Measurement of Spin Dependent Fragmentation Functions in e^+e^- Annihilation at the KEK B-Factory

Electromagnetic Interactions with Nucleons and Nuclei

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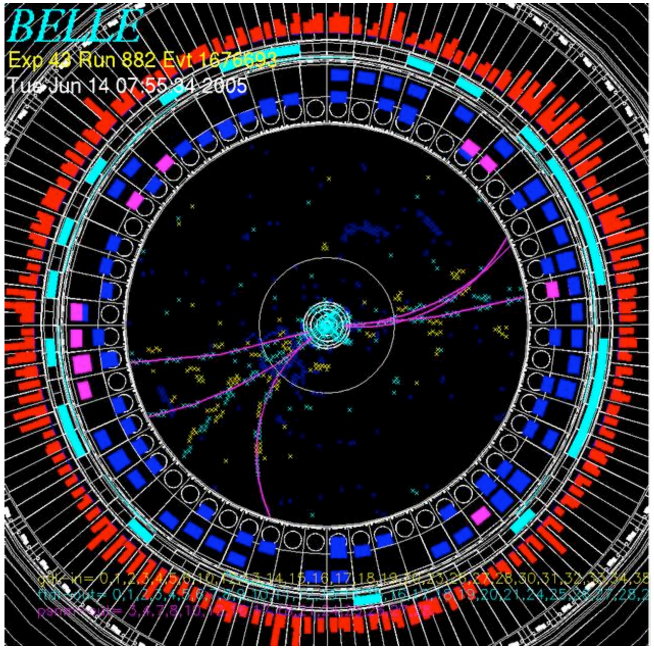


------------ Outline ------------

- Motivation
- First Measurements of Collins Asymmetries at LEP

  Bonivento, Matteuzzi, Kotzinian, (DELPHI note,1995),

  Efremov, Smirnova, Tkachev (Nucl. Phys. Proc. Suppl. 74, 1999)
- Experimental Method
- Collins Analysis & Results
- IFF Analysis & Results
- Future Plans

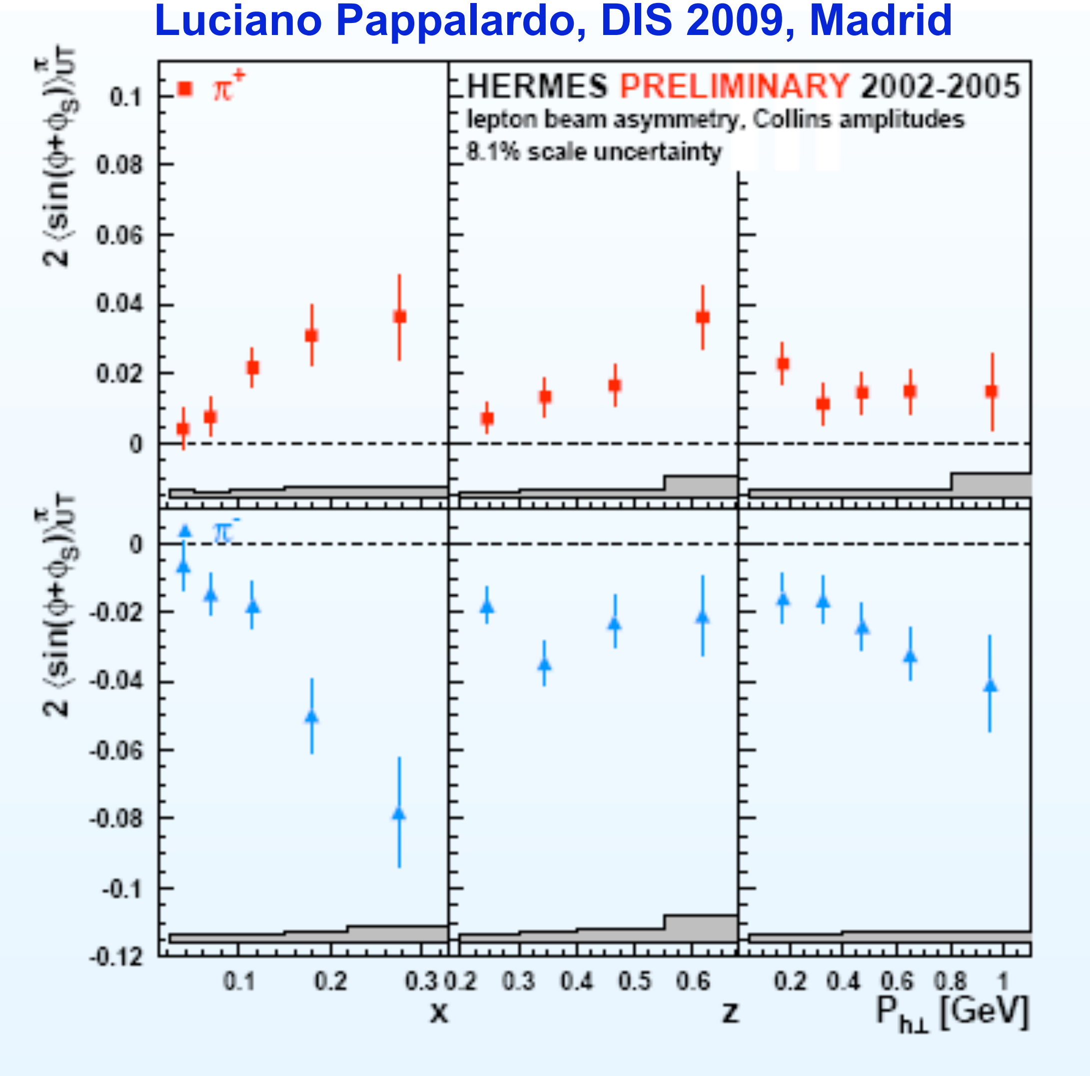
Why are Measurements of Spin Dependent Fragmentation Functions Interesting?

- o Very basic QCD process: Fundamental test case for any approach to solve QCD at soft scales.
- o Tests schemes of universality and factorization between e^+e^-, DIS and p-p collisions.
- o Symmetry properties.
- o Test evolution as fundamental QCD prediction.
- o Connection between microscopic (quark spin) and macroscopic observables (azimuthal hadron distribtion):

➔ Provides final state spin analyzer for the study of quark transversity distributions from data taken by HERMES, COMPASS, JLab, RHIC and in the future EIC.

Motivation Transversity Quark Distributions *δq(x)* from Collins- (*CFF*) and Interference-Fragmentation (*IFF*)

Collins Asymmetries from HERMES, eg. Luciano Pappalardo, DIS 2009, Madrid



Collins- and IFF- asymmetries in semi-inclusive deep inelastic scattering (SIDIS) and pp measure

~ *δq(x) x CFF(z)*

~ *δq(x) x IFF(z)*

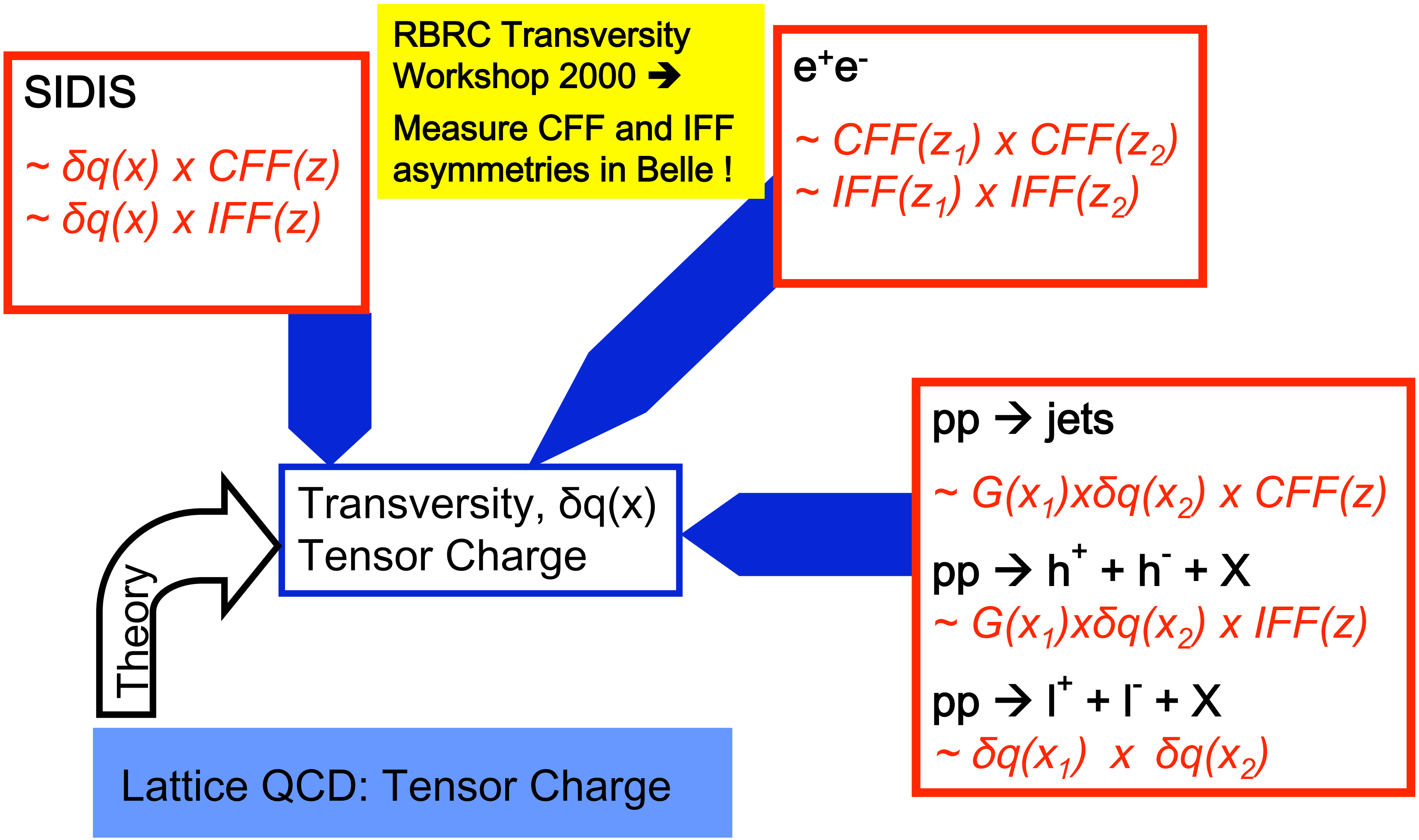
Collins- and IFF- asymmetries in e^+e^- annihilation are of the form

~ $CFF(z_1)$ x $CFF(z_2)$

~ $IFF(z_1)$ x $IFF(z_2)$

➔ global analysis to extract *δq(x)*

Global Analysis: Extract Transversity Distributions



Early Work in DELPHI: Collins Result

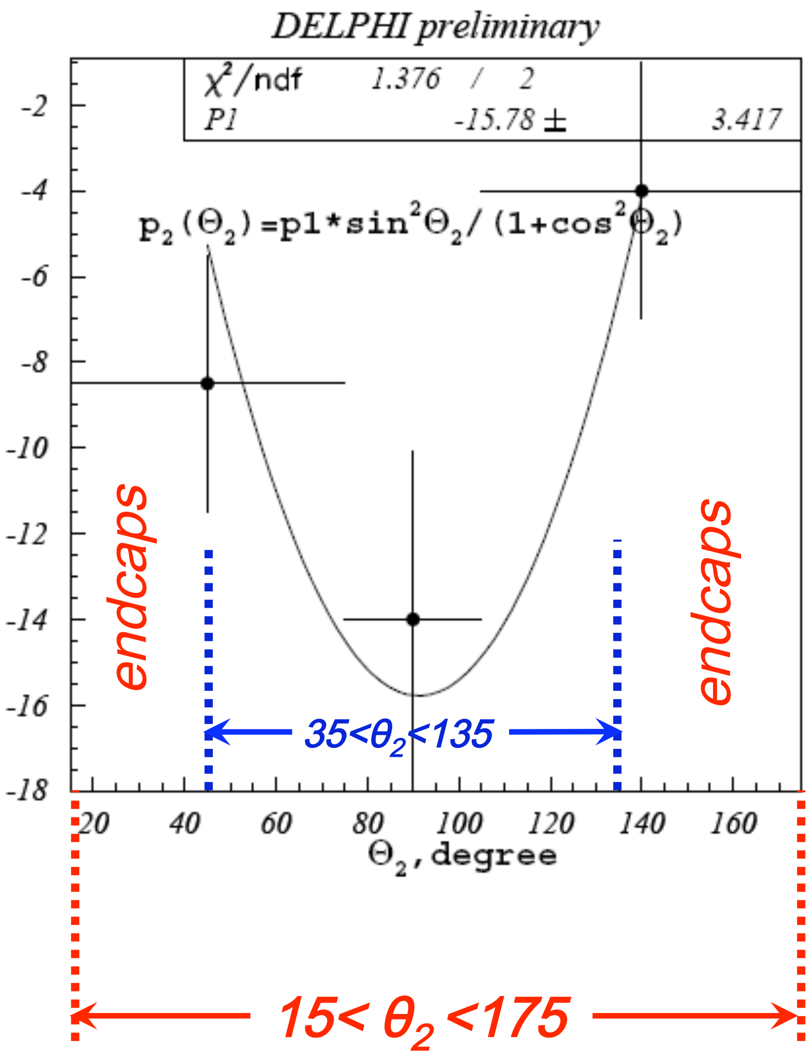
Efremov, Smirnova, Tkachev (Nucl. Phys. Proc. Suppl. 74, 1999)

Sample: 3.5 x 10^6 events at $\sqrt{s}=M_{Z_0}$
Analysis: di-hadron correlation for leading hadrons

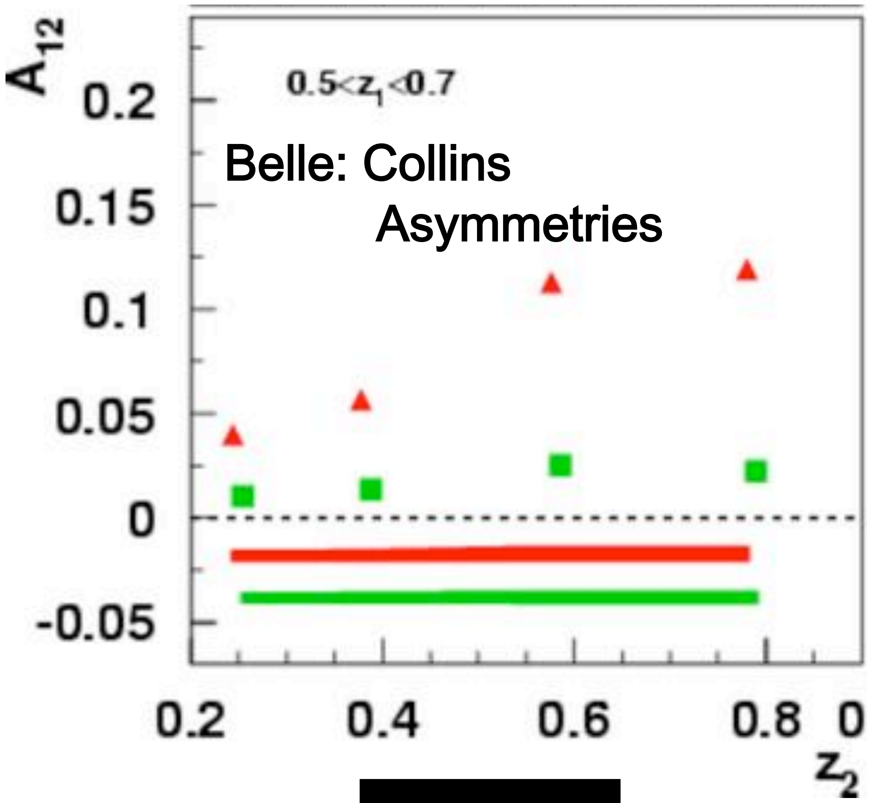
$$\left|\frac{H_1}{D_1}\right| = 6.2 \pm 1.7\% \ \ \text{(stat. error)}$$

$$\left|\frac{H_1}{D_1}\right| = 12.9 \pm 1.4\% \ \ \text{(stat. error)}$$

- First result on Collins Asymmetries in e^+e^-
- Monte Carlo for acceptance corrections
- Systematic errors were not estimated
- DELPHI result e^+e^- compatible with HERMES+ BELLE (Efremov, Goeke, Schweitzer)

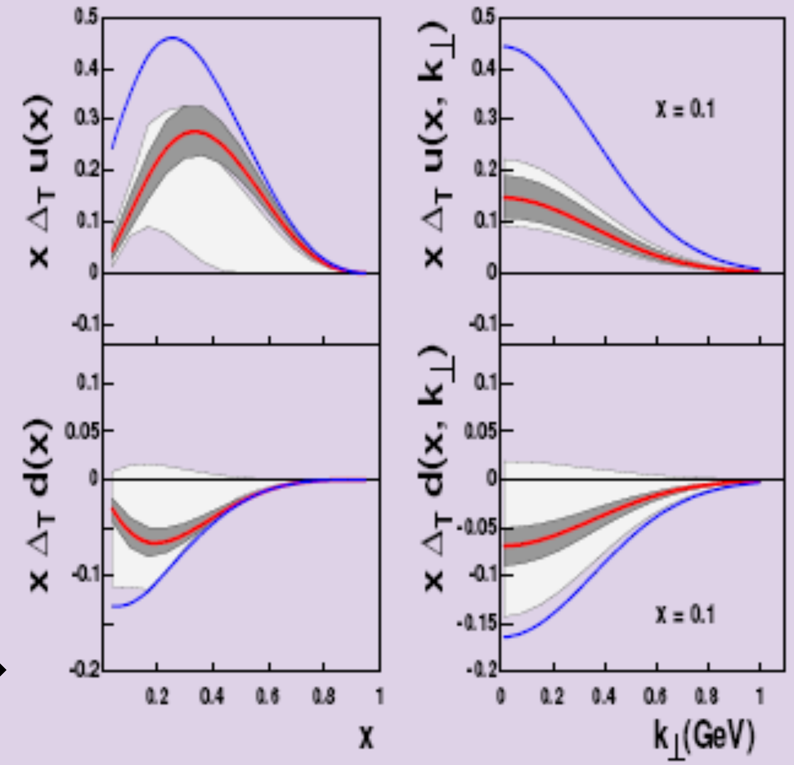


Combined Analysis of Collins Asymmetries in SIDIS + e^+e^- !



+ HERMES, & COMPASS data
➔ first extraction of δq(x) :

Anselmino et al.
Phys. Rev. D75:05032, 2007
Nucl. Phys. Proc. Suppl. 191, 2009



Collins Based Extraction of Transversity: Uncertainty from Transverse Momentum Dependences!

$$A_{UT}^{Collins} = \frac{\sum_q e_q^2 \int d\phi_S d\phi_h d^2k_\perp \delta q(x, k_\perp) \frac{d(\Delta\sigma)}{dy} H_{1,q}^{\perp}(z, p_\perp) \sin(\phi_S + \phi + \phi_q^h) \sin(\phi_S + \phi_h)}{\sum_q e_q^2 \int d\phi_S d\phi_h d^2k_\perp q(x, k_\perp) \frac{d(\Delta\sigma)}{dy} D_q^h(z, p_\perp)}$$

transversity

Collins FF

quark pdf

hadron FF

$k_\perp$ transverse quark momentum in nucleon

$p_\perp$ transverse hadron momentum in fragmentation

Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Prokudin, Turk Phys. Rev. D75:05032,2007

The transverse momentum dependencies are unknown and difficult to obtain experimentally!

IFF will provide alternative route of access independent of knowledge of transverse momentum dependencies.

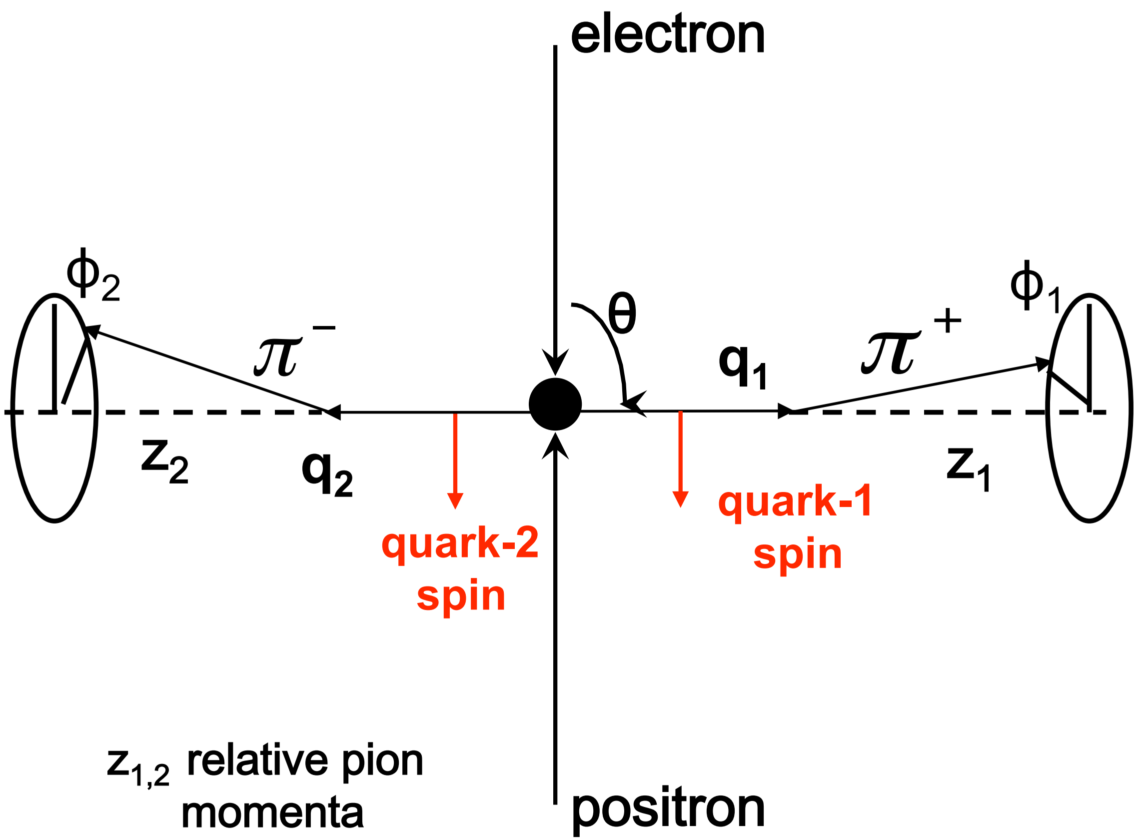
CFF or IFF in e^+e^- : Need Correlation between Hemispheres !

- Quark spin direction unknown: measurement of CFF or IFF in one hemisphere is not possible as the azimuthal modulation will average out.

- Example, correlation between two back-to-back hemispheres $\sin \varphi_i$ single spin asymmetries for CFF results in $\cos(\varphi_1+\varphi_2)$ modulation of the observed di-hadron yield.

⇒ Measurement of azimuthal correlations for pion pairs (CFF) or pairs of pion pairs (IFF) around the jet axis in events with back-to-back jets!

Collins Effect in di-Hadron Correlations In e^+e^- Annihilation into Quarks!



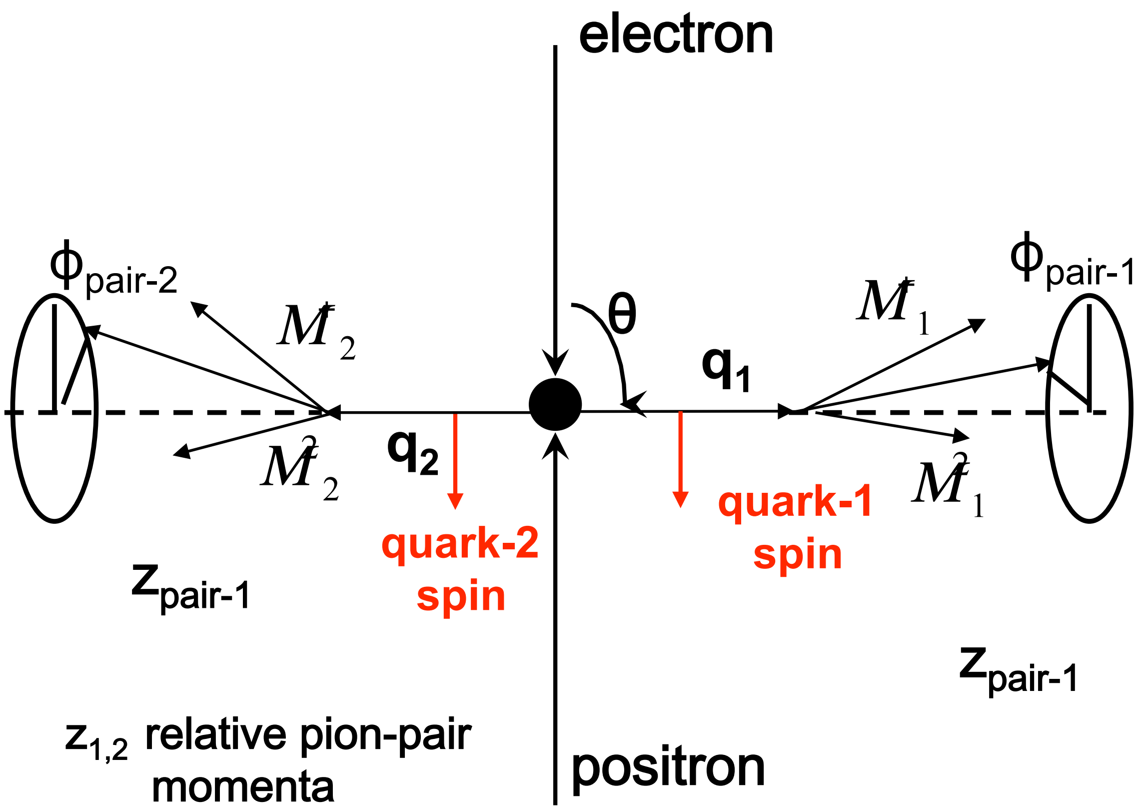
Collins effect in e^+e^- quark fragmentation will lead to azimuthal asymmetries in di-hadron correlation measurements:

$$N_{\pi_1,\pi_2}(\phi_1+\phi_2) \sim a_{12}\cos(\phi_1+\phi_2)$$

Experimental requirements:

- Small asymmetries → very large data sample!
- Good particle ID to high momenta.
- Hermetic detector
- Events with back-to-back jets

IFF in Correlation of di-Hadron Pairs in e^+e^- Annihilation into Quarks!



aHzMHzM 1211122(z) sin² N / 1+cos² N ∢∢ 22 pair 2222 pair pair

IFF in e^+e^- quark fragmentation leads to azimuthal asymmetries in the correlation of two hadron pairs:

$$N_{pair_1, pair_2}(\phi_{pair-1}+\phi_{pair-2}) \sim a_{12}\cos(\phi_{pair-1}+\phi_{pair-2})$$

Experimental requirements:

- Small asymmetries → very large data sample!
- Good particle ID to high momenta.
- Hermetic detector
- Events with back-to-back jets

KEKB: L>2.1 x 10^{34}cm^{-2}s^{-1} !!

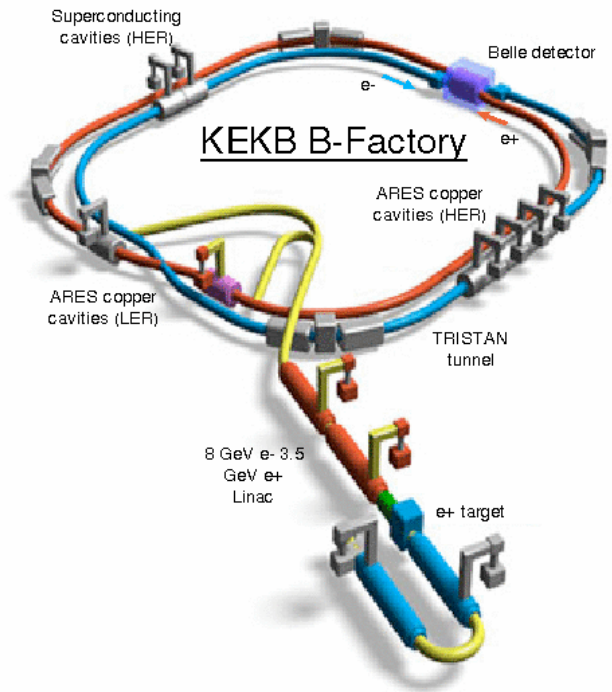
KEKB

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

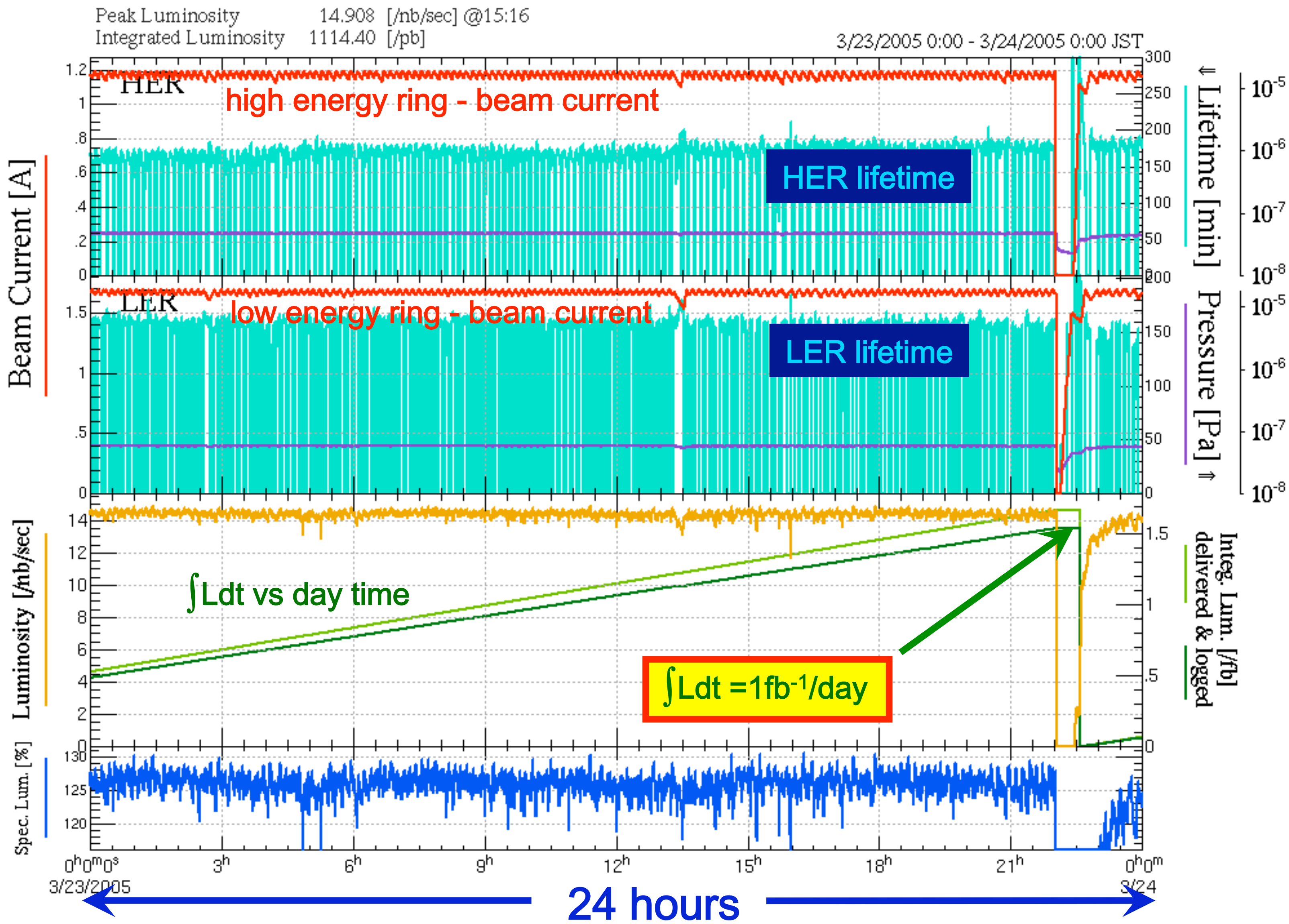
Average Trigger rates:

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

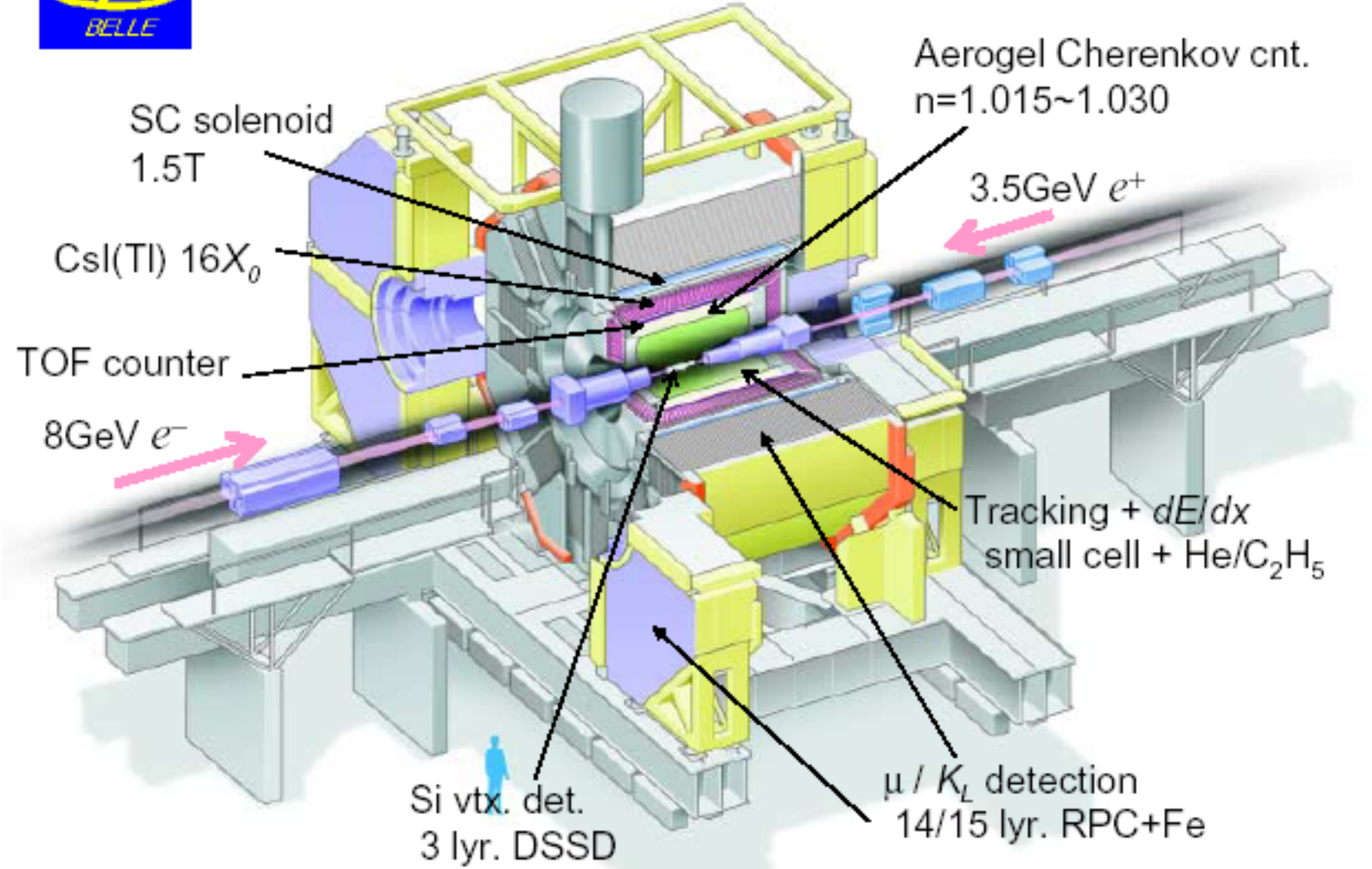
1.5 x 10^9 hadronic events
in analysis ~ 430 x DELPHI …



Luminosity vs Time for 24 hours at KEKB
Continuous Injection → Constant Collision Rate



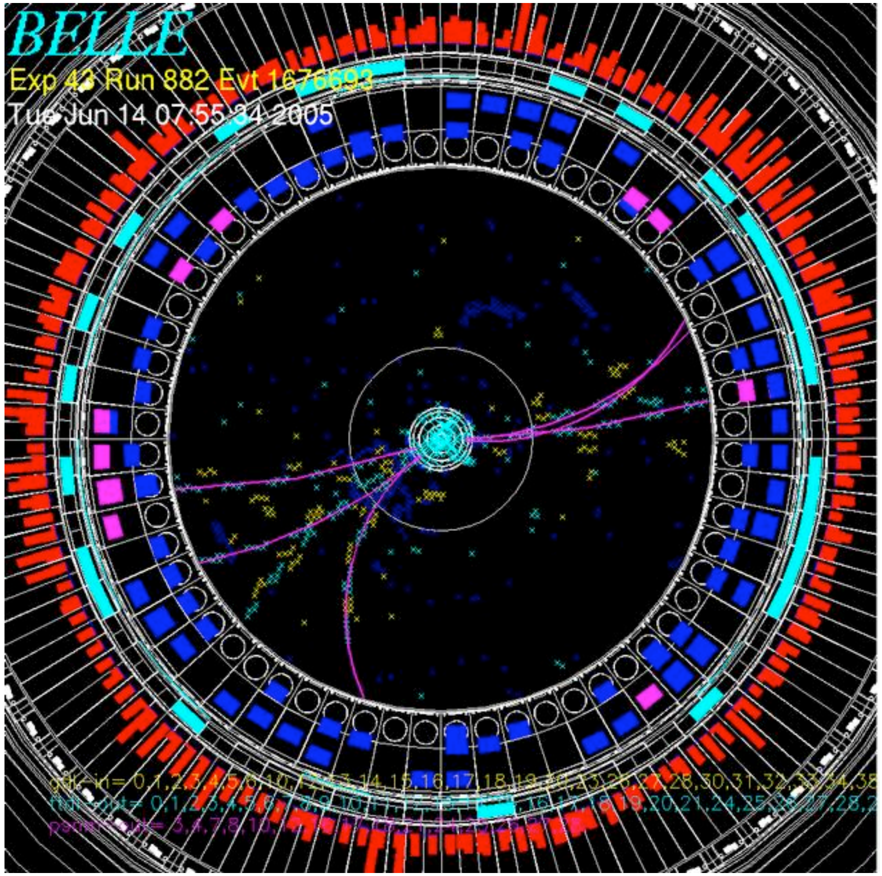
Belle Detector

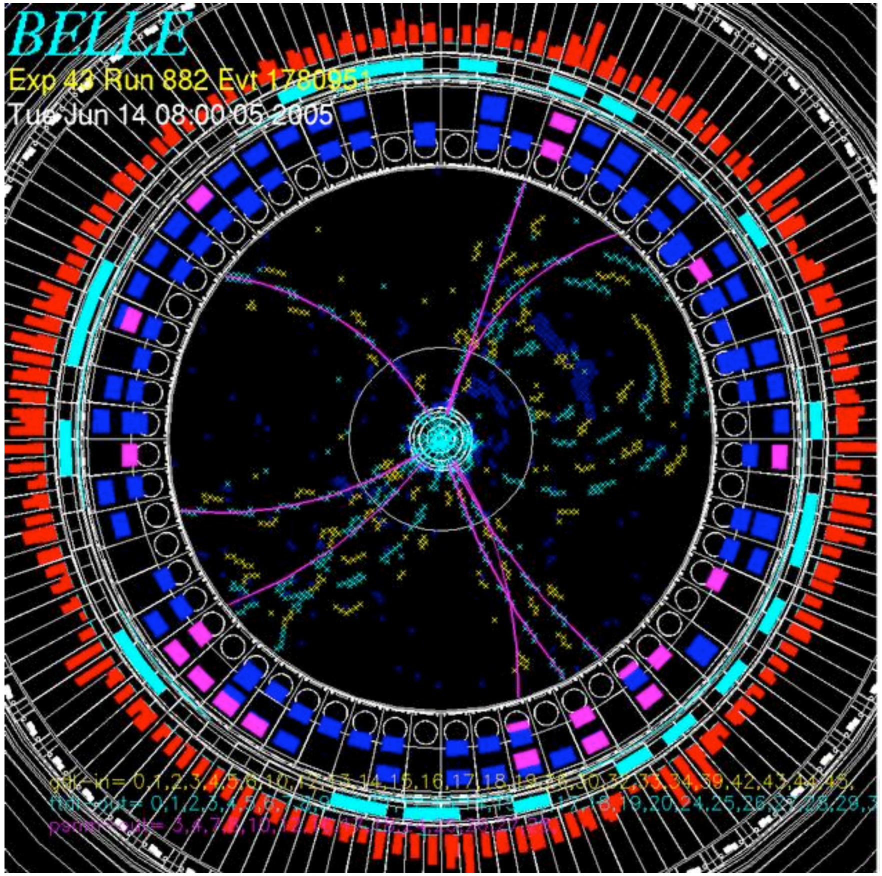


Large acceptance, good tracking and particle identification!

Hadronic Events observed with Belle

➔ 1.5 x 10^9 hadronic events in analysis



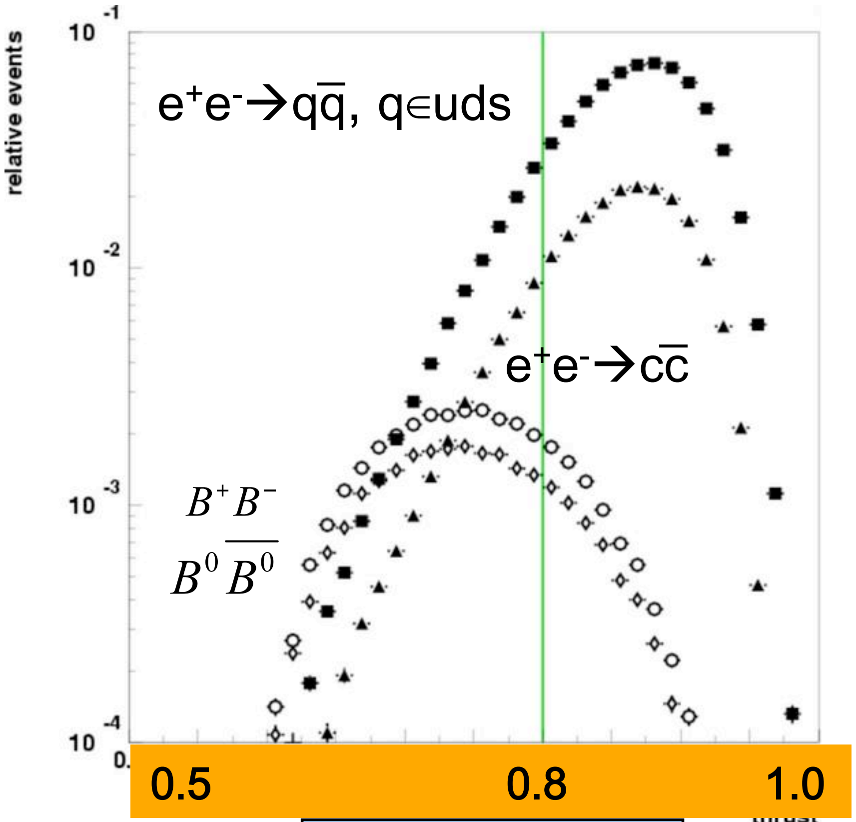


Thrust ~ 1

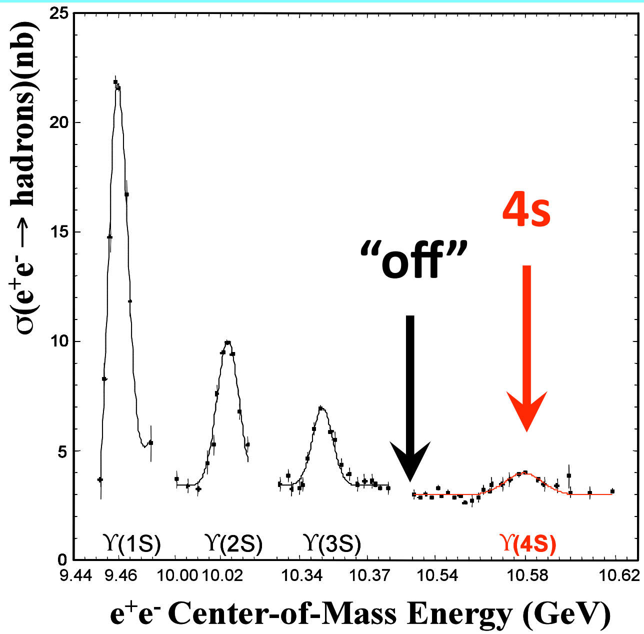
$$thrust = \frac{\sum_{i=\text{particles}} \vec{p}_i \cdot \hat{n}}{\sum_i |\vec{p}_i|}$$

~ 0.5

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



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



- small B contribution (<2%) in high thrust sample.
- keep >75% of cross-section continuum under ϒ (4S) resonance
  → 73 fb^{-1} off-resonance data in analysis
  & 588 fb^{-1} on-resonance data for IFF and slightly less for Collins analysis.
- charm contribution sizeable!

Measurement of Collins Asymmetries

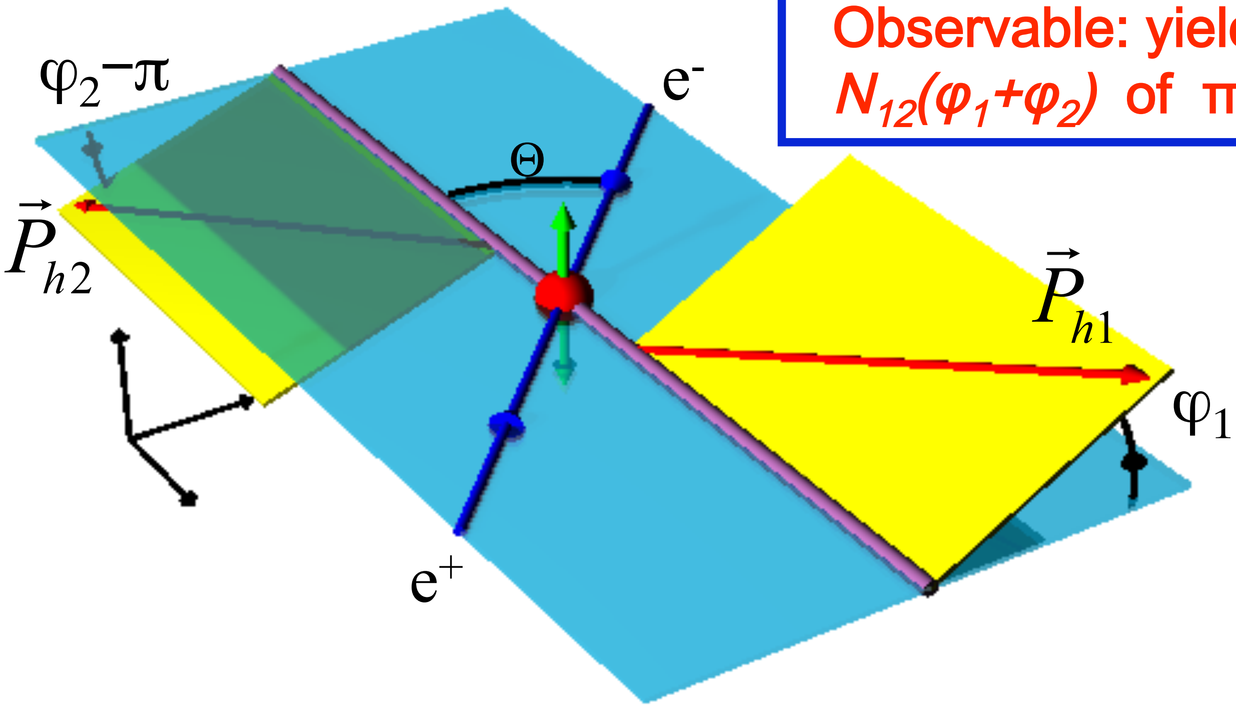
For Belle results see:

Phys.Rev.Lett.96:232002,2006 (on-resonance)
Phys.Rev.D78:032011,2008 (on+off-resonance)

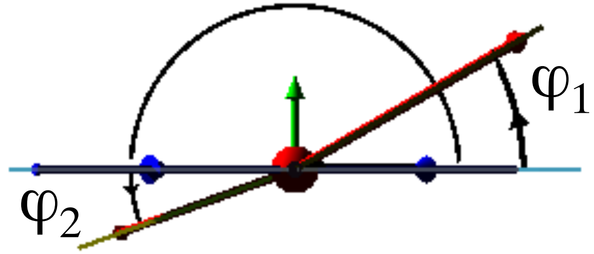
Theoretical aspects of the measurement :

Angular dependences in inclusive two-hadron production at BELLE. Daniel Boer, Nucl.Phys.B806:23-67,2009.

Collins Fragmentation: Angles and Cross Section: Thrust 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:

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

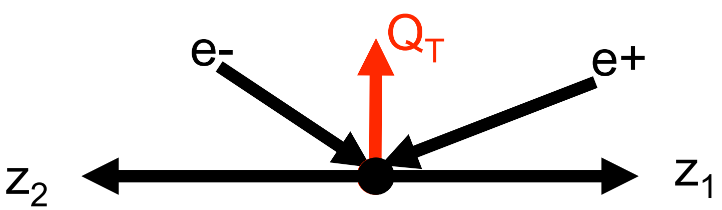
$$B(y) = y(1-y) \stackrel{cm}{=} \frac{1}{4}\sin^2\Theta$$

Polar angle dependence for s_z=0: quarks with transverse spin!

Complication: Radiative Contribution to the Di-Hadron Cross Section

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

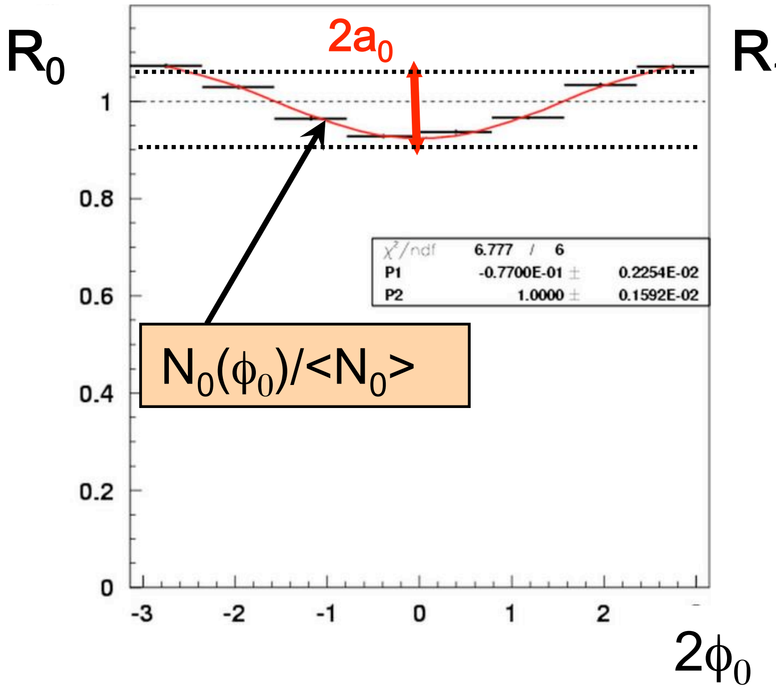
same $\cos(2\Phi_0)$ dependence as Collins effect …

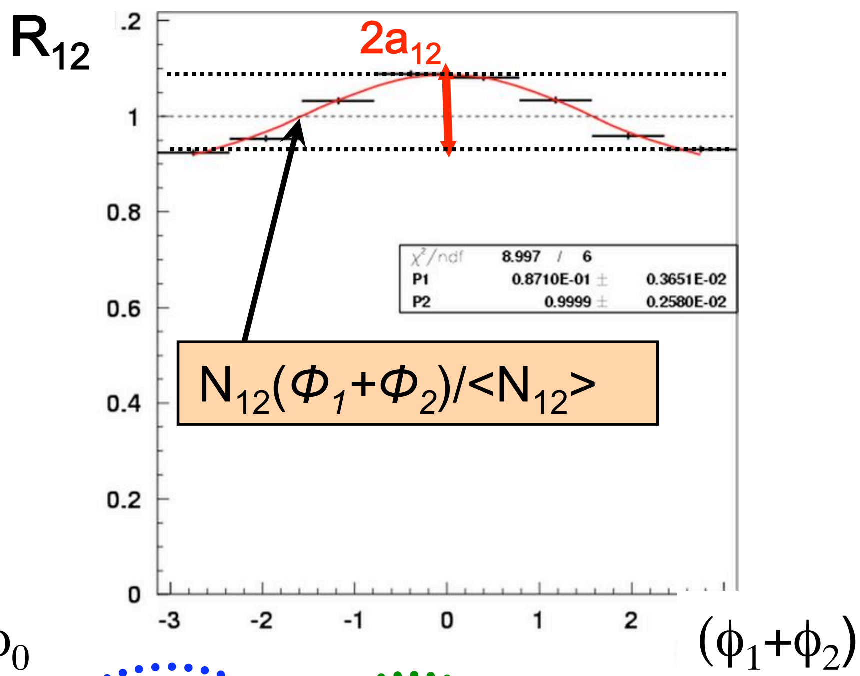


Frame:

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

Examples of Fits to Azimuthal Asymmetries





$$R_0 = \frac{N_0(2\phi_0)}{\langle N_0 \rangle} \propto \frac{aD_1\overline{D}_1 + \cos(2\phi_0)\left[bH_1\overline{H}_1 + cD_1\overline{D}_1\right]}{aD_1\overline{D}_1} = b_0 + a_0\cos(2\phi_0)$$

D_1 : spin averaged fragmentation function,

H_1: Collins fragmentation function

a_0 and a_{12} contain Collins
+ radiative effects
+ acceptance effects

Method to Eliminate Gluon Contributions: Double Ratios for Unlike- and Like Sign Pions

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

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

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

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

(I) radiative effects are charge independent and cancel.

(II) Acceptance effects cancel.

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

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

Cross checked against subtraction R^{UL}-R^{L} with identical results.

Consistency Checks for Double Ratio

(0) Check that Monte Carlo Double asymmetries are 0.

(1) Calibrate with “known” physics asymmetry:
Weak decays produce azimuthal asymmetries. Showed that double ratio method give correct asymmetry for tau-sample.

(2) Comparison of Double Ratio with Subtraction Method leads to identical results.

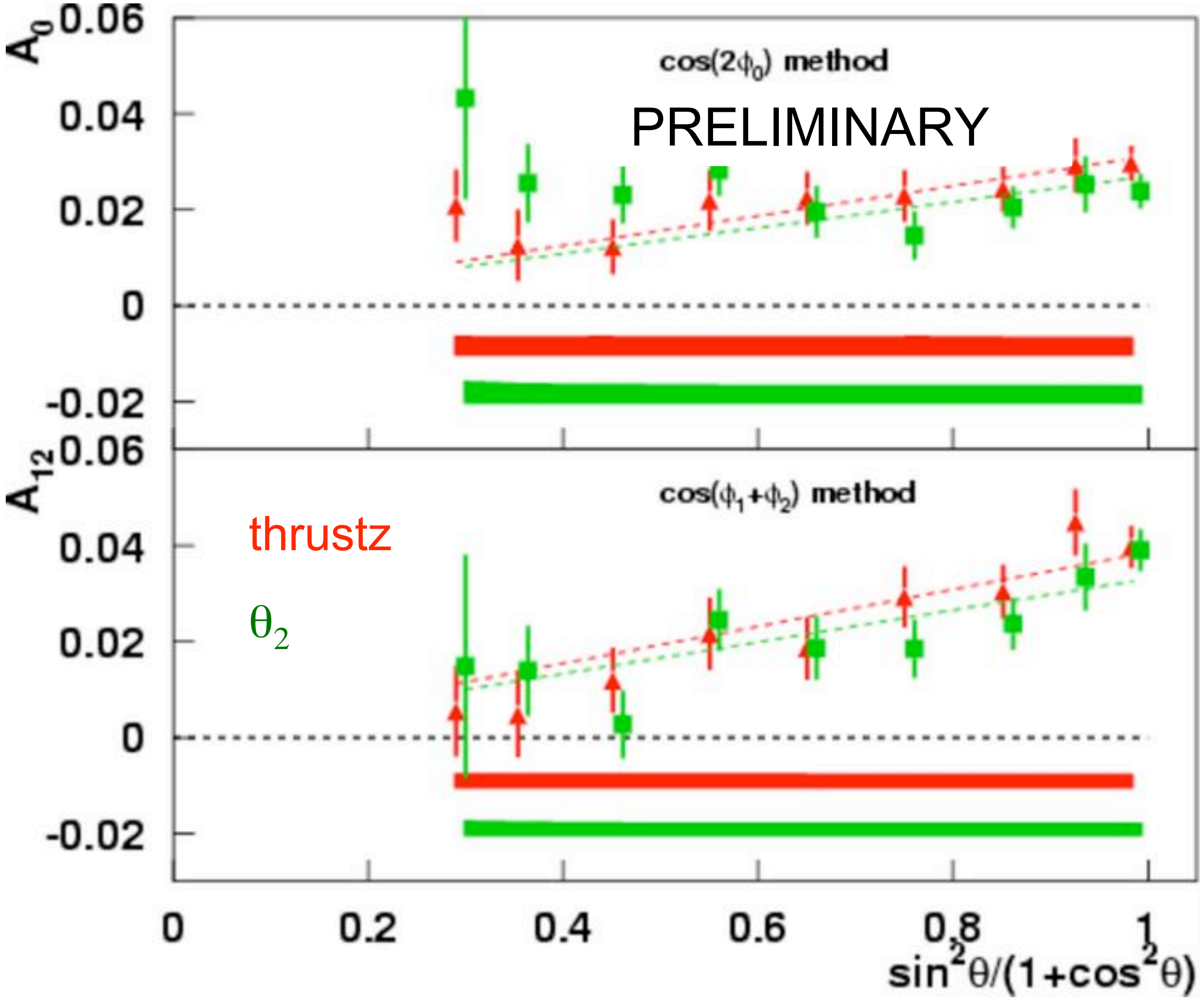
(3) Observe polar angle dependence $A_0 \sim \frac{\sin^2\theta}{(1+\cos^2\theta)}$

(4) Smaller asymmetry for lower thrust sample

(5) Null tests:

(a) mixed events give 0 asymmetry
(b) single side asymmetries average to 0

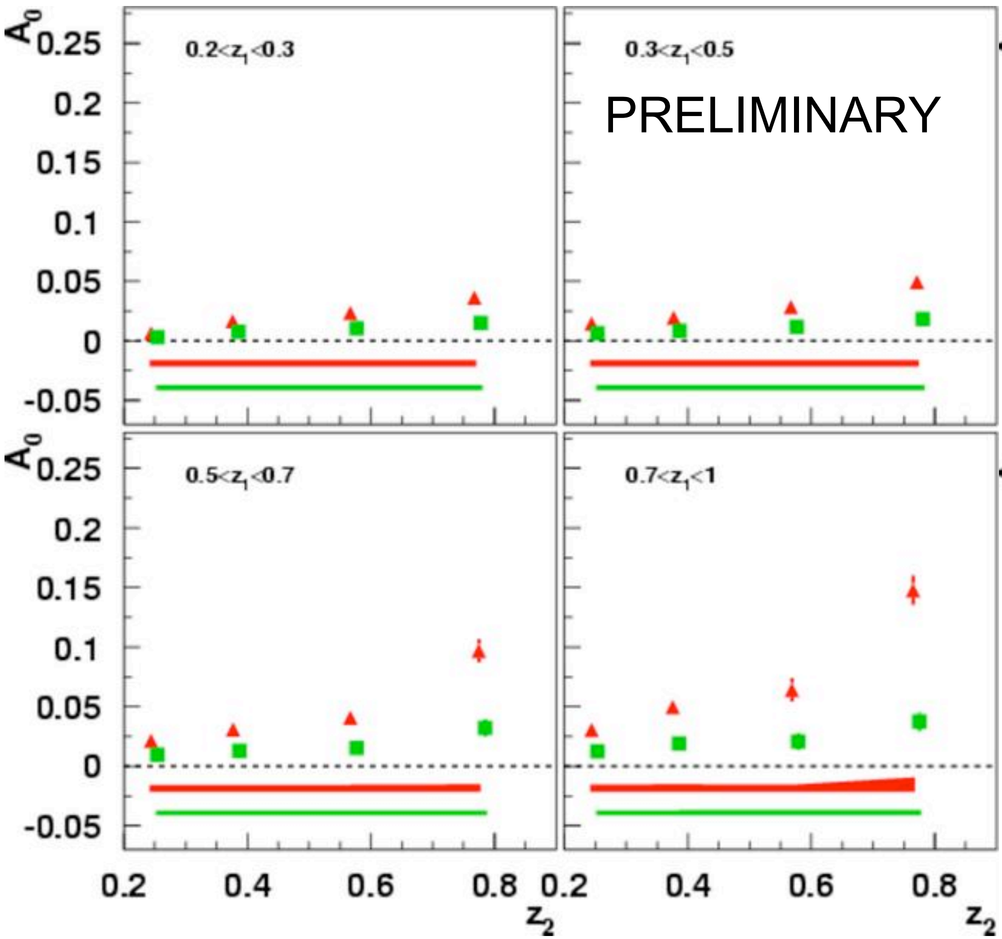
Collins Asymmetries: $\sin^2\theta/(1+\cos^2\theta)$ Binning (UL)



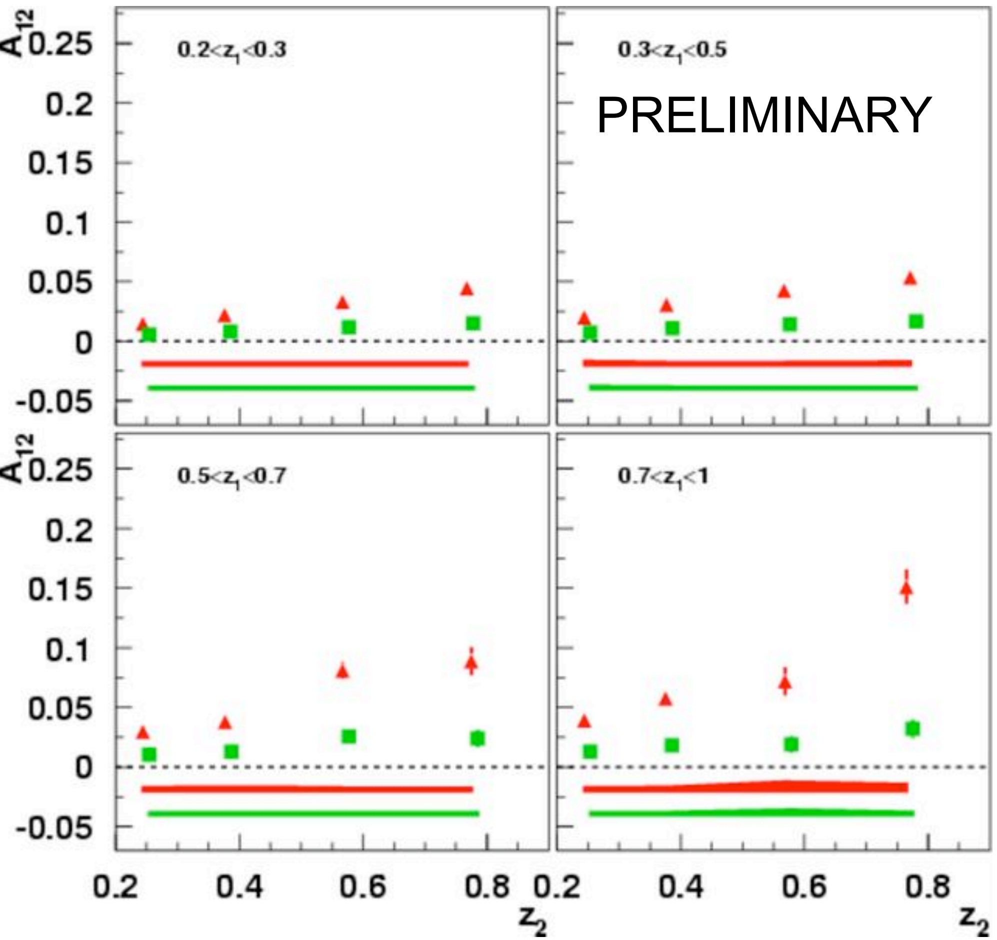
- Nonzero quark polarization ~ $\sin^2\theta$
- Unpolarized de-nominator ~ $1+\cos^2\theta$
- Clear linear behavior seen when using either thrustz or 2nd hadron as polar angle
- Better agreement for thrust axis (~approximate quark axis)

Collins Asymmetries : 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,

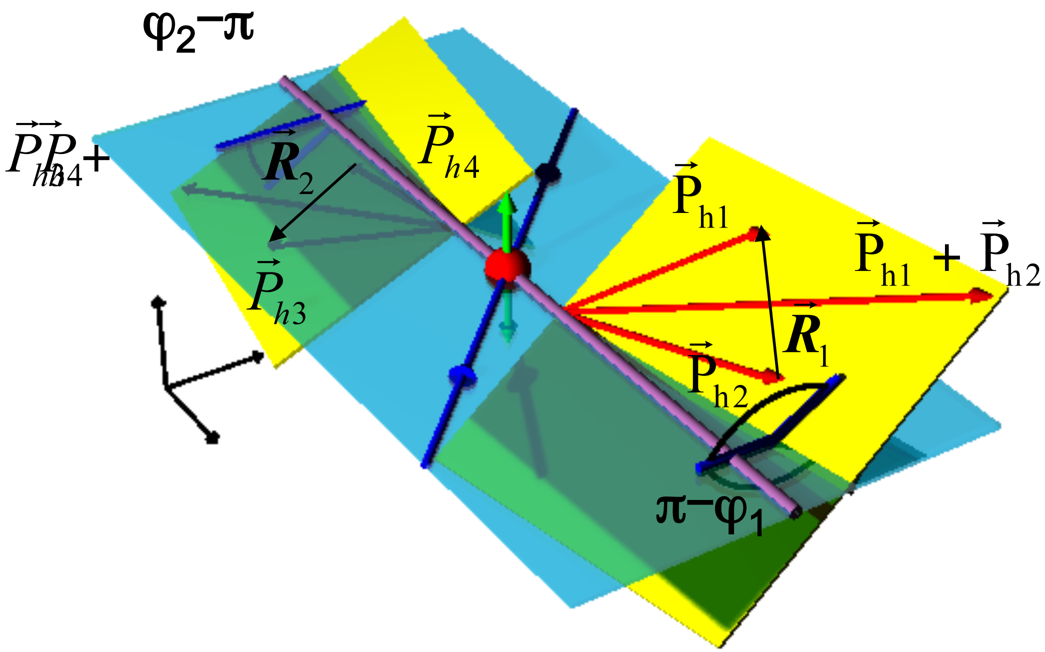
Measurement of IFF Asymmetries

Results first shown at the Spin Workshop in Dubna
in Anselm Vossen's talk

For theoretical aspects of the measurement :

X. Artru and J. C. Collins , Z. Phys C69, 1996.
D. Boer, R. Jakob, M. Radici, Phys. Rev. D67, 2003.

IFF: Angles and Cross Section: Thrust Method (e+e- CMS frame)



- $e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^-\pi^+)_{jet2}X$
- Find pion pairs in opposite hemispheres
- Measure azimuthal correlations of

$$\vec{R}_1 = \vec{P}_{h1} - \vec{P}_{h2}$$

and

$$\vec{R}_2 = \vec{P}_{h3} - \vec{P}_{h4}$$

$$N(z_1, z_2, H_1, H_2, m) \quad (\quad) \quad (\quad)\cos(\quad)$$

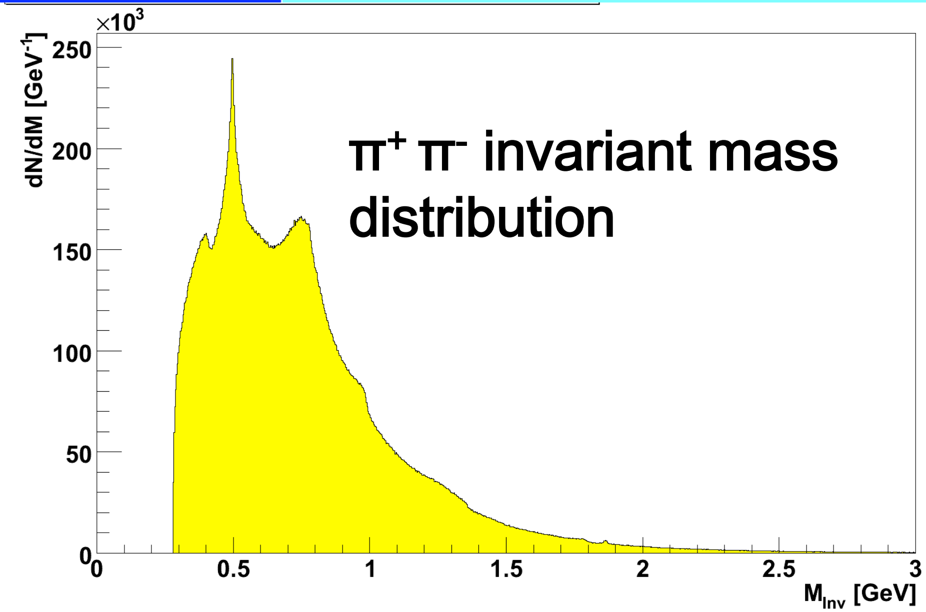
Amplitude of modulation directly measures IFF! (squared)

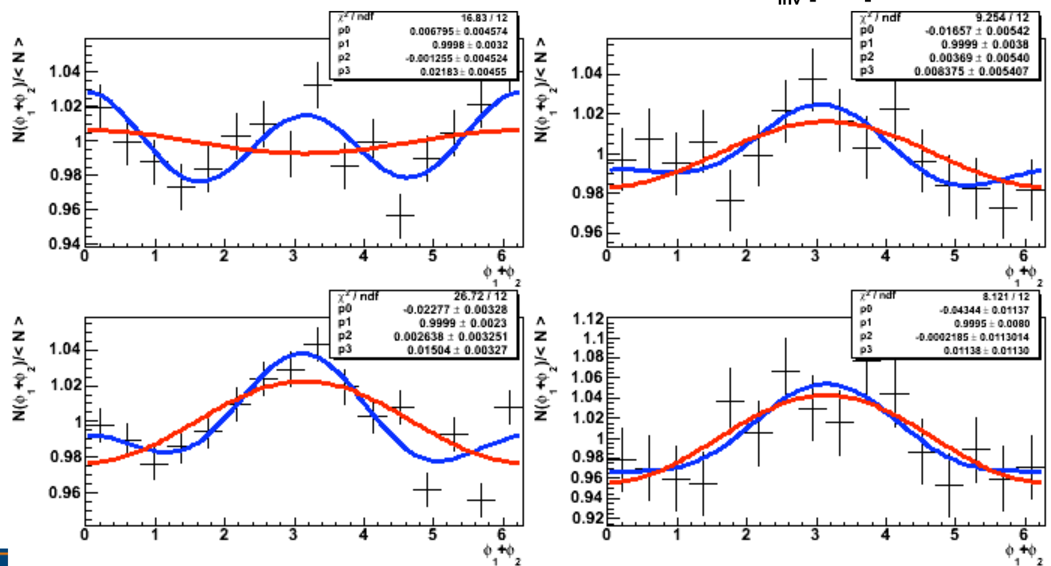
Here: z_1, z_2 relative momenta of first and second pair

Cuts and Binning

- Similar to Collins analysis, full off-resonance and on-resonance data: ~73 fb^{-1} (off) + 588 fb^{-1} (on).
- 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: $|T_z| < 0.75$
- Thrust > 0.8
- $z_{\pi-}$, $z_{\pi+} > 0.1$
- $z_1 = z_{\pi+_1} + z_{\pi+_2}$ and z_2 in 9x9 bins
- $m_{\pi\pi 1}$ and $m_{\pi\pi 2}$ in 8x8 bins: [0.25 - 2.0] GeV

Asymmetry Extraction





- Form normalized yields:

$$R_{12}(\phi_1+\phi_2) = \frac{N_{12}(\phi_1+\phi_2)}{\langle N_{12} \rangle}$$

- Fit with:

[illegible]

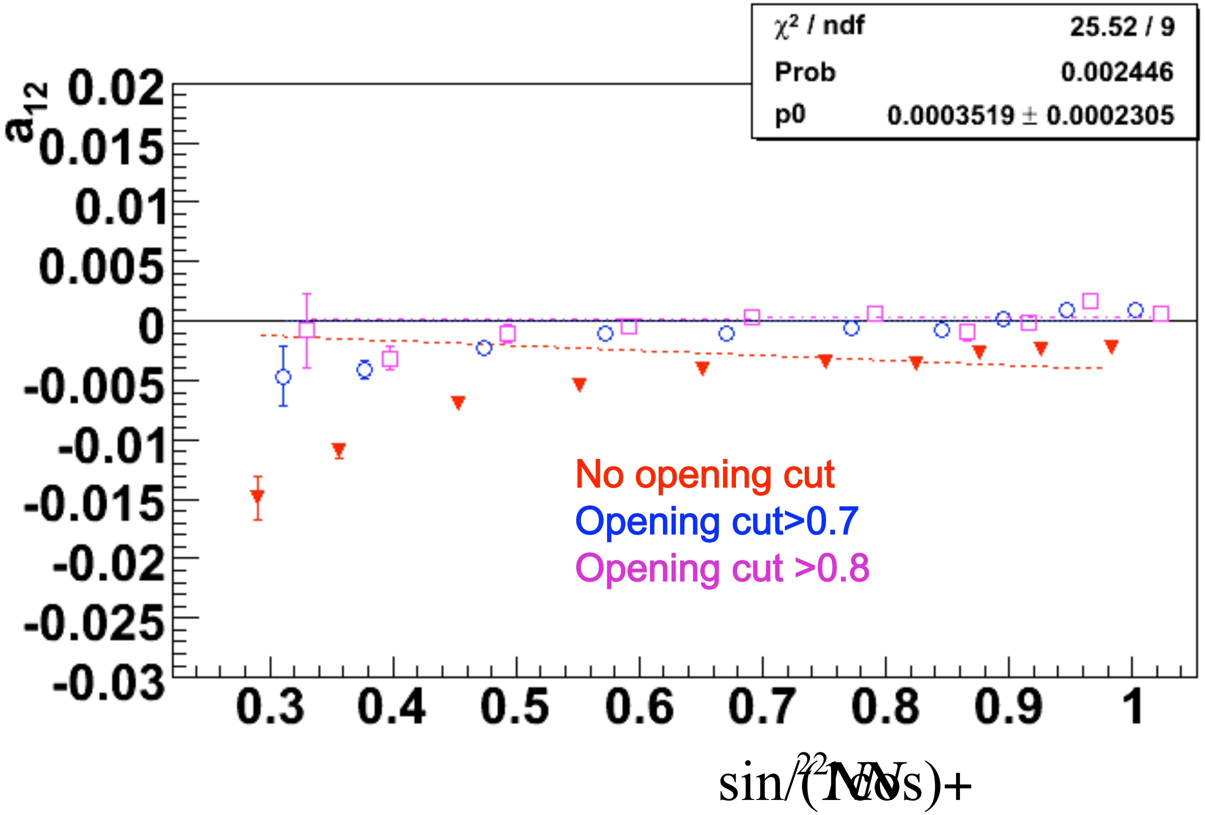
or

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

Amplitude a_{12} directly measures IFF squared!

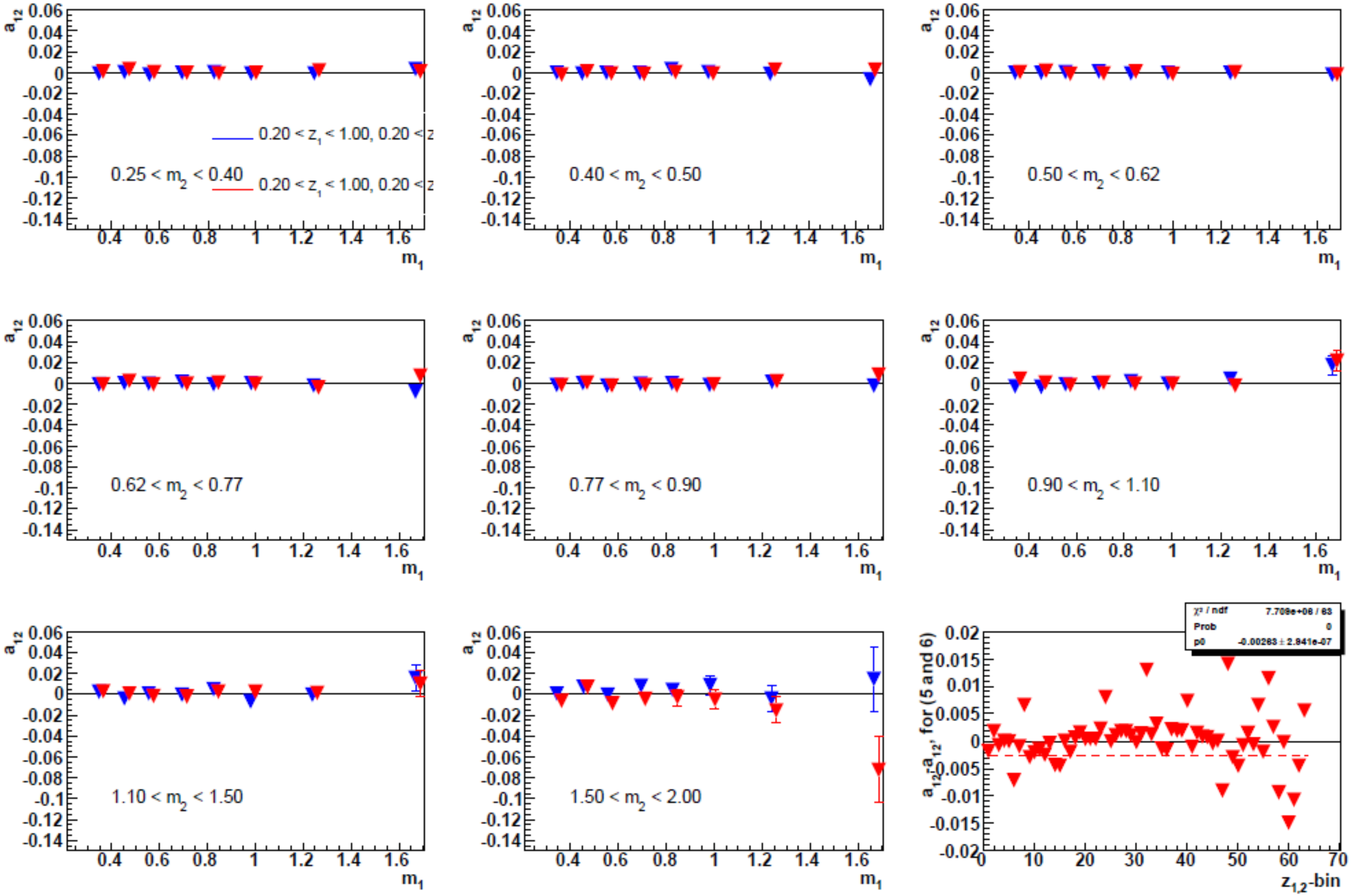
Zero Tests: (I) IFF not Included in MC!

- Small false asymmetry due to acceptance effect !
- Appearing at boundary of acceptance.
- Jet opening cut in CMS of 0.8 (~37 degrees) ➔ reduces acceptance effect to less than 0.001.
- Cut $\sin^2/(1+\cos^2) > 0.5$



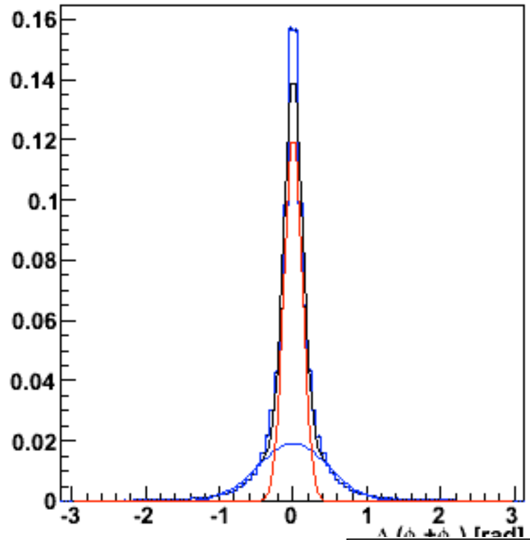
Zero Tests (II) : False Asymmetries ~ 0 in Mixed Events

Thrust Axis from Event n or n-1

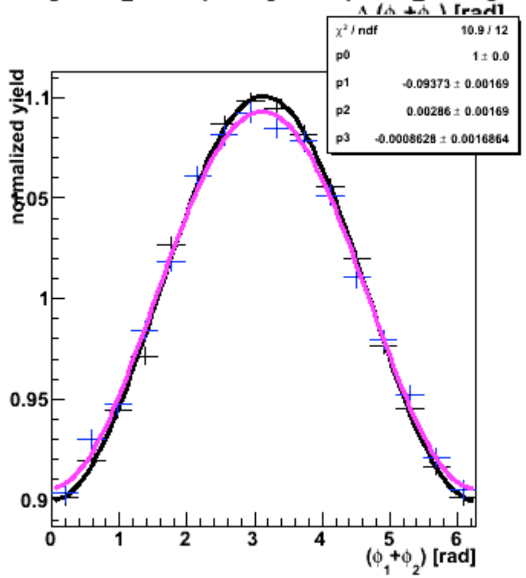


Impact of Smearing in Thrust Axis: Weighted MC Studies

- Inject asymmetries in Monte Carlo
- Reconstruction smears thrust axis,
- ~94% of input asymmetry is reconstructed
- Effect is understood, can be reproduced in Toy MC
- Asymmetries corrected



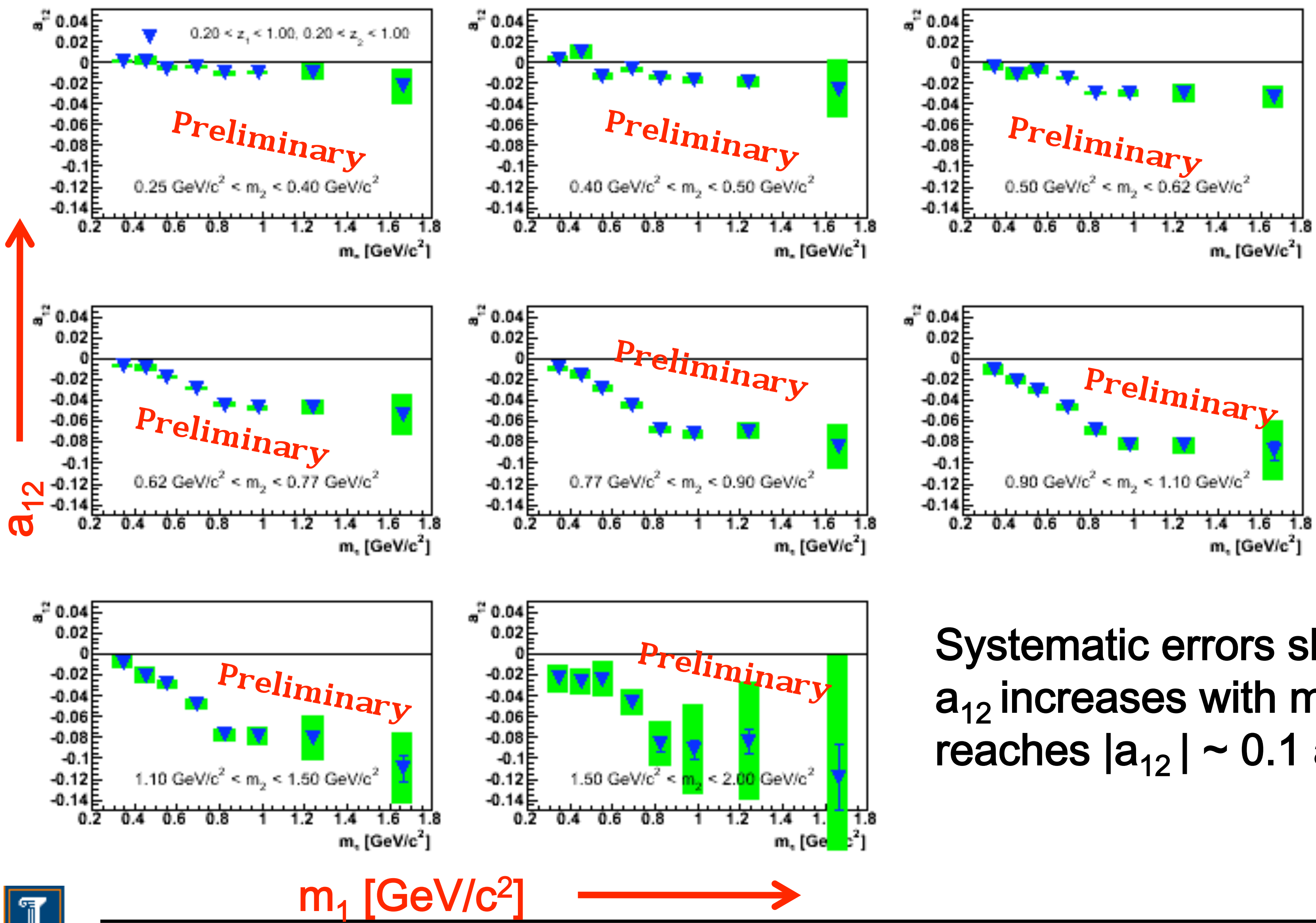
Smearing in azimuthal angle of thrust axis in CMS



Black: input
Purple: recon.

IFF- a_{12} vs Invariant Mass

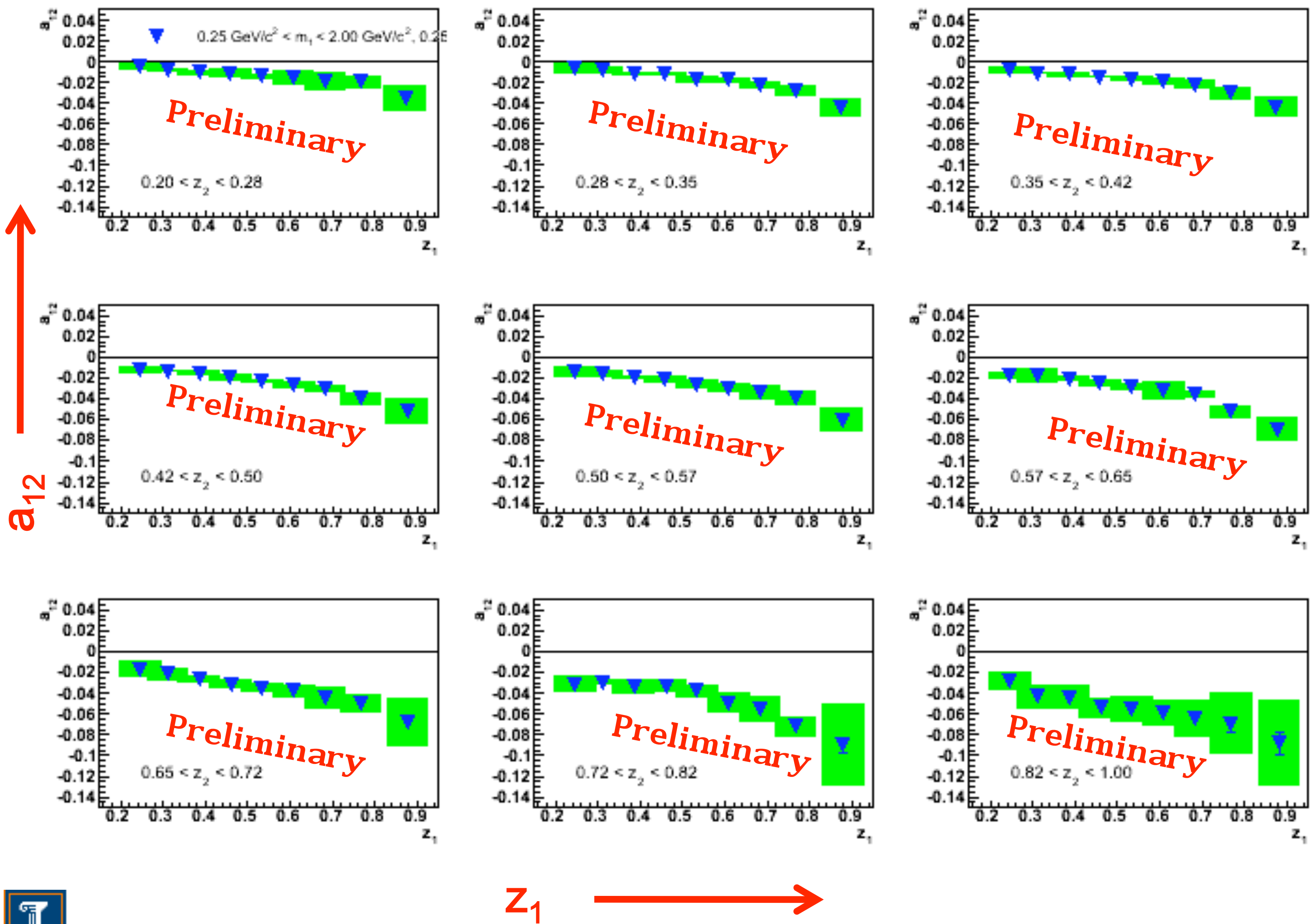
8x8 m_1 m_2 binning



Systematic errors shown.
a_{12} increases with m_1 and m_2
reaches $|a_{12}| \sim 0.1$ at large m_i.

IFF- a_{12} vs Pair Momentum Fraction z_i

9x9 z_1 z_2 binning



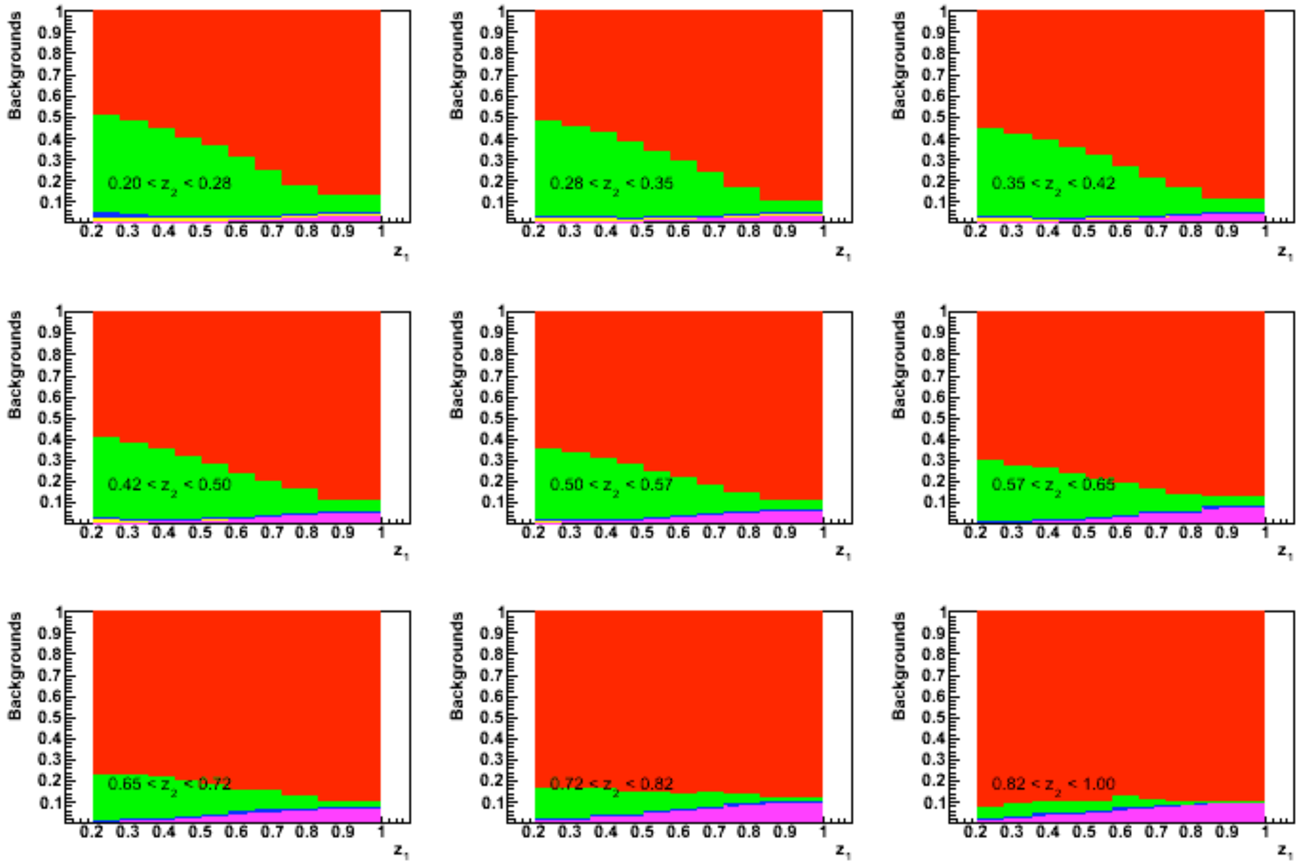
Systematic Errors

- Dominant:
  - MC asymmetries + its statistical error (~% level)
- Smaller contributions:
  - Mixed event asymmetries: ~ 0.001
  - Higher moments: < 0.001
  - Axis smearing
  - Tau contribution
  - Charm contributions
- Possible effects from gluon radiation not included in systematic error.

IFF vs Collins Asymmetries in e+e-

- a_{12} asymmetries directly measure IFF squared.
- IFF asymmetries provide analyzing power for quark spin without transverse momentum dependence.
- Double ratio approach to cancel contributions from radiative effects from Collins analysis not needed!

Subprocess Contributions:
uds, charm, tau, Bs



9x9 z_1 z_2 binning

tau contribution (only significant at high z)

charged B(<5%, mostly at higher mass)

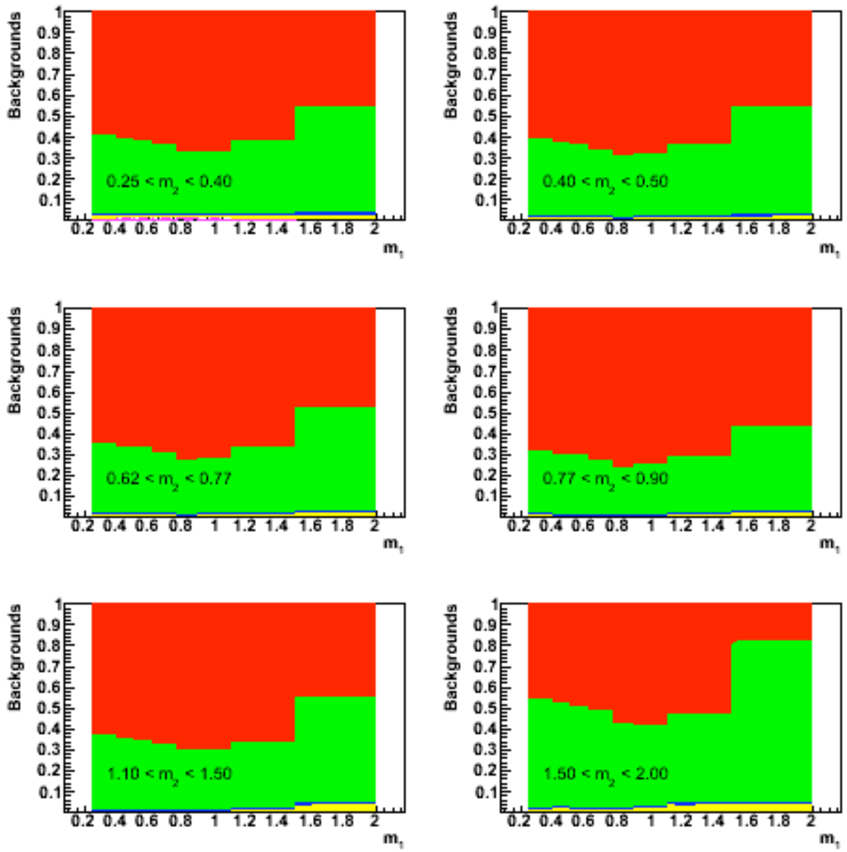
Neutral B (<2%)

charm(20-60%, mostly at lower z)

uds

Data not corrected for Charm contributions

Subprocess Contributions: uds, charm, tau, Bs



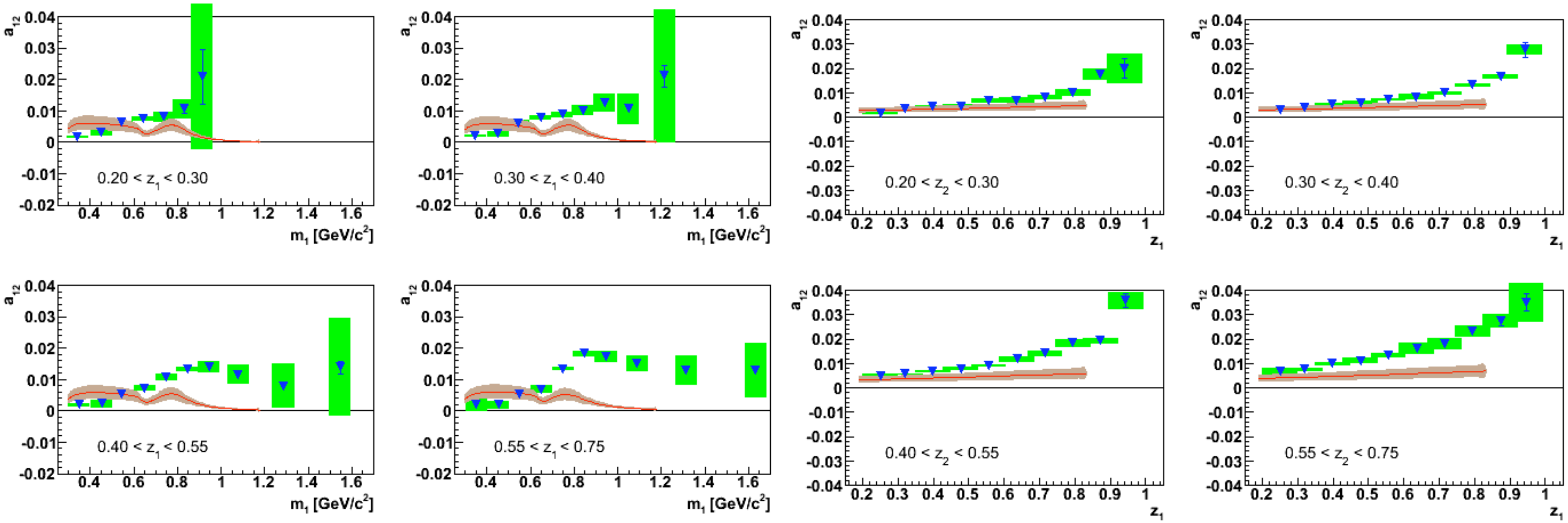
8x8 m_1 m_2 binning

charged B(<5%, mostly at higher mass)
Neutral B (<2%)
charm(20-60%, mostly at highest masses)
uds

Data not corrected for Charm contributions

Model Calculations for IFF

Bacchetta,Checcopieri,Mukherjee,Radici : Phys.Rev.D79:034029,2009.



Experimental results might contain effects from gluon radiation not contained in the model

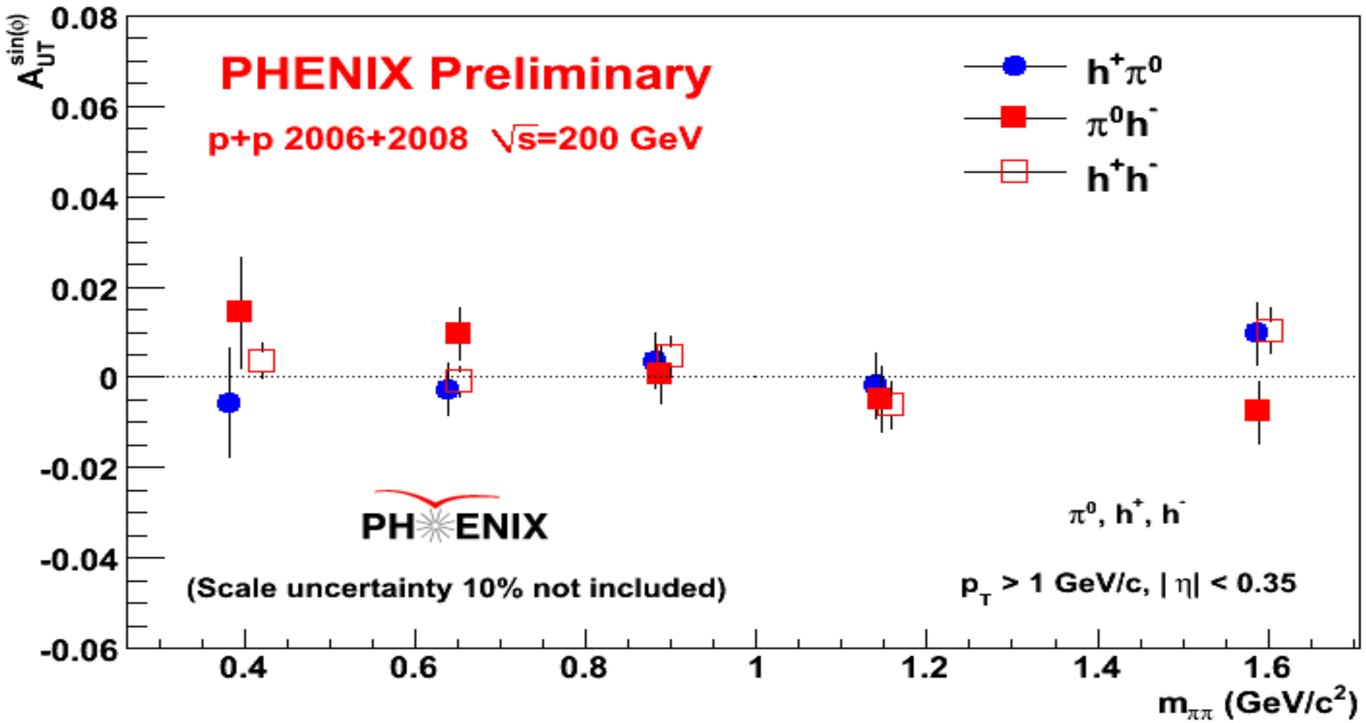
Mass dependence : magnitude at low masses comparable, high masses significantly larger (some contribution possibly from charm)

Z dependence : Rising behavior steeper in data

Measurements of Quark Transversity

	1991	2005	Underway	Future
p+p	E704, 1991 Large forward SSA	STAR, PHENIX, BRAHMS, 2004~2005 Inclusive A_N	RHIC IFF asym.	RHIC Collins asym. JParc, RHIC, FAIR Drell-Yan
SIDIS		HERMES 2005, COMPASS 2006 A_{UT}	COMPASS p target	JLab ^{3}He and 12 GeV
$e^+ + e^-$		BELLE 2006 Collins FF	BELLE IFF	BELLE k_T dep. Pol. & upol FF, pol. Lambda FF

First Example from RHIC IFF in PHENIX (Ruizhe Yang, UIUC)



As expected:No significant asymmetries seen at central-rapidity.

Need more statistics

Extend measurement in forward direction!

Summary

- Results on Collins asymmetries in e+e- have been finalized and published.
- First measurement of Interference Fragmentation Function!
- Studies of systematic effects to be finalized.
- Future goal: Combined analysis of SIDIS, pp, e^+e^- data with the goal to extract transversity quark distributions.

Future Plans

- Carry out IFF asymmetries for other species: (π^0,$\pi^{+,-}$), (K^+,K^-), (π^+,K^-), …
- Precision measurement of spin averaged FF for single inclusive hadrons (and for pairs!) as input to RHIC spin and SIDIS programs.
- Transverse momentum dependence of spin averaged FFs.
- Other spin dependent FFs: ρ, Λ