Spin dependent fragmentation function analysis at Belle

DIS 2007

München, April 17th

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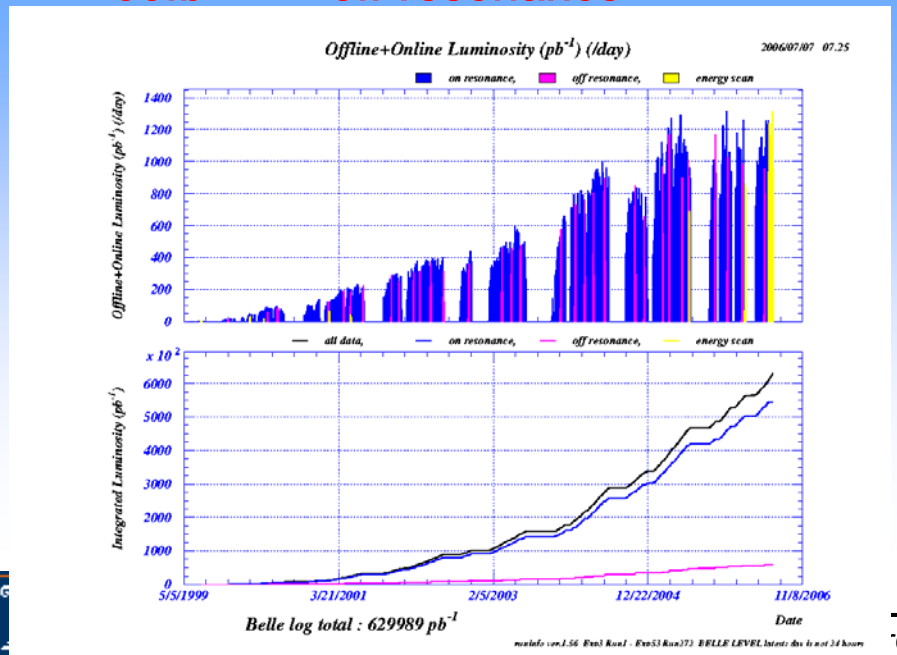
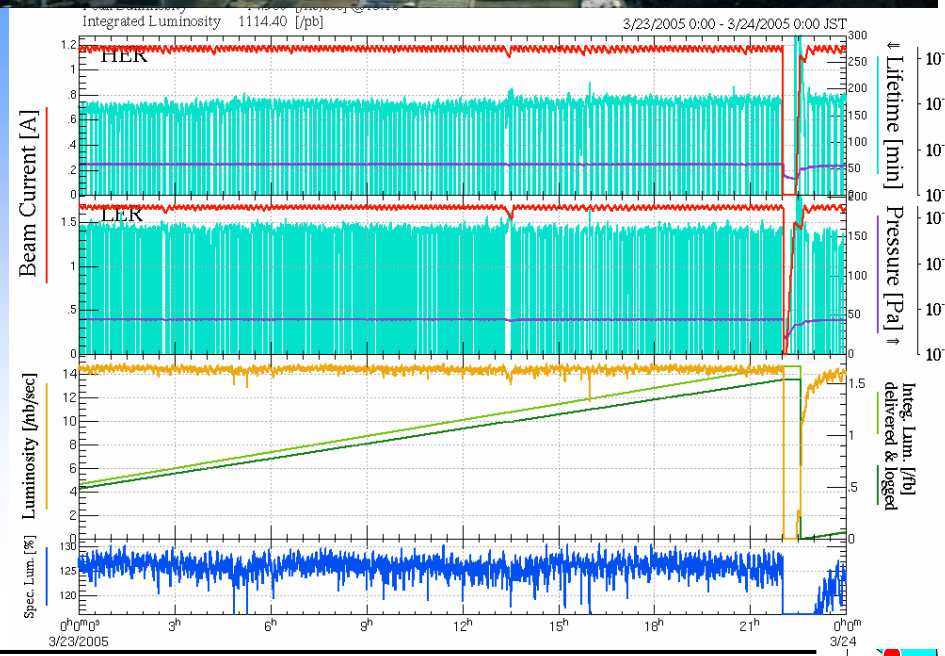
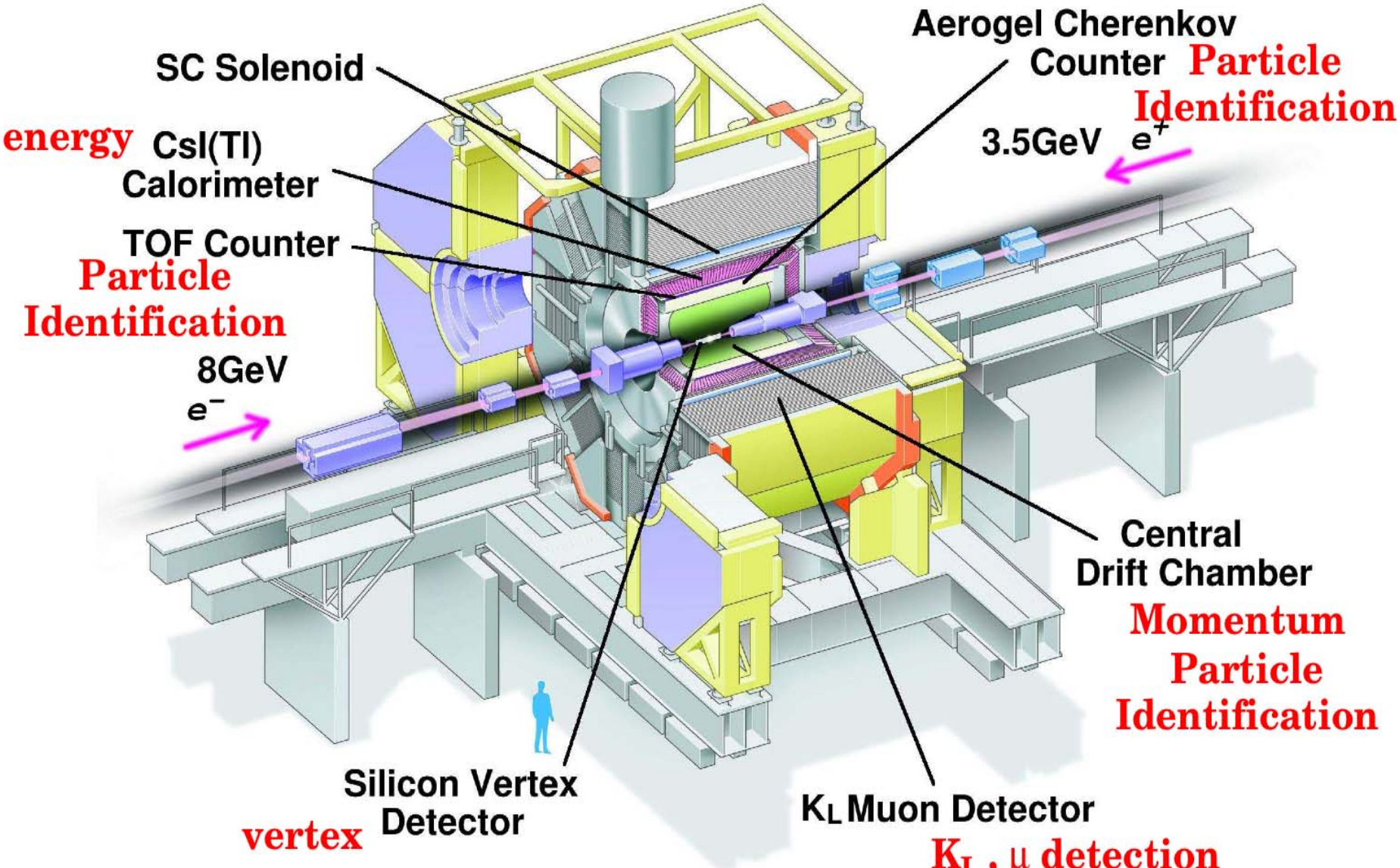
KEKB: $L>1.6\times10^{34}cm^{-2}s^{-1}$!!

- Asymmetric collider
- 8GeV e^- + 3.5GeV e^+
- $\sqrt{s}$ = 10.58GeV (Υ(4S))
- $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
- Off-resonance: 10.52 GeV
- $e^+e^- \rightarrow q\bar{q}$ (u,d,s,c)
- Integrated Luminosity: >700 fb^{-1}
- >60fb^{-1} => off-resonance



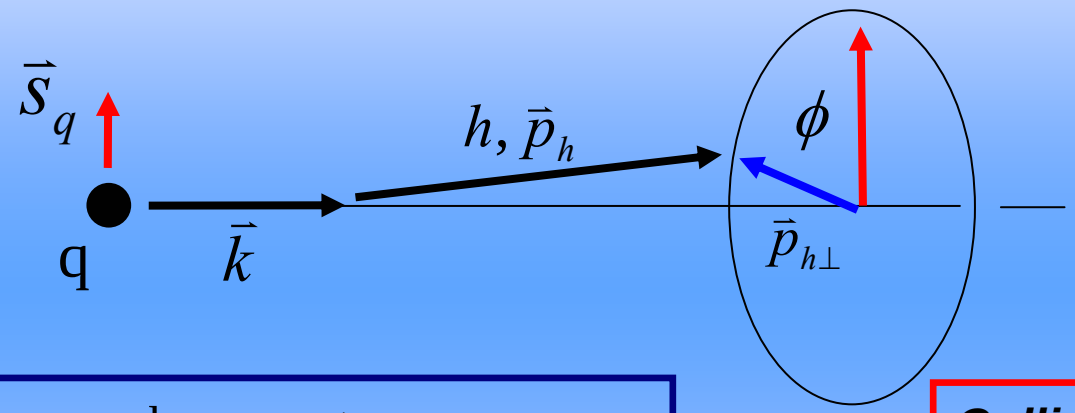


Belle Detector



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 with of a quark *q* with spin s_q into a spinless hadron *h* carries an azimuthal dependence:

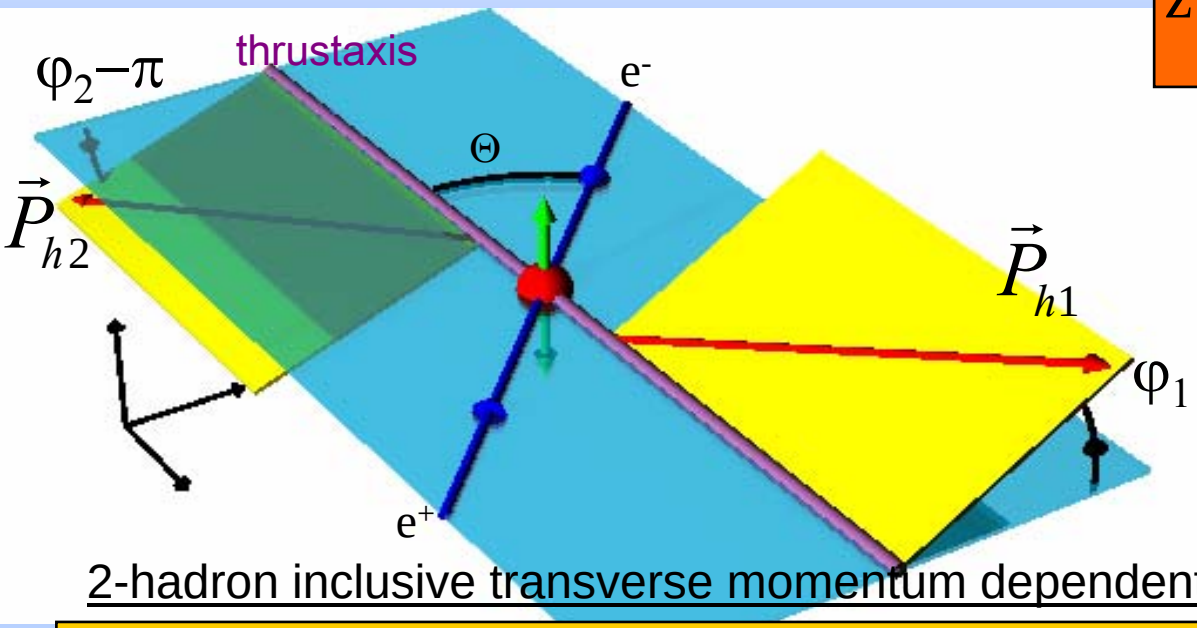
$$\propto \left(\vec{k} \times \vec{p}_{h\perp}\right) \cdot \vec{s}_q$$

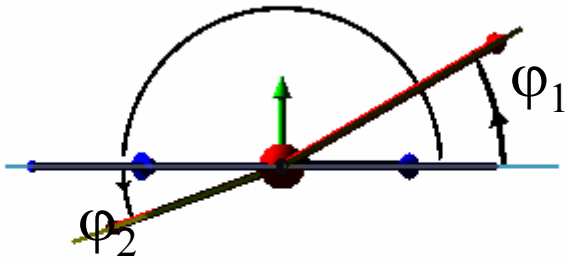
$$\propto \sin\phi$$

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:

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

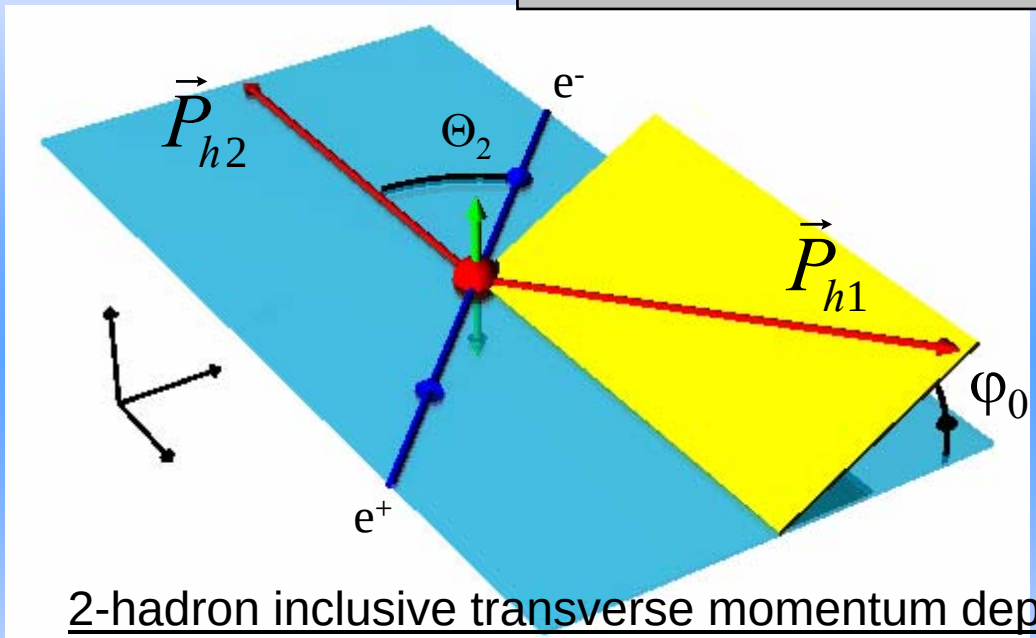
$$B(\Theta) \overset{cm}{=} \frac{1}{4}\sin^2\Theta$$

First $|k_T|$ moments of Collins Function $H_1^{\perp}$

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:

$$\frac{d\sigma\left(e^+e^- \to h_1 h_2 X\right)}{d\Omega dz_1 dz_2 d^2 q_T} = \cdots B(\Theta)\cos(2\varphi_0)\mathrm{I}\left[\left(2\hat{h}\cdot k_T \hat{h}\cdot p_T - k_T \cdot p_T\right)\frac{H_1^{\perp}\overline{H}_1^{\perp}}{M_1 M_2}\right]$$

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

Net (anti-)alignment of transverse quark spins

Applied cuts, binning

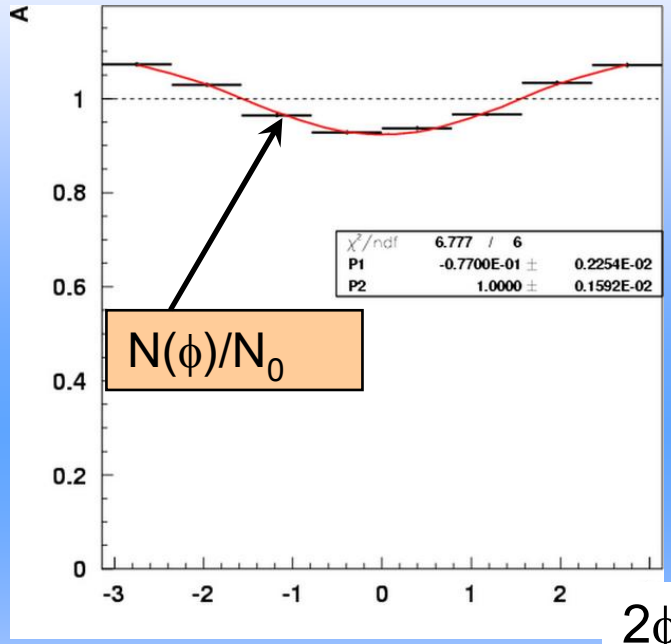
- Originally off_resonance data, now also on_resonance data (29.1 → 547 fb^{-1})
- Track selection:
  - pT > 0.1GeV
  - vertex cut: dr<2cm, |dz|<4cm
- Acceptance cut
  - $-0.6 < \cos\theta_l < 0.9$
- Event selection:
  - Ntrack $\geq$ 3
  - Thrust > 0.8
  - Z_1, Z_2>0.2

- Hemisphere cut

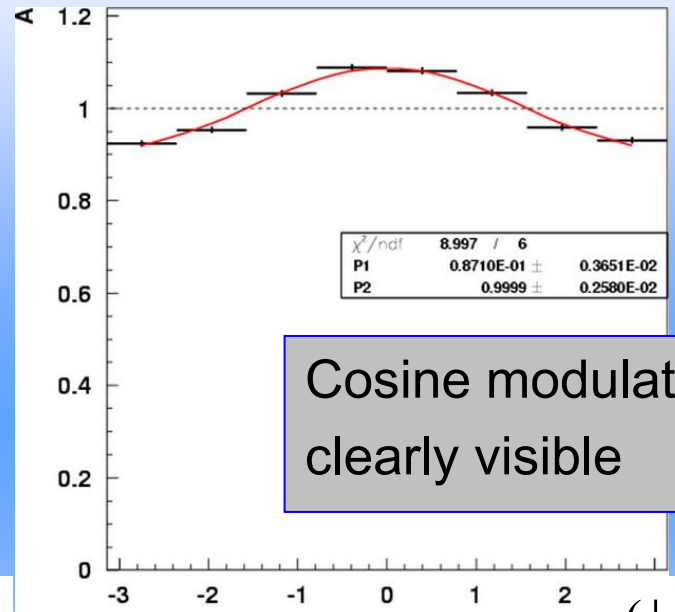
$$(P_{h2} \cdot \hat{n})\hat{n} \cdot (P_{h1} \cdot \hat{n})\hat{n} < 0$$

- Q_T < 3.5 GeV
- Pion PID selection

Examples of fits to azimuthal asymmetries



$2\phi_0$



Cosine modulations clearly visible

$(\phi_1+\phi_2)$

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

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:

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

Pros: Acceptance cancels out

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

Subtraction method:

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

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 π^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]): ANY charged $\pi\pi$ pairs are similar (and easier to handle) (C):

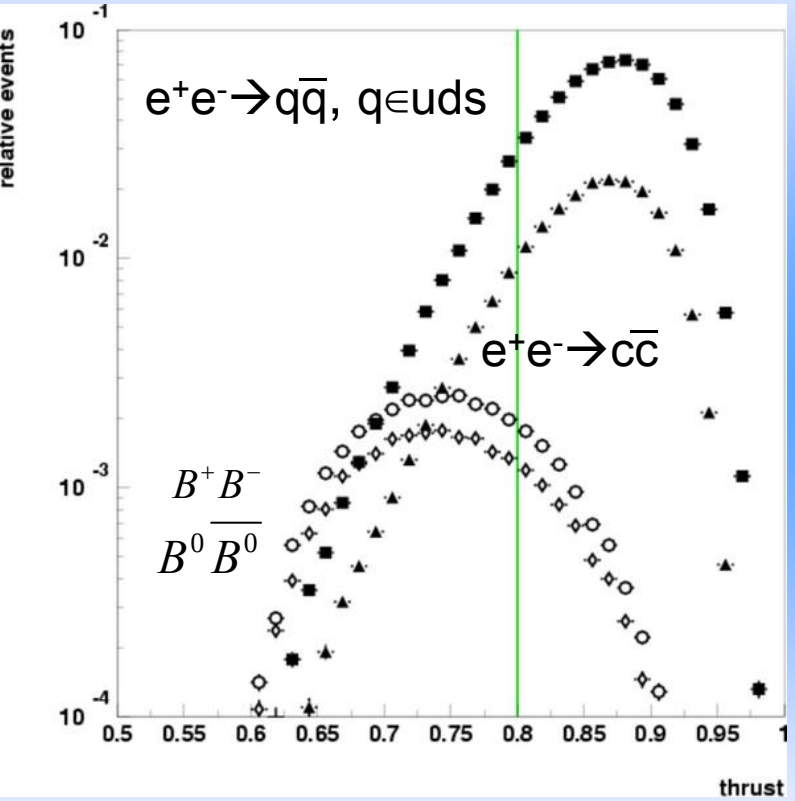
  (favored + unfavored) x (favored + unfavored)

➔Build new double ratios:

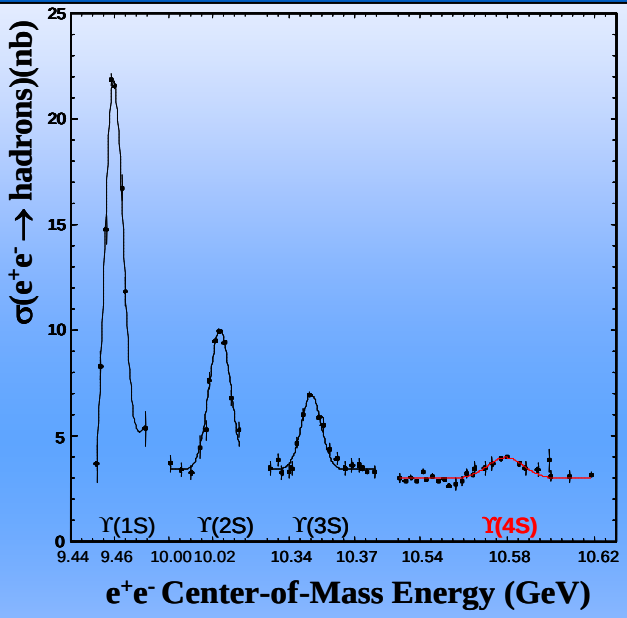
➔Unlike-sign/ charged $\pi\pi$ pairs (UC)

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

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



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

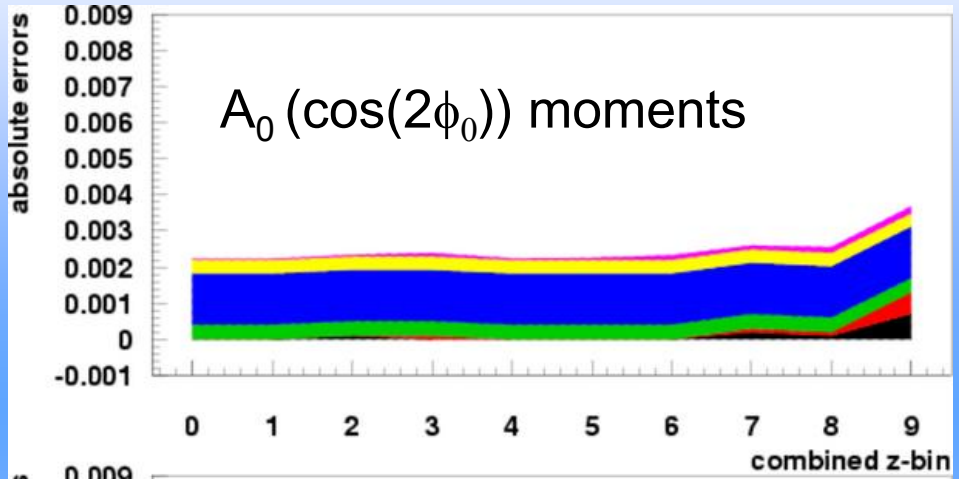


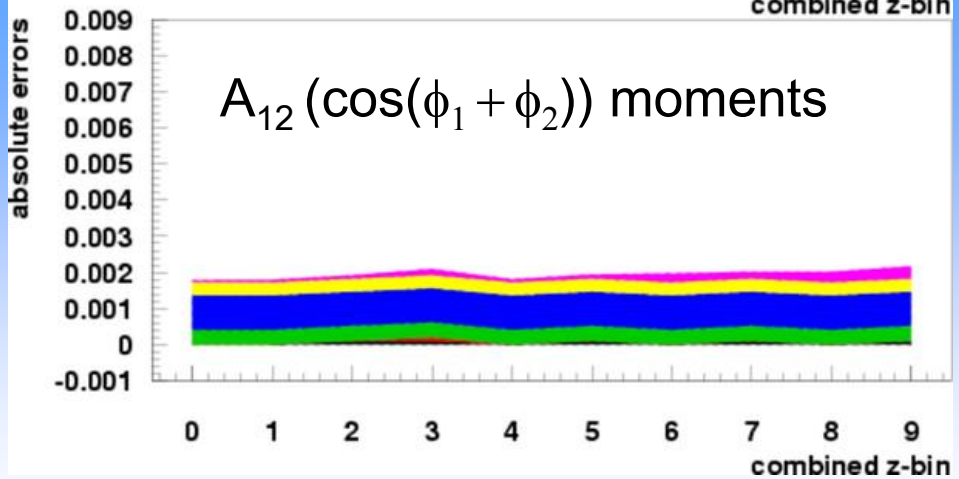
- small B contribution (<1%) in high thrust sample
- >75% of X-section continuum under Υ (4S) resonance
- 29 fb^{-1} ➔ 547 fb^{-1}
- many systematic errors reduce with more statistics
- Charm-tagged Data sample also increases

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
•Correction for charm contribution

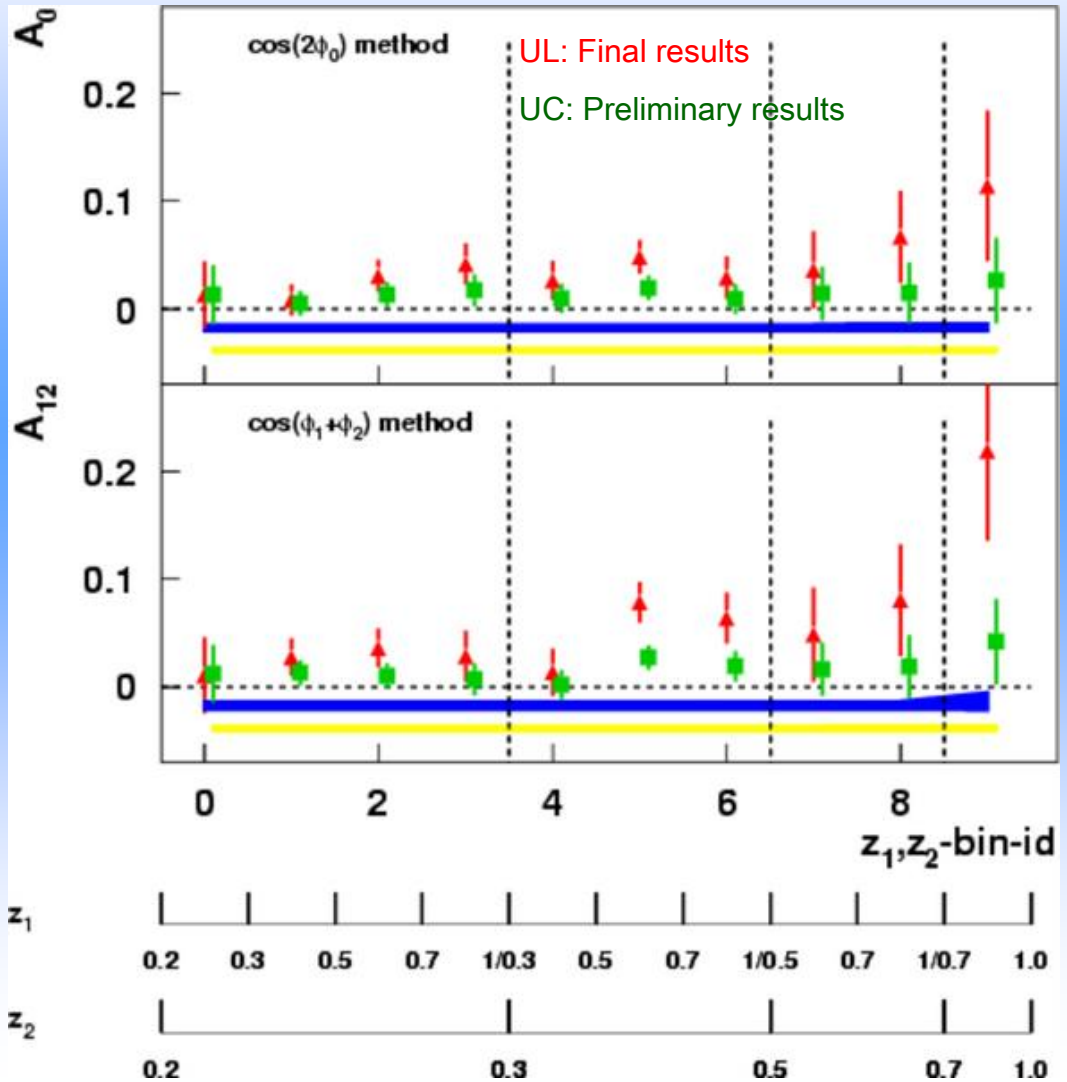




Final charm corrected results for $e^+ e^- \rightarrow \pi \pi X$ (29fb^{-1} of off-resonance data)

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

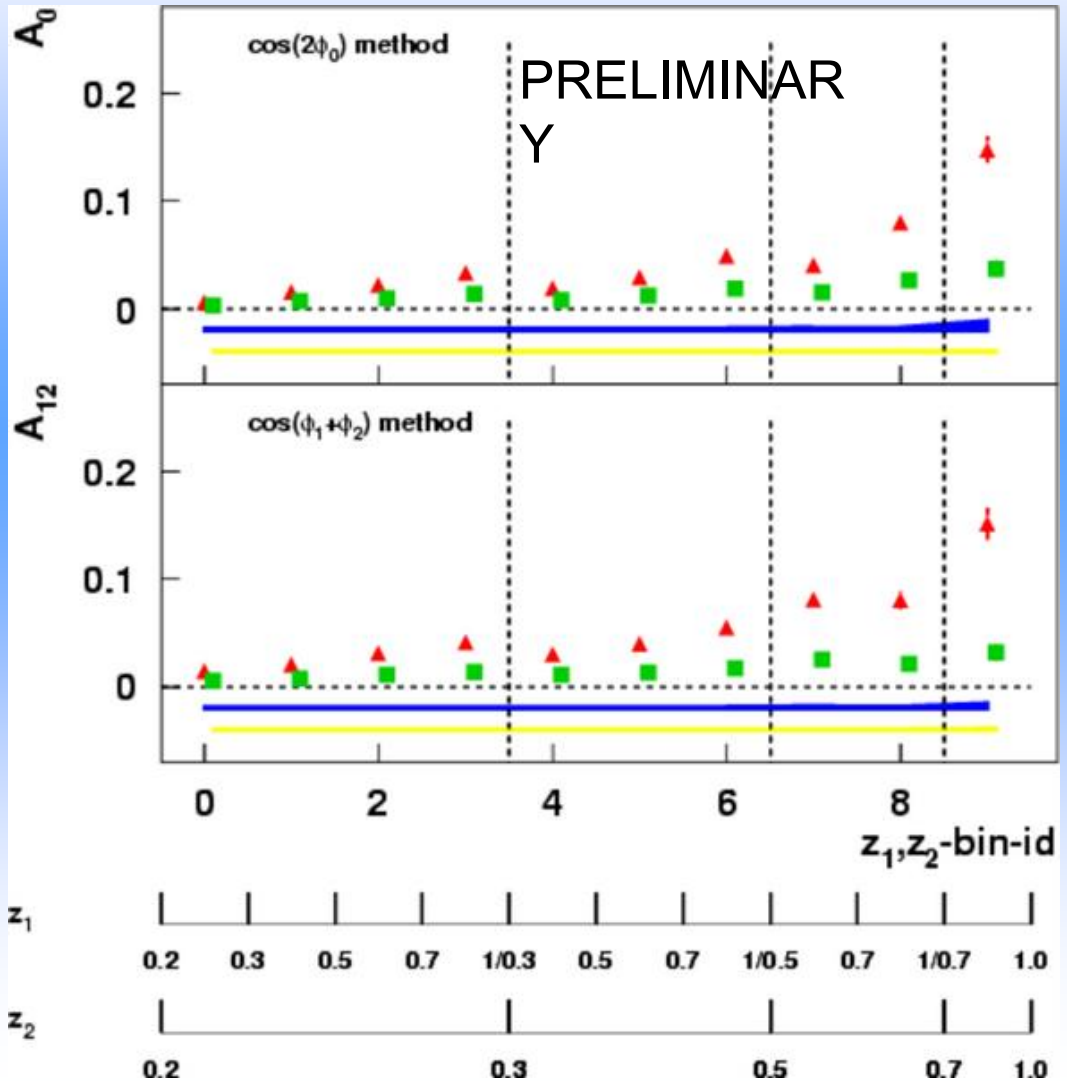
z-Integrated results:	
A_0(UL)	(3.06 ± 0.57 ± 0.55)%
A_{12}(UL)	(4.26 ± 0.68 ± 0.68)%
A_0(UC)	(1.27 ± 0.49 ± 0.35)%
A_{12}(UC)	(1.75 ± 0.59 ± 0.41)%



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

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

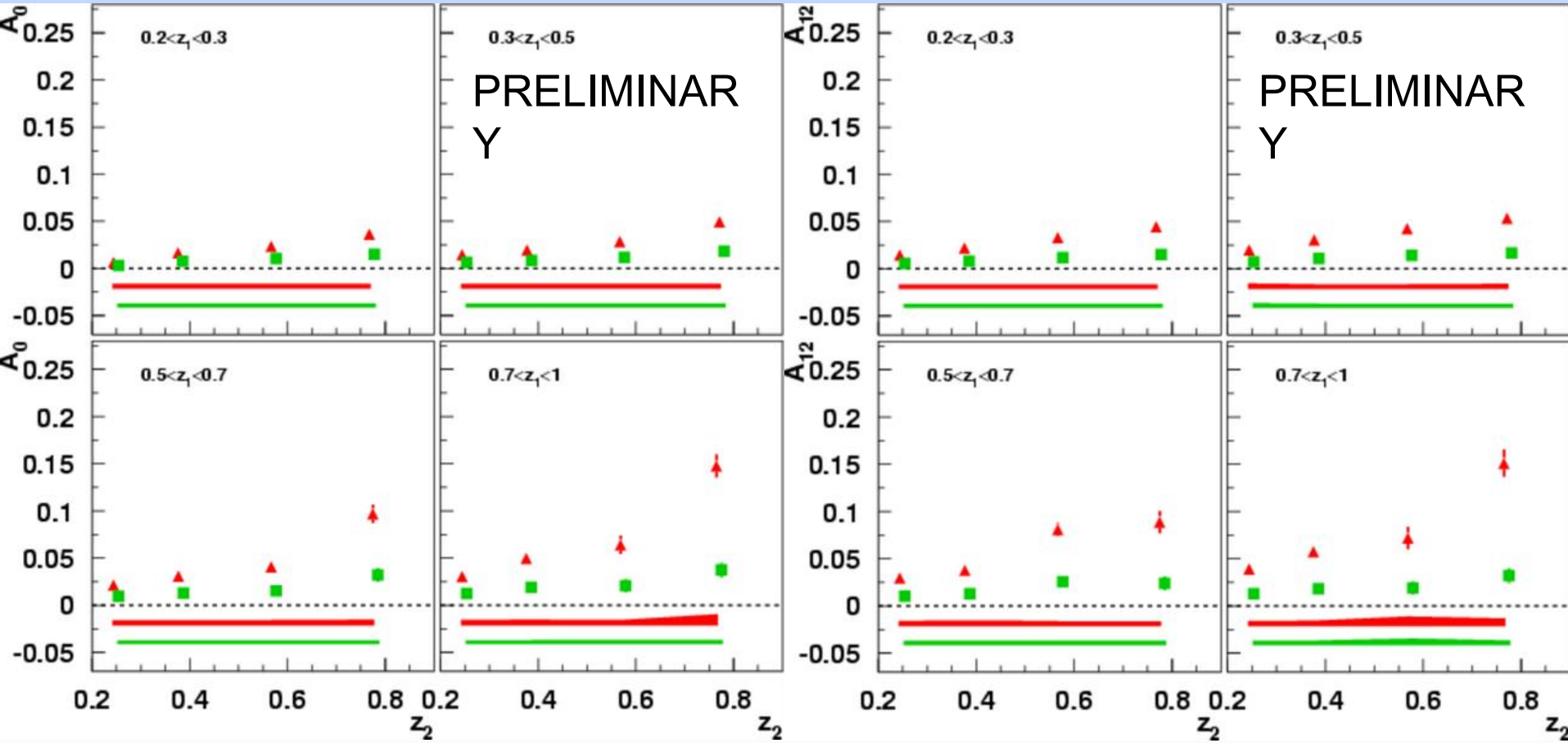
Integrated results:	
A_0(UL)	(2.67 ± 0.10 ± 0.26)%
A_{12}(UL)	(3.55 ± 0.08 ± 0.15)%
A_0(UC)	(1.11 ± 0.11 ± 0.22)%
A_{12}(UC)	(1.46 ± 0.09 ± 0.13)%



Collins asymmetries I: 4x4 z_1, z_2 binning

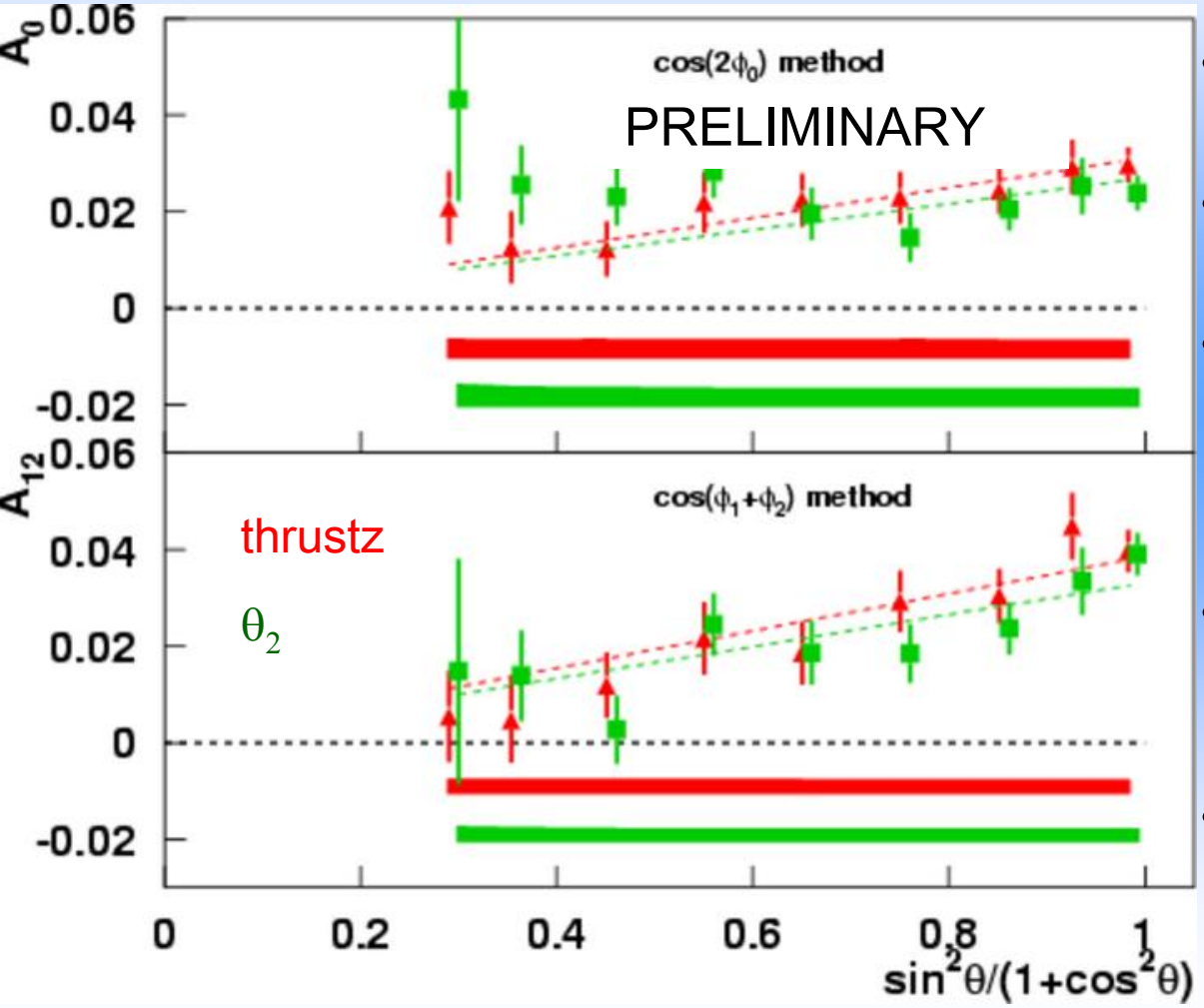
A_0 ($\cos(2\phi_0)$) moments

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



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

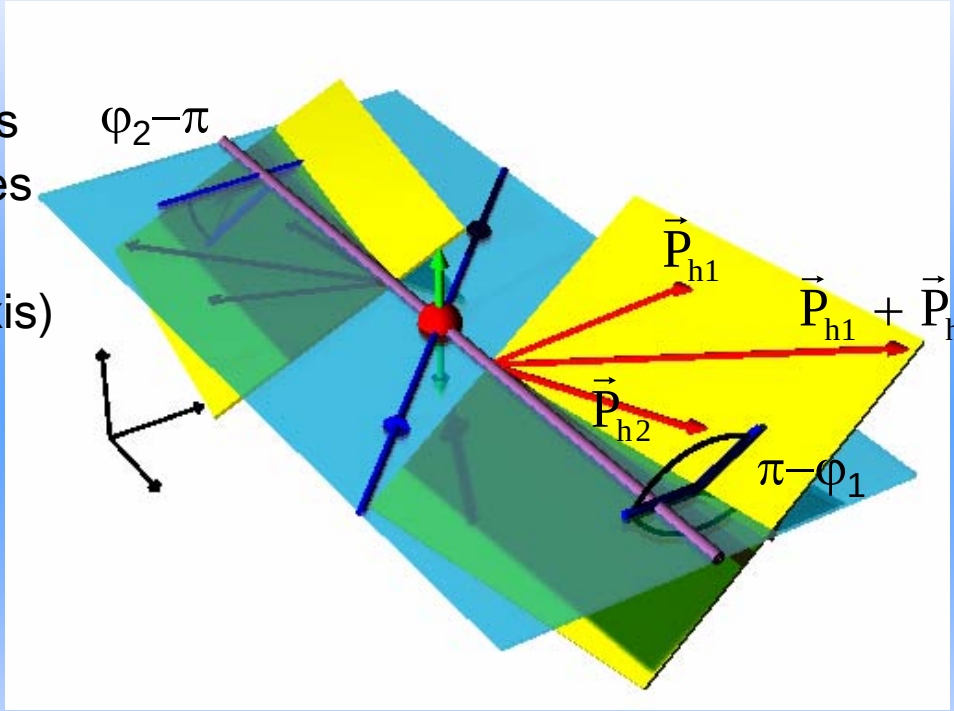
Collins asymmetries II: $\sin^2\theta/(1+\cos^2\theta)$ binning (UL)



- 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

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[PRD **67**,(2003)] and Artru,Collins[ZPhysC**69**(1996)]
- Early work by Collins, Heppelmann, Ladinsky [NPB**420**(1994)]



Model predictions by:

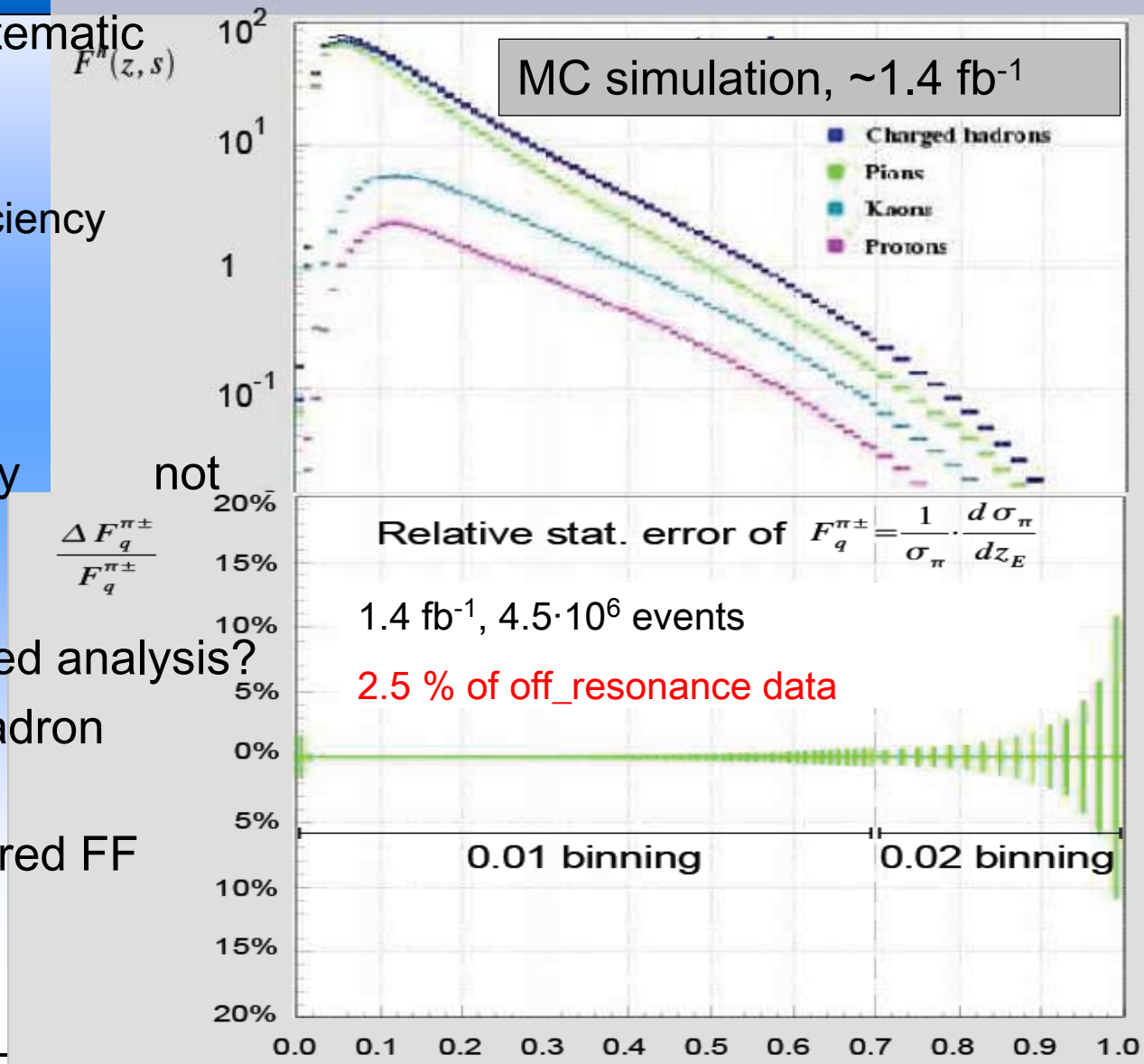
- Jaffe et al. [PRL **80**,(1998)]
- Radici et al. [PRD **65**,(2002)]

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

Unpolarized FFs

- Performed Systematic studies:
  - Smearing
  - Tracking efficiency
  - Acceptance
  - Energy scale
- Particle ID study not yet finished
- AKK: Try flavor tagged/enhanced analysis?
- How about 2 hadron analysis

→ favored,disfavored FF



$z_E = \frac{2E_\pi}{\sqrt{s}}$

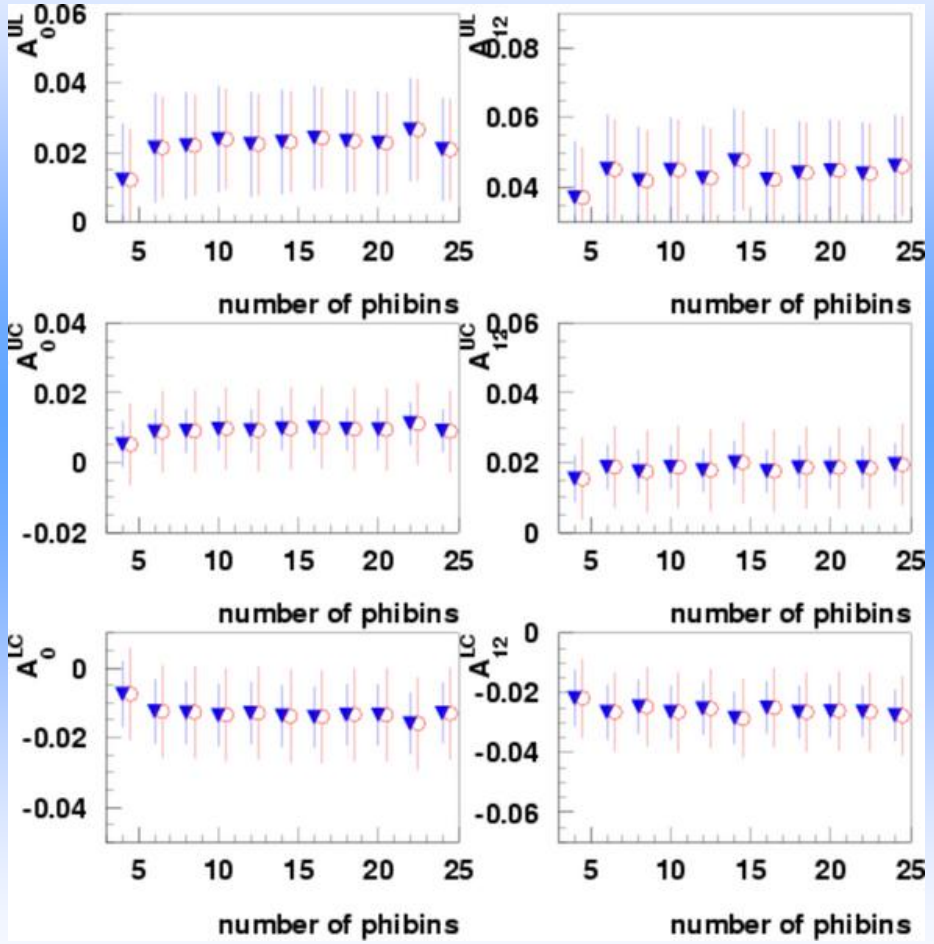
Summary and outlook

- Double ratios:
  - double ratios from data
  - most systematic errors cancel
- Analysis procedure passes all null tests
- Systematic uncertainties understood
- Statistics increased from 29 → 547 fb^{-1}
- → Significant nonzero asymmetry with double ratios are observed
- UL/C about half as large UL/L double ratios
- Data can be used for more sophisticated analysis
- Paper with 29 fb^{-1} U/L double ratios published (PRL96:232002,2006)

- Analysis almost finalized, smalller additions planned (k_t dependence of Collins effect, parameterizations)
- Interference fragmentation function analysis started
- Many more QCD/Spin related studies possible (unpol FFs, timelike DVCS, Λ Polarimetry)

Backup Slides

Why correction factors of 1.2 and 0.55?

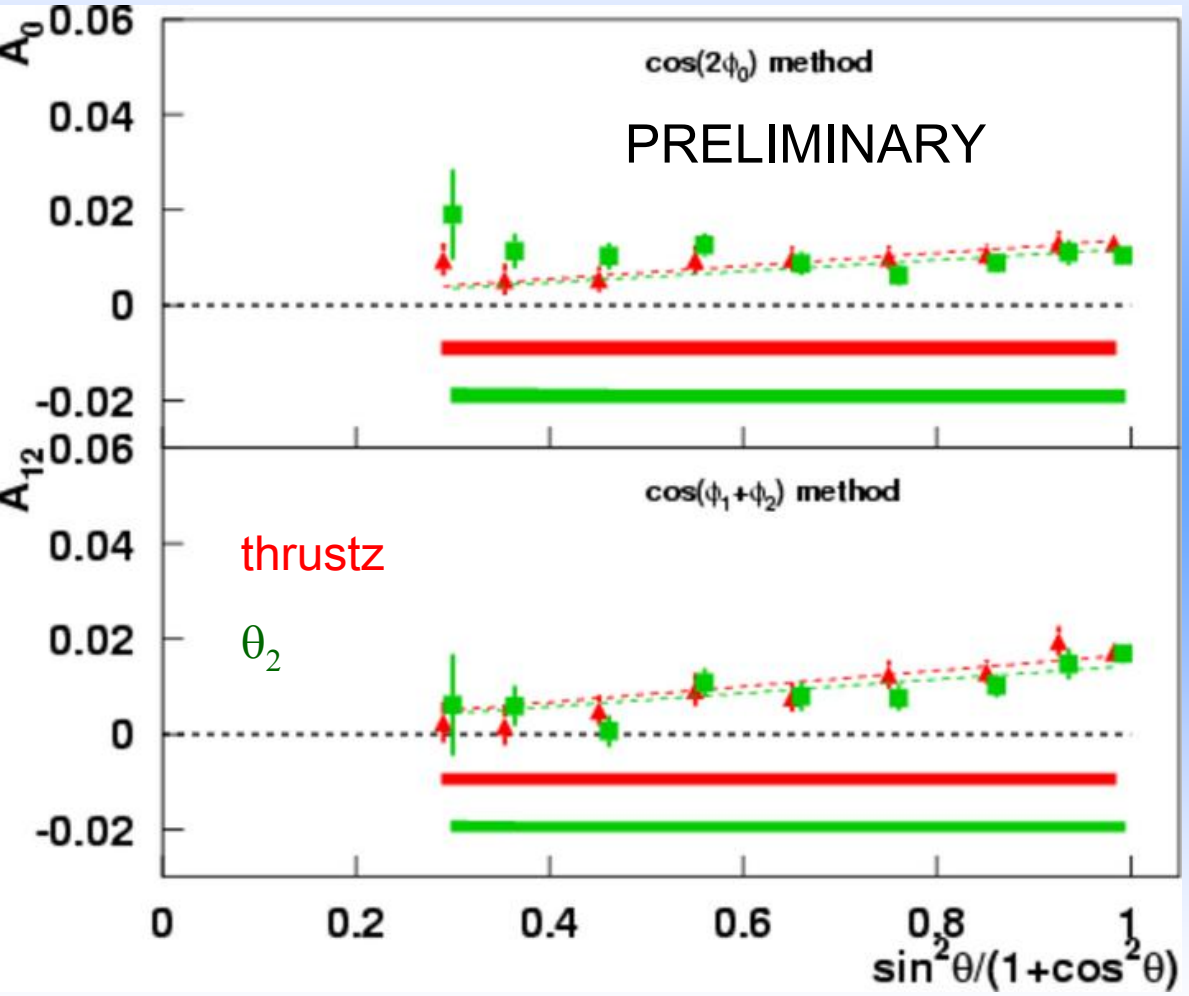


- Charged pion pairs are the sum of U and L

➔ Errors are correlated when building double ratios UC or LC

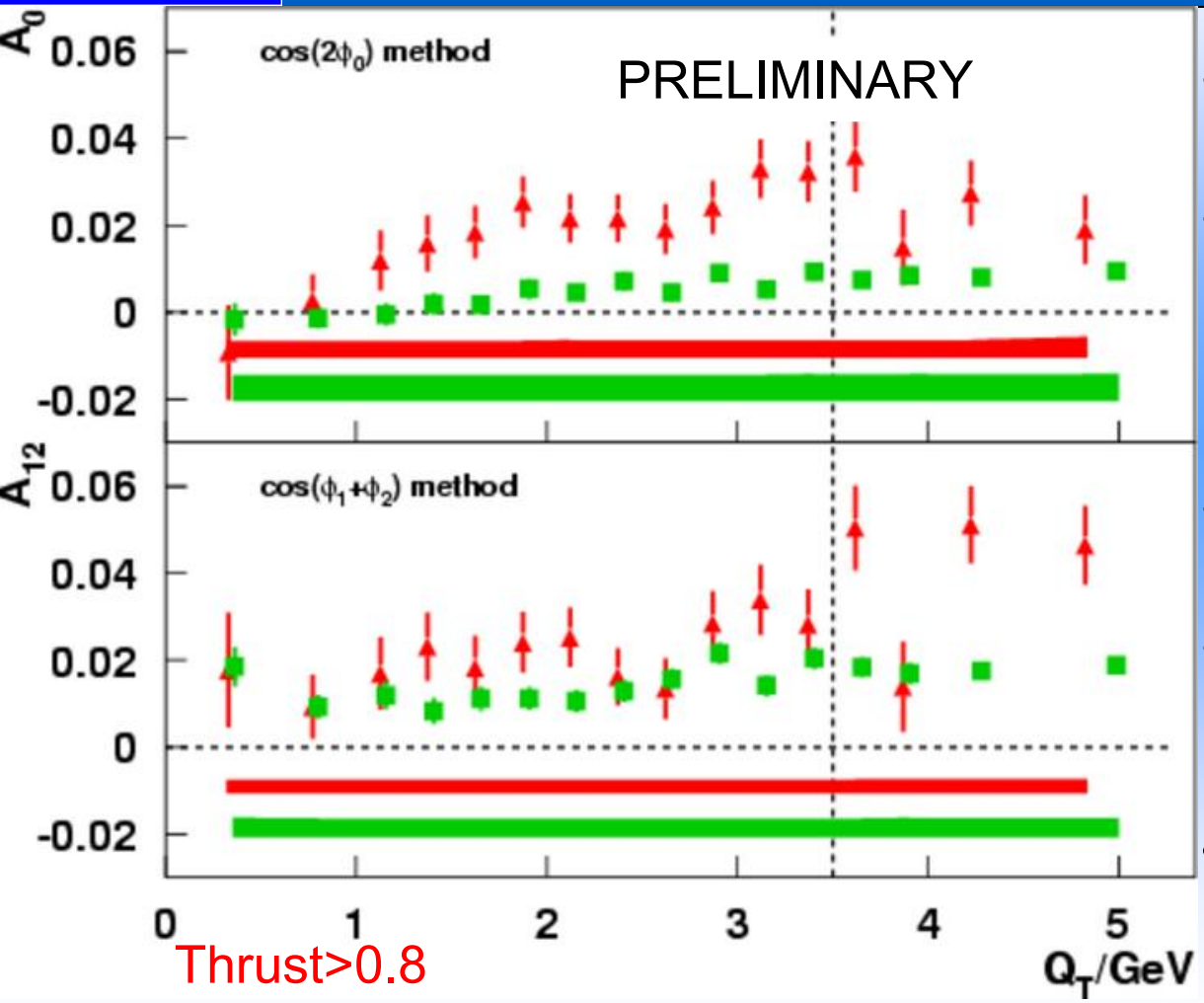
- Division of histograms takes correlation not into account
- Proper error calculation confirms correction factors found in correlation studies and χ^2 distributions

Collins asymmetries IIa: $\sin^2\theta/(1+\cos^2\theta)$ binning (UC)



- Nozeron 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)
- Similar behavior, smaller magnitude as UL asymmetries

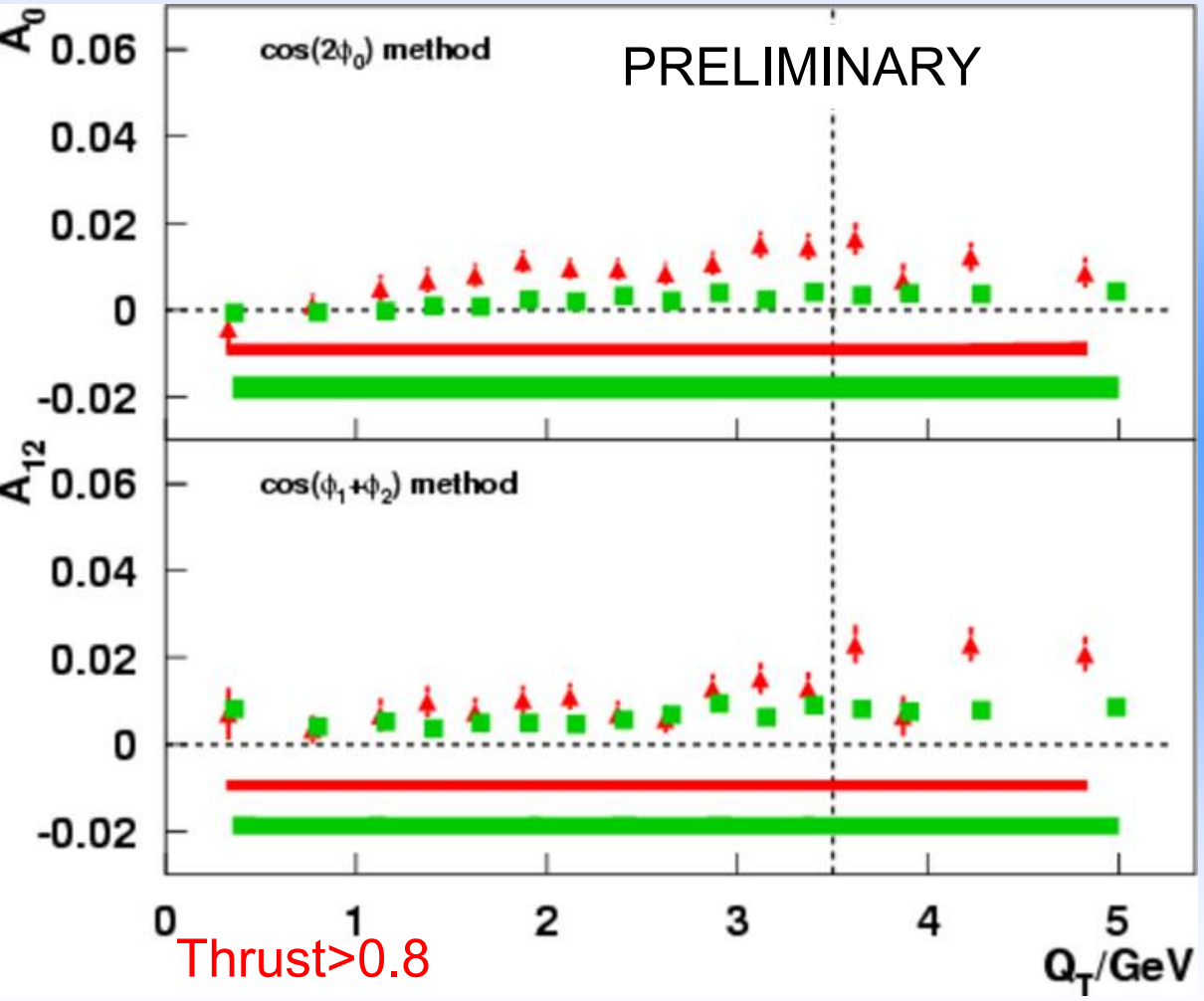
Collins asymmetries III: Q_T binning (UL)



- 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

Thrust<0.8 (not corrected for heavy quark contributions)

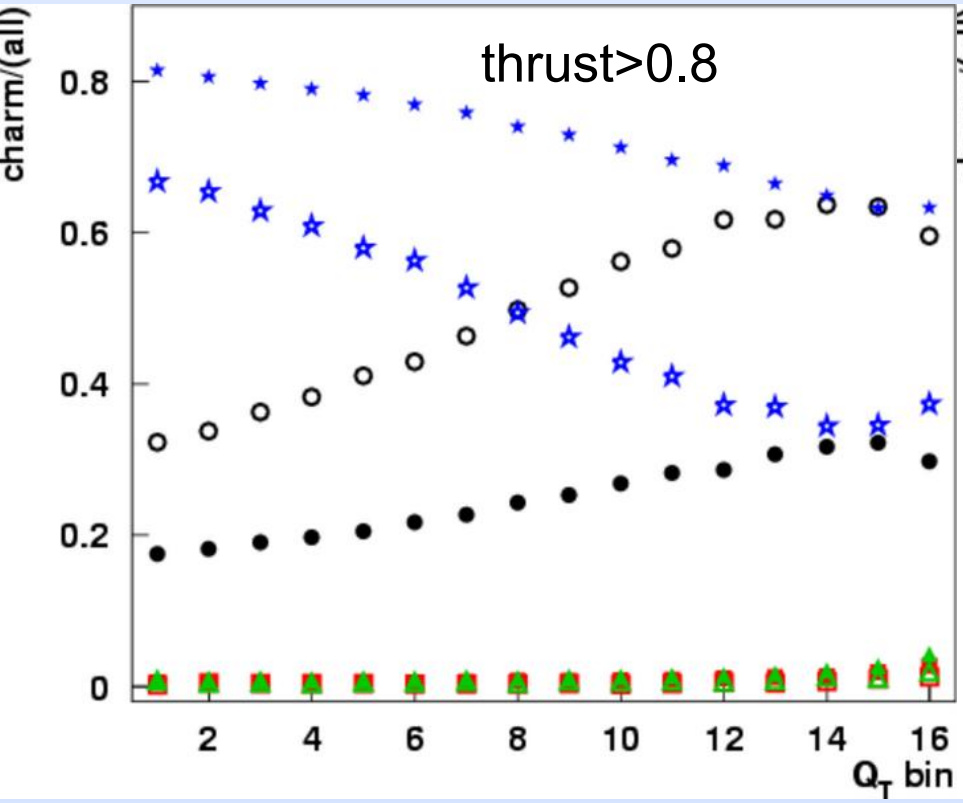
Collins asymmetries IIIa: Q_T binning (UC)

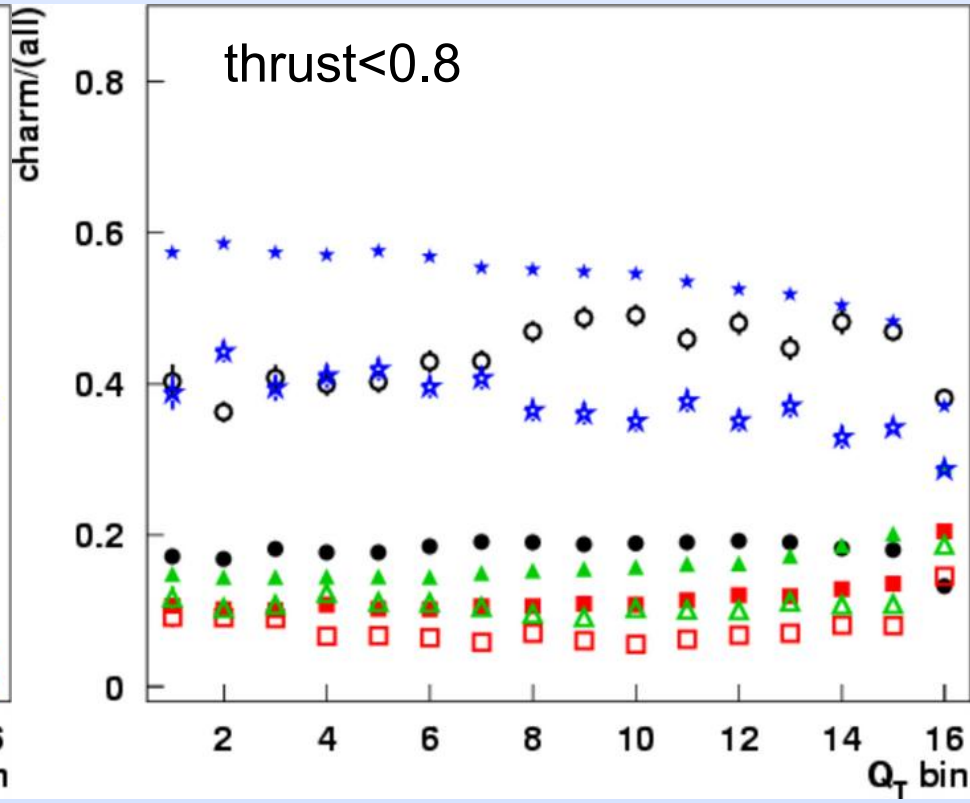


- Reduced asymmetries in low thrust sample
- At low thrust significant heavy quark contribution
- High Q_T (>3.5 GeV) asymmetries from beam related BG
- similar behavior, but smaller magnitude as UL asymmetries

Thrust<0.8 (not corrected for heavy quark contributions)

B, charm and uds contributions in the data





uds quarks
charm quarks
Charged B-mesons
Netral B-mesons

Open symbols: charm enhanced data sample used for charm correction
Full symbols: main data sample