

# Light quark and spin dependent fragmentation function measurements at Belle

## Outline:

- The Belle detector

Fragmentation workshop,  
Trento, February 26, 2008

- unpolarized fragmentation function measurements

- Understanding the systematics for precision measurements at high z  
M. Grosse Perdekamp

- Expected precision (University of Illinois)

- The Collins function measurements M. Ellinghaus (University of Illinois)

- Access to transversity over Collins fragmentation function

- Collins function measurements R. Szczerba (RBC/INR)

- Interference fragmentation function measurements

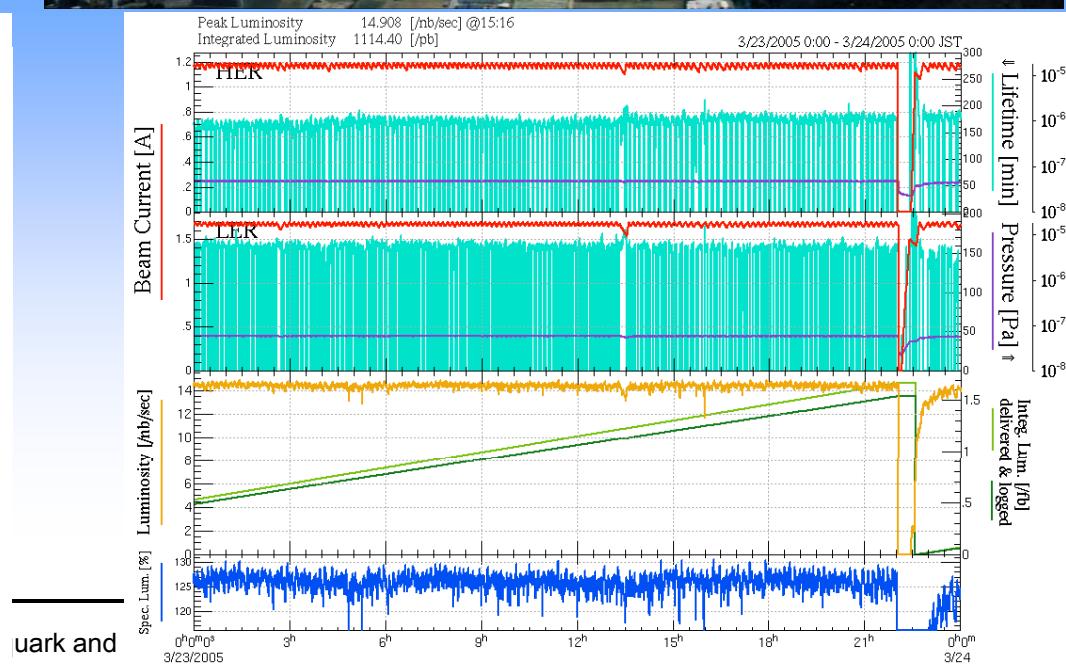
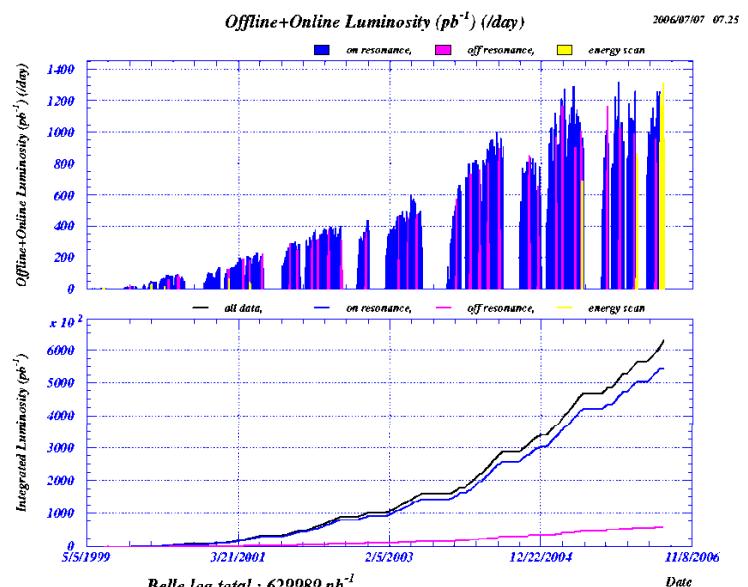
representing the Belle collaboration





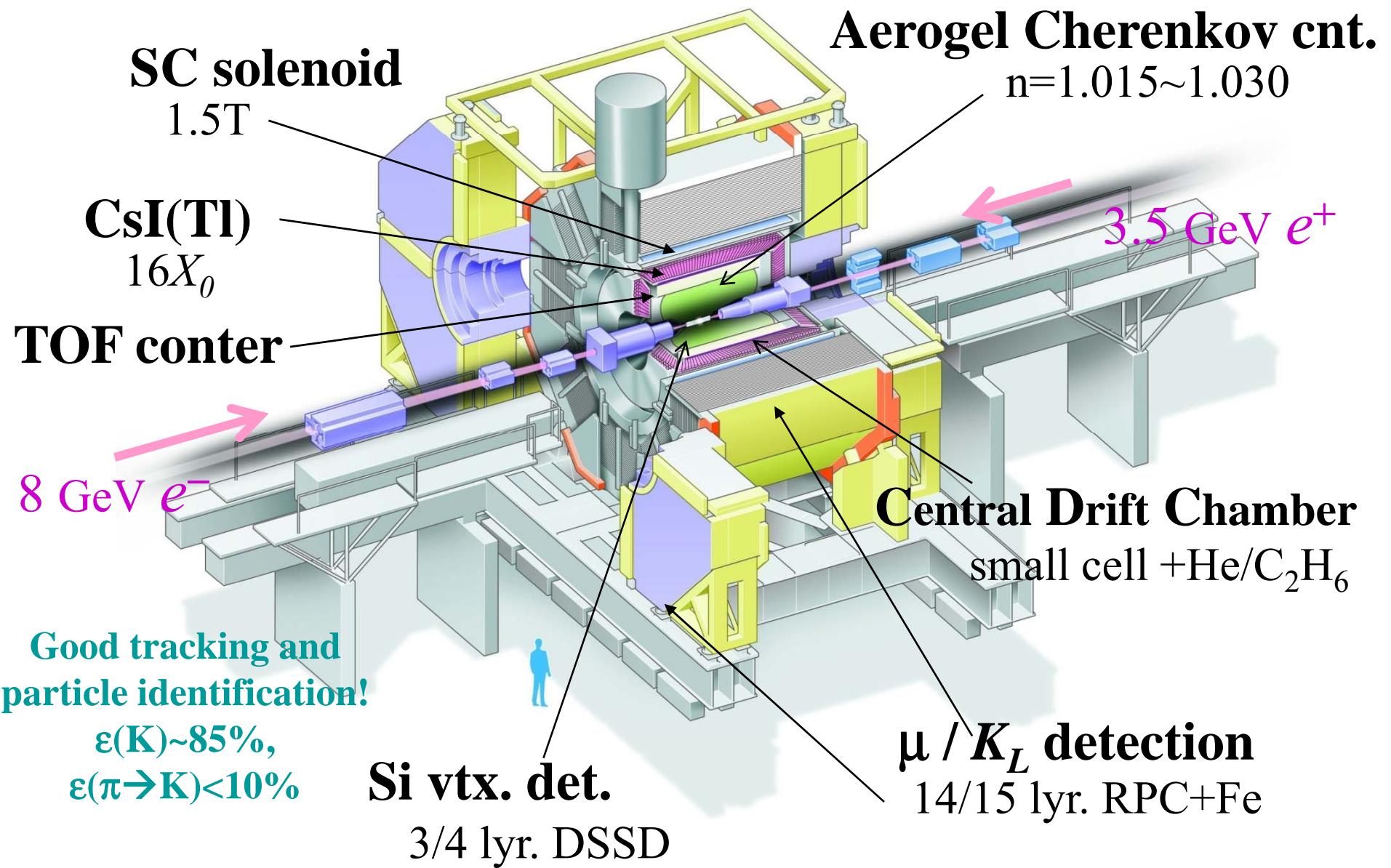
# KEKB: $L > 1.7 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$ !!

- Asymmetric collider
- 8GeV  $e^- + 3.5\text{GeV } e^+$
- $\sqrt{s} = 10.58\text{GeV (Y(4S))}$
- $e^+e^- \rightarrow Y(4S) \rightarrow B \bar{B}$
- Continuum production:  
10.52 GeV
- $e^+e^- \rightarrow q \bar{q}$  (u,d,s,c)
- Integrated Luminosity:  $> 700 \text{ fb}^{-1}$
- $> 60\text{fb}^{-1} \Rightarrow$  continuum



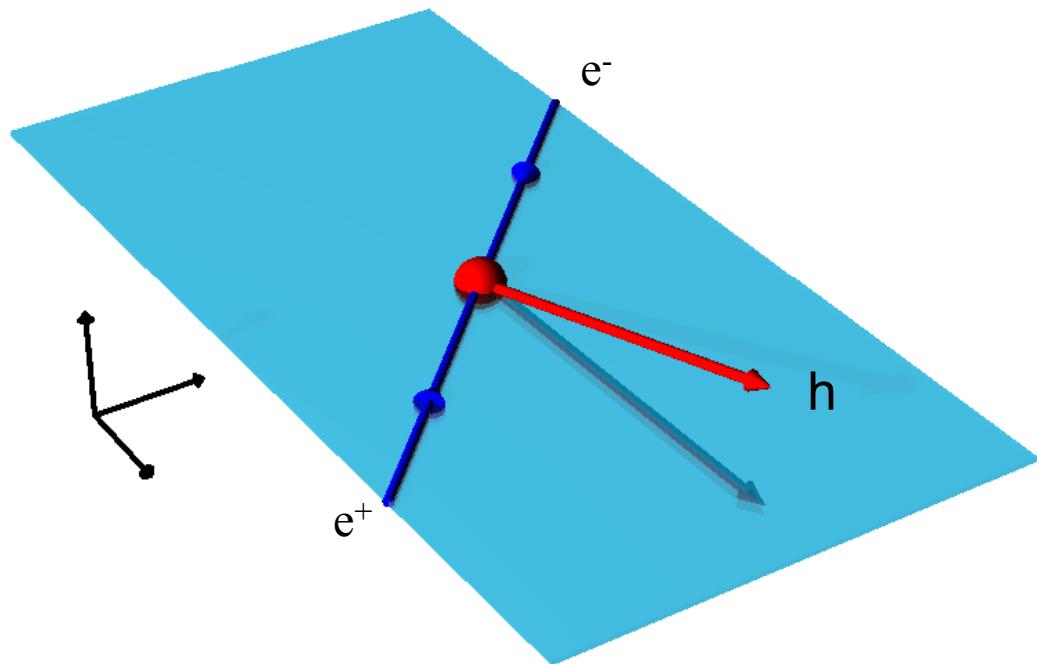
uark and

# Belle Detector





# Single hadron cross section



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

- Process:  
 $e^+ e^- \rightarrow hX$
- At leading order sum  
of unpolarized  
fragmentation  
functions from quark  
and anti-quark side

$$\text{LO } F^h(z, s) = \frac{\sum_q e_q^2 [D_q^h(z) + D_{\bar{q}}^h(z)]}{\sum_q e_q^2}$$

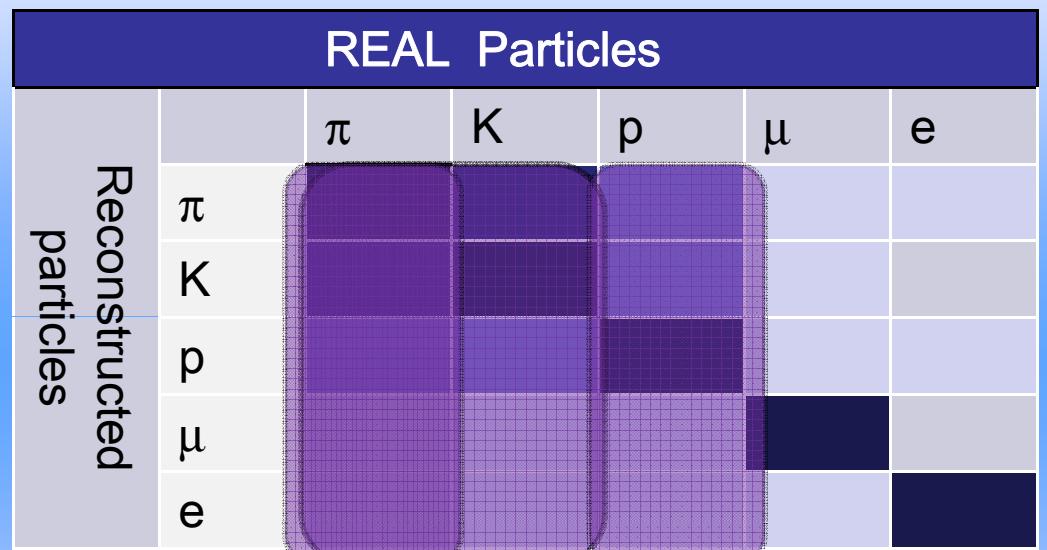
$$\text{NLO } F^h(z, s) = \sum_i \int_z^1 \frac{dz'}{z'} C_i(s; z' \alpha_s) D_q^h(z)$$





# Systematic studies

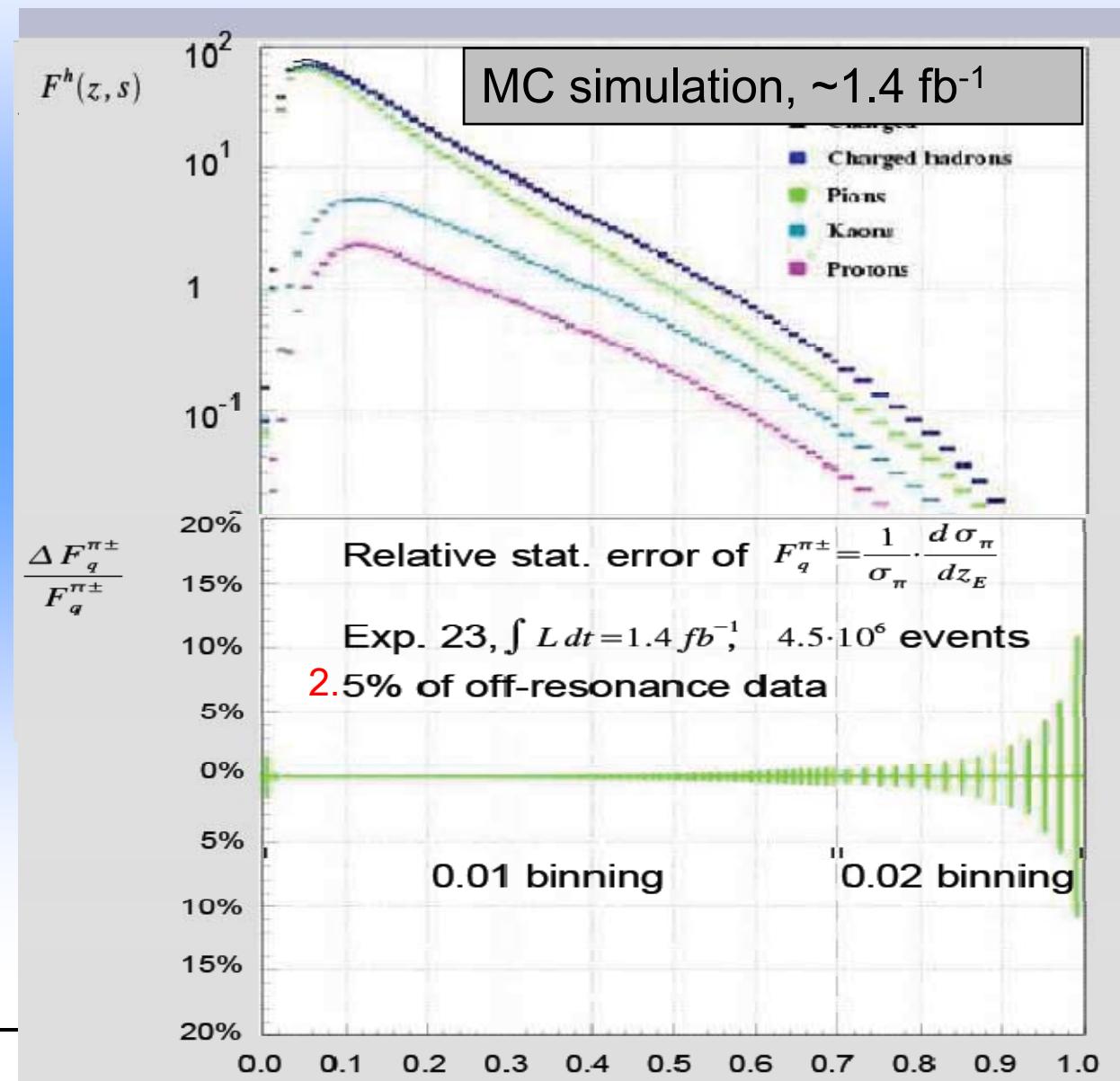
- Momentum scale and smearing – understood
- Particle identification:  
create PID efficiency matrix for K,π,p,e,μ  
→ Unfolding
  - Use  $D^* \rightarrow \pi D^0 \rightarrow \pi\pi K$  for K,π identification
  - Use  $\Lambda \rightarrow \pi P$  for P,π identification
- Acceptance correction





# Unpolarized FF as important input for all precise QCD measurements

- Statistics limited at low- $Q^2$  and high- $z$   
→ important for evolution
- Huge amount of Belle data can help
- Student working on unpol. FF extraction
- Favored/Disfavored disentangling by detecting hadron pairs (as in Collins analysis)?
- Also plans to measure  $\eta$  and  $\gamma$



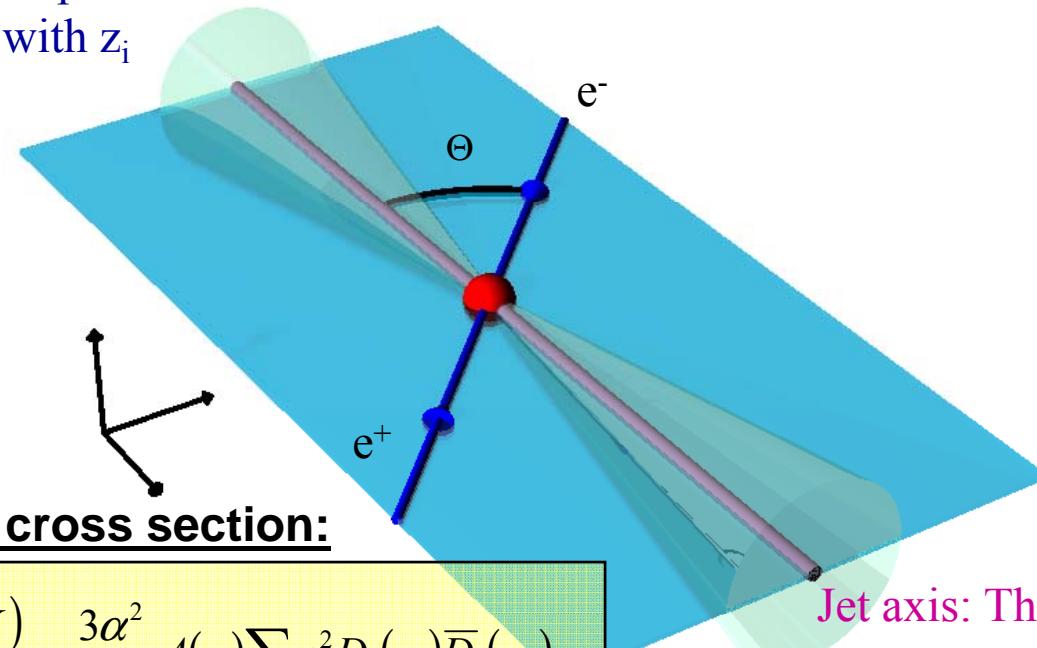


# Event Structure for Hadron pairs

e<sup>+</sup>e<sup>-</sup> CMS frame:

Near-side Hemisphere:

$h_i, i=1, N_h$  with  $z_i$



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

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

**Spin averaged cross section:**

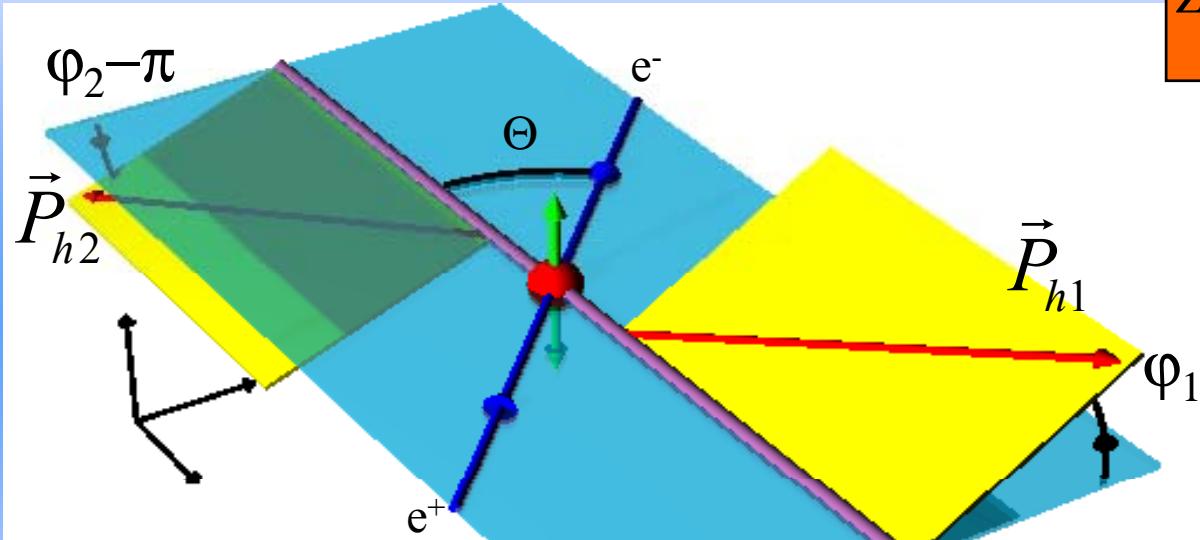
$$\frac{d\sigma(e^+e^- \rightarrow h_1h_2X)}{d\Omega dz_1dz_2} = \frac{3\alpha^2}{Q^2} A(y) \sum_{a,\bar{a}} e_a^2 D_1(z_1) \bar{D}_1(z_2)$$

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

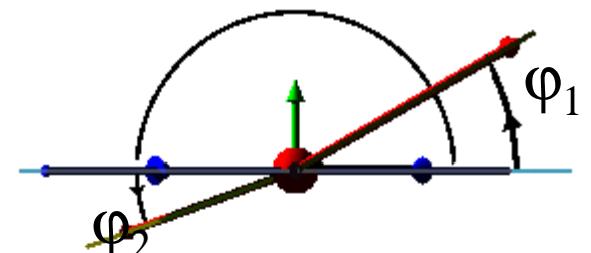


# Collins fragmentation in $e^+e^-$ : Angles and Cross section $\cos(\phi_1 + \phi_2)$ method

$e^+e^-$  CMS frame:



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



[D.Boer: PhD thesis(1998)]

2-hadron inclusive transverse momentum dependent cross section:

$$\frac{d\sigma(e^+e^- \rightarrow h_1 h_2 X)}{d\Omega dz_1 dz_2 d^2 q_T} = \dots B(y) \cos(\phi_1 + \phi_2) H_1^{\perp[1]}(z_1) \bar{H}_1^{\perp[1]}(z_2)$$

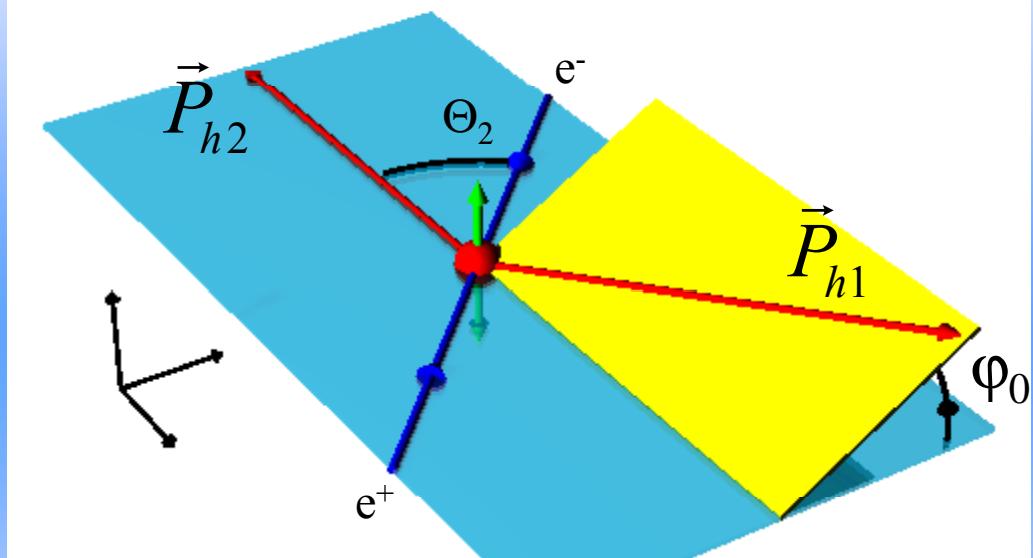
$$B(y) = y(1-y)^{\text{cm}} = \frac{1}{4} \sin^2 \Theta$$

Net (anti-)alignment of  
transverse quark spins



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

$e^+e^-$  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:

$$\frac{d\sigma(e^+e^- \rightarrow h_1 h_2 X)}{d\Omega dz_1 dz_2 d^2 q_T} = \dots B(\Theta) \cos(2\phi_0) I \left[ (2\hat{h} \cdot k_T \hat{h} \cdot p_T - k_T \cdot p_T) \frac{H_1^\perp \bar{H}_1^\perp}{M_1 M_2} \right]$$

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

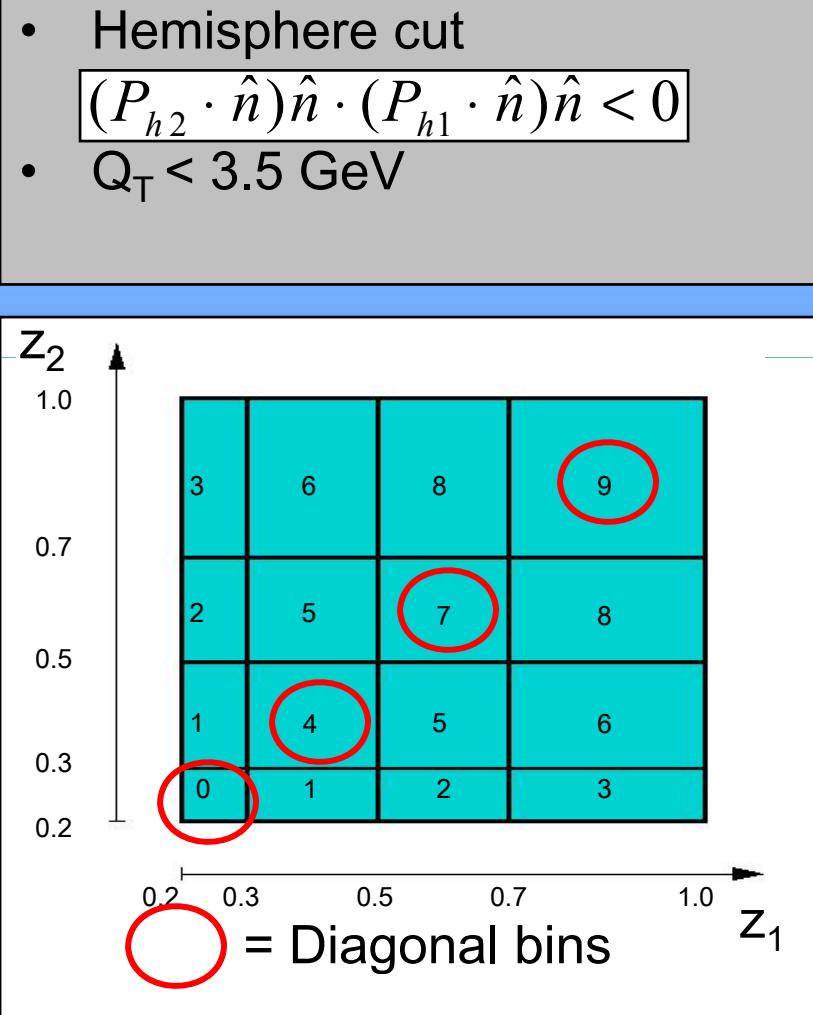
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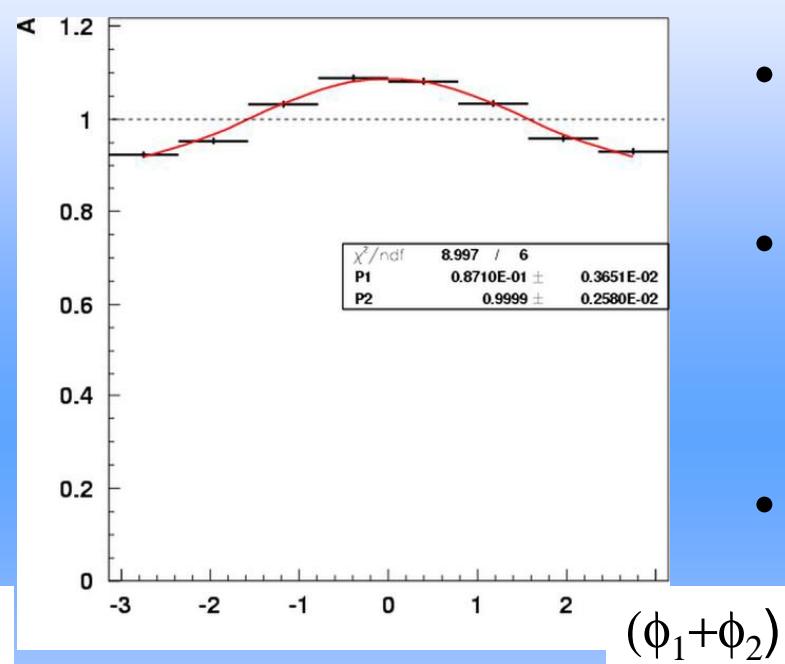
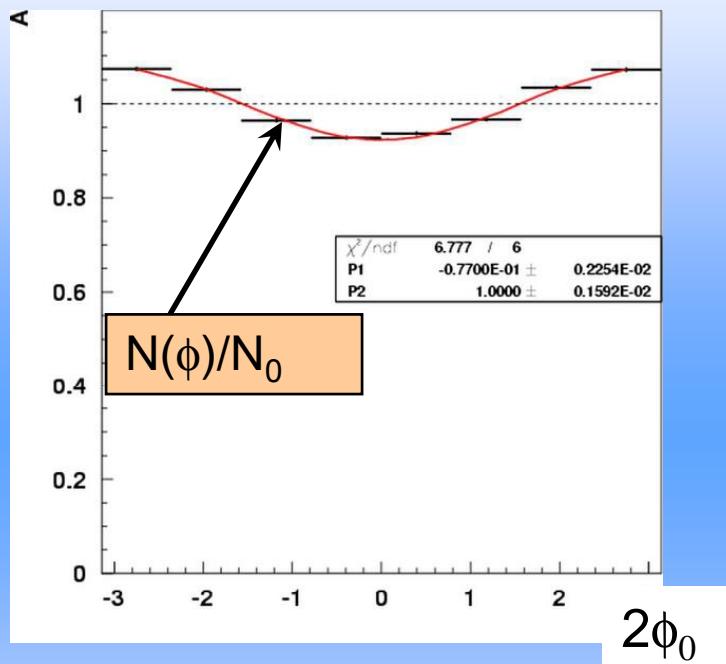
# Applied cuts, binning

- Off-resonance data
  - 60 MeV below Y(4S) resonance
  - $29.1 \text{ fb}^{-1}$
- → Later also on-resonance data:  
 $547 \text{ fb}^{-1}$
- Track selection:
  - $pT > 0.1 \text{ GeV}$
  - vertex cut:  
 $dr < 2 \text{ cm}, |dz| < 4 \text{ cm}$
- Acceptance cut
  - $-0.6 < \cos\theta_i < 0.9$
- Event selection:
  - $N_{\text{track}} \geq 3$
  - Thrust  $> 0.8$
  - $z_1, z_2 > 0.2$





# Examples of fits to azimuthal asymmetries



- Cosine modulations
- clearly visible
- P1 contains information on Collins function

$$\frac{N(\phi)}{N_0} = \frac{aD_1\bar{D}_1 + \cos(2\phi)(bH_1\bar{H}_1 + cD_1\bar{D}_1)}{aD_1\bar{D}_1} = P2 + P1 \cos(2\phi)$$

$D_1$ : 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:

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

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

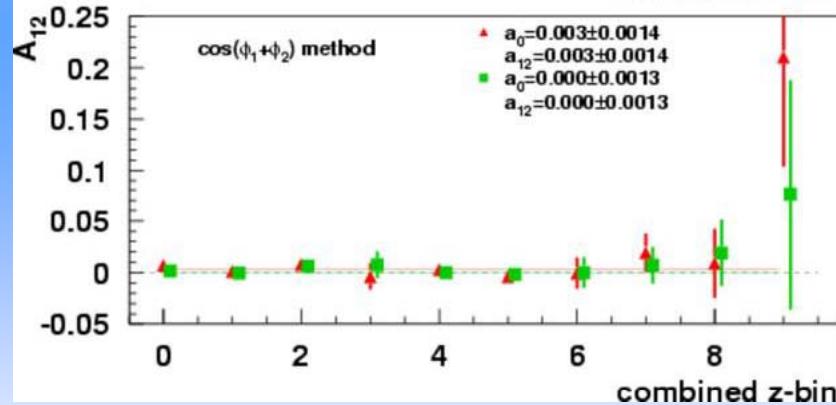
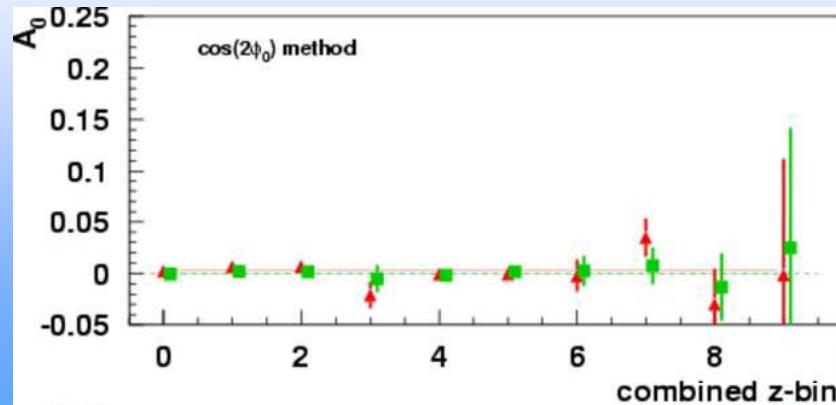
Cons: Acceptance effects remain

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

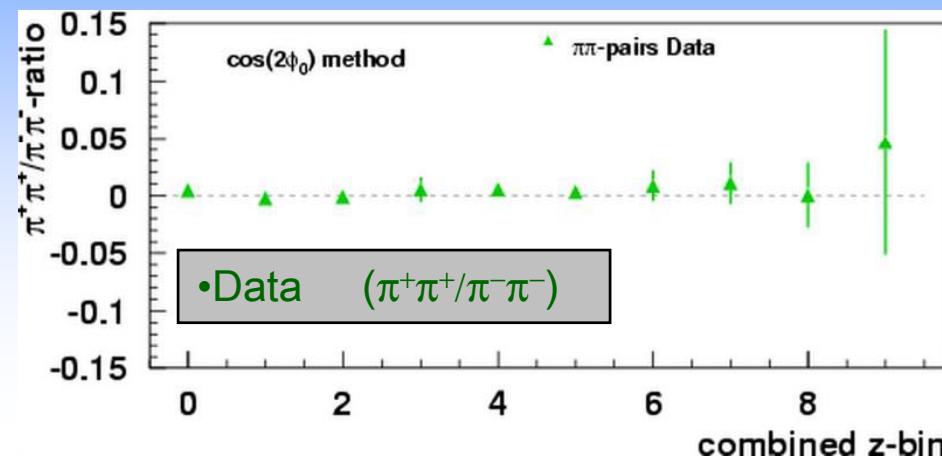
$$A := F = \cos(2\phi_0) \frac{\sin^2(\theta)}{1+\cos^2(\theta)} \left[ \frac{\sum_q e^2 (H^{Fav} \cdot \bar{H}^{Fav} + H^{Unf} \cdot \bar{H}^{Unf})}{\sum_q e^2 (D^{Fav} \cdot \bar{D}^{Fav} + D^{Unf} \cdot \bar{D}^{Unf})} - \frac{\sum_q e^2 (H^{Fav} \cdot \bar{H}^{Unf} + H^{Unf} \cdot \bar{H}^{Fav})}{\sum_q e^2 (D^{Fav} \cdot \bar{D}^{Unf} + D^{Unf} \cdot \bar{D}^{Fav})} \right]$$



# Testing the double ratios with MC



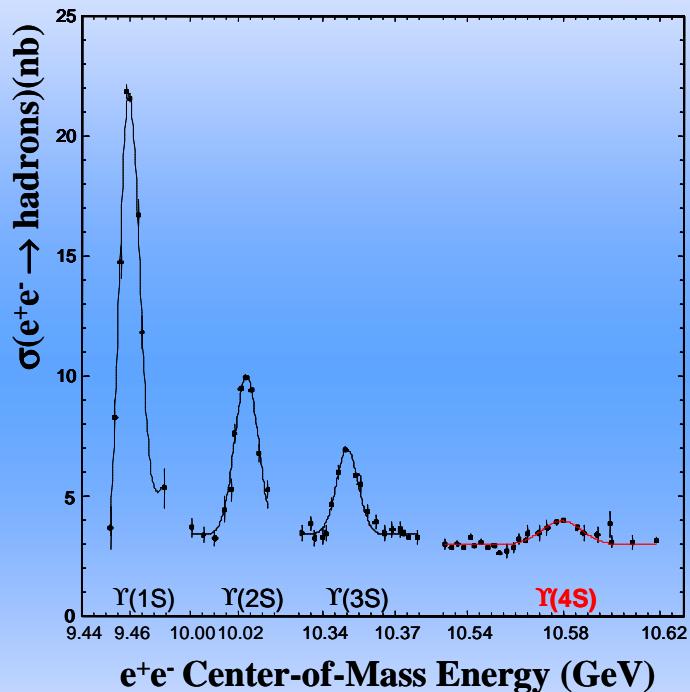
- uds MC (U/L double ratios)
- uds MC (U/C double ratios)
- U : Unlike sign pion pairs
- L : Like sign pion pairs
- C : all charged pion pairs





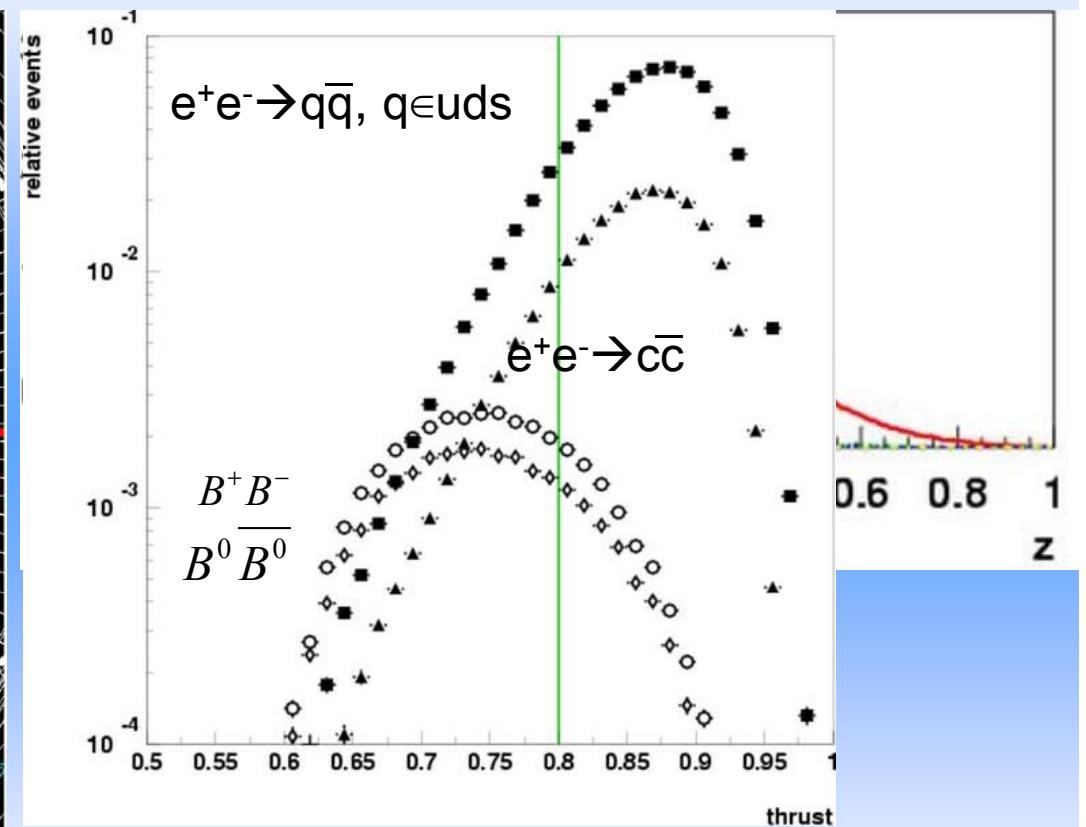
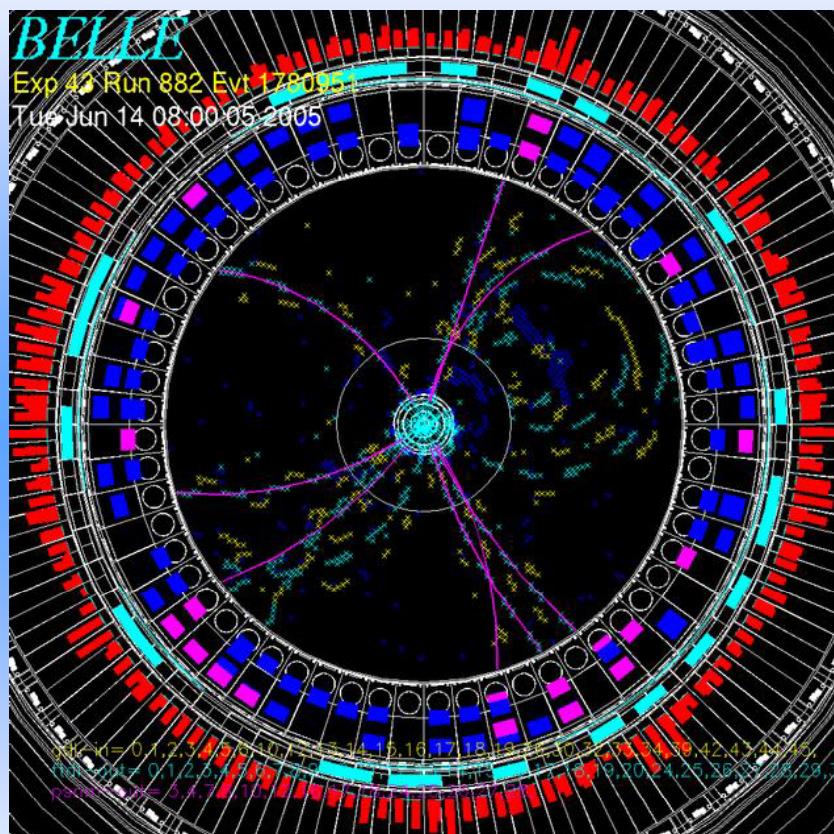
# What about the data under the resonance?

- More than 540  $\text{fb}^{-1}$  of on\_resonance data
- $\Upsilon(4S)$  is just small resonance
- More than 75% of hadronic cross section from open quark-antiquark production





# Why is it possible to include on\_resonance data? Different Thrust distributions



$$\text{thrust} = \frac{\sum_i |\mathbf{p}_i \cdot \hat{\mathbf{n}}|}{\sum_i |\mathbf{p}_i|}$$

- Charm-tagged Data sample (used for charm correction) also increases with statistics
- Largest systematic errors reduce with more statistics

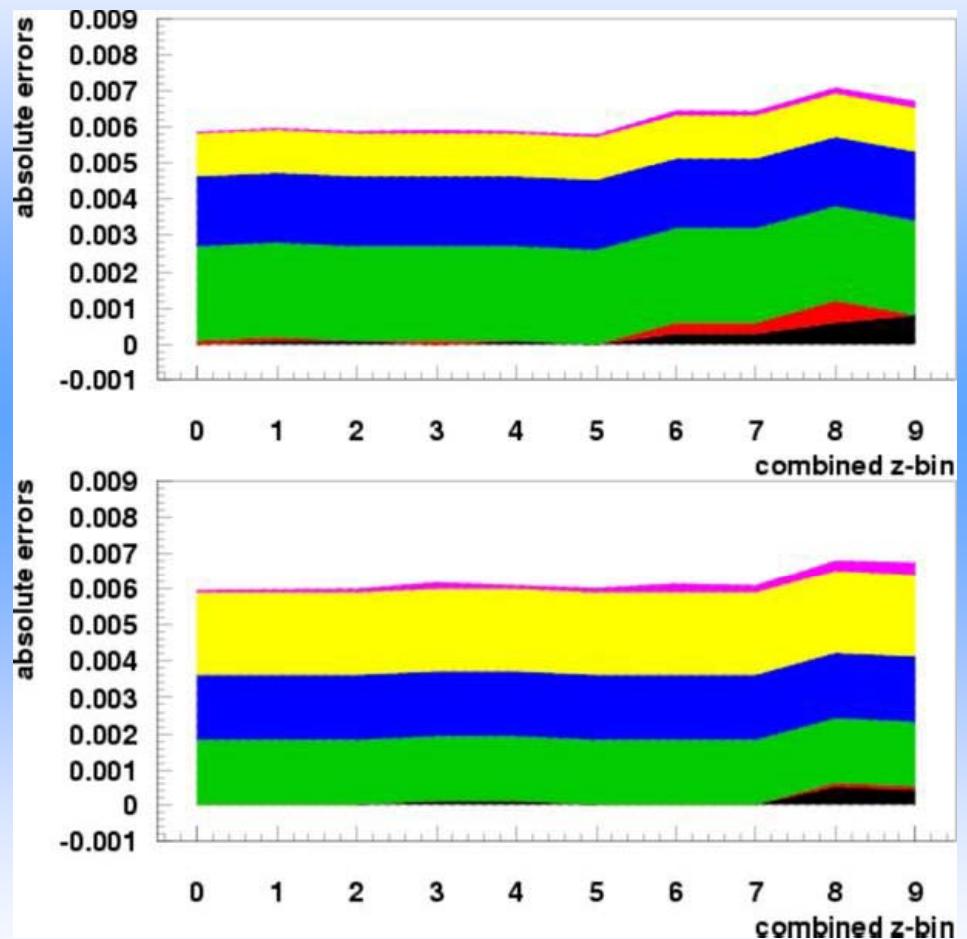




# Improved systematic errors (UC)

- Tau contribution
- PID error
- MC double ratios
- Charged ratios ( $\pi^+\pi^+ / \pi^-\pi^-$ )
- higher moments in Fit
- difference double ratio-subtraction method

• reweighted MC-asymmetries:  
→  $\cos(\phi_1 + \phi_2)$  asymmetries  
underestimated due to thrust axis  
reconstruction  
→ rescaled with 1.21  
• Correlation studies:  
→ statistical error rescaled by 1.02 (UL)  
and 0.55 (UC)  
• Beam polarization studies  
→ consistent with zero  
• Correction for charm events

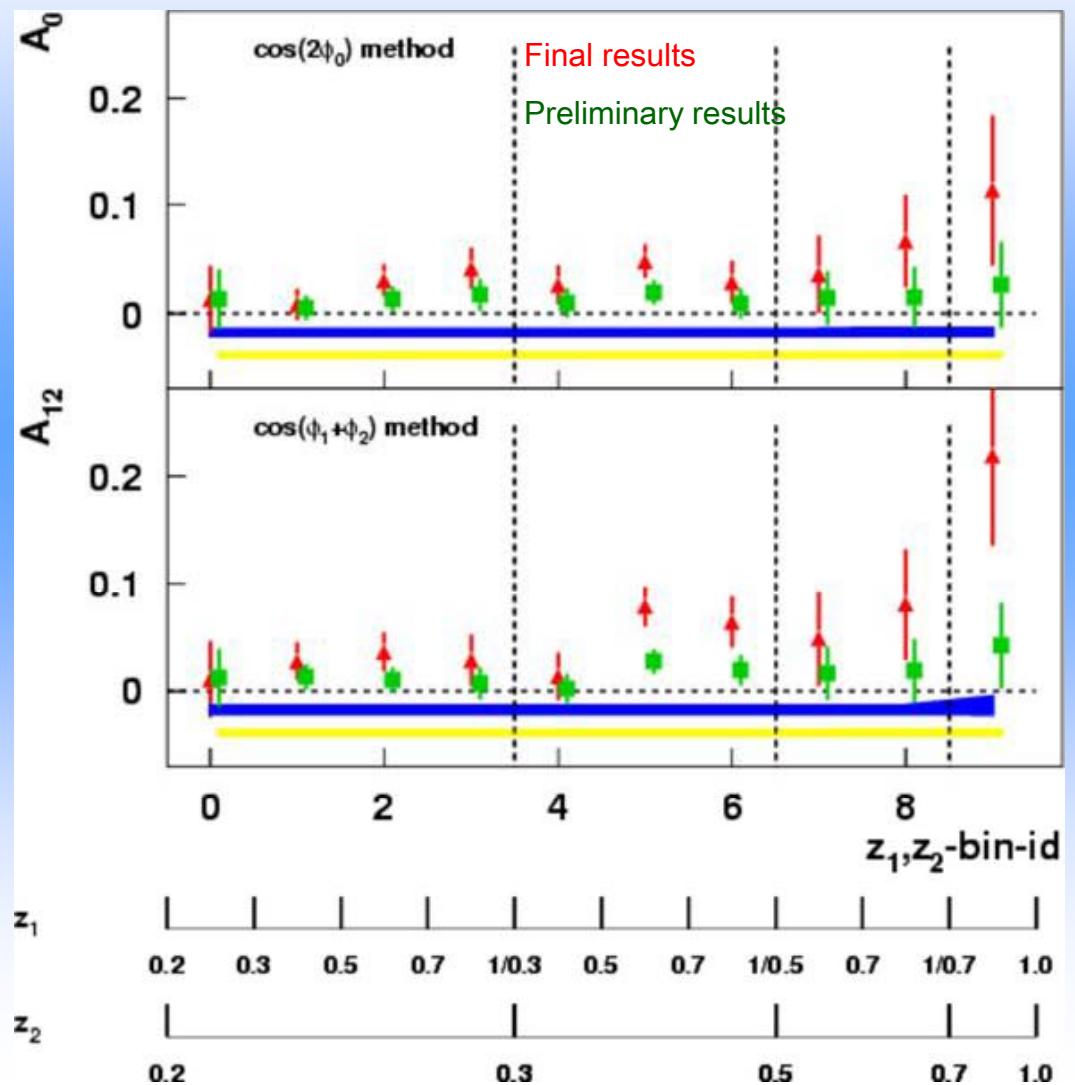


# Final charm corrected results for $e^+ e^- \rightarrow \pi \pi X$ (29fb $^{-1}$ of continuum data)

- Significant non-zero asymmetries
- Rising behavior vs.  $z$
- $\cos(\phi_1 + \phi_2)$  double ratios only marginally larger
- UC asymmetries about 40-50% of UL asymmetries
- First direct measurements of the Collins function

## Integrated results (constant fit):

$A_0(\text{UL})$	$(3.06 \pm 0.57 \pm 0.55)\%$
$A_{12}(\text{UL})$	$(4.26 \pm 0.68 \pm 0.68)\%$
$A_0(\text{UC})$	$(1.270 \pm 0.489 \pm 0.350)\%$
$A_{12}(\text{UC})$	$(1.752 \pm 0.592 \pm 0.413)\%$

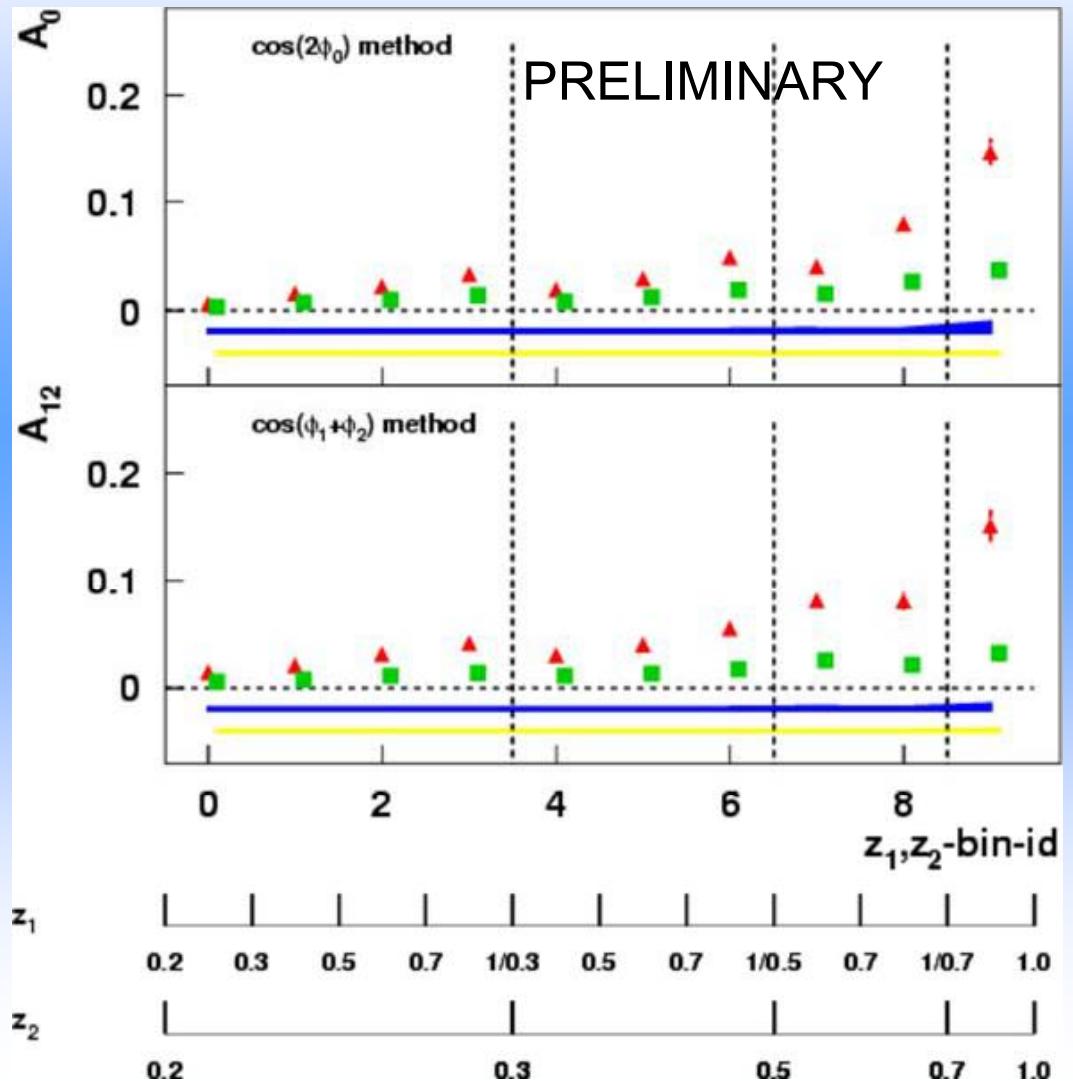


# Charm corrected results for $e^+ e^- \rightarrow \pi \pi X (547 \text{ fb}^{-1})$

- Significance largely increased
- Behavior unchanged
- Reduced systematic errors due to statistics
- Precise measurements of the Collins function

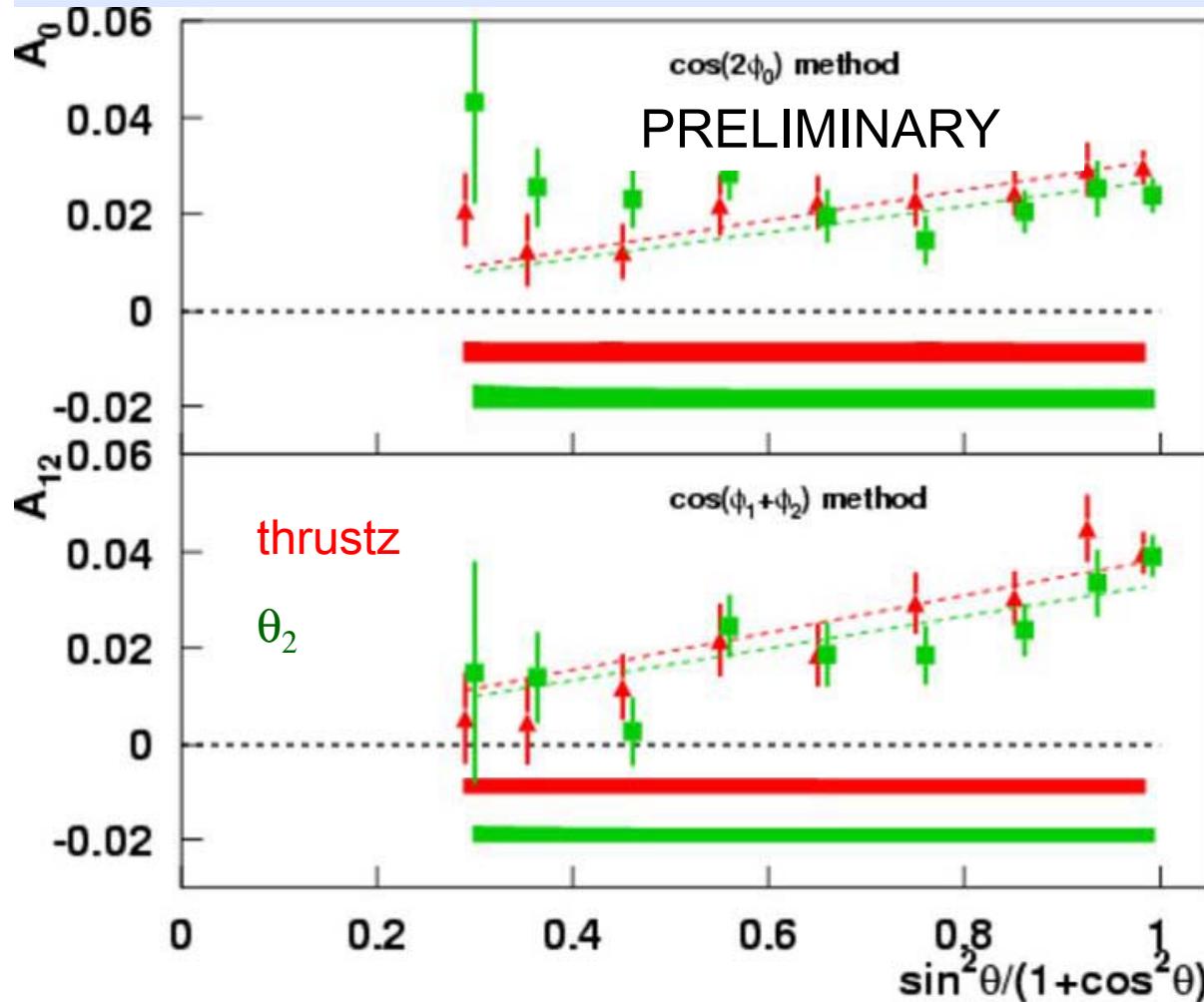
## Integrated results(constant fit):

$A_0(\text{UL})$	$(2.67 \pm 0.10 \pm 0.26)\%$
$A_{12}(\text{UL})$	$(3.55 \pm 0.08 \pm 0.15)\%$
$A_0(\text{UC})$	$(1.11 \pm 0.11 \pm 0.22)\%$
$A_{12}(\text{UC})$	$(1.46 \pm 0.09 \pm 0.13)\%$





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



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





# Towards a global transversity analysis

SIDIS experiments (HERMES and COMPASS, eRHIC) measure  $\delta q(x)$  together with either Collins Fragmentation function  $H_{I^\perp}(z)$  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

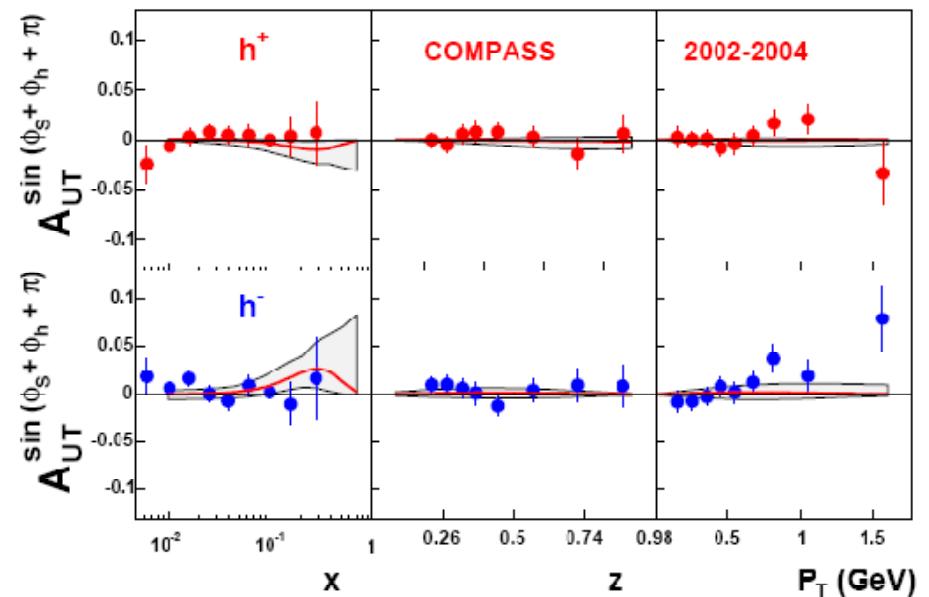
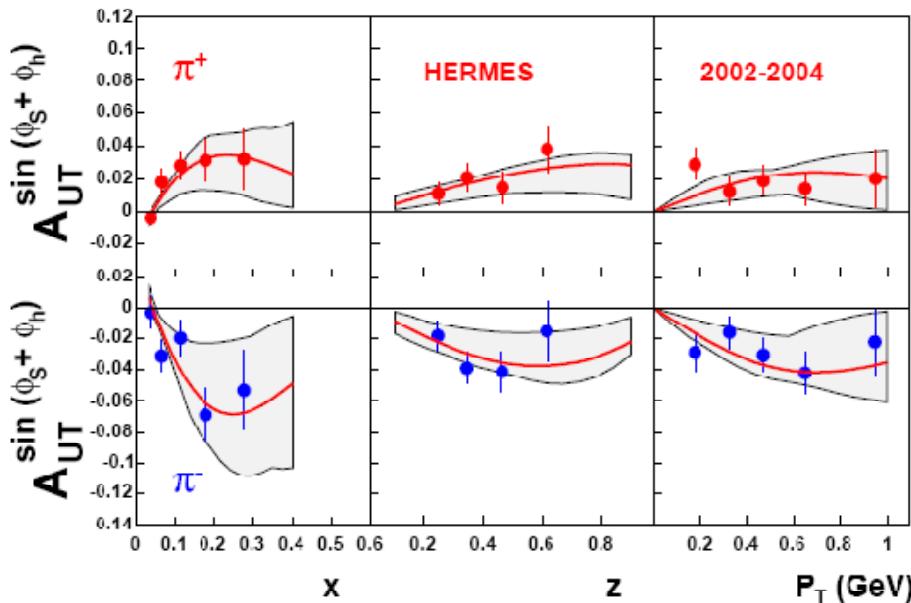
- Universality understood
- Evolution ?

Spin dependent Fragmentation function analysis in  $e^+e^-$  Annihilation yields information on the Collins and the Interference Fragmentation function !





# Global analysis by Anselmino et al: Phys.Rev.D75:054032,2007)



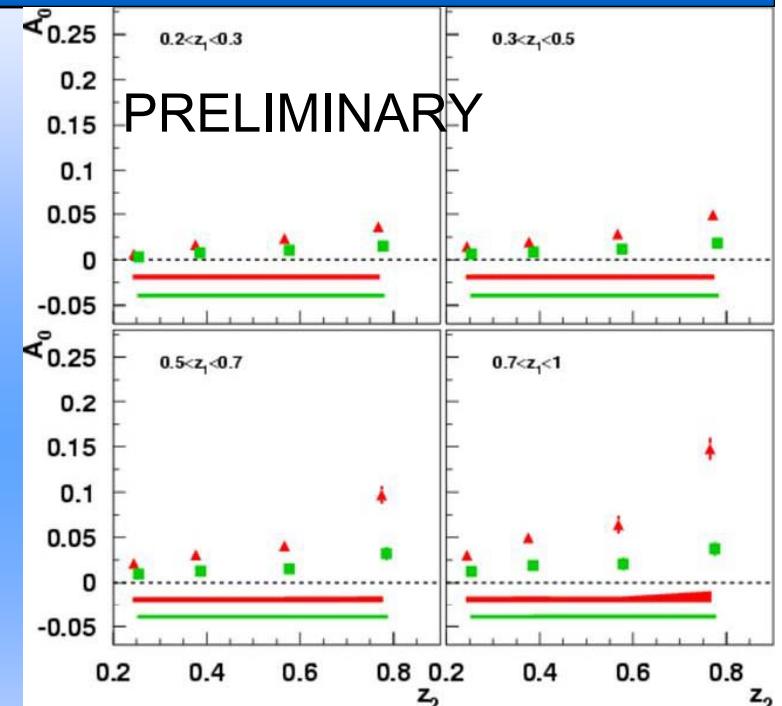
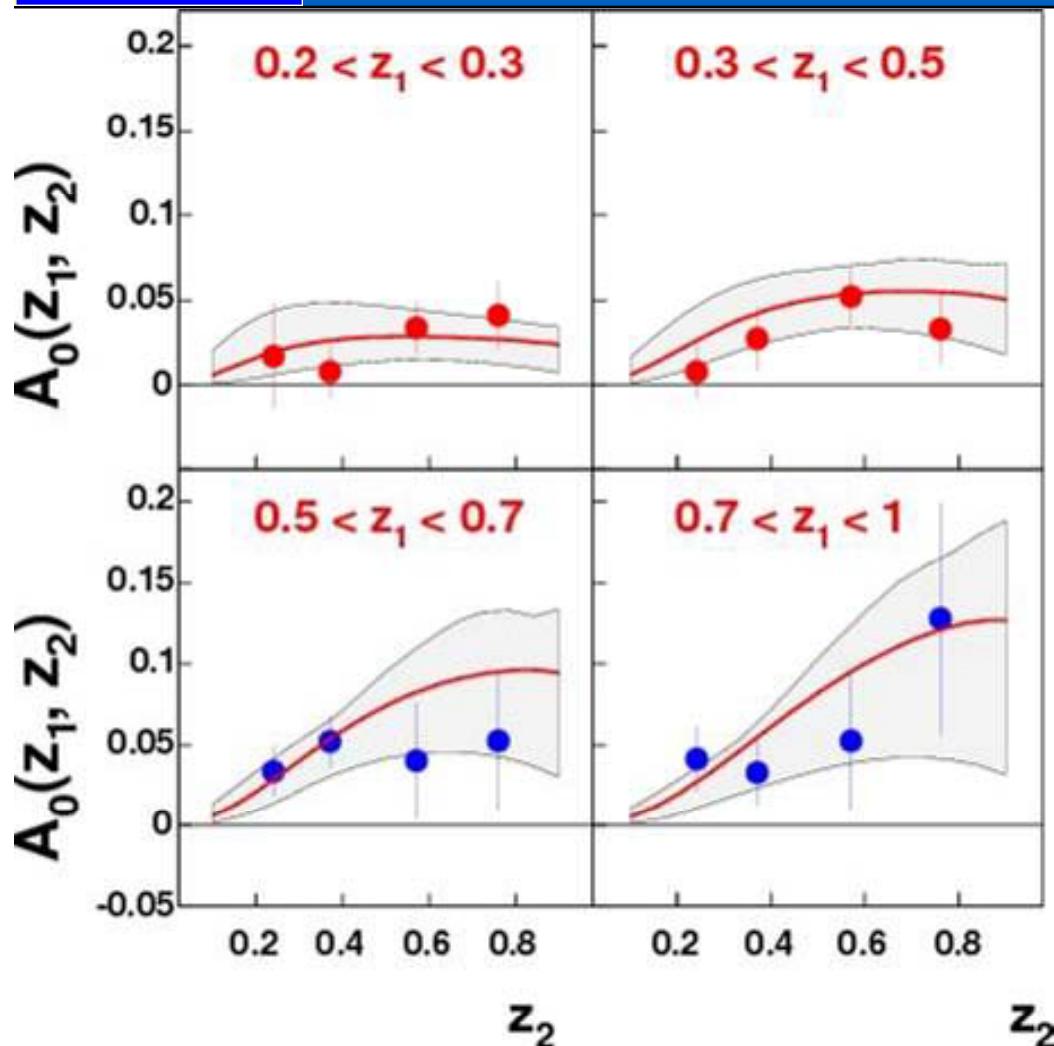
HERMES 2002-2004 p data:  
PRL 94, 012002 (2005)  
2005 data not yet included in fit

COMPASS 2002-2004 d data:  
PRL 94, 202002 (2005) and  
2005 and identified hadron data  
not yet included in fit:  
Nucl.Phys.B765:31-70,2007





# Global Analysis- Belle Collins function: asymmetries for double ratios of $\pi\pi^{\text{unlikesign}} / \pi\pi^{\text{likesign}}$ for $29 \text{ fb}^{-1}$



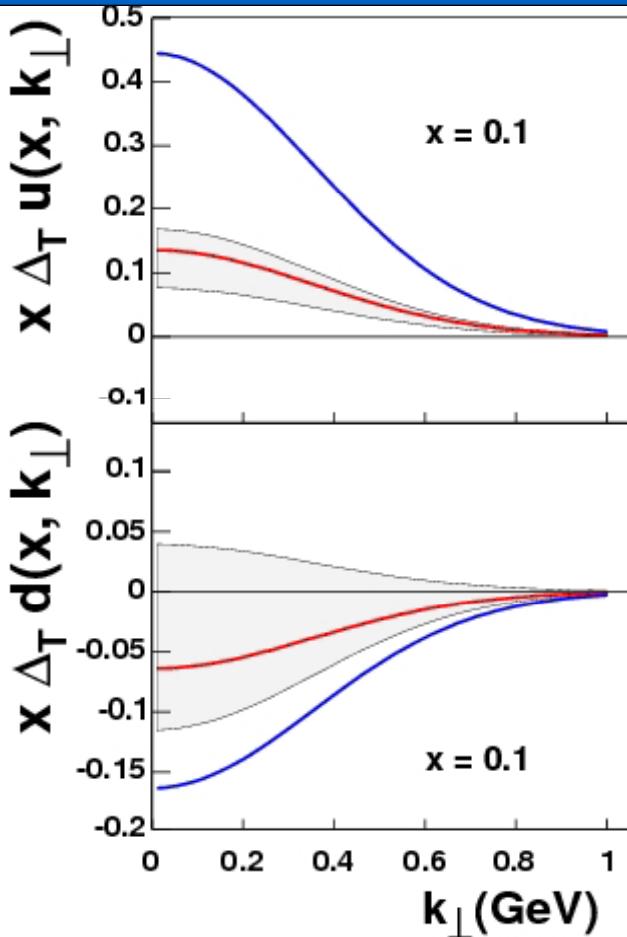
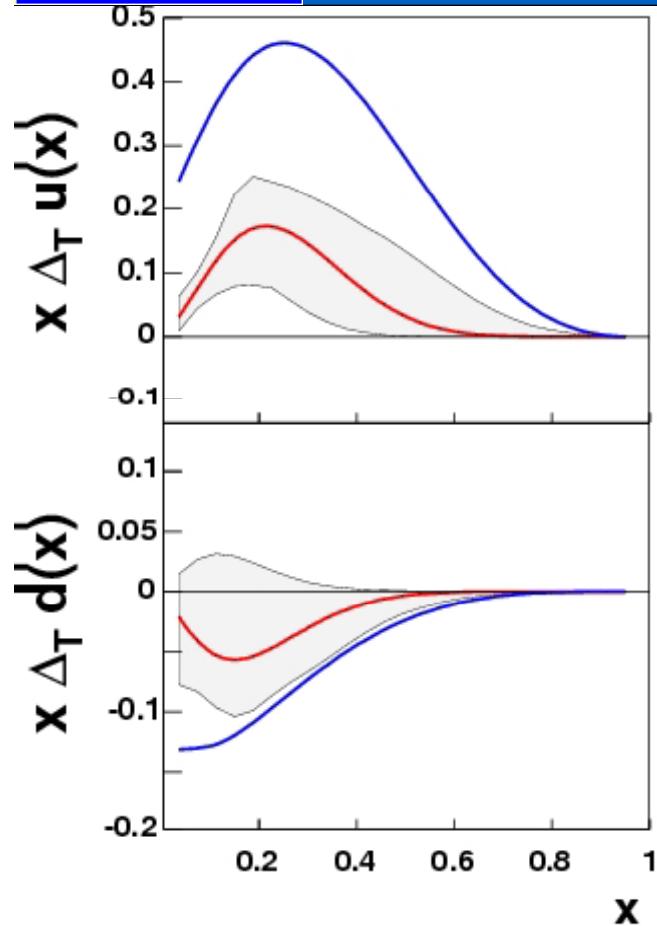
+ inclusion of Y(4S) data:  
 →  $>540 \text{ fb}^{-1}$  (not yet included in global fit)

Anselmino et al: Phys.Rev.D75:054032,2007,  
 data: RS et al.(Belle collaboration), PRL 96, 232002 (2006)





# First successful attempt at a global analysis for the transverse SIDIS and the BELLE Collins data



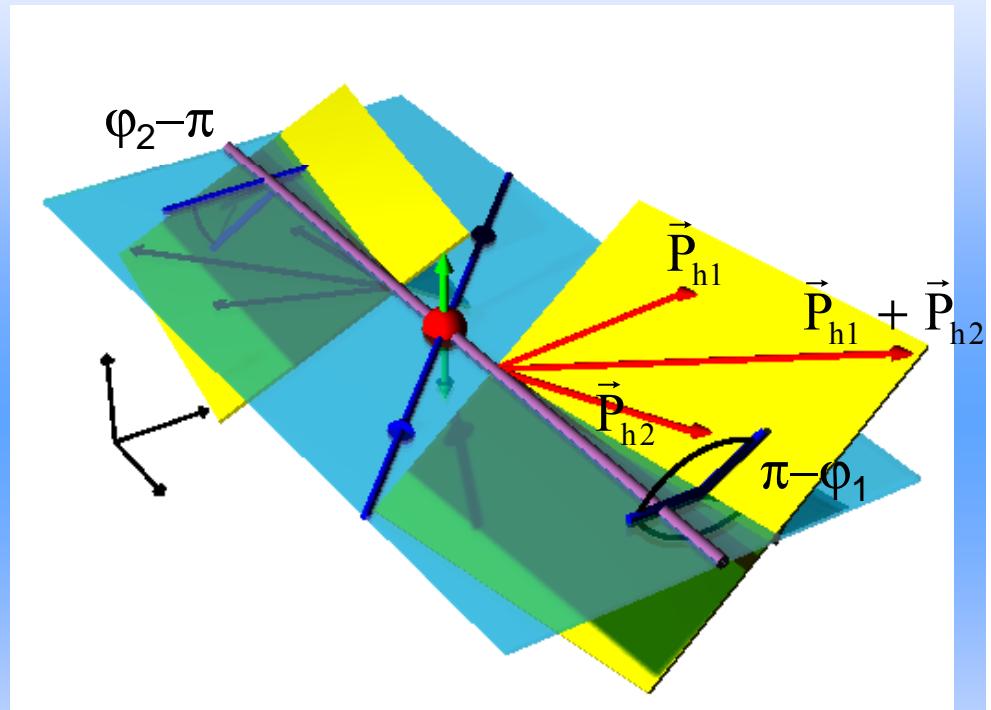
Anselmino et al: Phys.Rev.D75:054032,2007

- HERMES AUT p data
- COMPASS AUT d data
- Belle e+ e- Collins data
- Kretzer FF
- → First extraction of transversity (up to a sign)



# Interference Fragmentation – thrust method

- $e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^-\pi^+)_{jet2} X$
- Stay in the mass region around r-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[PRD 67,(2003)] and Artru,Collins[ZPhysC69(1996)]
- Early work by Collins, Heppelmann, Ladinsky [NPB420(1994)]



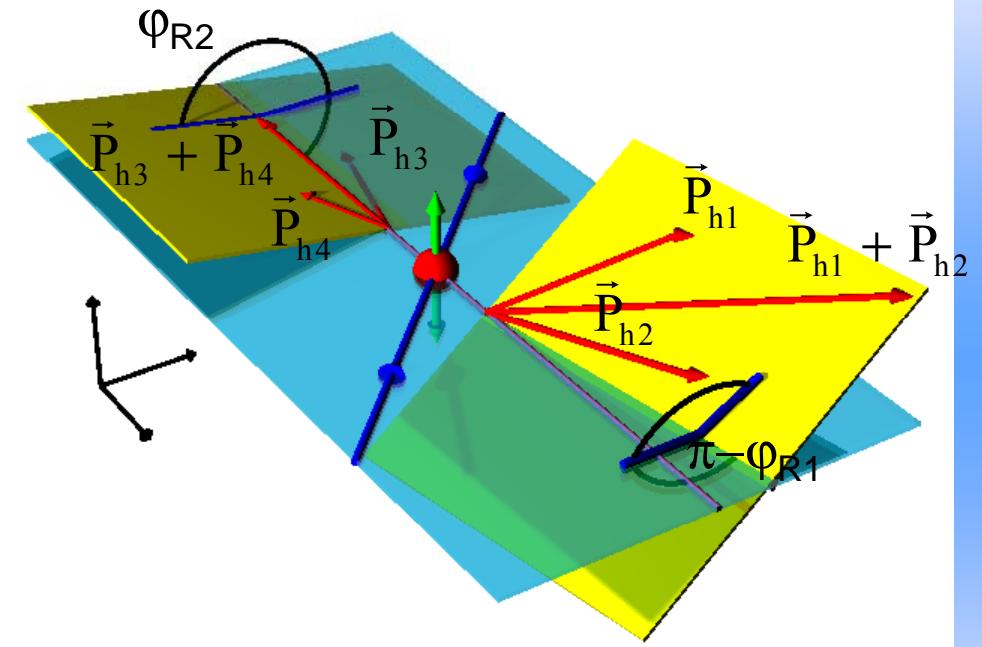
Model predictions by:

- Jaffe et al. [PRL 80,(1998)]
- Radici et al. [PRD 65,(2002)]

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



- 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



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

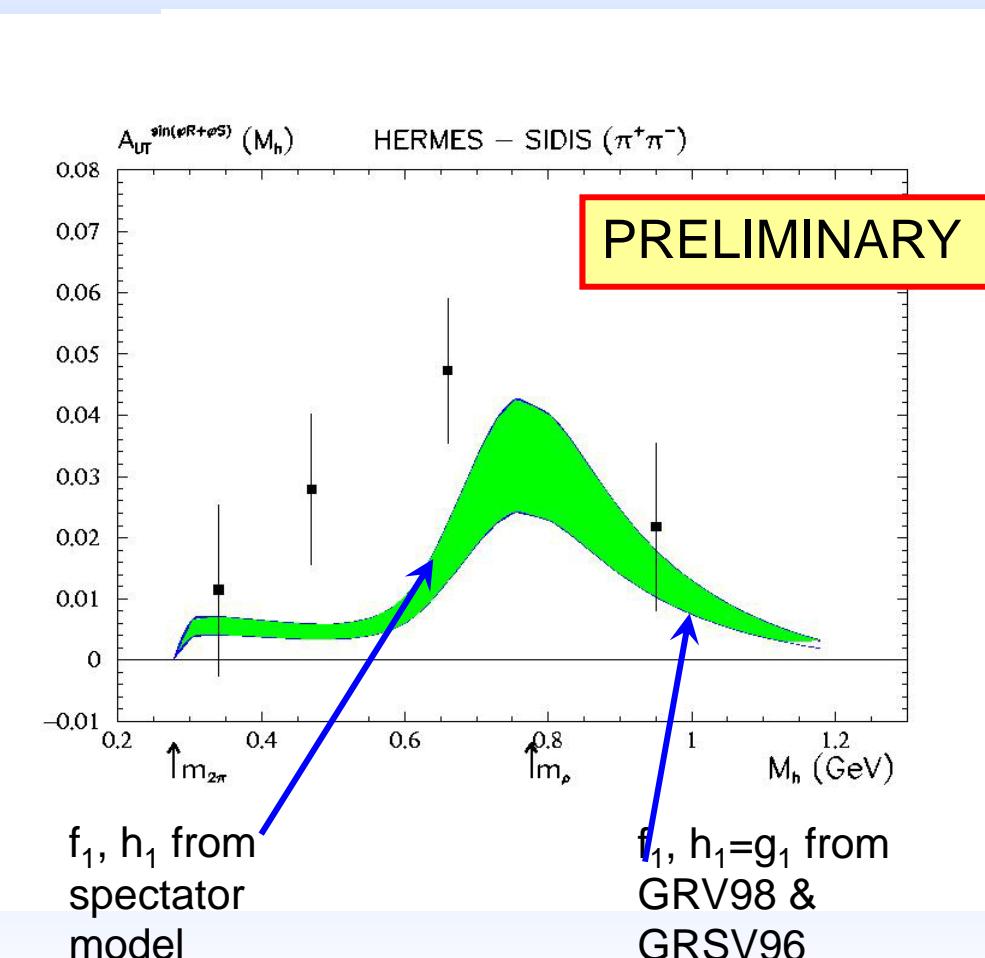


# Different model predictions for IFF

- Jaret Lettmaier [D65 (2002)] : Spectator model in the **s-p channel**
- Radici et al. [Phys. Rev. D65 (2002)] : Spectator model in the **s-p channel**
- no sign change observed (updated model)

-origin has Breit-Wigner like asymmetry)

-Tau RH





# Summary and outlook

- A first successful global analysis of transversity data using the HERMES, COMPASS and published Belle data
- Belle Collins data largely improved from  $29 \rightarrow 547 \text{ fb}^{-1}$
- Significant, nonzero asymmetries  $\rightarrow$  Collins function is large
- Long Collins paper is nearly finished

- Continue to measure precise spin dependent fragmentation functions at Belle
  - $kT$  dependence of Collins function
  - Favored/disfavored disentanglement
  - Interference Fragmentation function measurements (started)
- Measure precise unpolarized fragmentation functions of many final states
- $\rightarrow$  Important input for general QCD physics and helicity structure measurements
- Measure other interesting QCD-related quantities at Belle:
  - Chiral-odd  $\Lambda$ -fragmentation function
  - Event shapes
  - R-ratio with ISR

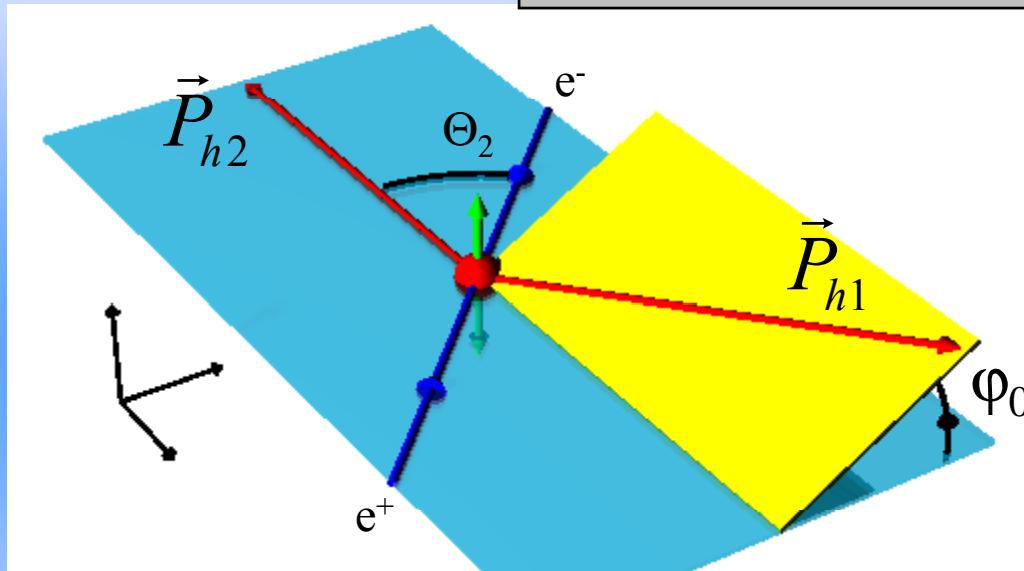




# Backup Slides



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



- Independent of thrust-axis
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[Boer,Jakob,Mulders:  
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$$B(\Theta) \stackrel{cm}{=} \frac{1}{4} \sin^2 \Theta$$

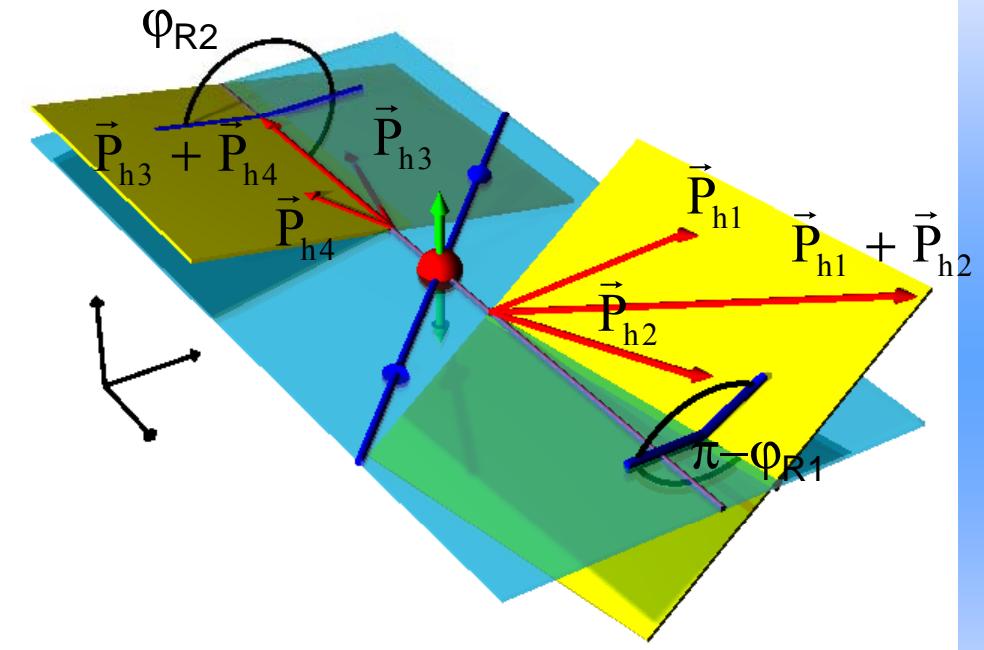
Net (anti-)alignment of  
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# Interference Fragmentation – “ $\phi_0$ “ method

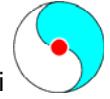
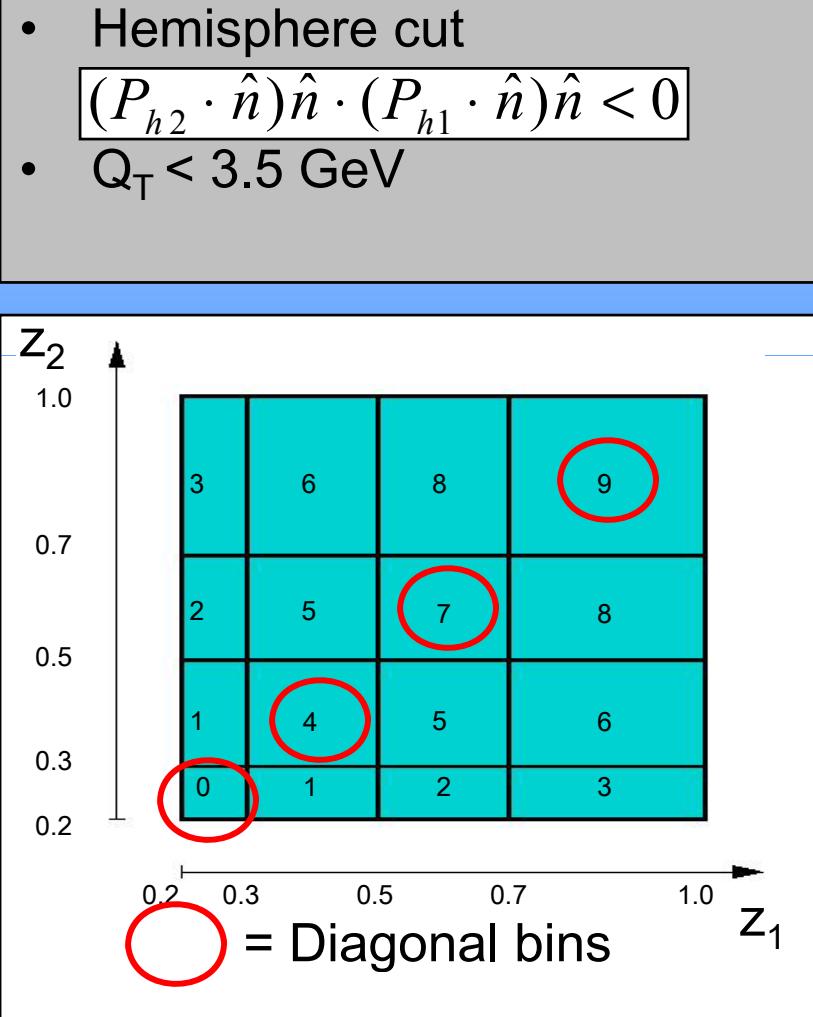
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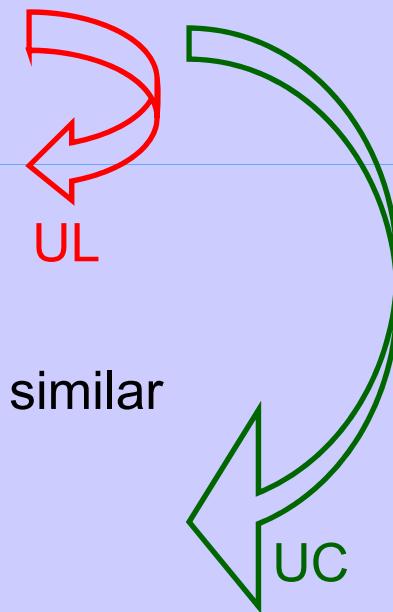




## Other Favored/Unfavored Combinations → charged pions or $\pi^0$

Challenge: current double ratios not very sensitive to favored to disfavored Collins function ratio → 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)
- P.Schweitzer([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	= $d \rightarrow \pi^+, u \rightarrow \pi^-, cc.$





# What would we see in $e^+e^-$ ?

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

