Inclusive hadron production at B factories

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Results on inclusive hadron production → fragmentation functions

- experimental hadron multiplicities in $e^+e^- \to q\bar{q}$ events

$$F^h(z, Q^2) = \frac{1}{\sigma_{tot}} \frac{d\sigma(e^+e^- \to hX)}{dz} \qquad [z = \frac{E_h}{\sqrt{s}/2}]$$

- theory hadron multiplicities

$$F^h(z, Q^2) = \sum_i C_i(z, \alpha_s) \otimes D_i^h(z, Q^2) \quad \text{where } f(z) \otimes g(z) = \int_z^1 \frac{dy}{y} f(y) g\left(\frac{z}{y}\right)$$

  - index i for initial partons (quarks, antiquarks, gluons) (in this case from $e^+e^- \to q\bar{q}$)
  - $C_i(z, \alpha_s)$ (coefficient functions) describe parton content of the process, known at NNLO
  - $\boldsymbol{D_i^h(z, Q^2)}$ **fragmentation functions**
- Q^2 evolution calculable in perturbative QCD: DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi)
- fragmentation functions depend also on the parton and hadron spins
  - spin-independent FF: unpolarized → hadron multiplicities
  - spin-dependent FF: polarized → hadron multiplicities azymuthal asymmetries
- experiments measure differential hadron multiplicities
- fragmentation functions are determined from global fits on hadron multiplicities data

High precision results on unpolarized light hadron fragmentation functions

- inclusive charged pion, charged kaon and proton production in BABAR, preliminary, new
  - updated preliminary results, BABAR internal review in final stage for paper submission
- charged pion and kaon Multiplicities in e^+e^- annihilations at Belle, preliminary
  - arXiv:1210.2137 [nucl-ex], DIS2012 proceedings

Results on polarized light hadron fragmentation functions

- Collins Asymmetries in inclusive hadron-pair production, BABAR, preliminary
  - arXiv:1211.5293 [hep-ex], ICHEP 2012 proceedings
- Azimuthal Asymmetries in Inclusive Production of Hadron Pairs, Belle
  - PRD 78, 032011 (2008), Erratum PRD D 86, 039905(E) (2012)
- Transverse Polarization Asymmetries of Charged Pion Pairs, Belle, PRL 107, 072004 (2011)
  - interference fragmentation functions

Interest of inclusive hadron production results from *B*-factories

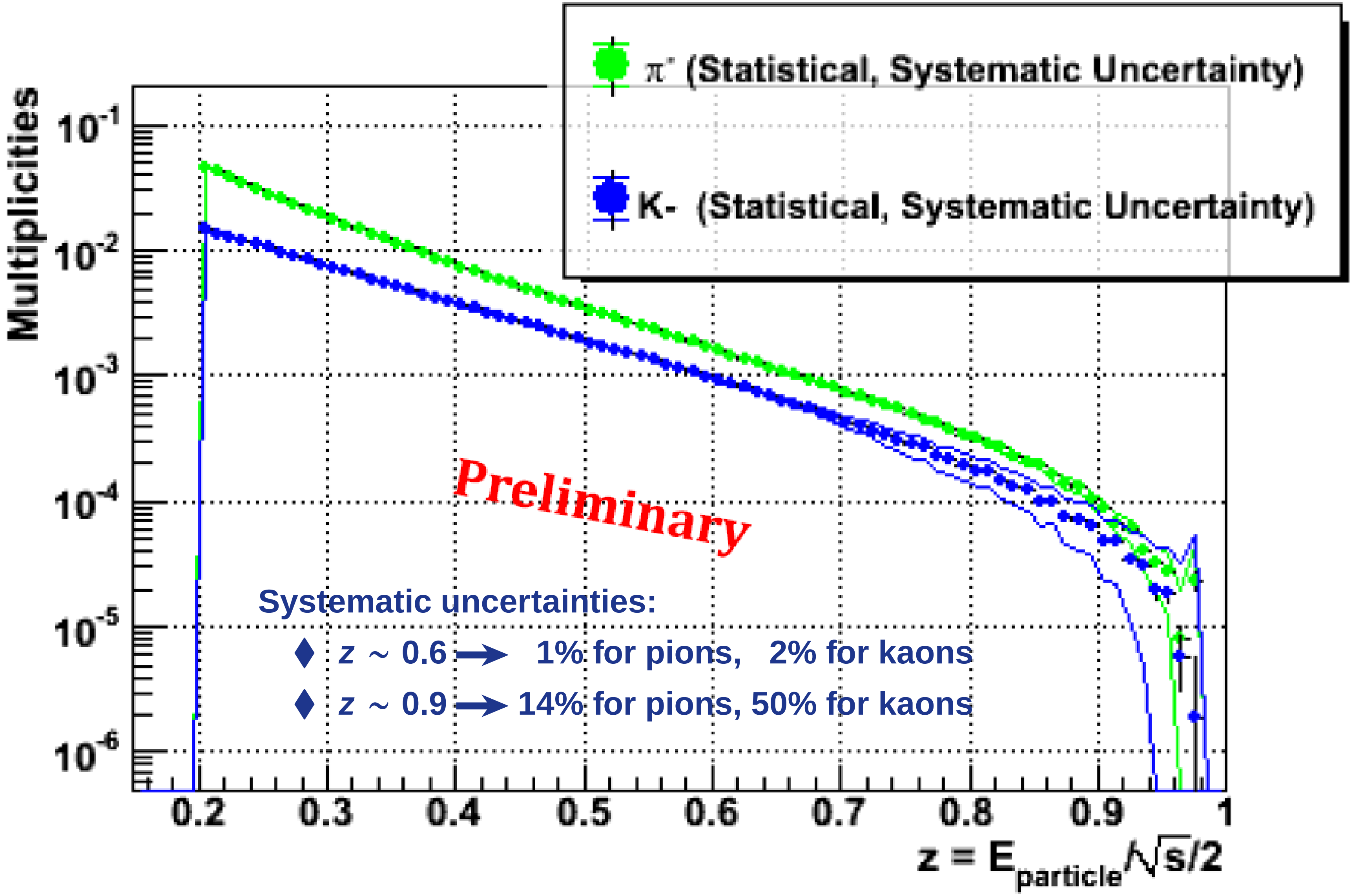
- unpolarized hadron multiplicities measurements
  - improve global fits for quark-gluon fragmentation functions
    - → improve access to flavor structure of the nucleon in semi-inclusive DIS and *pp* experiments
- polarized hadron multiplicities asymmetries measurements:
  - first time direct measurement of Collins and “interference fragmentation functions” effects
    - → access to transversity distribution functions of the nucleon

Unpolarized fragmentation functions results

Belle inclusive pion and kaon spectra, preliminary

- arXiv:1210.2137 [nucl-ex], DIS2012 proceedings
- motivation: improve precision on hadronic fragmentation functions from low energy e^+e^-
  - in particular improve knowledge of gluon fragmentation functions
- sample: $\sim$220$\cdot$10^6 e^+e^- annihilations at 10.52 GeV (below the $\Upsilon(4S)$)
- special care on PID
  - invert 5×5 id / mis-id matrix
  - calibrate id / mis-id probabilities on data control samples
- corrections for :
  - backgrounds (e.g. tau)
  - kinematic smearing, decay-in-flight, detector interaction/shower particles detector
  - tracking efficiencies and selection acceptance
  - initial state radiation

Pion and kaon multiplicities at Belle, preliminary

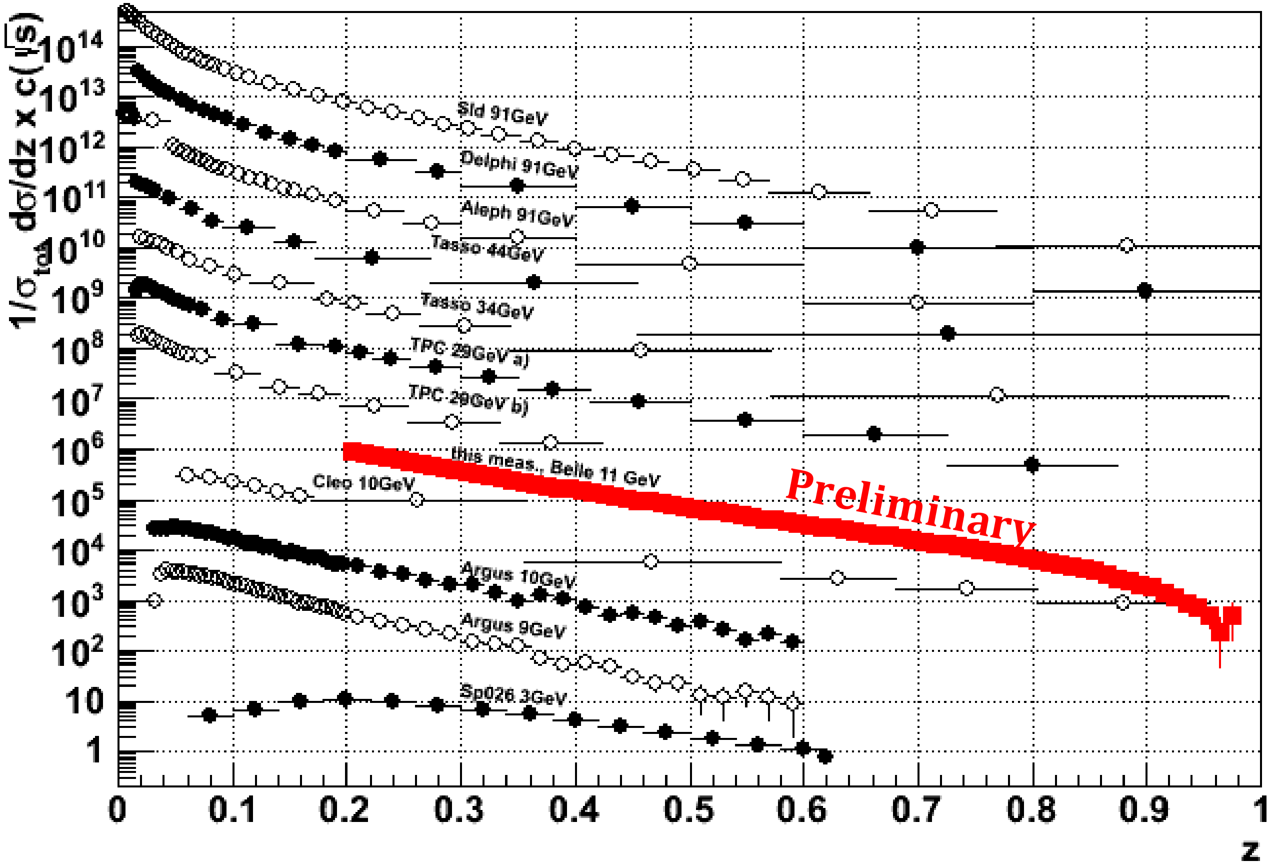


Systematic uncertainties:

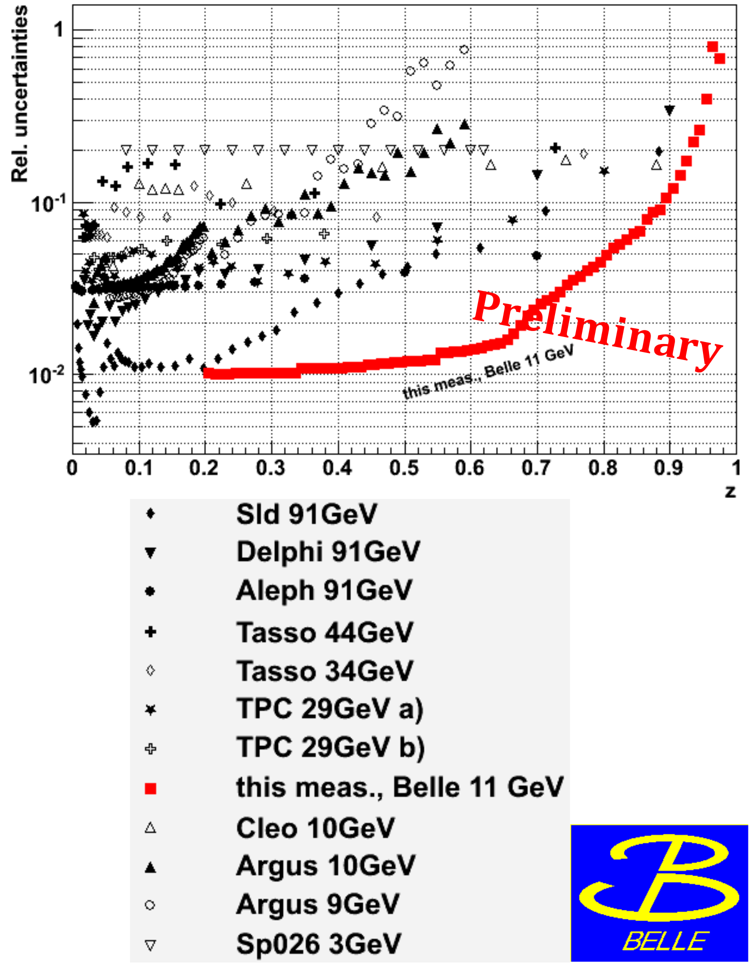
- $z \sim 0.6$ ⟶ 1% for pions, 2% for kaons
- $z \sim 0.9$ ⟶ 14% for pions, 50% for kaons

Pion multiplicities, comparison with existing data, Belle preliminary

selected data from e^+e^- collisions



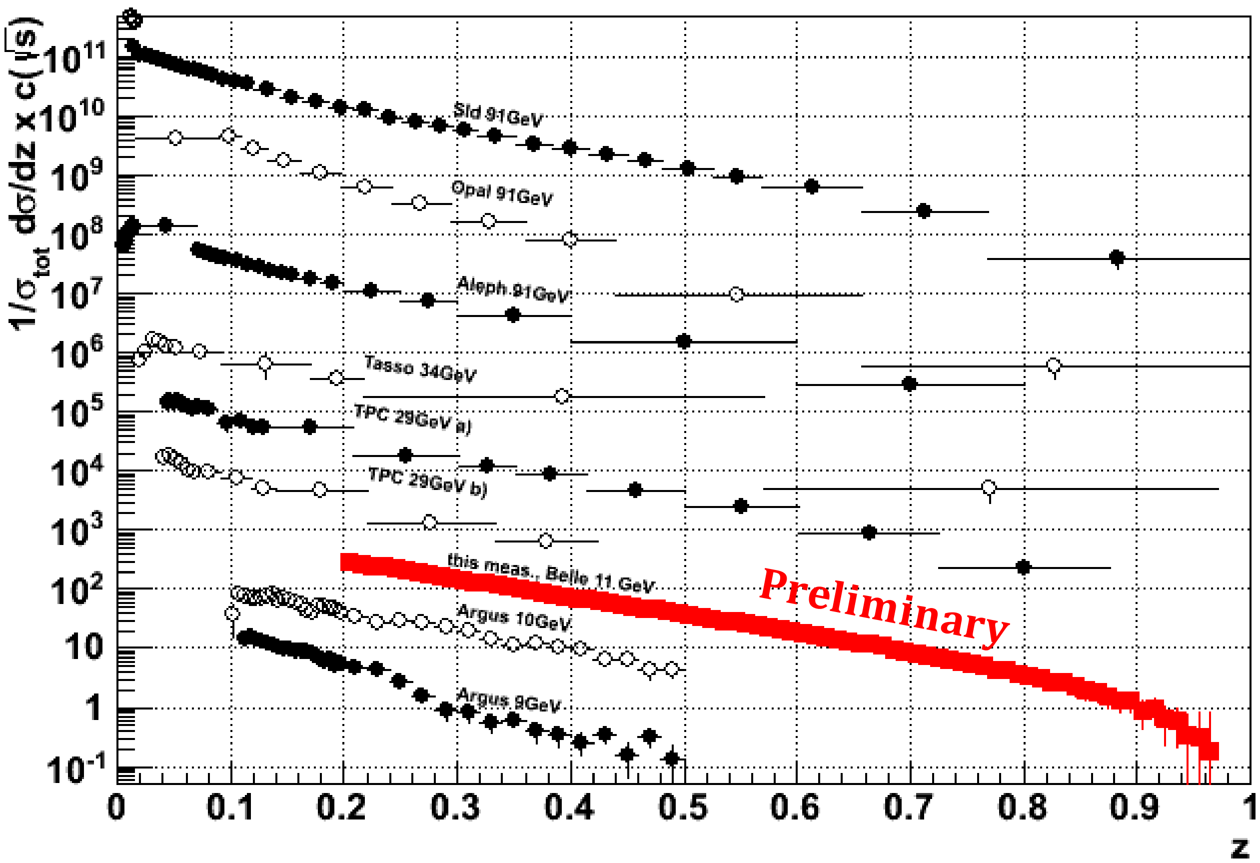
relative uncertainties



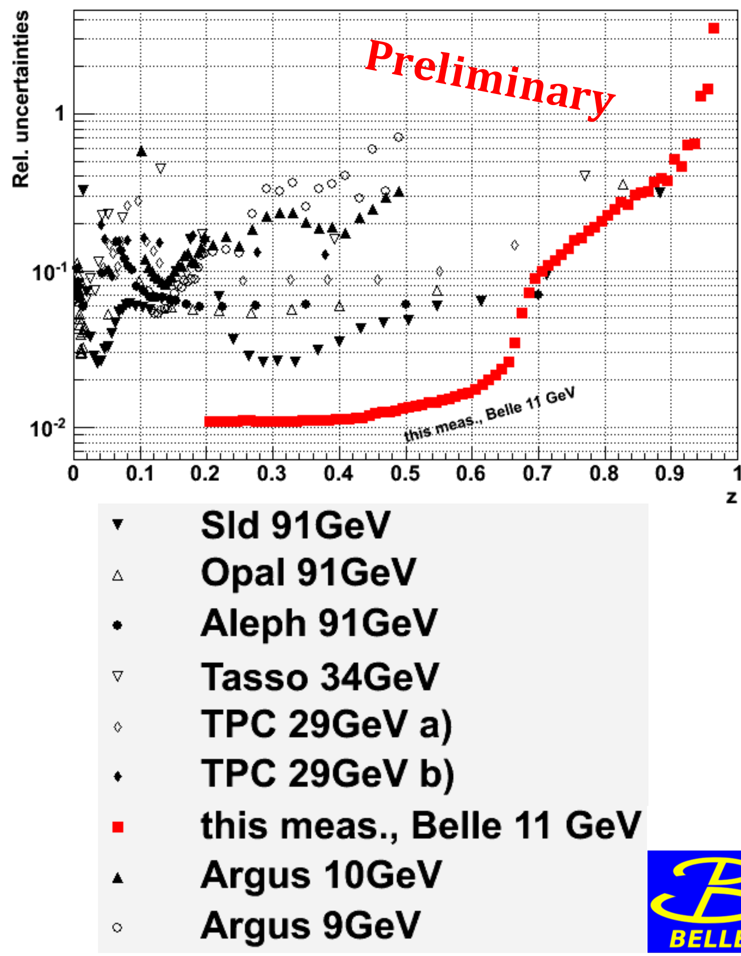
(plots from M.Leitgab, Fragmentation 2012)

Kaon multiplicities, comparison with existing data, Belle preliminary

selected data from e^+e^- collisions



relative uncertainties



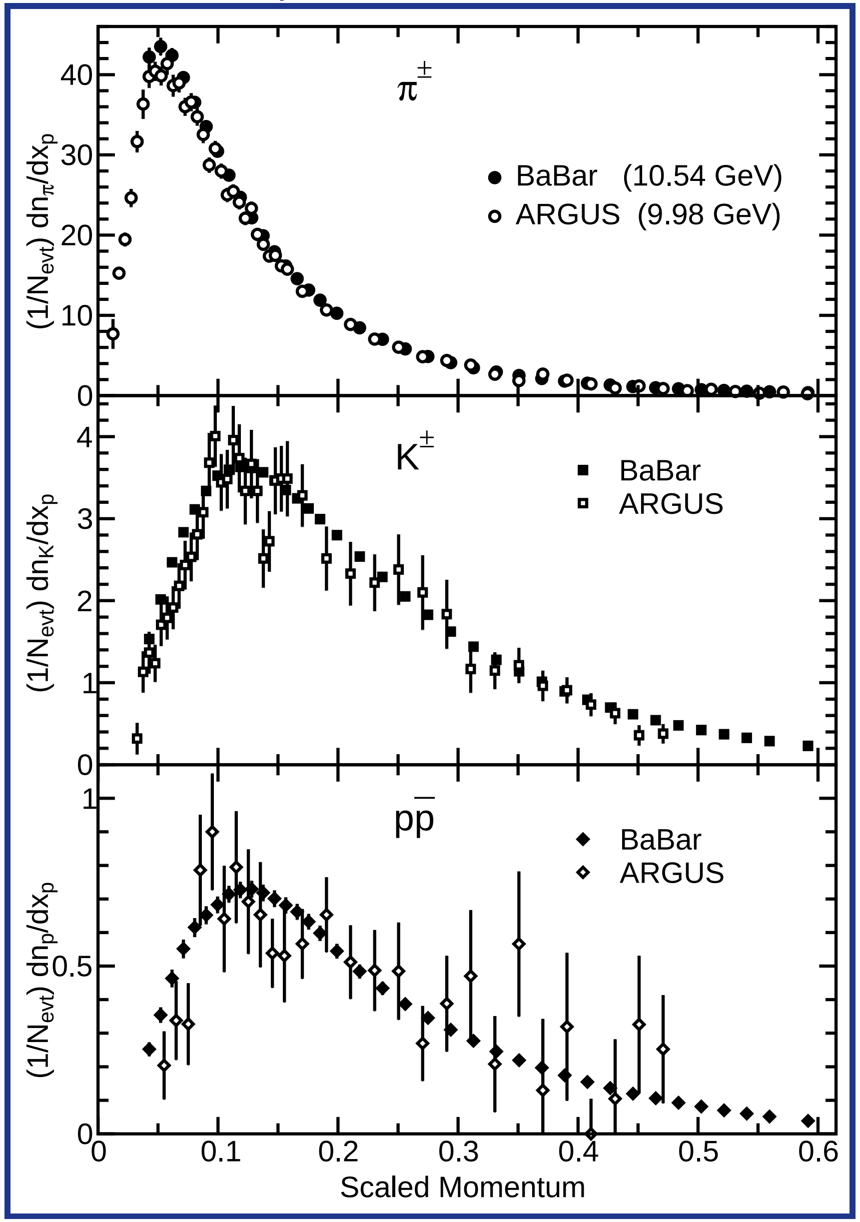
(plots from M.Leitgab, Fragmentation 2012)

Pion, kaon and proton multiplicities at BABAR, preliminary, new

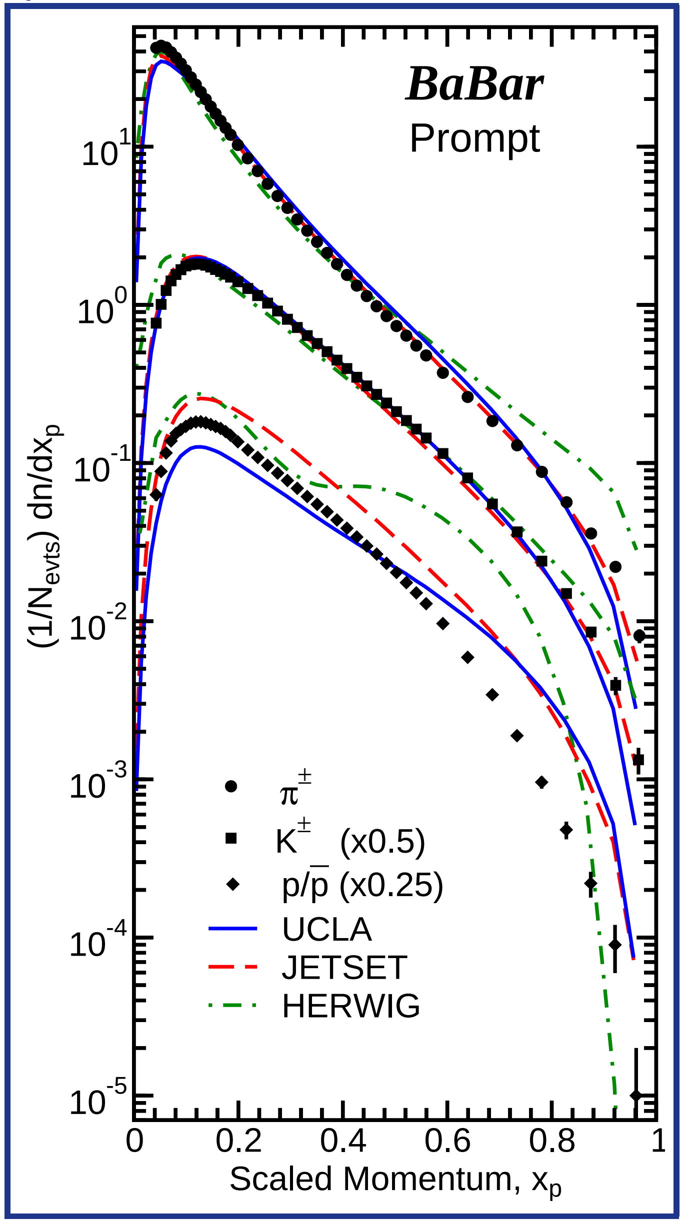
- update on previous Moriond 2004 prelim. results, still prelim. but paper is to be submitted soon
- samples:
  - $0.91\,\text{fb}^{-1}$ e^+e^- annihilations at 10.54 GeV (below the $\Upsilon(4S)$)
  - $3.6\,\text{fb}^{-1}$ e^+e^- annihilations at $\Upsilon(4S)$ peak for checks and calibrations
- precision dominated by systematics, achieved few % uncertainties up to large values of z
  - data control samples used to calibrate particle id / mis-id probabilities
  - data control samples used to improve MC-based backgrounds subtraction
  - control reconstruction effects comparing & combining 6 samples at different θ_{LAB}
- results are consistent with Belle

Pion, kaon and proton multiplicities at BABAR, preliminary, new

comparison with ARGUS



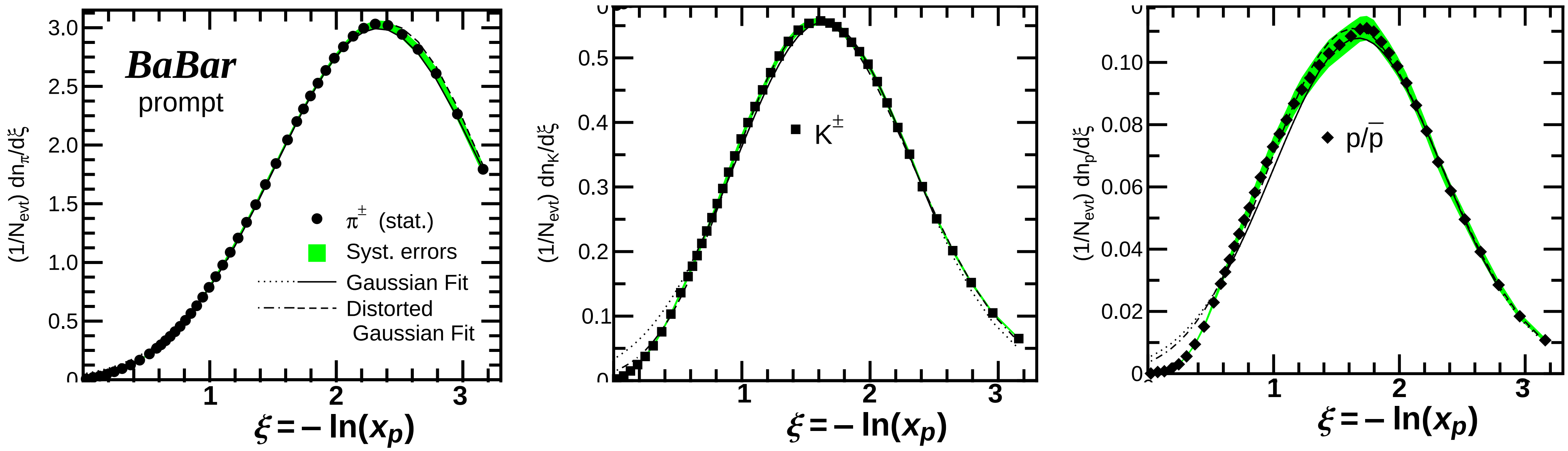
comparison with UCLA, JETSET, HERWIG



Pion, kaon and proton multiplicities at *BABAR*, preliminary, new

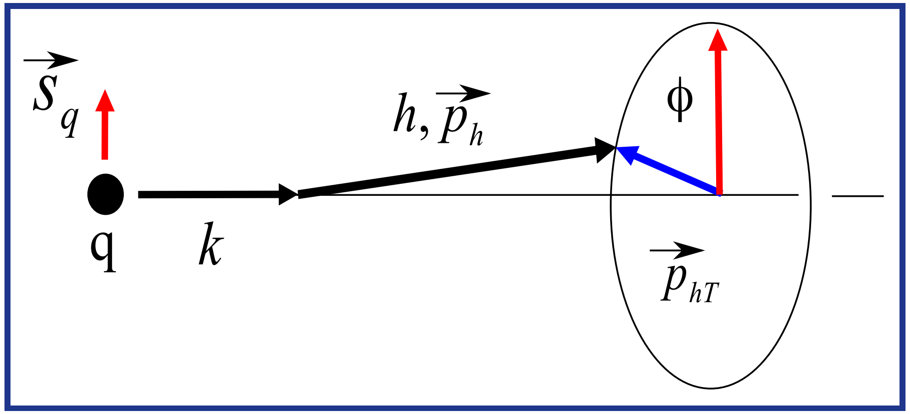
Modified Leading Logarithm Approximation (MLLA) with Local Parton-Hadron Duality (LPHD) ansatz predicts hadron multiplicities approx. Gaussian on $\xi = -\ln(x_p)$

plots show *BABAR* data compared to the MLLA predictions



Polarized fragmentation functions results

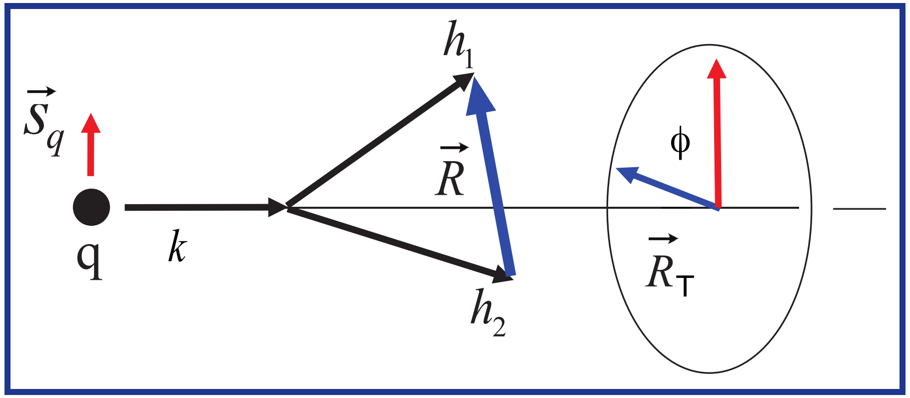
Polarized fragmentation functions: Collins term



- $D^h_{q\uparrow}(z, P^2_{h\perp}) = D^h_{1,q}(z, P^2_{hT}) + H^{\perp h}_{1,q}(z, P^2_{hT}) \frac{(\widehat{\mathbf{k}} \times \mathbf{P}_{hT}) \cdot \mathbf{S}_q}{zM_h}$
- polarized term $\propto (\widehat{\mathbf{k}} \times \mathbf{P}_{hT}) \cdot \mathbf{S}_q \propto \sin\phi$

  Collins effect

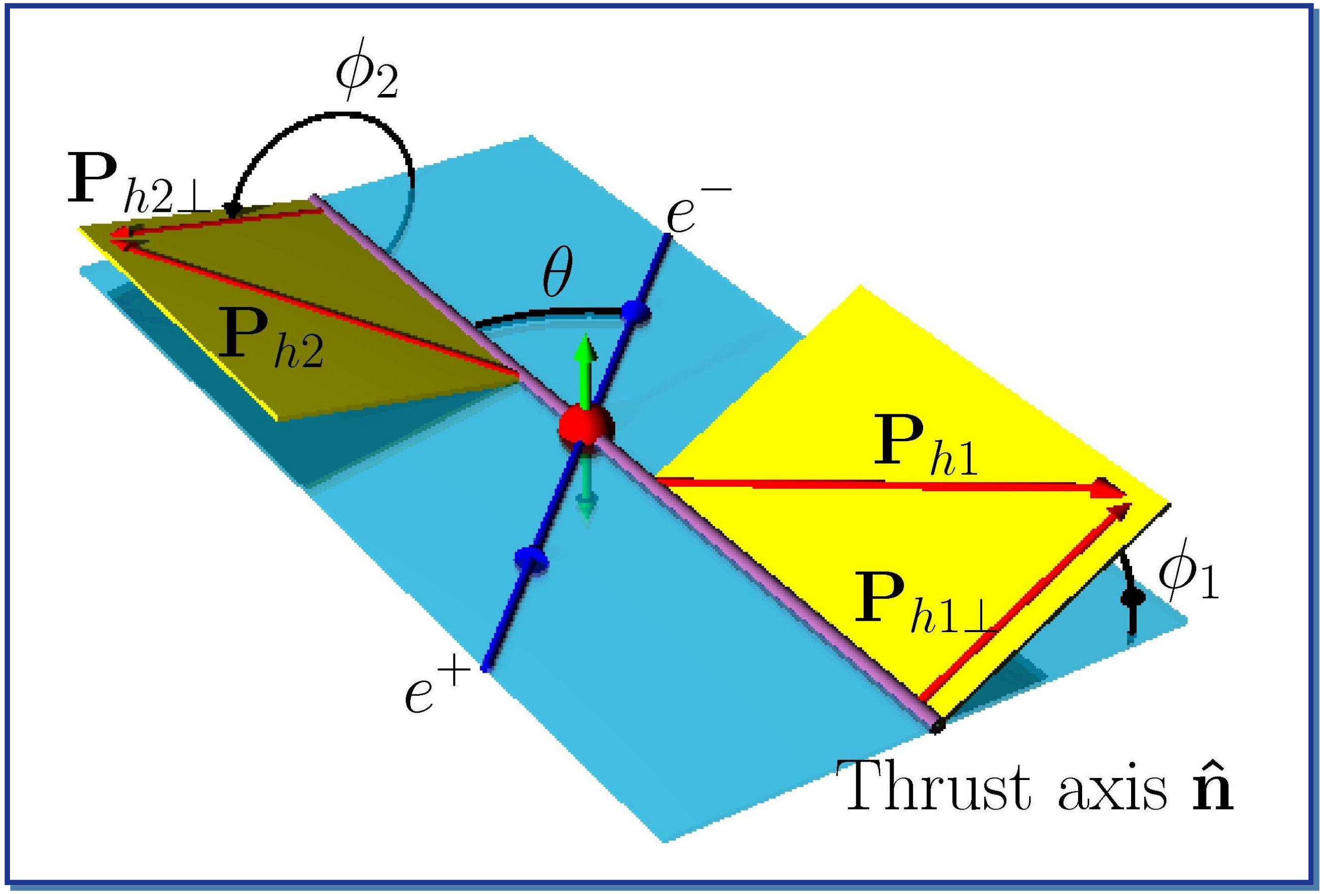
Polarized fragmentation functions: interference fragmentation function



- hadron pair multiplicity influenced by partons polarization
- polarized term $\propto (\widehat{\mathbf{k}} \times \mathbf{R}_T) \cdot \mathbf{S}_q \propto \sin\phi$

  interference fragmentation function effect

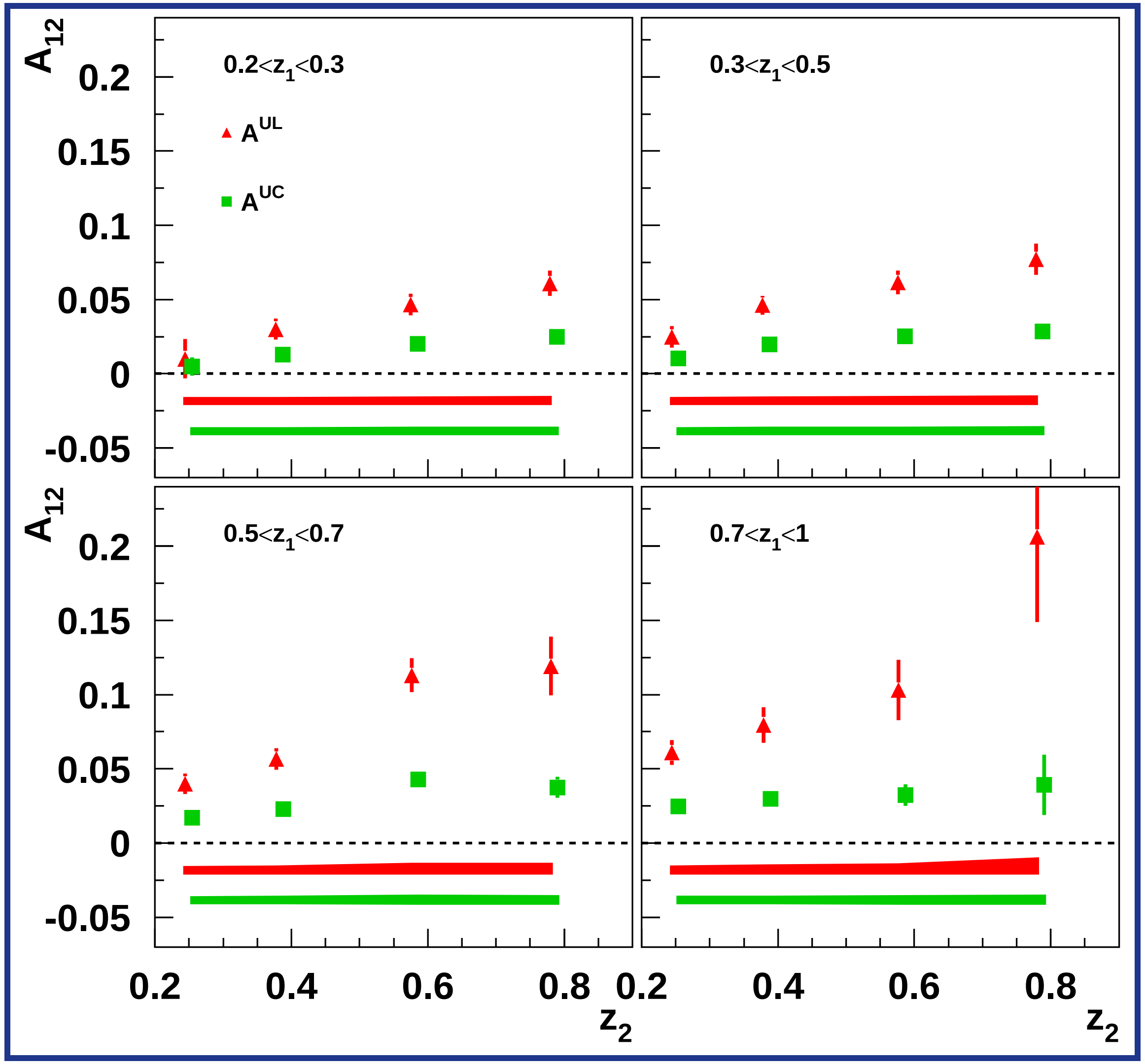
Collins asymmetries in $e^+e^- \to q\bar{q} \to \pi^+\pi^- X$



- entangled primary $q\bar{q}$ transverse spin components induce azymuthal asymmetries on hadron pair multiplicities, $\propto \cos(\phi_1 + \phi_2)$
- double ratio method: measure ratio of unlike-sign vs. like sign (UL) or vs. all (UC) → remove reconstruction acceptance effects

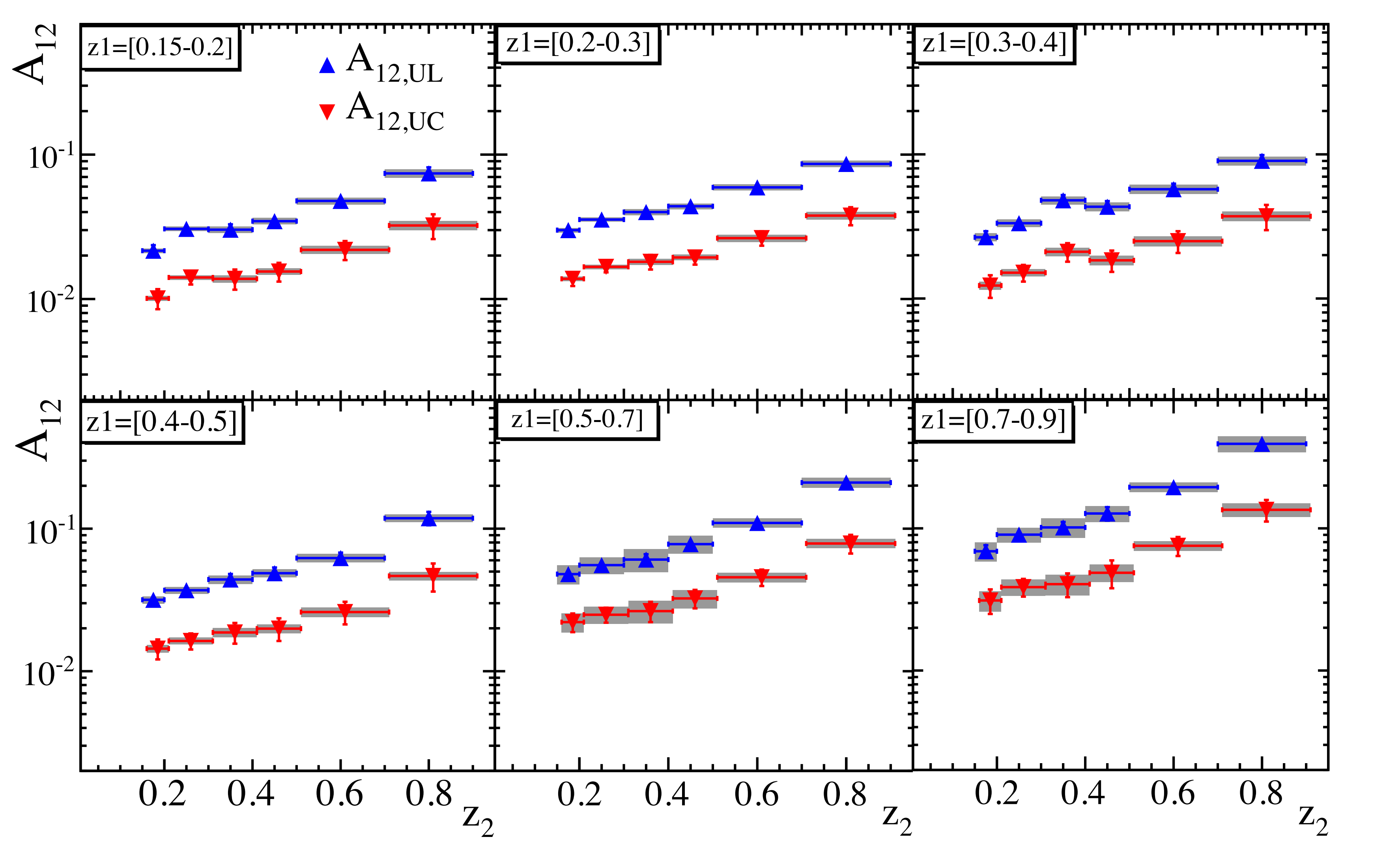
Collins Asymmetries vs. z_1, z_2 from Belle

- PRD 78 032011 (2008)
- erratum PRD 86, 039905(E) (2012)
  - thrust smearing corrections applied
- sample: 547 fb^{-1} e^+e^- annihilations at the $\Upsilon(4S)$ and 60 MeV below
- **Collins asymmetries**,
  - azimuthal $\cos(\phi_1 + \phi_2)$ modulations A_{12} of the normalized yield ratios of unlike-sign pion pairs over like-sign pion pairs A^{UL} (triangles), and of unlike-sign pion pairs over any charged pion pairs A^{UC} (squares) as a function of the fractional energy z_2 for 4 different bins of z_1, from top left to bottom right
  - systematics shown as bands (large correlations between bins)



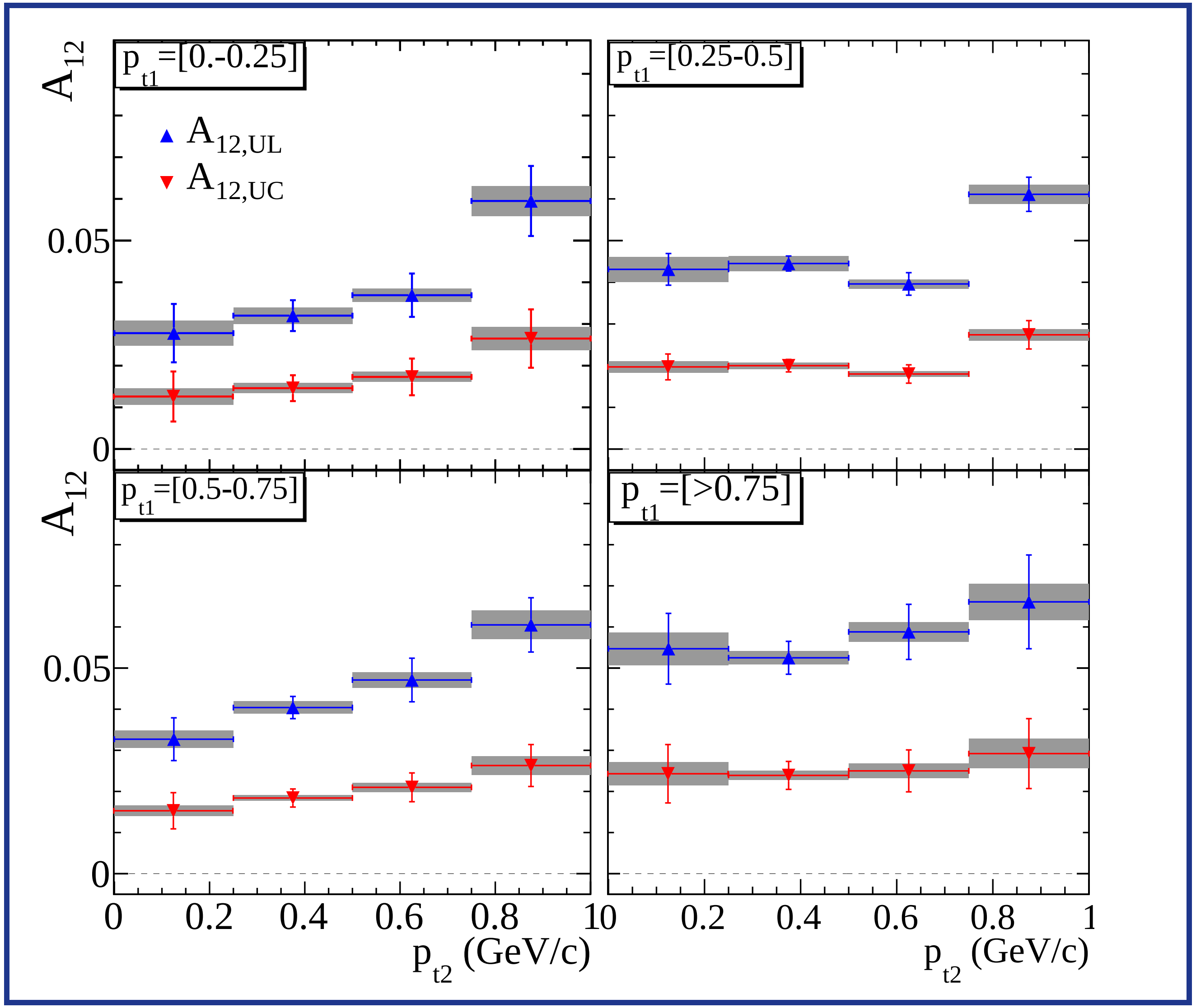
Collins Asymmetries vs. z_1, z_2 from BABAR, prelim. (ICHEP 2012, arXiv:1211.5293 [hep-ex])

- sample: 468 fb^{-1} e^+e^- annihilations at the $\Upsilon(4S)$



Collins Asymmetries vs. p_{t1}, p_{t2} from *BABAR*, prelim. (ICHEP 2012, arXiv:1211.5293 [hep-ex])

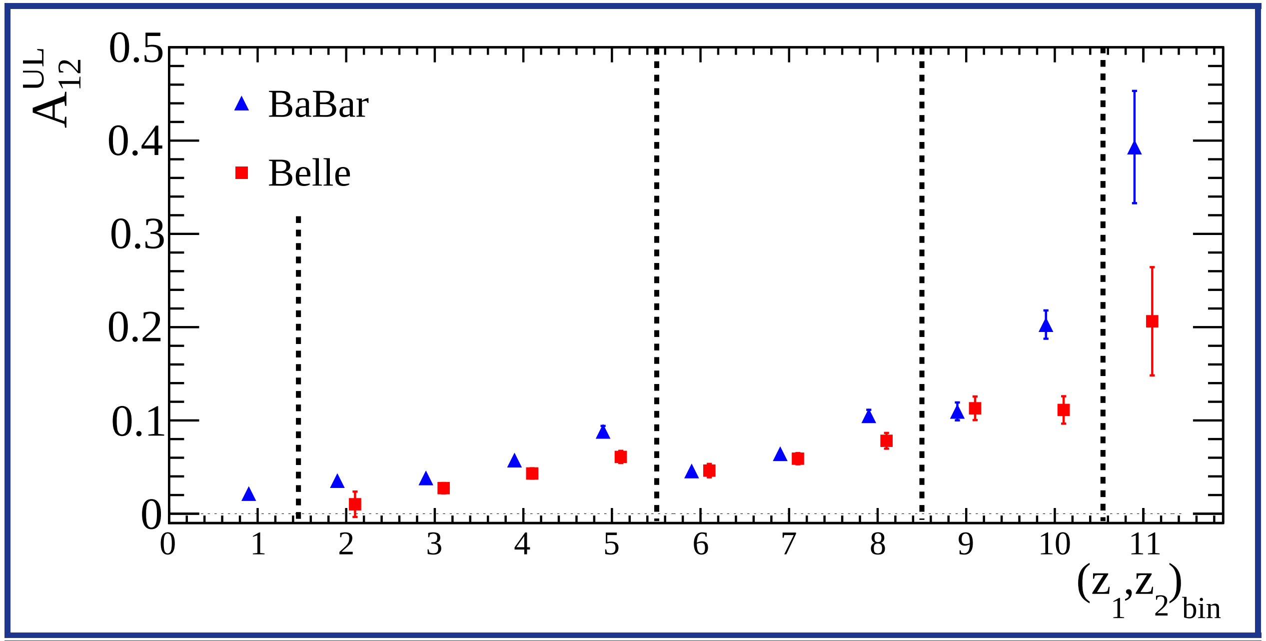
- sample: 468 fb^{-1} e^+e^- annihilations at the $\Upsilon(4S)$

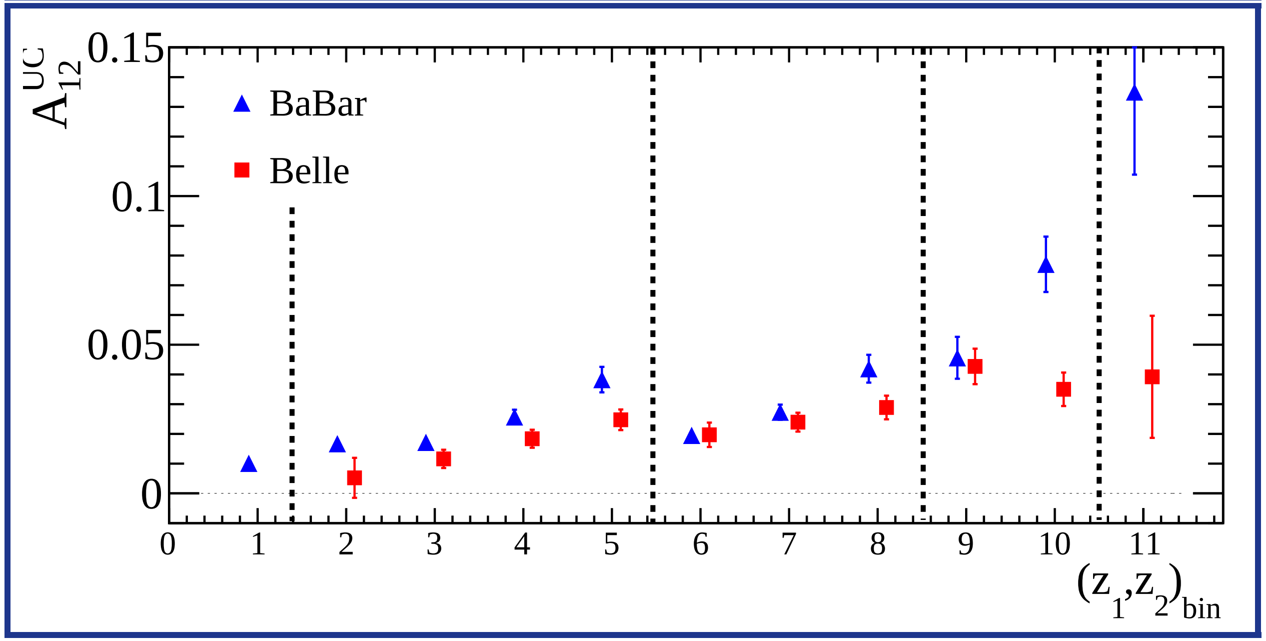


Collins Asymmetries: *BABAR* vs. Belle new

- *BABAR*: $0.15 < z < 0.9$
- Belle $0.2 < z < 1$
- 10+1 symmetrized z_1, z_2 bins
- courtesy of I.Garzia

Belle data after erratum paper

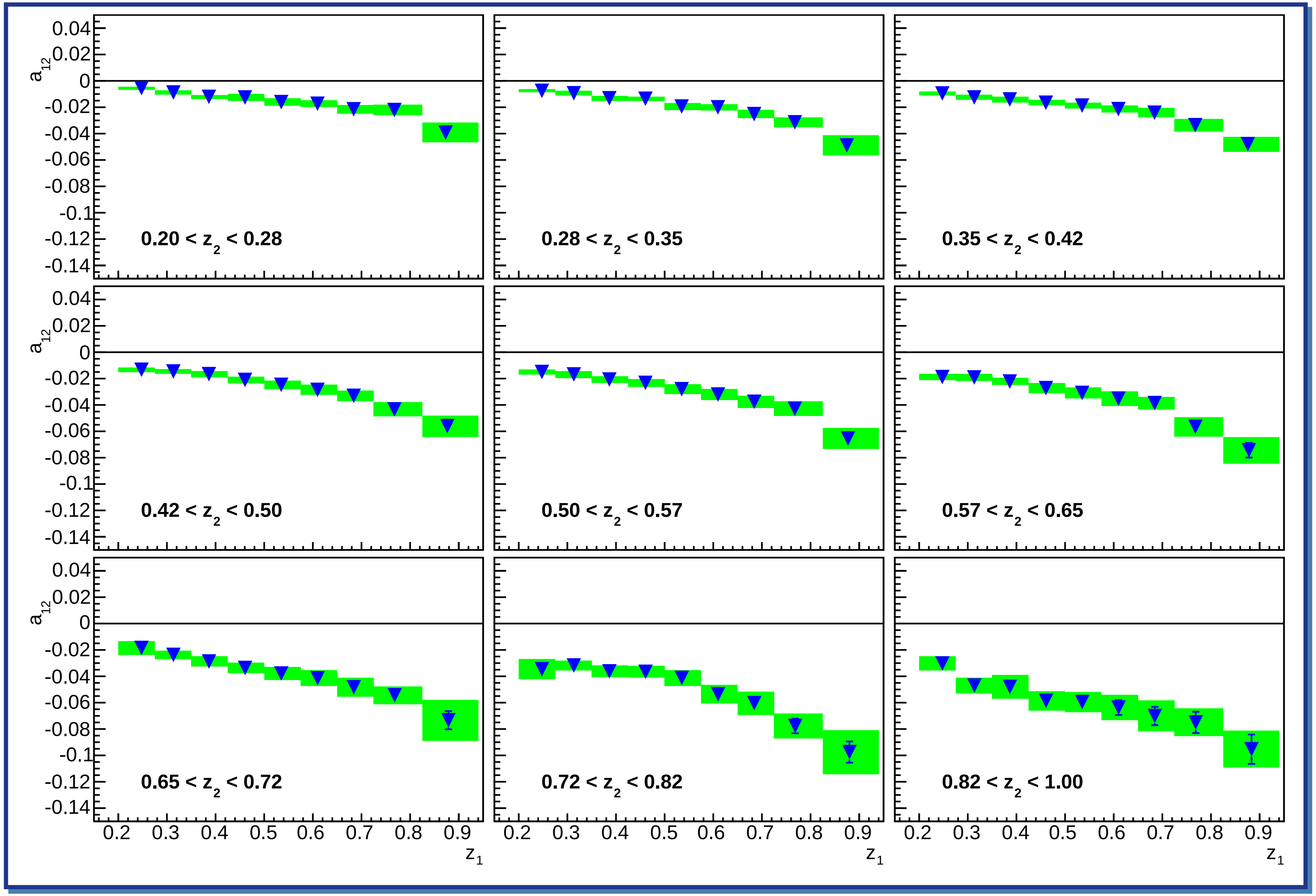




Interference fragmentation function asymmetries in Belle

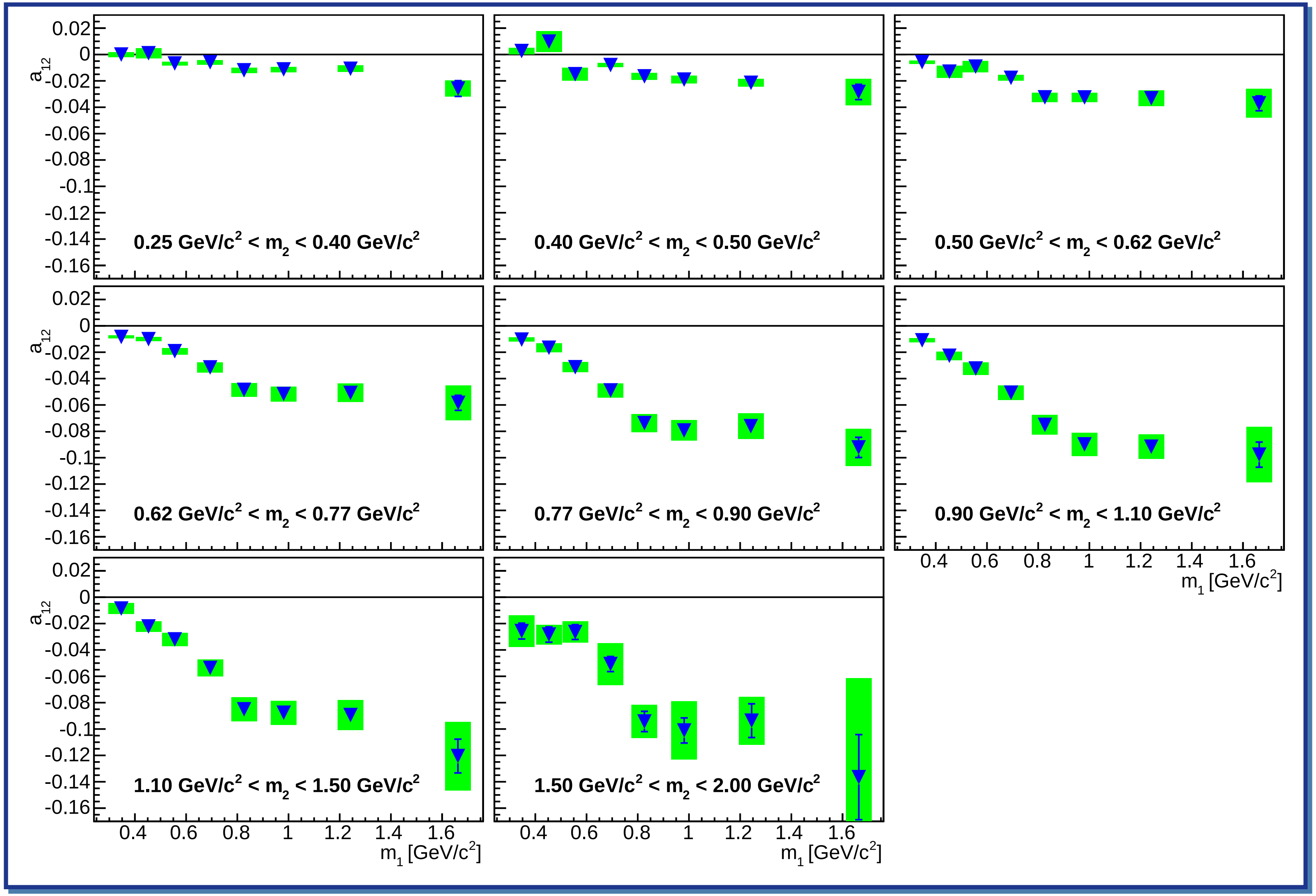
- PRL 107, 072004 (2011) "Transverse Polarization Asymmetries of Charged Pion Pairs"
- sample: 672 fb^{-1} e^+e^- annihilations at the $\Upsilon(4S)$ and 60 MeV below
- measure $\cos(\phi_1 + \phi_2)$ modulations a_{12} of normalized yield of charged pion pairs in opposite hemispheres
- $a_{12} = a_{12}(z_1, z_2, m_1, m_2)$
  - z_i fractional energies of pion pairs
  - m_i invariant masses of pion pairs

Belle IFF asymmetries as function of z_2 for 9 bins of z_1



filled areas represent the systematic uncertainties

Belle IFF asymmetries as function of invariant mass m_2 for 8 different bins of m_1



filled areas represent the systematic uncertainties

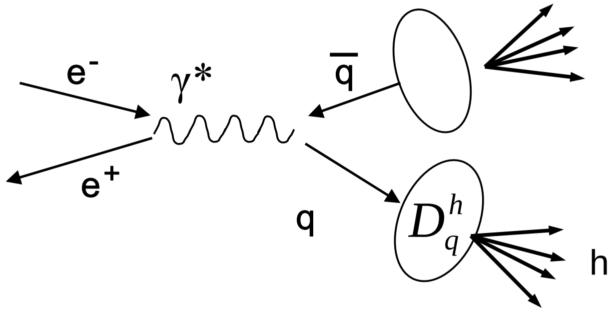
Conclusions

- B-factories provided:
  - more complete and precise light quark unpolarized fragmentation functions
  - first direct extraction of spin-dependent fragmentation asymmetries

Extra backup slides

Fragmentation function extraction from data

- In LO: FF D_i^h describes probability for a parton i to fragment into a hadron h



- FF at different energy scales relatable by DGLAP evolution equations
- FFs D_i^h can be extracted from e+e- data in pQCD analysis:

$$N^h(z,Q^2) = \frac{1}{\sigma_{\text{tot had}}} \frac{d\sigma(e^+e^- \to hX)}{dz} \qquad z \equiv \frac{E_h^{cms}}{\sqrt{s}/2}$$

$$\overset{\text{NLO QCD}}{=} \sum_{i=q,\bar{q},g} C_i^{NLO}(z,\alpha_s) \otimes D_i^h(z,Q^2)$$

measured: hadron multiplicity

extracted: FFs

Simultaneous pQCD fit for several $N^h(z,Q^2)$

B-factories

- e^+e^- annihilations at the $\Upsilon(4S)$, high luminosity
- general purpose detectors
- select hadronic jet-like events that are well contained in the detector
- clean events, accurate simulation (except Bhabhas)
- subtract well simulated tau pair background
- systematic-limited measurements, exploit statistics to reduce systematics

Careful particle identification

- Particle misidentification expected to be largest uncertainty:

particle identification probabilities $p(i \to j)$:
probability that particle of species *i* PID-selected as particle of species *j*.

Physical particle: π → Belle PID likelihood information from: Drift Chamber (dE/dx), Cherenkov, ToF, Calorimeter, Muon Detector →

Reconstructed particle:
- $p(\pi \to e)$ → e
- $p(\pi \to \mu)$ → μ
- $p(\pi \to \pi)$ → π
- $p(\pi \to K)$ → K
- $p(\pi \to p)$ → p

$$\vec{N}_x = \begin{pmatrix} N_e \\ N_\mu \\ N_\pi \\ N_K \\ N_p \end{pmatrix}$$

$$[P]_{ij} = \begin{pmatrix} p(e\to e) & p(\mu\to e) & p(\pi\to e) & p(K\to e) & p(p\to e) \\ p(e\to \mu) & p(\mu\to \mu) & p(\pi\to \mu) & p(K\to \mu) & p(p\to \mu) \\ p(e\to \pi) & p(\mu\to \pi) & p(\pi\to \pi) & p(K\to \pi) & p(p\to \pi) \\ p(e\to K) & p(\mu\to K) & p(\pi\to K) & p(K\to K) & p(p\to K) \\ p(e\to p) & p(\mu\to p) & p(\pi\to p) & p(K\to p) & p(p\to p) \end{pmatrix}$$

$$\vec{\tilde{N}}_j = \hat{P}\,\vec{N}_i$$

$$\vec{N}_i = \hat{P}^{-1}\,\vec{\tilde{N}}_j :$$ correction through inversion of matrix.

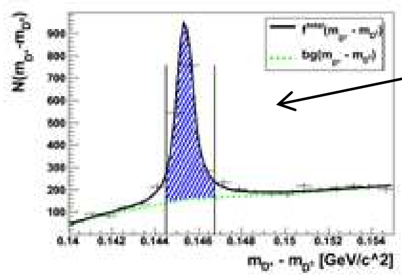
Particle identification performance measured on data control samples

- Experimental data based extraction of PID probabilities by decay sample study

e.g. $D^* \rightarrow D^0 \pi^+_{slow}$, $D^0 \rightarrow K^- \pi^+_{fast}$

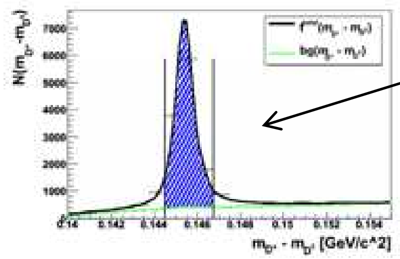
a) Kinematically reconstruct D*

b) extract PID probability from invariant mass plots



m_{D^*} - m_{D^0} for **K^- tracks** with p_{lab} in [1.4; 1.6] GeV/c, $\cos\theta_{lab}$ in [0.02; 0.21], **reconstructed as π**

$$p_{(K^- \rightarrow \pi^-)} = \frac{\text{(upper plot)}}{\text{(lower plot)}}$$



m_{D^*} - m_{D^0} for **K^- tracks** with p_{lab} in [1.4; 1.6] GeV/c, $\cos\theta_{lab}$ in [0.02; 0.21]

$$p_{(K^- \rightarrow \pi^-)} \approx 0.111 \pm 0.004$$

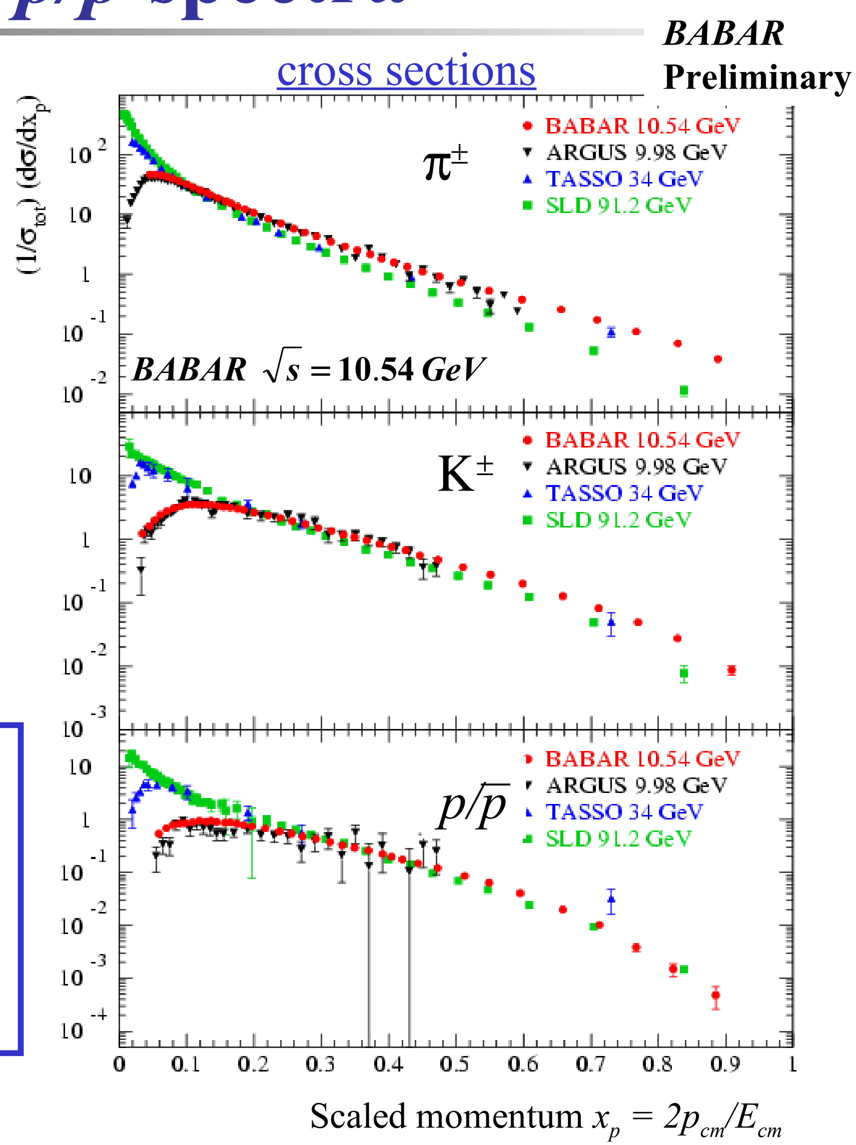
BELLE

Similar preliminary results from *BABAR* shown in Moriond QCD 2004 by F.Anulli

$\pi^\pm$, $K^\pm$, $\bar{p}/p$ spectra

- data samples used in these analysis:
  - 0.9 fb-1 off-resonance
  - 3.6 fb-1 on-resonance
- given:
  - excellent particle-ID system
  - tracking, photon, PID efficiencies calibrated from data

BABAR can reach few % precision level



- *BABAR* cover the full kinematics range
- precision comparable to that from measurements at $\sqrt{s}$ = 91 GeV
- test cross section scaling properties up to very high values of $x_p = 2p_{cm}/E_{cm}$