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# Fragmentation Functions: experimental results from BABAR

**Isabella Garzia**
On behalf of the BaBar Collaboration
INFN-Sezione di Ferrara
University of Ferrara

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# OUTLINE

**INTRODUCTION**

- Fragmentation Functions
  - Unpolarized and Collins fragmentation functions
- PEP-II and the BABAR detector at SLAC

**UNPOLARIZED FRAGMENTATION FUNCTIONS**

- Inclusive hadron production at BABAR
- Charged hadron identification
- BABAR preliminary results: $\pi^{\pm}$, $K^{\pm}$, $p/\bar{p}$ cross section and scaling properties

**COLLINS FRAGMENTATION FUNCTION**

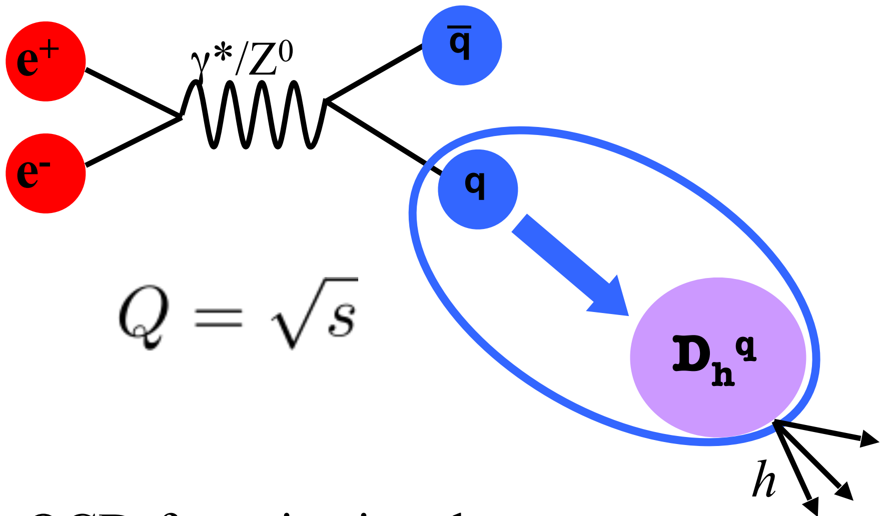
- Reference frames and analysis strategy
- BABAR preliminary results: Collins asymmetries *vs.* fractional energies, pion transverse momentum, and analysis axis polar angle

**ANTI-DEUTERON PRODUCTION**

- Production rate for $\Upsilon(nS)$ resonance decays and nearby continuum

**SUMMARY and CONCLUSIONS**

# Fragmentation Functions: a brief introduction




$$Q = \sqrt{s}$$

✓ Fragmentation Functions (FFs) describe the process of hadronization of a parton q

✓ **non-perturbative** objects but **universal**

✓ depend on the scaled energy of the hadron *h*:
$x = 2E_h/\sqrt{s}$

✓ The cleanest way to access FFs is $e^+e^- \rightarrow q\bar{q}$

QCD-factorization theorem:

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

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

process dependent short distance interaction

non-perturbative part

✓ $D_i^h$: new sets of function introduced: **parton fragmentation functions**

✓ $D_i^h(z,\mu^2)$ describes the probability that a parton i (i=u/ū,d/d̄,s/s̄,c/c̄,b/b̄,g) fragments into a hadron *h* a fraction *z* of the parton's momentum

✓ $\mu$ is the factorization scale. Separates short and long distance physics

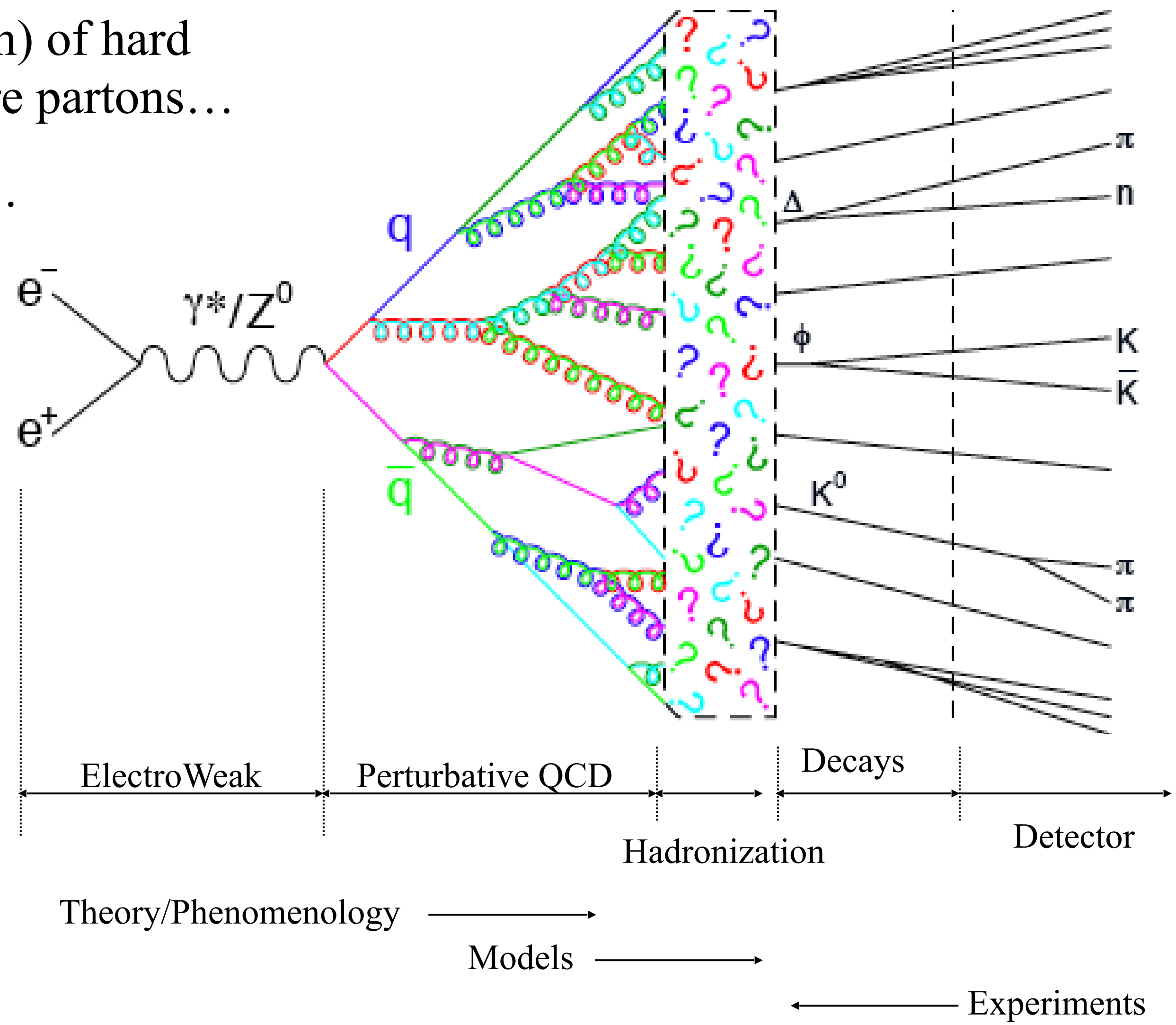
# What do we mean by fragmentation?

1) The process by which (a system) of hard quarks and/or gluons **radiate** more partons…

2) … that **combine** into hadrons…

3) … that **decay** into “stable” particles…

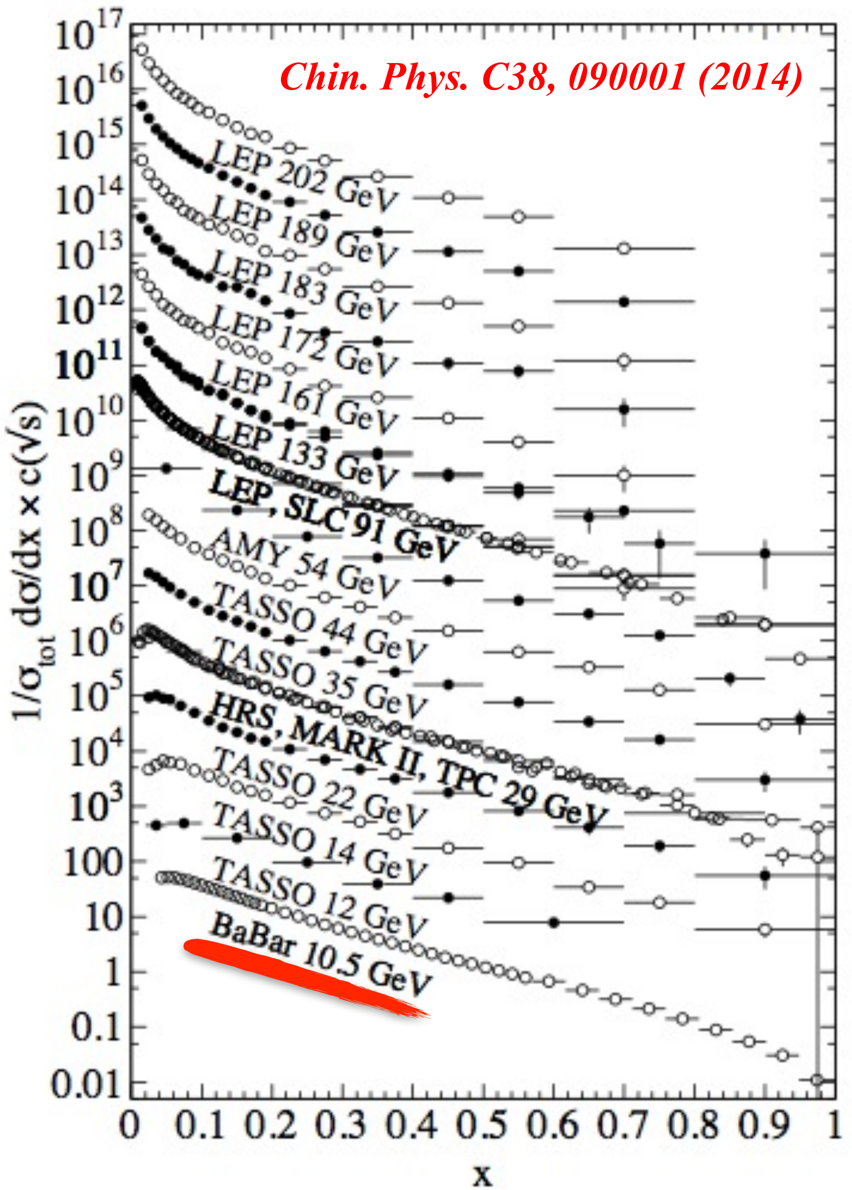
…that can be **observed** in a detector…




Experimentally, we push from the right, as example:

- measure all $K^\pm$
- then $\phi$
- subtracting $\phi$ daughters gets closer to primary $K^\pm$

# e⁺e⁻ data sets




- Perturbative QCD corrections lead to logarithmic scaling violations via the evolution equations (DGLAP)
- Most of data are obtained at LEP energies
- Measurement of both quark and antiquark fragmentation
- 3-jet fragmentation to access gluon FF difficult
- The information on how the individual q flavor fragments into h depends on the "tagging techniques"

- Many attempts to extract FF from $e^+e^-$ data: KKP, AKK, HKNS, Kretzer …

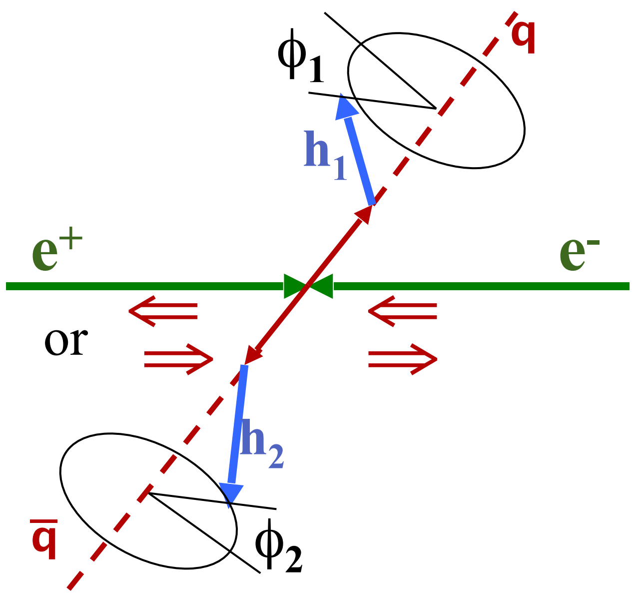
NPB 725,181(2006), NPB 803,42(2008), PRD 75,094009(2007), PRD 62,054001(2000), NPB 582,514(2000), NPB 803,42(2008);

- Global analysis: $e^+e^-$, SIDIS, and pp

PRD 75,114010(2007); PRD 76,074033(2007); PRD 86,074028(2012)

**Few data at high z and at low energy**
**BaBar data cover this region**

# 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**, $\gamma^*$ (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 $\sim\sin^2\theta$ ($\theta$ wrt the $e^+e^-$)

- exploit this correlation by using hadrons in opposite jets

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

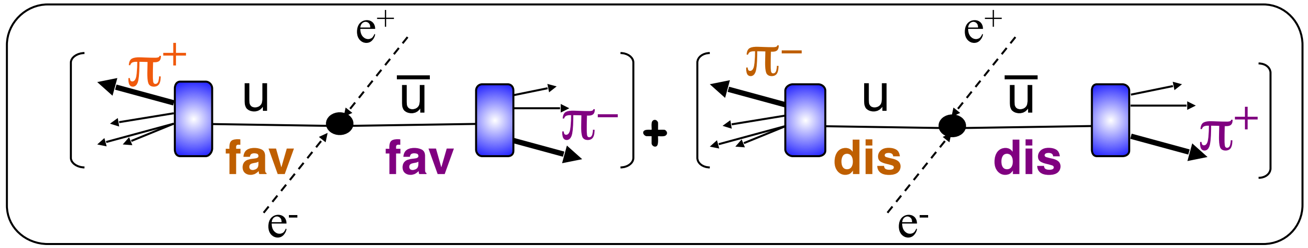
# Favored and Disfavored processes

Different combinations of charged pions ⇒ sensitivity to **favored** or **disfavored** FFs

- **favored** process: fragmentation of a quark of flavor q into a hadron with a valence quark of the same flavor: i.e.: $u \rightarrow \pi^+$, $d \rightarrow \pi^-$
- **disfavored** for $d \rightarrow \pi^+$, $u \rightarrow \pi^-$, and $s \rightarrow \pi^\pm$

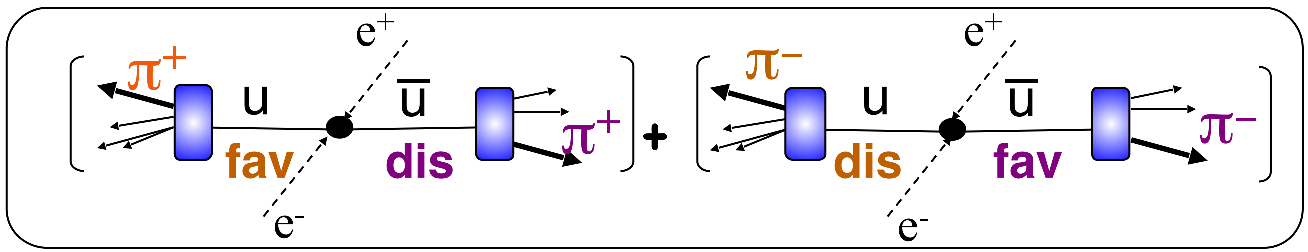
Unlike-sign pion pair = **U:**

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




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

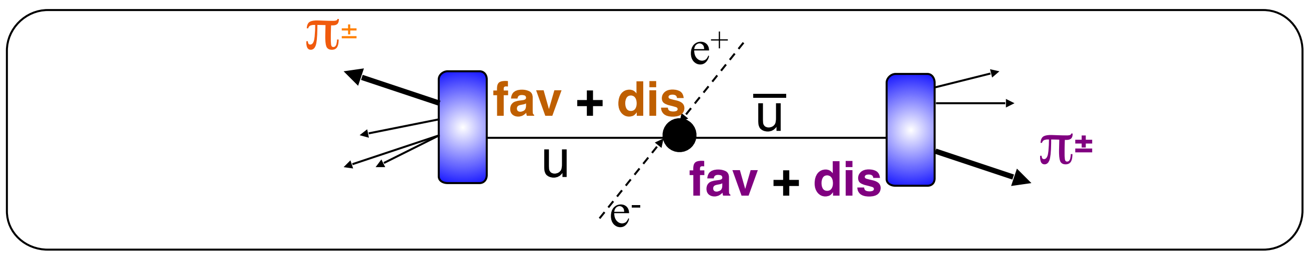
$\pi^\pm\pi^\pm$: **(fav x dis)+(dis x fav)**




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

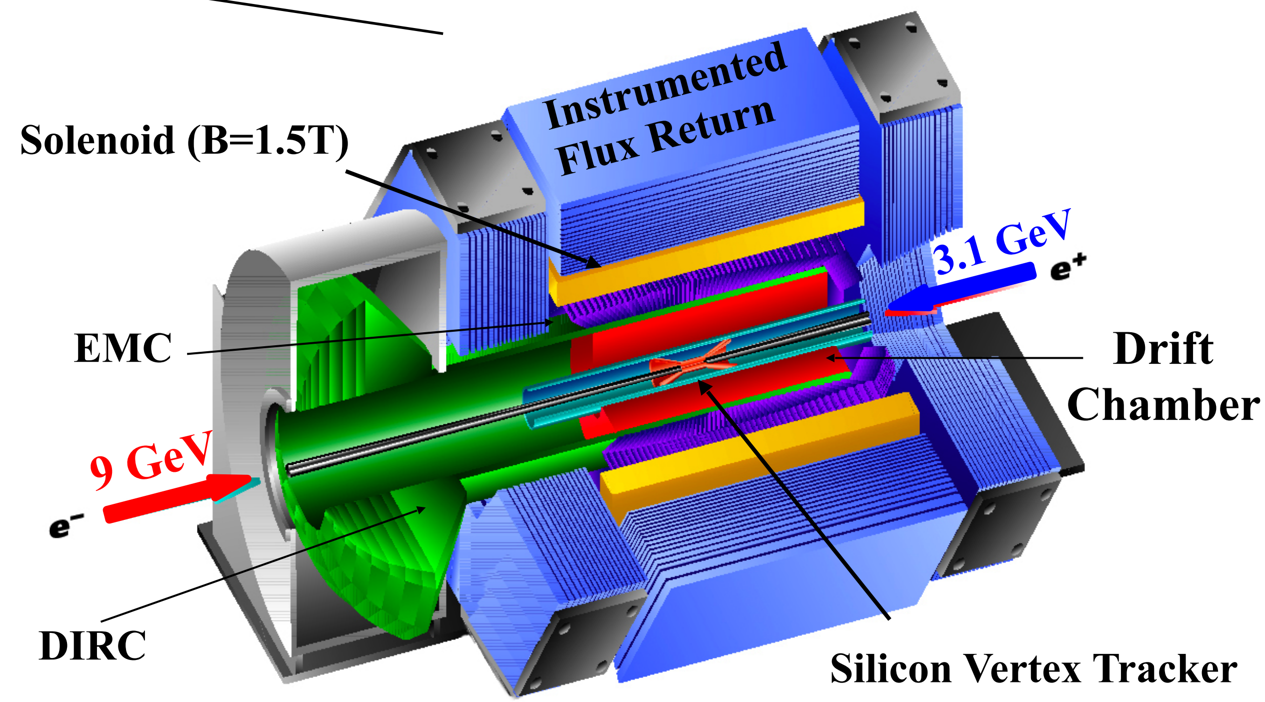
$\pi\pi$: **(fav + dis)x(fav + dis)**

$\pi=\pi^\pm$



# PEP-II and the BaBar detector at SLAC


- Asymmetric-energy $e^+e^-$ 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: **$\int\mathcal{L} \sim 500\ fb^{-1}$**




- Asymmetric detector
  - c.m. acceptance $-0.9 < \cos\theta^* < 0.85$ wrt $e^-$ beam
- Excellent performance
  - good tracking, mass resolution
  - good $\gamma$, $\pi^0$ reconstruction
  - full e, $\mu$, $\pi$, K, and p identification

# Inclusive hadron production @ BABAR

$e^+e^- \rightarrow \gamma^* \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c} \rightarrow hX\ (h = \pi^\pm, K^\pm, p/\bar{p})$

4 : 1 : 1 : 4 @ 10.54 GeV

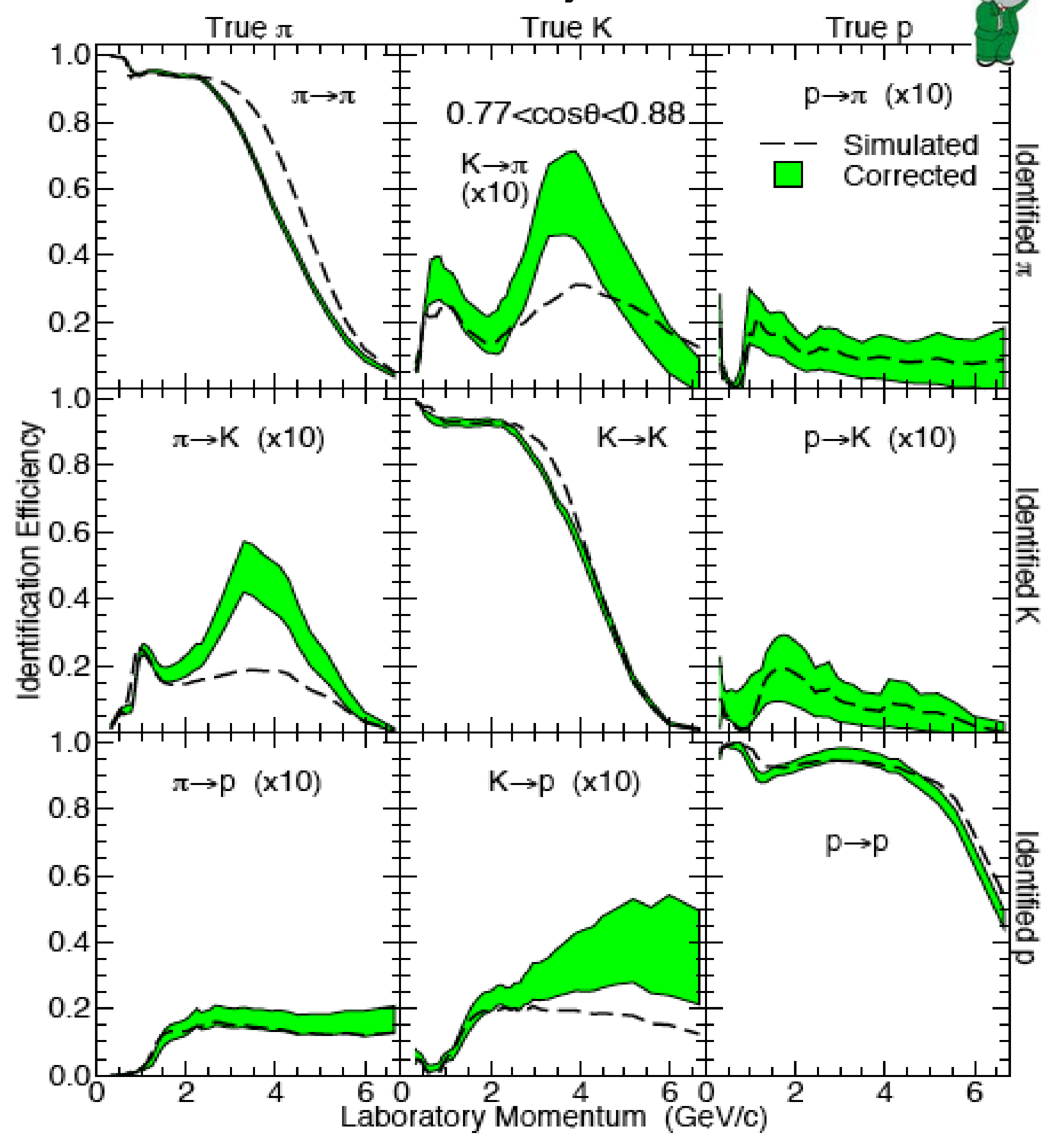
- ✓ J.P. Lees *et al.* (BaBar Collaboration), PRD **88**, 032011 (2013)
- ✓ Data samples used: 0.91 $fb^{-1}$ @ 10.54 GeV + 3.6 $fb^{-1}$ on-peak for checks and calibrations
- ✓ "**Prompt**" and "**conventional**" hadrons:
  - prompt: primary hadrons or products of a decay chain in which all particles have lifetimes shorter than $10^{-11}$ s
  - conventional: includes the decay daughters of particles with lifetimes in the range 1-3x$10^{-11}$ (i.e. $K^0_s$ and weakly decaying strange baryons)
- ✓ The uncertainties on the results are dominated by systematic contributions.

# Charged hadron identification

- Well-reconstructed tracks from the primary interaction point
- Excellent identification of $\pi^{\pm}$, $K^{\pm}$, and $p/\overline{p}$
  ⇒ 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

Efficiency matrix:

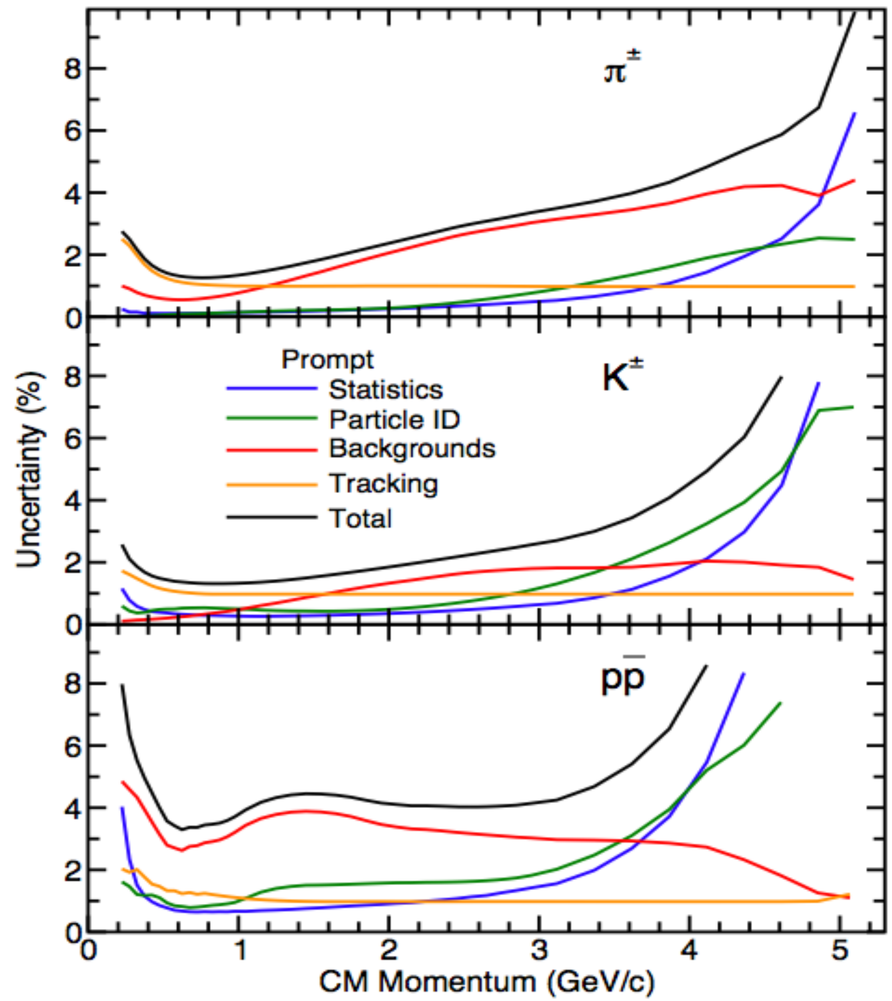


# Selection, corrections, and systematic checks

- We use $E_{ij}$ to construct the raw production rates $(1/N_{evt}^{sel})(dn_i/dp_{lab})$, defined as the number reconstructed particles per selected event per unit momentum in the lab frame
  - we count $n_j = n\sum_i E_{ij} f_i$, and calculate $f_i$, the true fraction of tracks of type i

- Correct these spectra for:
  - physics background: few-% (mostly $\tau^+\tau^-$)
  - interaction in the detector material (up to 4% at low momentum)
  - tracks and event selection efficiency, momentum resolution, transform to c.m. frame

- extensive systematic cross checks: data-MC comparison, check for θ, φ,… dependence, compare positive and negative charged tracks,…
  - largest contribution from particle identification, backgrounds, and tracking efficiencies

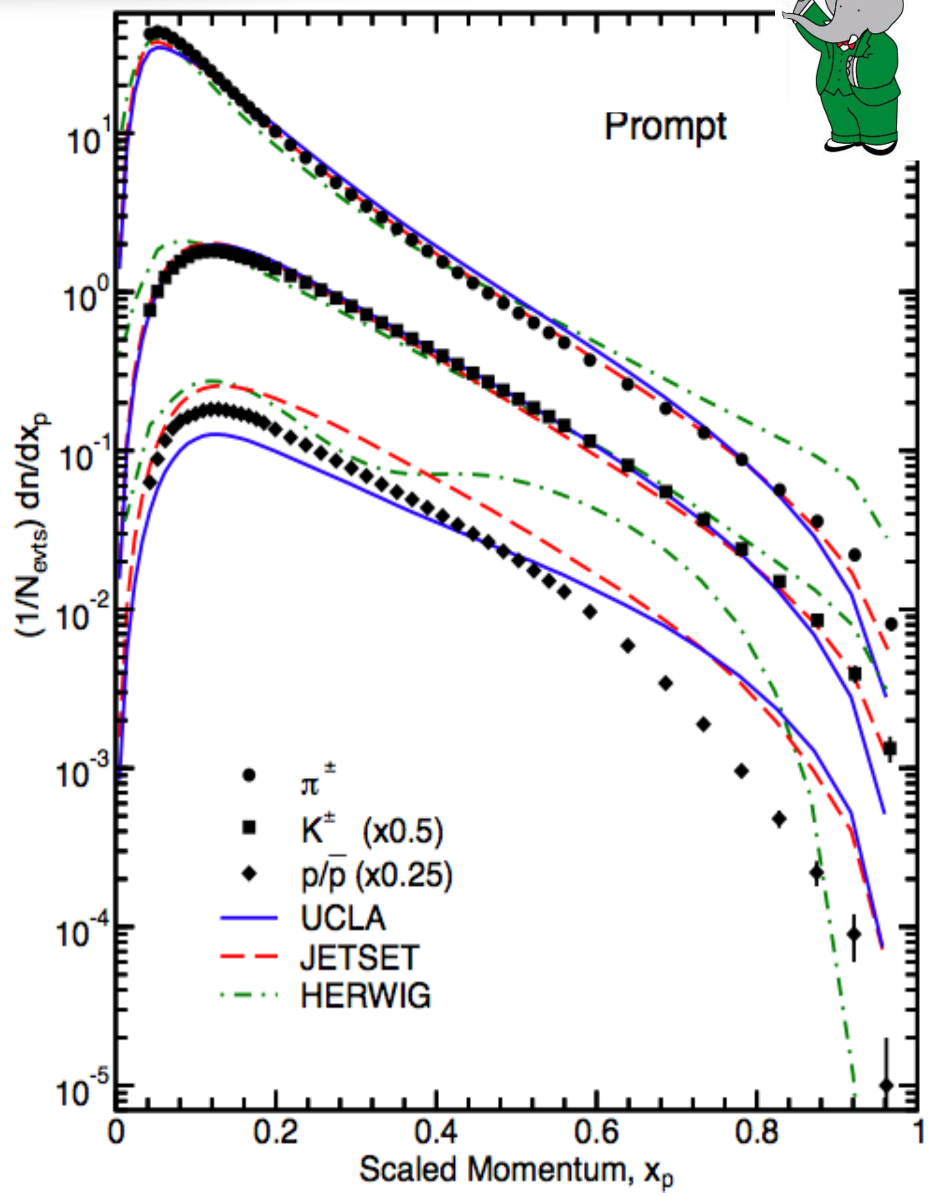


# BABAR results: test of hadronization models

- **Averaged results over θ, in terms of scaled momentum $x_p = 2p^*/E_{cm}$ [1]**
  - Coverage from 0.2 GeV/c to the kinematic limit of 5.27 GeV/c
  - precise data and coverage at high $x_p$

We compare our cross section with the predictions of three hadronization models:

- **Default parameters used**: (based on previous data: higher energies plus ARGUS data)
- **Large discrepancies in general**
  - all the models qualitatively describe the bulk of the spectra
  - no model describes any spectrum in detail
- **Peak positions consistent with data** (except for the HERWIG $K^{\pm}$)
- **Similar discrepancies observed at higher energies**

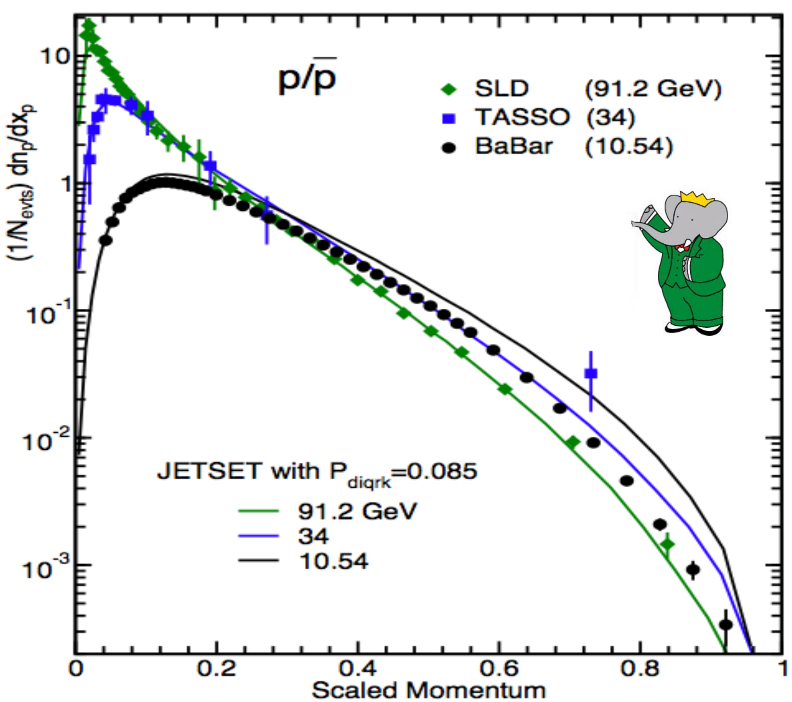



[1] The asterisk denotes quantities in the $e^+e^-$ c.m. frame

# Scaling Properties

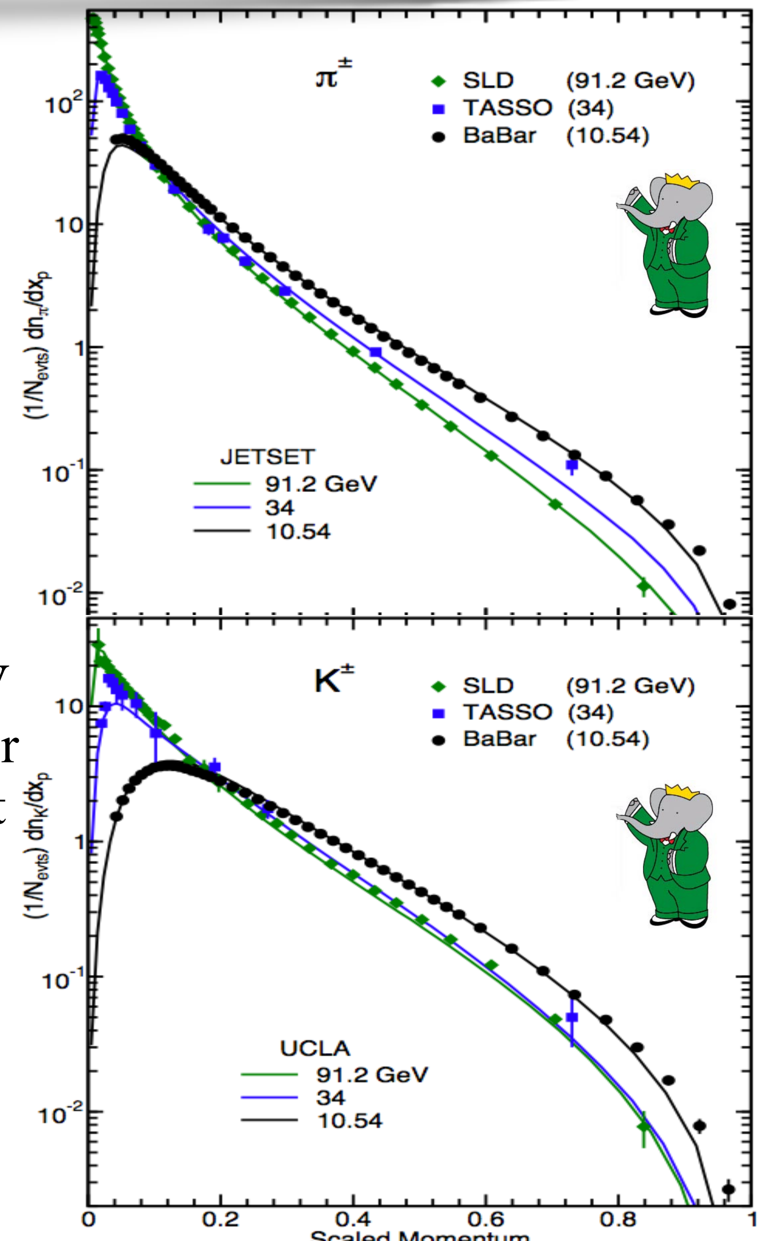
Consider π, K, and p from BABAR, TASSO and SLD

- **Strong scaling violation** at **high $x_p$** (running of $\alpha_s$) and at **low $x_p$** (pion mass)
- **K±**: the different flavor composition of the three samples modifies the expected scaling violation
  - models predict about 10%-15% more scaling violation than is observed

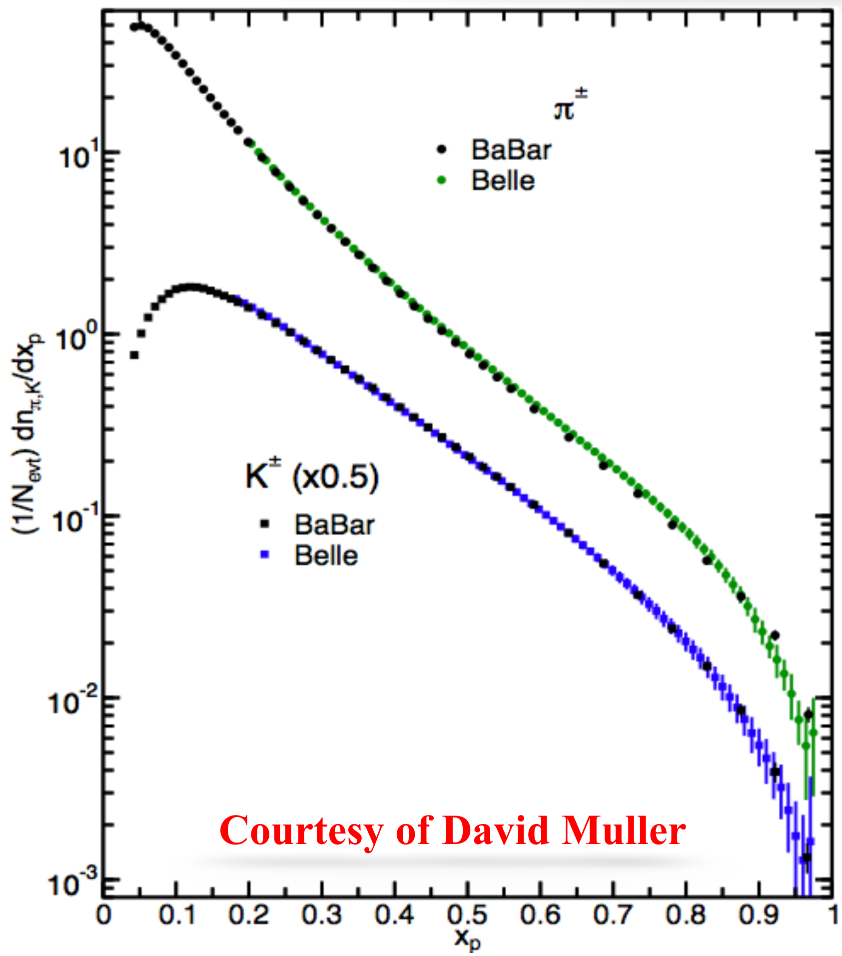



- p/p̄: the scaling prediction for 10.54 GeV is consistent with data for $x_p$<0.07, but exceeding it by as much as a factor 3 at $x_p$=0.8

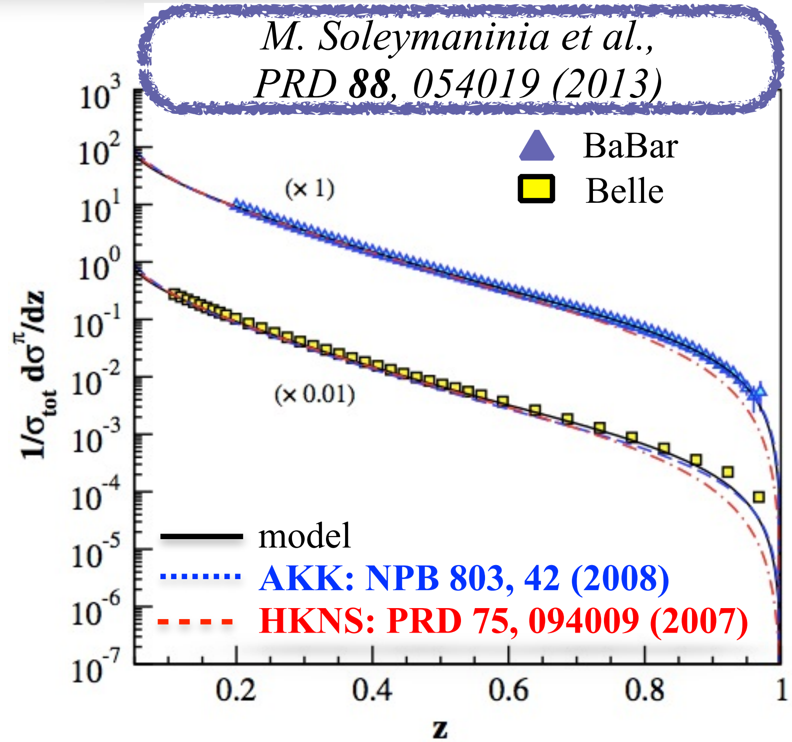
**Is there something missing?**



# 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 $\pi$ 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
- More details in **PRD 88, 054019 (2013)**

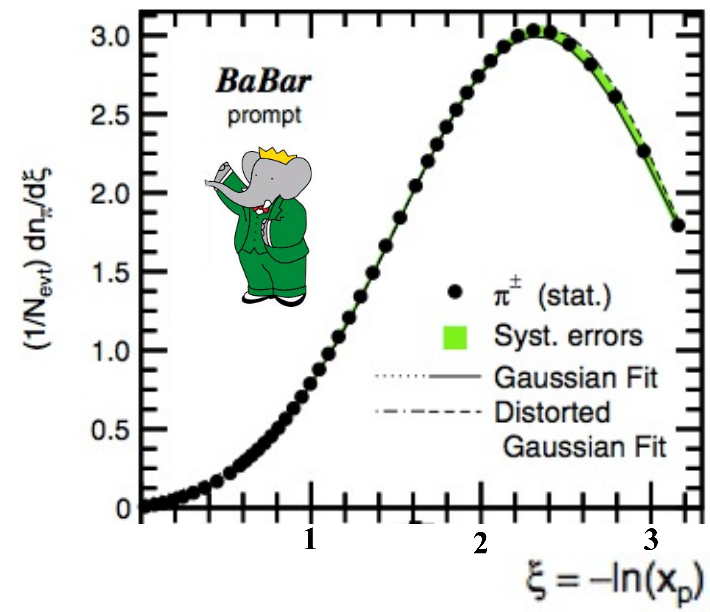
DSS **arXiv:1410.6027** (see also Marco Stratmann's talk)

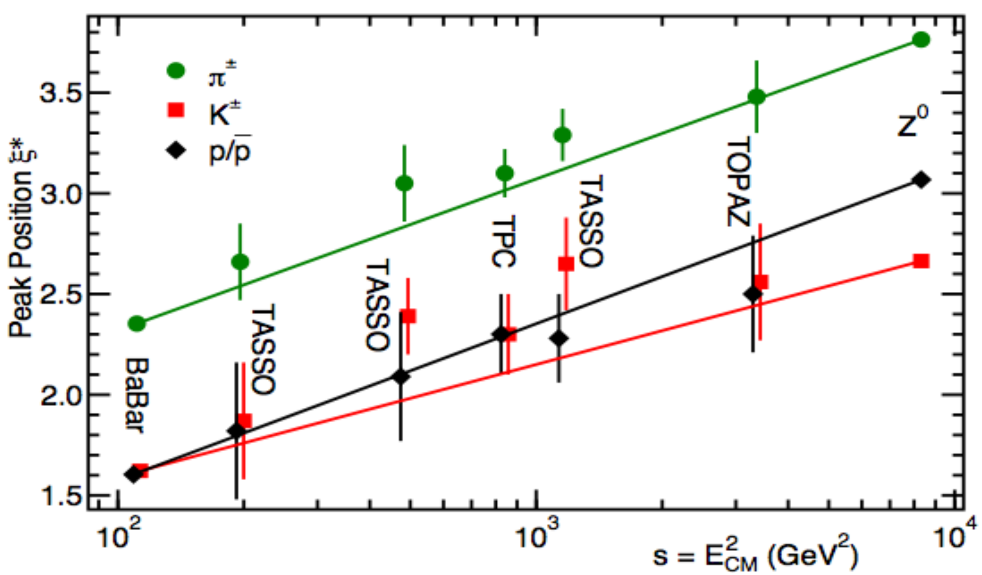
# Test of MLLA+LPHD QCD

Transform our cross section into the variable $\xi$=-ln($x_p$)

Modified Leading Logarithm Approximation (MLLA) with Local Parton-Hadron Duality (LPHD) ansatz:

- a Gaussian function should provide a good description of these spectra
    - fit the spectra with a (distorted) Gaussian function ==> **reasonable description of the data**
- the peak position $\xi^*$ should **decrease exponentially with increasing hadron mass at a given $E_{cm}$**
    - $\xi^*_\pi > \xi^*_K$, but $\xi^*_K \sim \xi^*_{p/\bar{p}}$ (consistent with behavior at higher E)
- should **increase logarithmically with $E_{cm}$ for a given hadron type**




- **BABAR and $Z^0$ data provide precise slope;** the other data are consistent with the line that joins BABAR and $Z^0$ data
- **Similar slopes of the lines for pions and protons; different for kaons ==> <u>changing flavor composition</u>** with increasing $E_{CM}$

# Collins Fragmentation Function @ BABAR

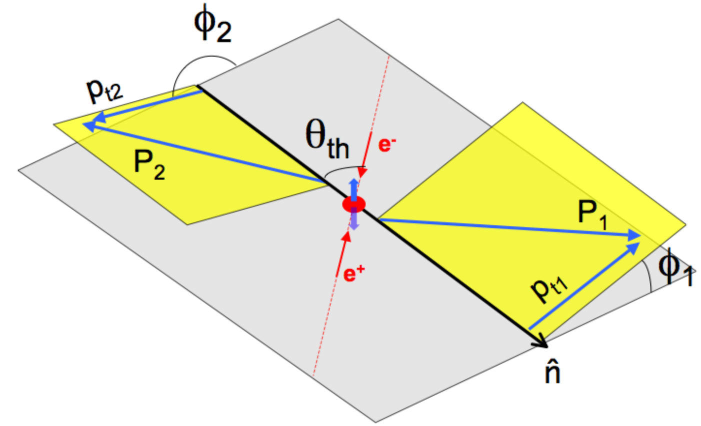
$$e^+e^- \rightarrow \gamma^* \rightarrow u\bar{u},d\bar{d},s\bar{s} \rightarrow \pi\pi X$$

✓ **J.P. Lees *et al.* (BaBar Collaboration), PRD 90, 052003 (2014)**
✓ Data samples used: 468 $fb^{-1}$ at ~10.58 GeV

# Analysis Reference Frames (RF)

**[See NPB 806, 23 (2009)]**

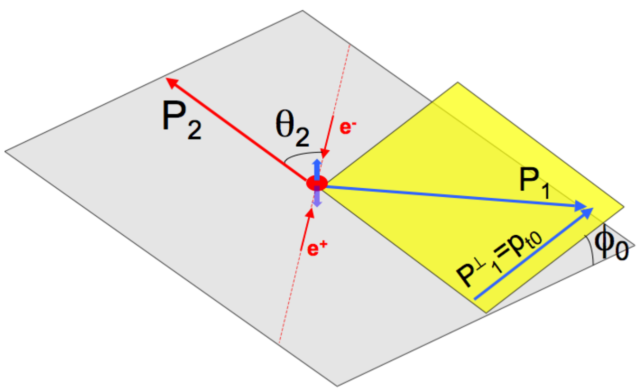
All quantities in $e^+e^-$ center of mass




## 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,…

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



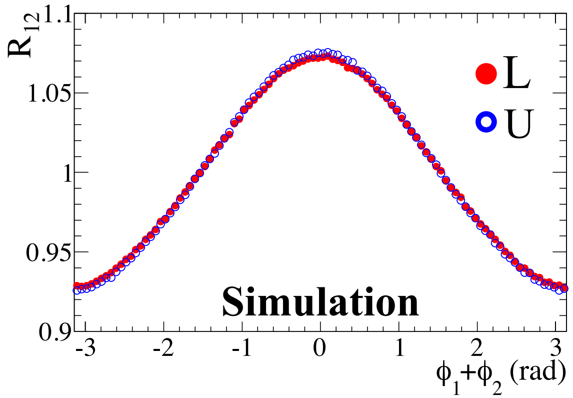

## RF0 or Second hadron momentum RF

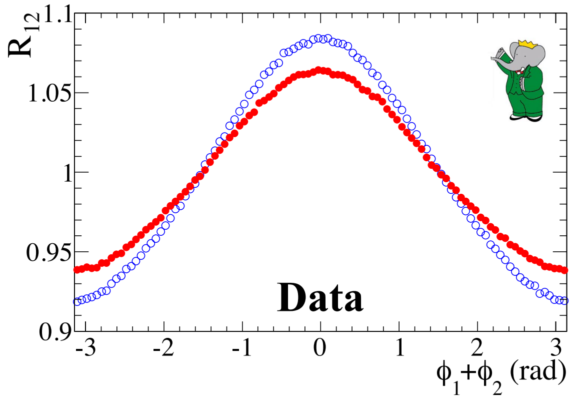
- Alternatively, just use **one track** in a pair
- Very clean experimentally (no thrust axis), less so theoretically
- Gives quark direction for higher pion momentum

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

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 ($\theta_{th}$, $\theta_2$)

# Raw asymmetries and Double Ratios



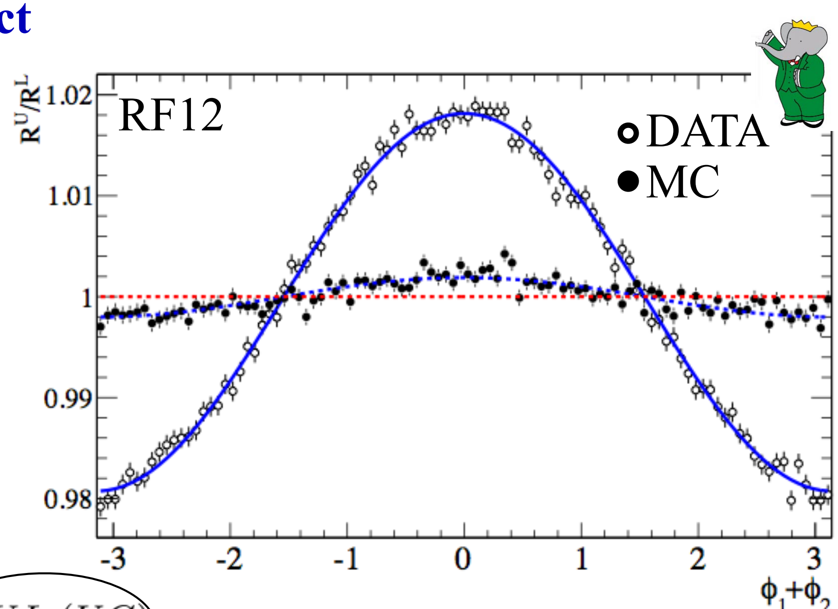




- **Collins asymmetry:**
  - consider all the **U** (unlike) and **L** (like) sign pion pairs
  - make histograms of $\phi_\alpha = \phi_1+\phi_2$ or $2\phi_0$ ($\alpha$=12,0)

- **The MC generator (JETSET) does not include the Collins effect**

  → flat distribution is expected
  - strong modulation due to acceptance of the detector
  - but similar distribution for **U** and **L** pairs

- Data shows difference between U and L distributions, that can be ascribed to the **Collins effect**




Acceptance effects can be reduced by performing the ratio of **U/L** sign pion pairs (or **U/C**):

- MC: consistent with a flat distribution
- Data: cosine modulation clearly visible

$$\frac{R^U_\alpha}{R^{L(C)}_\alpha} = \frac{N^U(\phi_\alpha)/<N^U(\phi_\alpha)>}{N^{L(C)}(\phi_\alpha)/<N^{L(C)}(\phi_\alpha)>} \rightarrow B^{UL(UC)}_\alpha + A^{UL,(UC)}_\alpha \cdot \cos(\phi_\alpha)$$

# Backgrounds: contributions and corrections

- In each bin, the data sample includes pairs from
  - signal uds events
  - $B\bar{B}$ events (small, mostly at low z)
  - $c\bar{c}$ events (important at low/medium z)
  - $\tau^+\tau^-$ events (important at high z)

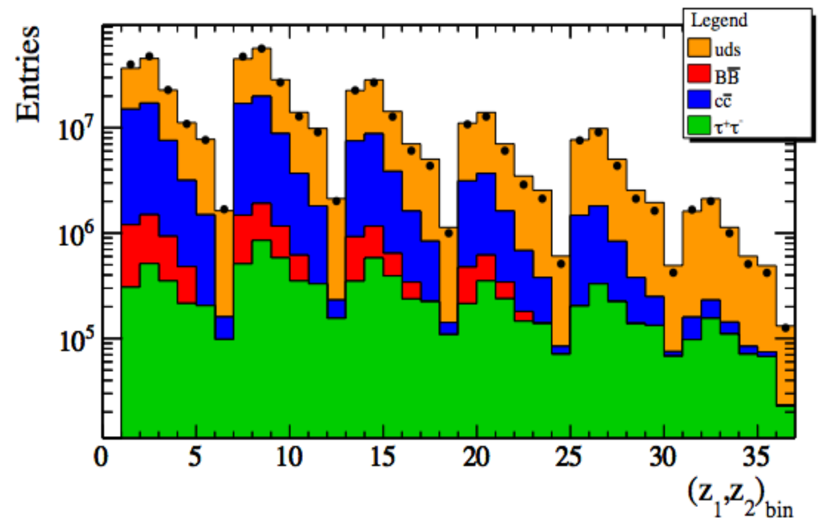
Fraction of ππ due to the $i^{th}$ bkg process

**True asymmetry**

$$A_\alpha^{meas} = (1 - \sum_i F_i) \cdot A_\alpha + \sum_i F_i \cdot A_\alpha^i$$

Bkg asymmetry

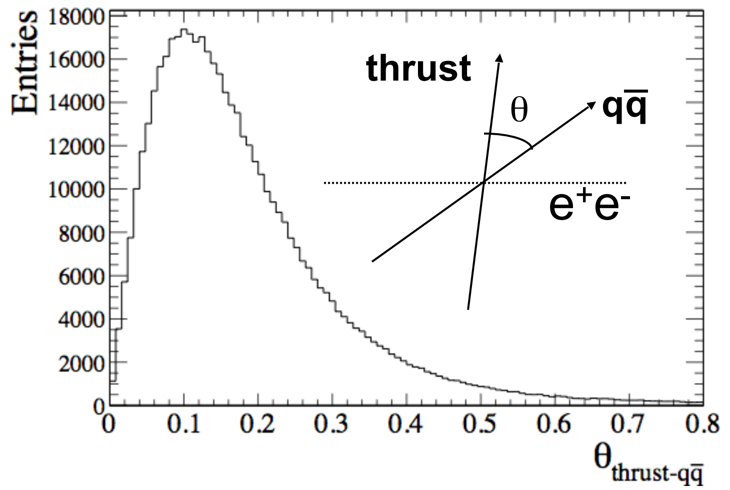
- We must calculate these quantities:
  - $F_i$ using MC sample; we assign MC-data difference in each bin as systematic error
  - $A^{B\bar{B}}$ must be zero; we set $A^{B\bar{B}} = 0$
  - $A^\tau$ small in simulation; checked in data; we set $A^\tau = 0$




- **Charm** background contribution is about 30% on average
  - Both fragmentation processes and weak decays can introduce azimuthal asymmetries
  - We used a **$D^{*\pm}$-enhanced control sample** to estimate its effect

$$\begin{cases} A_\alpha^{meas} = (1 - F_c - F_B - F_\tau) \cdot A_\alpha + F_c \cdot A_\alpha^{ch} \\ A_\alpha^{D^*} = f_c \cdot A_\alpha^{ch} + (1 - f_c - f_B) \cdot A_\alpha \end{cases}$$

# Asymmetry dilution




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

**RF12**: <u>large smearing</u> since the azimuthal angles $\phi_1$ and $\phi_2$ are calculated with respect to the thrust axis.

**RF0**: the azimuthal angle $\phi_0$ is calculated with respect to the second hadron momenta → small smearing due to PID and tracking resolution.

We estimate this and other effects using simulation:

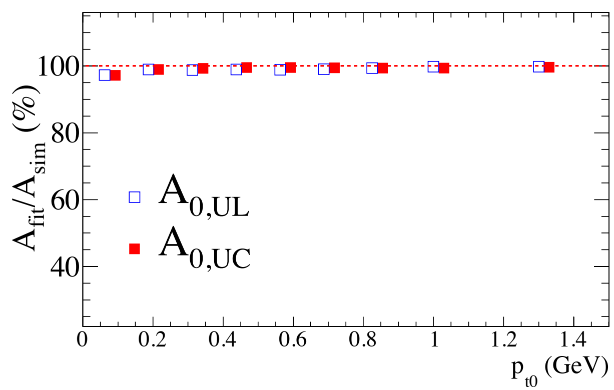
- re-weight MC events in order to reproduce a Collins-like effect
- Determine average dilution values for each bin of z, pt and *θ*

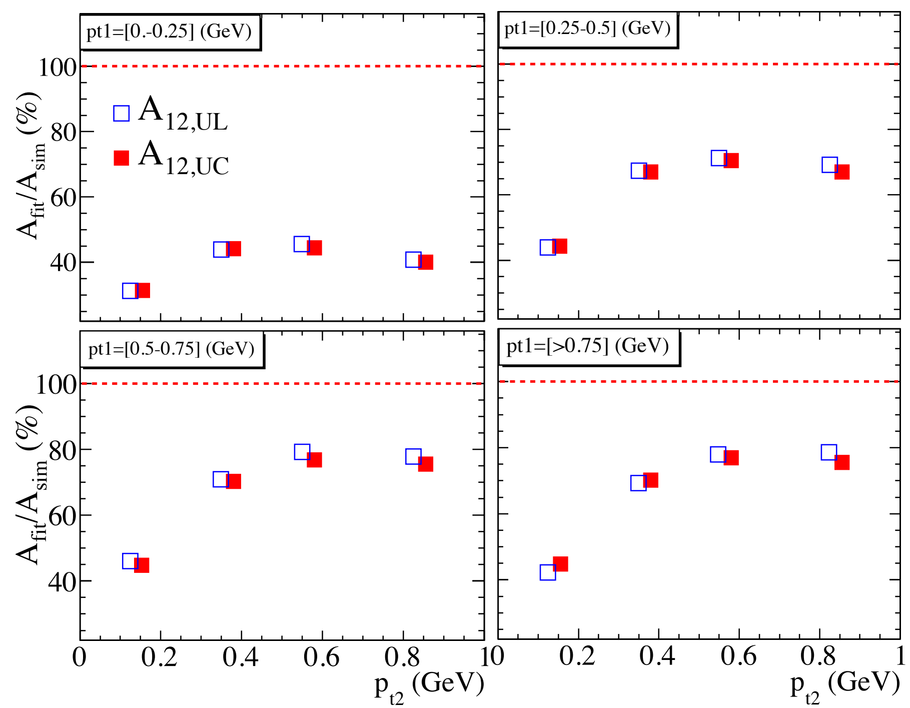
**RF12: correction ranges:**

**- (1.3-2.3) as a function of z**

**- (1.3-3) as a function of $p_t$**

**RF0:no correction needed.**

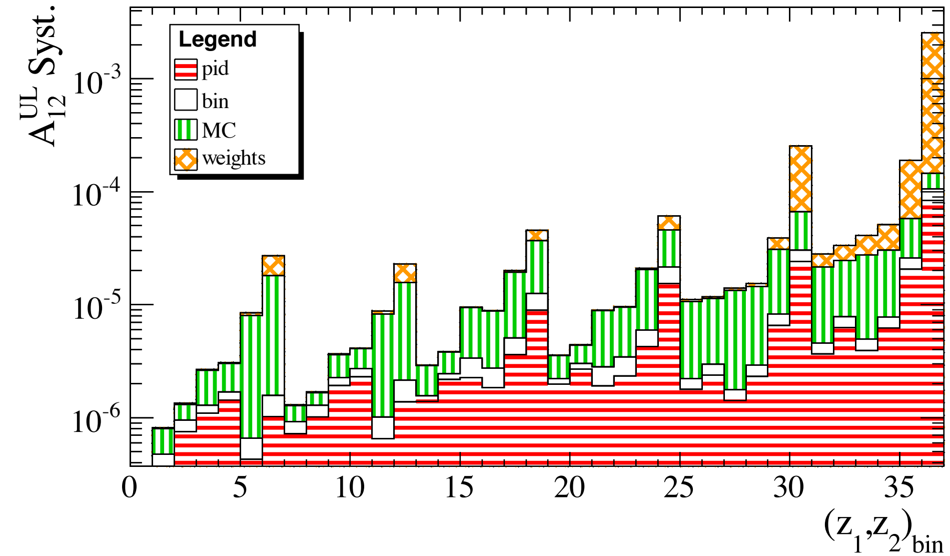


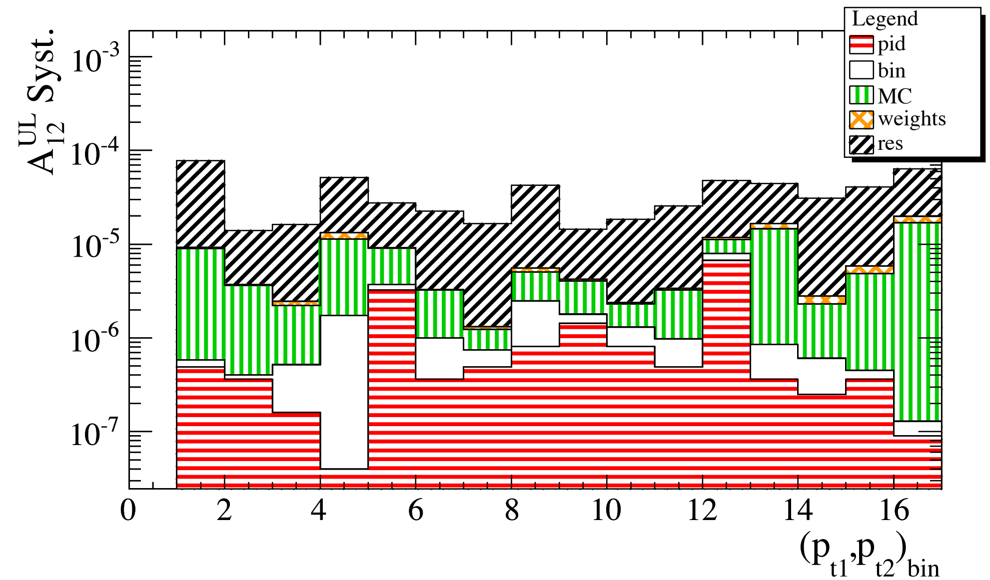



# Systematic uncertainties

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

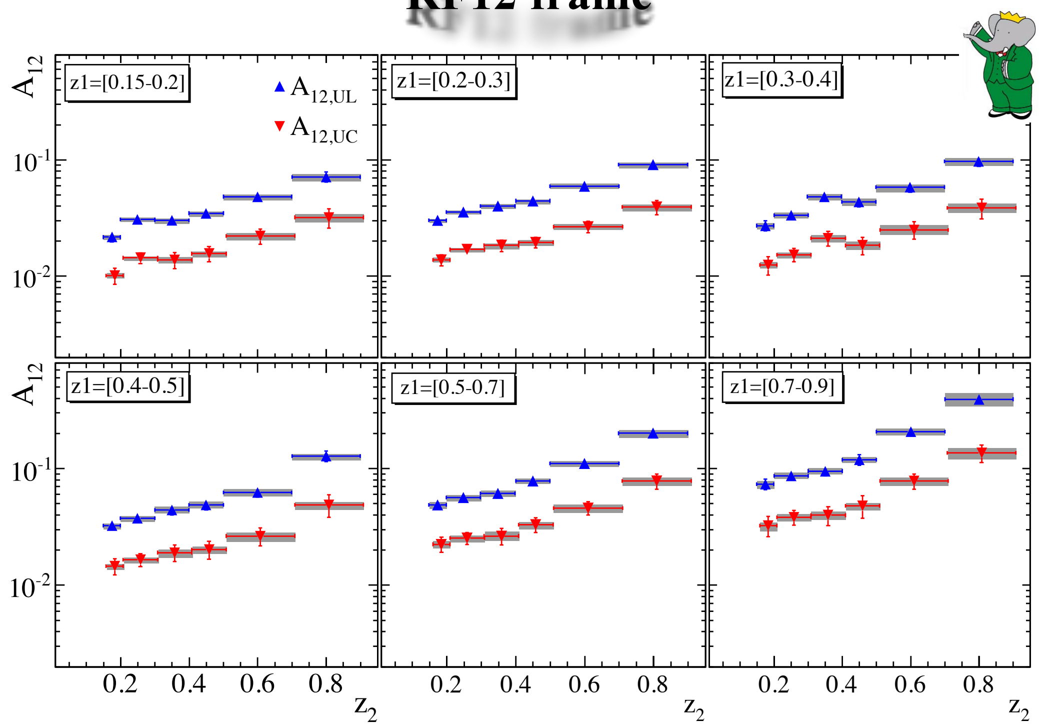
- **Particle identification (PID):** few percent change in the asymmetry by changing the PID cuts
- **Fit procedure:** different angular bin size leads to about 1% of deviation from standard bins
- **MC uncertainties:** we used different track selection requirements
- **Dilution method**
- Pion transverse **momentum resolution** (only for the asymmetry *vs.* ($p_{t1}$,$p_{t2}$)). The $p_t$ resolution is about 100 MeV on average ==> 10% effect on asymmetries for all bins, except for the lowest energies (30%)



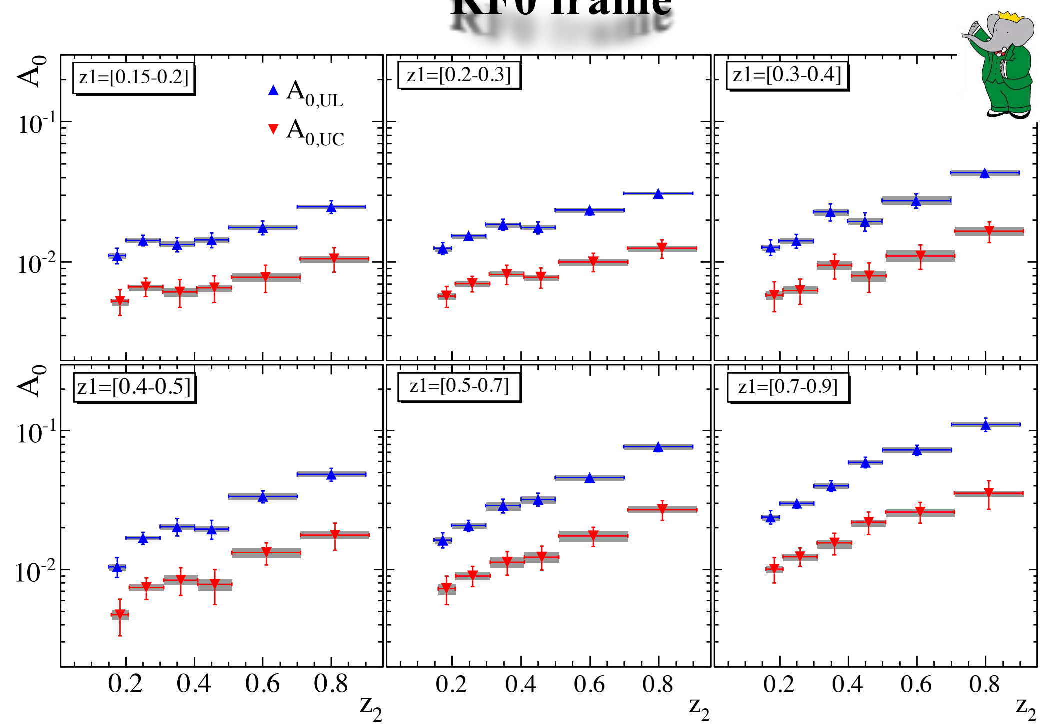



# Results: $A_{12,0}$ vs. $(z_1,z_2)$

**RF12 frame**

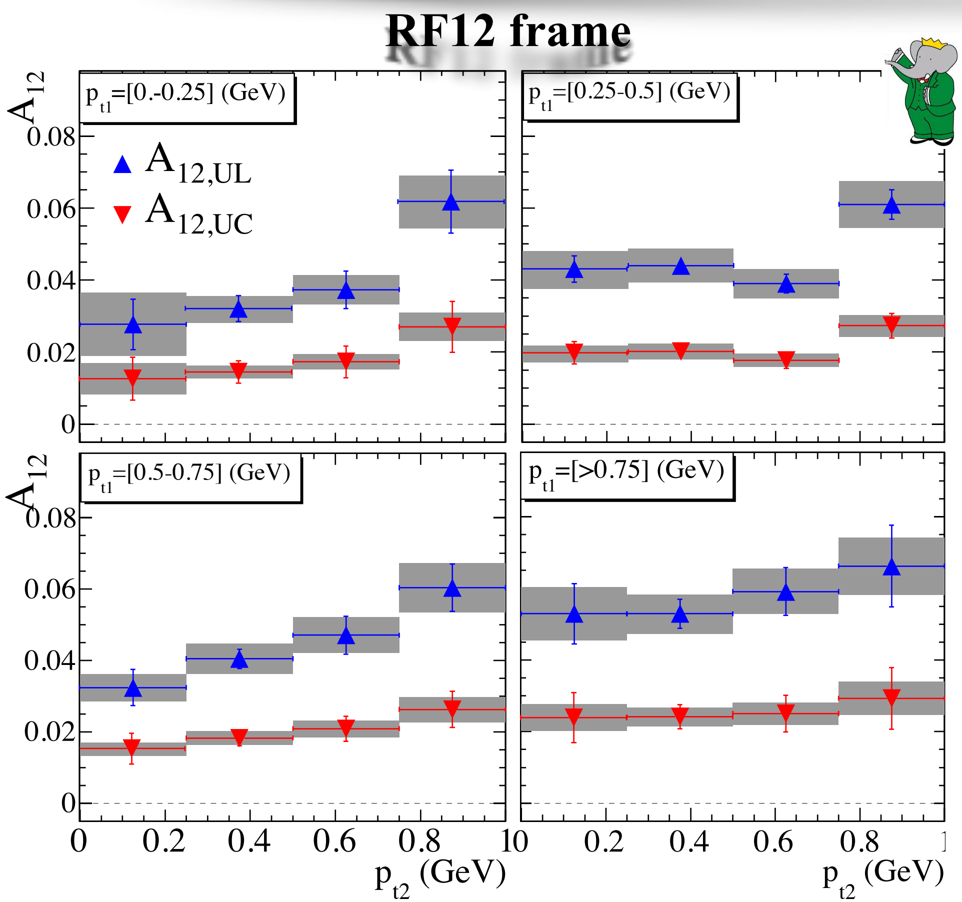


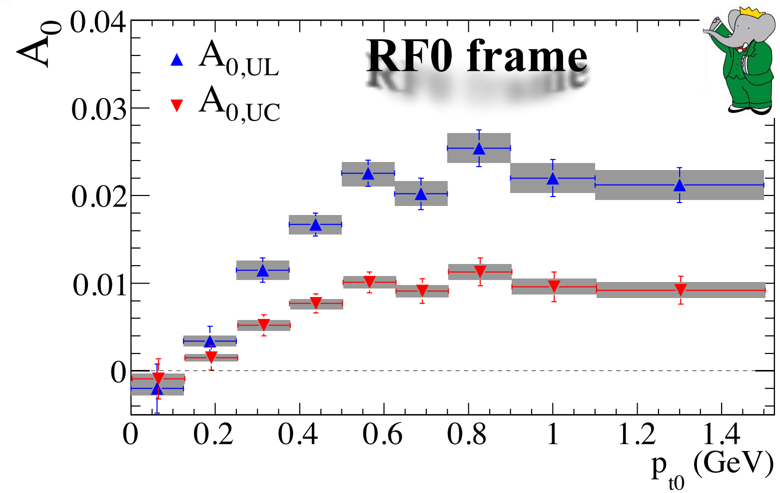

**RF0 frame**

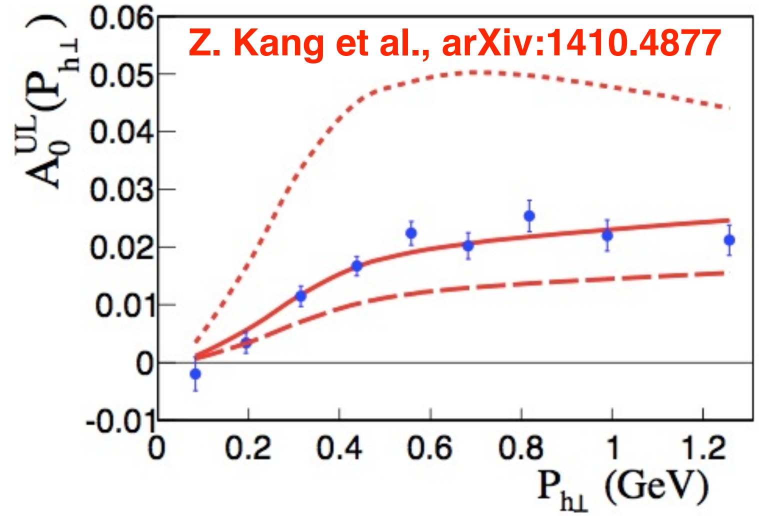



- Significant nonzero $A^{UL}$ and $A^{UC}$ in all bins
  - ⇒ strong dependence on $(z_1,z_2)$: $A_{12}$~1-39%, $A_0$~0.5-11%
  - ⇒ $A^{UC} < A^{UL}$ as expected; complementary information about the favored and disfavored fragmentation processes (PRD 73, 094025 (2006))
  - ⇒ consistent with $z_1 \Leftrightarrow z_2$ symmetry

# Results: $A_{12}$ vs. $(p_{t1},p_{t2})$; $A_0$ vs. $p_{t0}$




NLL': next-to-leading-logarithm approx

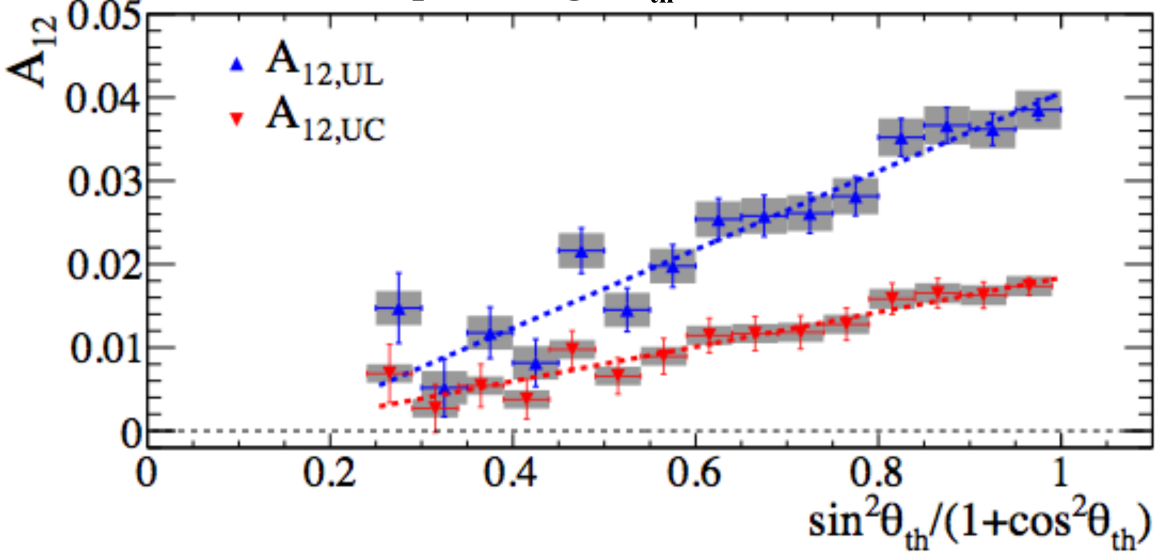
LL: leading double logarithm approx

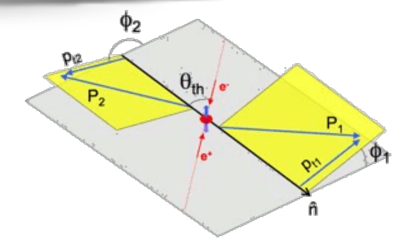
No TMD evolution

- **First measurement of Collins asymmetries *vs.* $p_t$ in $e^+e^-$ annihilation at $Q^2$~110(GeV/c)$^2$**
- only modest dependence on $(p_{t1},p_{t2})$;
- Interesting shape in RF0
- Test of evolution effect

# Results: $A_{12}$ vs. $\theta_{th}$; $A_0$ vs. $\theta_2$

**RF12: thrust polar angle $\theta_{th}$**

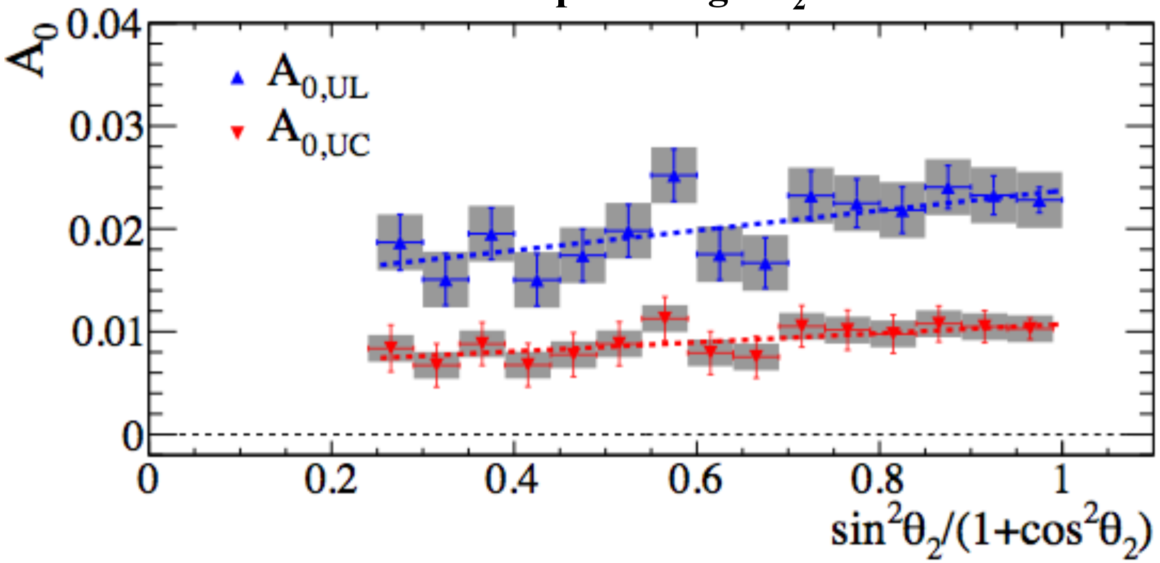


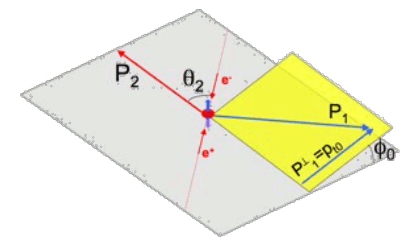



$$A_{12} \propto \frac{\sin^2\theta_{th}}{1+\cos^2\theta_{th}} \cos(\phi_1+\phi_2) \frac{H_1^\perp(z_1)\bar{H}_1^\perp(z_2)}{D_1(z_1)\bar{D}_1(z_2)}$$

==> Intercept consistent with zero, as expected (consistent with Belle results [R.Seidl *et al.*, PRD 86, 039905(E) (2012)])

**RF0: second-hadron polar angle $\theta_2$**



$$A_0 \propto \frac{\sin^2\theta_2}{1+\cos^2\theta_2} \cos(2\phi_0) \mathcal{F}\left[\frac{H_1^\perp(z_1)\bar{H}_1^\perp(z_2)}{D_1(z_1)\bar{D}_1(z_2)}\right]$$

==> The linear fit gives a non-zero constant parameter → the second hadron momentum provides a worse estimation of the $q\bar{q}$ direction (consistent with Belle results)

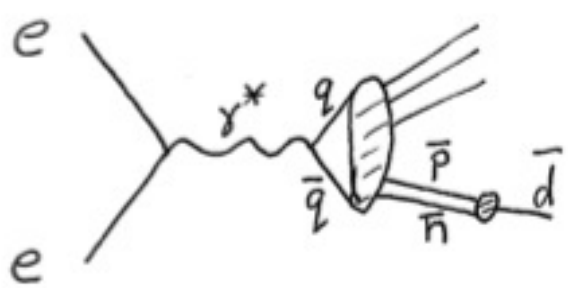
# Anti-deuteron production - via quarks or gluons

Dark matter (DM) annihilation to quarks and gluons would be a source of primary anti-deuteron ($\bar{d}$) in cosmic rays

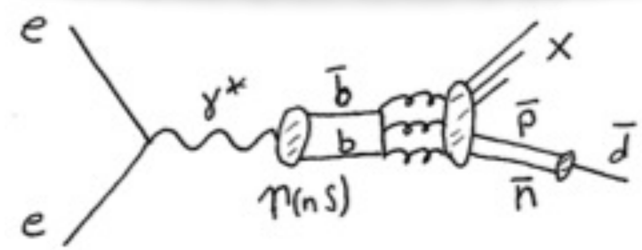
- the production from standard astrophysical sources is widely expected to be low
- the detection of an anomalous anti-deuteron flux would be evidence of DM annihilation to colored particles, such as quarks and gluons

**BUT**

- to predict the $\bar{d}$ flux from annihilating DM is necessary to know the fragmentation of q and g to $\bar{d}$ at different energies ==> dominant source of uncertainties (e.g., “coalescence model”) [arXiv:1006.0983; PLB 683,248(2010)]
- more data in hadronic and $e^+e^-$ collisions may help to reduce uncertainties




probe quark fragmentation via
$e^+e^- \rightarrow u\bar{u}, d\bar{d}, s\bar{s}$




$e^+e^- \rightarrow \Upsilon(nS)$ gives access to gluon fragmentation: $\Upsilon(nS) \rightarrow ggg, gg\gamma$.
Expected to be the dominant contribution due to the large barion production in gluon fragmentation

# Anti-deuteron production

J.P.Lees *et al.*, (BaBar Collaboration)
PRD **89**, 111102(R) (2014)

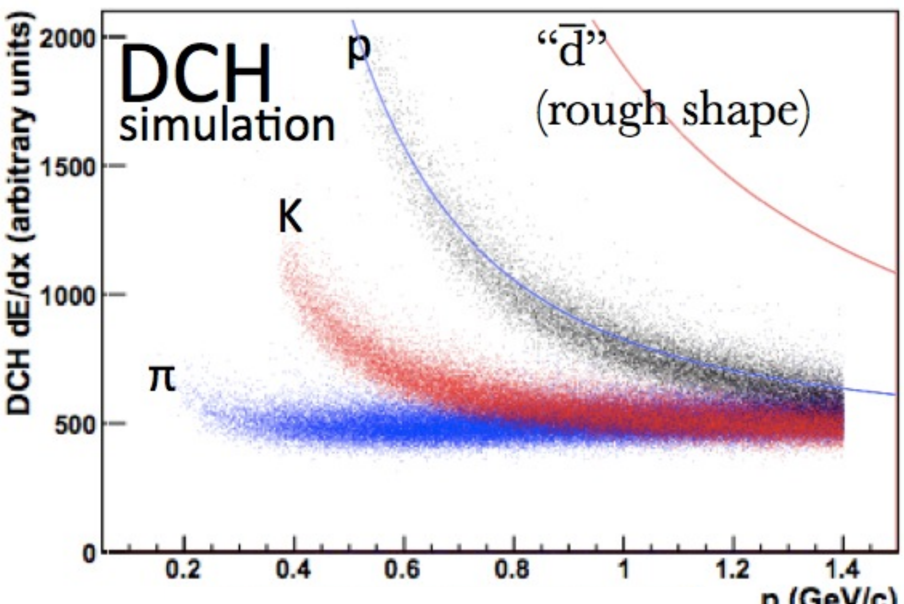
BABAR has made improved measurements of $\bar{d}$ production in $\Upsilon(nS)$ (i.e. via gluons) and in $e^+e^- \rightarrow q\bar{q}$ near $\sqrt{s}$~10.6 GeV

- Key element is the measurement of the combined **energy loss (dE/dx)** in the tracking system
- Deuterons well-separated from protons up to 1.5 GeV/c: **0.5<$p_{LAB}$<1.5 GeV/c**
- DIRC used as veto

**Datasets used**

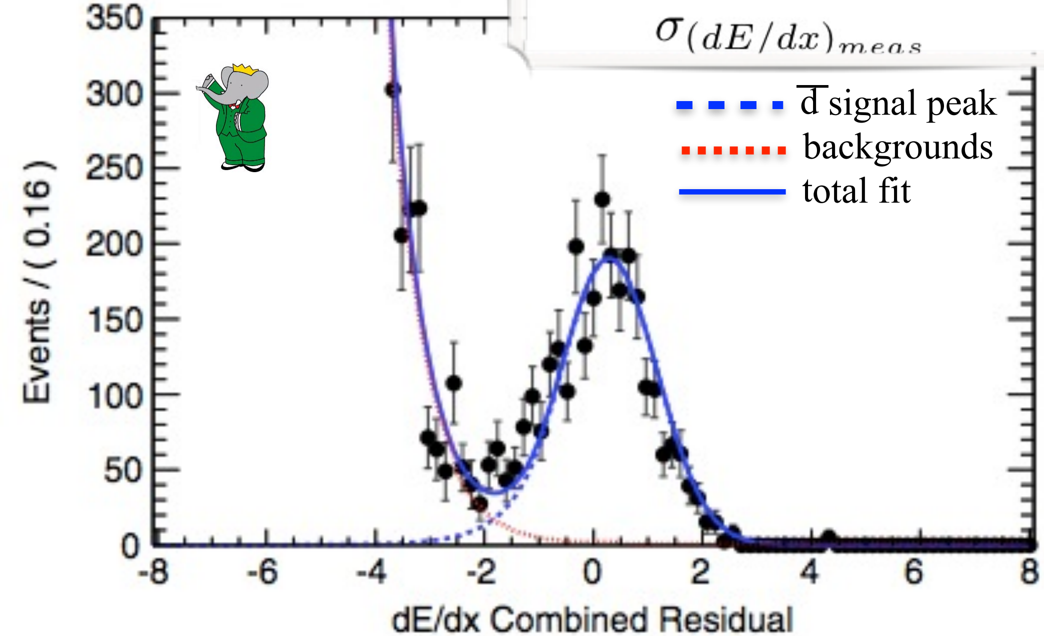
| Resonance | Onpeak | # of $\Upsilon$ Decays | Offpeak |
|---|---|---|---|
| $\Upsilon(4S)$ | 429 $fb^{-1}$ | $463 \times 10^6$ | 44.8 $fb^{-1}$ |
| $\Upsilon(3S)$ | 28.5 $fb^{-1}$ | $116 \times 10^6$ | 2.63 $fb^{-1}$ |
| $\Upsilon(2S)$ | 14.4 $fb^{-1}$ | $98.3 \times 10^6$ | 1.50 $fb^{-1}$ |

$\Upsilon(1S)$ sample via $\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$




(BaBar Coll.) NIM A 279,615 (2013)

$$\frac{\left[\left(\frac{dE}{dx}\right)_{meas} - \left(\frac{dE}{dx}\right)_{expec}\right]}{\sigma(dE/dx)_{meas}}$$




**Yields extracted by fitting (fireball function) the normalized residual of the combined dE/dx**

# Anti-deuteron production

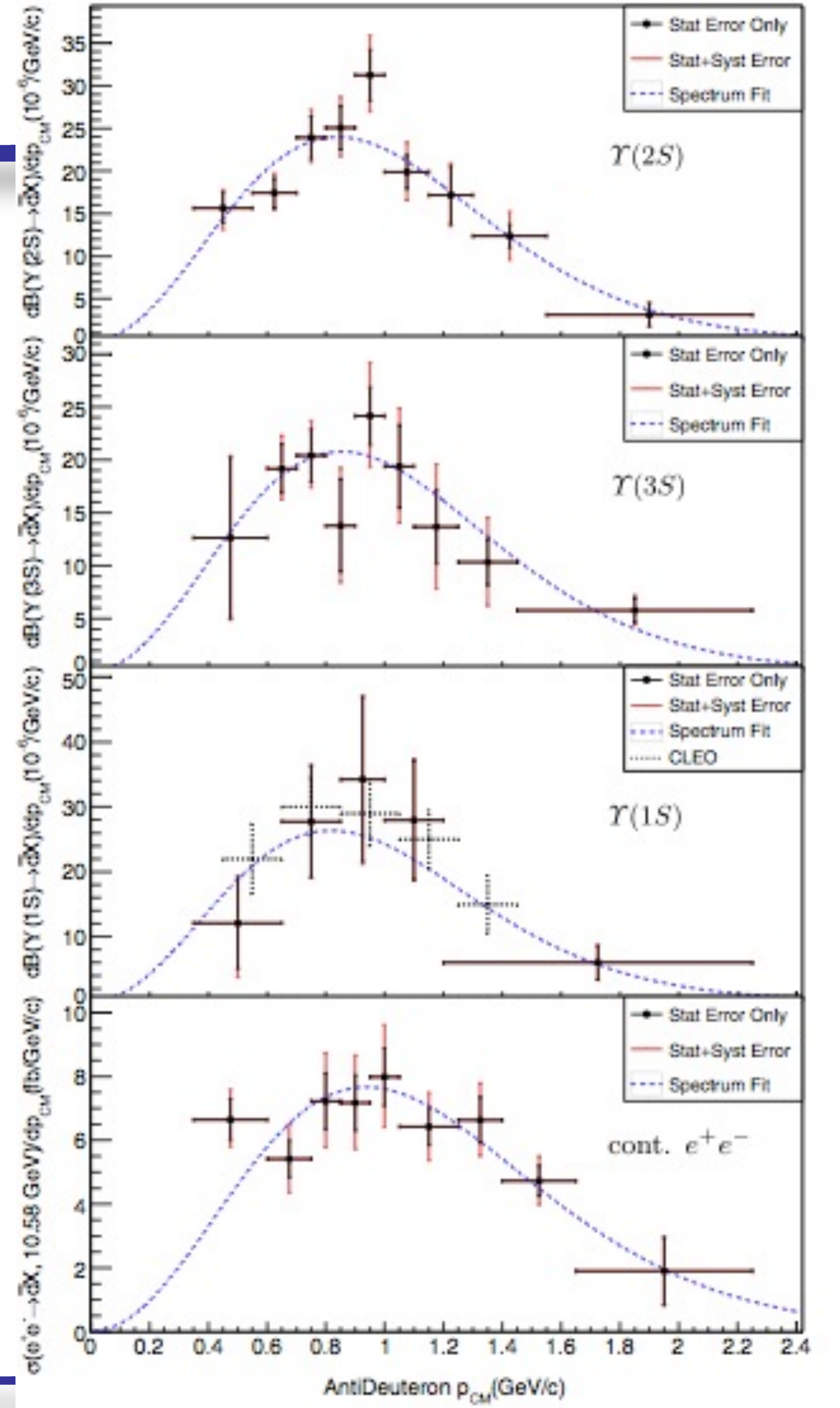
**J.P.Lees *et al.*, PRD 89, 111102(R) (2014)**

| Process | Rate |
|---|---|
| $\mathcal{B}(\Upsilon(3S) \to \bar{d}X)$ | $(2.33 \pm 0.15^{+0.31}_{-0.28}) \times 10^{-5}$ |
| $\mathcal{B}(\Upsilon(2S) \to \bar{d}X)$ | $(2.64 \pm 0.11^{+0.26}_{-0.21}) \times 10^{-5}$ |
| $\mathcal{B}(\Upsilon(1S) \to \bar{d}X)$ | $(2.81 \pm 0.49^{+0.20}_{-0.24}) \times 10^{-5}$ |
| $\sigma(e^+e^- \to \bar{d}X)$ $[\sqrt{s} \approx 10.58$ GeV$]$ | $(9.63 \pm 0.41^{+1.17}_{-1.01})$ fb |
| $\frac{\sigma(e^+e^- \to \bar{d}X)}{\sigma(e^+e^- \to \text{Hadrons})}$ | $(3.01 \pm 0.13^{+0.37}_{-0.31}) \times 10^{-6}$ |

- First measurements of $\bar{d}$ production in $e^+e^-$ annihilation at c.m. energy ≈ 10.58 GeV and ϒ(3S)
- Enhancement (one order of magnitude) of $\bar{d}$ production in *ggg* and *ggγ* decays as compared to the production from $q\bar{q}$
- No significant evidence of anti-deuteron production in ϒ(4S) decays

- Measured also by ARGUS Collaborations (*PLB*236, 102 (1990);)
- Good agreement with CLEO results on the ϒ(2S) and ϒ(1S):
  - - $\mathcal{B}(\Upsilon(2S)\to\bar{d}X)^{CLEO}$=(3.37±0.50±0.25)x10$^{-5}$
  - - $\mathcal{B}(\Upsilon(1S)\to\bar{d}X)^{CLEO}$=(2.86±0.19±0.21)x10$^{-5}$

(D.M. Asner *et al.*, PRD **75**, 012009 (2007))



# Summary and conclusions

## Unpolarized FF: inclusive spectra for $\pi^{\pm}$, $K^{\pm}$, and $p/\bar{p}$ hadrons in $e^+e^-$ annihilation

- precise data at the c.m. energy of 10.54 GeV and at high $x_p$
- consistent with, improvement upon, measurements at lower $E_{cm}$
- consistent with Belle data [M.Leitgab *et al.* (Belle Collaboration), PRL 111,062002(2013)]
- published in *Phys. Rev. D* ***88****,032011(2013)*

## Polarized FF: Collins effect for pion pairs

- as a function of fractional energies, transverse momenta (first measurement in $e^+e^-$ annihilation), reference axis polar angle, and four dimensional space $((z_1,z_2,p_{t1},p_{t2})$, RF12 only)
- z and $p_t$ dependence as expected, but $\theta$ dependence in RF0 shows differences from expectation
- general agreement with Belle data (R.Seidl *et al.* (Belle Collaboration), PRD 86, 039905(E) (2012))
- published in *Phys. Rev. D* ***90****,052003(2014)*
- ***Collins effect for KK pairs under investigation***

## Anti-deuteron results

- Probe quark and gluon fragmentation
- First measurement in $\Upsilon(3S)$ decays and $e^+e^-\rightarrow q\bar{q}$ near 10.58 GeV, most precise in $\Upsilon(2S)$ decays
- Published in *Phys. Rev. D* ***89****,111102 (R)(2014)*

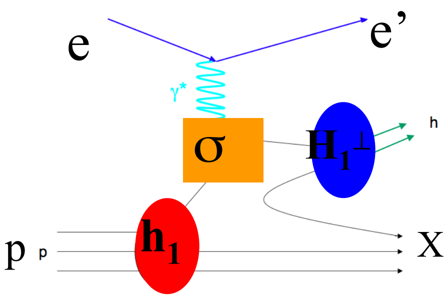
These results are important in order to deeply investigate the nucleon structure, to understand the hadronization processes and to probe dark matter annihilation

Stay tuned

# Thanks for your attention

# BACKUP SLIDES

# Extraction of Collins FF from data

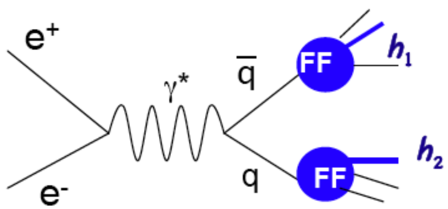



**SIDIS**
HERMES: PRL **94**, 012002 (2005)
COMPASS: NP **B765**, 31 (2007)

$$A_T \propto h_1(x_B) \otimes H_1^\perp(z)$$

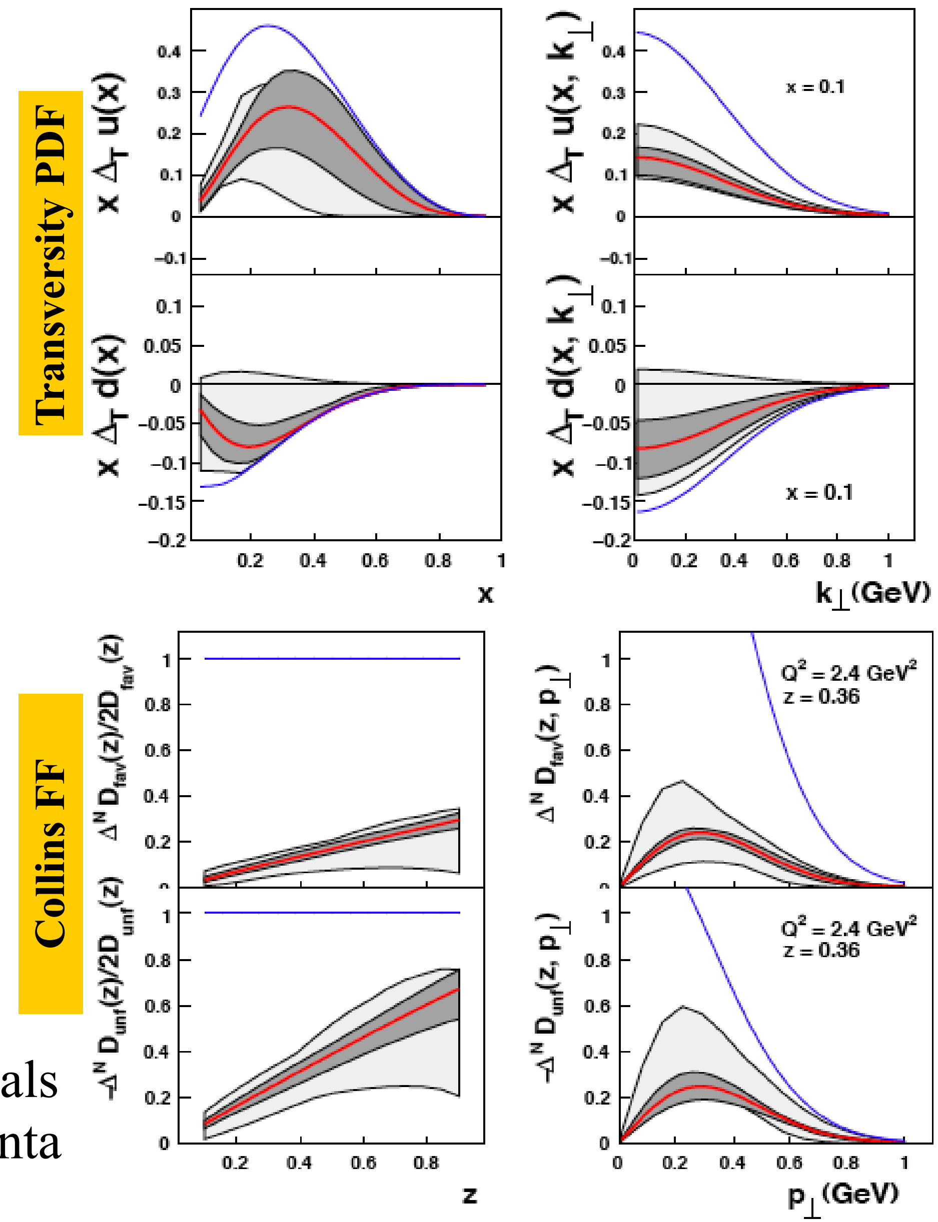
☛ G. Schnell

+




**$e^+e^-$ annihilation**
BELLE: PRL 96, 232002(2006),
PRD 78, 03201 (2008)

$$A \propto H_1^\perp(z_1) \otimes H_1^\perp(z_2)$$



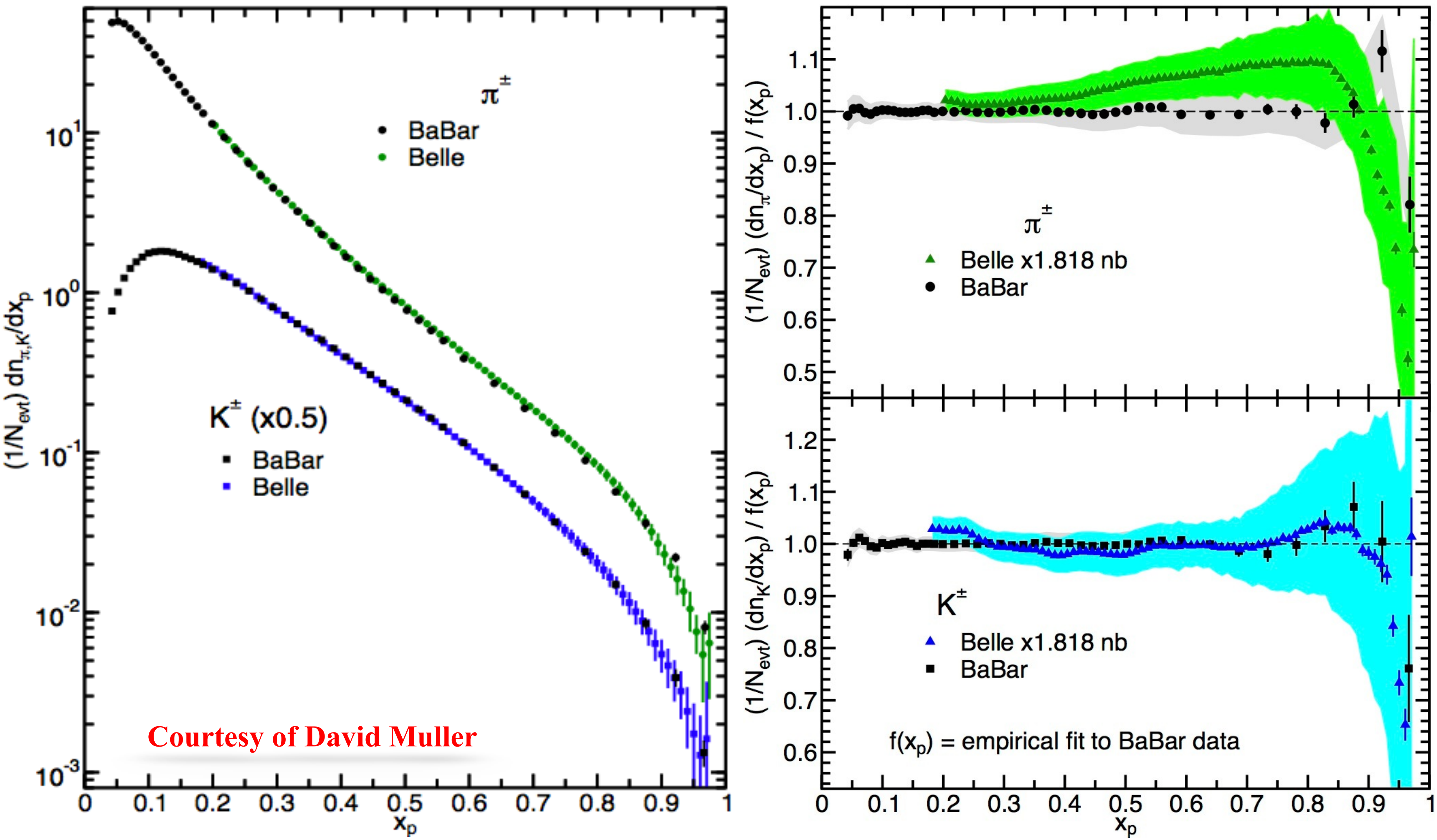

<u>GLOBAL ANALYSIS</u>: simultaneous determination of $H_1^\perp$ and the transversity parton distribution function $h_1$

*Anselmino et al., PRD 75, 054032(2007), NP Proc.Suppl. 191, 98(2009)*

**Improvements from BABAR studies:**

- Increase in the number of pion fractional energy intervals
- Collins asymmetry behavior vs. pion transverse momenta

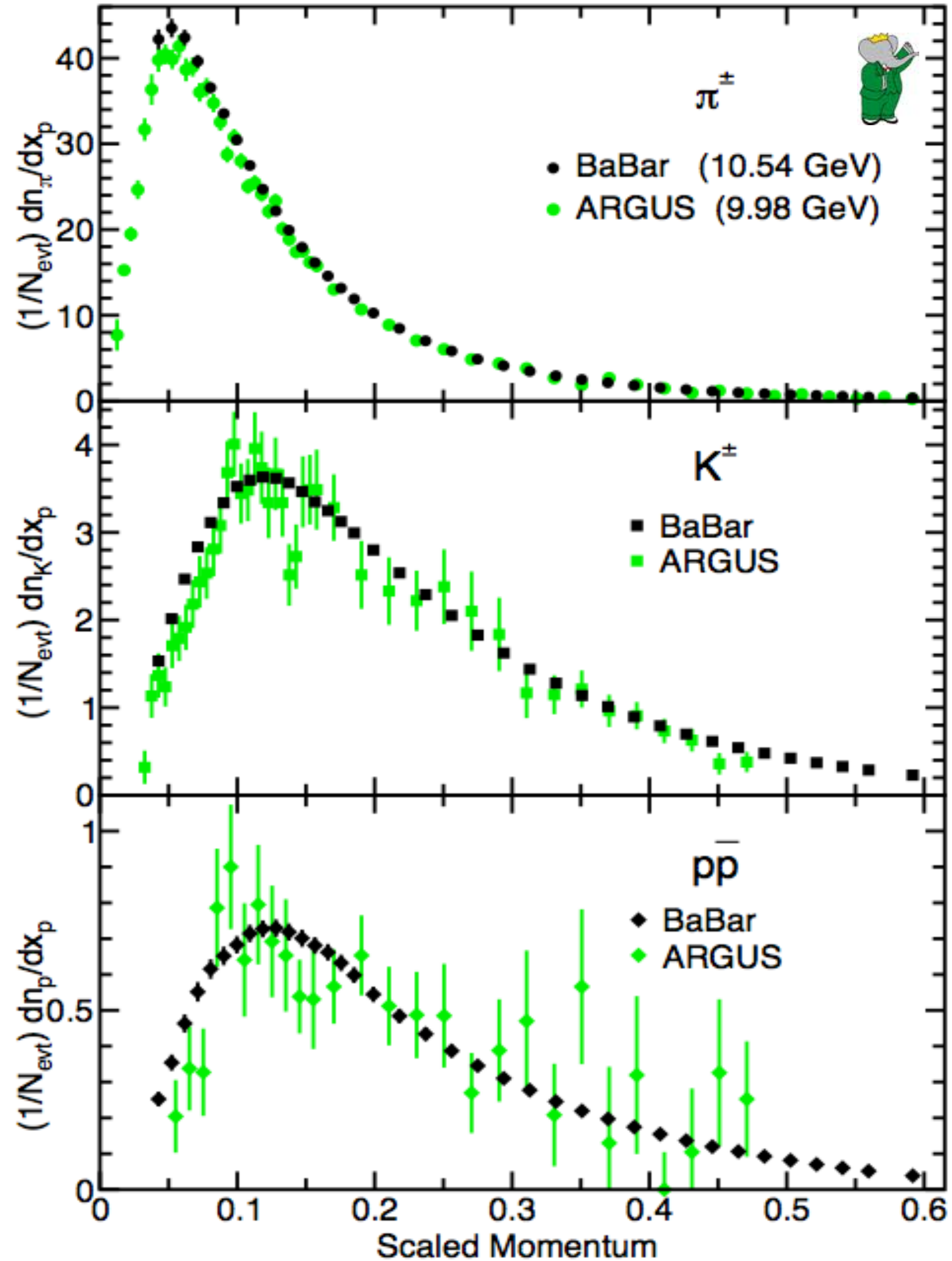
# BaBar/Belle comparison



# BABAR Results

- **Averaged results over θ, in term of scaled momentum $x_p = 2p^*/E_{cm}$**
  - coverage from 0.2 GeV/c to the kinematic limit of 5.27 GeV/c

- **Compare nicely with previous data from ARGUS**
  - consistent everywhere for $x_p$>0.1
  - mass driven scaling violation for $x_p$<0.1: ARGUS data systematically below
  - (BABAR) more precise
  - (BABAR) better coverage at high $x_p$
  - (ARGUS) extends to low momentum for π± → complementary information





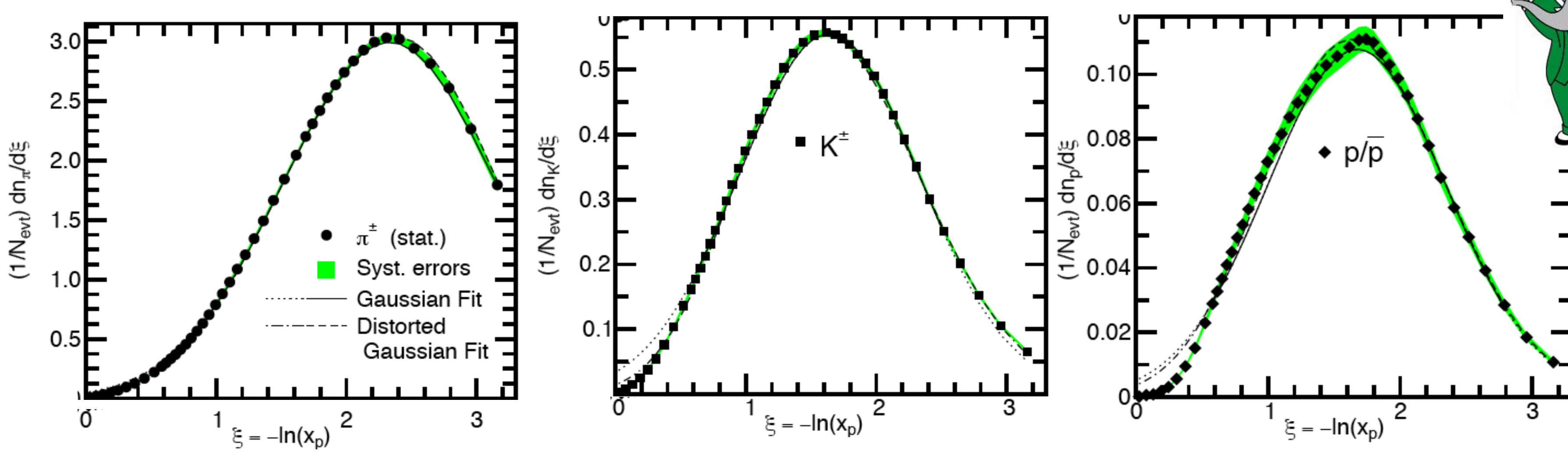
[1] H. Albrecht *et al.* (ARGUS Collaboration) Z. Phys. C **44**, 547 (1989).

# Test of MLLA+LPHD QCD

Transform our cross section into the variable $\xi$=-ln($x_p$)

**Test of QCD prediction**

Modified Leading Logarithm Approximation (MLLA) with Local Parton-Hadron Duality (LPHD) ansatz:
==> a Gaussian function should provide a good description of these spectra
==> the peak position $\xi^*$ should **decrease exponentially with increasing hadron mass at a given $E_{cm}$**
==> should **increase logarithmically with $E_{cm}$ for a given hadron type**

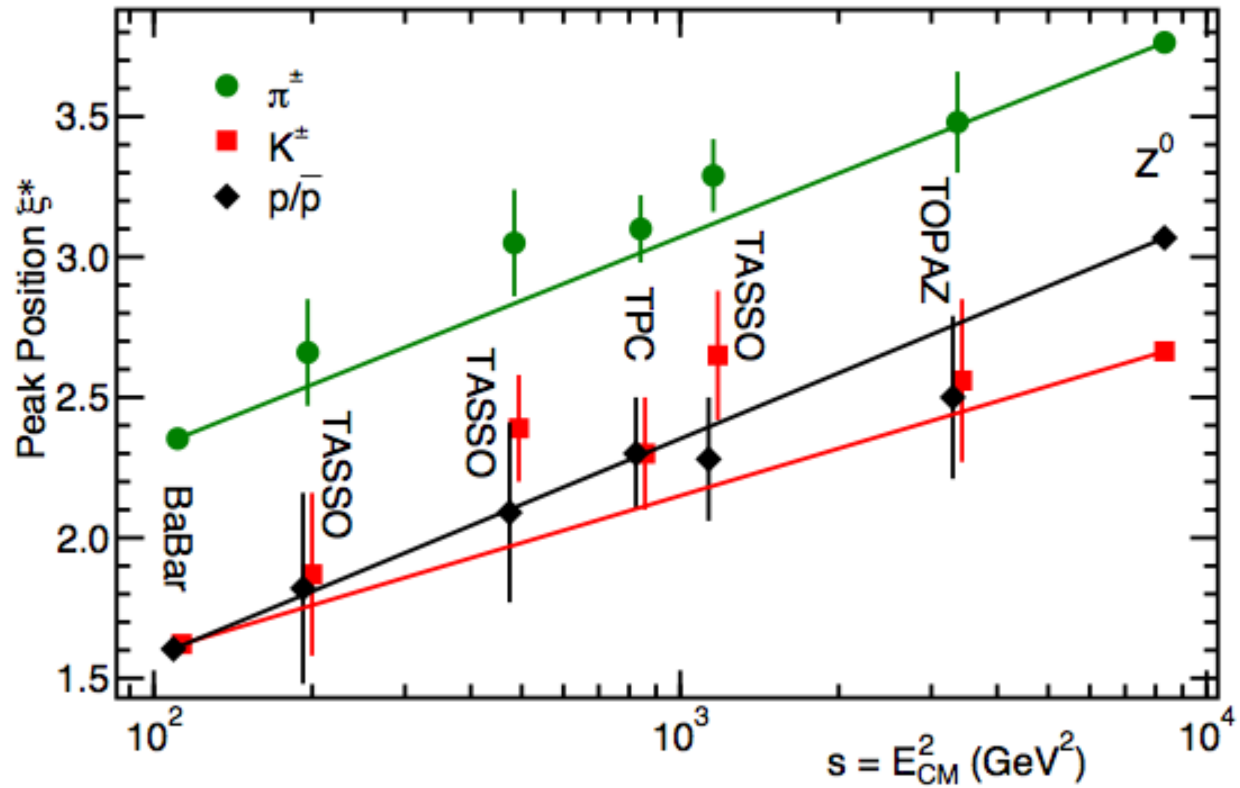



- Fit the spectra with a (distorted) Gaussian function ==> **reasonable description of the data**
- $\xi^*_\pi$ is higher than $\xi^*_K$ in agreement with the predicted drop, but $\xi^*_p$ is not lower than $\xi^*_K$
- Similar behavior observed at higher energies

# Test of MLLA+LPHD QCD: Peak Position

→ MLLA predicts that the peak position ξ*
- should **decrease exponentially with increasing hadron mass at a given $E_{cm}$**
- should **increase logarithmically with $E_{cm}$ for a given hadron type**

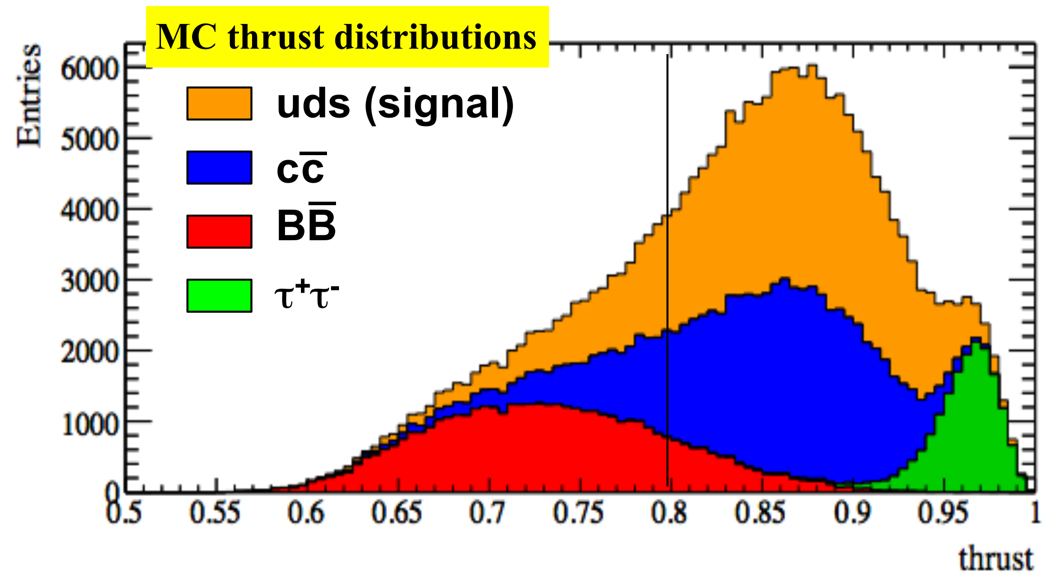
→ $\xi^*_\pi$ is higher than $\xi^*_K$ in agreement with the predicted drop, but $\xi^*_p$ is not lower than $\xi^*_K$ (or seems to follow different trajectories at higher energies)

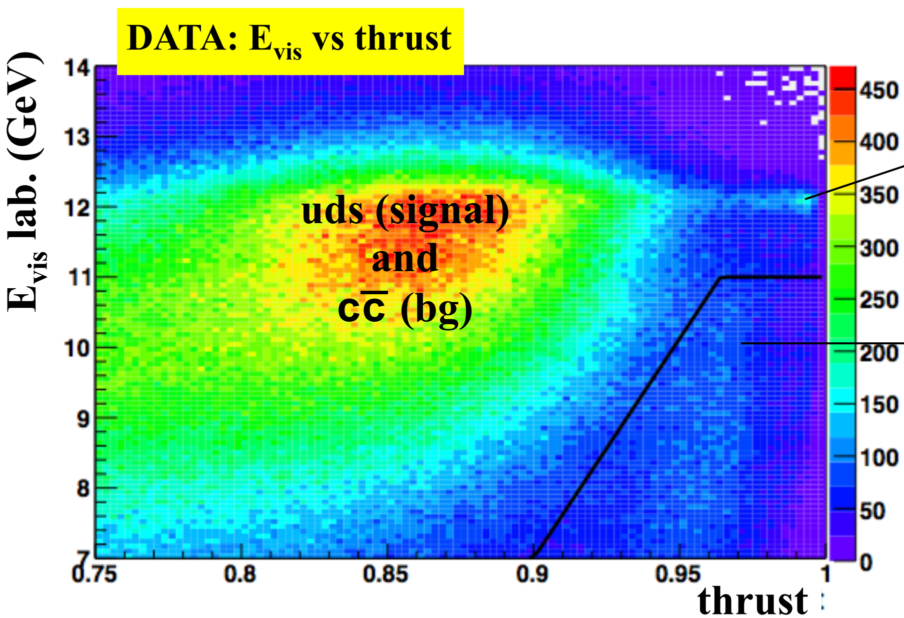



→ **BABAR and $Z^0$ data provide precise slope**
→ The other data are consistent with the line that joins BABAR and $Z^0$ data
→ **Similar slopes of the lines for pions and protons; different for kaons ==> <u>changing flavor composition</u>** with increasing $E_{CM}$

# Event and track selection

- Select hadronic events:
  - -number of well-reconstructed charged tracks > 2 from the interaction point
- Selection of two-jet topology events: **thrust>0.8**
- Events in the $\tau^+\tau^-$ region removed




BhaBha and $\mu^+\mu^-(\gamma)$ events, with $\gamma \rightarrow e^+e^-$ conversion

$\tau^+\tau^-$ region

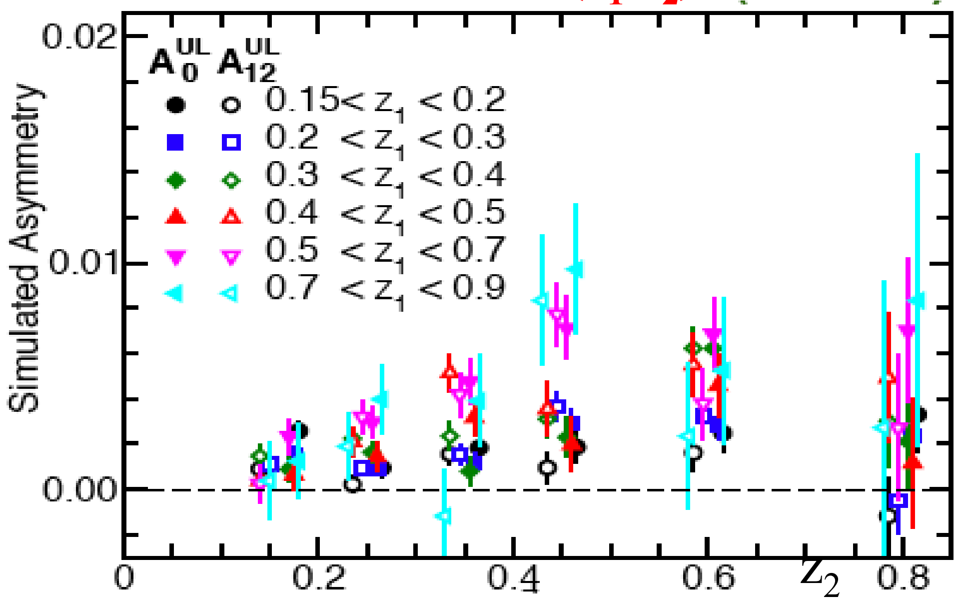
- Veto on electrons and muons
- Select of pions in the detector acceptance region: $0.41<\theta_{lab}<2.54$ rad
- **Pion fractional energies:**
  **$0.15<z=2E_h/\sqrt{s}<0.9$**

# Asymmetry binning and corrections

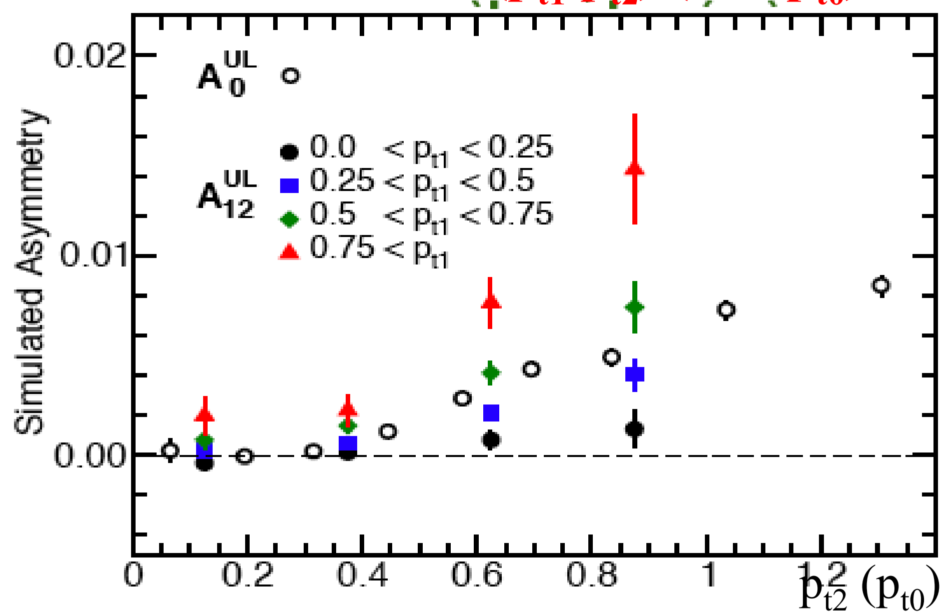
- The Collins effect is expected to depend on $z_1$, $z_2$, $p_{t1}$, $p_{t2}$ (or $p_{t0}$), as well as $\cos\theta_{th}$ (or $\cos\theta_2$)

  ⇒ analyze in bins of these quantities:

**6x6 bins in ($z_1$,$z_2$)**




**4x4 bins in ($p_{t1}$,$p_{t2}$) (9 in $p_{t0}$)**



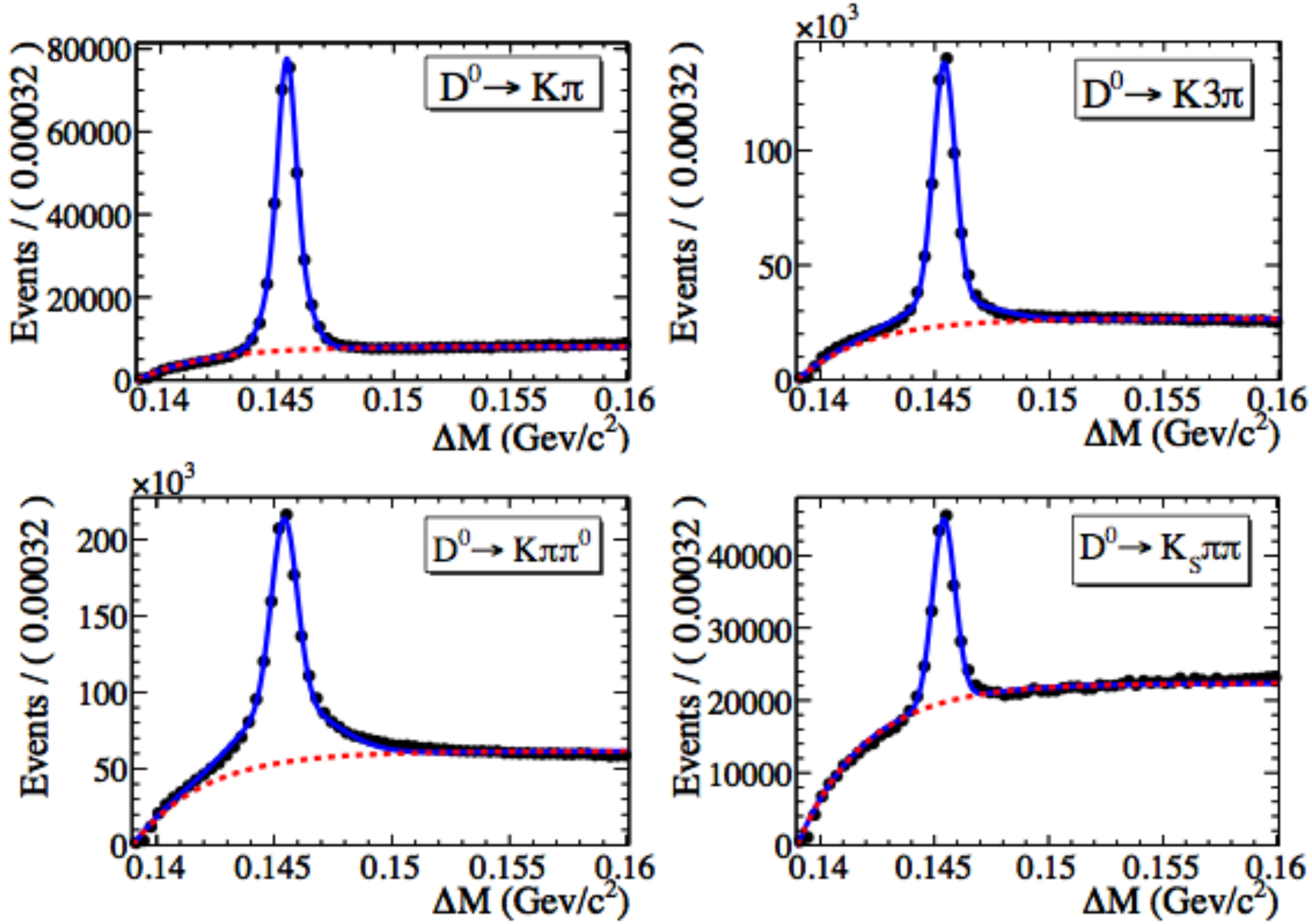

- Simulated asymmetries also depend on these quantities →must correct in each bin independently

  ⇒ Systematic on MC value evaluated by varying track selection/acceptance

- Asymmetry dilution due to the thrust axis approximation. The corrections in the RF12 frame range between 1.3-2.3 as a function of *z*, and between 1.3-3 as a function of $p_t$

  ⇒ No correction needed in the RF0 frame

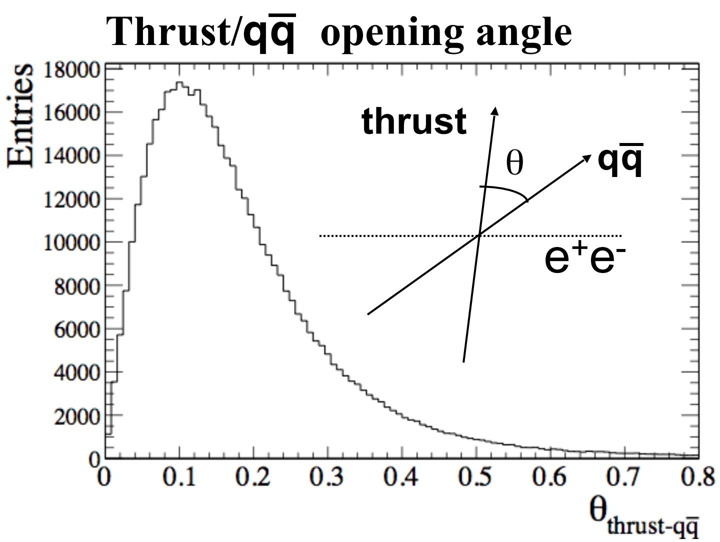
# $D^{*\pm}$-enhanced control sample




**$D^{*\pm} \to D^0\pi^\pm$**, $D^0 \to K\pi$ (mode 1)
$D^0 \to K3\pi$ (mode 2)
$D^0 \to K\pi\pi^0$ (mode 3)
$D^0 \to K_S\pi\,\pi$ (mode 4)

$1.835 < M_{D0} < 1.895$ GeV/c$^2$
$0.1425 < \Delta M < 0.149$ GeV/c$^2$
($\Delta M = M_{D^*} - M_{D0}$)

# Asymmetry dilution

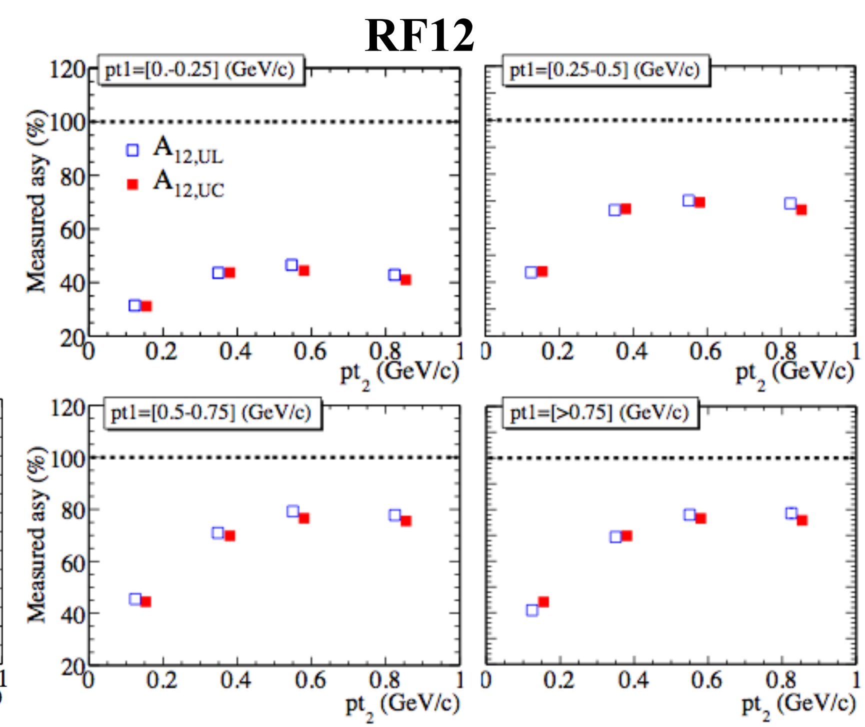



The experimental method assumes the thrust axis as $q\bar{q}$ direction: this is only a rough approximation

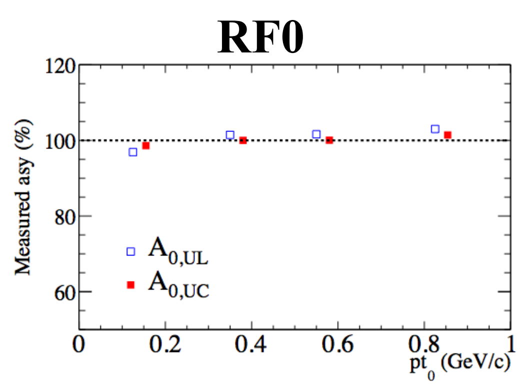
**RF12**: large smearing since the azimuthal angles $\phi_1$ and $\phi_2$ are calculated with respect to the thrust axis; additional dilution due to very energetic tracks close to the thrust axis.

**RF0**: the azimuthal angle $\phi_0$ is calculated with respect to the second hadron momenta → small smearing due to PID and tracking resolution.

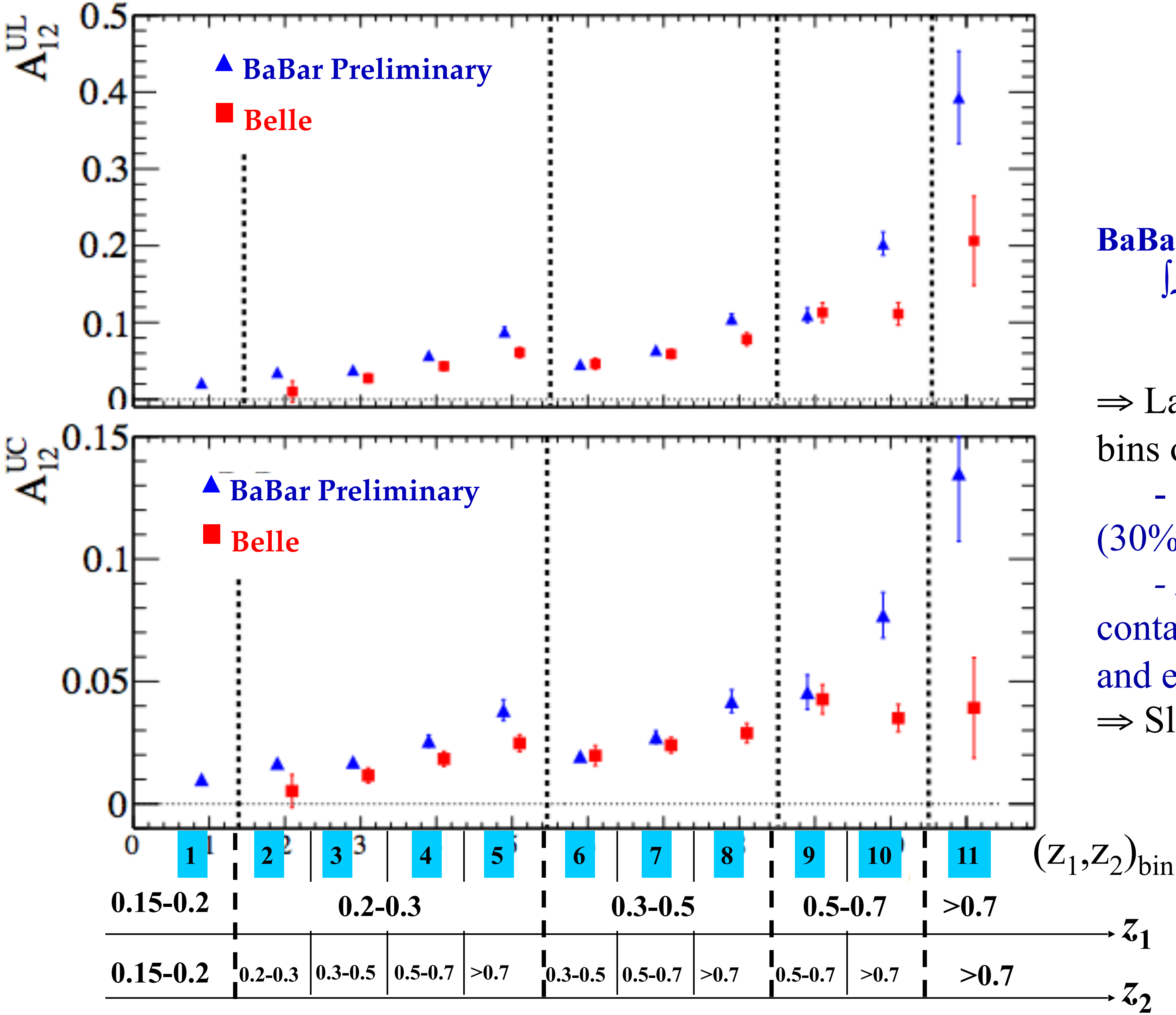
→We study the influence of the detector effects by correcting a posteriori the generated angular distribution: weights defined as $\mathbf{w^{UL(UC)}=1\pm a\bullet\cos(\phi_{gen12,0})}$ are applied to every selected pion pairs.

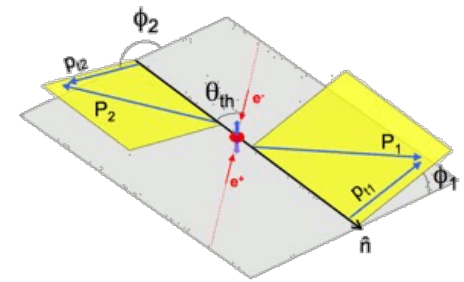



**RF12: correction performed for each bins of z and $p_t$: (1.3-2.3) as a function of z, and (1.3-3) as a function of $p_t$.**
**RF0:no correction needed.**



# RF12: Comparison of BaBar/Belle asymmetries




**BaBar (0.15<$z$<0.9)** $\int\mathcal{L}$~468 fb$^{-1}$

**Belle (0.2<$z$<1)** $\int\mathcal{L}$~547 fb$^{-1}$

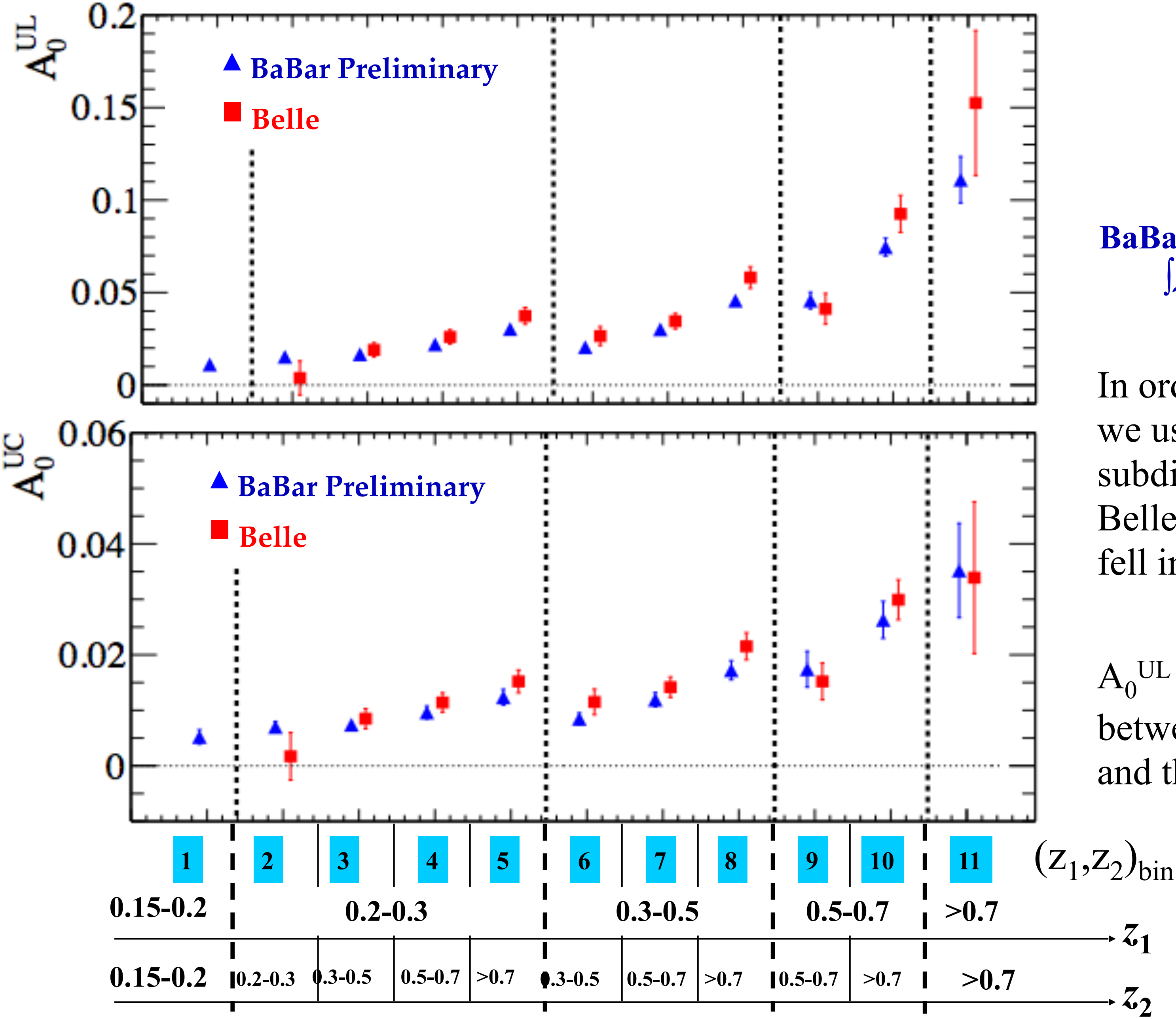
PRD 86, 039905(E) (2012)

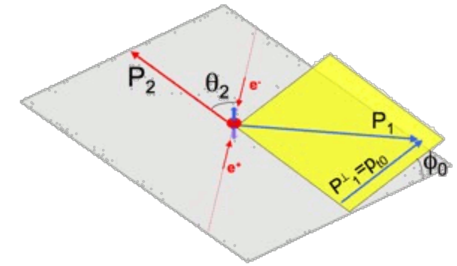
⇒ Large discrepancy in the last two bins of $z$:

- bin-by-bin correction factors (30%)
- $z$<0.9 to remove the contamination from μμγ background and exclusive events

⇒ Slightly higher at lower z

# RF0: Comparison of BaBar/Belle asymmetries




**BaBar (0.15<$z$<0.9)** $\int\mathcal{L}$~468 fb$^{-1}$

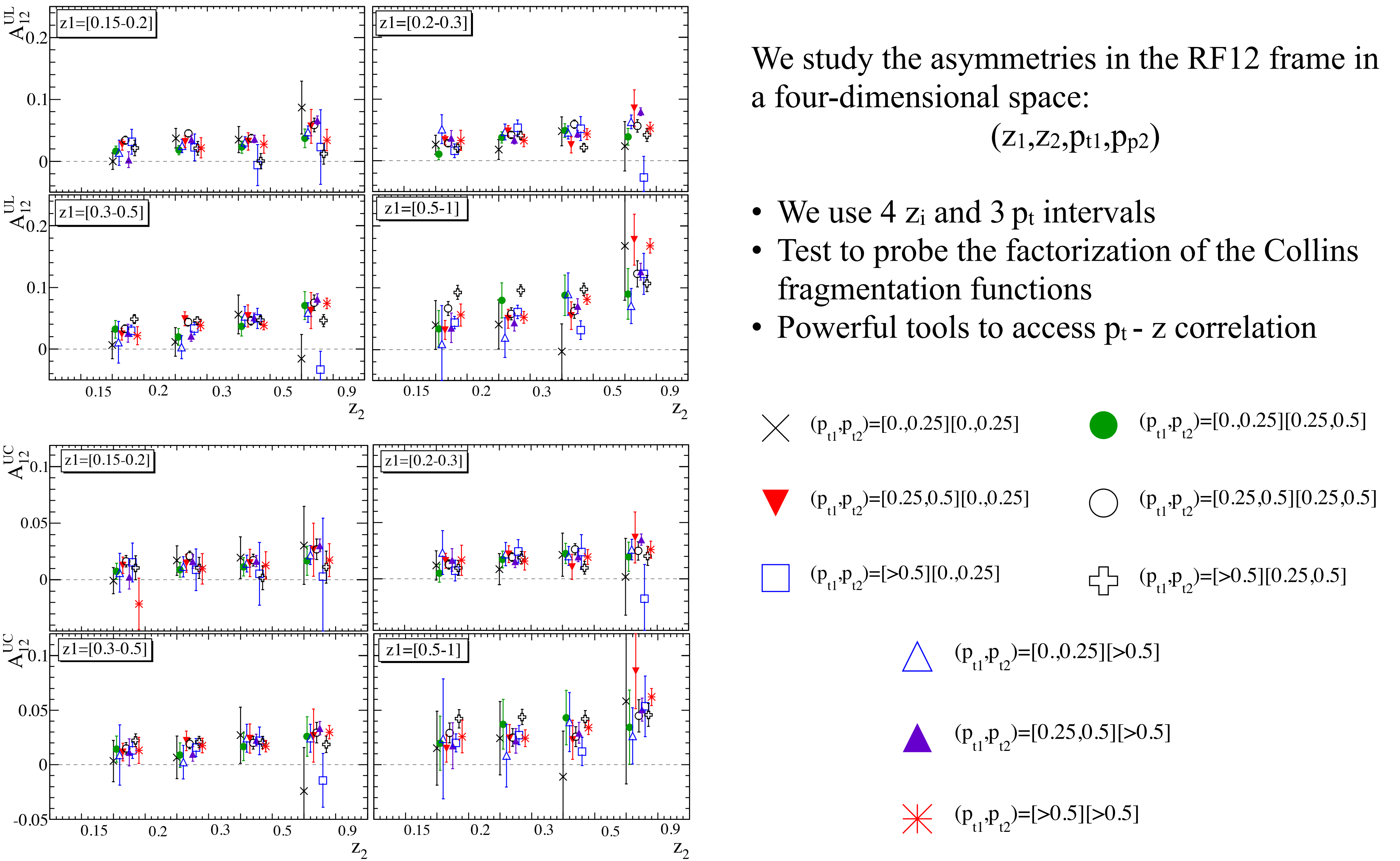
**Belle (0.2<$z$<1)** $\int\mathcal{L}$~547 fb$^{-1}$

PRD 86, 039905(E) (2012)

In order to perform this comparison, we used 10 (+1) symmetrized $z$-bin subdivisions, averaging the measured Belle and BaBar asymmetries which fell in the same symmetric bins

$A_0^{UL}$ and $A_0^{UC}$ : good agreement between the BaBar asymmetries and the Belle results.

# 4-D: asymmetry vs. $(z_1,z_2)\times(p_{t1},p_{t2})$




We study the asymmetries in the RF12 frame in a four-dimensional space:

$(z_1,z_2,p_{t1},p_{p2})$

- We use 4 $z_i$ and 3 $p_t$ intervals
- Test to probe the factorization of the Collins fragmentation functions
- Powerful tools to access $p_t$ - z correlation