Studies of fragmentation functions with the *BABAR* detector

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on behalf of the BABAR Collaboration

Parton Radiation and Fragmentation from LHC to FCC-ee,

CERN, November 21-22, 2016

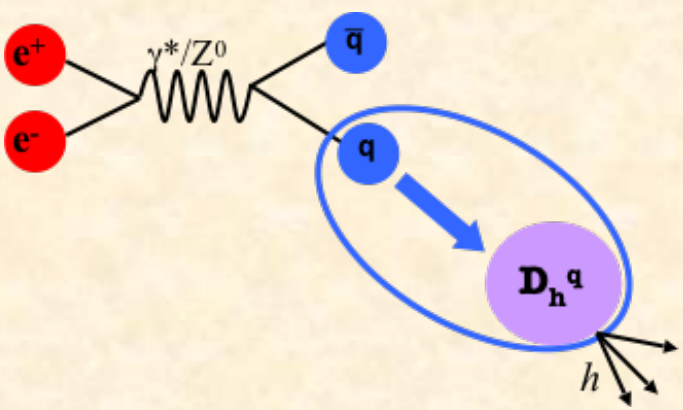
Outline:

- Fragmentation function definition

- Inclusive production of light hadrons at ~10 GeV
  - π, K, p/$\overline{\text{p}}$ production
- Inclusive studies on charmed baryons at ~10 GeV
  - Inclusive Λ_c and Ξ_c spectra
  - $\Lambda_c^+\overline{\Lambda}_c^-$ correlated production and popcorn mesons
- Measurement of Collins asymmetries:
  - $e^+e^- \rightarrow \pi\pi$ +X, πK +X, and KK +X

- Conclusions

Fragmentation functions definition



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

  $x = 2E_h/\sqrt{s}$

Total Fragmentation Function

Parton Fragmentation Function

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

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

process dependent short distance interaction

non-perturbative part

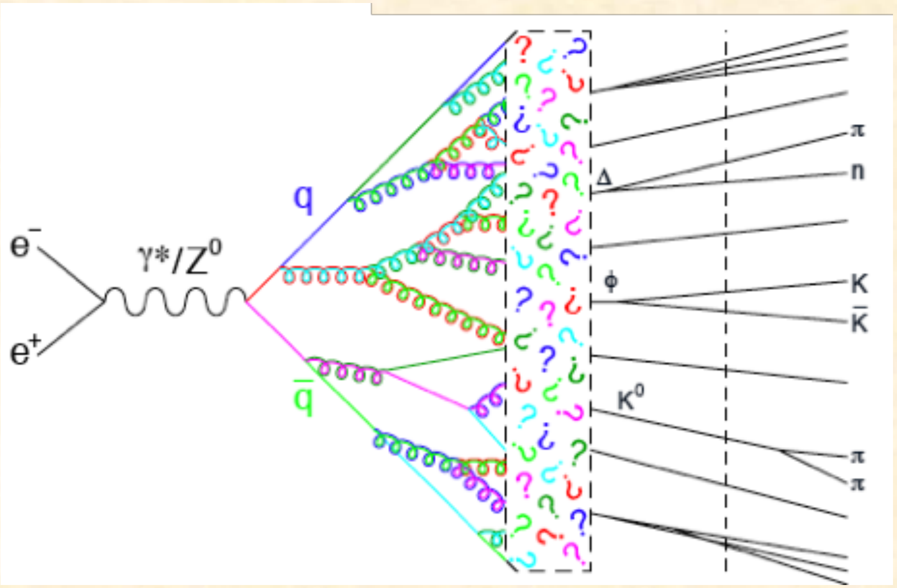
- $D_1^h(z,\mu^2)$ describes the probability that a parton *i* fragments into a hadron *h* carrying a fraction *z* of the parton momentum
- e^+e^- annihilation is the cleanest environment to study the fragmentation functions
  - but low sensitivity to gluon FF

Inclusive Hadronic Particle Spectra

- Perturbative QCD corrections lead to logarithmic scaling violations via the evolution equation (DGLAP)

- 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
- Measurement of both quark and antiquark fragmentation

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



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

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

Inclusive production of light hadrons

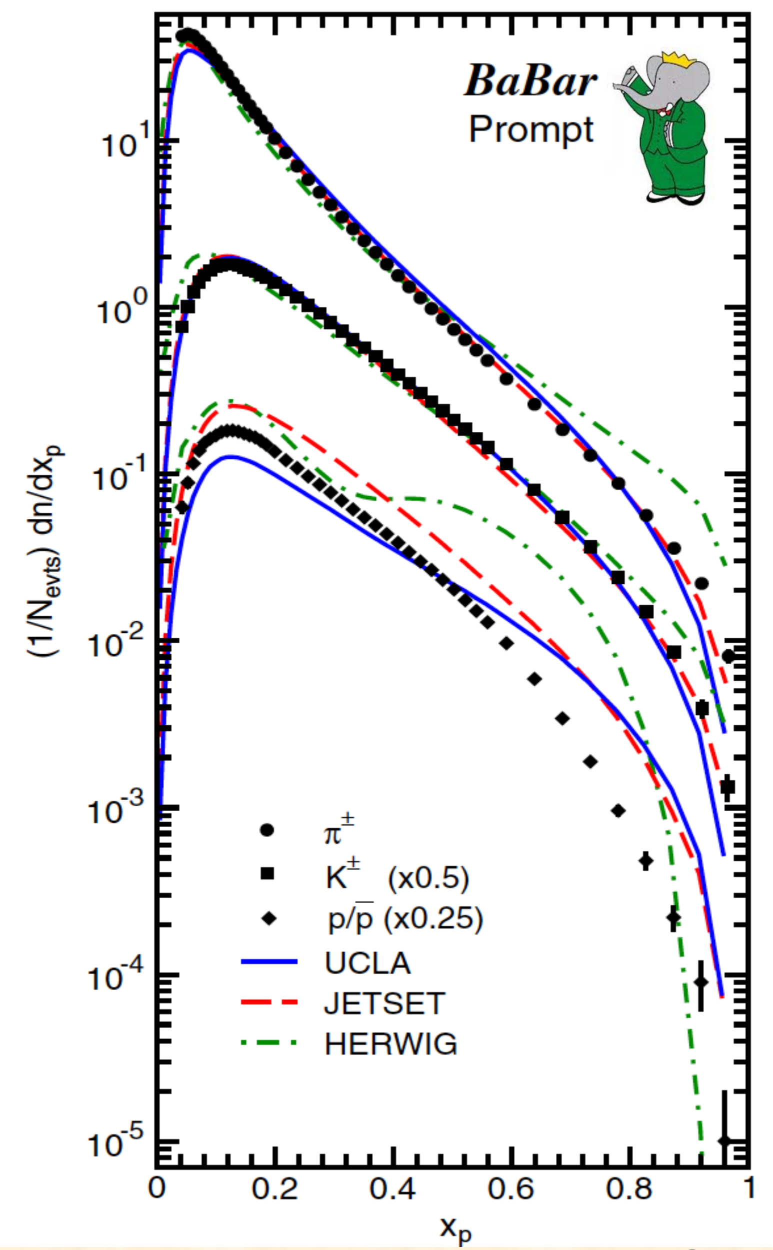
Phys. Rev D88, 032011 (2013)

- It uses a data sample of 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

Test of hadronization models

- Scaled momentum distribution: $x_p = 2p^*/E_{cm}$
  - Coverage: $0.2 < p^* < 5.27$ GeV/c
  - Syst. uncertainties from ~2% to ~10% in the highest momentum bins, dominate the full error
- Data consistent and much more precise than previous ARGUS data at similar energies
- Consistent also with Belle data, with some deviation at the highest momenta

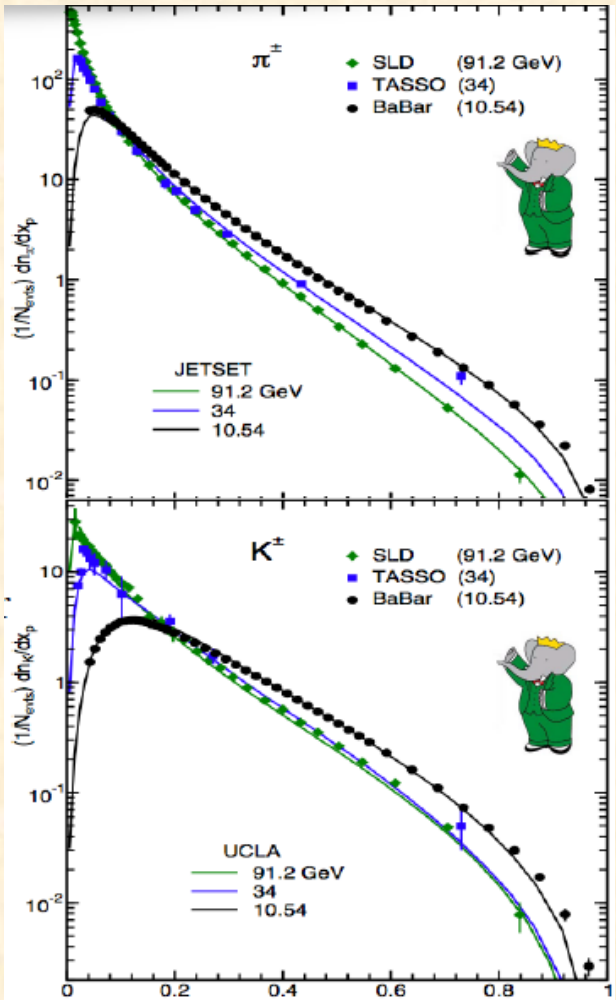
- Data are compared to predictions of three hadronization models
  - Parameters tuned on previous data from ARGUS and from higher energy experiments
- Consistency for pions and kaons within ~10%
  - but significant differences in shape
- Poor description of proton data



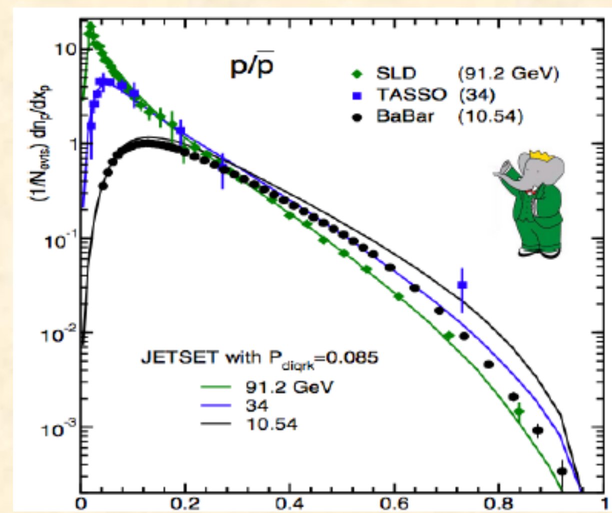
Scaling properties

- Hadronization should be scale invariant except for "small" effects of hadron masses, running of $\alpha_S, \ldots$

- Scaling violations at low x_p, due to masses are well known and modeled adequately (here JETSET is shown for comparison)



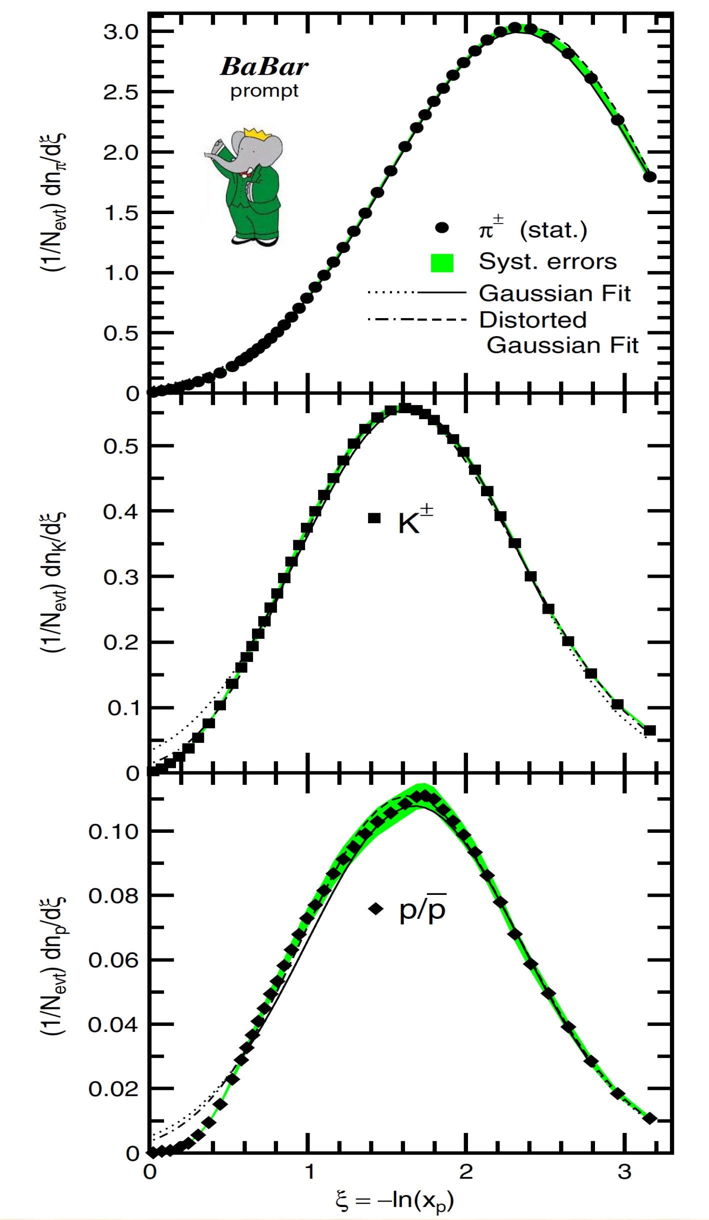
- Expect substantial scaling violations at high x_p:
  - Seen clearly in π and K data; reproduced by models (within a few % for π, and 15% for K)
  - Much smaller scaling violation in proton data than models predict



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}
- ξ^* should increase logarithmically with E_{cm} for a given hadron type

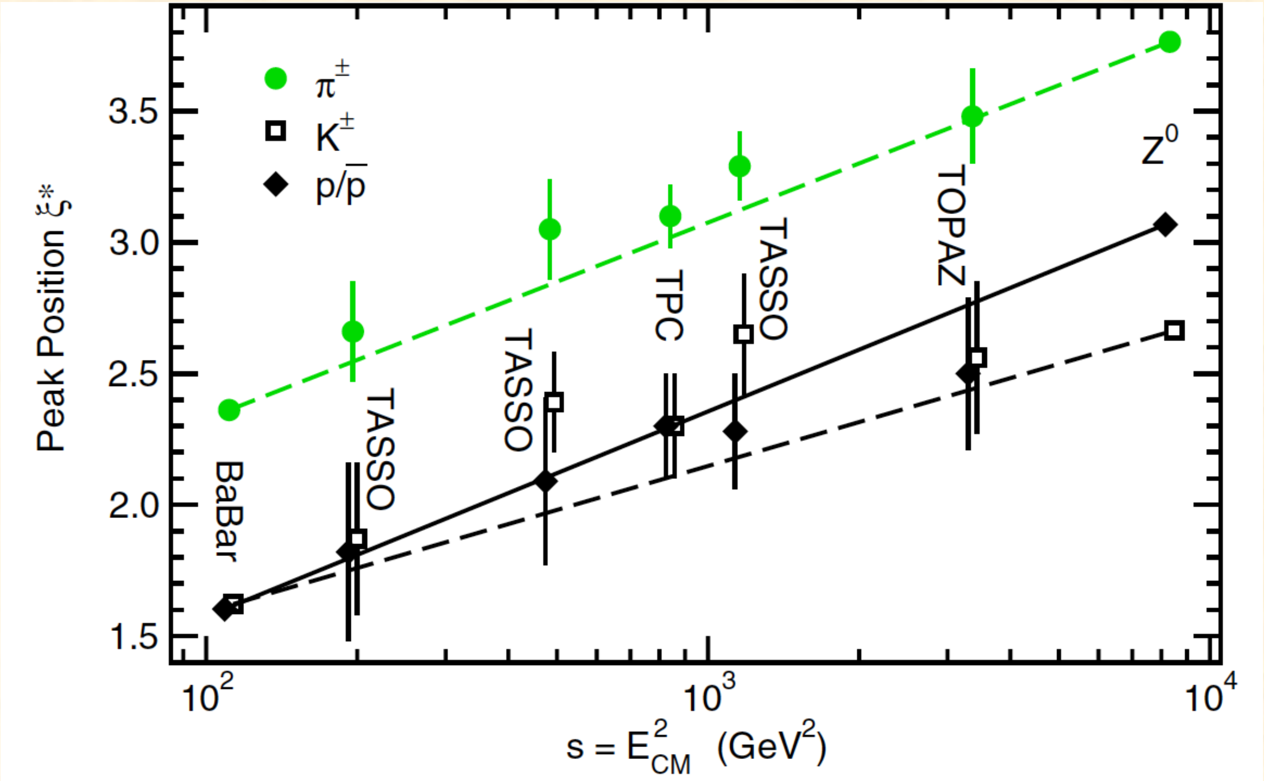


Peak position ξ^* from symmetric gaussian fits

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



- *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* $\to$ *charmed mesons/baryons*

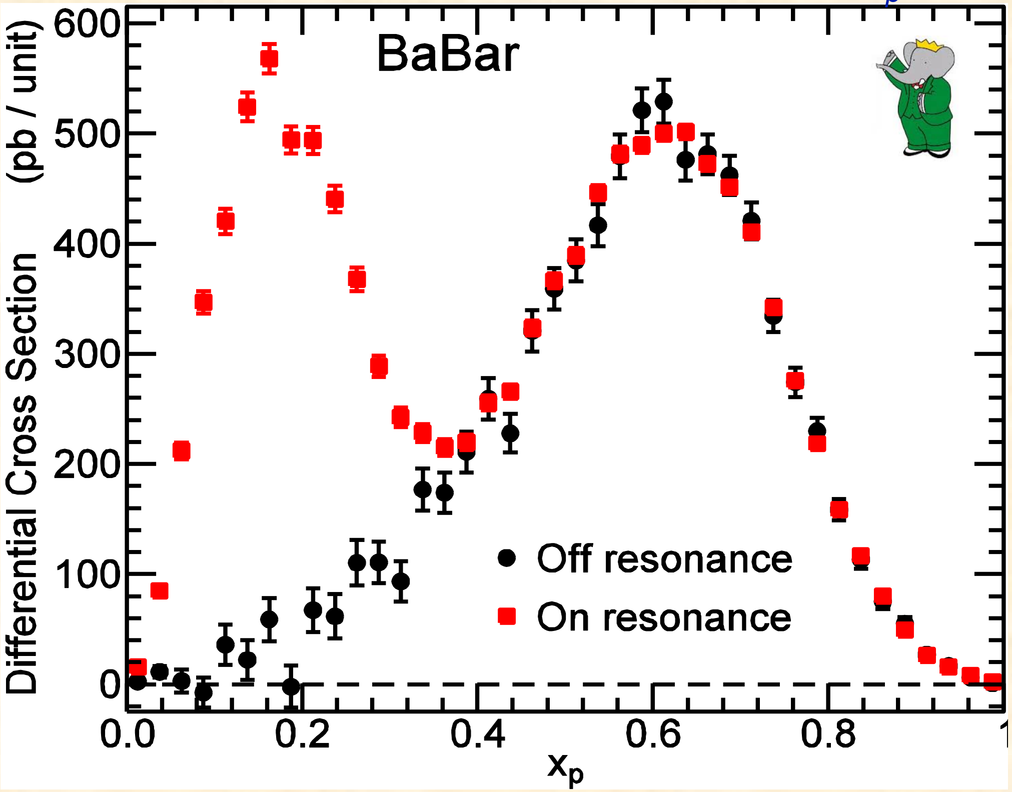
Inclusive Λ_c spectrum measurement

PRD 75, 012003 (2007)

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

- reconstruct $\Lambda_c^+ \to pK^- \pi^+$ 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 $e^+e^- \to c\bar{c}$ events from off-resonance data (E_{cm}=10.54 GeV)
- Determine $e^+e^- \to B\bar{B}$ events from on-resonance data subtracting the off-resonance cross section scaled by the different c.m. energy

Inclusive Λ_c spectrum measurement

PRD 75, 012003 (2007)

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

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

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

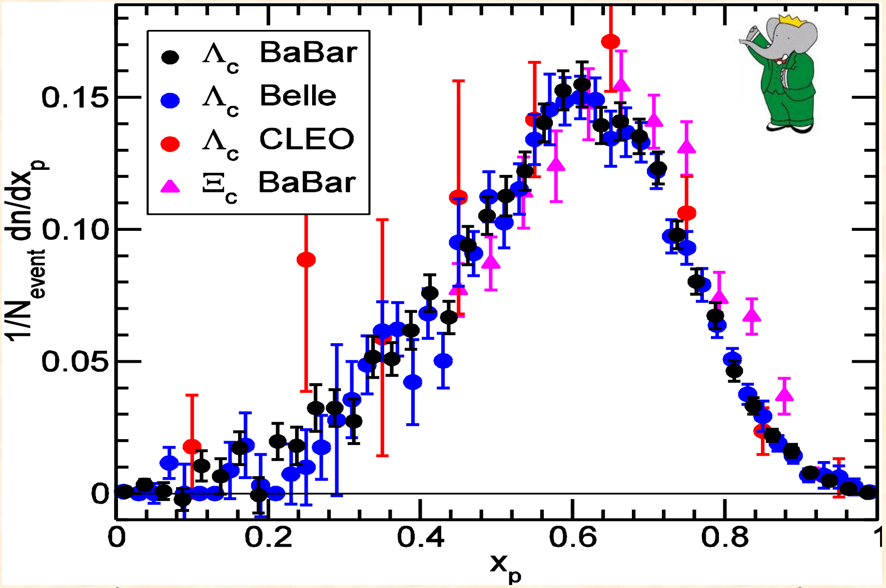
$$N^{c-jet}_{\Lambda_C} = 0.071 \pm 0.003(\text{exp}) \pm 0.018(\Lambda_C BF)$$

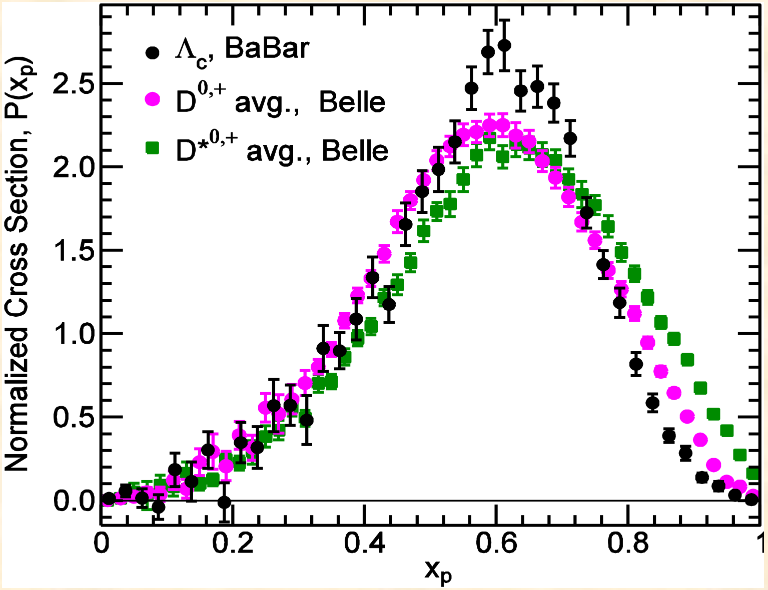
- Result consistent with previous CLEO and Belle measurements

➢ 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 $x_p \sim 1$



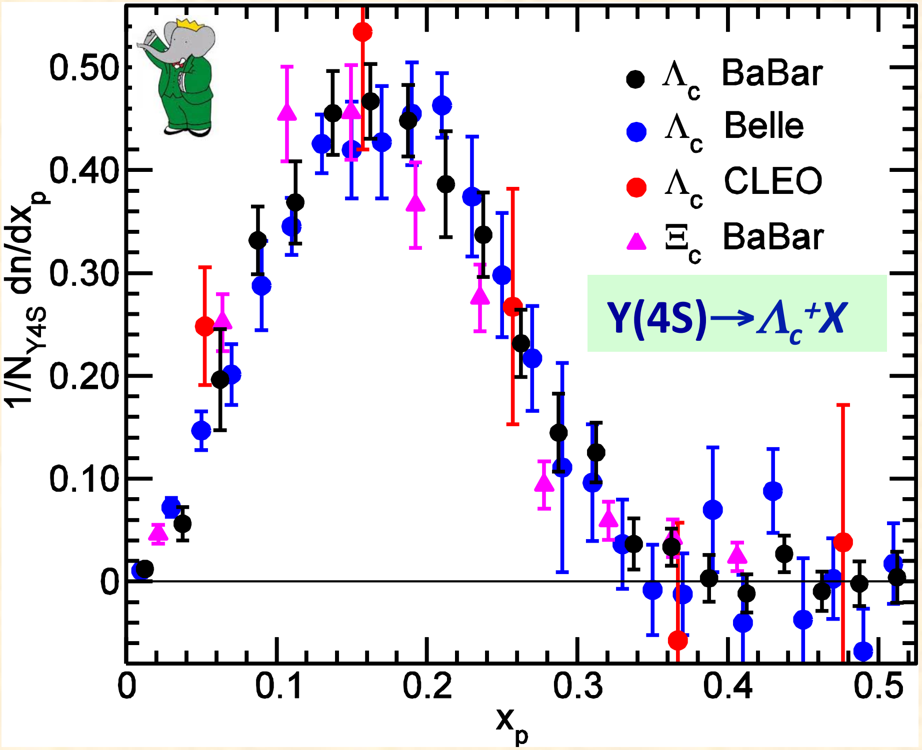


Inclusive Λ_c spectrum at the Y(4S)

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

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

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



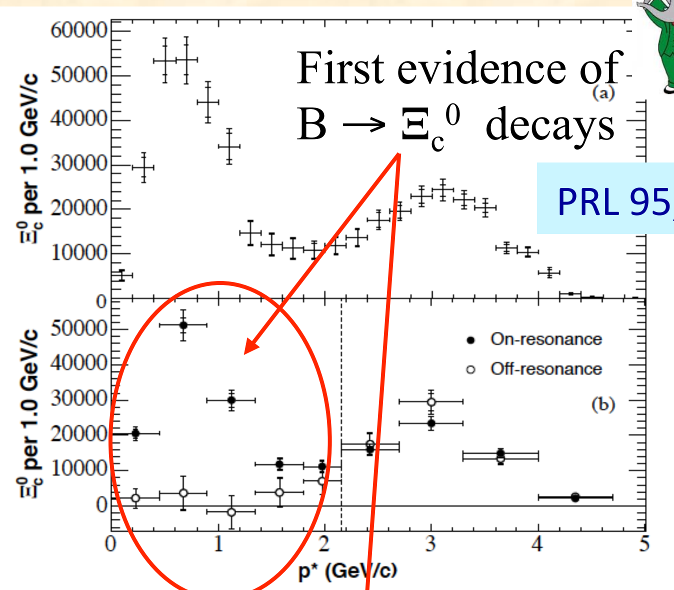
➤ Data suggest a dominance of quasi-two-body decays like:

- $B \to (\Lambda_c^+ \bar{p}\,,\ \Lambda_c^+ n\,,\ \Lambda_c^+ \Delta\,,\ \Sigma_c \bar{p}\ ) +\ m\pi$
- 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

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



PRL 95, 142003

B meson Branching Fraction

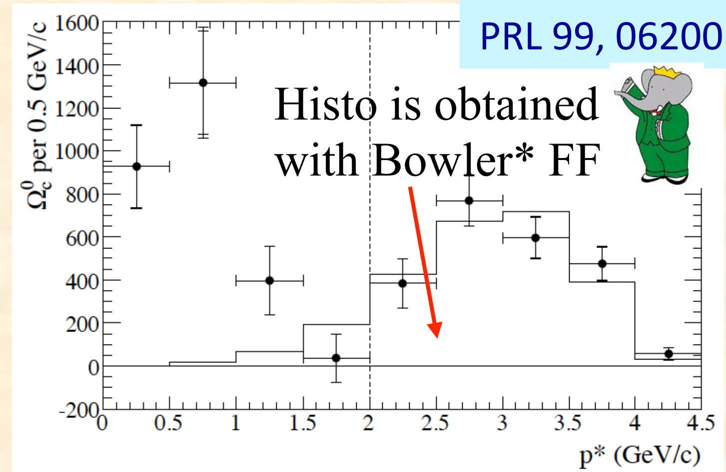
$$\mathcal{B}(B \to \Xi_c^0 X) \times \mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+) = (2.11 \pm 0.19 \pm 0.25) \times 10^{-4}$$

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



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

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

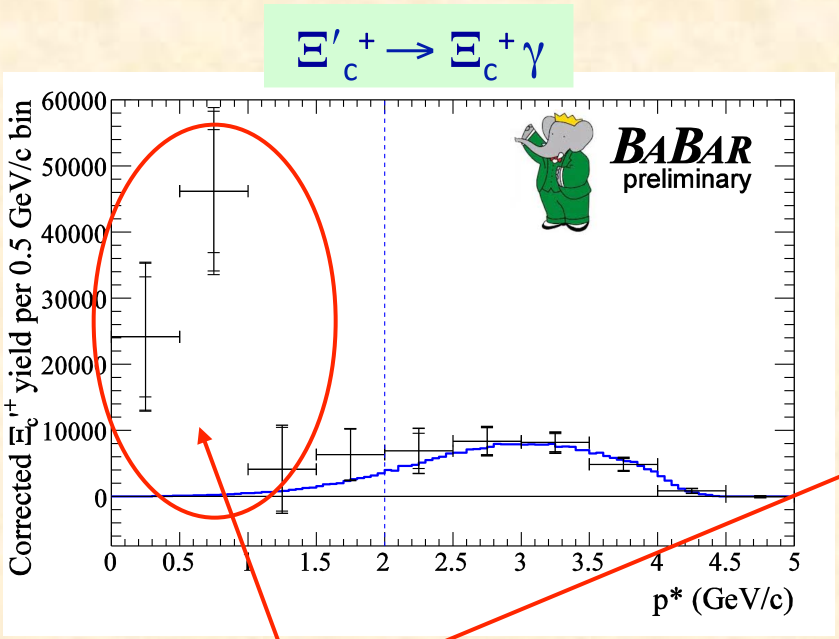
* M.G. Bowler, Z. Phys. C11, 169 (1981).

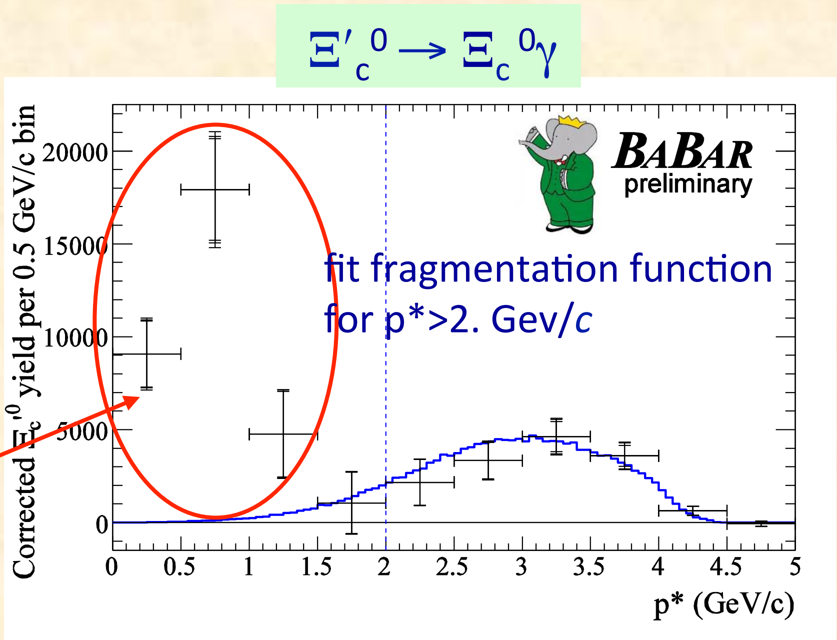
More c-baryons inclusive spectra: Ξ_c'

hep-ex/0607086

State	Mass (MeV/c²)	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 $\Xi'_c \to \Xi_c \gamma$





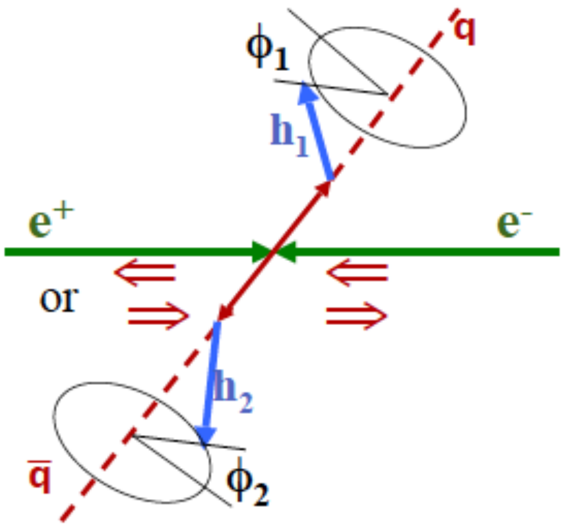
- first evidence of $B \to \Xi'_c$ decays

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

Measurement of Collins asymmetries for charged pions and kaons

- Phys.Rev. D90, 052003 (2014) : Collins asymmetries for pion pairs
- Phys.Rev. D92, 111101(R) (2015) : Collins asymmetries for $\pi\pi/\pi K/KK$ pairs

The Collins Fragmentation Function



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

"Standard" unpolarized FF

$$D_1^{q\uparrow}(z,\mathbf{P}_\perp;s_q) = D_1^q(z,P_\perp) + \frac{P_\perp}{zM_h} H_1^{\perp q}(z,P_\perp)\,\mathbf{s}_q\cdot(\mathbf{k}_q\times\mathbf{P}_\perp)$$

- $H_1^\perp$ 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 $\bar{q}$

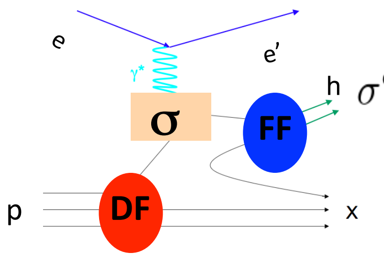
- in a given event, the spin directions are unknown, but they must be parallel
- they have a polarization component transverse to the q direction ~$\sin^2\theta$ (θ wrt the e^+e^-)

• exploit this correlation by using hadrons in opposite jets

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

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

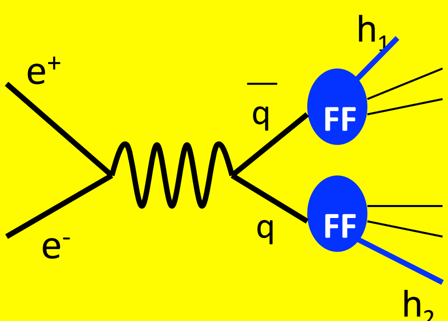
SIDIS

- 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).



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

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

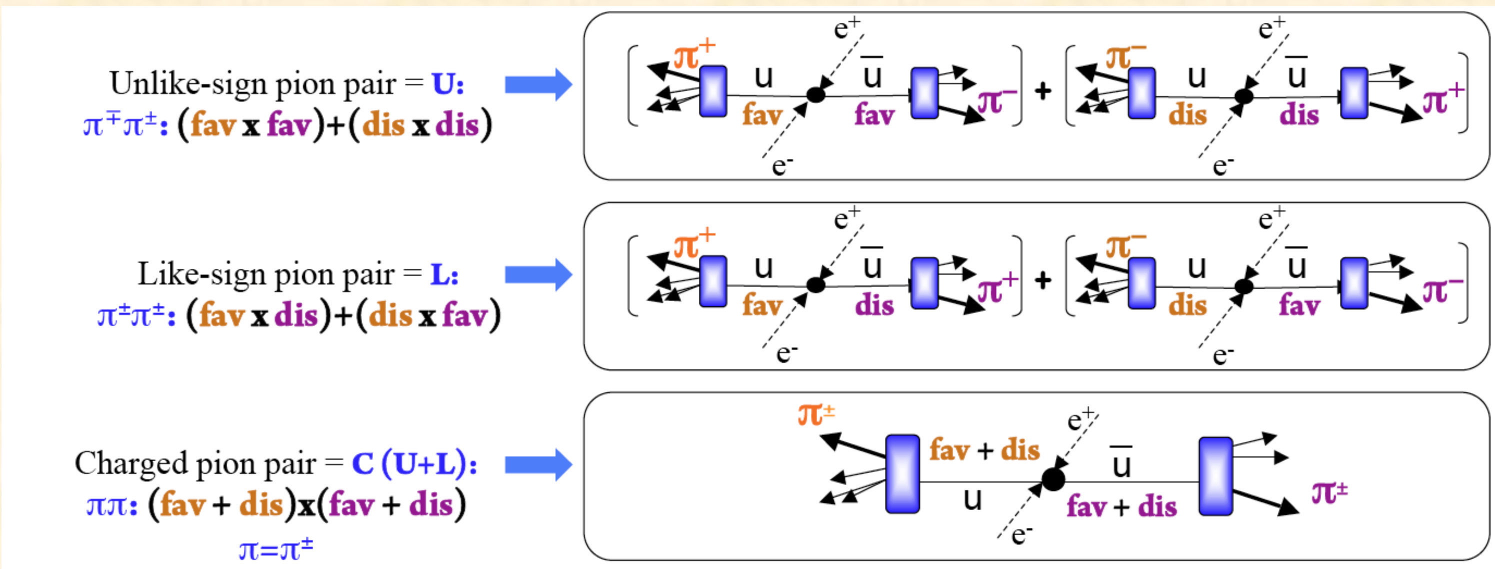
e^+e^- annihilation

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

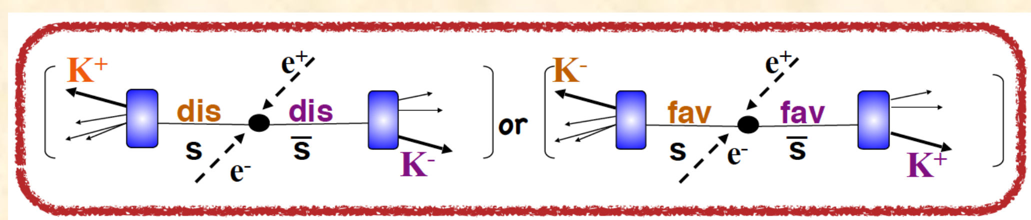
Collins effect in di-hadron correlation

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.* $d \to \pi^+, u \to \pi^-, s \to K^-, s \to \pi^\pm, \ldots$



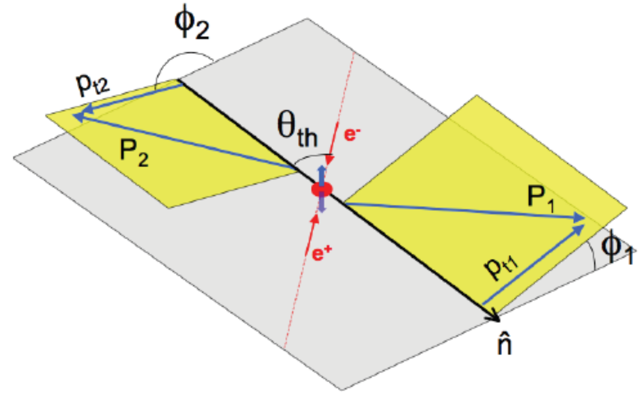
Similarly for Unlike-sign Kaon pairs:



Analysis reference frames

[See NPB 806, 23 (2009)]

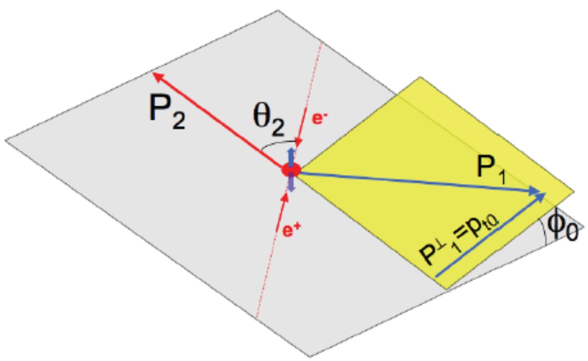
All quantities in e⁺e⁻ center of mass



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,…

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



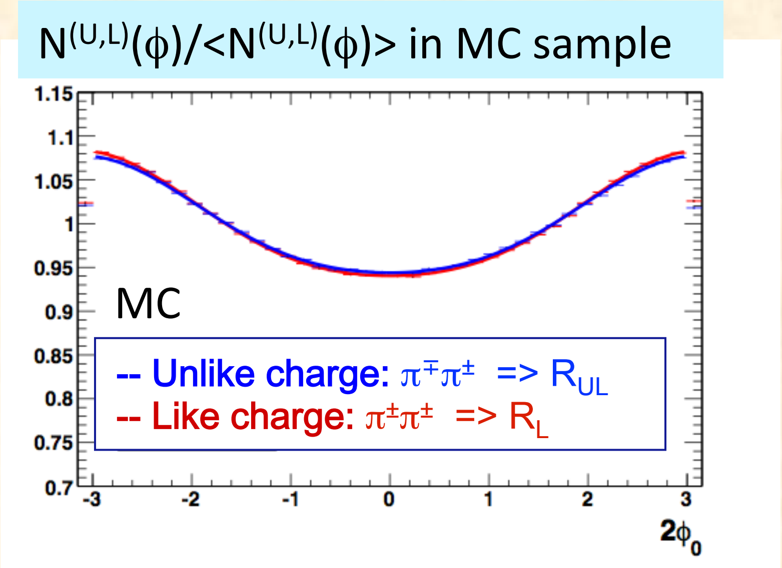
RF0 or Second hadron momentum RF

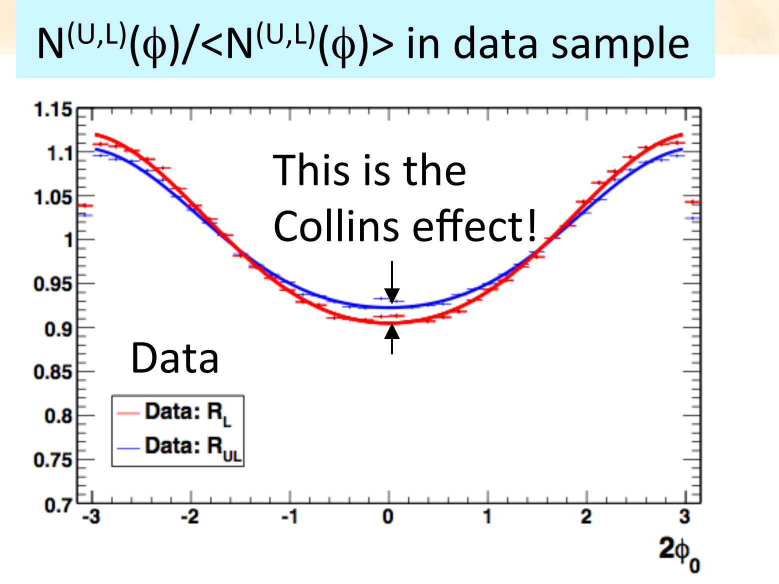
- Alternatively, just use **one track** in a pair
- Very clean experimentally (no thrust axis), less so theoretically
- Gives quark direction for higher pion momentum

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

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)

Extraction of asymmetry parameters from data





- **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

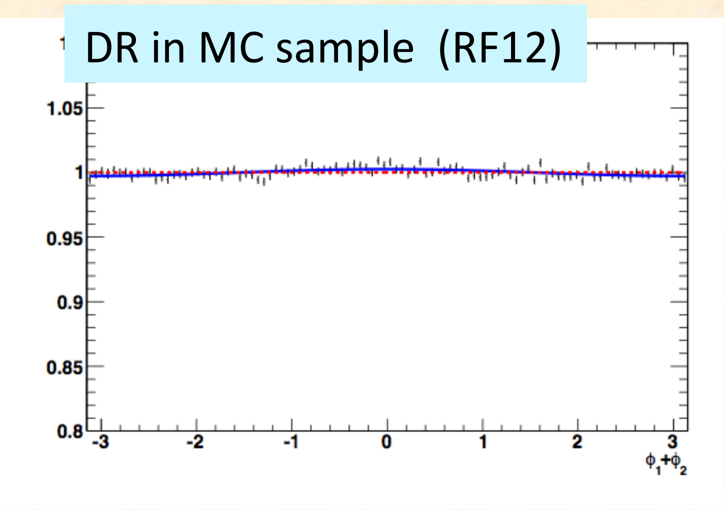
- <u>**Double Ratio (DR)** of Unlike-sign over Like-sign pion pairs</u>**:**

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

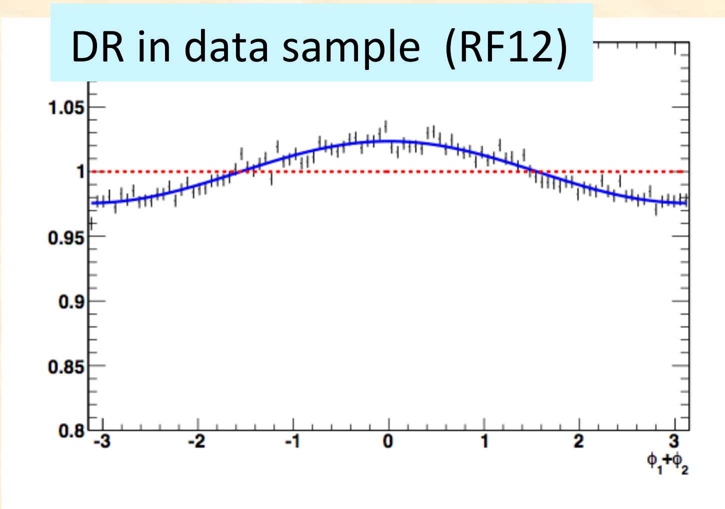
  - acceptances and radiative contributions do not depend on the charge combination of the pion pair;
  - approximation holds for small asymmetries.

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

Contains only the Collins effects and higher order radiative effects



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



Uncorrected Asymmetry

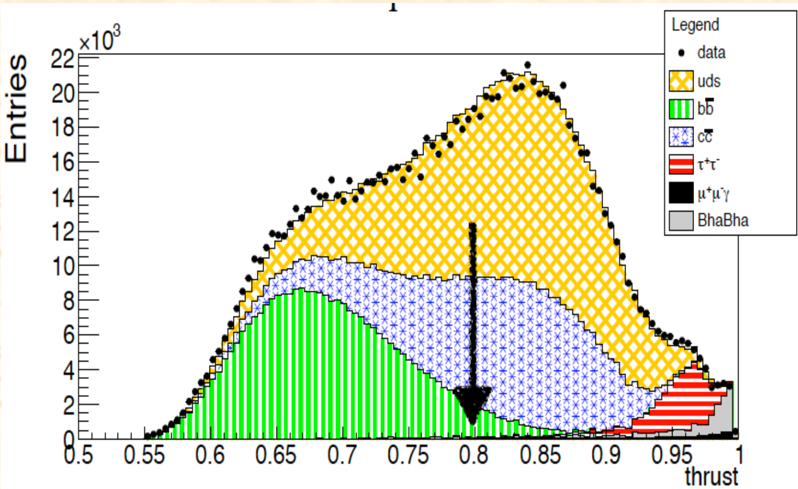
Analysis strategy

- 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

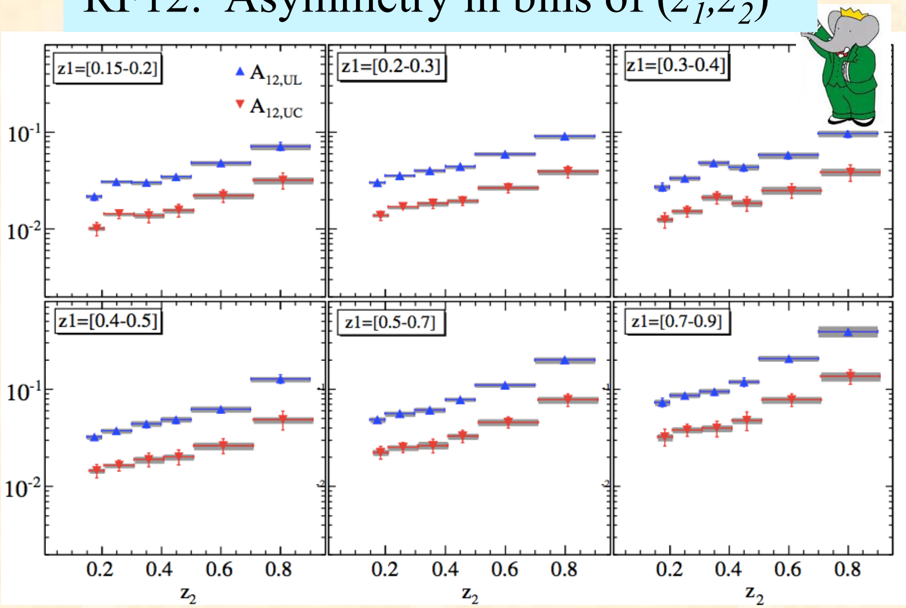


- Extract Collins Asymmetry from each set, as a function of kinematic variables

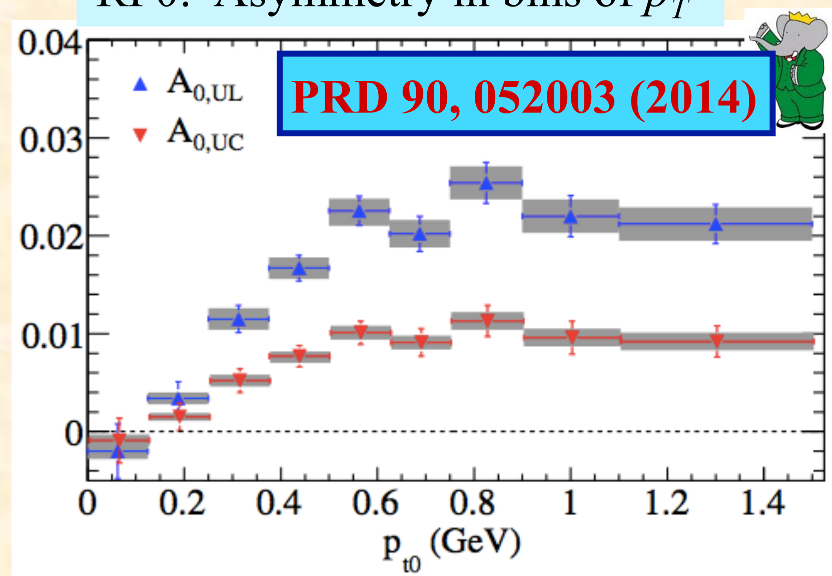
Collins asymmetries in pion pair production

Measurement of Collins asymmetries from double ratios in $e^+e^- \rightarrow \pi\pi X$ have been performed by Belle (PRD78,032011, Erratum PRD 86, 039905) and *BABAR* at $Q^2 \sim 110$ GeV^2, and by BESIII (PRL 116, 042001) at $Q^2 \sim 13$ GeV^2

RF12: Asymmetry in bins of (z_1,z_2)



RF0: Asymmetry in bins of p_T



Collins asymmetry measured by *BABAR* as function of:

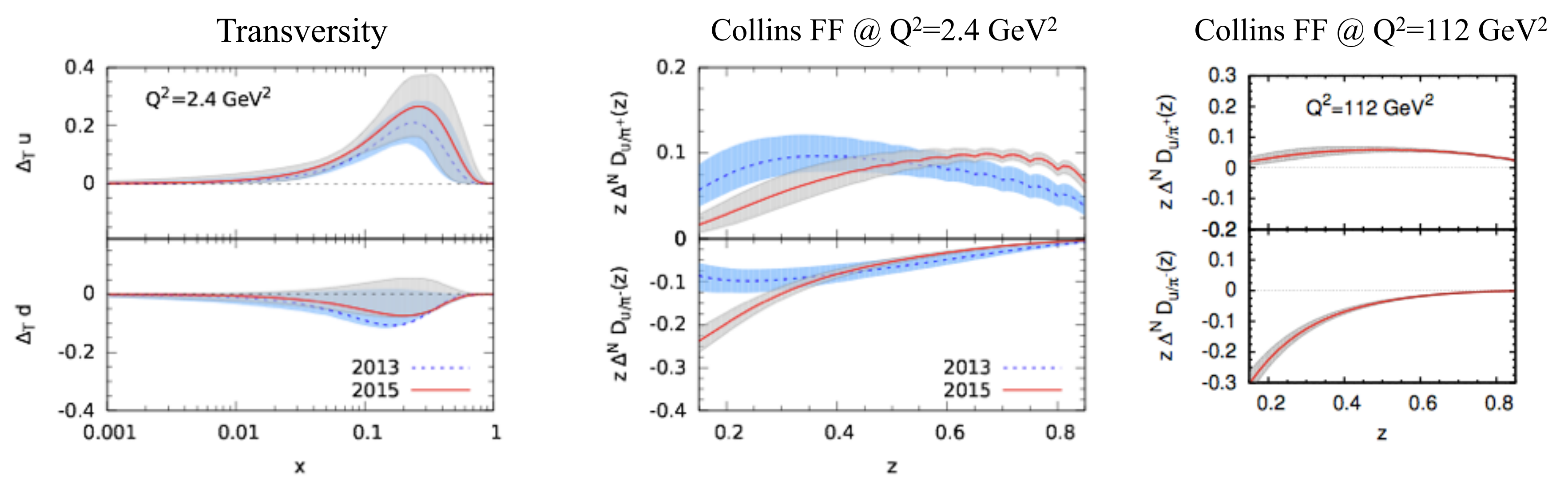
- 6×6 bins of pion fractional energy in both RF12 and RF0
- 4×4 bins of (p_{t1},p_{t2}) in RF12
- 9 bins of p_{t0} in RF0
- asymmetry measured also *vs*. $\sin^2\theta_{th}/(1+\cos^2\theta_{th})$ and $\sin^2\theta_2/(1+\cos^2\theta_2)$

A^{UL} and A^{UC} asymmetries strongly correlated as they are obtained from the same data sample

BABAR $\pi\pi$ results and global fits

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

***Anselmino et al*: arXiv:1510.05389**



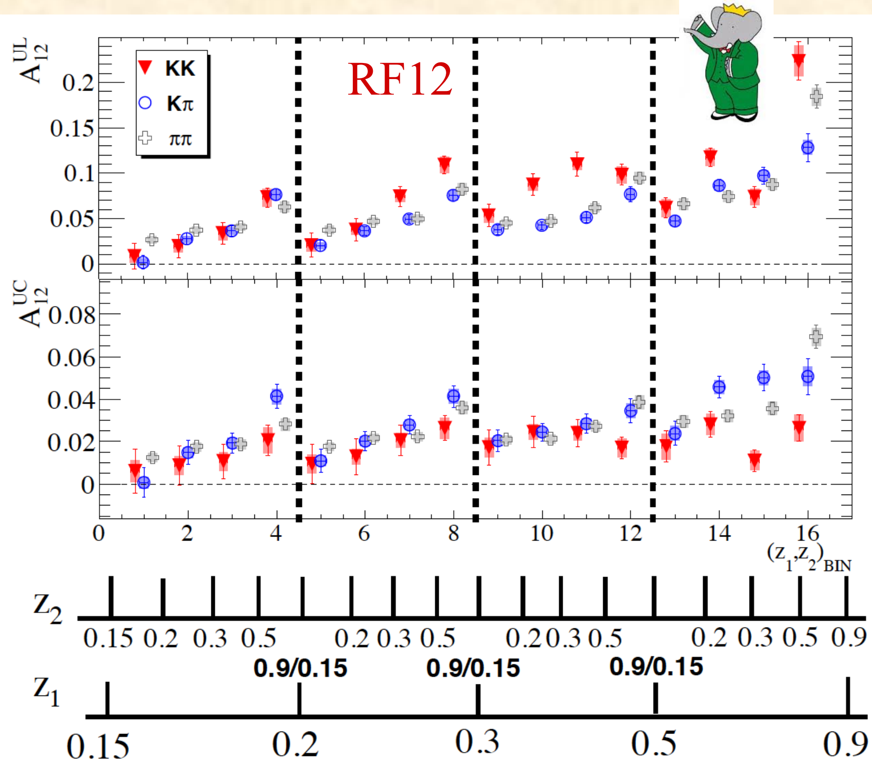
Comparison between old fit (SIDIS + Belle data) with new fit (*BABAR* $\pi\pi$ data added)

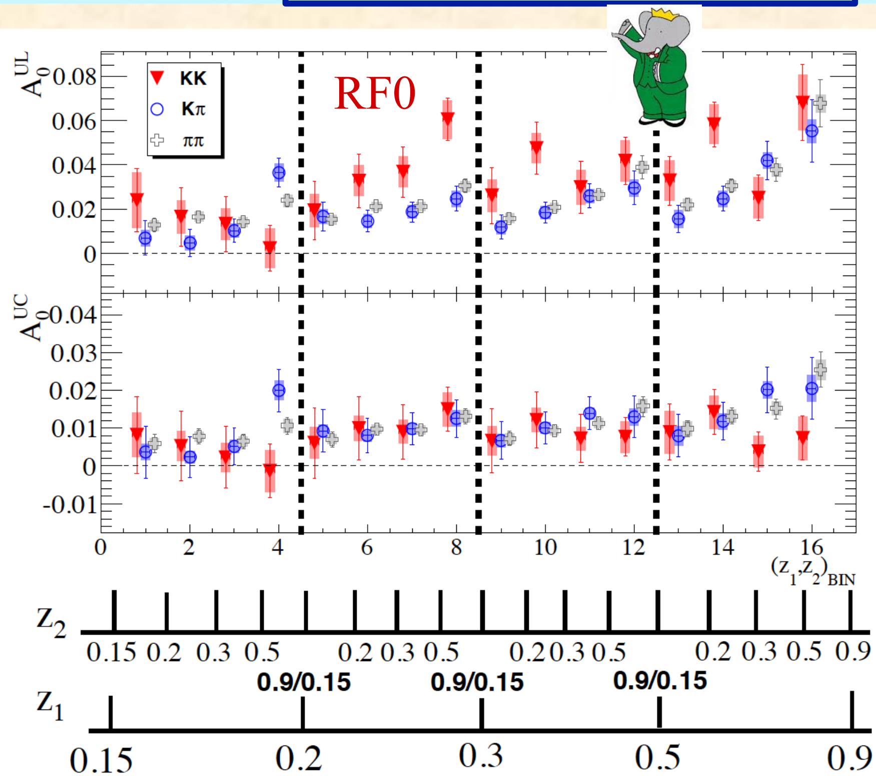
- Fit uncertainties significantly reduced in the new analysis
- Good consistency for the transversity function
- The differences seen for the Collins FF are mainly due to the different parametrization used:
  - old fit: *fav.* and *dis.* FFs have the same dependency on *z*, and could differ only for a renormalization constant
  - new fit: the *fav.* and *dis.* FFs are left uncorrelated

Collins asymmetries for *ππ, Kπ, KK* pairs

Measured Collins asymmetries reported in (z_1,z_2) bins

PRD 92, 111101(R) (2015)



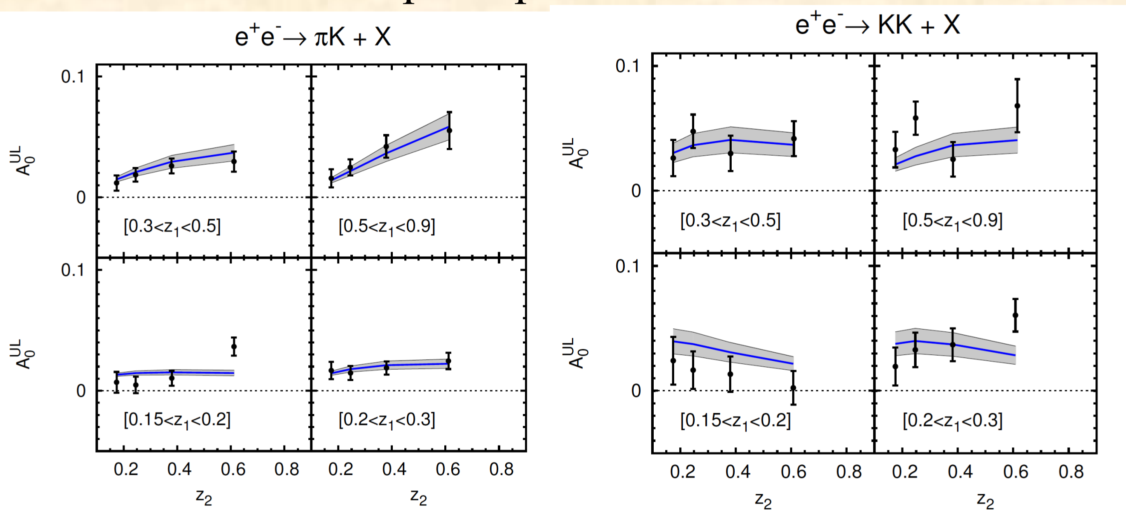


- Asymmetries rise as a function of *z*: more pronounced for U/L
- A^{UL} *KK* asymmetry slightly higher than pion asymmetry for high *z*
- *KK* asymmetry consistent with zero at lower *z*
- ππ results consistent with previous BABAR analysis

Extraction of the Collins FF from *BABAR* kaon data

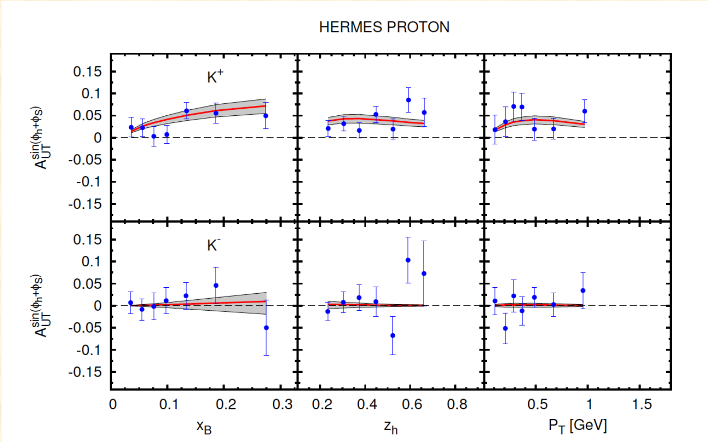
Anselmino et *al.*, arXiv:1512.02252

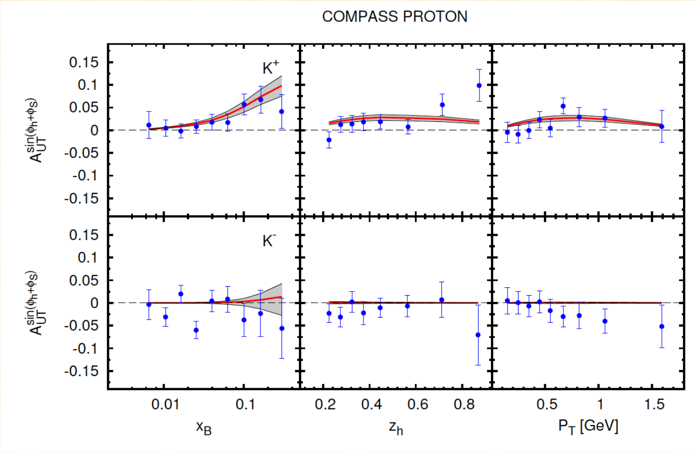
Fitted function superimposed to BABAR data



- It uses the pion fav. and disfav. Collins FF extracted in **arXiv: 1510.05389**,
- It assumes a simplified parametrization for 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





Summary

- *BABAR* is continuing the program of studying fragmentation processes, making use of the ~500 fb^{-1} of e^+e^- collisions at ~10.6 GeV

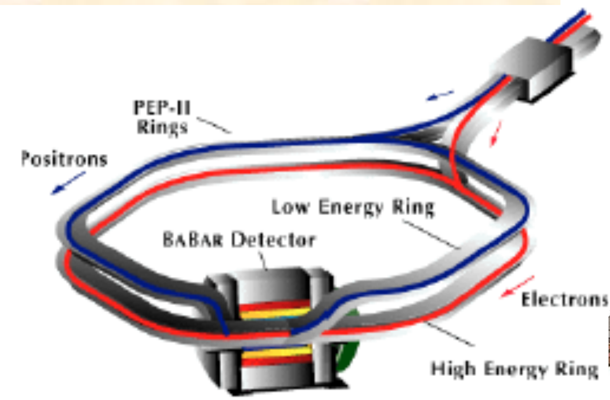
- Inclusive spectra have been measured for light hadrons (π,K,p) and for the lightest charmed baryon with great precision, and the data compared to several model predictions
  - Large discrepancies seen between models and proton data

- Collins asymmetries measured for charged hadron pairs in two-jet events.
  - Precise measurement of pion-pair asymmetries in fine bins of fractional energies and transverse momenta ⟹ **PRD 90, 052003 (2014)**
  - Simultaneous measurement of asymmetries for ππ, πK, and KK pairs as a function of fractional energies ⟹ **PRD 92, 111101(R) (2015)**
    - First information on kaon Collins FF in e^+e^- data
    - Results consistent with theoretical predictions (*e.g.* PL **B 659**, 234 (2009))
  - Global analyses of e^+e^- (*BABAR*+Belle) and SIDIS asymmetries for pions allow extraction of the transversity PDF and the pion Collins FFs.
  - πK and KK pairs results used to extract kaon Collins FF
    - Consistency with HERMES and COMPASS data on kaons indicates the validity of universality of the Collins FF

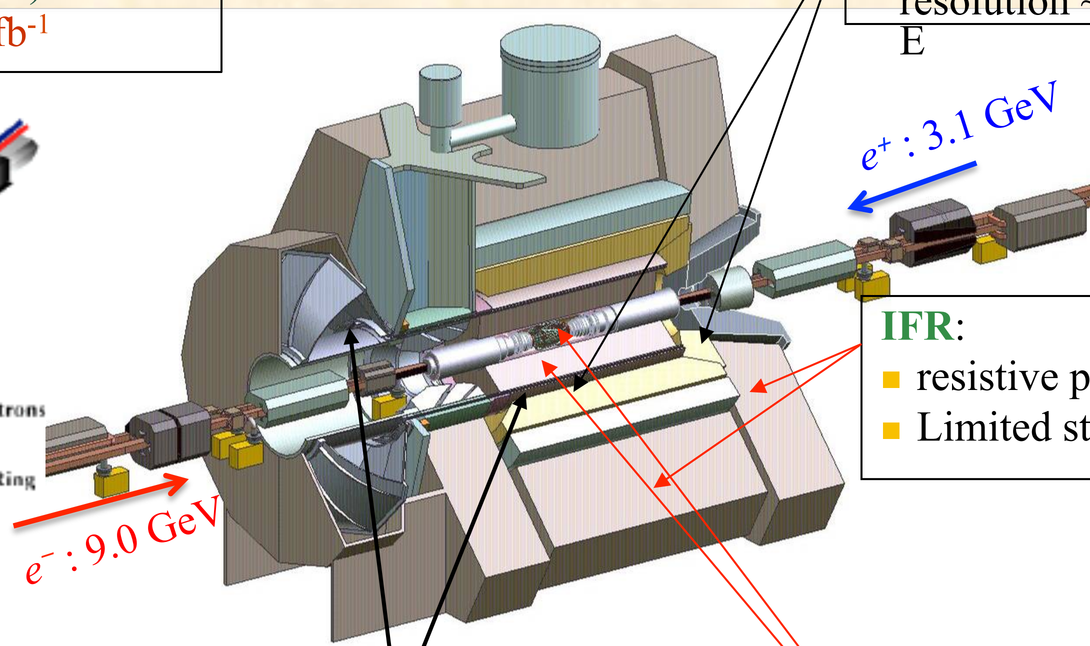
BACKUP SLIDES

PEPII and the *BABAR* detector

- **PEP-II** is an asymmetric e^+e^- collider operating at CM energy of Υ(4S).
- Integrated luminosity = 531 fb^{-1}

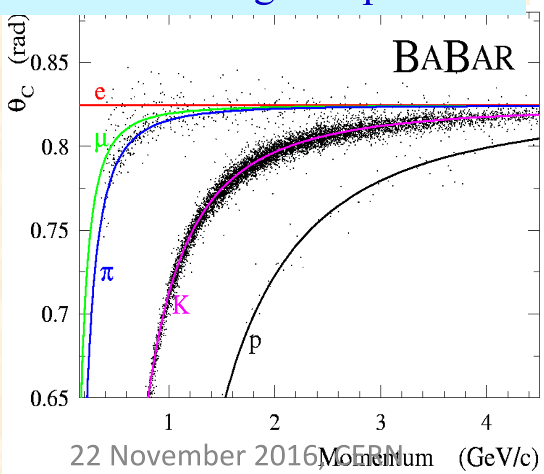


EMC:
- 6580 CsI(Tl) crystals, resolution ~1-2 % high E



IFR:
- resistive plate chambers
- Limited streamer tubes

Cherenkov angle *vs* p



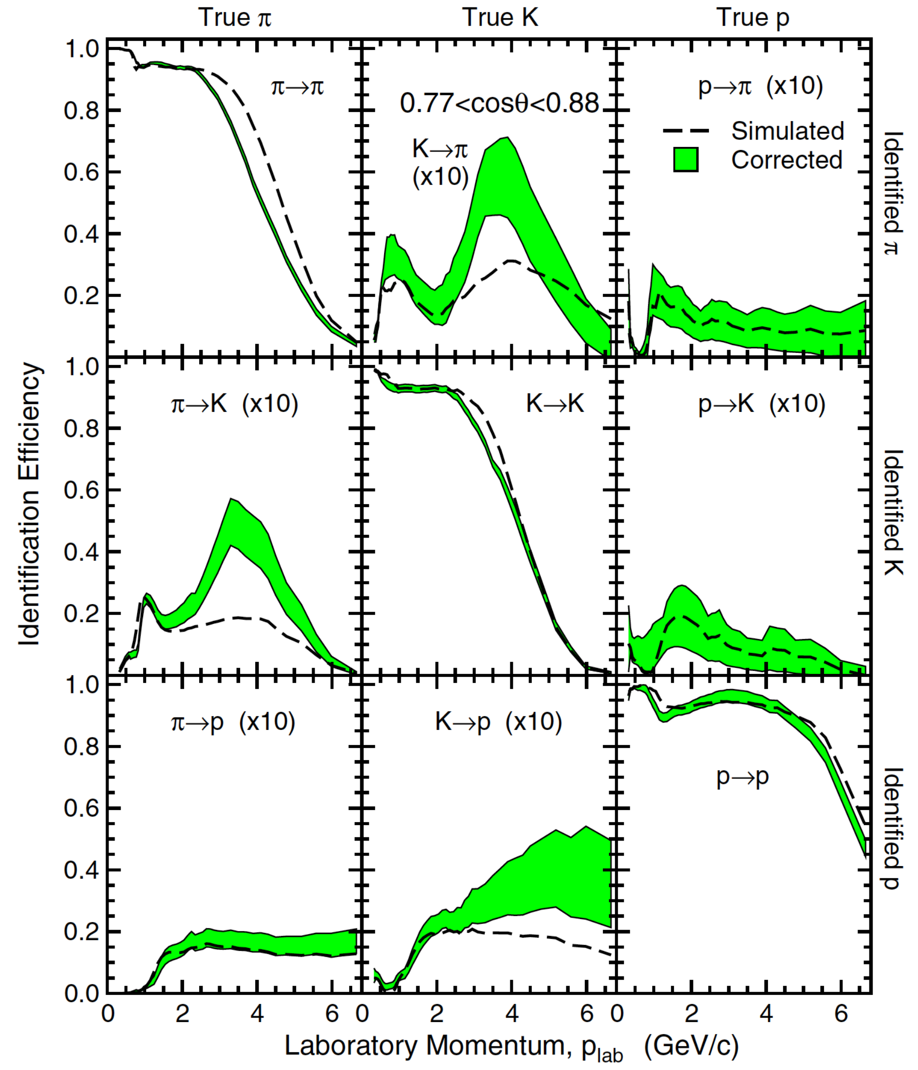
BaBar DIRC
- particle ID up to 4-5 GeV/c

BaBar SVT and DCH
- precision vertexing and tracking

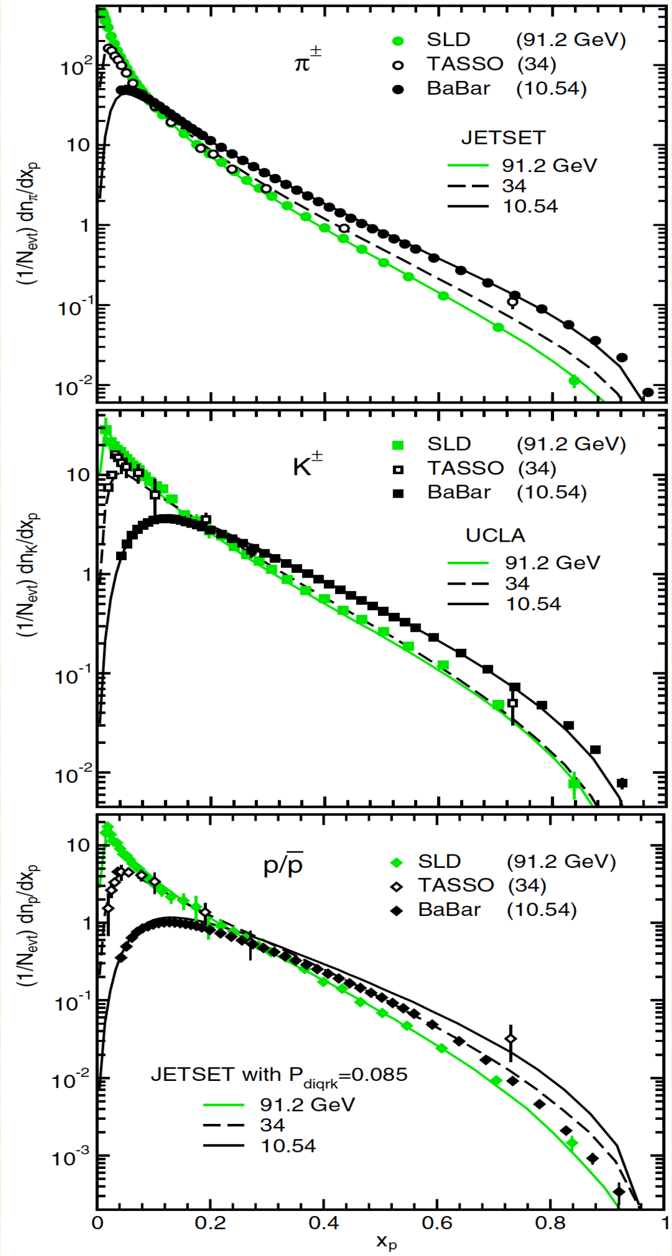
Charged hadrons identification

- Excellent identification of $\pi^{\pm}$, $K^{\pm}$, and $p/\bar{p}$
  ⇒ Cherenkov light plus dE/dx

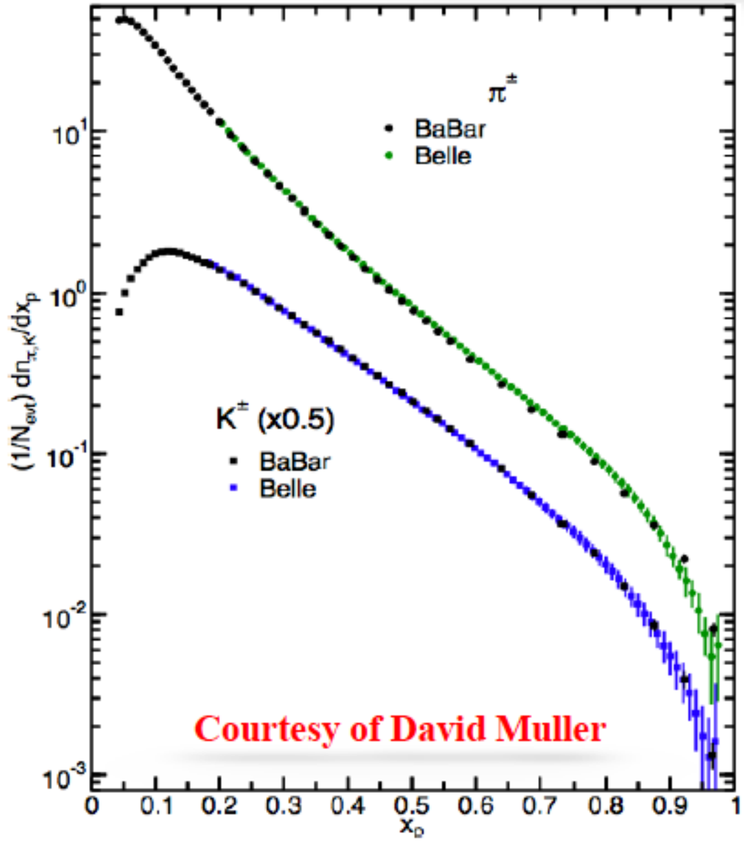
- Efficiency matrix E_{ij}: performance of our hadron identification procedure as a function of p_{lab}
  - very hight at low p_{lab} (good dE/dx)
  - plateau for p_{lab} where DIRC provides good separation
  - fall off at highest p_{lab}, where the Cherekov angles for different particles converge
- calibrated using data control samples
  → we derive corrections to the simulated efficiency matrix (green band)
- large efficiency over much of the momentum range
- few-% mis-identification



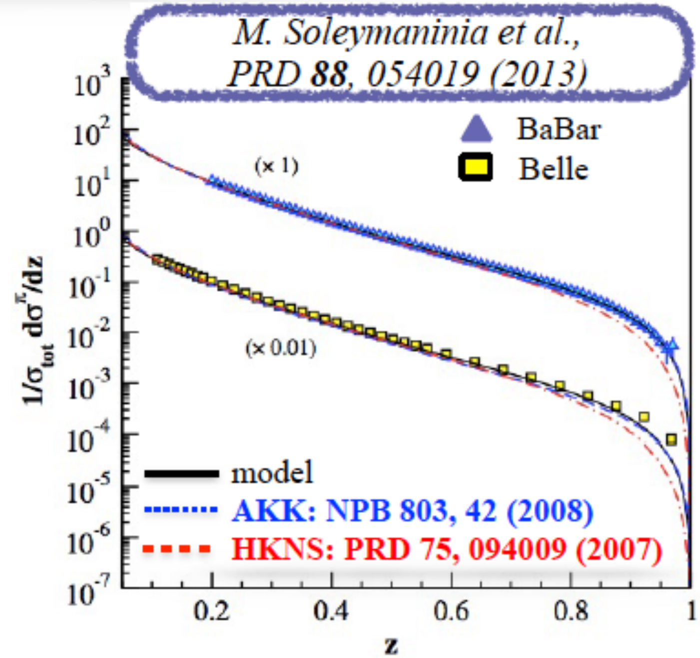
Scaling properties



BaBar/Belle comparison



- Belle have measured differential cross section $d\sigma/dz$ [PRL **111**, 062002 (2013)]
- we normalize arbitrarily to compare the shapes

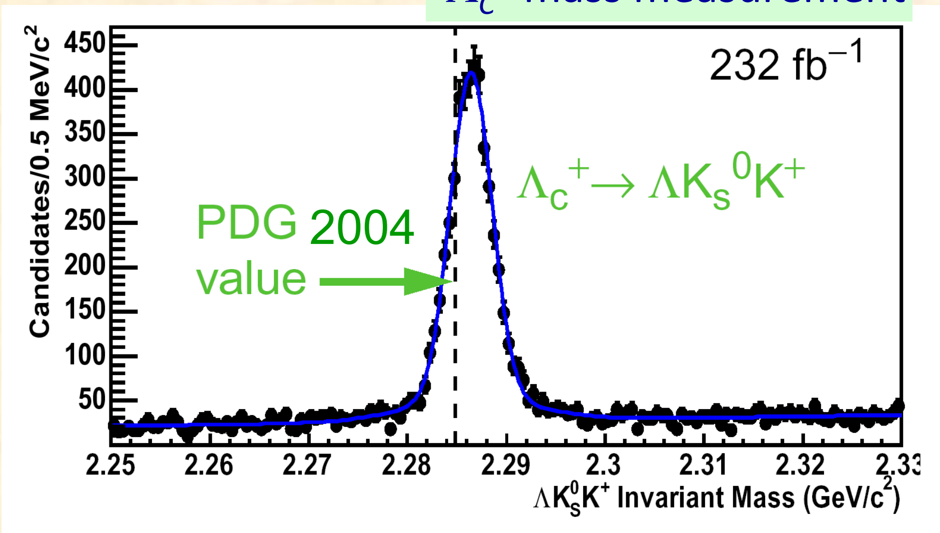


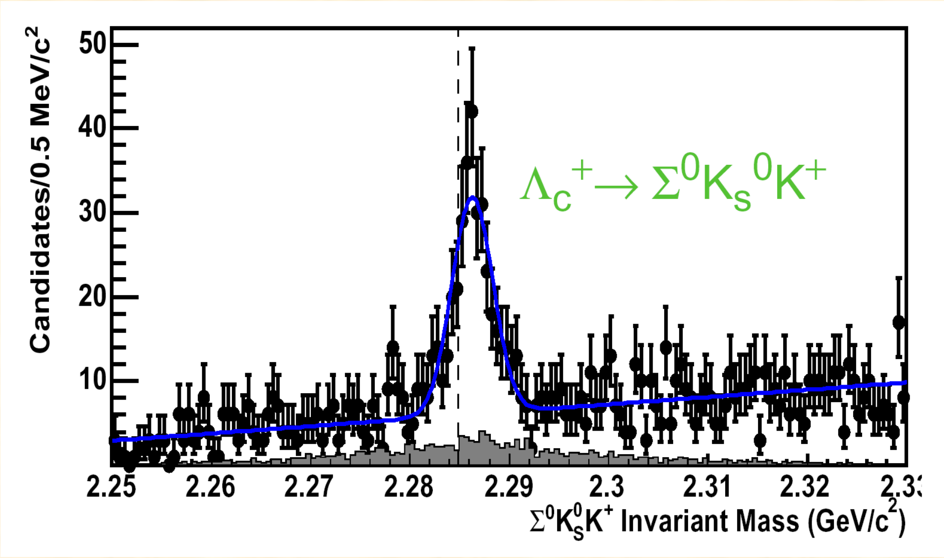
- FFs for π and K from a global analysis of SIDIS and e^+e^- data:
  - BaBar, Belle, TPC, TASSO, TOPAZ, ALEPH, OPAL, SLD, DELPHI + HERMES, COMPASS
  - quarks treated as massless particles
  - improvement of the accuracy of the global fit
- More details in PRD **88**, 054019 (2013)

Inclusive Λ_c studies

Λ_c^+ mass measurement

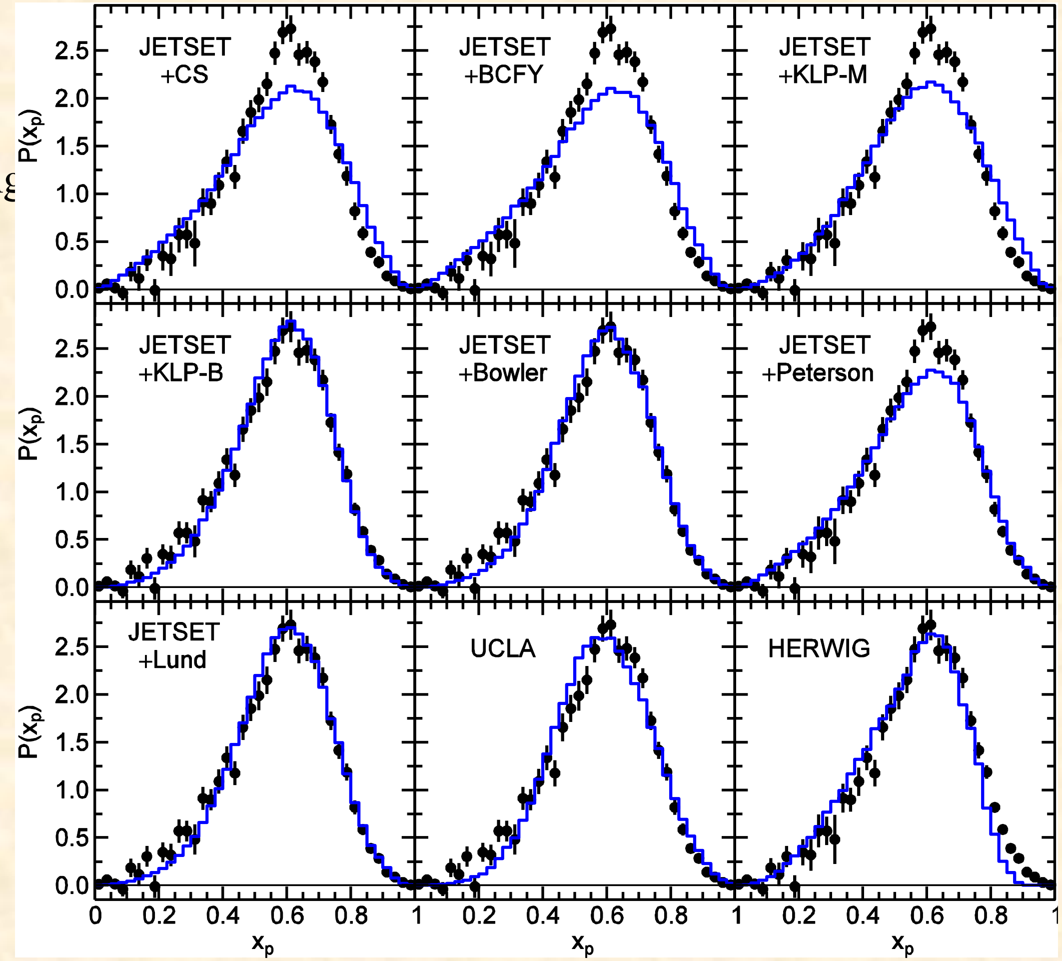
- The Λ_c^+ (*cud*) is the lightest c-baryon
- We precisely measured its mass reconstructing two low-Q decays, to minimize systematic uncertainties
- We find (PRD 72, (2005) 052006)
  - $m(\Lambda_c^+) = 2286.46 \pm 0.14$ MeV/c^2
- More precise and 2.5σ higher than the previous PDG value:
  - $m_{PDG}(\Lambda_c^+) = 2284.9 \pm 0.6$ 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

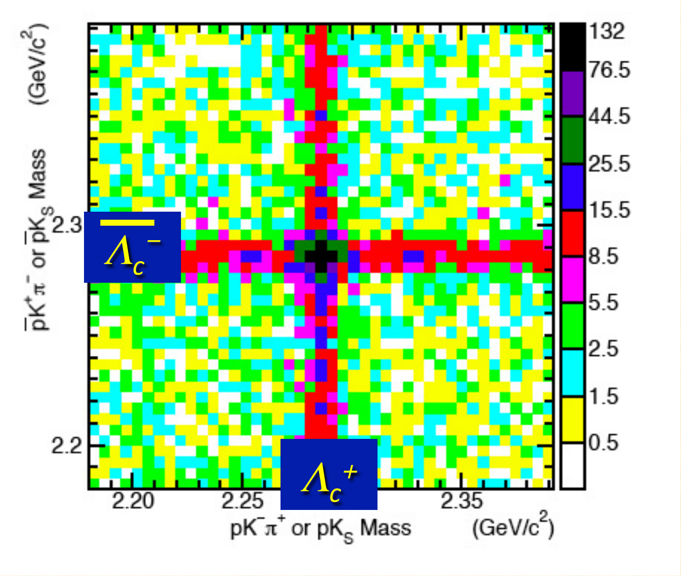
- These results indicate the needs of different functions for baryons and mesons (like in DIS, where there is a dependency on the number of spectator quarks)

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 $\frac{P(\Lambda_c \bar{\Lambda}_c X)}{P(\Lambda_c \bar{D}^{(*)} Y)} \approx 3.5$

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 !

The Collins Fragmentation Function

J.C. Collins
Nucl.Phys.B396,161 (1993)

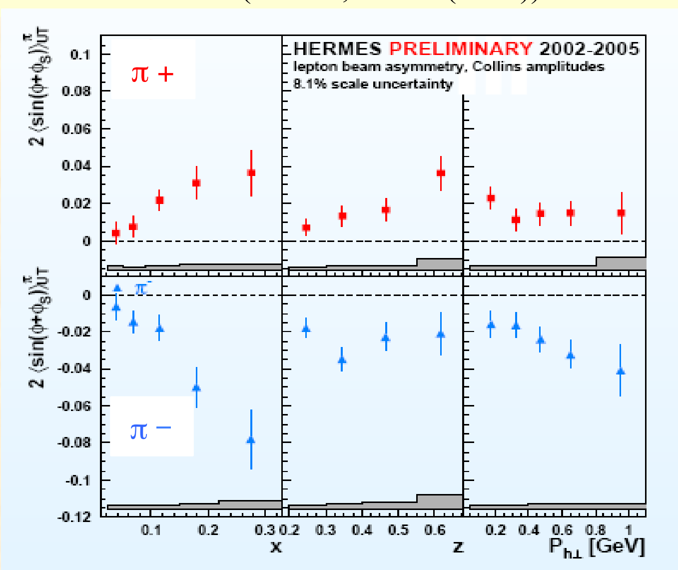
- Spin-dependent chiral-odd Fragmentation Function (FF)
- It is related to the probability that a transversely polarized quark will fragment into a spinless hadron

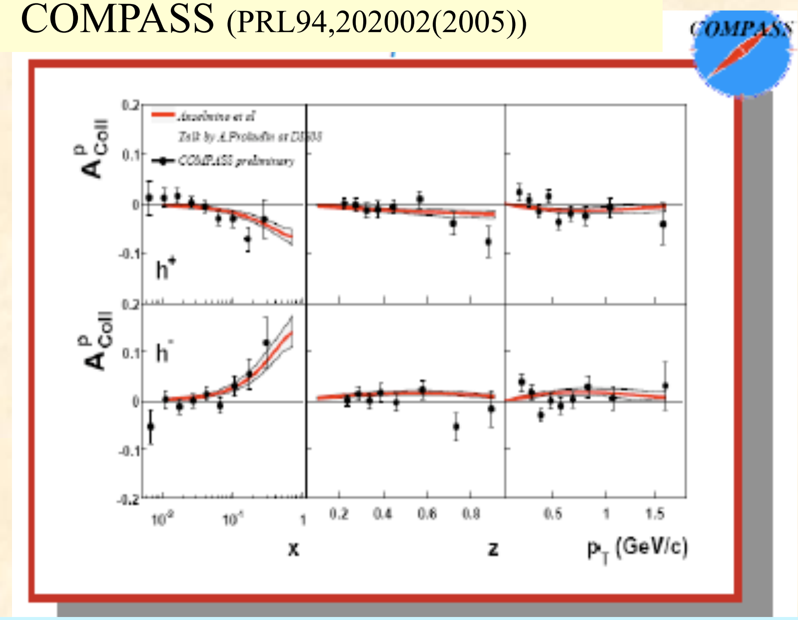
number density function:

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

unpolarized FF   CollinsFF

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





e+e- annihilations :
- not conclusive studies at LEP : DELPHI (Nucl.Phys.B79,554-556 (1999))
- **direct evidence of non-zero Collins FF** at KEKB: Belle (PRL96,232002(2006), PRD78,032011(2008))

BABAR $\pi\pi$ results compared to Belle and BESIII

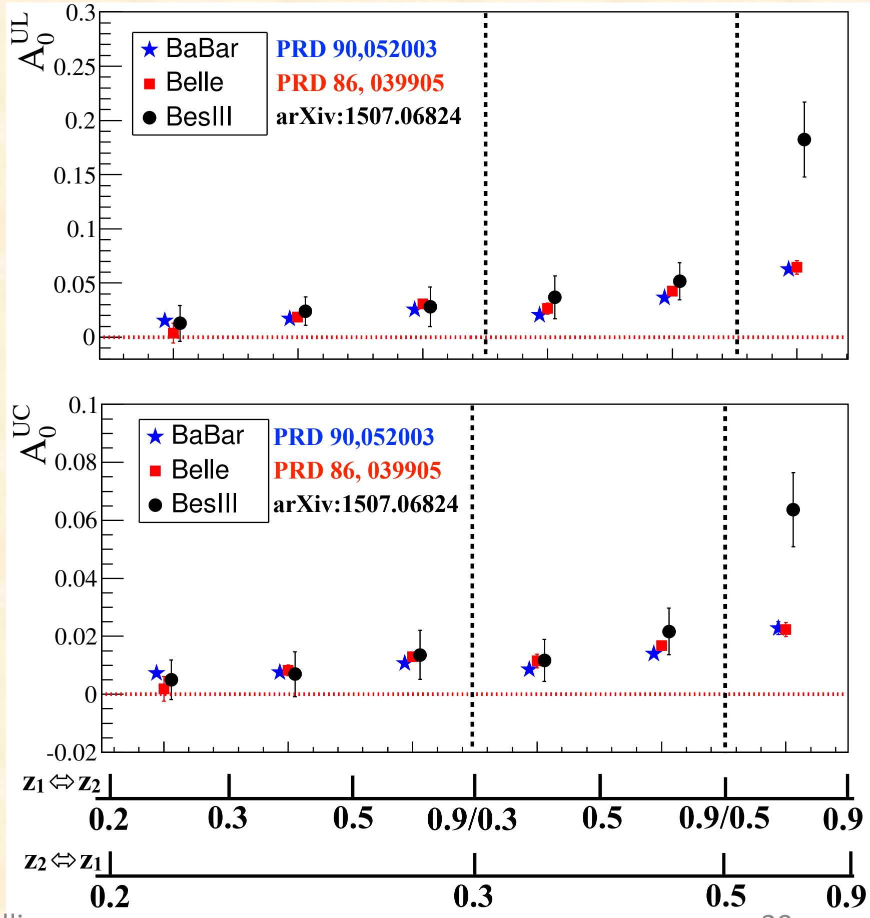
Extraction of the Transversity PDF and Collins FF combining SIDIS and e^+e^- data

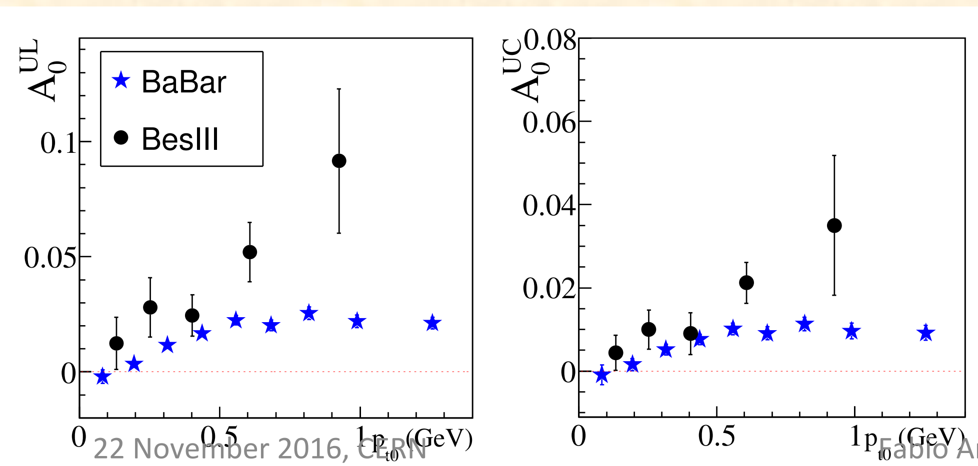
Comparison between different results obtained at different Q^2:

- **BaBar and Belle @ $Q^2 \sim 110$ GeV^2**
- **BESIII @ $Q^2 \sim 13$ GeV^2**

- BaBar and Belle results that fall in the larger BESIII z-bins are averaged taking into account the statistical and systematic uncertainties
- Good agreement between different data sets for low z
- BESIII larger asymmetries in the last z-bins: consistent with the prediction reported in *arXiv:1505.05589*
- Some tensions between BaBar and Belle for high z in the thrust frame (no BESIII data available)

Belle: PRD78, 032011 (2008)
(Erratum: PRD 86, 039905)
BESIII: PRL 116, 042001 (2016)





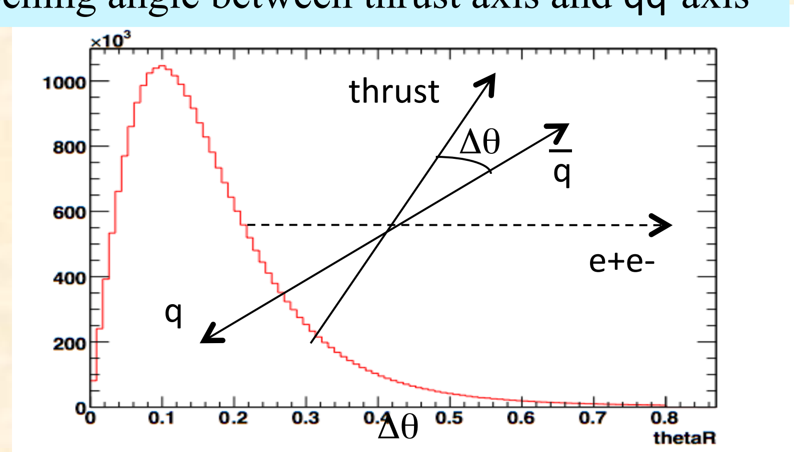
Extraction of the asymmetries

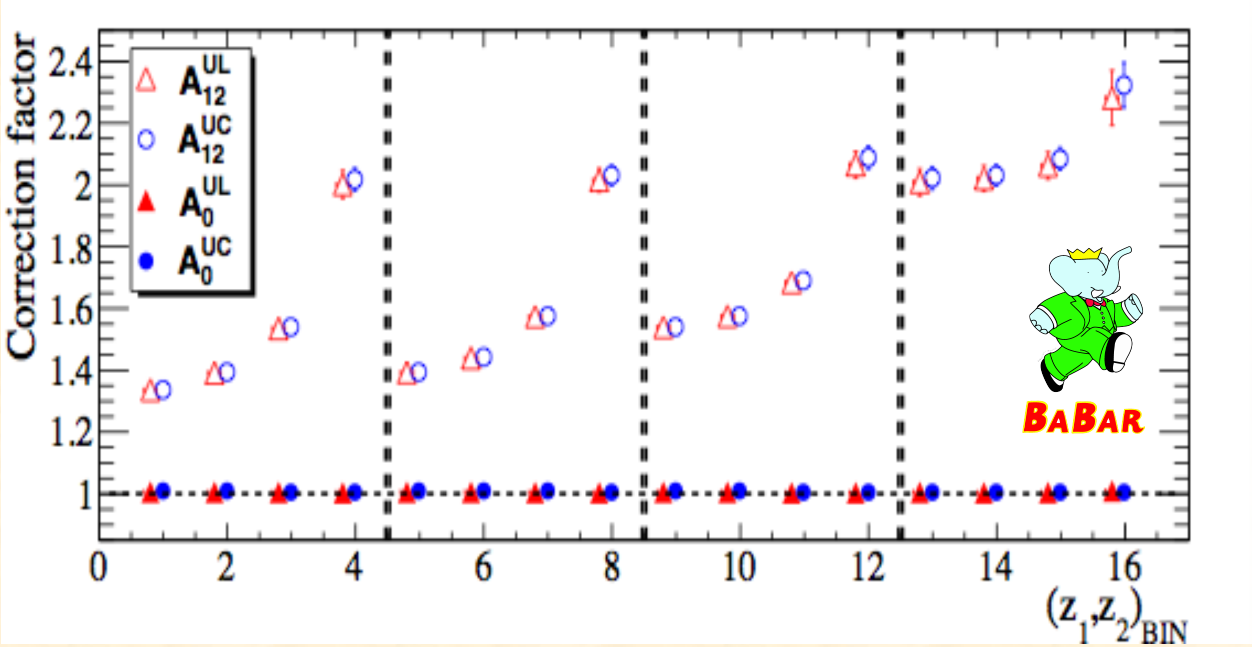
- The experimental method assumes the thrust axis as $q\bar{q}$ direction
- **This is only a rough approximation**

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 $\tau^+\tau^-$) and K/π misidentification in each fractional energy interval
- Fit independently the double ratio distributions of the three selected samples KK, Kπ, ππ

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

1. **Background sources:**

- mainly from **$e^+e^- \to c\bar{c}$ events** (more than 30%); smaller contribution from $B\bar{B}$, $\tau^+\tau^-$ ($A_{BB} \sim A_\tau \sim 0$)
- 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 ($F(f)_{\text{sig/bkg}}^{hh}$) of hadron pairs coming from signal (uds) and background events ($c\bar{c}$, $B\bar{B}$, $\tau^+\tau^-$) are obtained from MC simulation

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

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

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

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

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

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

↘ generated hadron pairs

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

Extraction of the asymmetries

$$
\begin{aligned}
A^{meas}_{KK} = \; & F^{KK}_{uds} \cdot (\xi^{(KK)}_{KK} A_{KK} + \xi^{(KK)}_{K\pi} A_{K\pi} + \xi^{(KK)}_{\pi\pi} A_{\pi\pi})+ \\
& F^{KK}_{c\bar{c}} \cdot (\xi^{(KK)c\bar{c}}_{KK} A^{ch}_{KK} + \xi^{(KK)c\bar{c}}_{K\pi} A^{ch}_{K\pi} + \xi^{(KK)c\bar{c}}_{\pi\pi} A^{ch}_{\pi\pi}) \\
A^{meas}_{K\pi} = \; & F^{K\pi}_{uds} \cdot (\xi^{(K\pi)}_{KK} A_{KK} + \xi^{(K\pi)}_{K\pi} A_{K\pi} + \xi^{(K\pi)}_{\pi\pi} A_{\pi\pi})+ \\
& F^{K\pi}_{c\bar{c}} \cdot (\xi^{(K\pi)c\bar{c}}_{KK} A^{ch}_{KK} + \xi^{(K\pi)c\bar{c}}_{K\pi} A^{ch}_{K\pi} + \xi^{(K\pi)c\bar{c}}_{\pi\pi} A^{ch}_{\pi\pi}) \\
A^{meas}_{\pi\pi} = \; & F^{\pi\pi}_{uds} \cdot (\xi^{(\pi\pi)}_{KK} A_{KK} + \xi^{(\pi\pi)}_{K\pi} A_{K\pi} + \xi^{(\pi\pi)}_{\pi\pi} A_{\pi\pi})+ \\
& F^{\pi\pi}_{c\bar{c}} \cdot (\xi^{(\pi\pi)c\bar{c}}_{KK} A^{ch}_{KK} + \xi^{(\pi\pi)c\bar{c}}_{K\pi} A^{ch}_{K\pi} + \xi^{(\pi\pi)c\bar{c}}_{\pi\pi} A^{ch}_{\pi\pi}) \\
A^{D^*}_{KK} = \; & f^{KK}_{uds} \cdot (\xi^{(KK)D^*}_{KK} A_{KK} + \xi^{(KK)D^*}_{K\pi} A_{K\pi} + \xi^{(KK)D^*}_{\pi\pi} A_{\pi\pi})+ \\
& f^{KK}_{c\bar{c}} \cdot (\xi^{(KK)c\bar{c}-D^*}_{KK} A^{ch}_{KK} + \xi^{(KK)c\bar{c}-D^*}_{K\pi} A^{ch}_{K\pi} + \xi^{(KK)c\bar{c}-D^*}_{\pi\pi} A^{ch}_{\pi\pi}) \\
A^{D^*}_{K\pi} = \; & f^{K\pi}_{uds} \cdot (\xi^{(K\pi)D^*}_{KK} A_{KK} + \xi^{(K\pi)D^*}_{K\pi} A_{K\pi} + \xi^{(K\pi)D^*}_{\pi\pi} A_{\pi\pi})+ \\
& f^{K\pi}_{c\bar{c}} \cdot (\xi^{(K\pi)c\bar{c}-D^*}_{KK} A^{ch}_{KK} + \xi^{(K\pi)c\bar{c}-D^*}_{K\pi} A^{ch}_{K\pi} + \chi^{(K\pi)c\bar{c}-D^*}_{\pi\pi} A^{ch}_{\pi\pi}) \\
A^{D^*}_{\pi\pi} = \; & f^{\pi\pi}_{uds} \cdot (\xi^{(\pi\pi)D^*}_{KK} A_{KK} + \xi^{(\pi\pi)D^*}_{K\pi} A_{K\pi} + \xi^{(\pi\pi)D^*}_{\pi\pi} A_{\pi\pi})+ \\
& f^{\pi\pi}_{c\bar{c}} \cdot (\xi^{(\pi\pi)c\bar{c}-D^*}_{KK} A^{ch}_{KK} + \xi^{(\pi\pi)c\bar{c}-D^*}_{K\pi} A^{ch}_{K\pi} + \xi^{(\pi\pi)c\bar{c}-D^*}_{\pi\pi} A^{ch}_{\pi\pi})
\end{aligned}
$$

= Collins asymmetries for light hadrons

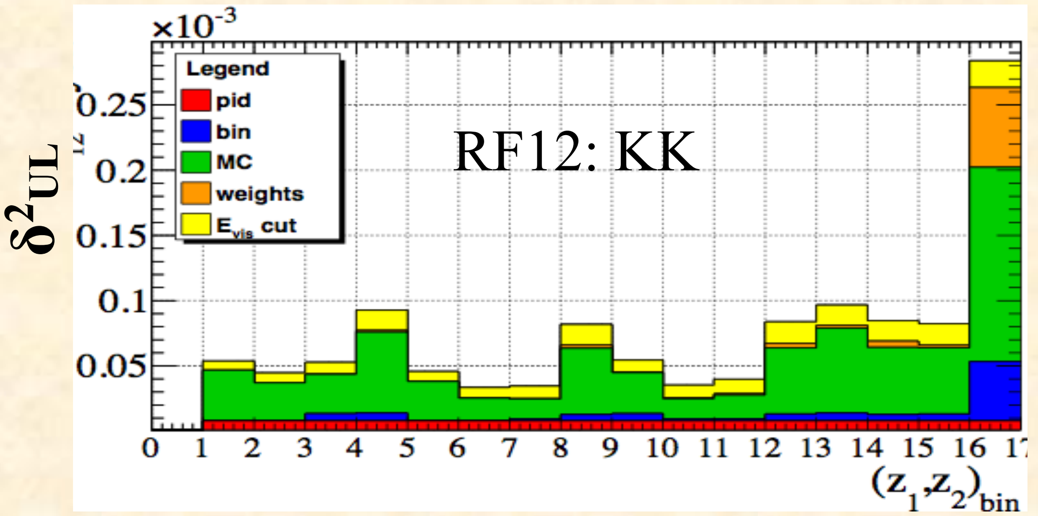
Systematic uncertainties

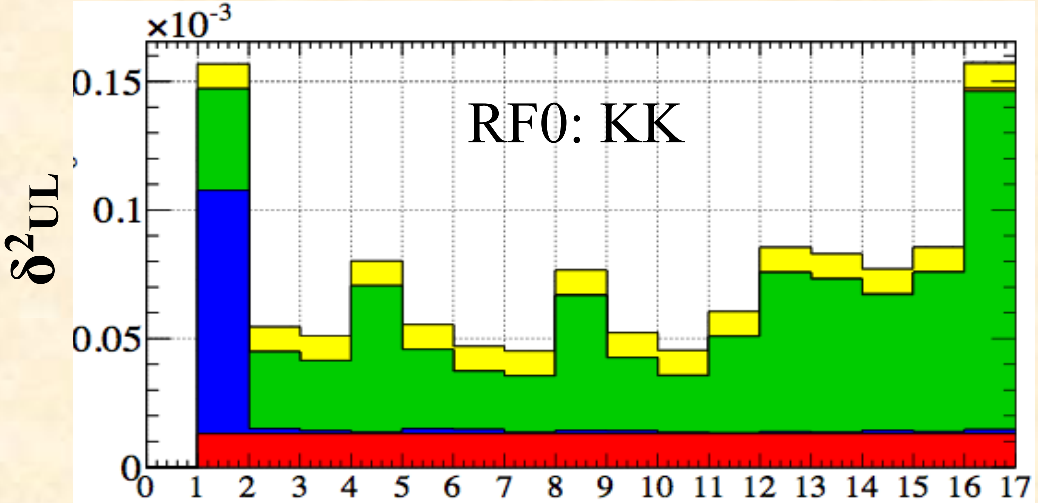
A large number of systematic checks were done. The main contributions come from:

- 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)