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Spin-Dependent Fragmentation Functions in e^+e^- annihilation

…….from an experimental point of view

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OUTLINE

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- Spin-Dependent fragmentation functions in e^+e^- annihilation processes
- The Belle, BaBar, and BESIII experiments

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    - Extraction of Collins function

DI-HADRON FRAGMENTATION FUNCTION
- Reference frames and analysis strategy
- Results
    - $H_1^{\sphericalangle}$ and $G_1^{\perp}$

SUMMARY and CONCLUSIONS

Introduction: Fragmentation Functions in e^+e^- annihilation processes

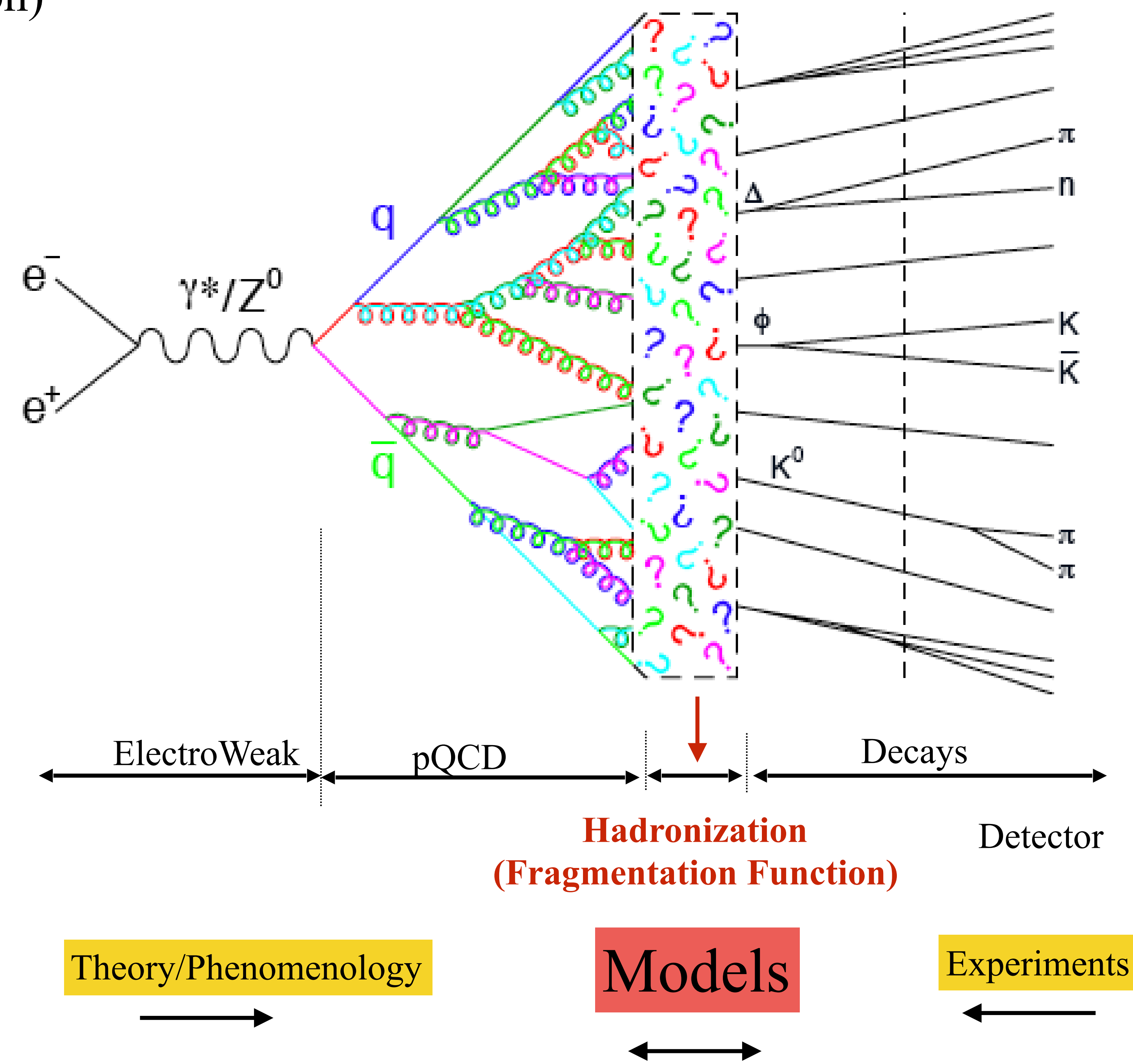
The process that transform quarks and gluons into colorless hadrons is referred as **FRAGMENTATION** (or hadronization)

$$e^+e^- \rightarrow q\bar{q}$$

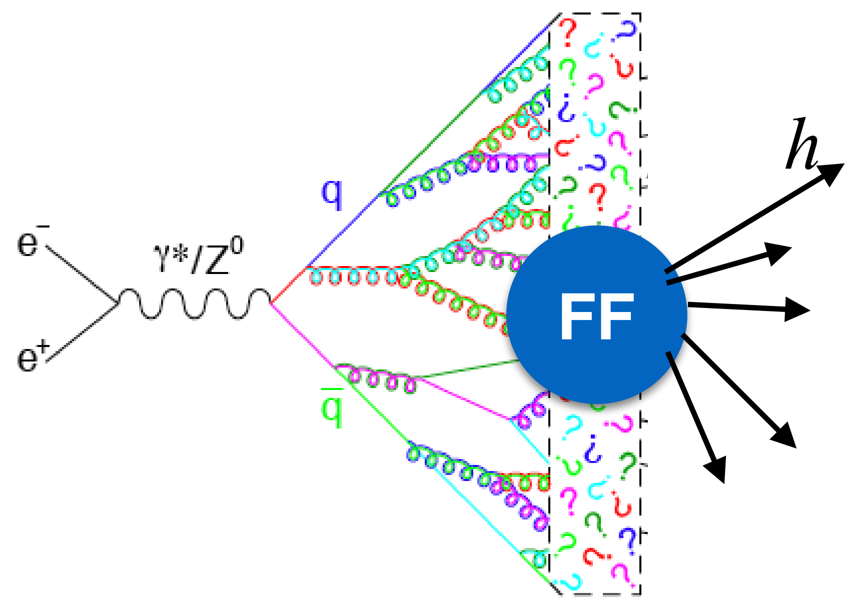
1. Quarks and antiquarks fragment via via radiation of gluons, each of which can radiate more gluons or split into a qqbar pair (pQCD)

2. **Hadronization**: the partons transform into primary hadrons

3. Unstable primary hadrons decay into more stable particles that reach detector elements



Introduction: Fragmentation Functions in e^+e^- annihilation processes



- Fragmentation Functions (FFs) are used to describe the hadronization processes of partons
  - *non-perturbative*
  - *universal* functions
  - depend on the scaled energy of the hadron *h*:
    $x = 2E_h/\sqrt{s}$
- e^+e^- annihilation environment offers the ideal conditions to access FFs (but limited sensitive to gluon FF and flavor dependence)

From the experimental point of view, the FFs describe final-state single particle energy distribution

- first observable: cross section in semi inclusive e+e- annihilation at center-of-mass energy $\sqrt{s}$

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

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

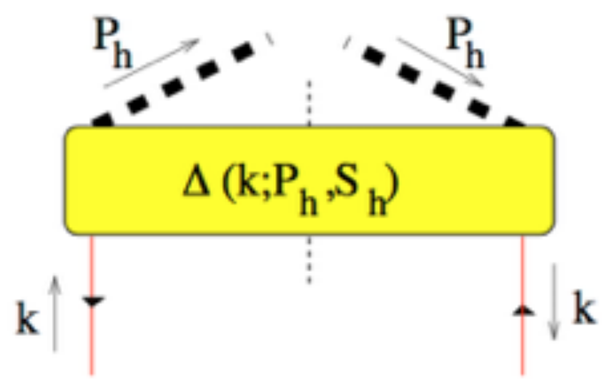
μ = factorization scale

process dependent short distance interaction

non-perturbative part: **parton fragmentation functions**

- $D_i^h(z,\boldsymbol{\mu}^2)$: probability that a parton i ($i=u/\bar{u},d/\bar{d},s/\bar{s},c/\bar{c},b/\bar{b},g$) fragments into a hadron *h* carrying a fraction *z* of the parton's momentum
- Collinear function: perturbative QCD corrections lead to logarithmic scaling violations via the evolution equations (DGLAP)

Correlation functions in a nutshell



$q \rightarrow h_1 X$

Assuming the factorization into hard and soft physics

- hard part: partonic cross sections are calculated using pQCD
- the soft part describes the hadronization. The information on how quark fragments into a hadron with momentum P_h and spin S_h is encoded in the **correlation function**:

$$\Delta_{ij}(k, P_h, S_h) = \sum_X \int \frac{d^4x}{(2\pi)^4}\, e^{ik\cdot x} \langle 0|\psi_i(x)|P_h, S_h; X\rangle\langle P_h, S_h; X|\overline{\psi}_j(0)|0\rangle$$

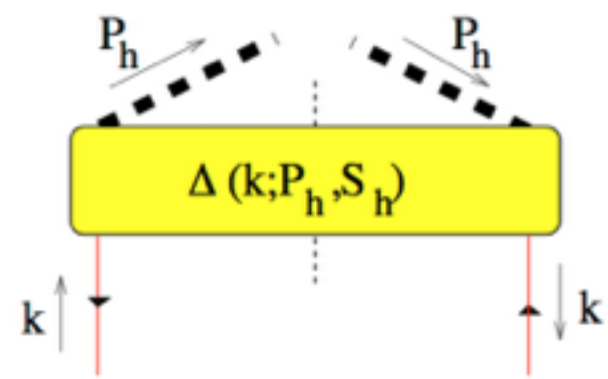
Collins, Soper, NPB 194, 445

General expression for **spin 1/2** hadron in the final state:

$$\begin{aligned}
\Delta(k,P,S) \;=\;& M A_1 + A_2 \not{P} + A_3 \not{k} + (A_4/M)\sigma^{\mu\nu} P_\mu k\nu + i A_5 (k\cdot S)\gamma_5 \\
+\;& M A_6 \not{S}\gamma_5 + (A_7/M)(k\cdot S)\not{P}\gamma_5 + (A_8/M)(k\cdot S)\not{k}\gamma_5 + \\
+\;& i A_9 \sigma^{\mu\nu}\gamma_5 \S_\mu P_\nu + i A_{10}\sigma^{\mu\nu}\gamma_5 S_\mu k_\nu + i(A_{11}/M^2)(k\cdot S)\sigma^{\mu\nu}\gamma_5 k_\mu P_\nu \\
+\;& (A_{12}/M)\epsilon_{\mu\nu\rho\sigma}\gamma^\mu P^\nu k^\rho S^\sigma
\end{aligned}$$

- Only terms which satisfy the condition of **hermiticity** and **P-invariance**
- Note that A_4, A_5, and A_{12} are T-odd

Correlation functions in a nutshell



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Collins, Soper, NPB 194, 445

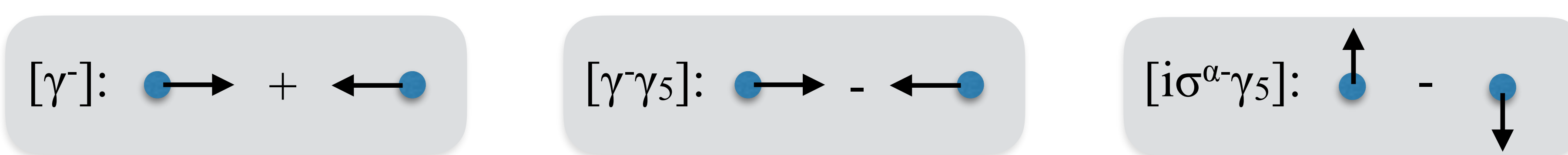
General expression for **spin 0** hadron in the final state:

$$\Delta(k, P, S) \;=\; M A_1 + A_2 \not{P} + A_3 \not{k} + (A_4/M)\sigma^{\mu\nu} P_\mu k\nu$$

FFs are obtained from the correlation function Δ by projection with Dirac matrices Γ, and integration over components of the quark momentum

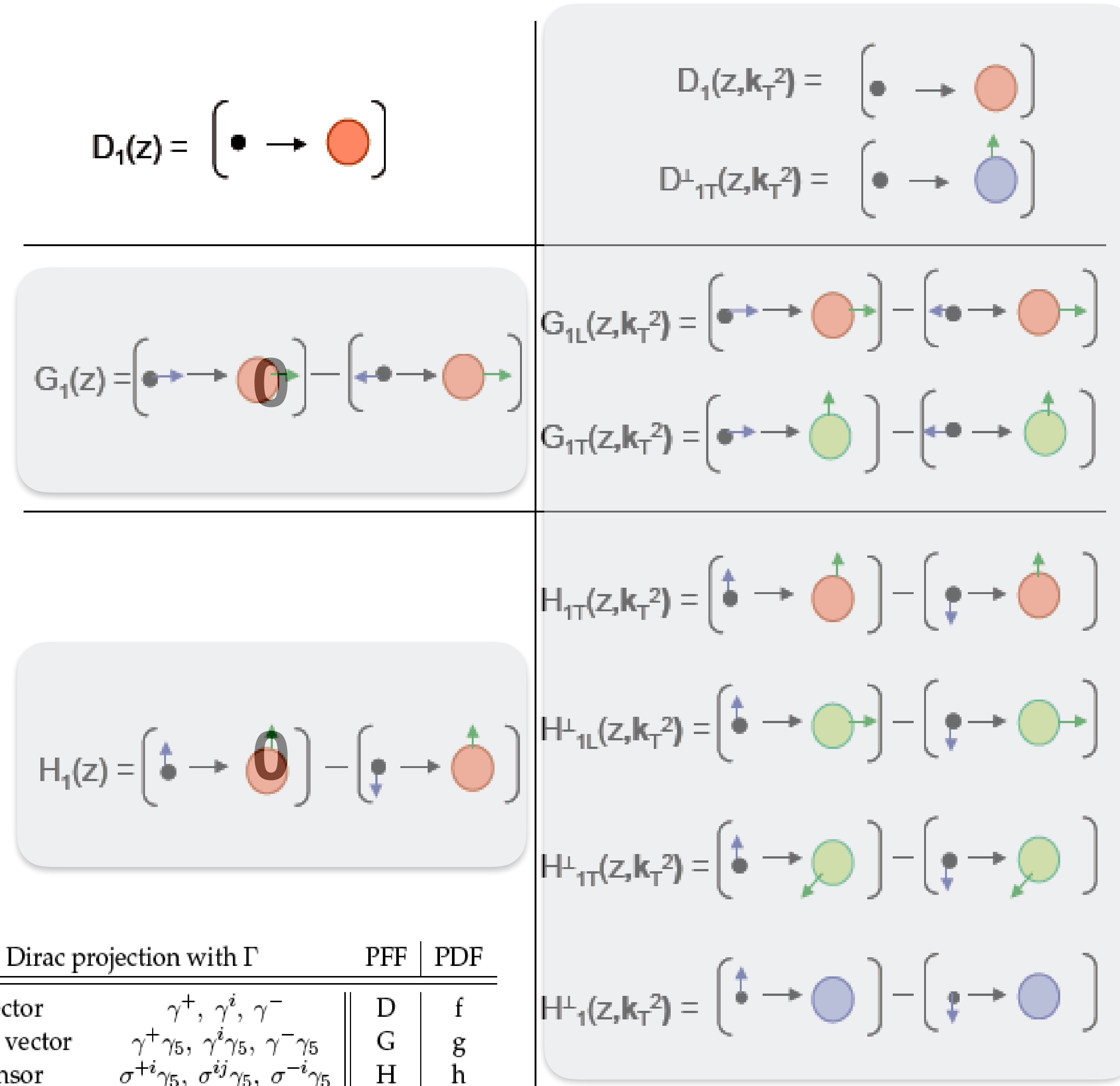
$$\Delta^{[\Gamma]}(z) \equiv \frac{1}{4z}\int dk^+ d^2\mathrm{k}_T \mathrm{Tr}(\Delta\Gamma)\Big|_{k^-=P_h^-/z}$$

- LC quantization
- $\Gamma \in \{\gamma^-, \gamma^-\gamma_5, i\sigma^{\alpha-}\gamma_5, \ldots\}$ determines quark spin states



Fragmentation Functions

FF for one unpolarized hadron
observed in a quark jet
(no k_T)



Dirac projection with Γ		PFF	PDF
vector	$\gamma^+, \gamma^i, \gamma^-$	D	f
axial vector	$\gamma^+\gamma_5, \gamma^i\gamma_5, \gamma^-\gamma_5$	G	g
tensor	$\sigma^{+i}\gamma_5, \sigma^{ij}\gamma_5, \sigma^{-i}\gamma_5$	H	h
(pseudo) scalar	$1, \gamma_5$	E	e

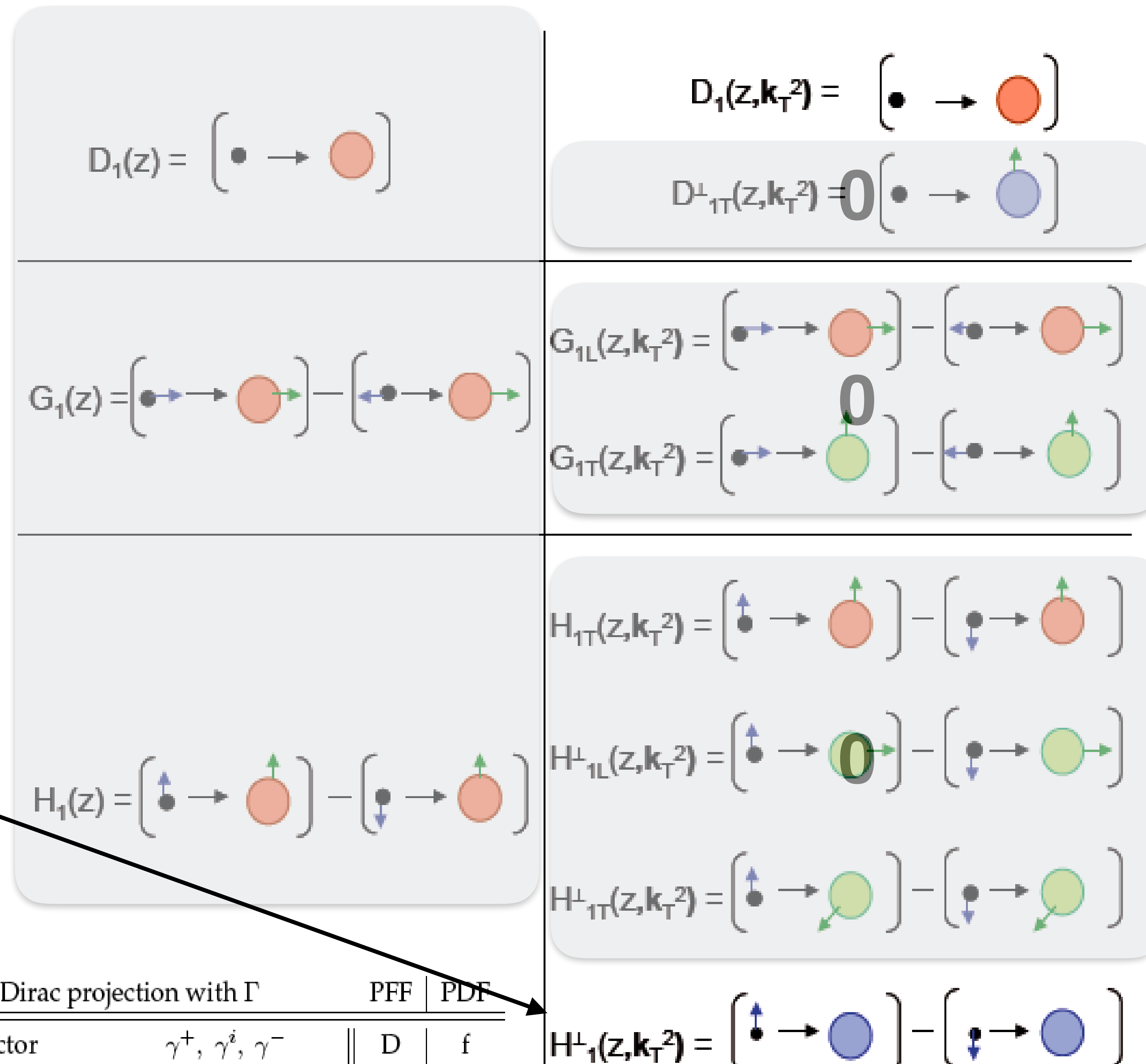
Fragmentation Functions

FF for one unpolarized hadron observed in a quark jet (no k_T)

FFs for one unpolarized hadron observed in a quark jet (with k_T)

T-odd FF: $H_1^\perp$ (Collins FF):

- chiral-odd function
- how a transversely polarized quark (anti-quark) fragments into unpolarized hadron
- quark transverse momentum dependence



	Dirac projection with Γ	PFF	PDF
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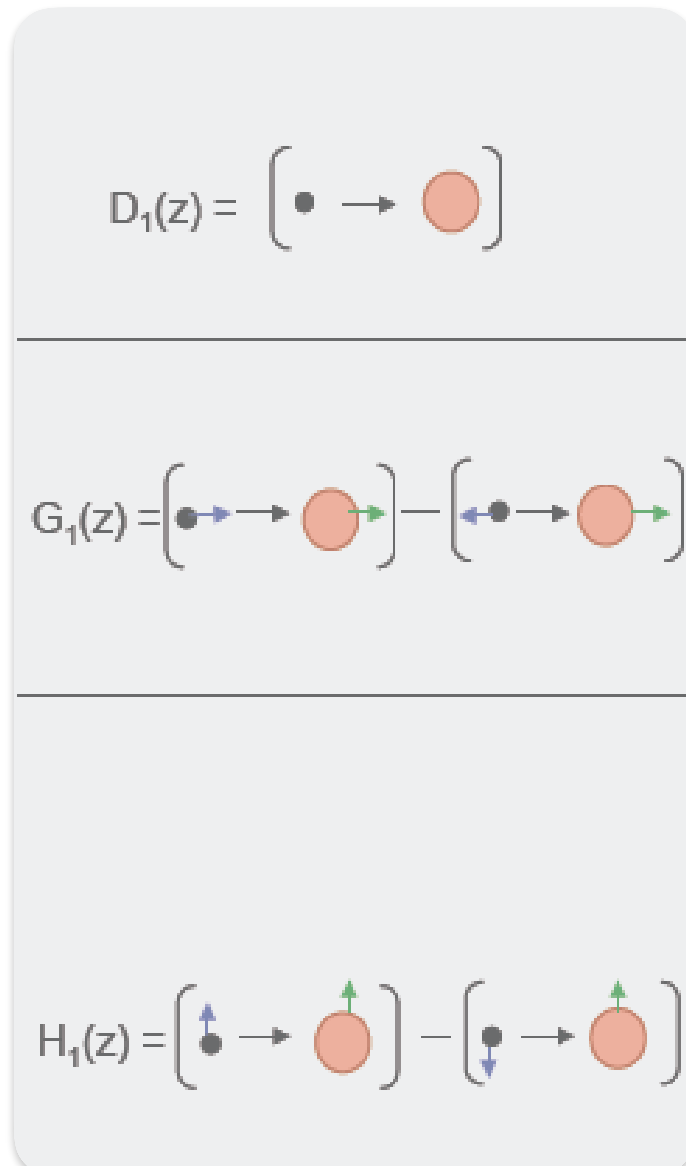
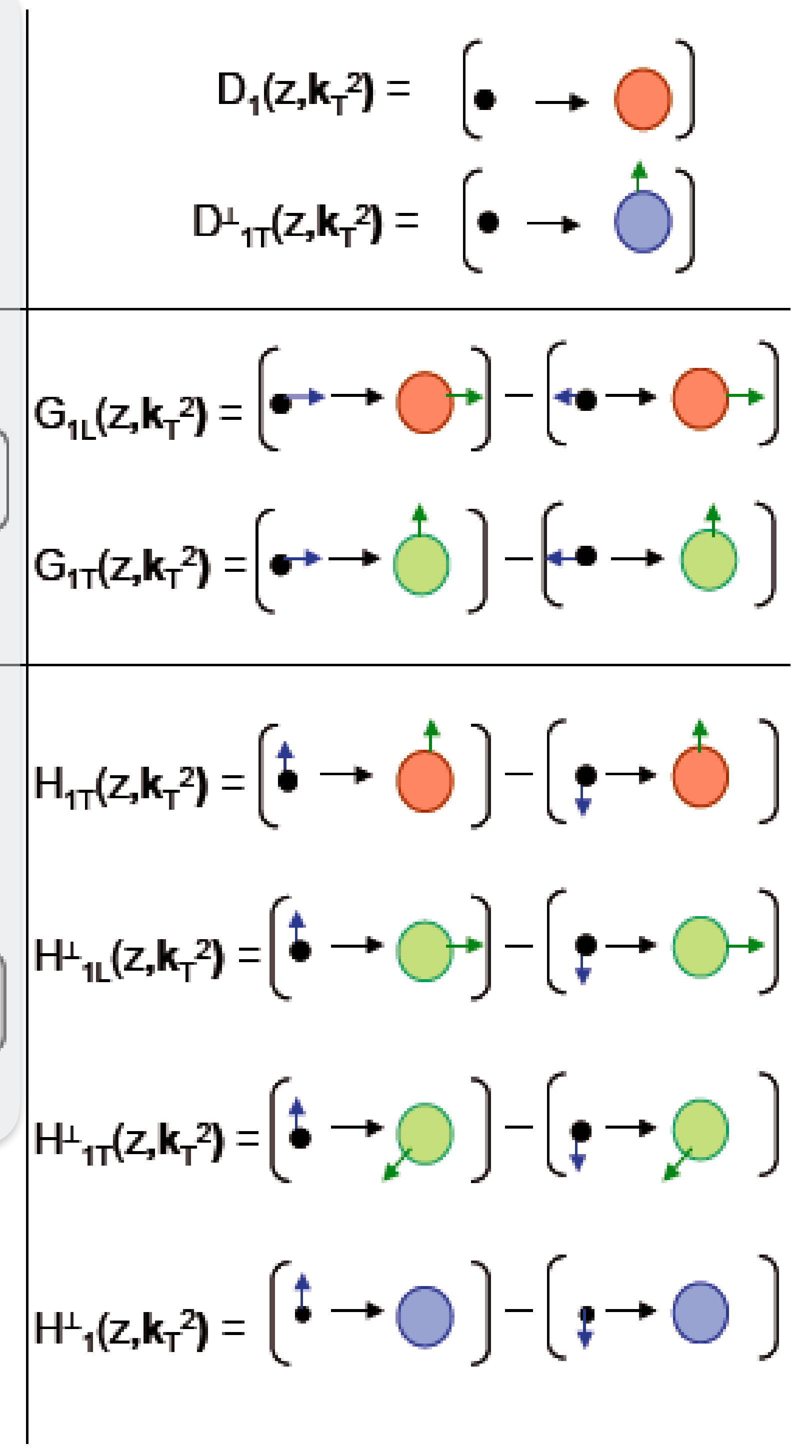
Fragmentation Functions

FF for one unpolarized hadron observed in a quark jet (no k_T)

FFs for one unpolarized hadron observed in a quark jet (with k_T)

FFs for spin 1/2 hadron observed in a quark jet (with k_T)





Dirac projection with Γ		PFF	PDF
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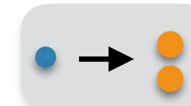
tensor	$\sigma^{+i}\gamma_5,\ \sigma^{ij}\gamma_5,\ \sigma^{-i}\gamma_5$	H	h
(pseudo) scalar	$1,\ \gamma_5$	E	e

Fragmentation Functions

$R \equiv P_1 - P_2$

FF for one unpolarized hadron observed in a quark jet (no k_T)

$$\Delta^{[\gamma^-]}(z_1, z_2, \mathbf{k}_T, \mathbf{R}_T) = D_1$$



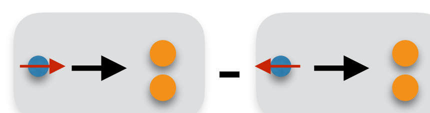
FFs for one unpolarized hadron observed in a quark jet (with k_T)

$$\Delta^{[\gamma^-\gamma^5]}(z_1, z_2, \mathbf{k}_T, \mathbf{R}_T) = \frac{\epsilon_T^{ij} R_{Ti} k_{Tj}}{M_1 M_2} G_1^{\perp}$$

$$\Delta^{[i\sigma^{i-}\gamma^5]}(z_1, z_2, \mathbf{k}_T, \mathbf{R}_T) = \frac{\epsilon_T^{ij} R_{Tj}}{M_1 + M_2} H_1^{\sphericalangle} + \frac{\epsilon_T^{ij} k_{Tj}}{M_1 + M_2} H_1^{\perp}$$

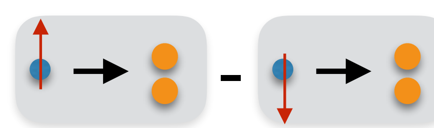
FFs for spin 1/2 hadron observed in a quark jet (with k_T)

FFs for two unpolarized hadrons observed in the same quark jet (with k_T)



$G_1^{\perp}$: T-odd FF

- chiral-even function
- log. polarized q → two unp. hadrons

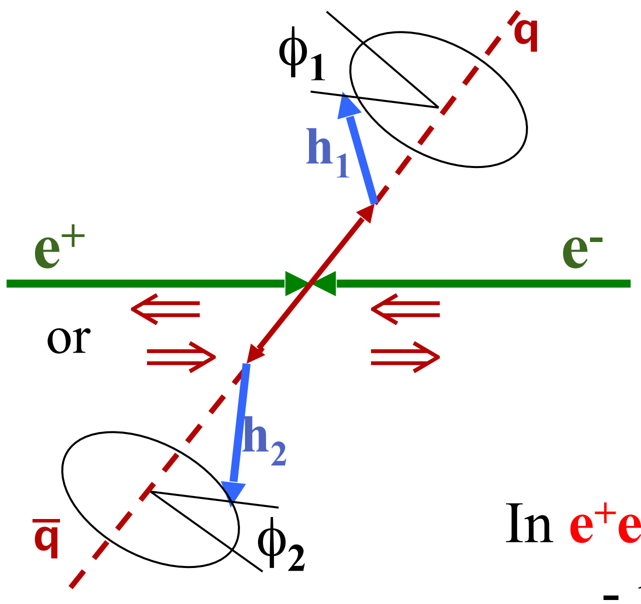


$H_1^{\sphericalangle}$: T-odd FF

- Chiral-odd function
- Transv. polarized q → two unp. hadrons

The relative momentum of the hadron pair is an additional degree of freedom: *the orientation of the two hadrons w.r.t. each other and the jet direction is an indicator of the quark transverse spin*

Collins Effect in e+e- annihilation



Probability density for finding unpolarized hadron from a transversely polarized q:

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

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

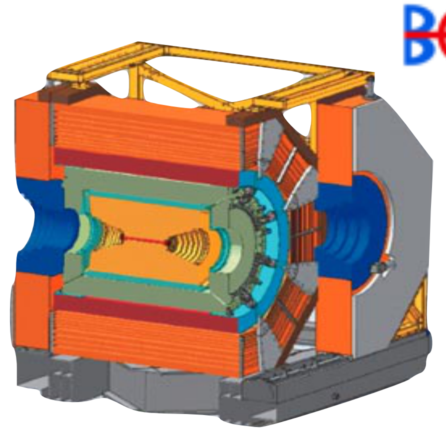
- in a given event, the spin directions are unknown, but they must be parallel
- they have a polarization component transverse to the q direction ~$\sin^2\theta$ (θ wrt the e^+e^-)
- exploit this correlation by using hadrons in opposite jets

- $H_1^\perp \neq 0 \Rightarrow$ leads to an asymmetry in the angular distribution of final state particles (Collins effect)
- First non-zero Collins effect observed in SIDIS PRL 94,012002(2005), NPB 765, 31(2007)
- First non-zero independent measurement of the Collins effect for pion pairs in e^+e^- annihilation by Belle Collaboration @ $\sqrt{s} \sim 10.6$ GeV (PRL 111,062002(2008), PRD 88,032011(2013))
  - Confirmed by BaBar @ $\sqrt{s} \sim 10.6$ GeV (PRD 90,052003 (2014); PRD 92,111101(R)(2015) for KK and Kπ)
  - Measured at BESIII @ $\sqrt{s} = 3.65$ GeV (PRL 116,42001(2016))

$$e^+e^- \rightarrow q\bar{q} \rightarrow h_1 h_2 X \ \ (q=u,\ d,\ s) \Longrightarrow \sigma \propto \cos(\varphi_i) H_1^\perp(z_1) \otimes H_1^\perp(z_2)$$

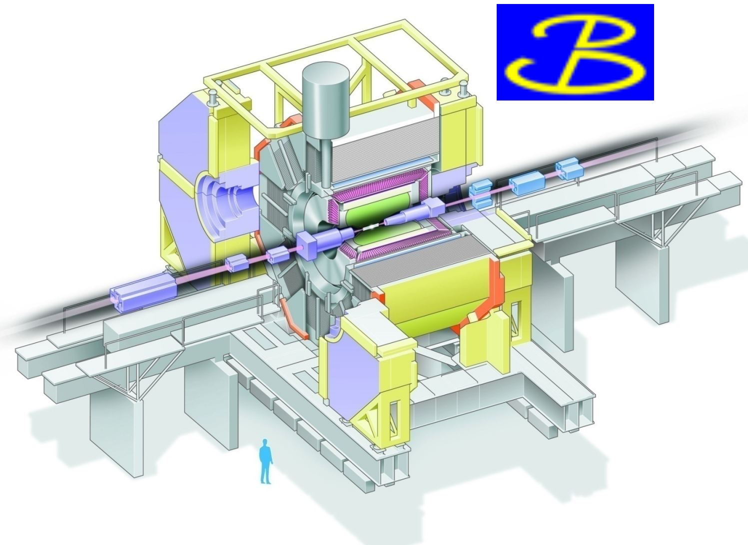
The BaBar, Belle and BESIII experiments

NIMA**614**,345(2010)



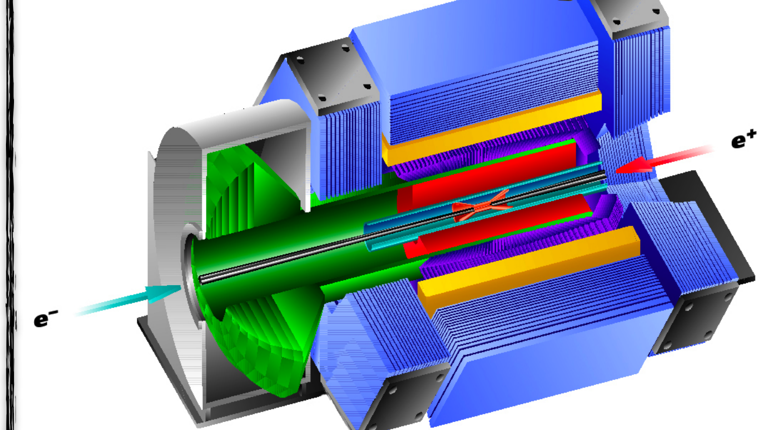
- Symmetric e^+e^- collider
- $\sqrt{s}$ = [2 - 4.6] GeV
- 62 pb^{-1} @ 3.65 GeV used for Collins studies
- Below open-charm threshold

- Asymmetric-energy e^+e^- collider
- $\sqrt{s} \sim 10.6$ GeV ($\Upsilon(4S)$)
- $\beta\gamma=0.425$
- $L \sim 1\ ab^{-1}$



NIMA**479**,117(2002)

NIMA**729**,615(2013)

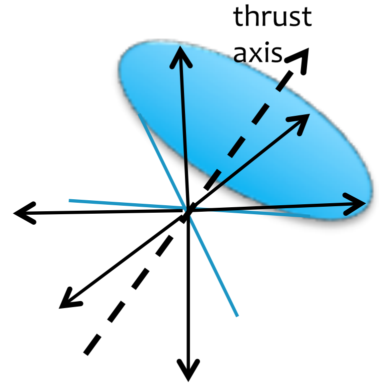


- Asymmetric-energy e^+e^- collider
- $\sqrt{s} \sim 10.6$ GeV ($\Upsilon(4S)$)
- $\beta\gamma=0.65$
- $L \sim 500\ fb^{-1}$

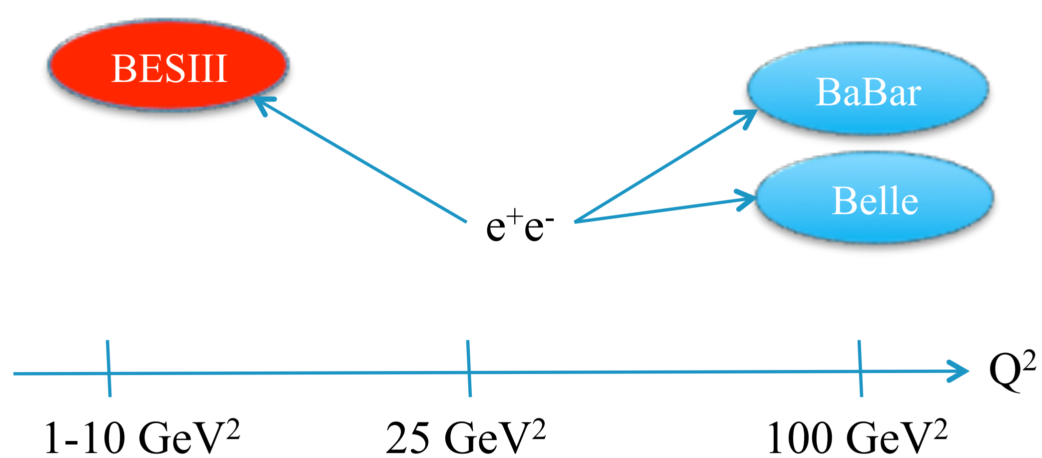
$$T = \sum_i \frac{|\mathbf{P} \cdot \hat{\mathbf{n}}|}{|P|}$$

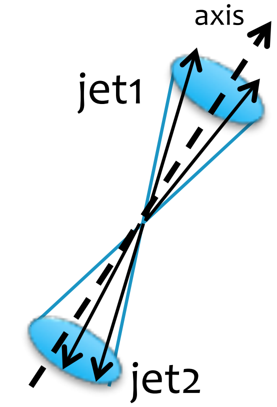
$$\text{thrust axis} \equiv \hat{\mathbf{n}}$$

$$0.5 \leq T \leq 1$$



T~0.5





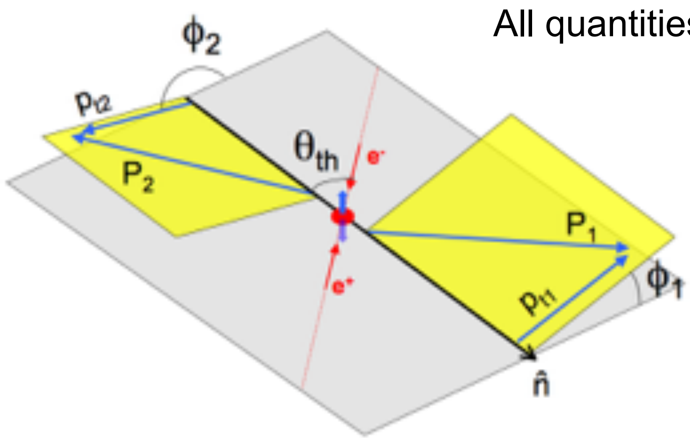
T~1

Analysis Strategies and Reference Frames

[See NPB 806, 23 (2009)]

RF12 or Thrust RF

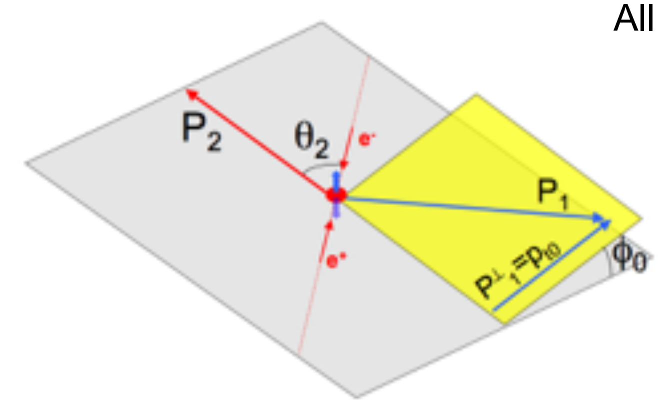
BaBar
Belle
~~BESIII~~



- **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



BaBar
Belle
BESIII

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

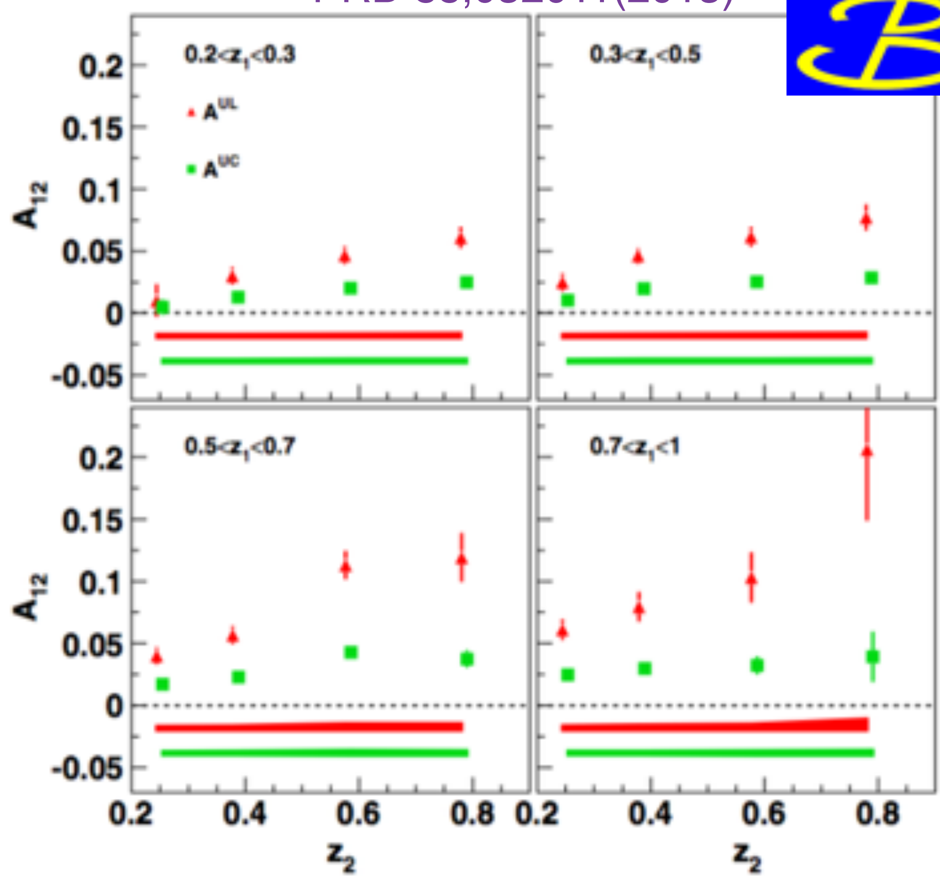
$$\sigma \sim 1 + \frac{\sin^2\theta_2}{1+\cos^2\theta_2}\cos(2\phi_0)\mathcal{F}\left[\frac{H_1^\perp(z_1)\bar{H}_1^\perp(z_2)}{D_1(z_1)\bar{D}_1(z_2)}\right]$$

- Azimuthal modulations (Collins effect) may be 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)
- Ratio of normalized distribution of pion pairs with opposite charge sign (R^U) / same charge sign (R^L): cancels detector effects (or $(R^{C=U+L})/R^L$) ⇒ sensitivity to fav. and dis. fragmentation processes

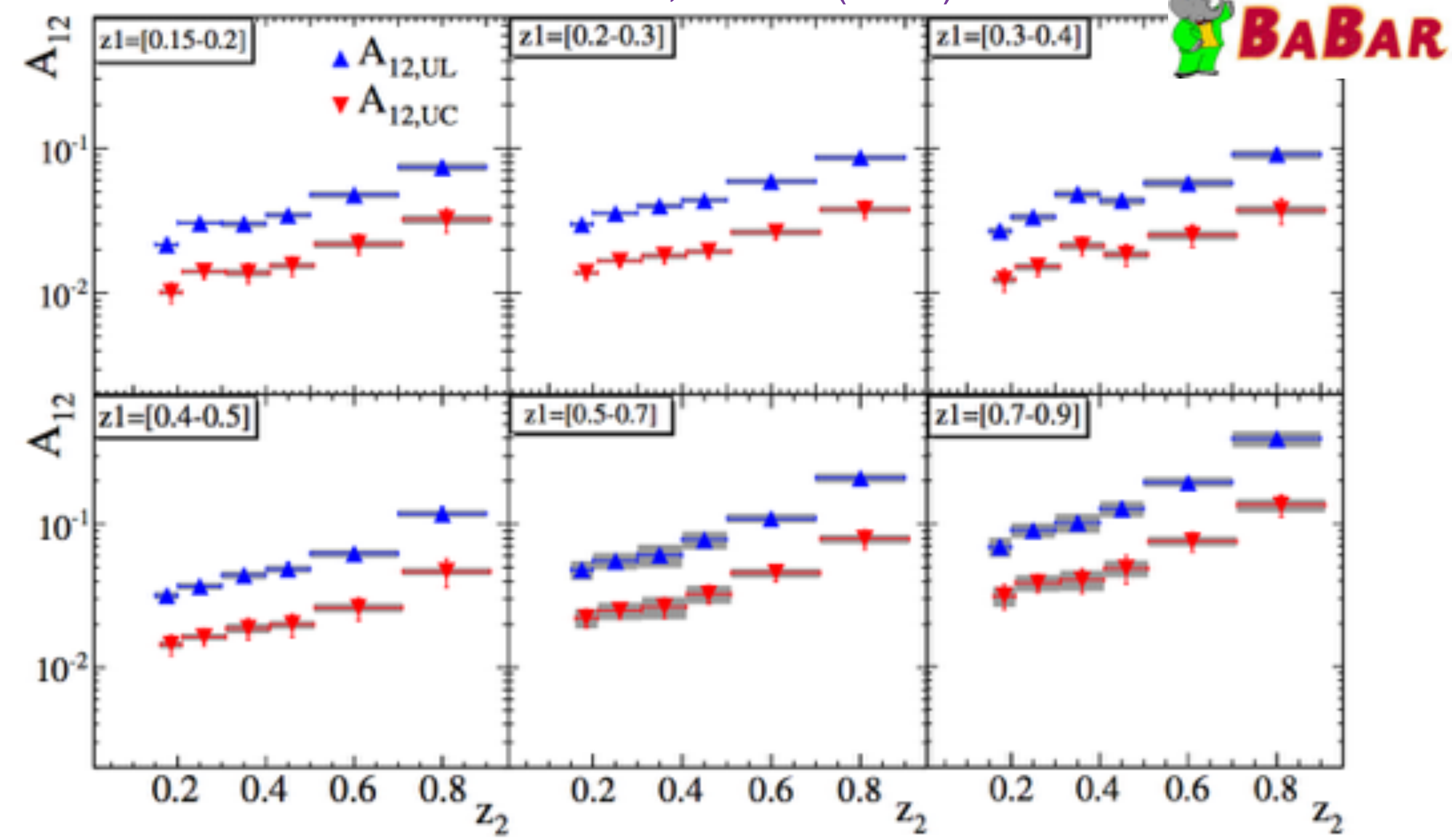
$$\frac{R_\alpha^U}{R_\alpha^{L(C)}} = \frac{N^U(\phi_\alpha)/<N^U(\phi_\alpha)>}{N^{L(C)}(\phi_\alpha)/<N^{L(C)}(\phi_\alpha)>} \rightarrow B_\alpha^{UL(UC)} + A_\alpha^{UL,(UC)}\cdot\cos(\phi_\alpha)$$

Collins Effect vs (z_1,z_2)

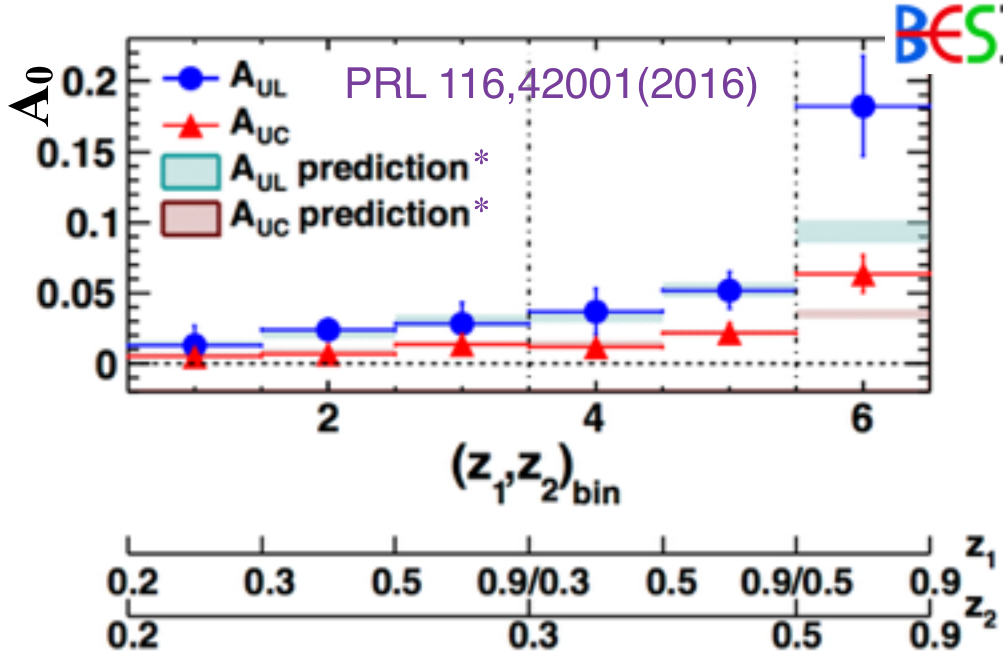
PRD 88,032011(2013)



PRD 90,052003 (2014)



PRL 116,42001(2016)

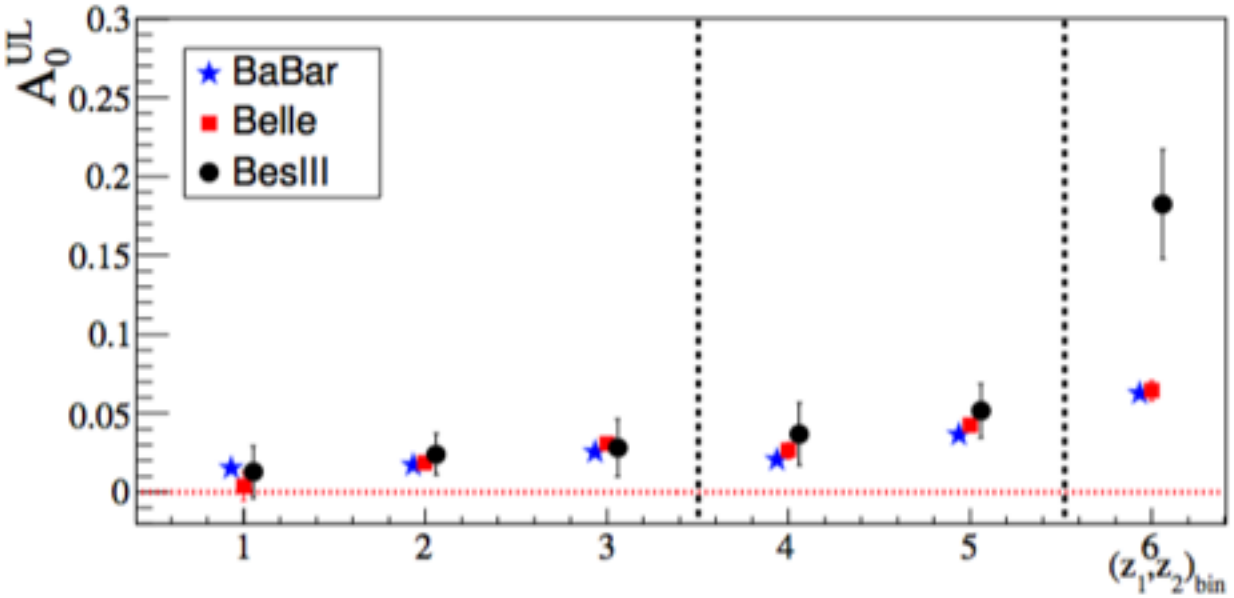


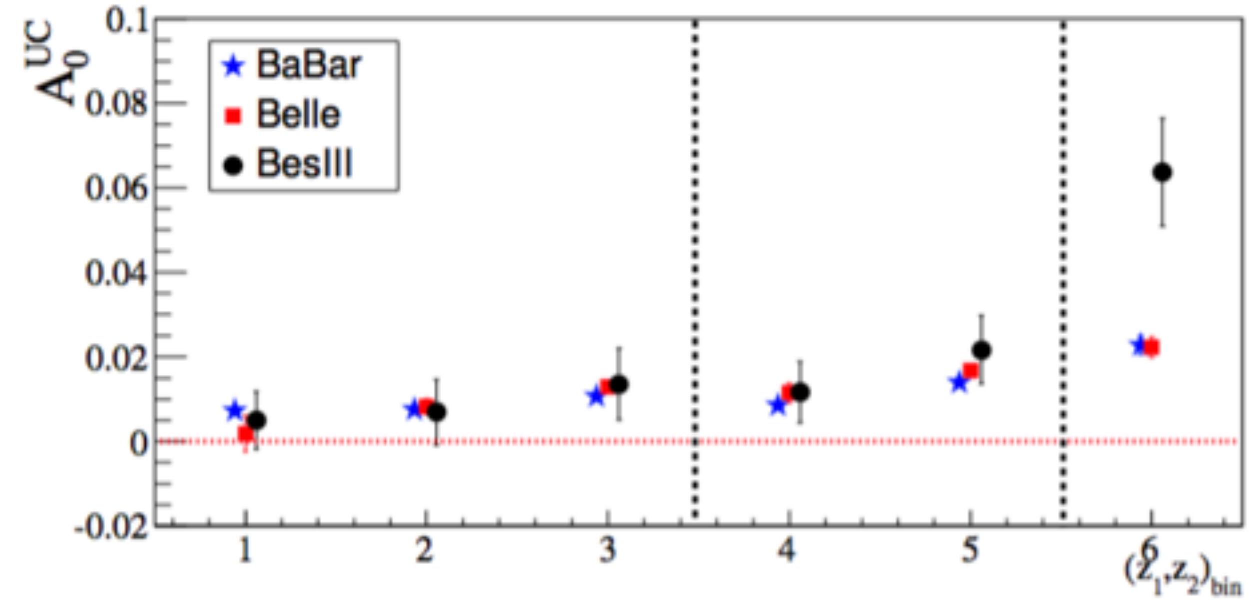
- Significant non-zero asymmetries A_{12}, A_0 in all bins
- Strong dependence on (z_1,z_2) observed in all the experiments
- A_{UC}<A_{UL} as expected; complementary informations about favored and disfavored fragmentation processes

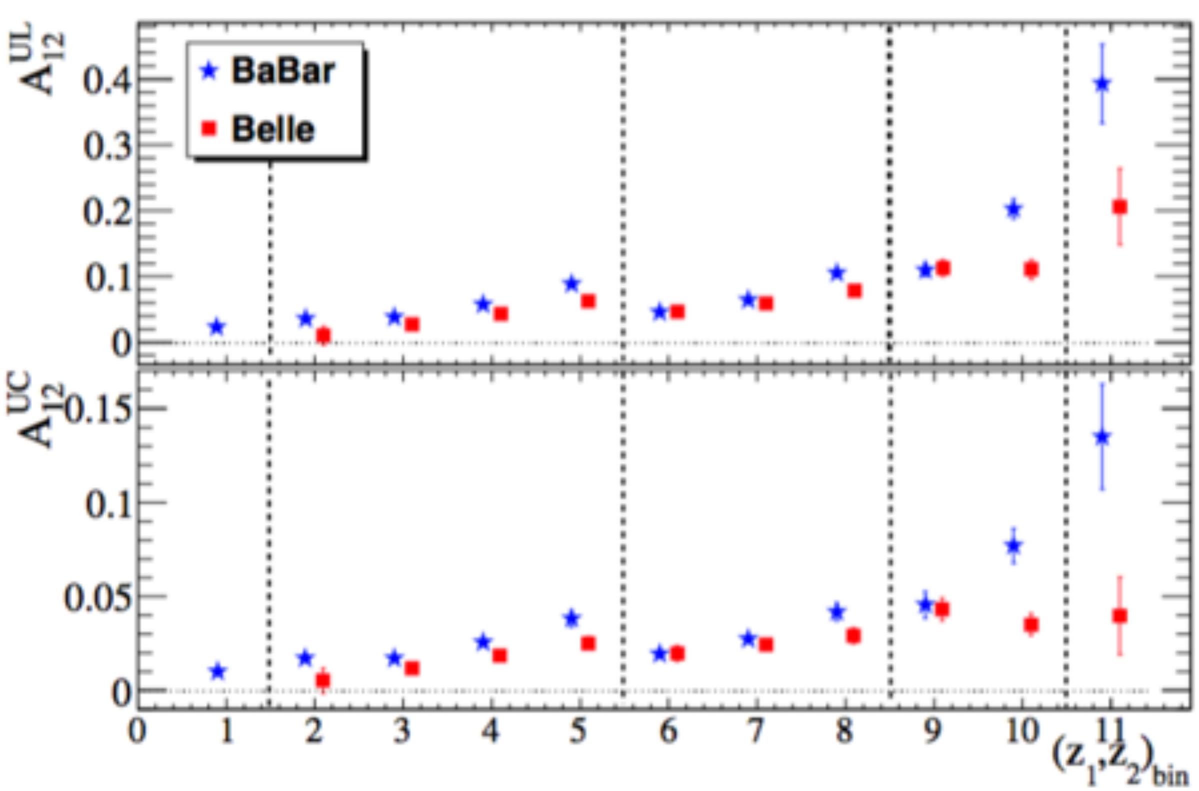
*PRD 93,014009(2016)

Collins Effect vs (z_1,z_2): comparisons

EPJA, 52, 1-15 (2016)



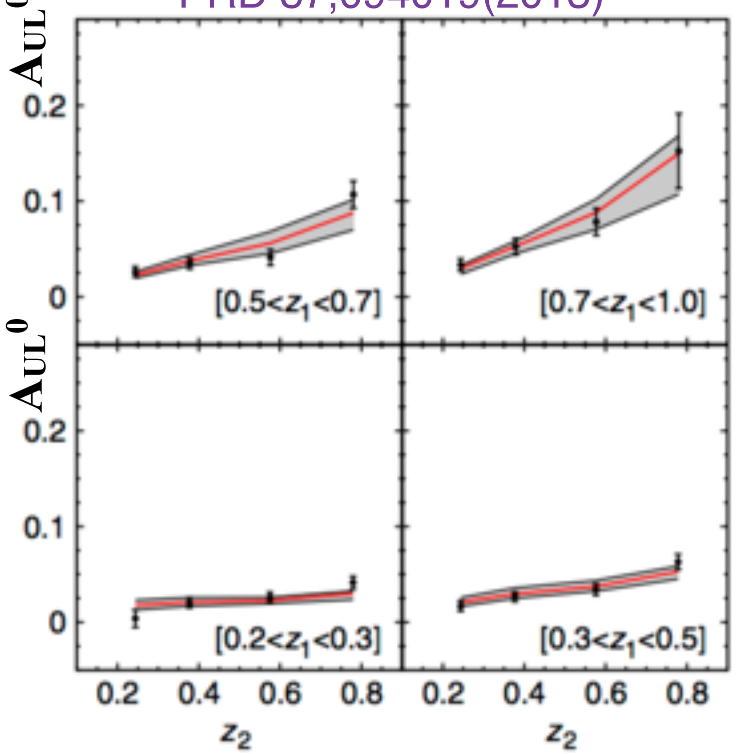




- Symmetric (z_1,z_2) bins are used for the comparisons: results falling in the same large (z_1,z_2) interval are averaged taking into account statistical and systematic uncertainties
- A_0 : very good agreement between BaBar and Belle data; larger asymmetry for BESIII in the last bin ($z_{1,2}$>0.5)
- A_{12}: some tensions between BaBar and Belle, which can be attributed to experimental features:
  - thrust axis corrections
  - background corrections
  - z<0.9 for BaBar, z<1 for Belle

Extracted Collins Functions

PRD 87,094019(2013)



- Polynomial parameterization:

$$\frac{\Delta^N D_{\pi^+/u^\uparrow,\bar{d}^\uparrow}(z,p_\perp)}{D_{\pi^+/u,\bar{d}}} = 2\mathcal{N}^C_{fav}(z)h(p_\perp)\frac{e^{-p_\perp/\langle p_\perp^2\rangle}}{\pi\langle p_\perp^2\rangle}$$

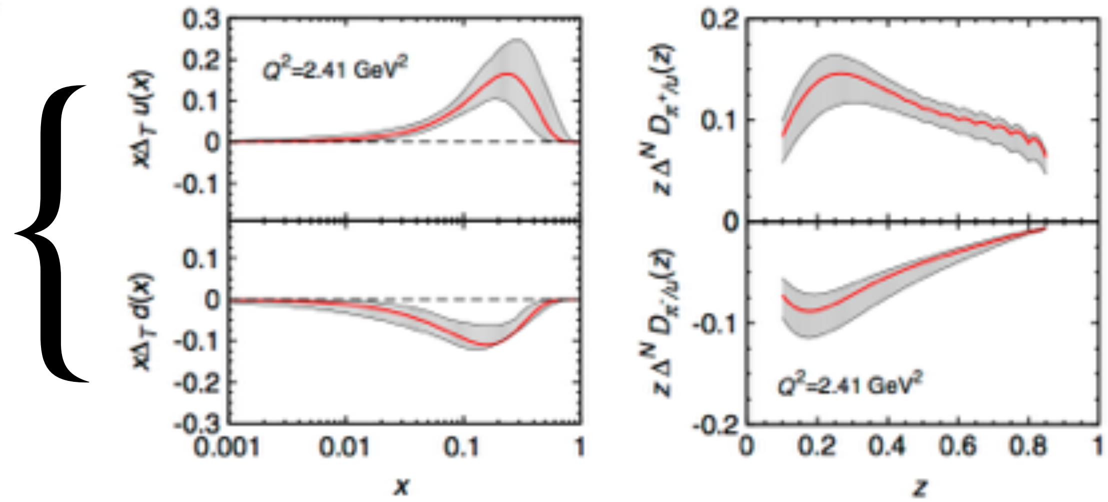
$$h(p_\perp) = \sqrt{2e}\frac{p_\perp}{M_h}e^{-p_\perp^2/M_h^2}$$

$$\mathcal{N}^C_{fav} = N^C_{fav}z[(1-a-b)+az+bz^2]$$

- global analysis: SIDIS+BELLE data (arXiv:1303.2076; PLB693,11; PRD86,032011)
- $z\Delta^N D_{h/q\uparrow}(z)=4zH_1^{\perp(1/2)q}(z)$
- tension between fav Collins function from A^0 and A^{12} (PRD87)

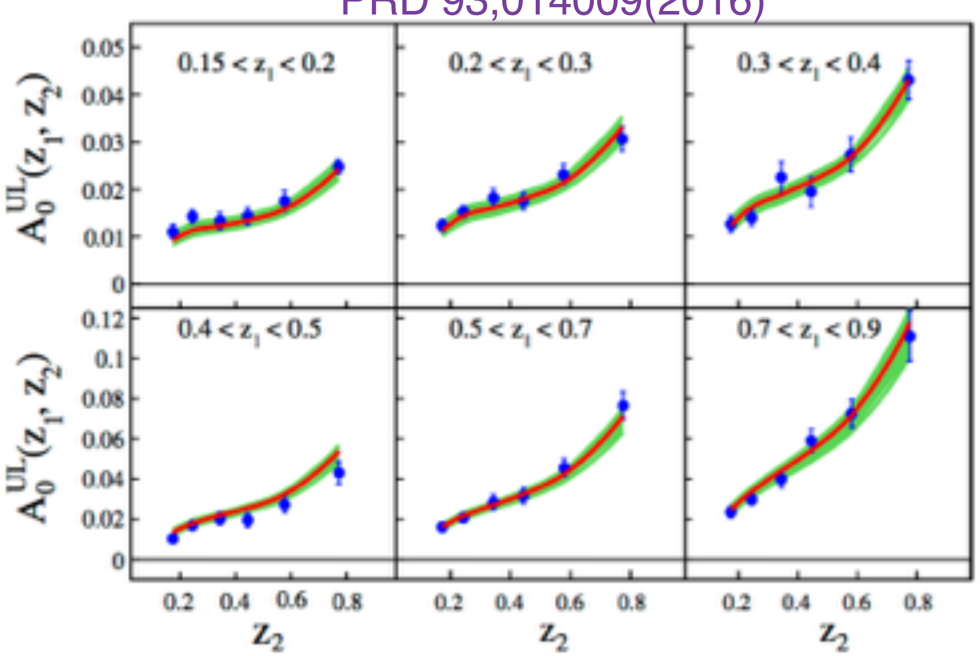
Transversity PDF

Fav. and dis. Collins FFs

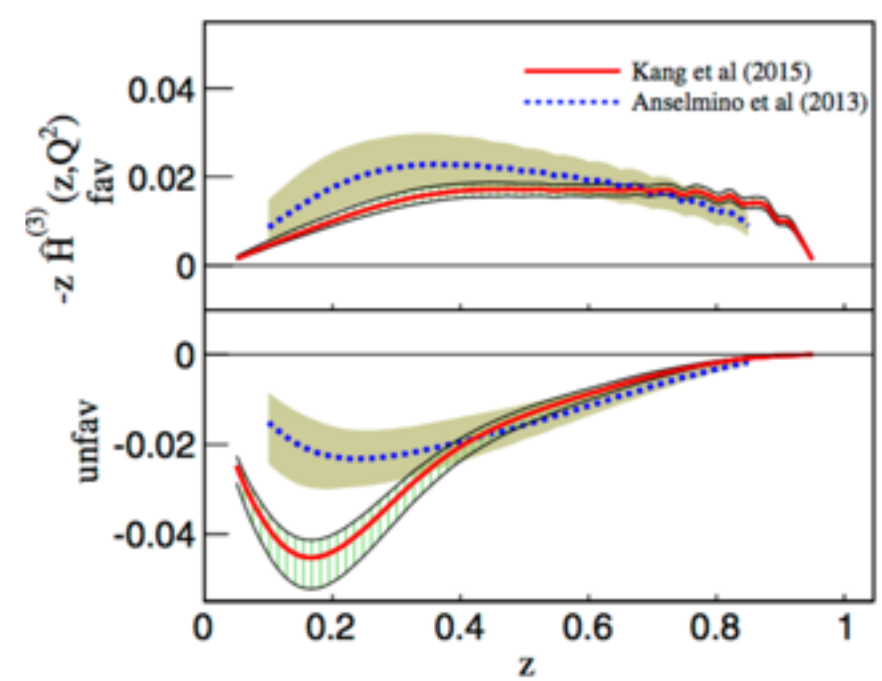


Note: ***no TMD evolution*** taken into account

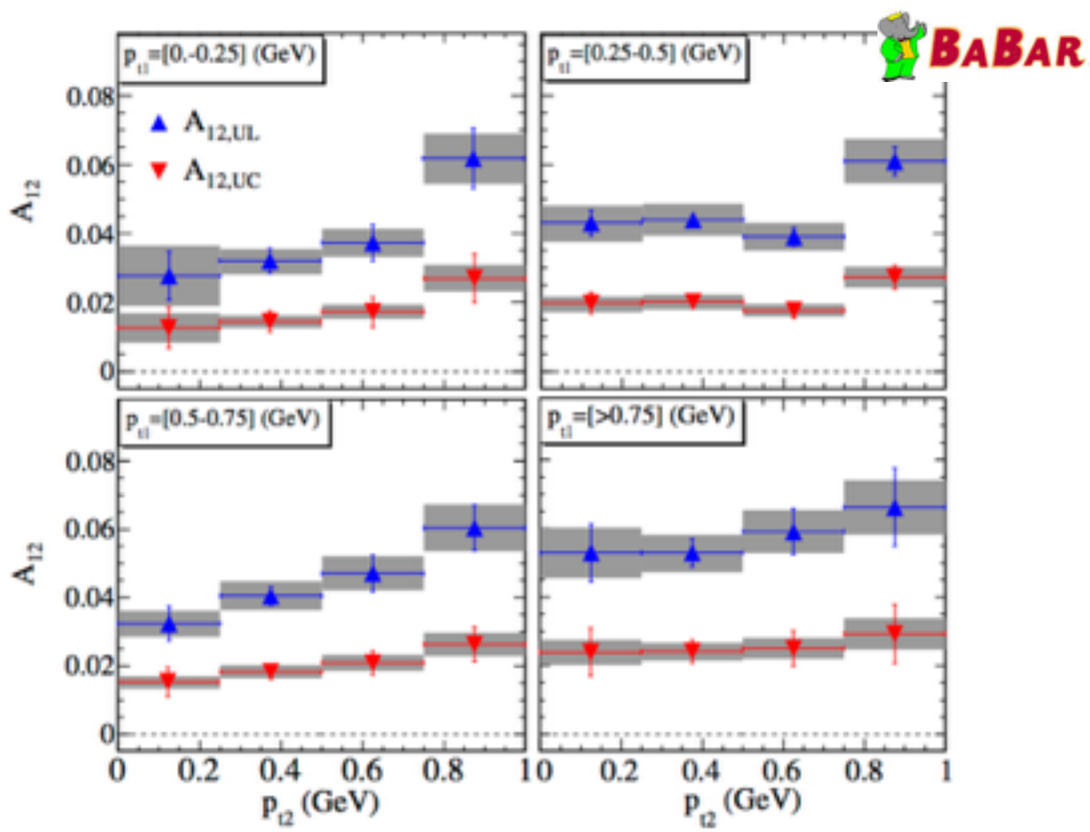
PRD 93,014009(2016)

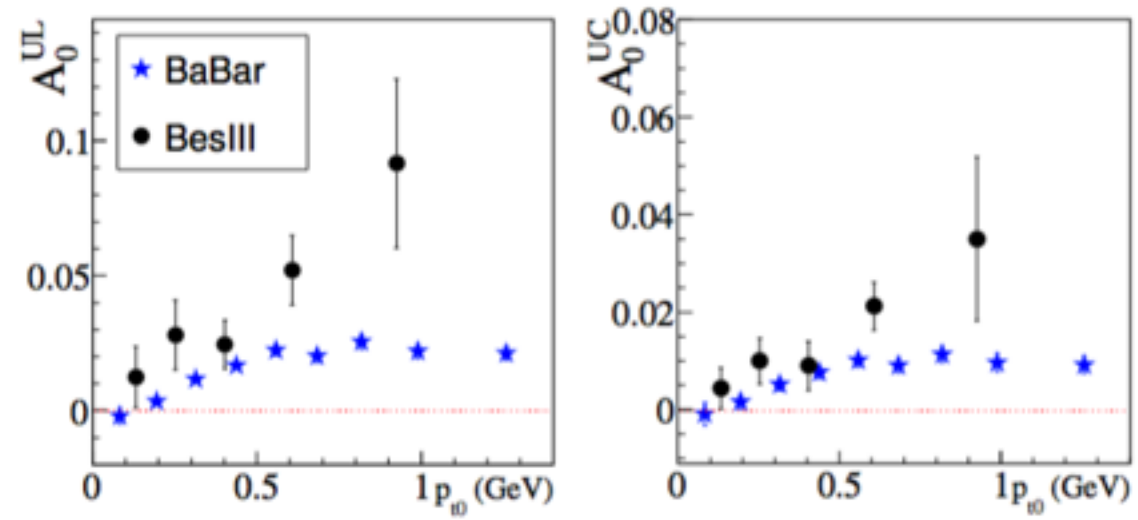


- Global fit ***with TMD evolution*** (PRL103,152002; PLB744,250; PLB673,127; PRL 107,072003, PRD90,052003; PRD78,032011)
- Good description of both Belle and BaBar data: magnitude and shape of the data are very well reproduced: fav. and dis. parameters allowed to be different and independent each other



Collins Effect vs pt and $\theta_{(th,2)}$

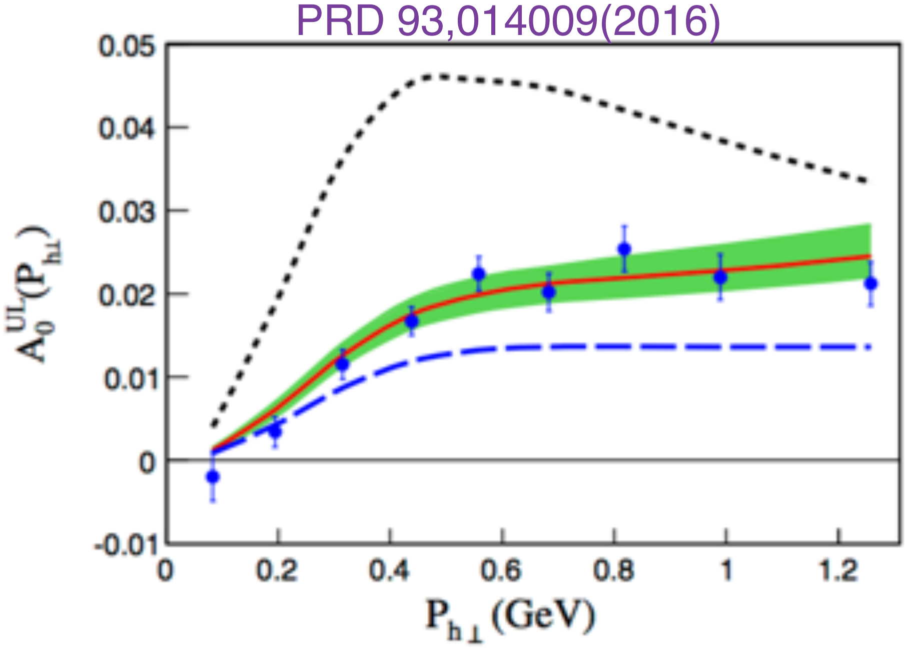




The asymmetries increase for increasing p_t:

- less pronounced for A_{12}, but large uncertainties due to the p_t resolution
- steeper p_t dependence for BESIII
  - different kinematic regions: $\langle z \rangle_{BESIII} > \langle z \rangle_{BaBar}$

PRD 93,014009(2016)



NLL': next-to-leading-logarithm approximation

LL: leading logarithmic calculation

No TMD evolution

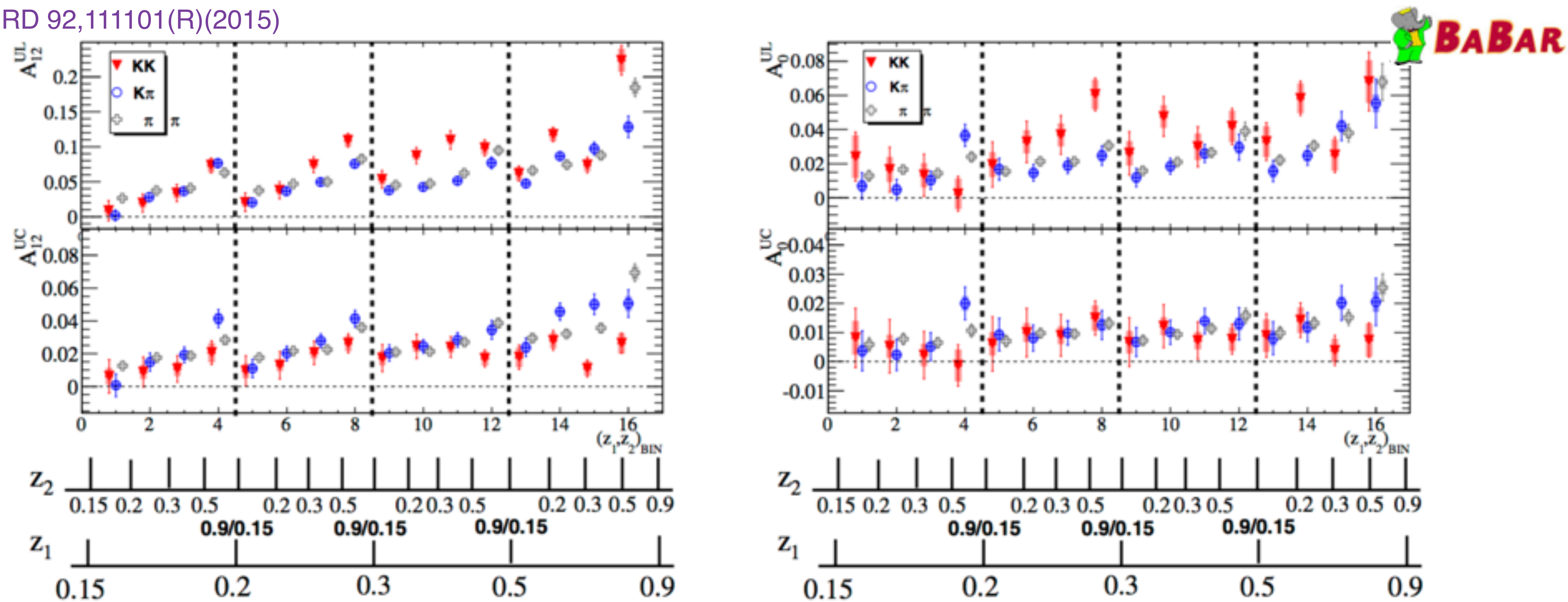
Calculation performed with fixed parameters from Table I in PRD93,014009

- A^{UL} and A^{UC} asymmetries are described very well
- TMD evolution at NLL' describes e^+e^- and SIDIS data adequately well
- better description including higher orders: improvement of the theoretical uncertainties

Collins Effect For KK and Kπ

Simultaneous measurement of KK, Kπ and ππ Collins asymmetries from BaBar data

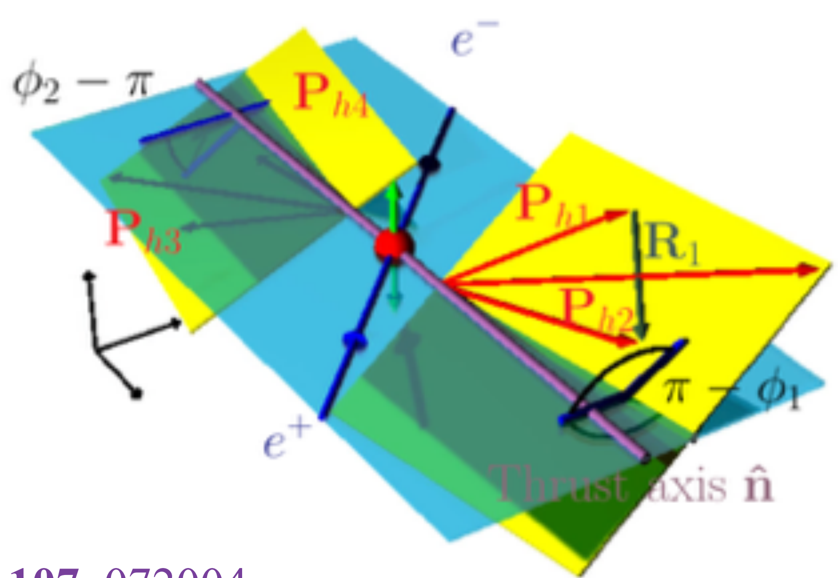
PRD 92,111101(R)(2015)



- Rising of the asymmetry 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 asymmetries consistent with previous measurements (PRD**90**, 052003)

Di-hadron Fragmentation Functions

$e^+e^- \to (h_1h_2)(h_3h_4)X$



PRL**107**, 072004

- The Collins effect is a challenging observable (both theoretically and experimentally) due to its $\mathbf{k}_T$ dependence
- ***Di-hadron or Interference FFs*** (IFFs) represent an alternative way to access spin information
  - complementary access to transversity
  - two hadrons orientation as indication the quark transverse spin
  - collinear model can be used for factorization

$$a_{12R}(z_1, z_2, m_1^2, m_2^2) \propto \frac{1}{2}\frac{\sin^2\theta}{1+\cos^2\theta} \cdot \frac{\sum_{q,\bar{q}} e_q^2 z_1^2 z_2^2 H_1^{\measuredangle,q}(z_1, m_1^2) H_1^{\measuredangle,\bar{q}}(z_2, m_2^2)}{\sum_{q,\bar{q}} e_q^2 z_1^2 z_2^2 D_1^q(z_1, m_1^2) D_1^{\bar{q}}(z_2, m_2^2)}$$

PRD**67**, 094003

$$R_{12} = \frac{N(\phi_1+\phi_2)}{\langle N \rangle} = a_{12}\cos(\phi_1+\phi_2) + b_{12} + c_{12}\sin(\phi_1+\phi_2) + d_{12}\cos(2(\phi_1+\phi_2))$$

$\propto H^{\measuredangle q}{}_1 \cdot H^{\measuredangle q}{}_1$

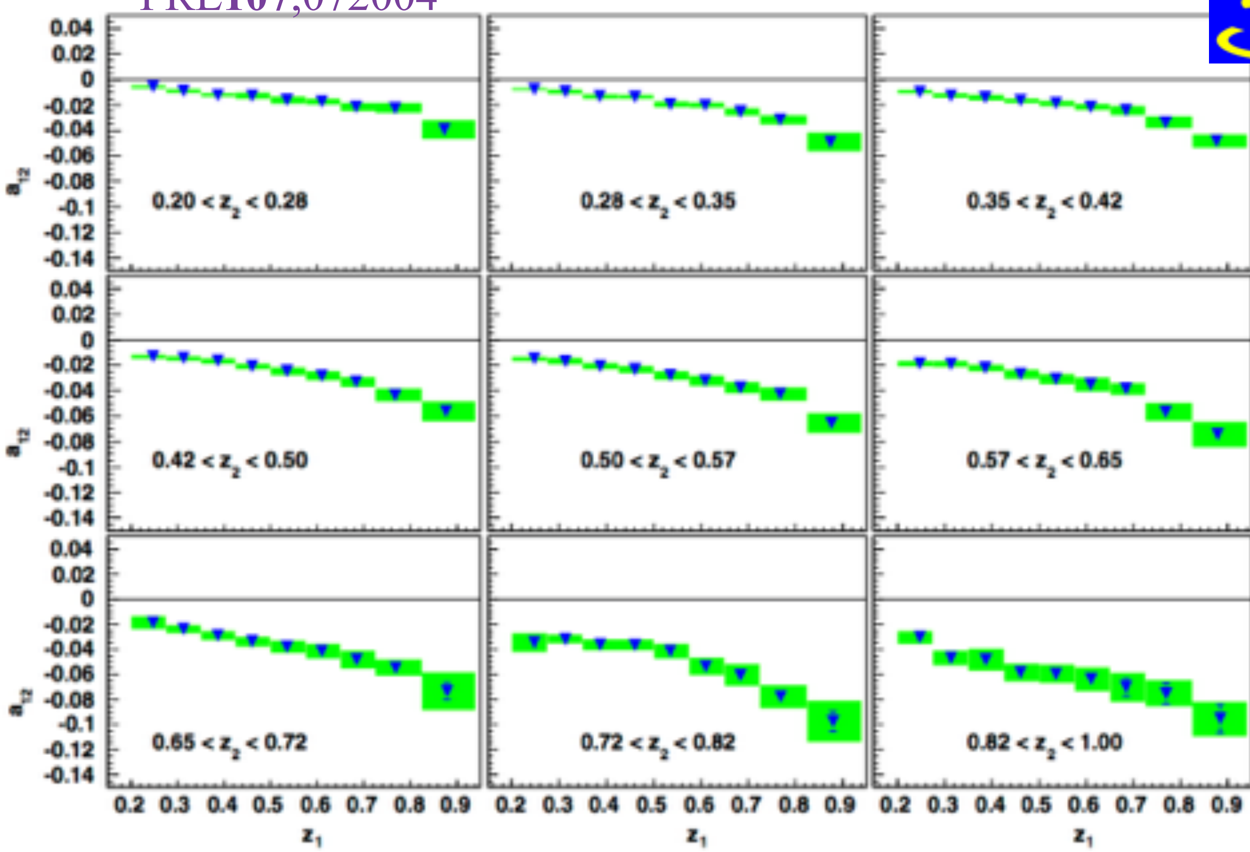
should be consistent with unity

higher-order terms (orthogonal terms, they should not interfere each other)

- 9×9 z_1, z_2 bins
- 8×8 m_1, m_2 bins

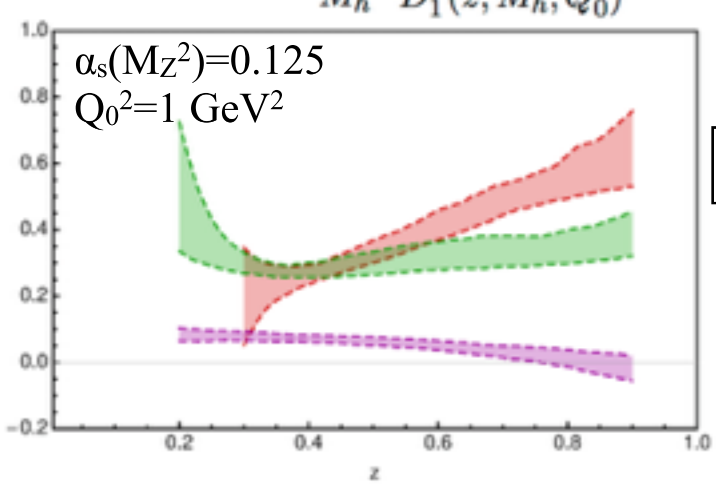
$H^{\sphericalangle}_1$ and transversity extraction

PRL**107**,072004



- Large azimuthal asymmetries for two $\pi^+\pi^-$ pairs in opposite hemispheres measured by Belle using 672 pb^{-1}
- Monotonically decreasing with fractional energy and invariant mass (see back-up)
- no sign change observed in contrast to what predicted in PRL**80**, 1166

$$R(z, M_h) = \frac{|\boldsymbol{R}|}{M_h} \frac{H_1^{\sphericalangle\, u}(z, M_h; Q_0^2)}{D_1^u(z, M_h; Q_0^2)}$$

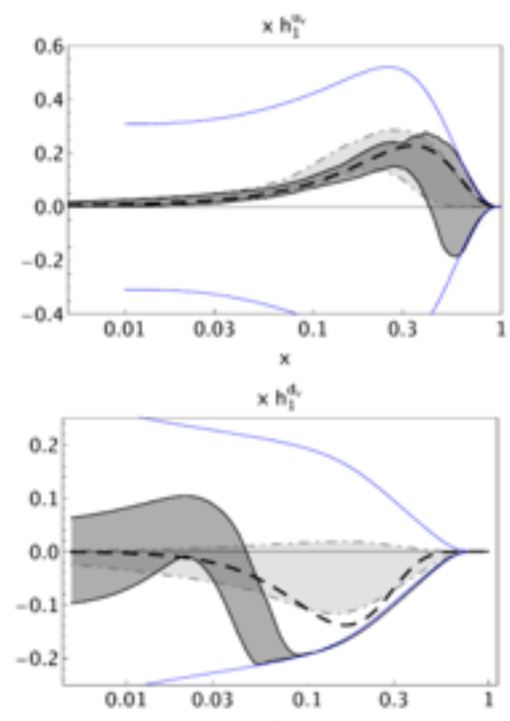


JHEP**05**(2015)123

- M_h=0.4 GeV
- M_h=0.8 GeV
- M_h=1 GeV

bands: 1σ unc.

- Global fit analysis, JHEP**05**(2015)123, in order to extract H_1^* and transversity (JHEP**06**,017; PRL**107**,072004, EPJ Web Conf. **85**, 02018) based on "replica method"
  - collinear factorization framework
  - transversity consistent with extraction from *PRD91, 014034** (different approach used)
  - disagreement for x≥0.1 w.r.t. the outcome of the Collins effect



* see bach-up for more details

$\alpha_s(M_Z^2)$=0.125
Q^2=2.4 GeV^2

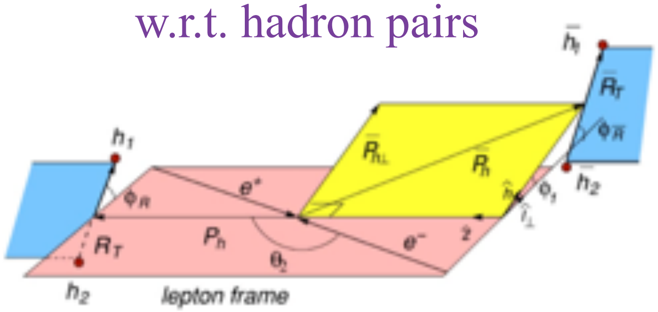
- JHEP**05** flexible scenario
- $H^{\perp}_1$ PRD**87** (DGLAP for collinear part)
- $H^{\perp}_1$ PRD**91** (TMD framework)
- Soffer bound

Di-hadron Fragmentation Functions

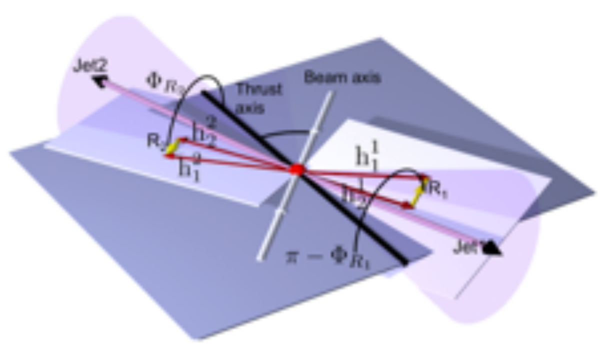
Starting from the fully integrated e^+e^- cross section into four unpolarized hadrons with two leading hadrons in each jet, authors of ref. PRD**67**, 094003 explicitly derive the asymmetry:

$$A(y,z,\bar{z},M_h^2\overline{M}_h^2) = \frac{\langle\cos(2(\phi_R-\phi_{\overline{R}}))\rangle}{\langle 1\rangle} = \frac{\sum_{a,\bar{a}} e_a^2 \frac{3\alpha^2}{2Q^2} z^2\bar{z}^2 A(y) \frac{1}{M_1M_2\overline{M}_1\overline{M}_2} G_1^{\perp a}(z,M_h^2)\overline{G}^{\perp a}(\bar{z},\overline{M}_h^2)}{\sum_{a,\bar{a}} e_a^2 \frac{6\alpha^2}{Q^2} A(y) z^2\bar{z}^2 D_1^a(z,M_h^2)\overline{D}_1^a(\bar{z},\overline{M}_h^2)}$$

PRD67,094003
asymmetric frame
w.r.t. hadron pairs



arXiv:1505.08020
symmetric frame

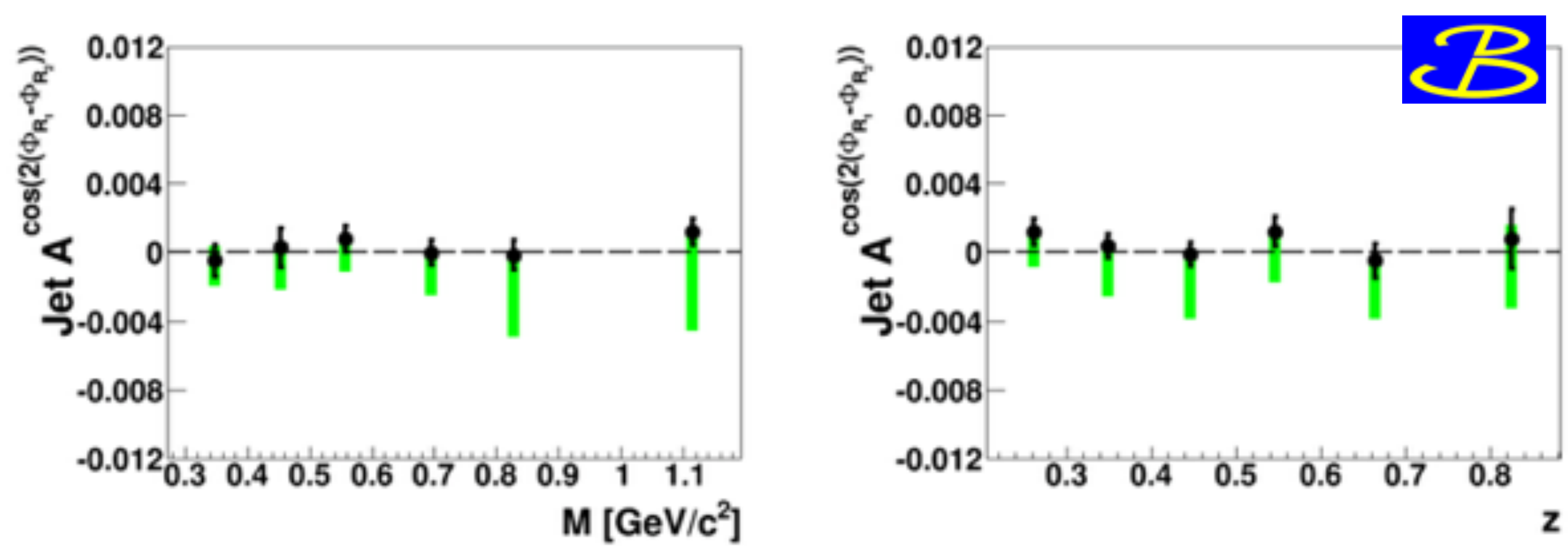


- longitudinally polarized quark IFF $G_1^\perp$
- chiral-even function related to the jet handedness
- asymmetric reference frame
- experimentally: switch to a symmetric frame
  - Belle preliminary: arXiv:1505.08020
  - angles are computed using the jet axis of di-jet event
  - jet axes reconstructed using anti-kT jet algorithm JHEP**0804**, 063

Two-dimensional χ^2 fit is performed to the normalized di-pion pairs:

$$1 + A^{\cos(\phi_{R1}+\phi_{R2})}\cos(\phi_{R1}+\phi_{R2}) + A^{\cos(2(\phi_{R1}-\phi_{R2}))}\cos(2(\phi_{R1}-\phi_{R2}))$$

→



NO SIGNAL observed at Belle

BUT more investigations about the thrust axis method and jet-axes reconstruction are needed

Summary and Conclusions

- Spin-dependent fragmentation functions provide key informations for understanding the hadronic structure and can also be used as a tool for the extraction of parton distribution functions
- e^+e^- annihilation experiments offer the ideal conditions to access FFs

one hadron FF	**without k_T**	**with k_T**
spin-0	D_1	$H_1^{\perp}$
spin-1/2	D_1, G_1, H_1	$D_{1T}^{\perp}$, $H_1^{\perp}$, G_{1T}, $H_{1L}^{\perp}$, $H_{1L}^{\perp}$
spin-1	D_1, D_{1LL}, G_1, H_1, H_{1LT}	$D_{1T}^{\perp}$, $H_1^{\perp}$, G_{1T}, $H_{1L}^{\perp}$, $H_{1L}^{\perp}$, $D_{1T}^{\perp}$, D_{1LT}, D_{1TT}, G_{1LT}, G_{1TT}, $H^{\perp}_{1LL}$, H'_{1LT}, $H^{\perp}_{1LT}$

two hadrons FF	**without k_T**	**with k_T**
spin-0	D_1, $H_1^{\sphericalangle}$	$G_1^{\perp}$, $H_1^{\perp}$

higher twist
T-odd

Summary and Conclusions

- Many attempts from Belle, BaBar and BESIII in order to study spin-dependent FF
  - Collins effects investigated as a function of several kinematic variables at two different center-of-mass energies
  - Di-hadron FFs: only Belle results available, but they could be studied also at BaBar and BESIII
  - lack of knowledge for the corresponding k_T dependence for the unpolarized functions. These informations are required to have a more reliable extraction from global fit analyses

- Prospects
  - Continue to measure precise spin-dependent FFs at Belle, BaBar and BESIII
  - Ongoing works:
    - π^0, η (Hairong Li from Indiana) Collins asymmetry (preliminary results will be ready soon)
    - K Collins asymmetries (F. Giordano, R. Seidl), and kT Collins dependence (BaBar)
    - $\pi\rho^0$ Collins asymmetry (Belle)
    - Unpolarized IFFs for pions and kaons (preliminary results will be ready for SPIN-2016) (A. Vossen)
  - More works planned
  - Measure other interesting QCD-related quantities:
    - Λ FFs $D_1^{\perp}(z,k_T)$, which is the fragmentation counterpart to the Sivers function (Yinghui Guan, KEK/Indiana; preliminary results will be ready for SPIN-2016)

BK slides

Transversity distributions from single- and di-hadron production

A. Martin, F. Bradamante, V. Barone, *PRD**91**, 014034*

- Extraction of the transversely point by point in x both from signal-hadron and di-hadron data
- no data parameterization used
- analyzing power determined from e+e- measurement (PRL107,072004):

$$|\tilde{a}_P^{hh}(Q^2)| = \left|\frac{\tilde{H}_{1u}^{\sphericalangle}(Q^2)}{\tilde{D}_{1u}^{hh}(Q^2)}\right| = \sqrt{-\frac{1}{5}(1+\mu^2)(5+\lambda^2)\frac{\langle 1+\cos^2\theta_2\rangle}{\langle \sin^2\theta_2\rangle}A_{e^+e^-}^{hh}(Q^2)},$$

$$\frac{\langle \sin^2\theta_2\rangle}{\langle 1+\cos^2\theta_2\rangle} = 0.7636,$$ μ=0.5 (charm contr.), λ=0.5 (strange contr.)

$$A_{e^+e^-}^{hh} = -0.0196 \pm 0.0002 \pm 0.0022$$

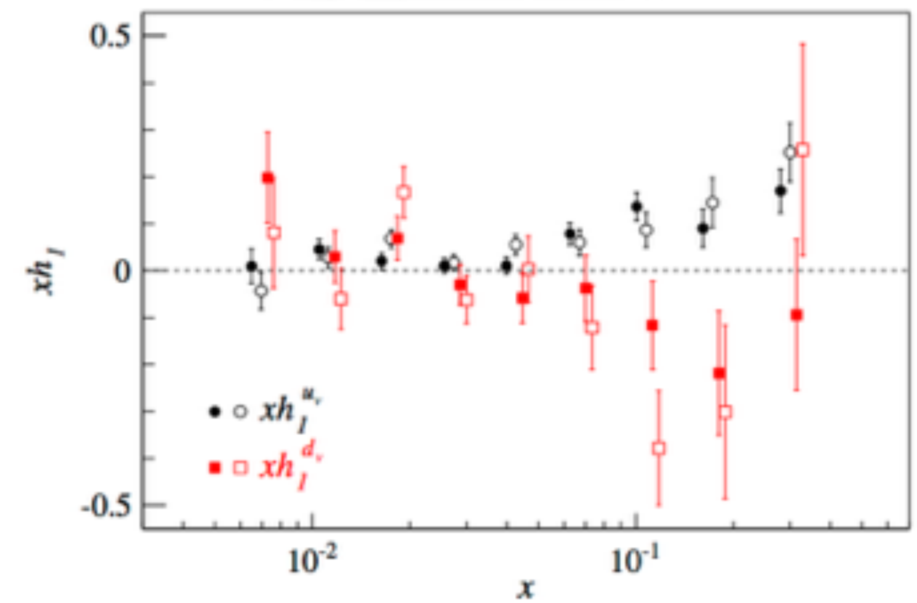
$$|\tilde{a}_P^{hh}(Q_B^2)| = 0.201 \quad \text{at } Q_B^2 \simeq 110\ \text{GeV}^2/c^2$$

- use infos from e+e- data to get the transversity distributions from the SIDIS data (COMPASS data only, without any corrections and neglecting Q^2 evolution of the analyzing power):

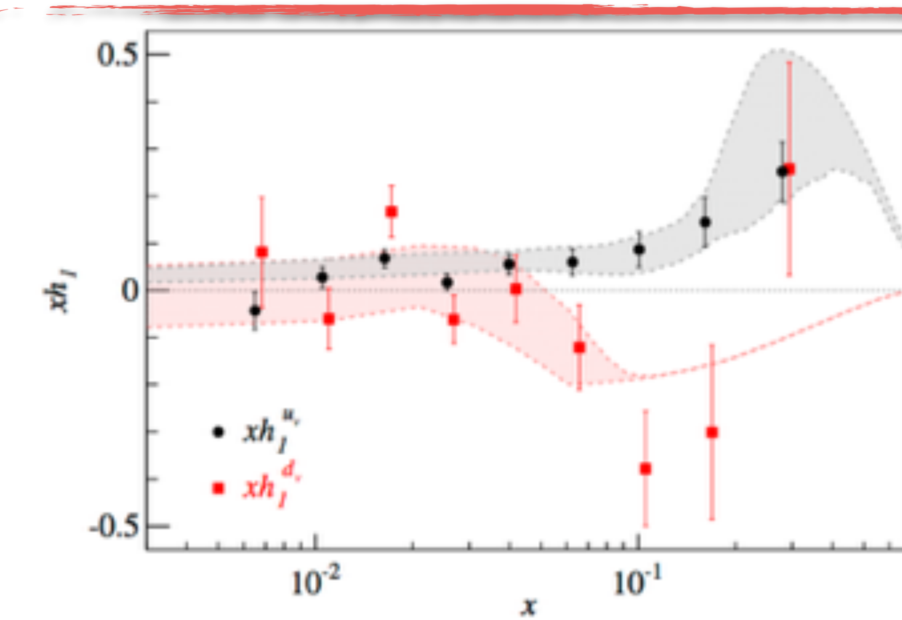
$$4xh_1^{u_v} - xh_1^{d_v} = \frac{1}{\tilde{a}_P^{hh}}(4xf_1^{u+\bar{u}} + xf_1^{d+\bar{d}} + \lambda xf_1^{s+\bar{s}})A_p^{hh},$$

$$xh_1^{u_v} + xh_1^{d_v} = \frac{1}{3}\frac{1}{\tilde{a}_P^{hh}}(5xf_1^{u+\bar{u}} + 5xf_1^{d+\bar{d}} + 2\lambda xf_1^{s+\bar{s}})A_d^{hh}$$

The transversity values obtained from the di-hadron asymmetries and from the Collins asymmetries are very well compatible: supports the fact that the same distributions are measured in the two processes



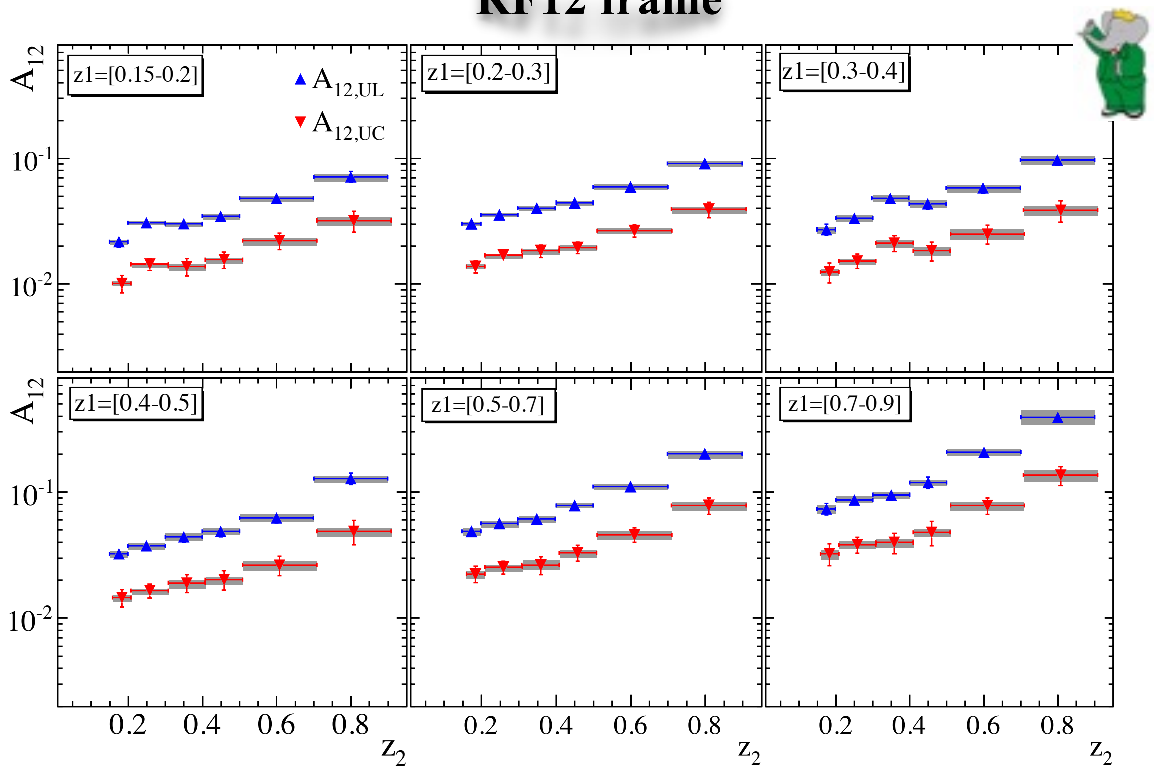
○ □ Transversity from di-hadron data
● ■ Transversity from Collins asymmetries



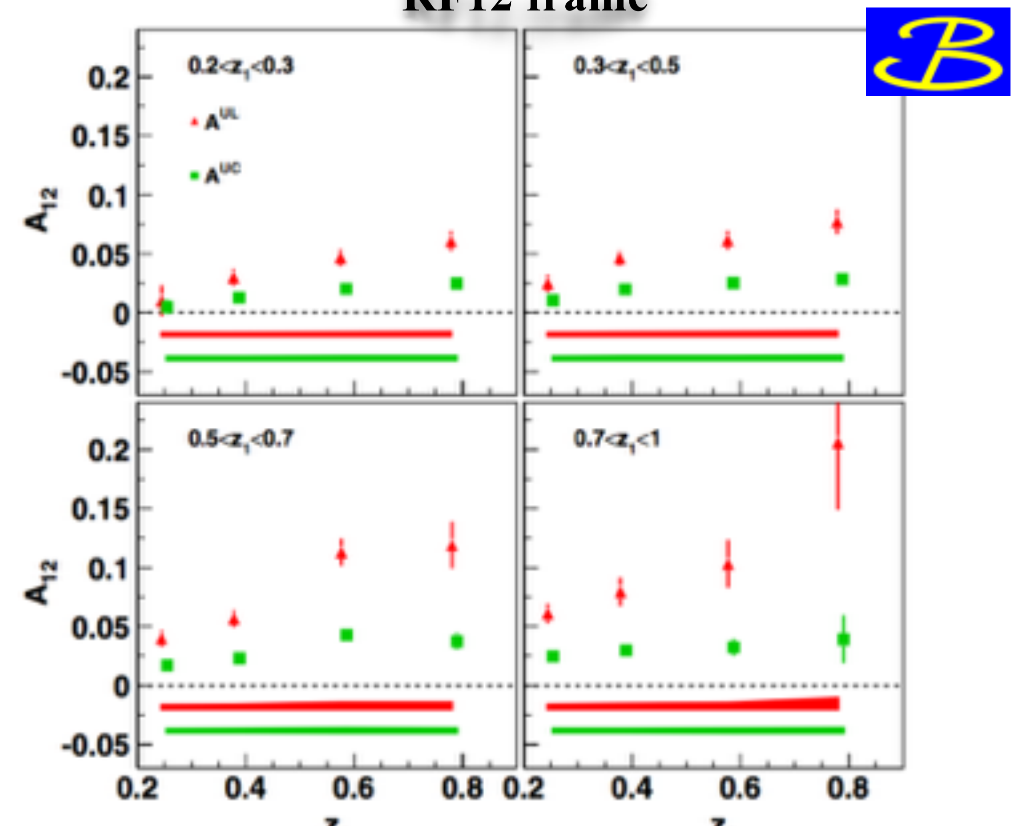
● ■ Transversity distribution extracted from di-hadron data
Bacchetta, Courtoy, Radici, JHEP03, 119 (Q^2=2.4 GeV^2)

Collins asymmetries vs z

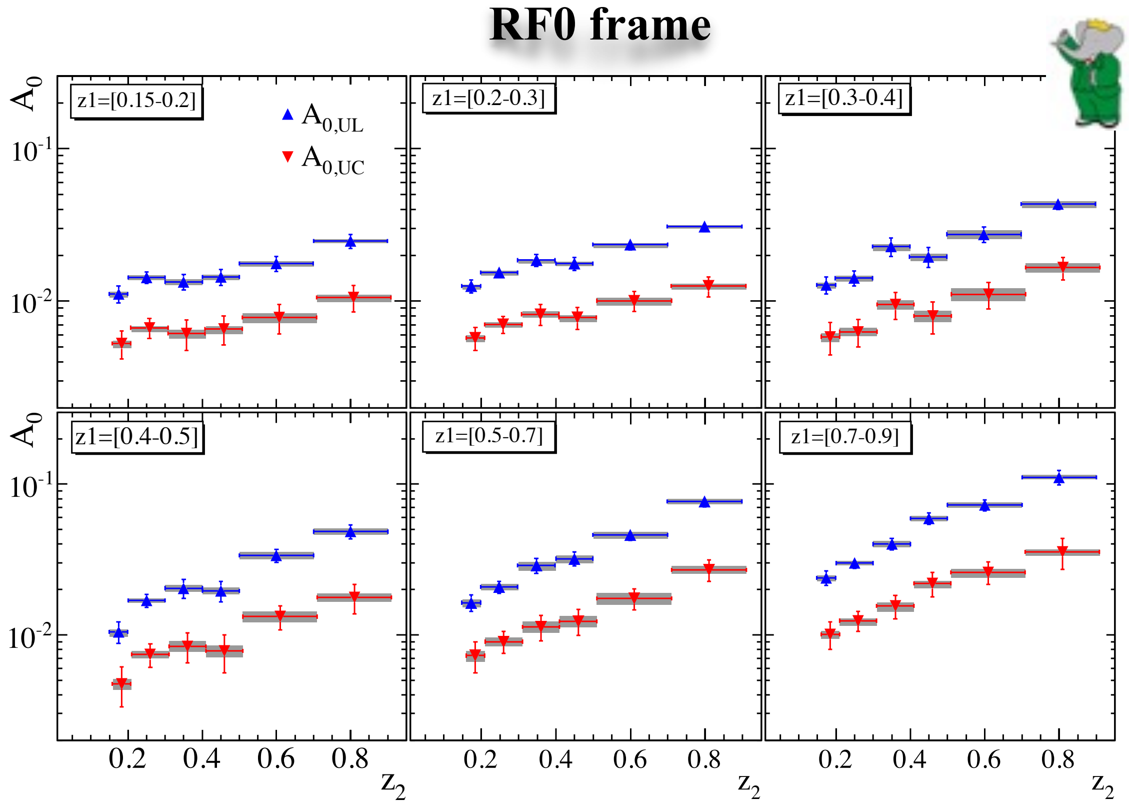
RF12 frame



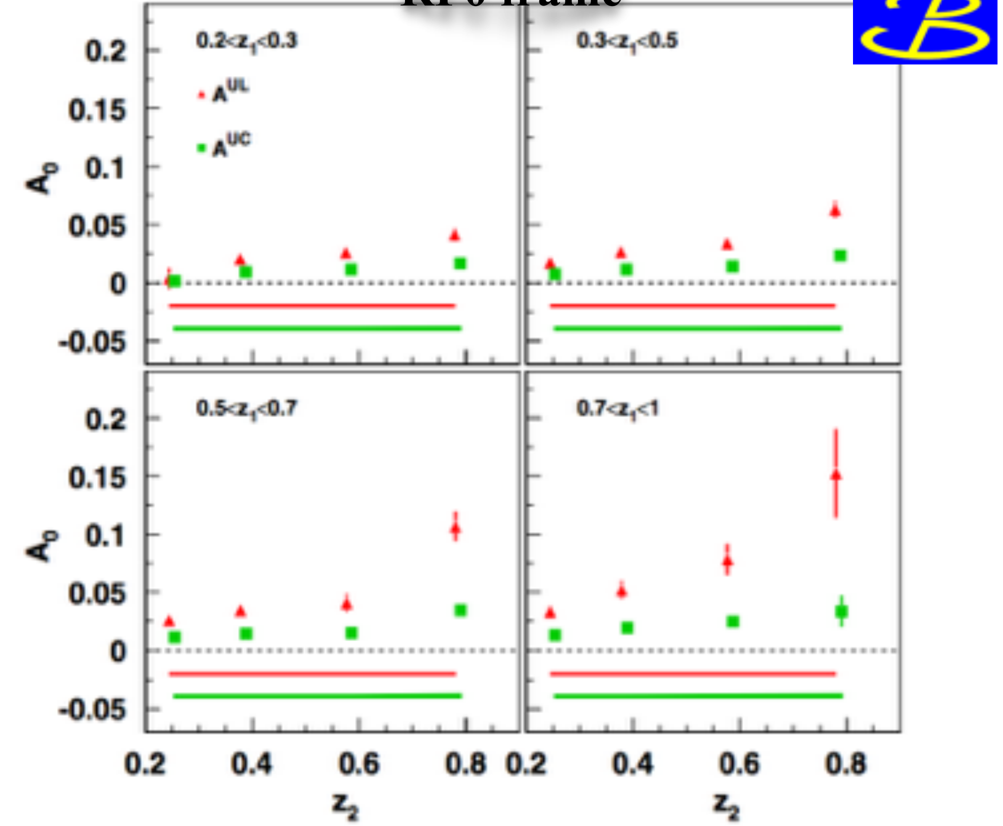
RF12 frame



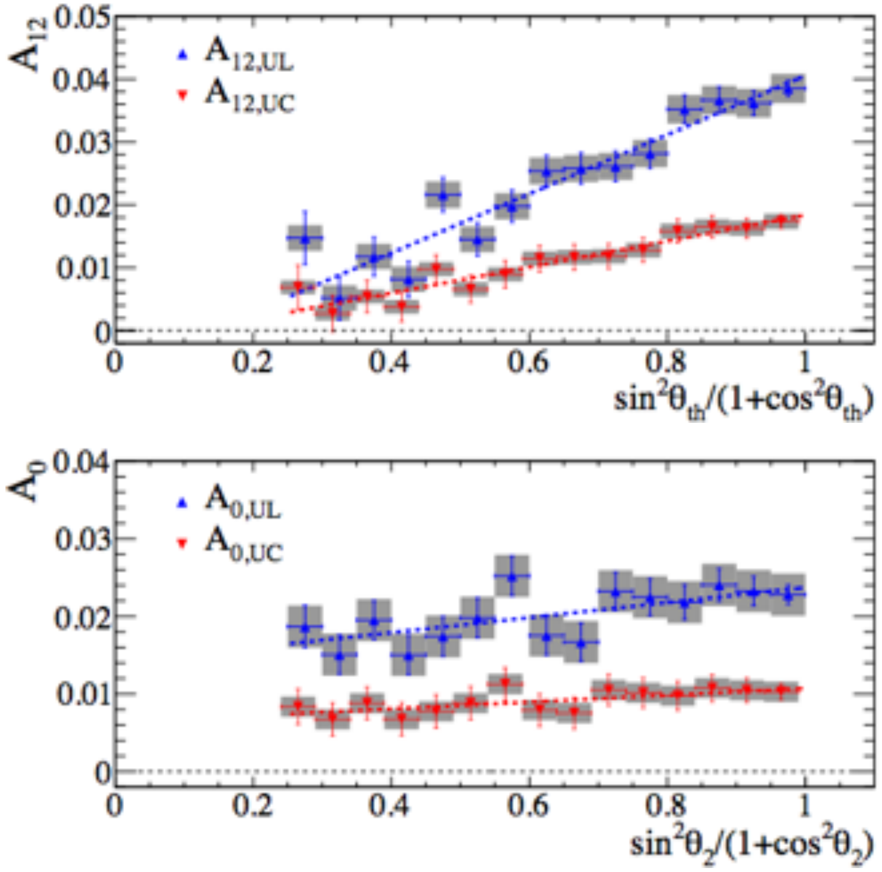
RF0 frame

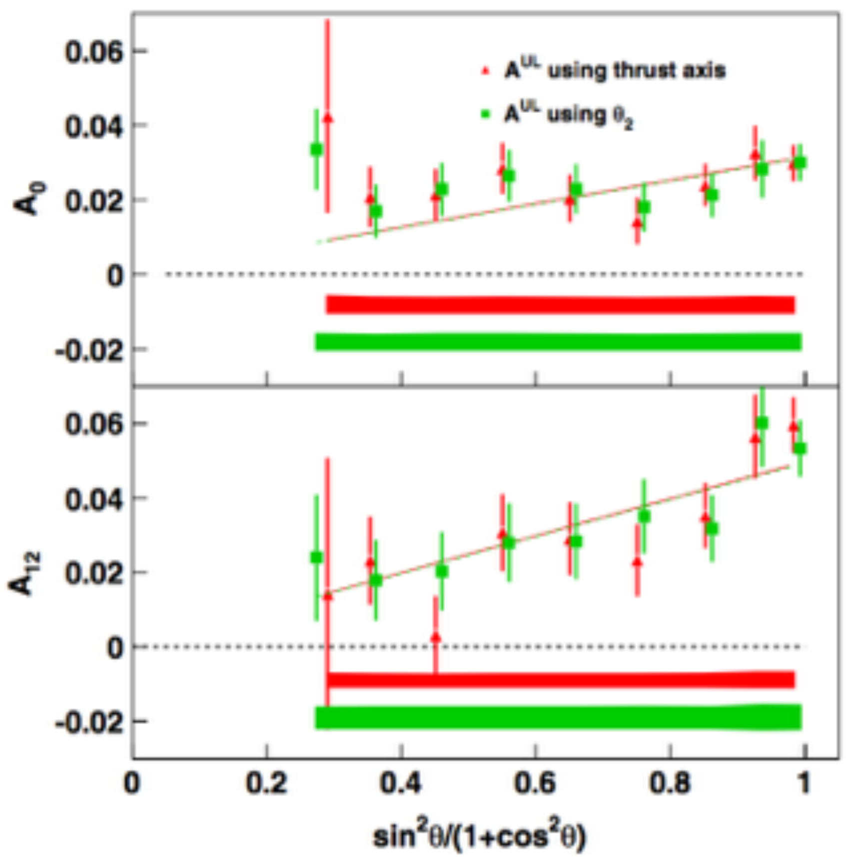


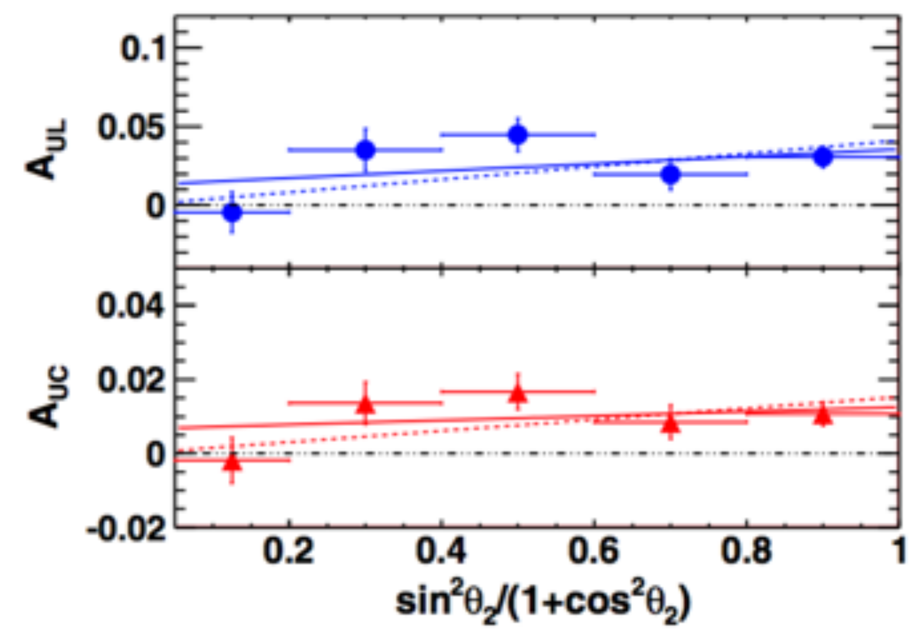
RF0 frame



Collins asymmetries vs $\sin^2\theta/(1+\cos^2\theta)$







RF12: thrust polar angle θ_{th}

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

==> Intercept consistent with zero, as expected

RF0: thrust polar angle θ_2

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

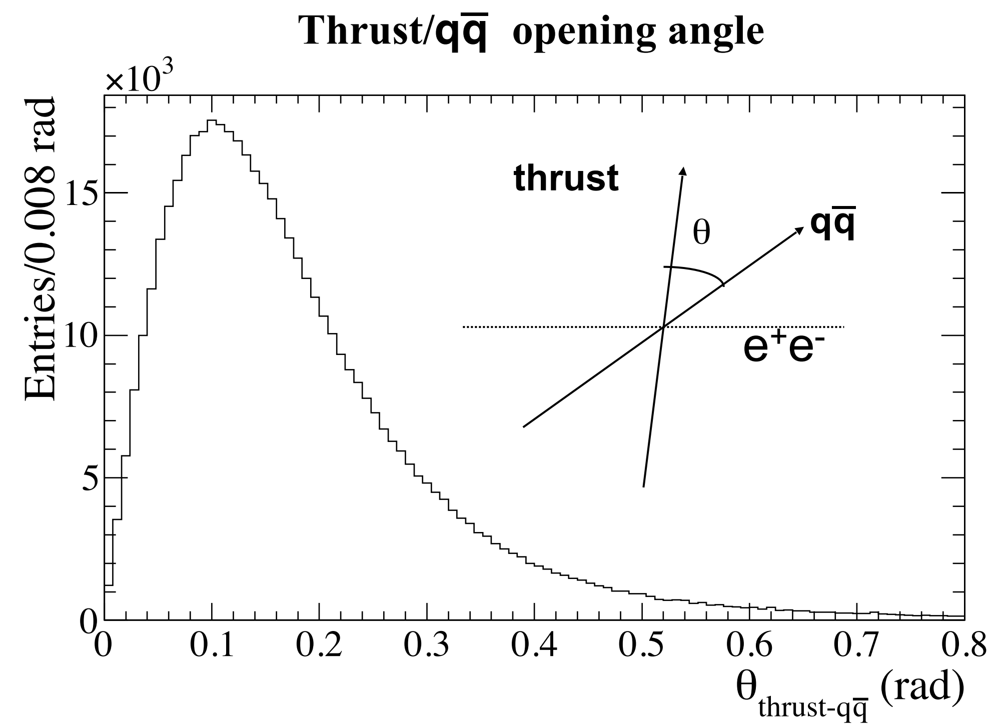
==> The linear fit gives a non-zero constant parameter → the second hadron momentum provides a worse estimation of the $q\bar{q}$ direction?

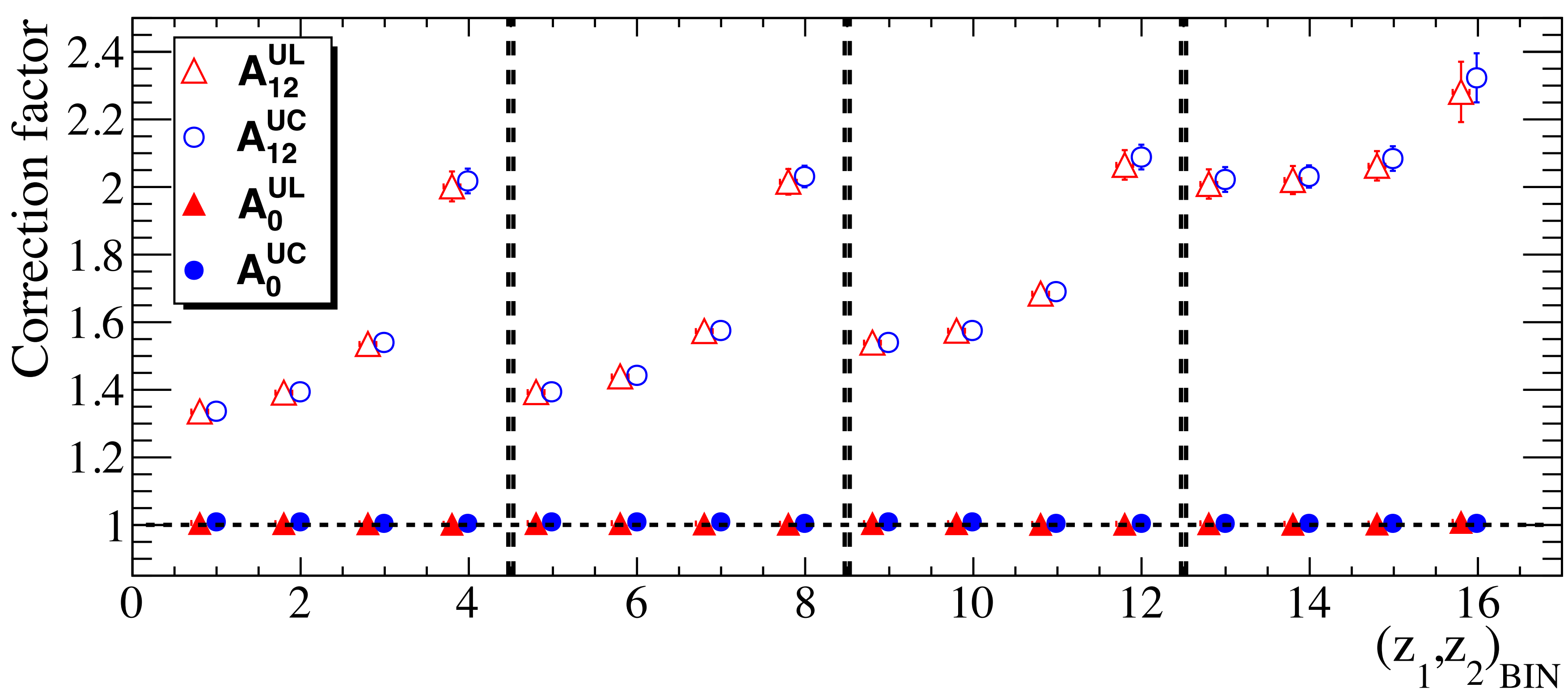
Effect of the thrust axis reconstruction

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

- RF12: the azimuthal angles are calculated respect to the thrust axis → large smearing;
- RF0: no thrust axis needed → smearing due only to PID and tracking resolution.

⇒ Using the MC sample,we introduce in the simulation several values of asymmetries, and we study the differences between the simulated and the reconstructed ones

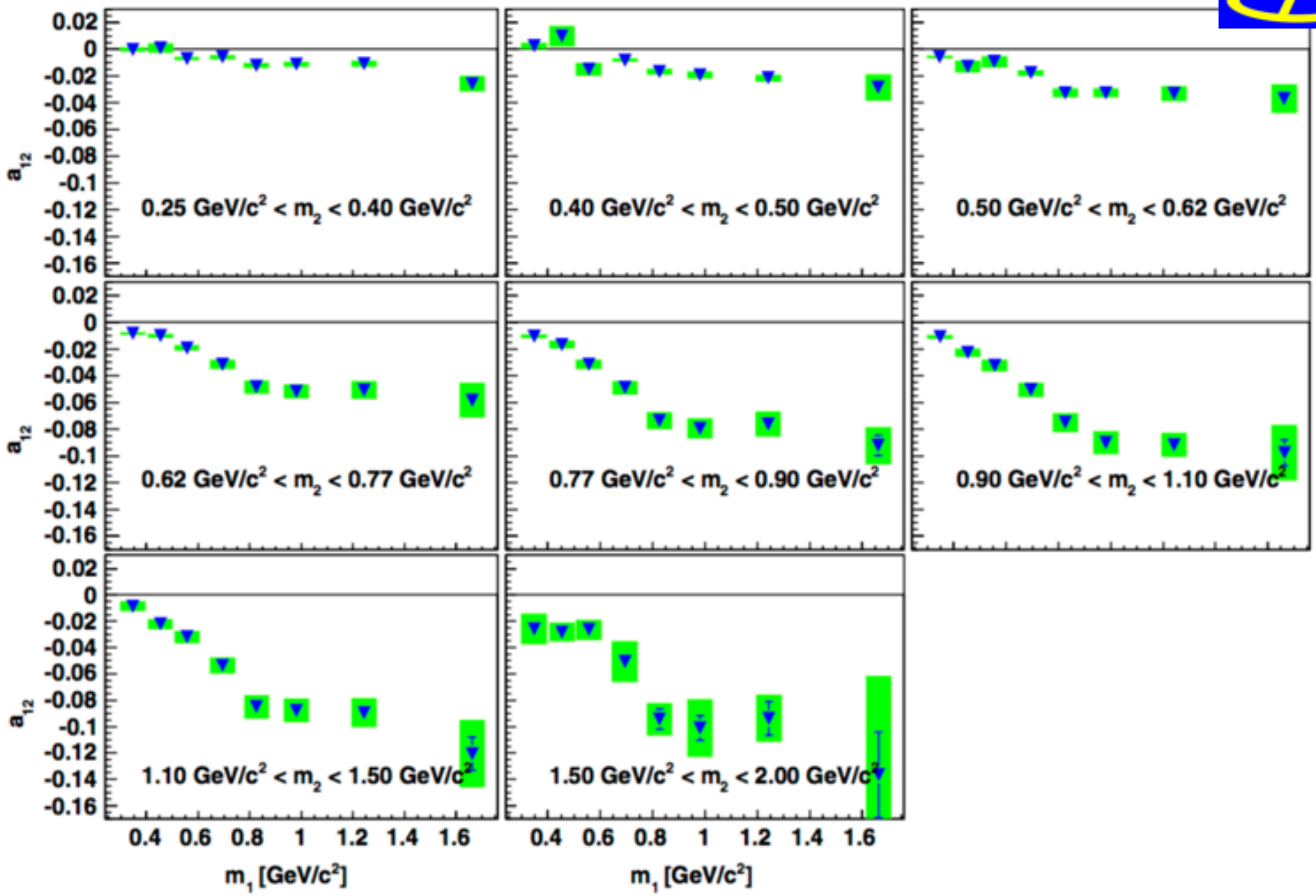




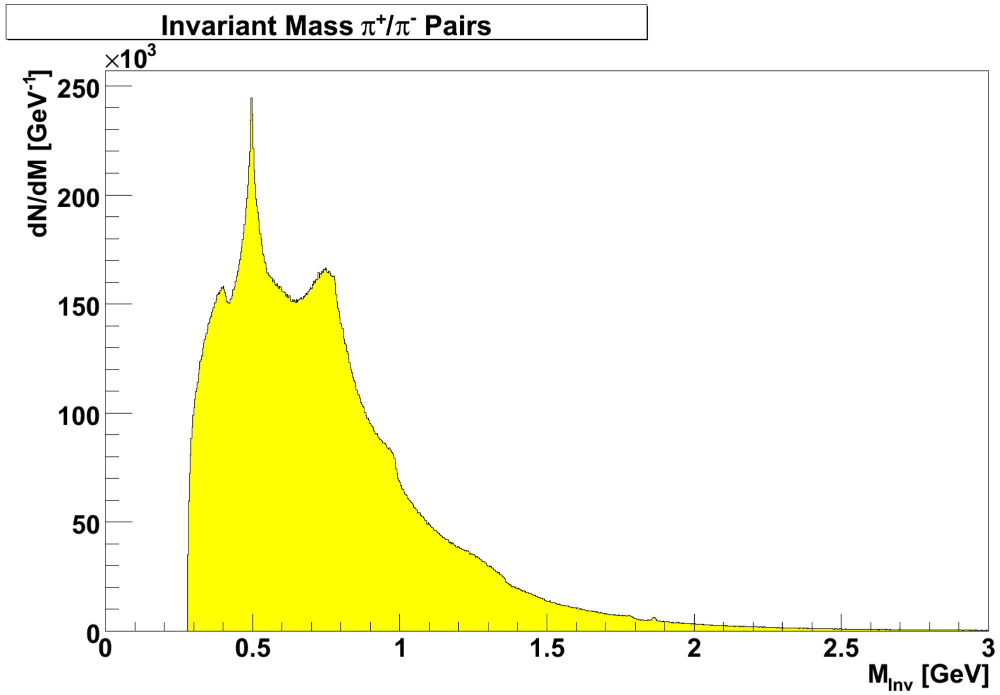
- RF12: strong dilution observed
  - correction ranges between 1.3 to 2.3 for increasing z
- RF0: no dilution observed
  - no correction needed

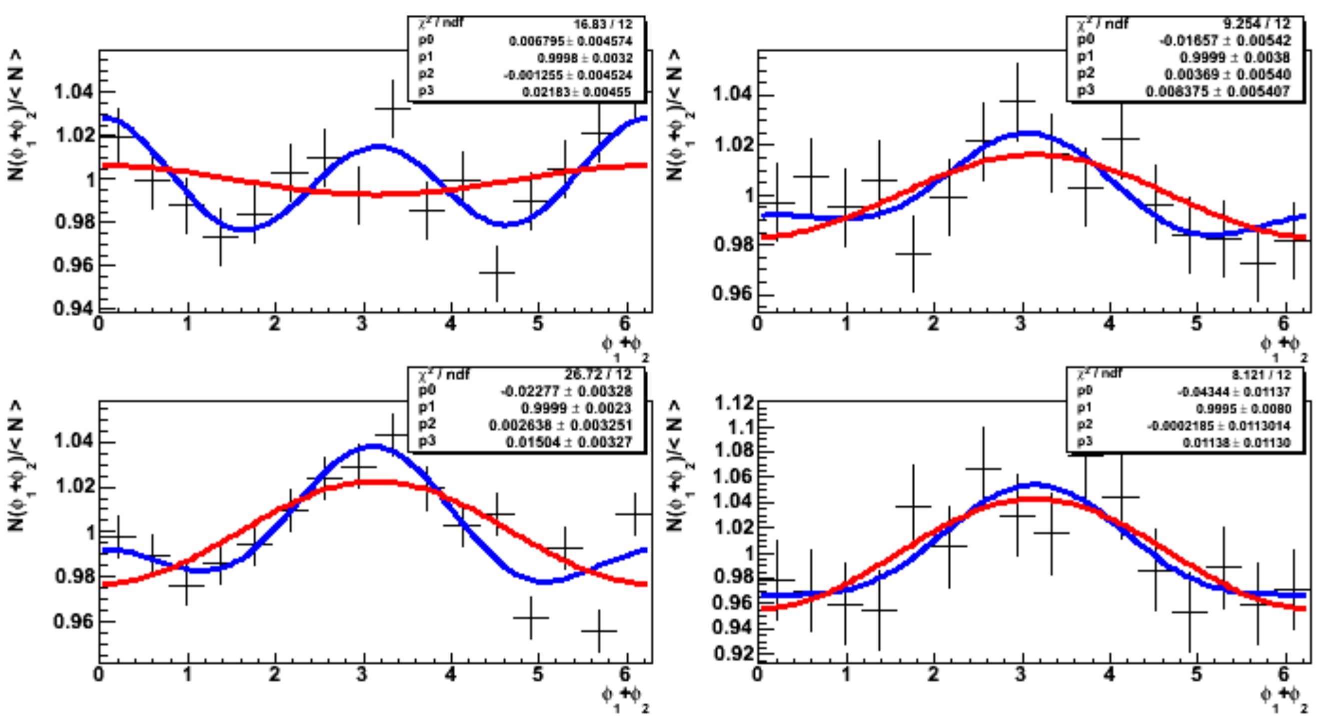
Same corrections applied for the three hadron pair combinations

Di-hadron FFs vs. m



Di-hadron FFs: asymmetry extraction





- Build normalized yields:

$$\frac{N(\phi_1+\phi_2)}{\langle N \rangle},$$

- Fit with:

$$a_{12}\cos(\phi_1+\phi_2)+b_{12}$$

or

$$a_{12}\cos(\phi_1+\phi_2)+b_{12}+$$
$$c_{12}\cos 2(\phi_1+\phi_2)+d_{12}\sin(\phi_1+\phi_2)$$

Amplitude a_{12} directly measures (IFF) x (-IFF) (no double ratios)

slide from Ralf Saidl, INT workshop - Feb 10, 2012

Global analysis

RHIC and SIDIS experiments measure:

Transversity $\delta q(x)$ X

Collins Fragmentation function

or Interference Fragmentation function (IFF)

2 Unknown
Functions measured
together

•Universality understood
•Evolution ?

Transversity

From e^+e^- experiments:

Collins X Collins - well studied for charged pion pairs; z dependence for KK and Kpi; other combinations can be studied

or IFF X IFF – charged pions