2)\cos(\varphi_{1R} + \varphi_{2R})$$

Different model predictions for IFF

- Jaffe at al. [Phys. Rev. Lett. **80** (1998)] : inv. mass behavior out of ππ-phaseshift analysis⇨sign change at ρ–mass

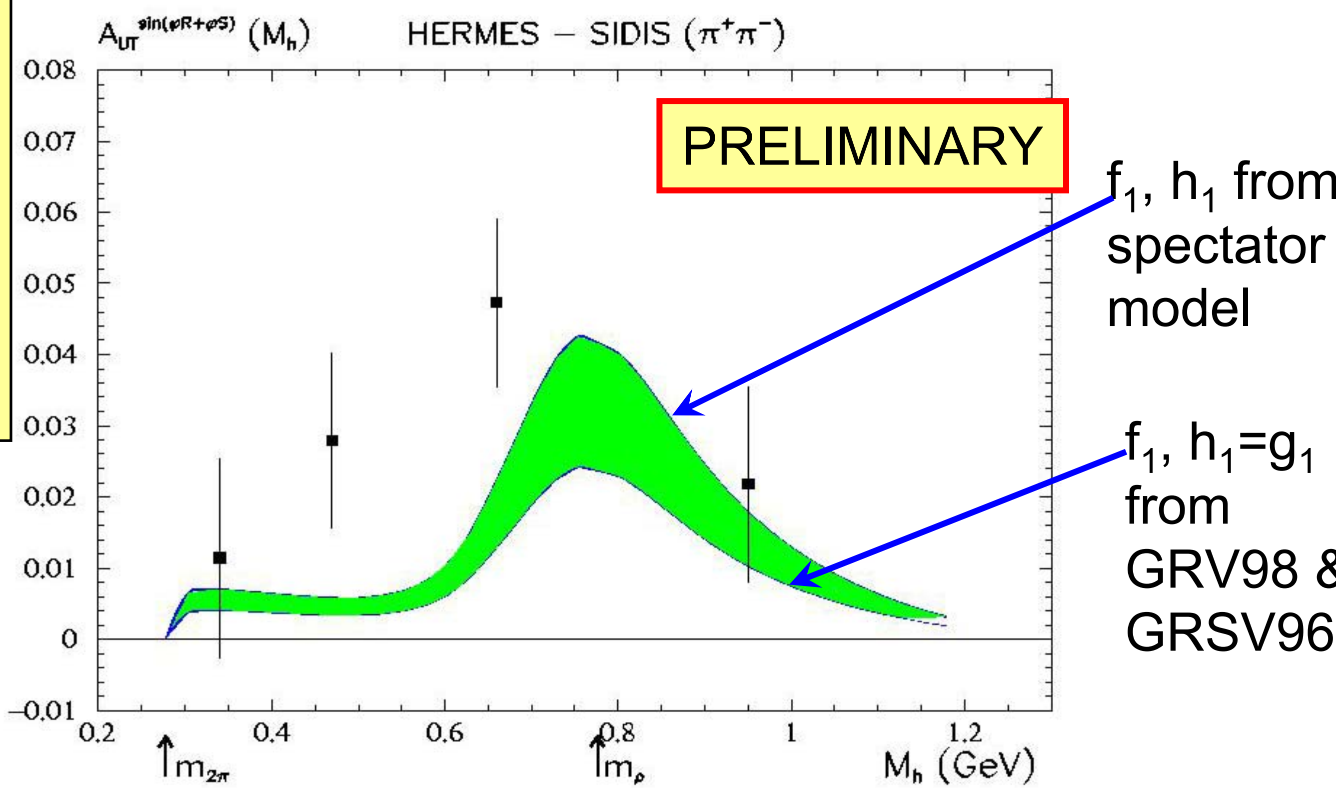
-originally no predictions on actual magnitudes

-Tang included some for RHIC-Spin



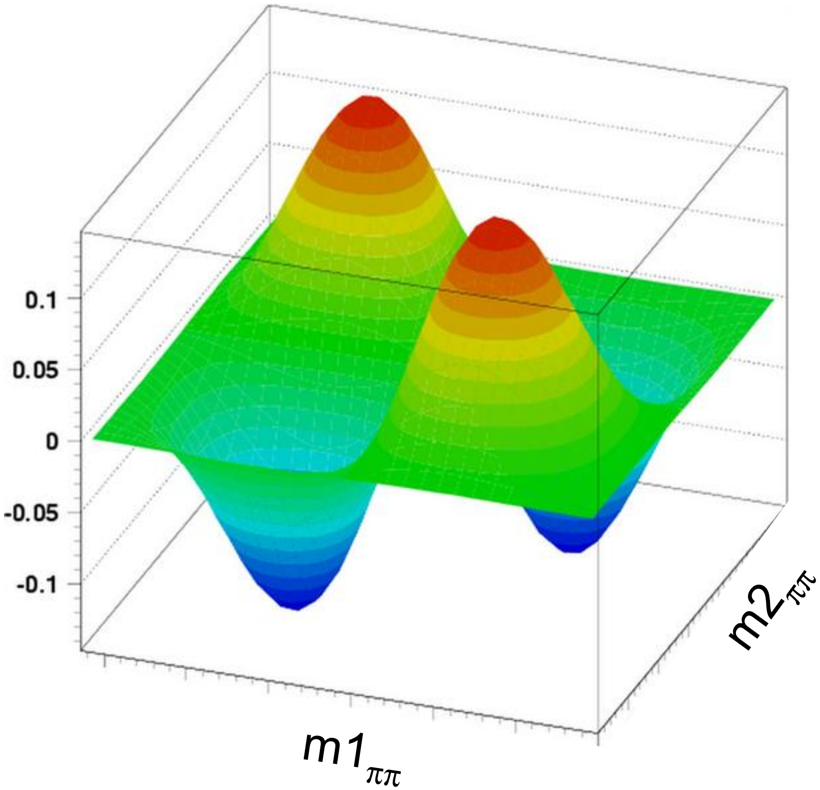
Different model predictions for IFF

- Radici et al. [Phys. Rev. **D65** (2002)] : Spectator model in the s-p channel ⇨ no sign change observed (updated model has Breit-Wigner like asymmetry)

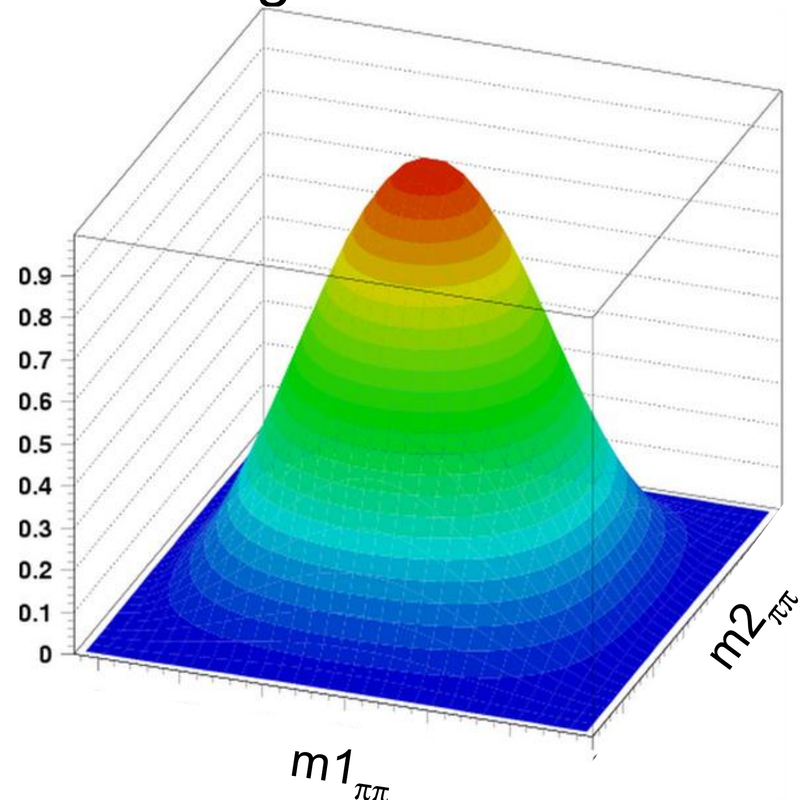


What would we see?

Simply modeled the shapes of these predictions in an equidistant Mass1 x Mass2 binning

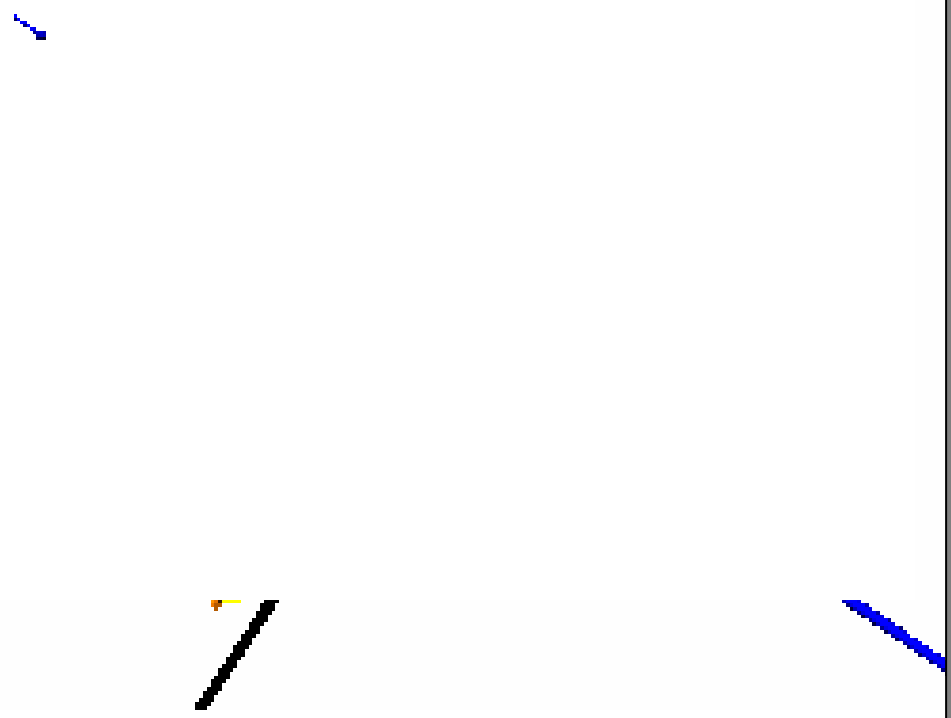


“Jaffe”



“Radici”

What do we see? I: events



- Animation of an event
- lepton tracks, thrust axis and all particle momenta in the CMS frame
- $P_{h1}=P_1+P_2$
- $P_{h2}=P_3+P_4$
- Plane defined by leptons and thrust
- Planes defined by hadron pairs

Summary and outlook

Summary:

- Double ratios:
  - double ratios from data
  - most systematic errors cancel
- Analysis procedure passes all null tests
- Main systematic uncertainties understood
- ➔ Significant nonzero asymmetry with double ratios are observed
- Naive LO analysis shows significant Collins effect
- Data can be used for more sophisticated analysis
- Paper (hep-ex/0507063) is submitted

Outlook:

- On resonance →10 x statistics
- Include π^0 and all charged $\pi\pi$ pairs into analysis:
  - ➔ Better distinction between favored and disfavored Collins function
- Interference fragmentation function analysis started
  - First look promising
- Include Vector Mesons into analysis:
  - ➔ Possibility to test string fragmentation models used to describe Collins effect
- Timelike DVCS at Belle?

Outline

- Motivation
  - Study transverse spin effects in fragmentation
  - Global transversity analysis
  - Feasibility → LEP analysis [hep-ph/9901216]
- The BELLE detector
- Collins analysis
  - Angular definitions and cross sections
  - Double Ratios to eliminate radiative/momentum correlation effects
  - An experimentalist's interpretation
- Summary

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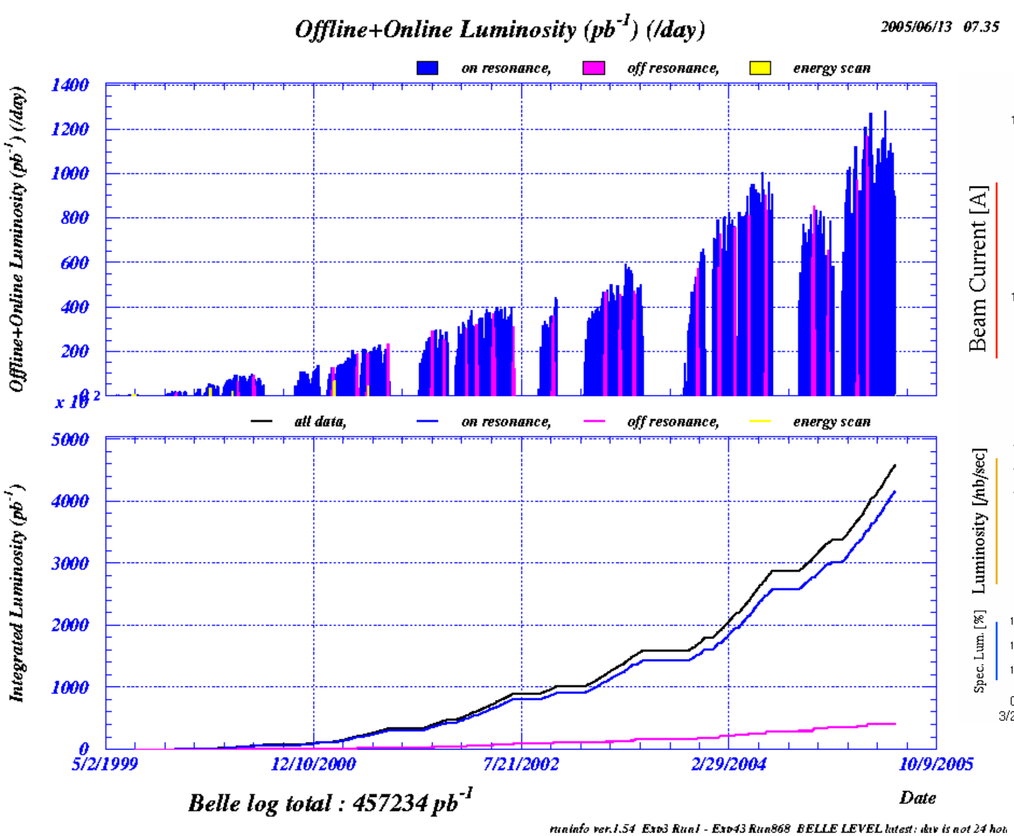

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2005/06/13 07.35
on resonance, off resonance, energy scan
Offline+Online Luminosity (pb-1) (/day)
x 10 2
all data, on resonance, off resonance, energy scan
Integrated Luminosity (pb-1)
5/2/1999
12/10/2000
7/21/2002
2/29/2004
10/9/2005
Belle log total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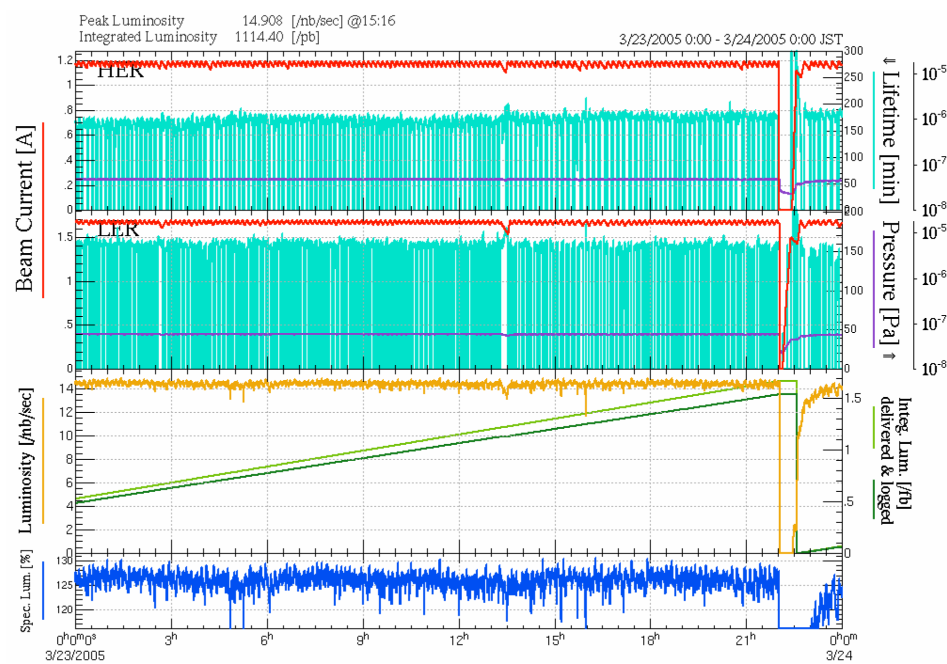

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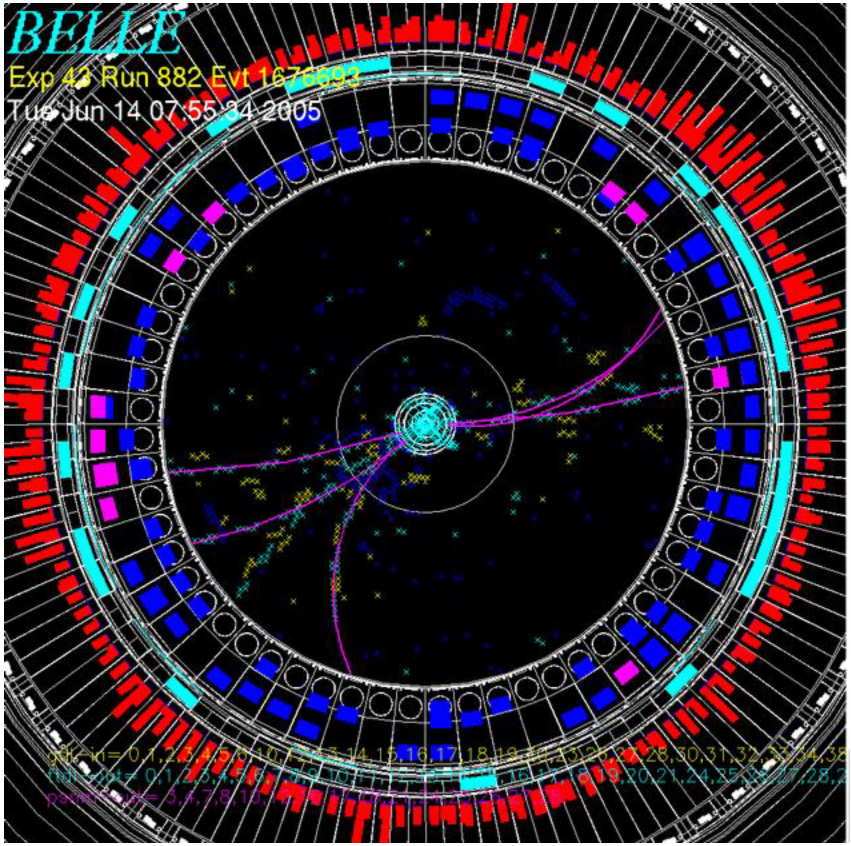
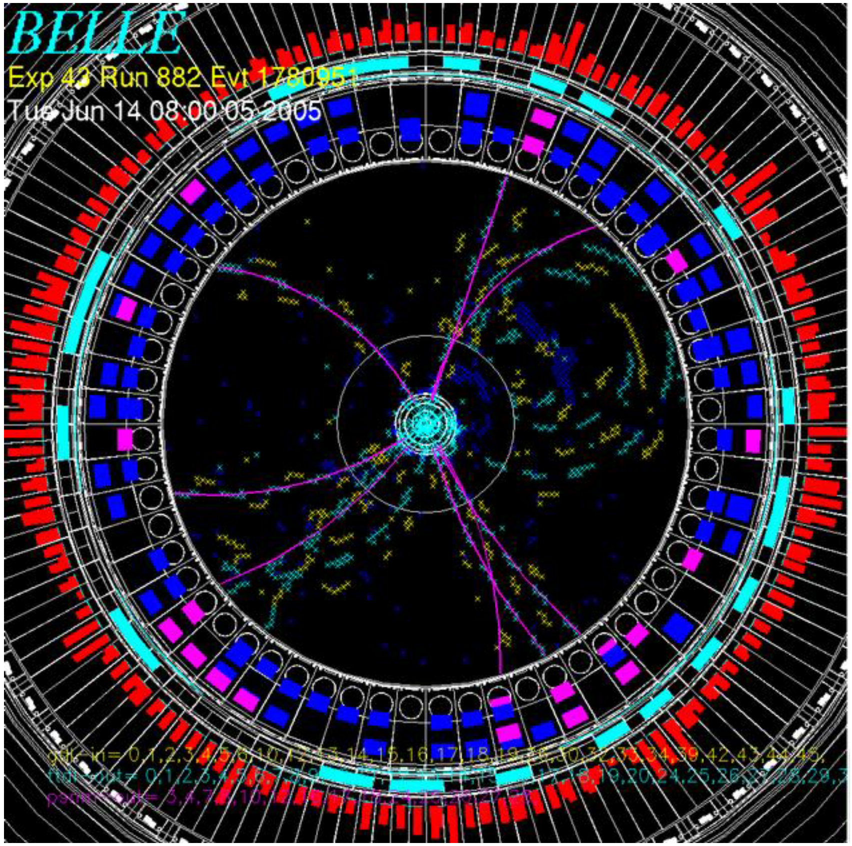
Typical hadronic events at Belle

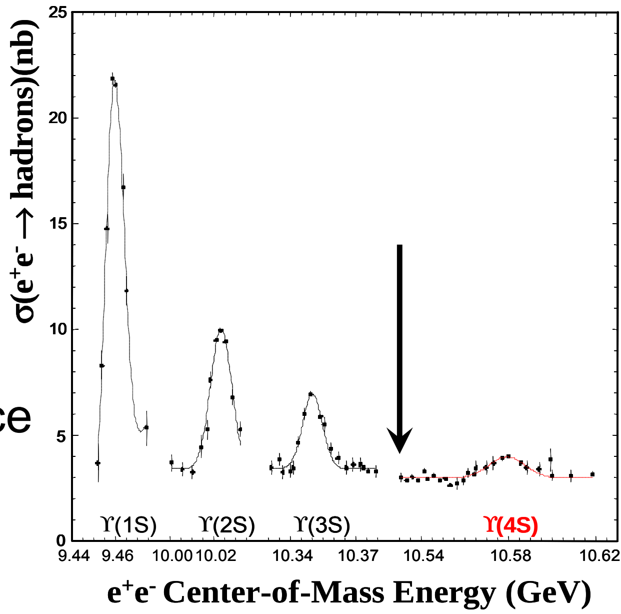




$$\text{thrust} = \frac{\sum_i |p_i \cdot \hat{n}|}{\sum_i |p_i|}$$

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 GeV*^{2})
  - can apply pQCD
  → Not too high energy ($Q^2 << M_Z^2$)
  -avoids additional complication from Z interference
- Sensitivity = A^2*sqrt(N)* ~ x19 *(60)* compared to LEP
  A_{Belle} / A_{LEP} ~ x2 (*A* scales as *ln* Q^2)
  L_{Belle} / L_{LEP} ~ x23 *(230)*

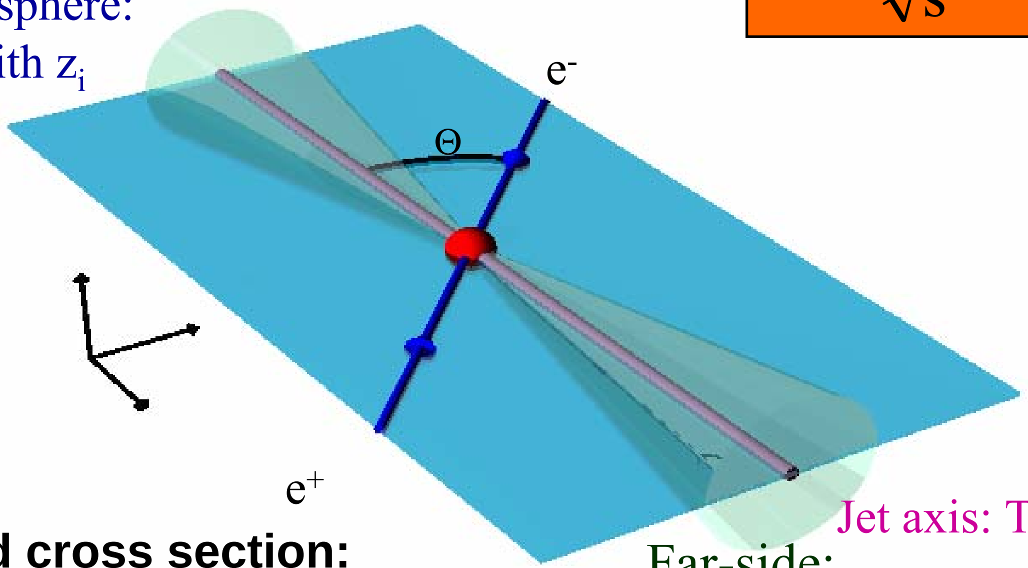


Event Structure at Belle

e⁺e⁻ CMS frame:

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

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:

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

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

What is the transverse momentum Q_T of the virtual photon?

- In the lepton CMS frame

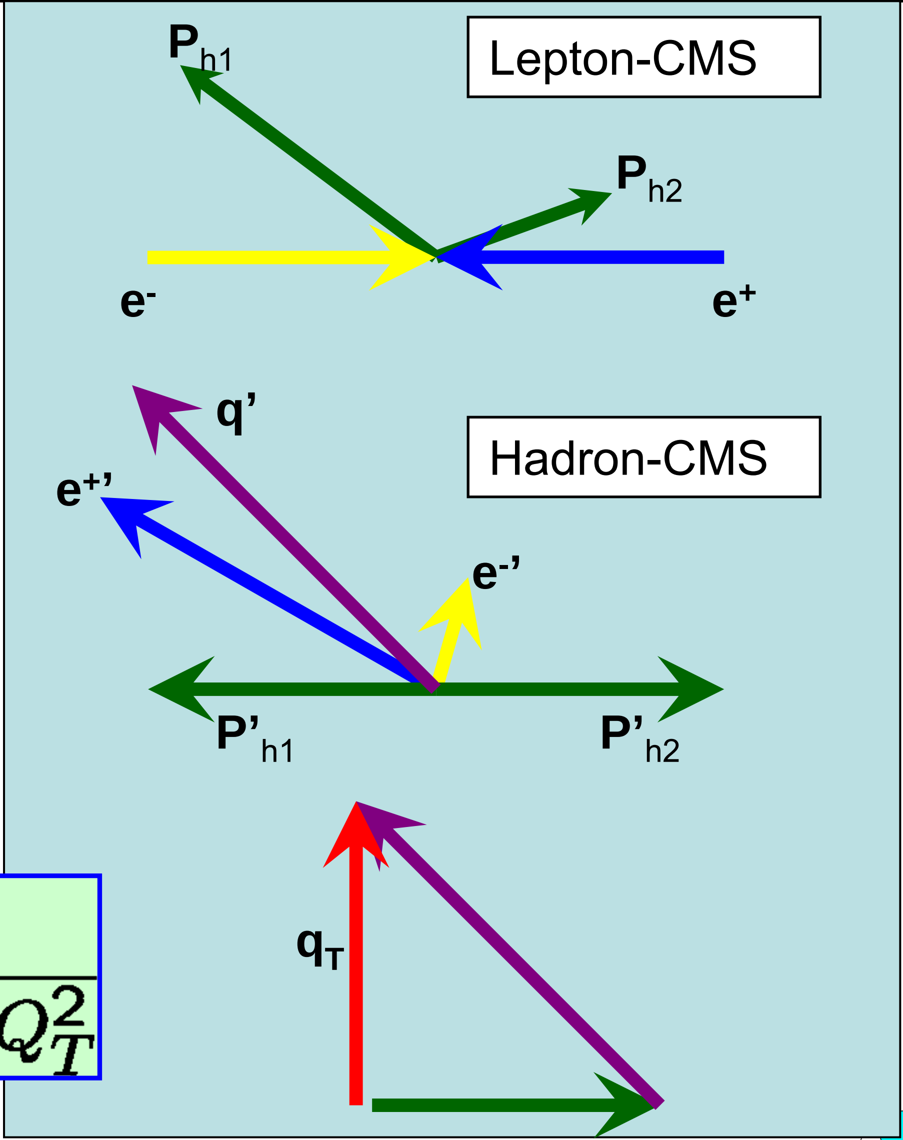
  $e^- = -e^+$ and the virtual photon is only time-like:

  $q^\mu = (e^{-\mu} + p^{+\mu}) = (Q,0,0,0)$
- Radiative (=significant BG) effects are theoretically best described in the hadron CMS frame where

  $P_{h1} + P_{h2} = 0$

  $\rightarrow q^{\mu\prime} = (q'_0, \mathbf{q}')$
- Inclusive Cross section for radiative events (acc. to D.Boer):

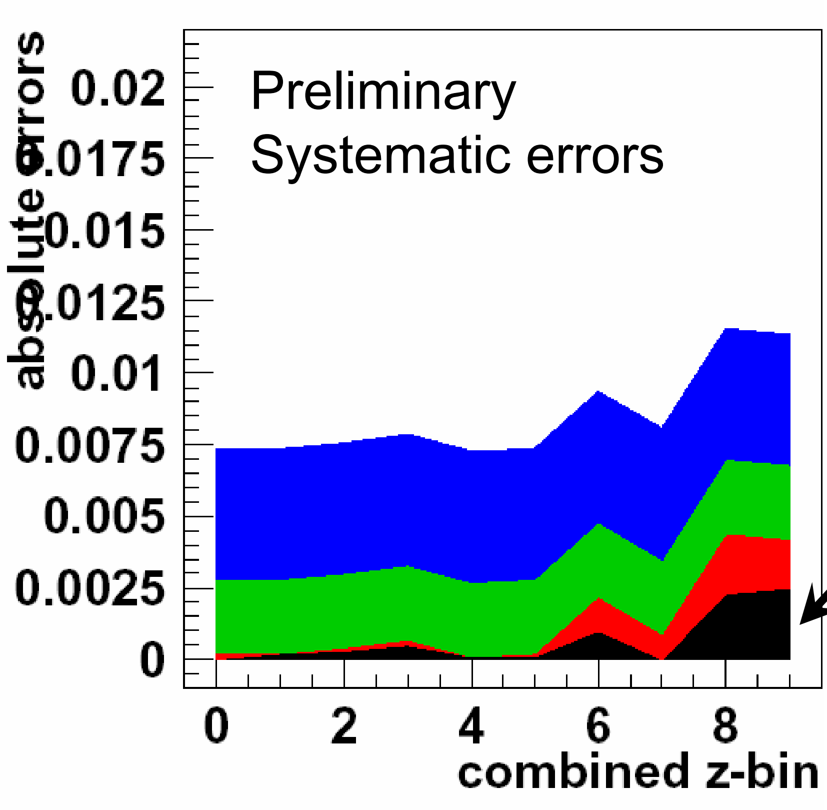
$$\frac{dN}{d\Omega} \propto \sin^2\theta \cos(2\phi_0) \frac{Q_T^2}{Q^2 + Q_T^2}$$



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($2\phi_{Lab}$) 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

Double Ratio vs Subtraction Method:



R – S < 0.002

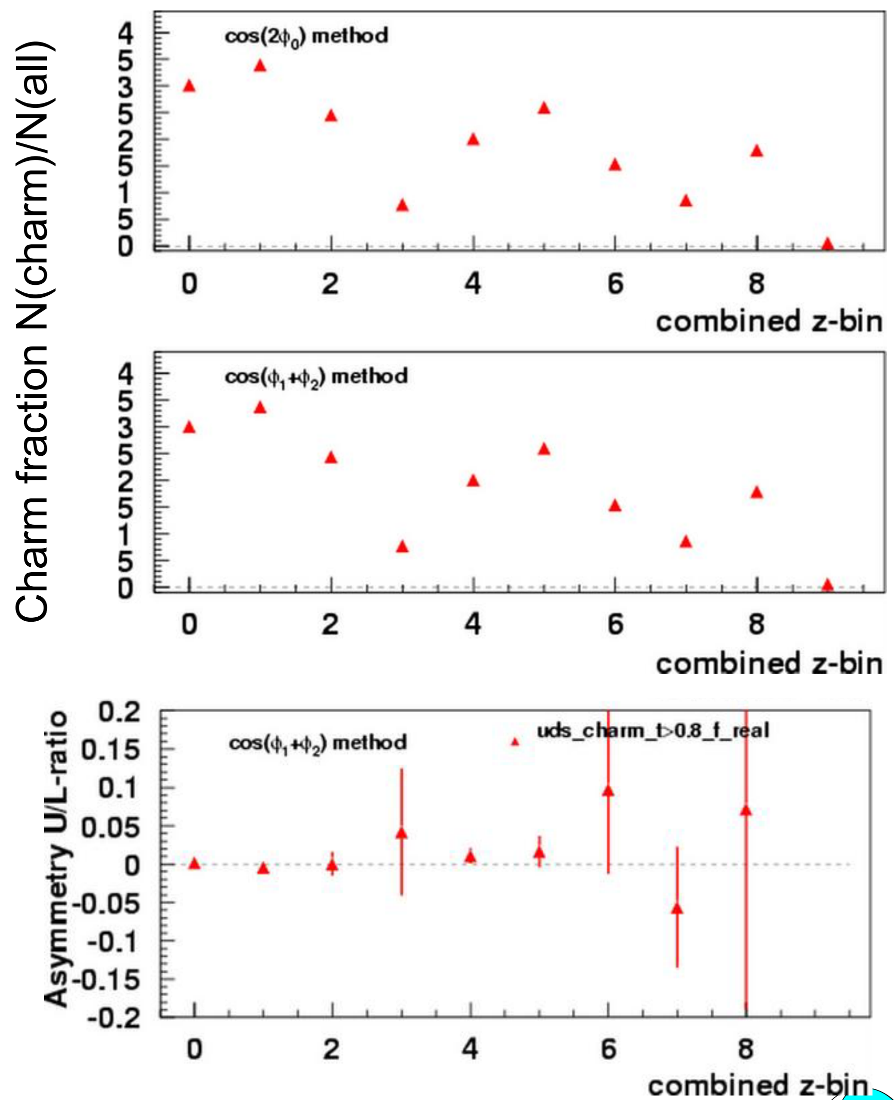
➔ The difference was assigned as a systematic error.

Systematics: charm contribution?

- Weak (parity violating) decays could also create asymmetries (seen in $\tau\ \bar{\tau} \rightarrow \pi\pi\nu\ \bar{\nu}$, overall τ dilution 5%)
- Especially low dilution in combined z-bins with large pion asymmetry
- Double ratios from charm MC compatible to zero

➔ Charm decays cannot explain large double ratios seen in the data

➔ Charm enhanced D^* Data sample used to calculate and correct the charm contribution to the double ratios (see hep-ex/0507063 for details)



Different charge combinations
→ additional information

- Unlike sign pairs contain either only favored or only unfavored fragmentation functions on quark and antiquark side:

$$D_1^{fav}(z_1)\overline{D_1^{fav}(z_2)} + D_1^{unfav}(z_1)\overline{D_1^{unfav}(z_2)}$$

- Like sign pairs contain one favored and one unfavored fragmentation function each:

$$D_1^{fav}(z_1)\overline{D_1^{unfav}(z_2)} + D_1^{unfav}(z_1)\overline{D_1^{fav}(z_2)}$$

Favored = $u \to \pi^+, d \to \pi^-$, cc.

Unfavored = $d \to \pi^+, u \to \pi^+$, cc.

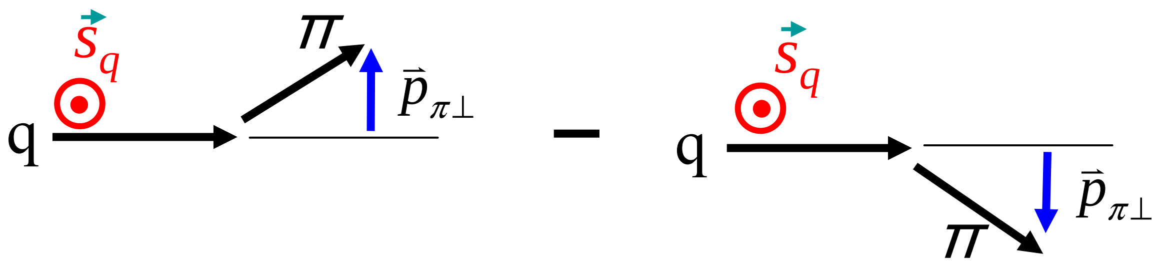
$$\frac{N(\phi)}{N_0} = \frac{aD_1\overline{D_1} + \cos(2\phi)\left(bH_1\overline{H_1} + cD_1\overline{D_1}\right)}{aD_1\overline{D_1}}$$

$$\frac{N(\phi)}{N_0} = 1 + \cos(2\phi)\left(\frac{bH_1\overline{H_1}}{aD_1\overline{D_1}} + c/a\right)$$

Collins Effect

$$A_T = \frac{N_L - N_R}{N_L + N_R} \neq 0\ !$$

N_L : pions to the left



N_R : pions to the right

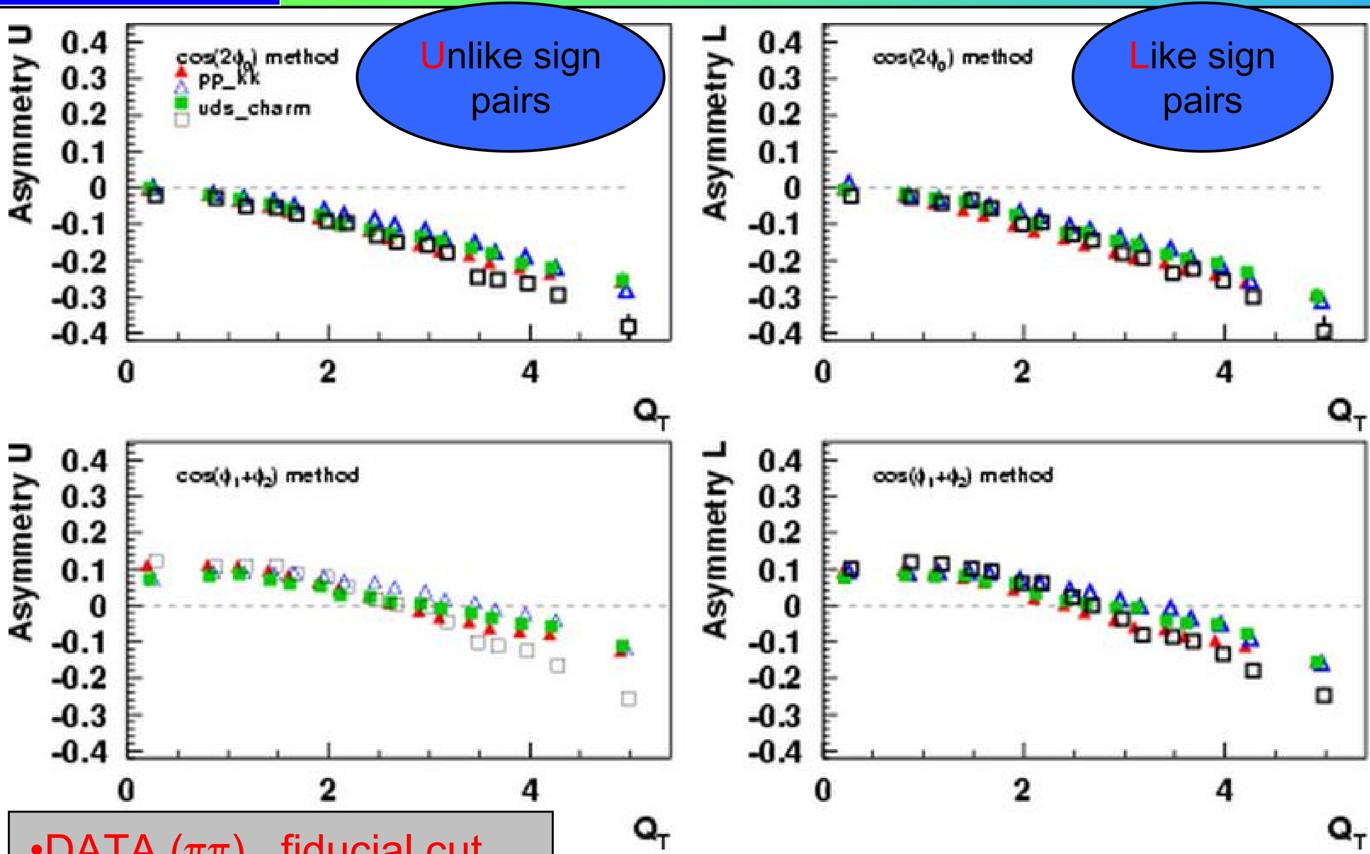
General Fragmentation Functions

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

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

unpolarized FF **Collins FF**

Raw asymmetries vs transverse photon momentum Q_T



- DATA (ππ) fiducial cut
- DATA (KK) fiducial cut
- UDS-MC fiducial cut
- CHARM-MC fiducial cut

- Already MC contains large asymmetries
- Strong dependence against transverse photon Momentum Q_T
- Expected to be due to radiative effects
- Difference of DATA and MC is signal

➔not so easy to determine