Results on Charged Pion Correlations and Prospects for Detecting P-odd Effects

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P- and CP-odd Effects in Hot and Dense Matter, BNL, 4/29/2010

Motivation

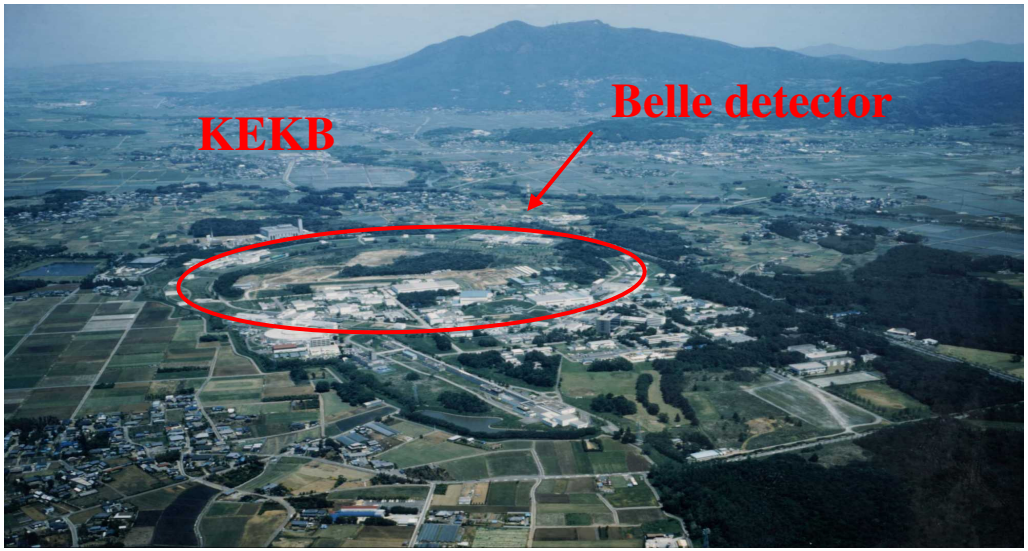
- Local Parity Violating Effects can lead to azimuthal Asymmetries in Quark Fragmentation (see Talk by Z. Kang)
- Can be measured in e^+e^- into light mesons
- At Belle we plan to extract local P-odd signals
- Similar Asymmetries for Single and Di-Hadrons have already been measured with high precision

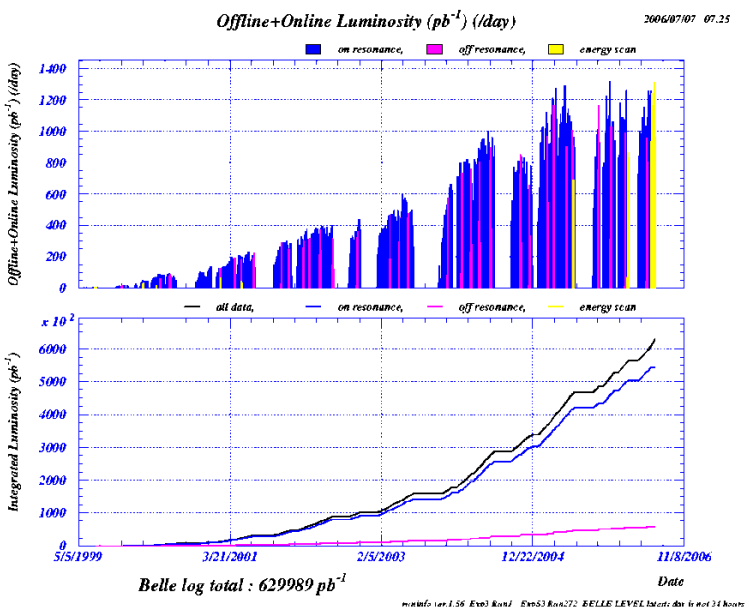
Outline

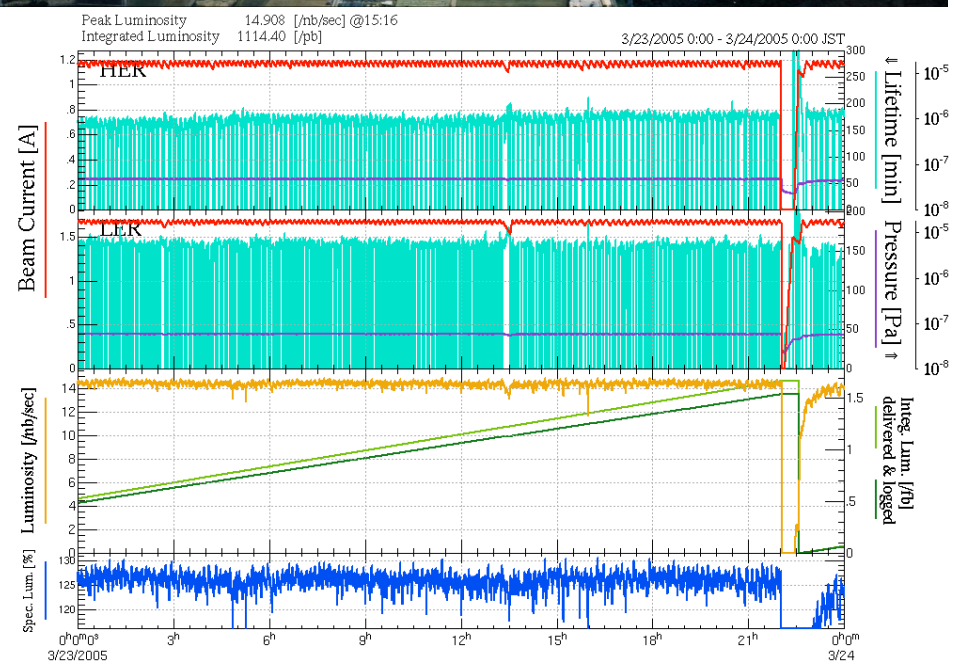
- Belle Experiment
- Origins of Azimuthal Asymmetries in Single Hadron Fragmentation
  - *Fragmentation in P-odd Bubbles*
  - *Collins Effect*
- Precision Measurements of Single Hadron Azimuthal Asymmetries in Quark Fragmentation
- Di-Hadron Measurements
  - *Advantages of Measuring relative Asymmetries*
  - *Example: Interference Fragmentation Function*
  - *Local Parity Violating Signal: Jet Handedness*
- Summary & Conclusion

KEKB: $L > 2.11 \times 10^{34} cm^{-2} s^{-1}$!!

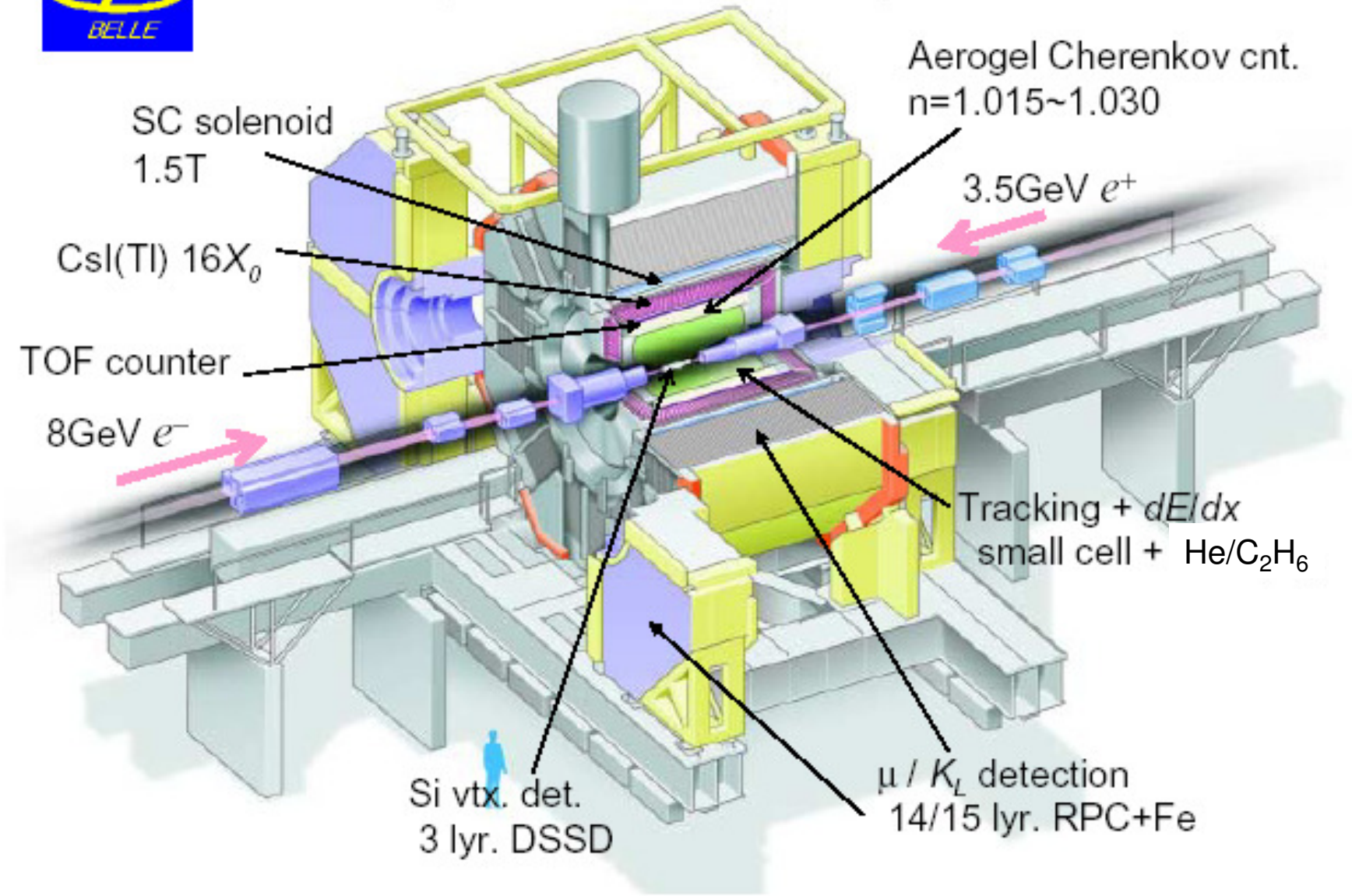
- Asymmetric collider
- 8GeV e^- + 3.5GeV e^+
- $\sqrt{s}$ = 10.58GeV ($\Upsilon(4S)$)
- $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
- Continuum production: 10.52 GeV
- $e^+e^- \rightarrow q\bar{q}$ (u,d,s,c)
- Integrated Luminosity: > 1000 fb^{-1}
- >70 fb^{-1} => continuum





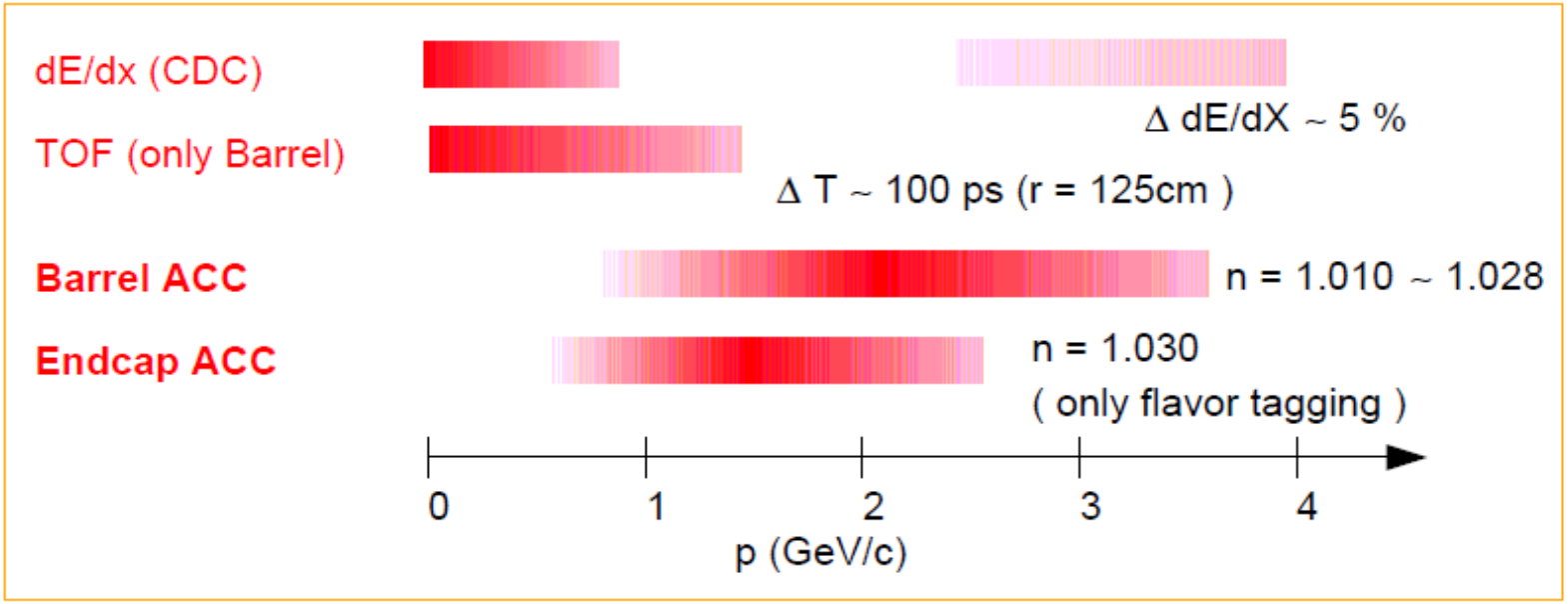


Belle Detector

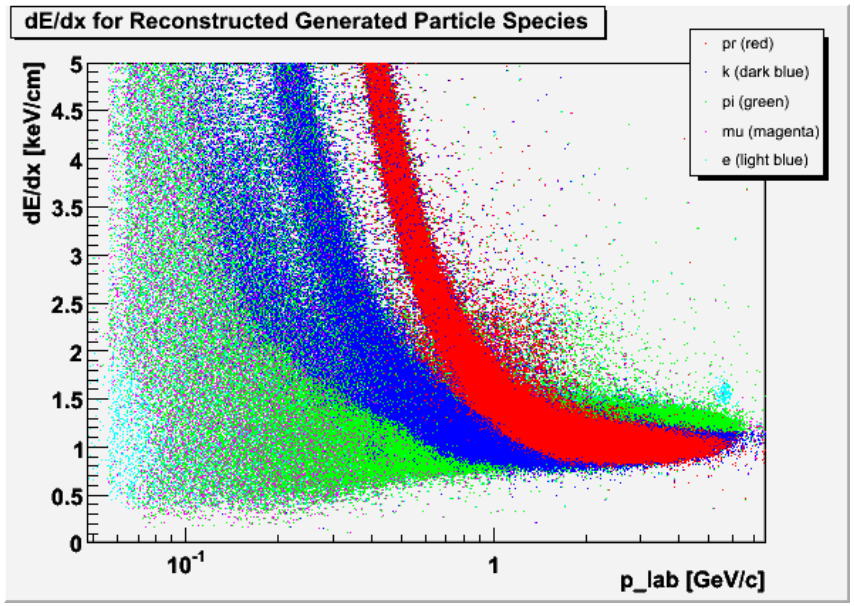


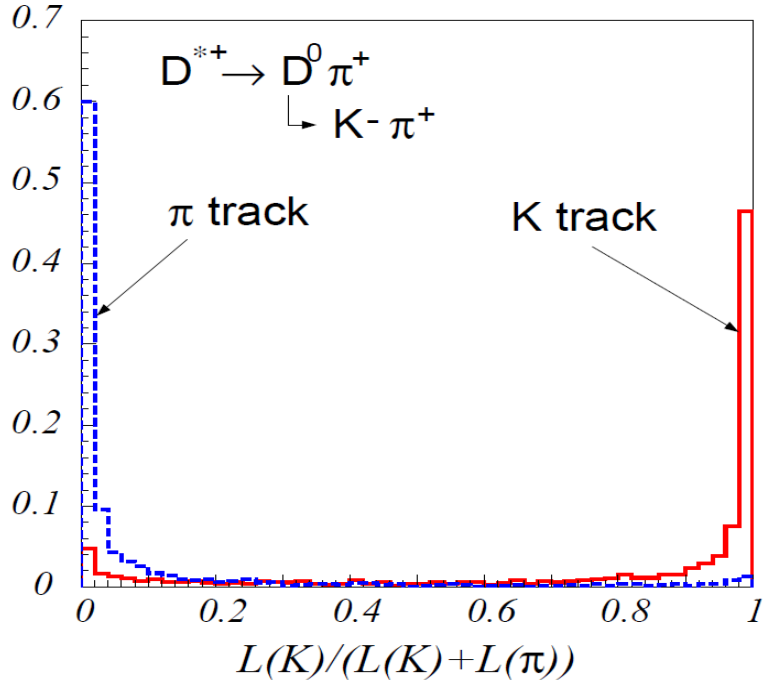
Large acceptance, good tracking and particle identification!

Belle PID

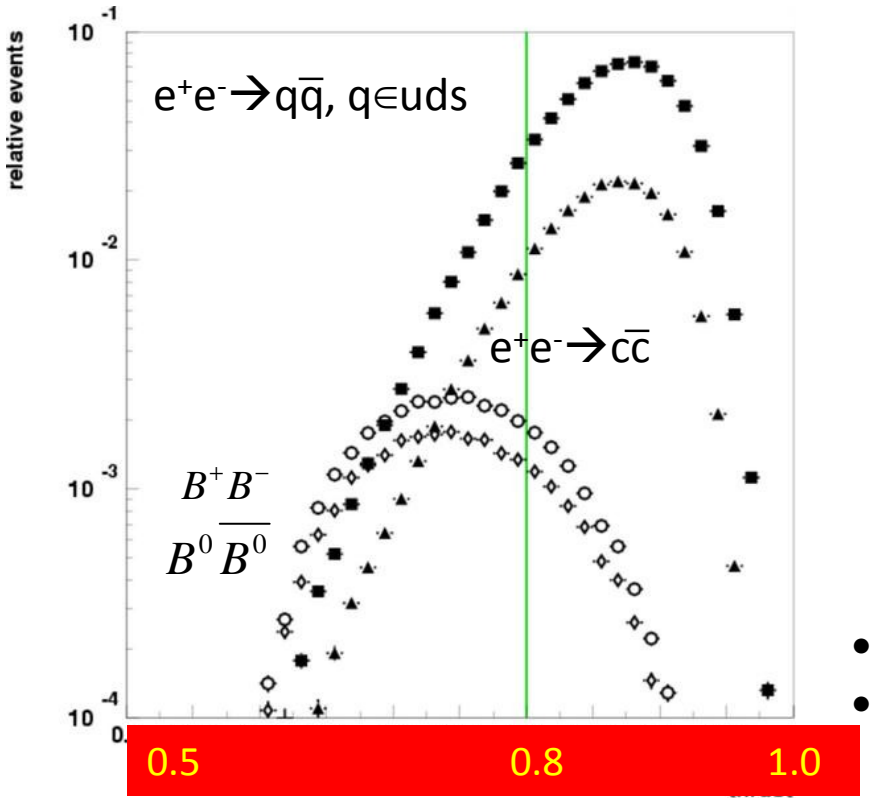

dE/dx (CDC)
Δ dE/dX ~ 5 %
TOF (only Barrel)
Δ T ~ 100 ps (r = 125cm)
Barrel ACC
n = 1.010 ~ 1.028
Endcap ACC
n = 1.030
(only flavor tagging)
0
1
2
3
4
p (GeV/c)

MC

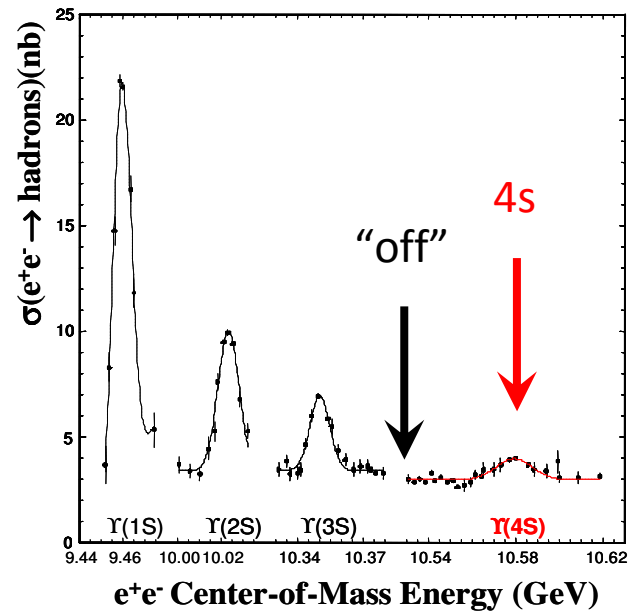

dE/dx for Reconstructed Generated Particle Species
pr (red)
k (dark blue)
pi (green)
mu (magenta)
e (light blue)
dE/dx [keV/cm]
p_lab [GeV/c]


D*+ → D0 π+
K- π+
π track
K track
L(K)/(L(K)+L(π))

Measuring Light Quark Fragmentation Functions on the ϒ(4S) Resonance

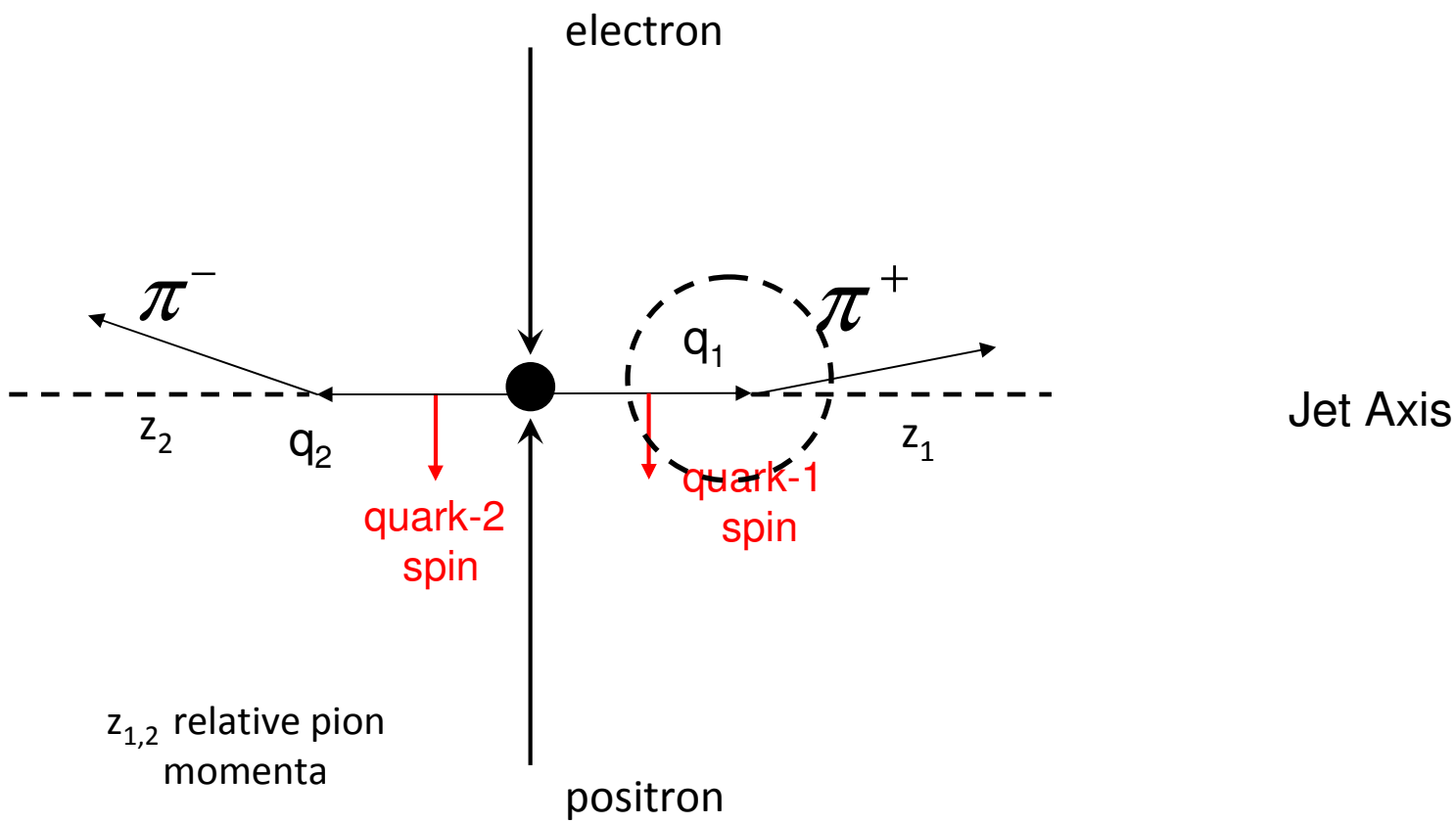


$$Thrust: T = \frac{\sum_i |p_i \cdot \hat{n}|}{\sum_i |p_i|}$$



- small B contribution (<1%) in high thrust sample
- >75% of X-section continuum under ϒ (4S) resonance
- 73 fb^{-1} ➔ 662 fb^{-1}

Event Topology



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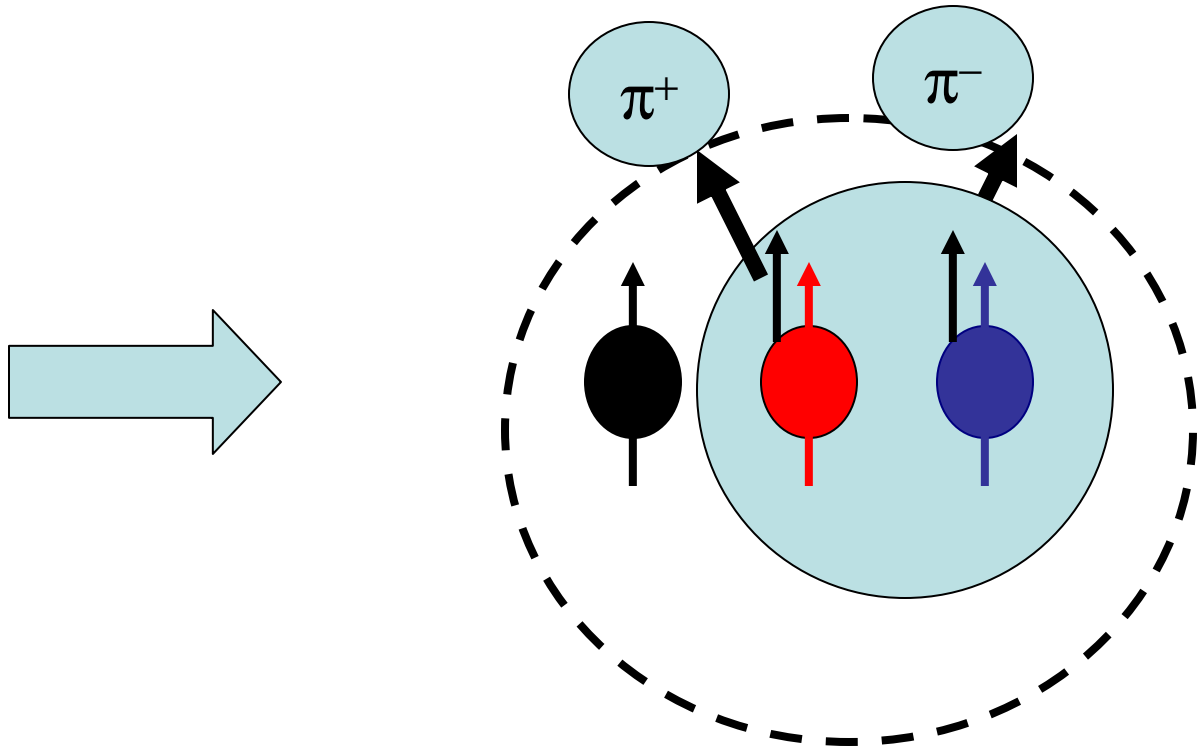
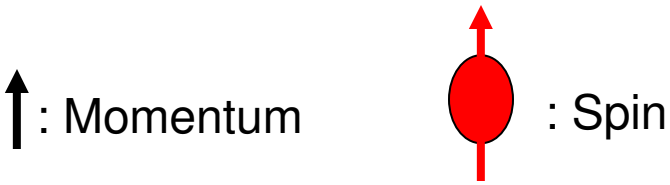
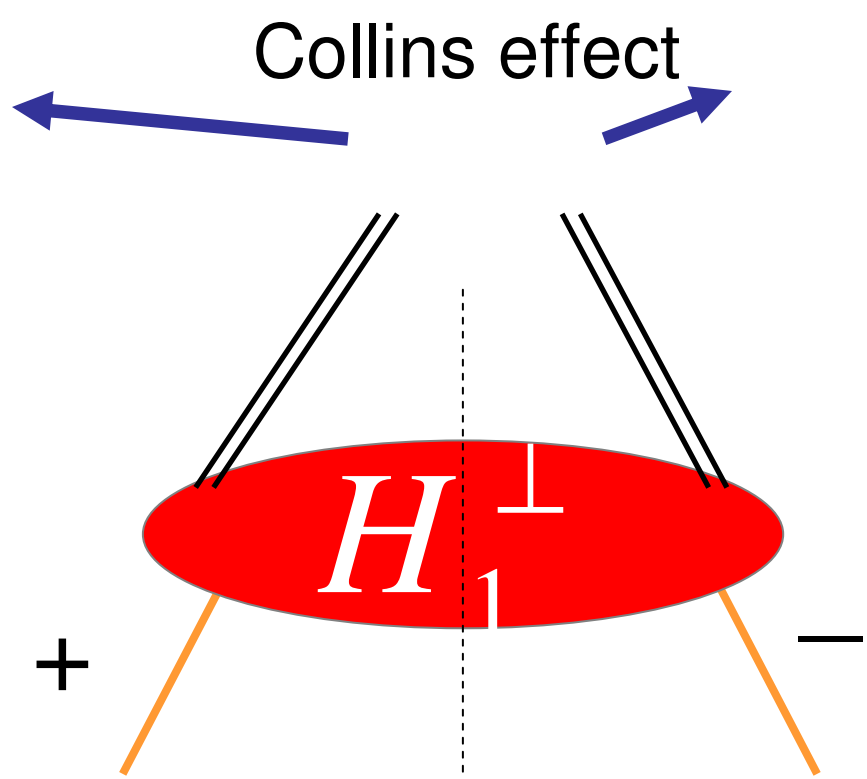
Fragmentation in P odd Bubbles leads to Azimuthal Asymmetries





- Fragmentation in P-odd bubble leads to left right asymmetry

Chiral odd FFs are Competing Source for Asymmetries

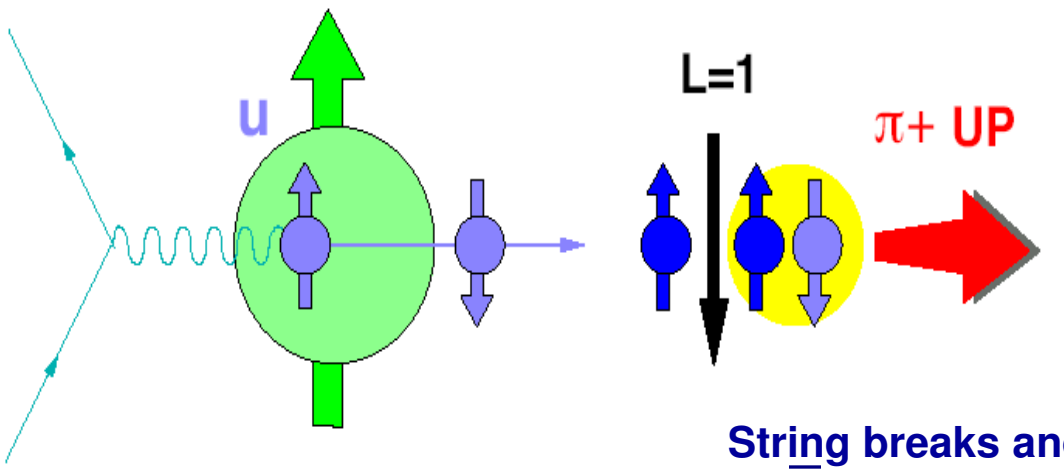


$H_1^\perp$ **: Collins FF**

J.C. Collins, Nucl. Phys. B396, 161(1993)

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 $d\bar{d}$-pair with spin -1 is inserted.

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

In Artru Model: favored (ie $u \rightarrow \pi^+$) and disfavored (ie $u \rightarrow \pi^-$) Collins function naturally of opposite sign

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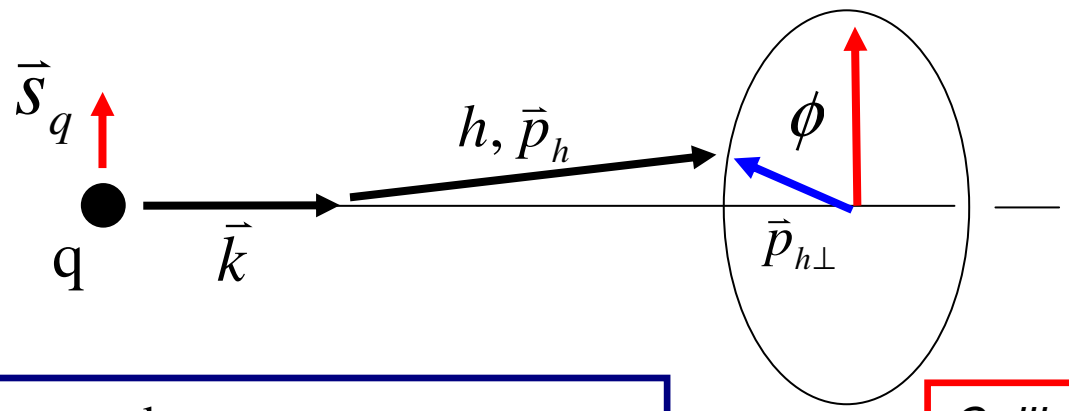
Tranverse Spin Dependent Azimuthal Asymmetries in Quark Fragmentation

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:

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

$$\propto \sin\phi$$

In e^+e^- : Need Correlation between Hemispheres !

- Quark spin direction unknown: measurement of Collins or P odd function in one hemisphere is not possible *sin* φ modulation will average out.

- Correlation between two hemispheres with *sin* φ_i single spin asymmetries results in $cos(\varphi_1+\varphi_2)$ modulation of the observed di-hadron yield.

- Collins FF and P odd FF lead to same observable

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

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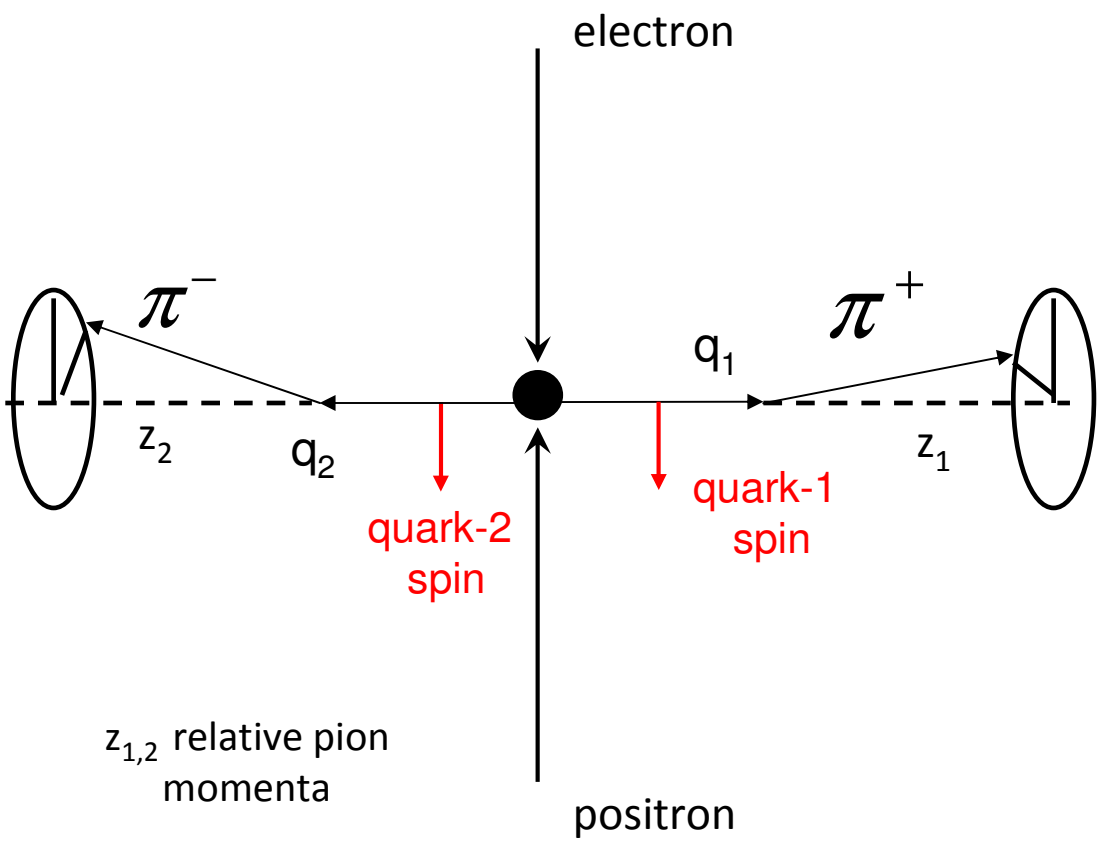
Azimuthal di-Hadron Correlations In e^+e^- Annihilation into Quarks!



Experimental requirements:

- Small asymmetries ➔ very large data sample!
- Good particle ID to high momenta.
- Hermetic detector

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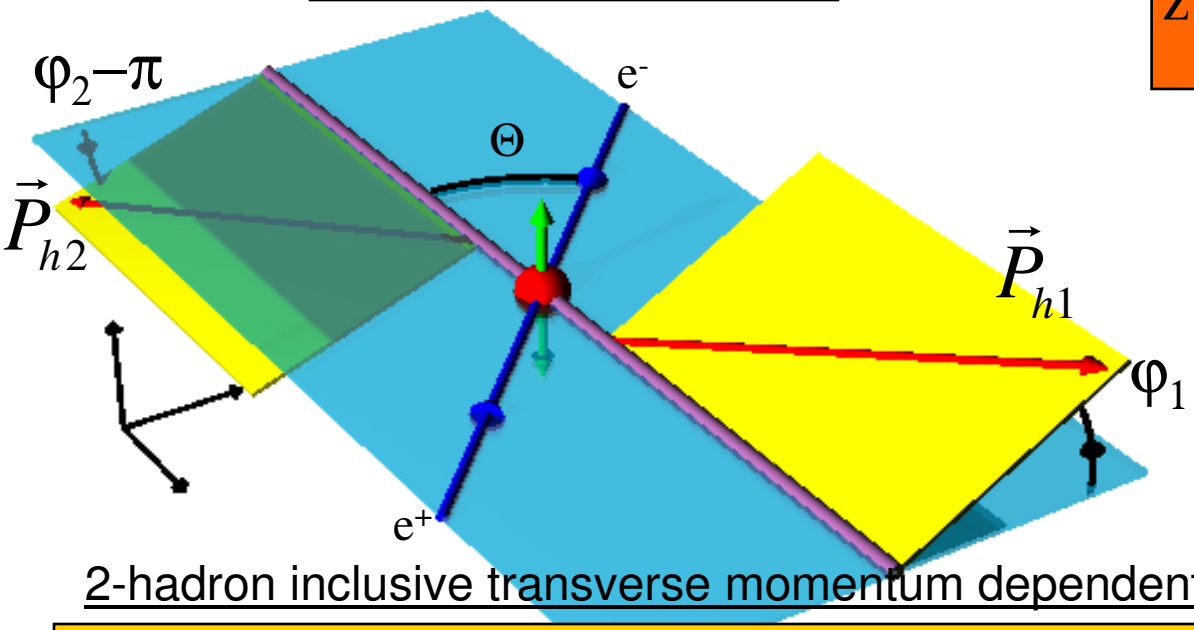
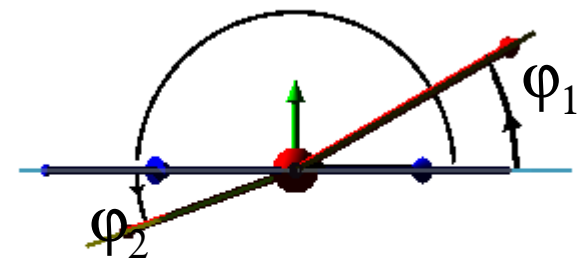
Azimuthal Asymmetries in e^+e^- : Angles and Cross section $\cos(\phi_1+\phi_2)$ method

e+e- CMS frame:

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





[D.Boer: **PhD thesis(1998)**]

2-hadron inclusive transverse momentum dependent cross section:

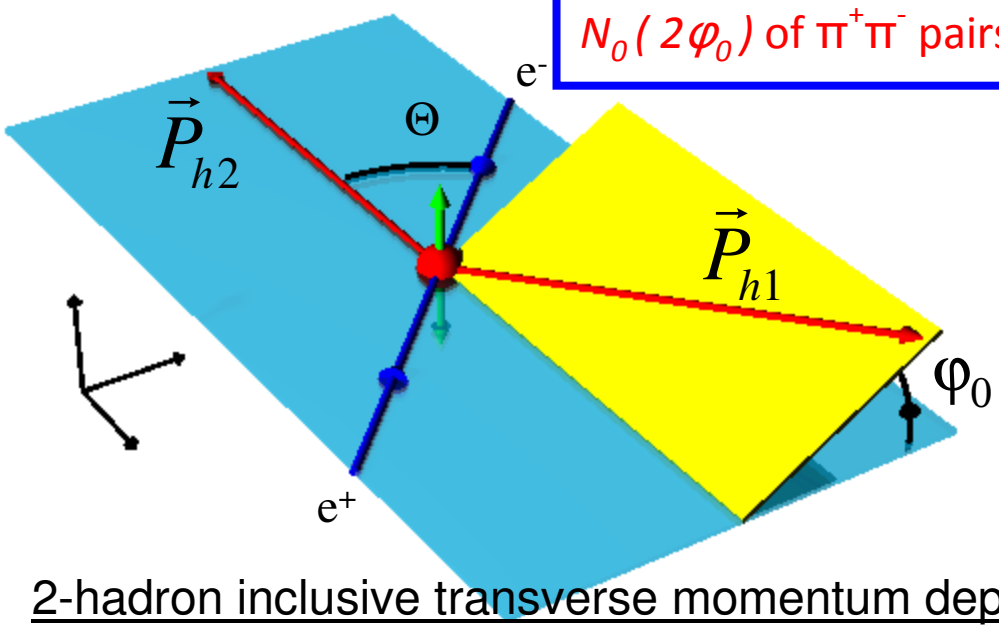
$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{d\Omega dz_1 dz_2 d^2\boldsymbol{q}_T} = \cdots B(y)\cos(\varphi_1+\varphi_2) H_1^{\perp[1]}(z_1)\overline{H}_1^{\perp[1]}(z_2)$$

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

Net (anti-)alignment of transverse quark spins

Collins Fragmentation: Angles and Cross Section
cos(2ϕ_0) Method (CMS Frame)

Observable: yield,
$N_0(2\varphi_0)$ of $\pi^+\pi^-$ pairs



Independent of thrust-axis

Convolution integral $\mathcal{I}$ over transverse momenta

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

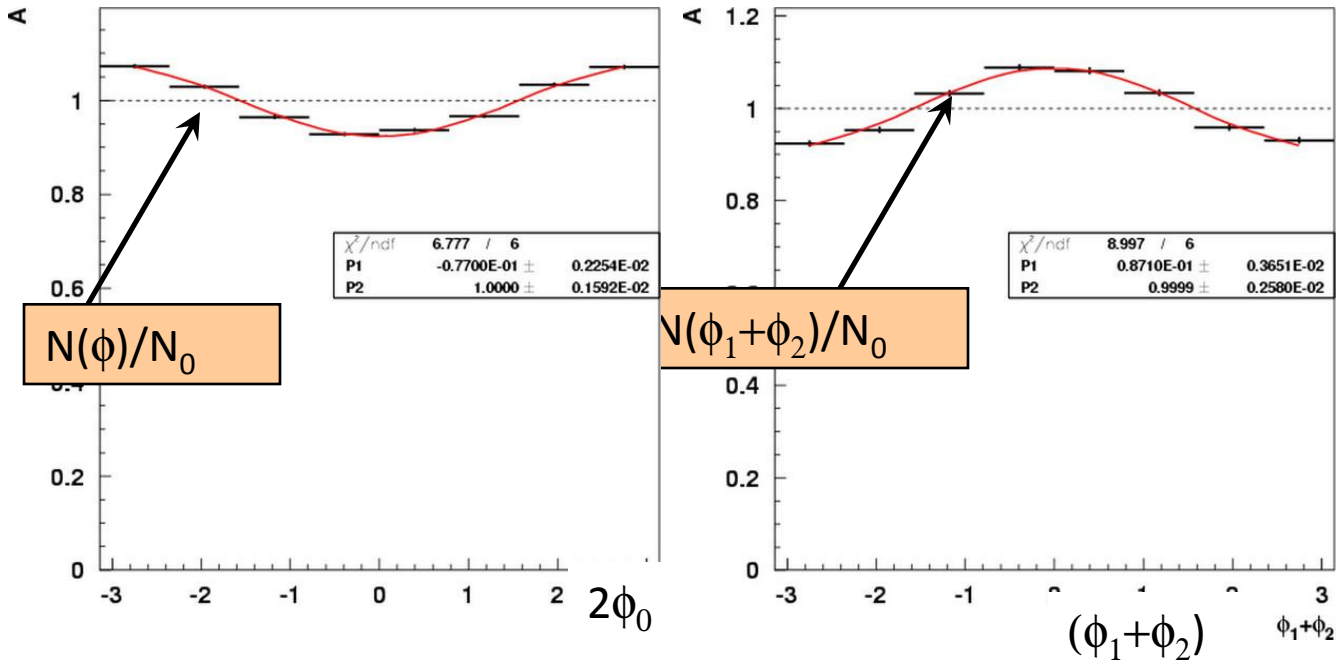
2-hadron inclusive transverse momentum dependent cross section:

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

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

Net anti-alignment of transverse quark spins

Examples of fits to azimuthal asymmetries



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

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

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 π^0

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

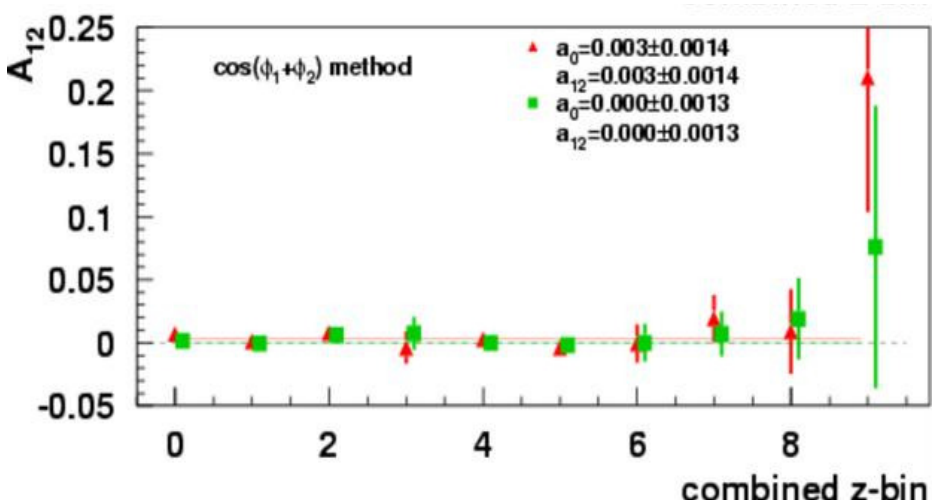
- Unlike-sign pion pairs (U):
  (favored x favored + unfavored x unfavored)
- Like-sign pion pairs (L):
  (favored x unfavored + unfavored x favored)
- $\pi^{\pm}\pi^0$ pairs
  (favored + unfavored) x (favored + unfavored) UL
- P.Schweitzer(**[hep-ph/0603054]**): charged $\pi\pi$ pairs are similar (and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

➔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.

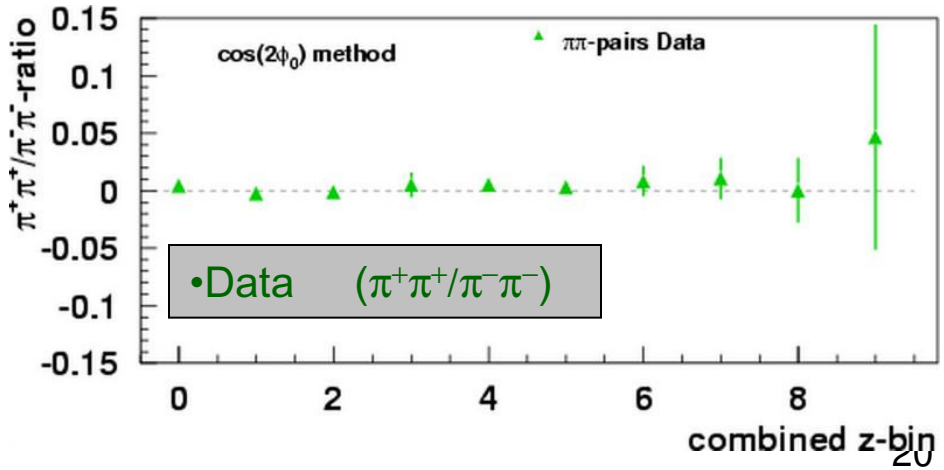
Testing the double ratios with MC



- Asymmetries do cancel out for MC
- Double ratios of $\pi^+\pi^+/\pi^-\pi^-$ compatible with zero
- Mixed event pion pairs 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 (UL/L double ratios)
- uds MC (UL/C double ratios)



- Data ($\pi^+\pi^+/\pi^-\pi^-$)

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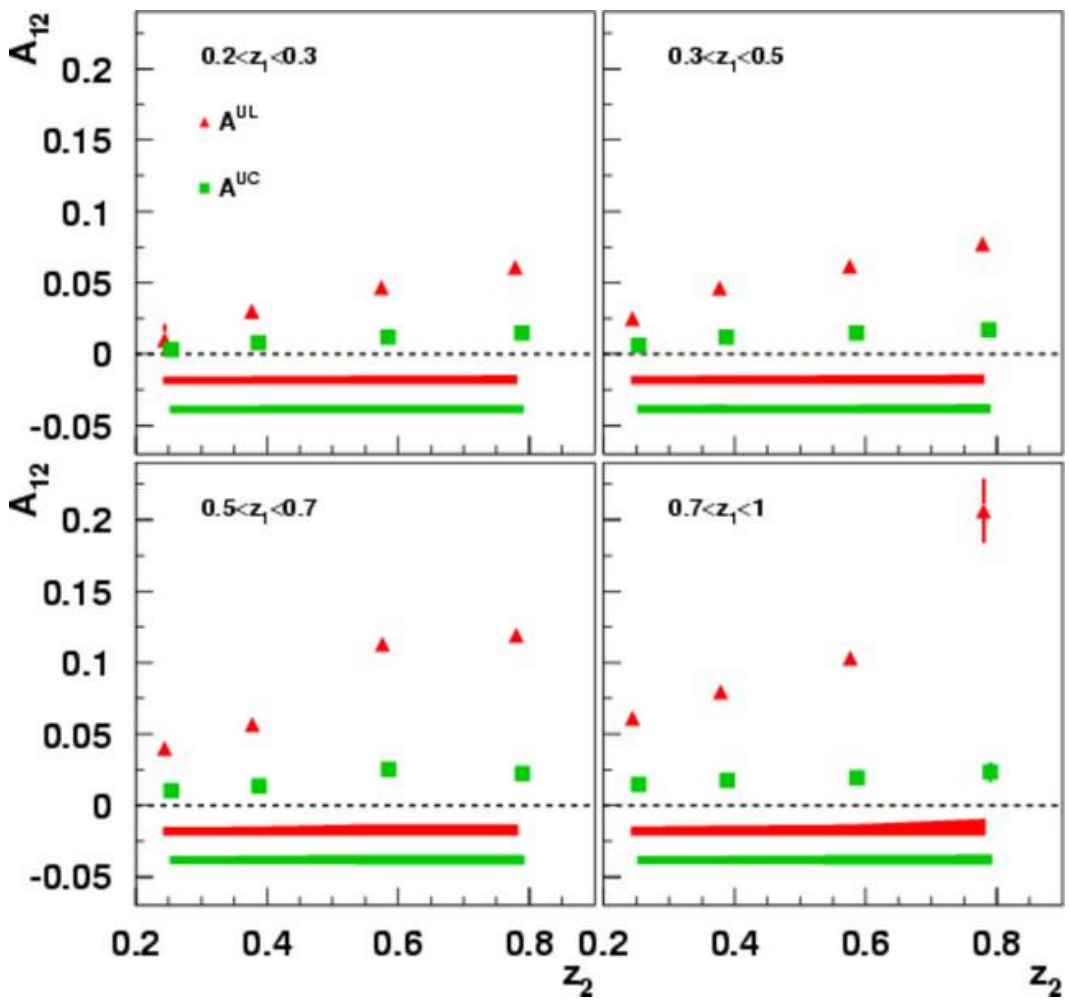
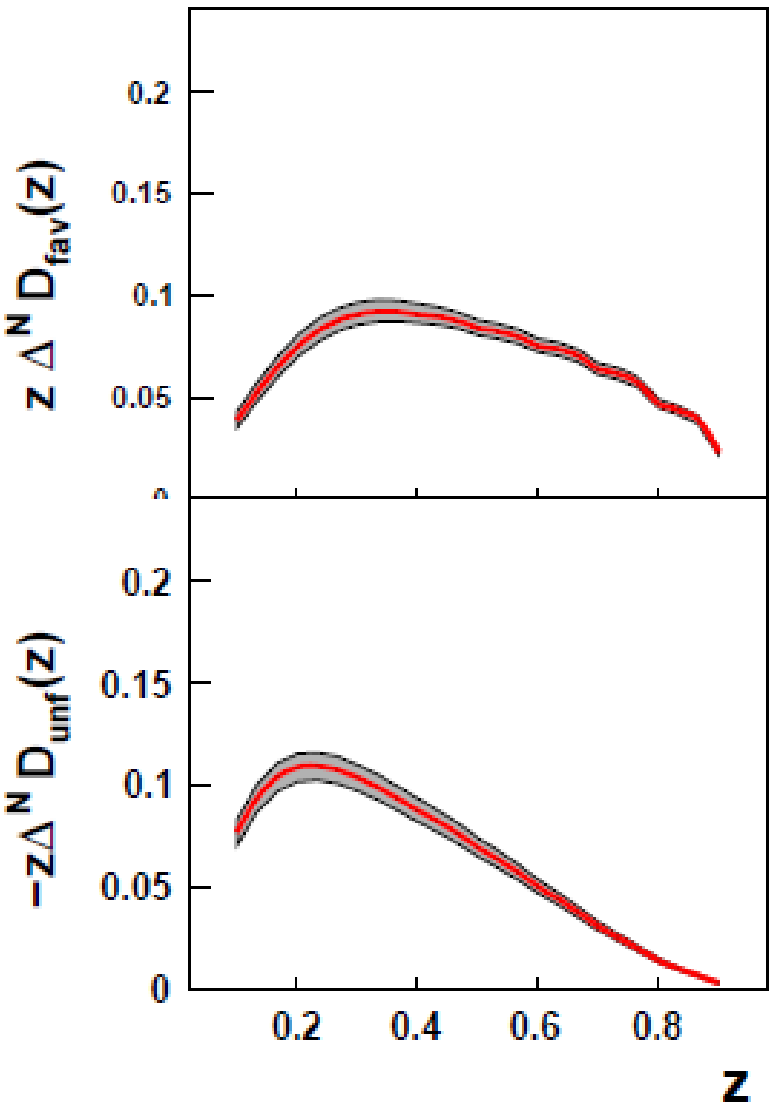
Collins Fragmentation at Belle



Belle 547 fb^{-1} data set
(Phys.Rev.D78:032011,2008.)

Extraction of the Collins FF

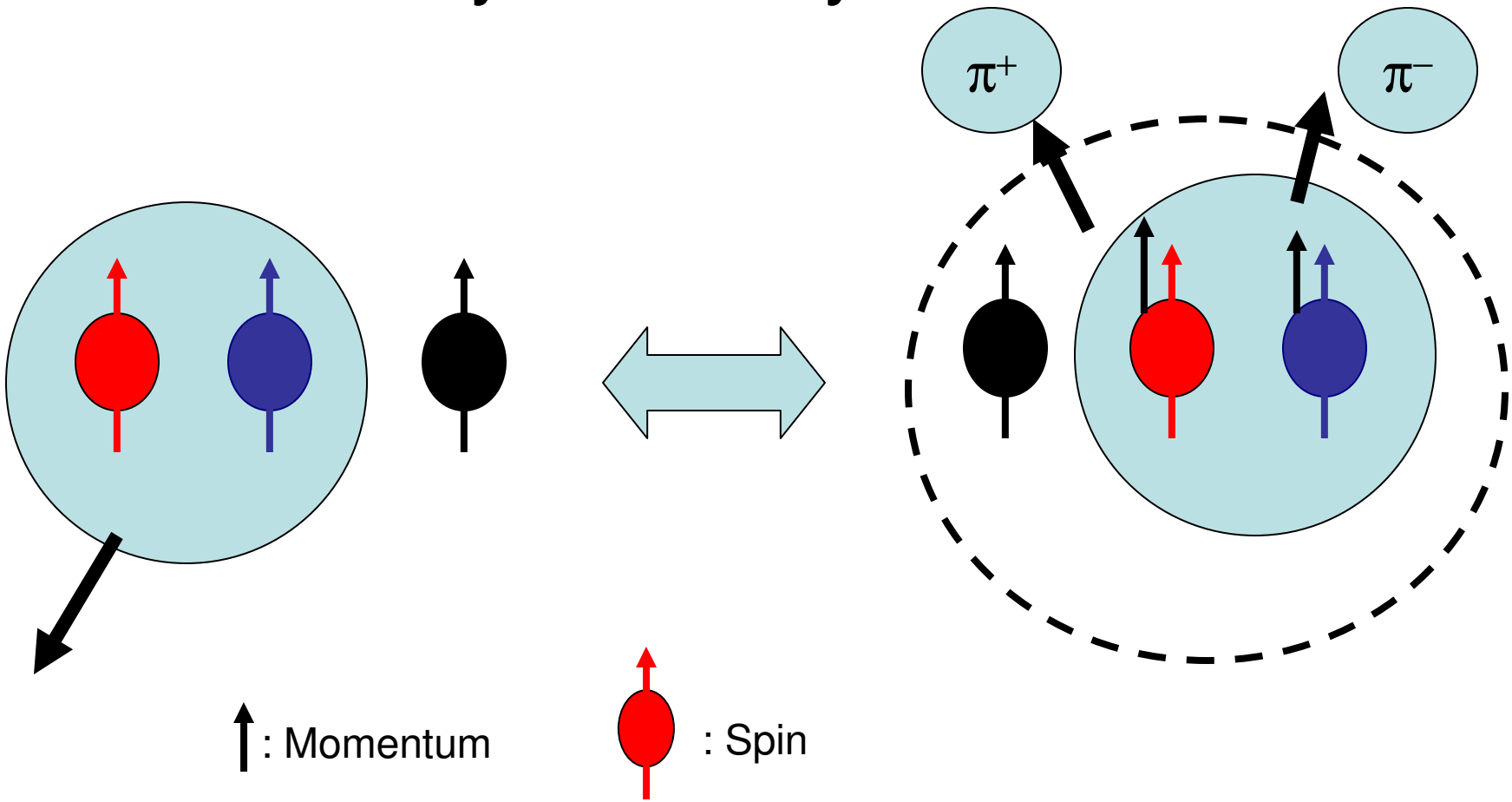


M. Anselmino, M. Boglione, (Turin U. & INFN, Turin) , U. D'Alesio, (Cagliari U. & INFN, Cagliari) , E. Leader, (Imperial Coll., London) , S. Melis, (INFN, Turin & Piemonte Orientale U., Alessandria) , F. Murgia, (INFN, Cagliari) , A. Prokudin, (Turin U. & INFN, Turin)

Talk given at 17th International Workshop on Deep-Inelastic Scattering and Related Subjects .
e-Print: **arXiv:0907.3999** [hep-ph]

Unfavored FF: different sign, similar magnitude

Mix of P-odd FF with Collins FF leads to Event by Event Asymmetries



- Coupling to Collins FF
- Averages out Event by Event since we do not know if quark or antiquark is in p-odd bubble

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Extracting Event by Event Correlations

- Correlation of $\tilde{H}_1^{\perp}$ and $H_1^{\perp}$ averages out event by event
- Extraction of moment in each event
- Distribution wider than in event mixed or MC
- This is work in progress

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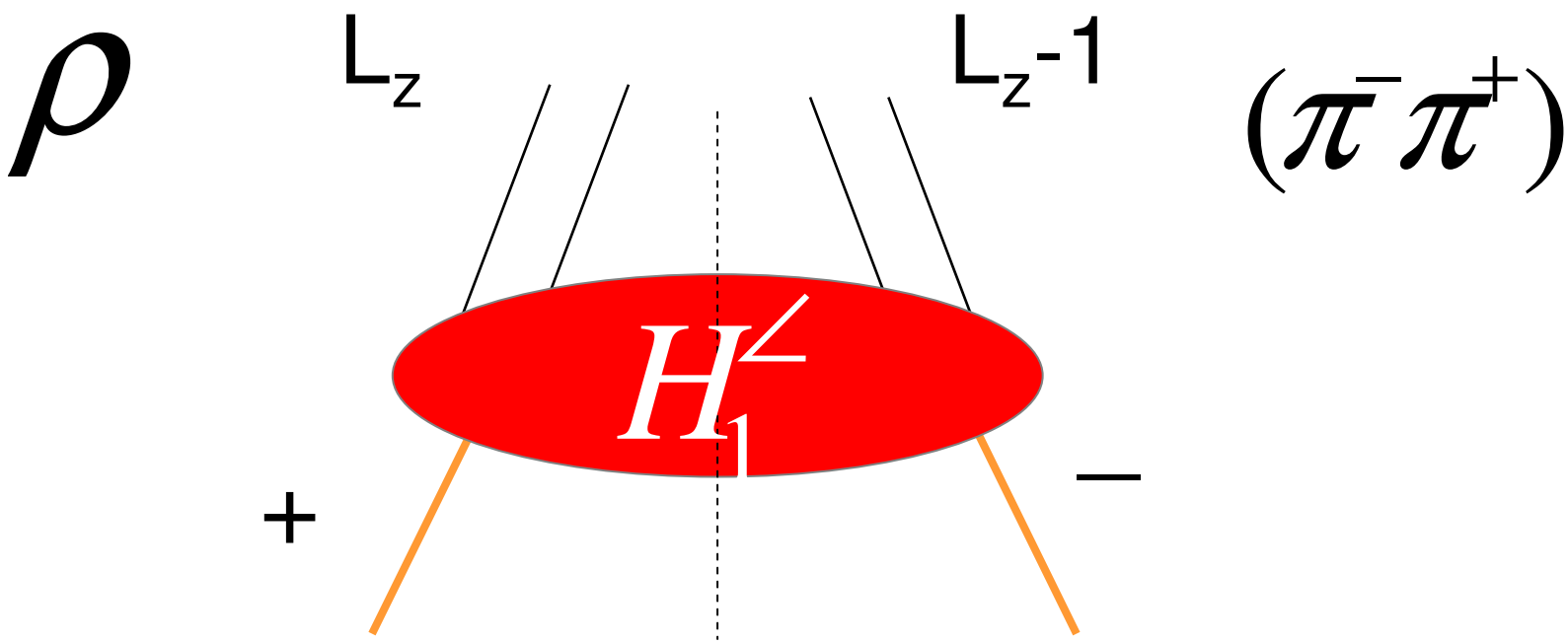
Two Hadron Azimuthal asymmetries

- Advantages:
  - Cancellation of systematic effects

- Disadvantages:
  - Dependence on decay phase space (M_{Inv})

Interference Fragmentation Function



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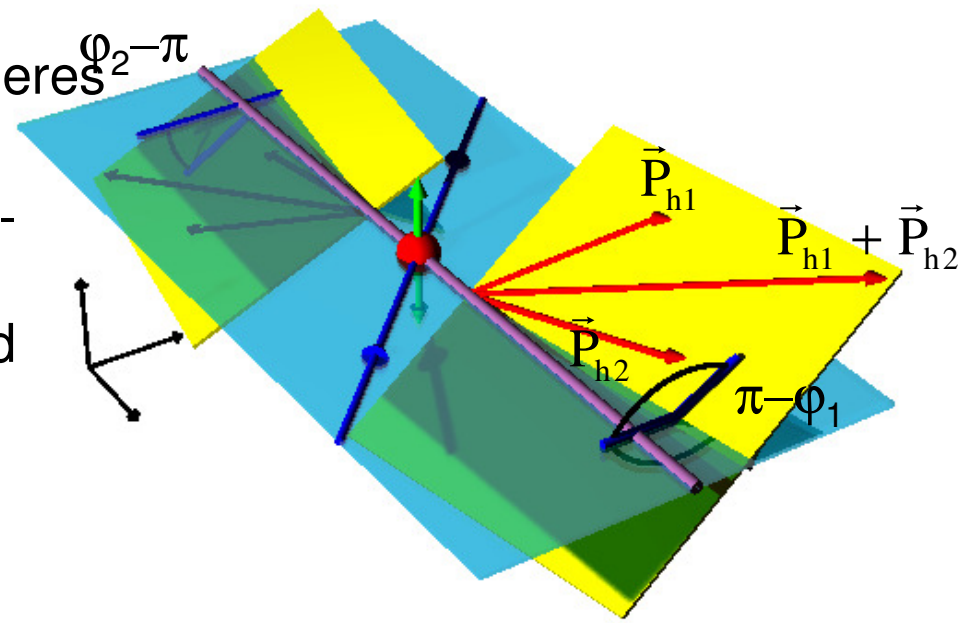
Interference fragmentation function

- $e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^-\pi^+)_{jet2}X$
- 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
- Early work by Collins, Heppelman, Ladinski



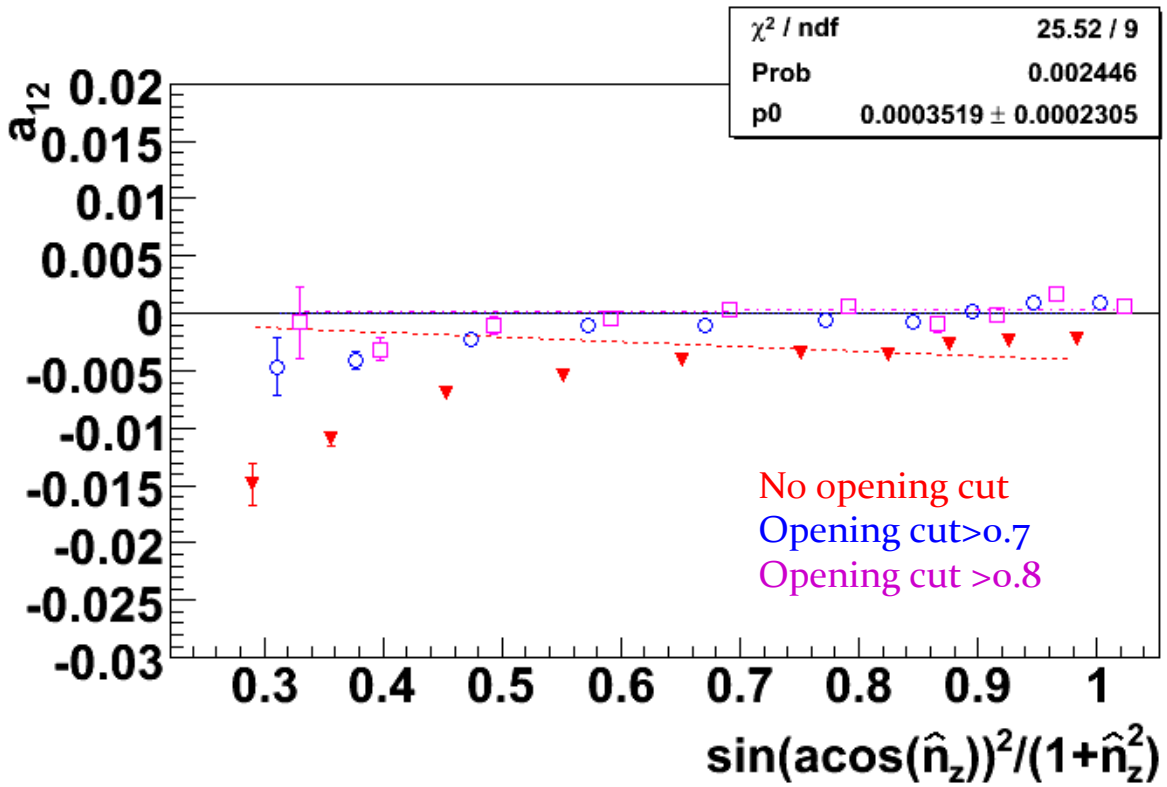
$$A \propto H_1^{\angle}(z_1, m_1)\overline{H}_1^{\angle}(z_2, m_2)\cos(\varphi_1+\varphi_2)$$

Model predictions by:

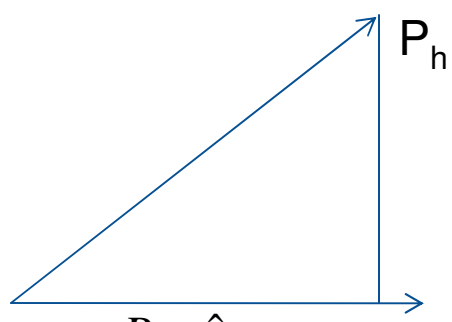
- Jaffe et al. [PRL **80,**(1998)]
- Radici et al. [PR**D 65,**(2002)]

Amplitude of modulation directly measures IFF! (squared)

Zero tests: MC

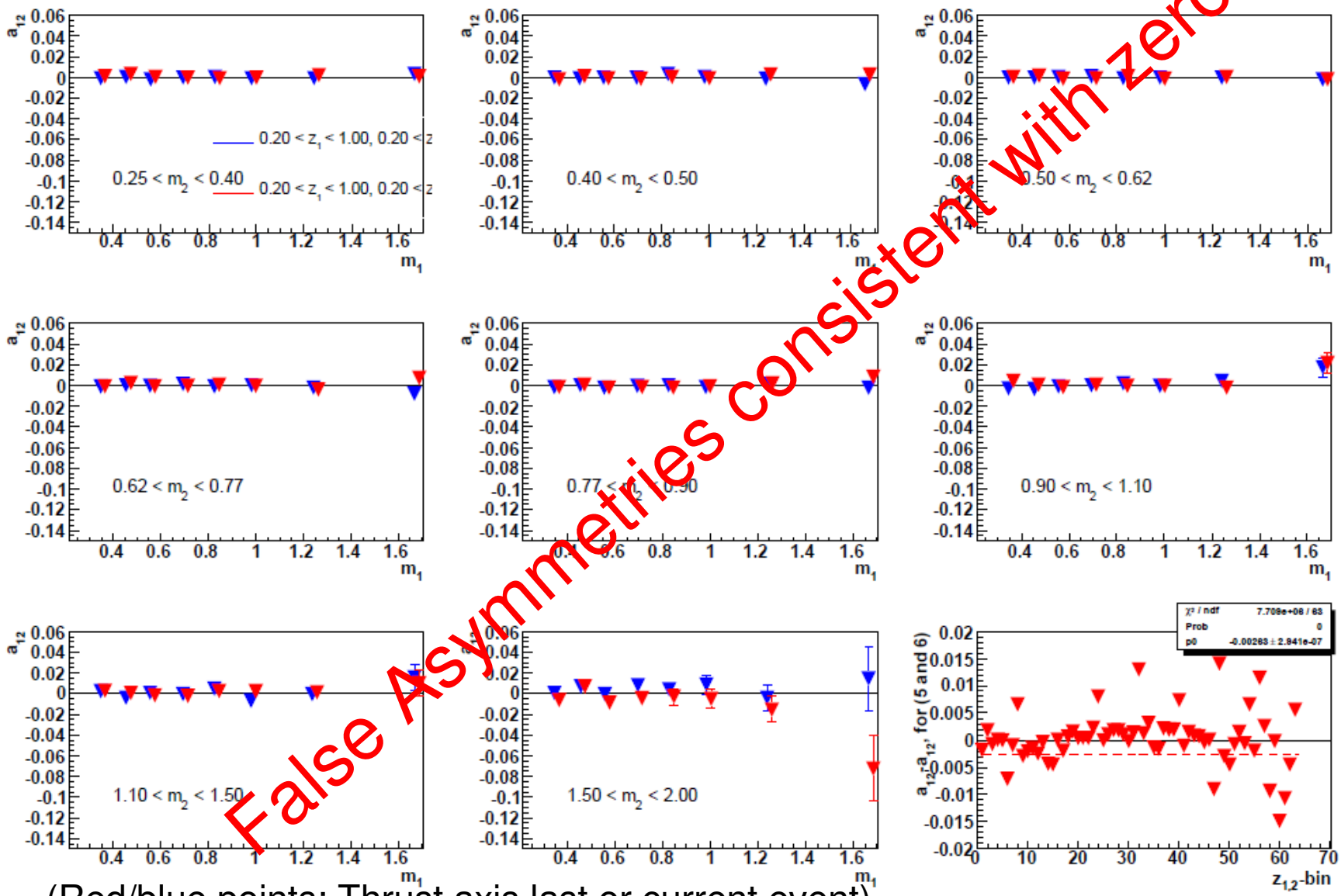


- A small asymmetry seen due to acceptance effect
- Mostly appearing at boundary of acceptance
- Opening cut in CMS of 0.8 (~37 degrees) reduces acceptance effect to the sub-per-mille level
- $\sin^2\theta/(1+\cos^2\theta) > 0.5$



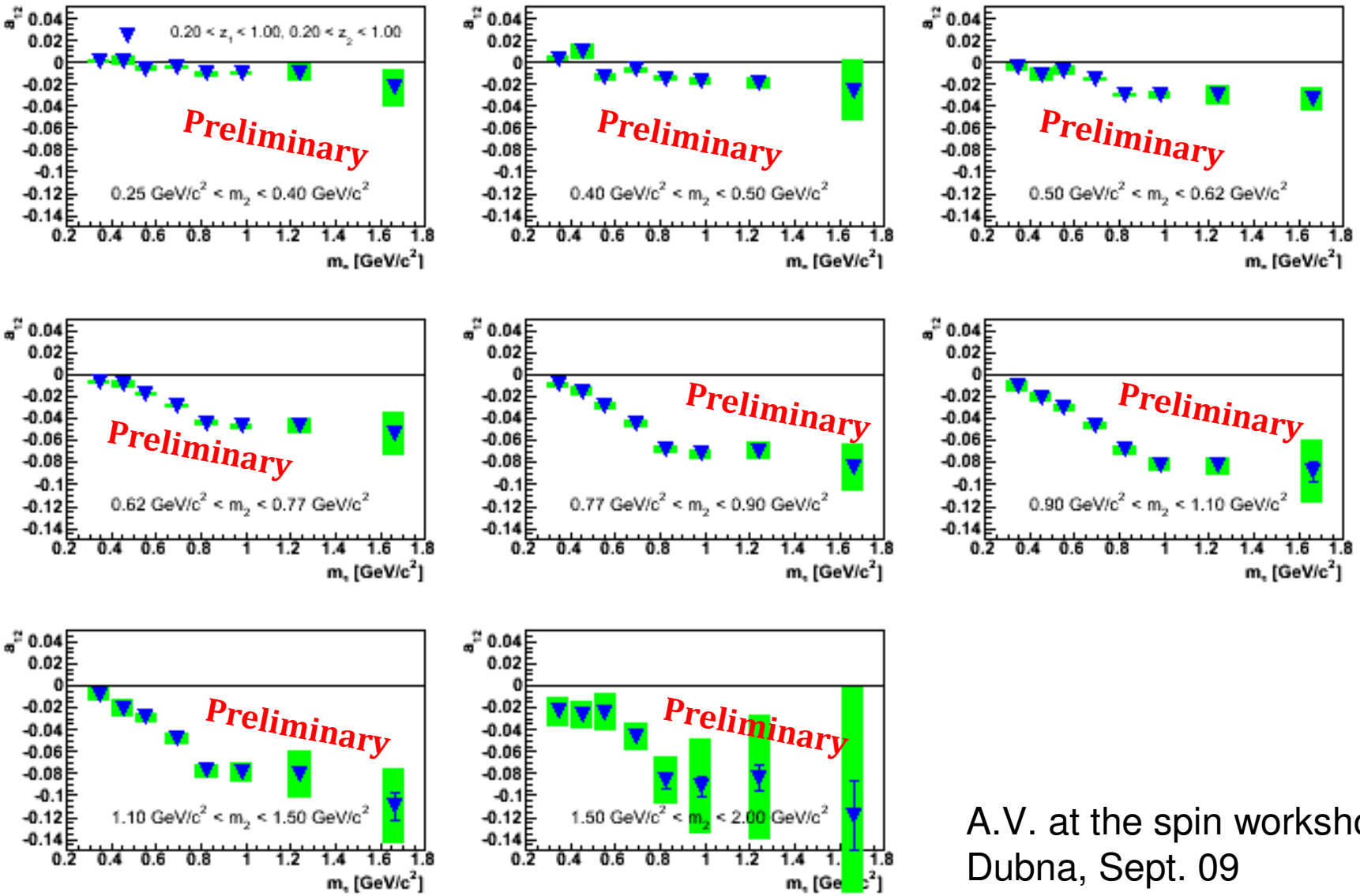
$$\frac{P_h \bullet \hat{n}}{|P_h|} = \cos(P,n)$$

Zero tests: Mixed Events



(Red/blue points: Thrust axis last or current event)

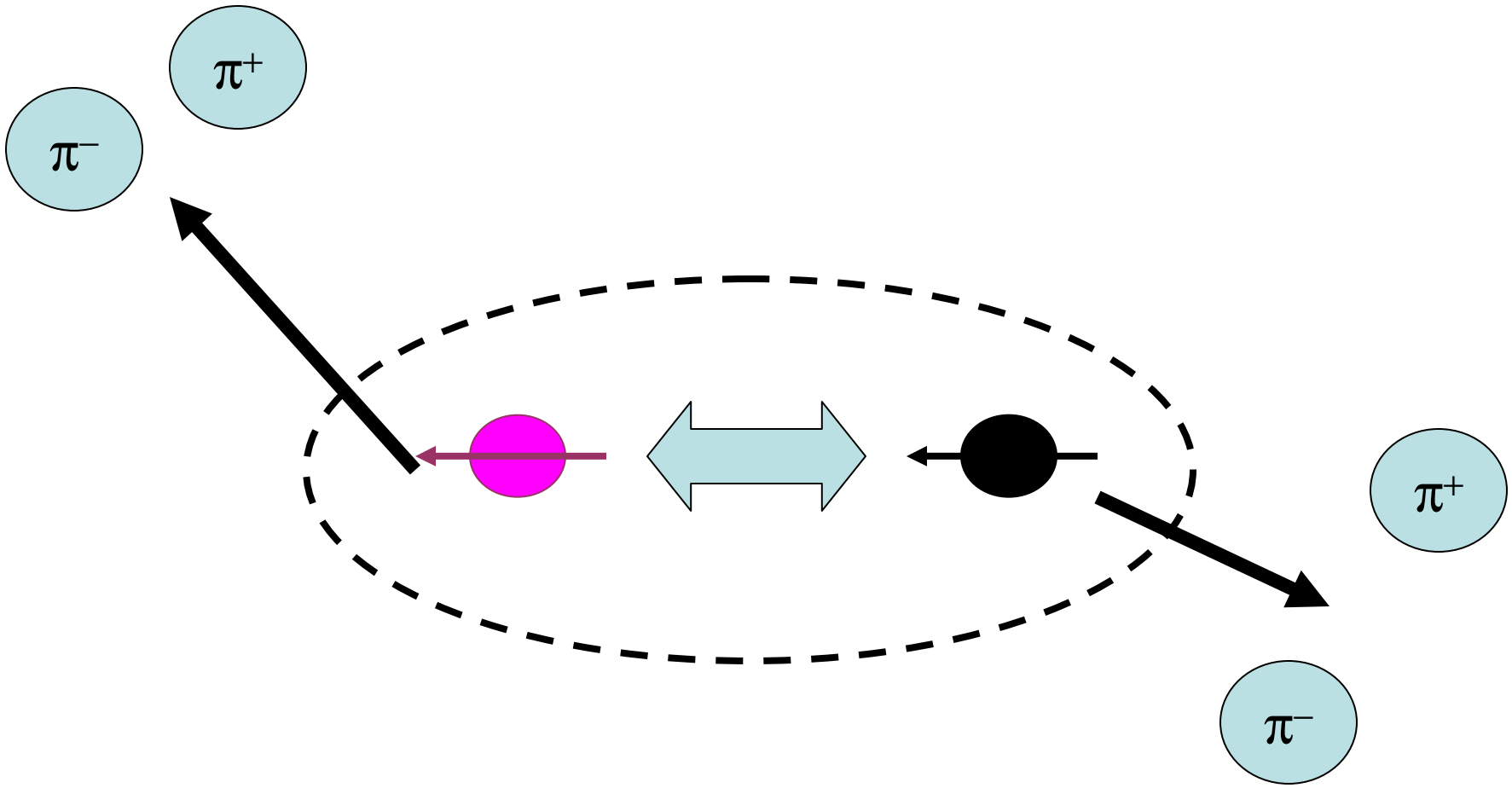
Belle: Asymmetries in $e^+ e^-$



A.V. at the spin workshop in Dubna, Sept. 09

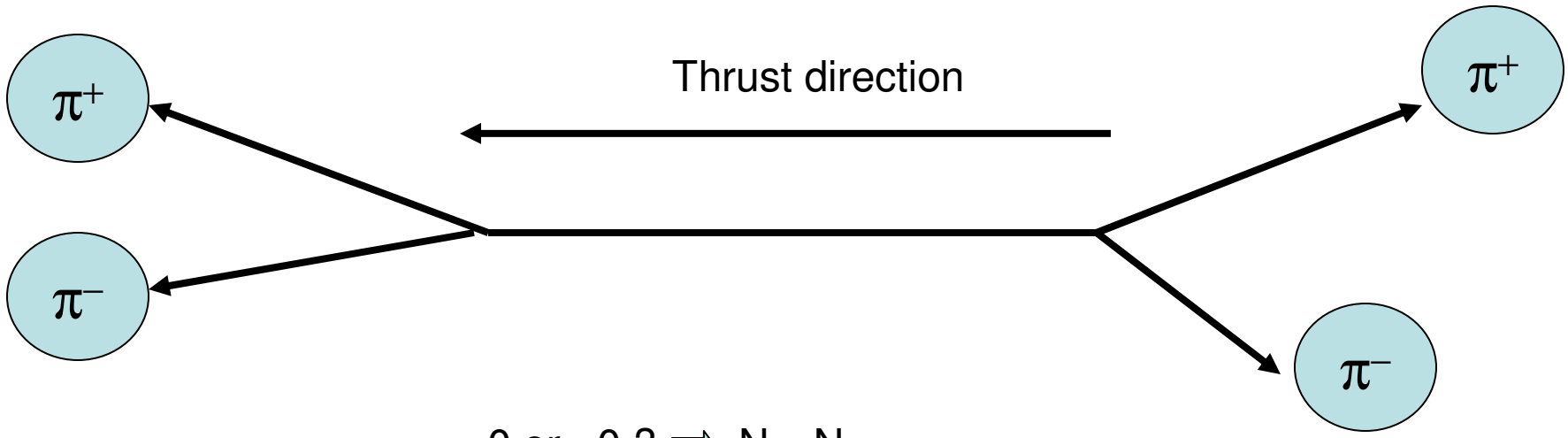
8x8 m_1 m_2 binning

Fragmentation in the Big Bubble



Efremov, Khazeev, Phys. Lett. B366, 311

Handedness



$$\frac{(\boldsymbol{k}_+ \times \boldsymbol{k}_-)\boldsymbol{t}}{|\boldsymbol{k}_+||\boldsymbol{k}_-|} = \sin\phi$$

>0 or <0 ? ⇨ N_R, N_L

$$H = \frac{N_R - N_L}{N_L + N_R},$$ For each event

- Handedness

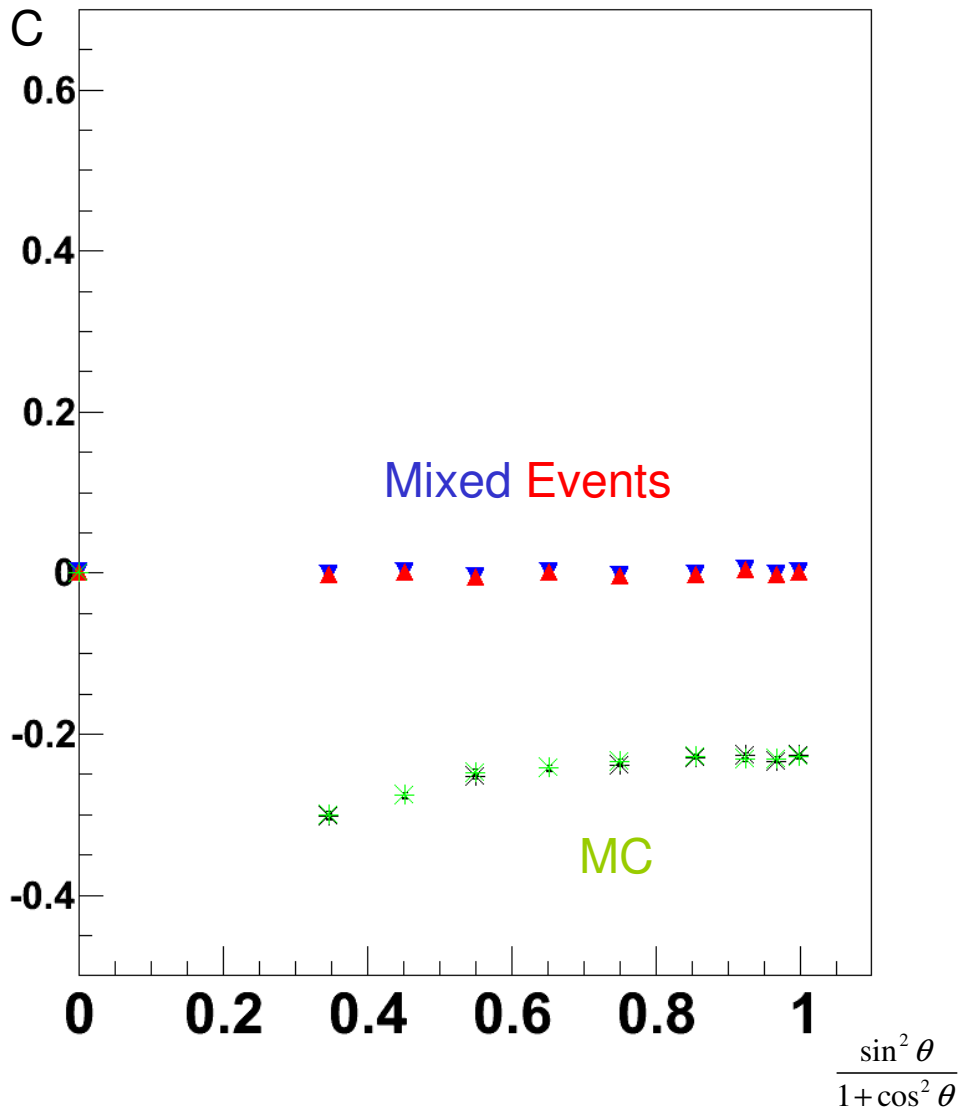
H < 0

H > 0

$$C = \frac{N_{LR} + N_{RL} - N_{RR} - N_{LL}}{N_{LR} + N_{RL} + N_{RR} + N_{LL}},$$

Handedness in MC

- How is parity described in Monte Carlo?



Summary

- The Belle Experiment is uniquely suited to measure Spin dependent Fragmentation Functions
- High Precision
- Experience with Extraction of CollinsFF and Interference FF Functions
- Extraction of parity violating Fragmentation Functions is work in progress

Outlook

- Construct Observables from charged Pions
- Kaon Asymmetries

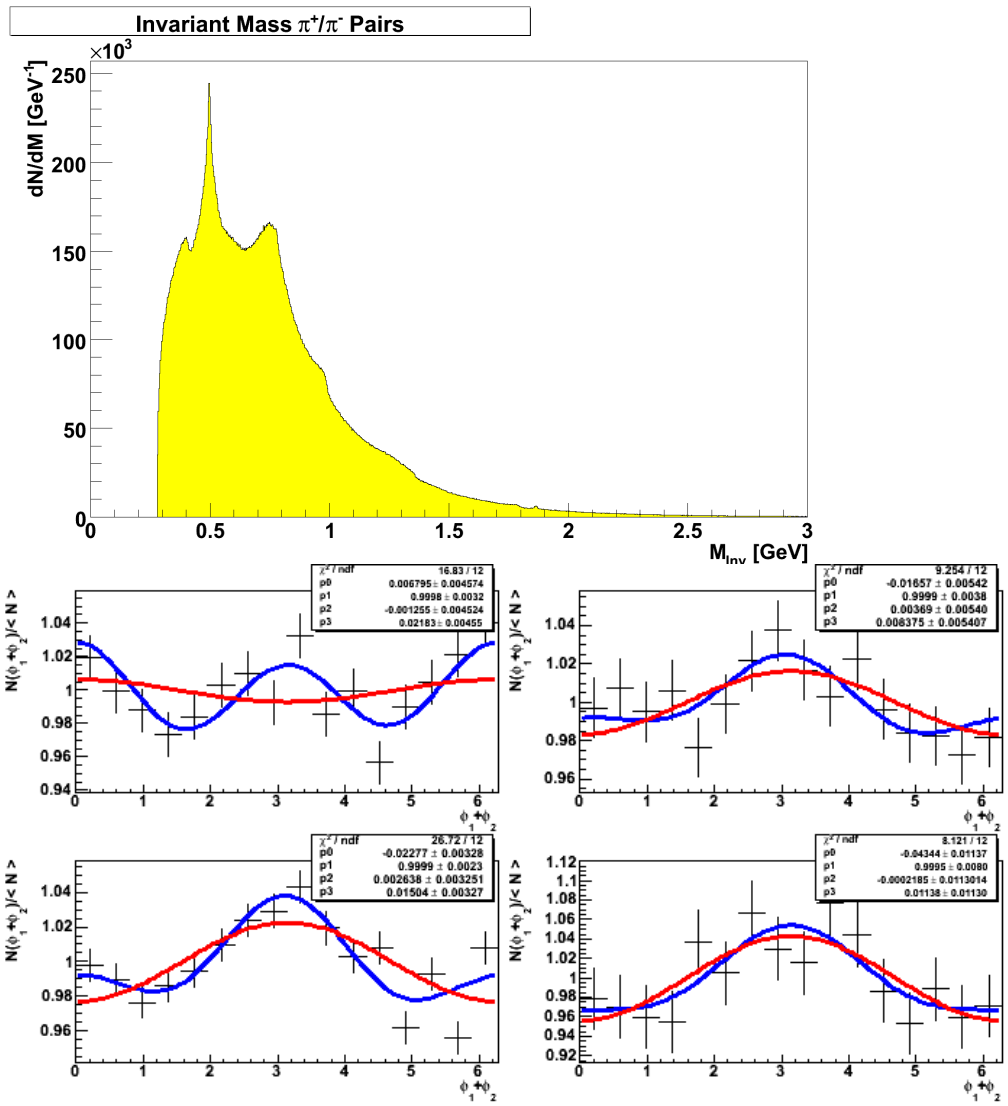
Belle II

- Super B factory (superkekb) **O**(10^2) larger ∫**L**dt
- Collect several ab^{-1}
- Enables kt dependent measurements

- Observables in polarized pp? → PHENIX

Backup

Asymmetry extraction



- Build normalized yields:

$$\frac{N(\phi_1+\phi_2)}{\langle N\rangle},$$

- Fit with:

$$a_{12}\cos(\phi_1+\phi_2)+b_{12}$$

or

$$a_{12}\cos(\phi_1+\phi_2)+b_{12}+$$
$$c_{12}\cos 2(\phi_1+\phi_2)+d_{12}\sin(\phi_1+\phi_2)$$

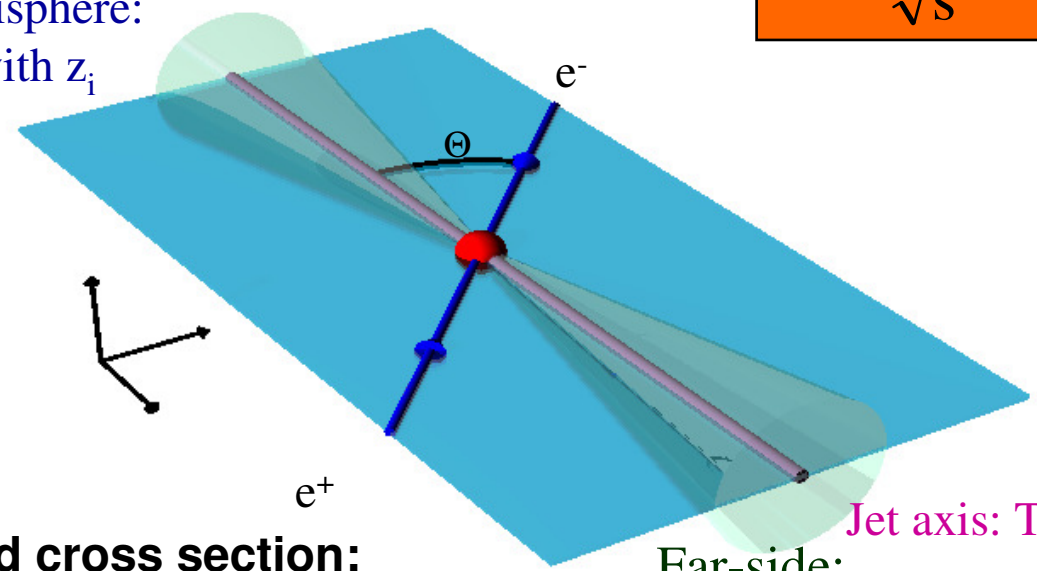
Amplitude a_{12} directly measures IFF! (squared)

Event Structure at Belle

e+e- CMS frame:

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

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

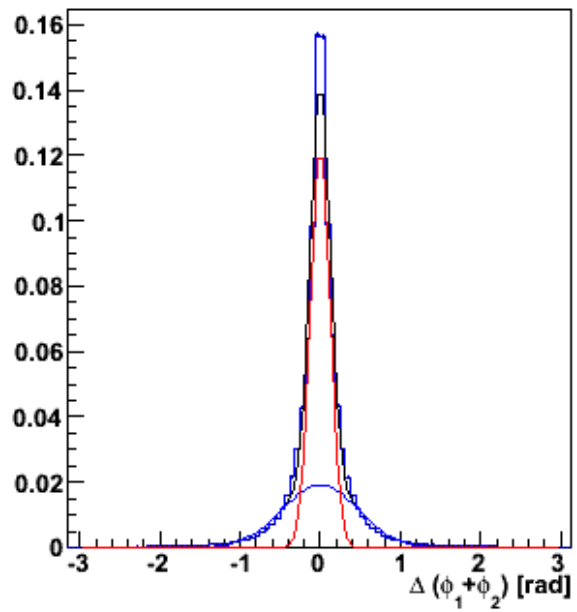
Spin averaged cross section:

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

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

Reconstructing the Quark–Antiquark Axis

- Reconstruction smears thrust axis,
- Effect is understood, can be reproduced in Toy MC
- Asymmetries corrected



Smearing
In azimuthal
Angle of thrust
Axis in CMS

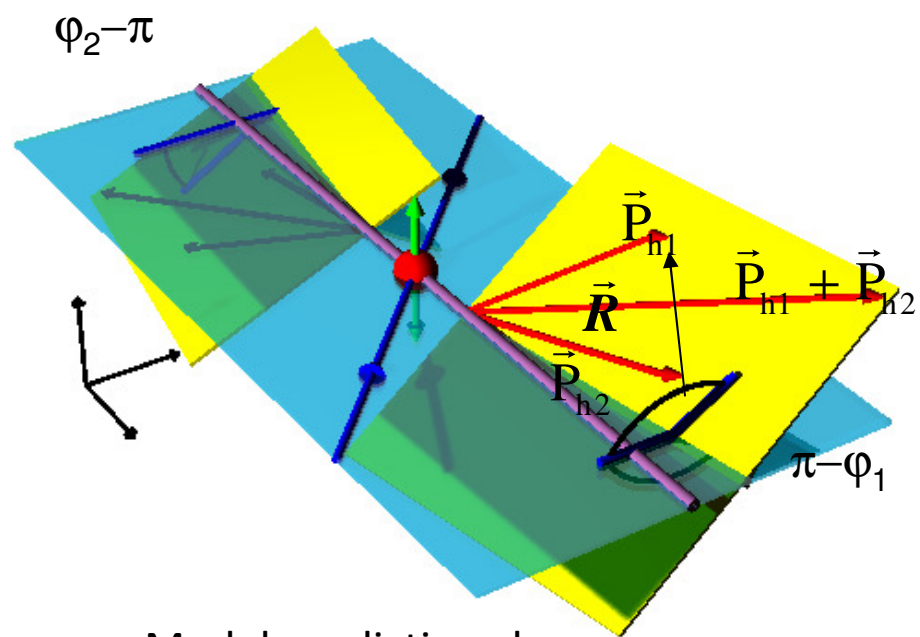
Cuts and Binning

- Similar to Collins analysis, full off-resonance and on-resonance data

  (7-55): ~73 fb^{-1} + 588 fb^{-1}
- Visible energy >7GeV
- PID: Purities in Pion/Pion Sample > 90%
- Same Hemisphere cut within pair ($\pi^+\pi^-$), opposite hemisphere between pairs
- All 4 hadrons in barrel region: $-0.6 < \cos(\theta) < 0.9$
- Thrust axis in central area: abs(thrustz)<0.75
- Thrust > 0.8
- $z_{had1,had2}>0.1$
- $z_1 = z_{had1}+z_{had2}$ and z_2 in 9x9 bins
- $m_{\pi\pi1}$ and $m_{\pi\pi2}$ in 8x8 bins: [0.25 - 2.0] GeV

Interference Fragmentation–thrust method

- $e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^-\pi^+)_{jet2}X$
- Find pion pairs in opposite hemispheres
- Measure azimuthal correlations of $\vec{R} = \vec{P}_{h1} - \vec{P}_{h2}$
- 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. [PR**D 65,**(2002)]

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

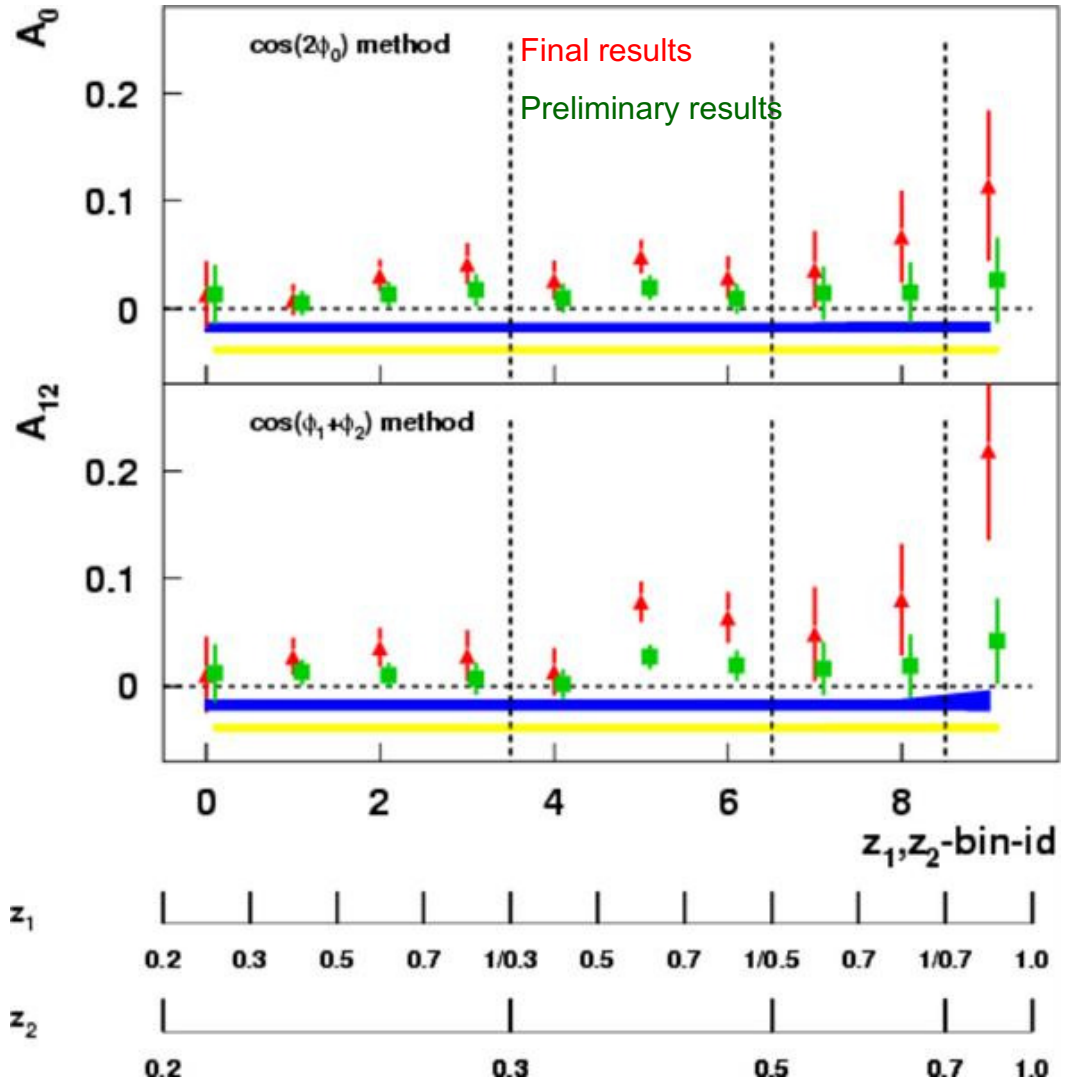
Amplitude of modulation directly measures IFF! (squared)

(Here: z_1 (z_2)relative momenta of first (second) pair)

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

- Significant non-zero asymmetries
- Rising behavior vs. z
- $\cos(\phi_1+\phi_2)$ double ratios only marginally larger
- UC asymmetries

Integrated results:	
A_0(UL)	(3.06 ± 0.57 ± 0.55)%
A_{12}(UL)	(4.26 ± 0.68 ± 0.68)%
A_0(UC)	(1.270 ± 0.489 ± 0.350)%
A_{12}(UC)	(1.752 ± 0.592 ± 0.413)%



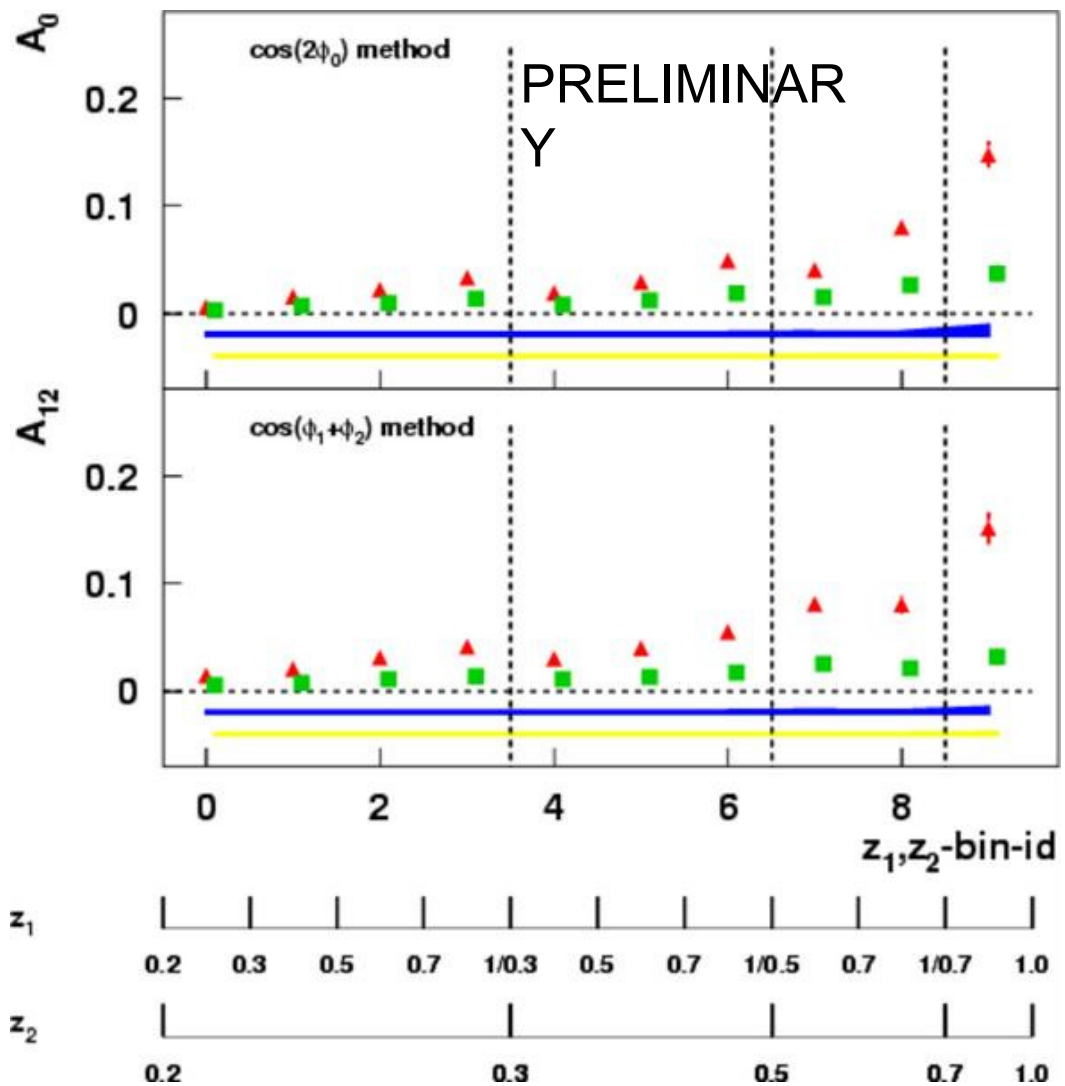
Collins function

Anselm Vossen

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

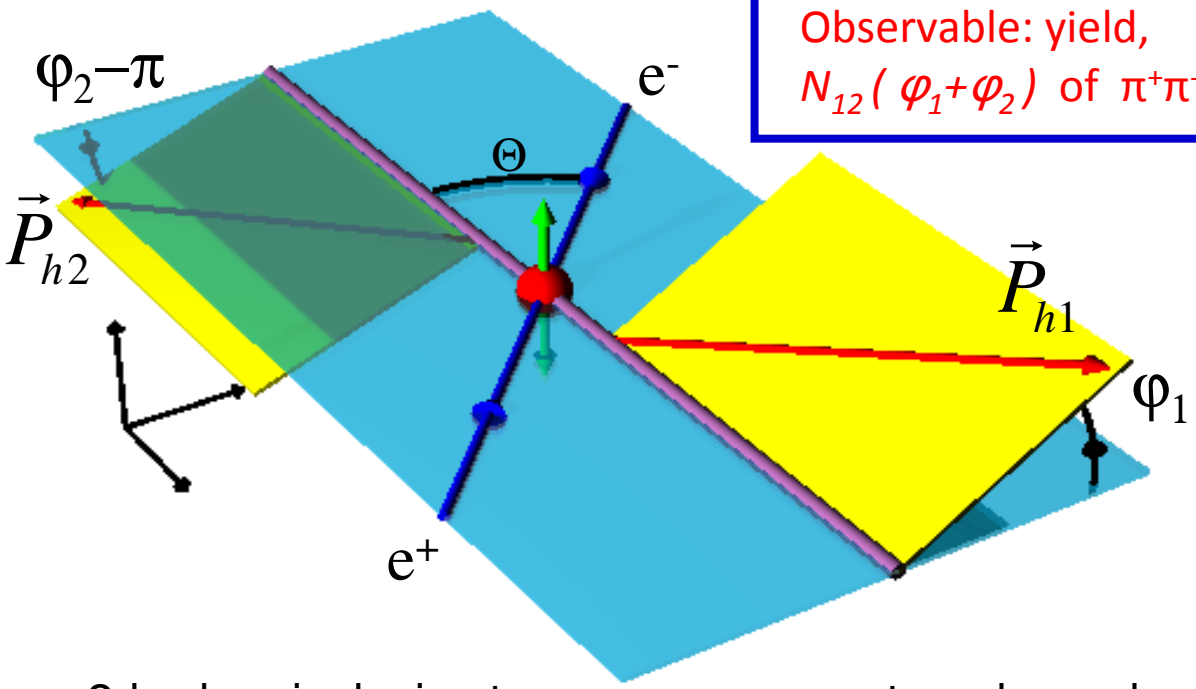
- Significance largely increased
- Behavior unchanged
- Reduced systematic errors due to statistics
- Precise

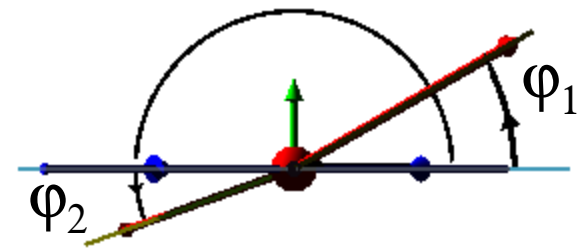
Integrated results:	
A_0(UL)	(2.67 ± 0.10 ± 0.26)%
A_{12}(UL)	(3.55 ± 0.08 ± 0.15)%
A_0(UC)	(1.11 ± 0.11 ± 0.22)%
A_{12}(UC)	(1.46 ± 0.09 ± 0.13)%



Collins Fragmentation: Angles and Cross Section: **cos(ϕ_1+ϕ_2) Method** (e+e- CMS frame)

Observable: yield,
$N_{12}(\varphi_1+\varphi_2)$ of $\pi^+\pi^-$ pairs





2-hadron inclusive transverse momentum dependent cross section:

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

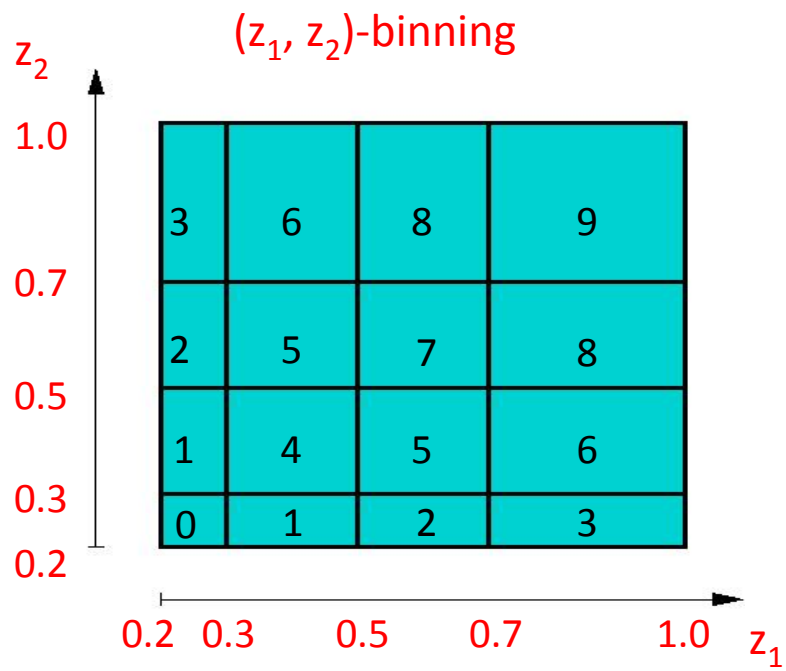
$$B(y) = y(1-y) \overset{cm}{=} \frac{1}{4}\sin^2\Theta$$

Net anti-alignment of transverse quark spins

Applied Cuts, Binning

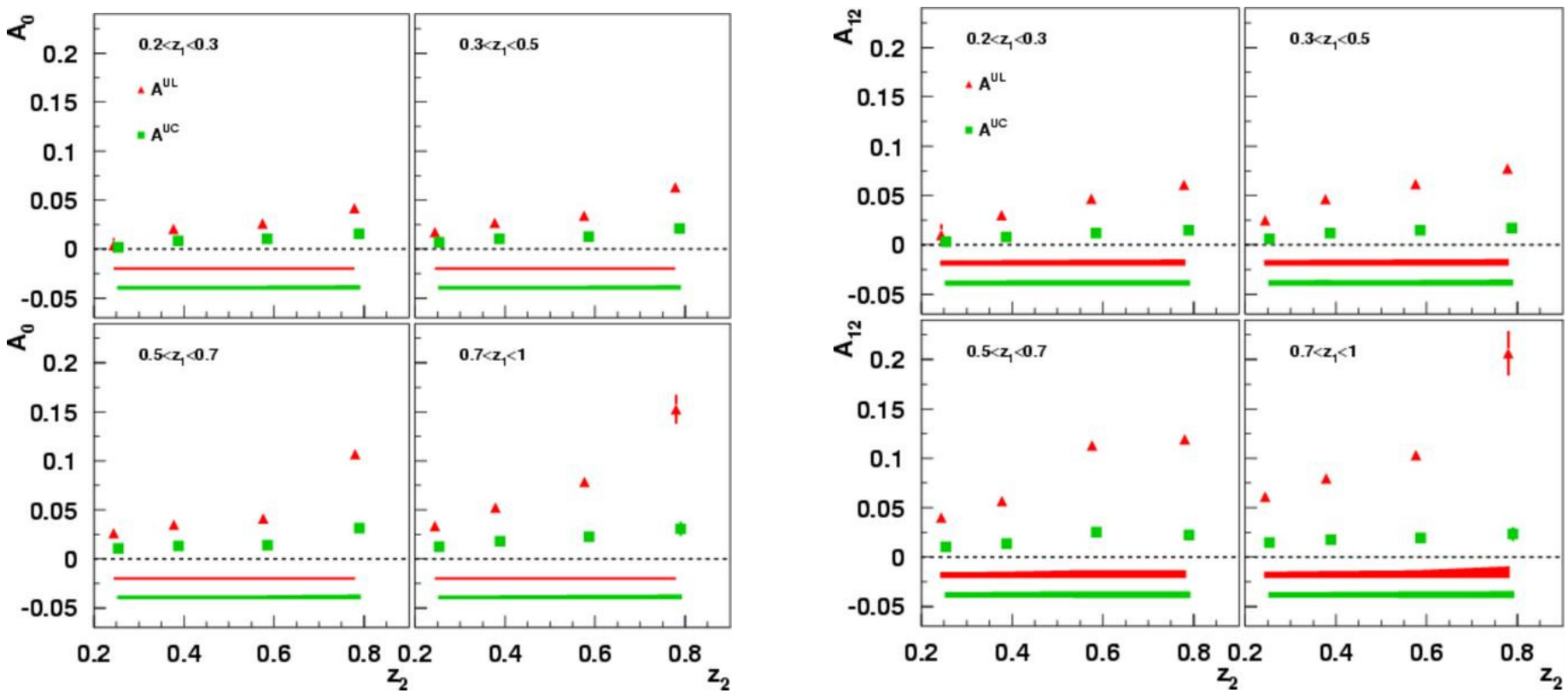
- Two data sets:
  off-resonance data (29.1 fb^{-1})
  on-resonance data (547 fb^{-1})
- Track selection:
  - $p_T > 0.1$GeV
  - vertex cut:
    dr < 2cm, |dz| <4cm
- Acceptance cut
  - $-0.6 < \cos\theta_i < 0.9$
- Event selection:
  - $N_{track} \geq 3$
  - Thrust > 0.8
  - $z_1, z_2 > 0.2$

- 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



Final Collins results

Belle 547 fb^{-1} data set (Phys.Rev.D78:032011,2008.)



Anselm Vossen

Applied cuts, binning

- Off-resonance data
  - 60 MeV below Υ(4S) resonance
  - 29.1 fb^{-1}

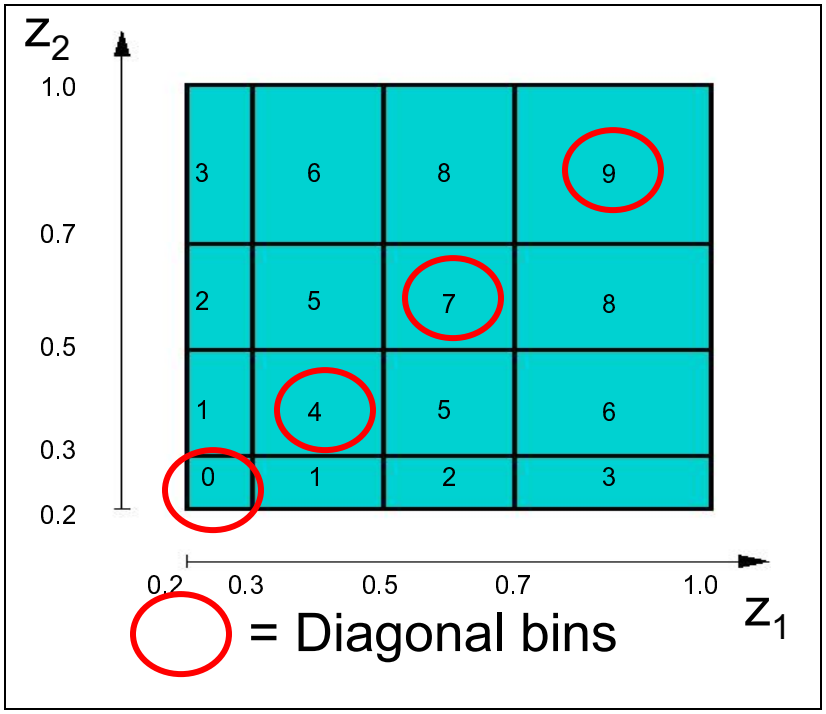
→ Later also on-resonance data: 547 fb^{-1}

- 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



Anselm Vossen

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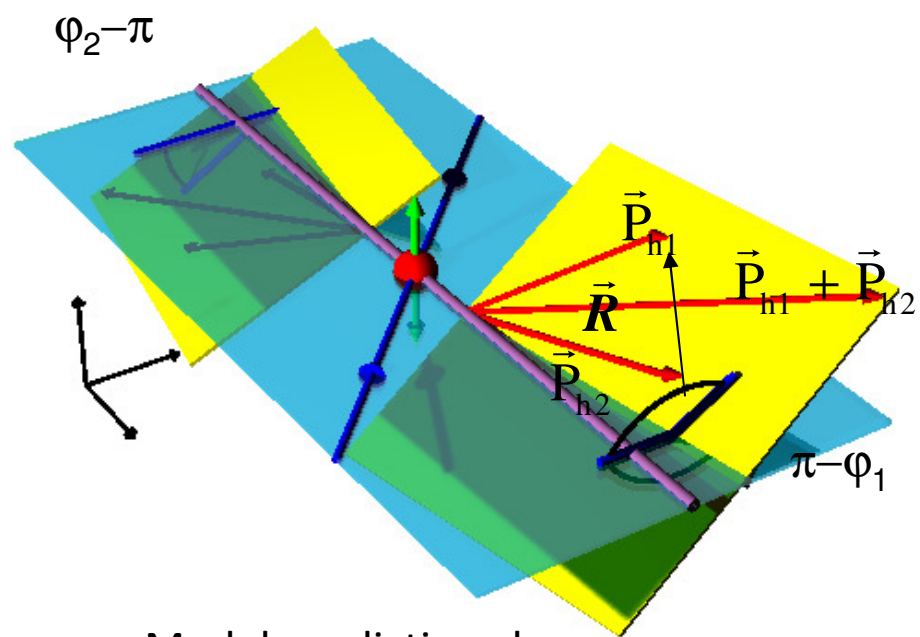

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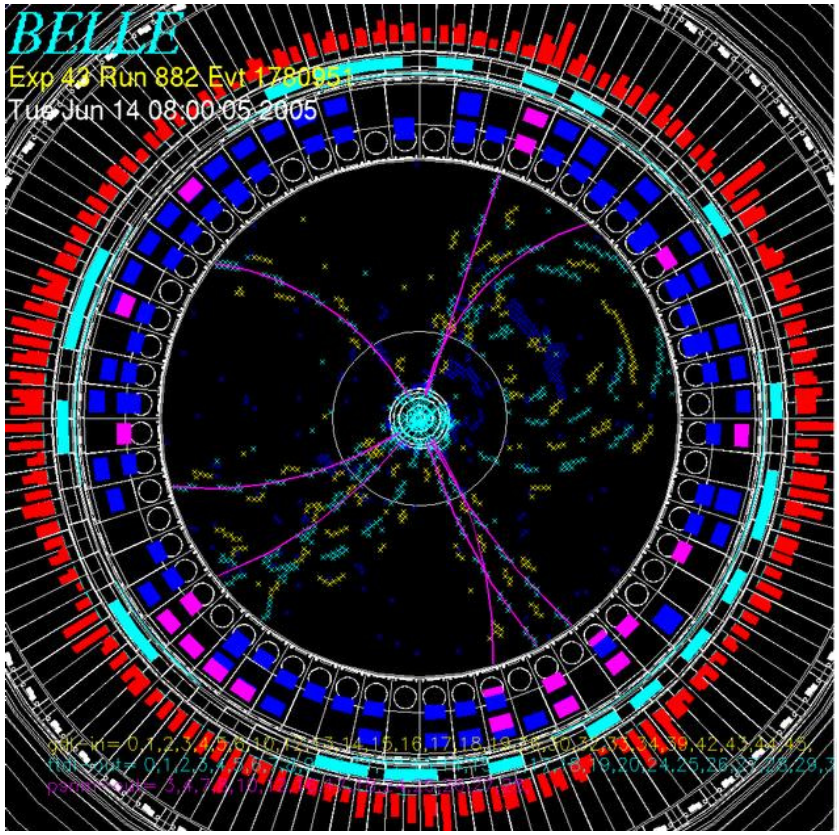
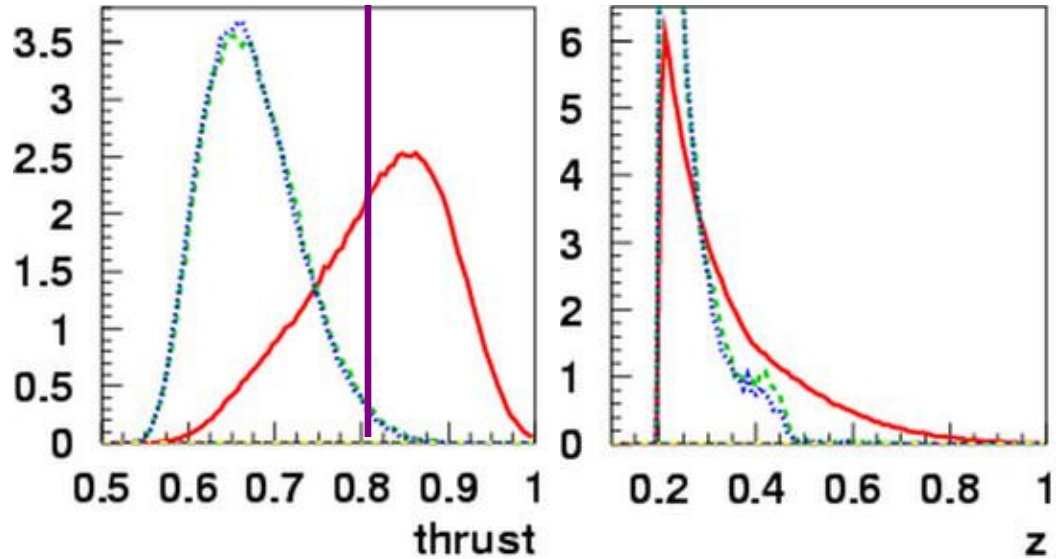
Amplitude of modulation directly measures IFF! (squared)

(Here: z_1 (z_2)relative momenta of first (second) pair)

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





- $e^+ e^- \rightarrow q\ \bar{q}$ (u d s) MC
- $\Upsilon(4S) \rightarrow B^+\ B^-$ MC
- $\Upsilon(4S) \rightarrow B^0\ \bar{B}^0$ MC

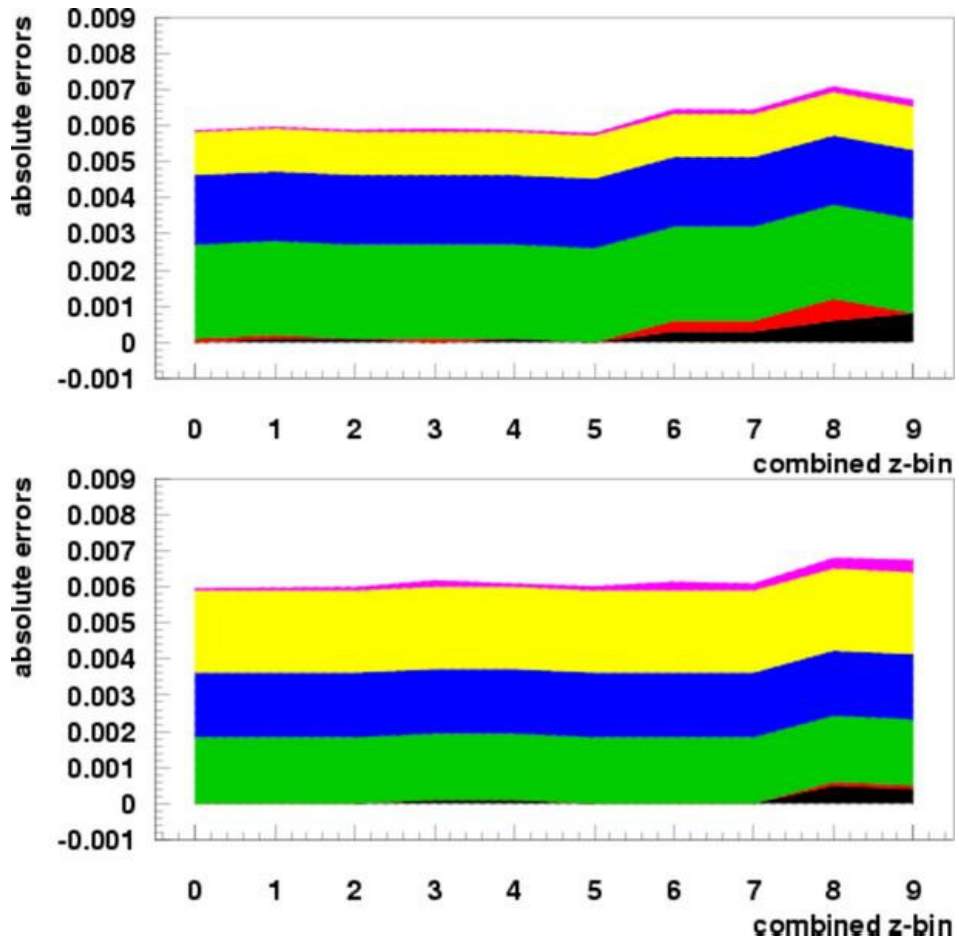
$$\text{thrust} = \frac{\sum_i |p_i \cdot \hat{n}|}{\sum_i |p_i|}$$

- Largest systematic errors reduce with more statistics
- Charm-tagged Data sample also increases with 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 →rescalied with 1.21
•Correlation studies:
→statististical error rescaled by1.02 (UL) and 0.55 (UC) – after rigorous errorcalculation correct
•Beampolarization studies
→consistent with zero
•Correction ofcharm events

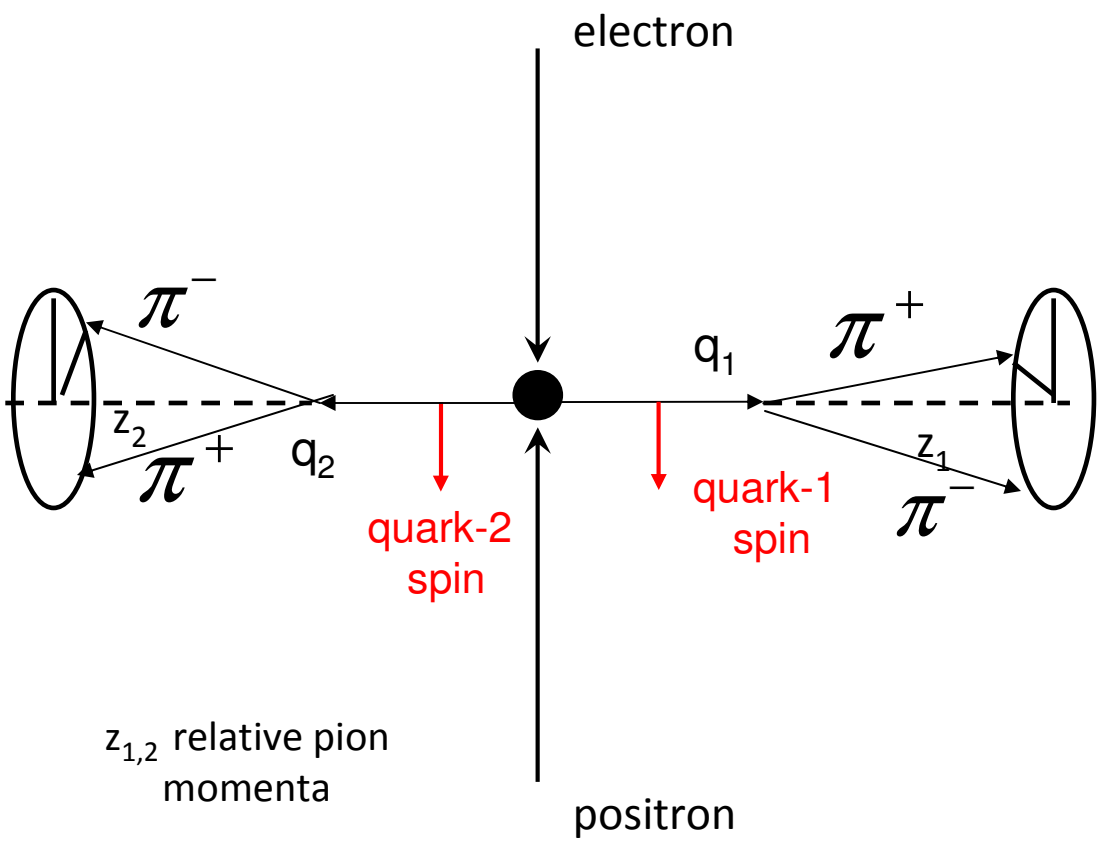


General Form of Fragmentation Functions

Number density for finding hadron h from a transversely polarized quark, q:

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

Handedness in e^+e^- Annihilation into Quarks!



Handedness: $\frac{(\boldsymbol{k}_+ \times \boldsymbol{k}_-)\boldsymbol{t}}{|\boldsymbol{k}_+||\boldsymbol{k}_-|} = \sin\phi$

>0 or <0 ?->N_R, N_L

$$H = \frac{N_R - N_L}{N_L + N_R},$$

For each event

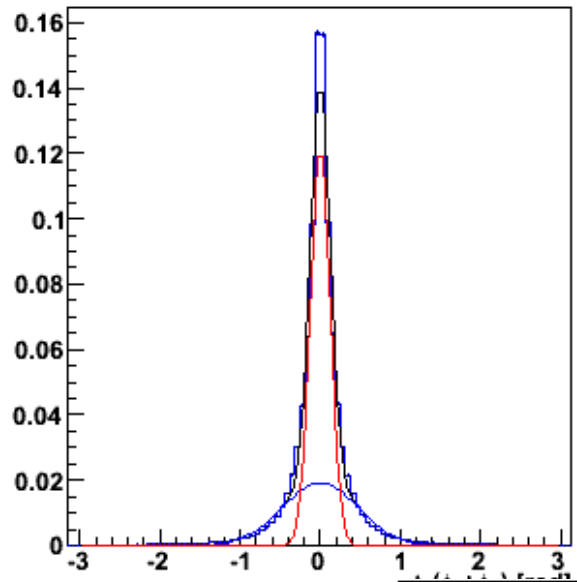
H < 0

H > 0

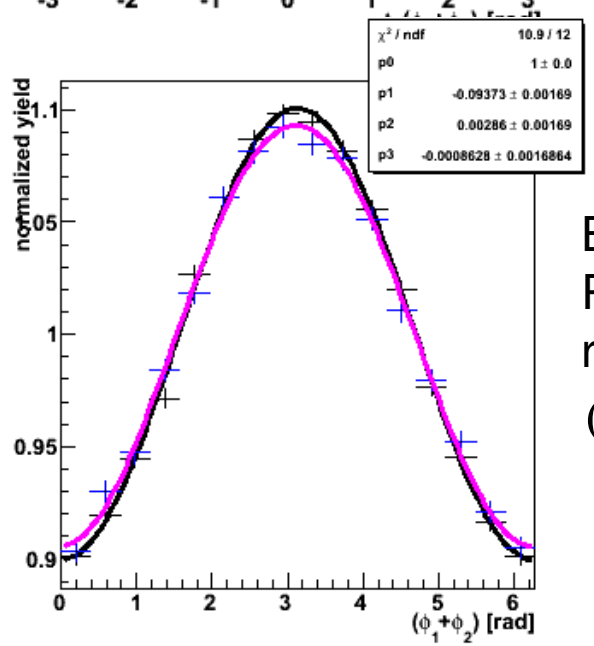
$$C = \frac{N_{LR} + N_{RL} - N_{RR} - N_{LL}}{N_{LR} + N_{RL} + N_{RR} + N_{LL}},$$

Reconstructing the Quark–Antiquark Axis

- Reconstruction smears thrust axis,
- Effect is understood, can be reproduced in Toy MC
- Asymmetries corrected

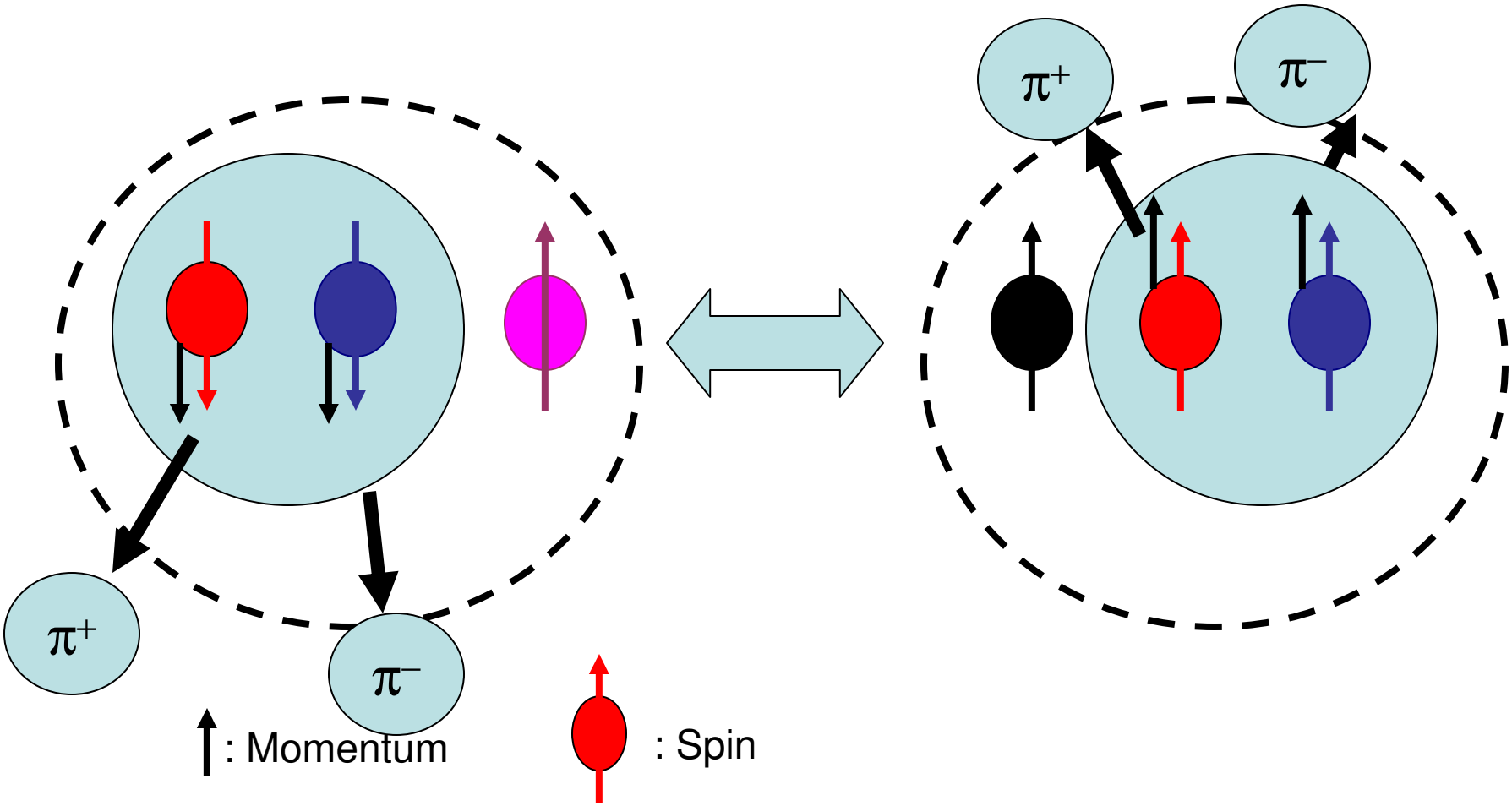


Smearing
In azimuthal
Angle of thrust
Axis in CMS



Black: injected
Purple
reconstructed
$(\phi_{1R} + \phi_{2R})$

Fragmentation in P odd Bubbles leads to Azimuthal Asymmetries



- Fragmentation in P-odd bubble leads to correlations in opposite hemispheres