Light Hadron Production @ BABAR

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OUTLINE

INTRODUCTION

- Hadron production in e^+e^- annihilation
  - Fragmentation Functions
- PEP-II and the BABAR detector at SLAC

UNPOLARIZED FRAGMENTATION FUNCTIONS

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

POLARIZED FRAGMENTATION FUNCTION

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

SUMMARY and CONCLUSIONS

Hadron production in e^+e^- annihilation

The $e^+e^- \rightarrow \gamma^*/Z \rightarrow hadrons$ process can be subdivided into four steps:

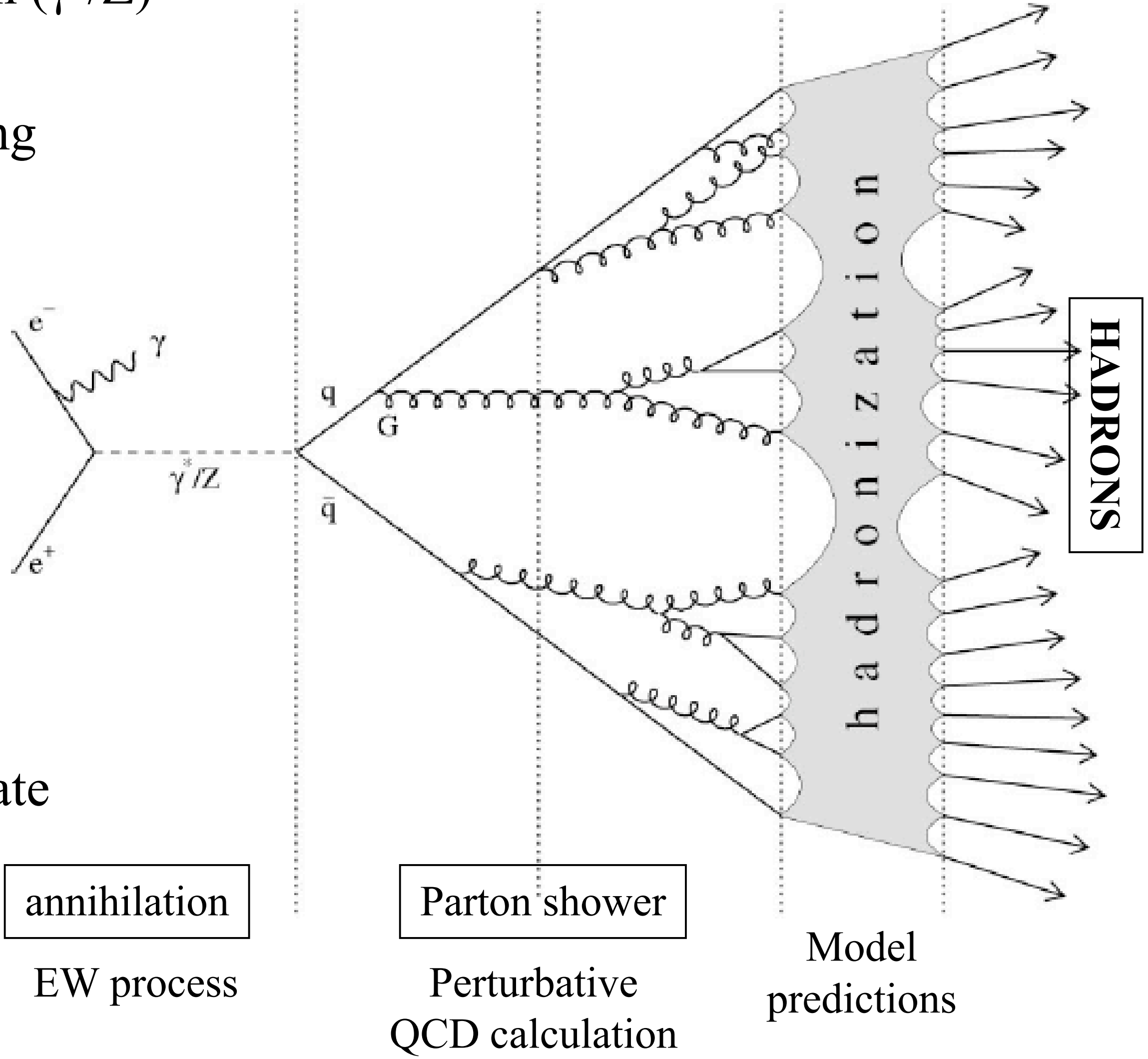
1) e^+e^- annihilate into an intermediate boson (γ^*/Z) which decays into a quark-antiquark pair

2) the radiation of gluons and gluon-splitting into $q\bar{q}$ pairs leads to a **parton shower**

3) the process of hadronization which summarizes the transition of quarks and gluons into hadrons

4) The hadrons **decay** into "stable" particles…that can be **observed** in a detector

ADVANTAGES:
- no interference between initial and final state
- 4-momentum of initial state fully transferred to the final state (no ISR)
- more e^+e^- data



annihilation

EW process

Parton shower

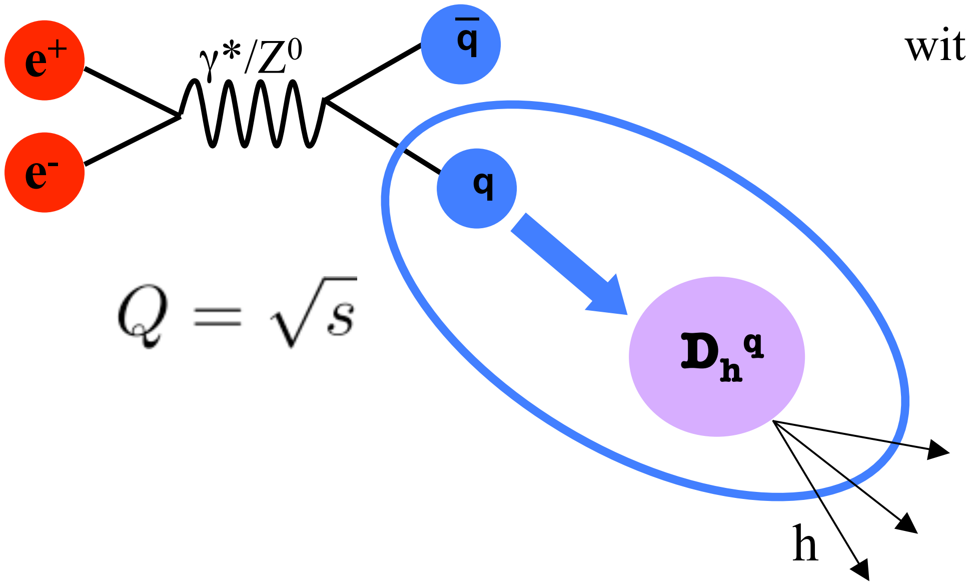
Perturbative QCD calculation

Model predictions

Fragmentation Function

Fragmentation functions (FFs) are the most important physics quantities in describing the hadron production in high energy reactions ==> they quantify the hadronization of quarks and/or gluons that occur when hadron is produced

$$e^+e^- \to \gamma/Z \to h + X \qquad \frac{1}{\sigma_0}\frac{d^2\sigma^h}{dx\,d\cos\theta} = \frac{3}{8}(1+\cos^2\theta)F_T^h + \frac{3}{4}\sin^2\theta\,F_L^h + \frac{3}{4}\cos\theta\,F_A^h$$



$$Q = \sqrt{s}$$

with $x=2E_h/\sqrt{s}$. Integrating over θ, we obtain the total FF:

$$\frac{1}{\sigma_0}\frac{d\sigma^h}{dx} = F^h(x,s) =$$

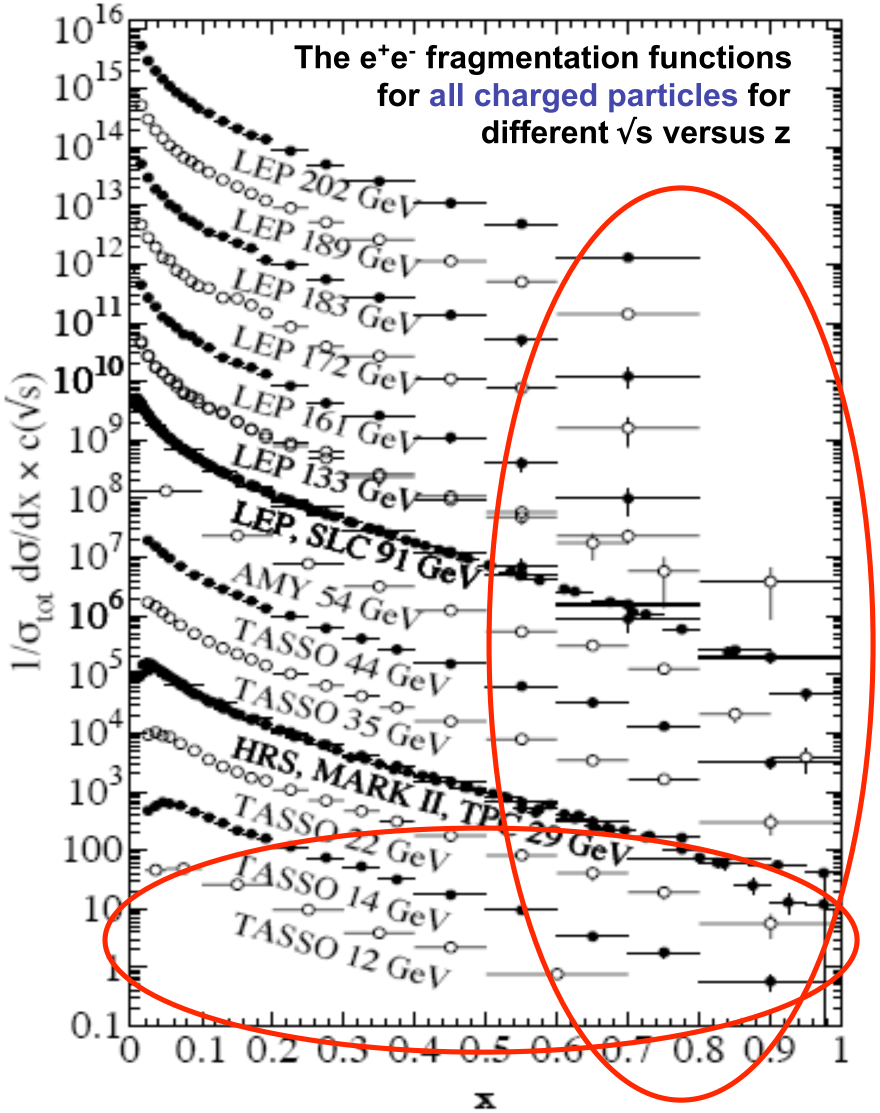
$$= \sum_i \int_x^1 \frac{dz}{z} C_i(z,\alpha_s(\mu),\frac{s}{\mu^2}) \boxed{D_i^h(\frac{x}{z},\mu^2)} + \mathcal{O}(\frac{1}{\sqrt{s}})$$

Coefficient functions; calculable in pQCD

Parton FF → non-perturbative informations

Ideally, given a (hard) parton i (i=u/ū,d/d̄,s/s̄,c/c̄,b/b̄,g), we want to find the **probability D_i^h** that it fragments into a hadron h carrying away a fraction z of the parton momentum

e^+e^- data


The e^+e^- fragmentation functions for **all charged particles** for different √s versus z

- Perturbative QCD corrections lead to logarithmic scaling violations via the evolution equations (DGLAP)
- Most of the data are obtained at the Z^0
- Measurement of both quark and antiquark fragmentation
- 3-jet fragmentation to access gluon FF difficult
- The information on how the individual q flavour 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);

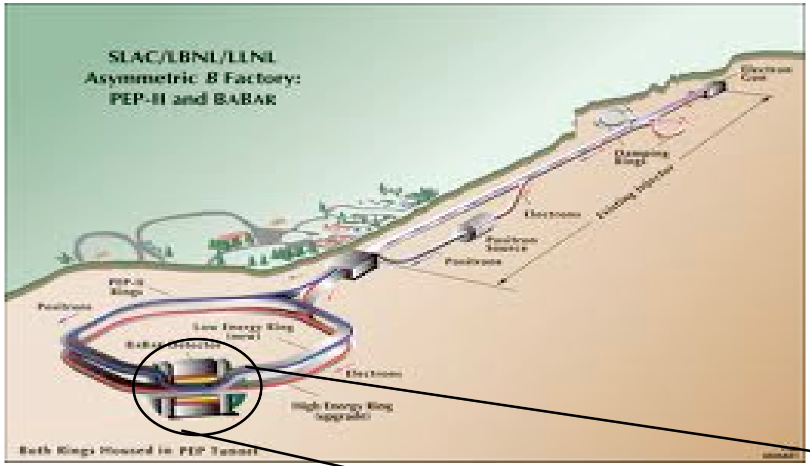
- Global analysis: e^+e^-, SIDIS, and pp

PRD 75,114010(2007), PRD 76,074033(2007), arXiv:1209.3240

➡ **Few data at high x and at low energy**

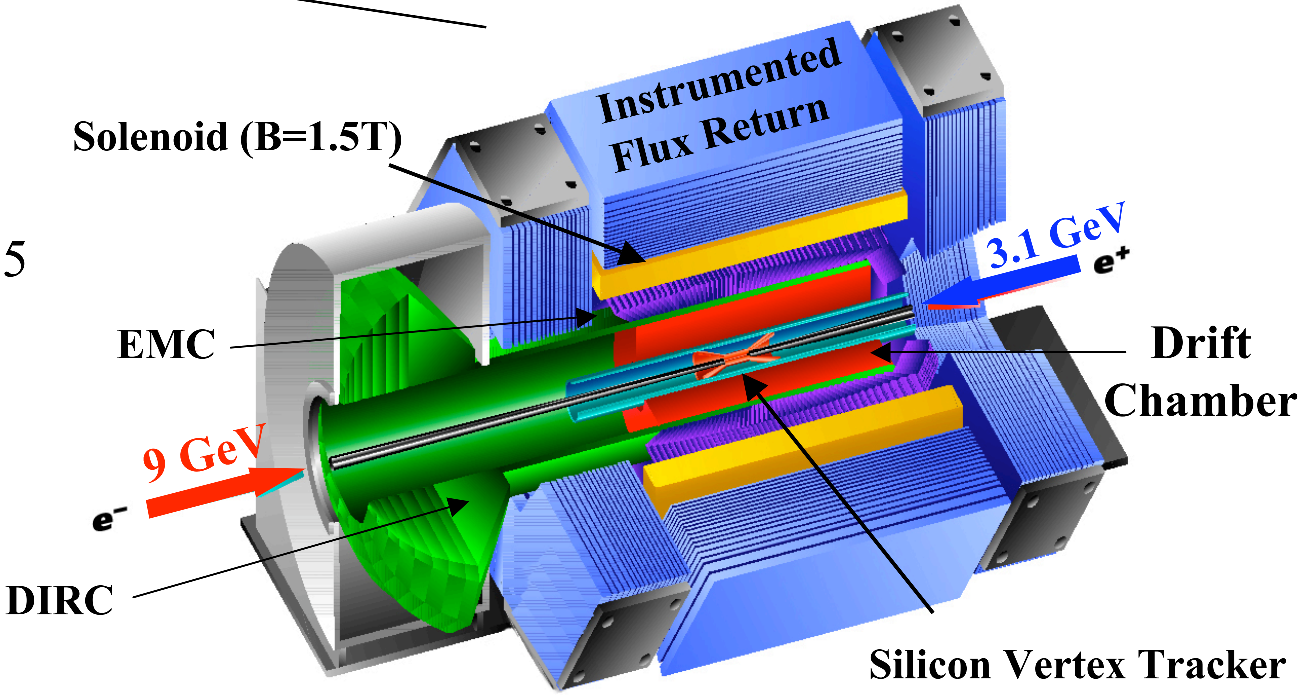
Less information for identified charged particles

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: **$\int \mathcal{L} \sim 500\ \mathrm{fb}^{-1}$**

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



Production of charged pions, kaons, and protons @ 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

- ✓ 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 1-3x10^{-11} (i.e. K^0_s and weakly decaying strange baryons)
- ✓ The uncertainties on the results are dominated by systematic contributions.

Hadronic event selection

2.2 million of events:

- 3 or more reconstructed charged-particle tracks and one good vertex (χ^2<0.01)
- Event well contained within the sensitive volume:
  - thrust axis well within DIRC detector acceptance region
  - $5 < E_{tot} < 14$ GeV
- reject leptonic events
  - Fox-Wolfram moment < 0.9
  - electron veto

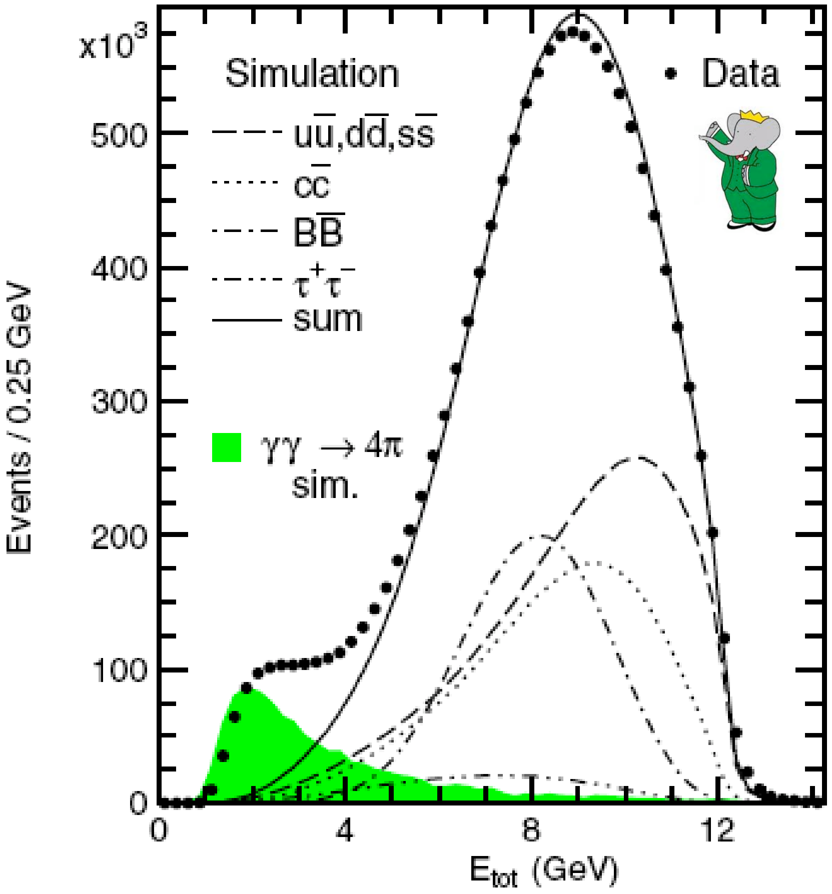
→ Consistency between data and simulation: E_{tot} distributions limit efficiency error to 0.5%

→ τ-pairs: 4% of events, but up to 20% of high-p_{lab} tracks

→ radiative Bhabhas: few % of high-p_{lab} forward/backward tracks

→ two-photon events: < 1%

→ negligible contribution from the other background sources



Charged hadron identification

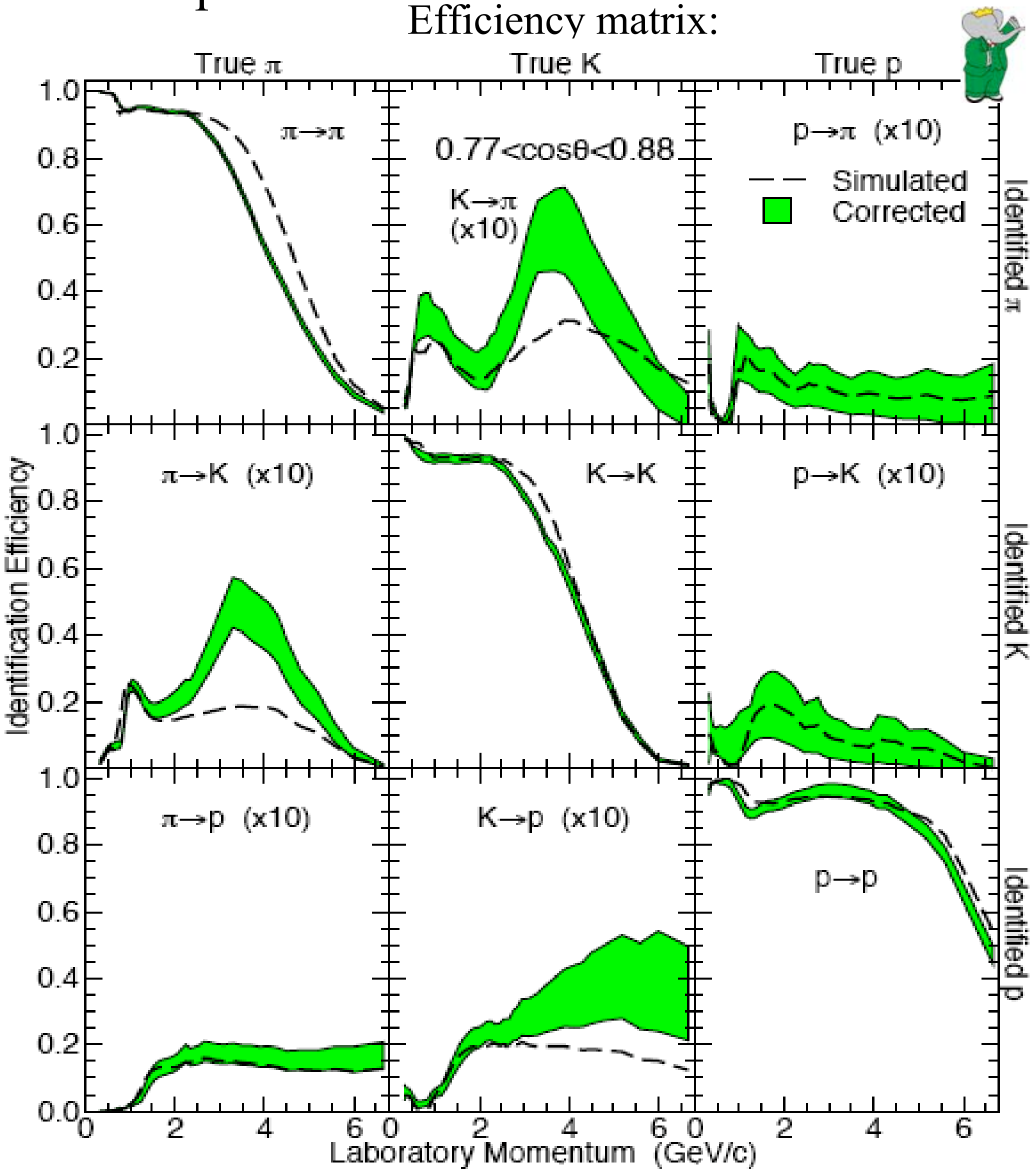
- Well-reconstructed tracks from the primary interaction point
- Excellent identification of $\pi^{\pm}$, $K^{\pm}$, and $p/\bar{p}$

  ⇒ 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

Efficiency matrix:

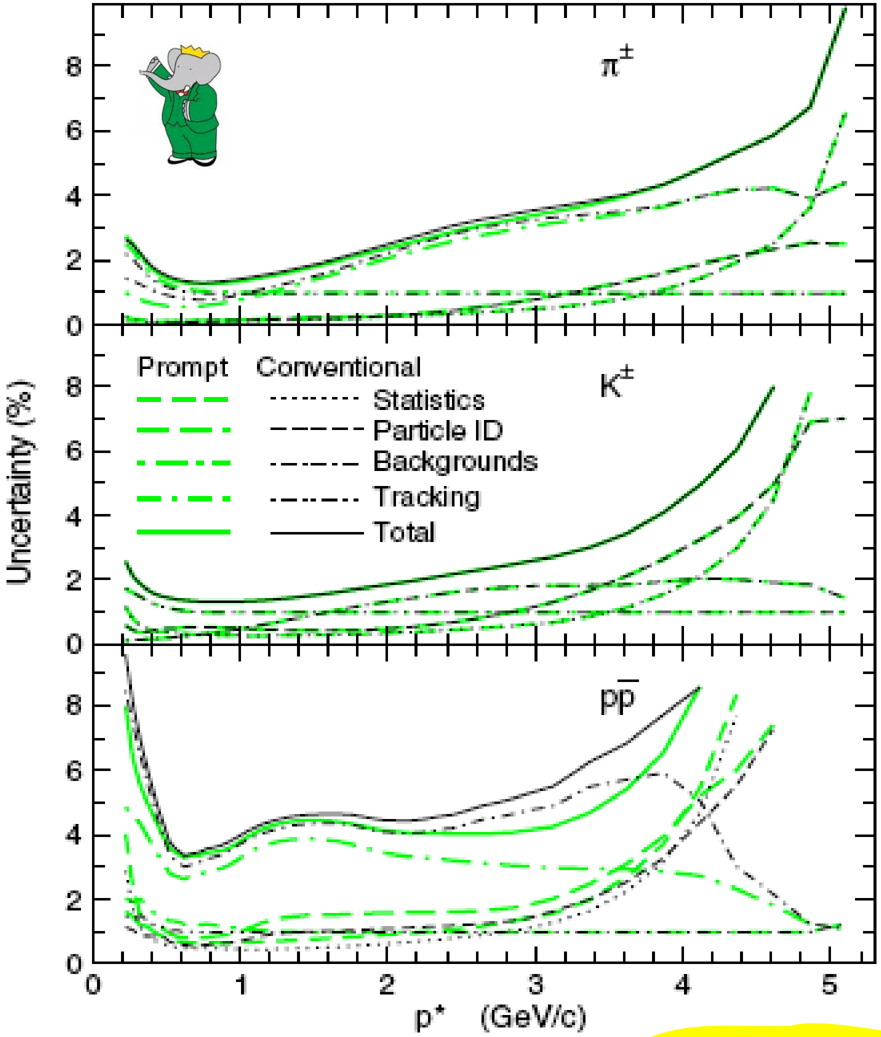


Differential cross section measurements

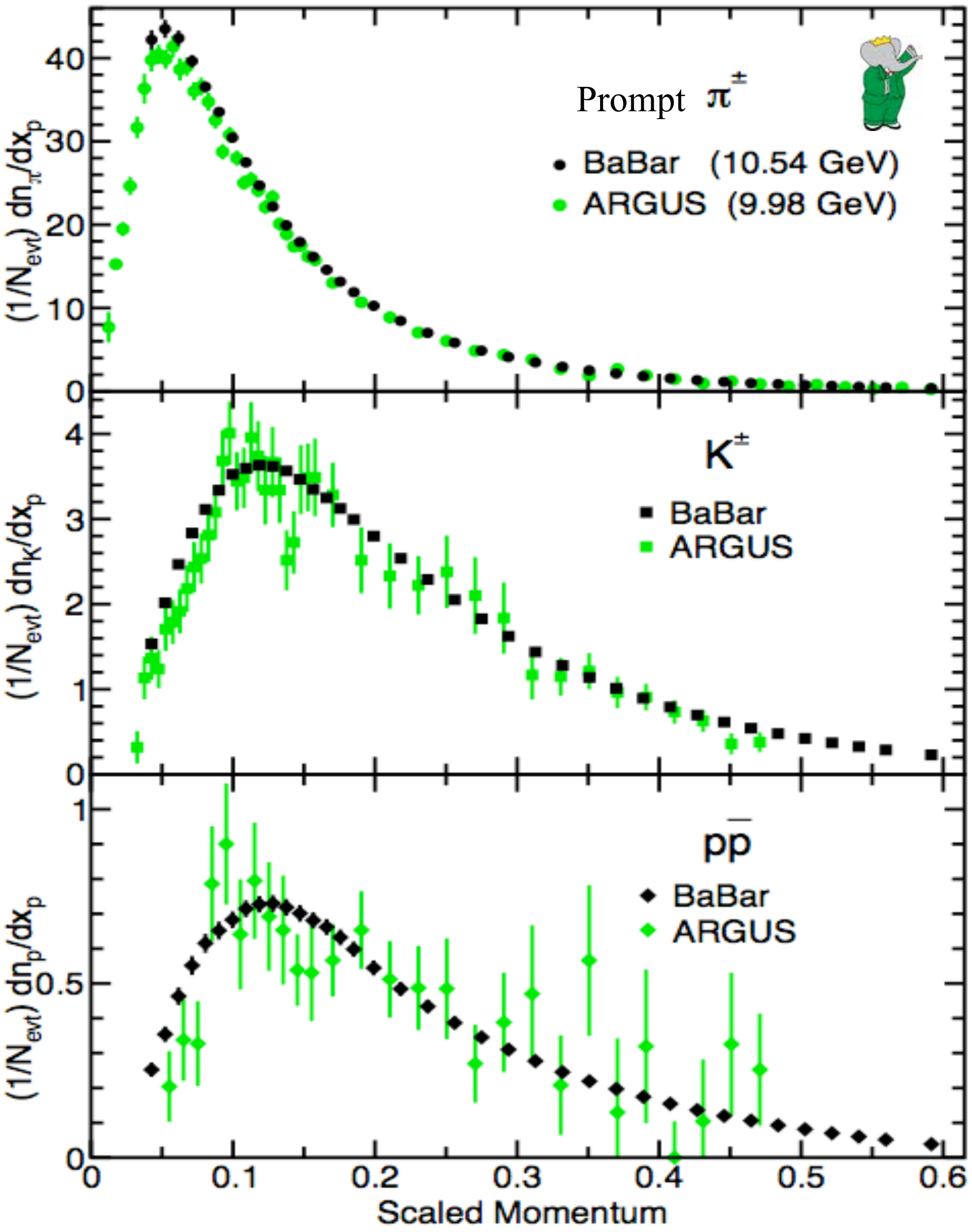
- We use E_{ij} to construct the raw production rates $(1/N_{evt}^{sel})(dn_i/dp_{lab})$, defined as the number reconstructed particles per selected event per unit momentum in the lab frame
  - we count $n_j = n\sum_i E_{ij} f_i$, and calculate f_i , the true fraction of tracks of type i

- Correct these spectra for
  - **physics background** (mostly $\tau^+\tau^-$) and normalize by the estimated number of hadronic events in the selected sample
  - interaction in the detector material (up to 4% at low momentum)
  - **track and event selection efficiencies, 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 uncertainties from particle identification, backgrounds, and tracking efficiencies



Cross section results



- **Cross section results 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

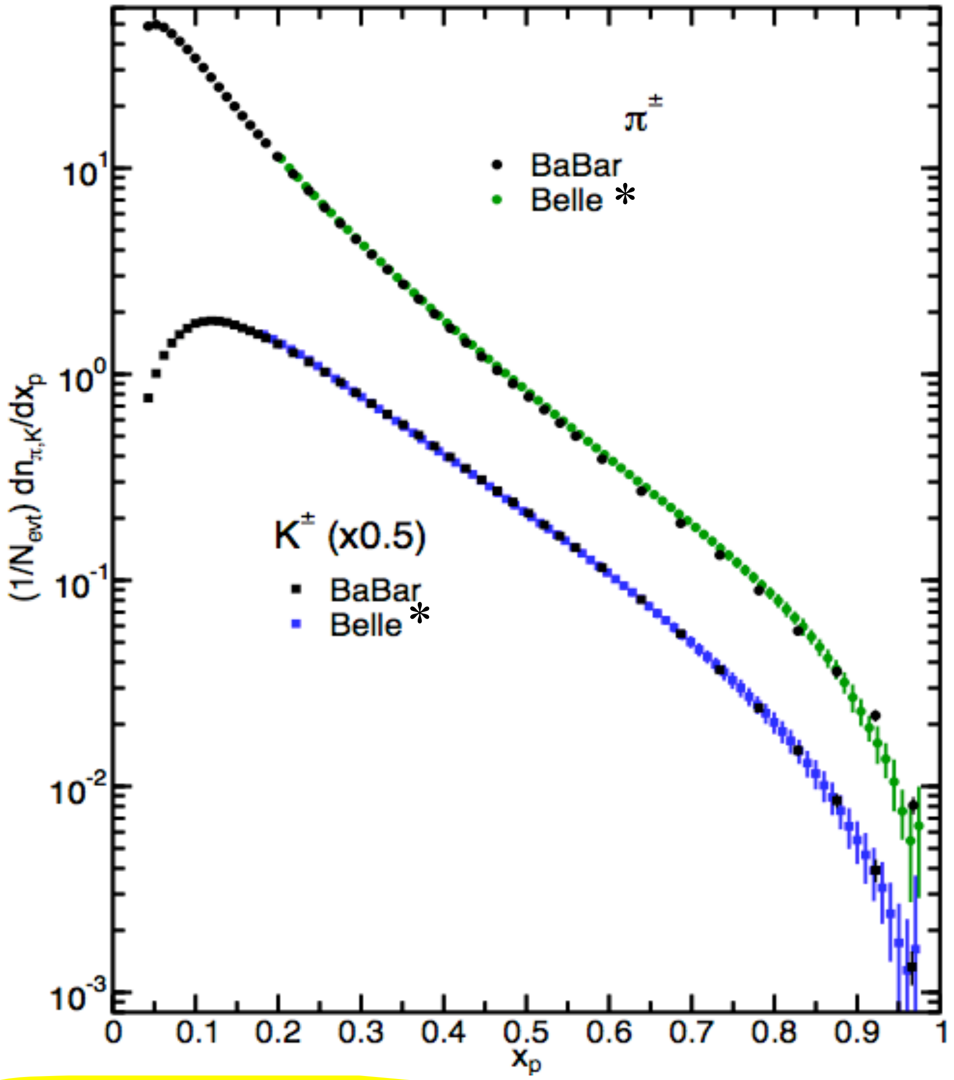
- **Compare nicely with previous data from ARGUS[1]**
  - consistent everywhere for $x_p>0.1$
  - mass driven scaling violation for $x_p<0.1$: ARGUS data systematically below
  - BABAR more precise
  - BABAR better coverage at high x_p
  - ARGUS extends to low momentum for π± → complementary information

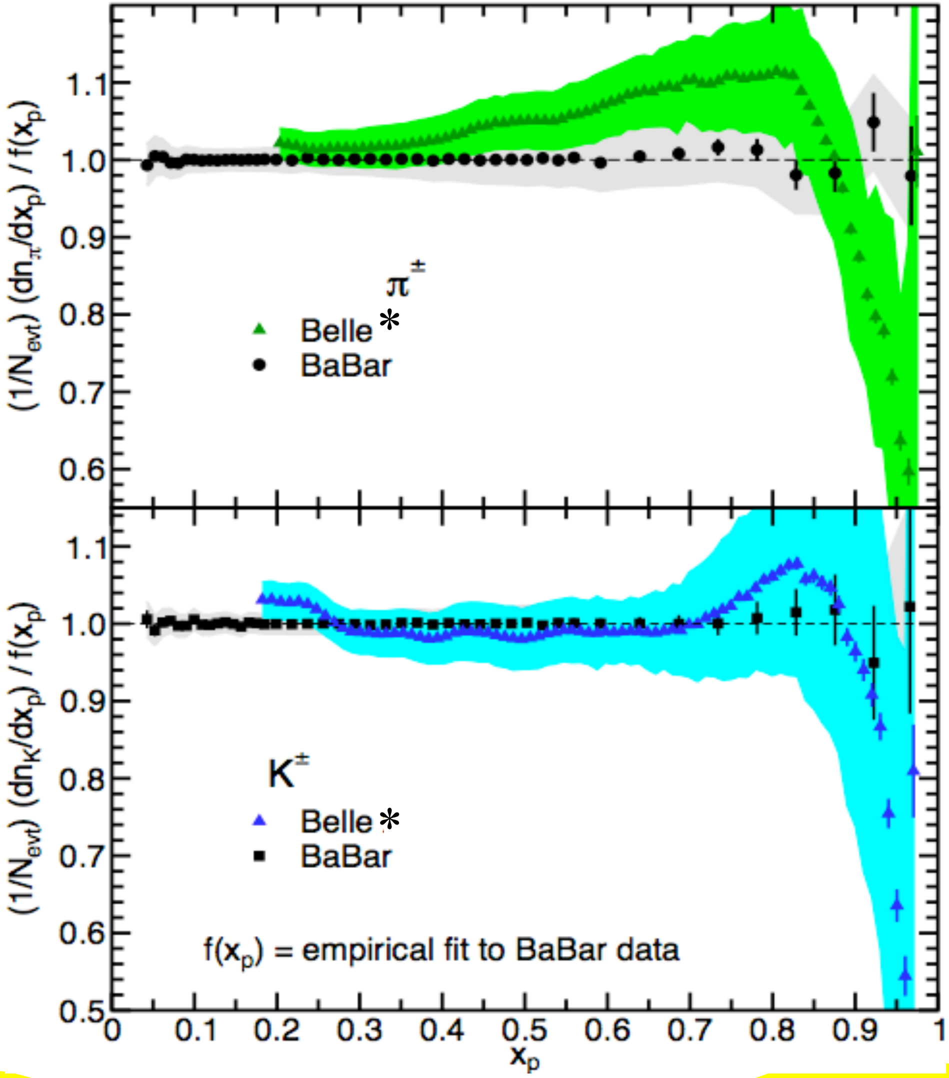
[1] H. Albrecht *et al.* (ARGUS Collaboration) Z. Phys. C **44**, 547 (1989).

BaBar/Belle comparison

- Belle have measured differential cross section *dσ/dz* [PRL **111**, 062002 (2013)]
  - we renormalize arbitrarily to compare the shapes

Courtesy of David Muller



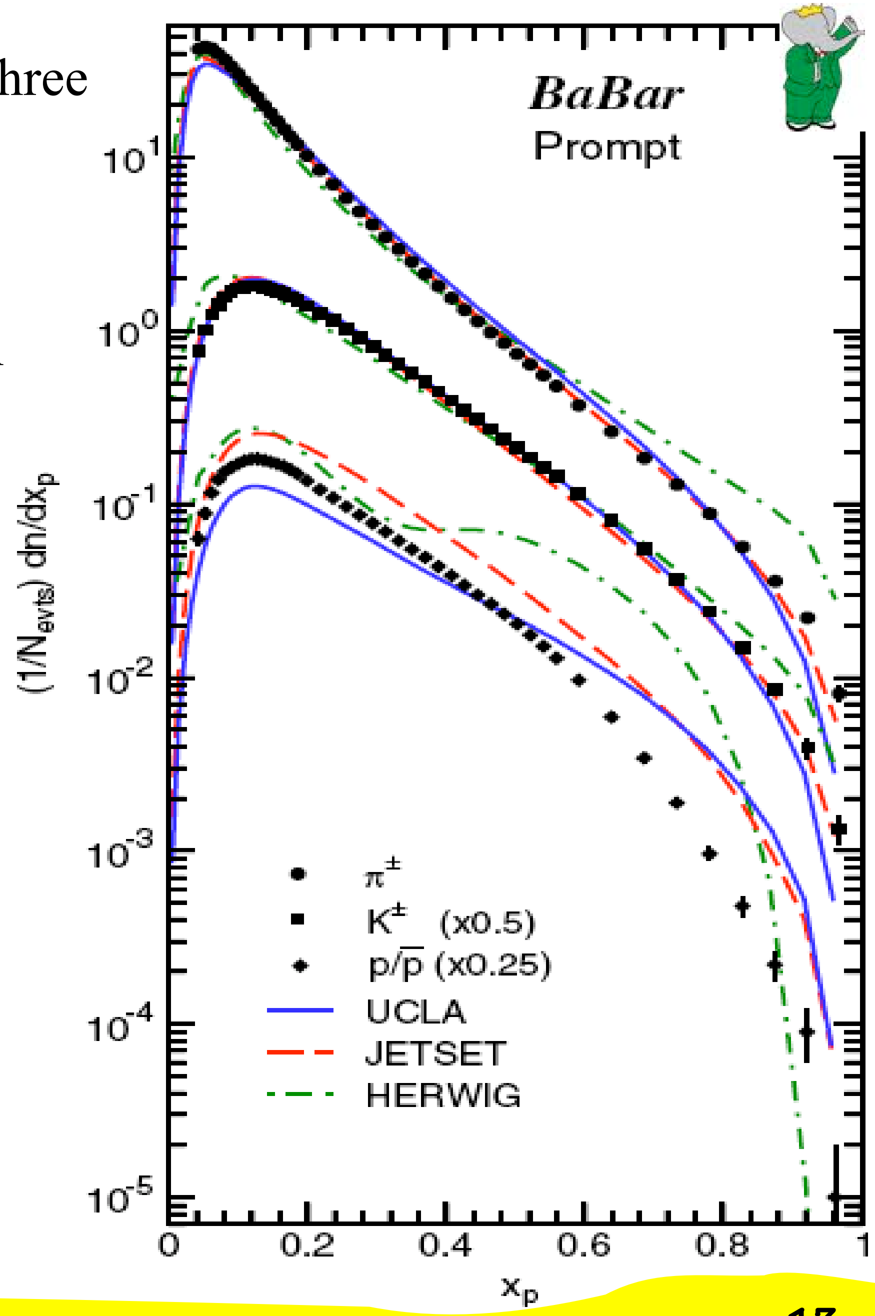


Comparison with hadronization models

We compare our cross section with the predictions of three hadronization models: **JETSET, HERWIG, UCLA**:

- each model contains free parameters controlling various aspects of the hadronization process
- many parameters for JETSET ⇒ model many hadron species in detail
- few free parameters for UCLA and HERWIG ⇒ global description

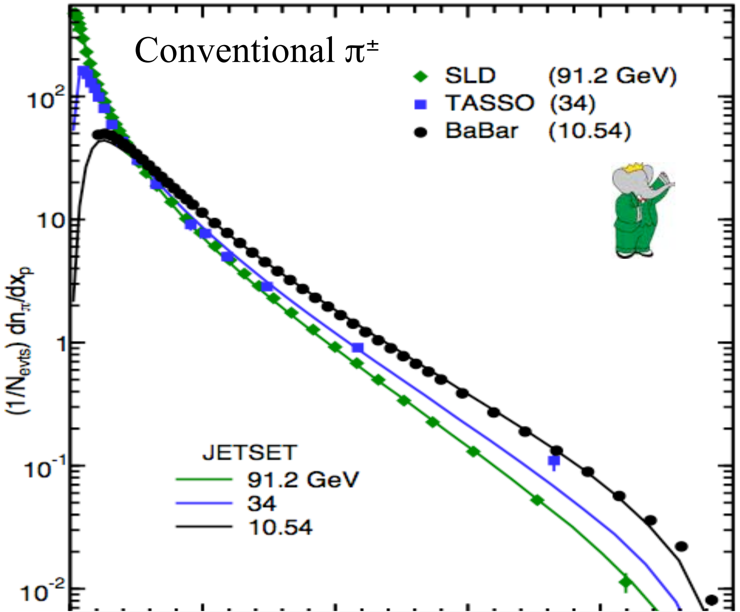
- **Default parameters used** (based on previous data: higher energies plus ARGUS data)
- **Large discrepancies in general**
  - all the models qualitatively describe the bulk of the spectra
  - no model describes any spectrum in detail
- **Peak positions consistent with data** (except for the HERWIG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

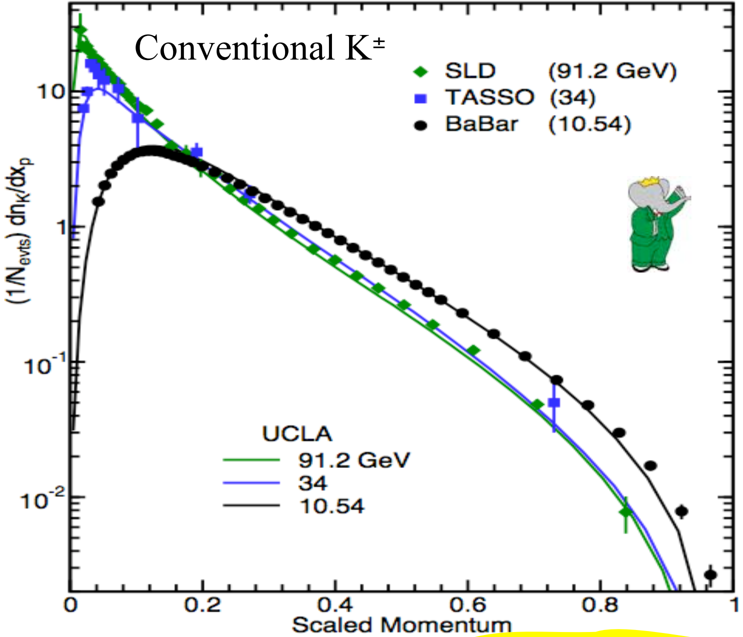


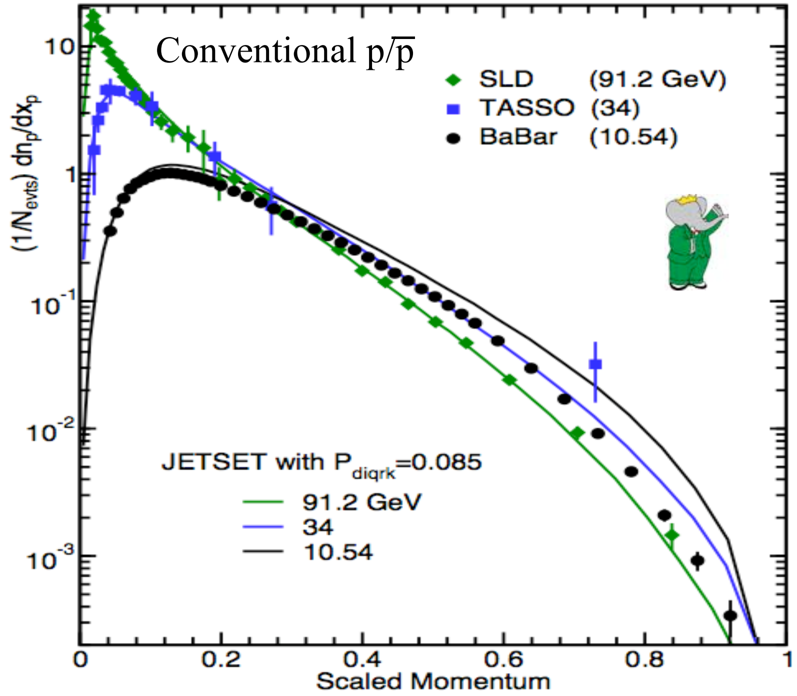
Scaling Properties

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

- **Strong scaling violation** at **high x_p** (running of α_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







- $p/\overline{p}$: 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 $x_p=0.8$

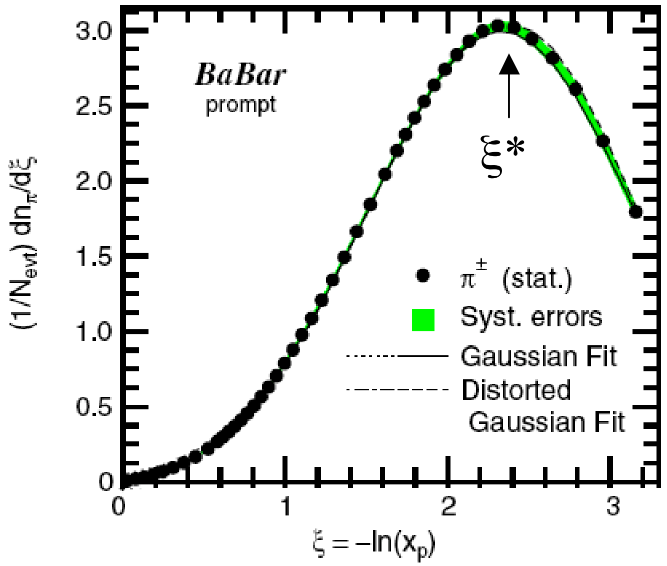
Is there something missing?

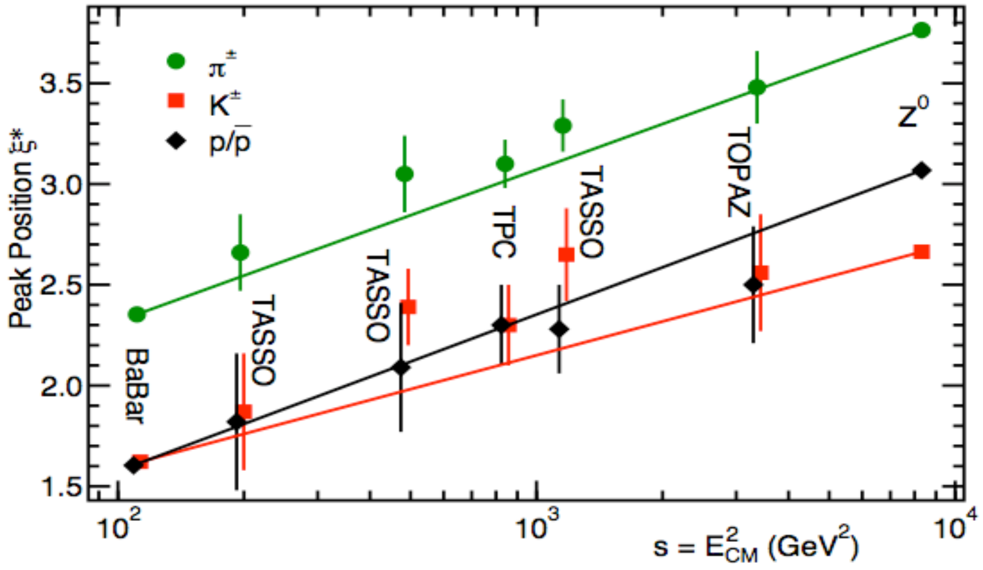
Test of MLLA+LPHD QCD

Transform our cross section into the variable ξ=-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 ξ^* 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}

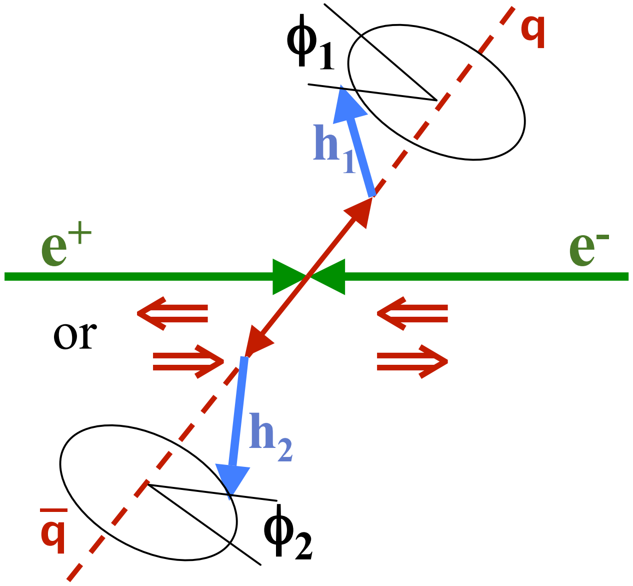
Inclusive production of charged pion pairs

Collins Fragmentation Function @ BABAR

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

- ✓ Preliminary results ⇒SUBMITTED TO PRD (**arXiv:1309.5278**)
- ✓ Data samples used: 468 fb^{-1} at E_{CM}~10.58 GeV

Collins Fragmentation Function



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

"Standard" unpolarized FF

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

- **$H_1^\perp$** 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

$$e^+e^-\rightarrow q\bar{q}\rightarrow \pi_1\pi_2 X\ \ (q=u,\,d,\,s) \Longrightarrow \sigma\propto\cos(\phi_i)H_1^\perp(z_1)\otimes H_1^\perp(z_2),$$

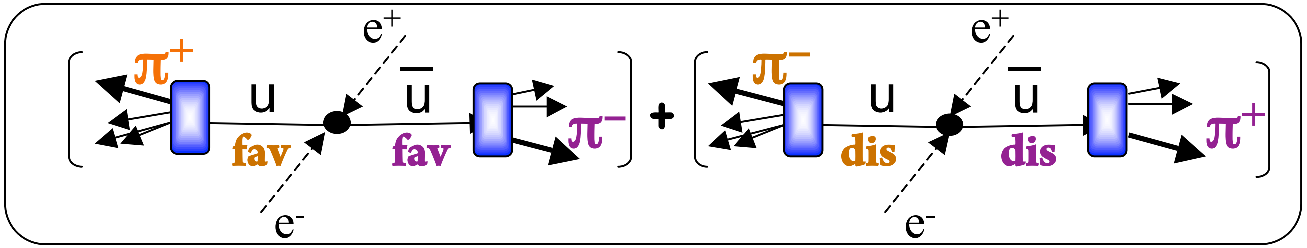
Favored and Disfavored processes

$e^+e^-\rightarrow q\bar{q}\rightarrow \pi_1^\pm\pi_2^\pm X$ ($q\bar{q}=u\bar{u}, d\bar{d}, s\bar{s}$)

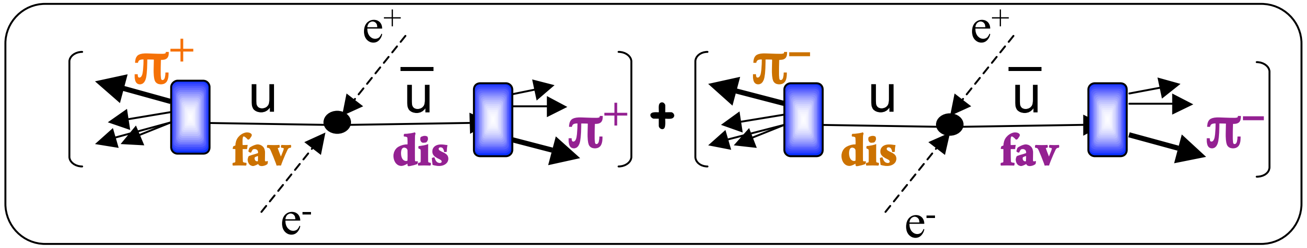
Different combinations of charged pions ⇒ sensitivity to **favored** or **disfavored** FFs

- **favored** fragmentation process describes the 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 $s\rightarrow\pi^\pm$

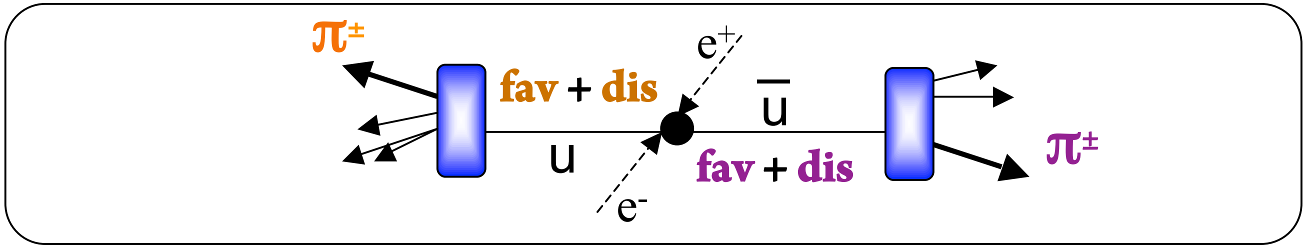
Unlike-sign pion pair = **U:**
$\pi^\mp\pi^\pm$: (fav x fav)+(dis x dis)



Like-sign pion pair = **L:**
$\pi^\pm\pi^\pm$: (fav x dis)+(dis x fav)

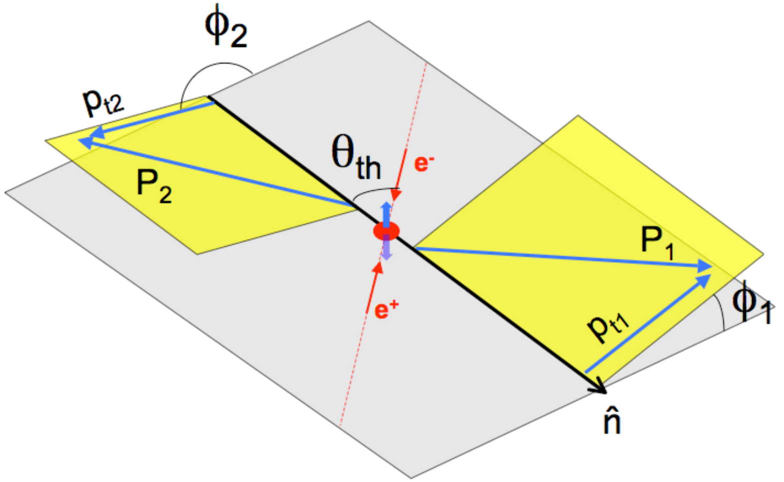


Charged pion pair = **C (U+L):**
ππ: (fav + dis)x(fav + dis)
$\pi=\pi^\pm$



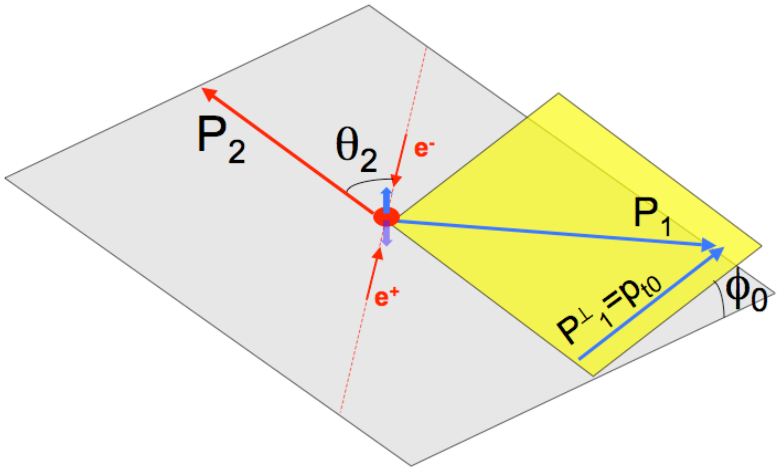
Analysis Reference Frame (RF)

RF12 or Thrust RF



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

RF0 or Second hadron RF



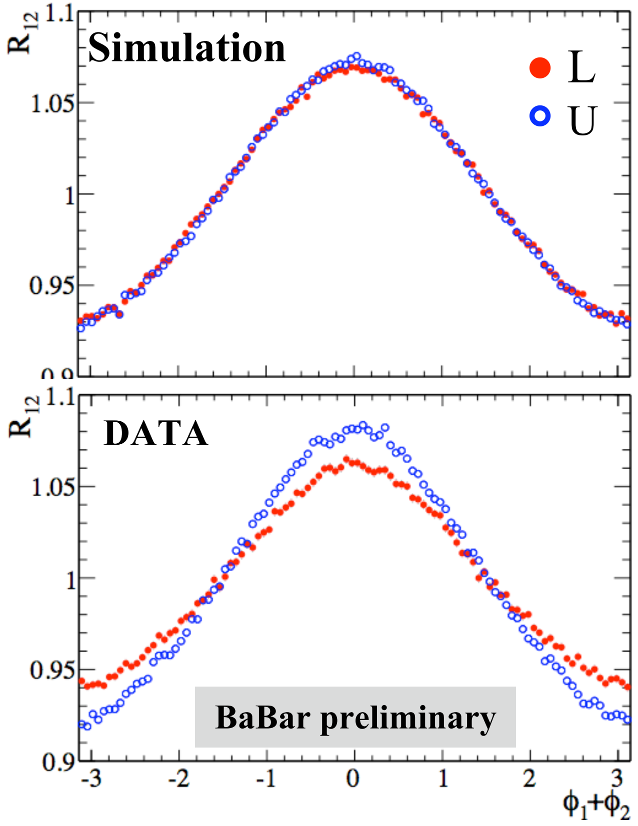
$$\sigma \sim 1 + \frac{\sin^2\theta_2}{1+\cos^2\theta_2} \cos(2\phi_0) \mathcal{F}\left[\frac{H_1^\perp(z_1)\bar{H}_1^\perp(z_2)}{D_1(z_1)\bar{D}_1(z_2)}\right]$$

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

[See NPB 806, 23 (2009)]

- Selection of hadronic events:
  -number of well-reconstructed charged tracks > 2 from the interaction point
- Selection of two-jet topology events: **thrust>0.8**
- Selection of pions in the detector acceptance region: $0.41<\theta_{lab}<2.54$ rad
- Pion fractional energies: **$0.15<z=2E_h/\sqrt{s}<0.9$**

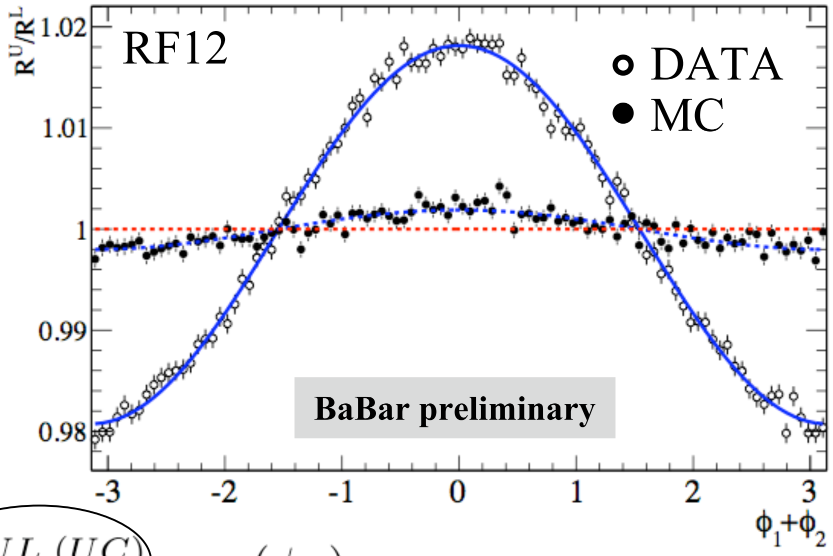
Raw asymmetries and double ratios



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

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

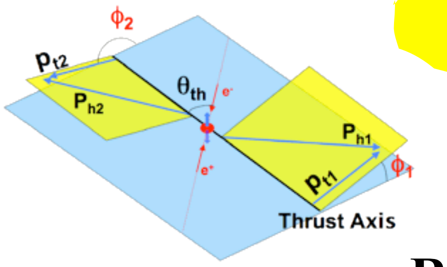
Asymmetry binning and corrections

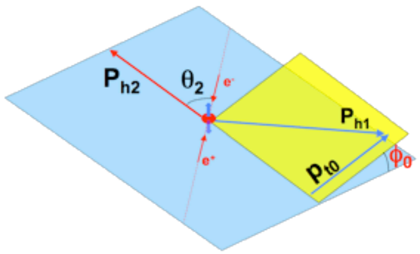
- The Collins effect is expected to depend on z_1, z_2, p_{t1}, p_{t2} (or p_{t0}), as well as $\cos\theta_{th}$ (or $\cos\theta_2$)
  ⇒ analyze in bins of these quantities
- Simulated asymmetries also depend on these quantities →must correct in each bin independently
  ⇒ Systematic on MC value evaluated 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
- Contribution of background events to the asymmetries:
  - $B\bar{B}$ events (very small, mostly at low z)
  - $\tau^+\tau^-$ events (small, important only at high z)
  - $c\bar{c}$ events (important at low/medium z) ==> contribution of about 30% on average
    - We used a **$D^{*\pm}$-enhanced control sample** to estimate its effect

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

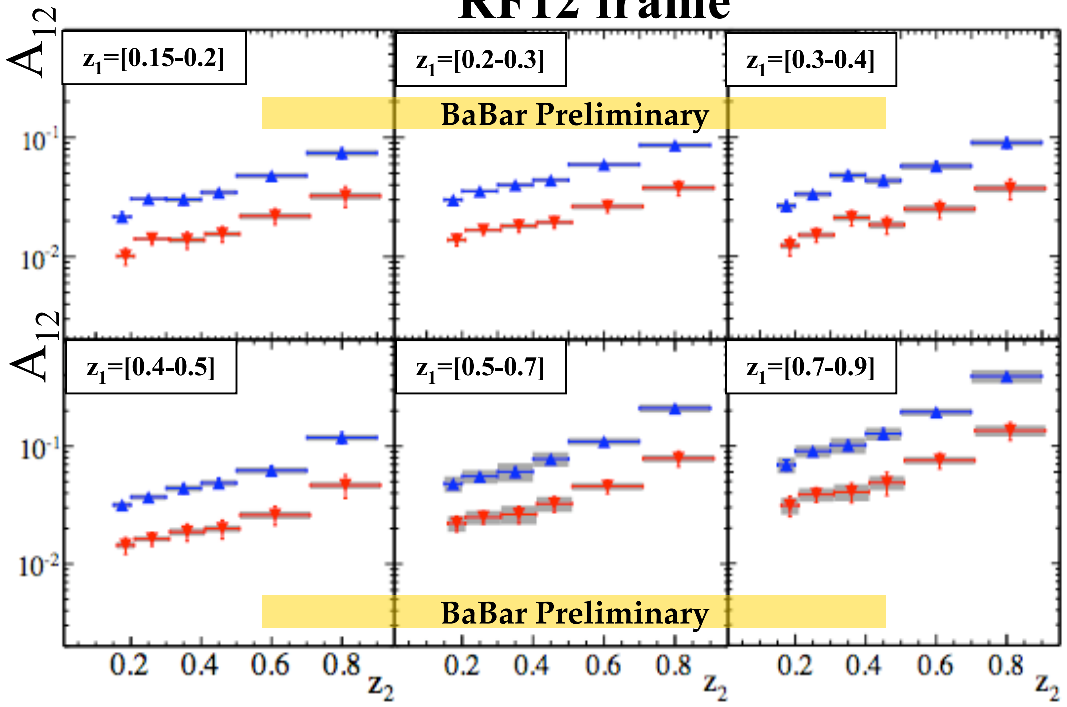
- F_i using MC samples
- $A^{B\bar{B}} = 0$
- A^τ small in simulation; checked in data; we set $A^\tau = 0$

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

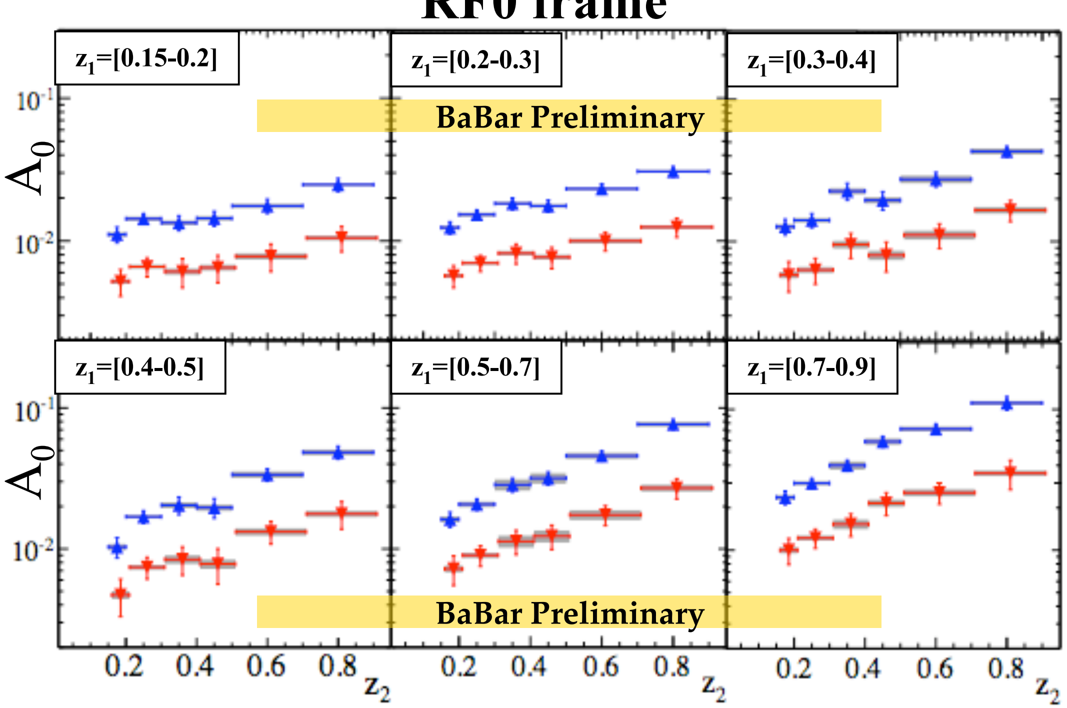




RF12 frame



RF0 frame



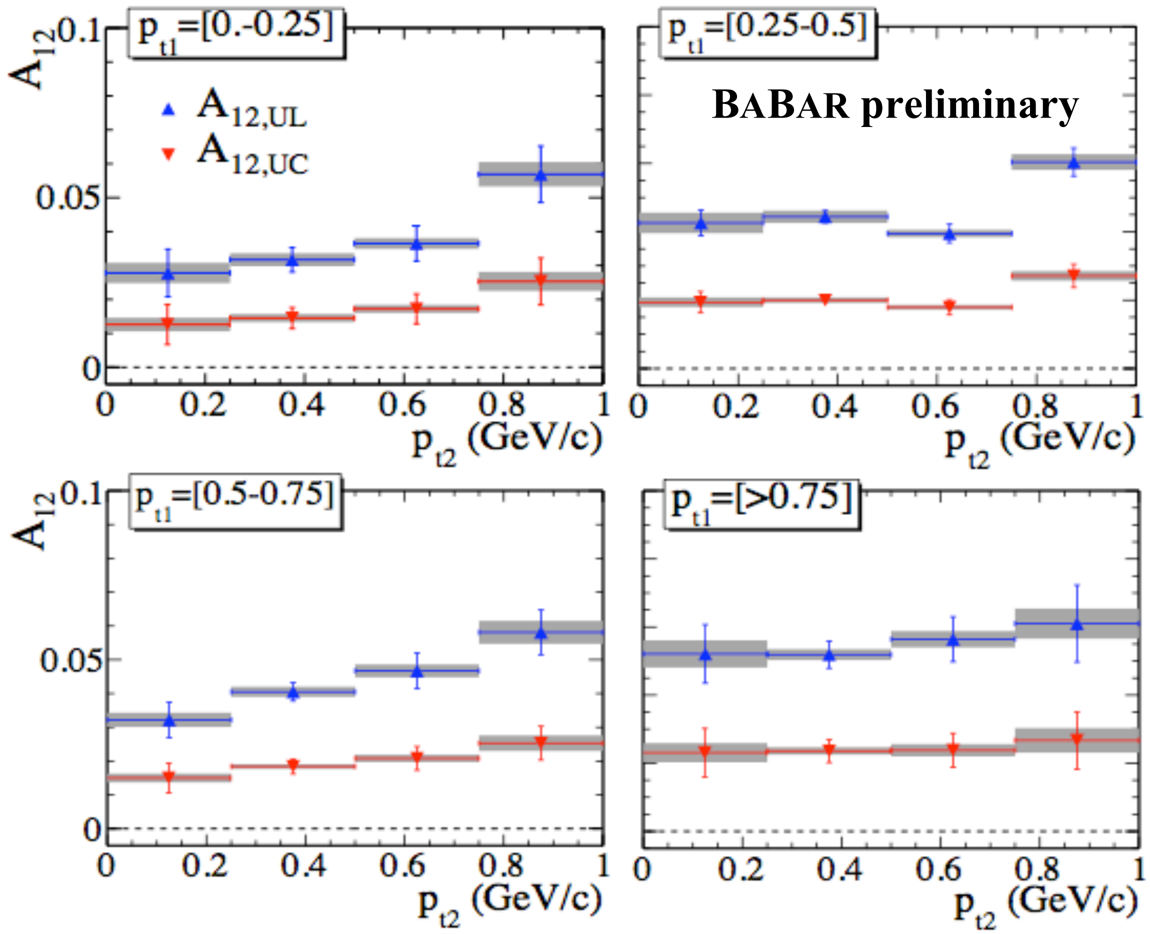
- **Very significant non-zero A^{UL} and A^{UC} in all bins**

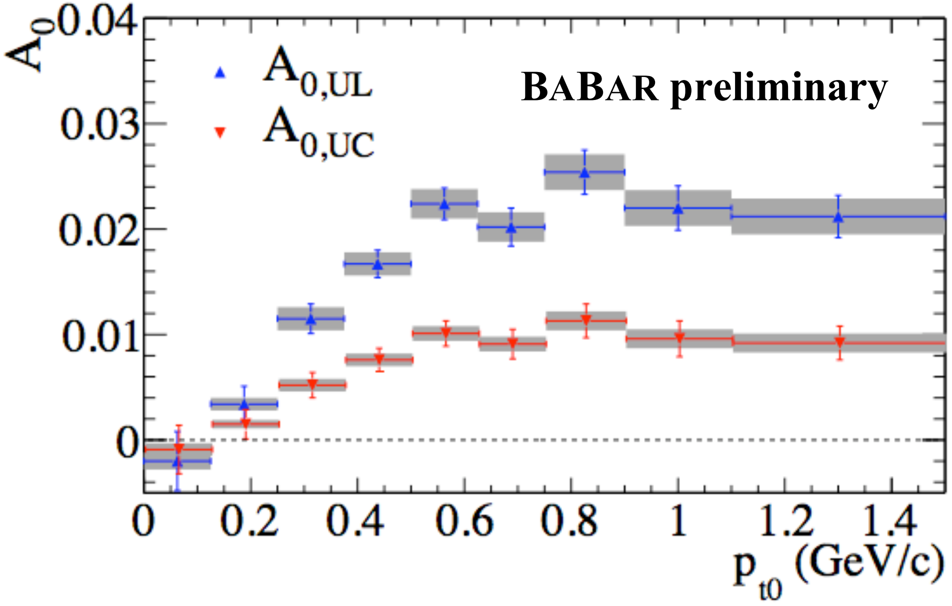
  ⇒ strong dependence on (z_1,z_2): A_{12}~1-39%, A_0~0.5-11%

  ⇒ $A^{UC} < A^{UL}$ 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}





FIRST MEASUREMENT of Collins asymmetries *vs.* p_t in e^+e^- annihilation at Q^2~110 $(GeV/c)^2$

- **non-zero A^{UL} and A^{UC}**
  - ⇒ only modest dependence on (p_{t1},p_{t2}); disagreement with the expectation ???
  - ⇒ $A^{UC} < A^{UL}$; complementary information on $H_1^{\perp,\,fav}$ and $H_1^{\perp,\,dis}$
  - ⇒ $A_0 < A_{12}$, but interesting structure in p_t

Summary and conclusions

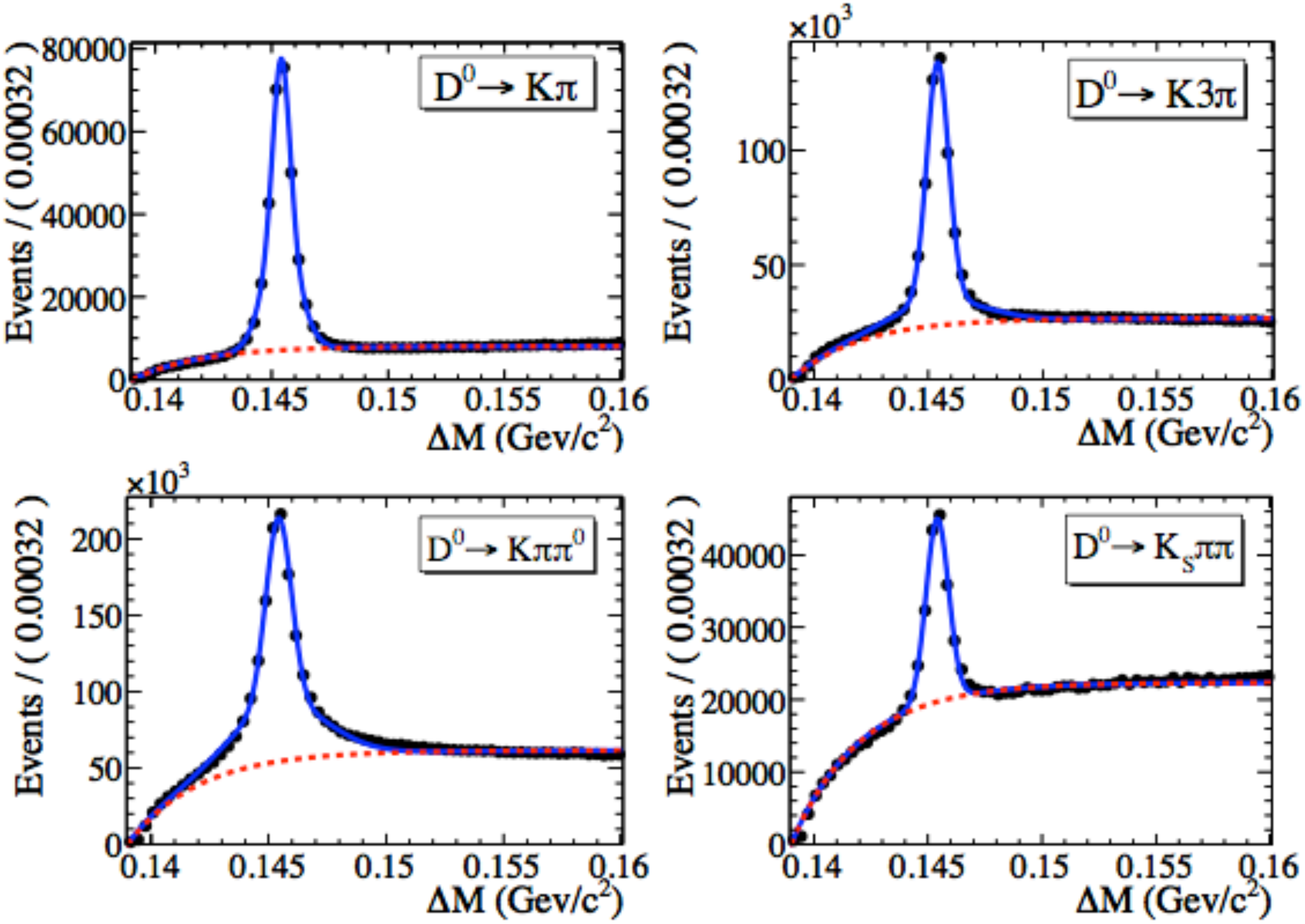
- Measurement of the inclusive spectra for $\pi^{\pm}$, $K^{\pm}$, and $p/\bar{p}$ hadrons in e^+e^- annihilation at the center of mass energy of 10.54 GeV at BABAR (PRD 88,032011(2013))
  - precise data at high x_p
  - consistent with ARGUS data
  - shape consistent with Belle results
  - Scaling properties:
    - no models predict the correct scaling properties for protons

- Collins effect for light quarks (uds) in two different reference frames (RF12 and RF0)
  - submitted to PRD (arXiv:1309.5278)
  - A_{12} and A_0 increase with increasing z_1, z_2
    - consistent with theoretical expectations
    - general agreement with Belle results (PRD 86, 039905(E) (2012))
  - A_{12} (A_0) increases with p_{t1}, p_{t2} (p_{t0}) for $0<p_t< 1$ GeV/c
    - first measurement in e^+e^- annihilation at $Q^2 \sim 110$ $(\mathrm{GeV}/c)^2$
    - important for understanding the evolution of the fragmentation function

Thanks for your attention

BACKUP SLIDES

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



$D^{*\pm} \to D^0\pi^{\pm}$, $D^0 \to K\pi$ (mode 1)

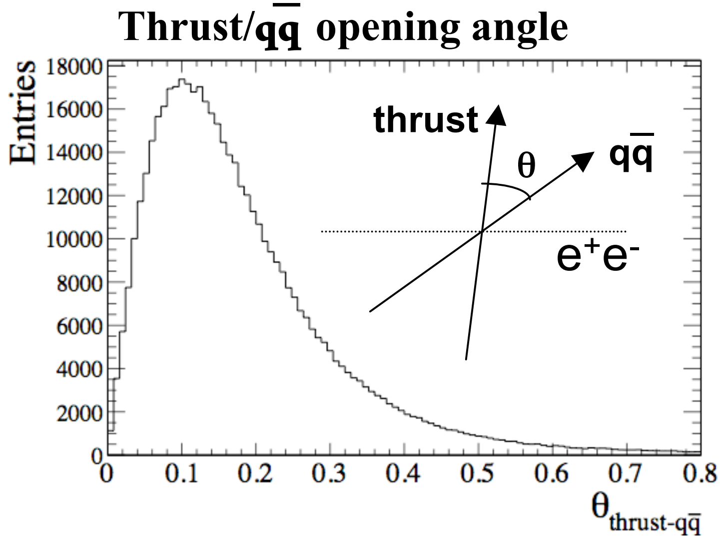
$D^0 \to K3\pi$ (mode 2)

$D^0 \to K\pi\pi^0$ (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


Thrust/$q\bar{q}$ opening angle

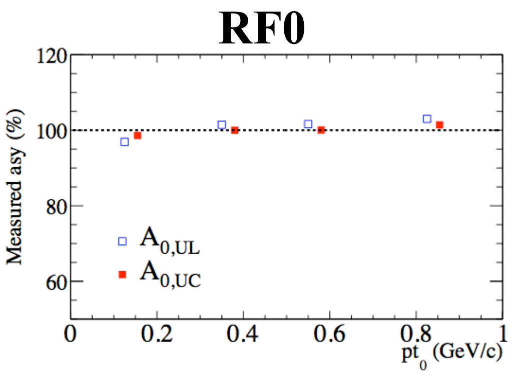
The experimental method assumes the thrust axis as **$q\bar{q}$** direction**:** this is only a rough approximation

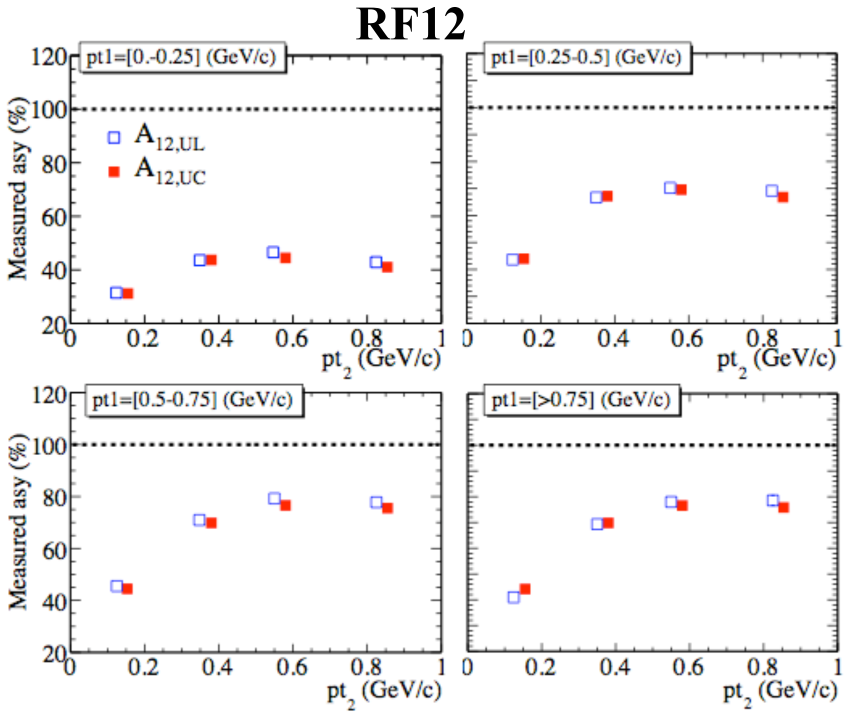
RF12: large smearing since the azimuthal angles ϕ_1 and ϕ_2 are calculated with respect to the thrust axis; additional dilution due to very energetic tracks close to the thrust axis.

RF0: the azimuthal angle ϕ_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 **$w^{UL(UC)}=1\pm a\bullet\cos(\phi_{gen12,0})$** 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.

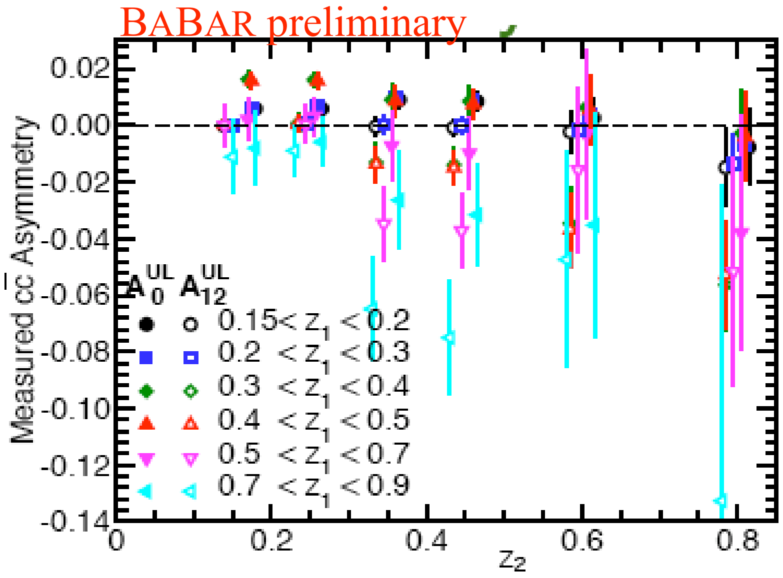

RF0

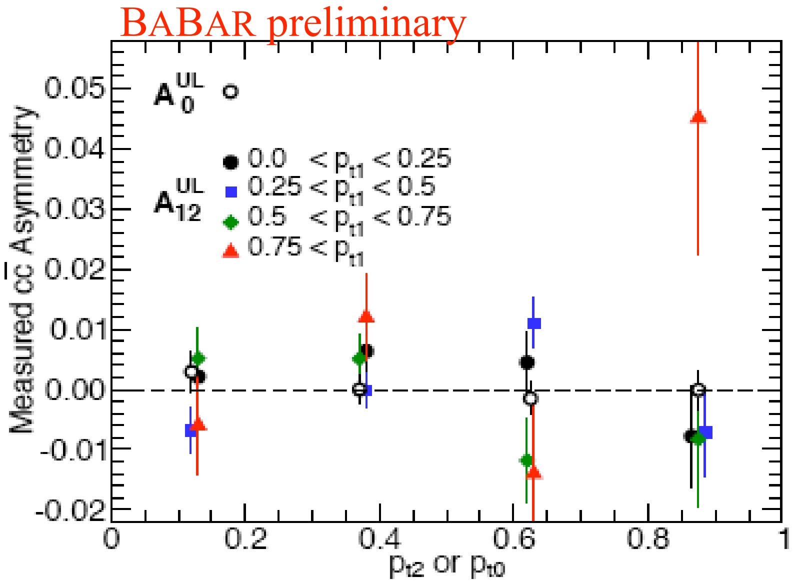

RF12

Extraction of the uds asymmetry

- Charm background contribution is about 30% on average
  - Both fragmentation processes and weak decays can introduce azimuthal asymmetries
  - We used a **D*±-enhanced control sample** to estimate its effect on a **bin-by-bin basis**
  - 4 complementary decay modes $D^{*\pm} \rightarrow D^0\pi^\pm$, with $D^0 \rightarrow K\pi, K3\pi, K\pi\pi^0, K_s\pi\pi$
  - mostly $c\bar{c}$ events, some $B\bar{B}$
- Again, f_i from MC, data-MC difference as systematic error

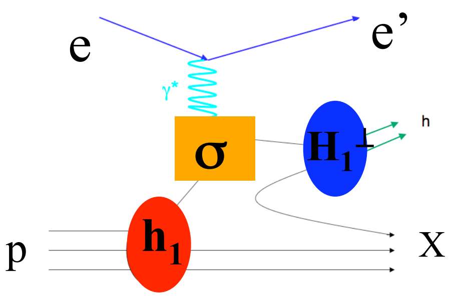
$$
\begin{aligned}
A_\alpha^{meas} &= (1 - F_c - F_B - F_\tau) \cdot A_\alpha + F_c \cdot A_\alpha^{ch} \\
A_\alpha^{D^*} &= f_c \cdot A_\alpha^{ch} + (1 - f_c - f_B) \cdot A_\alpha
\end{aligned}
$$





- the A^{ch} are very small (slightly negative?)

Extraction of Collins FF from data

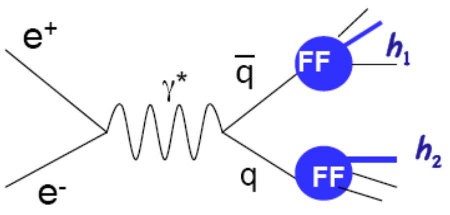


SIDIS

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

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

+



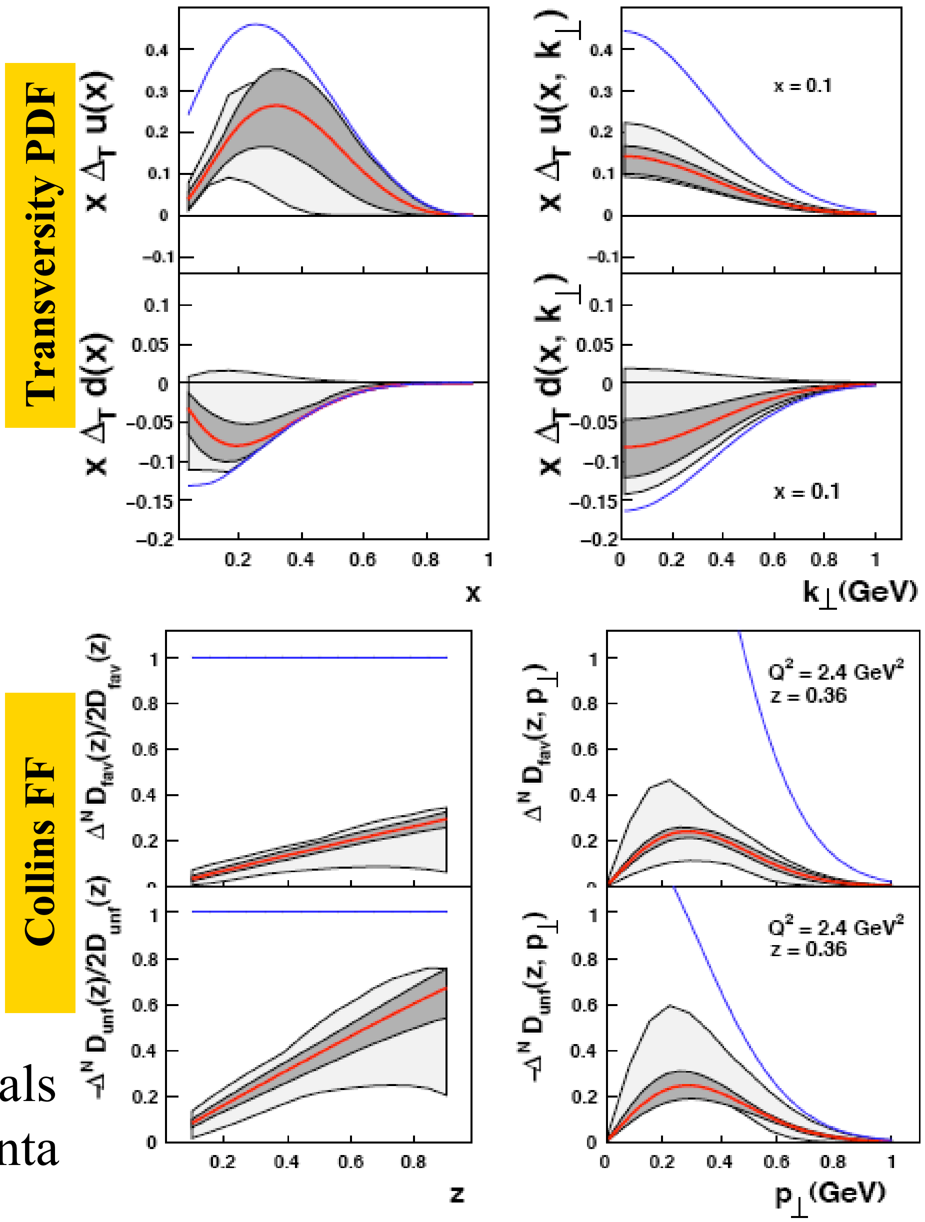
e^+e^- annihilation

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

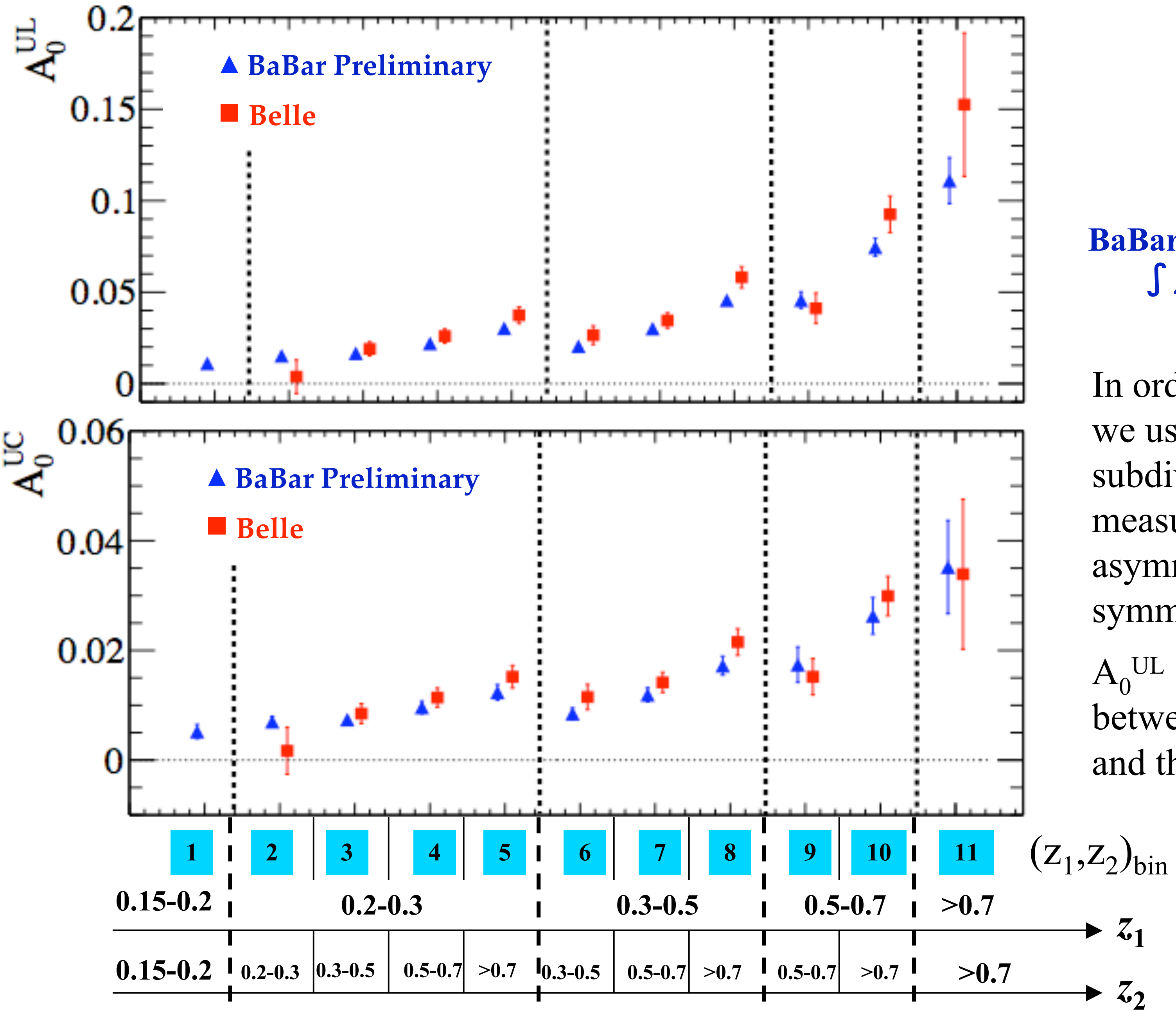
Anselmino et al., PRD 75, 054032(2007), NP Proc.Suppl. 191, 98(2009)

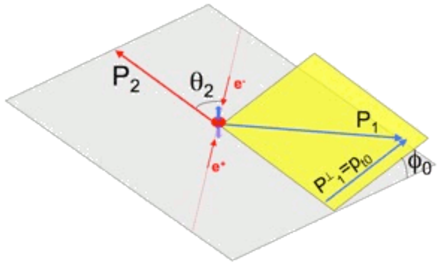


Improvements from BABAR studies:

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

RFO: Comparison of BaBar/Belle asymmetries





BaBar (0.15<z<0.9) **Belle (0.2<z<1)**

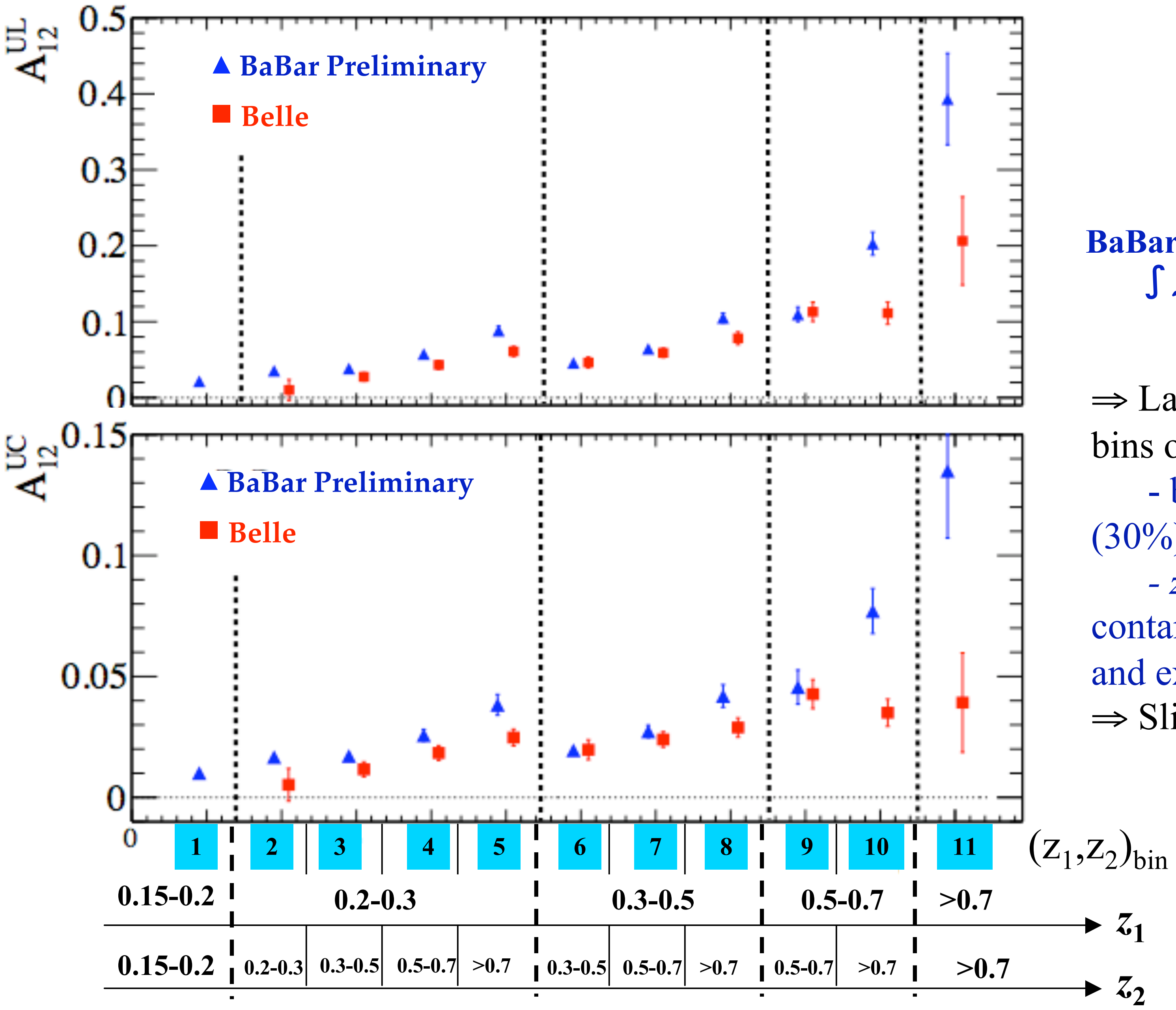
$\int \mathcal{L}$~468 fb^{-1} **$\int \mathcal{L}$~547 fb^{-1}**

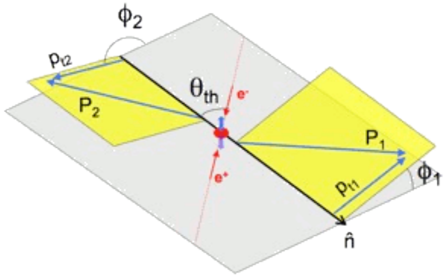
PRD 86, 039905(E) (2012)

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.

RF12: Comparison of BaBar/Belle asymmetries





BaBar ($0.15<z<0.9$) **Belle ($0.2<z<1$)**

$\int \mathcal{L} \sim 468\ \mathrm{fb}^{-1}$ **$\int \mathcal{L} \sim 547\ \mathrm{fb}^{-1}$**

PRD 86, 039905(E) (2012)

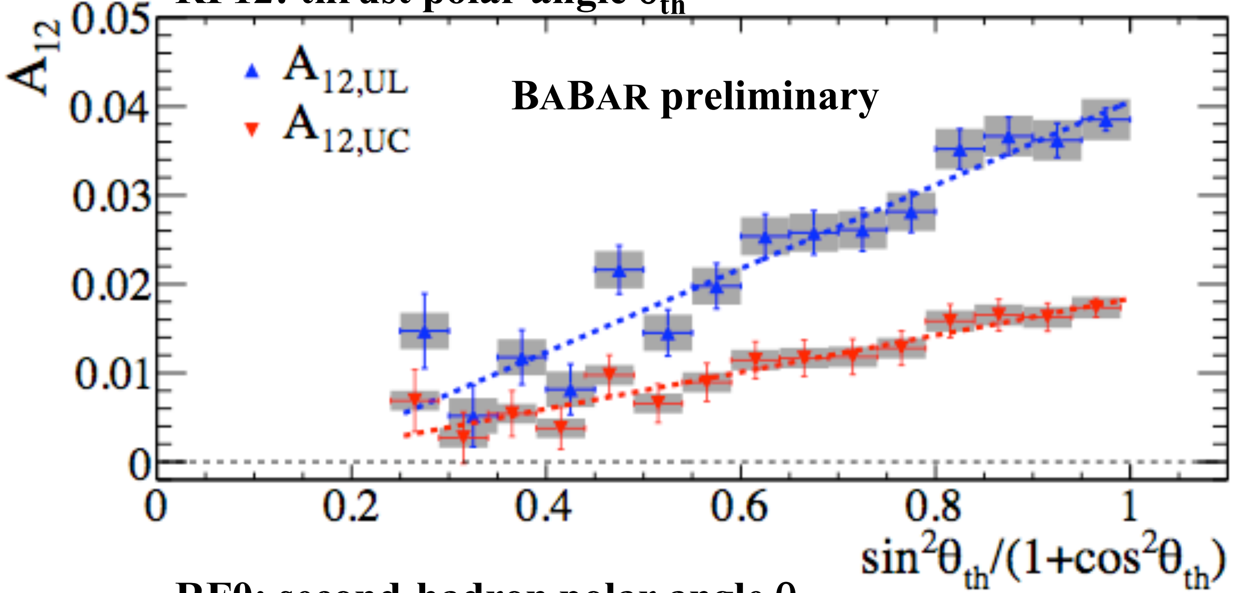
⇒ Large discrepancy in the last two bins of *z:*

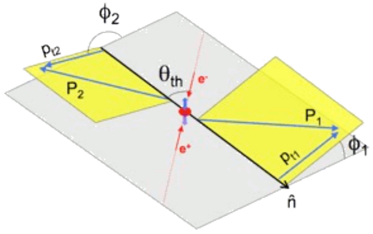
- bin-by-bin correction factors (30%)
- $z<0.9$ to remove the contamination from μμγ background and exclusive events

⇒ Slightly higher at lower z

Results: A_{12} vs. θ_{th}; A_0 vs. θ_2

RF12: thrust polar angle θ_{th}

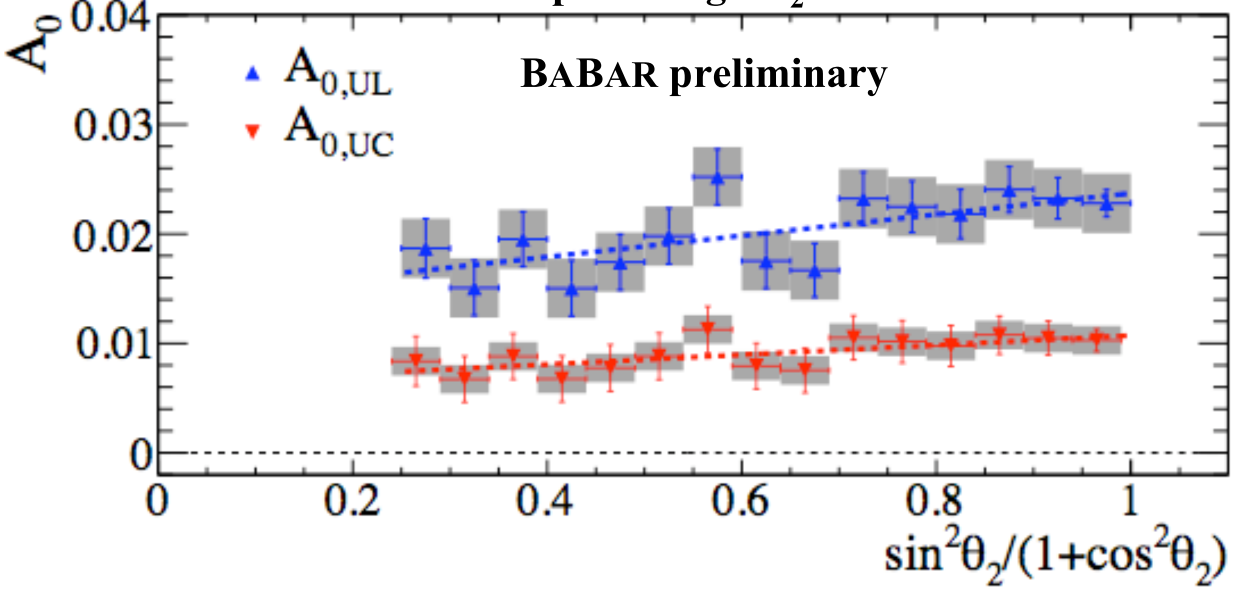


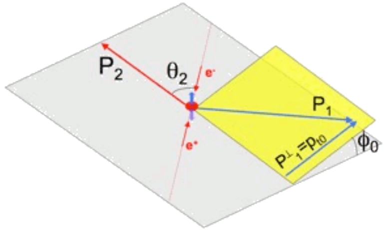


$$A_{12} \propto \frac{\sin^2\theta_{th}}{1+\cos^2\theta_{th}} \cos(\phi_1+\phi_2) \frac{H_1^\perp(z_1)\bar{H}_1^\perp(z_2)}{D_1(z_1)\bar{D}_1(z_2)}$$

==> Intercept consistent with zero, as expected (consistent with Belle results)

RF0: second-hadron polar angle θ_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)