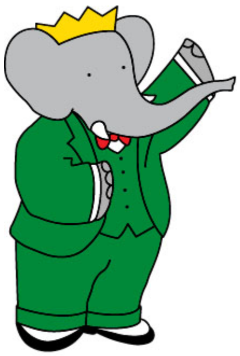

Studies of inclusive hadron production at *BABAR*

Ray F. Cowan
Representing the *BABAR* Collaboration

QCD Evolution Workshop
QCD2014
Santa Fe, NM
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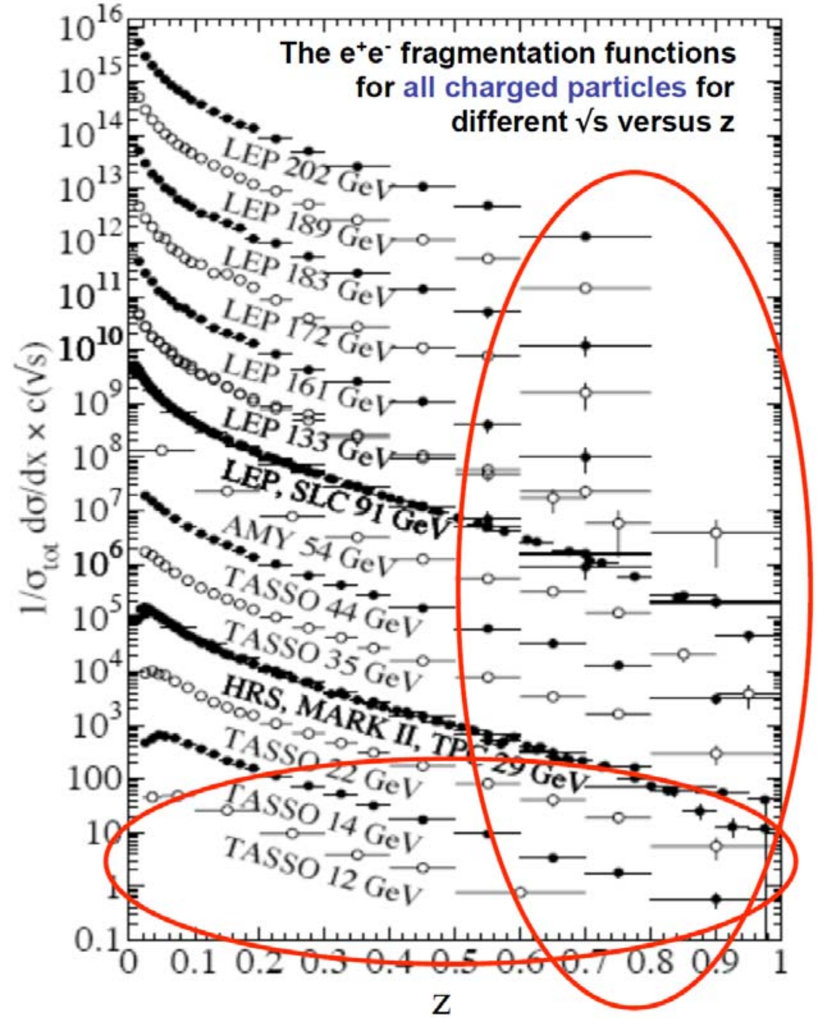
Massachusetts Institute of Technology

Topics

- Contributions to fragmentation studies from e^+e^- data
- Inclusive π, K, p cross sections
  - Charged hadron identification
  - Final results from *BABAR*: cross sections and scaling properties
- Collins asymmetries
  - As functions of momenta fractions z_1, z_2
  - As functions of transverse momenta p_{t1}, p_{t2}
    - First measurement
  - As functions of four-dimensional fit (z_1, z_2, p_{t1}, p_{t2})
  - As functions of thrust polar angle ϑ_{th}
- Anti-deuteron production
- Summary

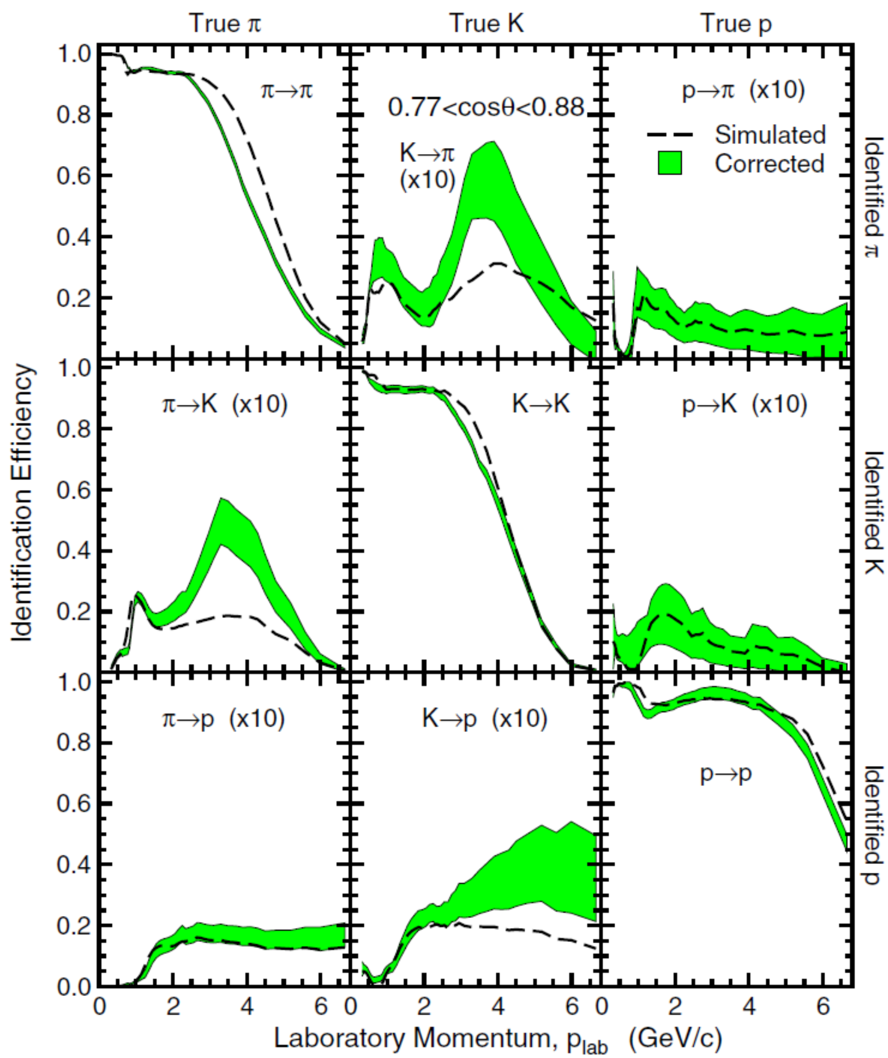
Contributions F.F. from e^+e^- studies

- Most data is from higher energies than the *B*-factories
- More information needed at low energies and high *z*
- Many attempts to extract FF from e^+e^- data
  - KKP, AKK, HKNS, Kretzer …
    - NPB **725**,181 (2006), NPB **803**, 42 (2008), PRD **75**, 094009 (2007), PRD **62**, 054001 (2000), NPB **582**, 514 (2000)
  - Global analyses of e^+e^-, SIDIS, and pp data
    - PRD **75**, 114010 (2007), PRD **76**, 074033 (2007), arXiv:1209.3240



Inclusive hadron production: $\pi^{\pm}$, $K^{\pm}$, $p/\bar{p}$

- A precision measurement using 0.91 fb^{-1} of $e^+e^- \rightarrow q\bar{q}$ ($q = udsc$) data at 10.54 GeV
  - Also 3.61 fb^{-1} for checks and calibrations
  - Results are systematics dominated
- Depends on DIRC, dE/dx
  - Good ID at low, medium p_{lab}
  - Falls off at higher p_{lab} as Cherenkov angles converge
  - Calibrated using data control samples
  - High efficiency over much of the momentum range
  - Few % mis-identification

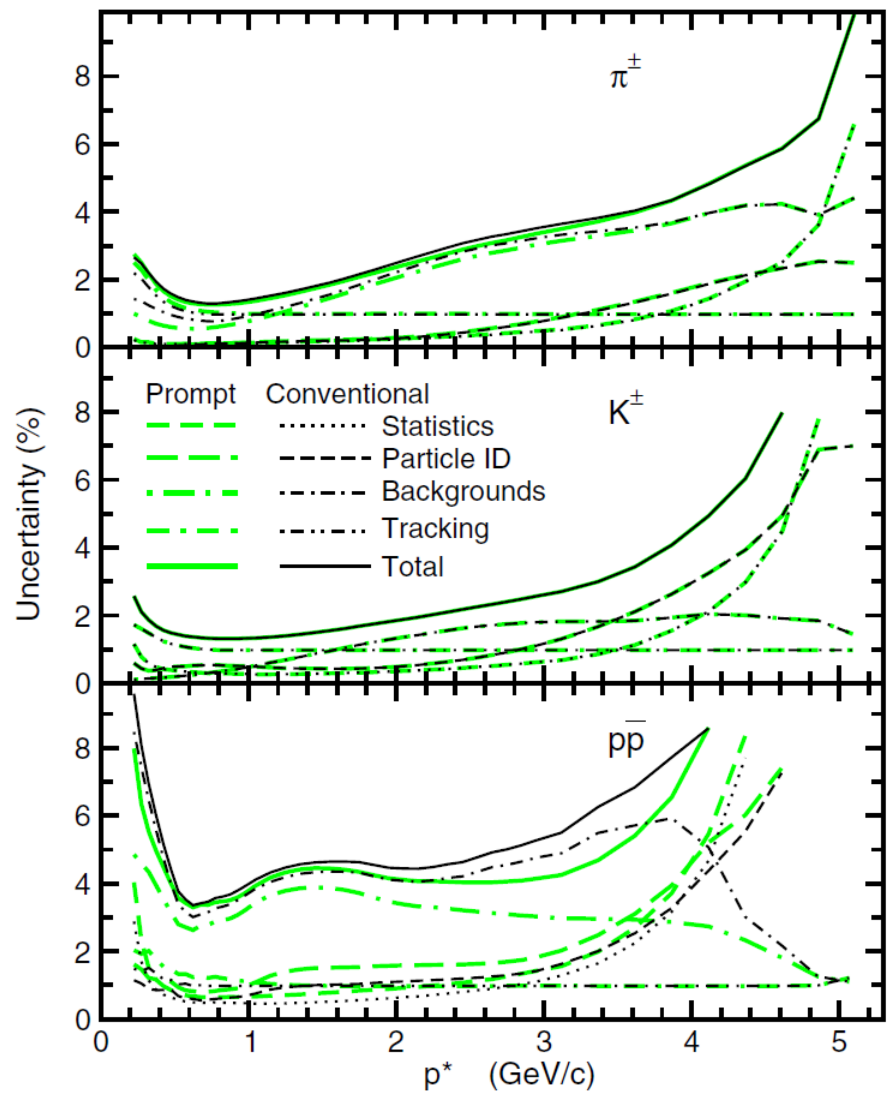


Efficiency matrix

Dashed lines: simulated; Green regions: corrected

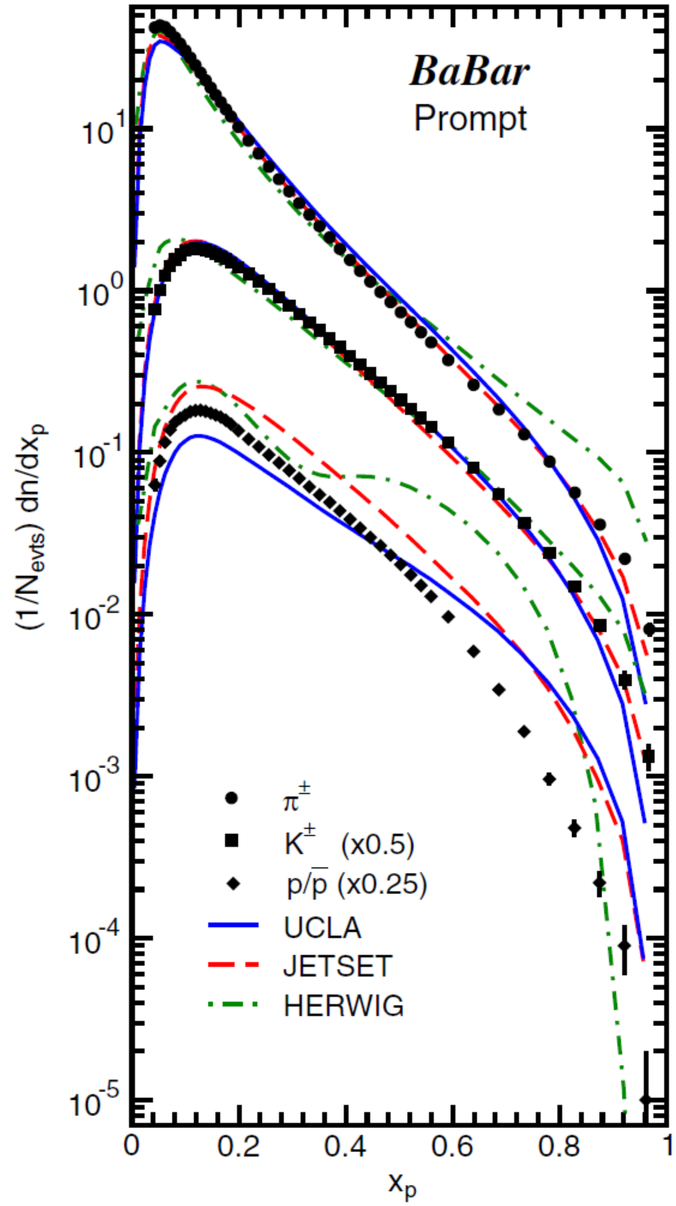
$\pi^{\pm}$, $K^{\pm}$, $p/\bar{p}$ selection, corrections, and systematics

- Require ≥ 3 charged tracks
- Event thrust axis well within DIRC acceptance
- Require tracks originate from interaction point (IP)
- Correct spectra for
  - Physics background of few % (esp. $\tau^{+}\tau^{-}$)
  - Interaction in materials
  - Efficiency and resolution
- Thorough systematics and cross-checks
  - Compare data to MC; angular dependencies; positive vs. negative charges, …
  - Largest effects from particle id, backgrounds, and tracking efficiencies



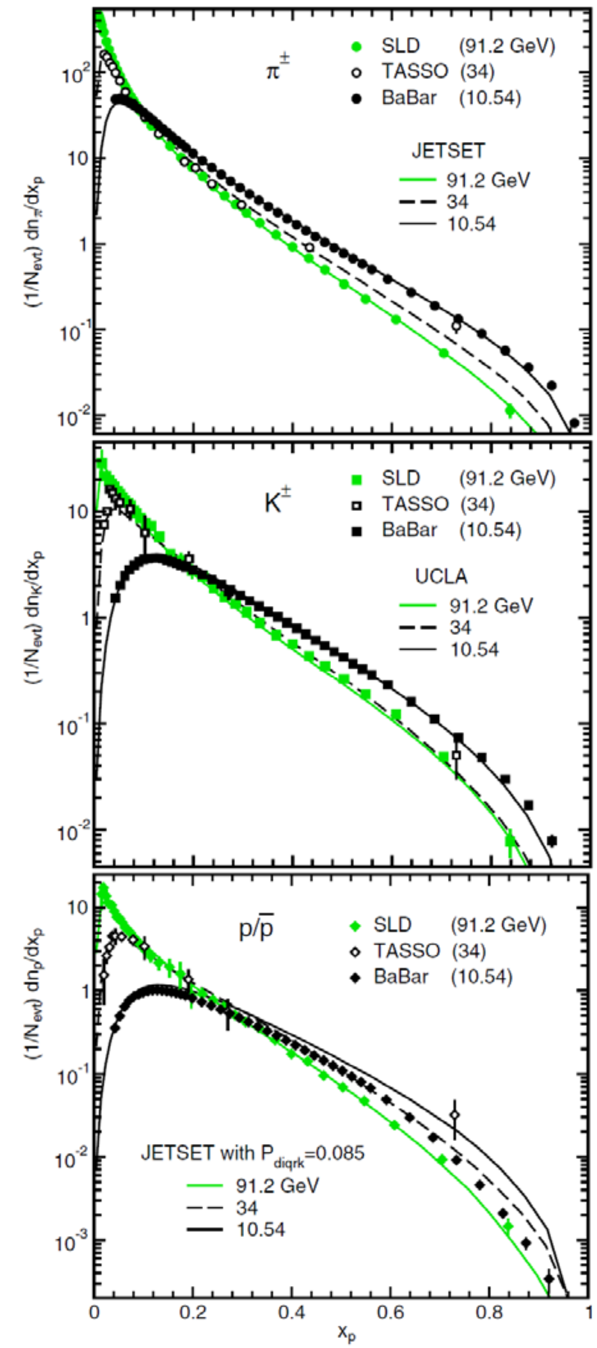
Results

- Results in terms of scaled momentum $x_p = 2p_{cm}/E_{cm}$
  - o Coverage from 0.2 GeV/c to 5.27 GeV/c
- Compare with hadronization models
  - o Using default parameters
- Generally significant discrepancies
  - o Qualitatively ok, but no model describes things in detail
  - o Peak positions are consistent
    - Except HERWIG $K^{\pm}$



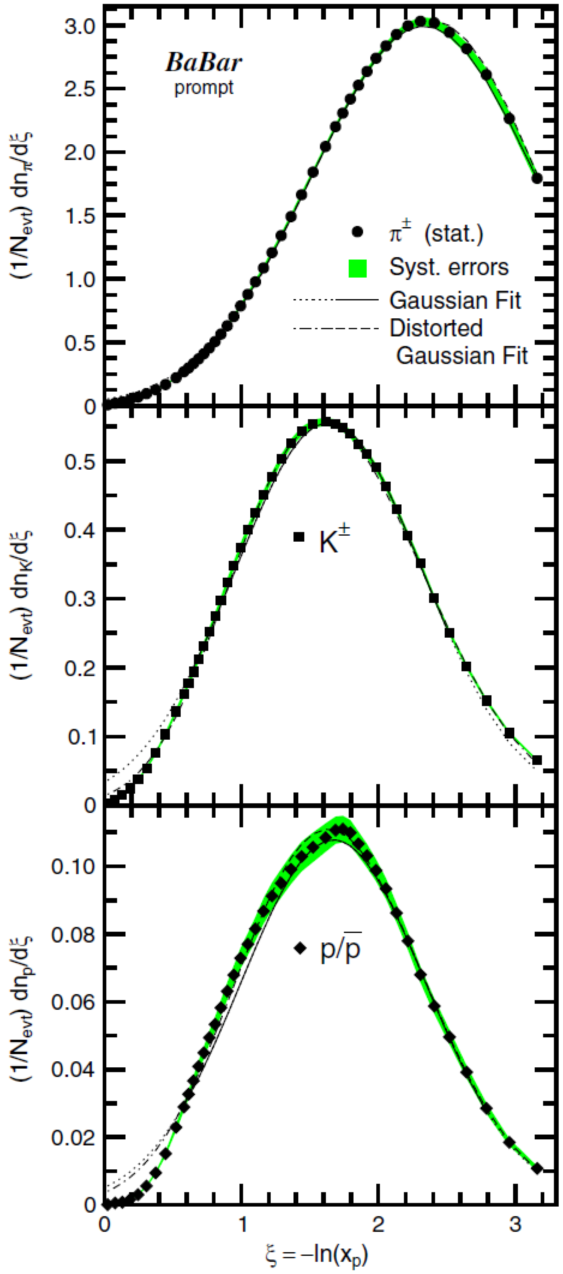
Scaling properties

- Consider π, K, and p from *BABAR*, TASSO and SLD
- Strong scaling violation at high x_p (running of α_s) and low x_p (pion mass)
- $K^{\pm}$: the different flavor composition of the three samples modifies the expected scaling violation
  - Models predict about 10%-15% more scaling violation than is observed
- $p/\bar{p}$: scaling prediction for 10.54 GeV is consistent with data for $x_p < 0.07$
  - But exceeds it by as much as a factor 3 at $x_p = 0.8$



Test of MLLA+LPHD QCD

- Modified Leading Logarithm Approximation (MLLA) with Local Parton-Hadron Duality (LPHD) ($\xi^* = -\ln x_p$)
  - o A Gaussian function should provide a good description of these spectra
  - o The peak position ξ^* should decrease exponentially with increasing hadron mass at a given E_{cm}
  - o Should increase logarithmically with E_{cm} for a given hadron type
- Fit the spectra with a (distorted) Gaussian function
  - o Gives a reasonable description of the data
  - o ξ^*_π is higher than ξ^*_K in agreement with the predicted drop, b
  - o But ξ^*_p is not lower than ξ^*_K
- • Similar behavior observed at higher energies



Collins asymmetries using charged pion pairs

- Parton fragmentation functions $D_h^q(z)$ parameterize the probability for parton $q \rightarrow$ hadron h ($q = g, u, \bar{u}, d, \bar{d}, \ldots$)
  - Where hadron h carries fraction z of the parton's momentum
- $D_h^i(z)$ include non-perturbative, long-distance effects
  - So cannot be calculated in pQCD
  - Can be derived from a starting distribution at a given energy scale
- Studies using e^+e^- annihilation provide very clean environment
  - No hadrons in the initial state
- Unpolarized fragmentation functions are now well known
  - Using data from LEP, SLC, KEKB, PEP-II
- Collins proposed use of single-particle distributions as a probe of the tranverse polarization of a quark
  - Look for a spin asymmetry in the azimuthal distribution of the hadron about the jet axis
  - Uses the Collins fragmentation function $H^{\perp}$

J.C. Collins, *Nucl.Phys.* B **396**, 161 (1993),
J.C. Collins, Phys.Lett. B **536**, 43 (2002).

Polarized fragmentation

- The fragmentation function $D_h^q(z)$ for a given transverse momentum of the outgoing hadron of mass M_h can be written

$$D_h^{q^\uparrow}(z, \mathbf{P}_h^\perp) = D_1^q(z, {P_h^\perp}^2) + H_1^{\perp q}(z, {P_h^\perp}^2) \frac{(\hat{\mathbf{k}} \times \mathbf{P}_h^\perp) \cdot \mathbf{S}_q}{z M_h}.$$

  - In terms of the leading-twist unpolarized $D_1^q(z)$
  - The Collins $H_1^{\perp,q}$ function
  - The spin of the decaying quark $\mathbf{S}_q$
  - The transverse momentum of the hadron $\mathbf{P}_h^\perp$
- This allows for an azimuthal asymmetry in φ of the hadrons around the quark momentum direction $\check{\mathbf{k}}$
  - φ is the angle between the plane perpendicular to the $\mathbf{S}_q$ and the plane formed by $\mathbf{P}_h^{\perp,q}$ and $\check{\mathbf{k}}$
- The amplitude of this asymmetry is called the Collins effect

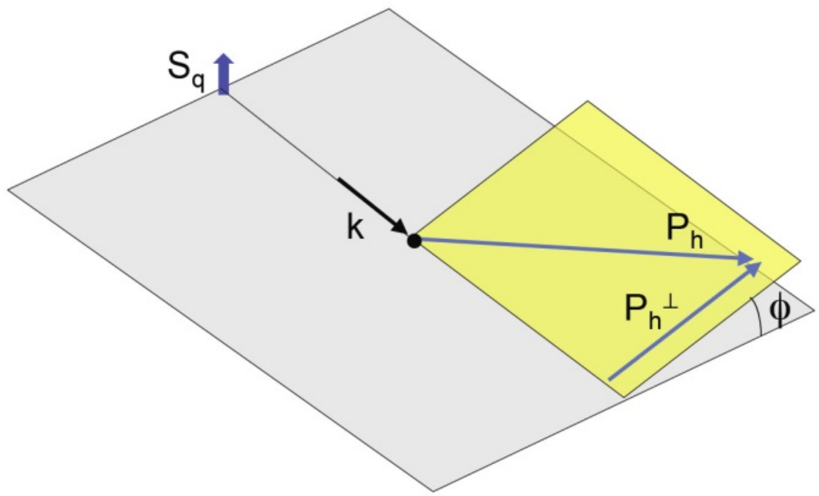
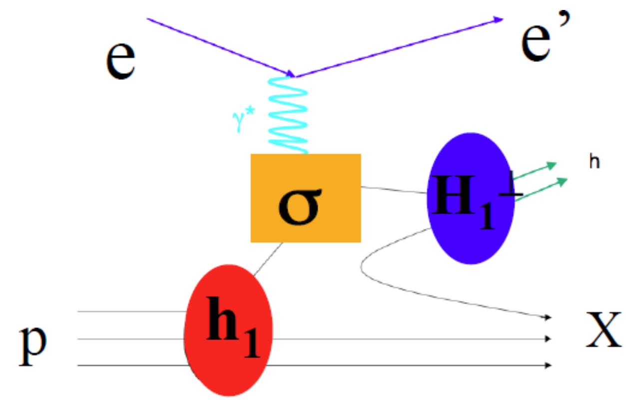
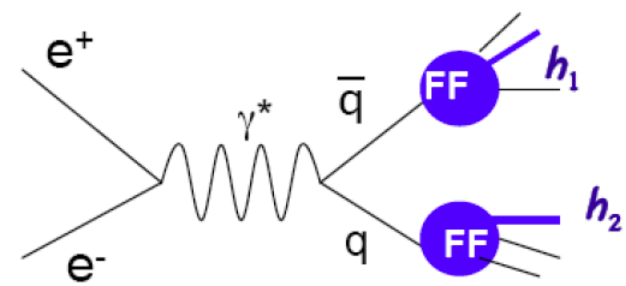


Illustration of the azimuthal angle φ in the case of a quark of momentum **k** and spin $\mathbf{S}_q$ fragmenting into a spin-0 hadron of momentum $\mathbf{P}_h$ with component $\mathbf{P}_h^\perp$ transverse to **k**

First evidence

- First seen in semi-inclusive, deep-inelastic scattering (SIDIS)
- In lepton scattering on polarized hydrogen
  - HERMES: PRL **94**, 012002 (2005); COMPASS: NP **B765**, 31 (2007)
- Extraction of Collins asymmetry requires knowledge of the twist-two, chiral-odd transversity function
- Can also be studied in $e^+e^- \rightarrow q\bar{q}$
  - Quark spin not known, but can be done using $e^+e^- \rightarrow h_1 h_2 X$ where h_i is a spin-0 hadron (π or K) from the fragmenting quark
  - Look at correlation of azimuthal angles of the hadrons in opposite hemispheres w.r.t. the jet axis
- Asymmetry $\propto$ to product of two Collins functions
  - First attempted by DELPHI (NP Proc. **74**, 49 (1999))
  - First seen by BELLE (PRL 96, 232002(2006), PRD 78, 03201 (2008))
- Combine these in a *global analysis*
  - Extract $H_1^{\perp}$ and the parton transversity distribution h_1



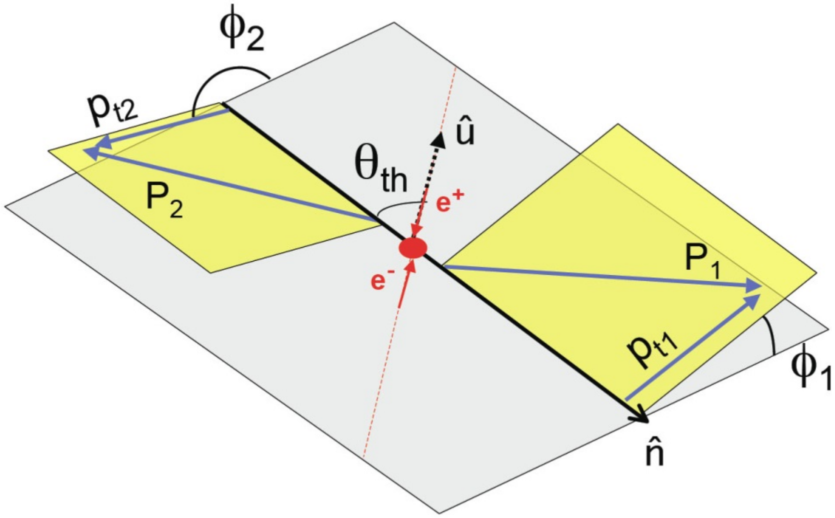


Anselmino et al., PRD 75, 054032(2007), NP Proc.Suppl. 191, 98(2009)

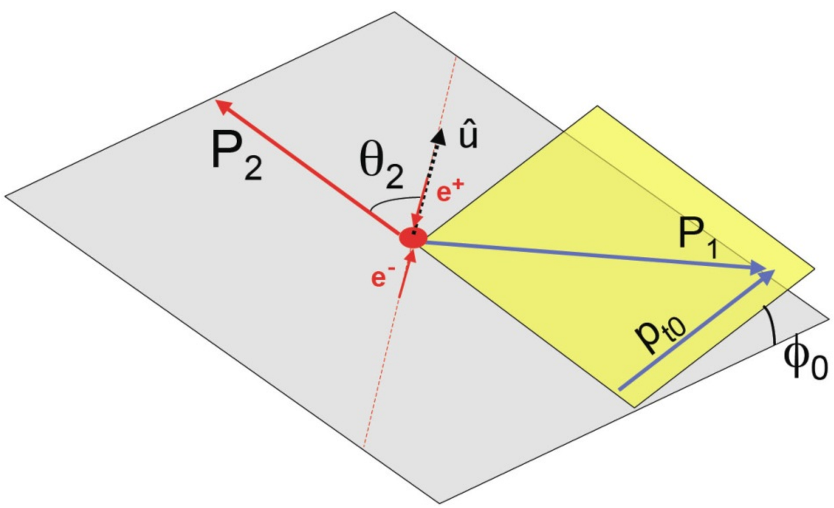
Reference frames

- Use two ref. frames, thrust (RF12) and second-pion (RF0)
- Collins asymmetries show up as azimuthal dependence of final-state pions π_1, π_2 about a chosen axis
  - RF12: Approximate the $q\bar{q}$ ref. axis by the event thrust
  - RF0: Use direction of π_2 as the reference axis
- Rate is dependent on angle φ_α
  - $\varphi_\alpha = \varphi_1 + \varphi_2$ (RF12) or $2\varphi_0$ (RF0)
- Cross section consists of a uniform part and a cosine-modulated part
- Depends on transverse moments of the fragmentation functions
  - $d\sigma \propto A + B\cos(\varphi_\alpha)$
  - $B \propto$ convolution of two Collins functions
- Divide the φ_α range into bins and extract

$$R(\phi_\alpha) = \frac{N(\phi_\alpha)}{N_{\mathrm{avg}}}$$



E. Farhi, *Phys.Rev.Lett.* **39**, 1587 (1977).



Boer *et al.*, *Nucl.Phys.* **B 504**, 345 (1997).

Like- and unlike-charge pion pairs

- We can use pion pairs of equal or opposite charges
  - Opposite charge case occurs via two favored or two disfavored processes

$$e^+e^- \to u\overline{u} \to \pi^\pm\pi^\mp X$$

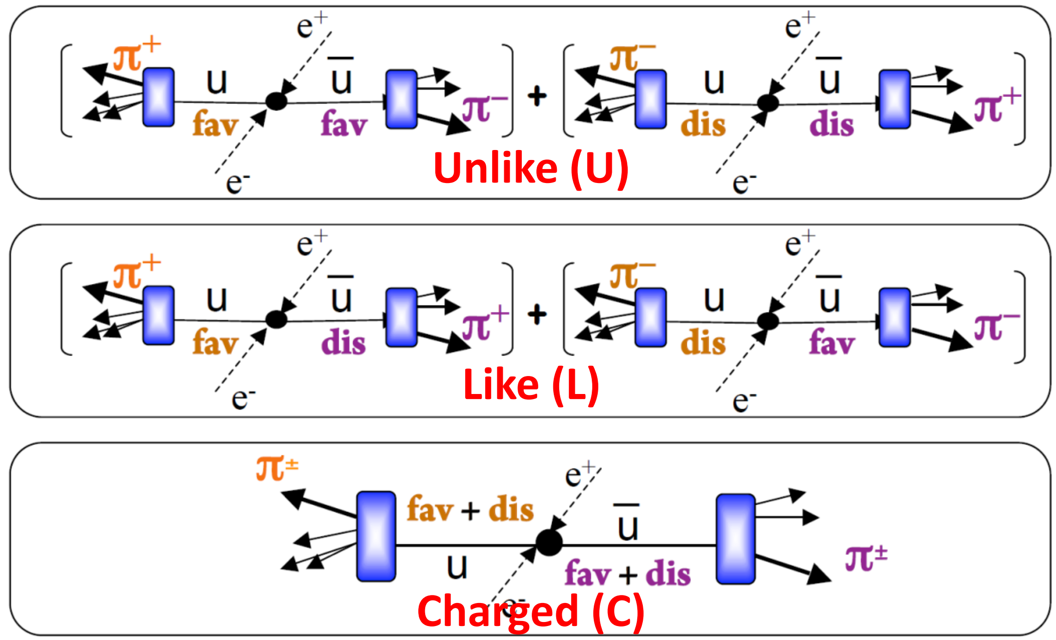
- Define favored and disfavored fragmentation functions:

$$D^{\rm fav}(z) = D_u^{\pi^+}(z) = D_d^{\pi^-}(z)$$

$$\overline{D}^{\rm fav}(z) = D_{\bar{u}}^{\pi^-}(z) = D_{\bar{d}}^{\pi^+}(z)$$

$$D^{\rm dis}(z) = D_u^{\pi^-}(z) = D_d^{\pi^+}(z) = D_s^{\pi^\pm}(z)$$

$$D^{\rm dis}(z) = D_u^{\pi^-}(z) = D_d^{\pi^+}(z) = D_s^{\pi^\pm}(z)$$



- Cross sections can be written as (U = unlike, L = like, C = charged)

$$N^U(\phi) = \frac{{\rm d}\sigma(e^+e^- \to \pi^\pm\pi^\mp X)}{{\rm d}\Omega {\rm d}z_1 {\rm d}z_2} \propto \frac{5}{9} D^{\rm fav}(z_1)\overline{D}^{\rm fav}(z_2) + \frac{7}{9} D^{\rm dis}(z_1)\overline{D}^{\rm dis}(z_2)$$

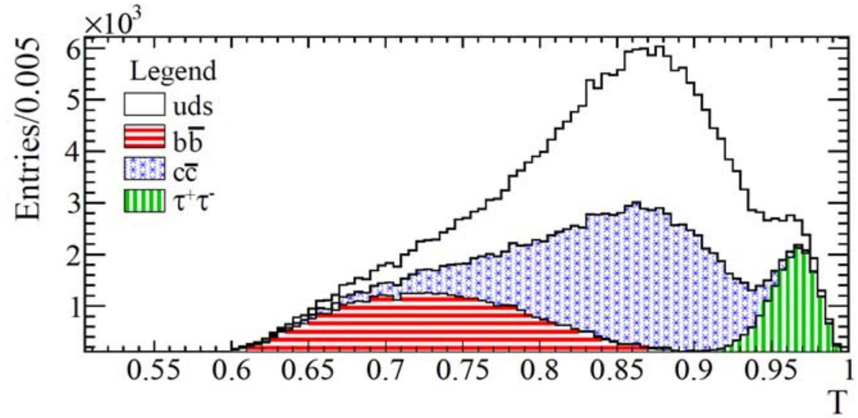
$$\phi \equiv \phi_1 + \phi_2 ({\rm RF12}) \text{ or } \phi_0 ({\rm RF0})$$

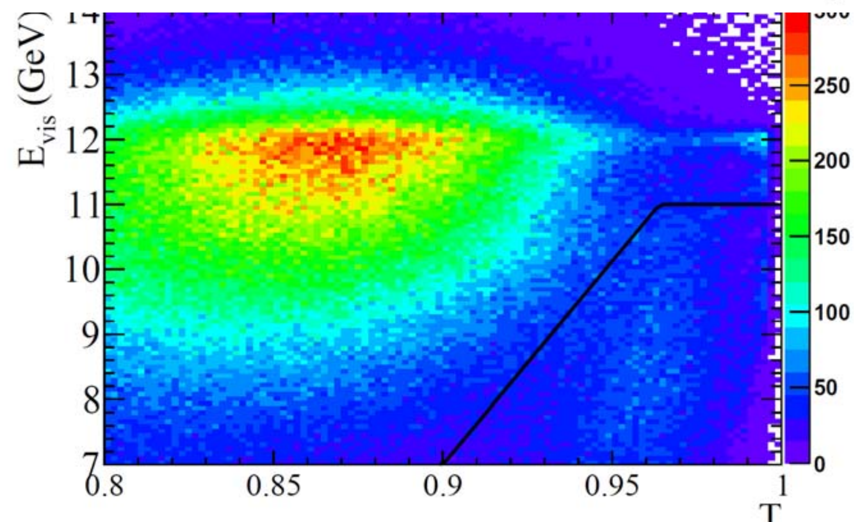
$$N^L(\phi) = \frac{{\rm d}\sigma(e^+e^- \to \pi^\pm\pi^\pm X)}{{\rm d}\Omega {\rm d}z_1 {\rm d}z_2} \propto \frac{5}{9} D^{\rm fav}(z_1)\overline{D}^{\rm dis}(z_2) + \frac{5}{9} D^{\rm dis}(z_1)\overline{D}^{\rm fav}(z_2) + \frac{2}{9} D^{\rm dis}(z_1)\overline{D}^{\rm dis}(z_2)$$

$$N^C(\phi) = \frac{{\rm d}\sigma(e^+e^- \to \pi\pi X)}{{\rm d}\Omega {\rm d}z_1 {\rm d}z_2} = N^U(\phi) + N^L(\phi) \propto \frac{5}{9}[D^{\rm fav}(z_1) + D^{\rm dis}(z_1)][\overline{D}^{\rm fav}(z_2) + \overline{D}^{\rm dis}(z_2)] + \frac{4}{9} D^{\rm dis}(z_1)\overline{D}^{\rm dis}(z_2)$$

Event selection

- Choose events with light quark fragmention
  - o Helicity is conserved only in the massless quark case
- Select multi-hadron events
  - o ≥ 3 charged particles
  - o Fox-Wolfram $R_2' < 0.98$
- Accept only charged tracks with
  - o At least 0.1 GeV/c momentum transverse to e^+e^- axis
  - o Track must originate near the I.P.
  - o Lie within detector solid-angle acceptance region
- Suppress events with energetic gluon emission (disrupts correlation between quark spins)
  - o Require event thrust $T > 0.8$
- Suppress $e^+e^- \rightarrow \mu^+ \mu^- \gamma$ and $e^+e^- \rightarrow e^+ e^- \gamma$ by the 3-hadron requirement above
  - o Suppress further by requiring in low-multiplicity events neither two most energetic tracks are identified as muons and that no electrons are present
- Plus additional requirements (see extra slides at end)
- Results in 10^8 pion pairs for the Collins analysis



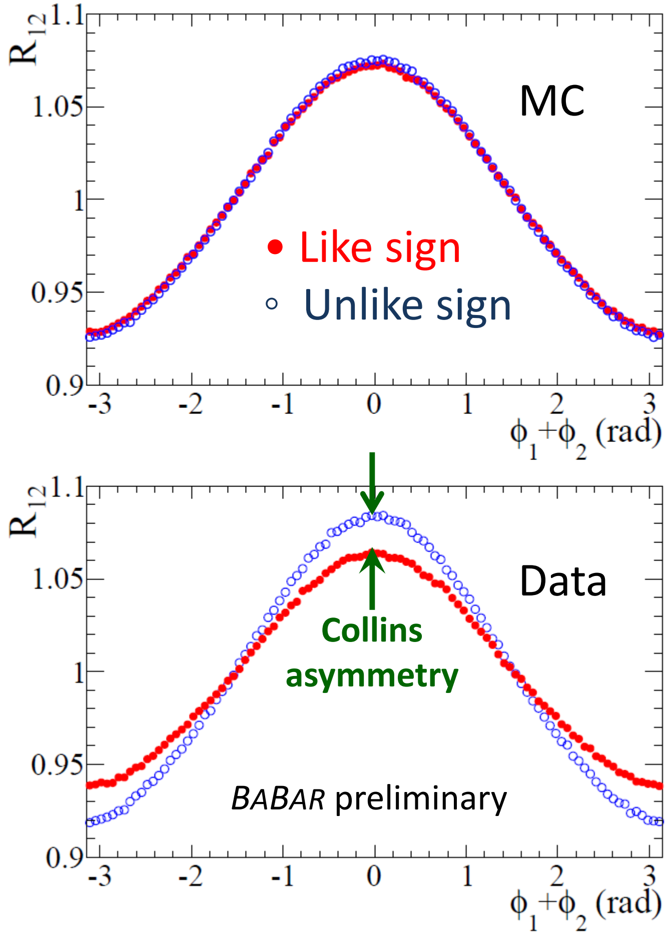


The Collins asymmetry analysis uses 468 fb^{-1}

- 424 fb^{-1} at the Υ(4S) peak
- 44 fb^{-1} at 40 MeV below the peak

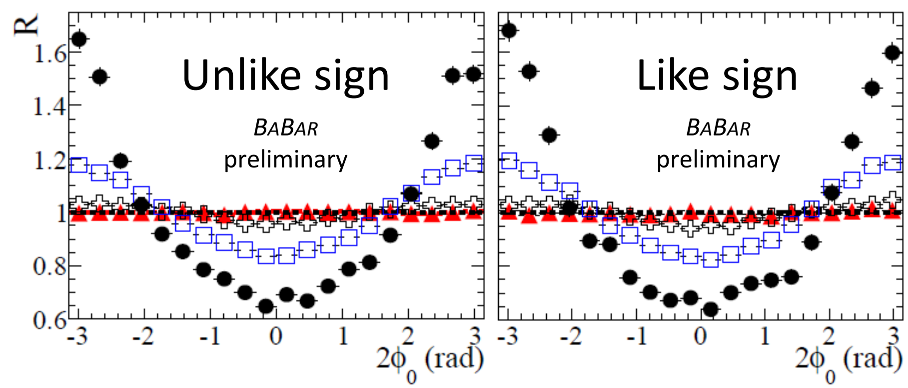
Azimuthal distributions

Normalized distributions (RF12)



- Simulation (MC) shows cosine dependence even though no asymmetry generated
  - Due to detector acceptance effects
  - Affects U and L samples similarly
- Data shows difference in U and L samples
  - This is due to the Collins asymmetry
- Detector effects are function of thrust direction
  - If thrust axis close to beam axis, more particles can be missed and thrust is reconstructed less well
- Two possible solutions:
  - Use detailed simulation studies to correct for detector asymmetries; or,
  - Eliminate most effects of detector asymmetries by using ratios of distributions (double ratios)

Normalized distributions (RF0)
Binned in $\cos(\vartheta_{th})$



▲ $0 < \cos(\vartheta_{th}) < 0.3$ ✚ $0.3 < \cos(\vartheta_{th}) < 0.5$
□ $0.5 < \cos(\vartheta_{th}) < 0.7$ ● $0.8 < \cos(\vartheta_{th}) < 0.9$

Asymmetry double ratios

- Reduce effects of detector asymmetries
  - Use double ratios of Like, Unlike, and Charged distributions

$$\frac{R^U_{12}}{R^L_{12}} = \frac{1+\frac{\sin^2\theta_{th}}{1+\cos^2\theta_{th}}\cos(\phi_1+\phi_2)\,G^U}{1+\frac{\sin^2\theta_{th}}{1+\cos^2\theta_{th}}\cos(\phi_1+\phi_2)\,G^L} \simeq 1+\frac{\sin^2\theta_{th}}{1+\cos^2\theta_{th}}\cos(\phi_1+\phi_2)\left\{G^U-G^L\right\}.$$

$$\frac{R^U_{12}}{R^C_{12}} \simeq 1+\frac{\sin^2\theta_{th}}{1+\cos^2\theta_{th}}\cos(\phi_1+\phi_2)\times\left\{G^U-G^C\right\}$$

  - Performed after integration over ϑ_{th}
- Good approximation for small values of the asymmetries
  - Where

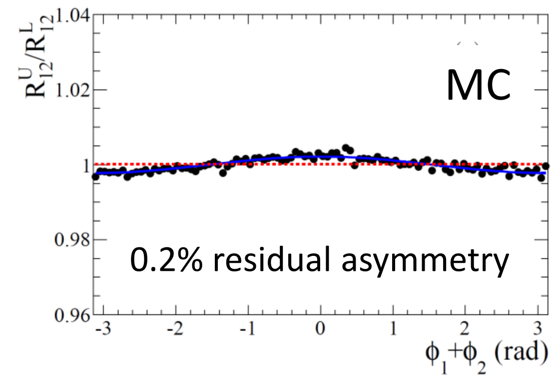
$$G^U \propto \frac{5H_1^{\mathrm{fav}}\overline{H}_1^{\mathrm{fav}}+7H_1^{\mathrm{dis}}\overline{H}_1^{\mathrm{dis}}}{5D_1^{\mathrm{fav}}\overline{D}_1^{\mathrm{fav}}+7D_1^{\mathrm{dis}}\overline{D}_1^{\mathrm{dis}}},$$

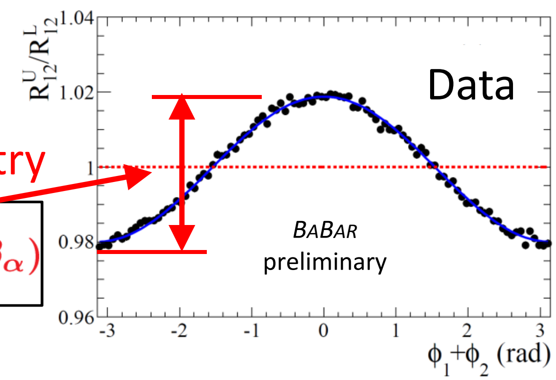
$$G^L \propto \frac{5H_1^{\mathrm{fav}}\overline{H}_1^{\mathrm{dis}}+5H_1^{\mathrm{dis}}\overline{H}_1^{\mathrm{fav}}+2H_1^{\mathrm{dis}}\overline{H}_1^{\mathrm{dis}}}{5D_1^{\mathrm{fav}}\overline{D}_1^{\mathrm{dis}}+5D_1^{\mathrm{dis}}\overline{D}_1^{\mathrm{fav}}+2D_1^{\mathrm{dis}}\overline{D}_1^{\mathrm{dis}}},$$

$$G^C \propto \frac{5(H_1^{\mathrm{fav}}+H_1^{\mathrm{dis}})(\overline{H}_1^{\mathrm{fav}}+\overline{H}_1^{\mathrm{dis}})+4H_1^{\mathrm{dis}}\overline{H}_1^{\mathrm{dis}}}{5(D_1^{\mathrm{fav}}+D_1^{\mathrm{dis}})(\overline{D}_1^{\mathrm{fav}}+\overline{D}_1^{\mathrm{dis}})+4D_1^{\mathrm{dis}}\overline{D}_1^{\mathrm{dis}}}$$

  - Asymmetries depend only on the favored and disfavored fragmentation functions
  - Gluon radiation and acceptance are independent of pion pair charges
- Study asymmetry ratios in 6 bins of z_1 and z_2

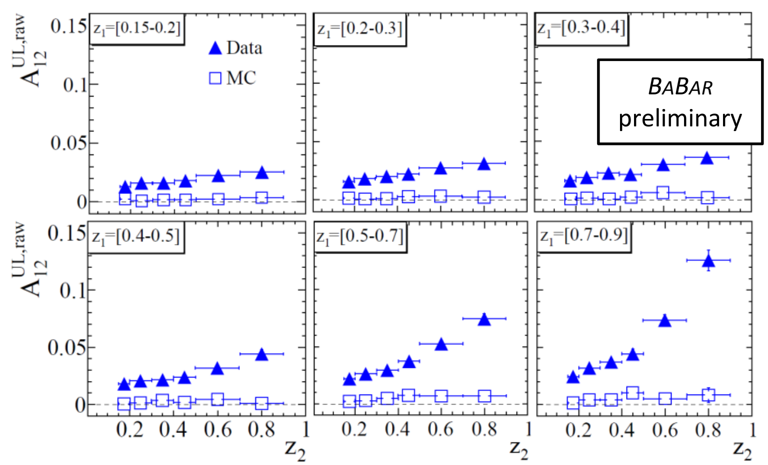
Unlike-to-Like





Collins asymmetry

$$\boxed{\frac{R^i_\alpha}{R^j_\alpha} = A^{ij}_\alpha + B^{ij}_\alpha\cdot\cos(\beta_\alpha)}$$



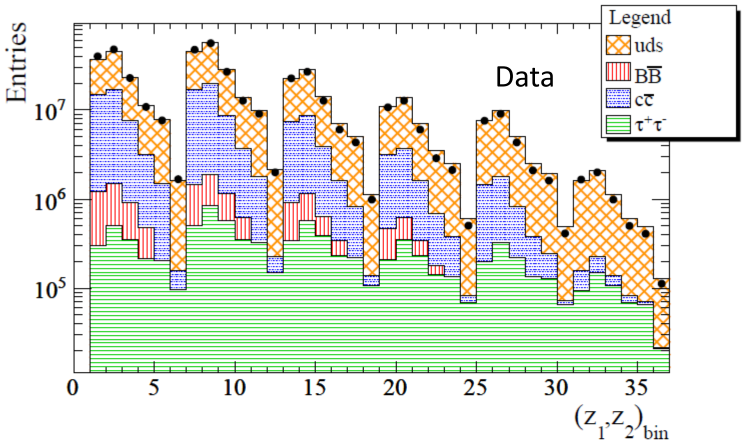
(Uncorrected, stat. errors only)

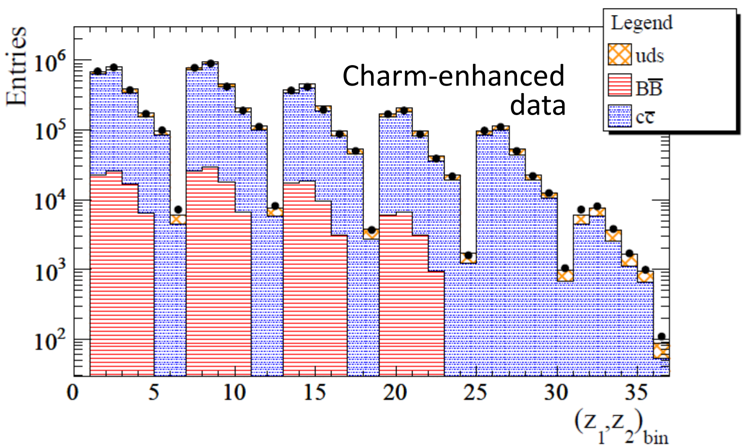
Backgrounds: contributions and corrections

- Potential, primary backgrounds are $e^+e^- \rightarrow \tau^+\tau^-$, $c\bar{c}$, and $B\bar{B}$
  - P.V. in τ weak decays can produce asymmetries
  - Charm asymmetries of interest
    - Suppressed by c quark mass
    - Would need more data
  - No significant Collins asymmetries expected in B decay
- Estimate background effects using

$$A_\alpha^{\mathrm{meas}} = \left(1 - \sum_i F_i\right) \cdot A_\alpha + \sum_i F_i \cdot A_\alpha^i$$

- For $\tau^+\tau^-$ use a control sample
  - Asymmetry ≈ few tenths %
  - Estimate F_τ using a MC sample for each z and p_t bin
  - F_τ is appreciable only at high z, where *uds* Collins effect is large
  - Set $A^\tau_\alpha = 0$
- $B\bar{B}$ events suppressed by event selection
  - $F_B < 2\%$, $z < 0.5$
  - Consequently little effect on the asymmetries
- $c\bar{c}$ events: larger fractions
  - Study charm-enhanced sample, with $f_c \approx 0.9$
  - Measure A^{D^*} a vs. z_1, z_2, p_t and apply correction



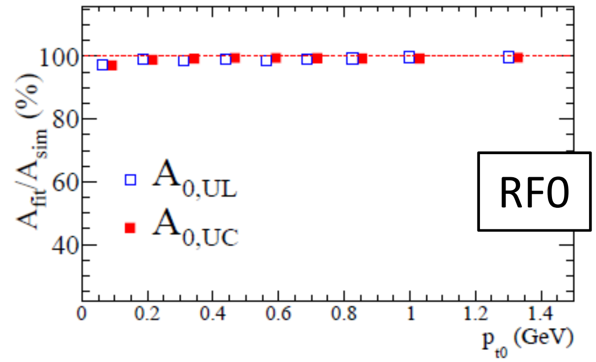


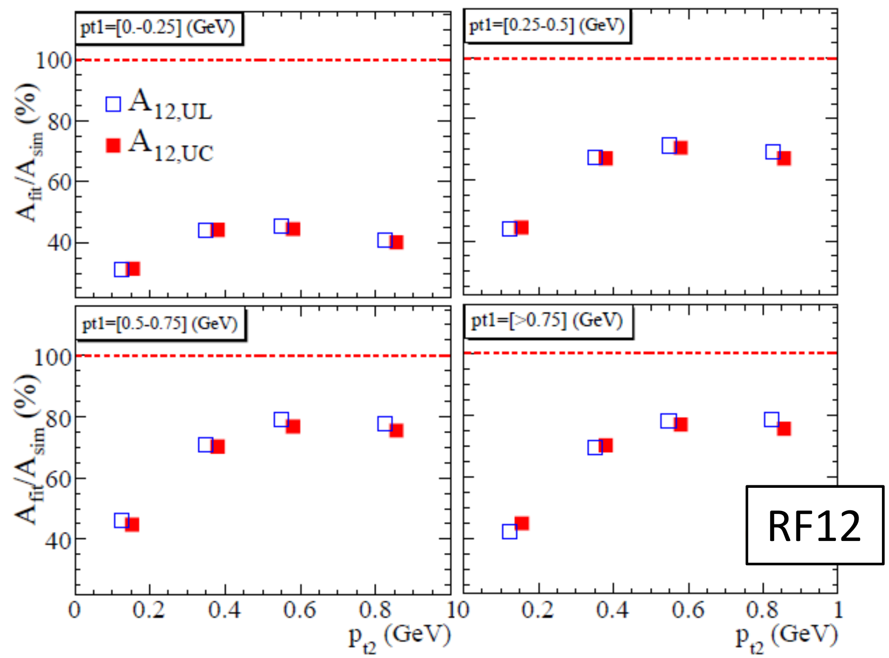
$$A_\alpha^{\mathrm{meas}} = (1 - F_c - F_B - F_\tau) \cdot A_\alpha + F_c \cdot A_\alpha^c \,,$$

$$A_\alpha^{D^*} = (1 - f_c - f_B) \cdot A_\alpha + f_c \cdot A_\alpha^c \,.$$

Asymmetry dilution correction

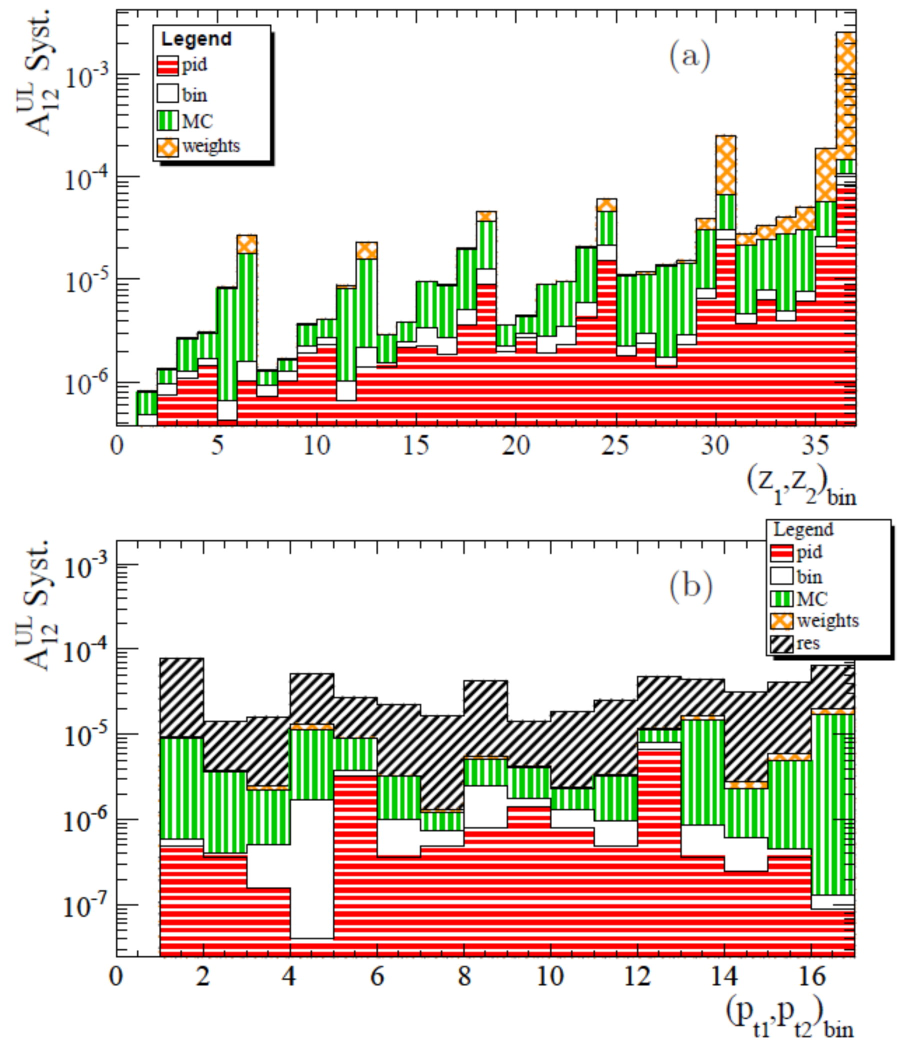
- Asymmetry dilution
  - From use of thrust axis to approximate $q\bar{q}\ \bar{B}\,\bar{B}$ axis
  - Average divergence from $q\bar{q}$ axis about 100 mrad
  - Results in asymmetry dilution
    - Mainly affects RF12 reference frame
    - Much smaller effect in RF0
- Estimate this and other effects using simulation
  - Re-weight MC events to produce a Collins-like effect in non-asymmetric generated events
  - Determine average dilution values for each z, p_t, and ϑ_{th} bin
  - Apply these as corrections





Checks and systematics

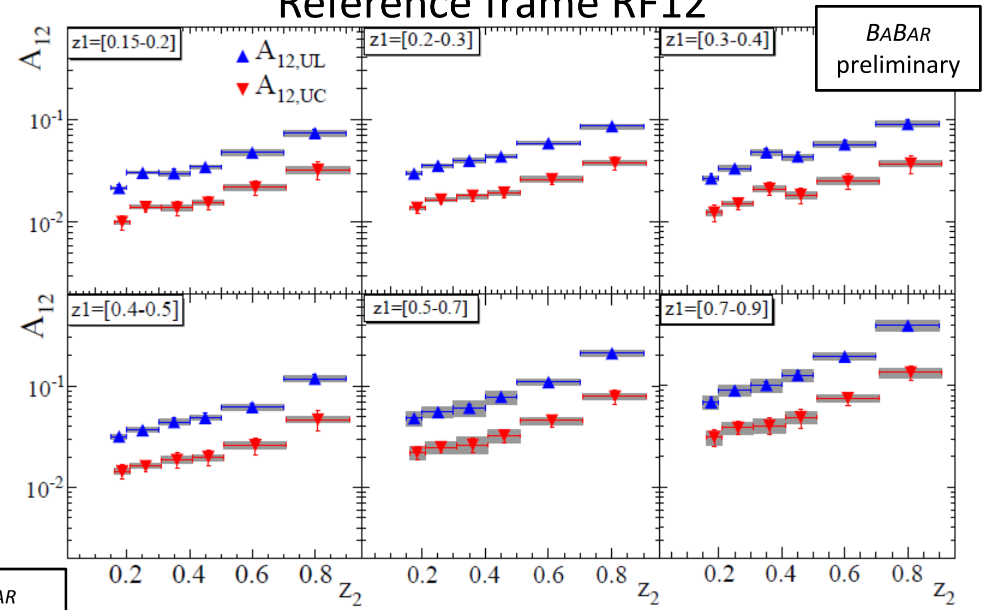
- Double-ratio methodology
  - Shows small asymmetry (≈ 0.2%) in *uds* MC generated without asymmetry
    - Check 3 MC samples
      - Use pion event-generated ("truth") momenta
      - –Use pion event-generated momenta only for pions associated with reconstructed tracks
      - Use standard, fully-reconstructed MC sample
    - Use $q\bar{q}$ axis instead of thrust axis
    - Vary track selection requirements
  - RF0: main effect is non-cancellation of detector effects in double ratio
  - RF12: main effect from use of thrust axis
  - Subtract biases from corrected asymmetries
    - Take quadrature combination of largest variation of tests with statistical uncertainty of the fit as systematic uncertainty
- Pion transverse momentum resolution
- Particle identification
- Fit procedure
- Test with same-sign pairs
- Check double-ratio method using subtraction
- Beam polarization
- Consistency across datasets



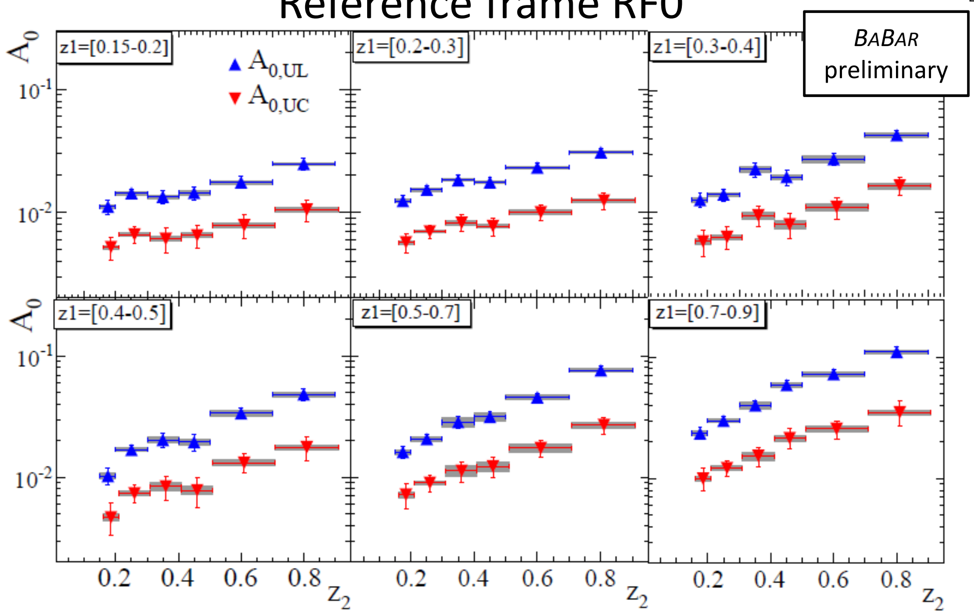
Results: z_1, z_2 bins

- Measured asymmetries reported as function of
  - z_1, z_2 and p_{t1}, p_{t2}
  - For reference frames RF12 and RF0
- UC asymmetries smaller than UL by about factor of 2
  - Reflects different amount of favored and dis-favored fragmentation functions to the ratios
- Asymmetries increase with increasing fractional energy

Reference frame RF12



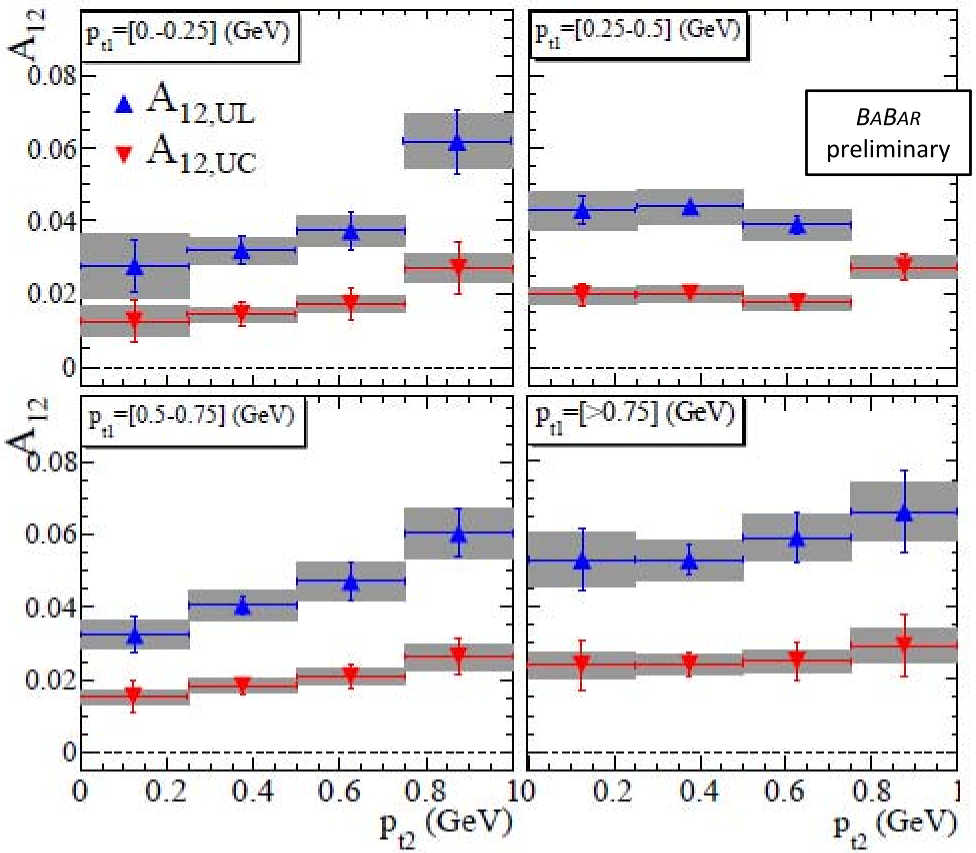
Reference frame RF0



Statistical errors shown as bars
Systematic errors shown as bands

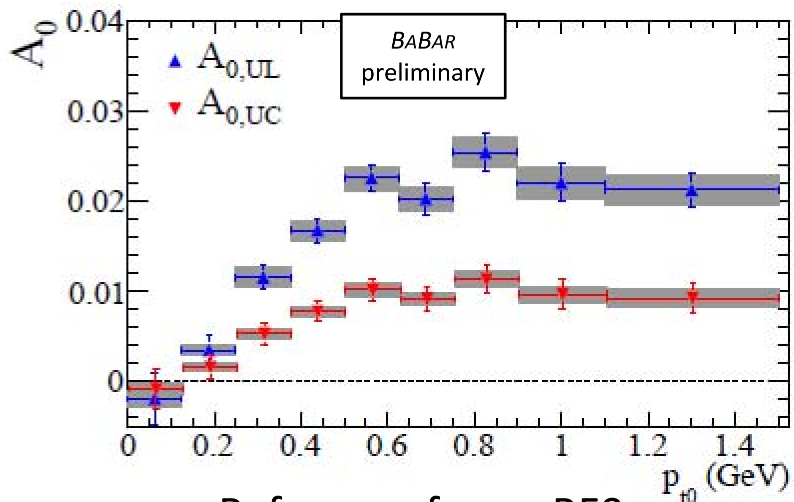
Results: p_{t1}, p_{t2} bins

- First measurement of Collins asymmetries as function of transverse pion momenta



Reference frame RF12

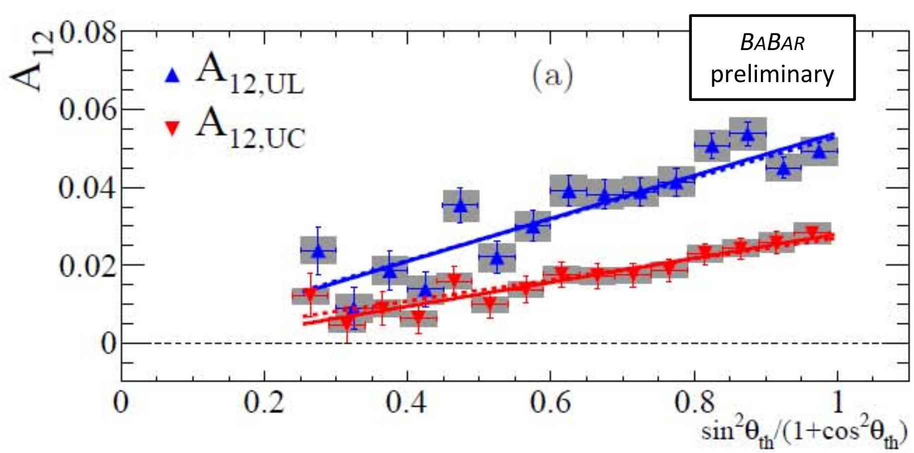
Statistical errors shown as bars
Systematic errors shown as bands

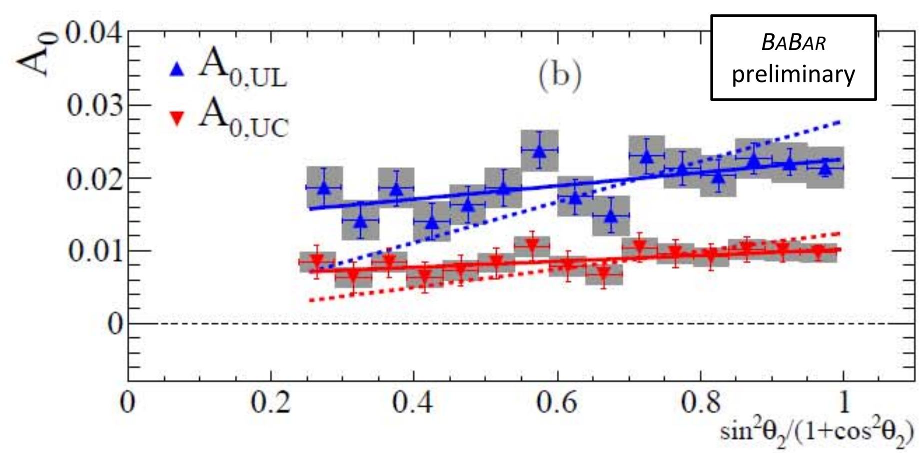


Reference frame RF0

Results: vs. polar angle

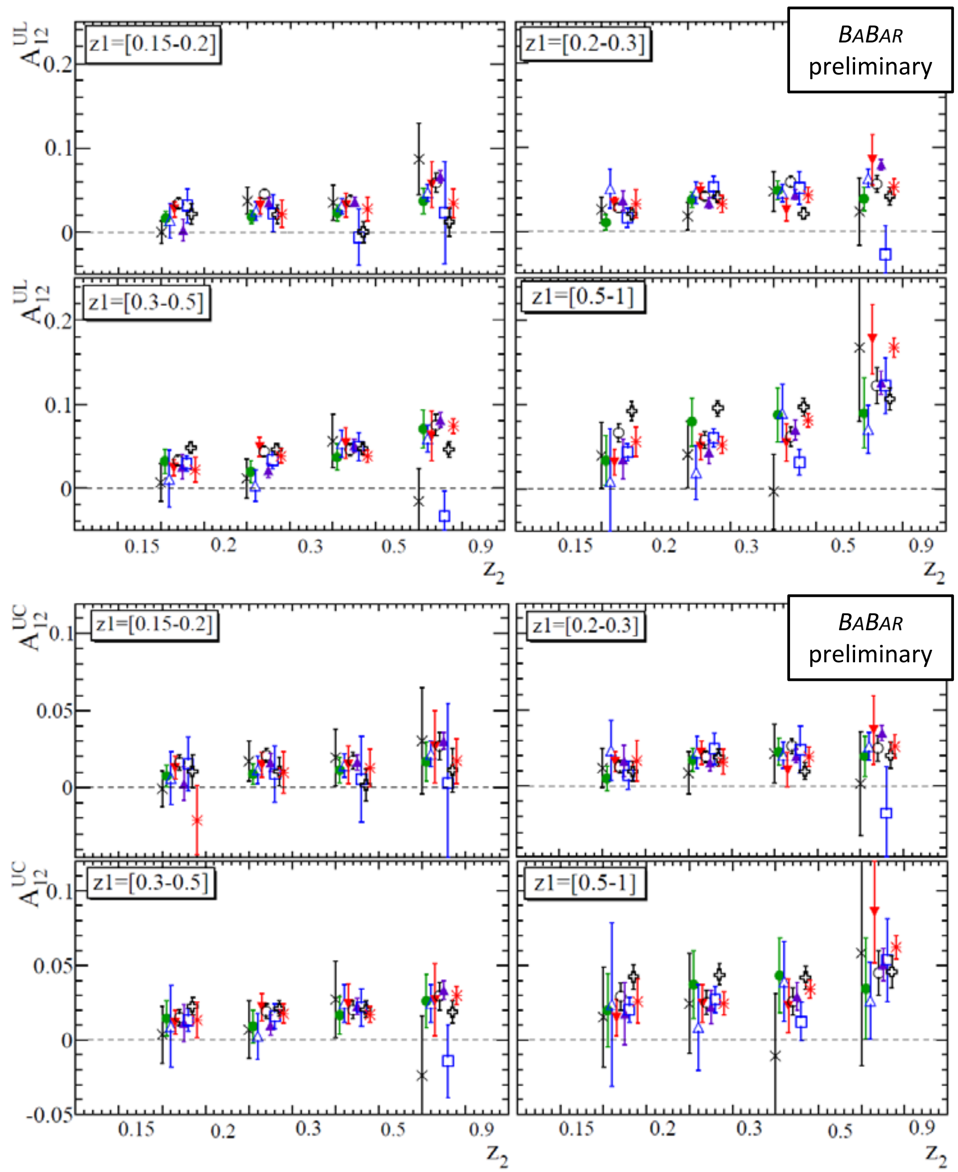
- Transverse polarization of $q\bar{q}$ pair
  - Proportional to $\sin^2 \theta$
- Collins asymmetries should show similar behavior
- Study angular dependence after integration over fractional energies and transverse momenta
  - A_{12} values are consistent with zero intercept
  - A_0 values are not—a linear fit gives non-zero constant term
  - RF0 frame known to give less accurate estimate of the $q\bar{q}$ direction

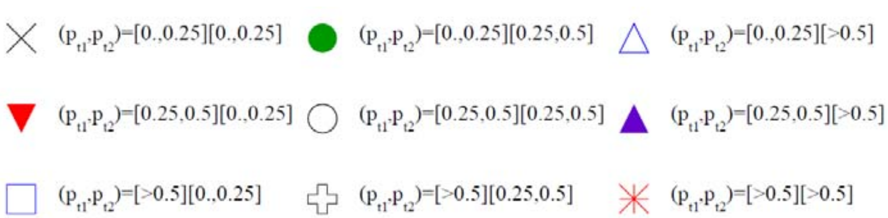




Four-dimensional (z_1, z_2, p_{t1}, p_{t2}) RF12

- Study RF12 in four-dimensional space
  - o (z_1, z_2, p_{t1}, p_{t2})
- Probes factorization of the Collins fragmentation function
- Use four z_i and three p_t intervals





Anti-deuteron production

- $e^+e^- \rightarrow q\bar{q}$ annihilations provide a clean probe of hadronization of quarks and gluons into anti-nuclei
  - Of interest in dark matter searches
  - Provide sensitive probe of dark matter annihilation
- $\bar{d}$ production observed by ARGUS and CLEO
  - In $\Upsilon(1S)$ and $\Upsilon(2S)$ decays
  - Rate ≈ 3 x 10^{-5}
- Update these values and observe $\bar{d}$ production in $\Upsilon(3S)$ decays and in $e^+e^- \rightarrow q\bar{q}$ near 10.6 GeV

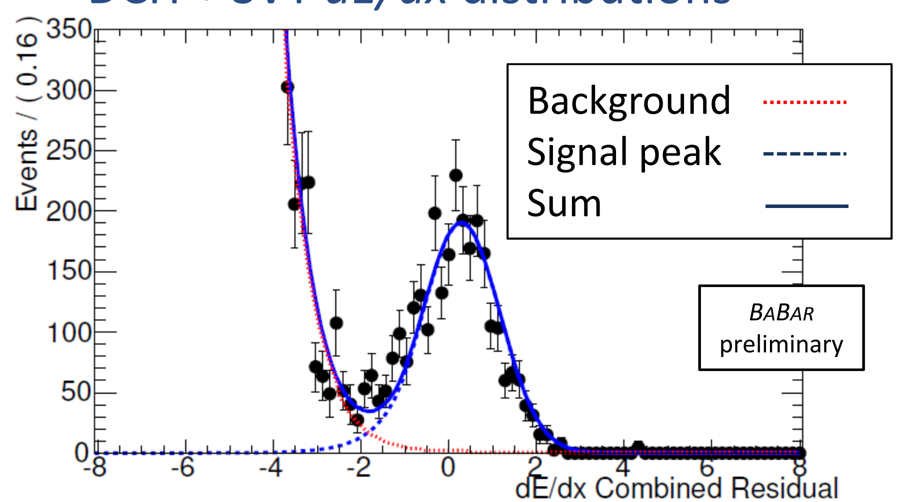
Datasets used

Resonance	Onpeak	# of Υ Decays	Offpeak
$\Upsilon(4S)$	$429\,\mathrm{fb}^{-1}$	463×10^6	$44.8\,\mathrm{fb}^{-1}$
$\Upsilon(3S)$	$28.5\,\mathrm{fb}^{-1}$	116×10^6	$2.63\,\mathrm{fb}^{-1}$
$\Upsilon(2S)$	$14.4\,\mathrm{fb}^{-1}$	98.3×10^6	$1.50\,\mathrm{fb}^{-1}$

Obtain $\Upsilon(1S)$ sample from
$\Upsilon(2S) \rightarrow \Upsilon(2S)\,\pi^+\pi^-$

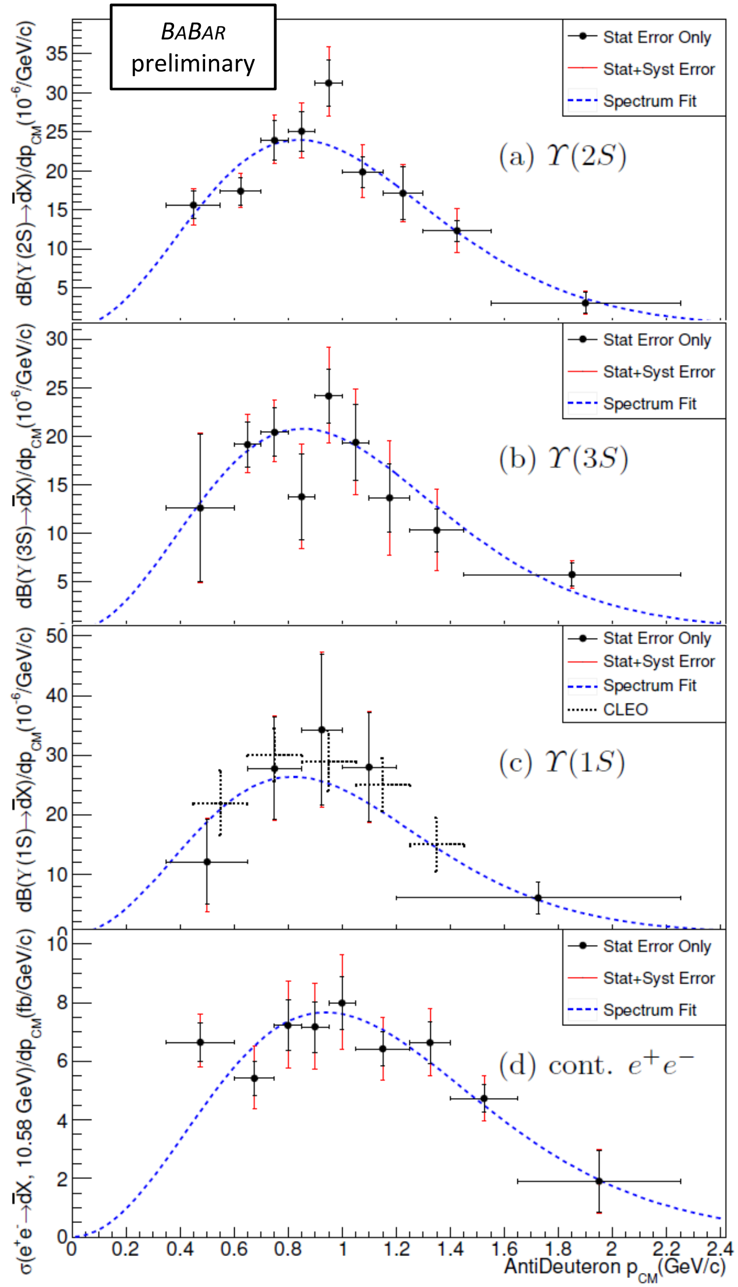
H. Albrecht *et al.*, *Phys.Lett.* B**236**, 102 (1990);
D. M. Asner *et al.*, *Phys. Rev.* D**75**, 012009 (2007).

- Event selection
  - Require ≥ 3 charged tracks
  - Fox-Wolfram $R_2' < 0.98$
  - Lie in drift chamber (DCH) acceptance: $-0.8 \leq \cos\vartheta_{\mathrm{lab}} \leq 0.92$
  - Momentum $0.5 \leq p_{\mathrm{lab}} \leq 1.5$ GeV/c (dE/dx for d, $\bar{d}$ well away from other species)
  - Transverse doca to I.P. be < 400 μm
  - Additional background and quality cuts
- Extract yields from combined DCH + SVT *dE/dx* distributions



Anti-deuteron production

- Systematics
  - Fit biases, background model, reconstruction efficiency, kinematic acceptance, material interaction, fake anti-deuterons, DOCA selection, event selection, normalization
- Results
  - Correct number of $\bar{d}$'s from fits for efficiencies
  - Compute total rates from differential spectra



Process	Rate
$\mathcal{B}(\Upsilon(3S) \to \bar{d}X)$	$(2.33 \pm 0.15^{+0.31}_{-0.28}) \times 10^{-5}$
$\mathcal{B}(\Upsilon(2S) \to \bar{d}X)$	$(2.64 \pm 0.11^{+0.26}_{-0.21}) \times 10^{-5}$
$\mathcal{B}(\Upsilon(1S) \to \bar{d}X)$	$(2.81 \pm 0.49^{+0.20}_{-0.24}) \times 10^{-5}$
$\sigma(e^+e^- \to \bar{d}X)$ $[\sqrt{s} \approx 10.58\,\mathrm{GeV}]$	$(9.63 \pm 0.41^{+1.17}_{-1.01}) f_B$
$\dfrac{\sigma(e^+e^- \to \bar{d}X)}{\sigma(e^+e^- \to \mathrm{Hadrons})}$	$(3.01 \pm 0.13^{+0.37}_{-0.31}) \times 10^{-6}$

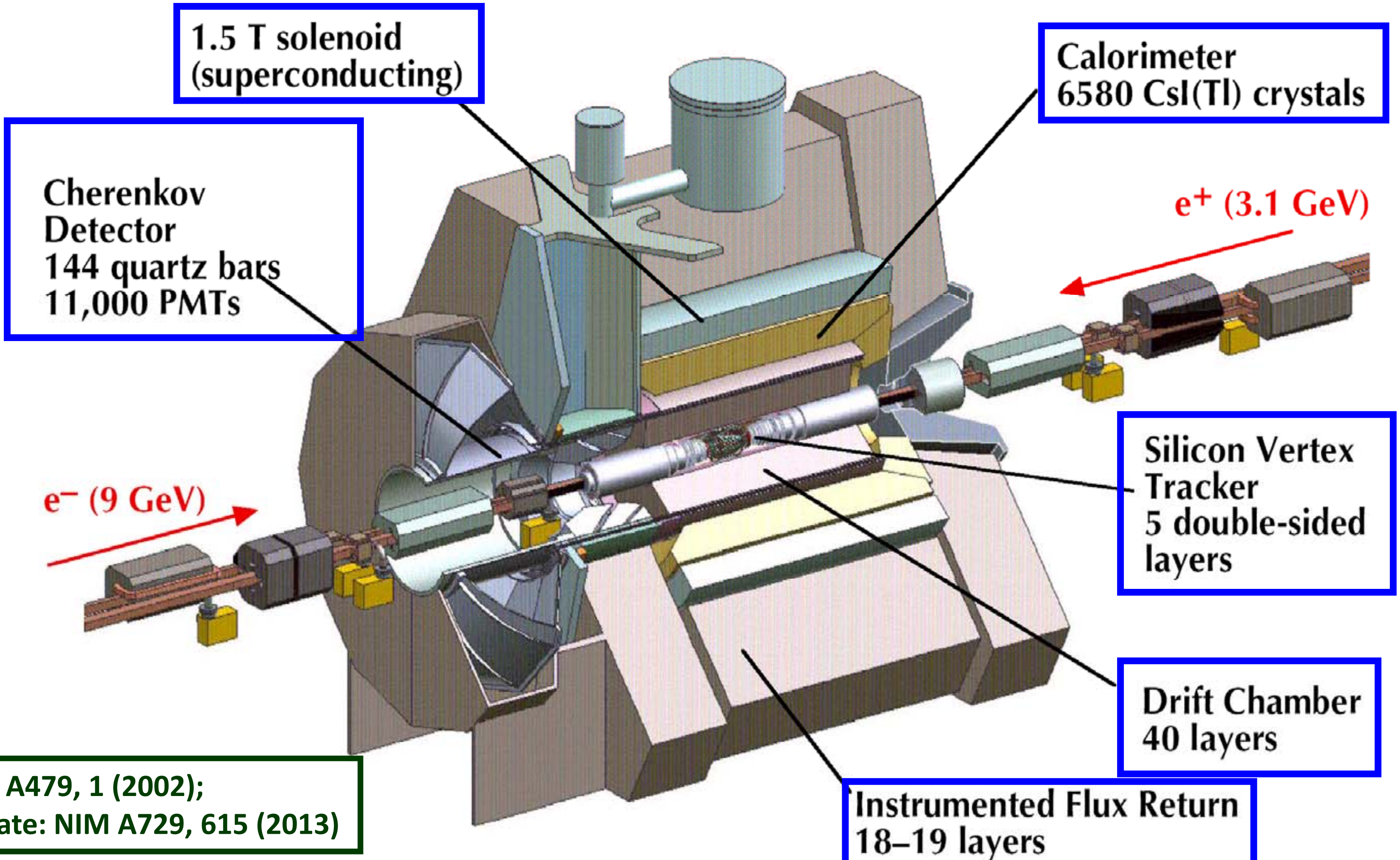
J.P. Lees et al., 1403.4409 [hep-ex], Submitted to *Phys.Rev. D* (RC)

Summary

- *BABAR* has measured inclusive production cross sections for $\pi^{\pm}$, $K^{\pm}$, $p/\bar{p}$ spectra at C.M. energy of 10.54 GeV
  - Using a small subsample of very high quality data
  - Published in *Phys. Rev. D* **88**, 032011 (2013)
- *BABAR* has measured Collins asymmetries
  - In $e^+e^- \rightarrow q\bar{q}$ events (submitted to *Phys. Rev. D*: arXiv:1309.5278 [hep-ex])
  - In multi-hadron events with two pions in opposite jets
    - Analysis using kaons underway
  - Asymmetries extracted from ratios of normalized distributions of like-sign, unlike-sign, and charged pion pairs
  - Report results as function of
    - Fractional energies, transverse pion momenta (first measurement), thrust axis polar angle, and four-dimensional space (RF12 only): $(z_1, z_2, p_{t1}, p_{t2})$
  - z and p_t dependence as expected, but polar angle dependence shows difference from expectations
- Anti-deuteron result submitted to PRD-RC in March 2014
  - Most precise measurement in $\Upsilon(2S)$ decays
  - First measurement in $\Upsilon(3S)$ decays and in $e^+e^- \rightarrow q\bar{q}$ near 10.58 GeV
  - arXiv:1403.4409 [hep-ex]

Extra slides

The *BABAR* detector at PEP-II

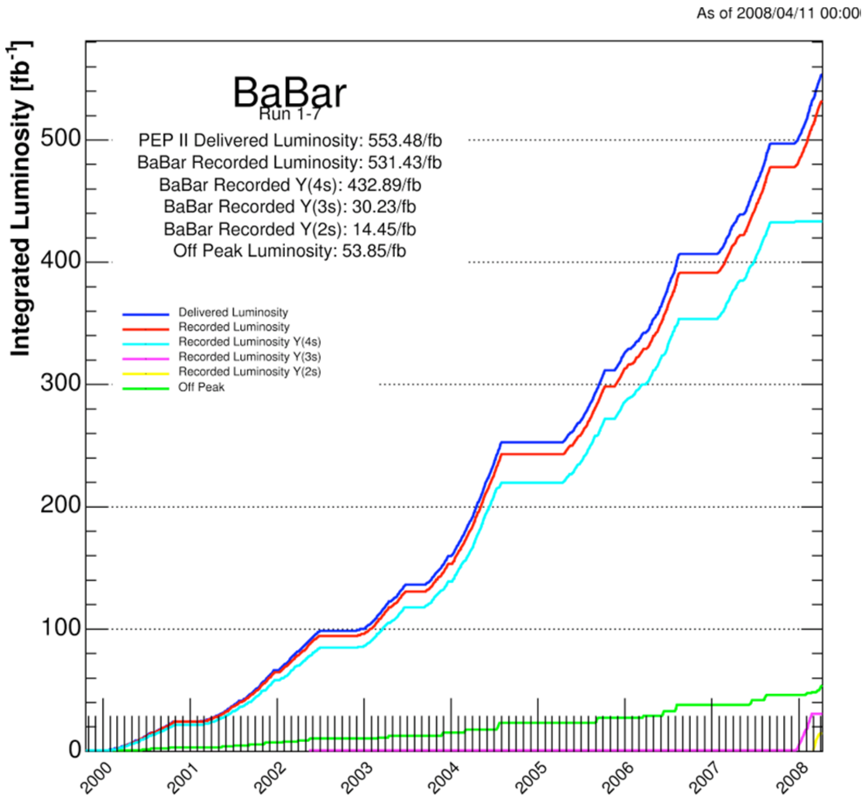


NIM A479, 1 (2002);
Update: NIM A729, 615 (2013)

BaBar Datasets

- PEP-II at SLAC is not only a *B* factory but also a charm and τ factory
  - o 470 x 10^6 *BB* pairs
  - o 690 x 10^6 *cc* pairs
  - o 500 x 10^6 $\tau^+\tau^-$ pairs
- Initial-state radiation (ISR) events: access to low-energy e^+e^- hadronic cross sections

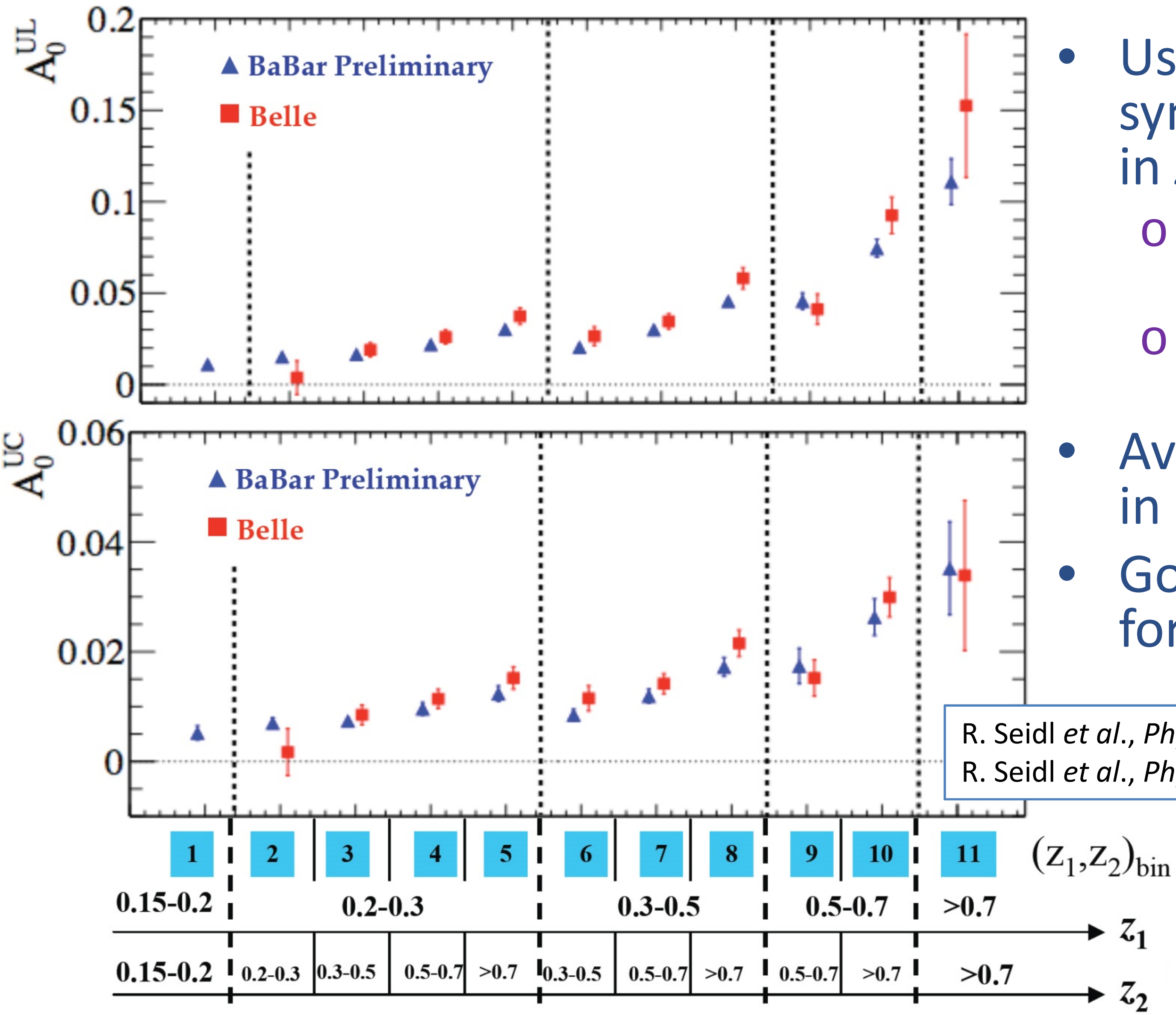
Sample	Integrated $\mathcal{L}$
$\Upsilon(4S)$	433 fb^{-1}
$\Upsilon(3S)$	30.2 fb^{-1}
$\Upsilon(2S)$	14.5 fb^{-1}
Off-peak	54 fb^{-1}
Scan	3.9 fb^{-1}



The Collins asymmetry analysis uses 468 fb^{-1}

- 424 fb^{-1} at the Υ(4*S*) peak
- 44 fb^{-1} at 40 MeV below the peak

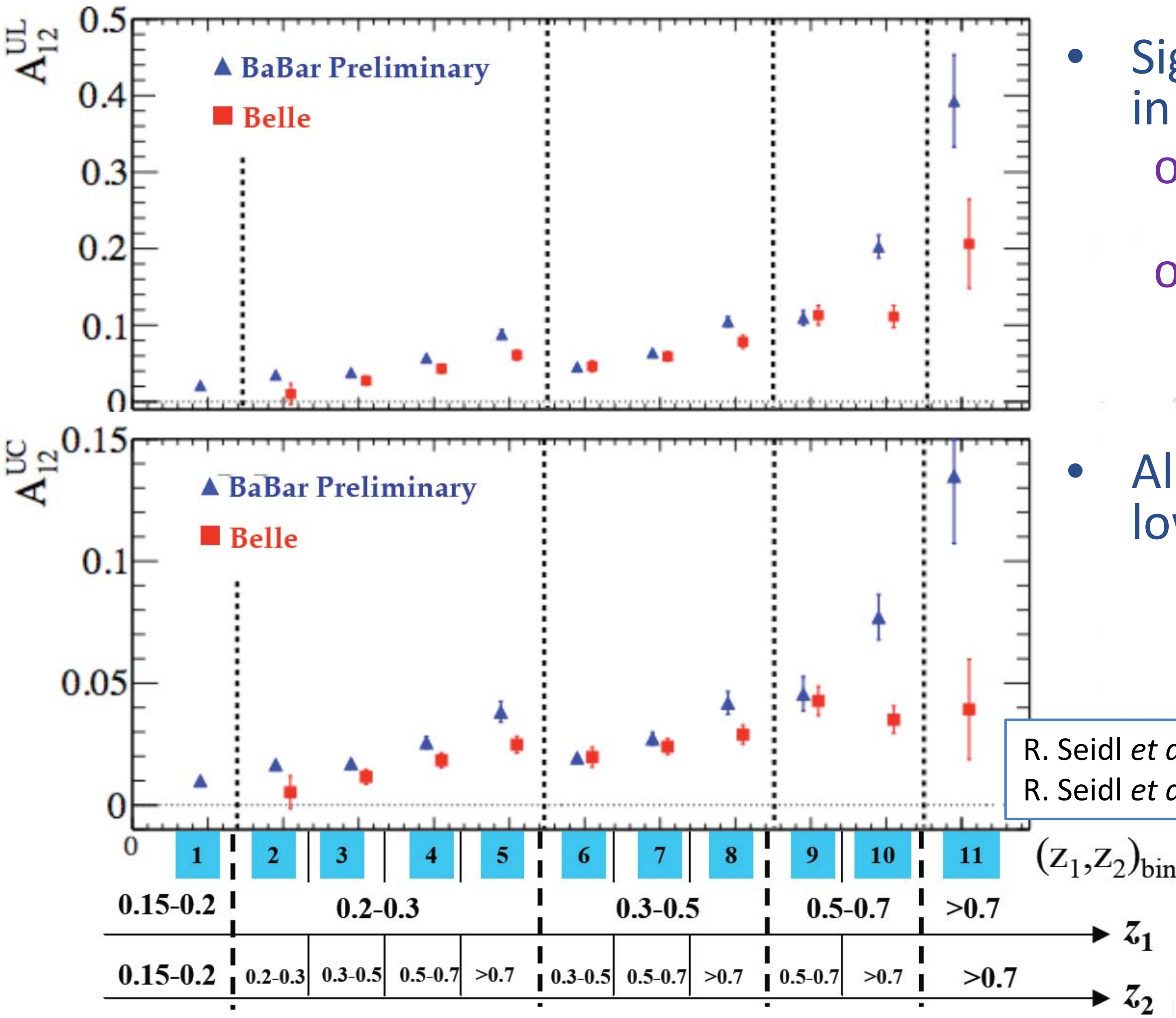
BaBar, Belle comparison using RF0



- Use 10+1 symmetrized bins in z_1, z_2
  - o BABAR: 468 fb^{-1}, $0.15 < z < 0.9$
  - o Belle: 547 fb^{-1}, $0.2 < z < 1$
- Average over data in each bin
- Good agreement for A_0^{UL} and A_0^{UC}

R. Seidl *et al.*, *Phys. Rev. D***78**, 032011 (2008);
R. Seidl *et al.*, *Phys. Rev. D***86**, 039905(E)(2012)

BABAR, Belle comparison using RF12



- Significant discrepancy in the last two bins in *z*
  - Bin-by-bin corrections factors (30%)
  - Limit $z < 0.9$ to remove contamination from $\mu\mu\gamma$ background and exclusive events
- Also a systematic shift at lower *z* as well

R. Seidl *et al.*, *Phys. Rev. D***78**, 032011 (2008);
R. Seidl *et al.*, *Phys. Rev. D***86**, 039905(E)(2012)

Analysis strategy

- Select hadronic events with two charged pions
  - One in each hemisphere
    - Defined as along and opposite to the thrust axis
- Perform the analysis in two reference frames
  - Thrust reference frame, RF12
  - Second-hadron ref. frame, RF0
- Allows direct comparison to Belle measurements
- Study light-quark pairs since helicity is conserved only in the massless-quark approximation
  - Also correlation between quark and anti-quark fragmentation may be lost for heavy quarks
- Study like-charge (L), unlike-charge (U), and charged (C) pion pairs
  - Gives sensitivity to favored and disfavored fragmentation functions
    - Favored: quark *q* → hadron with valence quark *q* of the same flavor.
      - $u \rightarrow \pi^{+}$, $d \rightarrow \pi^{-}$
    - Disfavored:
      - $u \rightarrow \pi^{-}$, $d \rightarrow \pi^{+}$

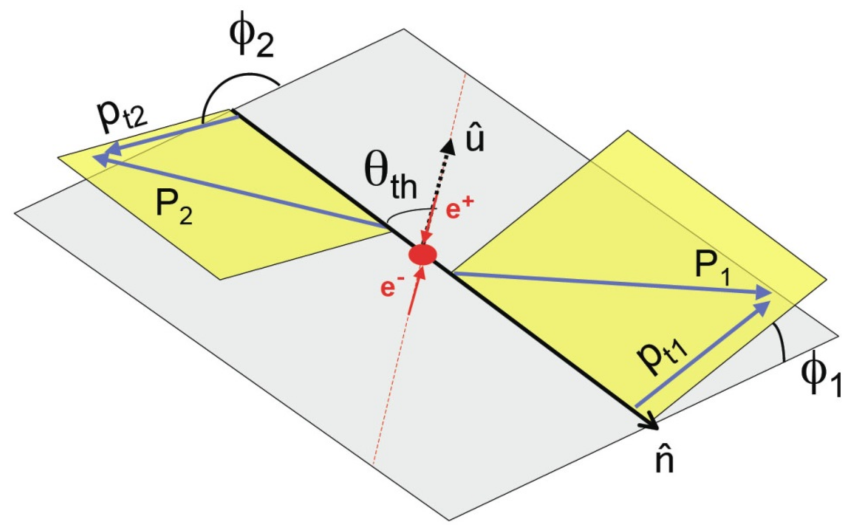
Boer *et al.*, *Nucl.Phys.* **B 504**, 345 (1997).

Boer *et al.*, *Nucl.Phys.* **B 806**, 23 (2009).

Thrust reference frame RF12

- Collins asymmetry show up as an azimuthal dependence of two final-state pions π_1, π_2 about the quark-antiquark axis
  - Approximate the $q\bar{q}$ axis by the event thrust axis
- Azimuthal angles φ_1, φ_2 of π_1, π_2 are defined relative to a plane
  - Perpendicular to the e^+e^- axis and containing the thrust axis
- Rate is dependent on the sum $\varphi_1 + \varphi_2$ as well as z_1, z_2
  - Cross section consists of a uniform part and a cosine-modulated part in $\varphi_1 + \varphi_2$
    - Depends on transverse moments of the fragmentation functions
- Cross section $d\sigma \propto A + B\cos(\varphi_1 + \varphi_2)$
- Divide the $\varphi_1 + \varphi_2$ range into bins and extract

$$R_{12}(\phi_1 + \phi_2) = \frac{N(\phi_1 + \phi_2)}{N_{\rm avg}}$$



$$\phi_{1,2} \equiv \text{sign}[\hat{\mathbf{n}} \cdot \{(\hat{\mathbf{u}} \times \hat{\mathbf{n}}) \times (\hat{\mathbf{n}} \times \hat{\mathbf{P}}_{1,2})\}] \times \arccos\left(\frac{\hat{\mathbf{u}} \times \hat{\mathbf{n}}}{|\hat{\mathbf{u}} \times \hat{\mathbf{n}}|} \cdot \frac{\hat{\mathbf{n}} \times \mathbf{P}_{1,2}}{|\hat{\mathbf{n}} \times \mathbf{P}_{1,2}|}\right)$$

E. Farhi, *Phys.Rev.Lett.* **39**, 1587 (1977).

Transverse moments are ($F = D_i^q$, $H_i^{\perp q}$):

$$F^{[n]}(z) = \int d|\mathbf{k}_T^2| \left(\frac{|\mathbf{k}_T|}{M_\pi}\right)^n F(z, \mathbf{k}_T^2)$$

where M_π = pion mass and the quark transverse momentum is $\mathbf{k}_T = \mathbf{P}_h^\perp / z$

Cross section in RF12

- The cross section for $e^+e^- \rightarrow \pi_1\pi_2\,X$ in terms of the pion fractional energies z_1, z_2 and $\varphi_1 + \varphi_2$ is

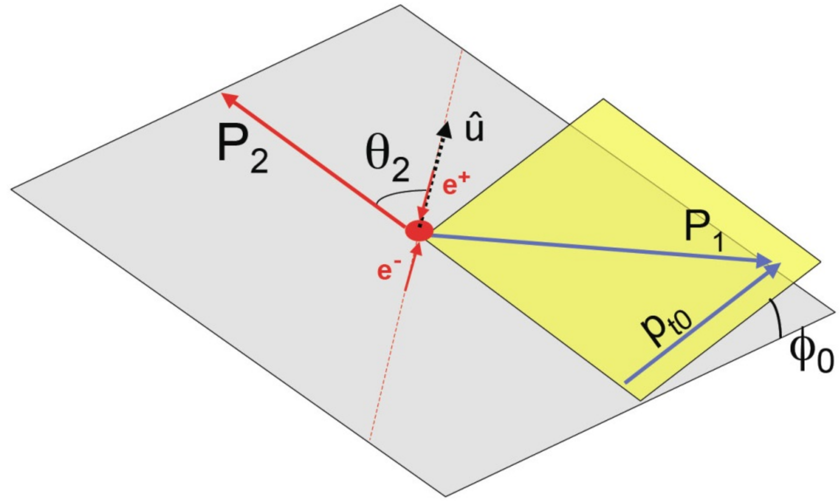
$$\frac{\mathrm{d}\sigma(e^+e^- \to \pi_1\pi_2 X)}{\mathrm{d}z_1\mathrm{d}z_2\mathrm{d}\phi_1\mathrm{d}\phi_2\mathrm{d}\cos\theta_{th}} = \sum_{q,\overline{q}} \frac{3\alpha^2}{Q^2}\,\frac{e_q^2}{4}\,z_1^2 z_2^2 \times \Big\{(1+\cos^2\theta_{th})\,D_1^{q,[0]}(z_1)\overline{D}_1^{q,[0]}(z_2) + \sin^2\theta_{th}\,\cos(\phi_1+\phi_2)\,H_1^{\perp q,[1]}(z_1)\overline{H}_1^{\perp q,[1]}(z_2)\Big\}$$

- Where
  - o $Q = \sqrt{s}$ is the c.m. energy
  - o e_q the charge of quark q
  - o Bar denotes antiquark fragmentation function

Second-pion reference frame RF0

- The Collins asymmetry can also be observed in a different reference frame
  - Use direction of π_2 as the reference axis
  - Instead of the thrust axis
- Scattering plane is defined by the e^+e^- axis and $\mathbf{P}_2$
  - $\mathbf{P}_2$ = the momentum of π_2
- Cross section consists of a uniform part and a $\cos(\varphi_0)$ modulated part
  - Also depends on a convolution integral F over π_1, π_2 transverse momenta
- $d\sigma \propto A' + B' \cos(\varphi_0)$
- Divide the φ_0 range into bins and extract

$$R_0(2\phi_0) = \frac{N(2\phi_0)}{N_{\text{avg}}}$$



$$\phi_0 = \text{sign}[\mathbf{P}_2 \cdot \{(\hat{\mathbf{u}} \times \mathbf{P}_2) \times (\mathbf{P}_2 \times \mathbf{P}_1)\}] \times \arccos\left(\frac{\hat{\mathbf{u}} \times \mathbf{P}_2}{|\hat{\mathbf{u}} \times \mathbf{P}_2|} \cdot \frac{\mathbf{P}_2 \times \mathbf{P}_1}{|\mathbf{P}_2 \times \mathbf{P}_1|}\right)$$

Boer *et al.*, *Nucl.Phys.* **B 504**, 345 (1997).

Convolution integral *F* over transverse momenta $\mathbf{P}_i^{\perp} = z_i \mathbf{k}_T$ is

$$\mathcal{F}(X\overline{X}) = \sum_{a,\bar{a}} e_a^2 \int d^2\mathbf{k}_T d^2\mathbf{p}_T \delta^2(\mathbf{p}_T + \mathbf{k}_T - \mathbf{q}_T) X(z_1, z_1^2\mathbf{k}_T^2)\overline{X}(z_2, z_2^2\mathbf{p}_T^2)$$

where $\mathbf{k}_T$ and $\mathbf{p}_T$ are the quark tranverse momenta

Cross section in RF0

- The cross section for $e^+e^- \rightarrow \pi_1\pi_2\, X$ in terms of the pion fractional energies z_1, z_2 and φ_0 is

$$\frac{\mathrm{d}\sigma(e^+e^- \to \pi_1\pi_2 X)}{\mathrm{d}z_1 \mathrm{d}z_2 \mathrm{d}^2\mathbf{q}_T \mathrm{d}\cos(\theta_2) d\phi_0} = \frac{3\alpha^2}{Q^2}\,\frac{z_1^2 z_2^2}{4} \times \Bigg\{ (1+\cos^2\theta_2)\,\mathcal{F}(D_1(z_1)\overline{D}_1(z_2)) + \sin^2\theta_2\,\cos(2\phi_0) \times \mathcal{F}\left[(2\hat{\mathbf{h}}\cdot\mathbf{k}_T\,\hat{\mathbf{h}}\cdot\mathbf{p}_T - \mathbf{k}_T\cdot\mathbf{p}_T)\frac{H_1^\perp(z_1)\overline{H}_1^\perp(z_2)}{M^2}\right]\Bigg\} \quad (1)$$

  - o Where $|\mathbf{q}_T| = Q_t$ = transverse momentum of the e^+e^- virtual photon in the two pion c.m. system
  - o Good to leading order in α_s and $1/Q$

Like- and unlike-charge pion pairs

- We can use pion pairs of equal or opposite charges
  - Opposite charge case occurs via two favored or two disfavored processes

$$e^+e^- \to u\overline{u} \to \pi^\pm\pi^\mp X$$

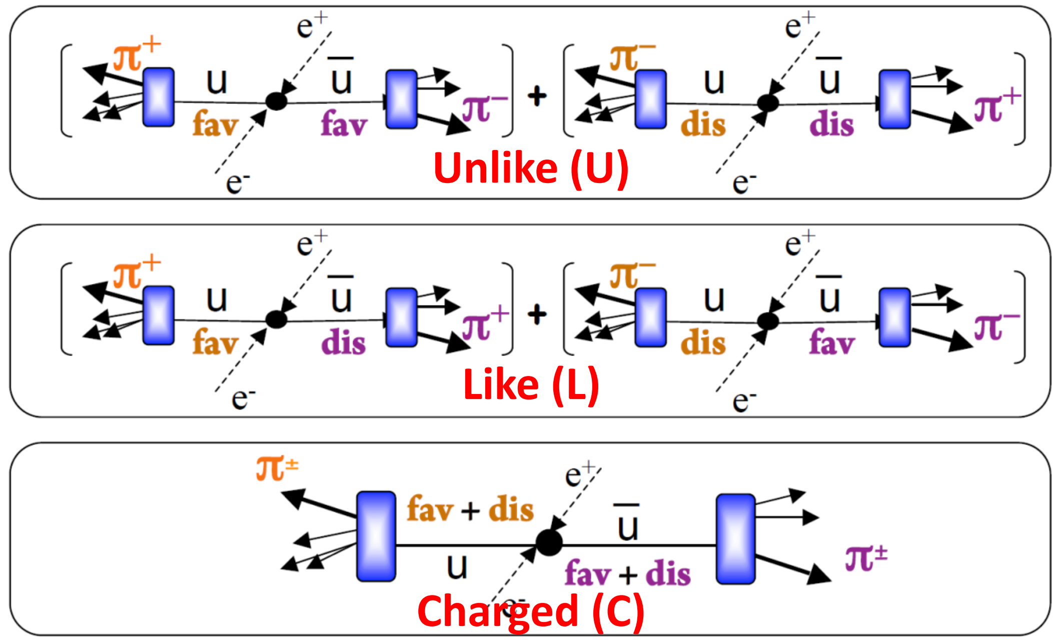
- Define favored and disfavored fragmentation functions:

$$D^{\mathrm{fav}}(z) = D_u^{\pi^+}(z) = D_{\bar{d}}^{\pi^-}(z)$$

$$\overline{D}^{\mathrm{fav}}(z) = D_{\bar{u}}^{\pi^-}(z) = D_{\bar{d}}^{\pi^+}(z)$$

$$D^{\mathrm{dis}}(z) = D_u^{\pi^-}(z) = D_d^{\pi^+}(z) = D_s^{\pi^\pm}(z)$$

$$D^{\mathrm{dis}}(z) = D_u^{\pi^-}(z) = D_d^{\pi^+}(z) = D_s^{\pi^\pm}(z)$$



- Cross sections can be written as (U = unlike, L = like, C = charged)

$$N^U(\phi) = \frac{\mathrm{d}\sigma(e^+e^- \to \pi^\pm\pi^\mp X)}{\mathrm{d}\Omega \mathrm{d}z_1 \mathrm{d}z_2} \propto \frac{5}{9} D^{\mathrm{fav}}(z_1)\overline{D}^{\mathrm{fav}}(z_2) + \frac{7}{9} D^{\mathrm{dis}}(z_1)\overline{D}^{\mathrm{dis}}(z_2)$$

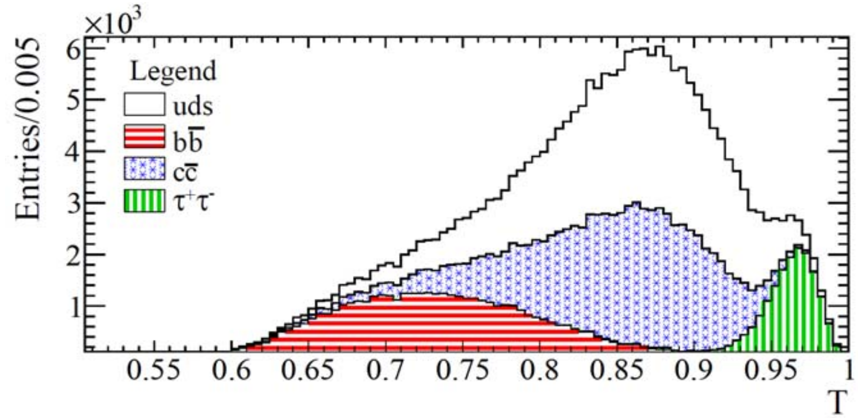
$$\phi \equiv \phi_1 + \phi_2(\mathrm{RF12}) \text{ or } \phi_0(\mathrm{RF0})$$

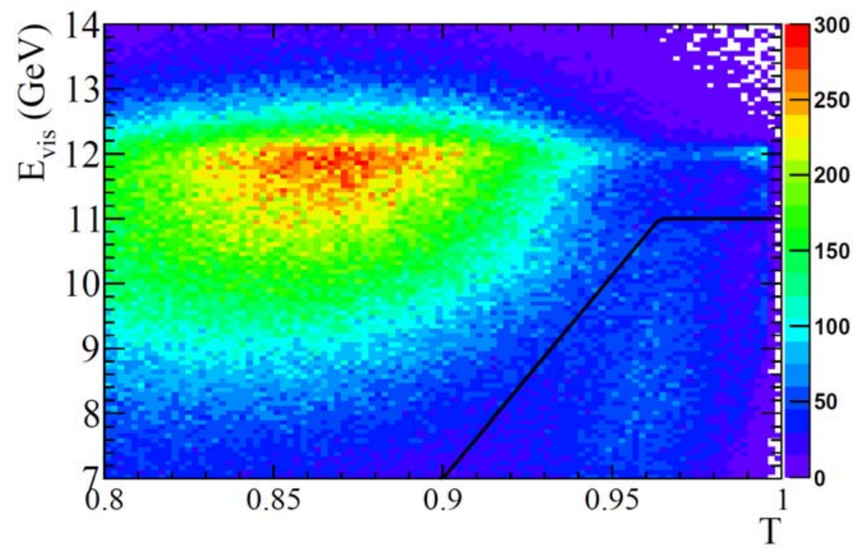
$$N^L(\phi) = \frac{\mathrm{d}\sigma(e^+e^- \to \pi^\pm\pi^\pm X)}{\mathrm{d}\Omega \mathrm{d}z_1 \mathrm{d}z_2} \propto \frac{5}{9} D^{\mathrm{fav}}(z_1)\overline{D}^{\mathrm{dis}}(z_2) + \frac{5}{9} D^{\mathrm{dis}}(z_1)\overline{D}^{\mathrm{fav}}(z_2) + \frac{2}{9} D^{\mathrm{dis}}(z_1)\overline{D}^{\mathrm{dis}}(z_2)$$

$$N^C(\phi) = \frac{\mathrm{d}\sigma(e^+e^- \to \pi\pi X)}{\mathrm{d}\Omega \mathrm{d}z_1 \mathrm{d}z_2} = N^U(\phi) + N^L(\phi) \propto \frac{5}{9}[D^{\mathrm{fav}}(z_1) + D^{\mathrm{dis}}(z_1)][\overline{D}^{\mathrm{fav}}(z_2) + \overline{D}^{\mathrm{dis}}(z_2)] + \frac{4}{9} D^{\mathrm{dis}}(z_1)\overline{D}^{\mathrm{dis}}(z_2)$$

Event selection (1)

- Choose events with light quark fragmention
  - o Helicity is conserved only in the massless quark case
  - o Heavy quarks may lose correlation between q and $\bar{q}$
- Select multi-hadron events
  - o ≥ 3 charged particles
  - o Fox-Wolfram $R_2' < 0.98$
    - Using charged tracks only
  - o $E_{\text{visible}} > 7$ GeV
    - Suppresses $\tau^+\tau^-$, energetic ISR, and $\gamma\gamma$ events
- Accept only charged tracks with
  - o At least 0.1 GeV/c momentum transverse to e^+e^- axis
  - o Track must originate near the I.P.
  - o Lie within detector solid-angle acceptance region
- Suppress events with energetic gluon emission (disrupts correlation between quark spins)
  - o Require event thrust $T > 0.8$
    - *uds* events peak near $T = 0.85$
    - Removes most *BB* events
- Suppress $e^+e^- \rightarrow \mu^+ \mu^- \gamma$ and $e^+e^- \rightarrow e^+ e^- \gamma$ by the 3-hadron requirement above
  - o But in $\mu^+ \mu^- \gamma$ case, if the photon converts, it may pass this cut
  - o Suppress further by requiring in low-multiplicity events neither two most energetic tracks are identified as muons and that no electrons are present



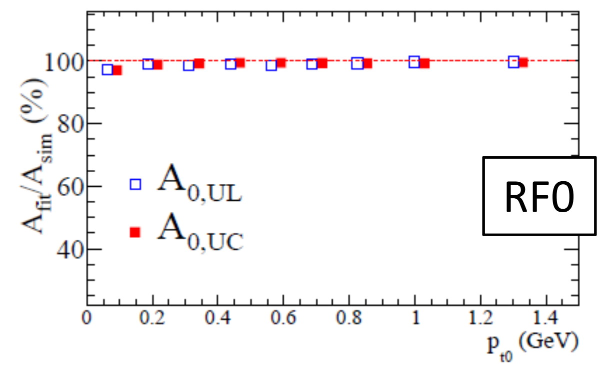


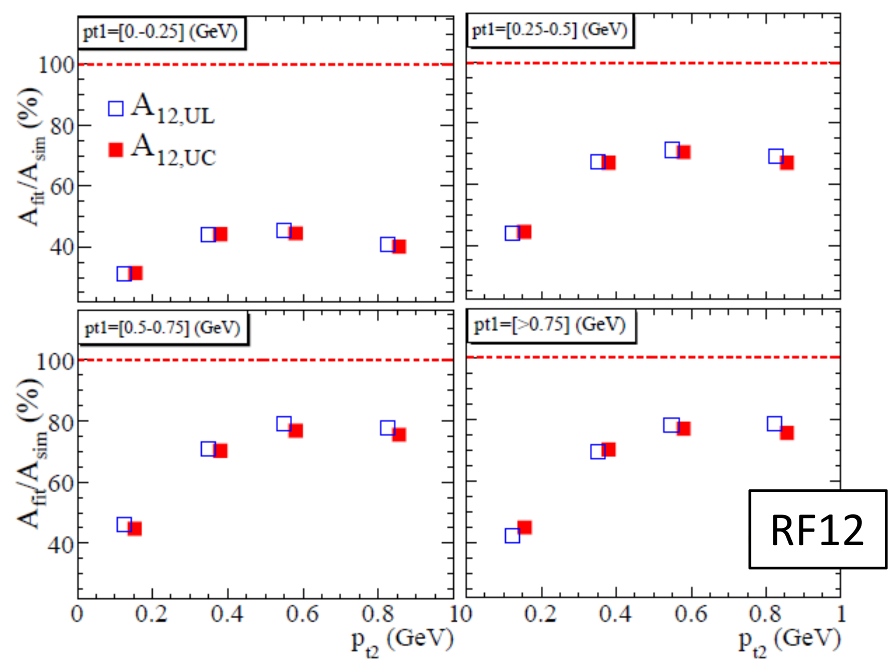
Event selection (2)

- Accept a track as candidate for Collins analysis if it
  - Is identified as a pion
  - Fails muon and electron selectors
- Require track to have $z < 0.9$
  - Reduces events from $b\bar{b}$ bound states
    - Which produce significant number of unlike-sign pairs
- Require $z > 0.15$
  - To avoid problems associating low-energy hadrons with the correct jet
- Require pions to be within 45^o of thrust axis
  - Reduces wrong-jet associations
- Require transverse momentum of the virtual photon Q_t to be > 3.5 GeV
  - Further reduces low-energy gluon radiative events
- Residual contributions from all remaining backgrounds are estimated and corrections made
  - Charm, $B\bar{B}$, $\tau^+\tau^-$
- Results in 10^8 pion pairs for the Collins analysis

Corrections, checks and systematics (1)

- Asymmetry dilution
  - o From use of thrust axis to approximate $q\bar{q}$ $\bar{B}\,\bar{B}$ axis
  - o Average divergence from $q\bar{q}$ axis about 100 mrad
  - o Results in asymmetry dilution
    - Mainly affects RF12 reference frame
    - Much smaller effect in RF0
- Estimate this and other effects using simulation
  - o Re-weight MC events to produce a Collins-like effect in non-asymmetric generated events
  - o Determine average dilution values for each z, p_t, and ϑ_{th} bin
  - o Apply these as corrections





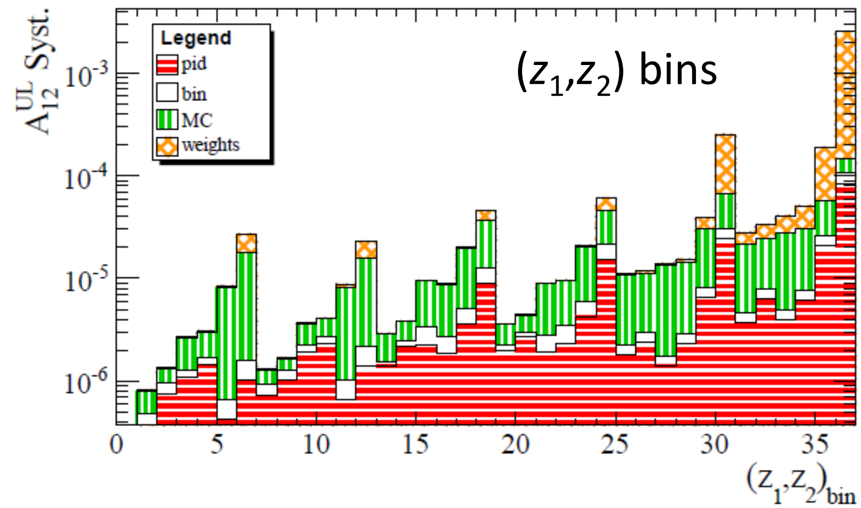
Corrections, checks and systematics (2)

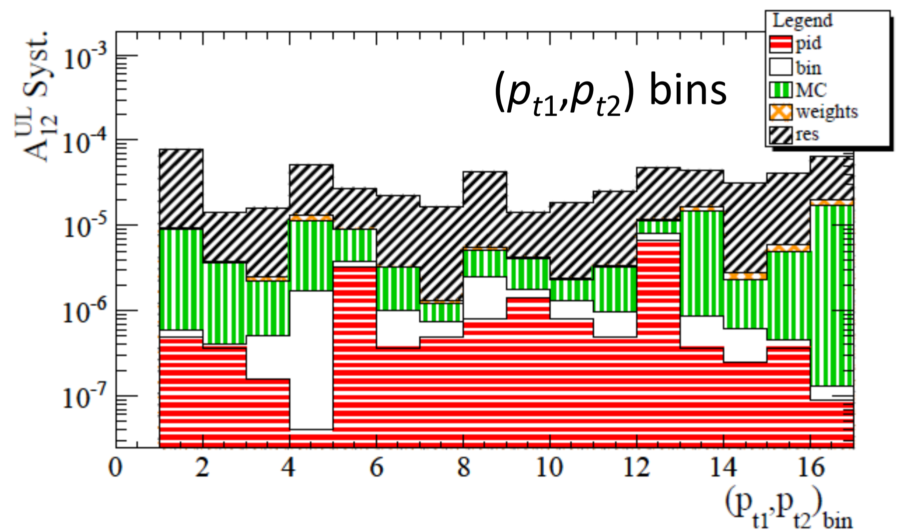
- Double-ratio methodology
  - Shows small asymmetry (≈ 0.2%) in *uds* MC generated without asymmetry
    - Check 3 MC samples
      - Use pion event-generated ("truth") momenta
      - Use pion event-generated momenta only for pions associated with reconstructed tracks
      - Use standard, fully-reconstructed MC sample
    - Use $q\bar{q}$ axis instead of thrust axis
    - Vary track selection requirements
  - RF0: main effect is non-cancellation of detector effects in double ratio
  - RF12: main effect from use of thrust axis
  - Subtract biases from corrected asymmetries
    - Take quadrature combination of largest variation of tests with statistical uncertainty of the fit as systematic uncertainty
- Other systematics
  - Pion transverse momentum resolution
    - 10% effect on asymmetries for all (p_t1,p_t1) bins except lowest (30% effect)
      - Assign as systematic
  - Particle identification
    - Pion pairs have about 96% purity; remaining 4% a true pion and a mid-identified kaon
    - Vary PID selection cuts (more and less stringent)
    - Results in at most few percent change in asymmetries
      - Assign as systematic
  - Fit procedure
    - Vary angular bin sizes, larger and smaller than standard
      - Deviations < 1%
      - Assign as systematic
    - Study re-use of pions in different pairs in same events
      - Pseudo-experiments show no bias in pull distributions
  - Test using same-sign pion pairs
    - Collins effect not a function of charge, but of favored- and disfavored transitions
    - Gives information on detector charge asymmetries
      - Results consistent with unity
  - Check D-R using subtraction method
    - Take difference instead of ratio of pion pair rates
      - Consistent with D-R method
  - Others: beam polarization, consistency across data sets

Systematics summary

- Dominant systematics
  - o At larger z
    - Bias observed in MC sample
    - Dilution correction factors
  - o At all values of p_t
    - p_t resolution
    - Bias observed in MC sample

Squared errors for A_{12}^{UL}





Antideuteron production systematics

Source	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(1S)$	Continuum
Fit Biases	0.5% — 2.0%	0.1% — 6.6%	0.1% — 2.0%	0.0% — 0.2%
Background Model	0.2% — 7.8%	3.1% — 12.0%	0.9% — 7.6%	0.0% — 8.9%
Reconstruction Efficiency	2.5% — 10.5%	5.2% — 17.0%	1.3% — 7.1%	3.0% — 7.3%
Kinematic Acceptance	0.5% — 10.3%	3.6% — 16.0%	0.6% — 2.9%	1.4% — 8.4%
Material Interaction	2.8% — 10.5%	4.3% — 17.0%	2.0% — 7.3%	2.9% — 7.4%
Fake antideuterons	$^{+0.0\%}_{-0.5\%}$ — $^{+0.0\%}_{-9.8\%}$	$^{+0.0\%}_{-1.1\%}$ — $^{+0.0\%}_{-3.0\%}$	$^{+0.0\%}_{-1.9\%}$ — $^{+0.0\%}_{-32.0\%}$	$^{+0.0\%}_{-0.6\%}$ — $^{+0.0\%}_{-5.4\%}$
DOCA Selection	$^{+5.8\%}_{-0.0\%}$	$^{+5.8\%}_{-0.0\%}$	$^{+5.8\%}_{-0.0\%}$	$^{+5.8\%}_{-0.0\%}$
Event Selection	2.3%	2.3%	1.1%	4.6%
Normalization	1.2%	1.2%	0.2%	0.6%