Spin Dependent Fragmentation at BaBar:

Collins Asymmetries in $e^+e^- \rightarrow u\bar{u}, d\bar{d}, s\bar{s} \rightarrow \pi^{\pm}\pi^{\pm}X$

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Workshop on Fragmentation Functions and QCD
November 9-11, 2012, RIKEN

Outline

- **Introduction**
- **Data Analysis**
  - event and $\pi^{\pm}\pi^{\pm}$ pair selection
  - Collins asymmetries A_{α}
  - backgrounds and dilutions
- **Results**
  - A_{α} vs. $\pi^{\pm}$ scaled energies
  - A_{α} vs. $\pi^{\pm}$ p_t wrt the thrust axis/each other
  - A_{α} vs. polar angle
- **Summary and outlook**

Introduction: recall the general idea

- Given a (hard) parton $k=u,d,s,c,b,\bar{u},\bar{d},\bar{s},\bar{c},\bar{b},g$ with energy E_k, momentum $p_k\hat{z}$, and polarization $j\hat{s}_k$

  we want the probability density

$$F_k^h(m_h,\ f_h,\ j_h,\ p_h,\ \theta_h,\ \phi_h,\ \hat{s}_h\ ;\ E_k,\ p_k,\ \hat{s}_k)$$

  to find a hadron h in its jet with: mass m_h, flavor f_h, spin j_h, polarization $\hat{s}_h$, momentum $(p_h\sin\theta_h\cos\phi_h,\ p_h\sin\theta_h\sin\phi_h,\ p_h\cos\theta_h)$

- We can integrate out/sum over many of these

- Today, consider: $F_h^q(z_h,\ \theta_h,\ \phi_h\ ;\ p_q,\ \tfrac{1}{2}\hat{y})$, $z_h = E_h / E_q$
  with pseudoscalar $h = \pi^\pm, K^\pm, \ldots$
  and transversely polarized $q=u\bar{u}d\bar{d}s\bar{s}$,
  $\hat{s}_q = \tfrac{1}{2}\hat{y}$

the Collins Fragmentation Function

- given a transversely polarized (light) quark $q=u,d,s,\bar{u},\bar{d},\bar{s}$
  with energy E_q
  momentum $p_q\hat{z}$
  polarization $s_q=\frac{1}{2}\hat{y}$

we can define the polarized FF

$$D_h^{q\uparrow}(z_h, \vec{p}_{\perp h}\,; \vec{s}_k) =$$

$$D_h^q(z_h, \vec{p}_{\perp h}) \quad + \quad \frac{p_{\perp h}}{z_h m_h} H_h^{q\uparrow}(z_h, \vec{p}_{\perp h}) \vec{s}_q \cdot (\vec{p}_q \times \vec{p}_{\perp h})$$

for any spinless h (or unpolarized h)
where $z_h = E_h / E_q$ (approx.)
$p_{\perp h} = (p_h \sin\theta_h \cos\phi_h,\ p_h \sin\theta_h \sin\phi_h,\ 0)$

- D_h^q is the "standard" unpolarized FF
- H_h^q is the Collins FF

the Collins Fragmentation Function (cont.)

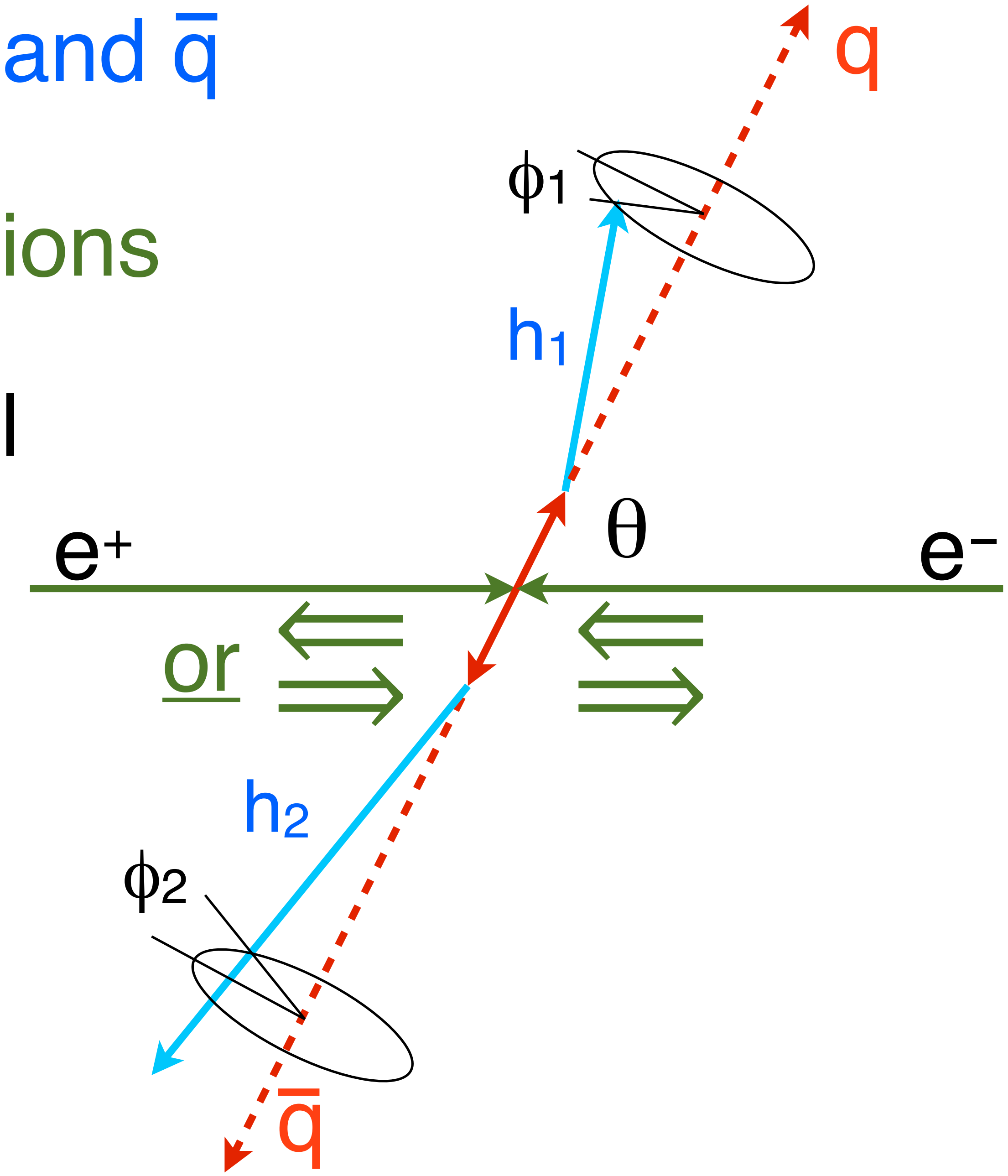
$$D_h^{q\uparrow}(z_h, \vec{p}_{\perp h}; \vec{s}_k) =$$

$$D_h^q(z_h, \vec{p}_{\perp h}) + \frac{p_{\perp h}}{z_h m_h} H_h^{q\uparrow}(z_h, \vec{p}_{\perp h}) \vec{s}_q \cdot (\vec{p}_q \times \vec{p}_{\perp h})$$

- H_h^q is the Collins FF
  - → could arise from a spin-orbit coupling
  - → leads to a $\cos\phi_h$ modulation
  - → expected to be stronger for high-z_h (leading) and high-p_t particles
- shown to be nonzero in semi-inclusive DIS (PRL 94, 012002) (NPB 765, 31)
  - → need to measure in e^+e^- out of fundamental interest
  - → ...and for the interpretation of SIDIS data
- Belle: published in 2006 (PRL 96, 232002), 2008 (PRD 78, 032011)
- Babar: preliminary results released last year
  update released this summer, shown today

Quark spin in e^+e^- annihilations

- spin-1 γ^* produces spin-½ q and $\bar{q}$
  - → in a given event:
    - the individual spin directions are unknown
    - but they must be parallel
  - → they have a polarization component transverse to the q direction, $\sim\sin^2\theta$



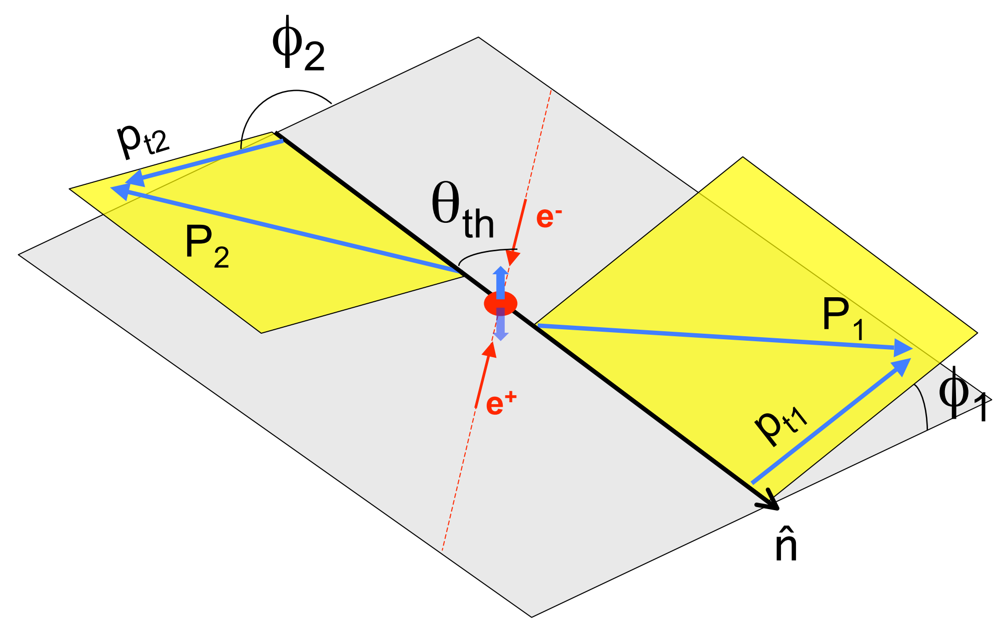
- exploit this correlation by using similar hadrons in opposite jets
- if q direction is known, then

$$d\sigma/d\phi_1 d\phi_2 d\ldots \sim (1+\cos^2\theta) D_{h1}^q \bar{D}_{h2}^q + \sin^2\theta \boxed{\cos(\phi_1+\phi_2)} H_{h1}^q \bar{H}_{h2}^q$$

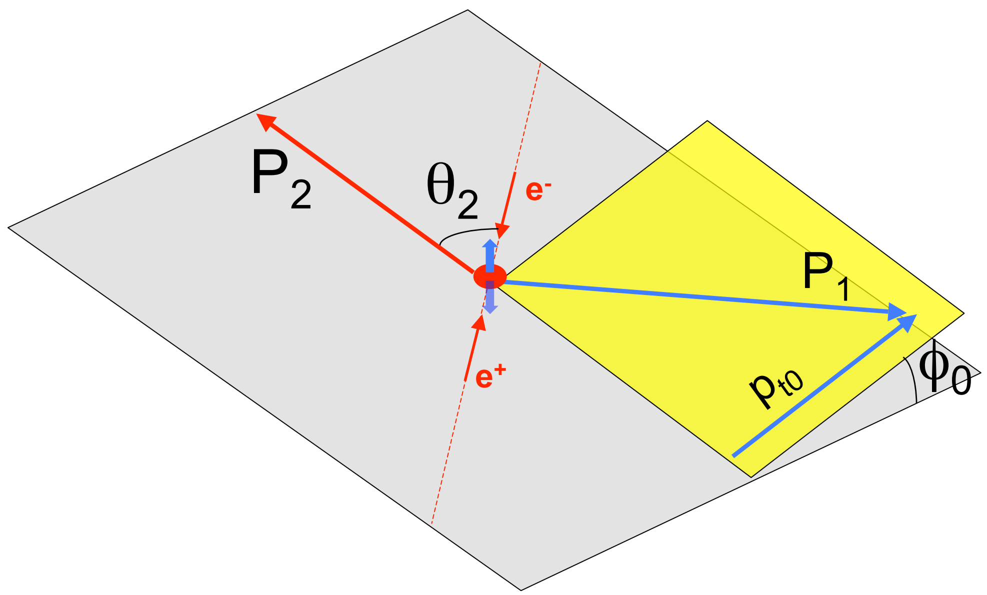
Reference Frames for the Measurement

(see NPB 806, 23)

- **RF12:** use the thrust axis to estimate the $q\bar{q}$ direction
  - → and the $\hat{T}$-$e^{\pm}$ plane to define ϕ_1, ϕ_2
  - → effect diluted by gluon radiation, detector resolution, ...
  - → so $d\sigma \sim A + B\sin^2\theta\cos(\phi_1+\phi_2)H^q_{h1}\bar{H}^q_{h2}$



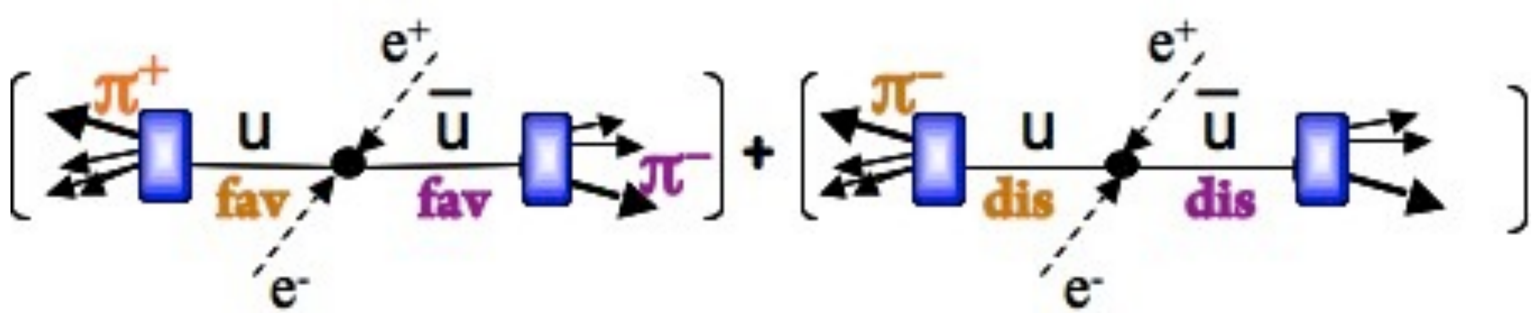
- **RF0:** alternatively, just use one track in a pair
  - → very clean experimentally, insensitive to T
  - → gives quark direction for high z_2
  - → now $d\sigma \sim F_1(D^q_{h1},\bar{D}^q_{h2}, \theta) + \cos(2\phi_0)F_2(H^q_{h1},\bar{H}^q_{h2}, \theta)$



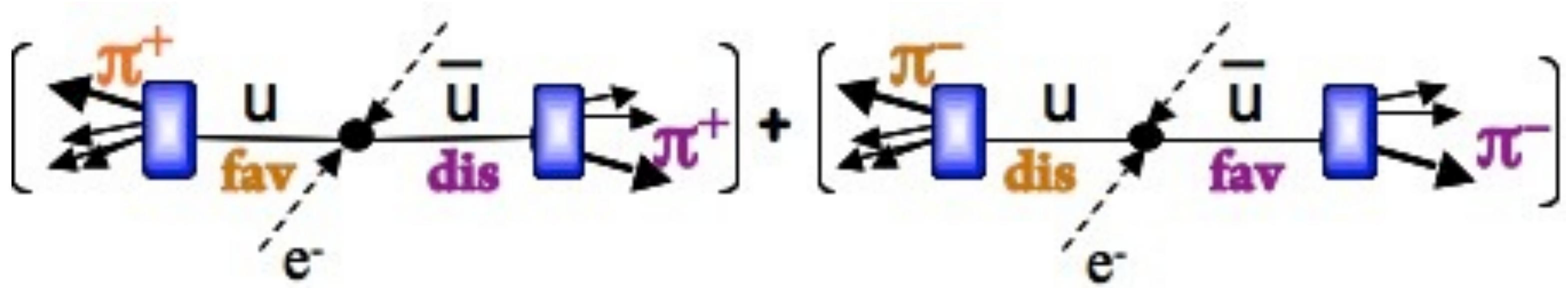
Favored and Disfavored Fragmentation Functions

- define a (dis)favored particle as one that could (not) contain the initial q or $\bar{q}$
  - → $u \to \pi^+$, $d \to \pi^-$, $\bar{u} \to \pi^-$, $\bar{d} \to \pi^+$ are favored (F)
  - → $u \to \pi^-$, $d \to \pi^+$, $\bar{u} \to \pi^+$, $\bar{d} \to \pi^-$ are disfavored (D)

- now consider Like (L) and Unlike (U) sign pairs
  - → U pairs can arise from FF or DD combinations



  - → L must be from FD or DF

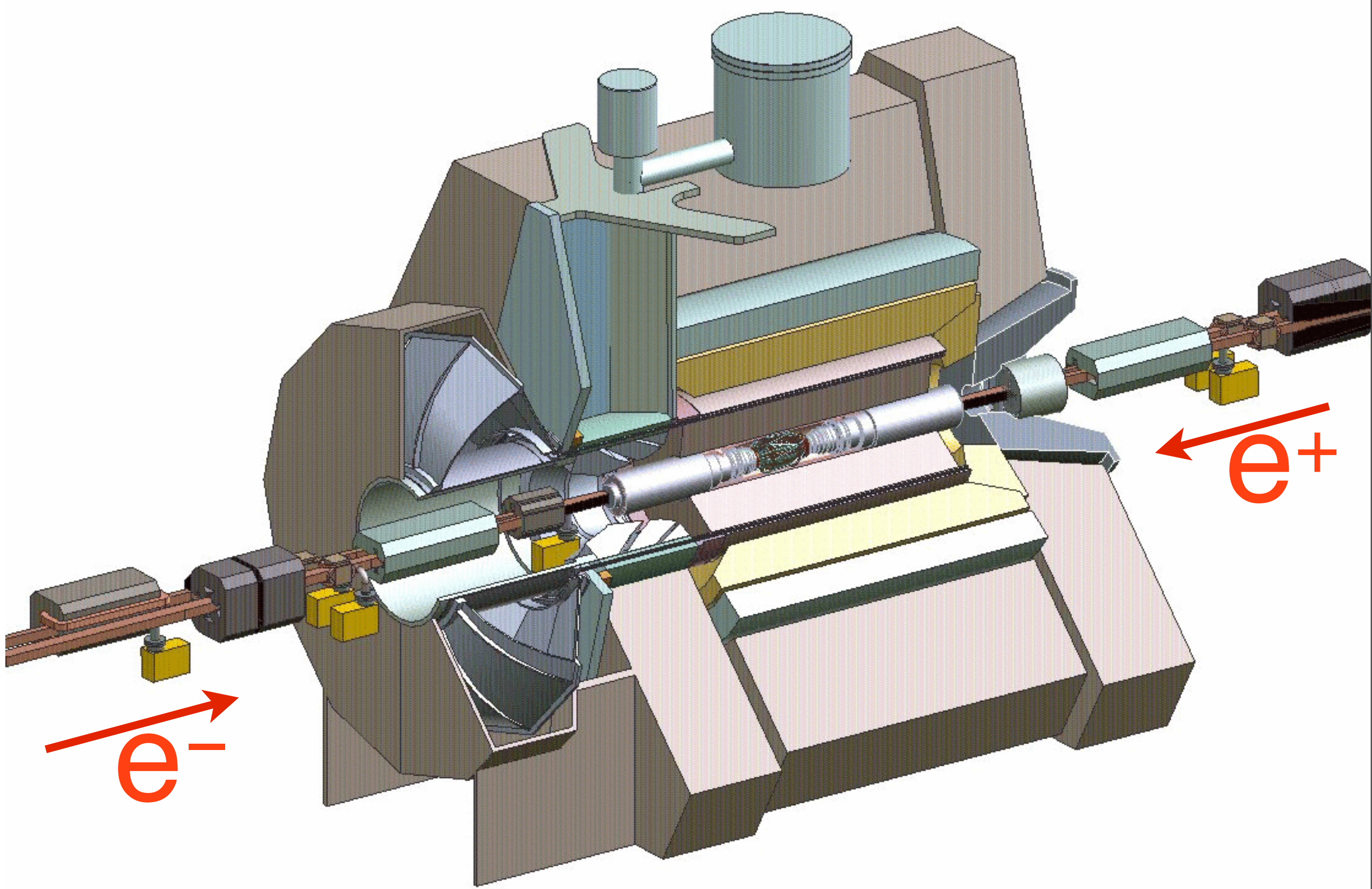


  - → also consider all pairs, C=U+L

The BaBar Experiment

- e^+e^- collisions at E_{CM}=10.6 GeV: hadronic final states
  $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, $c\bar{c}$, $\Upsilon(4S)$

- Different beam energies
  → E_{e-} = 9.0 GeV
  → E_{e+} = 3.1 GeV
  → c.m.-lab boost, $\beta\gamma$=0.55



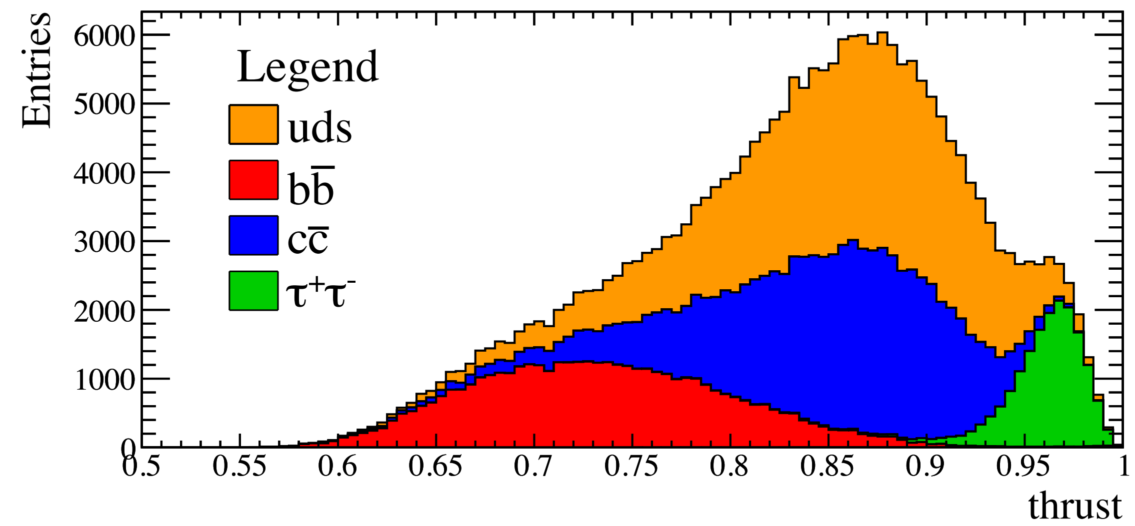
- Asymmetric detector
  → c.m. frame acceptance
  $-0.90 \sim \cos\theta^* \sim 0.85$
  wrt e^- beam

- with excellent performance
  → good tracking, mass resolution
  → good γ, π^0 recon.
  → full e,μ,π,K,p ID

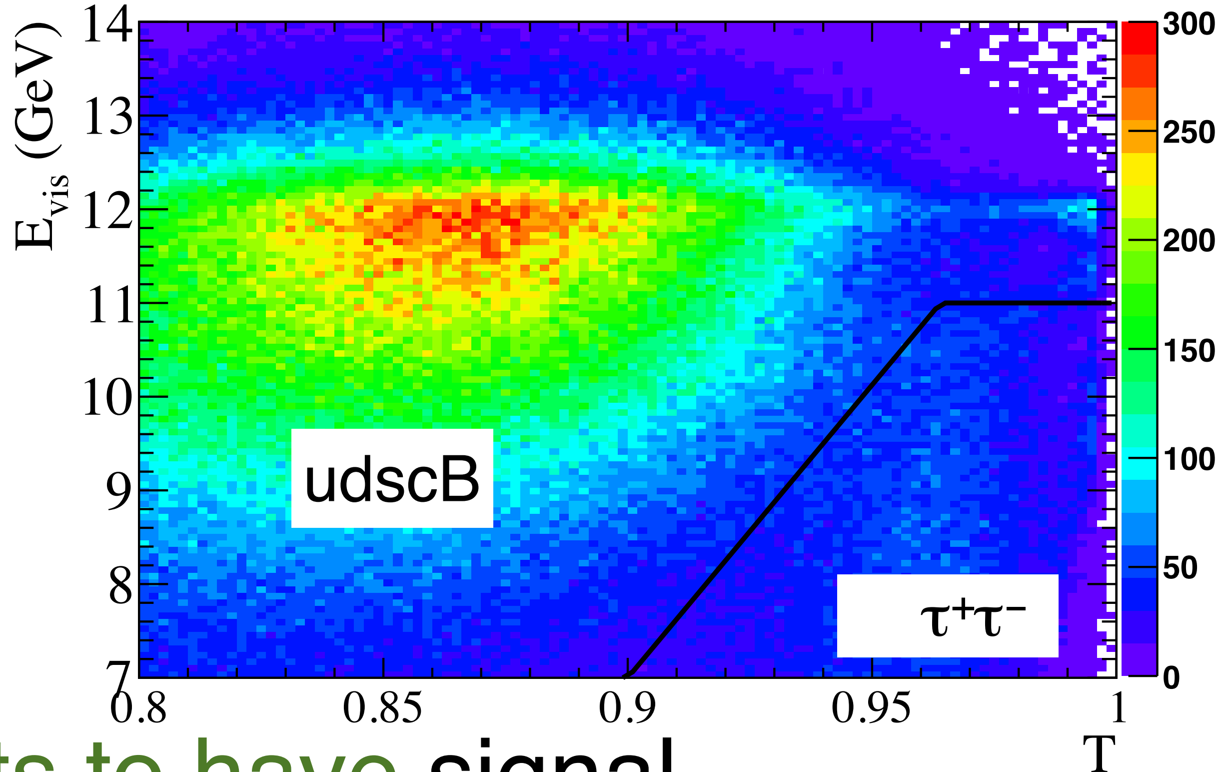
- High luminosity
  → ~468 fb^{-1} used here
  ↔ 1 billion
  $e^+e^-\to u\bar{u}$, $d\bar{d}$, $s\bar{s}$ events

Event Selection

- want:
  - → unbiased $u\bar{u}, d\bar{d}, s\bar{s}$ sample, especially for high-z $\pi^{\pm}$
  - → low track pair background
  - → a two-jet topology



- require:
  - → at least 3 charged tracks
  - → visible energy E_{vis}>7 GeV
  - → thrust value T>0.8
  - → remove $\tau^+\tau^-$ events in the T-E_{vis} plane



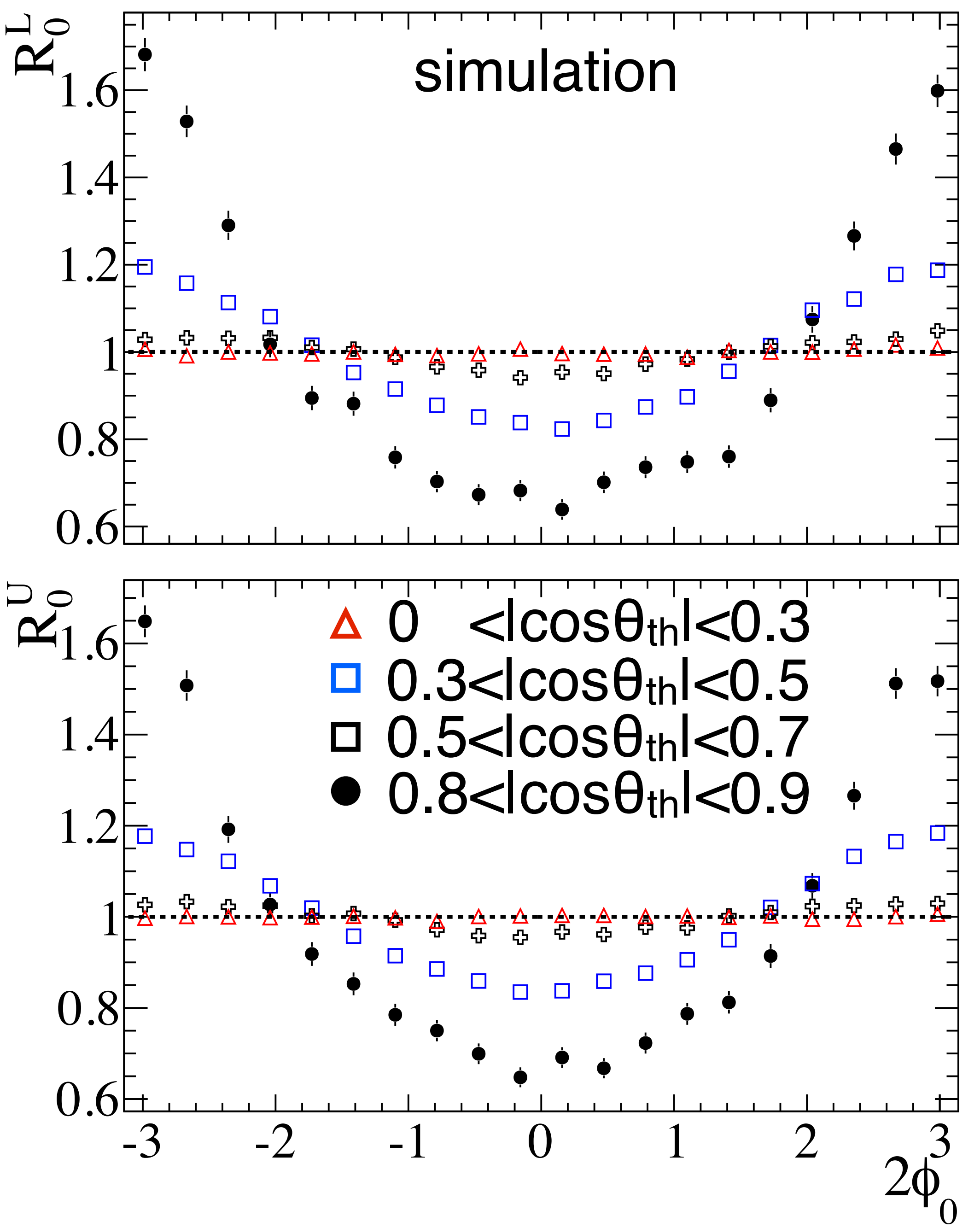
- efficient for:
  - → sufficiently 2-jet-like events to have signal
  - → $c\bar{c}$, $B\bar{B}$, $\tau^+\tau^-$ contributions understood/measured
  - → still some two-prong background...

Track (pair) Selection

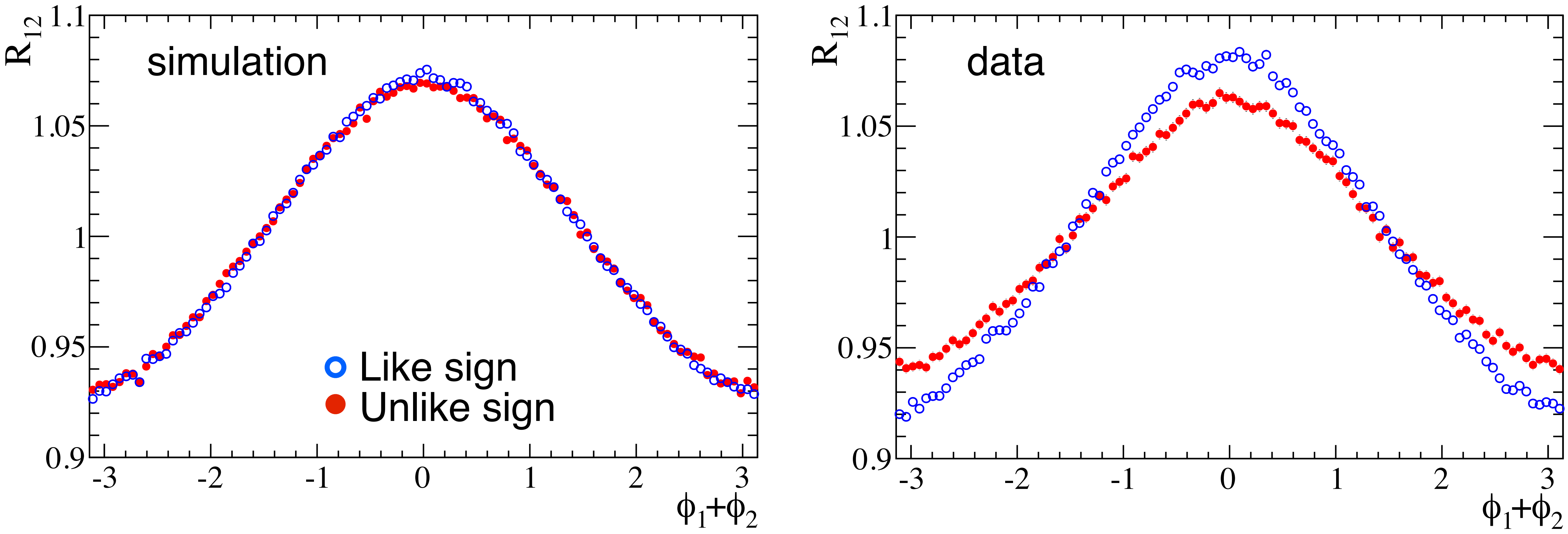
- within detector acceptance: → $0.41 < \theta < 254$ rad
- identification as $\pi^\pm$:
  → tight suppression of $K^\pm$, $p/\bar{p}$
  → very tight cuts against $e^\pm$, $\mu^\pm$
- max scaled energy, z<0.9, above which:
  → rate of signal $\pi^\pm$ is small (see yesterday's talk)
  → rate of signal $\pi^\pm\pi^\mp$ is very small
  → rate of signal $\pi^\pm\pi^\pm$ is zero
  → but there is some background
  →...and our simulation is not reliable...
- tracks must be assigned to the correct jet(!)
  → challenging at low E_{CM}
  → z>0.15, angle wrt T axis <45°
  → γ^* transverse momentum in the $\pi\pi$ cm frame, Q_t<0.35

Raw Azimuthal Distributions

- consider all selected U and L $\pi\pi$ pairs
  - → make histograms of $\phi_\alpha = \phi_1 + \phi_2$ or $2\phi_0$
  - → normalize by the average, $R_\alpha = N(\phi_\alpha) / \langle N \rangle$
- the simulation has no Collins effect, but it shows a strong $\cos\phi$-like effect
  - → due to acceptance of the detector
  - → depends strongly on θ
- we must understand and correct for this
  - → many studies performed; dep on z, p_t, ...
  - → can use only low $\cos\theta$ at low z ... but need the statistics at high z



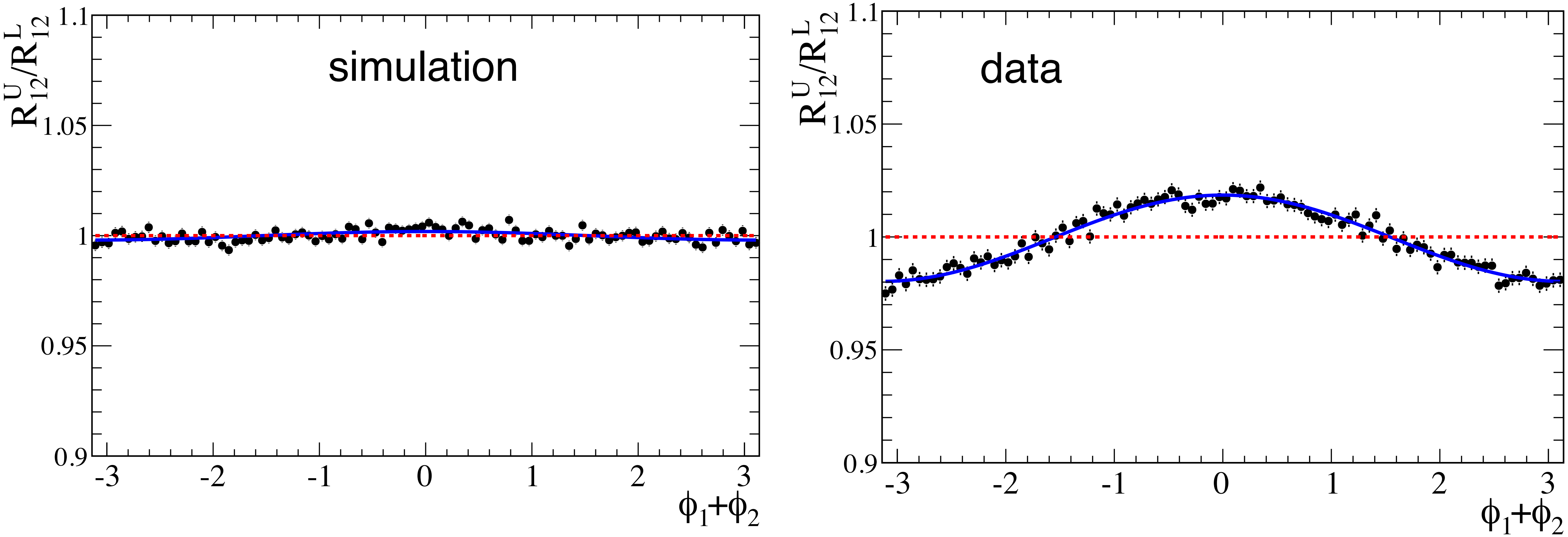
- the simulated effect is quite similar for U and L pairs
  → small difference makes sense in terms of different distributions of z, p_t
- and has opposite sign in RF12
  → nice consistency check on any signal



- the data show a large difference that can be ascribed to the Collins effect
  → simulation quite similar for L and U sign pairs, so ...

Double Ratios

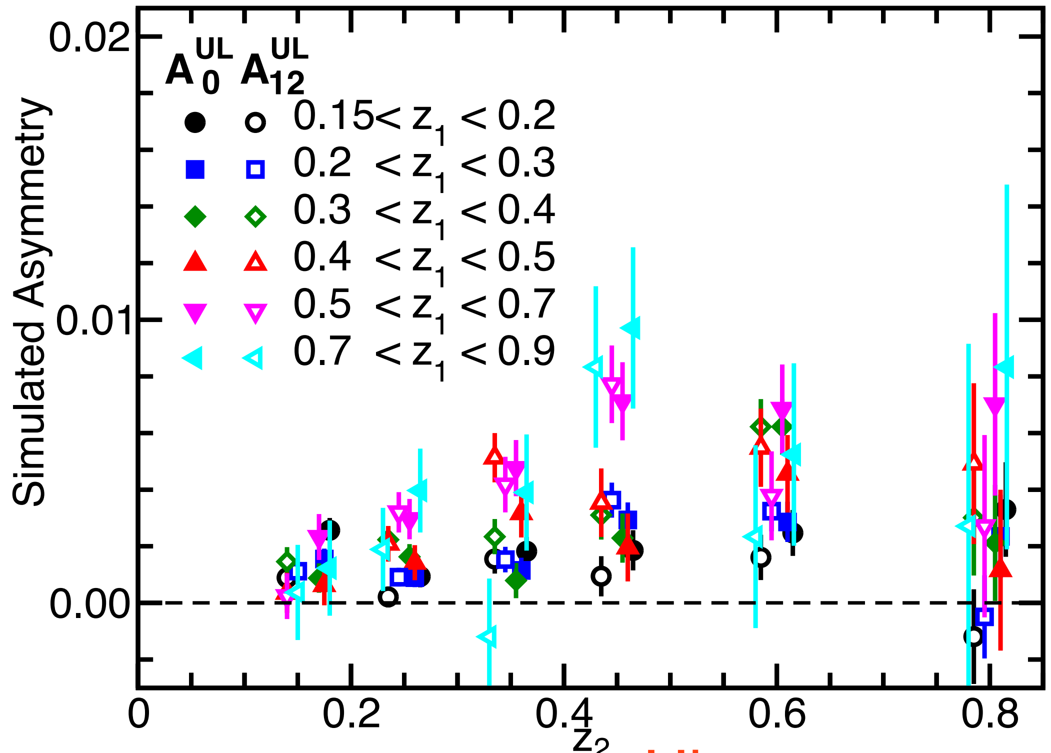
- reduce acceptance effects by taking the double ratios
  → $D^{UL} = R^{U}_{\alpha} / R^{L}_{\alpha}$
  → $D^{UC} = R^{U}_{\alpha} / R^{C}_{\alpha}$

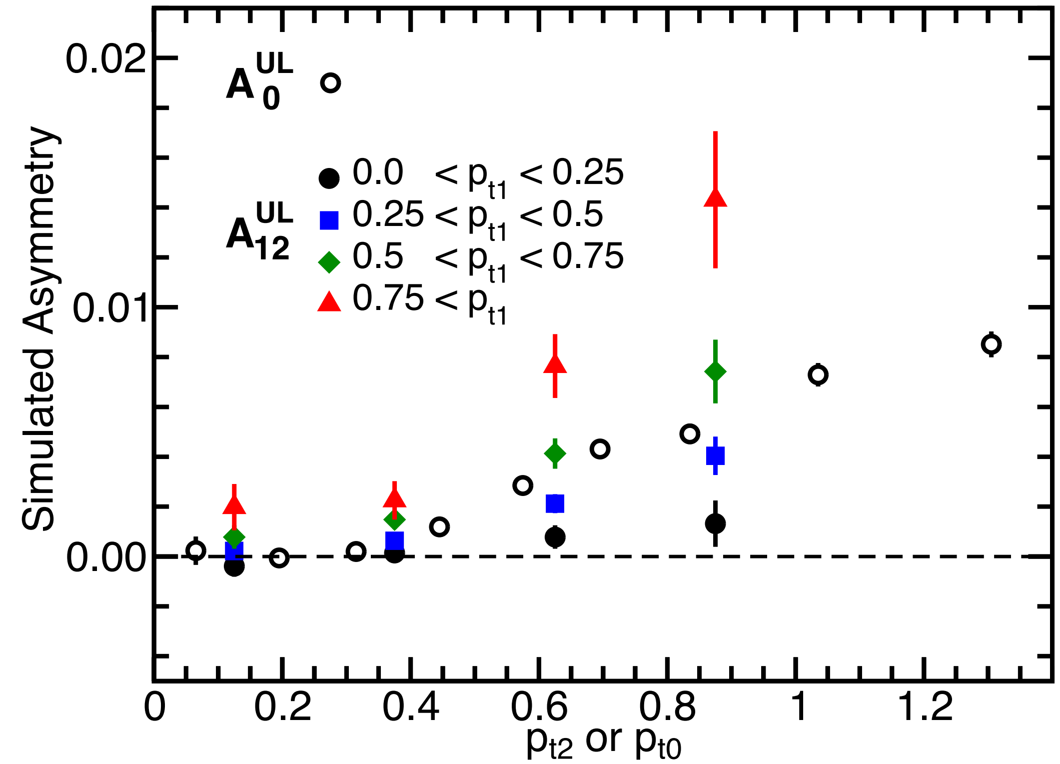


- Fit to the function $1+A^{UL}_{\alpha}\cos\phi_{\alpha}$ or $1+A^{UC}_{\alpha}\cos\phi_{\alpha}$
  → the Collins asymmetries A^{Ub}_{α} contain the information on the Collins effect
- subtract the fitted MC value from the data value
  → note dependence on z, p_t, ...

Analysis Bins

- Collins effects are expected to depend on z_1, z_2, p_{t1}, p_{t2} (or p_{t0}), as well as $\cos\theta$
  → analyze in bins of these quantities
  → use 6x6 bins in (z_1,z_2);   4x4 bins in (p_{t1},p_{t2}) (9 in p_{t0})

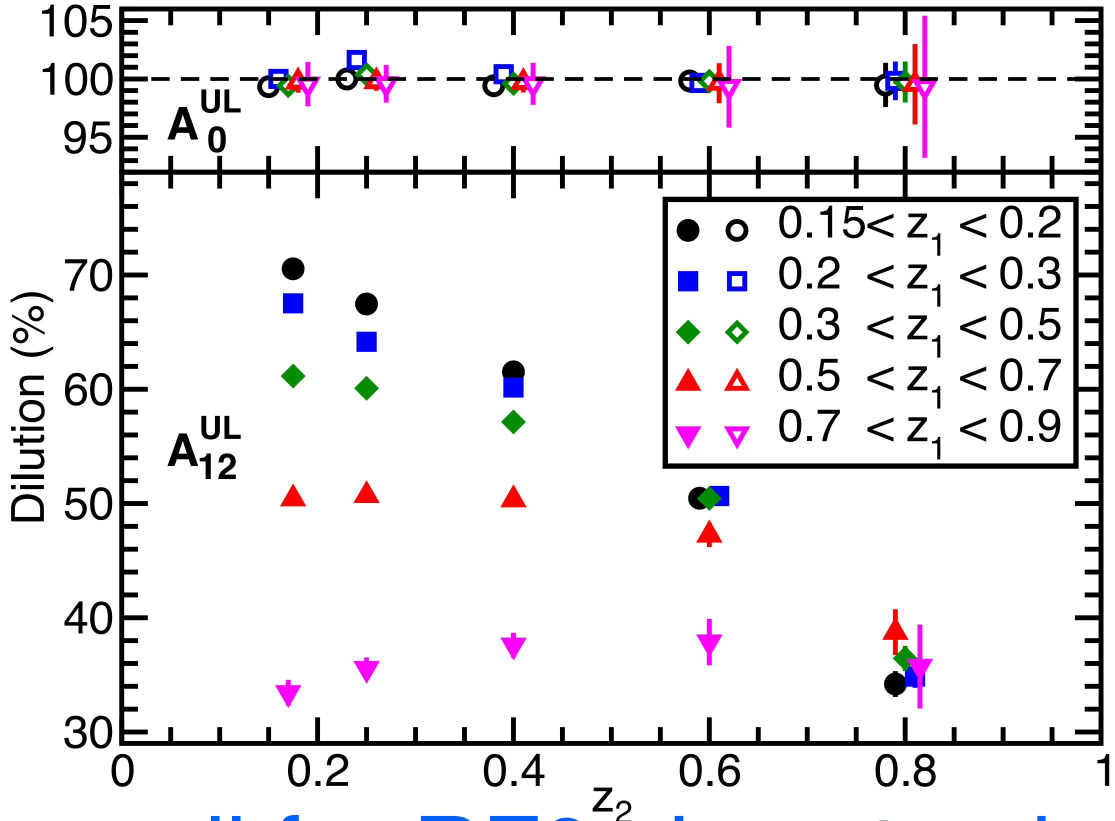


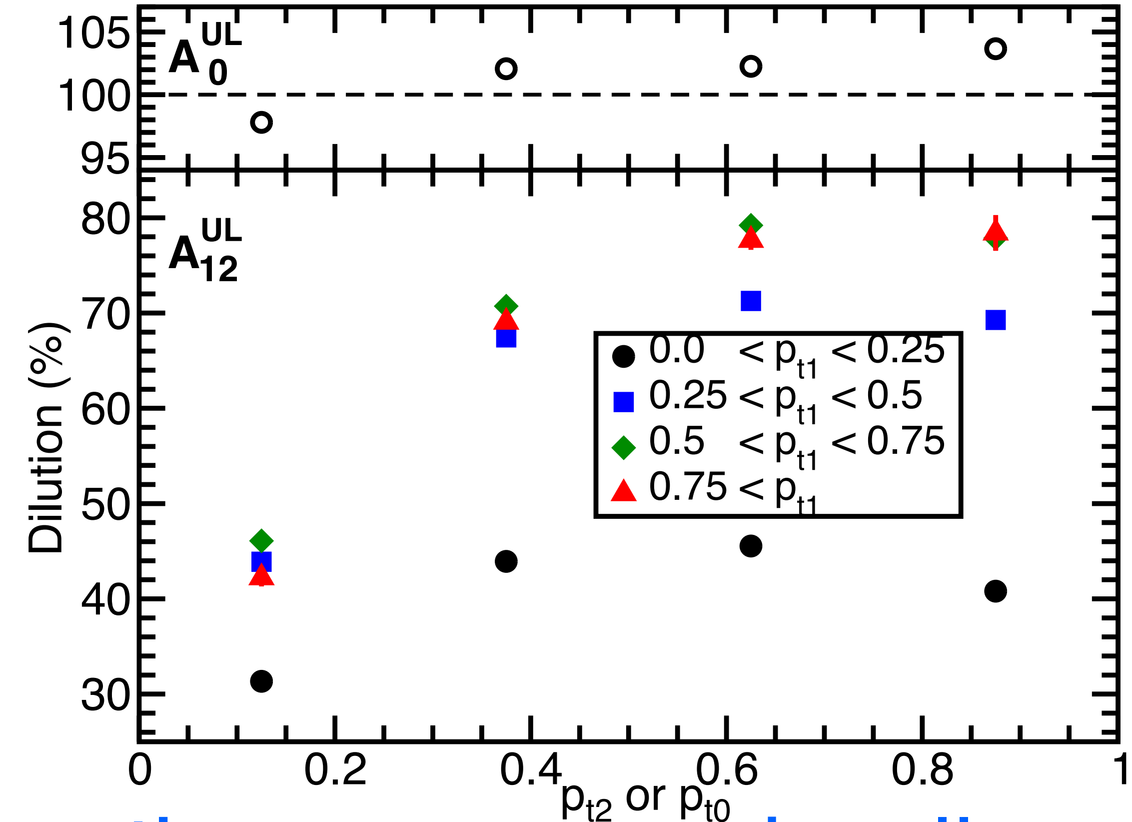


- the simulated A_α^{Ub} also depend on these quantities
  → must correct in each bin independently
- systematic on MC value evaluated by varying track selection/ acceptance
  → typically ~50% of correction; always << signal

Dilution

- the measured A_{α}^{UC} are different from the true values due to detector acceptance, resolution, ...
- studied using simulation reweighted to several A values
  → dilution A^{meas} / A^{input} depends on z, p_t

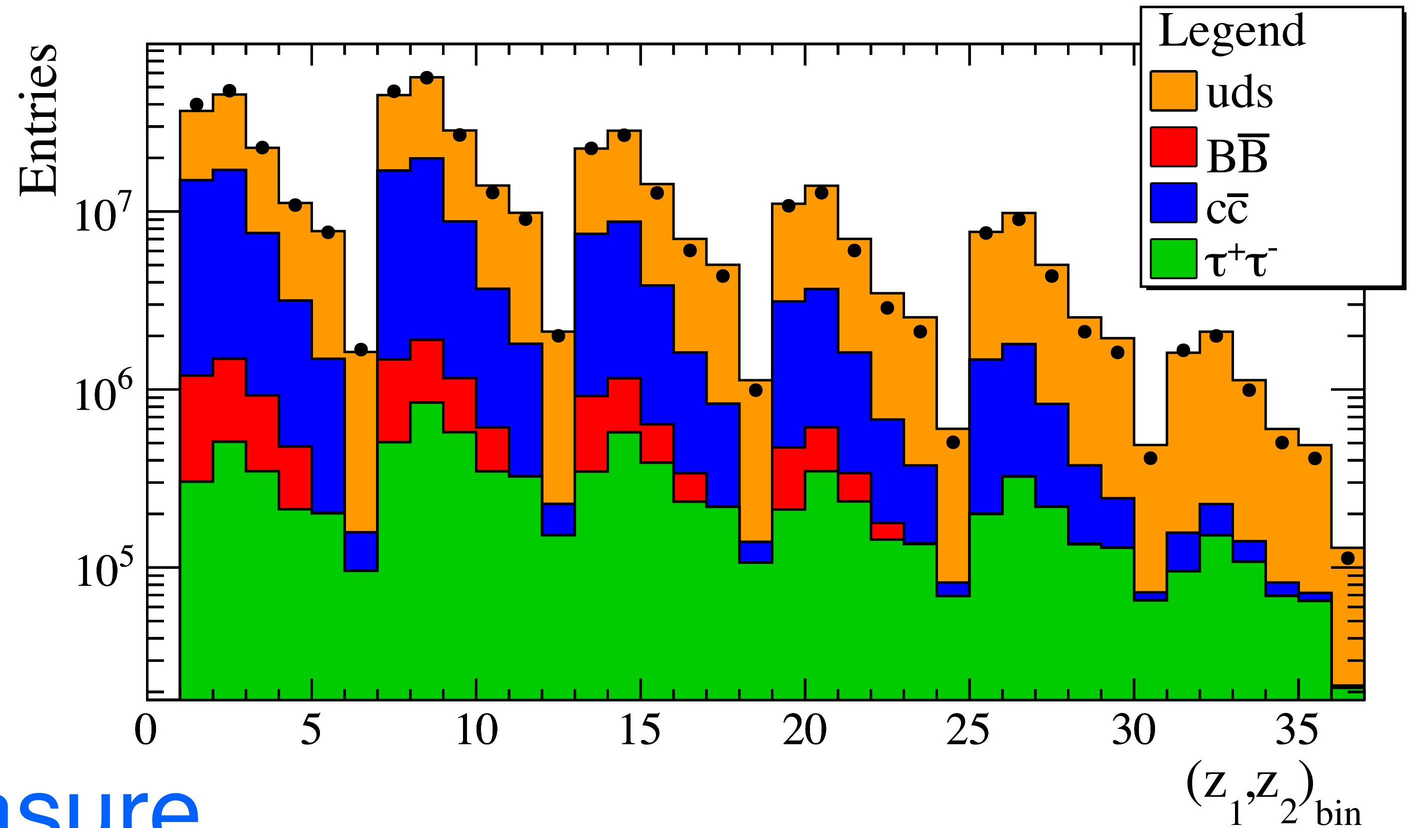




- small for RF0 since track directions measured well
  → assign no correction or error
- substantial in RF12, due to the use of the T axis
  → correction from MC with its stat. error as a systematic

Backgrounds

- the simulated sample composition includes pairs from:
  - → signal uds events
  - → $B\overline{B}$ events, small, mostly low z
  - → $c\overline{c}$ events, important at medium z
  - → $\tau^+\tau^-$ events, important at high z



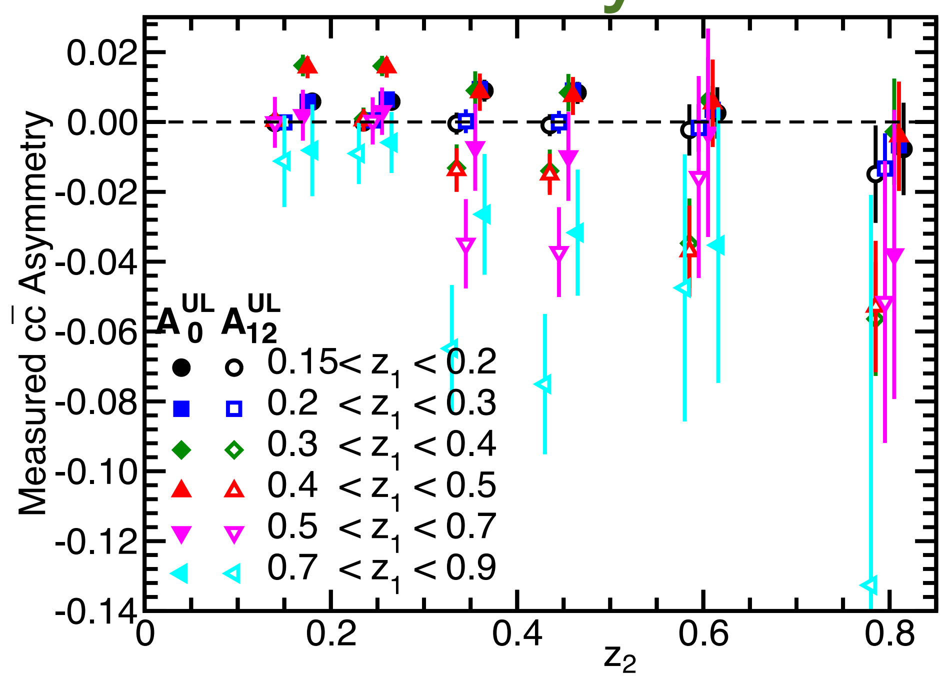
- in each bin, we will measure

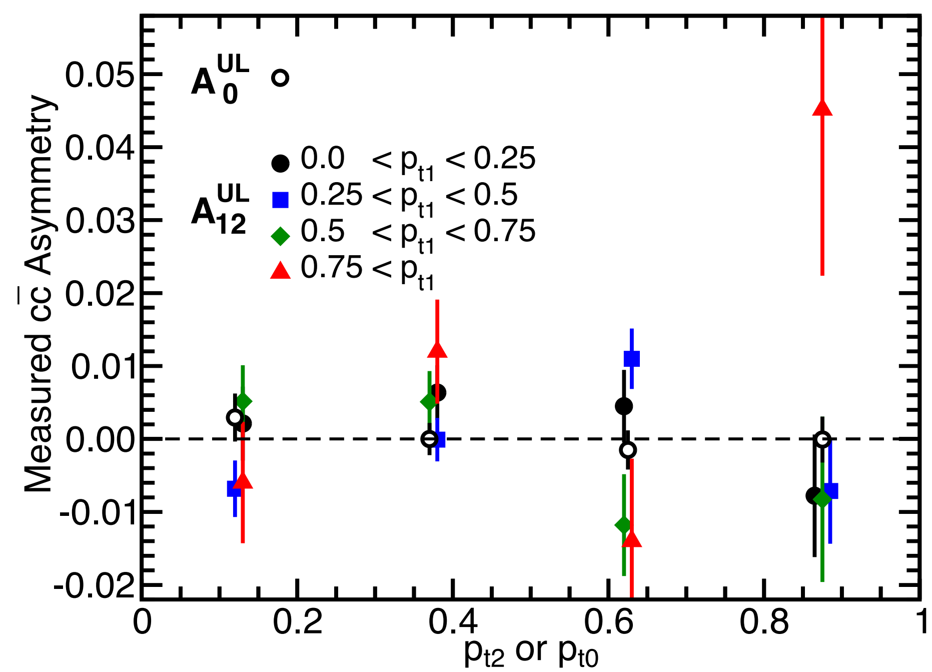
$$A^{meas} = F_{uds}A^{uds} + F_c A^c + F_B A^B + F_\tau A^\tau$$

  - → where F_i are the fractional contributions, $\Sigma_i F_i = 1$

- must understand these quantities
  - → use MC for F_i with data-MC diff in each bin as a syst
  - → A^B must be zero; checked in low-T data; set A^B=0±0
  - → A^τ small in sim; checked in data; set A^τ=0±0

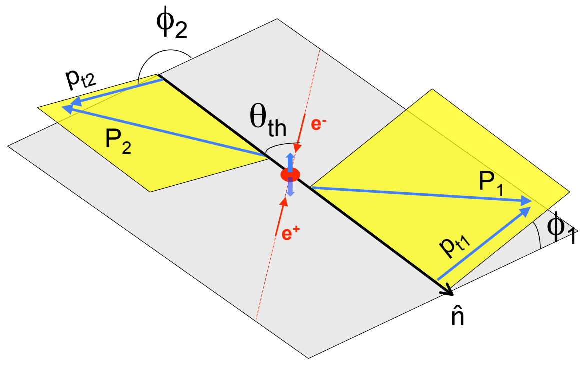
- $c\bar{c}$ events could have nonzero A_α due to prod., decay, ...
  → use control samples of events containing a D* meson
  → 4 complementary decay modes
  → mostly $c\bar{c}$ events, some $B\bar{B}$
- in each bin, solve
$$A^{meas} = F_{uds}A^{uds} + F_c A^c$$
$$A^{D^*} = f_{uds}A^{uds} + f_c A^c$$
  → again, f_i from MC; $f_{uds} = 1 - f_c - f_\tau - f_B$; data-MC differences taken as a systematic

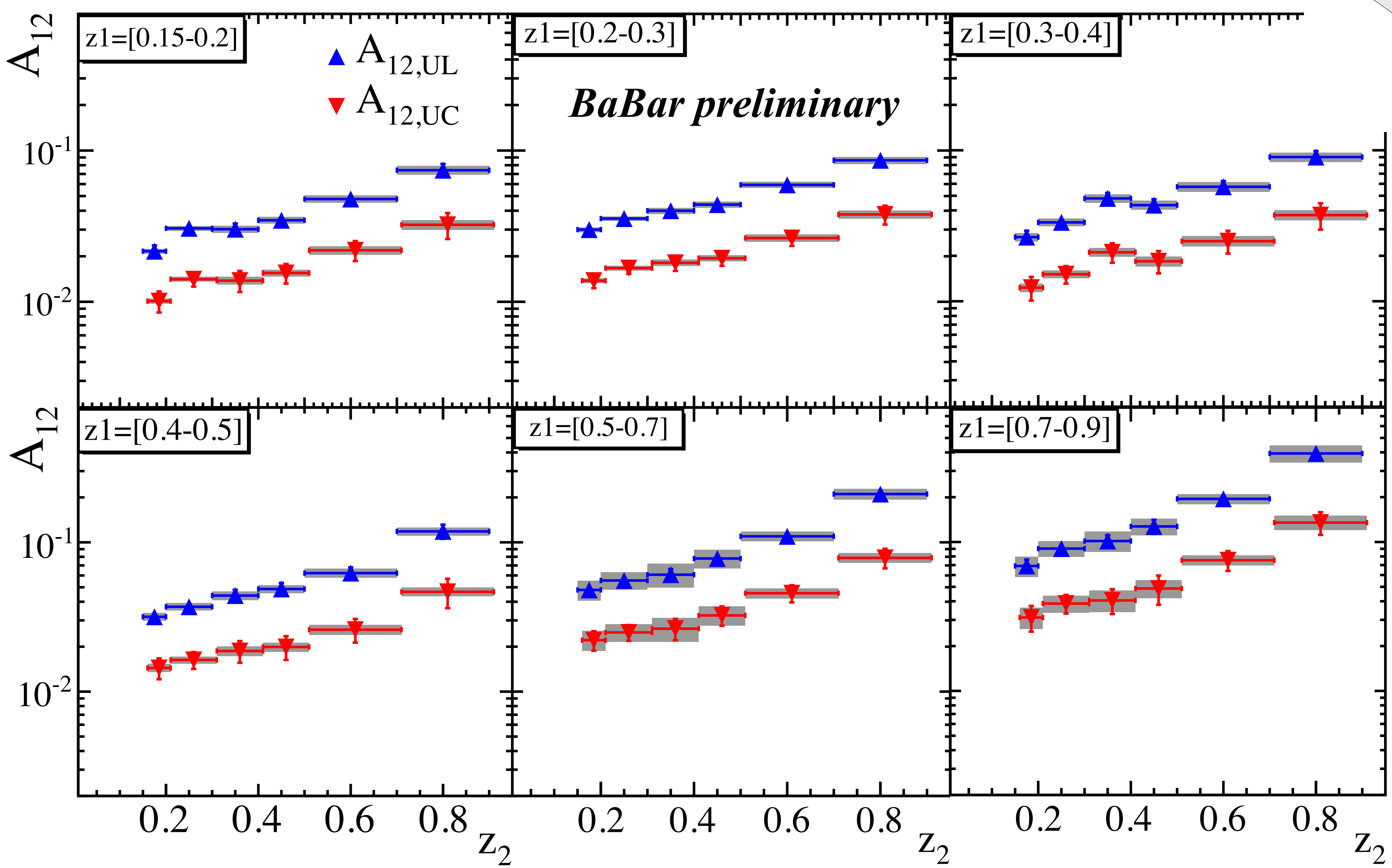




- the A^c are very small
  → perhaps slightly negative?

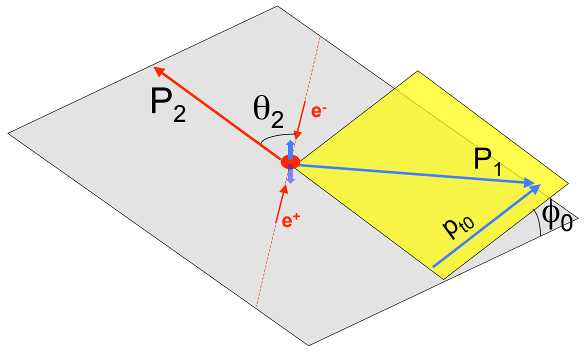
Results: RF12 frame, A12 vs. (z_1,z_2)

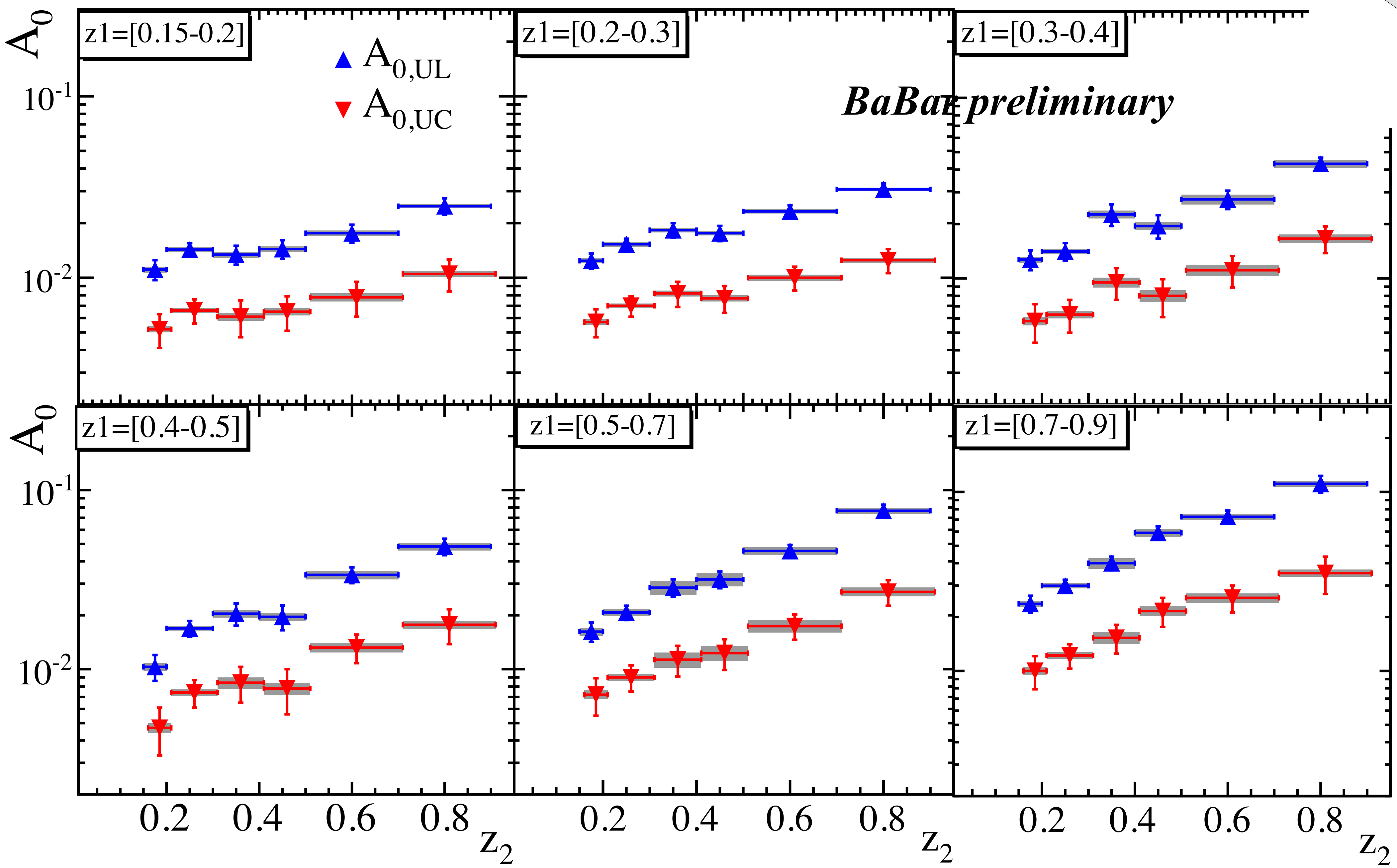




- very significant nonzero A^{UL} and A^{UC} in all bins
  → strong dependence on (z_1,z_2), 1-39%
  → $A^{UC} < A^{UL}$ as expected; complementary information
  → consistent with $z_1 \leftrightarrow z_2$ symmetry

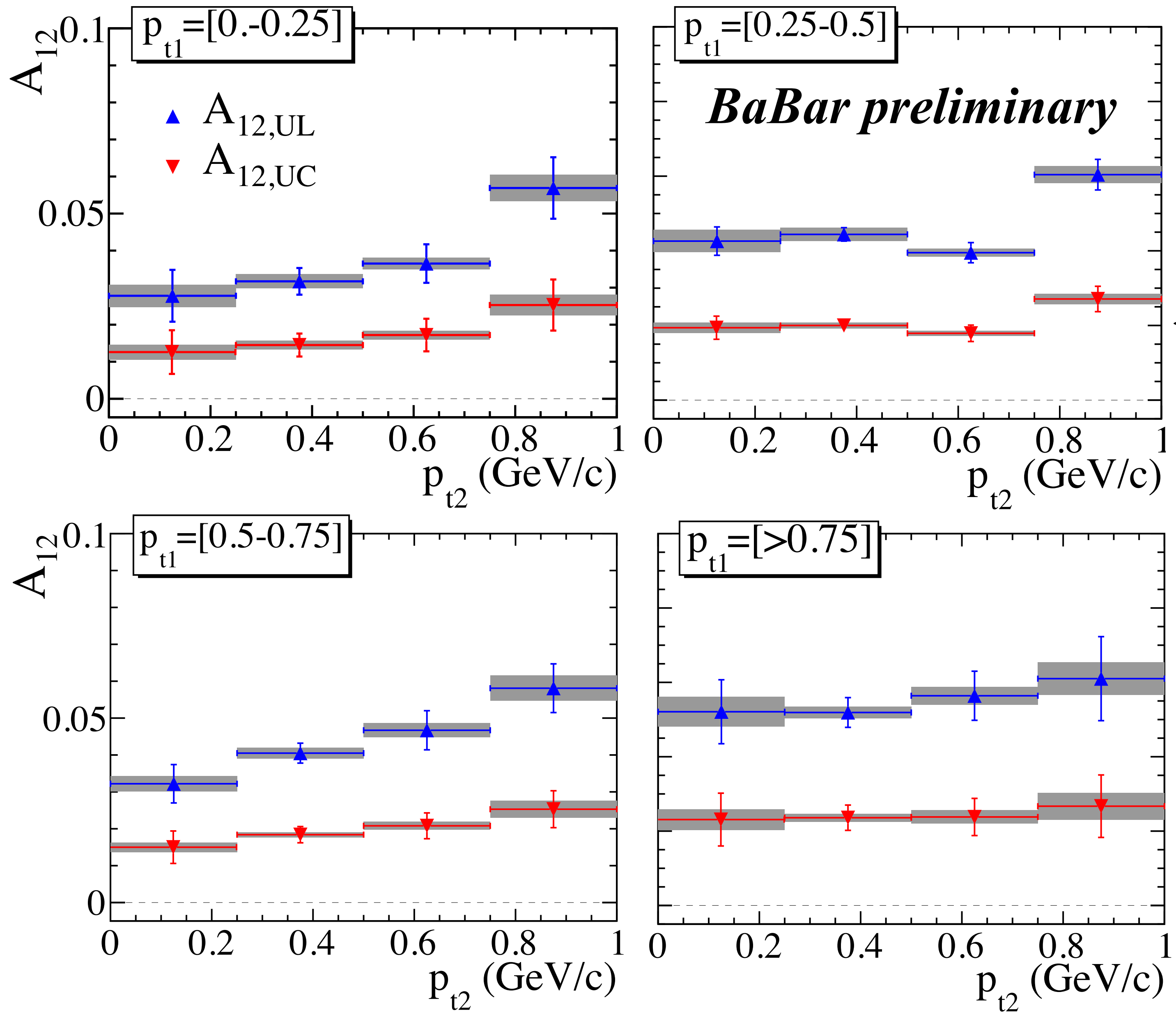
Results: RF0 frame, A_0 vs. (z_1,z_2)

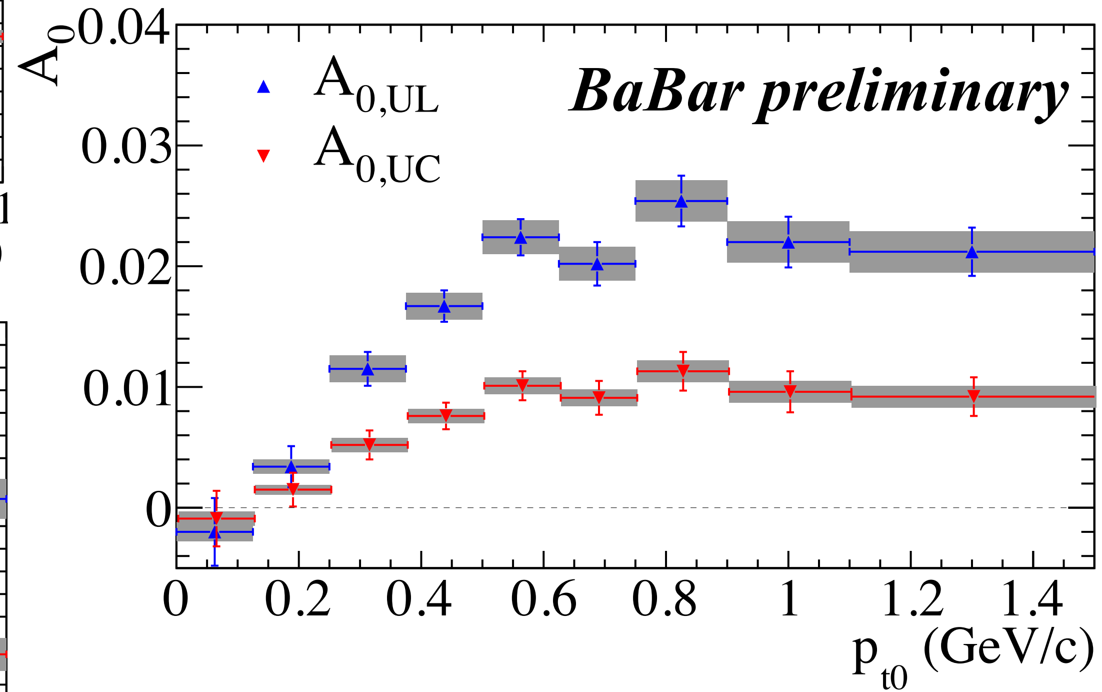




- very significant nonzero A^{UL} and A^{UC} in all bins
  - → strong dependence on (z_1,z_2), 0.5-11%
  - → smaller than A_{12}; lower correlation with q direction
  - → $A^{UC} < A^{UL}$, consistent with $z_1 \leftrightarrow z_2$ symmetry

Results: A_{12} vs. (p_{t1},p_{t2}) ; A_0 vs. p_{t0}

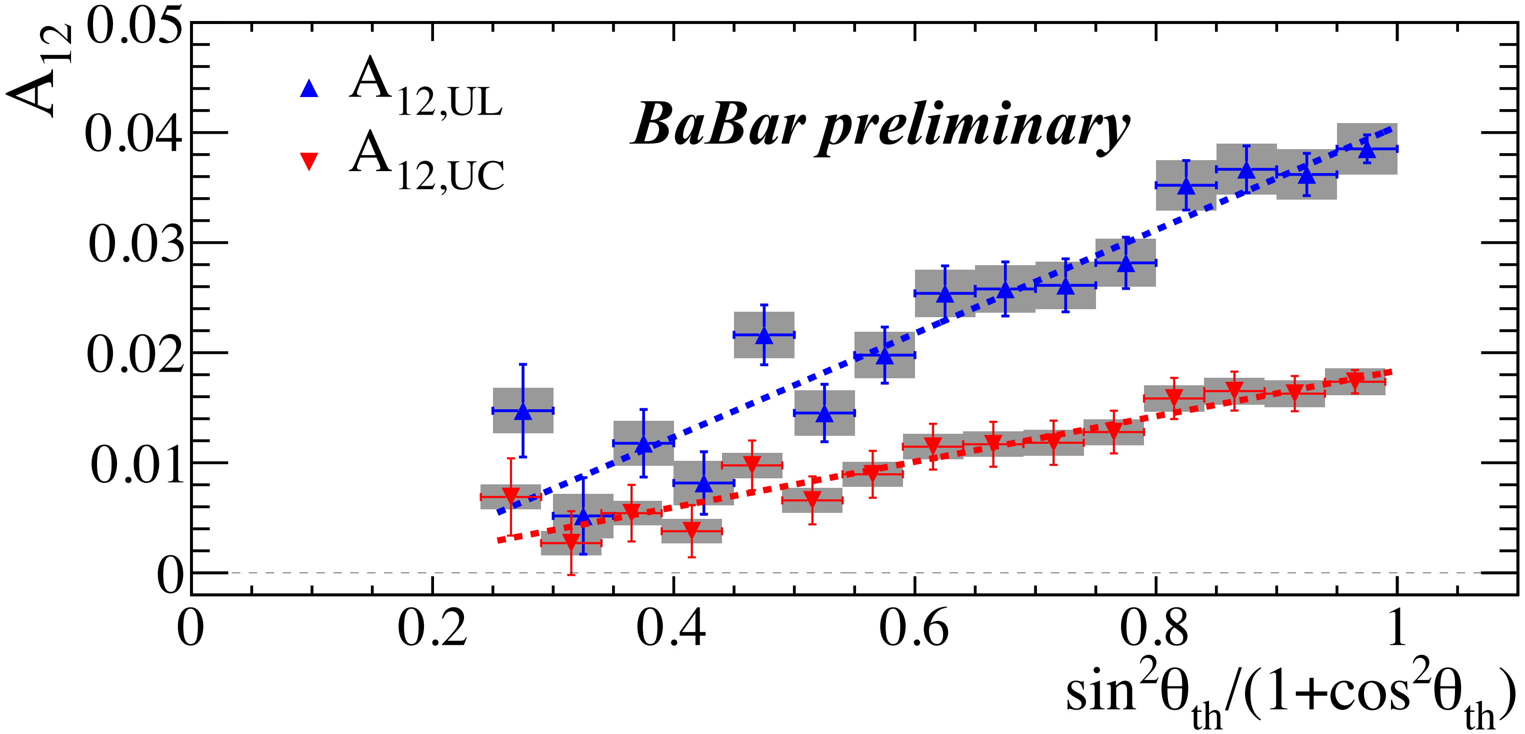




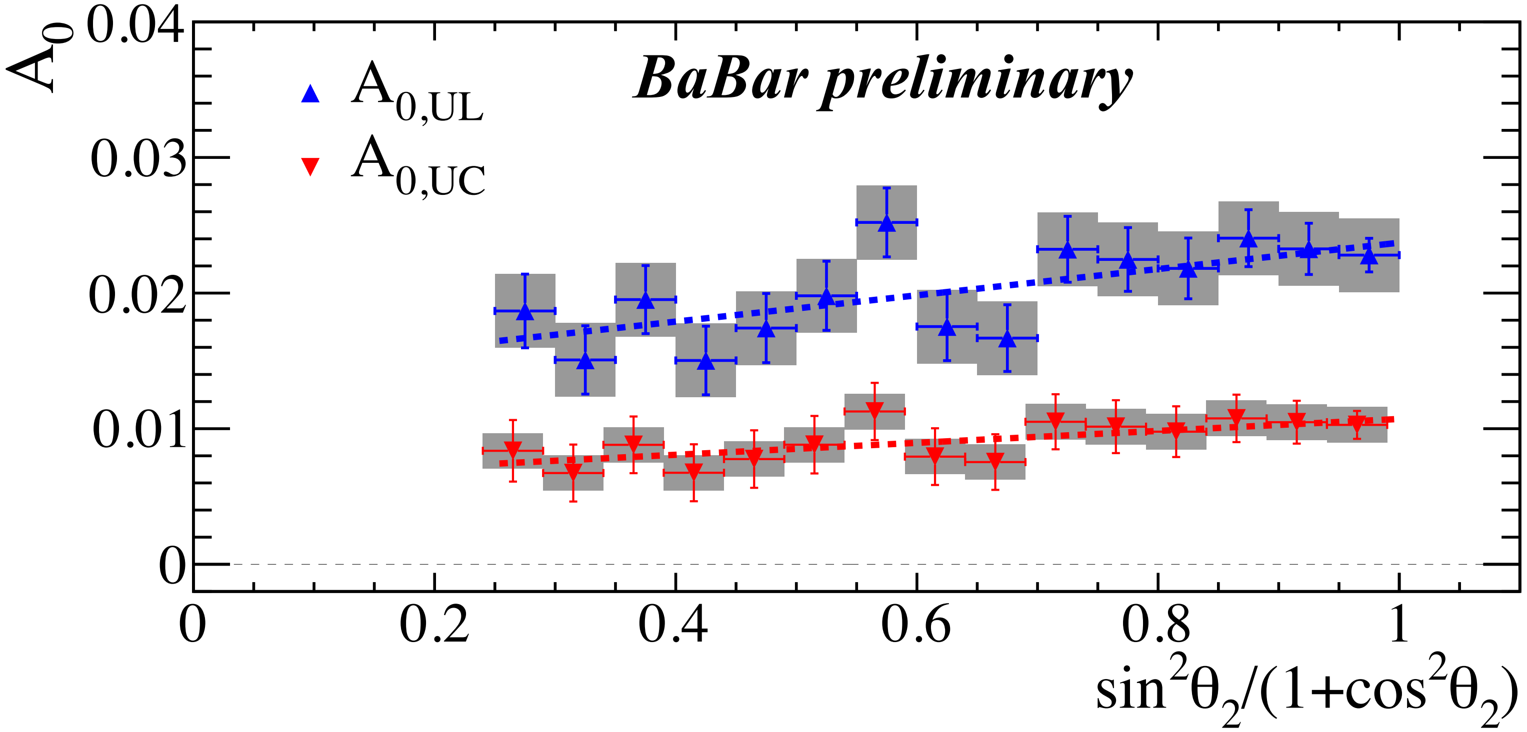
- nonzero A^{UL} and A^{UC} all but the lowest p_t bins
  - → only modest dependence on (p_{t1},p_{t2}), 1-2%/2.5-6.5%
  - → $A^{UC} < A^{UL}$, consistent with $p_{t1} \leftrightarrow p_{t2}$ symmetry
  - → $A_0 < A_{12}$, but interesting structure in p_t

Results: A_{12} vs. θ_{thrust}; A_0 vs. θ_2

- in RF12 frame, vs. θ_{thrust}; expect linearity in $\sin^2\theta / (1+\cos^2\theta)$
  - → both A^{UC} and A^{UL} consistent with linearity
  - → ...and with zero intercept



- in RF0 frame, vs. θ_2, unclear what to expect
  - → linear fits are ok
  - → intercept not consistent with 0
  - → probably not surprising; not a good measure of the q direction



Summary

- BaBar has measured Collins asymmetries for charged pion pairs in $e^+e^- \rightarrow u\bar{u}, d\bar{d}, s\bar{s} \rightarrow \pi^{\pm}\pi^{\pm}X$

	RF_{12}	RF_0
➞ in two distinct reference frames	RF_{12}	RF_0
➞ vs. π scaled energies	z_1, z_2	z_1, z_2
➞ vs. π transverse momenta	p_{t1}, p_{t2}	p_{t0}
➞ vs. polar angle	θ_{thrust}	θ_2

- A_{12}, A_0 increase with increasing z_1, z_2
  - ➞ consistent with expectations
  - ➞ consistent with Belle results
  - ➞ effect is stronger in leading particles
- A_{12} (A_0) increases with increasing p_{t1}, p_{t2} (p_{t0})
  - ➞ first measurement
  - ➞ consistent with, useful for refining expectations
- A_{12} (A_0) increases linearly with $\sin^2\theta/(1+\cos^2\theta)$
  - ➞ as (might be) expected

Backup Slides