BaBar and BESIII results on fragmentation functions

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Outline:

- Fragmentation function in e^+e^- annihilation

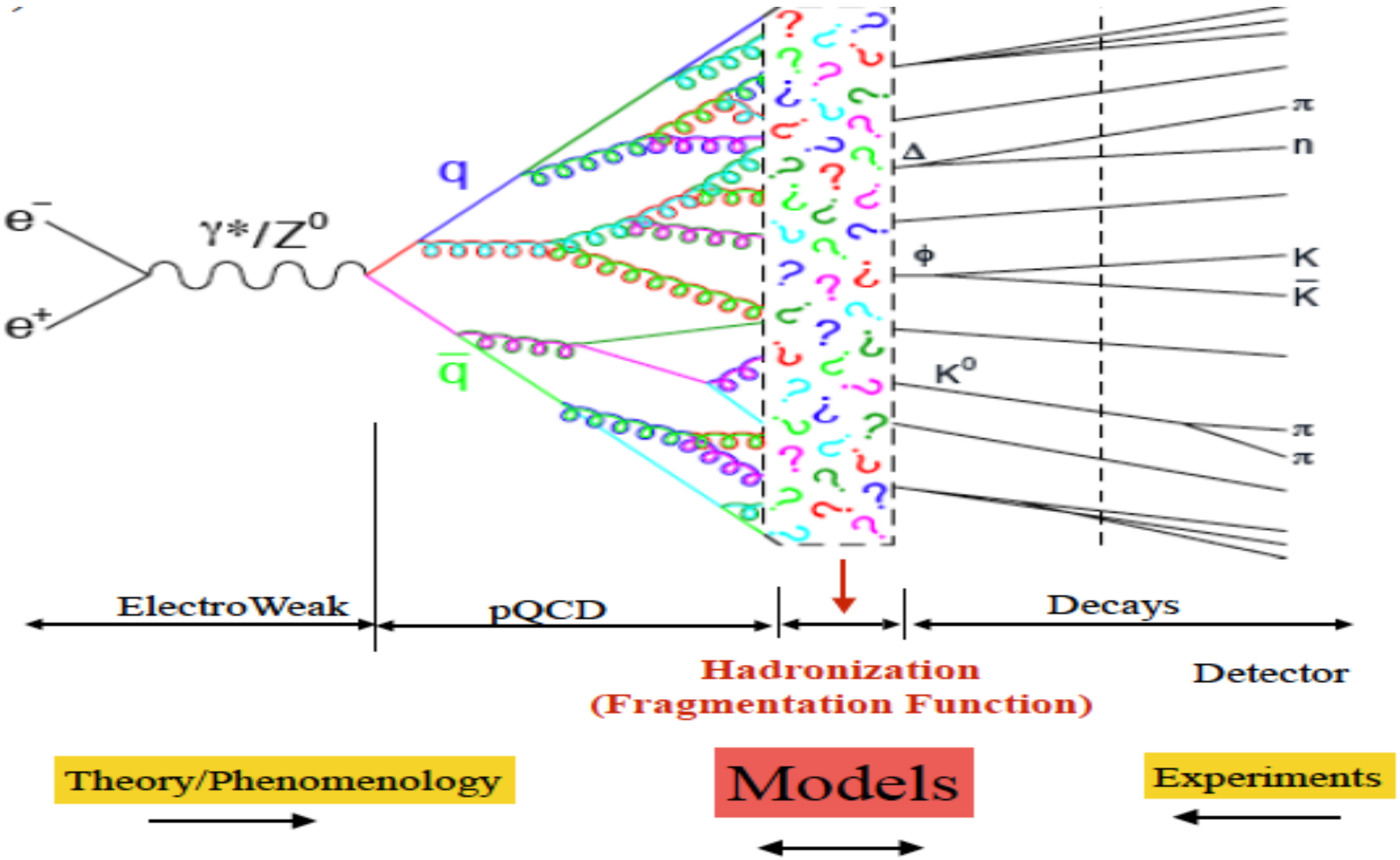
- Polarized Fragmentation functions
  - Measurement of Collins asymmetries:
    - $e^+e^- \rightarrow \pi\pi + X$, $\pi K + X$, and $KK + X$
    - Global fits

- Unpolarized Fragmentation functions
  - Inclusive production of light hadrons at ~10 GeV
    - π, K, p/$\overline{\mathrm{p}}$ production
    - Global fits
  - Inclusive studies on charmed baryons at ~10 GeV
    - Inclusive Λ_c, Ω_c and Ξ_c spectra

- Summary and perspectives

Fragmentation functions in e^+e^- annihilation

The process that transform quarks and gluons into colorless hadrons is referred to as **FRAGMENTATION** (or hadronization)



ElectroWeak

pQCD

Hadronization

(Fragmentation Function)

Decays

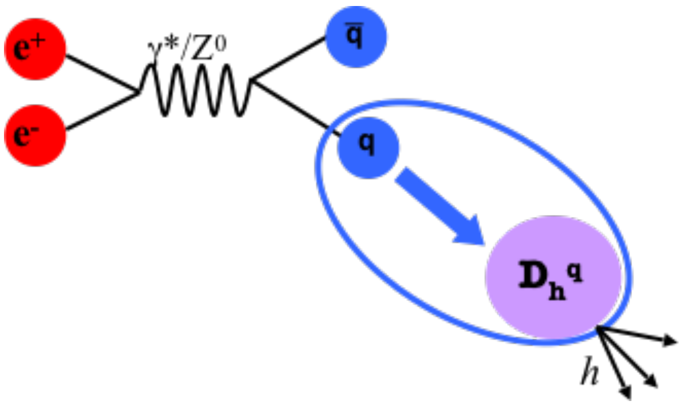
Detector

Theory/Phenomenology

Models

Experiments

Fragmentation functions in e^+e^- annihilation



- Fragmentation functions (FFs) describe the process of hadronization of a parton
- **Non-perturbative** objects
- **Universal** functions
- Depend on the scaled energy of the hadron *h*:

$$x = 2E_h/\sqrt{s},\ \text{with } \sqrt{s}=Q \text{ in } e^+e^-$$

Experimentally related to the final-state single particle energy distribution

Parton Fragmentation Function

$$\frac{1}{\sigma_0}\frac{d\sigma^{e^+e^-\to hX}}{dx} = F^h(x,s) = \sum_{i=q,\bar{q}}\int_x^1 \frac{dz}{z} C_i\left(z,\alpha_s(\mu),\frac{s}{\mu^2}\right)\boxed{D_i^h\left(\frac{x}{z},\mu^2\right)} + \mathcal{O}\left(\frac{1}{\sqrt{s}}\right)$$

$$\sigma_0 = \sum_q \frac{4\pi\alpha^2}{s}\left(1+\frac{\alpha_s}{\pi}+\ldots\right)$$

process dependent short distance interaction

non-perturbative part

- $D_1^h(z,Q^2)$ describes the probability that a parton *i* fragments into a hadron *h* carrying a fraction *z* of the parton momentum
- e^+e^- annihilation is the cleanest environment to study the fragmentation functions
  - parton momenta known, no need of PDFs, but low sensitivity to gluon FF

Polarized (*i.e.* spin-dependent) FFs

- Connection between microscopic (quark spin) and macroscopic observables (angular distributions and/or polarization of produced hadrons)

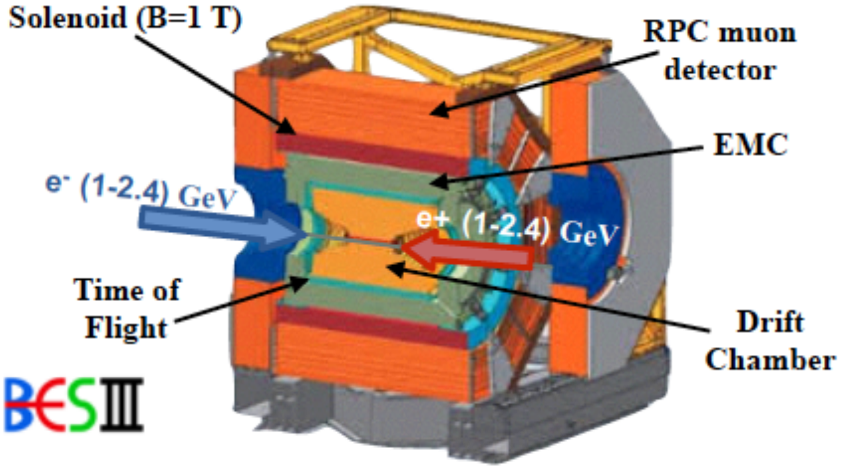
- Needed to:
  - test schemes of factorization and universality among e^+e^-, (SI)DIS, and *pp*
  - probe evolution as fundamental QCD prediction
  - in general test any approach to solve QCD at soft scale
- Spin analyzer for studying the transversity PDF
  - 3D structure of the nucleon

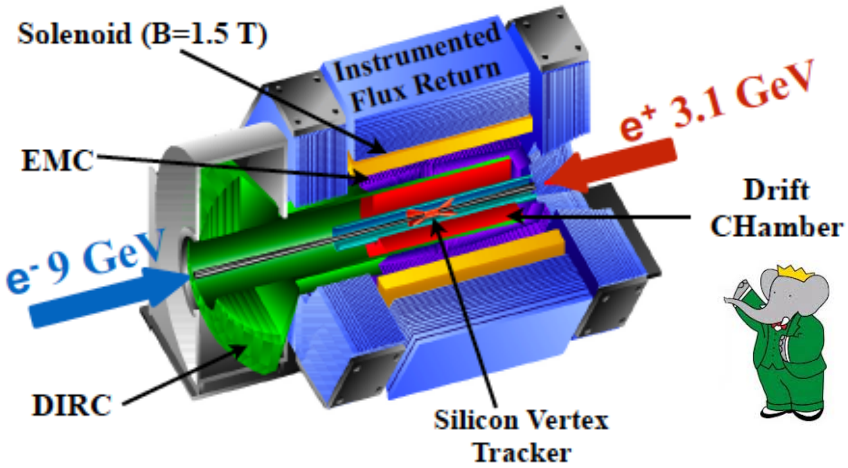
- Many FFs defined theoretically, depending on the polarization of the parton and of produced hadron(s)

- Great improvement in recent years thanks to new high-quality data collected in the different experimental schemes

Three players at low-medium Q^2

BESIII at $Q^2 \sim 13$ GeV^2, and *BABAR* and Belle at $Q^2 \sim 110$ GeV^2





- Beijing Electron Positron Collider II (BEPCII)
  - **Symmetric** e^+e^- collider
  - Beam energy: 1-2.3 GeV
  - 2008: test run
  - 2009-today: BESIII physics runs
- Luminosity: $\mathcal{L} \sim$ **62 pb^{-1}** @ 3.65 GeV used here (below open charm threshold)

NIM **A614**, 345 (2010)

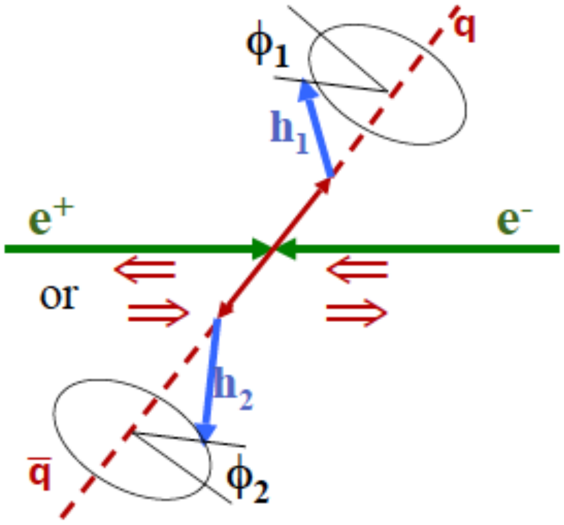
- PEP-II storage ring
  - **asymmetric** e^+e^- collider operating at the $\Upsilon(4S)$ resonance ($\sqrt{s}$=10.58 GeV)
    - High Energy Ring (HER): 9.0 GeV e^-
    - Low Energy Ring (LER): 3.1 GeV e^+
    - c.m.-lab boost, $\beta\gamma \approx 0.56$
- High luminosity: $\mathcal{L} \sim$ **468 fb^{-1}** used here

NIM **A479**, 1 (2002),
update: NIM **A729**, 615 (2013)

Note: Belle results will be covered by Gunar Schnell (today) and Ralf Seidl (tomorrow)

Collins asymmetries for charged pions and kaons

The Collins Fragmentation Function



Polarized FF (Collins FF): dependence on $z=2E_h/\sqrt{s}$, $P_\perp$, and s_q

$$D_1^{q\uparrow}(z,\mathbf{P}_\perp;s_q) = \overset{\text{“Standard” unpolarized FF}}{\overset{\downarrow}{D_1^q}}(z,P_\perp) + \frac{P_\perp}{zM_h}\boxed{H_1^{\perp q}(z,P_\perp)\,\mathbf{s}_q\cdot(\mathbf{k}_q\times\mathbf{P}_\perp)}$$

- **$H_1^\perp$** is the **polarized** fragmentation function or **Collins FF**
- **Chiral-odd** function
- could arise from a **spin-orbit** coupling
- leads to an asymmetry in the angular distribution of final state particles (**Collins effect**) NPB 396,161(1993)
- first non-zero Collins effect observed in SIDIS PRL 94,012002(2005) NPB 765, 31(2007)

In **e^+e^- annihilation**, γ^* (spin-1) → spin-1/2 q and $\bar{q}$

- in a given event, the spin directions are unknown, but they must be parallel
- they have a polarization component transverse to the q direction ~$\sin^2\theta$ (θ wrt the e^+e^-)

- exploit this correlation by using hadrons in opposite jets

$$e^+e^-\rightarrow q\bar{q}\rightarrow\pi_1\pi_2X\ \ (q=u,d,s) \Longrightarrow \sigma\propto\cos(\phi_i)H_1^\perp(z_1)\otimes H_1^\perp(z_2),$$

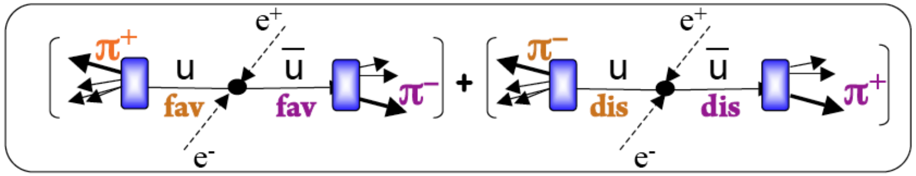
Collins effect in hadron-hadron correlation

Detection of hadron pairs with same or opposite charge sensitive to different combination of **favored** and **disfavored** FFs

- **favored FF:** one of the parent quarks matches a valence quark in the hadron,
  - i.e.: $u \to \pi^+, d \to \pi^-, s \to K^-, \ldots$
- **disfavored FF:** no such match, *i.e.* $d \to \pi^+, u \to \pi^-, s \to K^-, s \to \pi^\pm, \ldots$

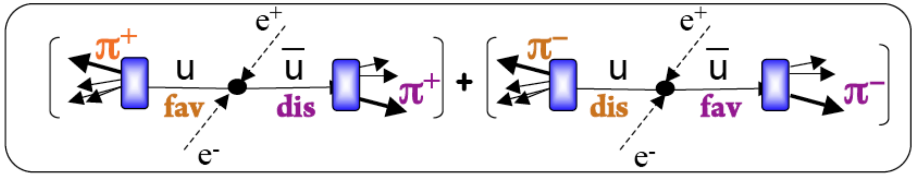
Unlike-sign pion pair = **U:**

$\pi^{\mp}\pi^{\pm}$: **(fav x fav)+(dis x dis)**



Like-sign pion pair = **L:**

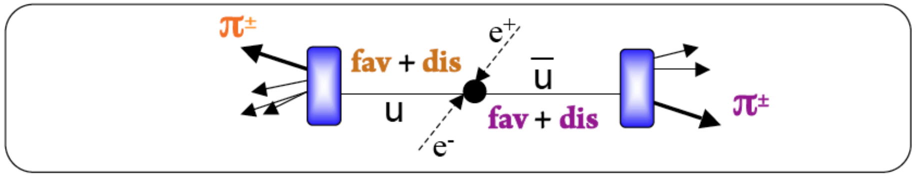
$\pi^{\pm}\pi^{\pm}$: **(fav x dis)+(dis x fav)**



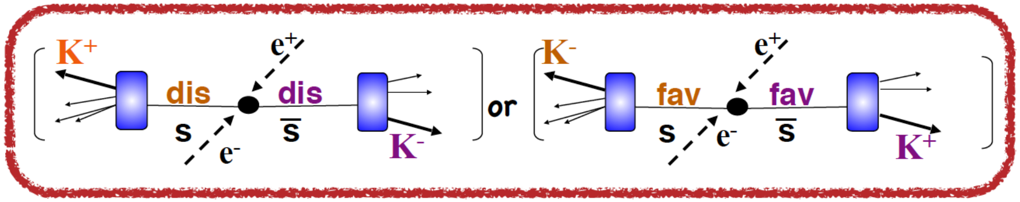
Charged pion pair = **C (U+L):**

$\pi\pi$: **(fav + dis)x(fav + dis)**

$\pi = \pi^{\pm}$



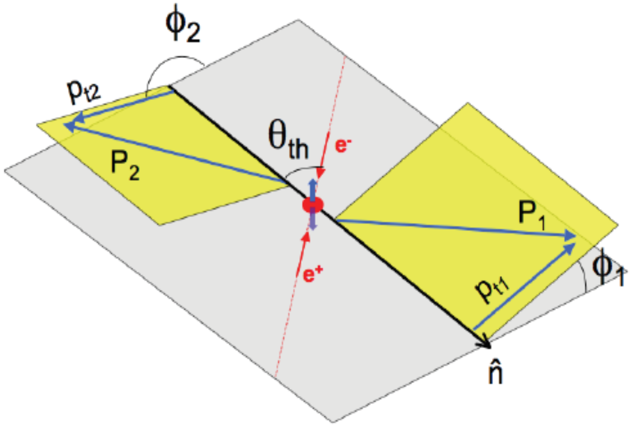
Similarly for Unlike-sign Kaon pairs:



Analysis reference frames

See D. Boer, NPB 806, 23 (2009)

All quantities in e^+e^- center of mass

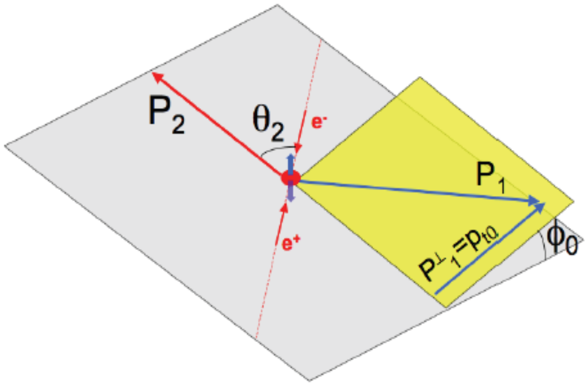


RF12 or Thrust RF

- **Thrust axis** to estimate the $q\bar{q}$ direction
- $\phi_{1,2}$ defined using thrust-beam plane
- Modulation diluted by gluon radiation, detector acceptance,…

$$\sigma \sim 1 + \frac{\sin^2\theta_{th}}{1+\cos^2\theta_{th}}\cos(\phi_1+\phi_2)\frac{H_1^\perp(z_1)\bar{H}_1^\perp(z_2)}{D_1(z_1)\bar{D}_1(z_2)}$$

RF0 or Second hadron momentum RF



- Alternatively, just use **one track** in a pair
- Very clean experimentally (no thrust axis), less so theoretically
- Gives quark direction for higher pion momentum

$$\sigma \sim 1 + \frac{\sin^2\theta_2}{1+\cos^2\theta_2}\cos(2\phi_0)\mathcal{F}\left[\frac{H_1^\perp(z_1)\bar{H}_1^\perp(z_2)}{D_1(z_1)\bar{D}_1(z_2)}\right]$$

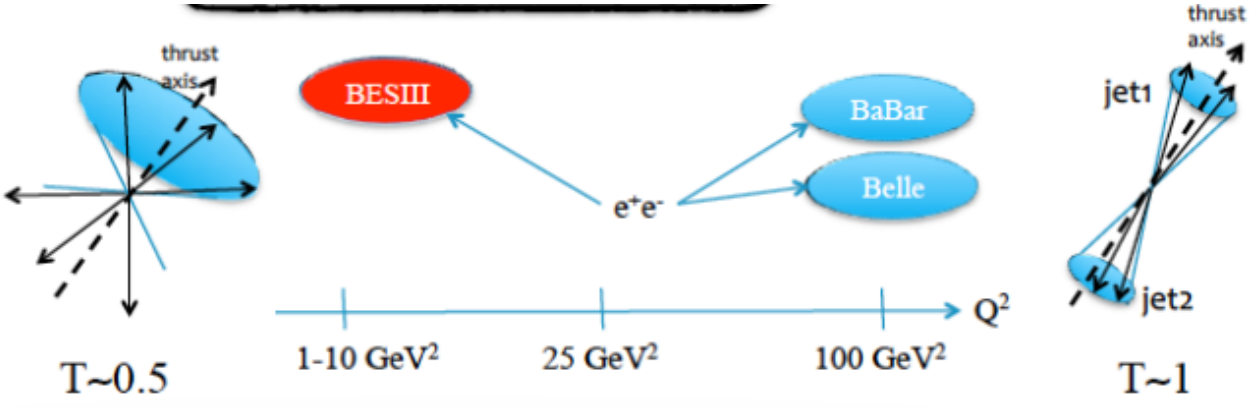
Collins effect is measured as a function of the pions fractional energy ($z_{1,2}=2E_\pi/\sqrt{s}$), pions transverse momentum (p_{t1},p_{t2},p_{t0}), and as a function of the polar angle of the reference axis (θ_{th}, θ_2)

Analysis reference frames

$$T = \sum_i \frac{|\mathbf{P}\cdot\hat{\mathbf{n}}|}{|P|}$$

thrust axis $\equiv \hat{\mathbf{n}}$

$0.5 \leq T \leq 1$

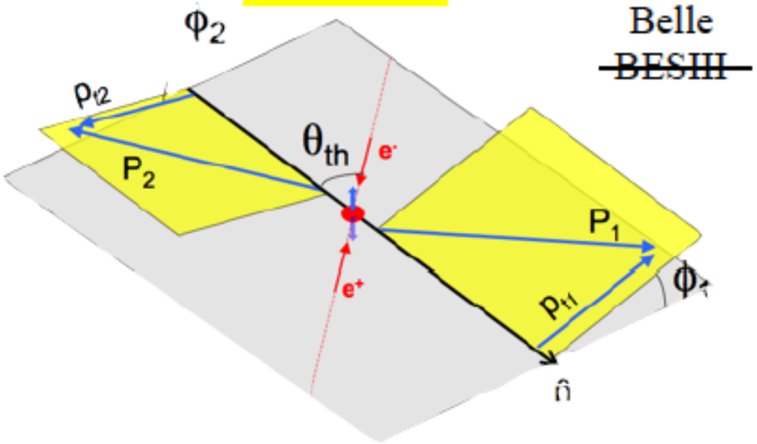


Events in BESIII much more spherical, and the two hemispheres are hardly identifiable

➔ only RF0 can be used at BESIII, pairing tracks with opening angle $\theta_{h1,h2} > 120^o$

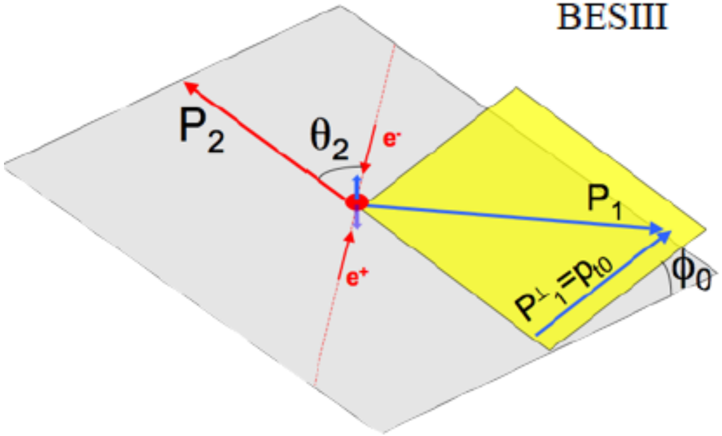
RF12

BaBar
Belle
~~BESIII~~



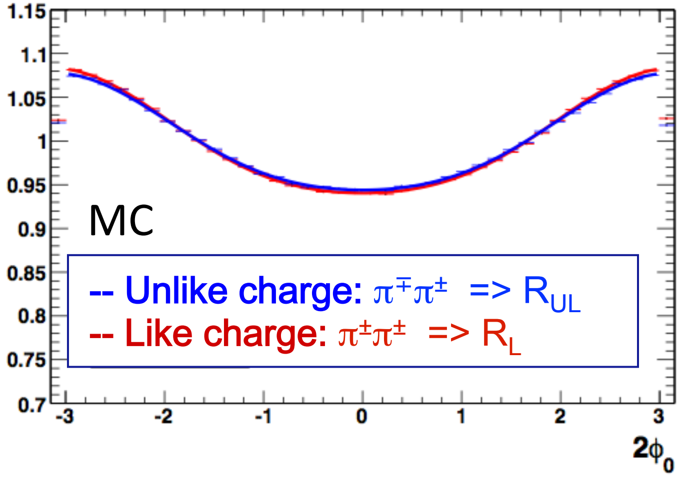
RF0

BaBar
Belle
BESIII

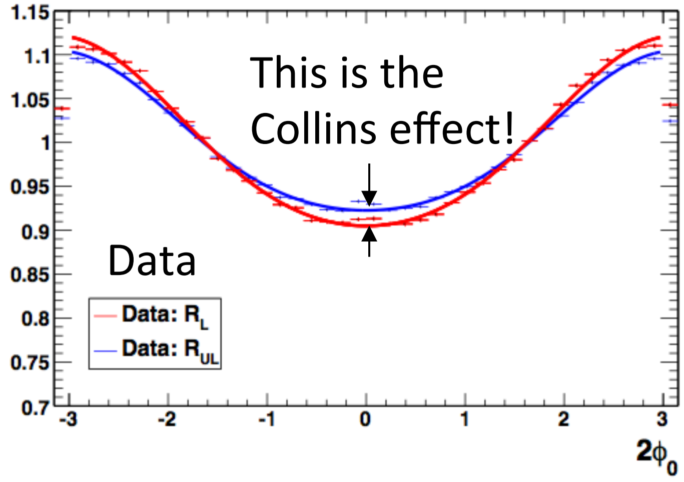


Extraction of asymmetry parameters from data

$N^{(U,L)}(\phi)/<N^{(U,L)}(\phi)>$ in MC sample



$N^{(U,L)}(\phi)/<N^{(U,L)}(\phi)>$ in data sample



- **Collins Asymmetries**
  - extracted from fit to the **normalized azimuthal** distribution

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

  - unpolarized contribution is flat
  - Collins FF contained in the cosine moment b
- The MC generator does not include polarized FF as the Collins FF
  - observed modulation in MC sample produced by detector acceptance
  - correction of these effects with MC would bring to too large systematic uncertainties
- Collins effect not sensitive to electric charge
  - U and L distribution coincident in MC
  - slightly different in data due different contribution of favored and unfavored FF

Double Ratios

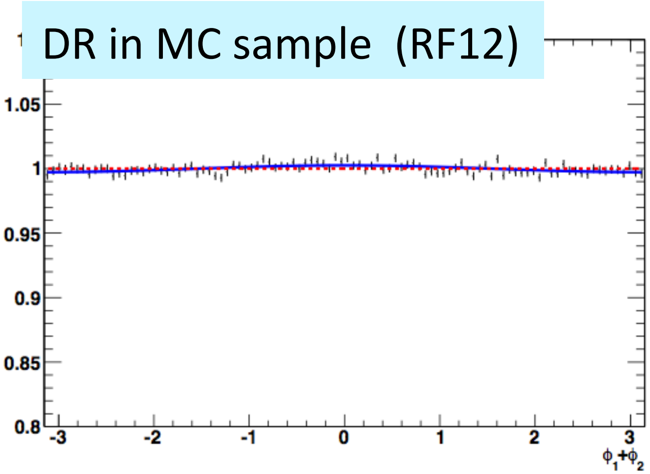
- **Double Ratio (DR)** of Unlike-sign over Like-sign pion pairs**:**

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

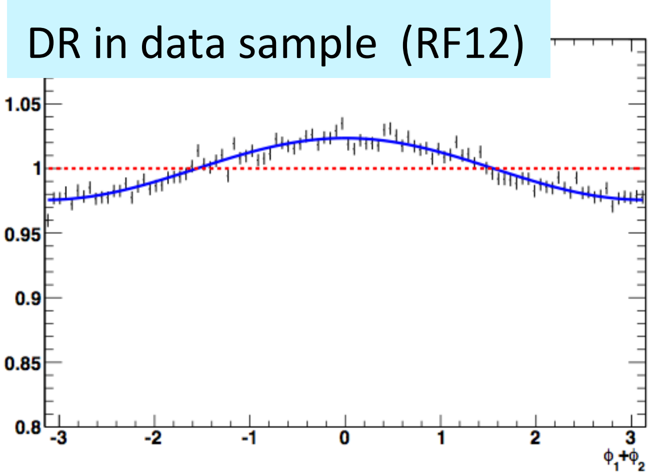
  - acceptances and radiative contributions do not depend on the charge combination of the pion pair;
  - approximation holds for small asymmetries.

$$\frac{R^U_\alpha}{R^L_\alpha} = \frac{N^U(\phi_\alpha)/<N^U(\phi_\alpha)>}{N^L(\phi_\alpha)<N^L(\phi_\alpha)>} \to P_0 + \boxed{P_1} \cdot \cos(\phi_\alpha)$$

Contains only the Collins effects and higher order radiative effects



DR in MC sample (RF12)



DR in data sample (RF12)

MC: small deviation from zero
==> assigned as a systematic error

Uncorrected Asymmetry

Analysis strategy

- Event and track selection
- Construction of spinless hadron pairs
  - KK, Kπ, ππ for BaBar
  - ππ for BESIII
- Measure of the azimuthal angles ϕ_1 and ϕ_2 in RF12 (BaBar), and ϕ_0 in RF0 (BaBar and BESIII)
- Construction of the normalized raw distributions for like (L), unlike (U) and charged (C=U+L) hadron pairs: $R^i = N^i(\phi)/\langle N \rangle$
- Calculation of the ratios of normalized distributions: U/L and U/C
  - fit to these distributions with the function b+a·cos(x)
- Evaluation of background contributions and extraction of the Collins asymmetries

BABAR results:

PRD 90, 052003 => ππ pairs

- A^{UL} and A^{UC}, in RF12 and RF0
- in bins of (z_1,z_2), (p_{t1},p_{t2}) or p_{t0}, $\sin^2\theta/(1+\cos^2\theta)$, and 4D-analysis in bins of (z_1,z_2,p_{t1},p_{t2})

PRD 92, 111101(R) => ππ, Kπ, KK pairs

- A^{UL} and A^{UC}, in RF12 and RF0
- in bins of (z_1,z_2)

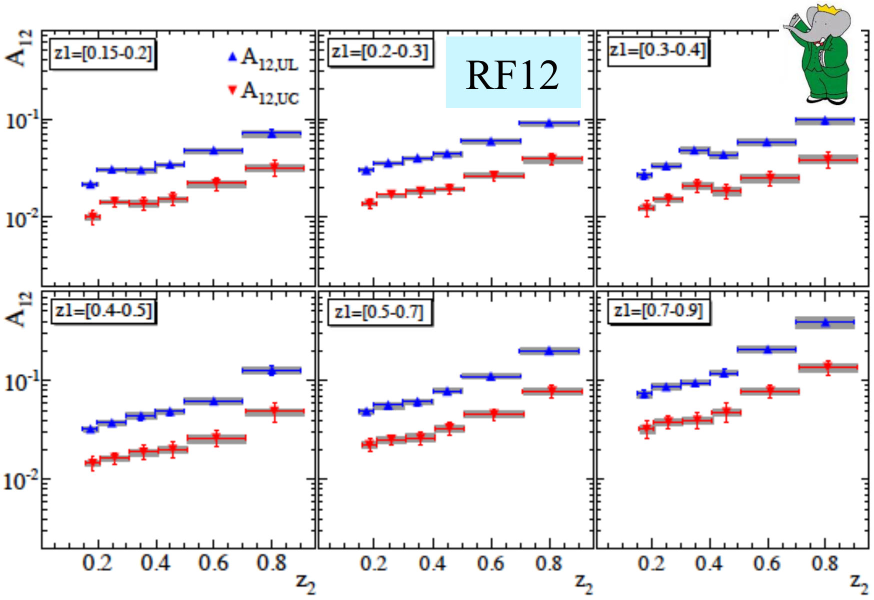
BESIII results:

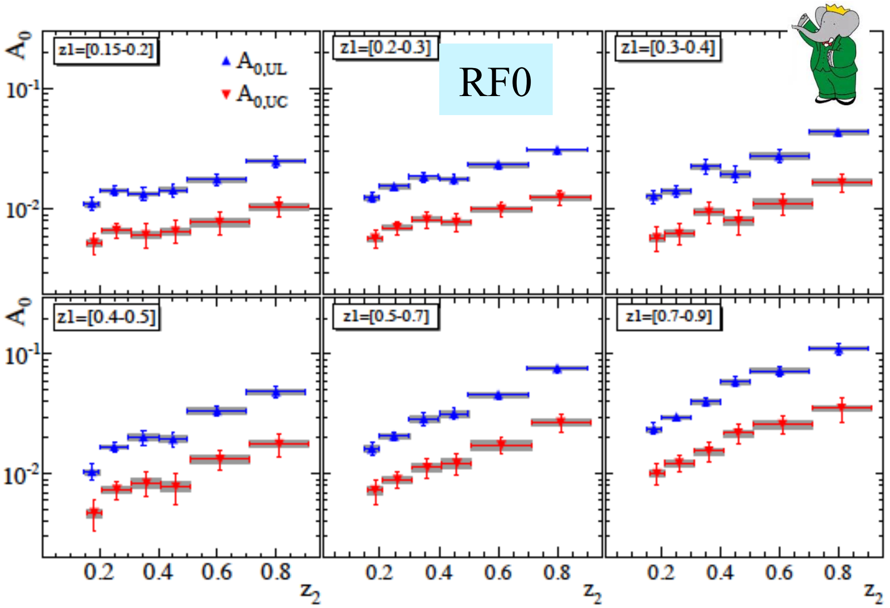
PRL 116, 042001 => ππ pairs

- A^{UL} and A^{UC} in RF0 only
- in bins of (z_1,z_2), p_{t0} and $\sin^2\theta/(1+\cos^2\theta)$

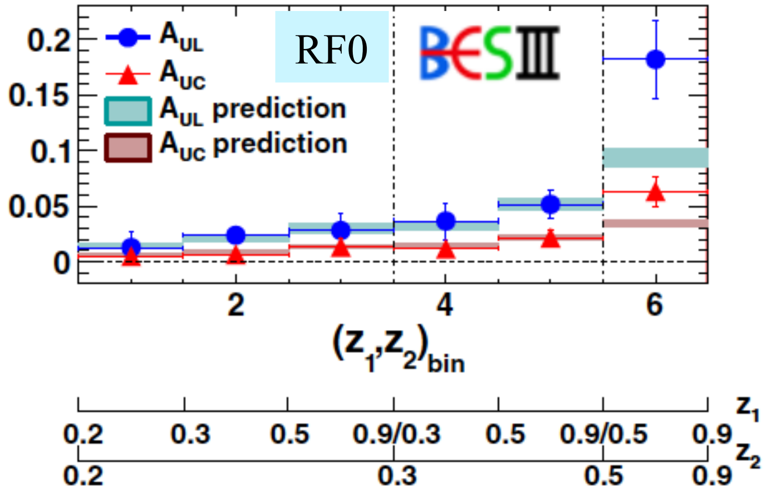
Collins effect in pion pair production: *A vs (z_1,z_2)*

Measurement performed by Belle (PRD78, 032011, Erratum PRD 86, 039905) and *BABAR* (PRD90, 052003) at $Q^2 \sim 110$ GeV^2, and by BESIII (PRL 116, 042001) at $Q^2 \sim 13$ GeV^2



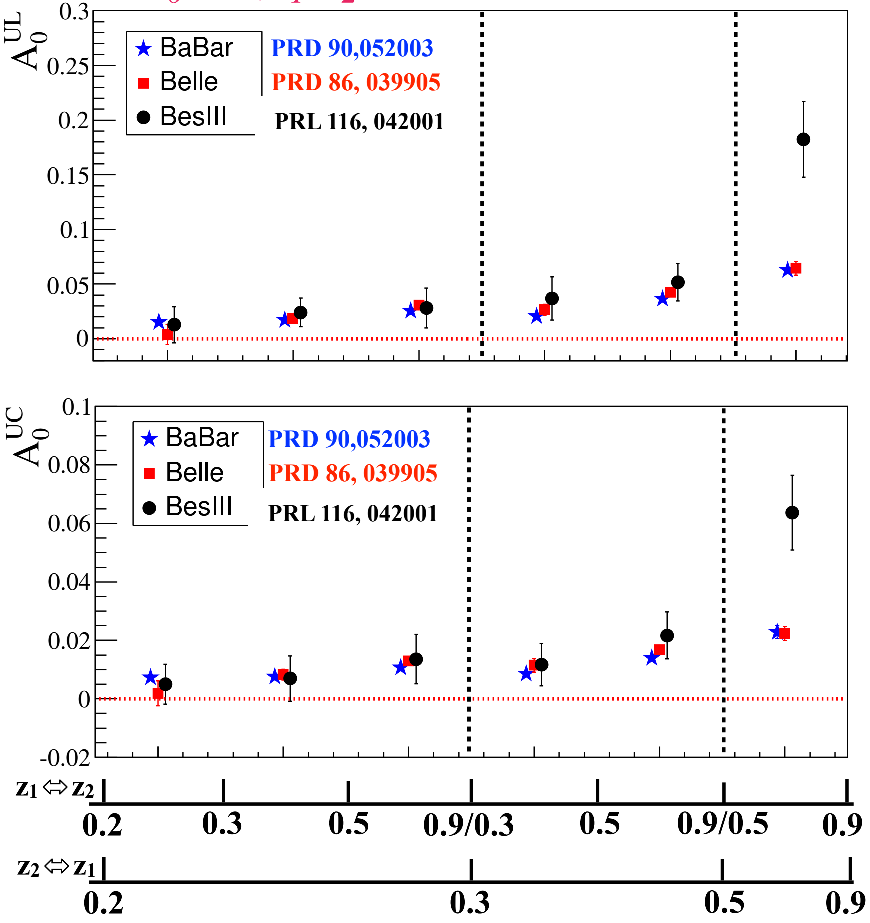


- Significant non-zero asymmetries A_{12}, A_0
- Strong dependence on (z_1,z_2) seen in all experiments
- $A^{UC} < A^{UL}$ as expected. Complementary information about favored and disfavored fragmentation
- BESIII data in agreement with predictions, with exception of the very high *z* region
  - Theory pred. [PRD93, 014009] based on *B*-factories results and evolution

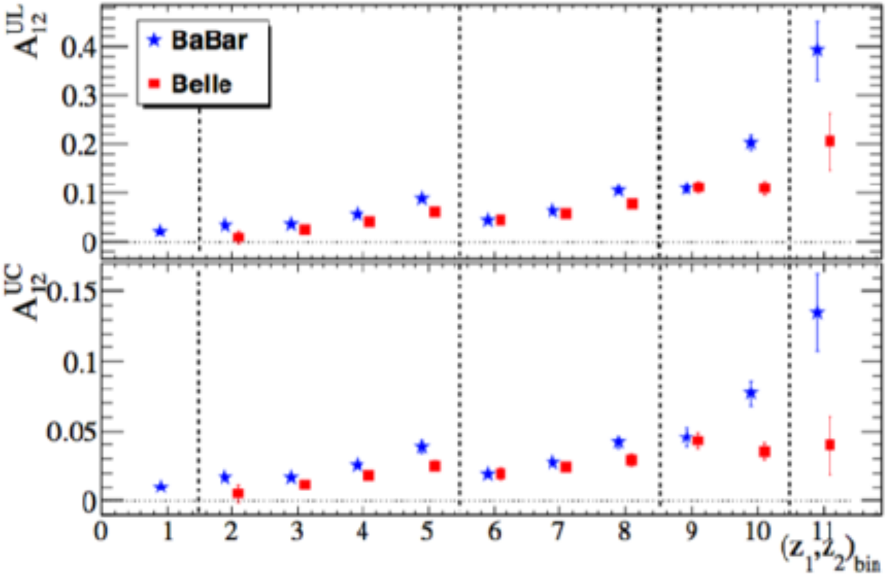


Comparison among measurements

A_0 vs (z_1,z_2)



A_{12} vs (z_1,z_2)



- *BABAR* & Belle data falling in the larger BESIII *z*-bins are averaged taking into account stat. and syst. uncertainties

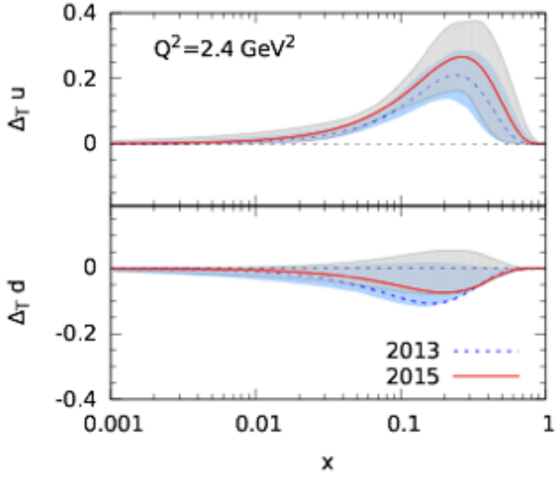
- Good agreement between different data sets
- Larger asymmetries measured for BESIII at highest *z*-values for A_0 asymmetries
  - consistent with theory predictions [Kang et al. PRD 93, 014009 (2016)]
- Some tension between *BABAR* and Belle on A_{12} asymmetries, which can be attributed to experimental features:
  - different thrust axis corrections
  - background corrections
  - $z < 0.9$ for *BABAR* *vs* $z < 1.0$ for Belle

$\pi\pi$ results and global fits

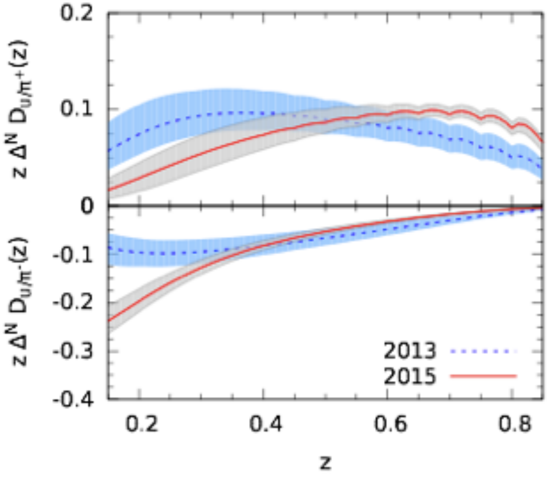
Extraction of the Transversity PDF and Collins FF combining SIDIS and e^+e^- data

Anselmino et al**:** PRD 92 114023 (2015)

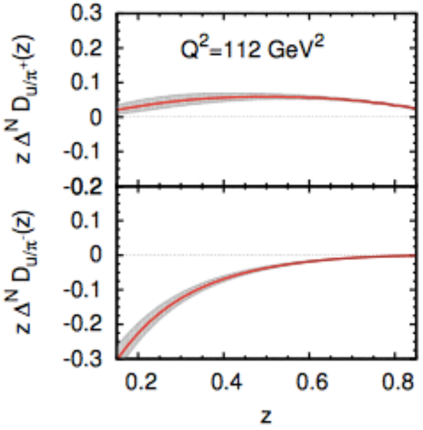
Transversity



Collins FF @ Q^2=2.4 GeV^2



Collins FF @ Q^2=112 GeV^2

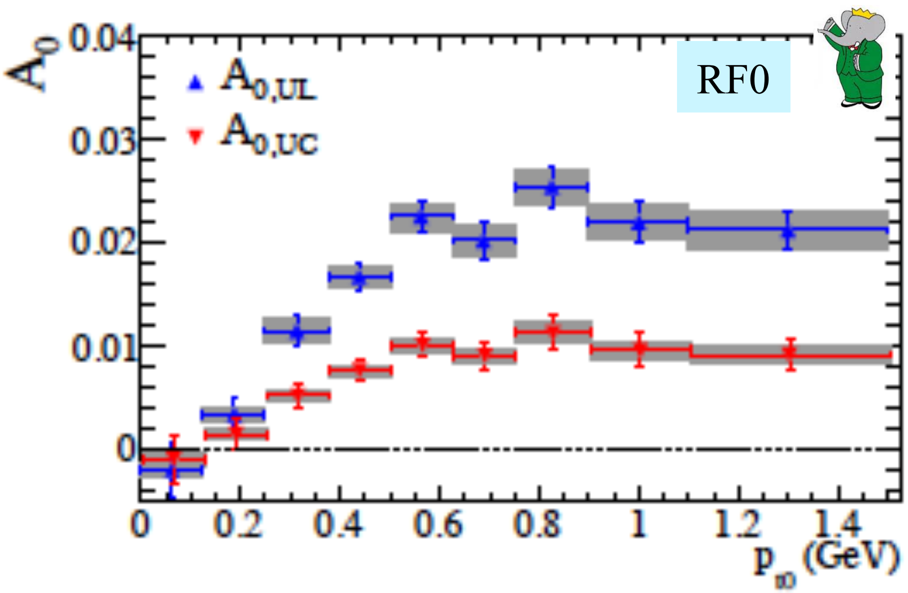


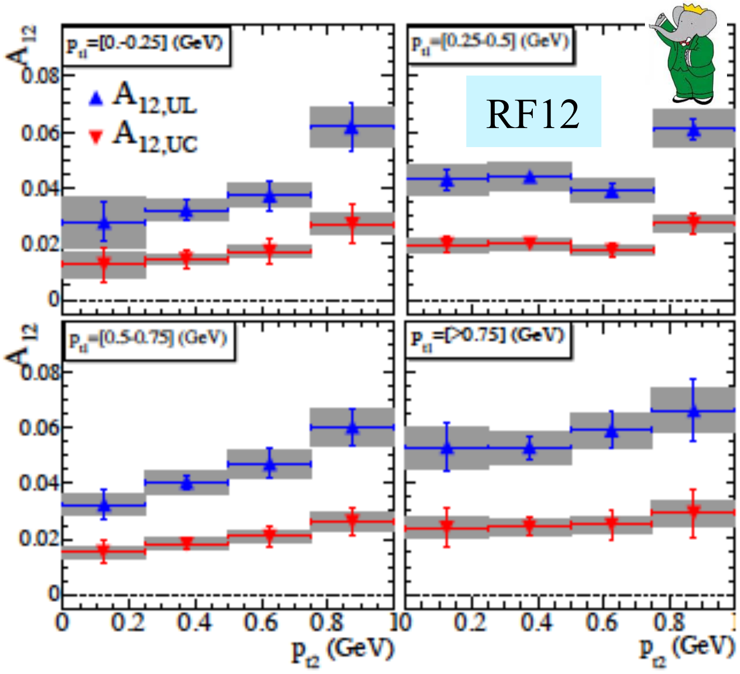
Comparison between old fit (SIDIS + Belle data) with new fit (*BABAR* $\pi\pi$ data added)

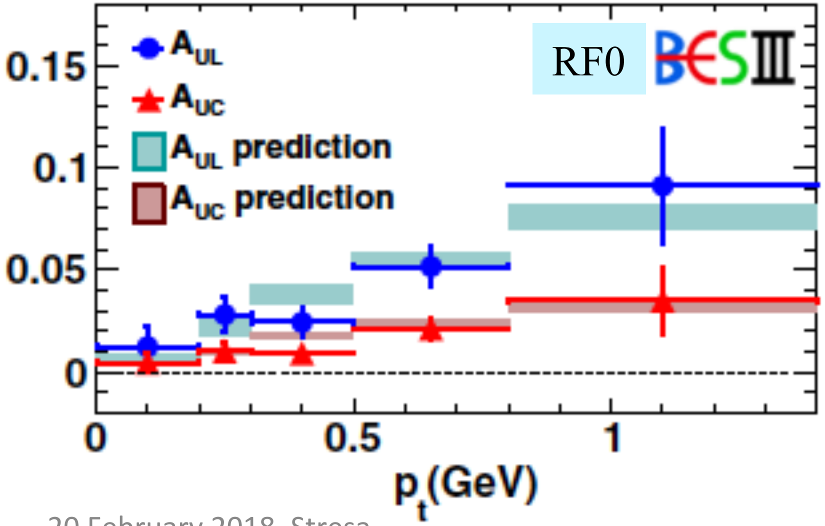
- Fit uncertainties significantly reduced in the new analysis
- Good consistency for the transversity function
- Differences seen for the Collins FF at Q^2=2.4 GeV^2 mainly due to the different parametrization used

Collins asymmetries *vs* hadrons transverse momenta

Measurements by *BABAR* [PRD90, 052003], and BESIII [PRL 116, 042001] but not by Belle







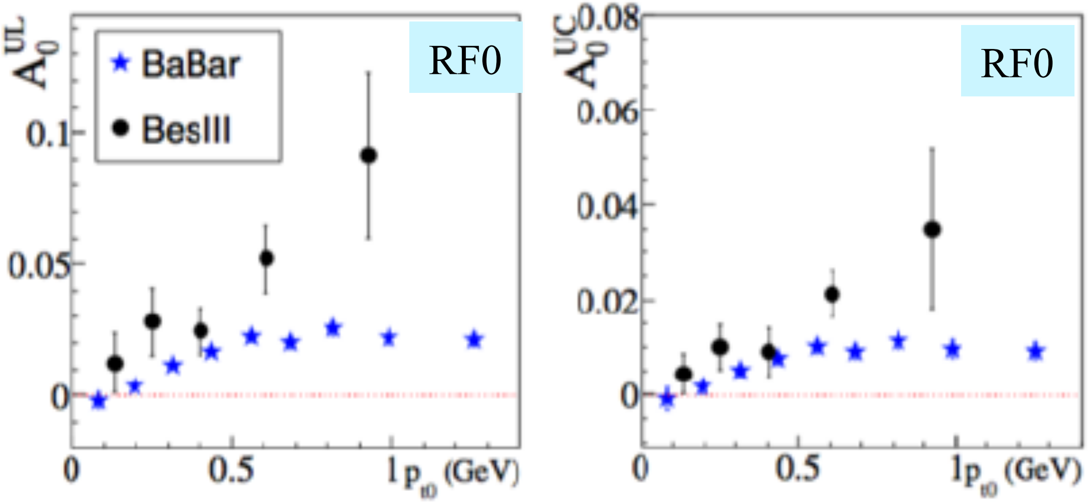
Asymmetries increase with p_t

- less pronounced for A_{12}, for which the p_t determination is subject to large uncertainties (~100-150 MeV)

- Good data-prediction agreement for BESIII

Collins asymmetries *vs* hadrons transverse momenta

BABAR [PRD90, 052003] and BESIII [PRL 116, 042001] data comparison



Steeper dependence on p_{t0} for BESIII

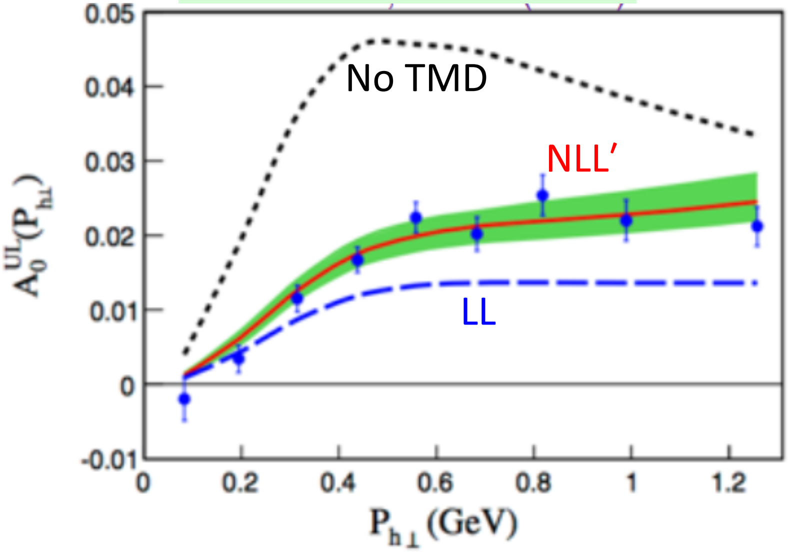
- different kinematic regions:

$<z>_{BESIII} \ > \ <z>_{BABAR}$

Global fit with TMD evolution including *BABAR* p_{t0} data

- A^{UL} and A^{UC} asymmetries well described
- TMD evolution at NLL describes both e^+e^- and SIDIS data adequately well
- Improvement of theoretical uncertainties with inclusion of higher orders

PRD 93, 014009 (2016)



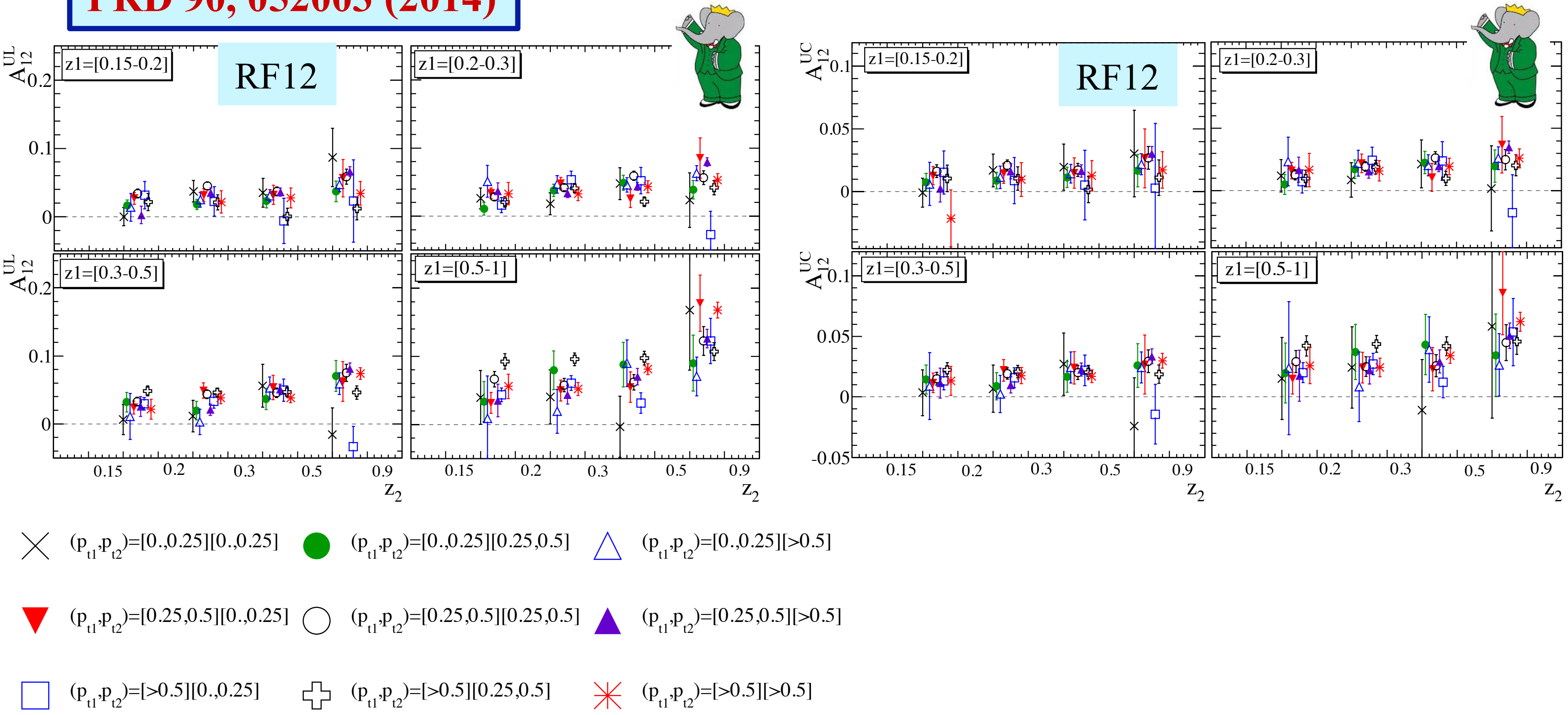
Multi-dimensional asymmetries

BABAR published also the Collins asymmetries measured in 4 dimensions: **(z_1, z_2, p_{T1}, p_{T2})** in **(4x4x3x3)** bins

Despite the limited statistics, some features can be recognized.

With two order of magnitude more data expected at Belle 2, these multi-dimensional asymmetries could be of paramount importance for global fits.

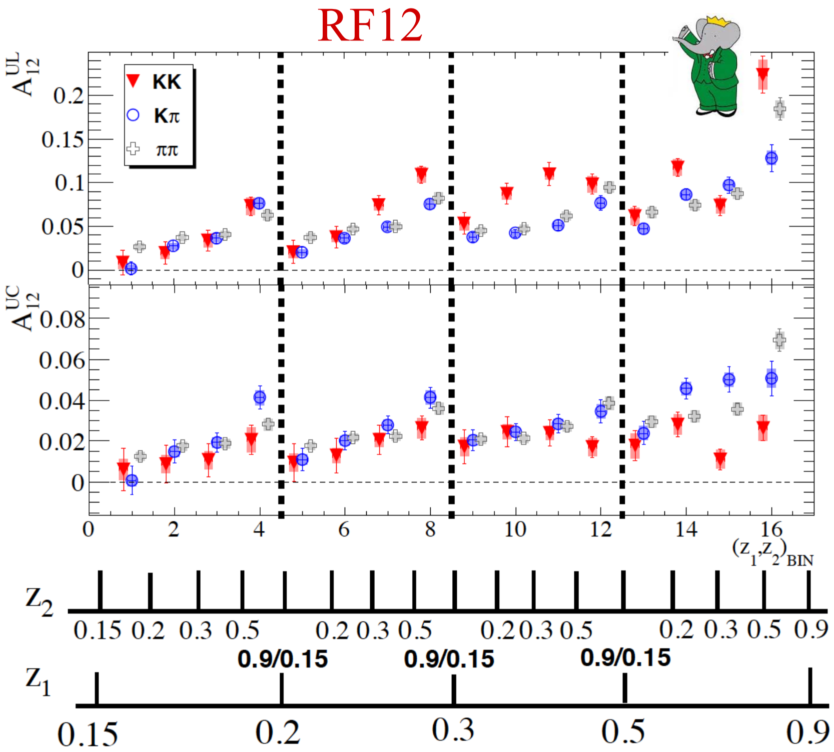
PRD 90, 052003 (2014)

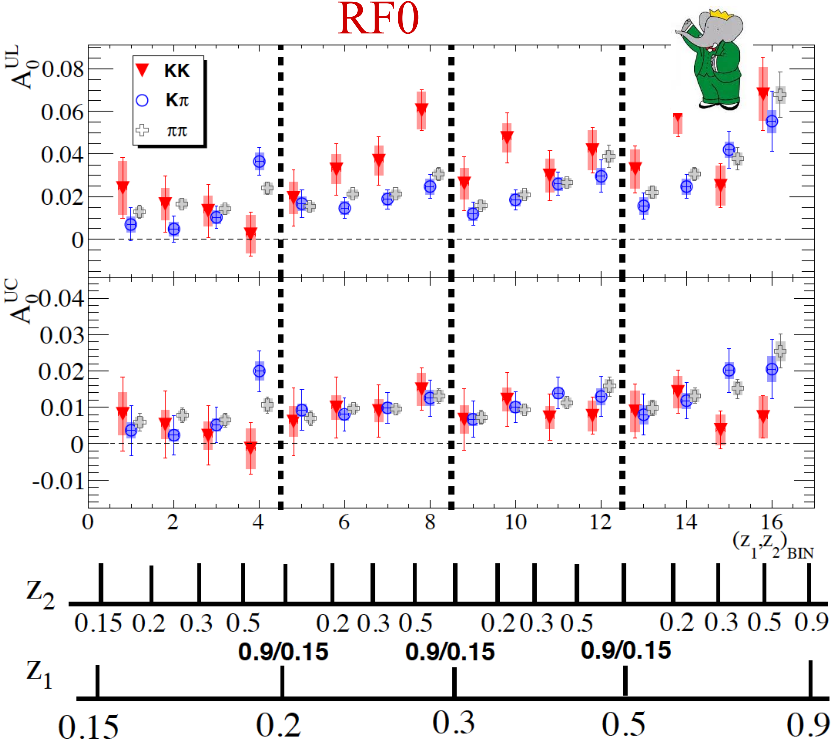


Collins asymmetries for $\pi\pi$, $K\pi$, KK pairs

Measured Collins asymmetries reported in (z_1,z_2) bins (performed only by *BABAR* until now)

PRD 92, 111101(R) (2015)

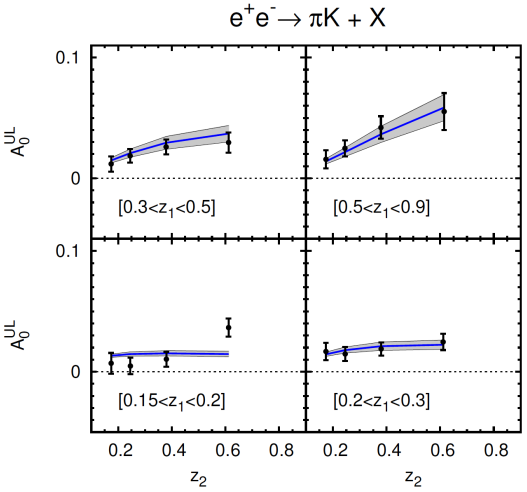


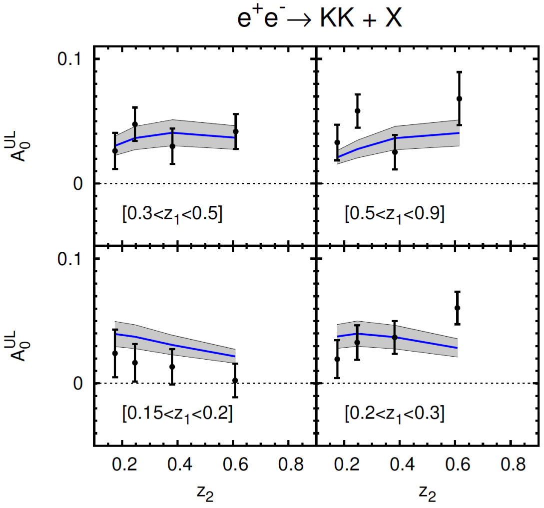


- Asymmetries rise as a function of z: more pronounced for U/L
- A^{UL} KK asymmetry slightly higher than pion asymmetry for high z
- KK asymmetry consistent with zero at lower z
- ππ results consistent with previous *BABAR* analysis
- Measurement of dependences on p_t in progress

Extraction of the Collins FF from *BABAR* kaon data

Fitted function superimposed to *BABAR* data



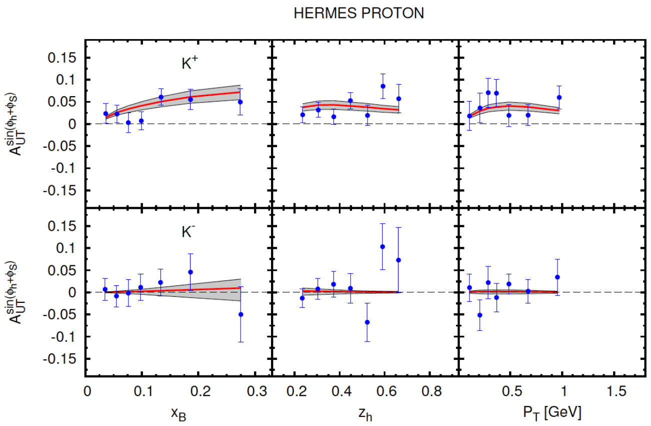


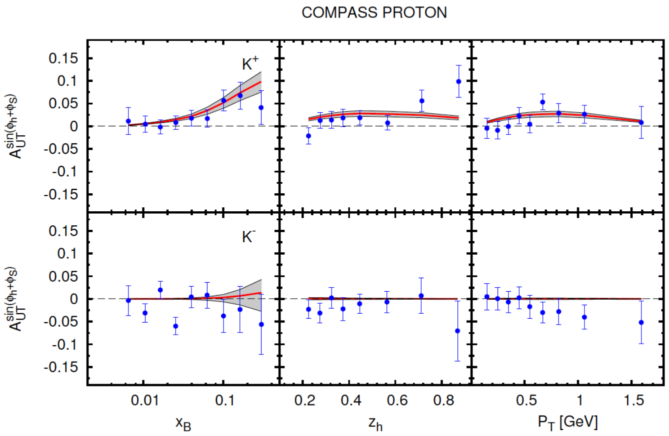
Anselmino et *al.*

PRD 93, 034025 (2016)

- It uses the pion fav. and disfav. Collins FF extracted in **PRD 92 114023 (2015)**
- Extract the corresponding kaon Collins FFs.

Test universality of Collins FF: Calculate SIDIS single spin asymmetries from the fitted function and compare with data ➔ good agreement observed





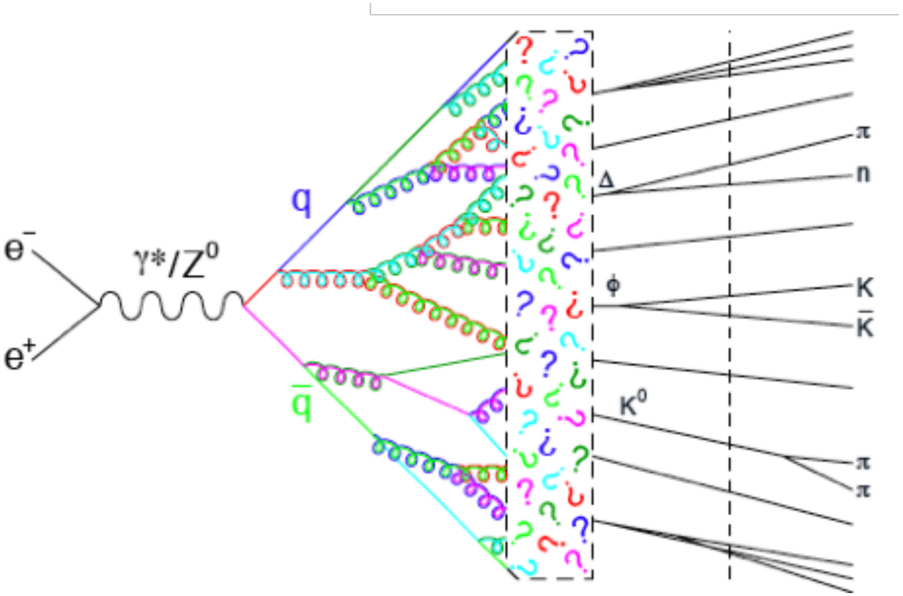
Inclusive hadronic particle spectra

Inclusive Particle Spectra at Q~10 GeV

- Unpolarized cross sections, integrated over angles and p_T

- Precise measurements of IPS at different energies needed to:
  - better comprehend fragmentation processes
  - check consistency with a number of fragmentation models
  - test scaling violation
  - test QCD predictions
- Most of data collected at LEP energies

- **Limited precision measurements at low-energy before *B*-factories**



- Inclusive Spectra measured by *BABAR*:
  - 3 light mesons ($\pi^{\pm}$, $K^{\pm}$, η)
  - 1 light baryon (p/p̄)
  - 4 Heavy baryons (Λ_c, Ξ_c, Ξ'_c, Ω_c)

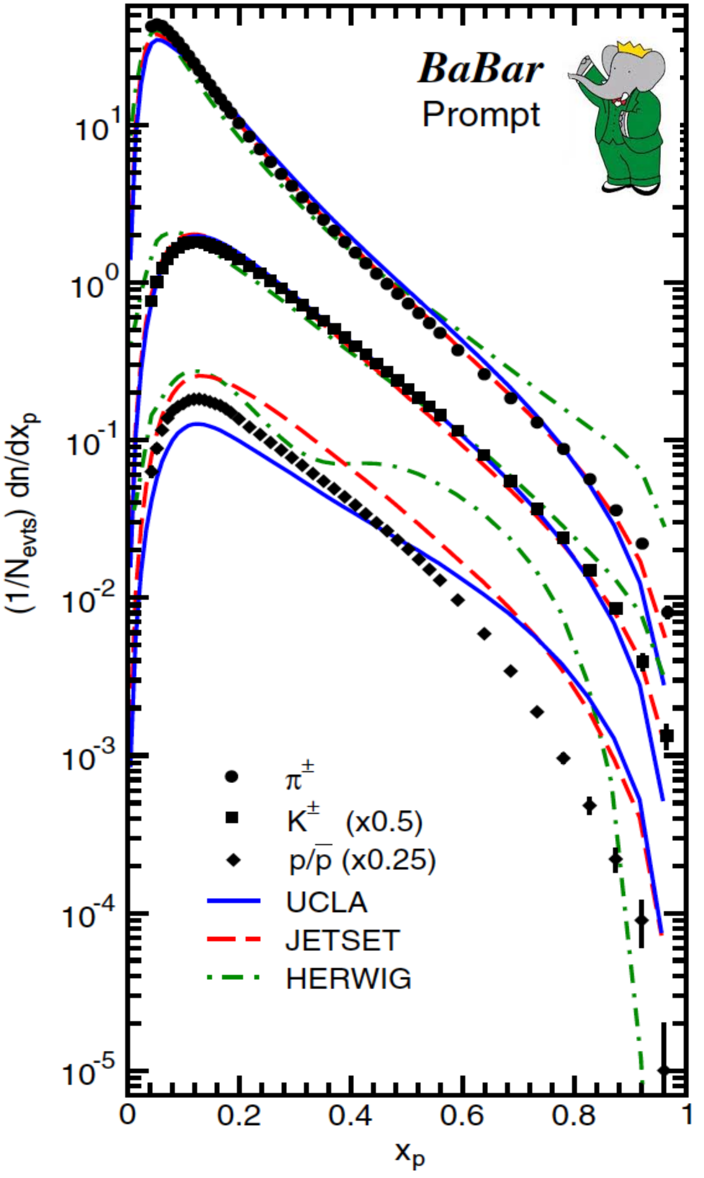
- Measurements performed both at $\sqrt{s}$=10.54 GeV and at ϒ(4S) mass peak

Inclusive light hadrons production

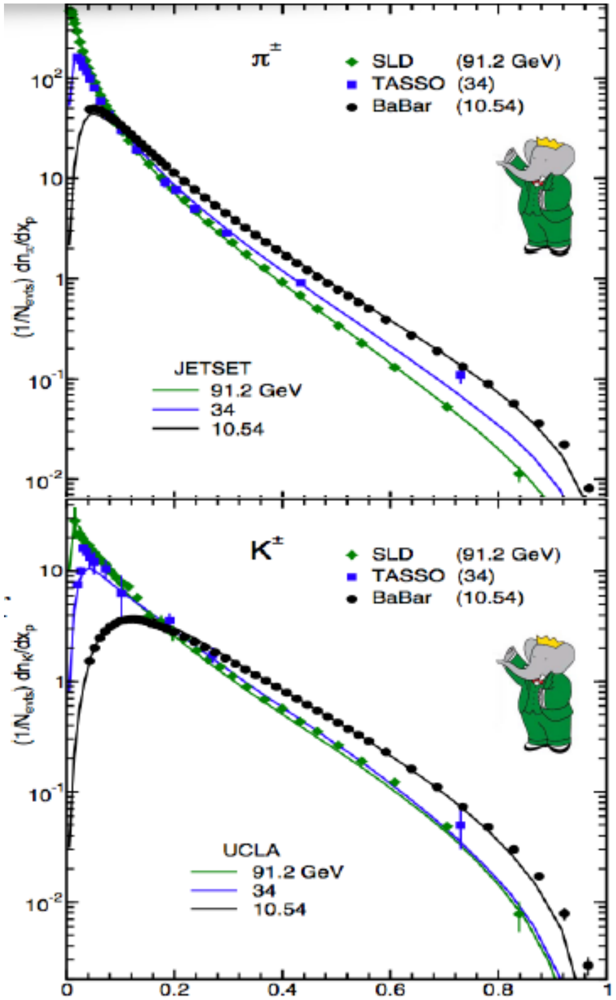
- Data sample: 0.9 fb^{-1} @Y(4S) and 3.6 fb^{-1} at 10.54 GeV.
- Measured both *conventional* and *prompt* hadrons cross sections:
  - prompt: primary hadrons or products of a decay chain where all particles have a lifetime shorter than 10^{-11}s
  - conventional: includes weak decay products of K_S and strange baryons

- Scaled momentum distribution: $x_p = 2p^h/E_{cm}$
  - Coverage: $0.2 < p^h < 5.27$ GeV/c
  - Syst. uncertainties from ~2% to ~10% in the highest momentum bins, dominate the full error
- Data consistent with ARGUS and Belle data, with some deviation at the highest momenta
- Consistency of pion and kaon data with models within ~10%, but significant differences in shape
- Poor description of proton data

Phys. Rev D88, 032011 (2013)

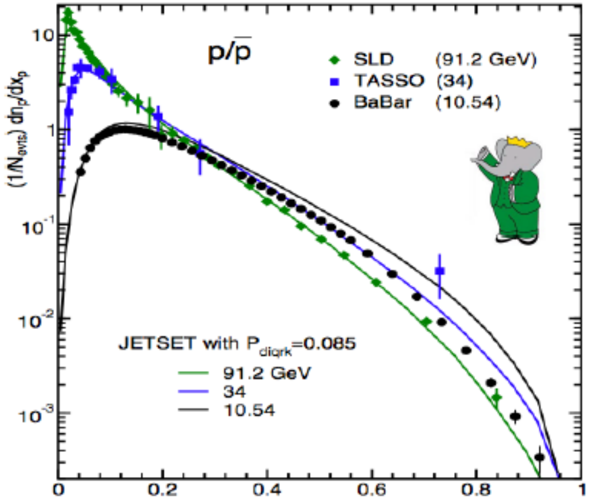


Scaling properties



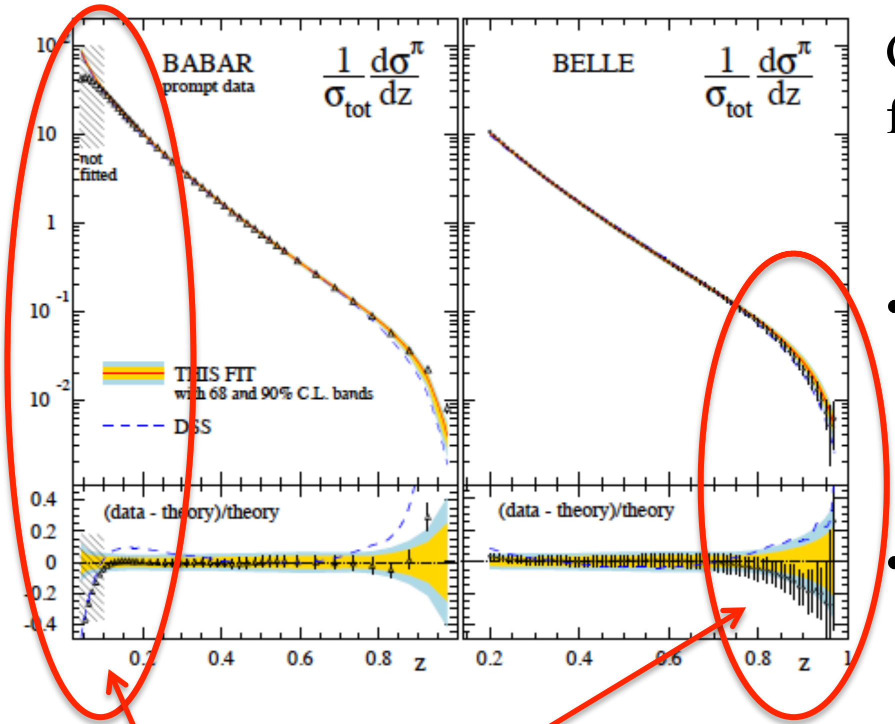
- Hadronization should be scale invariant except for “small” effects of hadron masses, running of α_S, …
- Scaling violations at low x_p, due to masses are well known and modeled adequately (here JETSET is shown for comparison)

- Expect substantial scaling violations at high x_p:
  - Seen clearly in π and K data; reproduced by models (within a few % for π, and 15% for K)
  - Much smaller scaling violation in proton data than models predict



New DSS fit for pion data

de Florian et al.Phys. Rev. D91, 014035 (2015)



Global QCD analysis of parton-to-pion fragmentation at NLO

➔ extract $D_i^{\pi+}(z,Q_0)$; Q_0=1GeV

$i = u+\bar{u}, d+\bar{d}, s, c \quad D_{\bar{u}}=D_d, D_{\bar{s}}=D_s, D_{\bar{c}}=D_c$

- w.r.t. previous DSS analysis it uses the new precise data from *BABAR*, Belle, Hermes and COMPASS
- Good description of *B*-factories data

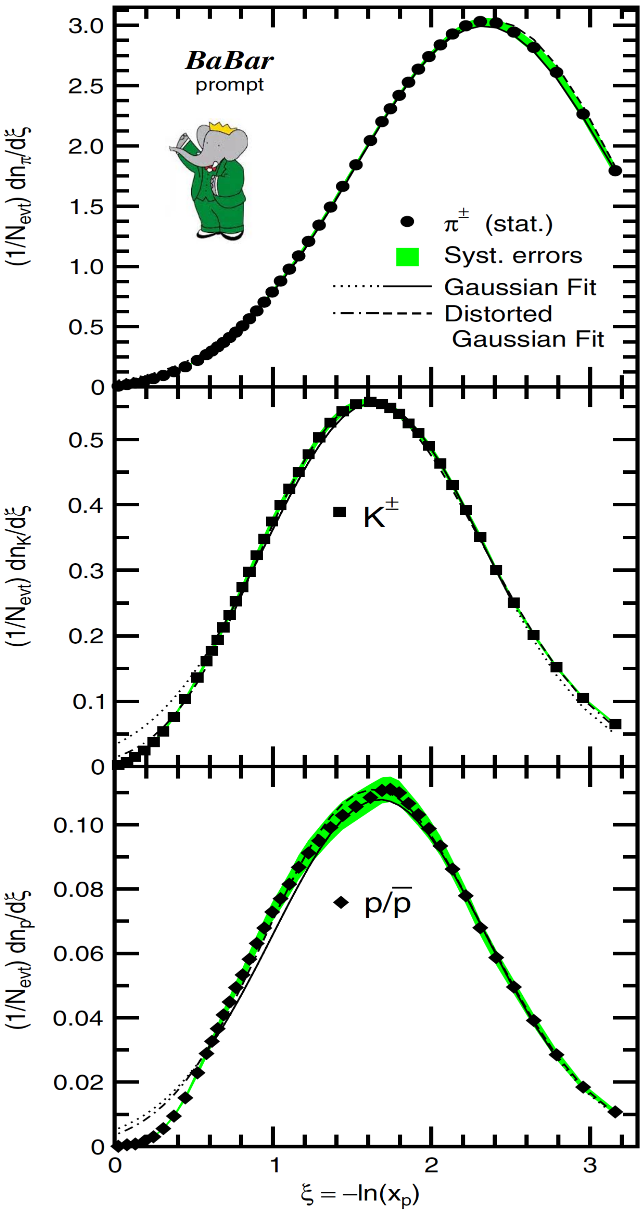
Belle used the entire data set => the precise and fine binning data up to *z*~1. The fit seems to overshoot data for z ≳0.8:
missing logarithmic corrections?

BABAR data extend down to *z*~0.04. The fit deviate from data already around *z*~0.11, due to neglected hadron-mass effects

Test of MLLA+LHPD QCD predictions

In the Modified Leading Logarithmic Approximation (MLLA) with Local Parton Hadron Duality (LHPD) ansatz [Azimov, Z.Phyis.C27,65 (1985)]:

- the multiplicity distributions versus $\xi = -\ln(x_p)$ should be Gaussian near the peak;
- The peak position ξ* should decrease esponentially with increasing hadron mass at a given E_{cm}



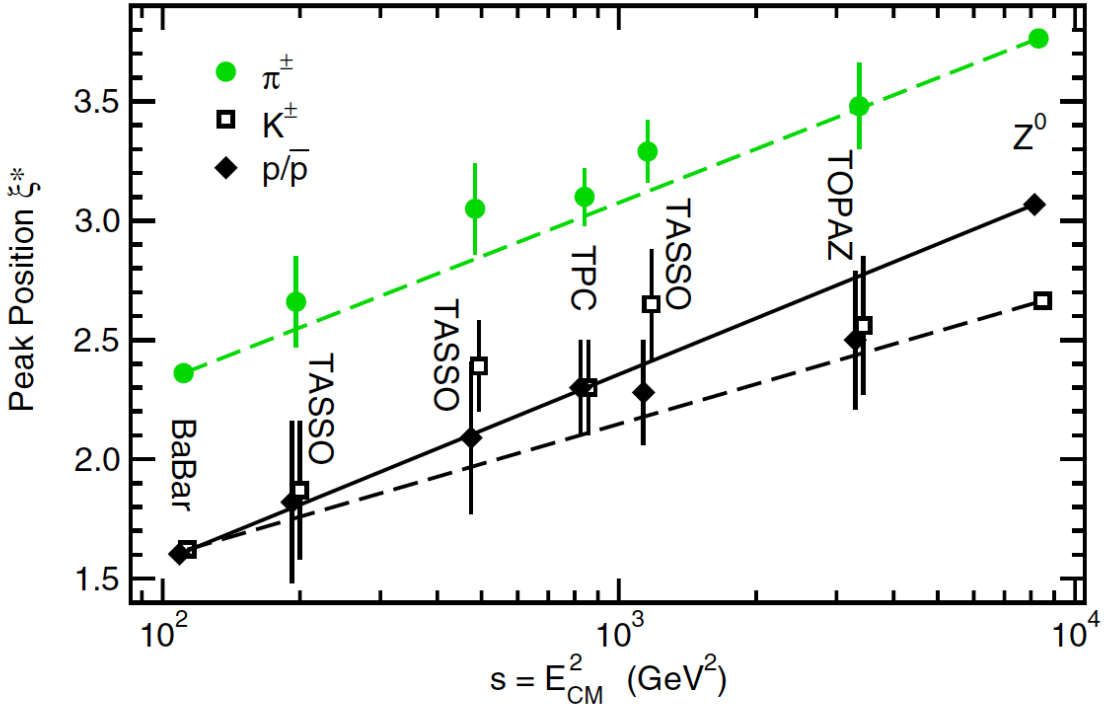
Peak position ξ* from symmetric gaussian fits

	$\pi^{\pm}$	$K^{\pm}$	$p/\bar{p}$
Prompt	2.337 ± 0.009	1.622 ± 0.006	1.647 ± 0.019
Conventional	2.353 ± 0.009	1.622 ± 0.006	1.604 ± 0.013

it is observed $\xi^*_p \approx \xi^*_K$

Test of MLLA+LHPD QCD predictions

ξ^* should increase logarithmically with *s* for a given hadron type



- *BABAR* and Z^0 data provide precise determination of the slopes
- All data are consistent with the expected logarithm dependence with the center-of-mass energy
- Similar slopes for pions and protons, different for kaons
  - possibly due to flavor composition changing with E_{cm}

Inclusive production of charmed hadrons

- Phys.Rev. D75, 012003 (2007) : Inclusive Λ_c production
- Phys.Rev.Lett. 95, 142003 (2005) : Production and decay of Ξ_c
- Phys.Rev.Lett. 99, 062001 (2007) : Production and decay of Ω_c
- hep-ex/0607086 : Ξ_c' production

Charm production at *BABAR*

- Heavy hadrons produced in e^+e^- annihilations provide a laboratory for the study of heavy-quark jet fragmentation
- Relevant quantities are
  - Relative production rates for different spin, parity, …
  - Associated momentum spectra
  - Differences among mesons and baryons
- Measurements at 10.54 GeV, below $B\overline{B}$ production threshold, are the ideal place to study $e^+e^- \to c\bar{c}$ reactions, and test charm fragmentation functions, the charmed hadrons being made of one of the leading quarks
- Large amount of data to study $b \to c$ decays from inclusive measurements at the Υ(4S):
  - *B-mesons* → *charmed mesons/baryons*

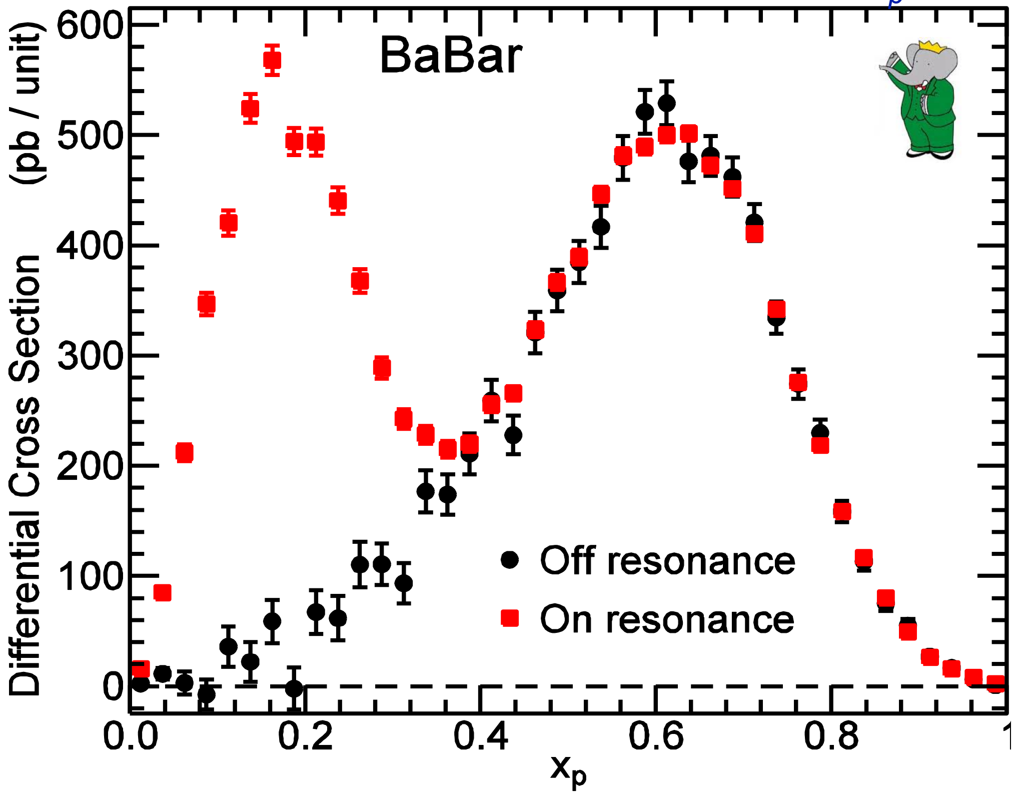
Inclusive Λ_c spectrum measurement

PRD 75, 012003 (2007)

9.5 fb^{-1} off-resonance
81 fb^{-1} on-resonance

- reconstruct $\Lambda_c^+ \rightarrow pK^-\pi^+$ from tracks consistent from originating from interaction point
- evaluate track efficiencies from data in two-dimensional (p,θ) bins
- weight events according to inverse efficiency matrix
- fit mass peak in each x_p bin

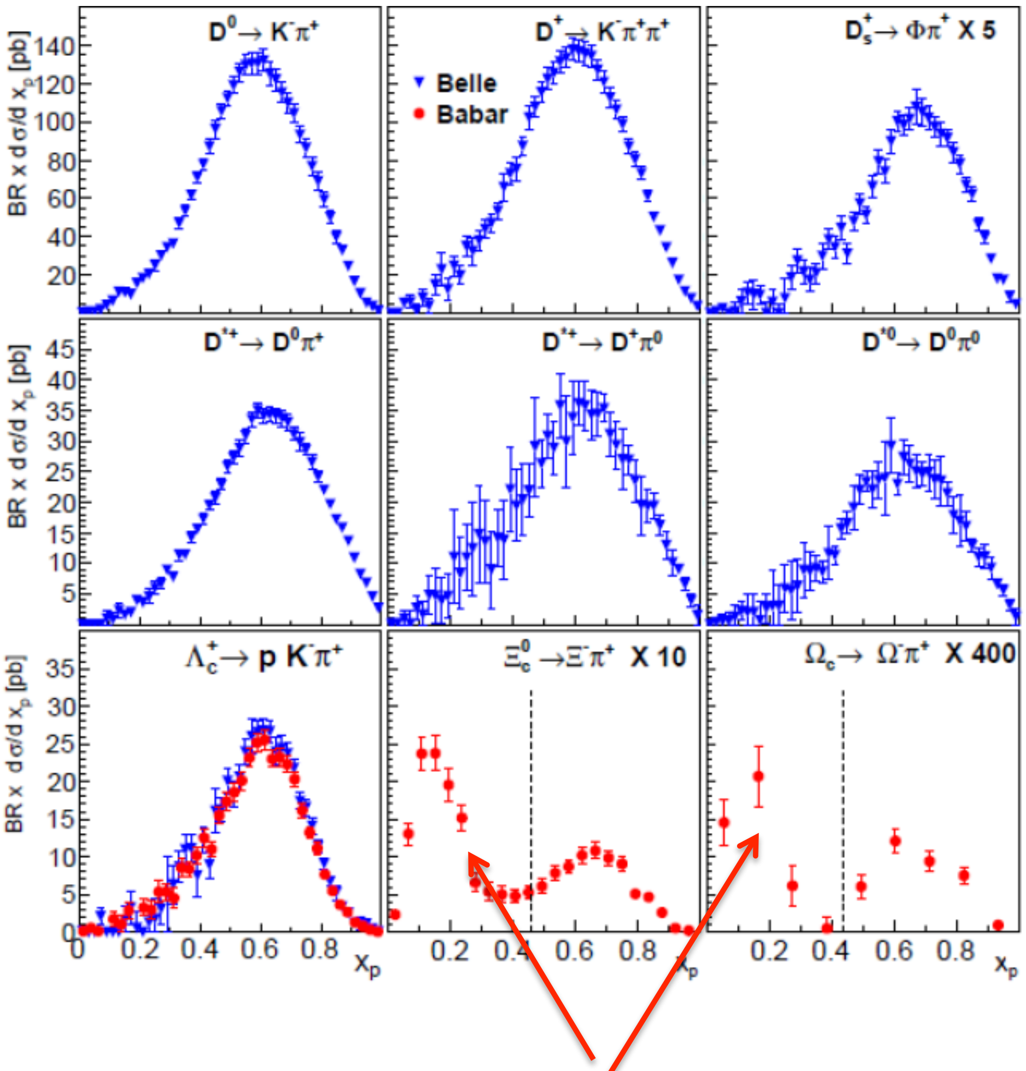
differential cross-section *vs* x_p



➤ Determine $e^+e^- \rightarrow c\bar{c}$ events from off-resonance data (E_{cm}=10.54 GeV)

➤ Determine $e^+e^- \rightarrow B\bar{B}$ events from on-resonance data subtracting the off-resonance cross section scaled by the different c.m. energy

Charmed hadrons inclusive cross sections



from Υ(4S) decays

PRL.95, 142003 (2005)(Babar)
PRD73, 032002 (2006) (Belle)
PRD75, 012003 (2007)(Babar)
PRL 99, 062001 (2007)(Babar)

- Heavier particles generally plotted vs normalized momentum $x_p = p^h/p^h{}_{max}$
- Charmed hadrons contains large fraction of charm-quark momentum
  - Distributions peak at large x_p
- Differences on peak position and distribution shape seen among the various hadrons

Summary

- Great improvement in recent years in the knowledge of FFs and PDFs, necessary for a complete 3D pictures of hadrons.
  - Interplay between measurement of different physics processes and theoretical calculations (global fits with different assumptions and approaches)

- e^+e^- collisions provide the most clean environment for studying FFs, complementary to SIDIS and *pp* collisions with polarized targets
- Recent results at Q^2~110 and ~13 GeV^2
  - Collins asymmetries for charged hadron pairs in two-jet events:
    - ππ, πK, and KK pairs (for ππ also A vs p_t)
  - Di-hadrons asymmetries measured for pion pairs => $H^{\sphericalangle}$ and $G_1^{\perp}$
    - Consistency between extraction of h_1 with Collins or di-hadrons asymmetries in SIDIS and e^+e^-. Implications on Q^2 evolution of TMDs
  - Measurement of single hadron multiplicities for several light and heavy hadrons
  - Measurement of di-hadrons multiplicities
- Several analysis ongoing and/or planned at each experiment

BABAR and BESIII perspectives

- Studies in progress (*i.e.* the close future):

  - p_t dependence of Collins asymmetries for KK and Kπ pairs
    - the analysis is presently stopped, but we plan to resume it in a few months
    - we tested the Double Ratio (DR) method, and look for the possibility to measure the asymmetries directly from normalized distribution rather than from DR
- *BABAR* plans (or better the wishlist)
  - Lack of manpower and approaching of the end of *BABAR* activities force us to carefully choose the analyses to attack next (if any) => suggestions welcome
  - Differential cross section *vs* p_t of inclusive particle production => determination of $D_{1,q}{}^{h}(z,Q^2,k_T)$
  - Di-hadron FFs also for kaons (multiplicities and/or asymmetries)
- BESIII:
  - Despite the fact that it will run for other 7-8 years, the manpower for this physics topics is presently negligible
  - Minimal plans (here also open to suggestions)
    - Collins asymmetries for kaons
    - Single-hadron production multiplicities

BACKUP SLIDES

Inclusive Λ_c studies

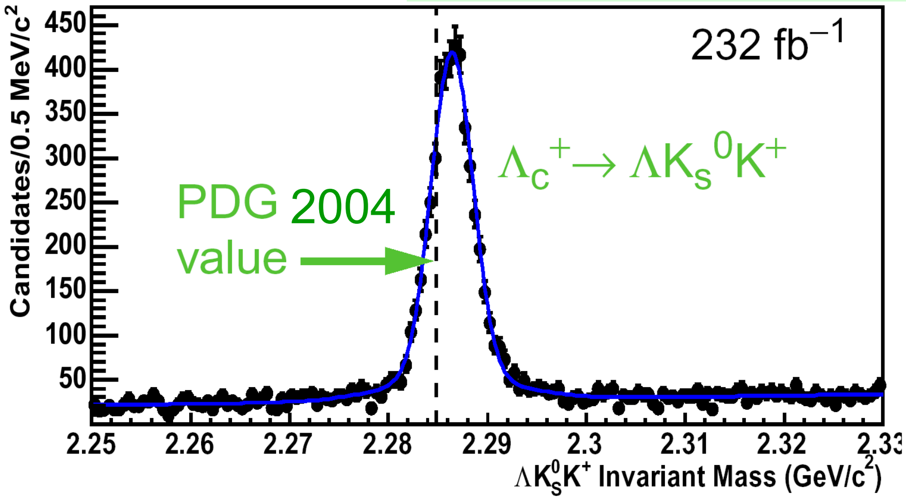
Λ_c^+ mass measurement

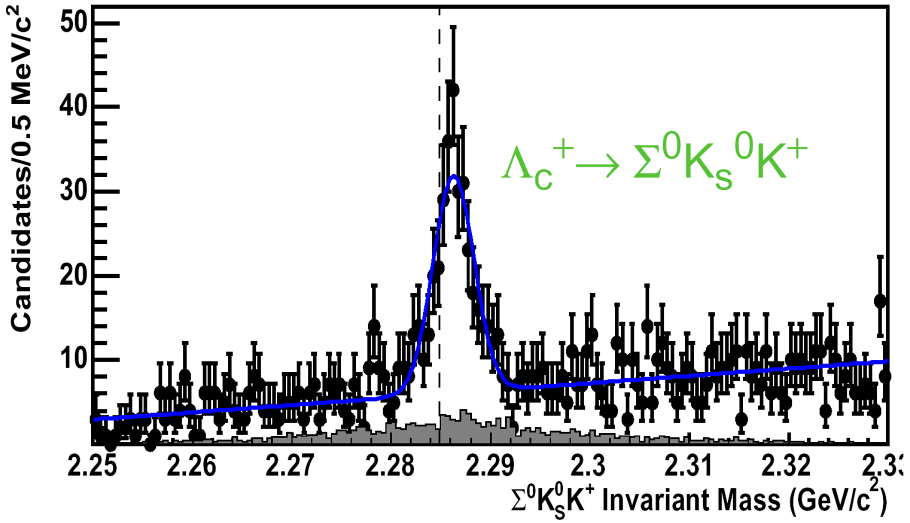
- The Λ_c^+ (*cud*) is the lightest c-baryon

- We precisely measured its mass reconstructing two low-Q decays, to minimize systematic uncertainties

- We find (PRD 72, (2005) 052006)
  - m(Λ_c^+) = 2286.46 ± 0.14 MeV/c^2

- More precise and 2.5σ higher than the previous PDG value:
  - $m_{PDG}(\Lambda_c^+)$ = 2284.9 ±0.6 MeV/c^2



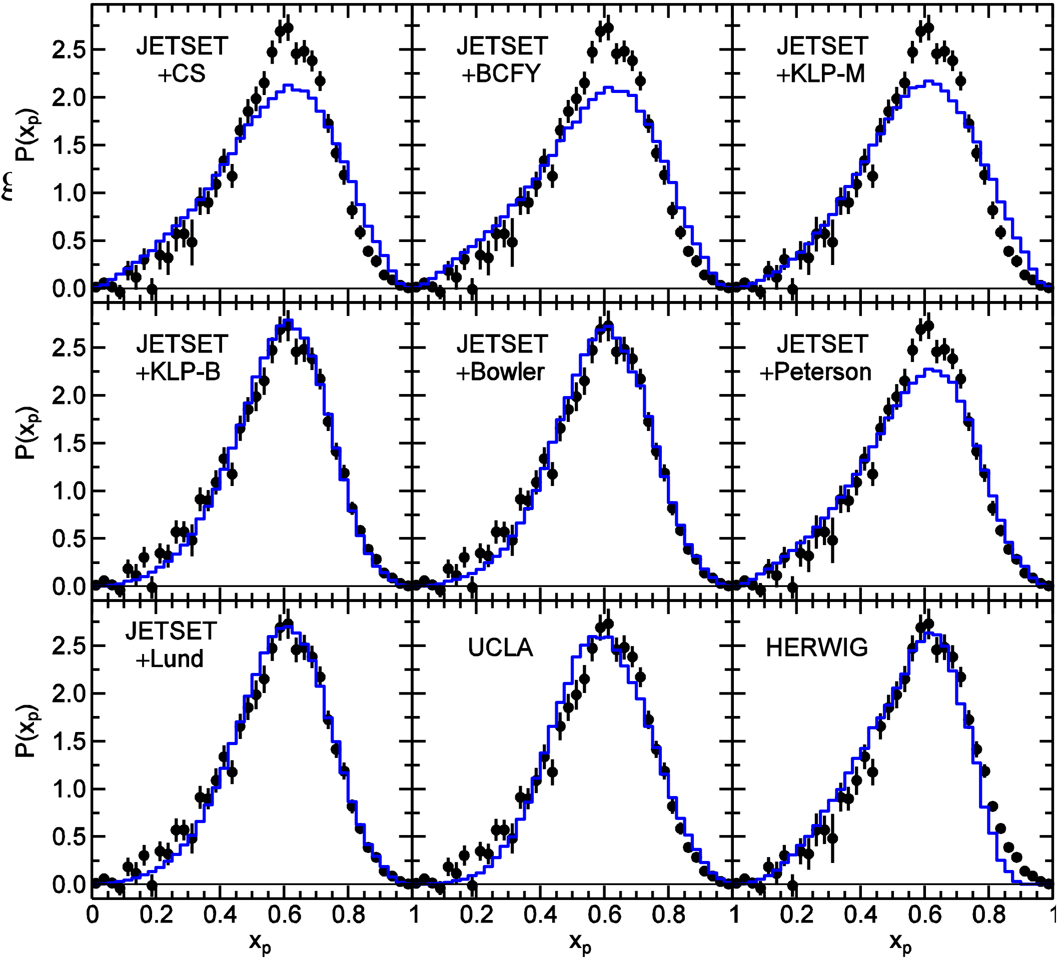


Inclusive Λ_c spectrum measurement

- Several fragmentation functions implemented in JETSET generator
  - distributions affected by JETSET simulation of gluon radiation
  - test each models against our data using a binned χ^2

- No model seems to correctly reproduce the data, but
- The fitted values of the free parameters are quite different from those used for light hadrons and charmed mesons

- These results indicate the needs of different functions for baryons and mesons (like in DIS, where there is a dependency on the number of spectator quarks)



Inclusive Λ_c spectrum measurement

PRD 75, 012003 (2007)

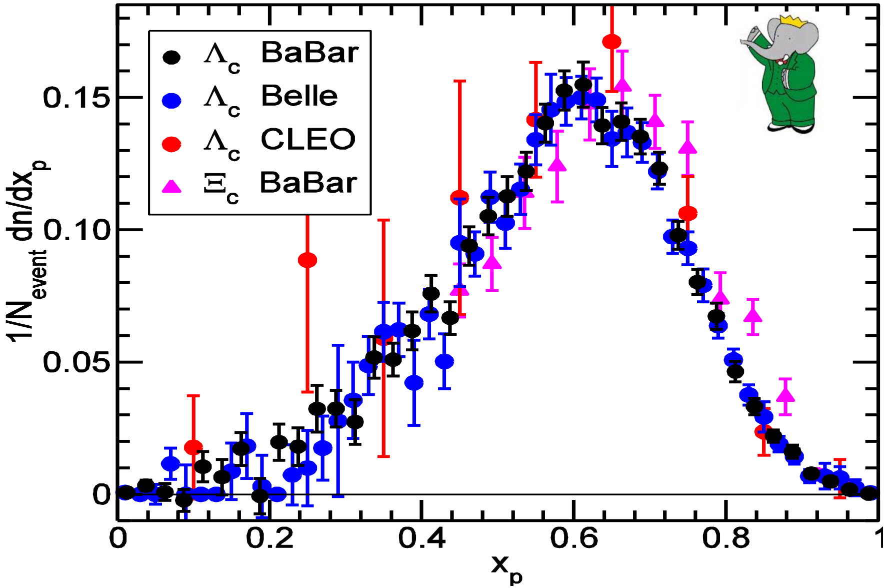
- We measure (at E_{cm}=10.54 GeV):
- $<x_p> = 0.574 \pm 0.009$
- Total rate per event:

$$\boxed{N^{q\bar{q}}_{\Lambda_C} = 0.057 \pm 0.002(\exp) \pm 0.015(\Lambda_C BF)}$$

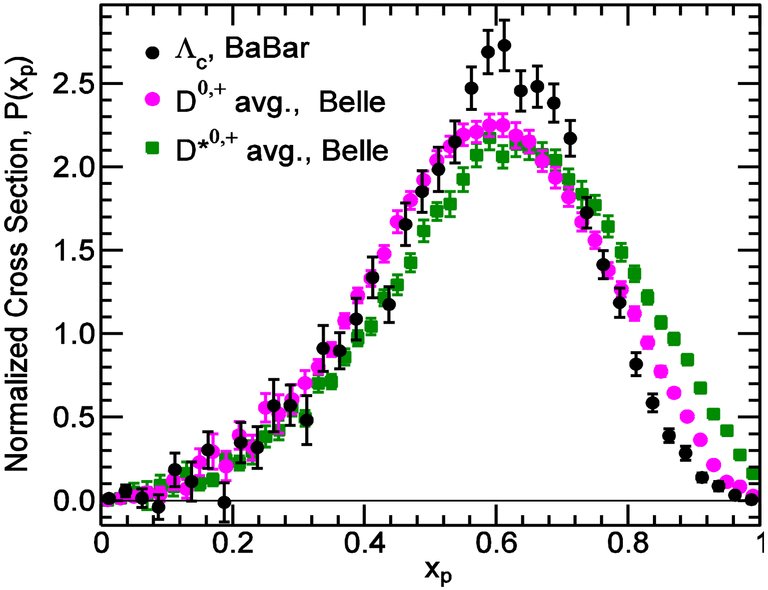
- assuming Λ_C^+ from $e^+e^- \to cc$, we get a production rate per c-jet of:

$$\boxed{N^{c-jet}_{\Lambda_C} = 0.071 \pm 0.003(\exp) \pm 0.018(\Lambda_C BF)}$$

- Result consistent with previous CLEO and Belle measurements



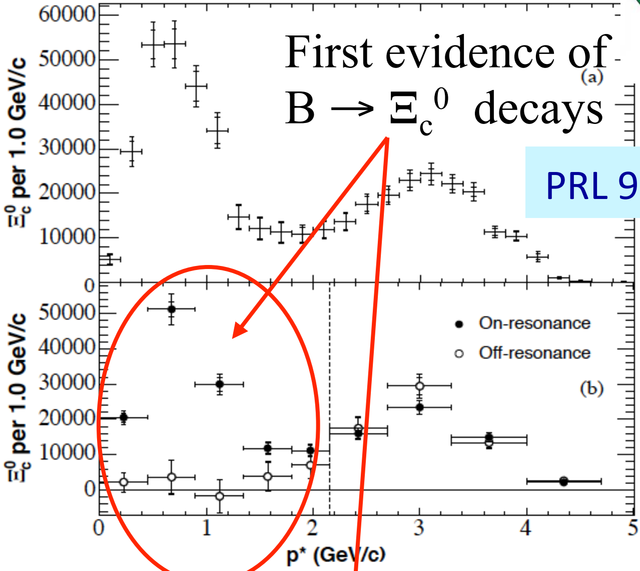
- ➢ Compare to other baryons or mesons
- ➢ Λ_C peak slightly lower w.r.t. Ξ_c
- ➢ D mesons (both PS and V state), show broader peaks and differ significantly for $x_p \sim 1$



More *c*-baryons inclusive spectra: Ξ_c^0 and Ω_c^0

- Measurements based on a data set of 230 fb-1

- Ξ_c^0 reconstructed in two decay modes
  - measured ratio of BFs



First evidence of $B \to \Xi_c^0$ decays

PRL 95, 142003

B meson Branching Fraction

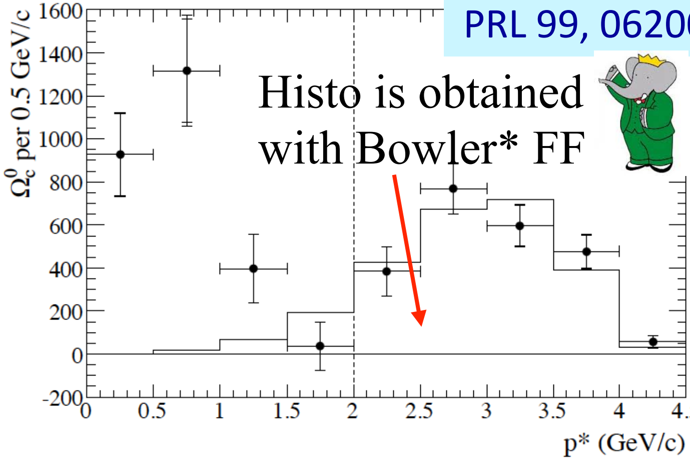
$$\mathcal{B}(B \to \Xi_c^0 X) \times \mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+) = (2.11 \pm 0.19 \pm 0.25) \times 10^{-4}$$

Integrated cross section from cc

$$\sigma\left(e^+e^- \to \Xi_c^0 X\right) \times BF\left(\Xi_c^0 \to \Xi^- \pi^+\right) = \left(388 \pm 39 \pm 41\right) \text{ fb}$$

- Ω_c^0 reconstructed in 4 decay modes
  - measured ratio of BFs

PRL 99, 062001



Histo is obtained with Bowler* FF

B meson Branching Fraction

$$BF\left(B \to \Omega_c^0 X\right) \times BF\left(\Omega_c^0 \to \Omega^- \pi^+\right) = \left[5.2 \pm 0.9(\text{exp}) \pm 0.5(\text{model})\right] \times 10^{-6}$$

Integrated cross section for continuum production

$$\sigma\left(e^+e^- \to \Omega_c^0 X\right) \times BF\left(\Omega_c^0 \to \Omega^- \pi^+\right) = 11.2 \pm 1.3\,(\text{exp}) \pm 1.0\,(\text{model}) \text{ fb}$$

* M.G. Bowler, Z. Phys. C11, 169 (1981).

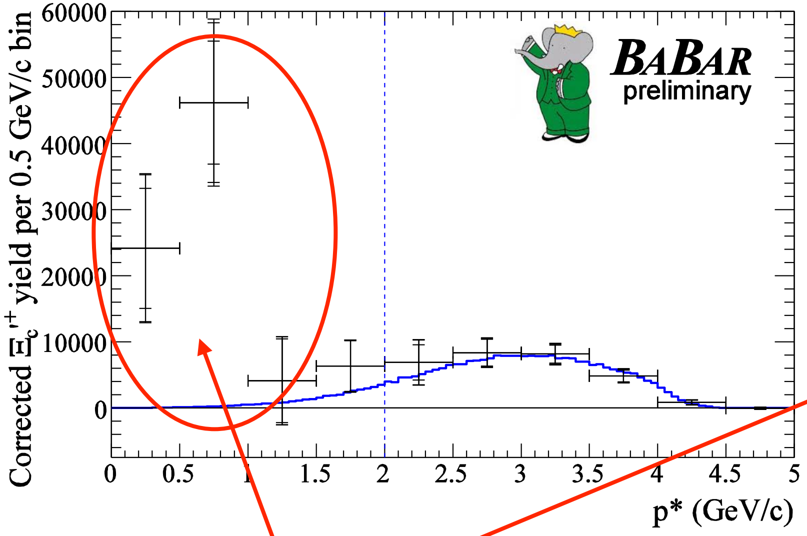
More *c*-baryons inclusive spectra: Ξ_c'

hep-ex/0607086

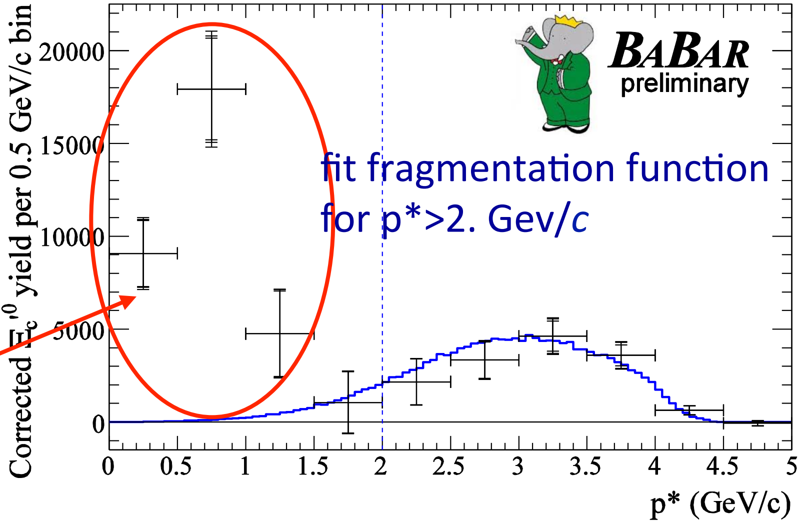
State	Mass (MeV/c^2)	J^P
Ξ_c	2470	1/2$^+$
Ξ_c'	2575	1/2$^+$
Ξ_c^*	2645	3/2$^+$

- Ξ'_c first observed by CLEO in 1999
- $\Delta m = m(\Xi'_c) - m(\Xi_c) = 107$ MeV/c^2
  - electromagnetic decay $\Xi'_c \rightarrow \Xi_c \gamma$

$\Xi'^{+}_c \rightarrow \Xi_c^{+}\gamma$



$\Xi'^{0}_c \rightarrow \Xi_c^{0}\gamma$



fit fragmentation function for p*>2. Gev/*c*

➢ first evidence of $B \rightarrow \Xi'_c$ decays

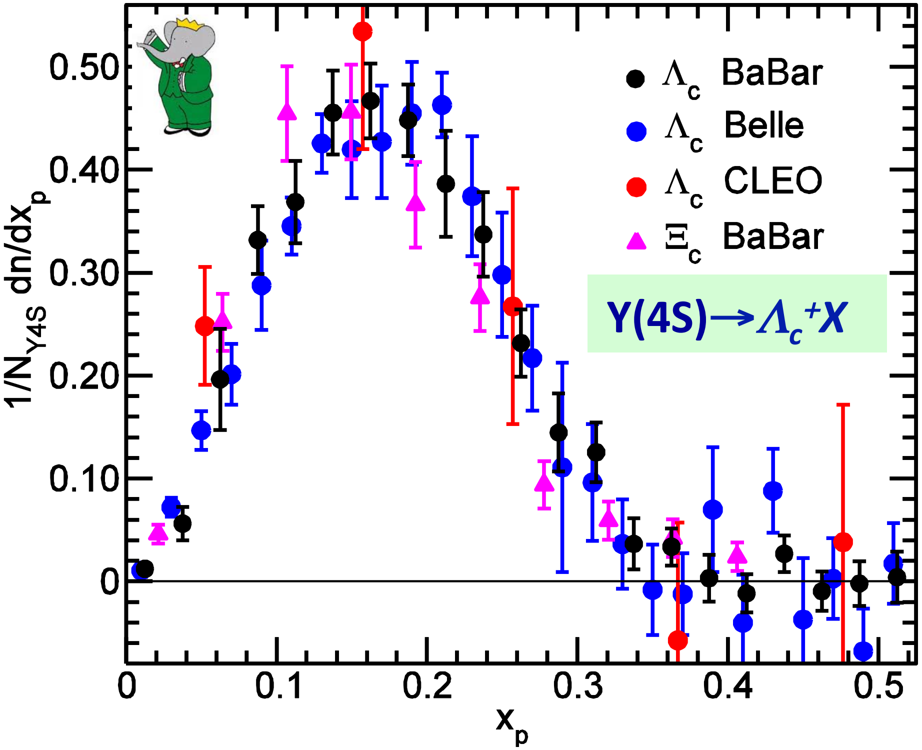
$$\begin{aligned}\mathcal{B}(B \rightarrow \Xi_c'^{+} X) \times \mathcal{B}(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+) &= (1.69 \pm 0.17(\text{exp.}) \pm 0.10(\text{model})) \times 10^{-4} \\ \mathcal{B}(B \rightarrow \Xi_c'^{0} X) \times \mathcal{B}(\Xi_c^0 \rightarrow \Xi^-\pi^+) &= (0.67 \pm 0.07(\text{exp.}) \pm 0.03(\text{model})) \times 10^{-4}\end{aligned}$$

Inclusive Λ_c spectrum at the Y(4S)

- Spectrum for Y(4S) decays obtained subtracting the much harder $e^+e^- \rightarrow cc$ spectrum
- Kinematic limit $x_p = 0.47$
- Shape consistent with previous results
- We measure

$$\boxed{N^{Y}_{\Lambda_C} = 0.091 \pm 0.006(\exp) \pm 0.024(\Lambda_C BF)}$$

- *i.e.* (4.5 ±1.2)% of $B_{u,d}$ decays include a Λ_c



➢ Data suggest a dominance of quasi-two-body decays like:

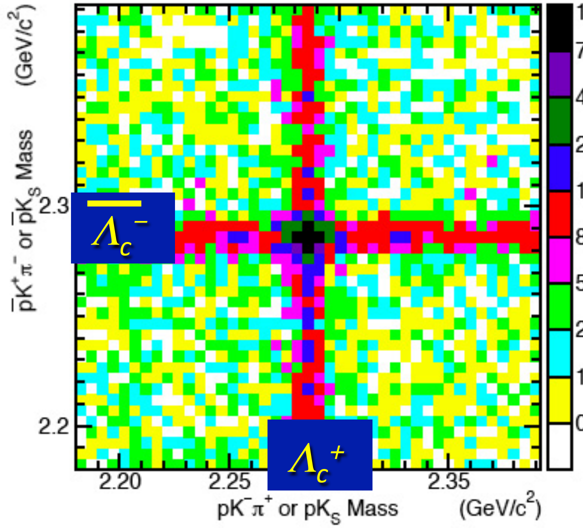
- $B \rightarrow (\Lambda_c^+\bar{p}\,,\ \Lambda_c^+n\,,\ \Lambda_c^+\Delta\,,\ \Sigma_c\bar{p}\ ) +\ m\pi$
- comparing with MC simulations the favorite range for the number of pions is $3 < m < 5+$
- also *B* decays into 2 charmed baryons seem to contribute significantly

Correlated $\Lambda_c^+\bar{\Lambda}_c^-$ production

- What about baryon number conservation?
  - Measurements at high energies shows small rapidity differences between Baryon-antiBaryon couples ==> "local baryon correlation"
  - if "local" correlation and two charmed baryons produced from leading *c*-quarks, we expect to see two more baryons ==> kinematically suppressed @ E_{cm}~10 Gev
  - CLEO measured $\dfrac{P(\Lambda_c\bar{\Lambda}_c X)}{P(\Lambda_c\bar{D}^{(*)}Y)} \approx 3.5$

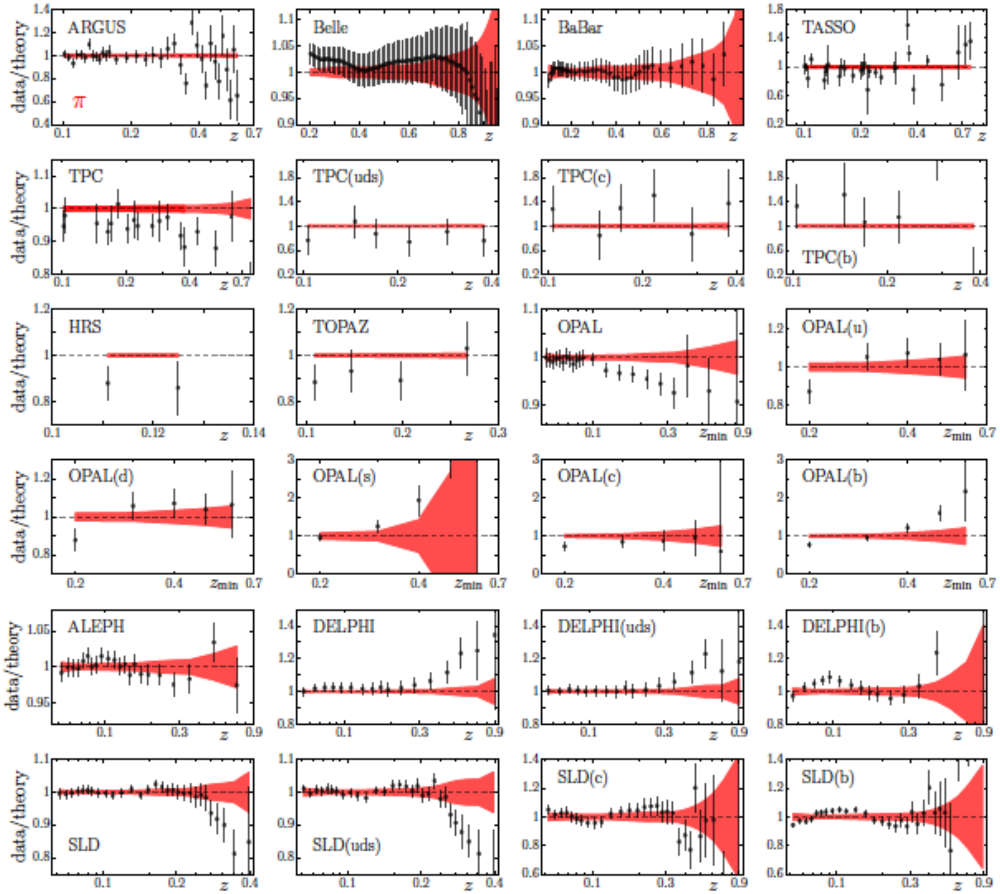
PRD 63, 112003 (2001)

- BABAR looks for $e^+e^- \to \Lambda_c^+\bar{\Lambda_c}^- X$ events
- Observe 649 ± 31 events vs ~150 expected ==> ratio of ~4.2 consistent with CLEO result
- very few additional baryons observed
- most of additional tracks are pions produced at the e^+e^- vertex ==> we measure 2.6 ± 0.3 $\pi^\pm$/event
- there is room for additional ~1.3 "popcorn" π^0/event
- 2.2 units of rapidity differences observed on average



All indicate these are "jetty" events with long-range baryon number conservation !

MC analysis of FFs from SIA data



Sato et al.
arXiv:1609.00899

Good data-theory agreement also in this study, but uncertainties are still large

FIG. 5: Ratio of experimental single-inclusive e^+e^- cross sections to the fitted values versus z (or $z_{\min}$ for OPAL data [32, 33]) for pion production. The experimental uncertainties are indicated by the black points, with the fitted uncertainties denoted by the red bands. For the BaBar data [40] the prompt data set is used.

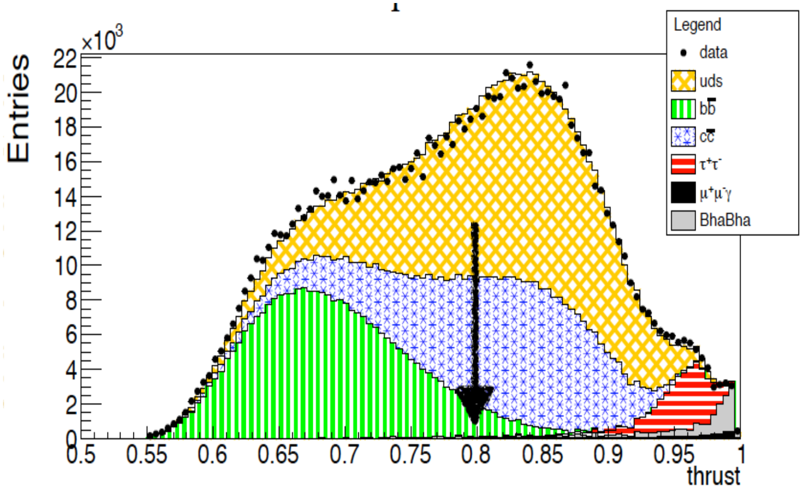
Analysis strategy

- Two analyses performed at BABAR:
  1. $e^+e^- \rightarrow X + \pi\pi$ PRD 90, 052003
     - asymmetries as a function of pions z and p_T
  2. $e^+e^- \rightarrow X + \pi\pi/\pi K/KK$ PRD 92, 111101(R)
     - simultaneous extraction of asymmetries for $\pi\pi$, πK, and KK pairs

Analysis strategy:

- Perform event and particle selections
- Separate into $\pi\pi$, KK and $K\pi$ candidate sets and subdivide into Like and Unlike charge
  - Charged data set is the combination of U and L.
- Measure azimuthal angle distributions for each set in both reference frames
  - Take the ratios of Unlike to Like and Unlike to Charged normalized distributions
  - Subtract background contributions and correct for particle misidentification

Selection of two jets topology: thrust > 0.8



- Extract Collins Asymmetry from each set, as a function of kinematic variables

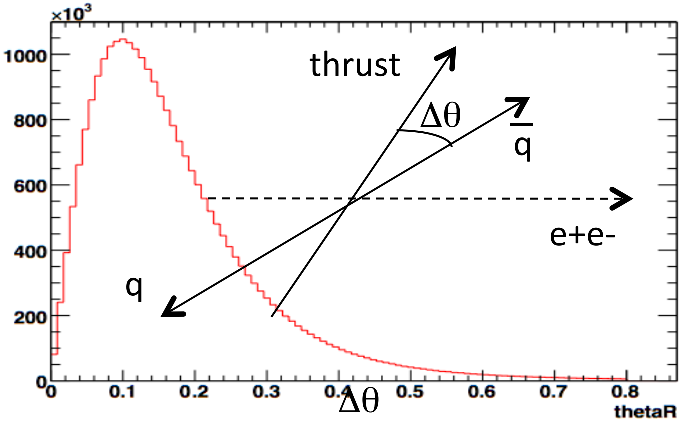
Extraction of the asymmetries

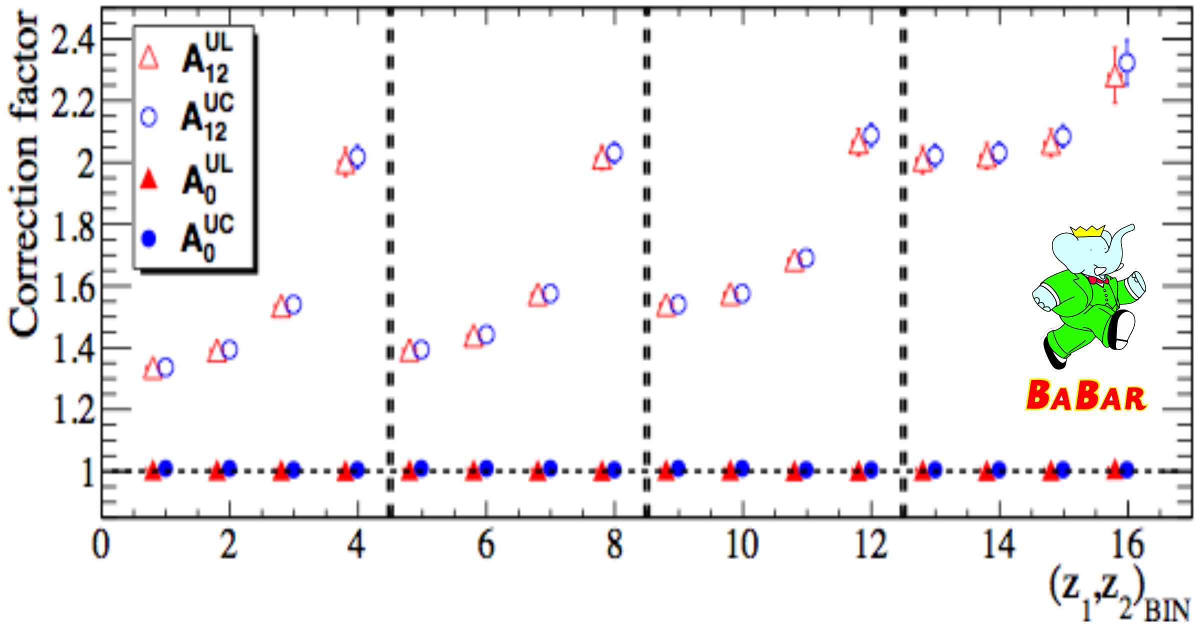
- The experimental method assumes the thrust axis as $q\bar{q}$ direction
- **This is only a rough approximation**

Introduces dilution of asymmetry in RF12. Correct through MC study

No dilution effect in RF0

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





Extraction of the asymmetries

- Simultaneous extraction of the asymmetries corrected for background (mainly charmed hadron decays, but also BB and τ+τ−) and K/π misidentification in each fractional energy interval
- Fit independently the double ratio distributions of the three selected samples KK, Kπ, ππ

$$A_{KK}^{\mathrm{meas}} = F_{uds} \cdot A_{KK}^{Collins} + \sum_i F_i^{KK} \cdot A_{KK}^{i}$$

1. **Background sources:**

- mainly from **$e^+e^- \to c\bar{c}$ events** (more than 30%); smaller contribution from $B\bar{B}$, $\tau^+\tau^-$ (A_{BB}~A_τ~ 0)
- construct a D^*-enhanced MC and data control samples to estimate the charm contribution

$D^{*\pm} \to D^0\pi^\pm$, $D^0 \to K\pi$, $D^0 \to K3\pi$, $D^0 \to K\pi\pi^0$, $D^0 \to K_S\pi\,\pi$

- The fractions ($F(f)_{\mathrm{sig/bkg}}{}^{hh}$) of hadron pairs coming from signal (uds) and background events ($c\bar{c}$, $B\bar{B}$, $\tau^+\tau^-$) are obtained from MC simulation

$$\begin{cases} A_{KK}^{\mathrm{meas}} = F_{uds}^{KK} \cdot A_{KK}^{Collins} + F_{c\bar{c}}^{KK} \cdot A_{KK}^{charm} \\ A_{KK}^{D^*} = f_{uds}^{KK} \cdot A_{KK}^{Collins} + f_{c\bar{c}}^{KK} \cdot A_{KK}^{charm} \end{cases}$$

Extraction of the asymmetries

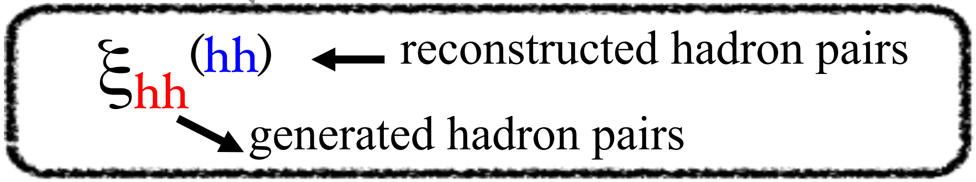
- Simultaneous extraction of the asymmetries corrected for background (mainly charmed hadron decays, but also BB and τ+τ−) and K/π misidentification in each fractional energy interval
- Fit independently the double ratio distributions of the three selected samples KK, Kπ, ππ

$$A_{KK}^{\mathrm{meas}} = F_{uds} \cdot A_{KK}^{Collins} + \sum_i F_i^{KK} \cdot A_{KK}^i$$

2. K/π misidentification:

- Evaluate from MC the fraction ($\xi_{hh}^{(hh)}$) that a given hadron pair is reconstructed as KK, Kπ, or ππ pair

$$A_{KK}^{\mathrm{meas}} = F_{uds} \cdot \left(\sum_{nm} \xi_{nm}^{(KK)} \cdot A_{nm}^{Collins} \right) + F_{c\bar{c}}^{KK} \cdot \left(\sum_{nm} \xi_{nm}^{(KK)} \cdot A_{nm}^{charm} \right)$$



$\xi_{hh}^{(hh)}$ ← reconstructed hadron pairs

↘ generated hadron pairs

3. Solve the system of equations to extract all asymmetry parameters

Extraction of the asymmetries

$$
\begin{aligned}
A_{KK}^{meas} = \;& F_{uds}^{KK}\cdot(\xi_{KK}^{(KK)}\boxed{A_{KK}}+\xi_{K\pi}^{(KK)}\boxed{A_{K\pi}}+\xi_{\pi\pi}^{(KK)}\boxed{A_{\pi\pi}})+\\
& F_{c\bar{c}}^{KK}\cdot(\xi_{KK}^{(KK)c\bar{c}}A_{KK}^{ch}+\xi_{K\pi}^{(KK)c\bar{c}}A_{K\pi}^{ch}+\xi_{\pi\pi}^{(KK)c\bar{c}}A_{\pi\pi}^{ch})\\
A_{K\pi}^{meas} = \;& F_{uds}^{K\pi}\cdot(\xi_{KK}^{(K\pi)}A_{KK}+\xi_{K\pi}^{(K\pi)}A_{K\pi}+\xi_{\pi\pi}^{(K\pi)}A_{\pi\pi})+\\
& F_{c\bar{c}}^{K\pi}\cdot(\xi_{KK}^{(K\pi)c\bar{c}}A_{KK}^{ch}+\xi_{K\pi}^{(K\pi)c\bar{c}}A_{K\pi}^{ch}+\xi_{\pi\pi}^{(K\pi)c\bar{c}}A_{\pi\pi}^{ch})\\
A_{\pi\pi}^{meas} = \;& F_{uds}^{\pi\pi}\cdot(\xi_{KK}^{(\pi\pi)}A_{KK}+\xi_{K\pi}^{(\pi\pi)}A_{K\pi}+\xi_{\pi\pi}^{(\pi\pi)}A_{\pi\pi})+\\
& F_{c\bar{c}}^{\pi\pi}\cdot(\xi_{KK}^{(\pi\pi)c\bar{c}}A_{KK}^{ch}+\xi_{K\pi}^{(\pi\pi)c\bar{c}}A_{K\pi}^{ch}+\xi_{\pi\pi}^{(\pi\pi)c\bar{c}}A_{\pi\pi}^{ch})\\
A_{KK}^{D^*} = \;& f_{uds}^{KK}\cdot(\xi_{KK}^{(KK)D^*}A_{KK}+\xi_{K\pi}^{(KK)D^*}A_{K\pi}+\xi_{\pi\pi}^{(KK)D^*}A_{\pi\pi})+\\
& f_{c\bar{c}}^{KK}\cdot(\xi_{KK}^{(KK)c\bar{c}-D^*}A_{KK}^{ch}+\xi_{K\pi}^{(KK)c\bar{c}-D^*}A_{K\pi}^{ch}+\xi_{\pi\pi}^{(KK)c\bar{c}-D^*}A_{\pi\pi}^{ch})\\
A_{K\pi}^{D^*} = \;& f_{uds}^{K\pi}\cdot(\xi_{KK}^{(K\pi)D^*}A_{KK}+\xi_{K\pi}^{(K\pi)D^*}A_{K\pi}+\xi_{\pi\pi}^{(K\pi)D^*}A_{\pi\pi})+\\
& f_{c\bar{c}}^{K\pi}\cdot(\xi_{KK}^{(K\pi)c\bar{c}-D^*}A_{KK}^{ch}+\xi_{K\pi}^{(K\pi)c\bar{c}-D^*}A_{K\pi}^{ch}+\chi_{\pi\pi}^{(K\pi)c\bar{c}-D^*}A_{\pi\pi}^{ch})\\
A_{\pi\pi}^{D^*} = \;& f_{uds}^{\pi\pi}\cdot(\xi_{KK}^{(\pi\pi)D^*}A_{KK}+\xi_{K\pi}^{(\pi\pi)D^*}A_{K\pi}+\xi_{\pi\pi}^{(\pi\pi)D^*}A_{\pi\pi})+\\
& f_{c\bar{c}}^{\pi\pi}\cdot(\xi_{KK}^{(\pi\pi)c\bar{c}-D^*}A_{KK}^{ch}+\xi_{K\pi}^{(\pi\pi)c\bar{c}-D^*}A_{K\pi}^{ch}+\xi_{\pi\pi}^{(\pi\pi)c\bar{c}-D^*}A_{\pi\pi}^{ch})
\end{aligned}
$$

○ = Collins asymmetries for light hadrons

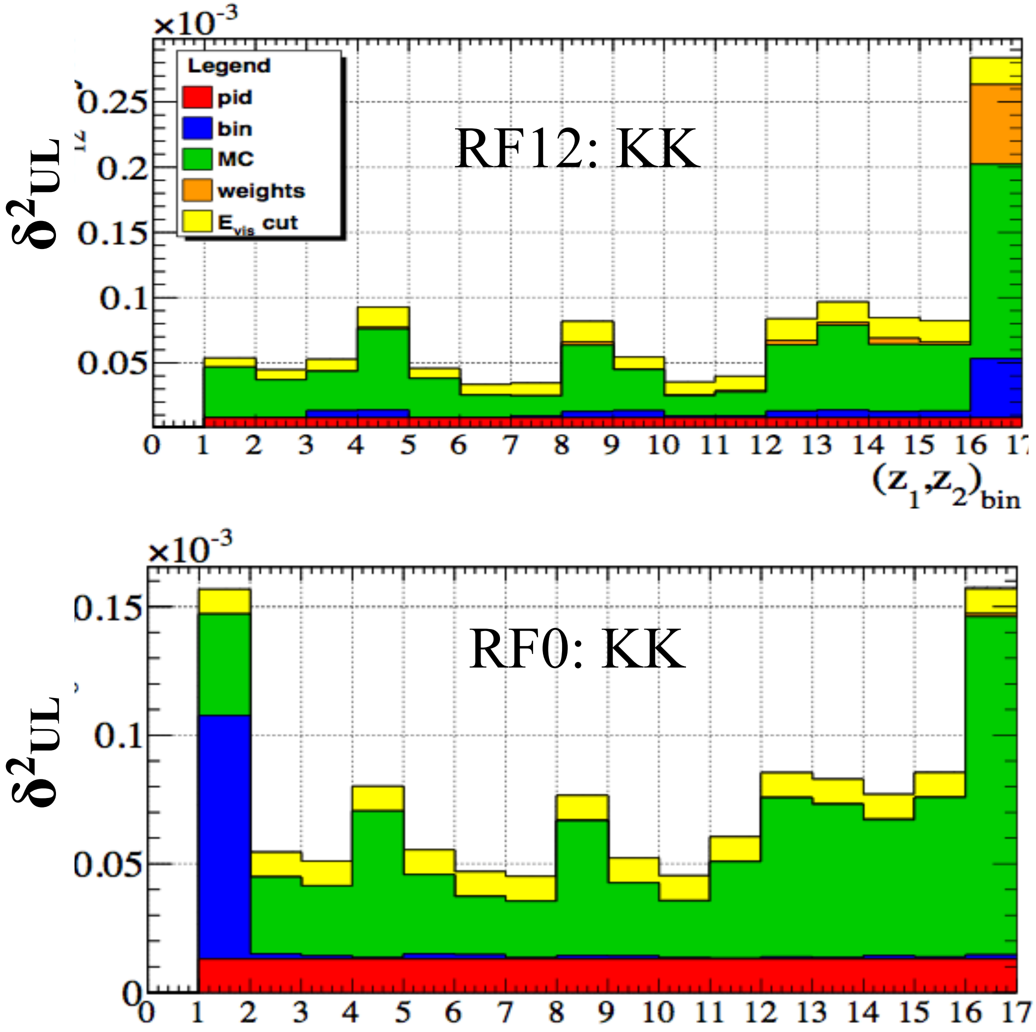
Systematic uncertainties

A large number of systematic checks were done. The main contributions come from:

- MC uncertainties
- Particle identification (PID)
- Fit procedure
- Dilution method
- E_{vis} cut

Additional checks show negligible effects, such as:

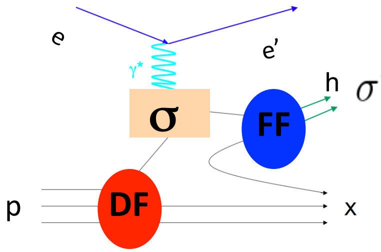
- Beam polarization studies
- Asymmetry consistency between different data taking period
- Possible coupling between Collins and detector effect



Sum in quadrature of systematic uncertainties (absolute values)

Use Collins FF to extract Transversity

SIDIS: Semi Inclusive Deep Inelastic Scattering



Factorization theorem:

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

$$\sigma \propto \sin(\phi_h + \phi_s) h_1(x_B) \otimes H_1^{\perp}(z_1)$$

Transversity function

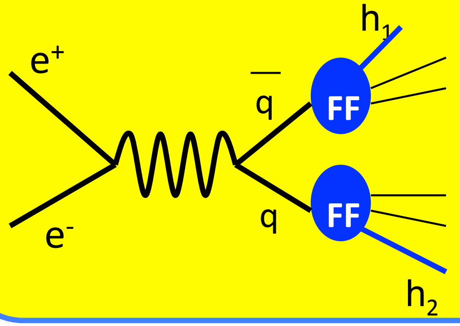
SIDIS

- Unpolarized lepton beam off transversely polarized nucleon target
  - non-zero Collins effects
  - spin direction known
  - two chiral-odd functions

  Transversity PDF & Collins FF

Global analysis of **SIDIS (HERMES & COMPASS) and** ***e+e- (BELLE, BABAR, BESIII)*** data

==> simultaneous determination of Transversity (h_1) and Collins functions (CFF).



$$e^+e^- \to q\bar{q} \to h_1 h_2 X \quad (q = u,d,s)$$

$$\sigma \propto \cos(\phi_i) H_1^{\perp}(z_1) \otimes H_1^{\perp}(z_2)$$

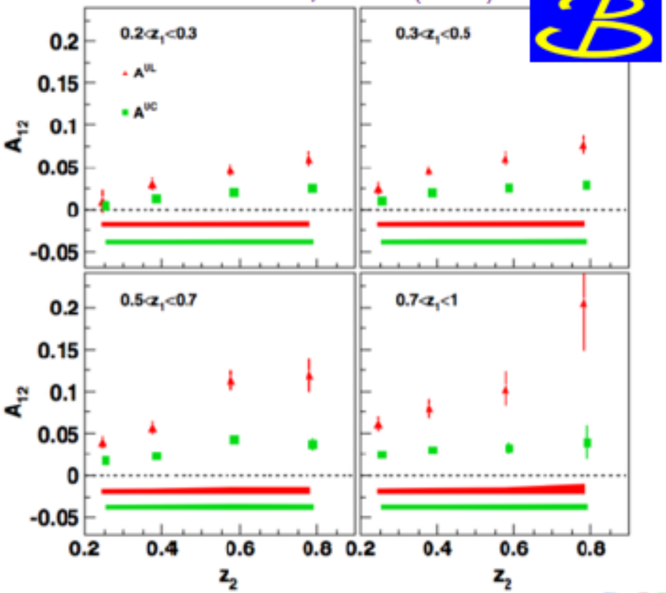
e^+e^- annihilation

- γ* (spin-1) goes to spin-1/2 q and $\bar{q}$
  - **Two Collins functions contribute to the cross section**

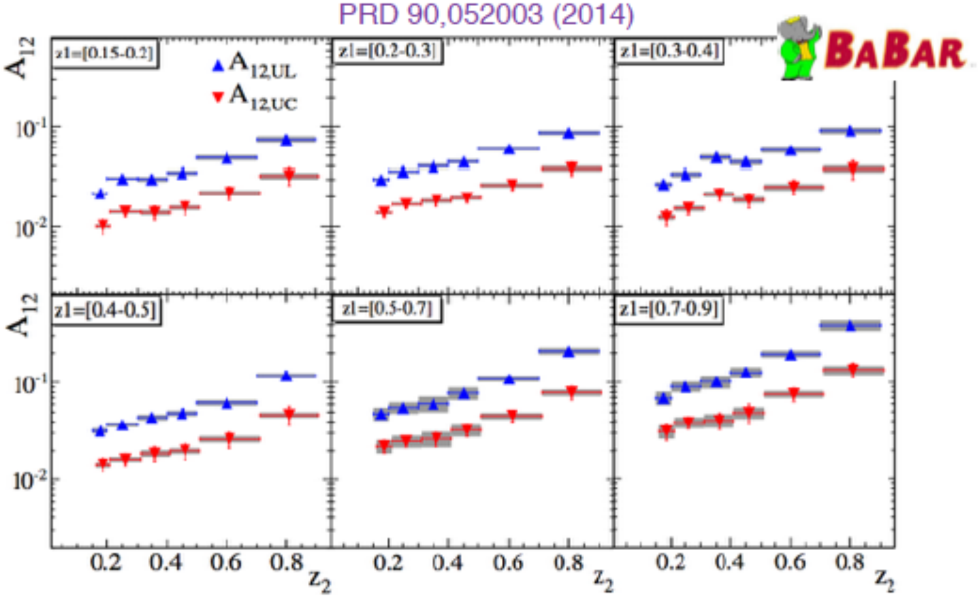
Collins effect in pion pair production: *A vs* (z_1,z_2)

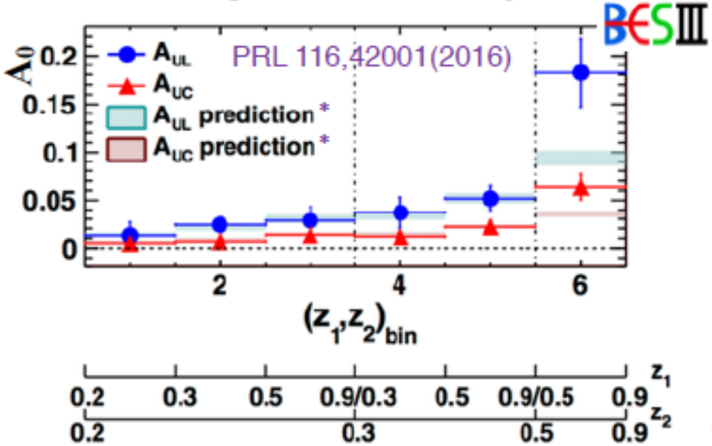
Measurement performed by Belle (PRD78, 032011, Erratum PRD 86, 039905) and *BABAR* (PRD90, 052003) at $Q^2 \sim 110\ \mathrm{GeV}^2$, and by BESIII (PRL 116, 042001) at $Q^2 \sim 13\ \mathrm{GeV}^2$

PRD 88,032011(2013)



PRD 90,052003 (2014)





*PRD 93,014009(2016)

- Significant non-zero asymmetries A_{12}, A_0 in all bins
- Strong dependence on (z_1,z_2) observed in all the experiments
- $A_{UC} < A_{UL}$ as expected; complementary informations about favored and disfavored fragmentation processes