Study of Collins Asymmetries at BaBar

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Transverse Polarization Phenomena In Hard Scattering

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Fragmentation Functions (FFs)

Fragmentation: hadron production from quark, antiquark or gluon.
FFs: probability that a parton fragments into an hadron carrying away a fraction of parton's momentum.

Unpolarized FF

- Most of data are obtained at LEP energies
- At lower CMS energies and higher x, very little data are avalaible
- BaBar and Belle → results on FF for heavy quarks
- BaBar → light-quark analysis ongoing
- Many attempts to extract FF from e^+e^- data: KKP, AKK, Kretzer…

  → Large difference between different fits

(Nucl.Phys. B725,181(2006), Nucl.Phys. B803,42(2008), Phys.Rev. D75,094009 (2007) , Phys.Rev. D62,054001(2000), Nucl.Phys. B582,514(2000));

Spin-dependent FFs

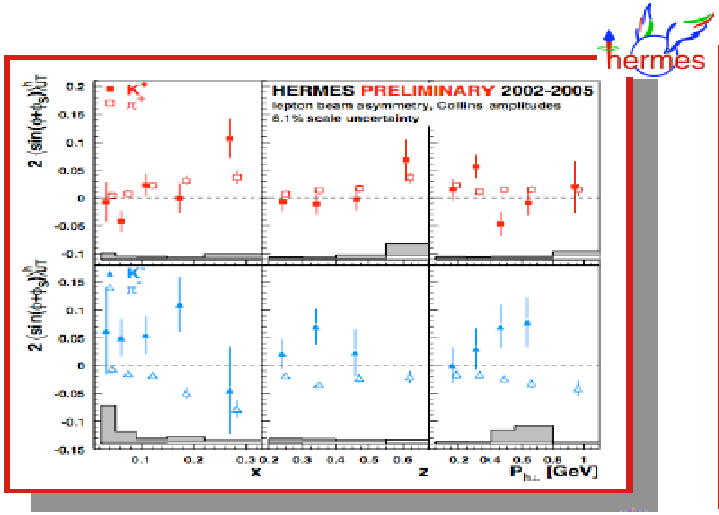
- Fundamental test for any approach to solve QCD at soft scales
- Test schemes of universality and factorization between e^+e^-, DIS, and p-p collision
- Test evolution as fundamental QCD prediction
- Connection between microscopic (quark spin) and macroscopic observables (azimuthal distribution of the hadrons produced)
- **Final spin analyzer for the study of the transversity parton distribution functions**

Collins FF

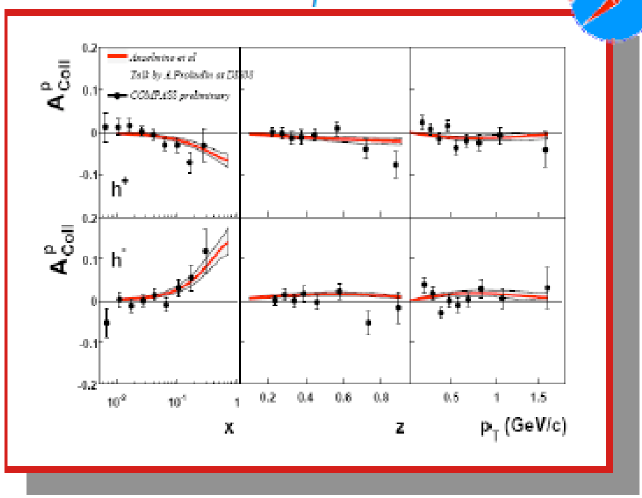
- Spin dependent FF
- Chiral-odd function
- The Collins FF (CFF) is related to the probability that a transversely polarized quark will fragment into a spinless hadron:

Unpolarized FF → D_1^q; **Collins FF** → $H_1^{\perp q}$

$$D_{hq\uparrow} = D_1^q(z, P_{h\perp}^2) + H_1^{\perp q}(z, P_{h\perp}^2)\frac{\hat{k} \times \vec{P}_{h\perp} \cdot \vec{S}_q}{zM_h}$$



COMPASS proton data

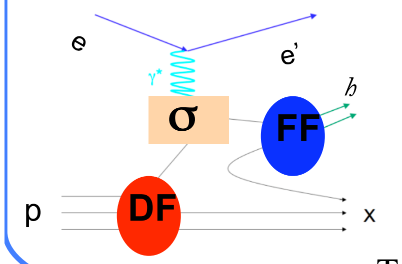


First experimental evidence of non zero Collins FF for pions came from SIDIS experiments: HERMES (PRL94,012002(2005)), COMPASS (PRL94,202002(2005))

- **B-Factories e^+e^- →** **direct evidence of non-zero Collins FF**: DELPHI (Nucl.Phys.B79,554-556 (1999)), BELLE (PRL96,232002(2006), PRD78,032011(2008))

Global analysis: first extraction of Transversity

SIDIS: Semi Inclusive Deep Inelastic Scattering



Factorization theorem:

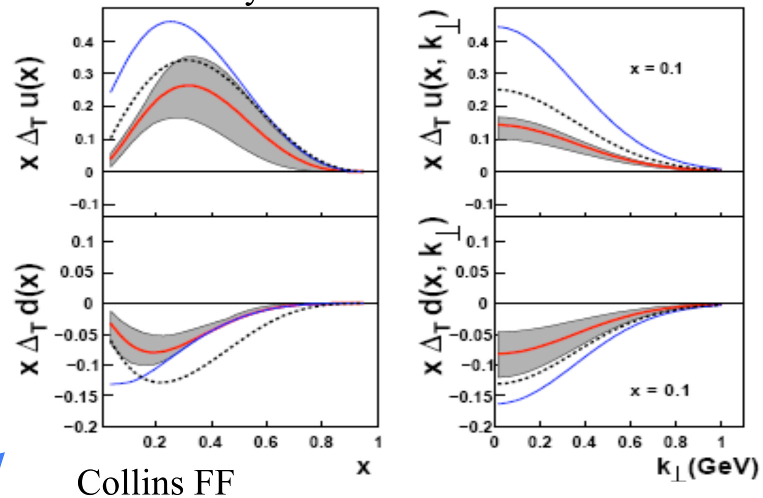
$$\sigma^{ep\to ehX} = \sum_q DF \times \sigma(eq \to eq) \times FF$$

$A_T \propto h_1(x) \times CFF(z)$

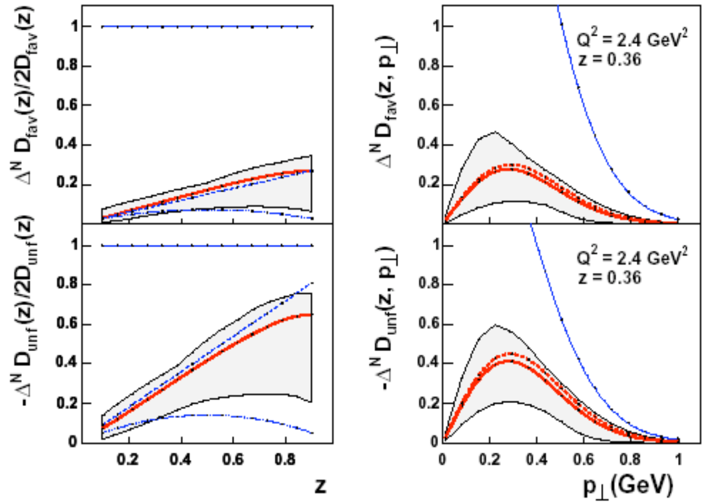
Transversity function

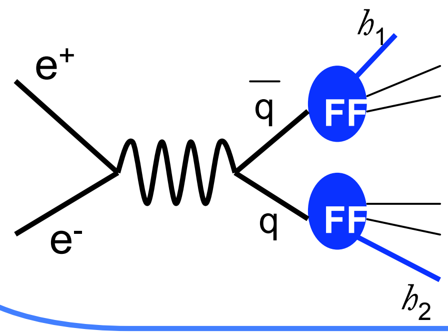
Global analysis (HERMES & COMPASS & BELLE): simultaneous determination of Transversity(h_1) and Collins functions (CFF).

Transversity PDF



Collins FF





$e^+e^- \to h_1 h_2 X$

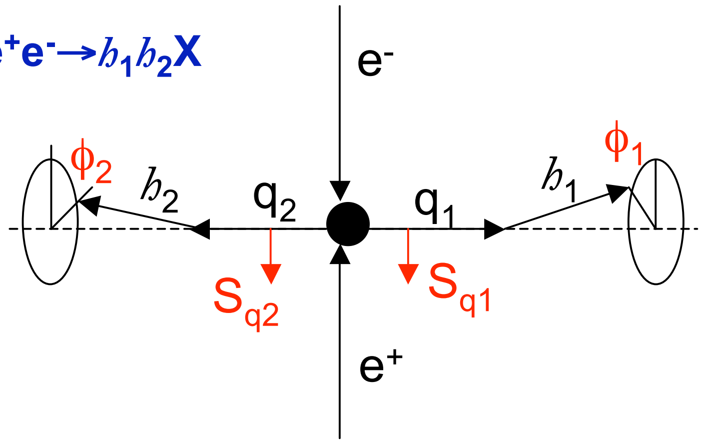
Collins and IFF asymmetries in e^+e^- annihilation are:

$\propto CFF(z_1) \times CFF(z_2)$

Anselmino et al., PR**D75**,05032(2007)
Nucl.Phys. Proc. Suppl. **191**,(2009)

Collins effect in di-hadron correlation

$e^+e^- \rightarrow h_1 h_2 X$



- quark spin direction unknown: measurements of Collins FFs in one jet is not possible;
- **Correlation between two hemispheres: cosine modulation of the observed di-hadron yield.**

Detect pion pairs with same or opposite charge ⇨ sensitivity to favored and disfavored FFs

- favored fragmentation processes describe the fragmentation of a quark of flavor q into an hadron with a valence quark of the same flavor: i.e.: ($u \rightarrow \pi^+$) and ($d \rightarrow \pi^-$)
- disfavored for ($d \rightarrow \pi^+$) and ($u \rightarrow \pi^-$).

UnLike sign pion pairs:	Like sign pion pairs:
$\pi^{\mp}\pi^{\pm}$ (UL): (fav x fav)+(dis x dis)	$\pi^{\pm}\pi^{\pm}$ (L): (fav x dis)+(dis x fav)

Different combination of fav and dis FFs in the cross section:

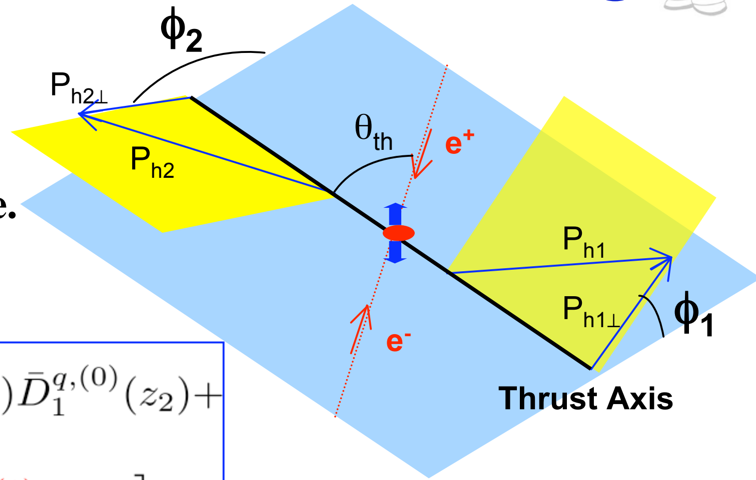
$$N^{UL} = \frac{d\sigma(e^+e^- \rightarrow \pi^{\pm}\pi^{\mp}X)}{d\Omega dz_1 dz_2} \approx (1+cos^2\theta)\sum_q e_q^2 (D_1^{fav}\bar{D}_2^{fav} + D_1^{dis}\bar{D}_2^{dis})$$

$$N^{L} = \frac{d\sigma(e^+e^- \rightarrow \pi^{\pm}\pi^{\pm}X)}{d\Omega dz_1 dz_2} \approx (1+cos^2\theta)\sum_q e_q^2 (D_1^{fav}\bar{D}_2^{dis} + D_1^{dis}\bar{D}_2^{fav})$$

Reference Frames (RF)

$\phi_1+\phi_2$ or Thrust RF

θ: angle between the e^+e^- axis and the thrust axis;
$\phi_{1,2}$: azimuthal angles between $P_{h1(h2)}$ and the scattering plane.



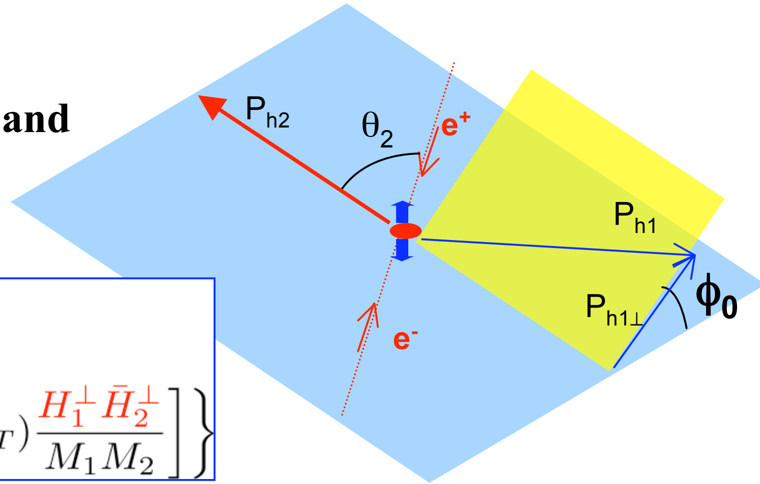
All quantities in e+e- center of mass

$$\frac{d\sigma(e^+e^-\to h_1h_2X)}{d\Omega dz_1dz_2d\phi_1d\phi_2} = \sum_{q,\bar{q}}\frac{3\alpha^2}{Q^2}\frac{e_q^2}{4}z_1^2z_2^2\Big[(1+cos^2\theta)D_1^{q,(0)}(z_1)\bar{D}_1^{q,(0)}(z_2)+ + sin^2(\theta)cos(\phi_1+\phi_2)H_1^{\perp,(1),q}(z_1)\bar{H}_1^{\perp,(1),q}(z_2)\Big]$$

Daniel Boer
Nucl. Phys. **B** 806,23-67(2009)
[arXiv:0804.2408v2]

$2\phi_0$ or P_{h2} RF

θ_2: angle between the e^+e^- axis and P_{h2};
ϕ_0: angle between the plane spanned by P_{h2} and the e^+e^- axis, and the direction of P_{h1} perpendicular to P_{h2}.



All quantities in e+e- center of mass

$$\frac{d\sigma(e^+e^-\to h_1h_2X)}{d\Omega dz_1dz_2d^2\vec{q}_T} = \frac{3\alpha^2}{Q^2}z_1^2z_2^2\Big\{A(y)\mathcal{F}[D_1\bar{D}_2]+ + B(y)cos(2\phi_0)\mathcal{F}\Big[(2\hat{h}\cdot\vec{k}_T\hat{h}\cdot\vec{p}_T-\vec{k}_T\cdot\vec{p}_T)\frac{H_1^{\perp}\bar{H}_2^{\perp}}{M_1M_2}\Big]\Big\}$$

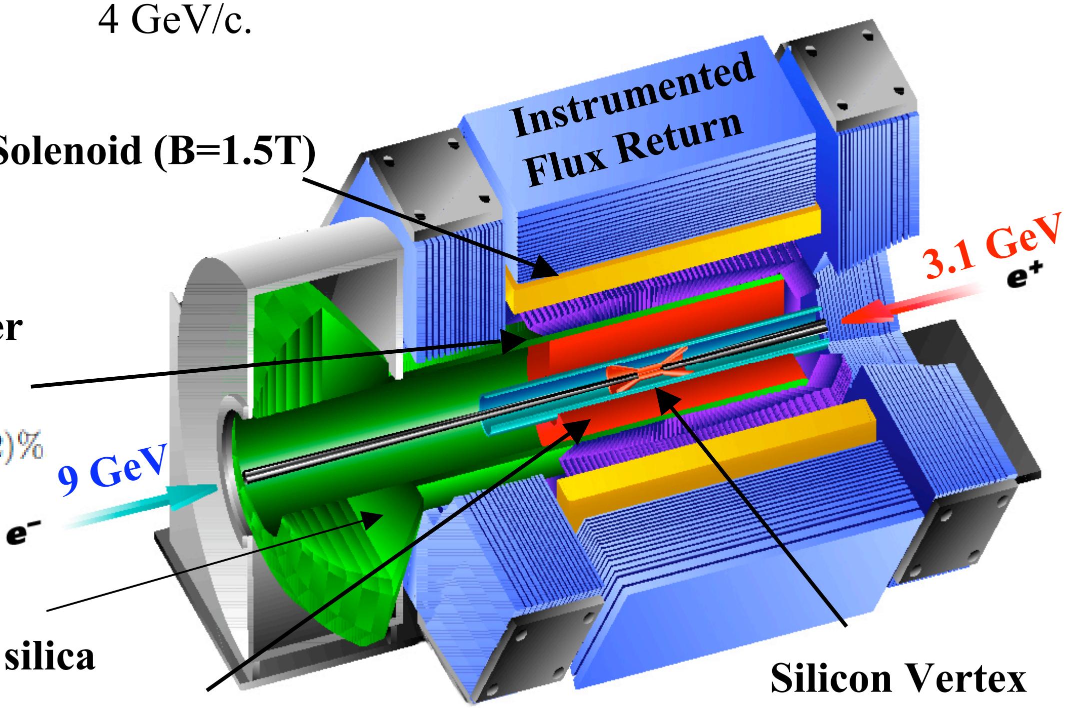
PEP-II and BaBar Detector @ SLAC

- Asymmetric-energy collider
- High Energy Ring (**HER**): 9.0 GeV e^-
- Low Energy Ring (**LER**): 3.1 GeV e^+
- $\beta\gamma \approx 0.56$

- SVT: 5 Layers → Precise measurement of the decay vertex;
  σ_z=65µm, σ_d=55µm;
- DCH resolution: $\boldsymbol{\sigma_{p_T}/p_T = (0.13\pm0.01)\% * p_T + (0.45\pm0.03)\%}$
- PID:
  - Low momenta: dE/dx in the DCH and SVT;
  - DIRC: above 700 MeV/c; >3σ K/π separation up to 4 GeV/c.

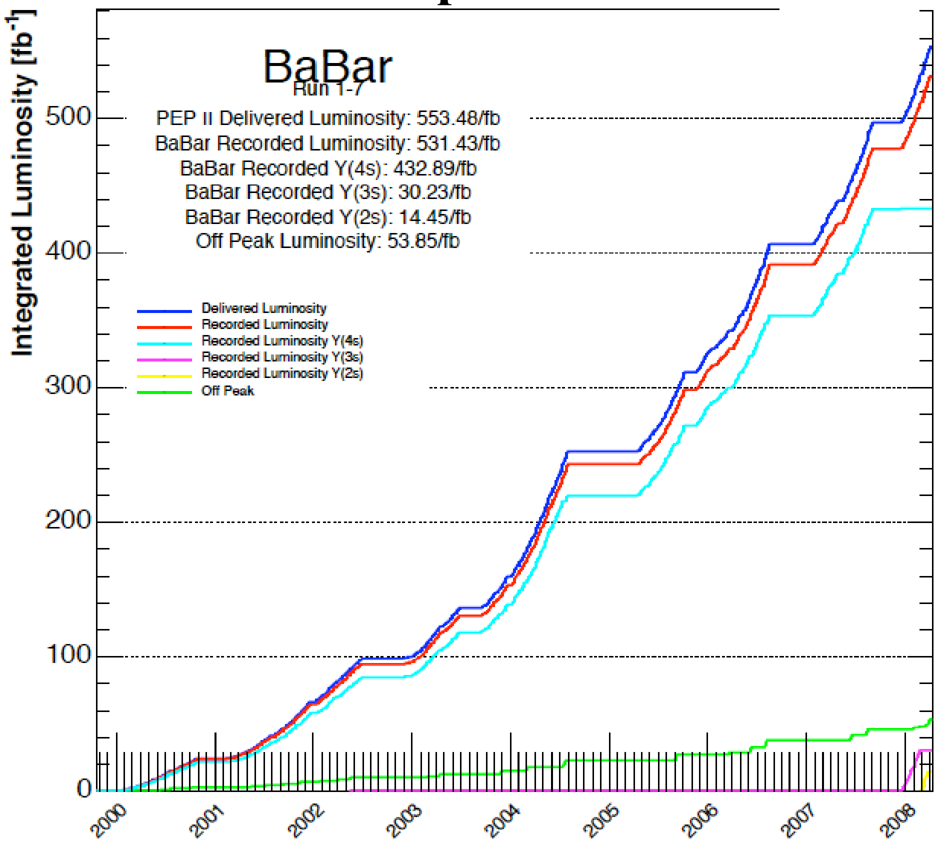
Electromagnetic Calorimeter
6580 CsI(Tl) crystals

$$\frac{\sigma_E}{E} = \frac{(2.32 \pm 0.30)\%}{\sqrt[4]{E(\mathrm{GeV})}} \oplus (1.85 \pm 0.12)\%$$



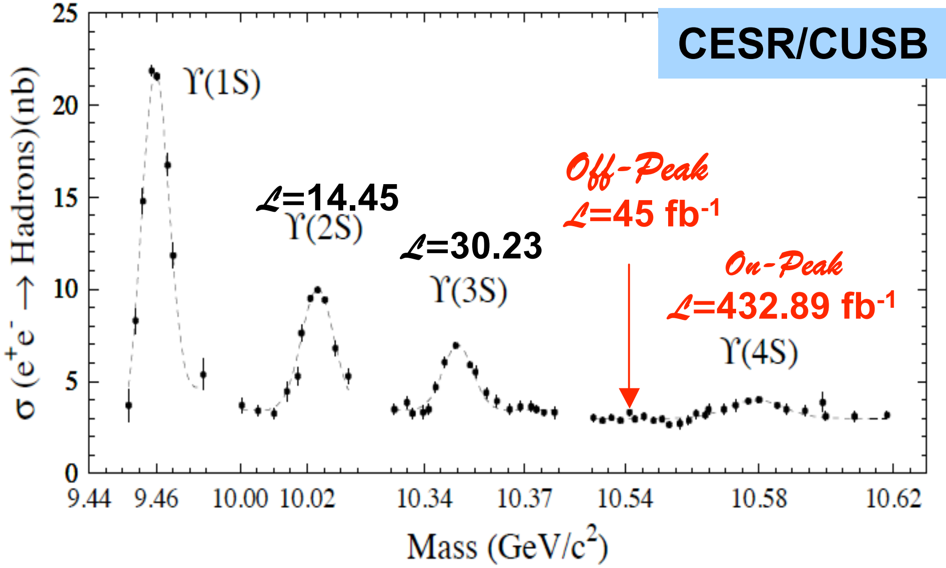
PEP-II Luminosity

October 1999 - April 2008



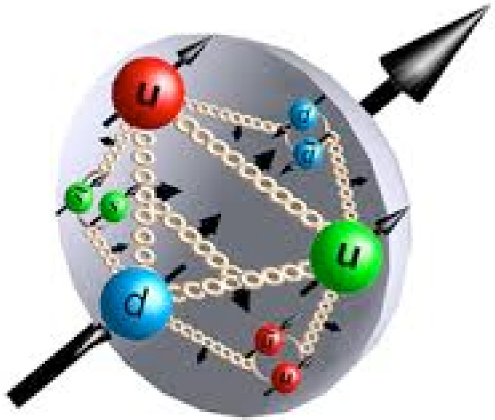
- $\sqrt{s}$=10.58 GeV: $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
- Off-resonance: $\sqrt{s}$=10.54 GeV

$e^+e^- \rightarrow$	Cross section (nb)
$u\bar{u}$	1.39
$d\bar{d}$	0.35
$s\bar{s}$	0.35
$c\bar{c}$	1.30
$b\bar{b}$	1.05
$\tau^+\tau^-$	0.94



Analysis

Measurement of Collins Asymmetries at BaBar



Collins FFs @ BaBar

Analysis Strategy

The analysis for the preliminary results is based on the full off-peak sample (45 fb^{-1}) .

$e^+e^- \rightarrow \pi\pi X$

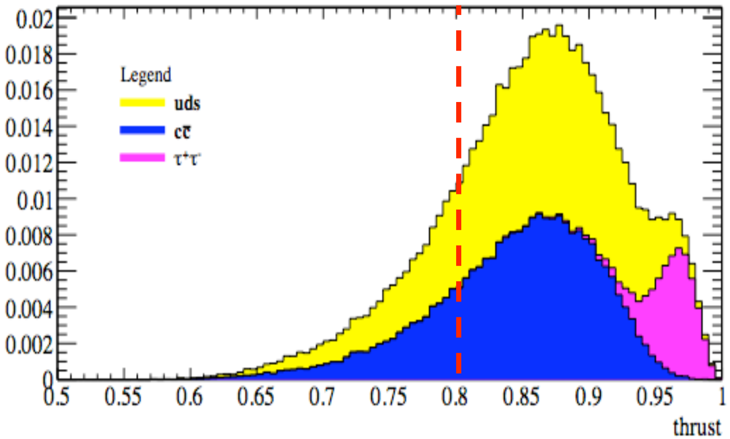
1. Event and tracks selection
2. Assumption: thrust axis in e^+e^- CM as the $q\bar{q}$ direction
3. Selection of pions in opposite jets according to the thrust axis
4. Measurement of the azimuthal angles (ϕ_i) in the two reference frames (see slide 7)
5. Fit to the azimuthal distributions
6. Estimate and subtraction of tau and charm contributions
7. Study of systematic effects

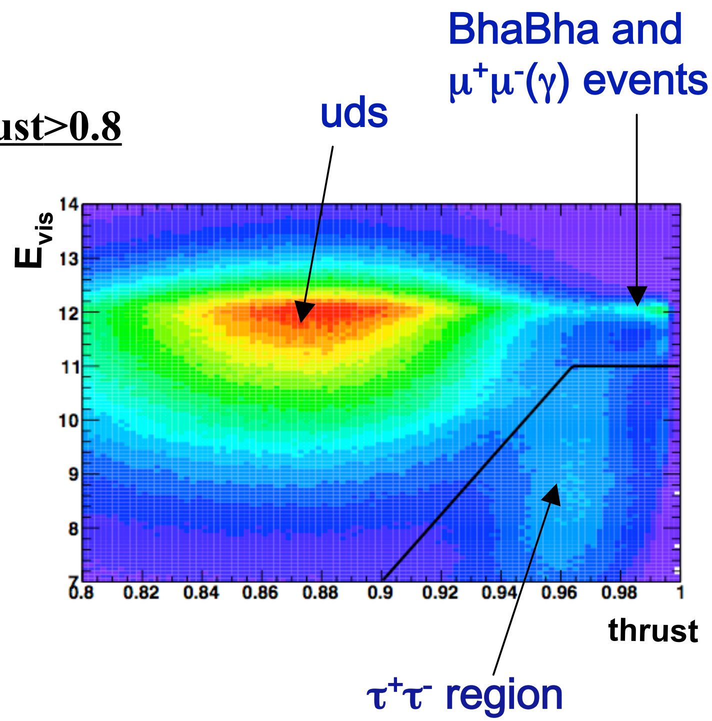
Events and Tracks Selection

1) Preselection:
- → Selection of multi-hadron events
- → Visible energy: $\mathbf{E_{vis} > 7\ GeV}$

2) Tracks in the DIRC acceptance for the PID

3) Selection of two-jet topology events requiring **thrust>0.8**





4) $\mu^{\pm}$ and $e^{\pm}$ veto, and Tight pion ID required

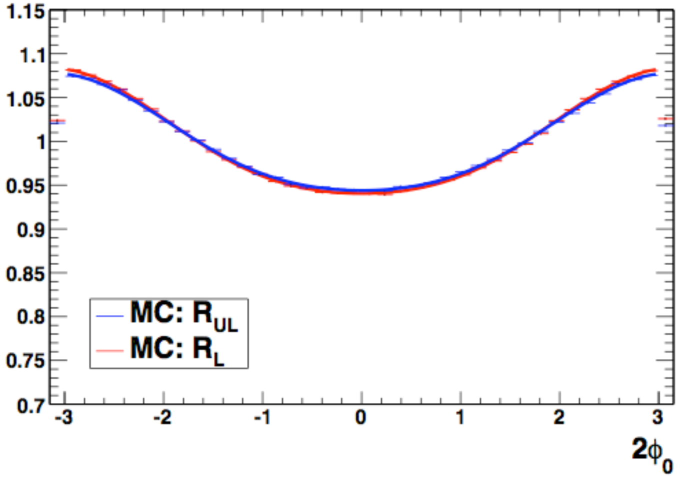
5) Events in the $\tau^{+}\tau^{-}$ region removed

6) Analysis restricted to pion fractional energies $\mathbf{z=2E_h/\sqrt{s} > 0.2}$
- for small z values the mass correction terms become important

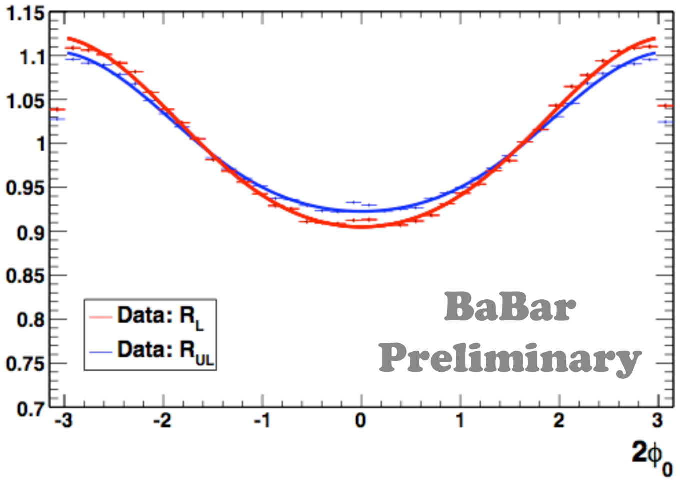
7) $\mathbf{Q_t<3.5\ GeV}$, where Q_t is the transverse momentum of the virtual photon in the pions CMS

Raw Asymmetries

MC



Data



Accessing the Collins Asymmetries: measurement of cosine modulation of hadron pairs (N(ϕ)) on top of a flat distribution due to unpolarized part of the fragmentation function (normalized raw distribution):

$$R_\alpha = \frac{N(\phi_\alpha)}{< N_\alpha >} = a + b \cdot cos(\phi_\alpha)$$

Information about the Collins asymmetry

In the MC sample, the polarized FF (Collins FF) are not implemented → flat distribution at generator level

Reconstructed distribution affected by large detector acceptances effects

Double Ratio

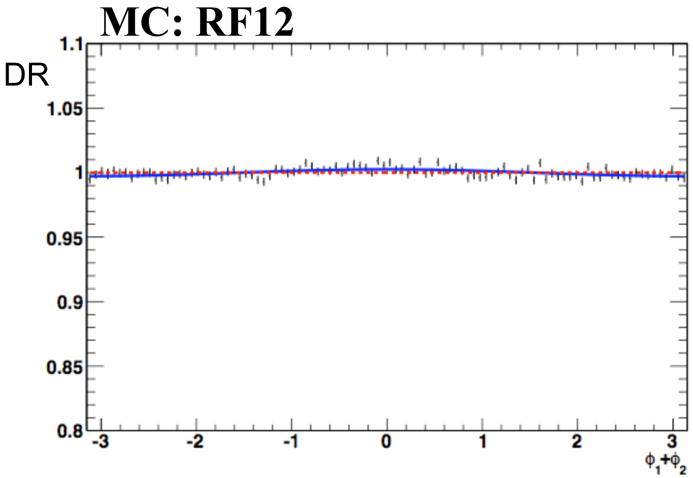
Double Ratio (DR) of Un-Like sign over Like sign pion pairs**:**

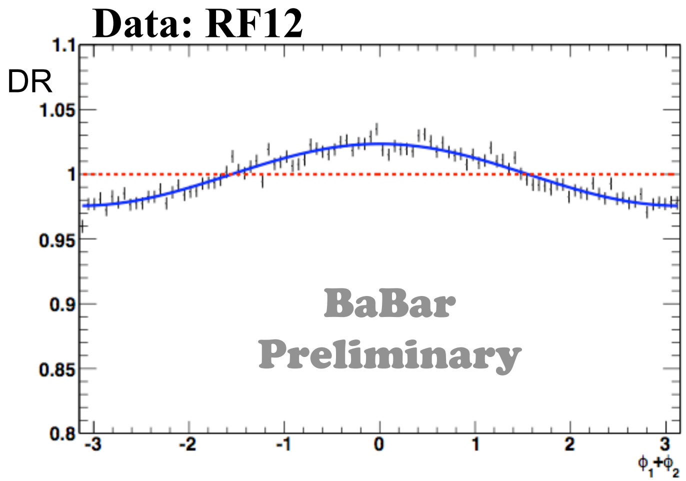
➲eliminate the acceptance effects and the first order radiative effects

- acceptances and radiative contributions do not depend on the charge combination of the pion pair;
- approximation holds for small asymmetries.

$$\frac{R_{UL}}{R_L} = \frac{N^{UL}(\phi)/ < N^{UL}(\phi) >}{N^{L}(\phi)/ < N^{L}(\phi) >} \rightarrow P_0 + P_1 \cdot \cos(\phi)$$

Contain only the Collins effects and higher order radiative effects (referring to P_1)





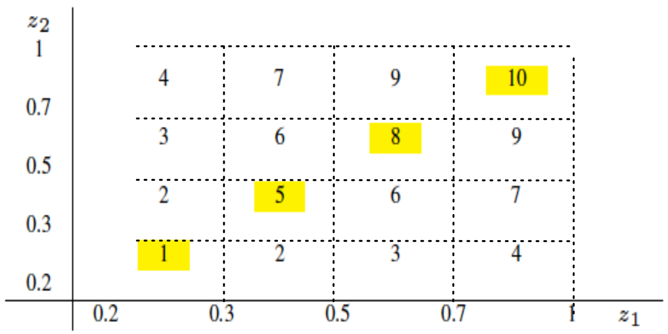
MC: we measure a small deviation from zero (~0.2%),and assign a systematic error for that

Asymmetry values before any correction

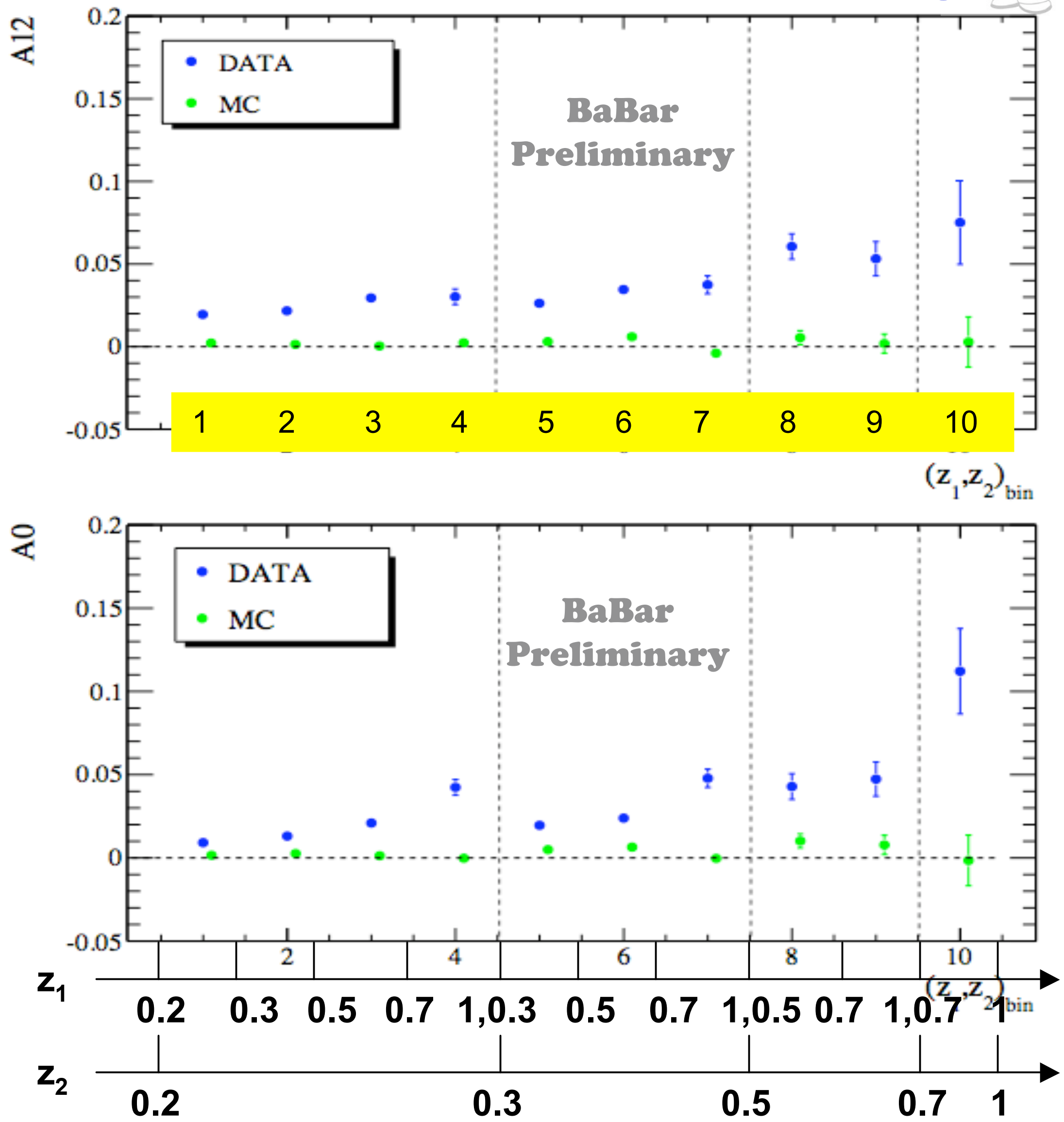
RF12: (2.39±0.07)%
RF0: (1.71±0.07)%

Measured Asymmetry *vs z*

The large amount of data (~10^8 light quark events), allows the extraction of the asymmetries in bins of fractional energies (z) of selected pions. We choose the following 10 symmetric bin subdivision:



This choice allows a direct comparison with Belle results obtained on off-peak data.



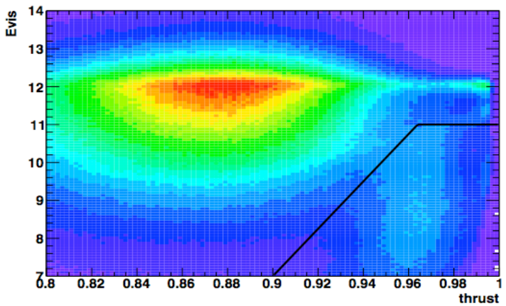
Asymmetry dilution due to Tau and Charm events

Measured asymmetries are diluted by the presence of background sources:

$$A_{measured} = (1 - \sum_i D_i) \cdot A_{uds} + \sum_i D_i \cdot A_{i,bkg}$$

D_i = fraction of pion pairs due to the i-th background process.

$e^+e^- \to \tau^+\tau^-$ CONTRIBUTION



- Using τ-MC, and the τ-enhanced data sample in the region removed, we find **A_τ=0**;
- The cut reduces tau contamination to **$D_\tau \approx 3\%$** (it ranges from about 1 to 18% in the individual z-bins);
- we correct the data as follows:

$$A_{uds} = \frac{A_{measured}}{1 - D_\tau}$$

$e^+e^- \to c\bar{c}$ CONTRIBUTION

In this case, both fragmentation processes and weak decays can introduce azimuthal asymmetries.
Use a D*-enhanced data sample for estimating the charm-induced asymmetry.

$$A_{measured} = (1 - D) \cdot A_{uds} + D \cdot A_{charm}$$

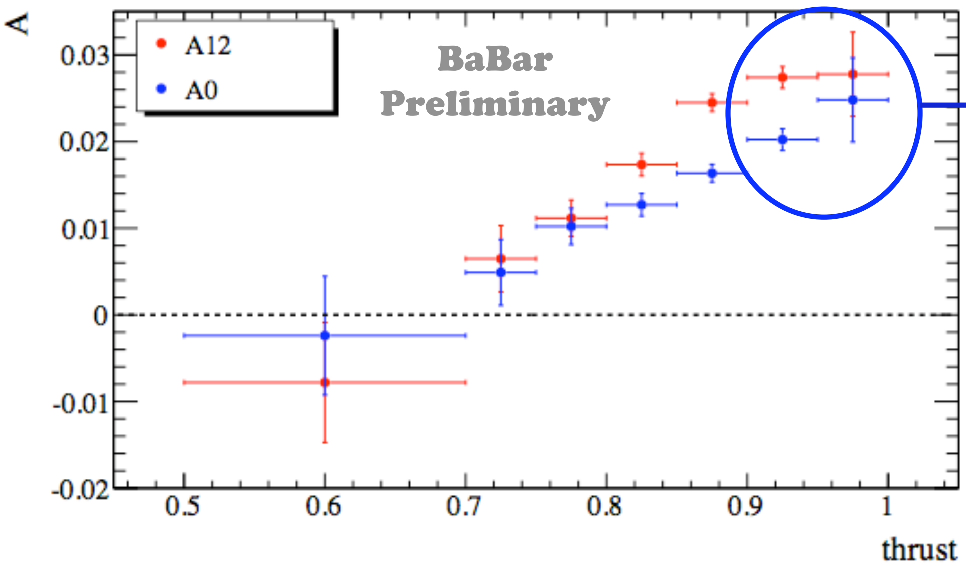
$$A_{D^*} = d \cdot A_{charm} + (1 - d) \cdot A_{uds}$$

D ~ 25%
d ~ charm fraction in the D*-enhanced data sample

Solving the system equations, we extract A_{uds} and A_{charm}

Measured asymmetry vs thrust

We studied also the behaviour of the asymmetry as a function of the thrust value.



Tau correction applied.

- Linear dependence of $A_{12,0}$ on thrust
- The asymmetry is consistent with zero at low thrust value

This behavior is essentially due to two effects:

1) **More spherical events, higher multiplicity**
2) **Gluon emission**

$q\bar{q}$ correlation lost.

Study of systematic effects

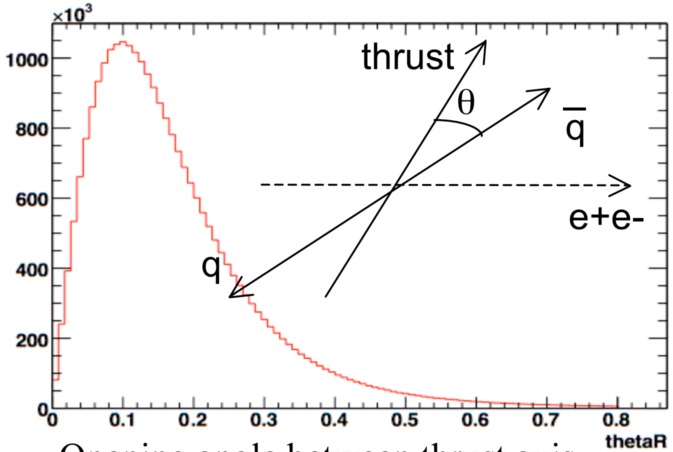
The measurements are affected by a number of systematic effects

- If needed, we correct the asymmetries and assign a systematic error
- In other cases, we only check that no unexpected features are present
- When possible we evaluate the correction independently for each z-bin

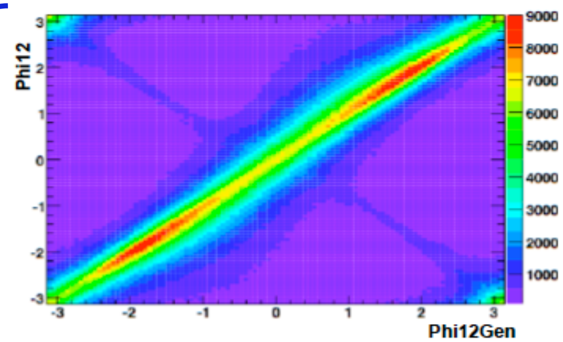
Dilution due to the thrust reconstruction

The experimental method assume the thrust axis as $\mathbf{q\bar{q}}$ direction:

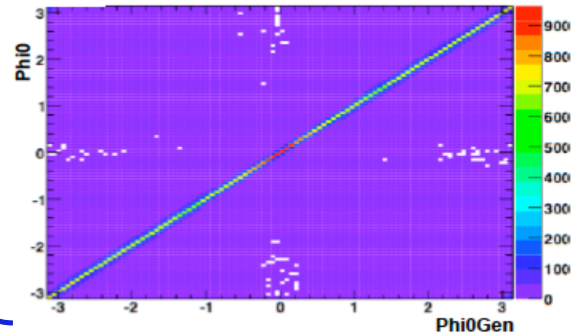
- **This is only a rough approximation**



Opening angle between thrust axis and $q\bar{q}$ axis:



- RF12: the azimuthal angles are calculated with respect to the thrust axis → large smearing

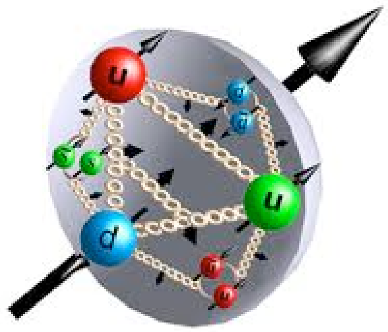


- RF0: the azimuthal angle is calculated with respect to the momentum of the second hadron → small smearing due to PID and tracking resolution

The MC generator does not include the Collins FF→ we introduce a modulation to the generated angular distribution by applying a different weight to every selected pion pair: $w^{UL,L} = 1 \pm a^{*}\cos(\phi_{gen12,0})$

	DR12		DR0	
	Average A_{12}	Correction factor	Average A_0	Correction factor
We found:	$(59.2 \pm 2.2)\%$	1.68 ± 0.06	$(99.8 \pm 3.2)\%$	1.002 ± 0.03

Preliminary Results

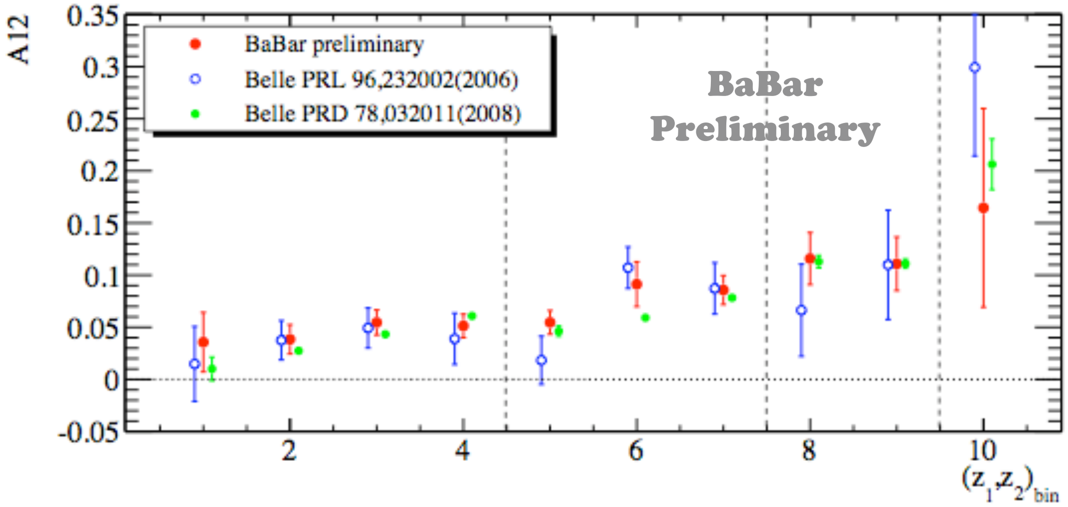


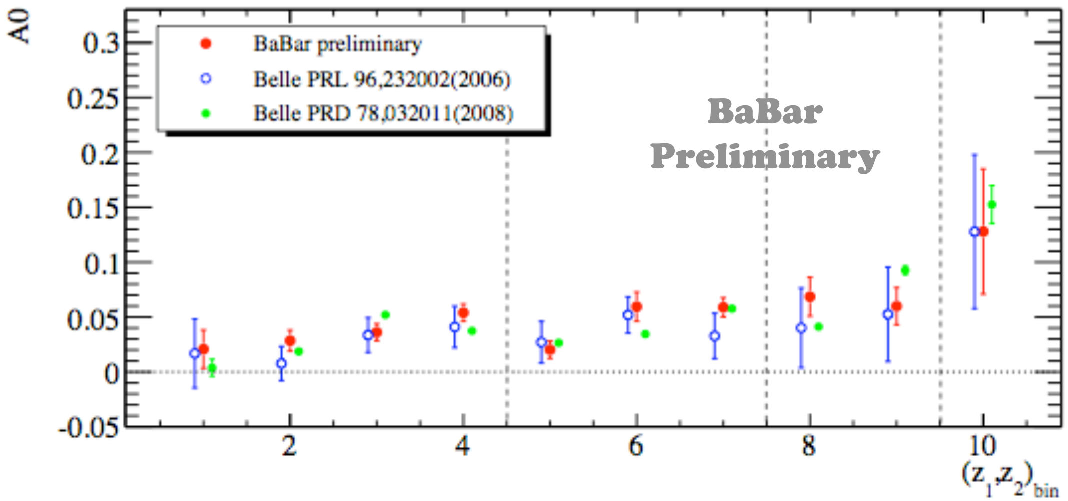
Results: Asymmetry *vs* (z_1,z_2) bins

BaBar preliminary: $\mathcal{L}\approx 45\ fb^{-1}$

Belle Off-peak: $\mathcal{L}\approx 29\ fb^{-1}$

Belle full statistics (supersede previous results) $\mathcal{L}\approx 547\ fb^{-1}$





- In the later Belle publication (Phys.Rev.D**78**,032011(2008)), they estimated a new correction factor of 1.66±0.04 due to the thrust approximation as the real $\mathbf{q\bar{q}}$ axis. Therefore, the **Belle off-peak results** for the RF12 frame, **are corrected by a factor 1.66/1.21**

- Results of the **full Belle statistic analysis** have been average in symmetric (z_1,z_2) bins

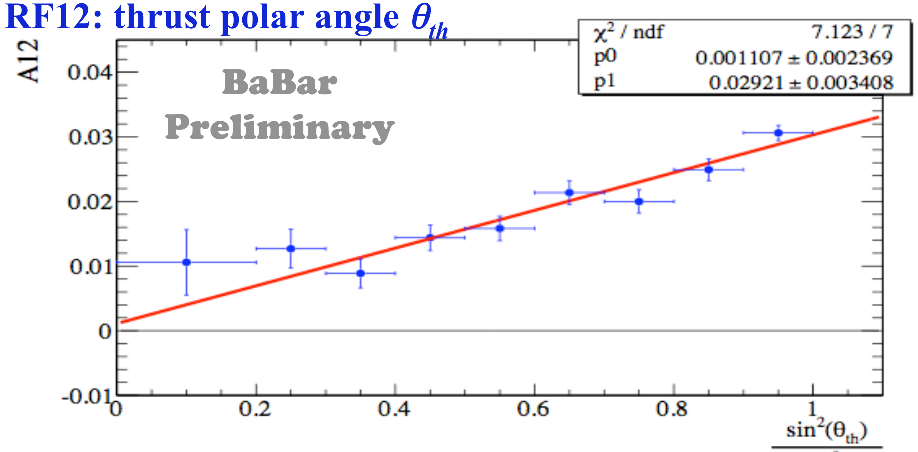
- Agreement with Belle data in both reference frame

Results: Asymmetry vs "theta$_{th}$" and "theta$_2$"

$$\frac{R_{12}^{UL}}{R_{12}^{L}} \propto 1 + \frac{sin^2\theta_{th}}{1+cos^2\theta_{th}} cos(\phi_1+\phi_2)\left\{G^{UL}-G^{L}\right\} \qquad \frac{R_{0}^{UL}}{R_{0}^{L}} \propto 1 + \frac{sin^2\theta_{2}}{1+cos^2\theta_{2}} cos(2\phi_0)\left\{G^{UL}-G^{L}\right\}$$

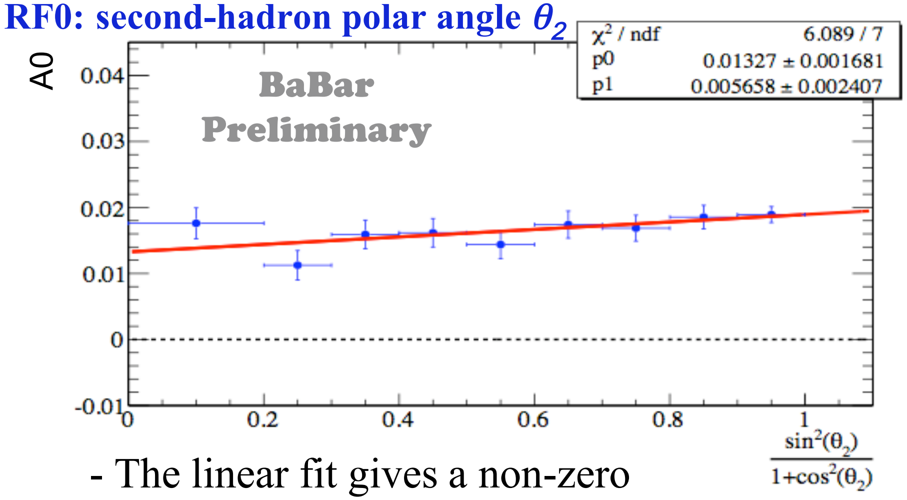
• Two different polar angles appear in the DR expressions for the two reference frames:

RF12: thrust polar angle θ_{th}



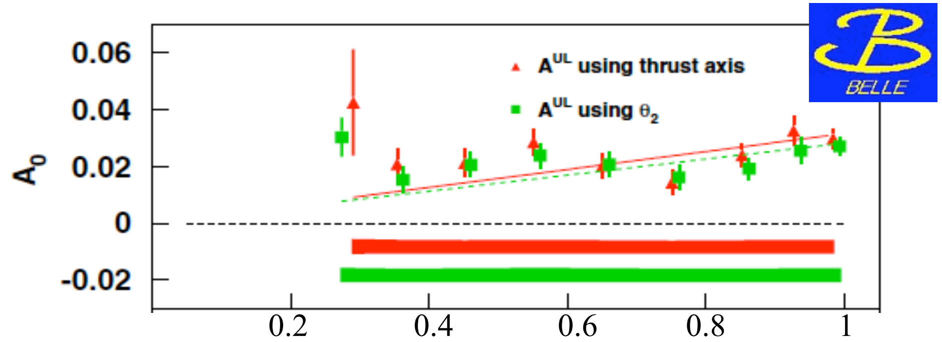
- Intersect consistent with zero, as expected

RF0: second-hadron polar angle θ_2



- The linear fit gives a non-zero constant parameter

- **Similar result found by Belle** →



Conclusions and Plans

-We present a preliminary measurement of the Collins Asymmetry in the sample of 45 fb^{-1} of data collected at 10.54 GeV by the BaBar Detector

- Measurement performed in two different reference frames

- Clear evidence of non-zero asymmetries in light-quark fragmentation
- Measured asymmetries increase with fractional energies of the pions, in agreement with expectations

- A roughly linear dependence of the asymmetries on thrust value is seen

- The expected behaviour of the asymmetries as a function of $\sin^2\theta/(1+\cos^2\theta)$ seems not to hold for A_0, when the polar angle of the second hadron is considered

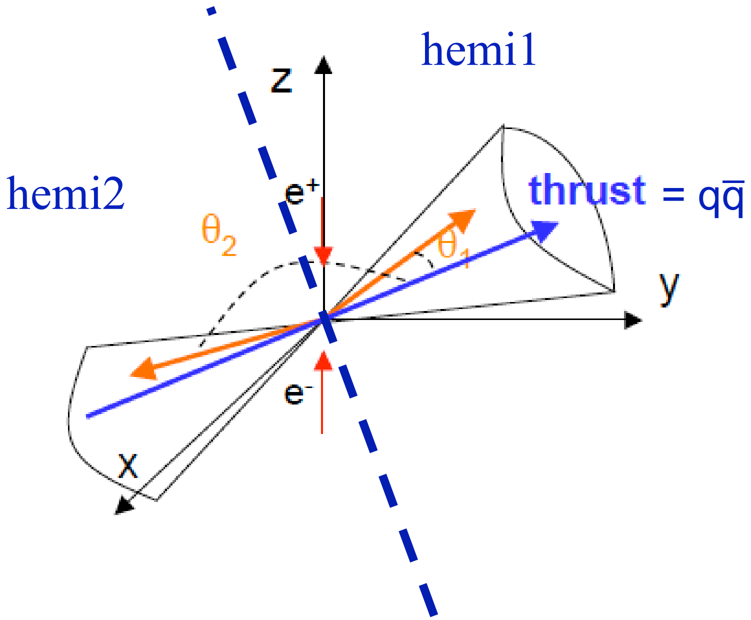
- There is an overall good agreement with Belle data

-These preliminary results are the starting point for a more complete study on the full BaBar data sample

Thanks for your attention

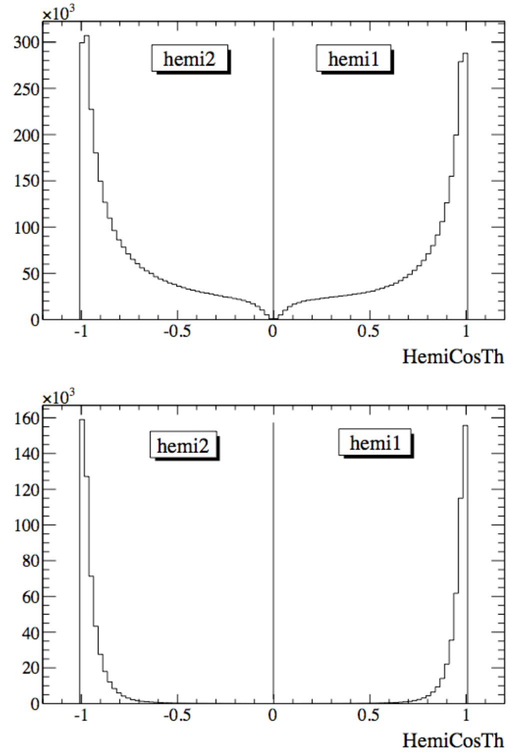
Backup slides

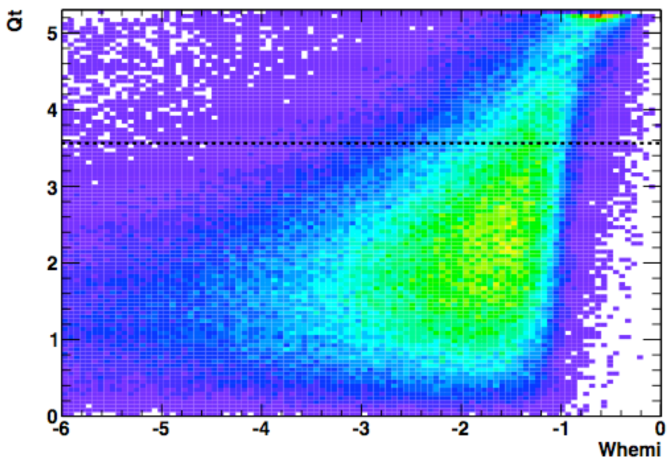
EVENTS AND TRACKS SELECTION



Before cuts

After cuts





$W_{hemi}=(P_1{*}\hat{n})(P_2{*}\hat{n}) < 0$

Whemi near to zero: higher probalility that one of the two tracks has been assigned to the wrong hemisphere® we can suppress this effect selecting pairs with Qt<3.5 GeV, where Qt is the transverse momentum of the virtual photon in the pions CMS

Study of systematic effects

The measurements are affected by a number of systematics effects
- If needed, we correct the asymmetries and assign a systematic error
- In other cases, we only check that no unexpected features are present
- When possible we evaluate the correction indipendently for each z-bin

- Dilution because of thrust reconstruction
- Test of the DR methods on Montecarlo
- Particle identification
- Fit bin size
- Higher harmonic contributions
- $\pi^+\pi^+/\ \pi^-\pi^-$ Double Ratio test
- Single Spin Asymmetries (SSA)
- Subtraction and Double Ratio (DR) methods
- Beam polarization studies
- Toy MC studies

Double Ratio

Double Ratio (DR) of Un-Like sign over Like sign pion pairs:

➲**eliminate the acceptance effects and the first order radiative effects**

- acceptances and radiative contributions do not depend on the charge combination of the pion pair
- approximation hold for small asymmetries

$$\frac{R_{12}^{UL}}{R_{12}^{L}} = \frac{1+\frac{\sin^2\theta}{1+\cos^2\theta}\cos(\phi_1+\phi_2)\,G^{UL}}{1+\frac{\sin^2\theta}{1+cos^2\theta}\cos(\phi_1+\phi_2)\,G^{L}} \simeq 1+\frac{\sin^2\theta}{1+\cos^2\theta}\cos(\phi_1+\phi_2)\left\{G^{UL}-G^{L}\right\}$$

$$G^{UL} = \frac{\sum_q e_q^2 \mathcal{F}(H_1^{fav}H_2^{fav}+H_1^{dis}H_2^{dis})}{\sum_q e_q^2 (D_1^{fav}D_2^{fav}+D_1^{dis}D_2^{dis})} \qquad G^{L} = \frac{\sum_q e_q^2 \mathcal{F}(H_1^{fav}H_2^{dis}+H_1^{dis}H_2^{fav})}{\sum_q e_q^2 (D_1^{fav}D_2^{dis}+D_1^{dis}D_2^{fav})}$$

$$\frac{R_{UL}}{R_L} = \frac{N^{UL}(\phi)/<N^{UL}(\phi)>}{N^{L}(\phi)/<N^{L}(\phi)>} \rightarrow P_0 + P_1\cos(\phi)$$

Contain only the Collins effects and higher order radiative effects

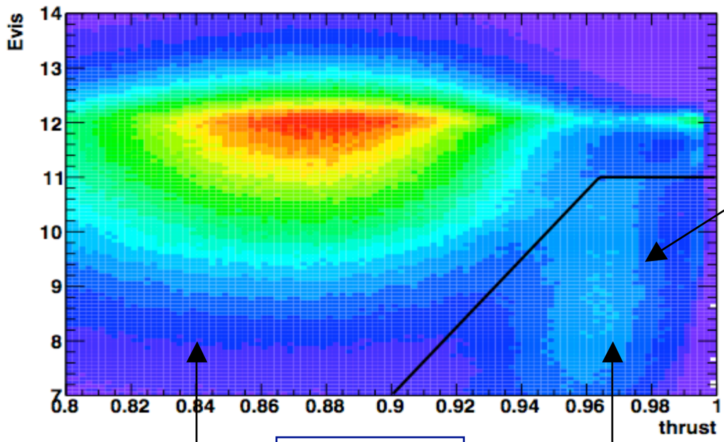
Asymmetry dilution due to Tau and Charm events (I)

Measured asymmetries are diluted by the presence of background sources:

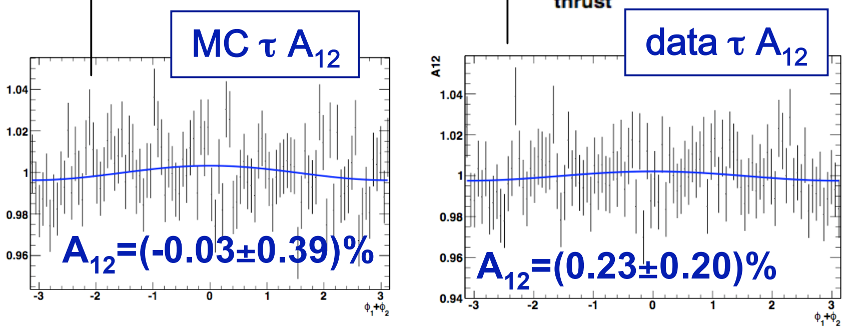
$$A_{measured} = (1 - \sum_i D_i) \cdot A_{uds} + \sum_i D_i \cdot A_{i,bkg}$$

D_i = fraction of pion pairs due to the i-th background process.

$e^+e^- \to \tau^+\tau^-$ CONTRIBUTION



- Using τ-MC, and the τ -enhanced data sample in the cutted region, we find $A_\tau=0$
- The cut reduce tau contamination to $D_\tau \approx 3\%$ (it ranges from about 1 to 18% in the individual z-bins)



- We correct the data as follow:

$$A_{uds} = \frac{A_{measured}}{1 - D_\tau}$$

75% of ττ events

Asymmetry dilution due to Tau and Charm events (II)

$e^+e^- \to c\bar{c}$ CONTRIBUTION

In this case, both fragmentation processes and weak decays can introduce azimuthal asymmetries.
Use a D*-enhanced data sample for estimating the the charm-induced asymmetry. (D_{charm} ~25%)

- generic $c\bar{c}$ MC
- data sample

relative contribution **$D=N_{cc}/N_{all}$**

- D*-enhanced MC sample
- D*-enhanced data sample

relative contribution **$d=N_{ccD*}/N_{D*}$**

$$\begin{cases} A_{measured} = (1-D)\cdot A_{uds} + D\cdot A_{charm} \\ A_{D^*} = d\cdot A_{charm} + (1-d)\cdot A_{uds} \end{cases}$$

Solving the system equations, we extract A_{uds} and A_{charm}

Summary of main Systematic Errors

z-bins	RF12					RF0				
	Bins	PID	Weight	MC	total	Bins	PID	Weight	MC	total
1	0.0002	0.0015	0.0013	0.0022	0.30%	0.0004	0.0041	0.0007	0.0029	0.51%
2	0.0005	0.0007	0.0014	0.0020	0.26%	0.0007	0.0035	0.0009	0.0029	0.47%
3	0.0009	0.0013	0.0020	0.0041	0.48%	0.0019	0.0024	0.0012	0.0029	0.44%
4	0.0008	0.0014	0.0018	0.0023	0.34%	0.0009	0.0010	0.0017	0.0029	0.36%
5	0.0021	0.0021	0.0022	0.0030	0.48%	0.0000	0.0016	0.0006	0.0050	0.53%
6	0.0011	0.0029	0.0028	0.0060	0.73%	0.0015	0.0024	0.0014	0.0050	0.59%
7	0.0027	0.0011	0.0031	0.0020	0.47%	0.0005	0.0005	0.0019	0.0029	0.35%
8	0.0008	0.0011	0.0042	0.0054	0.70%	0.0032	0.0027	0.0022	0.0102	1.12%
9	0.0069	0.0035	0.0040	0.0020	0.89%	0.0021	0.0032	0.0020	0.0078	0.89%
10	0.0223	0.0041	0.0060	0.0028	2.36%	0.0186	0.0096	0.0041	0.0029	2.15%
all	0.0007	0.0022	0.0019	0.0020	0.36%	0.0006	0.0023	0.0010	0.0029	0.39%

All systematic errors are added in quadrature;