FAIRNESS - FAIR next generation scientists

Exploring the nucleon structure: Fragmentation Functions from e+e- annihilation experiment

ISABELLA GARZIA

UNIVERSITY OF FERRARA AND INFN-FERRARA

Università degli Studi di Ferrara

INFN

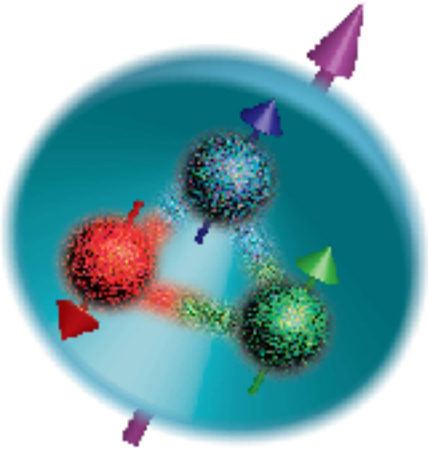
HOTEL & SPA MEDITERRANEAN VILLAGE, PARALIA (PIERIA, GREECE)

THURSDAY, MAY 26, 2022

Introduction

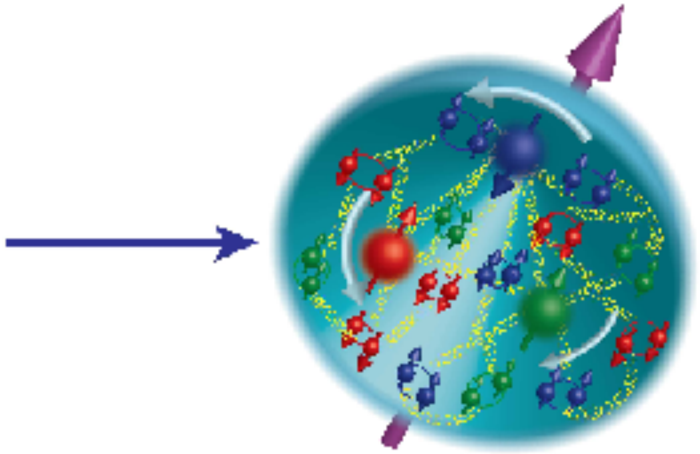
QCD picture of the nucleon

Naive picture



three non-relativistic quarks

Realistic picture



infinite number of relativistic quarks and gluons

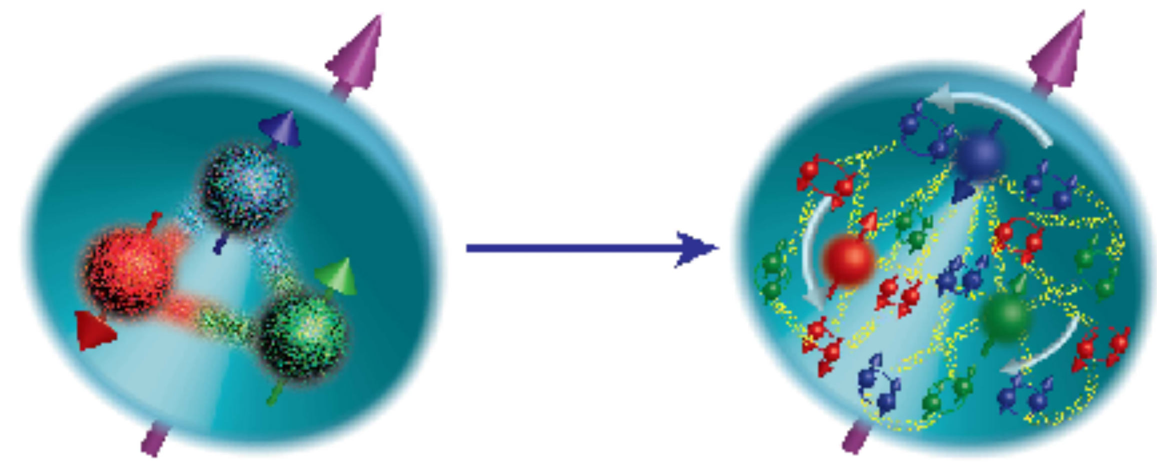
Parton Distribution Functions (PDFs)

https://www.annualreviews.org/doi/pdf/10.1146/annurev-nucl-011720-042725

Introduction

Naive picture | Realistic picture

QCD picture of the nucleon



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infinite number of relativistic quarks and gluons

Parton Distribution Functions (PDFs)

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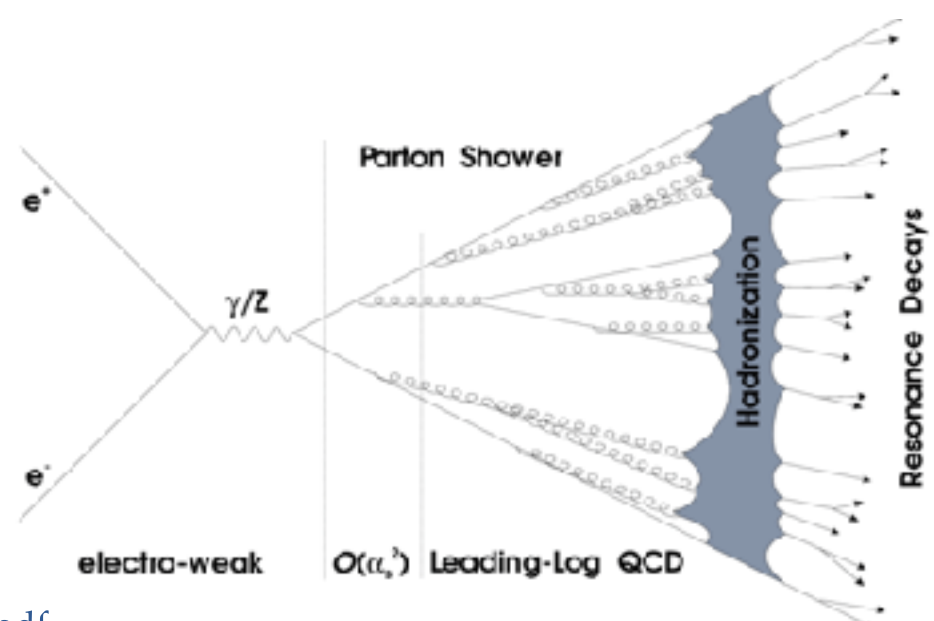
Hadron formation

- How many particles and how many jets created?
- What fraction of the initial parton momenta do they carry?

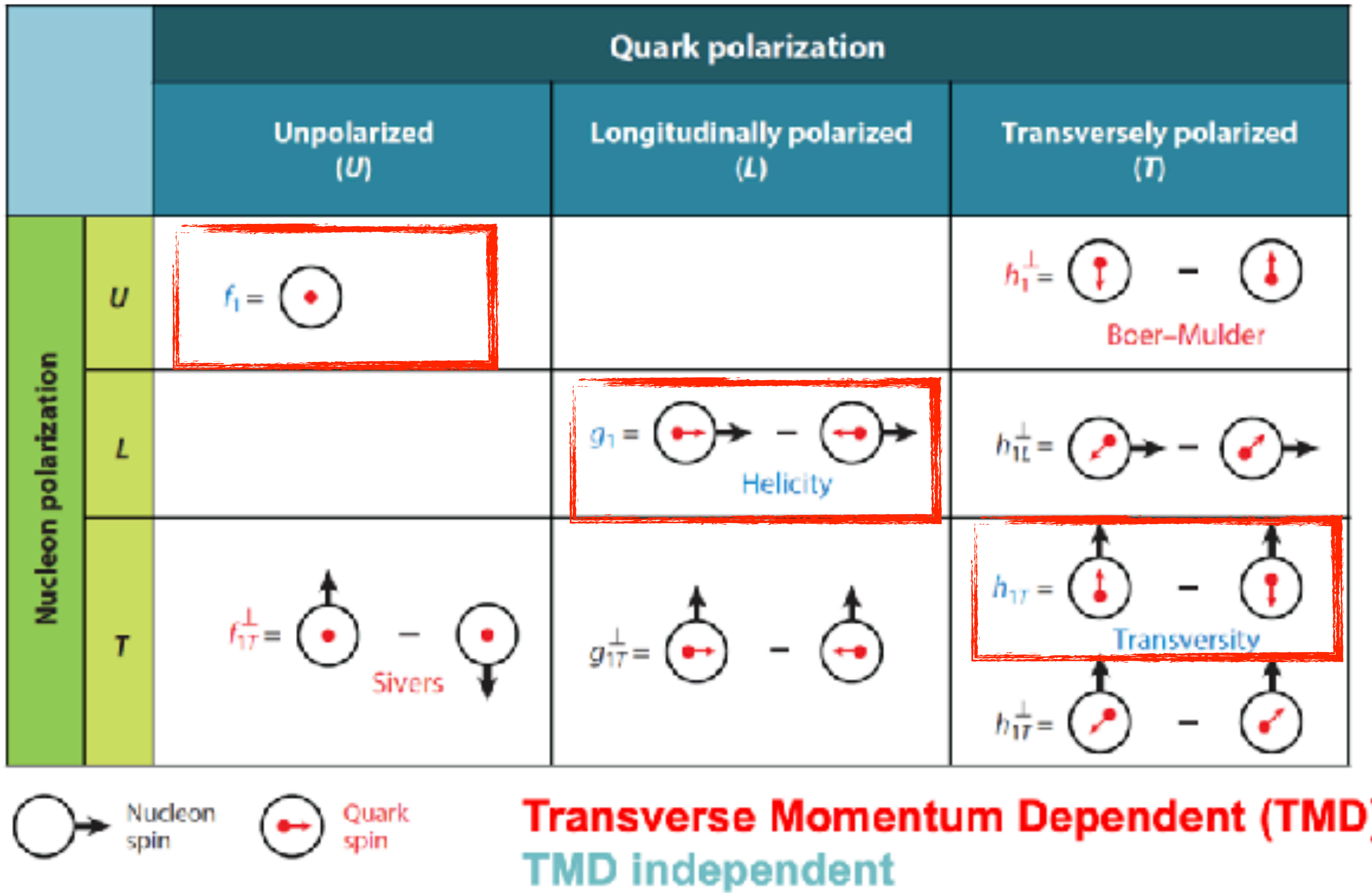


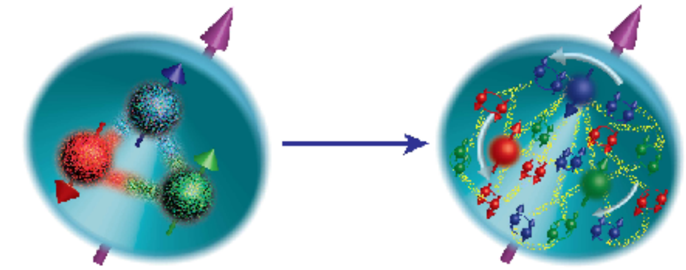
Fragmentation Functions (FFs)

https://pdg.lbl.gov/2019/reviews/rpp2019-rev-frag-functions.pdf

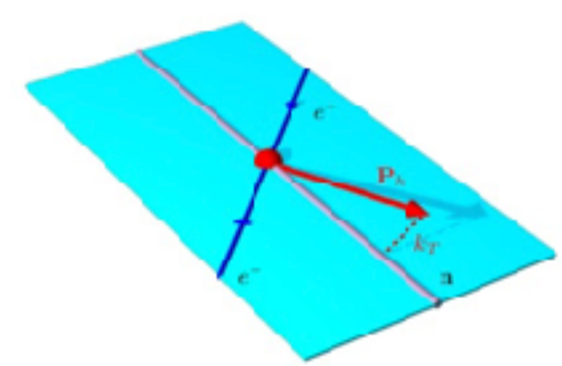
Universal *and* ***non-perturbative*** *objects*

Parton Distribution Functions





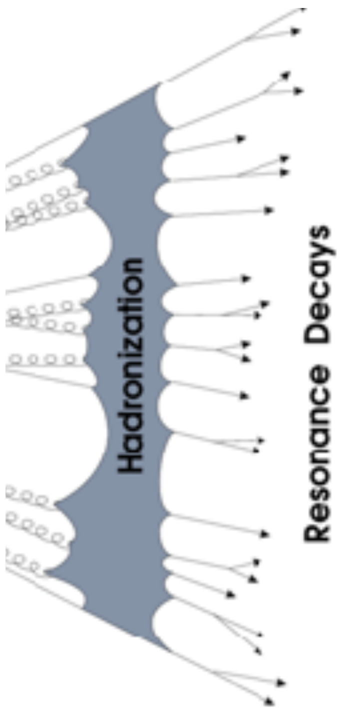
f_1, g_1, and **h_1 :** three leading-twist PDFs
- probability interpretation;
- complete description of the nucleon structure at leading-twist level;
- provide 2-dim (collinear) picture of the nucleon structure
- TMD: 3-D picture



h1: Transversity PDF

- Describe the distribution of quark's transverse spin in a transversely polarized nucleon
- Chiral-odd

Fragmentation Functions



FFs: formation of colourless hadrons starting from a coloured partonic initial state;

- probability that a parton *i* fragments into an hadron *h* carrying away a fraction *z* of the parton's momentum

quark pol. / hadron pol.

	U	L	T
U	D_1		$H_1^\perp$
L		G_{1L}	$H_{1L}^\perp$
T	$D_{1T}^\perp$	G_{1T}	$H_1,\ H_{1T}^\perp$

$H_1^\perp$: Collins FF

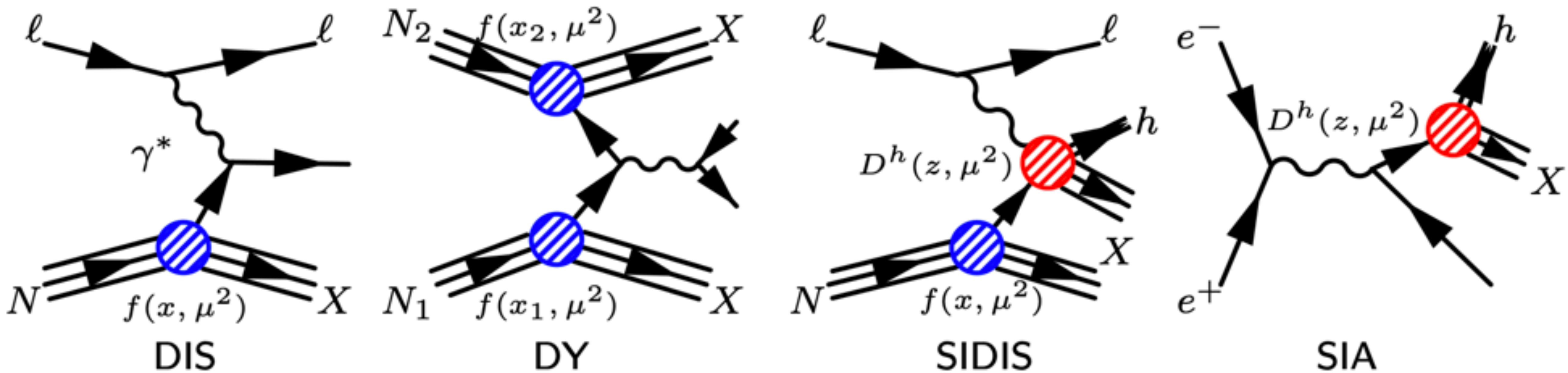
- Chiral-odd function

Transverse Momentum Dependent (TMD) FFs ⇒ to study the spin-dependent observables

- tools to investigate the 3D-structure of nucleons
- when only spinless hadrons (π, K) are considered, we have only D_1 and $H_1^\perp$
- TMDs evolution

How to access PDFs and FFs

- Physical observables are written as a convolutions of coefficient functions and PDFs/FFs
- *QCD factorization theorem*: separate the cross sections into a perturbatively calculable scattering contributions and non-perturbative one encoded in PDFs/FFs



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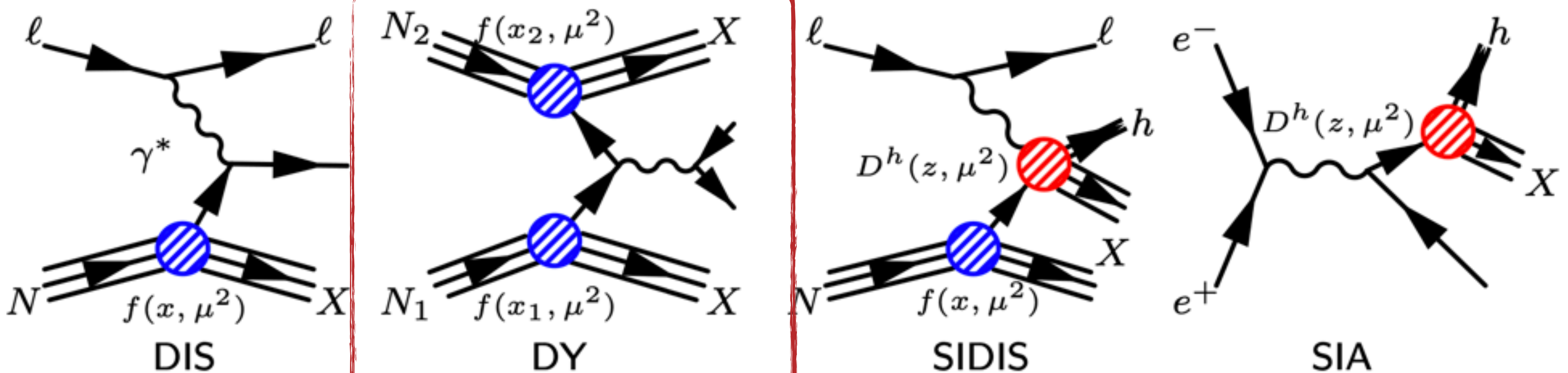
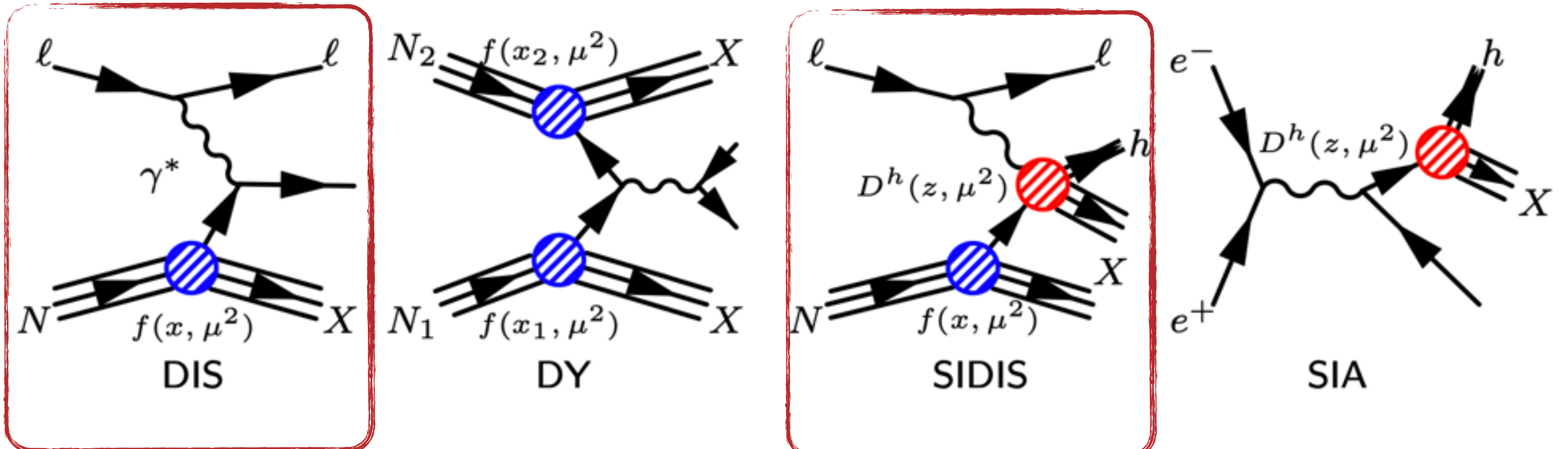


Direct access to PDFs;
Sensitive to gluon FFs;
large z behaviour;
Large theoretical uncertainties;
no sensitive to heavy quarks

How to access PDFs and FFs

- Physical observables are written as a convolutions of coefficient functions and PDFs/FFs
- *QCD factorization theorem*: separate the cross sections into a perturbatively calculable scattering contributions and nonperturbative one encoded in PDFs/FFs



Flavour/charge separation
SIDIS: needed input on FFs;
Limited access to gluons

How to access PDFs and FFs

- Physical observables are written as a convolutions of coefficient functions and PDFs/FFs
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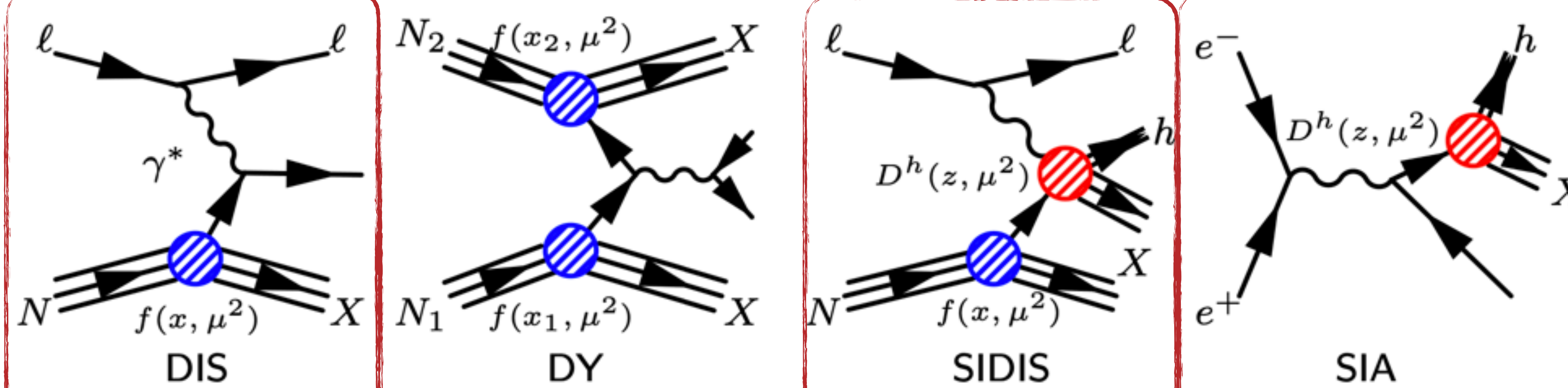
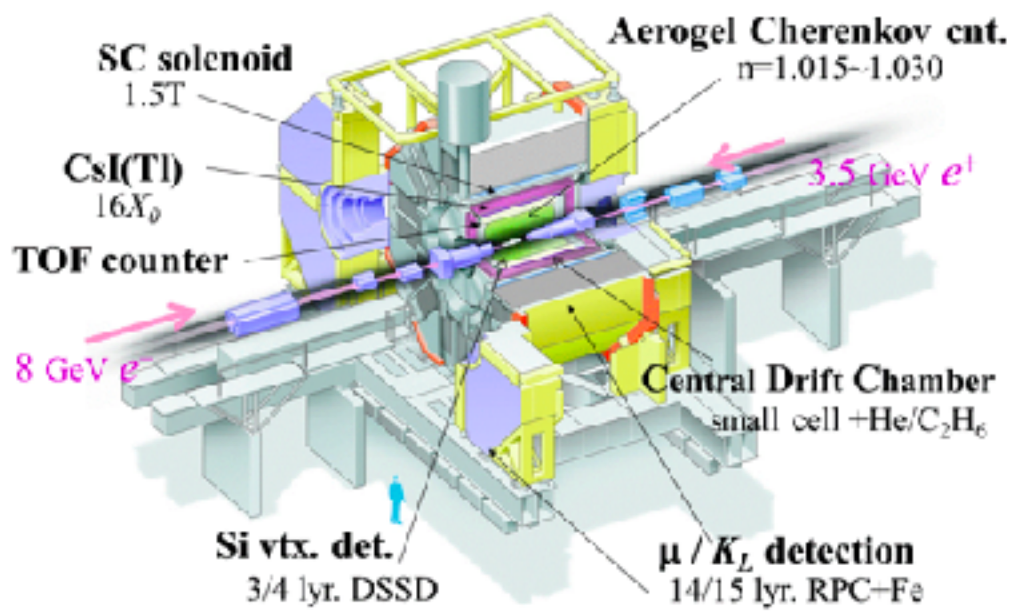


Flavour/charge separation
SIDIS: needed input on FFs;
Limited access to gluons

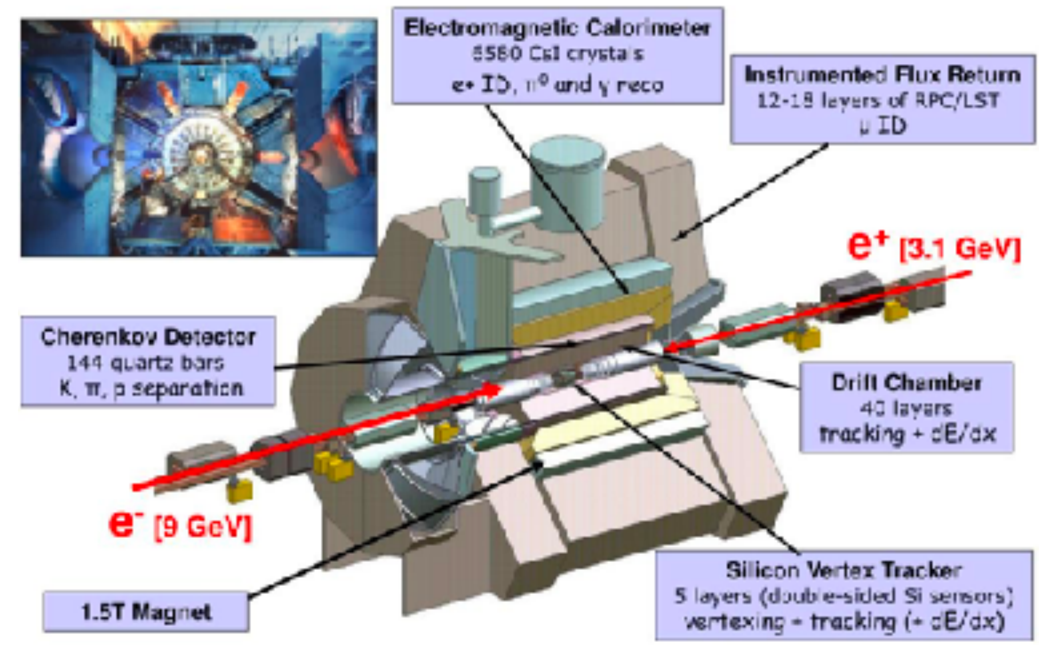
Clean process, high statistic;
Sensitivity to heavy quarks;
Limited in flavour separation;
Limited access to gluon FFs

Belle, BaBar, BESIII detectors

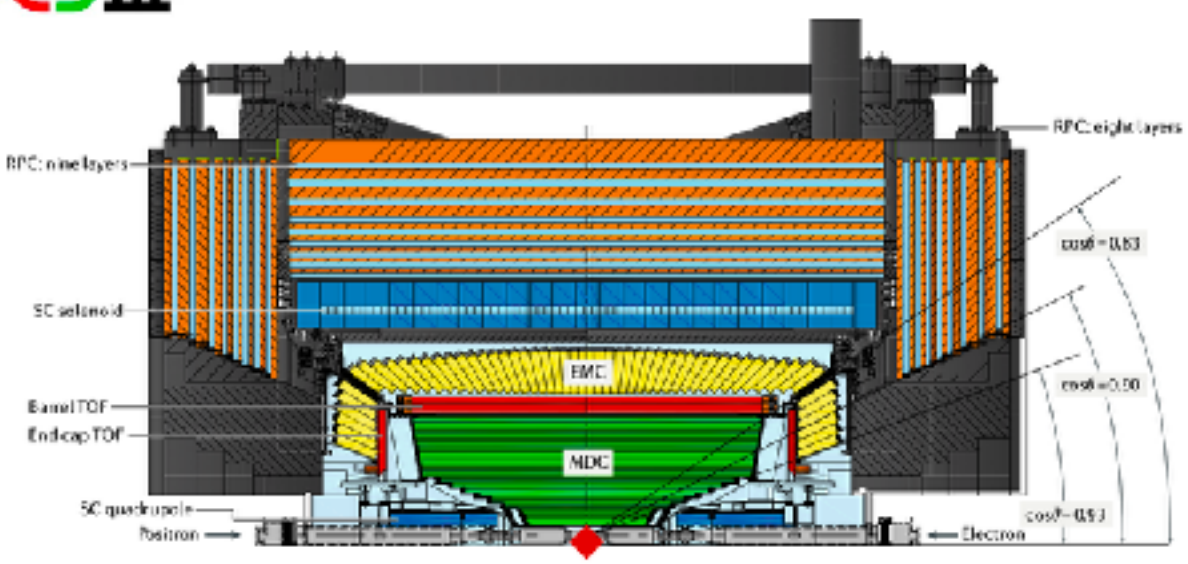
Belle Detector

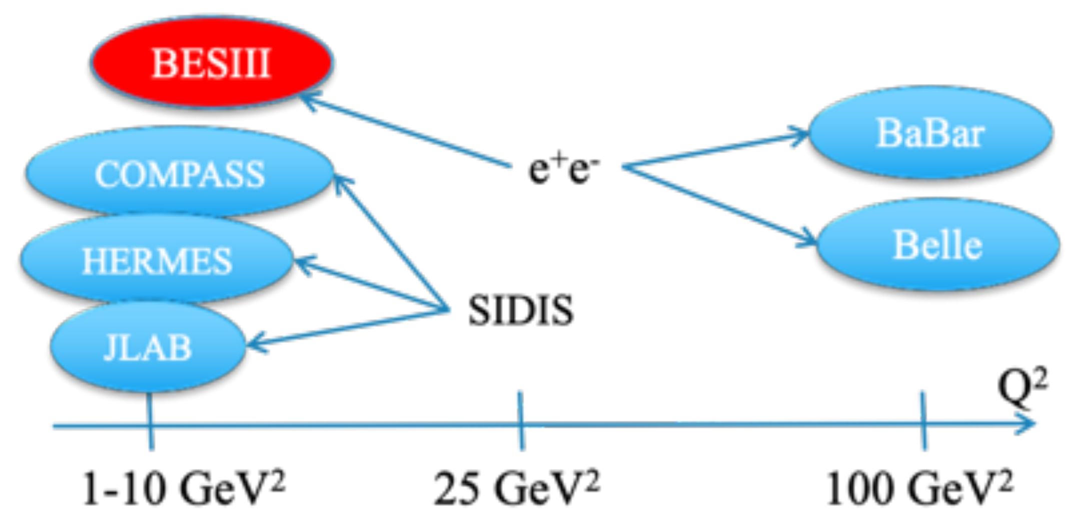


BaBar Detector

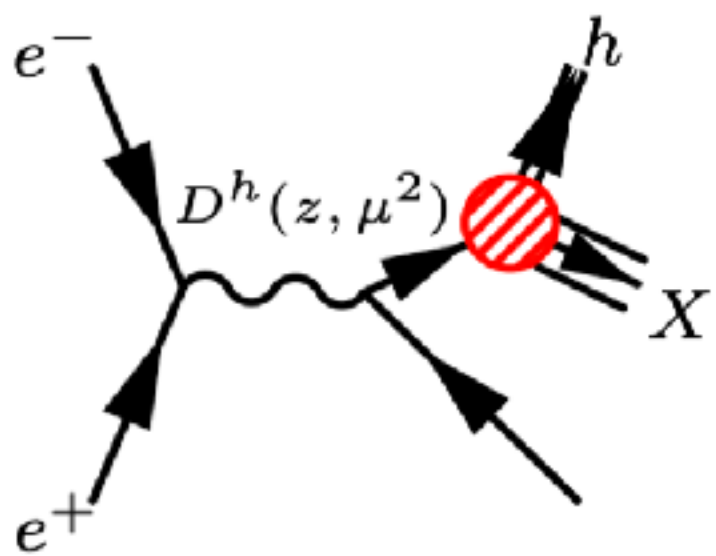


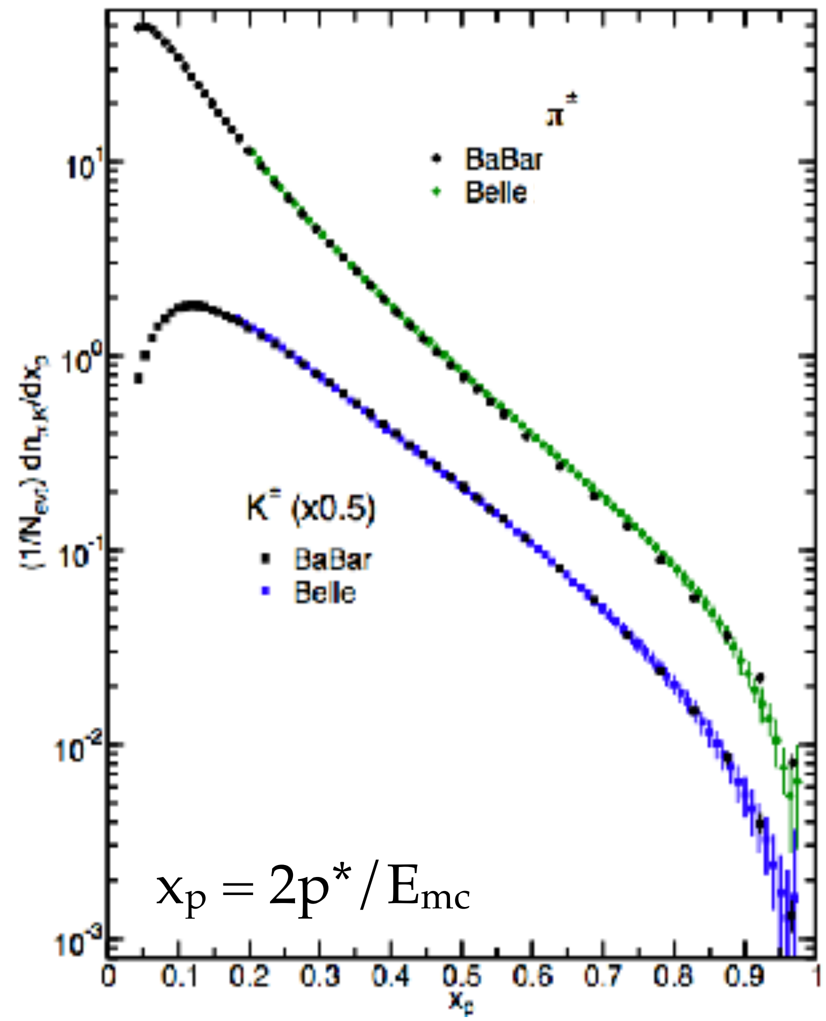
BESIII Detector





Unpolarised FFs



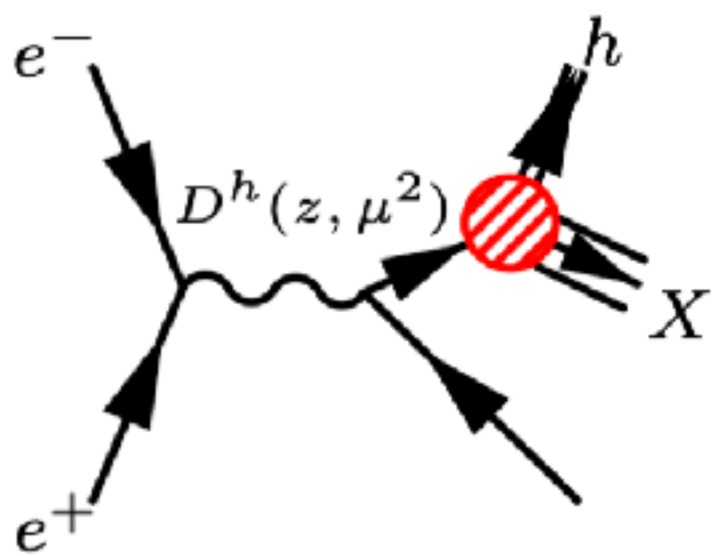


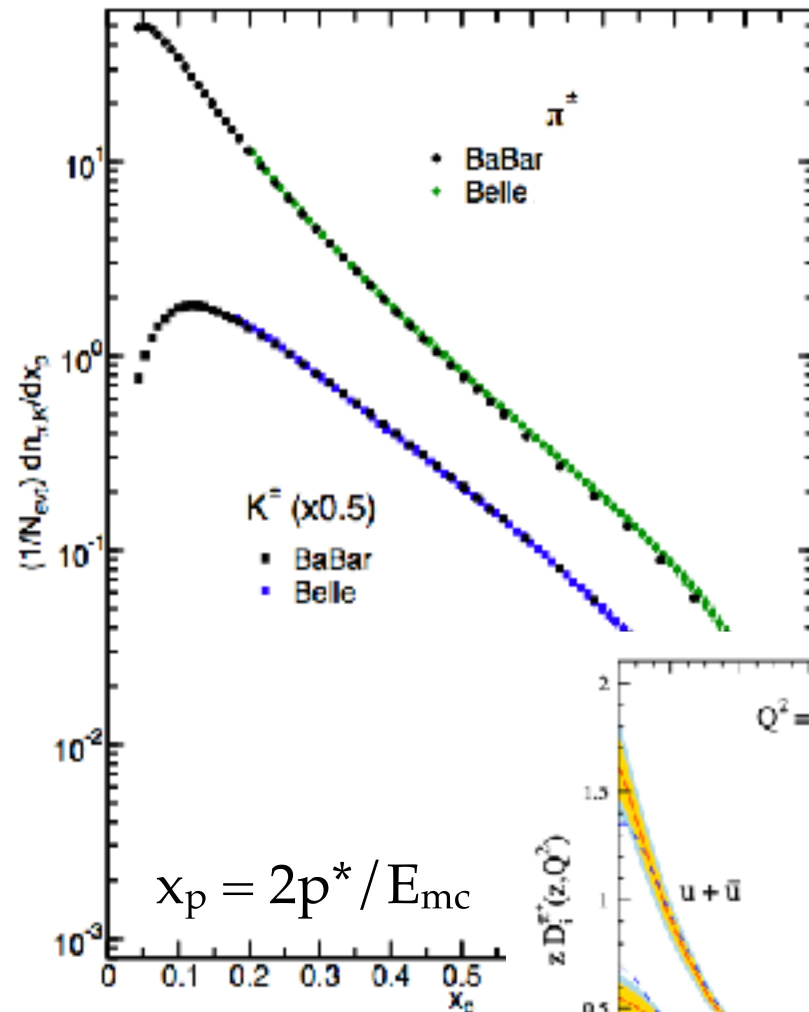
BaBar: PhysRevD.88.032011

Belle: PhysRevLett.111.062002

**arbitrary normalisation in order to compare the shape*

Unpolarised FFs





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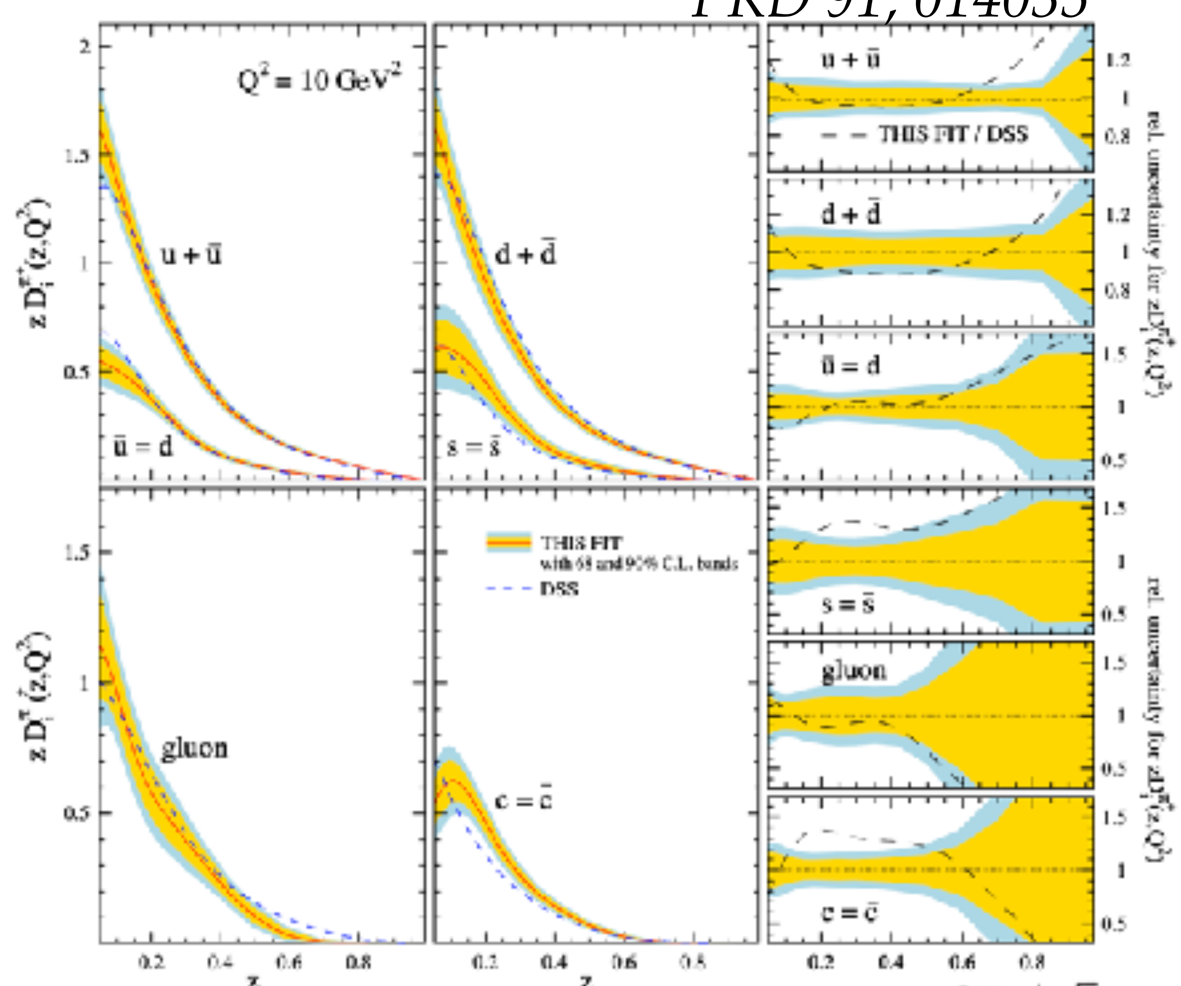
Belle: PhysRevLett.111.062002
**arbitrary normalisation in order to compare the shape*

PRD 91, 014035



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

- Global fit analysis (e+e-, SIDIS and pp data) performed in order to extract the FFs for gluons and different quark flavours
  - DSS fit: PRD 91, 014035 (it includes Belle and BaBar data)

Inclusive light hadrons productions

- Data set used: 0.9 fb^{-1} @ $\Upsilon(4S)$ and 3.6 fb^{-1} at 10.54 GeV
- measured both *prompt* and *conventional* hadron cross section
  - *prompt*: primary hadrons or products of a decay chain where all particles have a lifetime shorter than 10^{-11} s
  - *conventional*: includes weak decay products of KS and strange baryons
- Scaled momentum distribution: $x_p = 2p^*/E_{mc}$ (0.2<p<5.27 GeV/c)

JETSET model:

- represent the color field between the parton by a "string", and according to an iterative algorithm breaks the string into several pieces, each corresponding to a primary hadron
- **large number of free parameters** (models many hadron species)

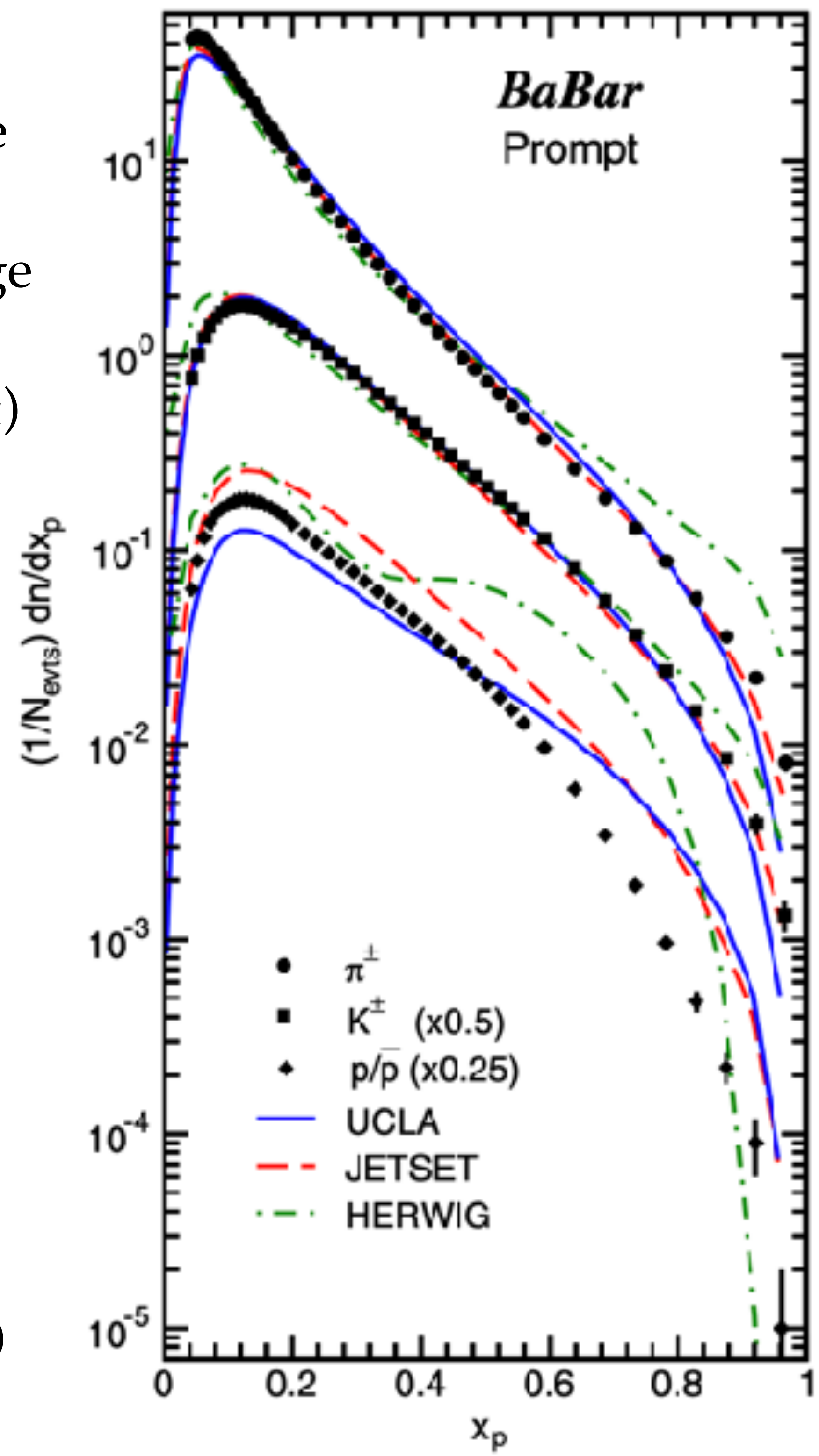
HERWIG model:

- splits the gluons produced into $q\bar{q}$ pairs, combines these quark and antiquark locally to form colorless "clusters", and decay these "clusters" into primary hadrons
- **few free parameters**

UCLA model:

- generates whole events according to weights derived from phase space and Clebsch-Gordan coefficients
- **few free parameters**

PRD88,032011

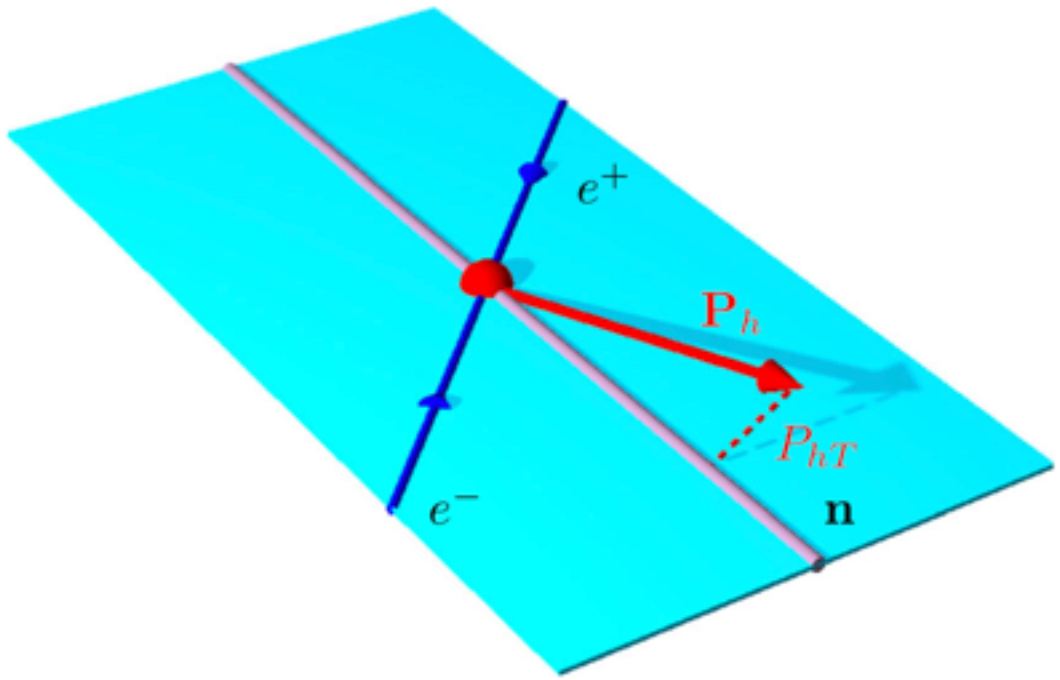


- Good qualitative description of the bulk spectra (no the details)

TMD single-hadron production cross sections @ Belle

*PRD **99**, 112006*

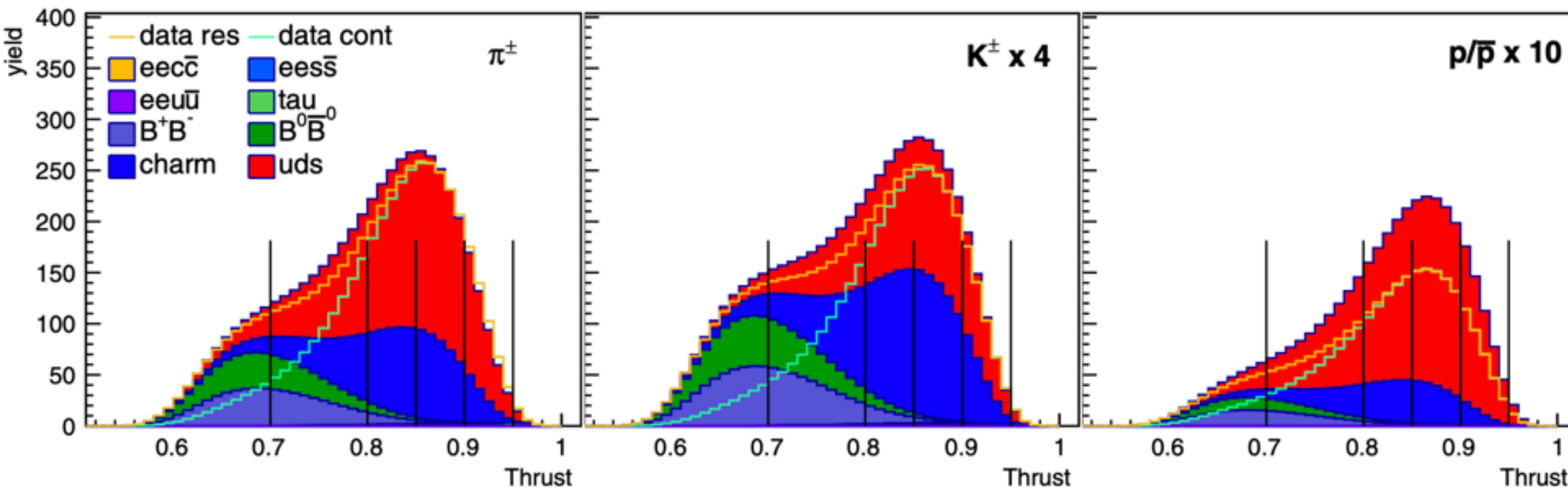
$$D_1^h(z, \mu^2, k_T)$$



Definition of thrust event shape variable:

$$T \overset{\max}{=} \frac{\sum_h |\mathbf{P}_h^{\mathrm{CMS}} \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h^{\mathrm{CMS}}|}.$$

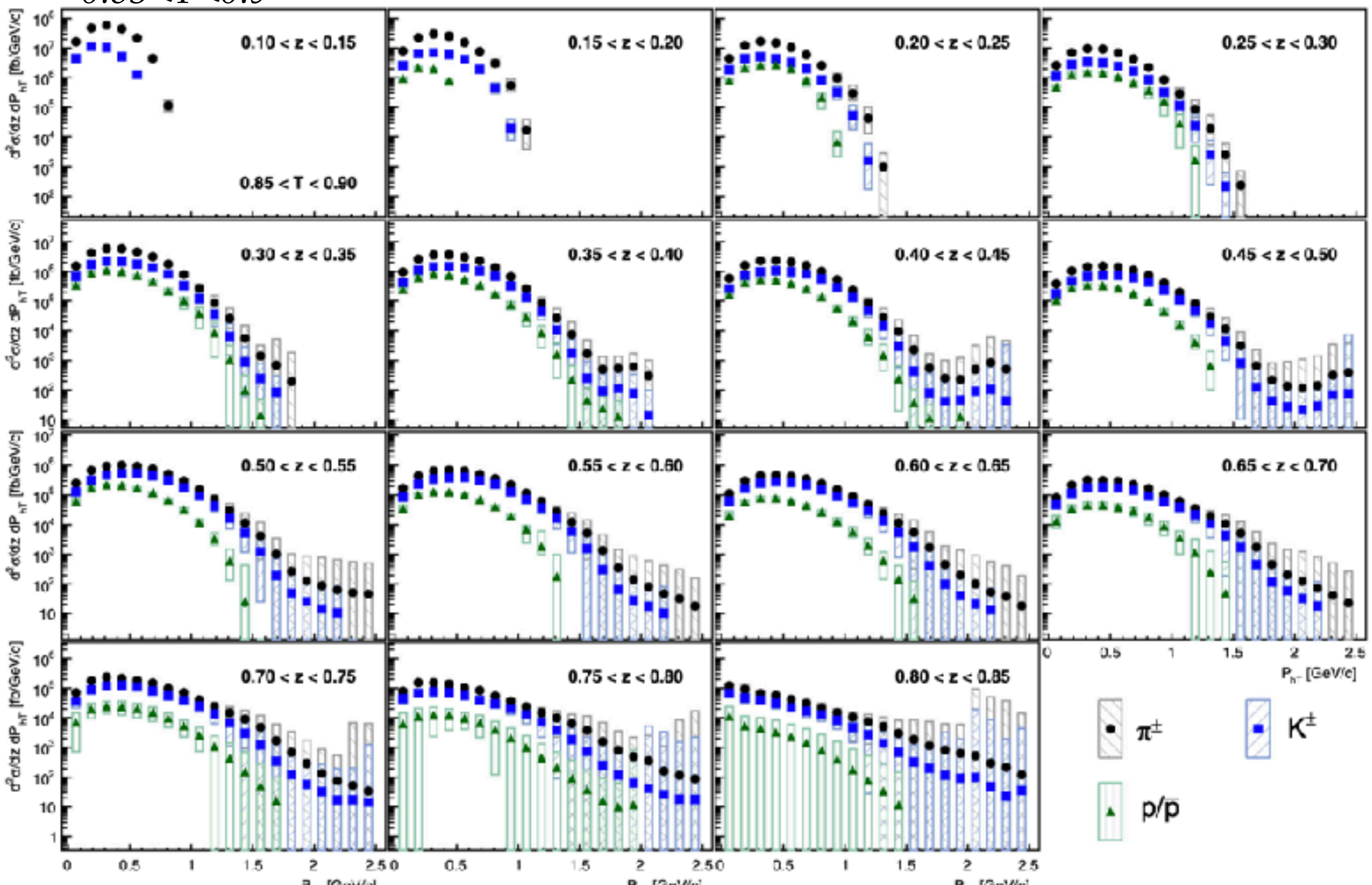
$$z = 2E_h/\sqrt{s}, \qquad \mathbf{p}_T = -z\mathbf{k_T}$$



TMD single-hadron production cross sections @ Belle

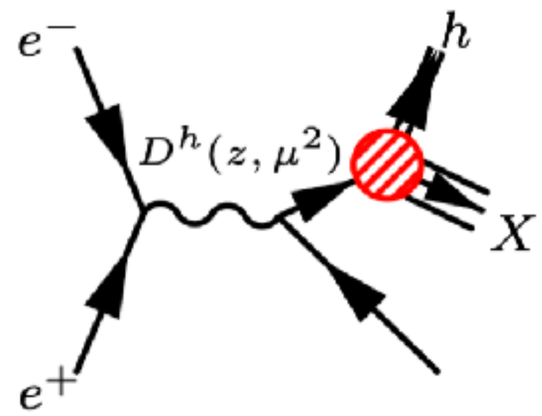
0.85<T<0.9

*PRD **99**, 112006*



First direct measurements for pions, kaons and protons: better understanding of transverse spin phenomena and important role in the future electron-ion collider to pin down the transverse-momentum structure of nucleons and its transverse spin

Polarised FF: the Collins effect



$H_1^\perp$?

chiral-odd function

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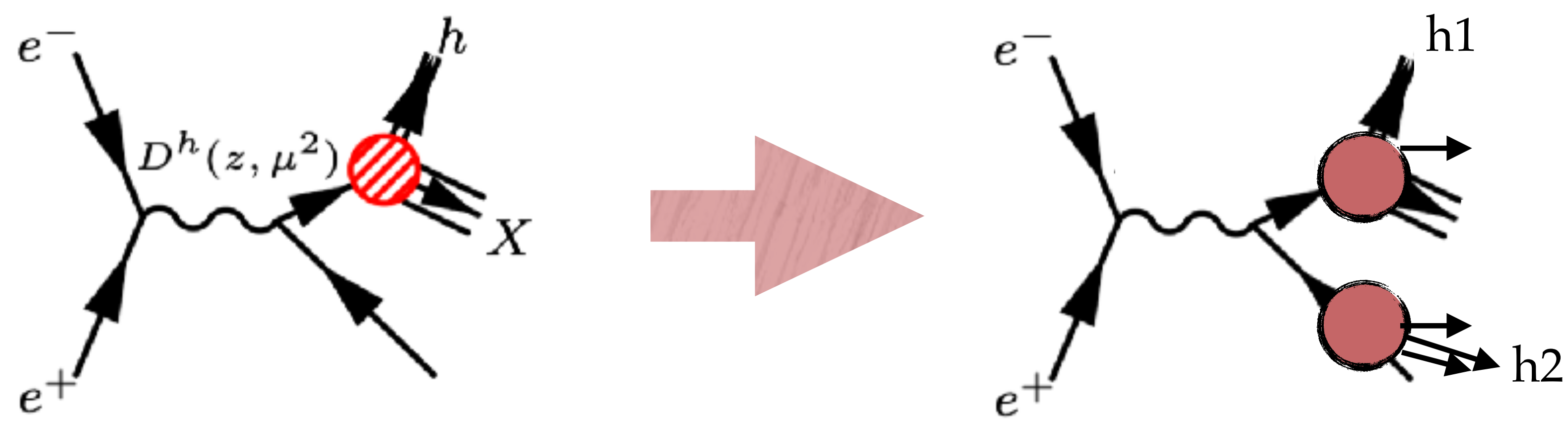


q↑→hX: $D_1^{q\uparrow}(z,\mathbf{P}_\perp;s_q) = D_1^q(z,P_\perp) + \frac{P_\perp}{zM_h} H_1^{\perp q}(z,P_\perp)\,\mathbf{s}_q\cdot(\mathbf{k}_q\times\mathbf{P}_\perp)$

Unpolarized FF

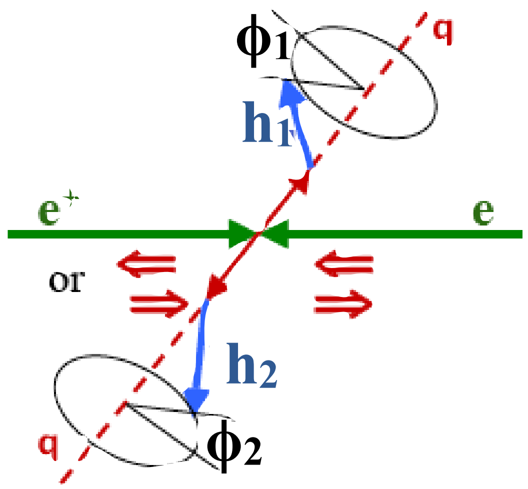
Collins FF [NP**B 396**, 161 (1993)]: related to the probability that a transversely polarized quark (q↑) fragments into a spinless hadron

- Evolution of TMD objects
- Global analysis (PRD 78,032011 (2007); PRD 87,094019 (2013), PRD 91,014034 (2015)):
  - combines Semi Inclusive Deep Inelastic Scattering (SIDIS) and e^+e^- data
  - extraction of $H^\perp_1$ and transversity parton distributions h_1 for the "u" and "d" quarks

Collins effect in e^+e^- annihilation

In $e^+e^- \to q\bar{q}$, spins unknown, but $s_q \parallel s_{\bar{q}}$

- exploit this correlation by using hadrons in opposite jets
- define **favored** ($u\to\pi^+$, $d\to\pi^-$) and **disfavored** ($d\to\pi^+$, $u\to\pi^-$, $s(\bar{s})\to\pi^\pm$) FFs

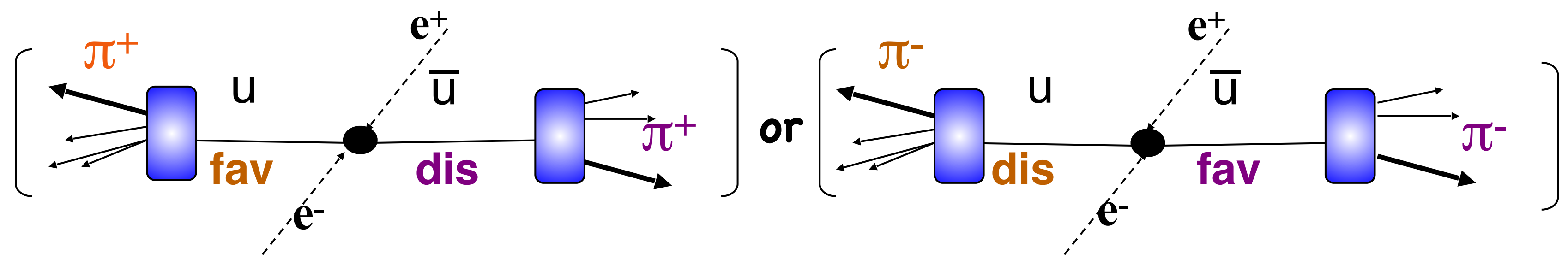


$$e^+e^- \to q\bar{q} \to h_1 h_2 X \ \ (q=u,d,s) \ \Rightarrow \sigma \propto \cos(\phi_1+\phi_2) H_1^{\perp(h1)} \times H_1^{\perp(h2)}$$

Azimuthal modulation wrt the quark spin direction: Collins effect (or Collins asymmetry)

Example: Like $\pi\pi$ pairs (L)

Collins asymmetry for $\pi\pi$



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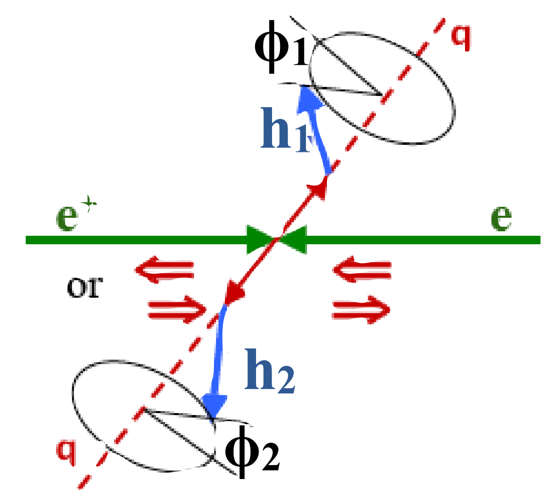
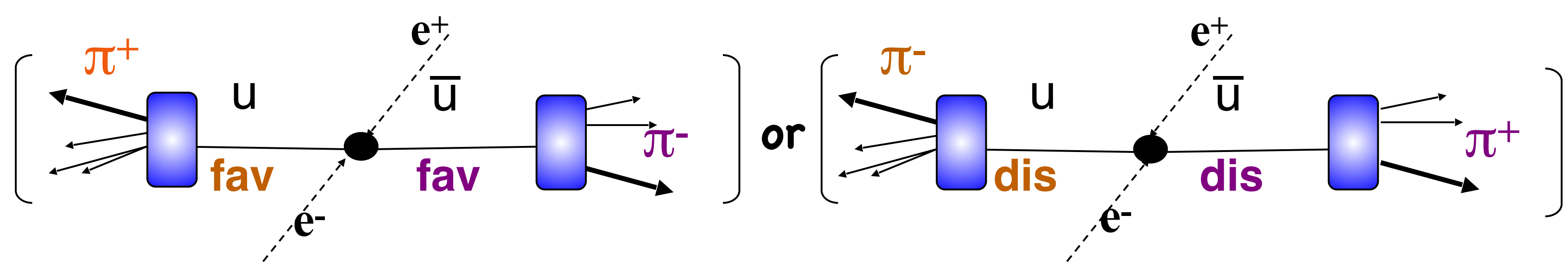


$e^+e^-\to q\bar{q}\to h_1h_2X$ (q=u,d,s) $\Rightarrow \sigma\propto\cos(\phi_1+\phi_2)H_1^{\perp(h1)}\times H_1^{\perp(h2)}$

Azimuthal modulation wrt the quark spin direction:
Collins effect (or Collins asymmetry)

Example: Unlike $\pi\pi$ pairs (U)

Collins asymmetry for $\pi\pi$



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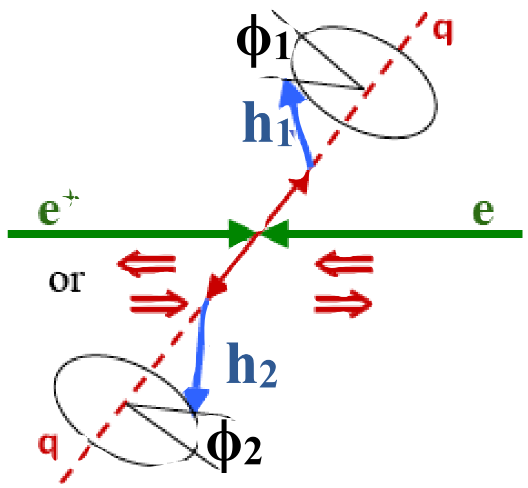

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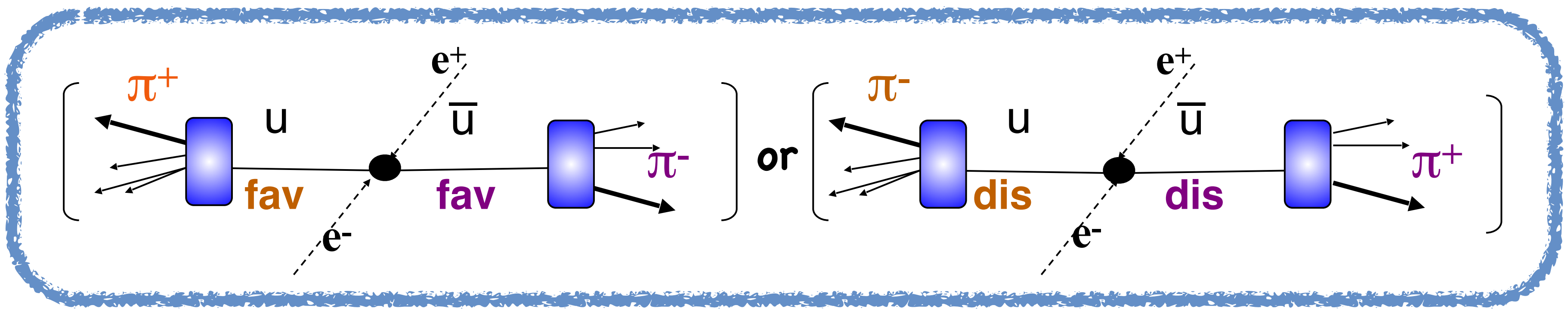
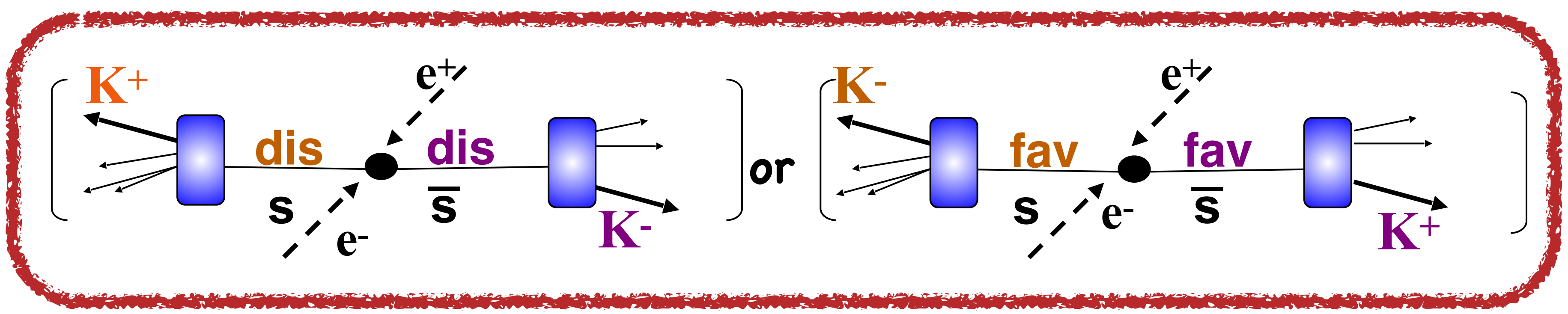


Example: Unlike KK pairs (U)

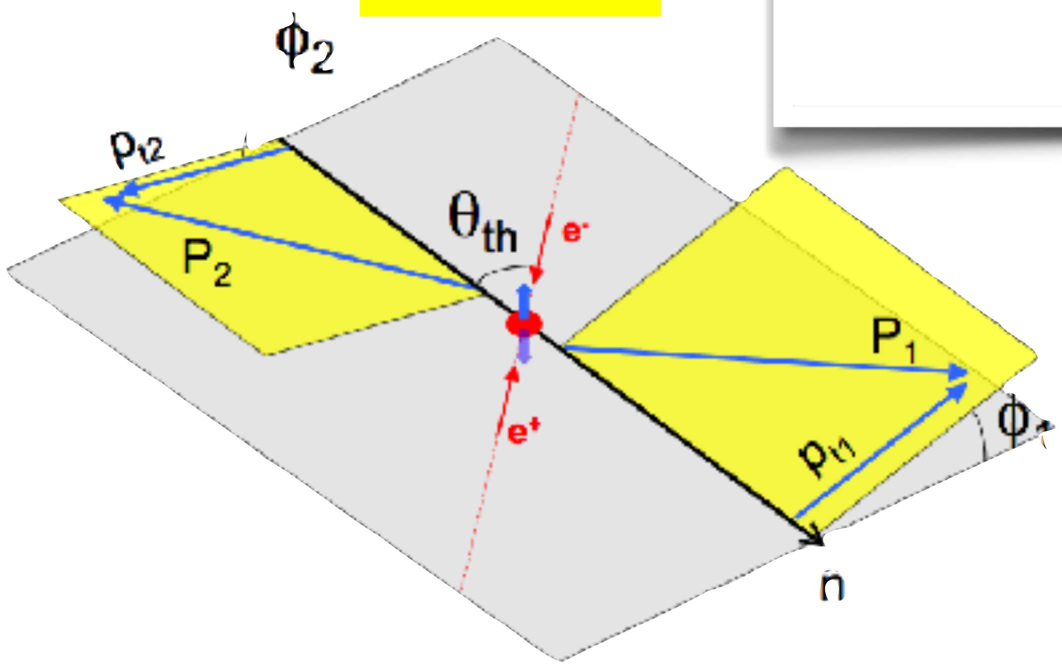
Collins asymmetry for KK:



Reference Frames

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

RF12

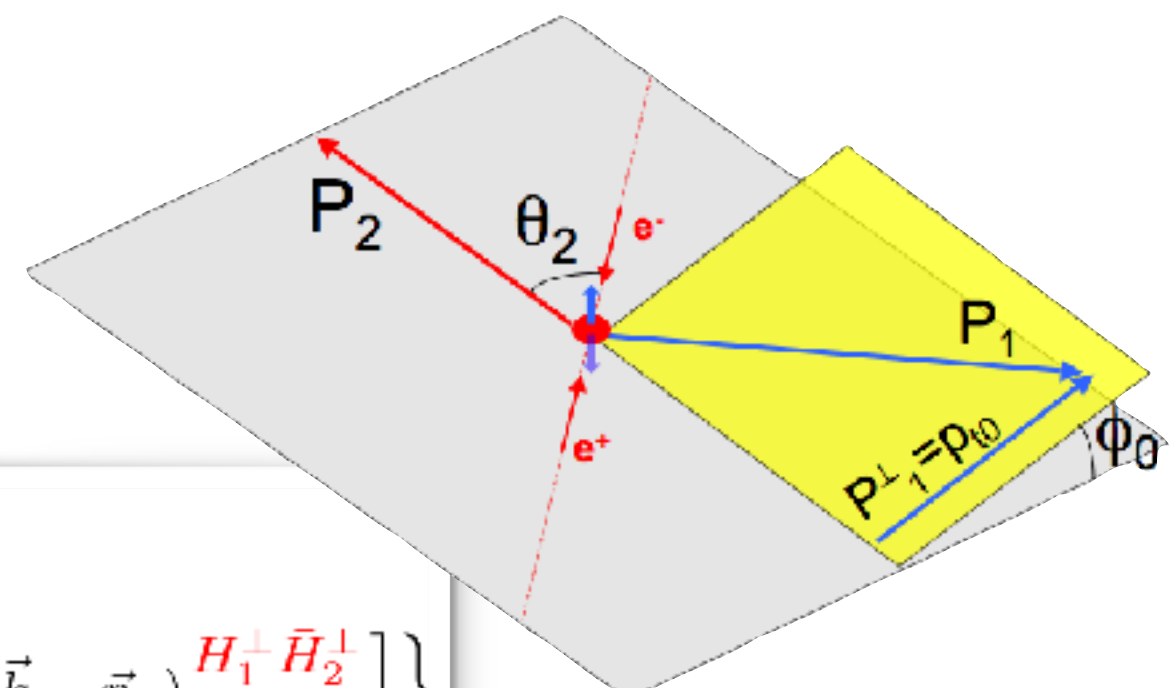


$$\frac{d\sigma(e^+e^-\to h_1h_2X)}{d\Omega dz_1 dz_2 d\phi_1 d\phi_2} = \sum_{q,\bar{q}} \frac{3\alpha^2}{Q^2}\frac{e_q^2}{4} z_1^2 z_2^2 \Big[(1+\cos^2\theta) D_1^{q,(0)}(z_1)\bar{D}_1^{q,(0)}(z_2) + \sin^2(\theta)\cos(\phi_1+\phi_2) H_1^{\perp,(1),q}(z_1)\bar{H}_1^{\perp,(1),q}(z_2)\Big]$$

All quantities in e+e- center of mass

θ: angle between the e^+e^- axis and the thrust axis;
$\varphi_{1,2}$: azimuthal angles between $P_{h1(h2)}$ and the scattering plane

RF0



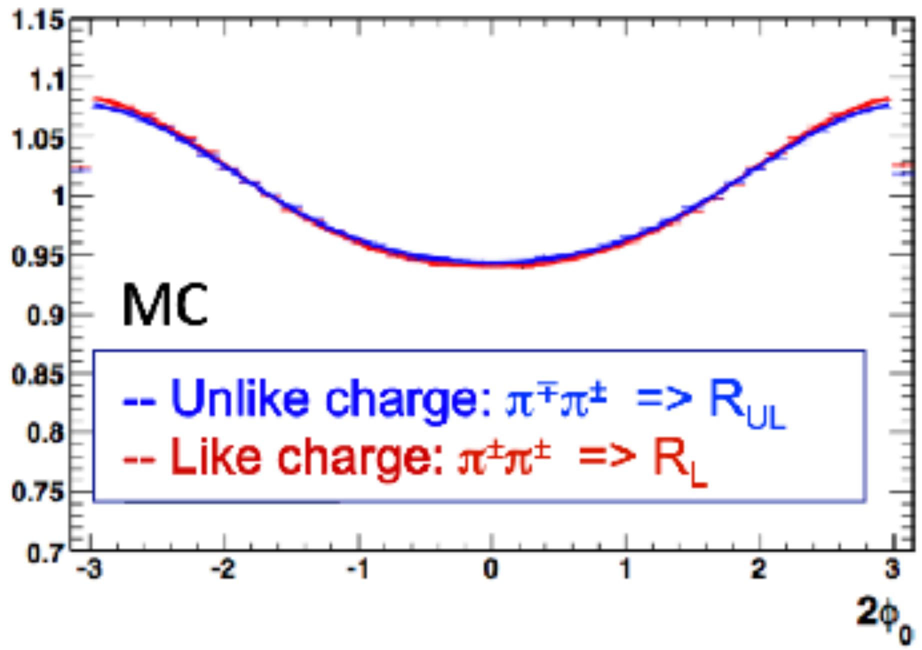
θ_2: angle between the e^+e^- axis and P_{h2};
φ_0: angle between the plane spanned by P_{h2} and the e^+e^- axis, and the direction of P_{h1} perpendicular to P_{h2}.

All quantities in e+e- center of mass

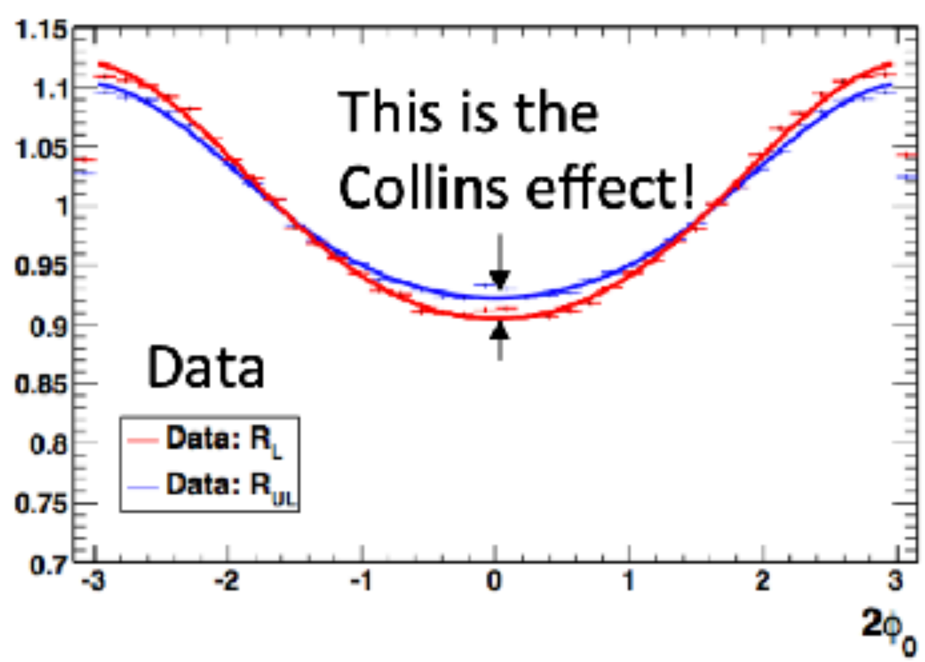
$$\frac{d\sigma(e^+e^-\to h_1h_2X)}{d\Omega dz_1 dz_2 d^2\vec{q}_T} = \frac{3\alpha^2}{Q^2} z_1^2 z_2^2 \Big\{A(y)\mathcal{F}[D_1\bar{D}_2] + B(y)\cos(2\phi_0)\mathcal{F}\Big[(2\hat{h}\cdot\vec{k}_T\,\hat{h}\cdot\vec{p}_T - \vec{k}_T\cdot\vec{p}_T)\frac{H_1^\perp \bar{H}_2^\perp}{M_1M_2}\Big]\Big\}$$

Asymmetry Measurements from Data

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



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



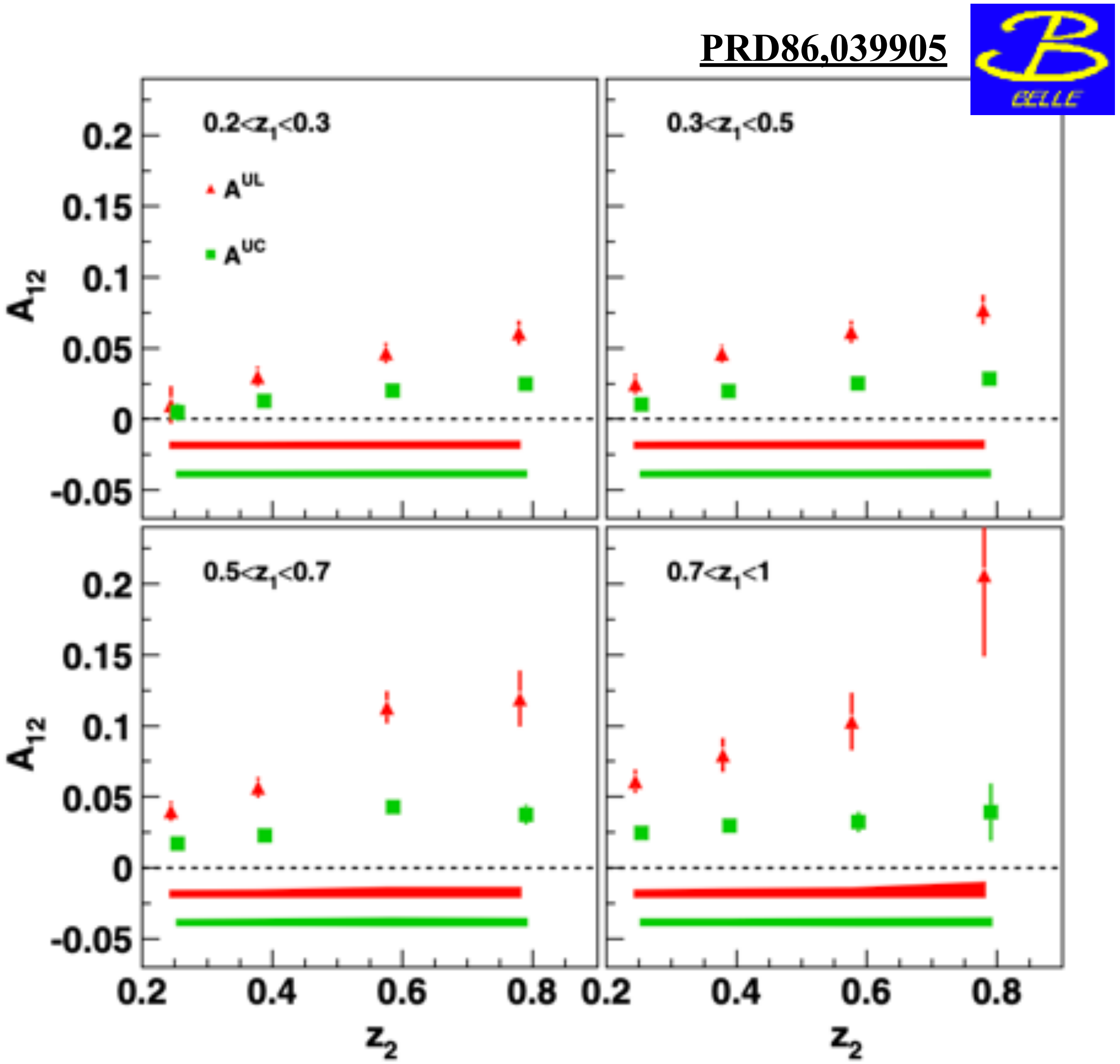
- Collins asymmetries extracted from fit to the normalised azimuthal distribution

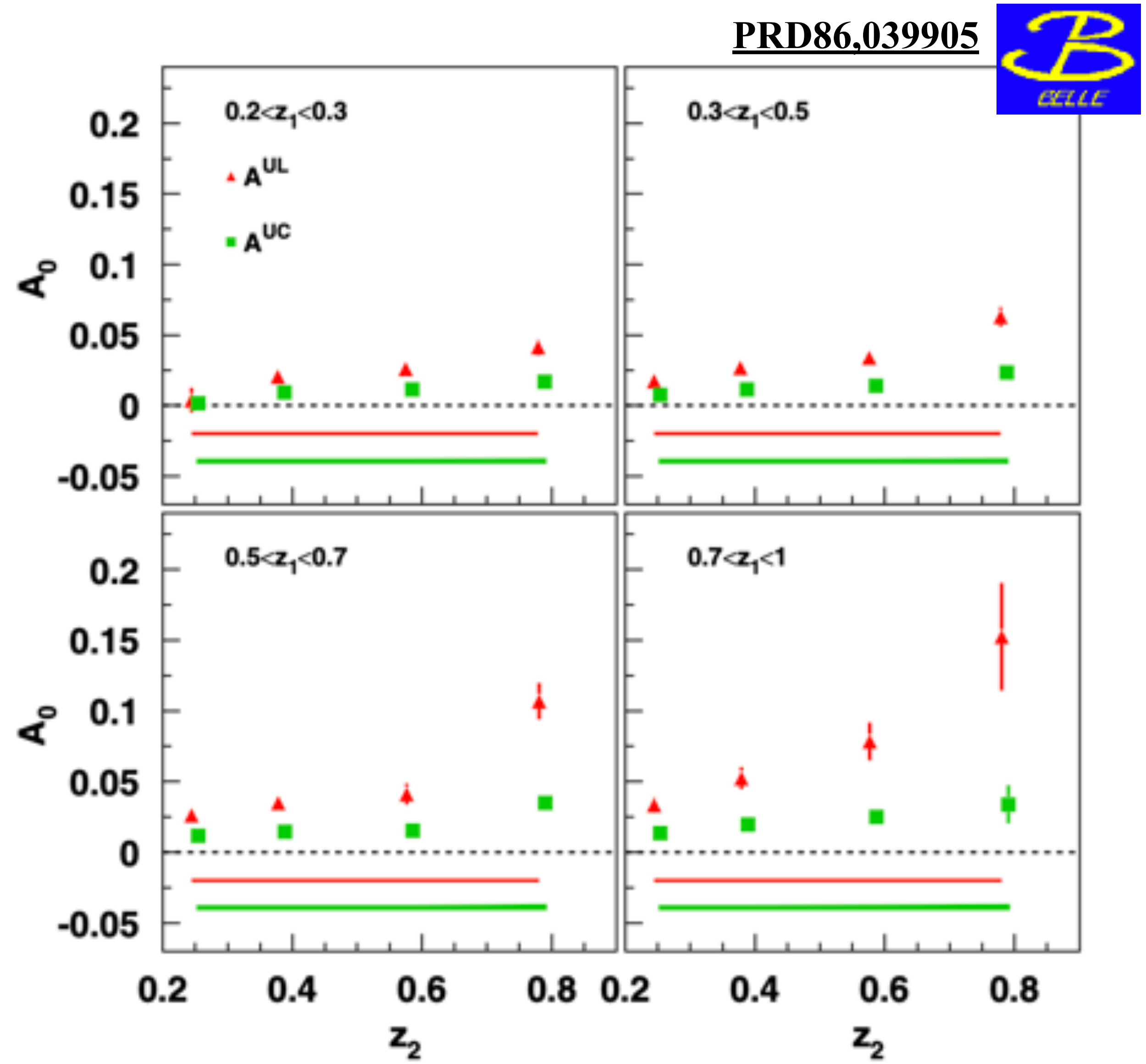
$$R_\alpha = \frac{N(\phi_\alpha)}{< N_\alpha >} = a + b \cdot \cos(\phi_\alpha)$$

- MC generator does not include polarised FFs as the Collins FF
  - modulation observed in MC sample produced by detector acceptance
  - correction of these effects would bring too large systematic uncertainties
- Ratio of U and L distributions
  - Collins effect is not sensitive to the electric charge
  - U and L sigli different in data due to the different contribution of favoured and disfavoured FFs

Collins FFs Results

First measurement of Collins effects in e+e− annihilation (PRL 96,232002) !!!



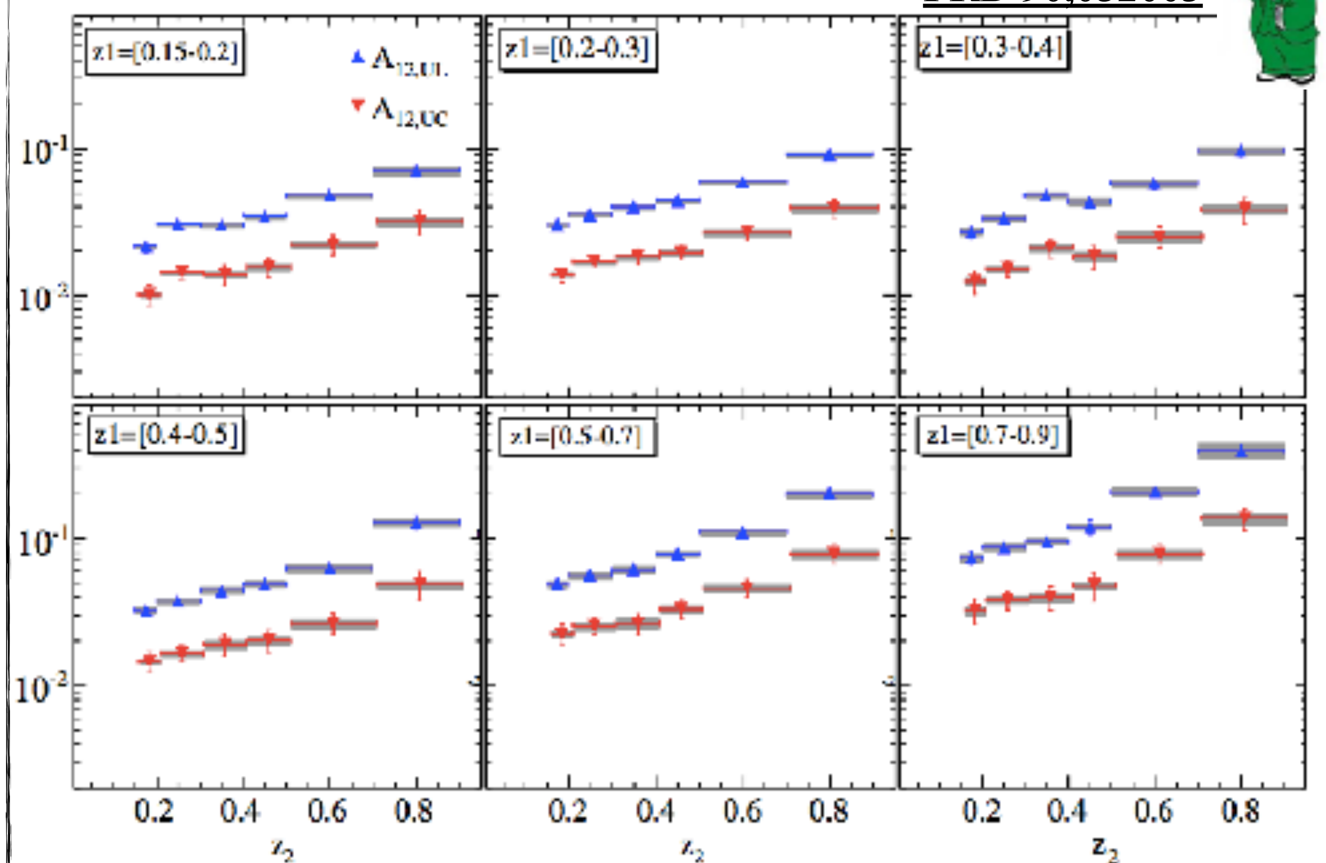


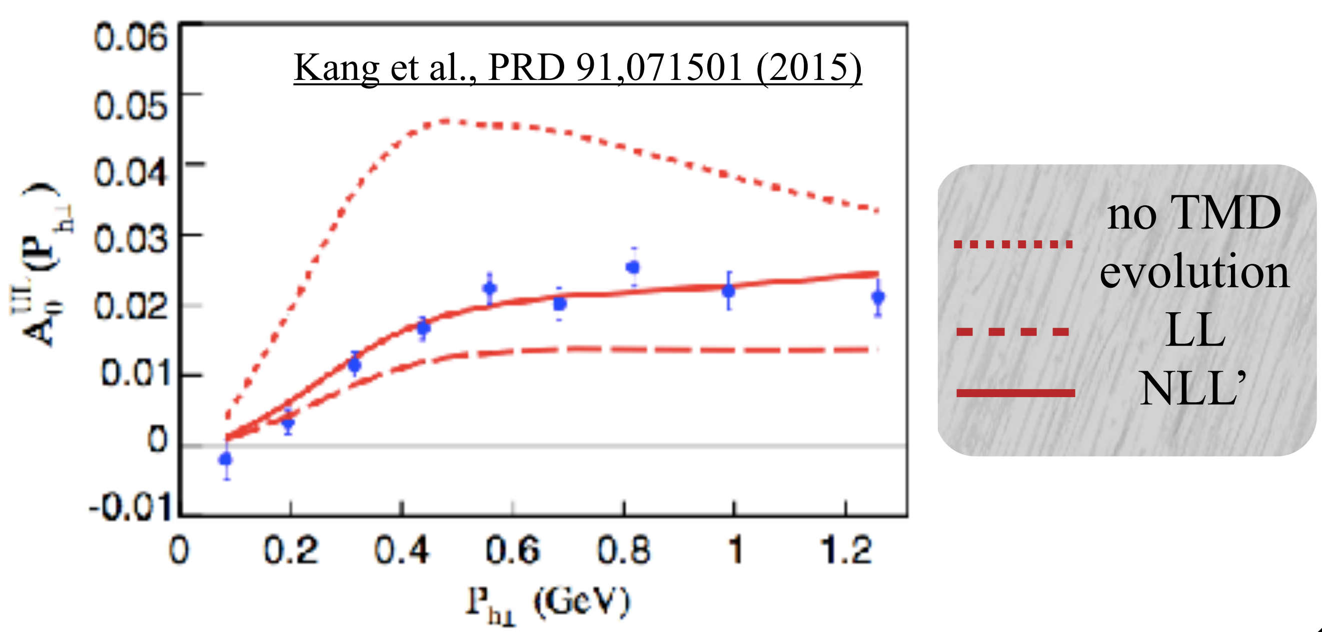
- $\mathcal{L}$ ~ 547 fb^{-1} at ~10.58 GeV
- Non-zero asymmetries increasing with z

Collins FFs Results

$\mathcal{L}$ ~ 468 fb^{-1} at ~10.58 GeV

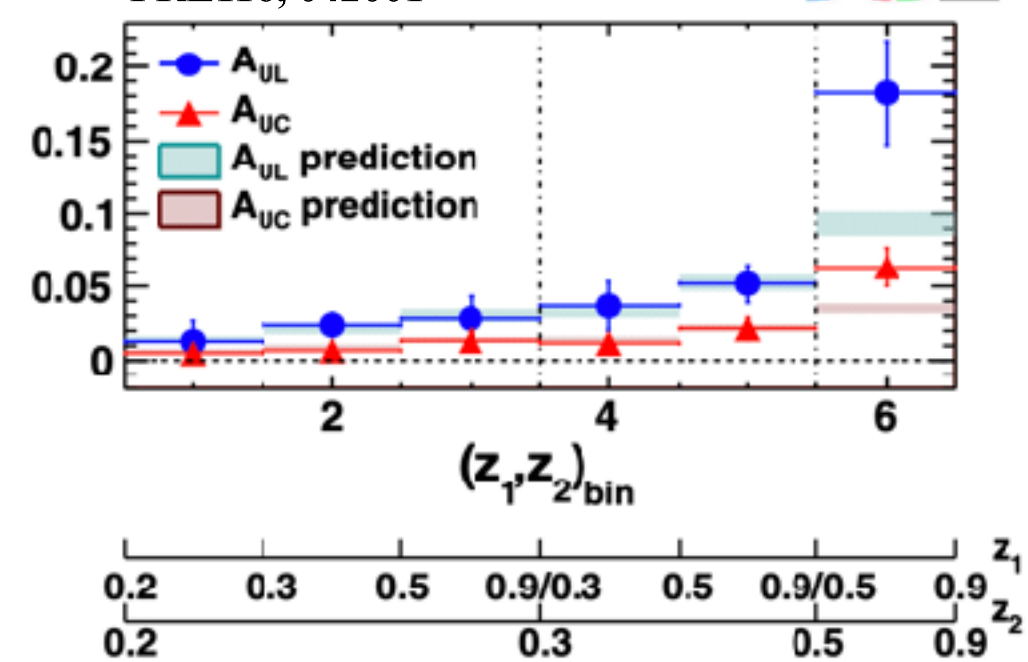
PRD 90,052003

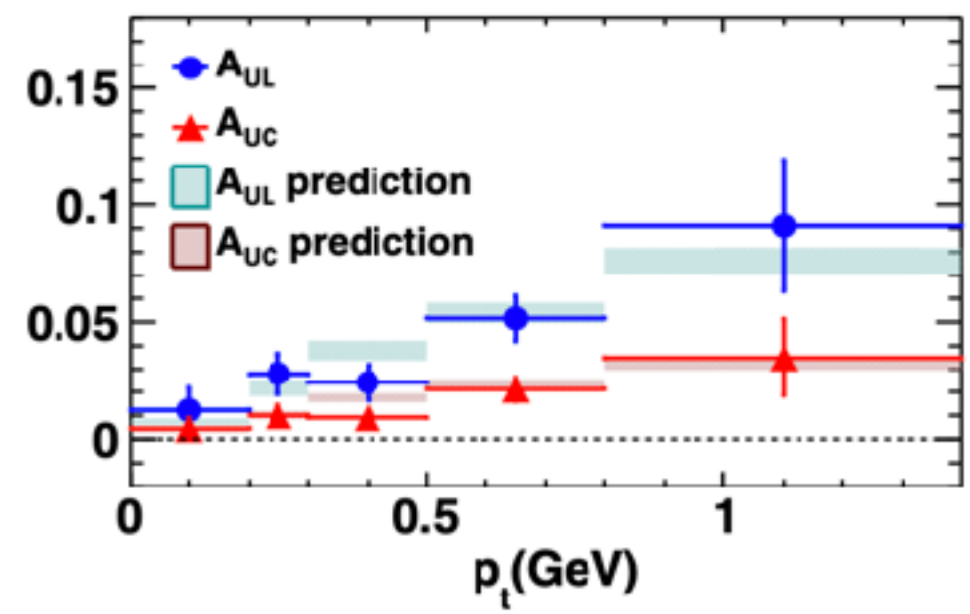




$\mathcal{L}$ ~ 62 pb^{-1} at ~3.65 GeV

PRL116, 042001





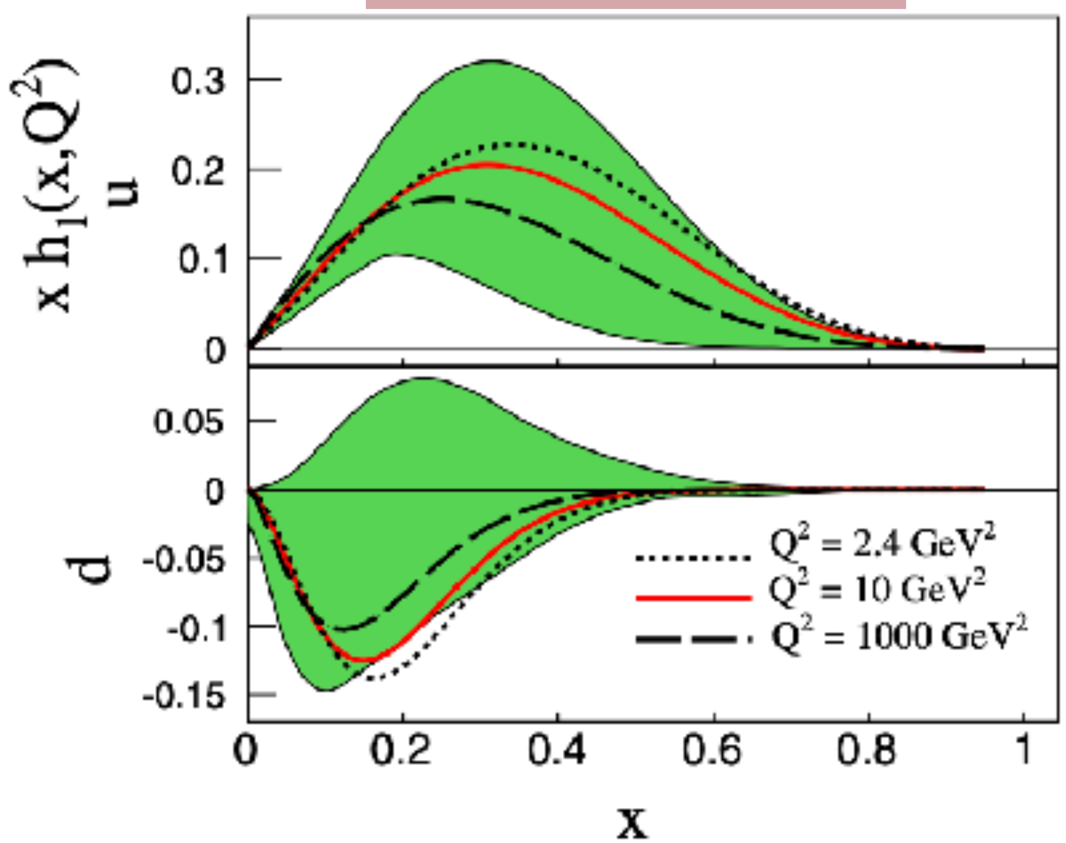
Extraction of h₁ and Collins FF

PRD**93**,014009

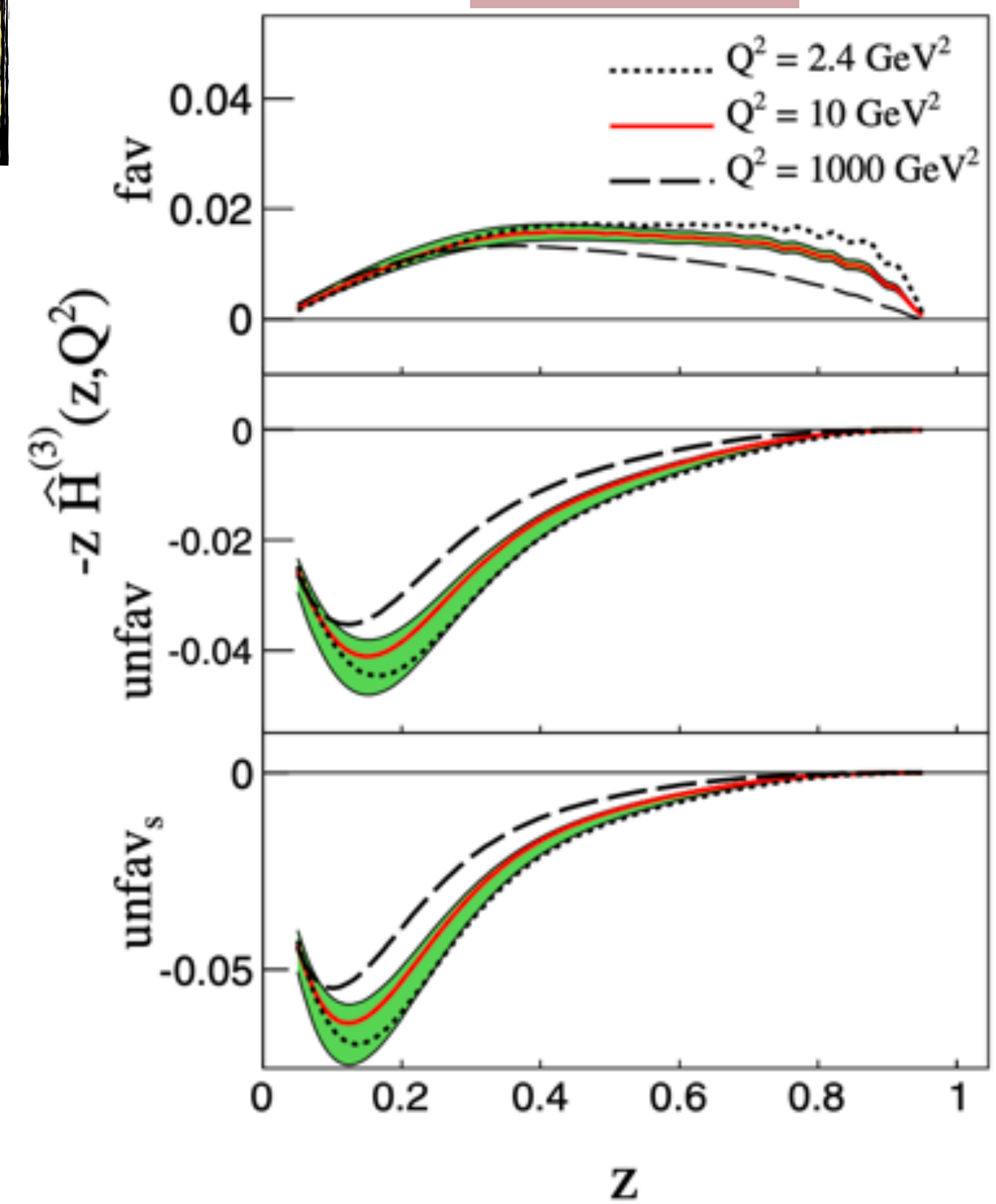
- First extraction: Anselmino et al. PRD**75**,054032
- Global analysis with SIDIS (HERMES (PRL**103**,152002), COMPASS (PLB**744**,250; PLB**673**,127)) + BaBar RF0 data (PRD**90**,052003) and Belle RF0 (PRD**78**,032011) data

Full QCD dynamics taken into account, including TMD evolution effects at the NLL' order and perturbative QCD corrections at the NLO

Transversity PDFs



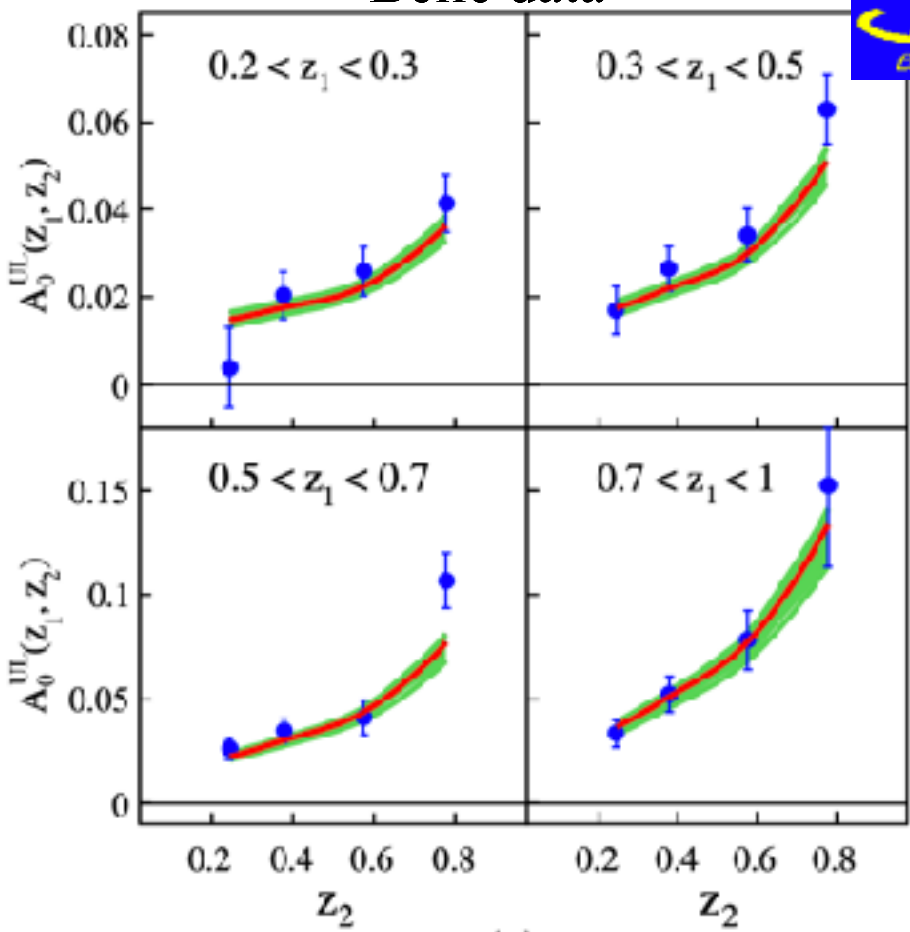
Collins FFs



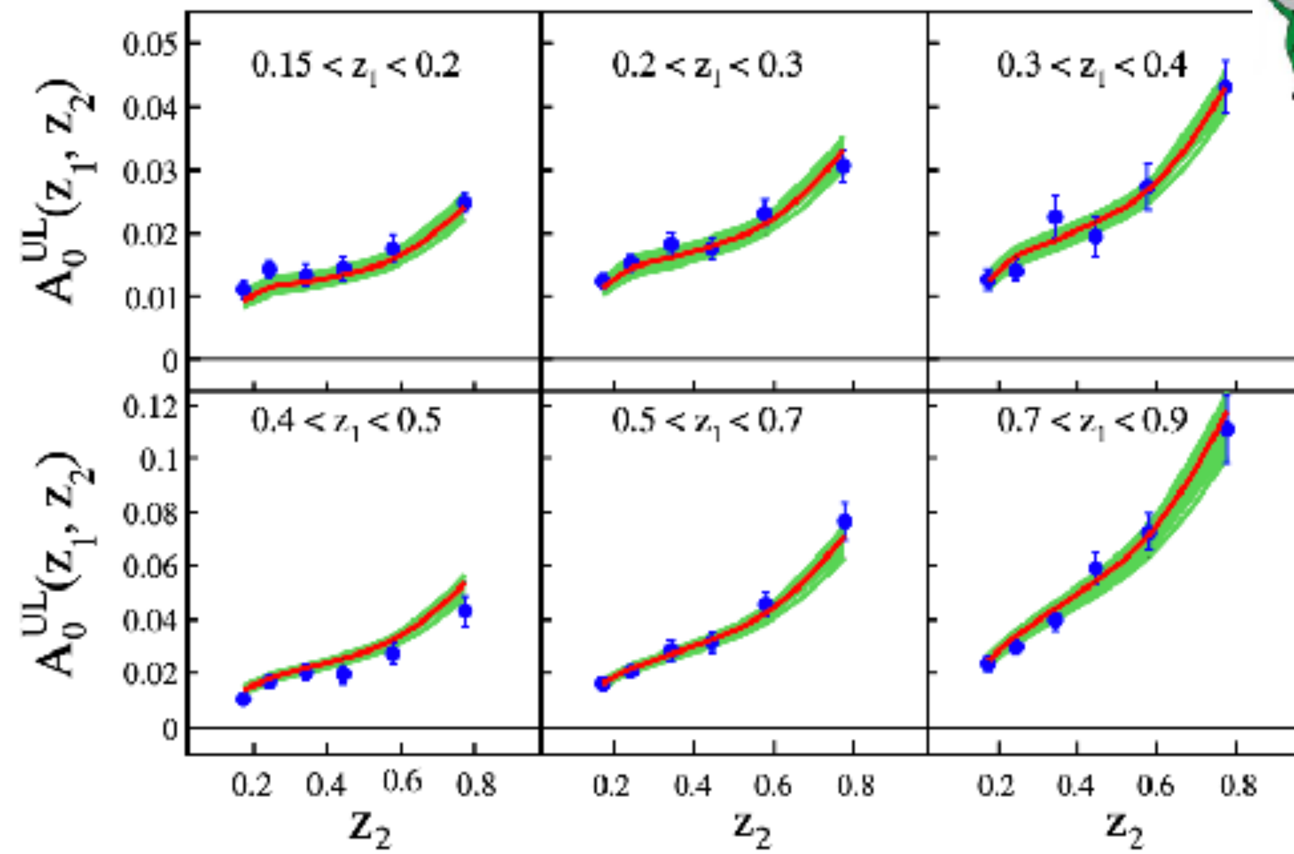
Extraction of Collins FF: data description

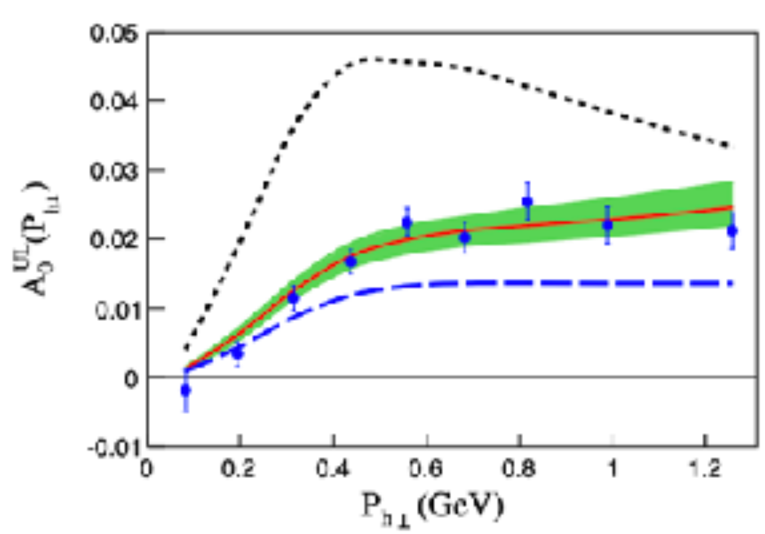
PRD**93**,014009

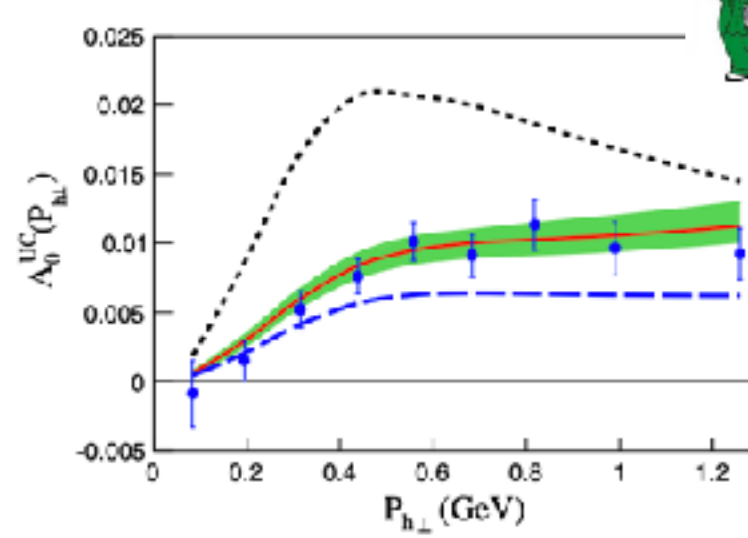
Belle data



BaBar data







NLL’ calculations

LL calculation

no TMD evolution

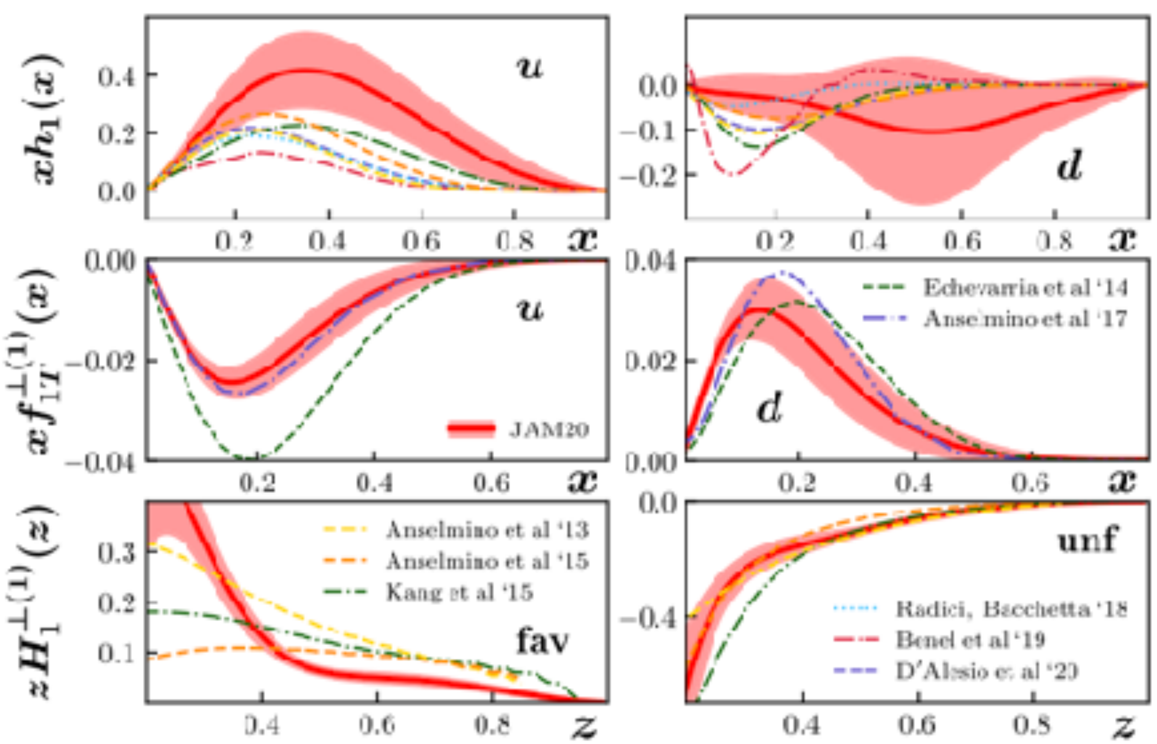
e^+e^- data are very sensitive to the inclusion of higher order corrections

First Global Analysis

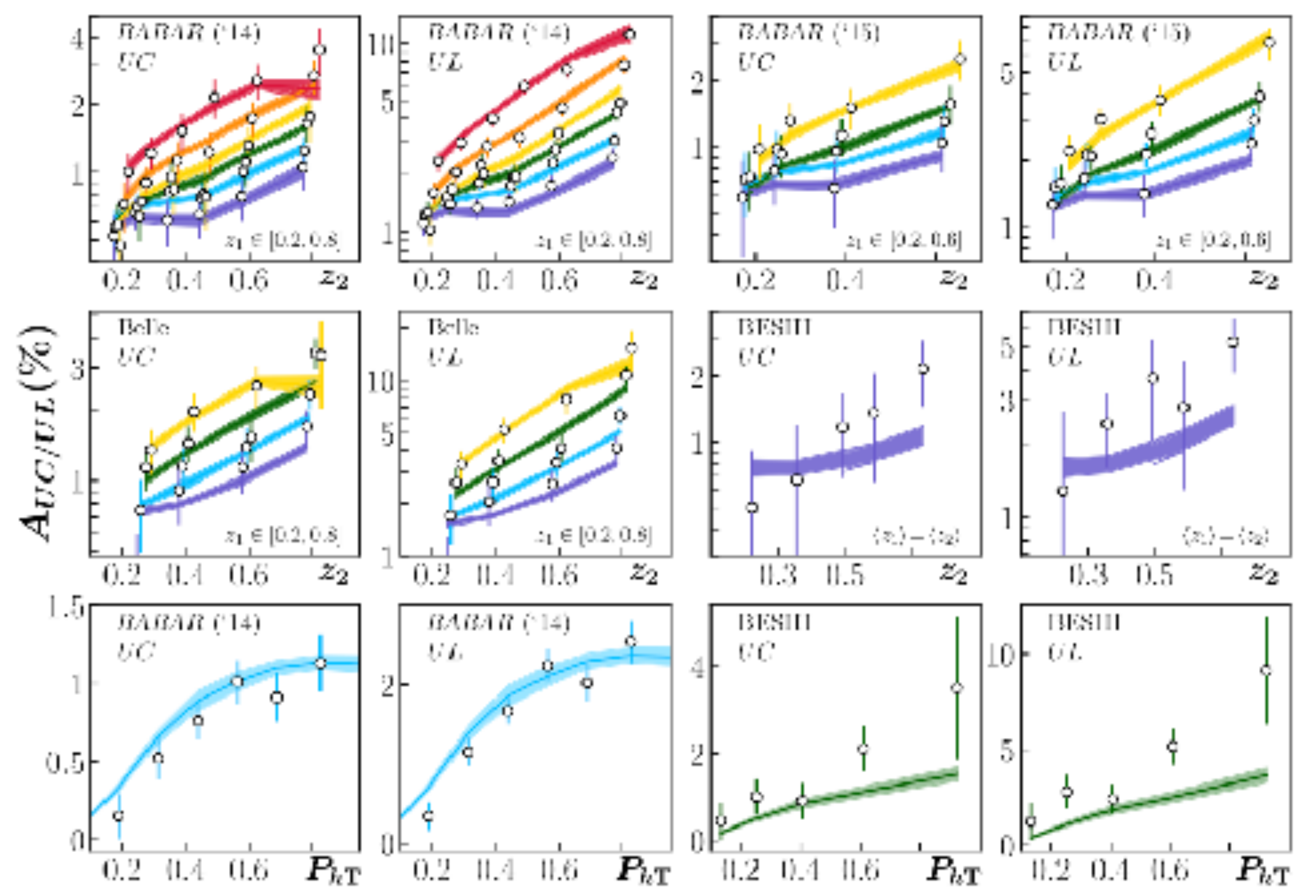
PRD102,054002

First simultaneous QCD global analysis with SIDIS, e+e- annihilation, DY and proton-proton collisions

- Test of universality
- Indication that transverse-spin asymmetries in high-energy collisions have a common origin
- Extracted quark tensor charges are in excellent agreement with lattice QCD



Anselmino'13, Anselmino'15, Anselmino'17, Benel'19, D'Alessio'20, Echevarria'14, Kang'15, Radici-Bacchetta'18

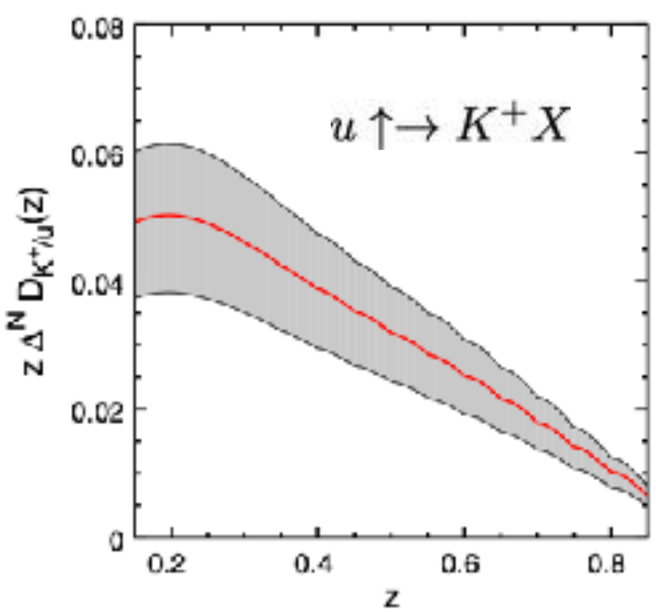


Comparison between theory and data
(BaBar, Belle, BESIII)

Extraction of Collins FF for Kaons

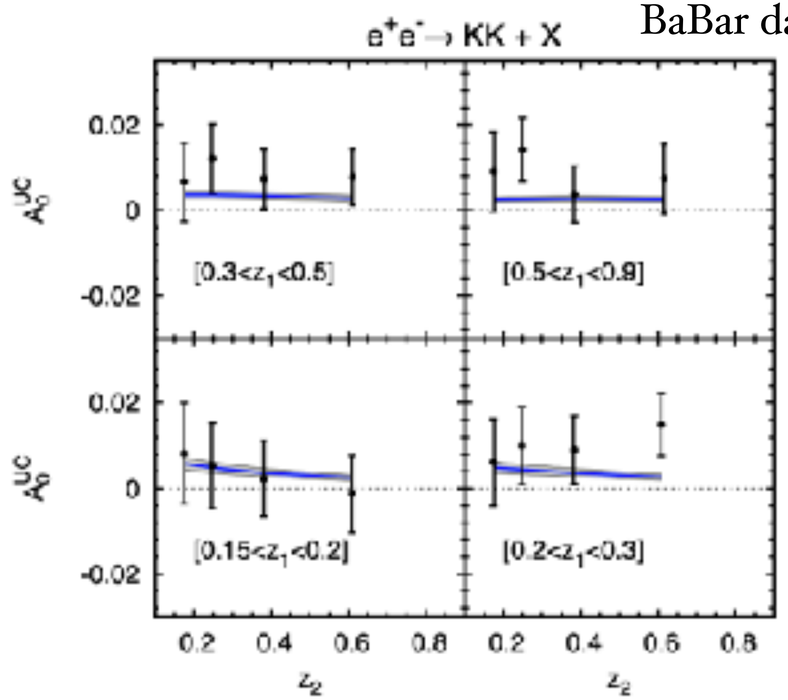
PRD **93**,034025

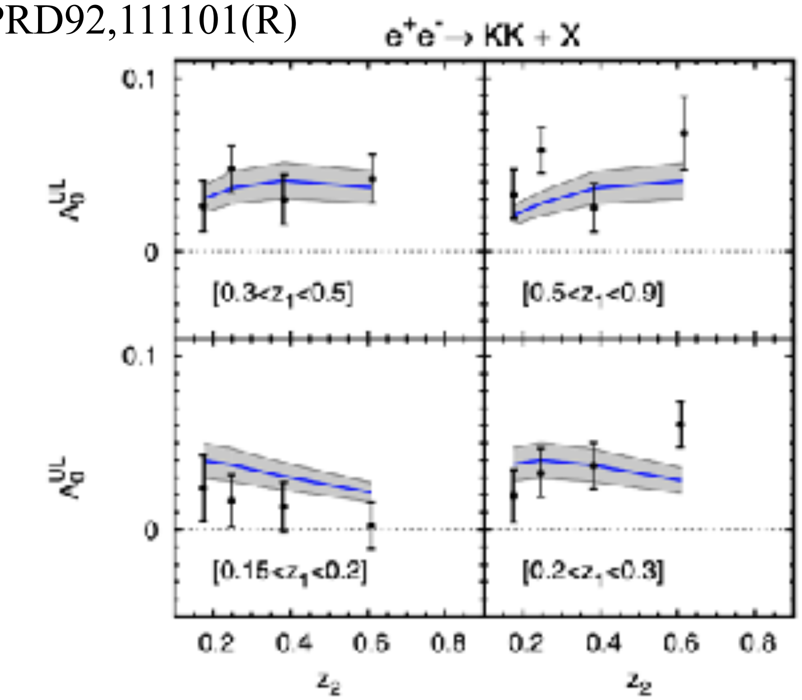
- Pions FF from previous analysis
- Similar parametrisation for kaon favoured and disfavoured FFs as used for pions

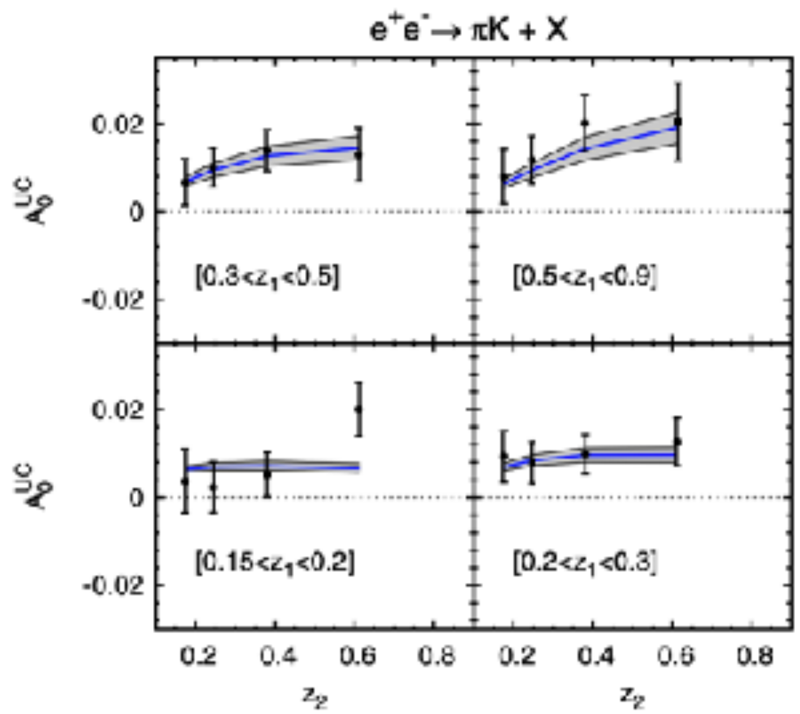


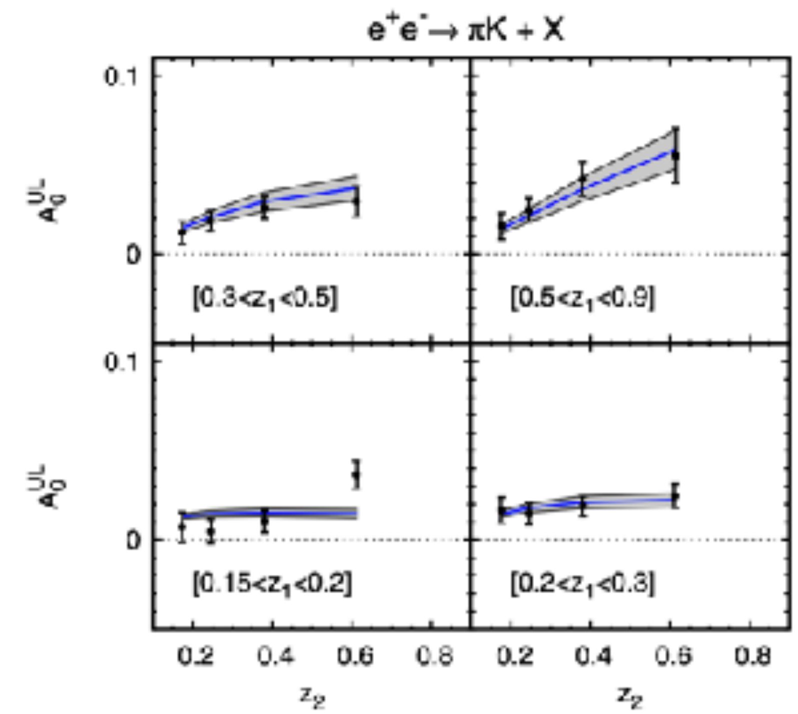
- Positive favored Collins function and a disfavoured contribution compatible with zero
- Large uncertainty
- No definitive conclusions can be extracted for strange Collins FF nor on the disfavoured ones

BaBar data: PRD92,111101(R)



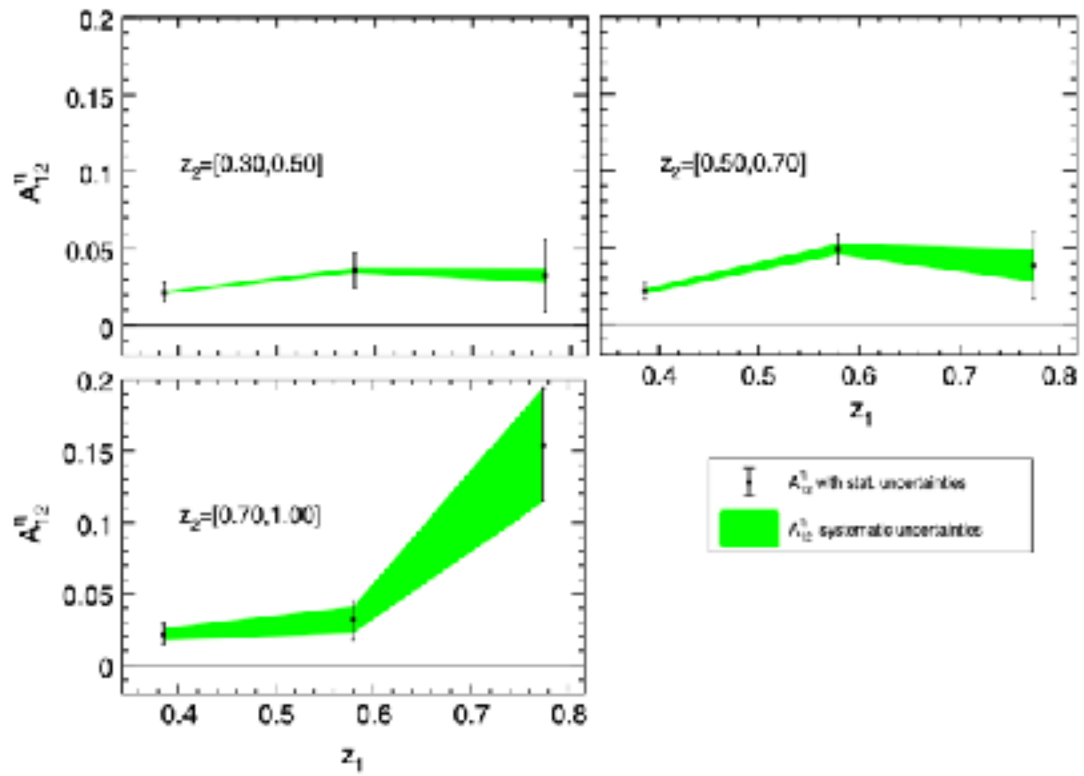


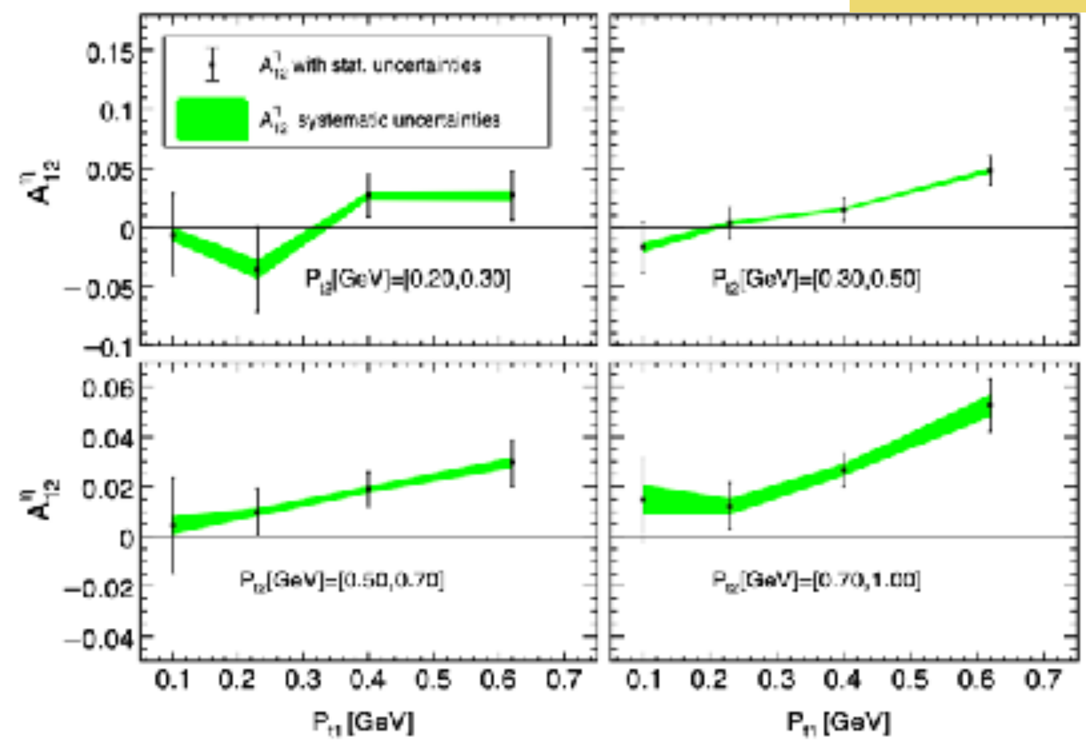




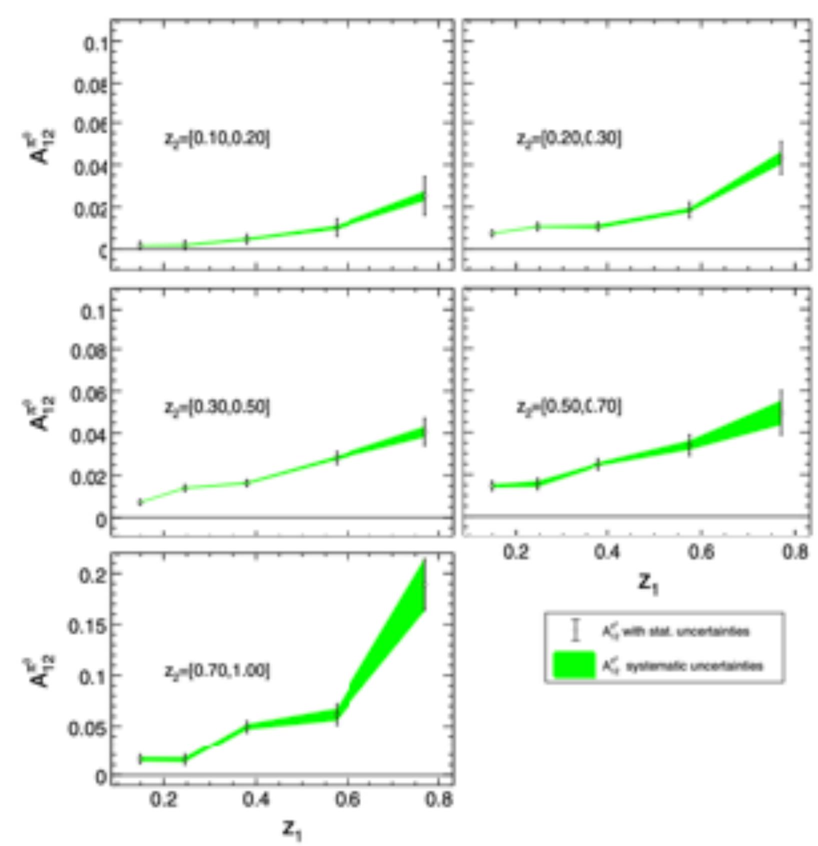
Azimuthal asymmetries of back-to-back $\pi^{\pm}\eta/\pi^{\pm}\pi^{0}$ from Belle

PRD **100**,092008





- RF12 (thrust reference frame) only
- π^0:
  - Significant asymmetries that rise with z
  - Continuous rise with Pt1 consistent with a linear behaviour
- η:
  - Larger uncertainties
  - The rise with z is much less pronounced
  - Rise of the asymmetry with increasing pt
  - Charm contribution ~ 20-30% larger than neutral pions sample
  - for those bins with similar charm contributions η and π^0 asymmetries are fully consistent



$\Lambda/\overline{\Lambda}$ hyperon polarization at Belle

PRL **122**,042001

- $e^+e^- \to \Lambda(\overline{\Lambda})X$ and $e^+e^- \to \Lambda(\overline{\Lambda})h^{\pm}X$ using 800.4 fb^{-1} collected by Belle at or near $\sqrt{s}$=10.58 GeV

$$D_{1T}^{\perp\Lambda/q}(z, p_\perp^2)$$

==> production of transversely polarized Λ hyperons from unpolarised quark
==> chiral-even function (the sign of this function can be easily determined)

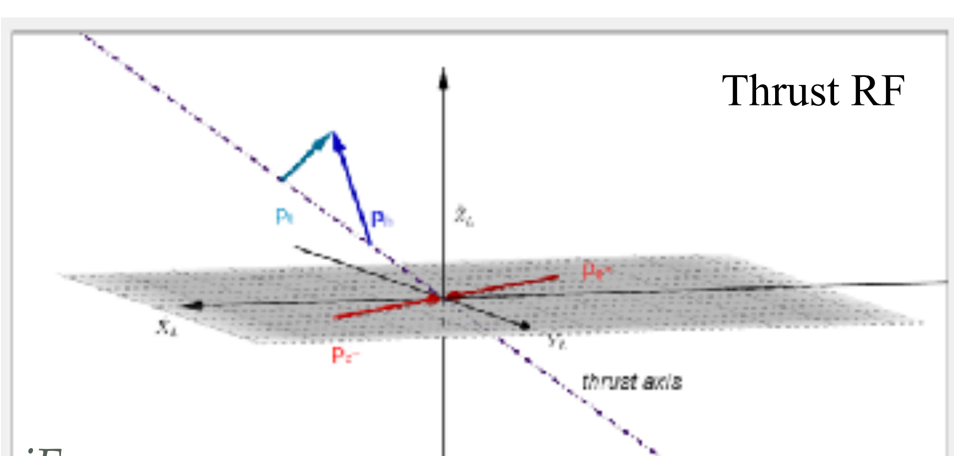
Distribution of protons from Λ decays with a transverse polarisation P:

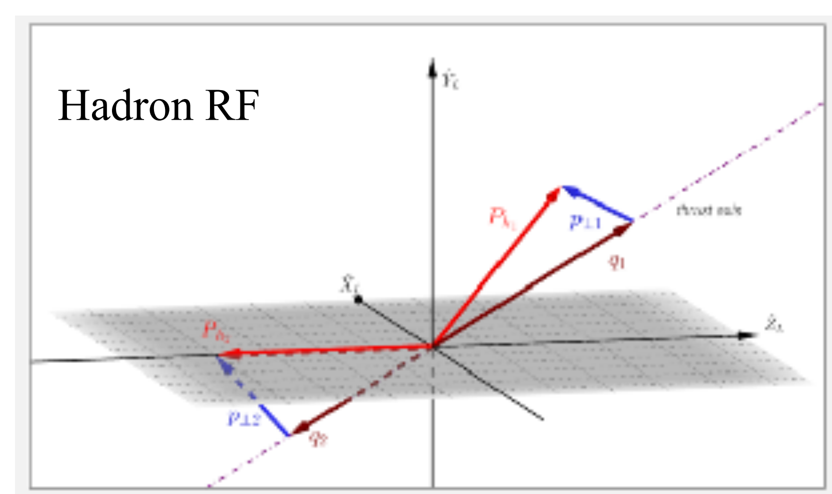
$$\frac{1}{N}\frac{dN}{d\cos\theta} = 1 + \alpha P \cos\theta,$$

$$P_\Lambda(z, p_\perp) = \frac{\sum_q e_q^2 \frac{4zp_\perp\sqrt{s}}{z^2 s + 4p_\perp^2} \Delta^N D_{\Lambda^\uparrow/q}(z, p_\perp)}{\sum_q e_q^2 2\pi D_{\Lambda/q}(z, p_\perp)} \times \frac{\int d(\cos\theta)\sin(2\theta)}{\int d(\cos\theta)(1+\cos^2\theta)}$$

PRD **100**,014029

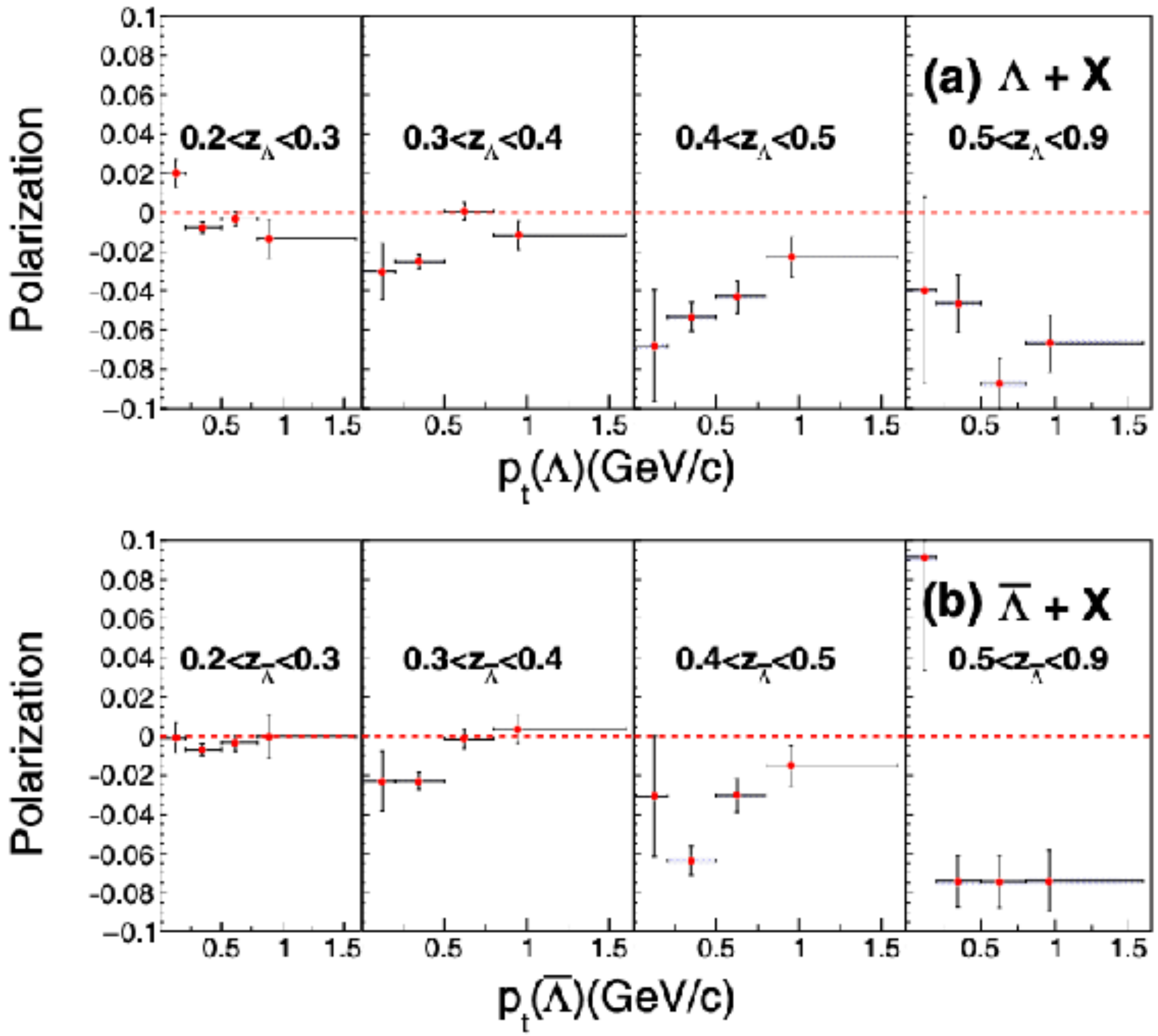
θ: angle between the axis $\hat{n} \propto \hat{T} \times \hat{p}_\Lambda$ and the proton momentum in the Λ rest frame; α is the world average value of the parity-violating decay asymmetry for the Λ (from PDG)
==> Significant transverse polarization is observed





$\Lambda/\bar{\Lambda}$ hyperon polarization at Belle: results

PRL **122**,042001

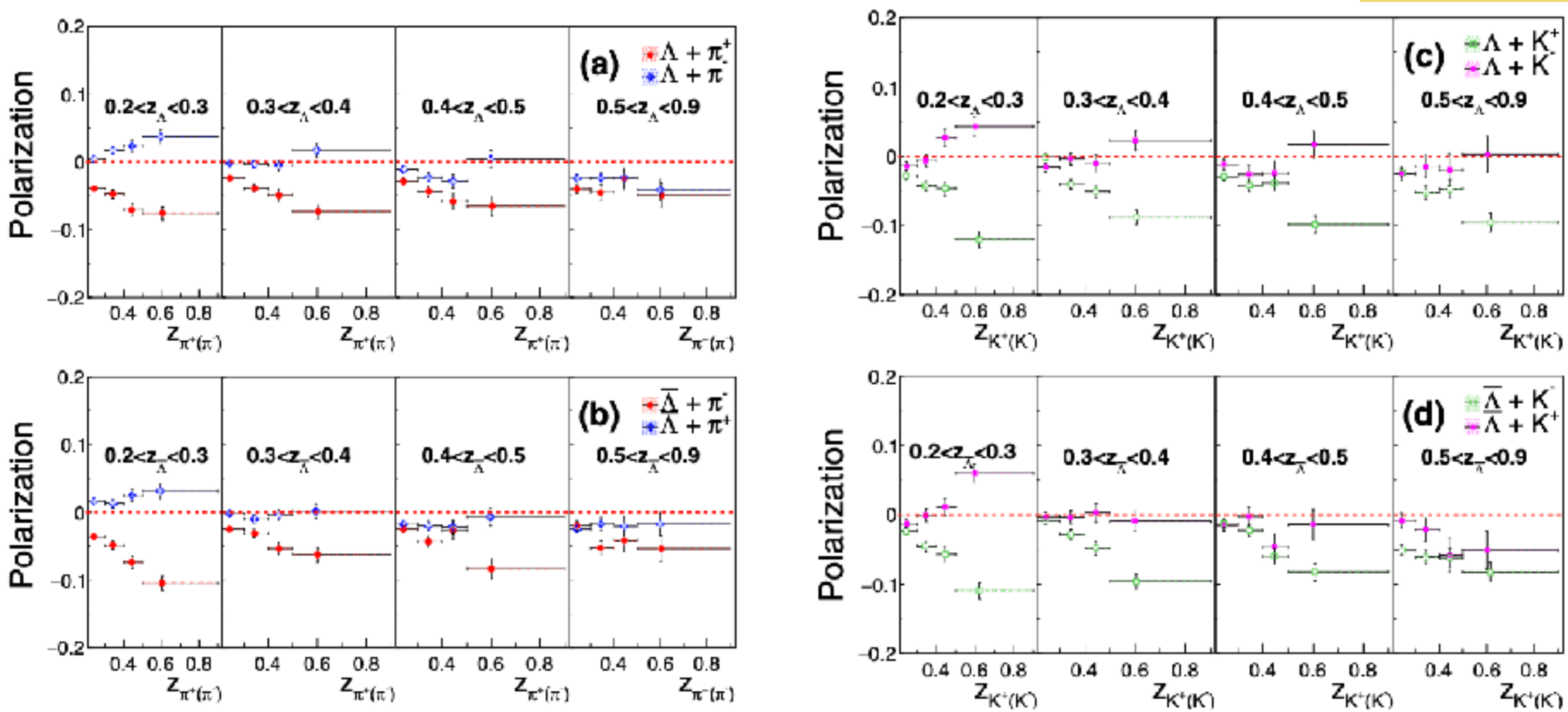


Complex p_t dependence

- z_Λ>0.5: increasing asymmetry with pt; opposite behaviour for intermediate z_Λ
  - different quark flavour contributions in different kinematic regions (s quark contribution is dominant in the highest z_Λ bin; u quark and charm contribution in the intermediate regions)
  - large charm contribution in intermediate z-bins

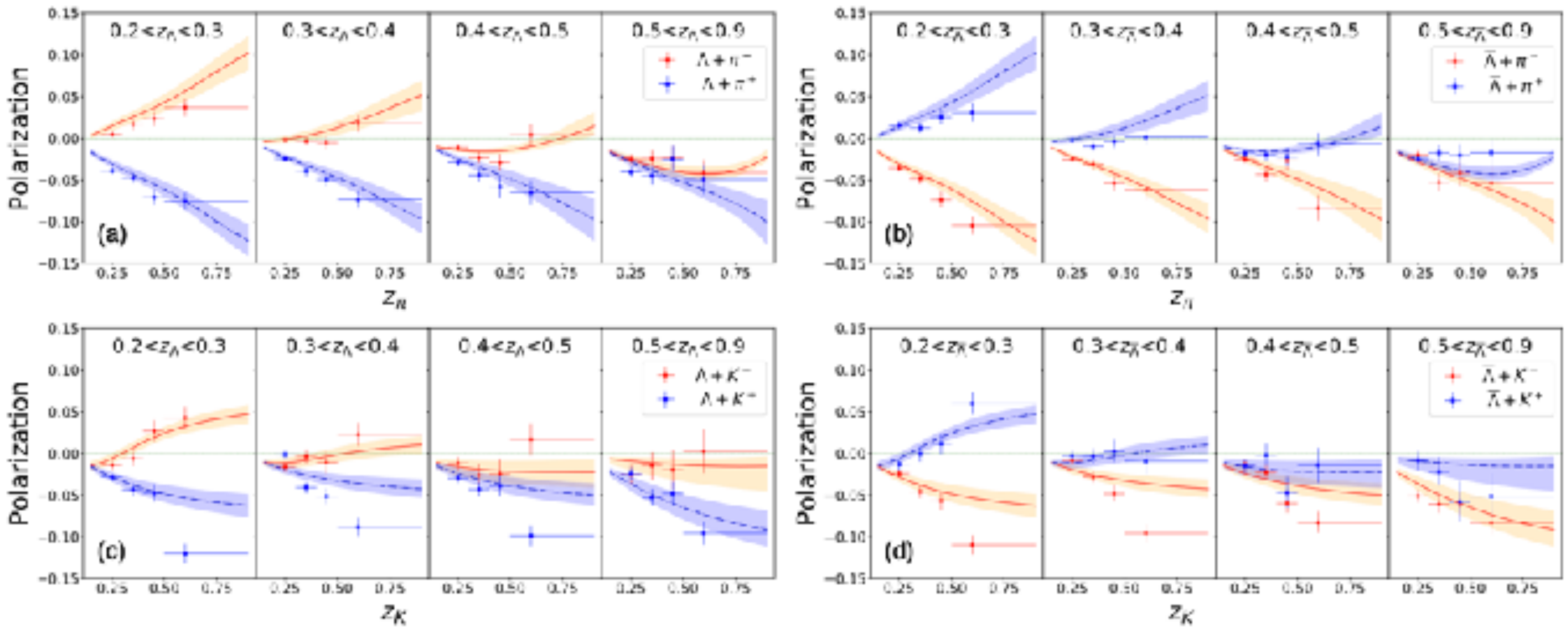
$\Lambda/\bar{\Lambda}$ hyperon polarization at Belle: results

PRL **122**,042001



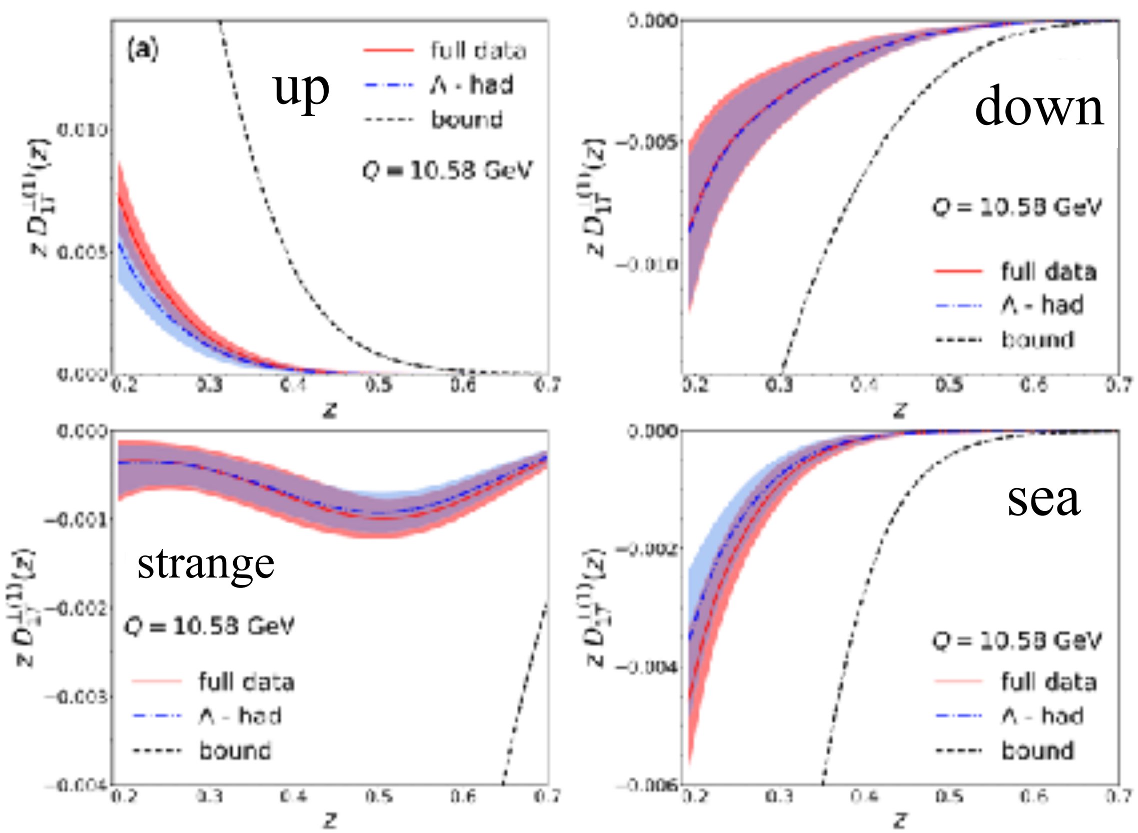
- low z_Λ: opposite site and increasing magnitude
- Sensitivity to the flavour dependence by selecting a light hadron in the opposite hemisphere:
  - Λ polarization from s quark is negative: negative asymmetry observed in ΛK^+X at high z_Λ, where s to Λ fragmentation dominates
  - In $\Lambda\pi^-X$ and ΛK^-X $u\rightarrow\Lambda$ fragmentation dominates at low z_Λ: u fragmentation to Λ is positive

First extraction of Λ polarised FF from Belle data



First extraction from Belle data within a TMD approach: D'Alessio, Murgia, Zaccheddu

PRD **102**,114015



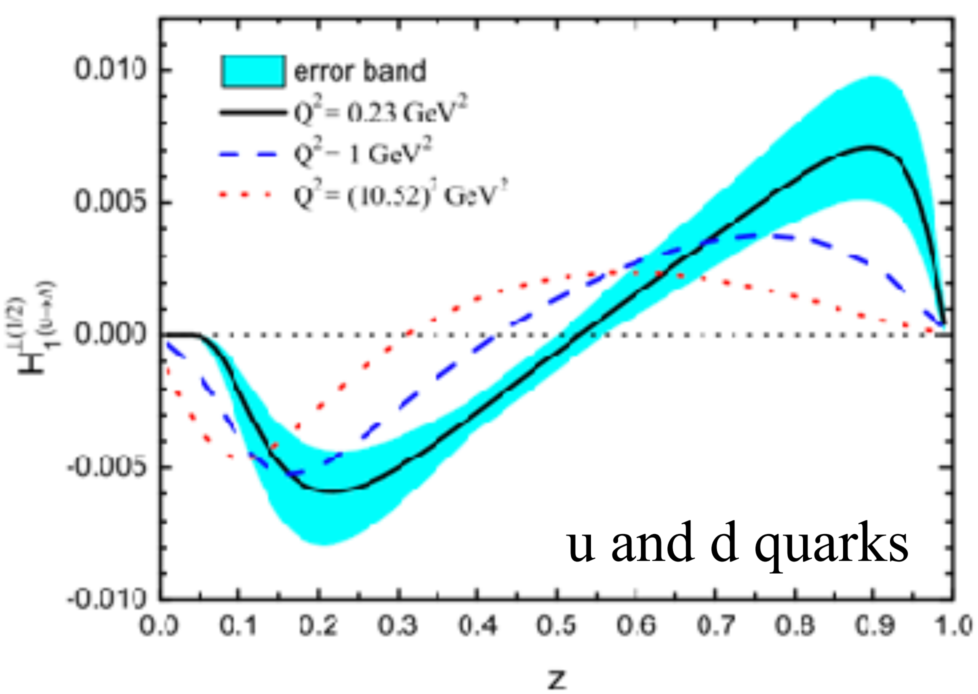
- Clear separation in flavour achieved
- The needed of sea-quark polarised FF is well supported
- Extracted the first pt dependence

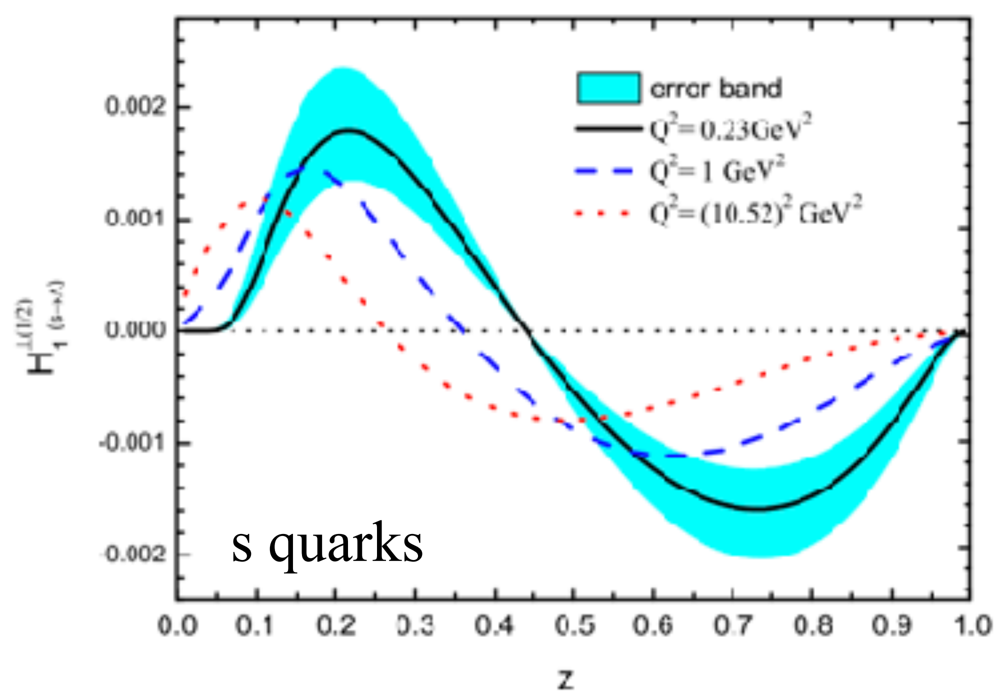
Higher statistic and complementary studies in other processes needed for a deeper understanding of this TMD-FF and solving the long-standing puzzle of the observed spontaneous transverse hyperon polarisation

Λ hyperon Collins FFs prediction

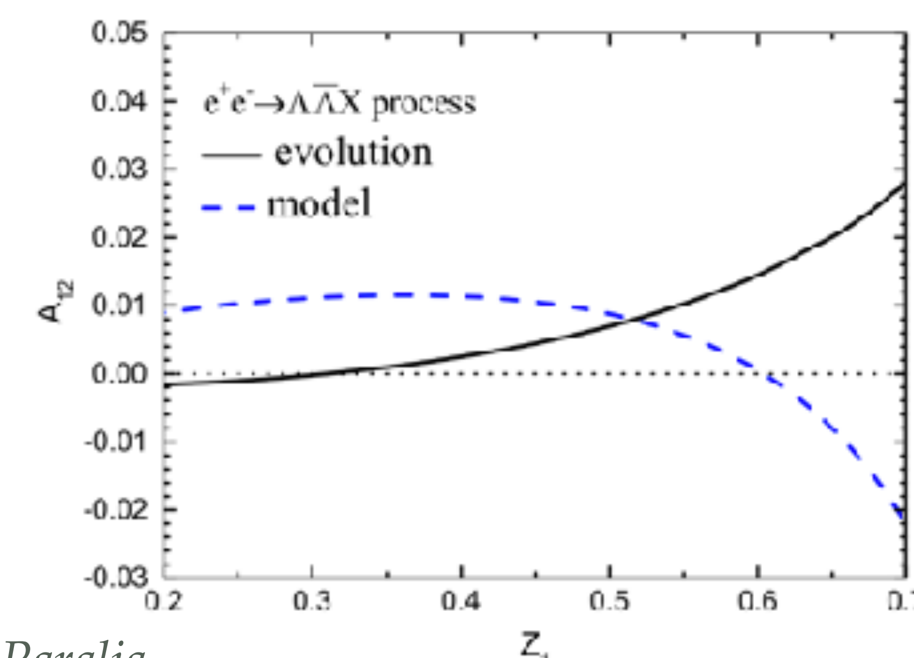
PRD97,114015

- Theoretical expectation from Collins FFs for Λ hyperon: $e^+e^- \to \Lambda\bar{\Lambda}X$
  - Process accessible in e^+e^- facilities
  - Collins FF: complementary information to $D_{1T}^{\perp}$





- Azimuthal asymmetry prediction in RF12 frame for $0.2<z_1<0.7$ (integrated over z_2)
- Increasing asymmetry with z, of the order of several percent



Summary and Conclusions

FFs and PDFs are fundamental tools for understanding of hadrons structure
Many other topics not covered in this talk

- Di-hadron FF studies: PRL 107,072004
- Form Factors
  - Timelike and Spacelike region
- Generalized Parton Distribution functions (GPDs) and Transition Distribution Amplitudes (TDA)

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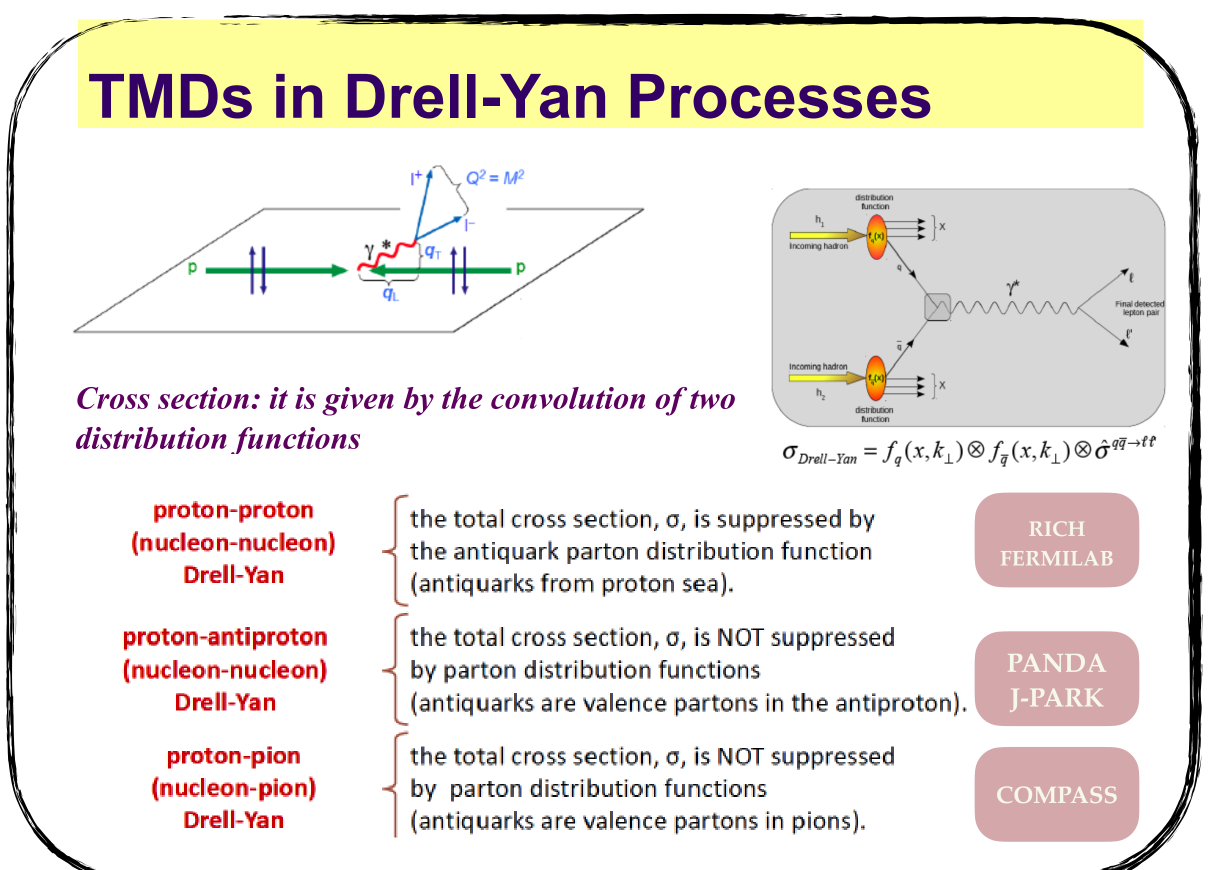

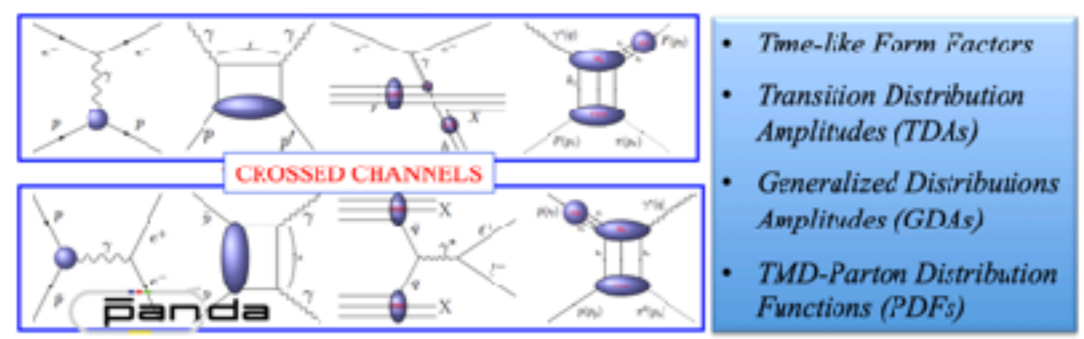

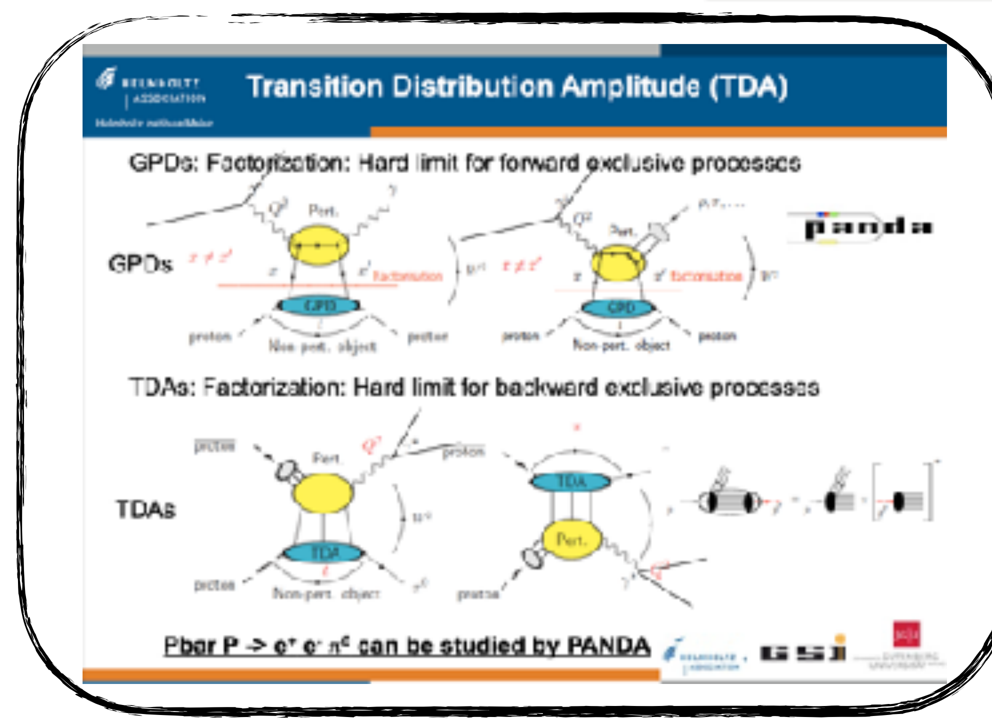

https://indico.cern.ch/event/129438/contributions/116456/attachments/88748/127038/transversity2011_Maas.pdf

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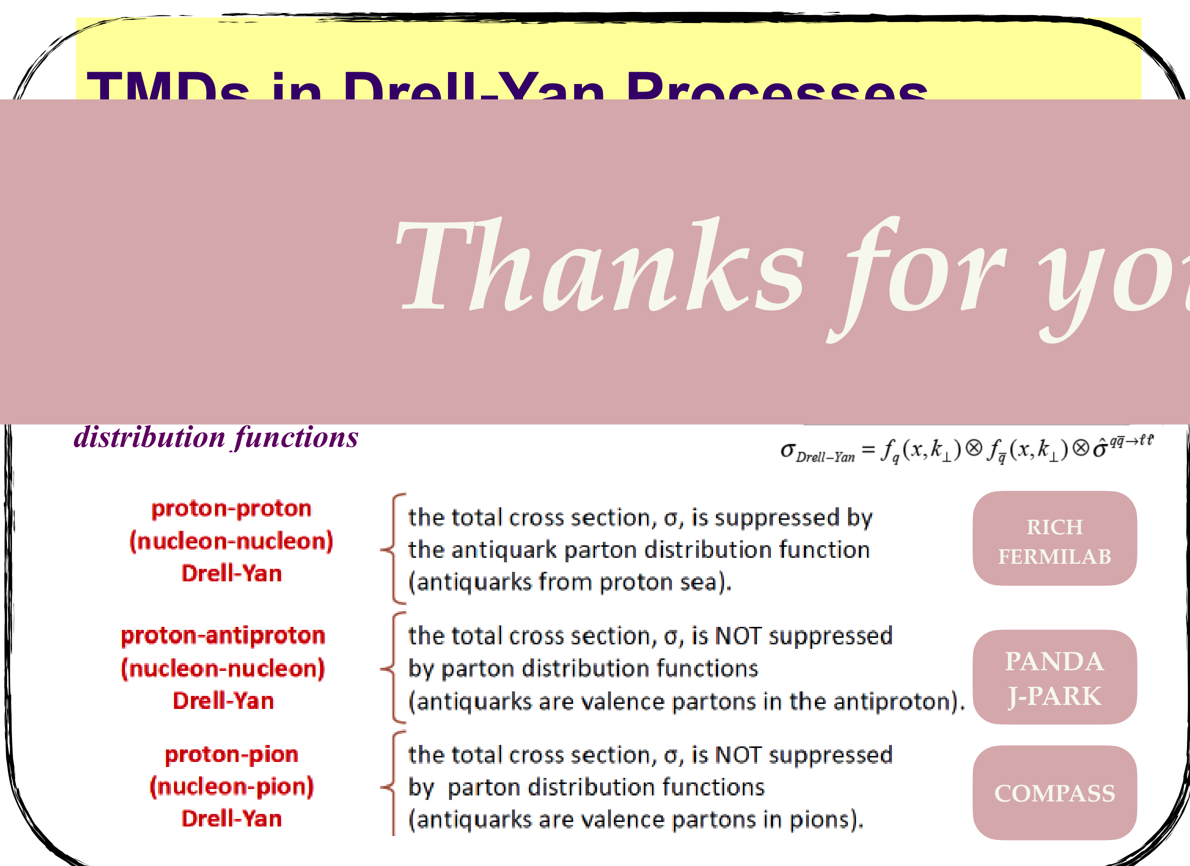
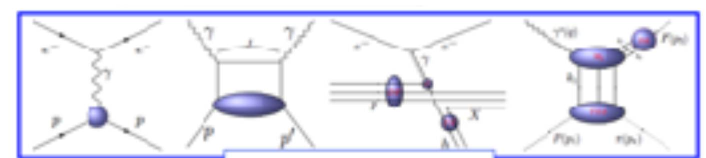
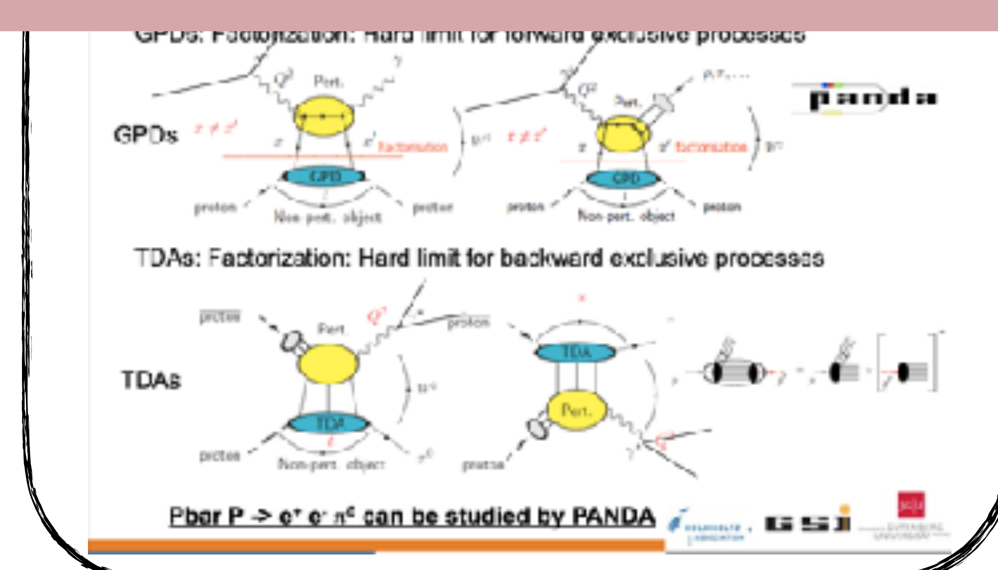


$\sigma_{Drell-Yan} = f_q(x,k_\perp) \otimes f_{\bar{q}}(x,k_\perp) \otimes \hat{\sigma}^{q\bar{q}\to\ell\ell}$

proton-proton (nucleon-nucleon) Drell-Yan	the total cross section, σ, is suppressed by the antiquark parton distribution function (antiquarks from proton sea).	RICH FERMILAB
proton-antiproton (nucleon-nucleon) Drell-Yan	the total cross section, σ, is NOT suppressed by parton distribution functions (antiquarks are valence partons in the antiproton).	PANDA J-PARK
proton-pion (nucleon-pion) Drell-Yan	the total cross section, σ, is NOT suppressed by parton distribution functions (antiquarks are valence partons in pions).	COMPASS



- *Time-like Form Factors*
- *Transition Distribution Amplitudes (TDAs)*



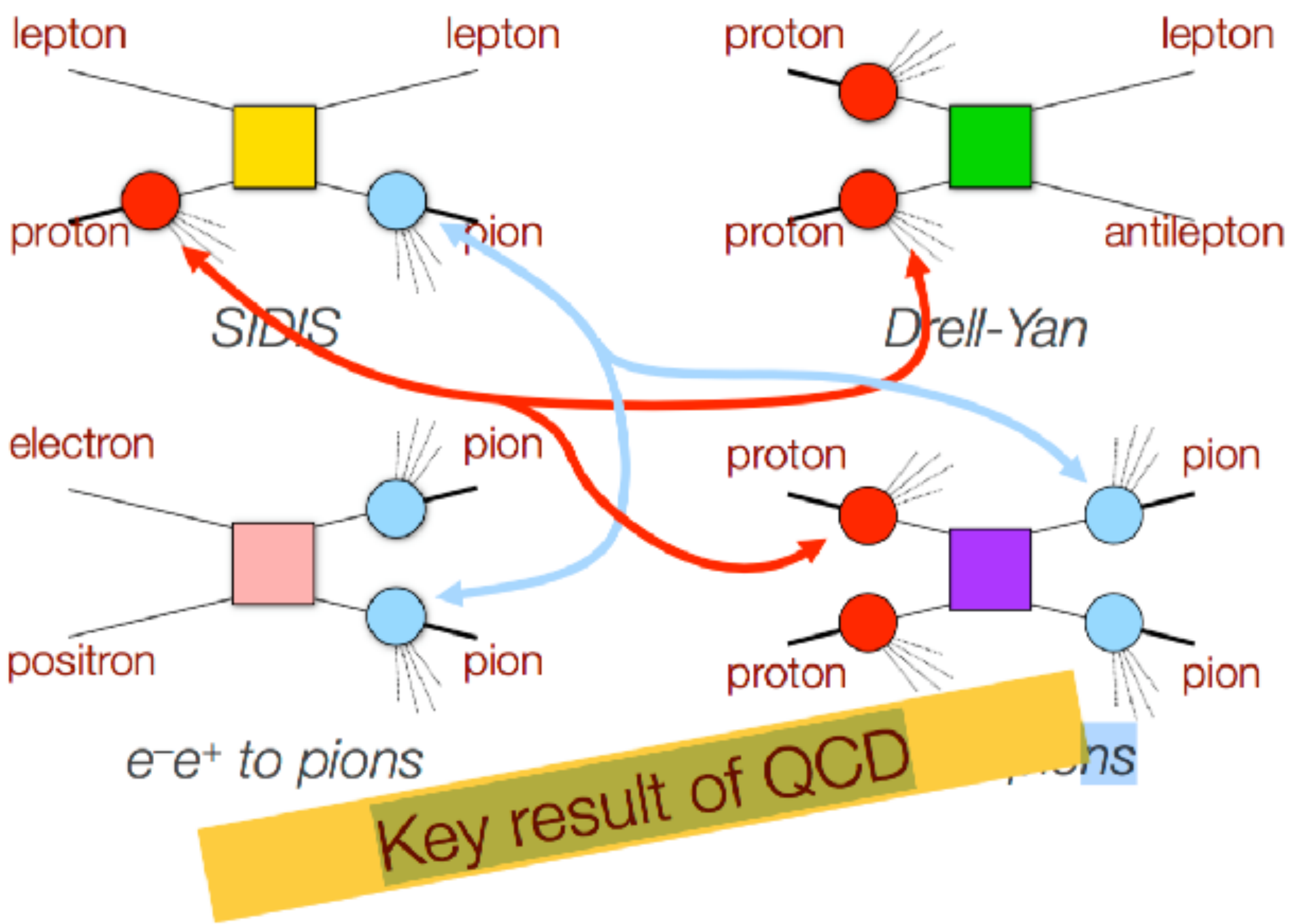
Thanks for your attention

https://indico.cern.ch/event/129438/contributions/116456/attachments/88748/127038/transversity2011_Maas.pdf

Backup

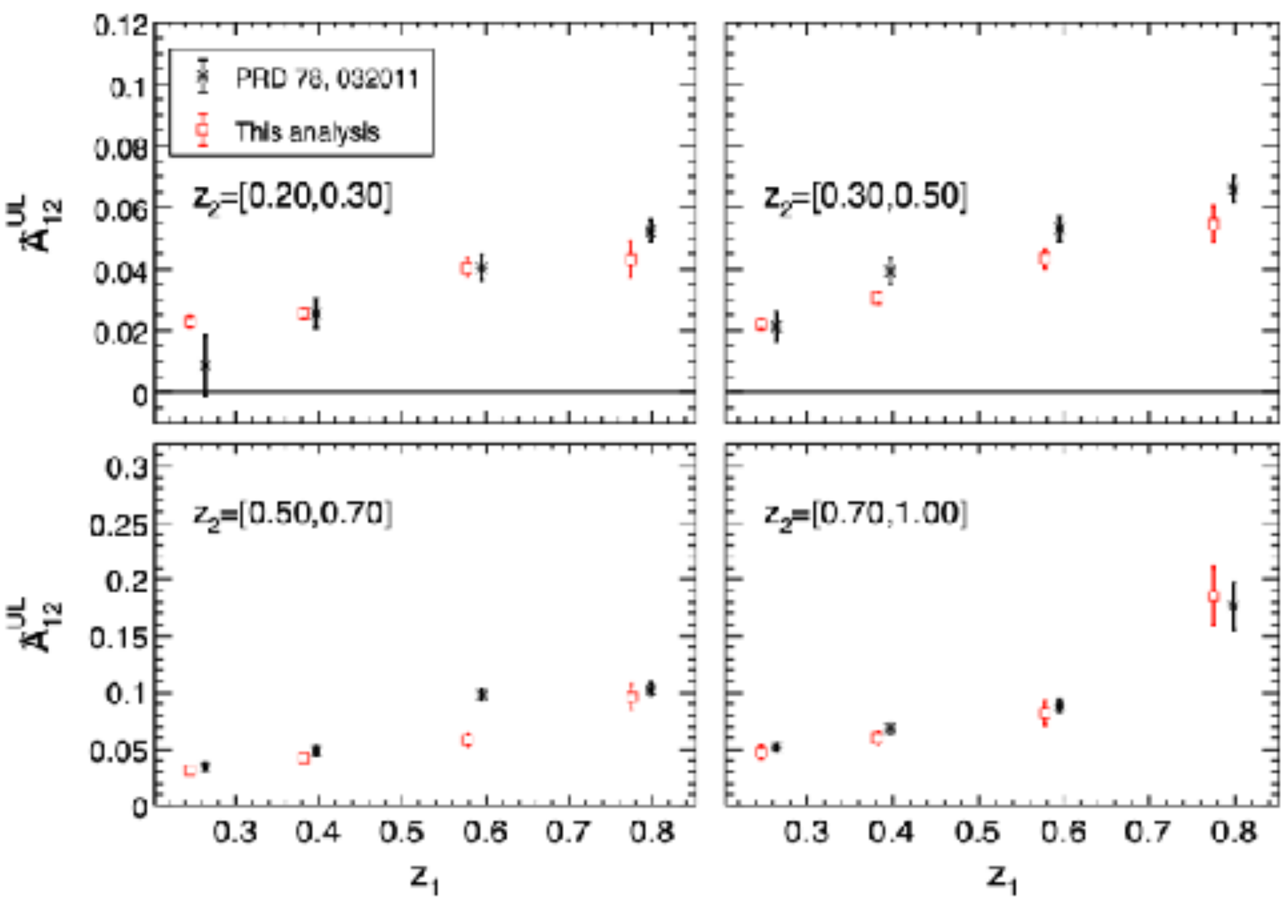
Universality

FF: independent of how the parton was produced
PDF: process independent nature



Azimuthal asymmetries of back-to-back $\pi^\pm$ - (π^0,η, $\pi^\pm$) from Belle

PRD100,092008



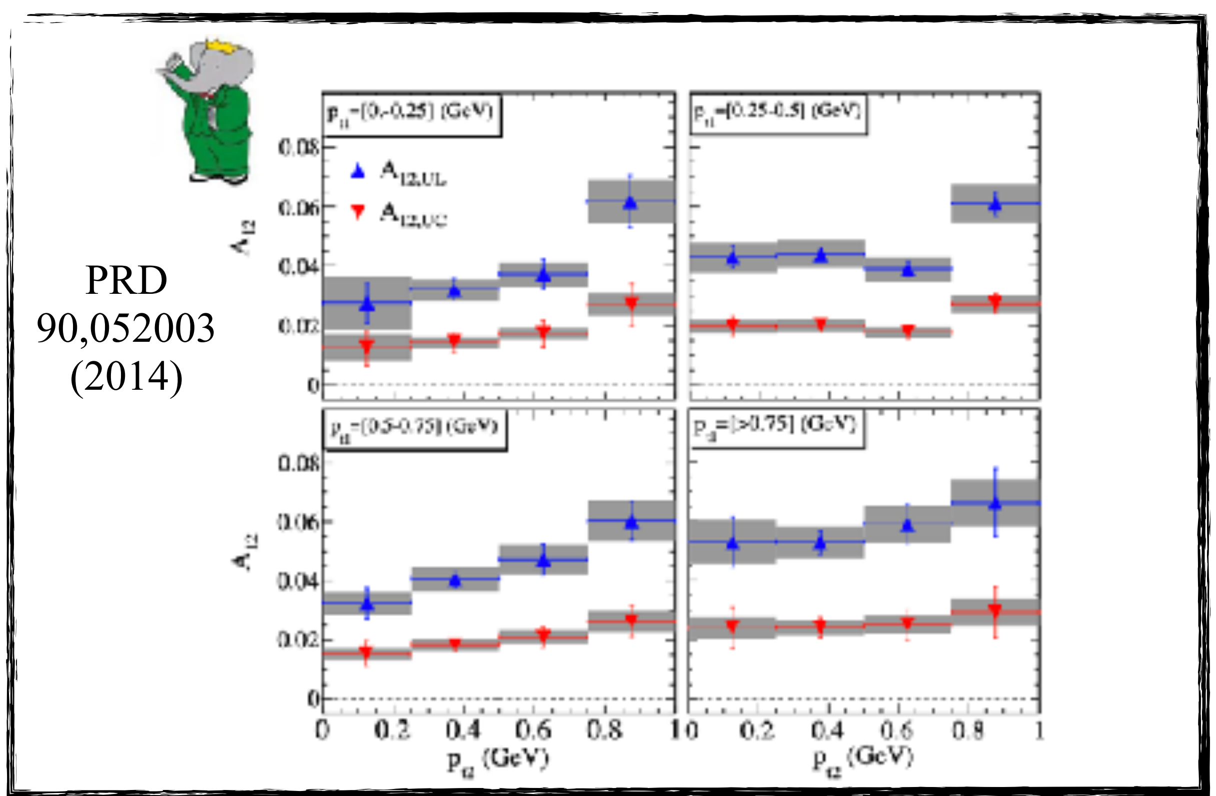
New Belle analysis: RF12 only

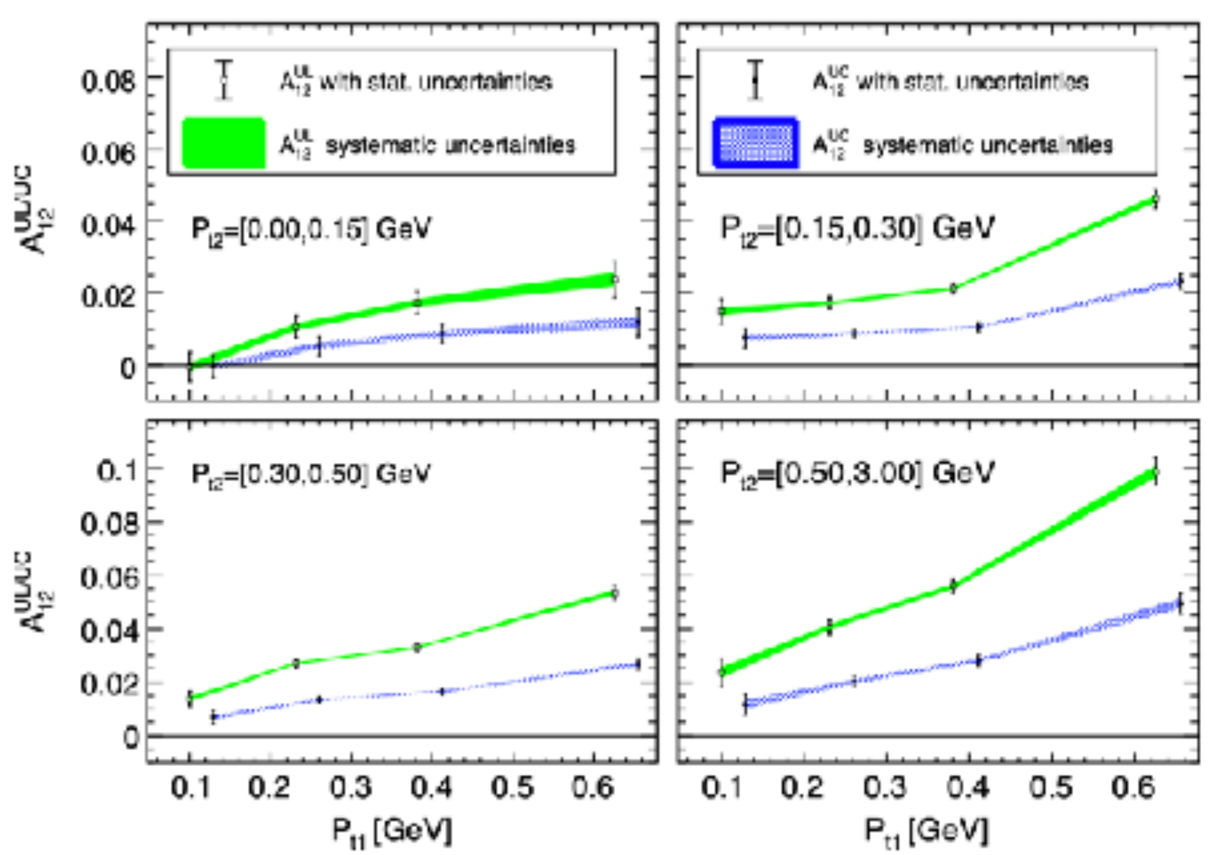
- No charm correction: only the estimated charm fractions are provided
- bin-by-bin generated-thrust axis correction (not the qqbar axis)
- Pt smering correction
- MC asymmetry subtraction

Only for results comparison:

- Vanishing charm asymmetry
- No thrust axis correction
- Kinematic factors taken into account

PRD 90,052003 (2014)





Results: RF0

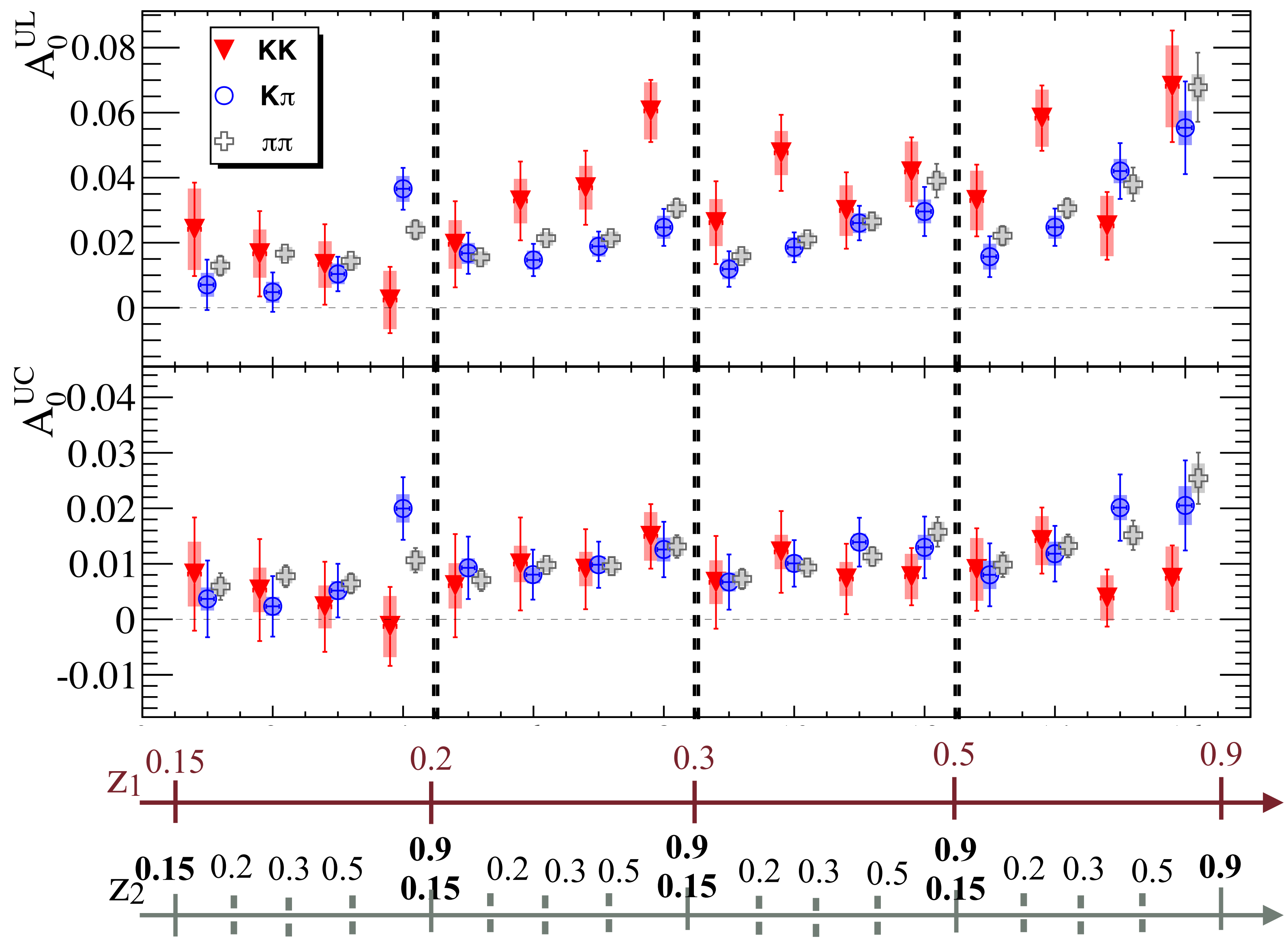
PRD92,111101(R)

Simultaneous measurement of KK, Kπ and ππ Collins asymmetries

- all corrections are applied

- 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

Note that A^{UL} and A^{UC} asymmetries are obtained using the same data sample, and are strongly correlated

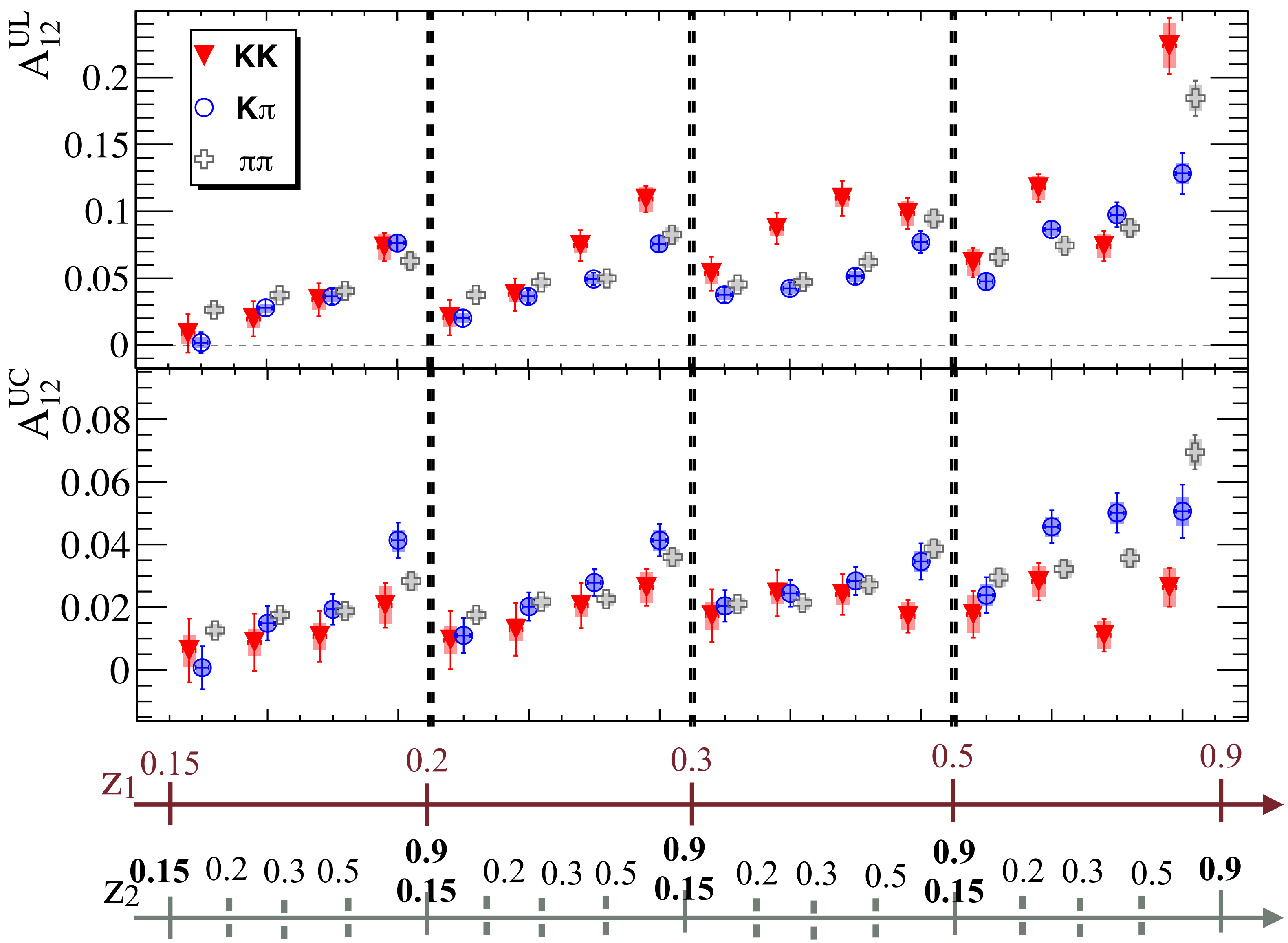


Results: RF12

PRD92,111101(R)

Simultaneous measurement of KK, Kπ and ππ Collins asymmetries

- all corrections are applied



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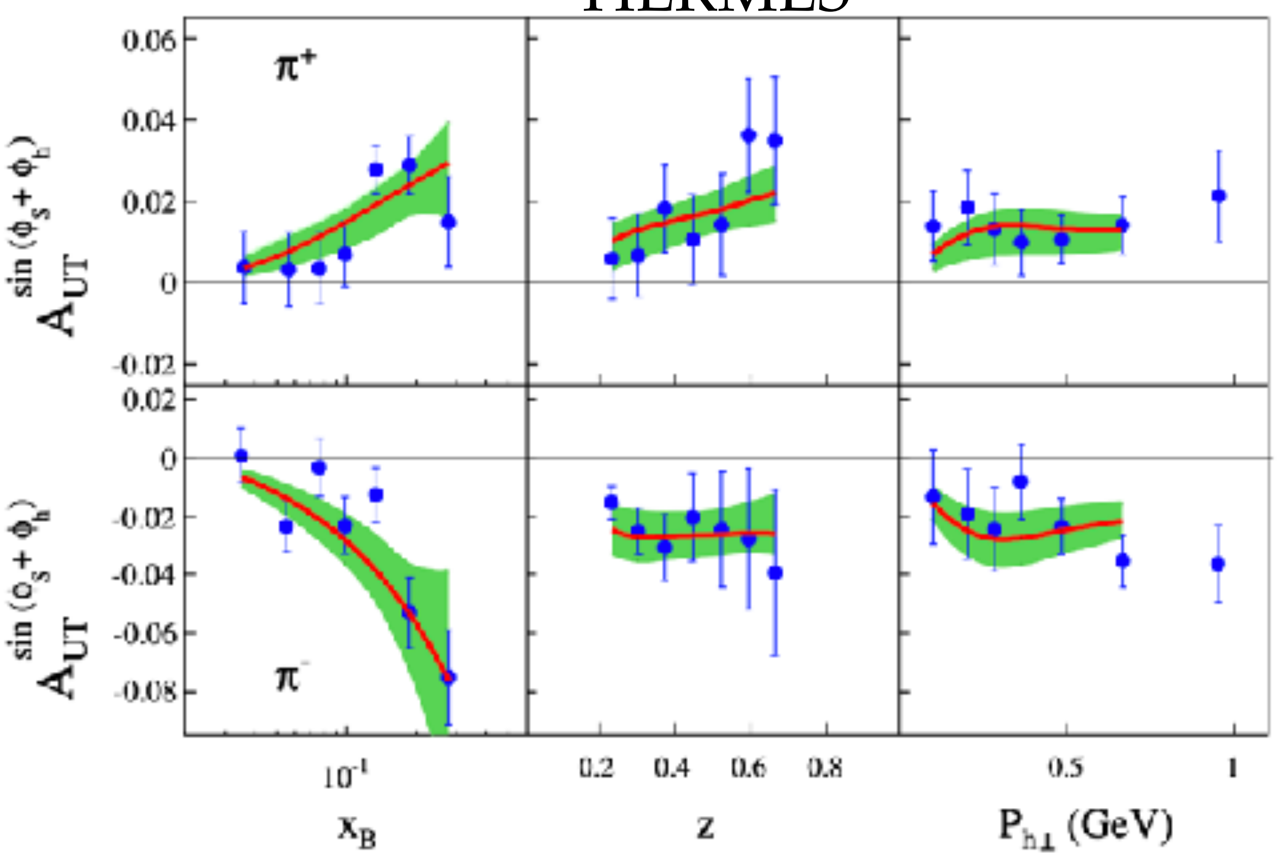
Extraction of Collins FF: data description

PRD93,014009

HERMES



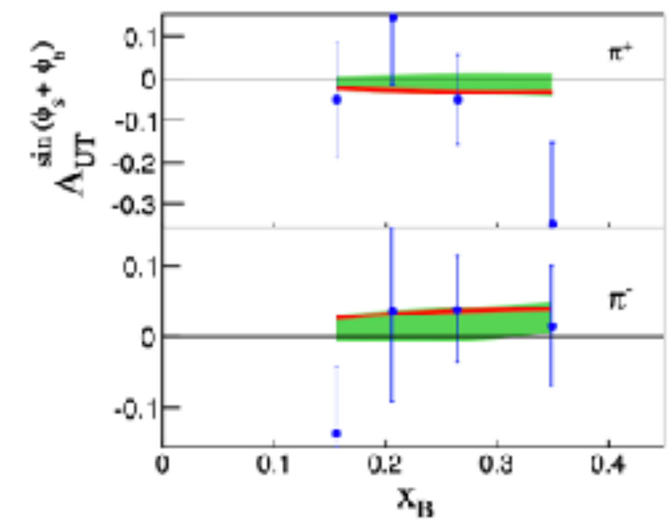
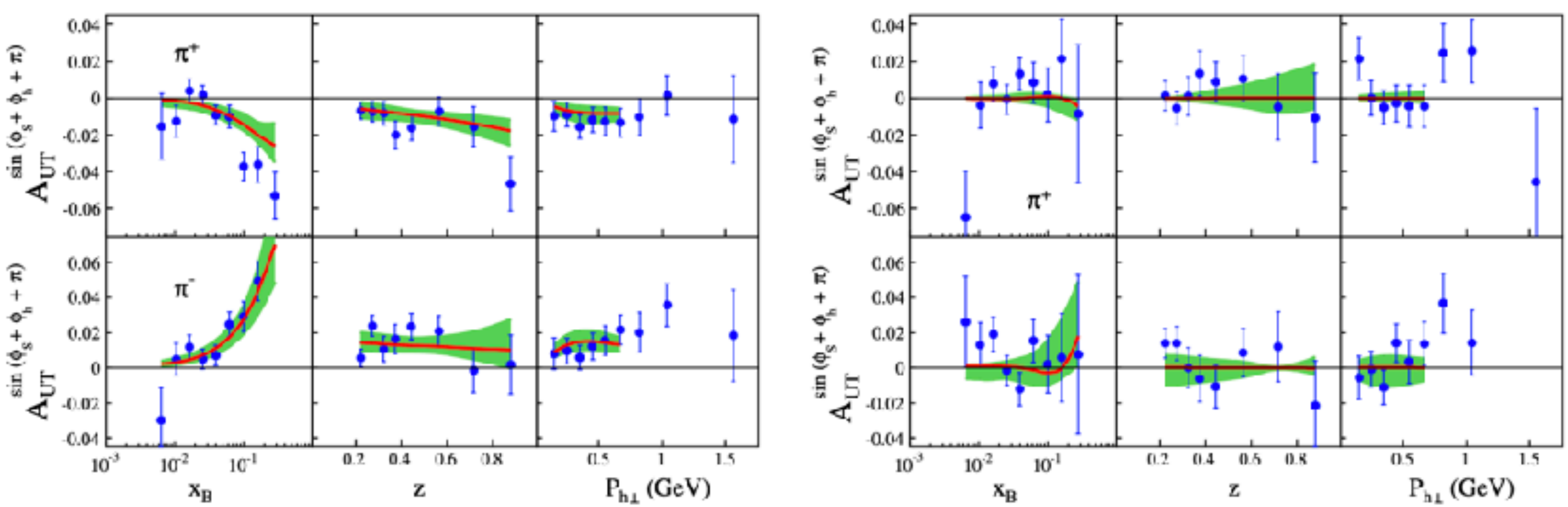


FIG. 14. Description of Collins asymmetries measured by the JLab's HALL A [9] as a function of x_B on the effective neutron target. The shaded region corresponds to our estimate of a 90% C.L. error band.



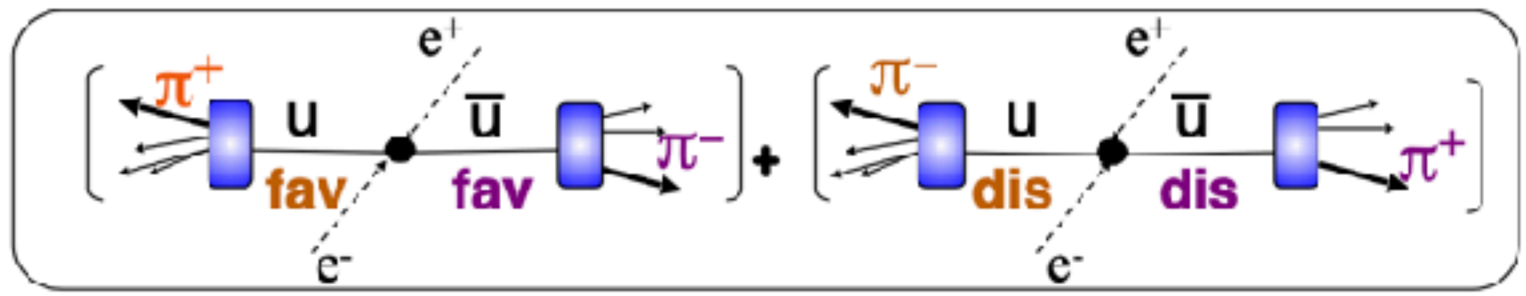
COMPASS

Favored and Disfavored processes

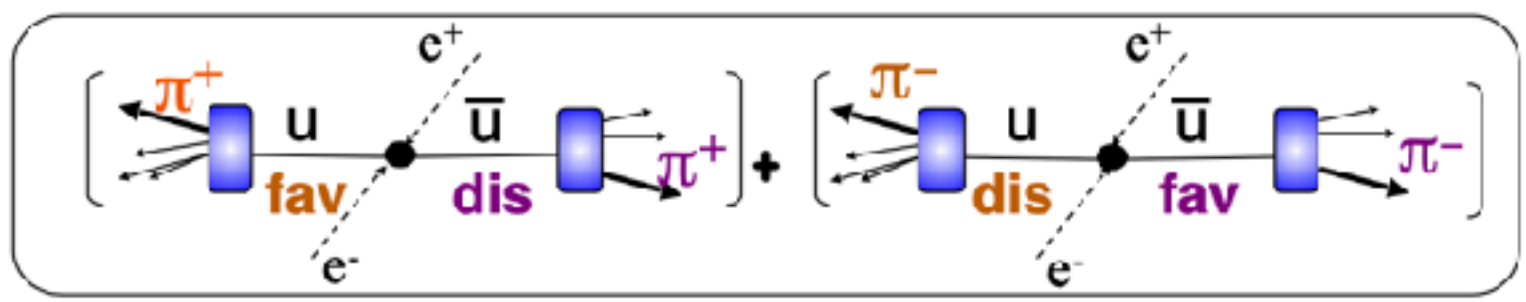
Different combinations of charged pions ⇒ sensitivity to **favored** or **disfavored** FFs

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

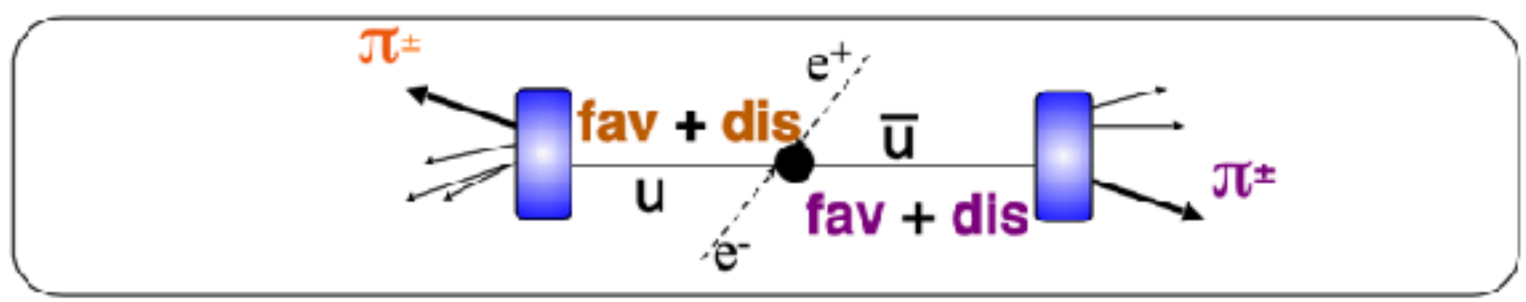
Unlike-sign pion pair = **U:**
$\pi^\mp\pi^\pm$: **(fav x fav)+(dis x dis)**



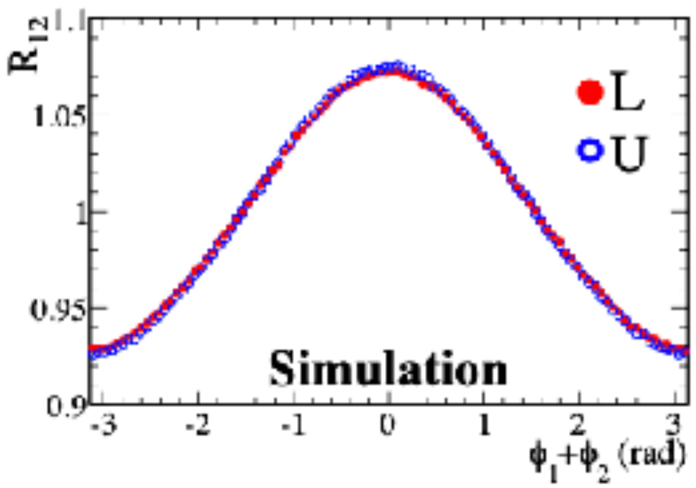
Like-sign pion pair = **L:**
$\pi^\pm\pi^\pm$: **(fav x dis)+(dis x fav)**

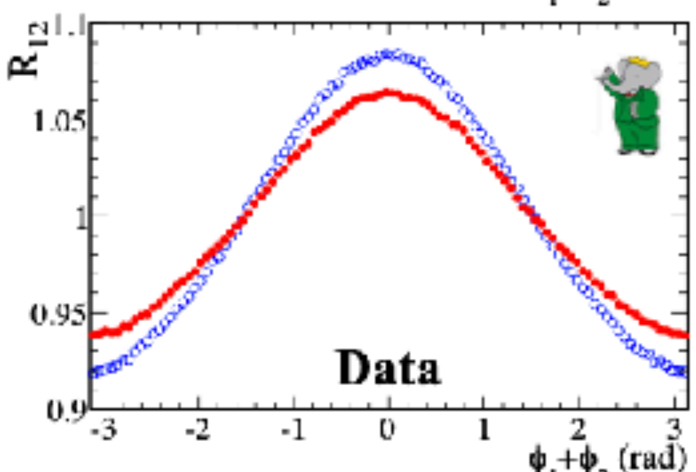


Charged pion pair = **C (U+L):**
$\pi\pi$: **(fav + dis)x(fav + dis)**
$\pi = \pi^\pm$



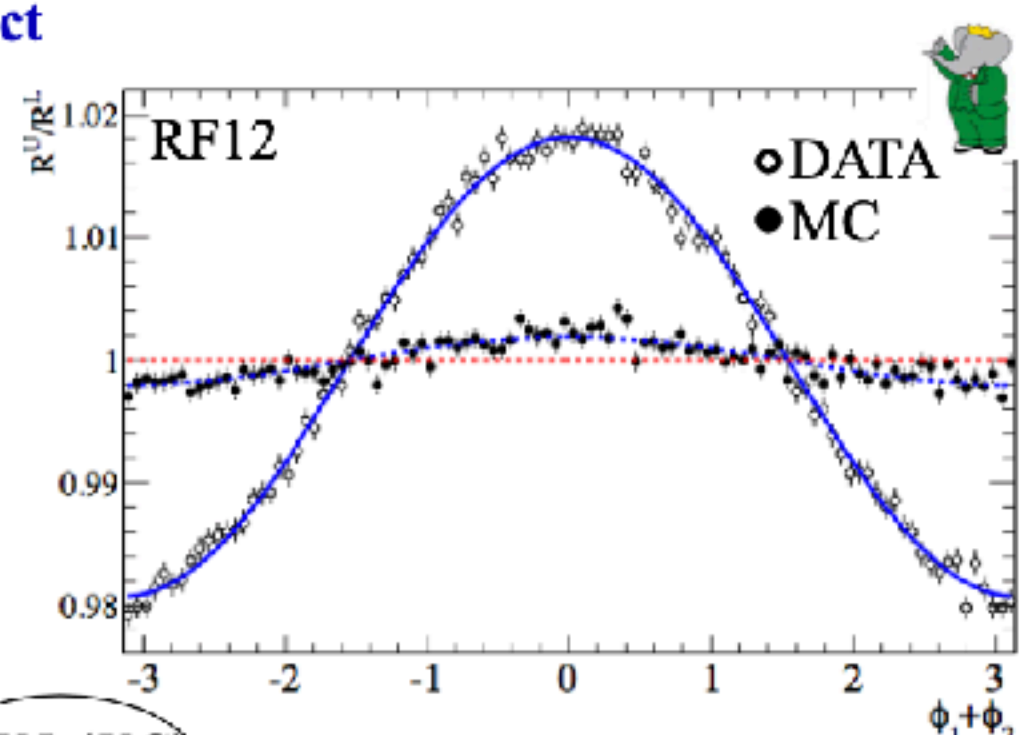
Raw asymmetries and Double Ratios





- **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

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

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)

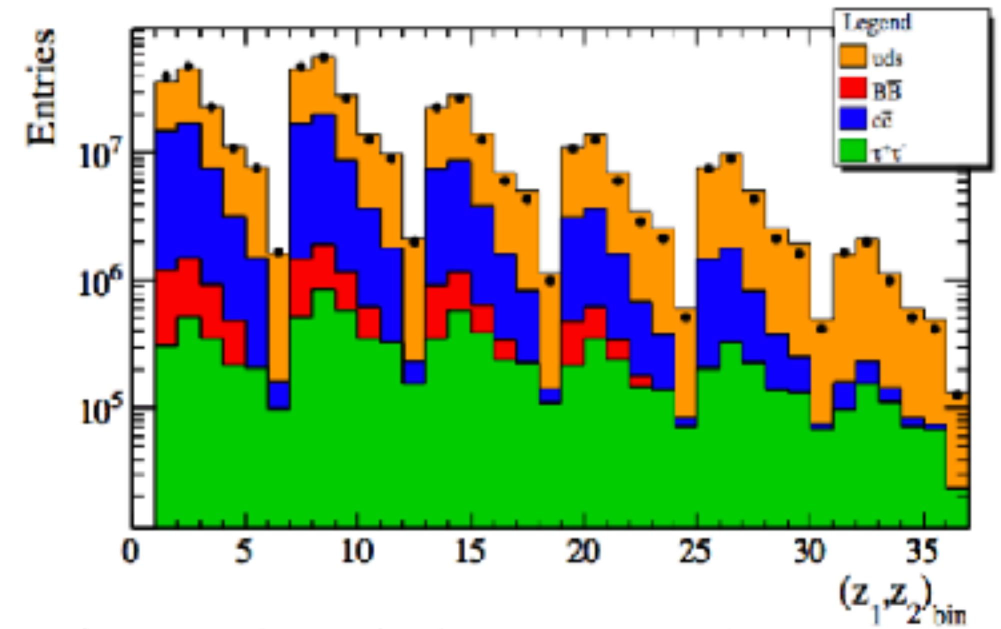
Fraction of ππ due to the i[th] bkg process

True asymmetry

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

Bkg asymmetry

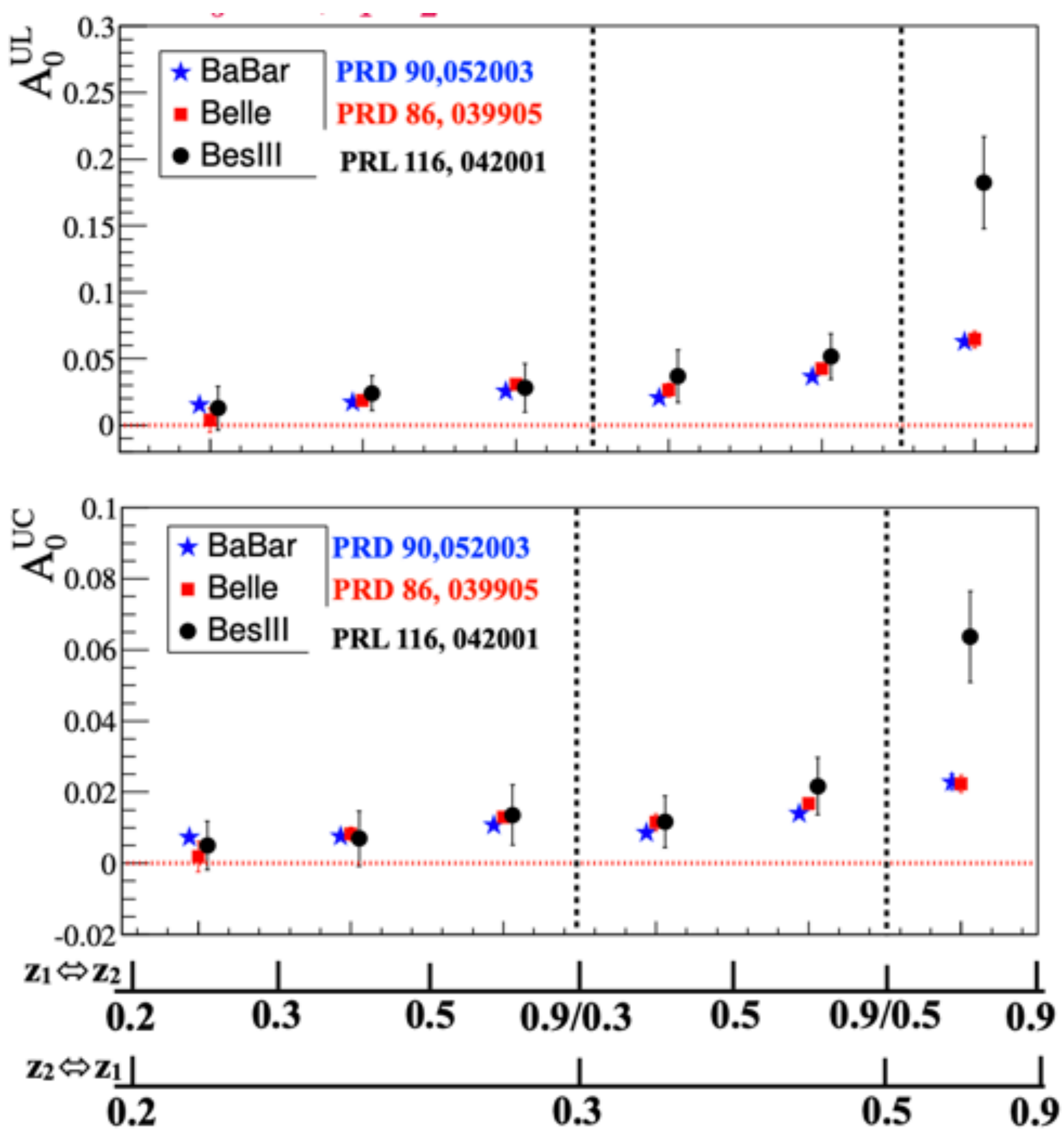
- We must calculate these quantities:
  - F_i using MC sample; we assign MC-data difference in each bin as systematic error
  - $A^{B\bar{B}}$ must be zero; we set $A^{B\bar{B}} = 0$
  - A^τ small in simulation; checked in data; we set $A^\tau = 0$

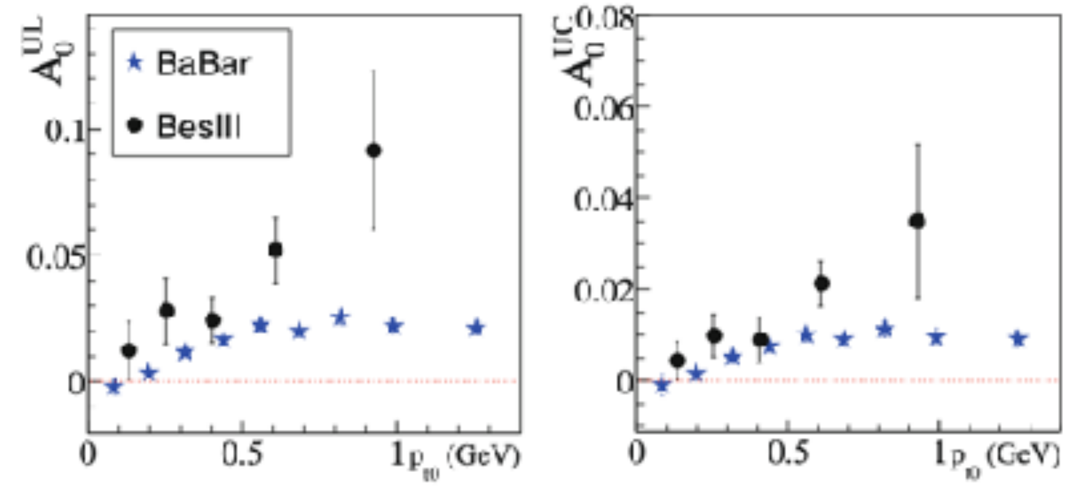


- **Charm** background contribution is about 30% on average
  - Both fragmentation processes and weak decays can introduce azimuthal asymmetries
  - We used a **D*±-enhanced control sample** to estimate its effect

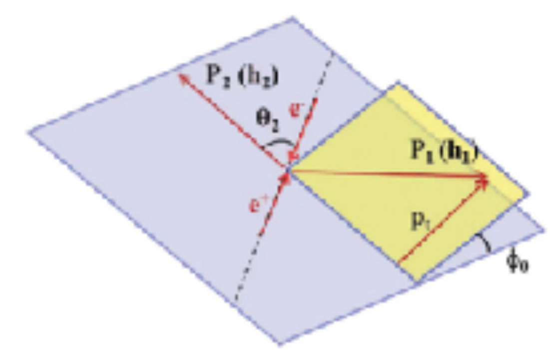
$$\begin{cases} A_\alpha^{meas} = (1 - F_c - F_B - F_\tau) \cdot A_\alpha + F_c \cdot A_\alpha^{ch} \\ A_\alpha^{D^*} = f_c \cdot A_\alpha^{ch} + (1 - f_c - f_B) \cdot A_\alpha \end{cases}$$

Collins FFs Results Comparison

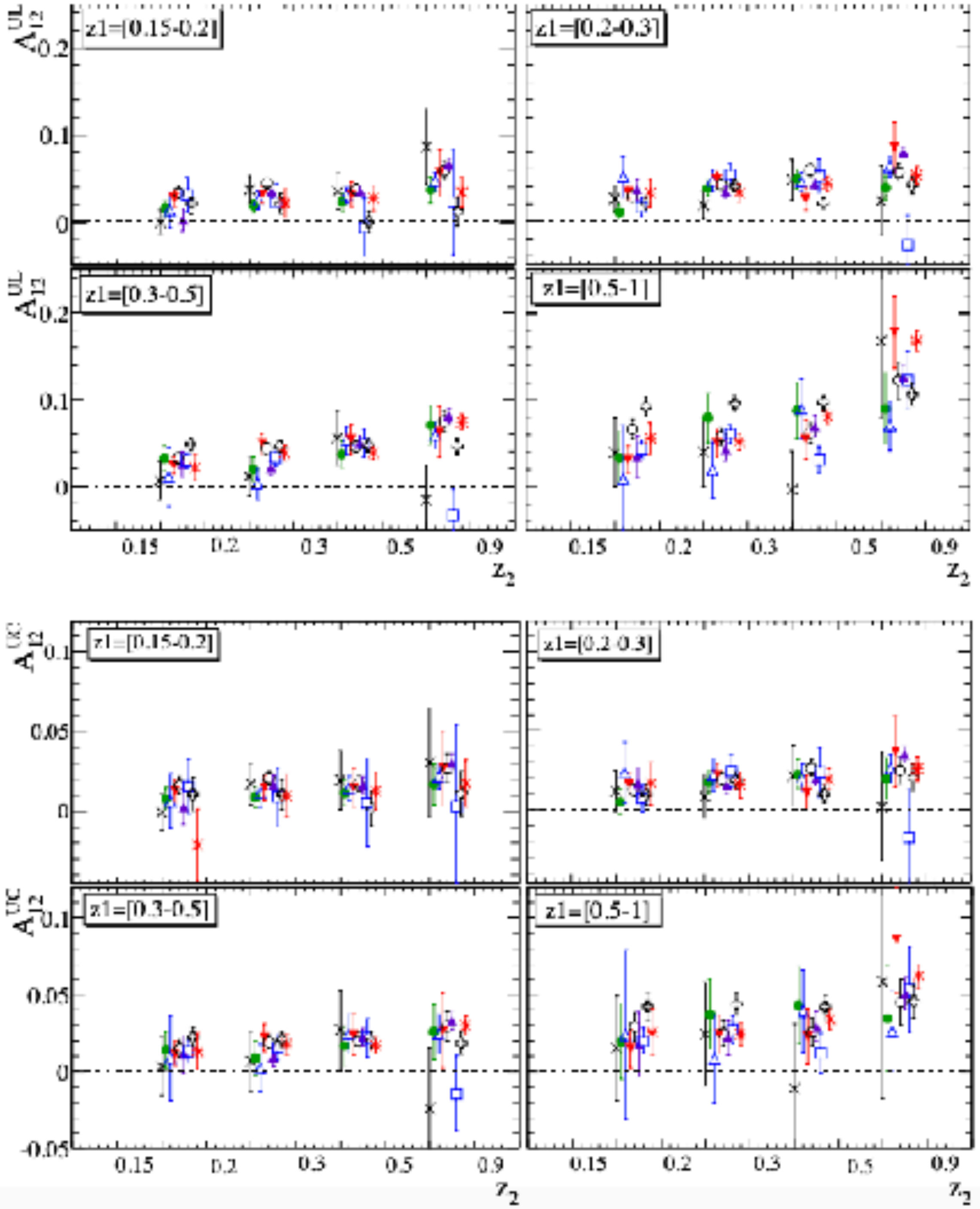




- Larger asymmetry from BESIII data, in agreement with the prediction (PRD93,014009)



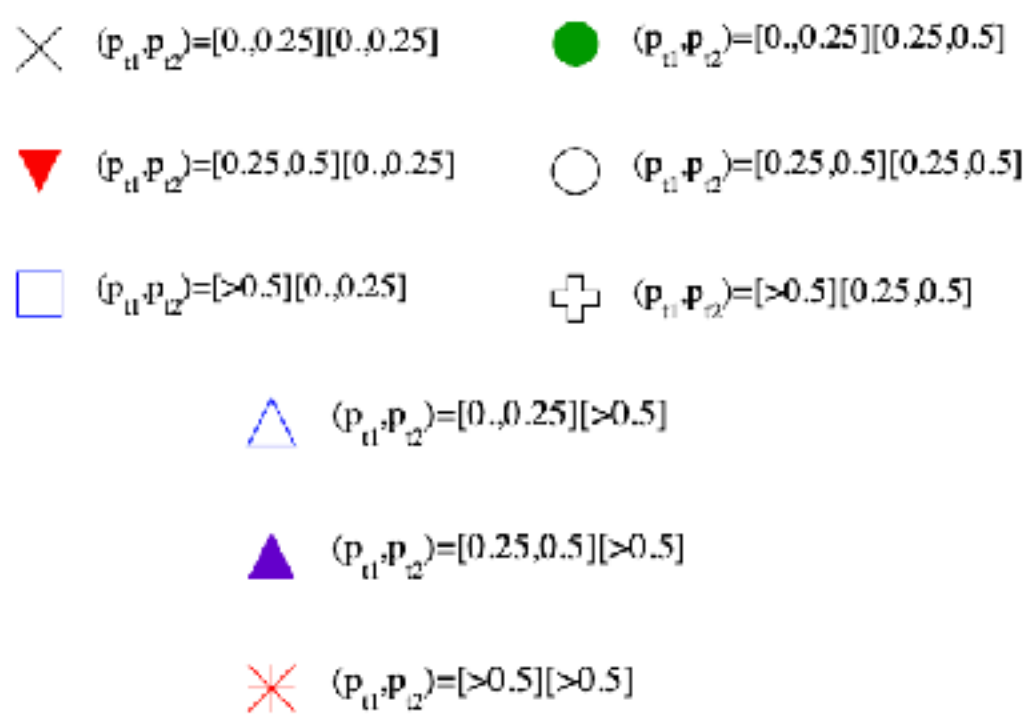
4-D: asymmetry vs. $(z_1,z_2)\times(p_{t1},p_{t2})$



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



Azimuthal asymmetries of back-to-back $\pi^\pm$ - $(\pi^0, \eta, \pi^\pm)$ from Belle

PRD100,092008

$$\mathcal{R}_{12}^{UL} \approx 1 + \cos(\phi_{12}) \frac{\sin^2(\theta)}{1+\cos^2(\theta)} \times \left\{ \frac{5(H_1^{\perp,\mathrm{fav}} \otimes H_1^{\perp,\mathrm{fav}} + H_1^{\perp,\mathrm{dis}} \otimes H_1^{\perp,\mathrm{dis}}) + 2H_{1,s\to\pi}^{\perp,\mathrm{dis}} \otimes H_{1,s\to\pi}^{\perp,\mathrm{dis}}}{5(D_1^{\mathrm{fav}} \otimes D_1^{\mathrm{fav}} + D_1^{\mathrm{dis}} \otimes D_1^{\mathrm{dis}}) + 2D_{1,s\to\pi}^{\mathrm{dis}} \otimes D_{1,s\to\pi}^{\mathrm{dis}}} - \frac{10H_1^{\perp,\mathrm{fav}} \otimes H_1^{\perp,\mathrm{dis}} + 2H_{1,s\to\pi}^{\perp,\mathrm{dis}} \otimes H_{1,s\to\pi}^{\perp,\mathrm{dis}}}{10D_1^{\mathrm{fav}} \otimes D_1^{\mathrm{dis}} + 2D_{1,s\to\pi}^{\mathrm{dis}} \otimes D_{1,s\to\pi}^{\mathrm{dis}}} \right\},$$

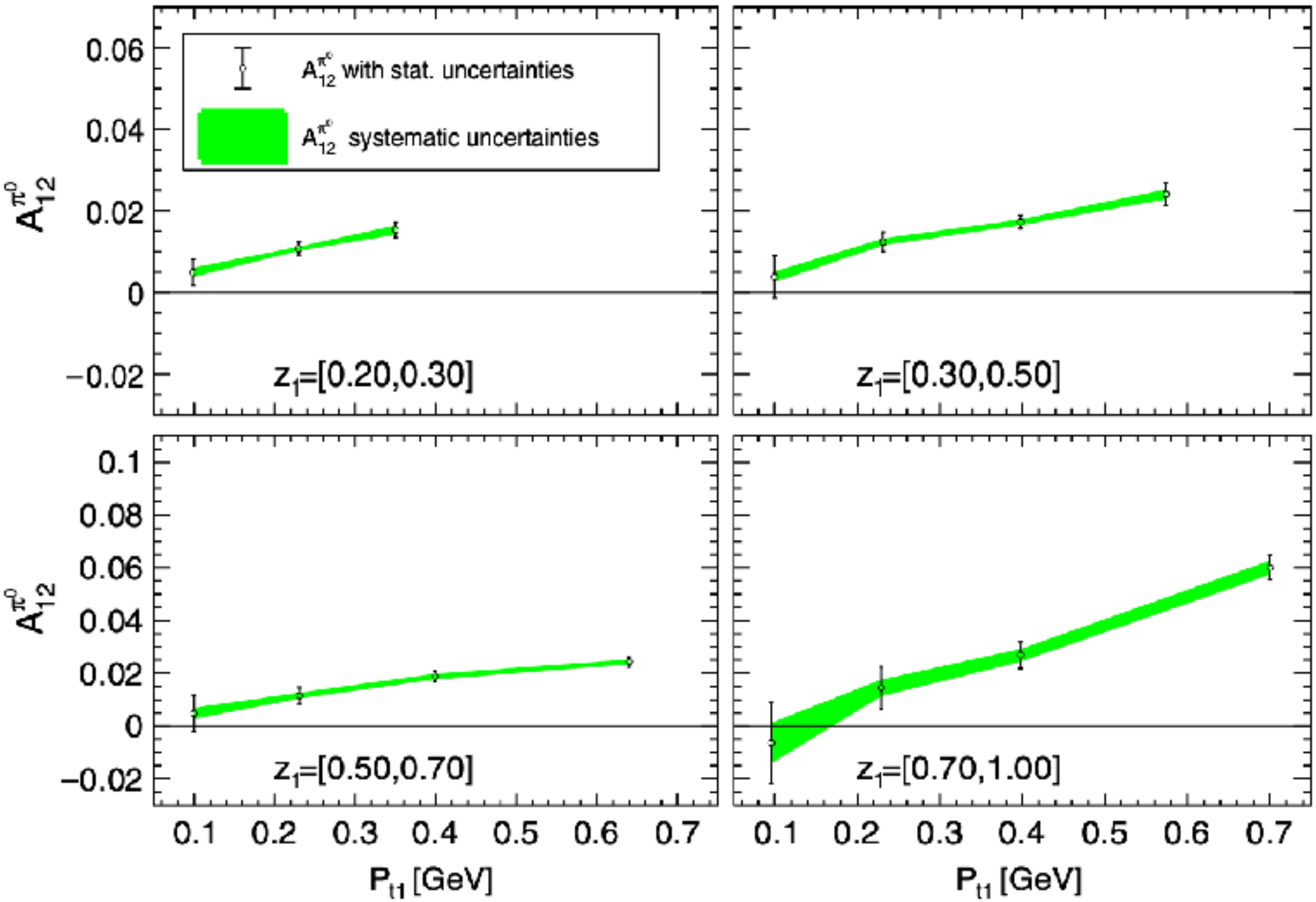
$$\mathcal{R}_{12}^{UC} \approx 1 + \cos(\phi_{12}) \frac{\sin^2(\theta)}{1+\cos^2(\theta)} \times \left\{ \frac{5(H_1^{\perp,\mathrm{fav}} \otimes H_1^{\perp,\mathrm{fav}} + H_1^{\perp,\mathrm{dis}} \otimes H_1^{\perp,\mathrm{dis}}) + 2H_{1,s\to\pi}^{\perp,\mathrm{dis}} \otimes H_{1,s\to\pi}^{\perp,\mathrm{dis}}}{5(D_1^{\mathrm{fav}} \otimes D_1^{\mathrm{fav}} + D_1^{\mathrm{dis}} \otimes D_1^{\mathrm{dis}}) + 2D_{1,s\to\pi}^{\mathrm{dis}} \otimes D_{1,s\to\pi}^{\mathrm{dis}}} - \frac{5(H_1^{\perp,\mathrm{fav}} + H_1^{\perp,\mathrm{dis}}) \otimes (H_1^{\perp,\mathrm{fav}} + H_1^{\perp,\mathrm{dis}}) + 4H_{1,s\to\pi}^{\perp,\mathrm{dis}} \otimes H_{1,s\to\pi}^{\perp,\mathrm{dis}}}{5(D_1^{\mathrm{fav}} + D_1^{\mathrm{dis}}) \otimes (D_1^{\mathrm{fav}} + D_1^{\mathrm{dis}}) + 4D_{1,s\to\pi}^{\mathrm{dis}} \otimes D_{1,s\to\pi}^{\mathrm{dis}}} \right\},$$

$$\mathcal{R}_{12}^{\pi^0} = \frac{R_{12}^{0\pm}}{R_{12}^{L}} \approx 1 + \cos(\phi_{12}) \frac{\sin^2(\theta)}{1+\cos^2(\theta)} \times \left\{ \frac{5(H_1^{\perp,\mathrm{fav}} + H_1^{\perp,\mathrm{dis}}) \otimes (H_1^{\perp,\mathrm{fav}} + H_1^{\perp,\mathrm{dis}}) + 4H_{1,s\to\pi}^{\perp,\mathrm{dis}} \otimes H_{1,s\to\pi}^{\perp,\mathrm{dis}}}{5(D_1^{\mathrm{fav}} + D_1^{\mathrm{dis}}) \otimes (D_1^{\mathrm{fav}} + D_1^{\mathrm{dis}}) + 4D_{1,s\to\pi}^{\mathrm{dis}} \otimes D_{1,s\to\pi}^{\mathrm{dis}})} - \frac{10H_1^{\perp,\mathrm{fav}} \otimes H_1^{\perp,\mathrm{dis}} + 2H_{1,s\to\pi}^{\perp,\mathrm{dis}} H_{1,s\to\pi}^{\perp,\mathrm{dis}}}{10D_1^{\mathrm{fav}} \otimes D_1^{\mathrm{dis}} + 2D_{1,s\to\pi}^{\mathrm{dis}} \otimes D_{1,s\to\pi}^{\mathrm{dis}}} \right\}.$$

$$\mathcal{R}_{12}^{\eta} = \frac{R_{12}^{\eta\pm}}{R_{12}^{L}} \approx 1 + \cos(\phi_{12}) \frac{\sin^2(\theta)}{1+\cos^2(\theta)} \times \left\{ \frac{5(H_1^{\perp,\mathrm{fav}_\eta} + H_1^{\perp,\mathrm{dis}_\eta}) \otimes (H_1^{\perp,\mathrm{dis}} + H_1^{\perp,\mathrm{fav}}) + 4H_{1,s\to\eta}^{\perp} \otimes H_{1,s\to\pi}^{\perp,\mathrm{dis}}}{5(D_1^{\perp,\mathrm{fav}_\eta} + D_1^{\perp,\mathrm{dis}_\eta}) \otimes (D_1^{\perp,\mathrm{dis}} + D_1^{\perp,\mathrm{fav}}) + 4D_{1,s\to\eta} \otimes D_{1,s\to\pi}^{\mathrm{dis}})} - \frac{10H_1^{\perp,\mathrm{fav}} \otimes H_1^{\perp,\mathrm{dis}} + 2H_{1,s\to\pi}^{\perp,\mathrm{dis}} \otimes H_{1,s\to\pi}^{\perp,\mathrm{dis}}}{10D_1^{\perp,\mathrm{fav}} \otimes D_1^{\perp,\mathrm{dis}} + 2D_{1,s\to\pi}^{\mathrm{dis}} \otimes D_{1,s\to\pi}^{\mathrm{dis}}} \right\}.$$

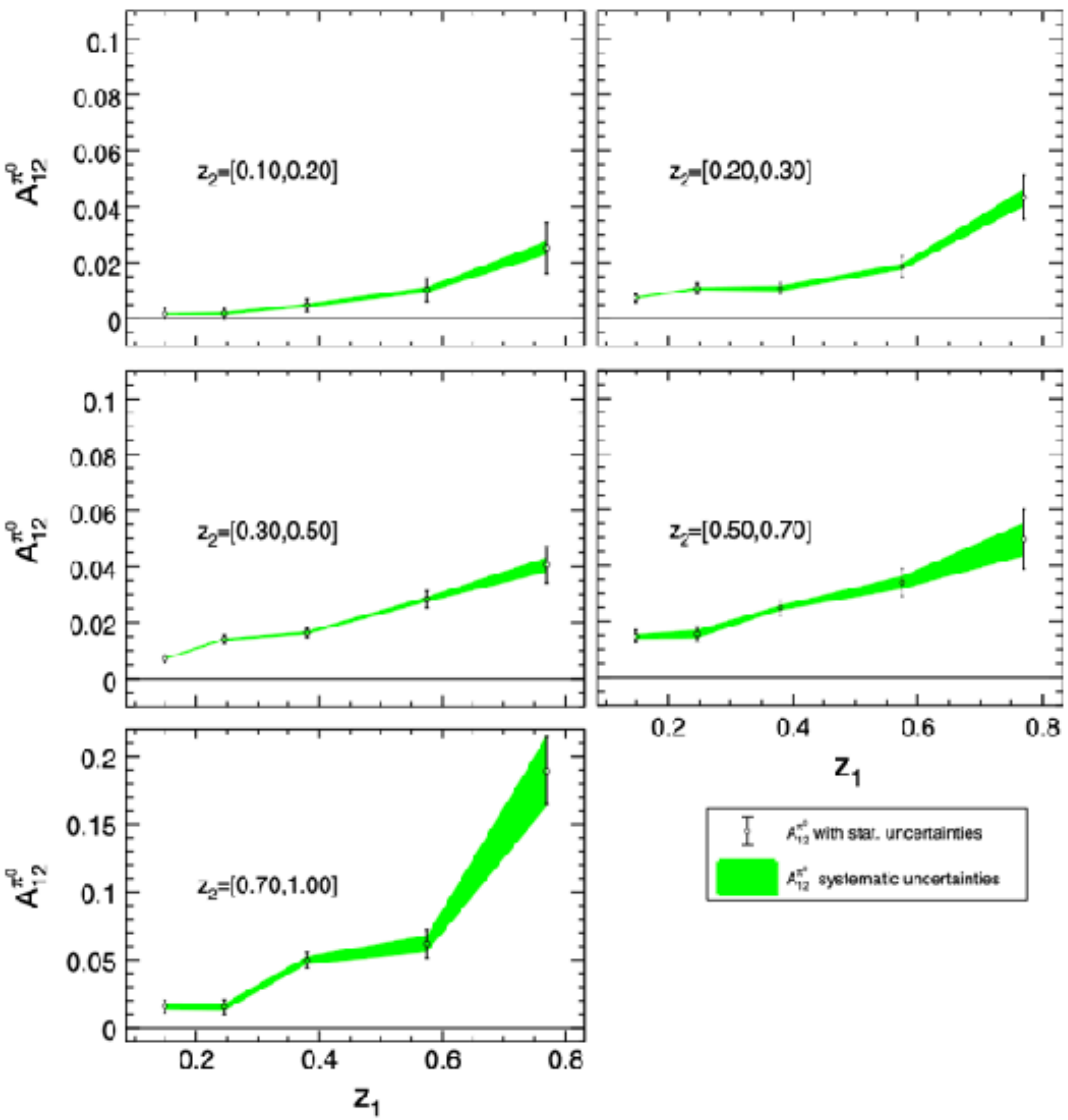
Azimuthal asymmetries of back-to-back $\pi^{\pm}$ - (π^0,η, $\pi^{\pm}$) from Belle

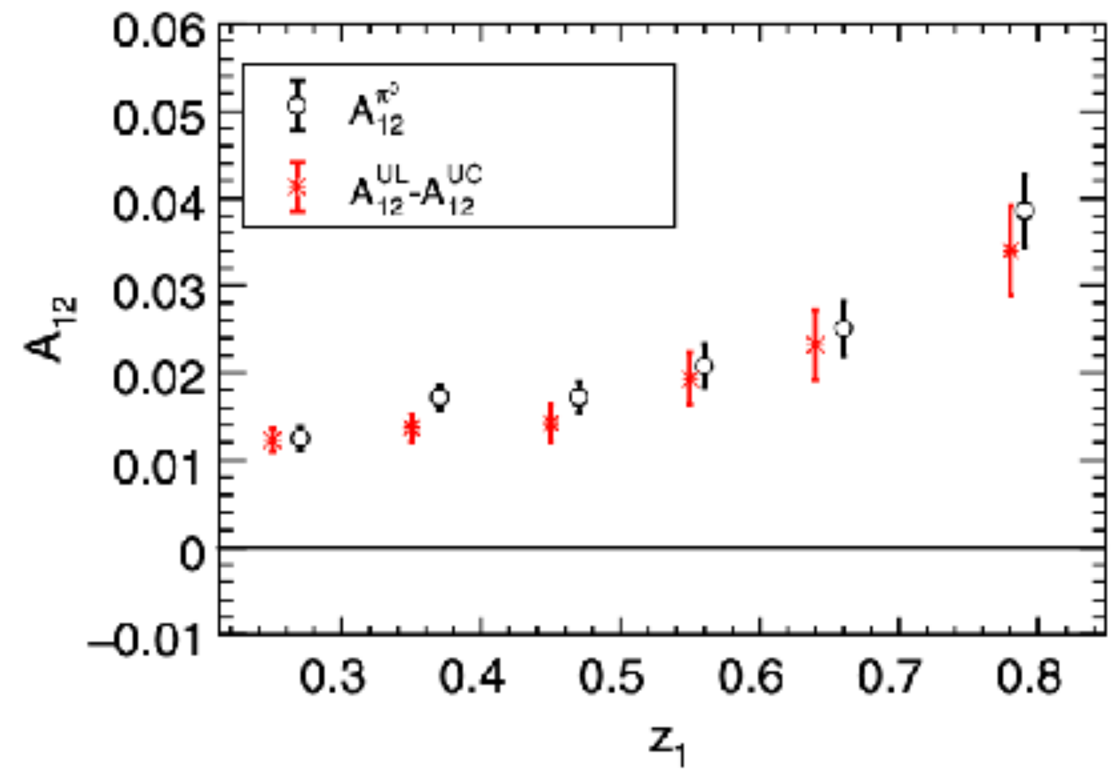
PRD100,092008



Azimuthal asymmetries of back-to-back $\pi^{\pm}\pi^{0}$ from Belle

PRD100,092008

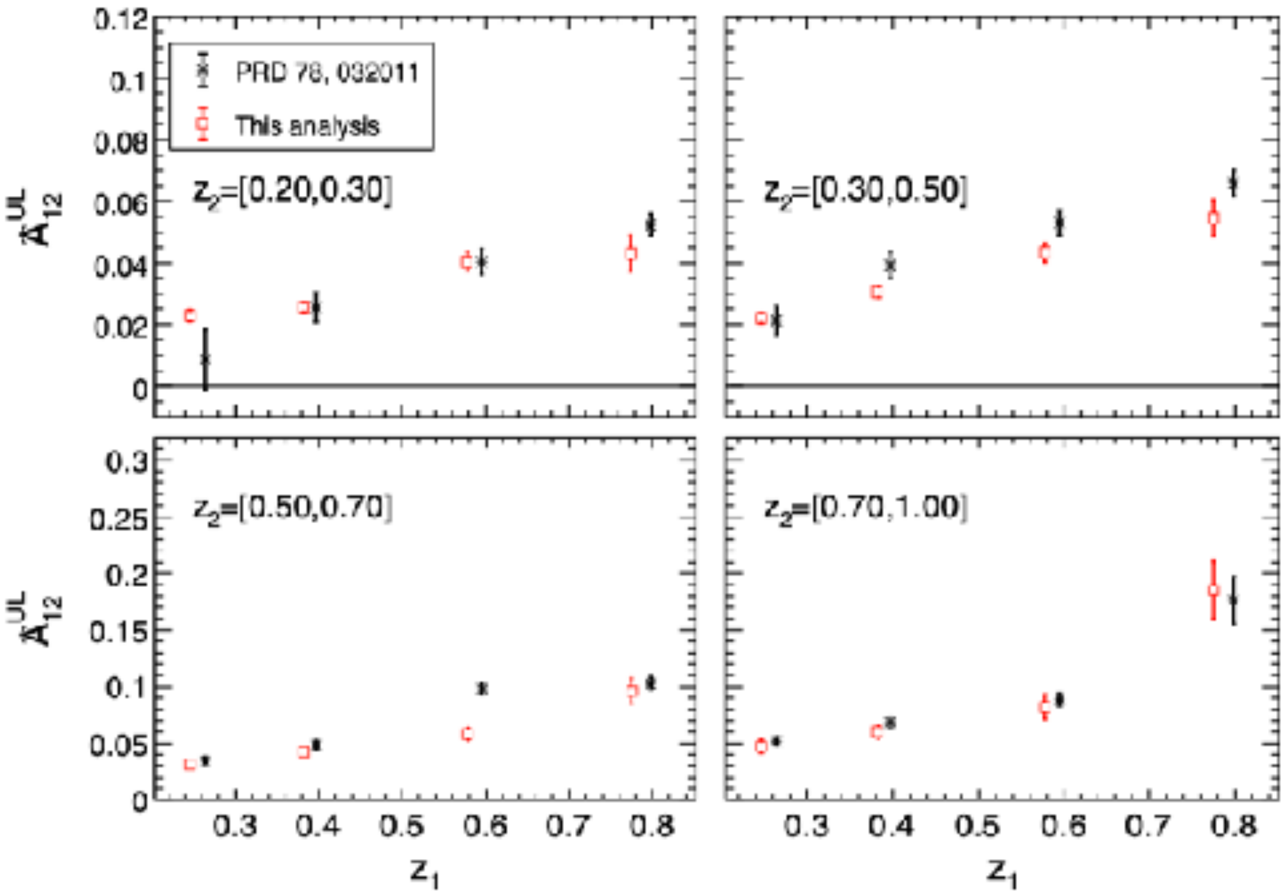




- Good agreement between A^{UL}-A^{UC} and $A^{\pi 0}$ as expected from isospin relation (taking into account statistical and systematic uncertainties)

Azimuthal asymmetries of back-to-back $\pi^{\pm}$ - (π^0,η, $\pi^{\pm}$) from Belle

PRD100,092008



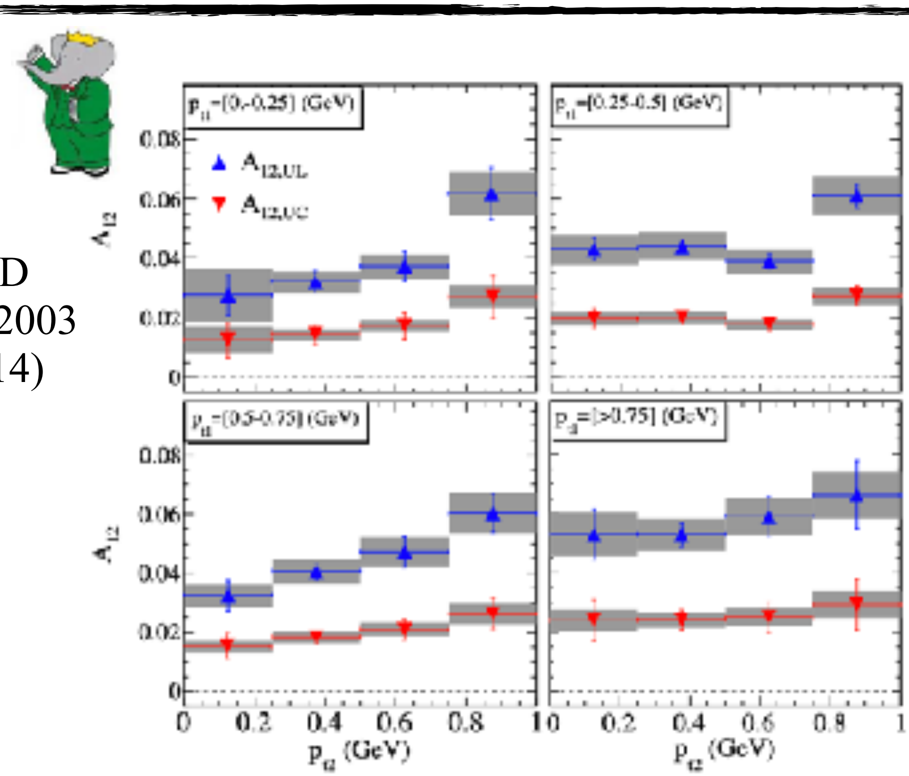
New Belle analysis: RF12 only

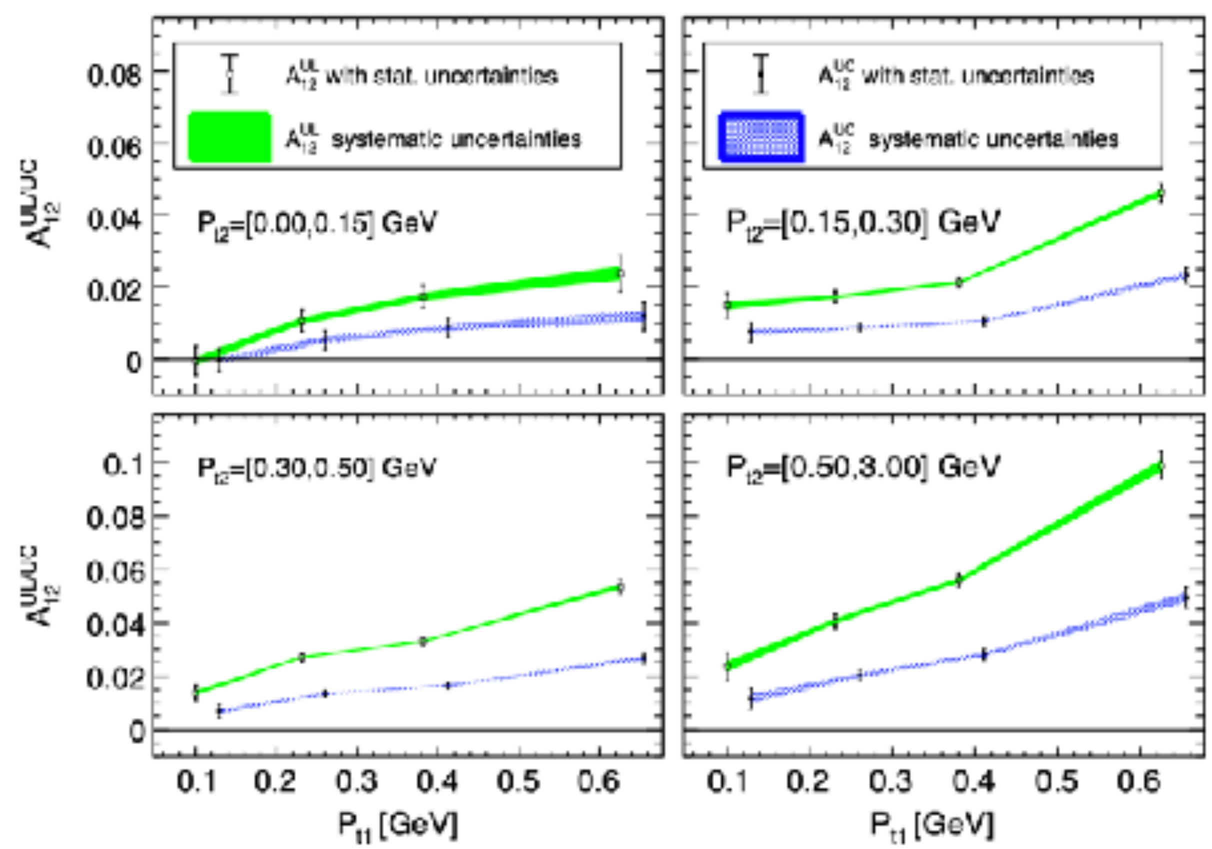
- No charm correction: only the estimated charm fractions are provided
- bin-by-bin generated-thrust axis correction (not the qqbar axis)
- Pt smering correction
- MC asymmetry subtraction

Only for results comparison:

- Vanishing charm asymmetry
- No thrust axis correction
- Kinematic factors taken into account

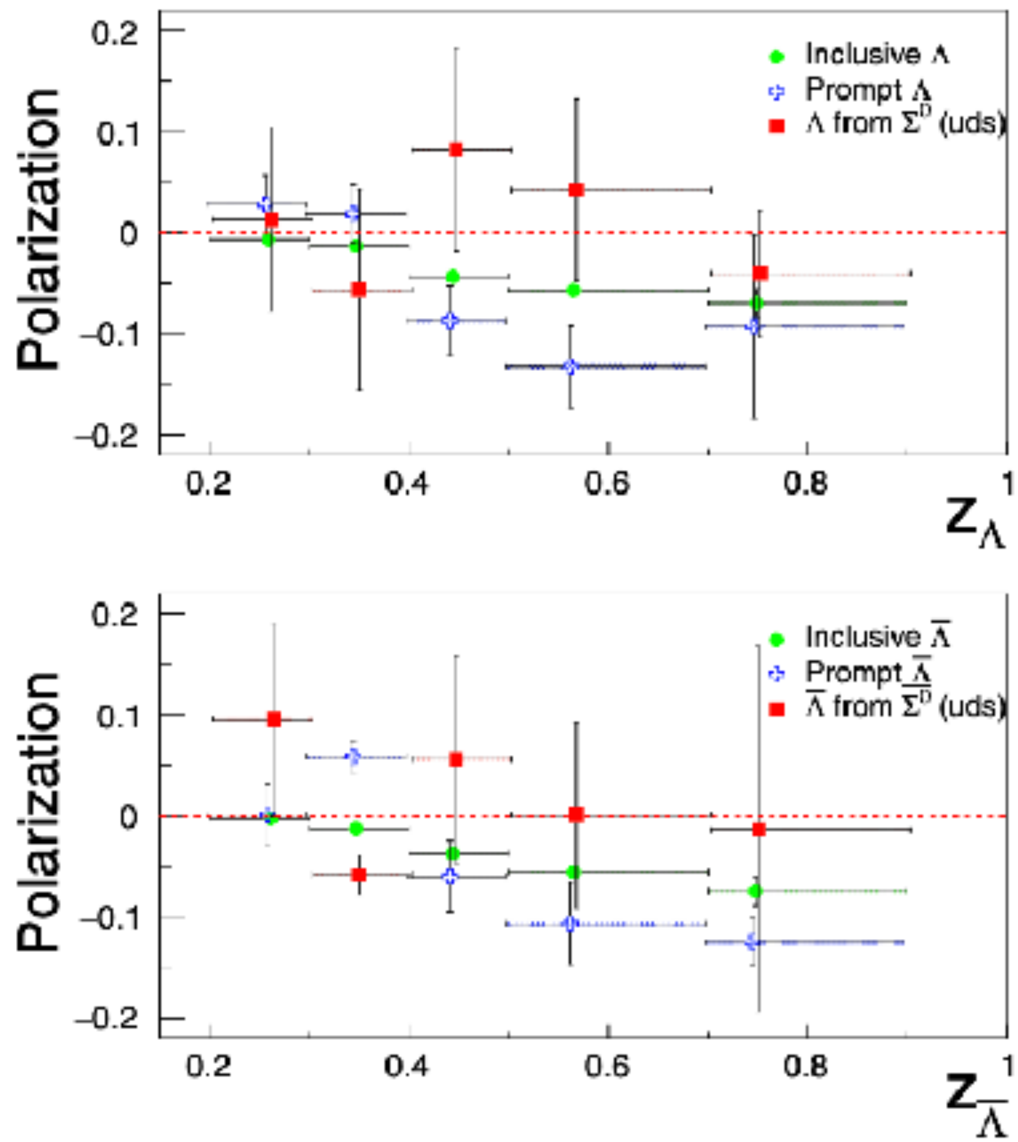
PRD 90,052003 (2014)





$\Lambda/\bar{\Lambda}$ hyperon polarization at Belle

PRL122,042001



- Charm corrected unfolded transverse polarisation also obtained ==> large statistical uncertainties

$\bar{\Lambda}/\Lambda$ hyperon polarization

PRD **100**,014029

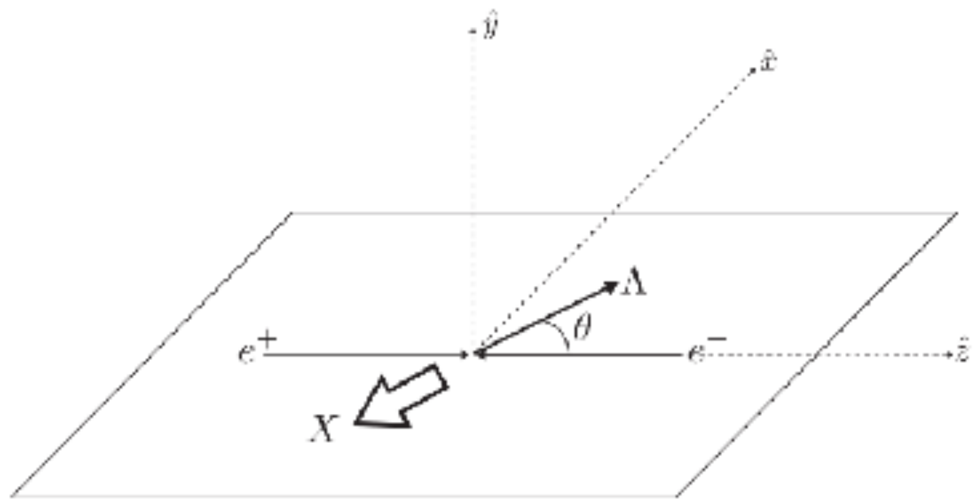
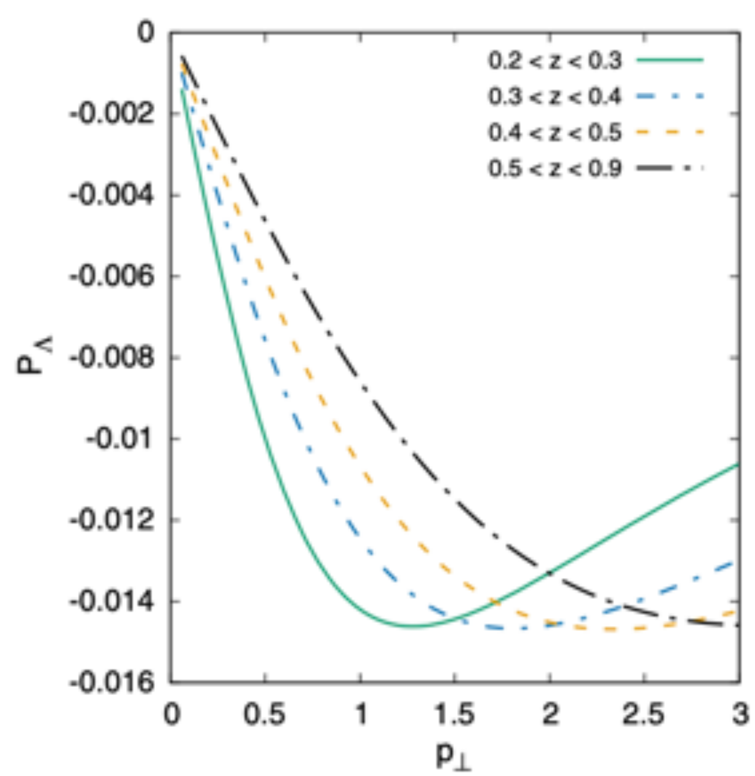
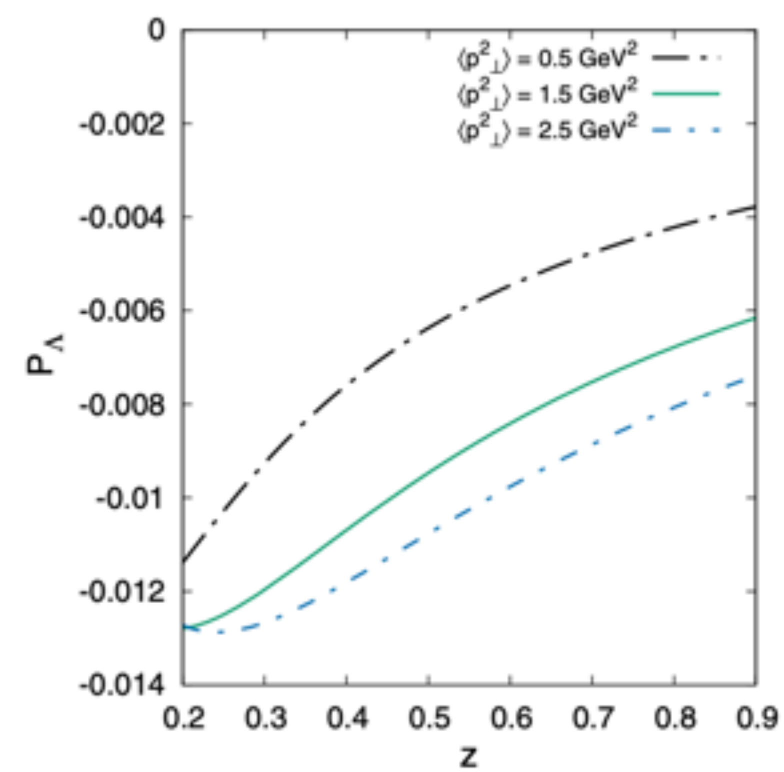


FIG. 1. Definition of the c.m. reference frame for the process $e^+e^- \to \Lambda X$.

$$P_\Lambda(z,\cos\theta) = \frac{\sum_q e_q^2 \int p_\perp dp_\perp \frac{4zp_\perp\sqrt{s}}{z^2 s + 4p_\perp^2} \Delta^N D_{\Lambda^\uparrow/q}(z,p_\perp)}{\sum_q e_q^2 D_{\Lambda/q}(z)} \times \frac{\sin(2\theta)}{1+\cos^2\theta} \tag{21}$$

$$P_\Lambda(z,p_\perp) = \frac{\sum_q e_q^2 \frac{4zp_\perp\sqrt{s}}{z^2 s + 4p_\perp^2} \Delta^N D_{\Lambda^\uparrow/q}(z,p_\perp)}{\sum_q e_q^2 2\pi D_{\Lambda/q}(z,p_\perp)} \times \frac{\int d(\cos\theta)\sin(2\theta)}{\int d(\cos\theta)(1+\cos^2\theta)} \tag{22}$$





Helicity Formalism: TMD Fragmentation Functions for quarks

Quark Polarisation States determine the Hadron ones

$$\rho^{h,S_h}_{\lambda_h,\lambda'_h}\,\hat{D}_{h/q,s_q}(z,\mathbf{k}_{\perp h}) = \sum_{\lambda_q,\lambda'_q} \rho^{q,s_q}_{\lambda_q,\lambda'_q}\,\hat{D}^{\lambda_h,\lambda'_h}_{\lambda_q,\lambda'_q}(z,\mathbf{k}_{\perp h})$$

$$P^h_j\,\hat{D}_{h/q,s_q} = \hat{D}^h_{S_j/q,s_q} - \hat{D}^h_{-S_j/q,s_q} = \Delta\hat{D}^h_{S_j/s_q}.$$

Helicity density matrix

$$\rho^{i,s_i}_{\lambda_i,\lambda'_i} = \frac{1}{2}\begin{pmatrix} 1+P^i_z & P^i_x - iP^i_y \\ P^i_x + iP^i_y & 1-P^i_z \end{pmatrix}$$

8 independent Fragmentation Functions

		Hadron		
	Pol. States	U	L	T
Quark	U	$\hat{D}_{h/q}$		$\Delta\hat{D}^h_{S_Y/q}$
	L		$\Delta\hat{D}^{h/q}_{S_Z/s_L}$	$\Delta\hat{D}^{h/q}_{S_X/s_L}$
	T	$\Delta^N D_{h/q^\uparrow}$	$\Delta\hat{D}^{h/q}_{S_Z/s_T}$	$\Delta\hat{D}^{h/q}_{S_X/s_T}$ / $\Delta^-\hat{D}^{h/q}_{S_Y/s_T}$

Amsterdam notation:

Collins $\Delta^N D_{h/q^\uparrow} \longleftrightarrow H_1^\perp$

Polarizing $\Delta D^h_{S_Y/q} \longleftrightarrow D_{1T}^\perp$

$$\begin{cases}\Delta^- D^{h_1}_{S_Y/s_T} \\ \Delta D^{h_1}_{S_X/s_T}\end{cases} \leftrightarrow \begin{cases} H_1 \\ H_{1T}^\perp\end{cases}$$

SIDIS cross section

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\Big\{ \Big[F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{UU}^{\cos(\phi)} + \epsilon\cos(2\phi) F_{UU}^{\cos(2\phi)}\Big]$$

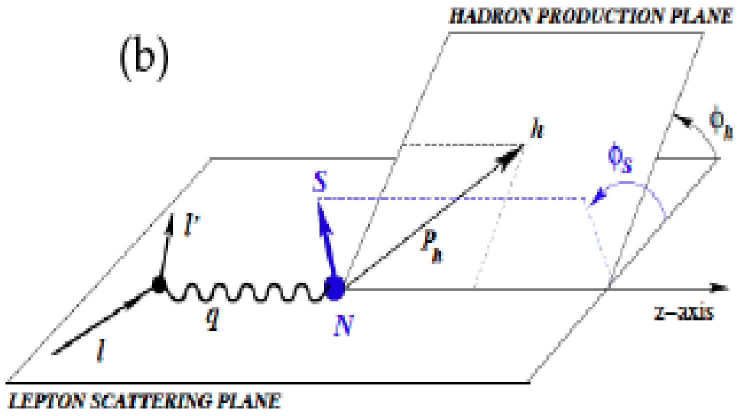
$$+ \lambda_l \Big[\sqrt{2\epsilon(1-\epsilon)}\sin(\phi) F_{LU}^{\sin(\phi)}\Big]$$

$$+ S_L \Big[\sqrt{2\epsilon(1+\epsilon)}\sin(\phi) F_{UL}^{\sin(\phi)} + \epsilon\sin(2\phi) F_{UL}^{\sin(2\phi)}\Big]$$

$$+ S_L\,\lambda_l \Big[\sqrt{1-\epsilon^2} F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi) F_{LL}^{\cos(\phi)}\Big]$$

$$+ S_T \Big[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) + \epsilon\sin(\phi+\phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S) F_{UT}^{\sin(3\phi-\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(\phi_S) F_{UT}^{\sin(\phi_S)} + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi-\phi_S) F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ S_T\,\lambda_l \Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S) F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_S) F_{LT}^{\cos(\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi-\phi_S) F_{LT}^{\cos(2\phi-\phi_S)}\Big]\Big\}$$



Unpolarized proton and lepton

Longitudinally polarized proton, unpolarized lepton

Longitudinally polarized proton, polarized lepton

Transversely polarized proton, unpolarized lepton

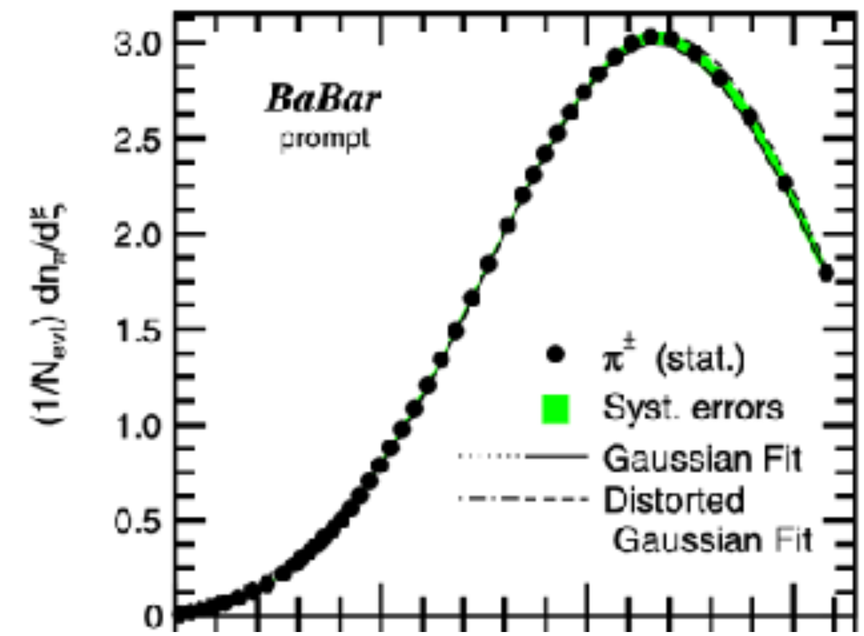
Transversely polarized proton, polarized lepton

JHEP093(07)

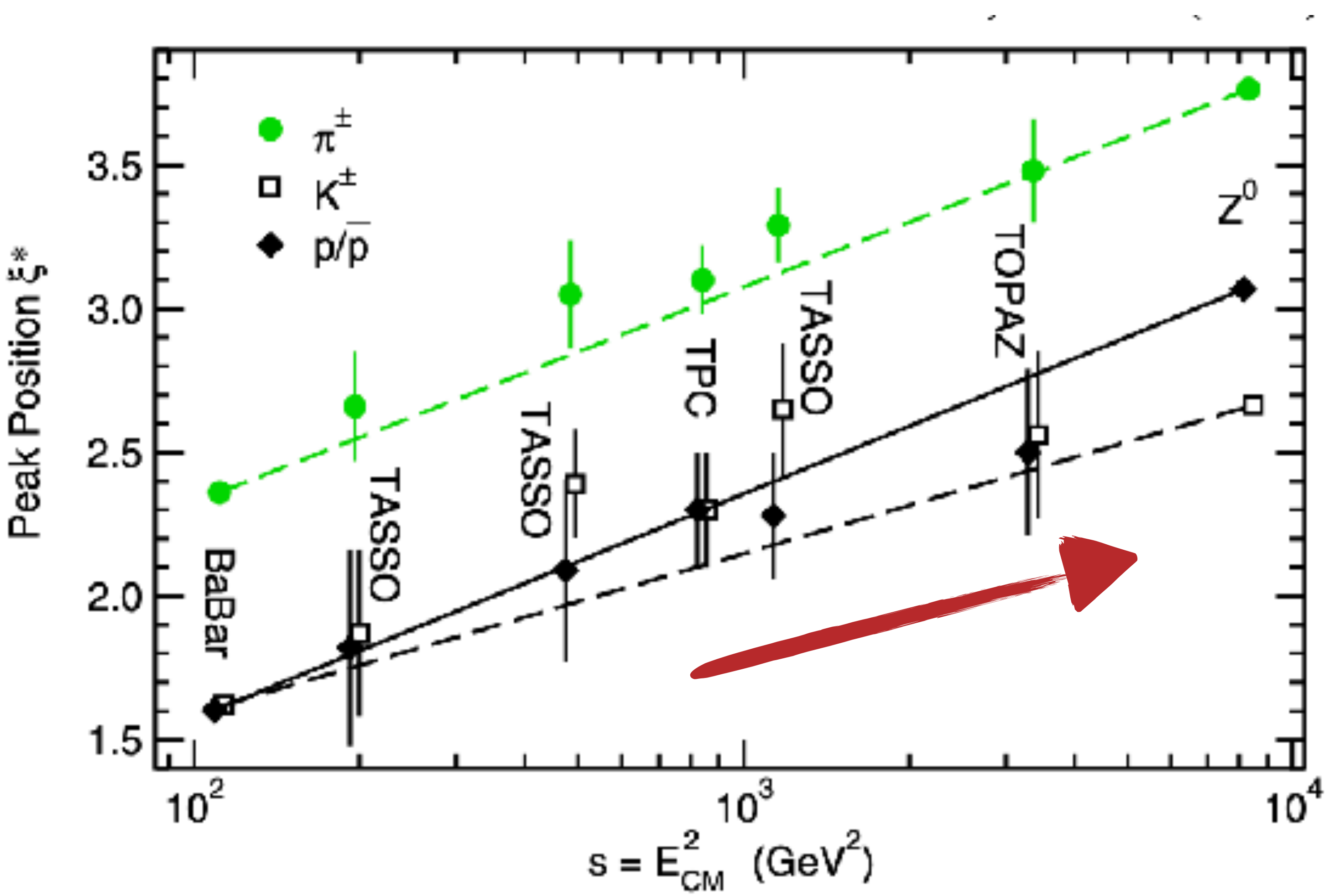
Single hadron FF		
Unpolarized ingredients	**Polarized ingredients**	**Flavor sensitivity**
Single hadron cross sections: $e^+e^- \to hX$ $D^{h}_{1,q}(z, Q^2)$ PRL111 (2013) 062002 PRD101(2020) 092004	Azimuthal asymmetries: $e^+e^- \to (h)(h)X$, $\cos(\phi_1 + \phi_2)$ $H^{\perp(1)h}_{1,q}(z, Q^2)$ PRL 96 (2006) 232002 PRD 78 (2008) 032011	Unpol SIDIS, pp: $\frac{d\sigma}{dz}$ $e^+e^- \to (h)(h)X$ PRD92 (2015) 092007 PRD101(2020) 092004 and scale dependence
Transverse momentum dependent FFs: $e^+e^- \to (h)X$ $D^{h}_{1,q}(z, k_T, Q^2)$ PRD 99 (2019) 112006	Transverse momentum dependent asymmetries $e^+e^- \to (h)(h)X$, $\cos(\phi_1 + \phi_2), Q_t$ $H^{\perp h}_{1,q}(z, k_T, Q^2)$ PRD100 (2019) 92008	Polarizing Λ fragmentation PRL 122 (2019), 042001 $D^{\perp h}_{1,q}(z, k_T, Q^2)$
Dihadron FF (IFF)		
Unpolarized ingredients	**Polarized ingredients**	**Flavor sensitivity**
Dihadron cross sections $e^+e^- \to (hh)X$ $D^{h_1 h_2}_{1,q}(z, m, Q^2)$ PRD96 (2017) 032005	Azimuthal asymmetries: $e^+e^- \to (hh)(hh)X$, $\cos(\phi_1 + \phi_2)$, $H^{h_1,h_2,\sphericalangle}_{1,q}(z, Q^2, M_h)$ PRL107 (2011) 072004	Unpol SIDIS, pp: $\frac{d^2\sigma}{dz\,dm}$

Test of MLLA+LHPD QCD predictions

Modified Leading Logarithmic Approximation (MLLA) with Local Parton-Hadron Duality (LHPD) ansatz (Z.Phys.C27,65):
1) the multiplicity distributions vs $\xi = -\ln(x_p)$ should be Gaussian near the peak



$\xi = -\ln(x_p)$



2) the peak position should decrease exponentially with increasing hadron mass at a given E_{cm}

- observed that $\xi_K \approx \xi_p$

3) ξ^* should increase logarithmically with E_{mc} for a given hadron type

- similar slope for pions and protons, different for kaons
- possibly due to flavour composition changing with E_{cm}

$\Lambda/\overline{\Lambda}$ hyperon polarization at Belle

PRL **122**,042001

- $e^+e^-\rightarrow\Lambda(\overline{\Lambda})X$ and $e^+e^-\rightarrow\Lambda(\overline{\Lambda})h^{\pm}X$ using 800.4 fb^{-1} collected by Belle at or near $\sqrt{s}$=10.58 GeV

$$D_{1T}^{\perp\Lambda/q}(z, p_\perp^2)$$

==> production of transversely polarized Λ hyperons from unpolarised quark
==> chiral-even function (the sign of this function can be easily determined)

Distribution of protons from Λ decays with a transverse polarisation P:

$$\frac{1}{N}\frac{dN}{d\cos\theta} = 1 + \alpha P \cos\theta,$$

hadron polarisation vector along ↑ direction

PRD **100**,014029

$$\hat{D}_{h\uparrow/q}(z,\boldsymbol{k}_\perp) = \frac{1}{2}\hat{D}_{h/q}(z,\boldsymbol{k}_\perp) + \frac{1}{2}\Delta^N D_{h\uparrow/q}(z,\boldsymbol{k}_\perp)\frac{\hat{\boldsymbol{P}}_h\cdot(\boldsymbol{p}_q\times\boldsymbol{k}_\perp)}{|\boldsymbol{p}_q\times\boldsymbol{k}_\perp|}$$

θ: angle between the axis $\hat{n}\propto\hat{T}\times\hat{p}_\Lambda$ and the proton momentum in the Λ rest frame; α is the world average value of the parity-violating decay asymmetry for the Λ (from PDG)
==> Significant transverse polarization is observed