Fragmentation Functions at e^+e^- machines

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Probing Strangeness in Hard Processes
Laboratori Nazionali di Frascati
Frascati, 18-21 October 2010

Outline

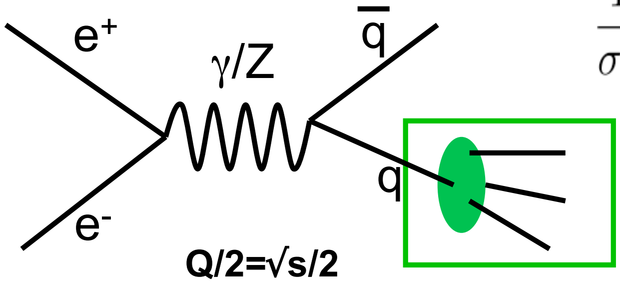
- ✰ Introduction
- ✰ Unpolarized Fragmentation Function
- ✰ Available data sets
- ✰ Present data about FF (DSS)
- ✰ Preliminary BaBar results

- ✰ Collins Fragmentation Function (Collins FF)
- ✰ Collins FF Results
- ✰ Interference Fragmentation Function (IFF)
- ✰ IFF results
- ✰ Summary and conclusion

Introduction: Unpolarized Fragmentation Function

Definition ($e^+e^- \to \gamma/Z^0 \to h+X$)

Fragmentation: hadron production from quark, antiquark or gluon.
The Fragmentation Function (FF) $D_i^h(x,s)$ is defined as the momentum distribution of hadron h inside a jet of flavour i and hardness Q.
- **$x=2E_h/\sqrt{s}$ whit Q the momentum of the intermediate γ or Z boson.**



$$\frac{1}{\sigma_0}\frac{d\sigma^h}{dx} = F^h(x,s) = \sum_i \int_x^1 \frac{dz}{z} C_i(z, \alpha_s(\mu), \frac{s}{\mu^2}) D_i^h(\frac{x}{z}, \mu^2) + \mathcal{O}(\frac{1}{\sqrt{s}})$$

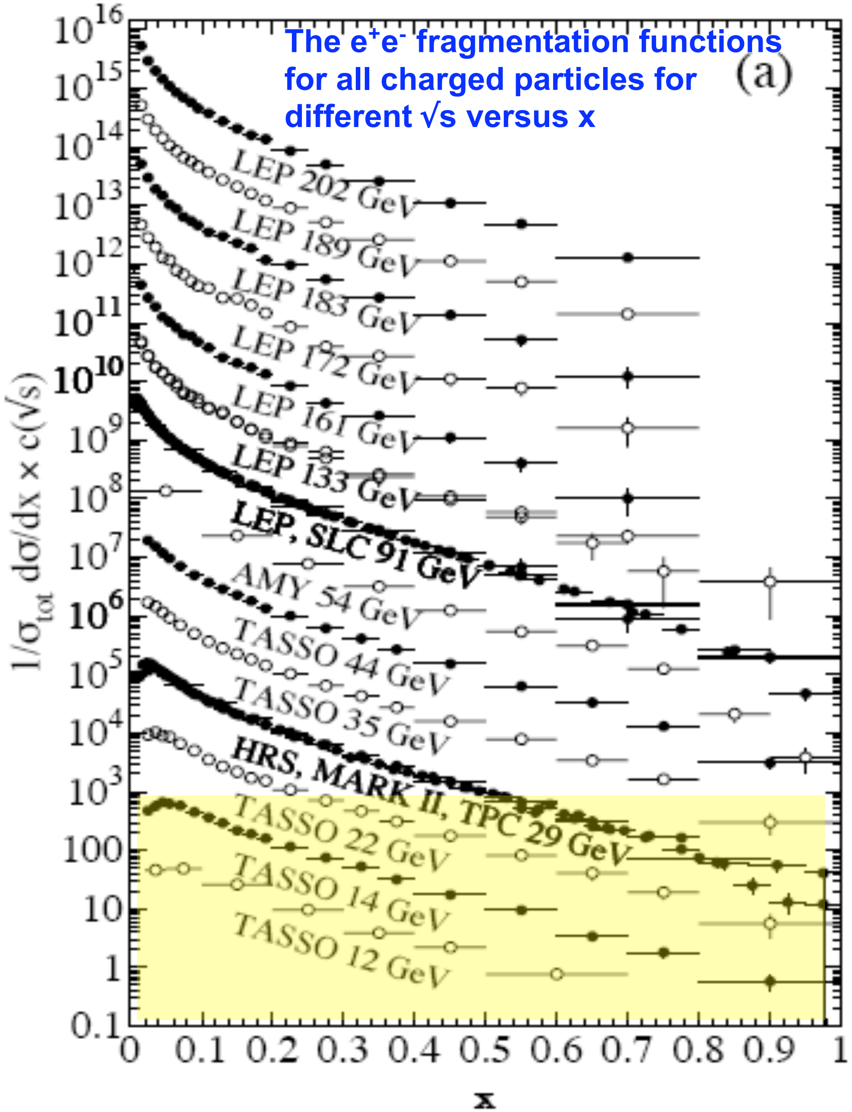
Coefficient function; calculated in perturbative QCD

Parton Fragmentation Functions; Non perturbative and **universal**; determined from experiments.

Interpretation:

FF $D^h_i(z,\mu^2)$ can be seen as the probability that a parton i fragments into a hadron h carrying away a fraction z of the parton's momentum (analogus to Parton Distribution Functions).

Present data about FF

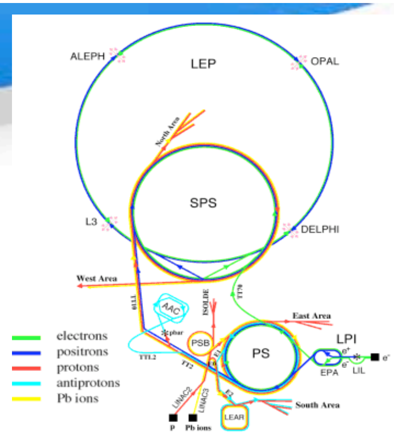


Perturbative QCD corrections lead to logarithmic scaling violations via the evolution equations (DGLAP):

$$\frac{\delta}{\delta ln\mu^2} D_i(x,\mu^2) = \sum_j \int_x^1 \frac{dz}{z} P_{ji}(z,\alpha_s(\mu^2)) D_j(\frac{x}{z},\mu^2)$$

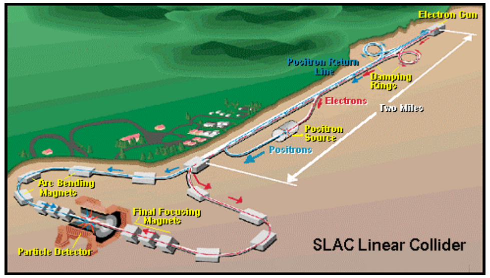
- Most of data are obtained at LEP energies;
- At lower CMS energies and higher x, very little data are available;
- No information on how to disentangle quark from antiquark fragmentation;
- The information on how the individual q flavour fragment into h depends on the “tagging techniques”;
- 3-jet fragmentation to access gluon FF difficult (not yet well constrained).

Data sets



First measurements done in e^+e^- collision:

- **@CERN (LEP): ALEPH, DELPHI, L3, OPAL;**
- **@DESY (PETRA, DORISII): PLUTO, TASSO, ARGUS**
- **@SLAC (SLC): SLD.**



Most recent data sets:

- **B-factories e^+e^-: BABAR (@SLAC), BELLE (@KEK).**

Data from ep and pp:

- **Deep Inelastic Scattering: H1, HERMES, COMPASS, ZEUS;**
- **Hadronic Collision (RHIC): BRAHMS, PHENIX, STAR;**

Situation of Fragmentation Function

- Many attempts to extract FF from e^+e^- data: KKP, AKK, HKNS, Kretzer …
  - Uncertainty ranges of determined FF where not estimated;
  - 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));

Global analysis: DeFlorian, Sassot, Stratmann (DSS)

e^+e^- : Clean processes, high statistic, sensitivity to heavy quarks;
No gluons, no flavour/charge separation

e^-p : Flavour/charge separation, comparison with e^+e^- frame (Breit frame)

hh : charge separation, sensitive to gluons, large z behavior
Large theoretical uncertainties, not sensitive to heavy quarks.

Current knowledge on FF: DSS

DeFlorian, Sassot, Stratmann, Phys. Rev. D75, 114010 (2007)

New sets of pion and kaon fragmentation functions obtained in nex-to-leading order combined analysis of single-inclusive hadron production in e^+e^- annihilation, pp collinsions and SIDIS.

Data used in NLO global analysis for **pion** FF	
TPC (√s=29GeV)	Inclusive,"uds,c,b" tag
TASSO(√s=34/44GeV)	Inclusive
SLD (Z^0)	Inclusive,"uds,c,b" tag
ALEPH	Inclusive
DELPHI (Z^0)	Inclusive,"uds,c,b" tag
OPAL (Z^0)	Inclusive,"u,d,s,c,b" tag
HERMES	π^+, π^-
PHENIX (RHIC)	π^0
STAR (RHIC)	π^0
BRAHMS (RHIC)	π^+, π^-

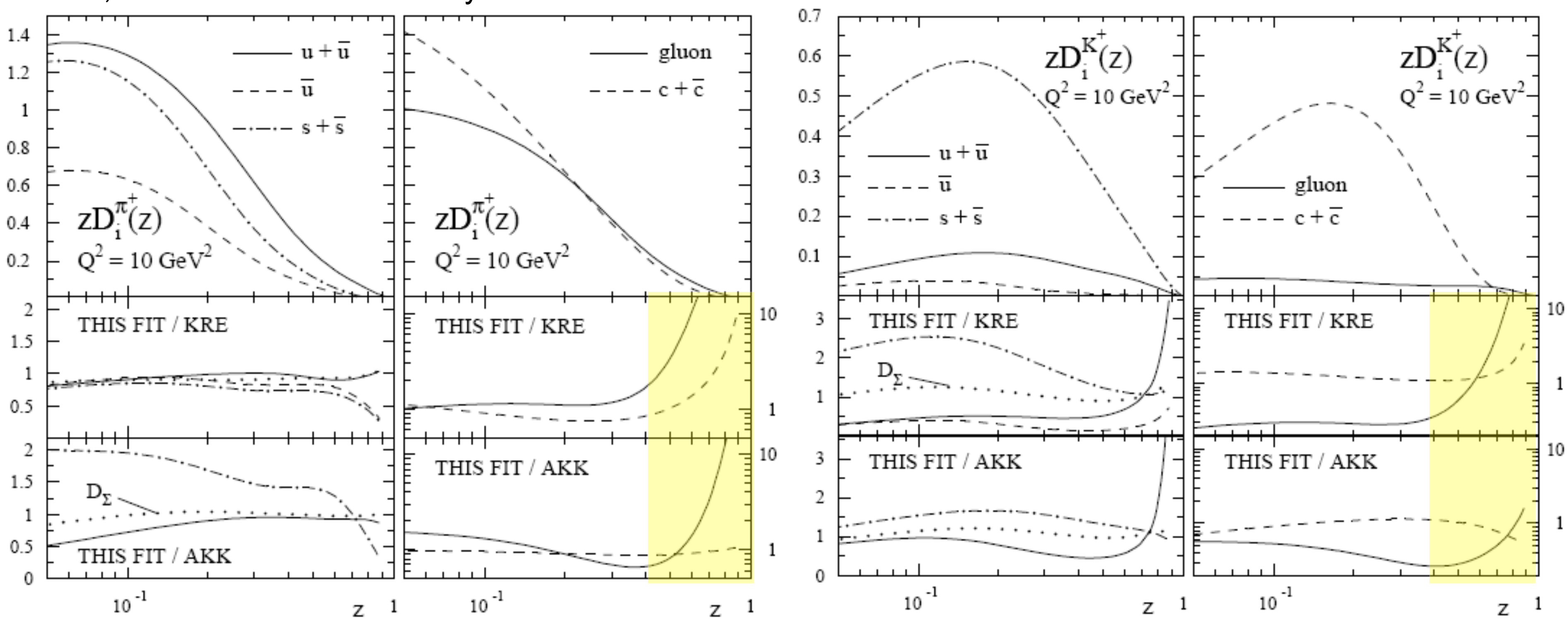
Data used in NLO global analysis for **kaon** FF	
TPC (√s=29GeV)	Inclusive
SLD (Z^0)	Inclusive,"uds,c,b" tag
ALEPH	Inclusive
DELPHI (Z^0)	Inclusive,"uds,b" tag
OPAL (Z^0)	Inclusive,"u,d,s,c,b" tag
HERMES	k^+, k^-
STAR (RHIC)	k^0_s
BRAHMS (RHIC)	k^+, k^-

DSS fit results

Phys. Rev. D75, 114010 (2007)

HERMES data: constrain the separation between favored and unfavored distribution;
RHIC data: stringent constraints on the gluon FF and on the large z behavior;

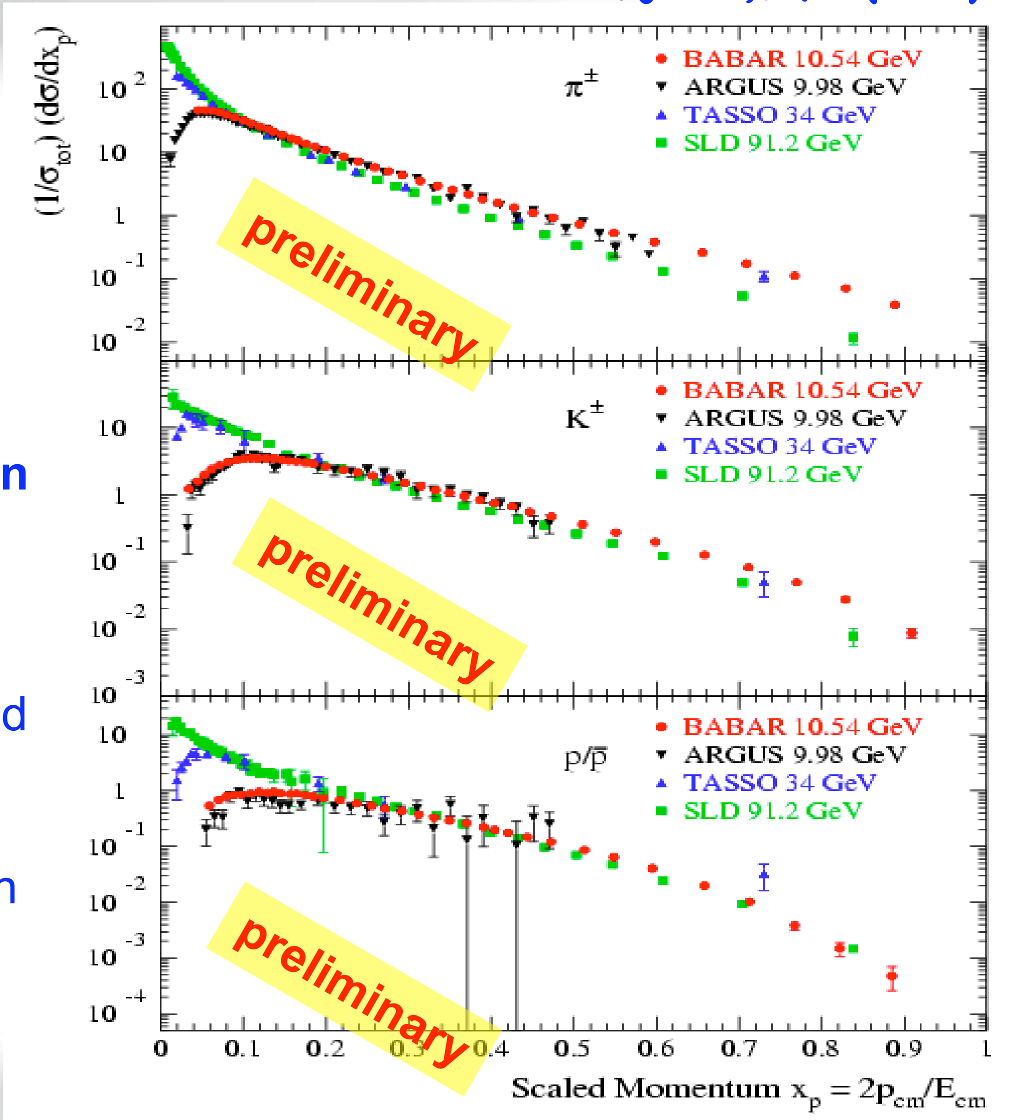
AKK, KRE NLO sets based only on SIA data



Hadron production in **BABAR/BELLE** would open up the possibility for studies of scaling violations with unprecedented precision and allow to reduce the present uncertainties.

BaBar Incluive Hadronic Particle Spectra

D. Muller
EPJ-C33,s572 (2004)

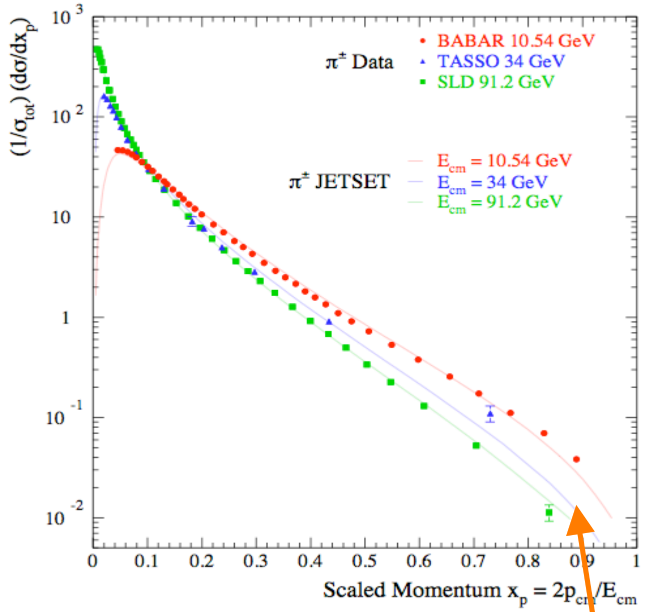


- BaBar measurement based on:
  - **0.9 fb^{-1}** @10.54GeV (below Υ(4S)); (10.58GeV ⇒ Υ(4S) peak).
- **Plot scaled momentum distribution compared to ARGUS, TASSO and SLD data**
- Good consistency between BaBar and ARGUS data (ARGUS extends to lower values; BaBar covers the high side of the spectrum until the end with good precision, limited only by sistematic effects).

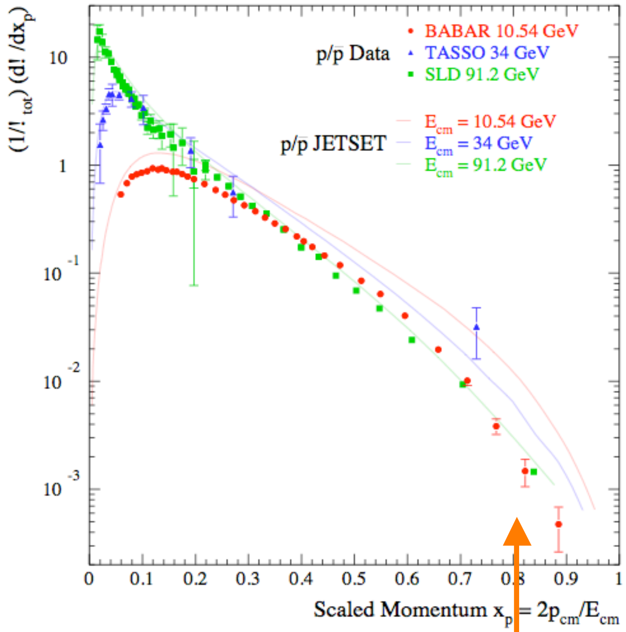
BaBar Incluive Hadronic Particle Spectra

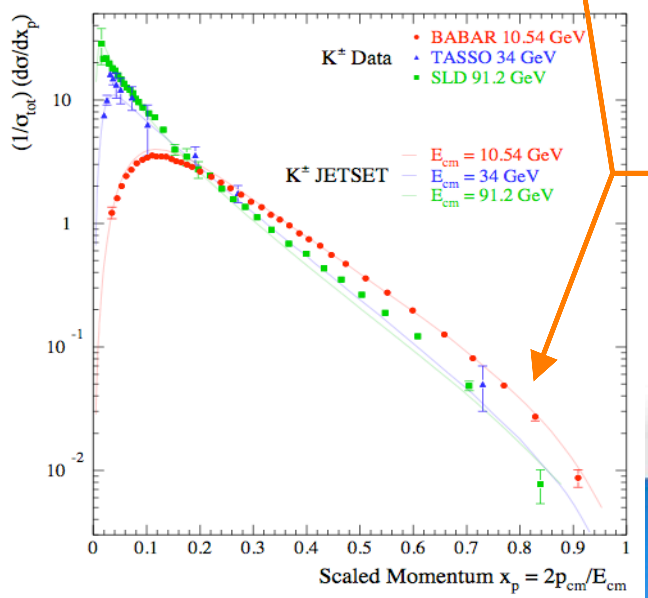
D. Muller
EPJ-C33,s572 (2004)

Cross section scaling



- Hadronization should be scaled invariant except for "small" effects of hadron masses, running α_s,…
- Scaling violation at low x_p, due to masses, are well know and modelled adequately (here JETSET is shown for comparison)





- Expect substantial scaling violation at high x_p:
  - seen clearly in π and k data;
  - NOT seen in $p/\bar{p}$ data! Wrong model predictions.

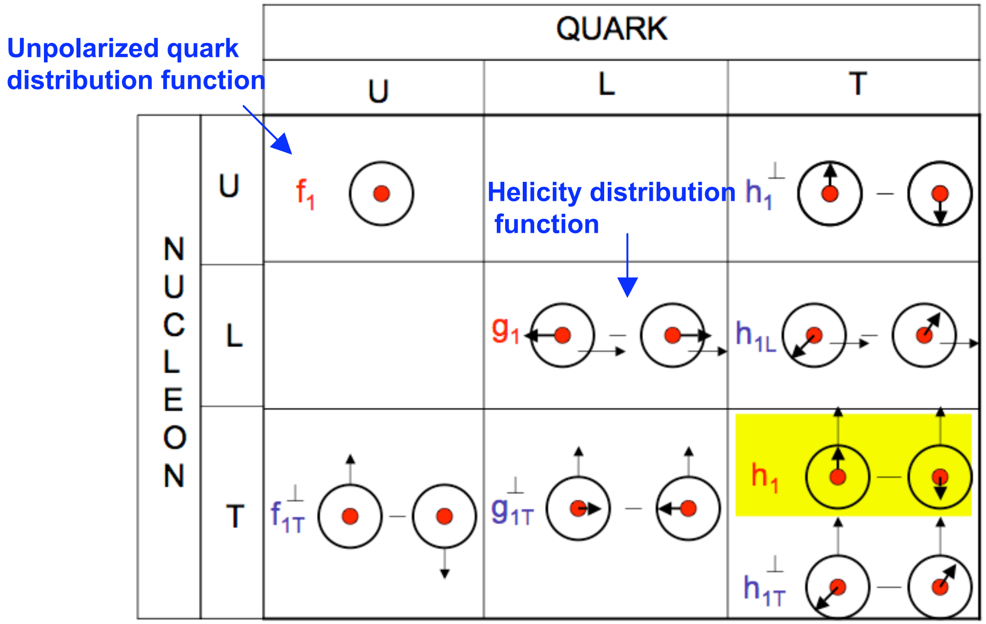
Spin Dependent Fragmentation Function

- Tests of universality and factorization between e^+e^-, DIS and p-p collisions;
- Connection between microscopic (quark spin) and macroscopic observables (azimuthal hadron distribution);
- Provides final state spin analyzer for the study of quark transversity distributions from data taken by HERMES, COMPASS, JLab and RHIC experiments.

Outline

- Introduction;
- Collins Fragmentation Function;
- Interference Fragmentation Function;
- Results;

Motivation:trasversity quark distribution from Collins FFand Interference FF



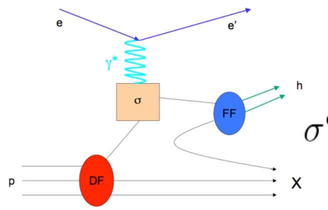
After averanging over the quark transverse momentum, three parton distribution functions are needed at leading twist for a complete description of the momentum and spin distribution of the quarks inside the nucleon (red in figure).

Transverse Momentum Dependent (TDM) distribution function arise when the transverse momentum of the quark is not integrated over, blue in the figure (non collinear phenomena).

Transversity distribution function: describes the distribution of the quark's transverse spin in a transversely polarized nucleon → it remains the less known fundamental quark distribution function.

Motivation:trasversity quark distribution from Collins FFand Interference FF

SIDIS: Semi Inclusive Deep Inelastic Scattering

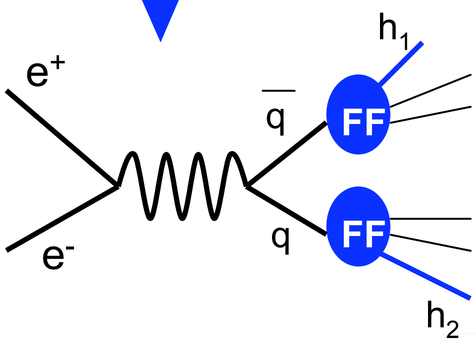


Factorization theorem:

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

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

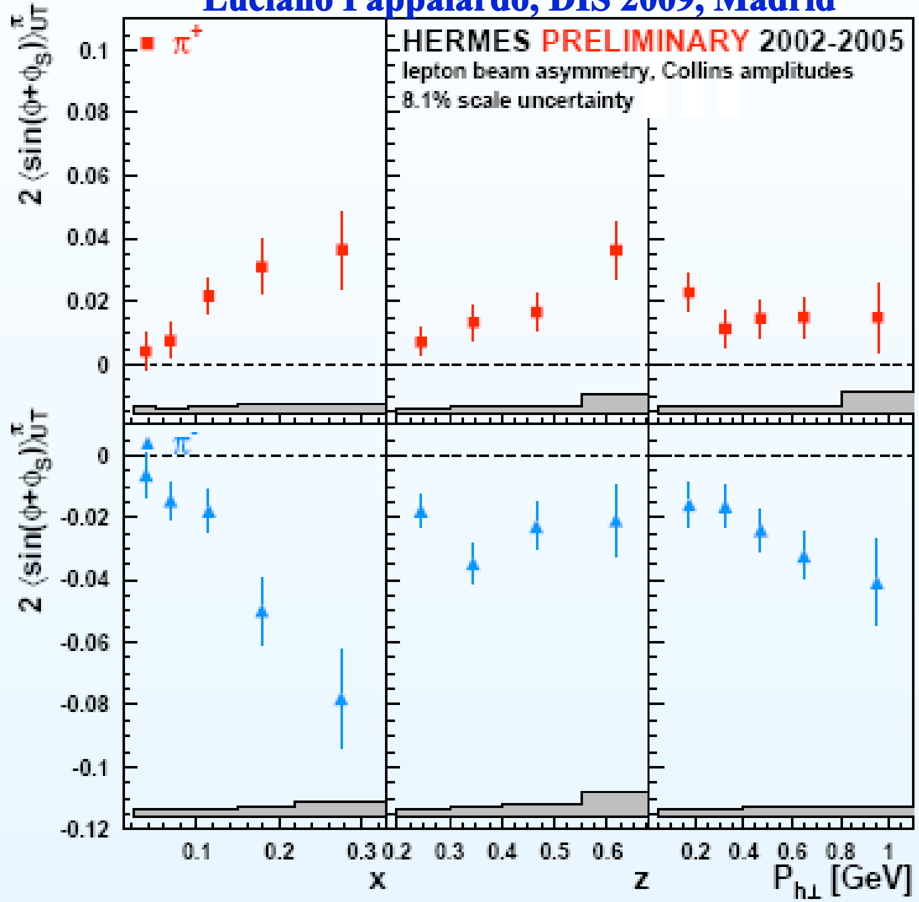
Global analysis to extract Transversity (h_1)



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

$\propto CFF(z_1)xCFF(z_2)$
$\propto IFF(z_1)xIFF(z_2)$

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



Collins FF

$e^+e^- \rightarrow h_1h_2X$

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

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

Unpolarized FF

Polarized FF (Collins FF)

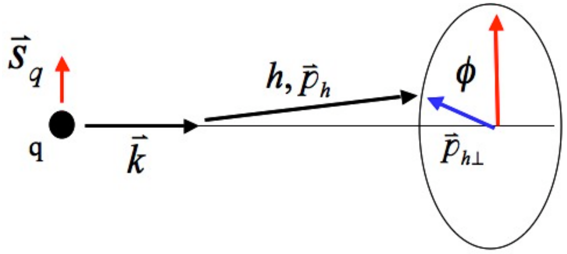
- **Quark spin direction unknown: measurement of Collins function in one hemisphere is not possible (the sin(ϕ) modulation will average out)**
- **Correlation between two hemispheres results in $\cos(\phi_1 + \phi_2)$ (or $\cos(2\phi_0)$) modulation of the observed di-hadron yield.**

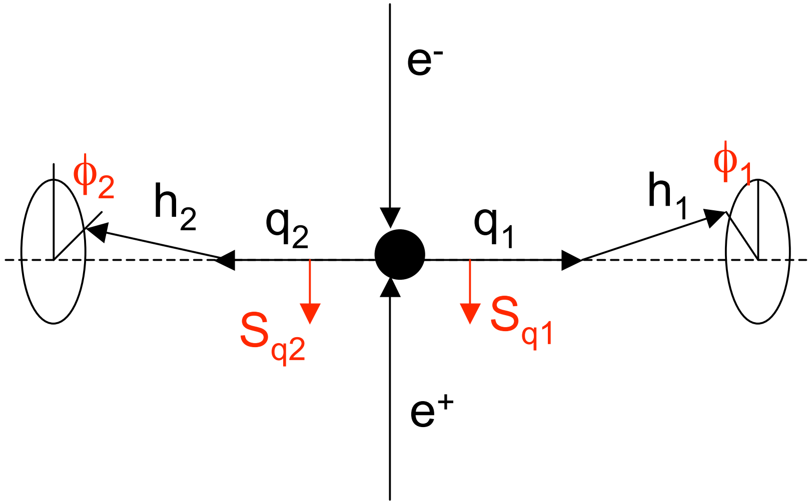
→ **Measurement of azimuthal correlations for pion pairs (CFF) or pairs of pion pairs (IFF) around the jet axis in events with back-to-back jets!**

Collins effect in di-hadron correlation

Collins Effect: Fragmentation of a quark q with Spin S_q into a spinless hadron h carries an azimuthal dependence

$$\propto (k \times p_{h,\perp})^* S_q$$





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

$$N_{h1h2}(\phi_1+\phi_2) \sim a_{12}\cos(\phi_1+\phi_2)$$

Experimental requirements:

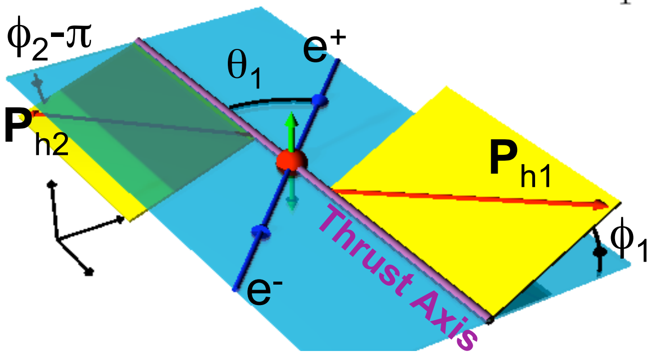
- small asymmetries need large data sample;
- the essetial experimental requirements for FF measurements is the ability to identify hadron pair and to precisely measure the momenta and charge sign⇒good Particle Identification
- Large acceptance;
- Good tracking.

Analysis Reference Frame

Daniel Boer
Nucl. Phys. B 806(2009)
[arXiv:0804.2408v2]

(RF12) →

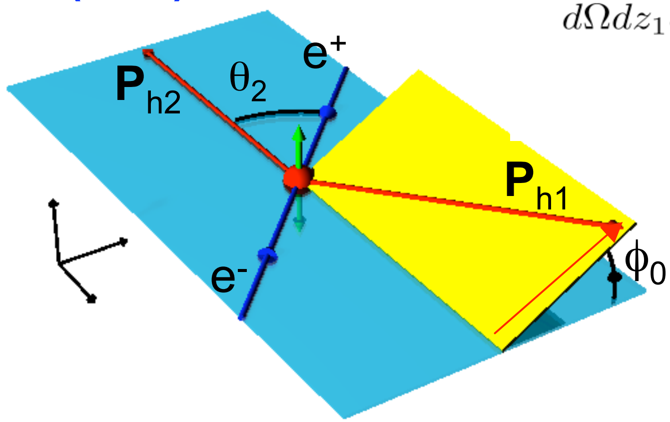
$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{d\Omega dz_1 dz_2 d\phi_1 d\phi_2} = \sum_{q,\bar{q}} \frac{3\alpha^2}{Q^2}\frac{e_q^2}{4} z_1^2 z_2^2 \Big[(1+cos^2\theta) D_1^{q,(0)}(z_1)\bar{D}_1^{q,(0)}(z_2) + sin^2(\theta) cos(\phi_1+\phi_2) H_1^{\perp,(1),q}(z_1)\bar{H}_1^{\perp,(1),q}(z_2)\Big]$$



θ_1: angle between the lepton axis and the thrust axis;
$\phi_{1,2}$: azimuthal angles of the two hadrons between the scattering plane and the transverse hadron momenta P_{hiT}.

(RF0) →

$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{d\Omega dz_1 dz_2 d^2\vec{q}_T} = \frac{3\alpha^2}{Q^2} z_1^2 z_2^2 \Big\{A(y)\mathcal{F}[D_1\bar{D}_2] + B(y) cos(2\phi_0)\mathcal{F}\Big[(2\hat{h}\cdot\vec{k}_T\hat{h}\cdot\vec{p}_T - \vec{k}_T\cdot\vec{p}_T)\frac{H_1^\perp \bar{H}_2^\perp}{M_1 M_2}\Big]\Big\}$$



θ_2: angle between the lepton axis and the second hadron momentum P_{h2};
ϕ_0: angle between the plane spanned by one hadron momentum and the lepton momenta and the transverse momentum of the second hadron with respect to the first hadron momentum.

Asymmetries extraction

***Accessing the Collins Asymmetries*: measurement of the cosine modulation of hadron pairs ($N(\phi_1+\phi_2)$, $N(2\phi_0)$) on the top of flat distribution due to unpolarized part of fragmentation function (<N>).**

Normalized distribution:
(Raw Asymmetries)

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

b contains Collins +radiative effects + acceptance effects

Method to eliminate the acceptance and radiative effects: **Double Ratio** of Raw Asymmetries:

$$R = \frac{R^{UnLike}}{R^{Like}} = \frac{N^{UL}(\phi_\alpha)}{< N >} / \frac{N^{L}(\phi_\alpha)}{< N >} \propto 1 + cos(\phi_\alpha) A^{UL/L}(z_1, z_2)$$

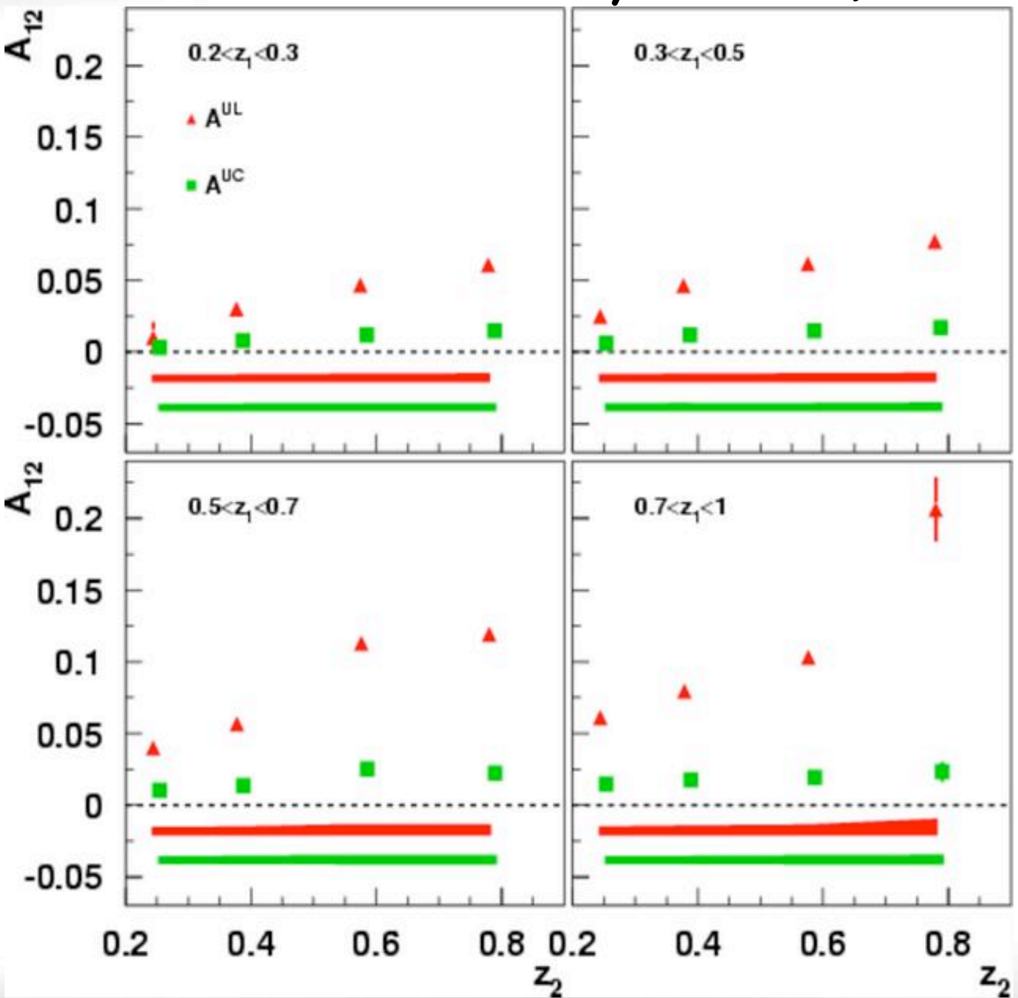
$$A^{UL/L}(z_1, z_2) \propto \frac{H_1^{fav} H_2^{fav} + H_1^{dis} H_2^{dis}}{D_1^{fav} D_2^{fav} + D_1^{dis} D_2^{dis}} - \frac{H_1^{fav} H_2^{dis} + H_1^{dis} H_2^{fav}}{D_1^{fav} D_2^{dis} + D_1^{dis} D_2^{fav}}$$

➾ Asymmetries generated by QCD radiative events and acceptance effects are charge independent and cancel;
➾ Different combination of favored and disfavored FF

$A^{UL/L}$ contains only Collins Asymmetries and higher order radiative effects.

Final Collins results ($e^+e^- \rightarrow \pi\pi X$)

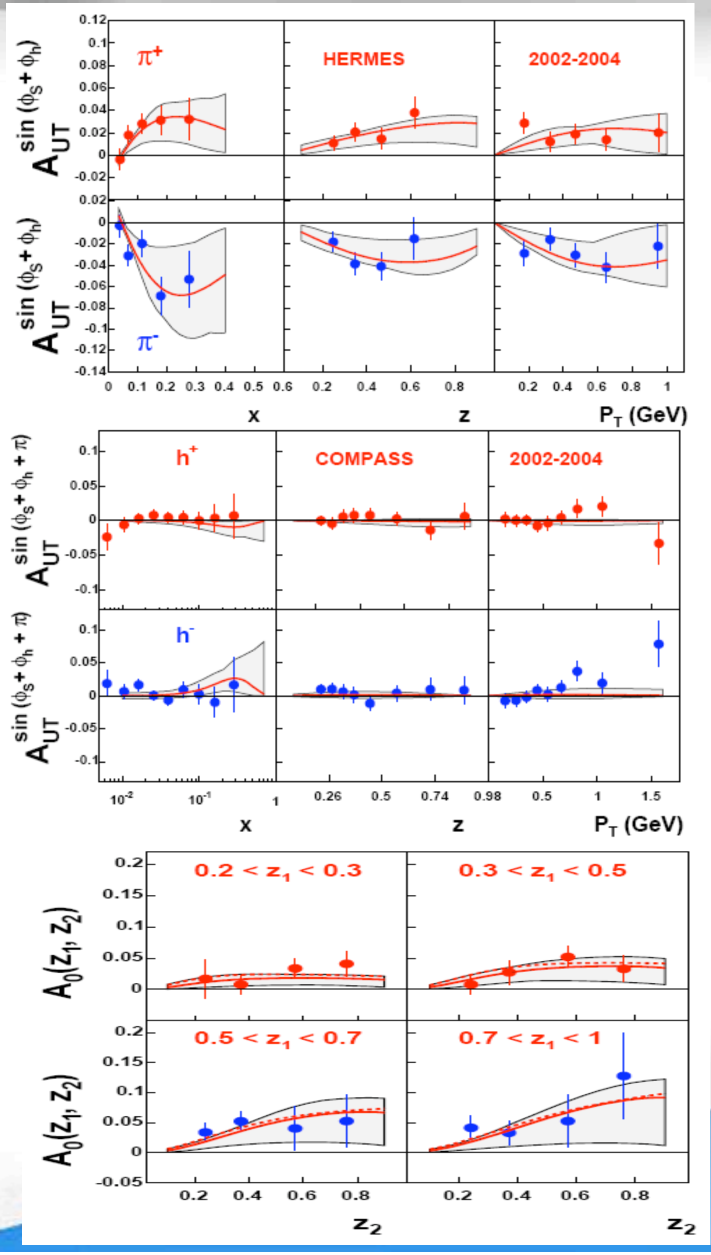
R.Seidl et al., (Belle Collaboration)
Phys. Rev. D78,032011



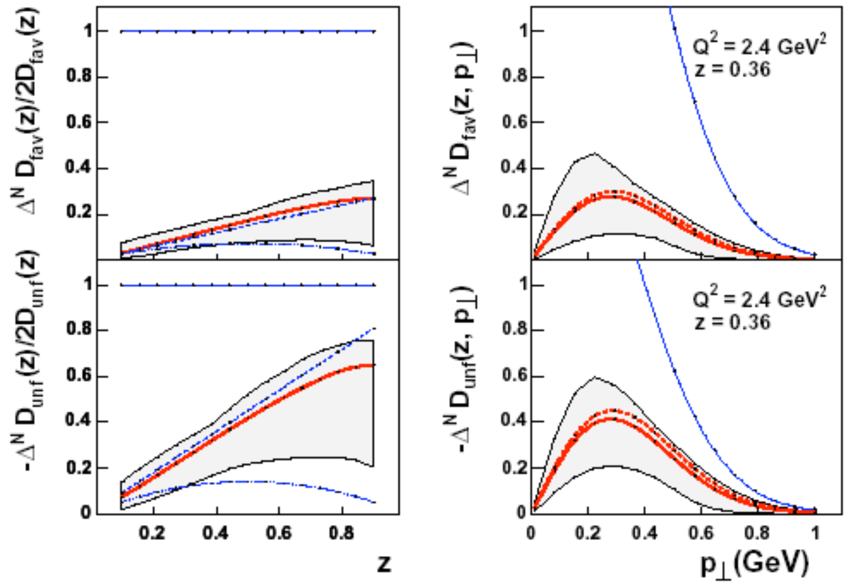
4x4 z_1 vs z_2 binned analysis
(z= fractional energy of the pion)

- **First results obtained by Belle Collaboration with pions.**
  (PRL96,232002 29fb^{-1} @10.52 GeV and PRD78,032011 55fb^{-1} @10.52 GeV, 492fb^{-1} @10.58GeV)
- **Non zero asymmetries**
- BaBar analysis ongoing

Global analysis results



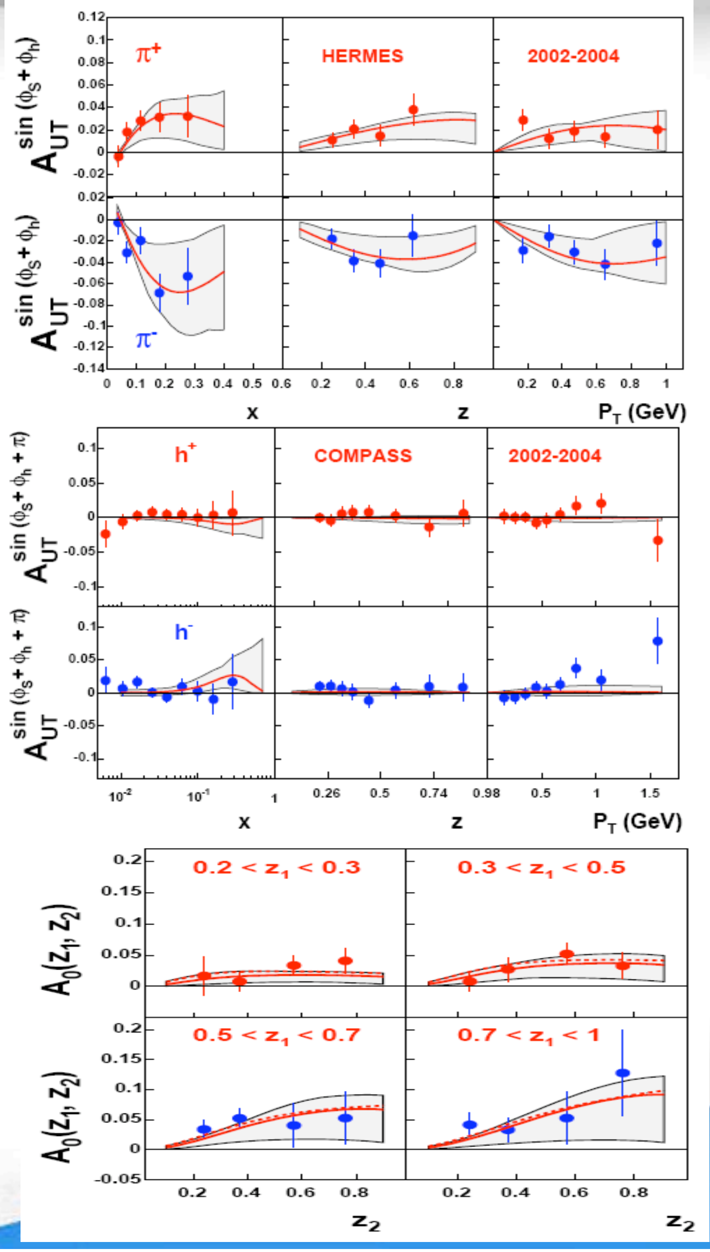
Phys.Rev.D75:054032,2007,
update in Nucl.Phys.Proc.Suppl.191:98-107,2009



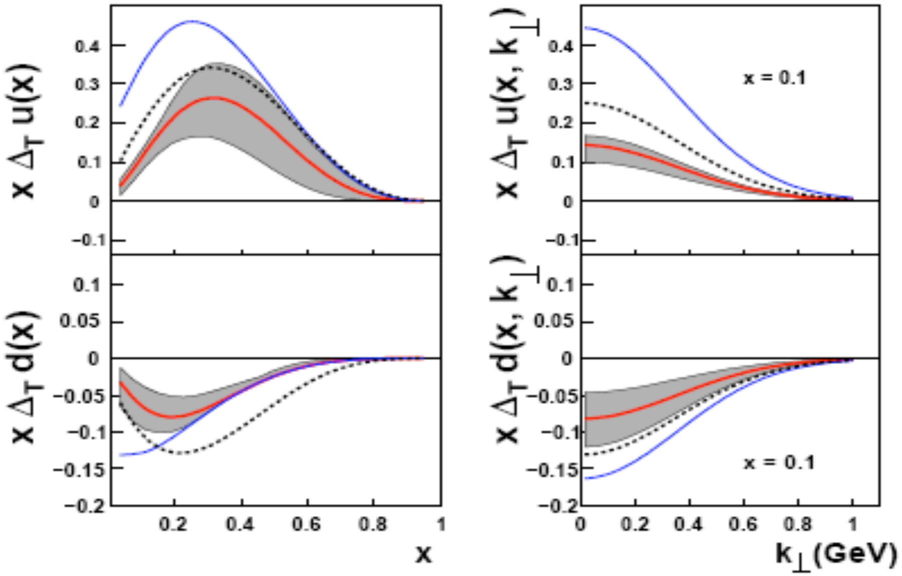
Favoured and unfavoured Collins FF

- **HERMES A_{UT} p data**
- **COMPASS A_{UT} d data**
- **Belle $e^+ e^-$ Collins data**

Global analysis results



Phys.Rev.D75:054032,2007,
update in Nucl.Phys.Proc.Suppl.1
91:98-107,2009

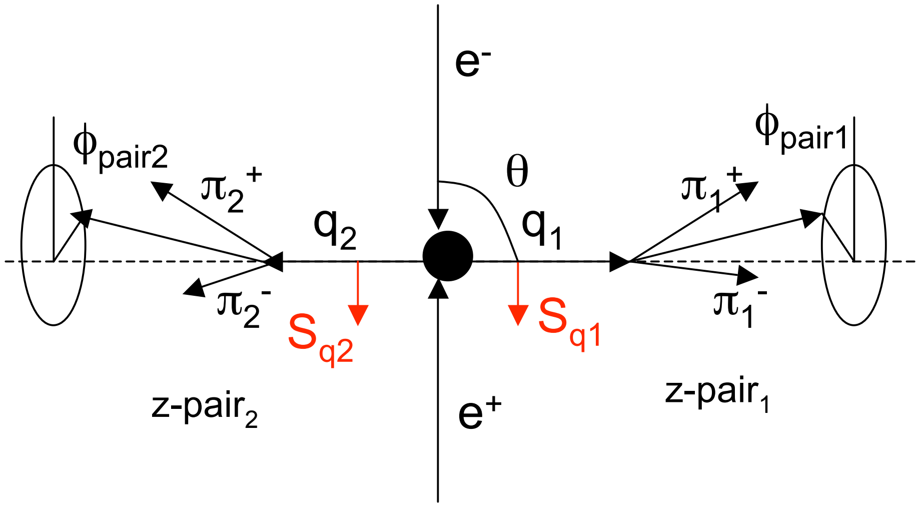


➔ **First extraction of transversity**

- **HERMES A_{UT} p data**
- **COMPASS A_{UT} d data**
- **Belle $e^+ e^-$ Collins data**

IFF in correlation of hadron pairs

Independent way to extract transversity, involving collinear FF: we consider the semi-inclusive production of two hadrons inside the same current jet: the fragmentation $q \rightarrow (\pi^+ \pi^-)X$ is described by an (extended) Dihadron FF (or IFF).



DiFF (IFF): represents the probability that at some hard scale a parton hadronizes in two hadrons with fractional energies z_1 and z_2.

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

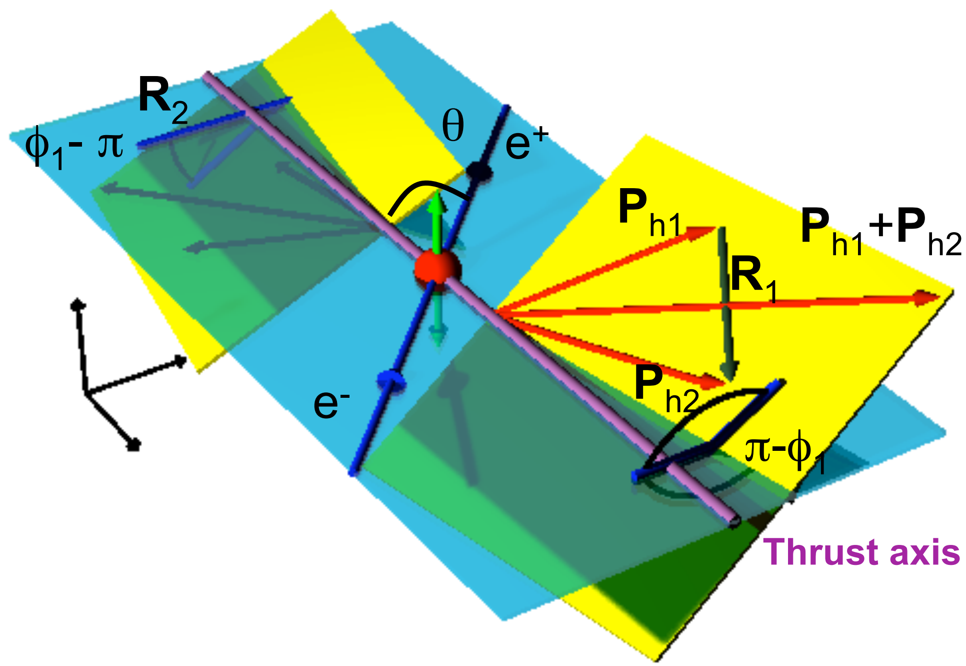
$$N_{pair1,pair2}(\phi_{pair1}+\phi_{pair2}) \sim a_{12}\cos(\phi_{pair1}+\phi_{pair2})$$

$$a_{12} \propto \frac{\sin^2(\theta)}{1+\cos^2(\theta)} H_1(z_{pair1}, M^2_{hpair1}) H_1(z_{pair2}, M^2_{hpair2})$$

Interference Fragmentation Function

- $e^+e^- \to (\pi^+ + \pi^-)_{jet1} (\pi^+ + \pi^-)_{jet2} X$;
- detection pion pairs in opposite hemispheres;
- Observe azimuthal angle between the event plane the two two-pion-pairs;
- Transverse momentum is integrated (not TMD): universal, easy evolution, directly applicable to SIDIS and proton data;
- Analysis in z-bin and M_h-bin

$R = P_{h1} - P_{h2}$



Theoretical paper:
J.Collins, S.Heppelmann, G.Ladinsky, Nucl.Phys. B420,565(1994)
A.Bianconi, S.Boffi, R.Jakob, M.Radici, Phys.Rev. D62,034008(2002);
A.Bacchetta, M.Radici, Phys.Rev. D69,074026(2004)
A.Bacchetta, F.Ceccopieri, A.Mukherjee, M.Radici, Phys.Rev. D79,034029(2009)
(model prediction for e^+e^-)

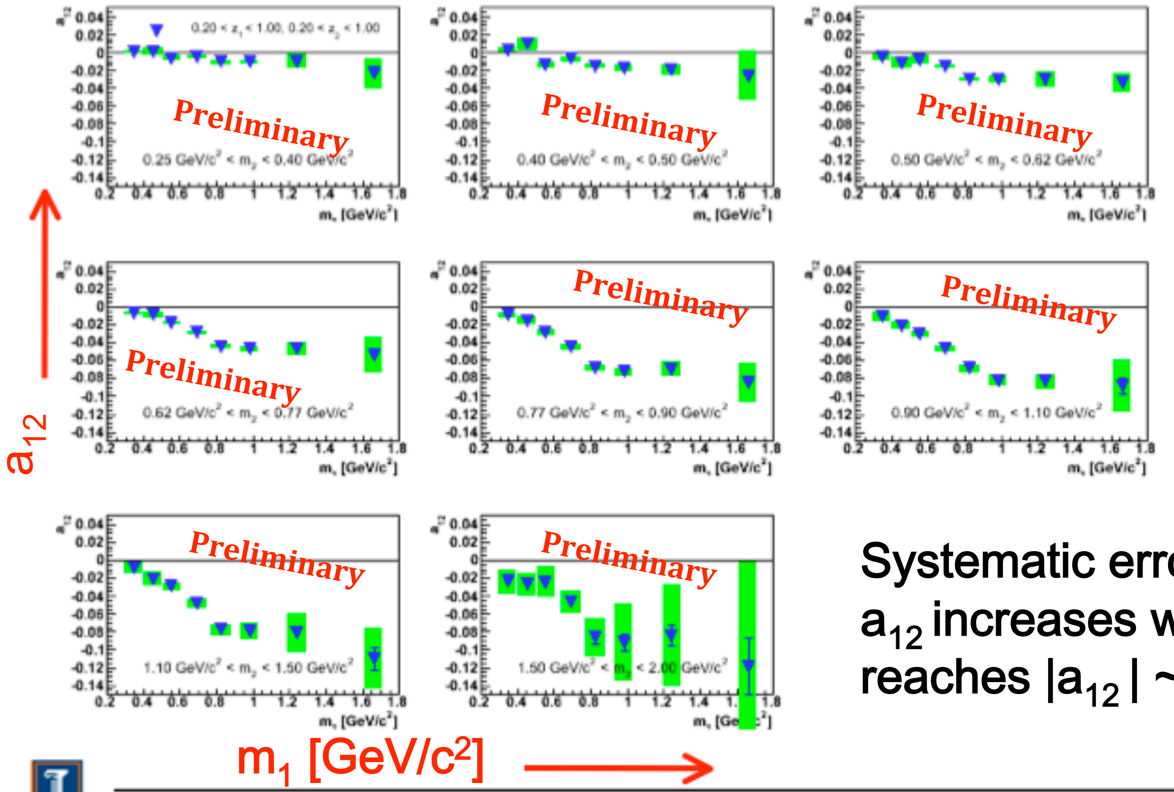
IFF: Belle Preliminary Results

8th European Research Conference, Milosm September 27th – October 2nd 2009

M. Grosse Perdekamp talk

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 $|a_{12}|$ ~ 0.1 at large m_i.

Summary I

Unpolarized FF

⇨ We have precise data such from LEP and SLD at $Q=M_Z$, so that accurate small Q^2 data are needed for probing the Q^2 evolution ⇒ BaBar and Belle data contribuition expected;

⇨ Many attempts to extract FF from e^+e^- data: KKP, AKK, HKNS, Kretzer… with large difference between different fits;

⇨ First Global analysis extraction of FF for pions and kaons (DSS):

- ★ good global description of all e^+e^-, ep and pp data;
- ★ pions FF well determined; kaons less.

Summary II

Collins FF

➾ Significant non-zero Collins asymmetries found by Belle Collaboration (long paper published);
➾ BaBar Collins Asymmetries analysis ongoing;
➾ First global analysis done.

Interference FF

➾ Preliminary measurement of the Interference FF by Belle Collaboration
➾ Large asymmetries seen, rising with z and invariant mass (in agreement to theoretical prediction).

Future plans:

Carry out CFF asymmetries for the kaons system and the IFF asymmetries for other species: $(\pi^0,\pi^{+,-})$, (K^+,K^-), (π^+,K^-), …

Thanks to M. Grosse Perdekamp and R. Seidl for they helpfulness and suggestions

Backup slides

Raw asymmetires and Double Ratio

Fit function:
a+b*cos(ϕ)

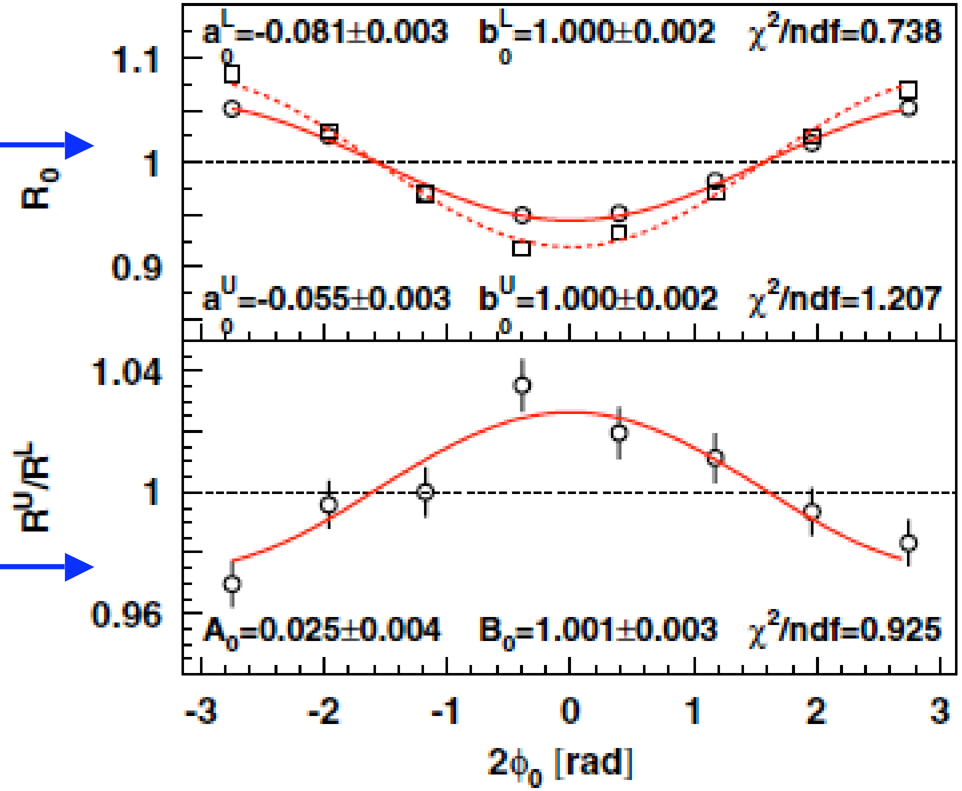
Collins asymmetries not included in Monte Carlo simulation

Raw Asymmetries in the RF0

b_0 ~1;
a_0: raw asymmetry parameter (include the acceptance effects and radiative effects)

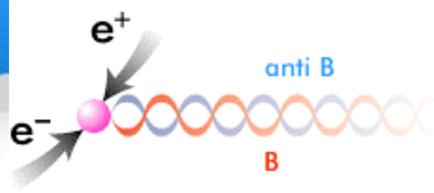
Double Ratio in the RF0

B_0~1;
A_0: contains only the Collins Asymmetries and higher order radiative effects.



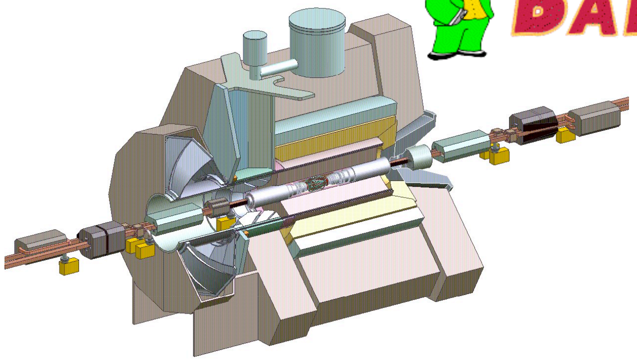
PRL96,232002 29fb^{-1} @10.52 GeV

B-factories facilities

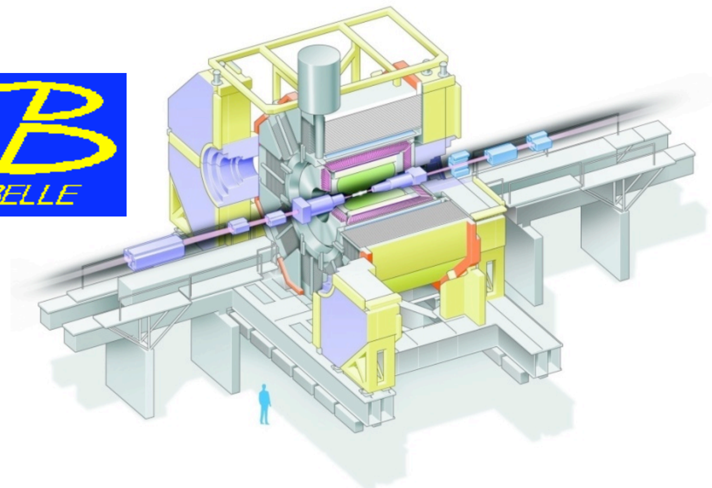


The B-factories, PEPII and KEK, consist of asymmetric electron-positron beams. The center of mass energy is selected to be on the peak on the Υ(4S) meson (10.58Gev/c^2), which decay more than 96% into BB meson pairs.

BABAR



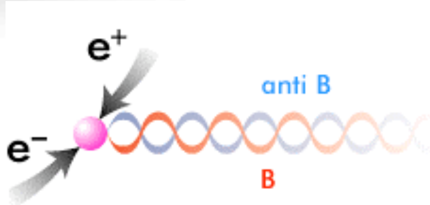
BELLE



- **9 GeV e^- - 3.1 GeV e^+;**
- **$\sqrt{s}$=10.58 GeV (Υ(4S));**
- **continuum production: 10.54 GeV;**
- **Excellent PID and vertex production;**
- **L~500fb^{-1}**

- **8 GeV e^- - 3.5 GeV e^+;**
- **$\sqrt{s}$=10.58 GeV (Υ(4S));**
- **continuum production: 10.52 GeV;**
- **much available data;**
- **L>1000fb^{-1}**

B-Factories



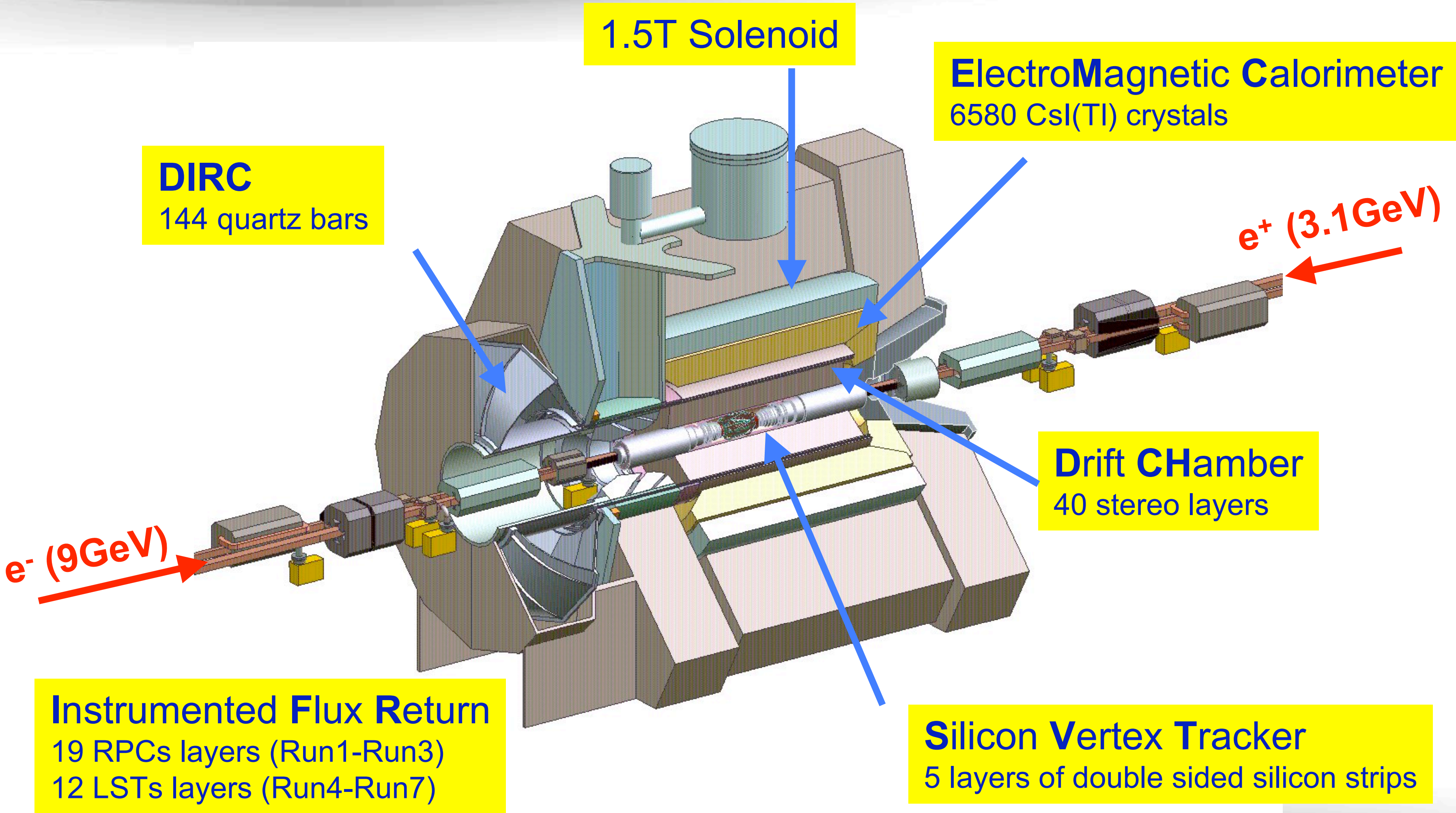
The B-factories, PEPII and KEK, consist of asymmetric electron-positron beams. The center of mass energy is selected to be on the peak on the Υ(4S) meson (10.58Gev/c^2), which decay more than 96% into $B\overline{B}$ meson pairs.

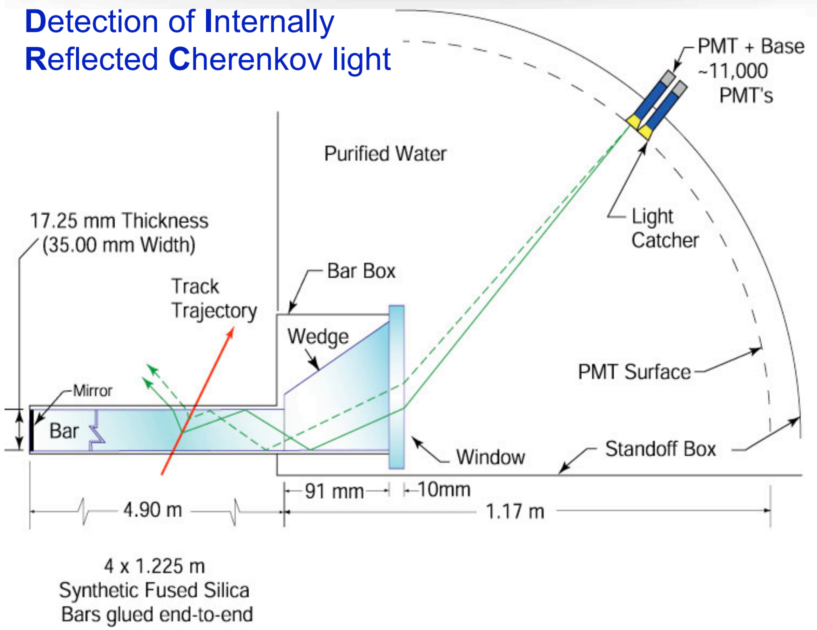
Physics program:

- The principal physics goal of the B-factories is to test the Kobayashi-Maskawa picture of CP violation by measuring the angle of the unitary triangle;
- precision measurements of decays of bottom and charm mesons of the τ lepton;
- search for rare processes;
- the very clean environment make BaBar suitable also for inclusive studies of hadron production:

Study of the azimuthal asymmetries in the inclusive production of two back-to-back hadron in the reaction: $e^+e^- \rightarrow h_1 h_2 X$

BaBar detector





- DIRC: is employed primarily for the separation of π and k from about 500 MeV/c;
- total internal reflection of light;
- only one bar end is instrumented with photon detector.
- a charged particle with v>c/n generates a cone of Cherenkov photons where $\theta_C=1/(\beta n)$;
- 3D-device: measure of time for γ to travel from the point of origin to the PMT ($\sigma(\Delta t)$~1.7ns).

π/K separation power:

measure Cherenkov angle resolution as a function of track momentum for pions and kaons, kinematically identified in D* decays.