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January 27, 2025

Spin-dependent hadronization in Pythia

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Lund University and INFN Trieste

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Outline

- ❑ Introduction
- ❑ Implementation of spin effects for DIS
  - ❑ Collins and 2h asymmetries
- ❑ Implementation of spin effects for e^+e^-
  - ❑ Collins asymmetries
- ❑ Conclusions

StringSpinner: spin in the Pythia generator

- **PYTHIA 8** standard tool in particle physics,
  capable of simulating several processes: DIS, e+e-, pp, pA, ..
  detailed and precise simulations, many physics ingredients
  lacking of spin effects in hadronization

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- Spin important for studies of the nucleon structure and hadronization
  Collins effect → Collins asymmetries in SIDIS and e^+e^- → transversity PDF and Collins FF
  interference FF → dihadron asymmetries in SIDIS, Artru-Collins asymmetries in e^+e^-
  polarizing FF → Λ transverse polarization, e.g. in e^+e^-
  $G_1^\perp$ FF → beam spin asymmetries in SIDIS, .. → $e(x)$ ..
  jet func. → ..

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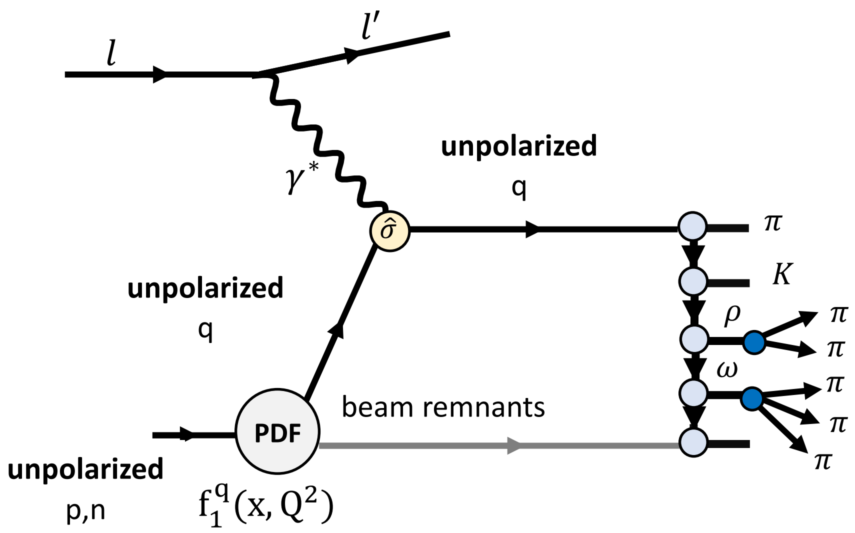
  jet func. → ..

- Spin effects implemented in Pythia for DIS and $\mathrm{e}^+\mathrm{e}^-$ by StringSpinner
  public package AK, L. Lönnblad, CPC **272** (2022) 108234; CPC **292** (2023) 108886
  can be downloaded from gitlab https://gitlab.com/albikerbizi/stringspinner
  sample main program for DIS
  $\mathrm{e}^+\mathrm{e}^-$ not available yet from gitlab, will be soon

Implementation of spin effects for DIS

Spin in Pythia for DIS

- Let Pythia generate the process in the standard way and change behaviour through the UserHooks class, e.g. in hadronization → parton showers OFF
- Allow for target polarization → parametrizations of transversity PDFs h_1^q for $q = u_v, d_v$
    - Alternatively, let the user chose the polarization of each quark
- Evaluate the polarization of the fragmenting quark
- Apply rules of the string+$^3P_0$ model in hadronization



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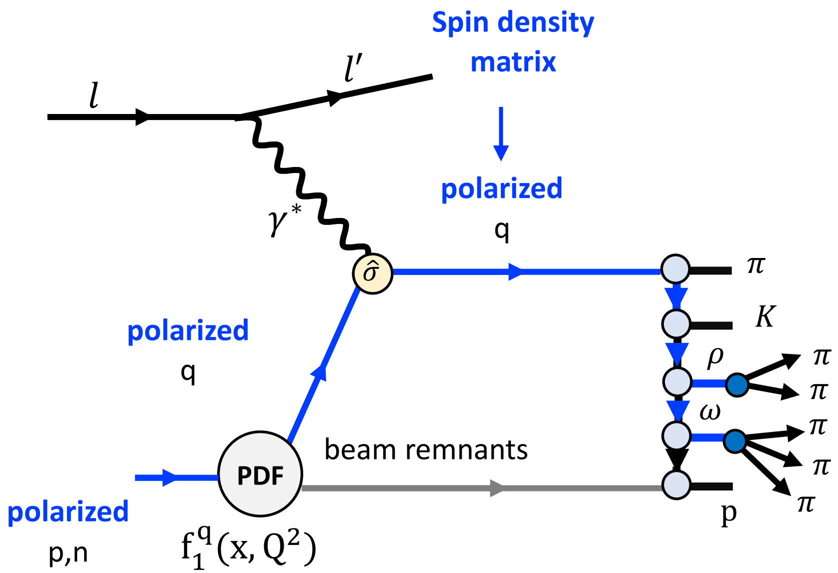

Transversity $h_1^q(x)$
or arbitrary polarization of quarks

AK, L. Lönnblad, CPC **272** (2022) 108234;
CPC **292** (2023) 108886

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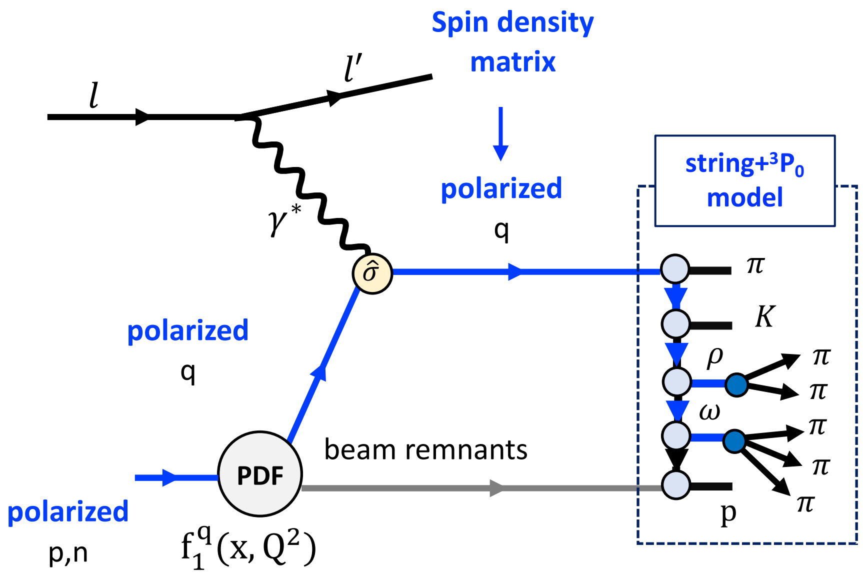

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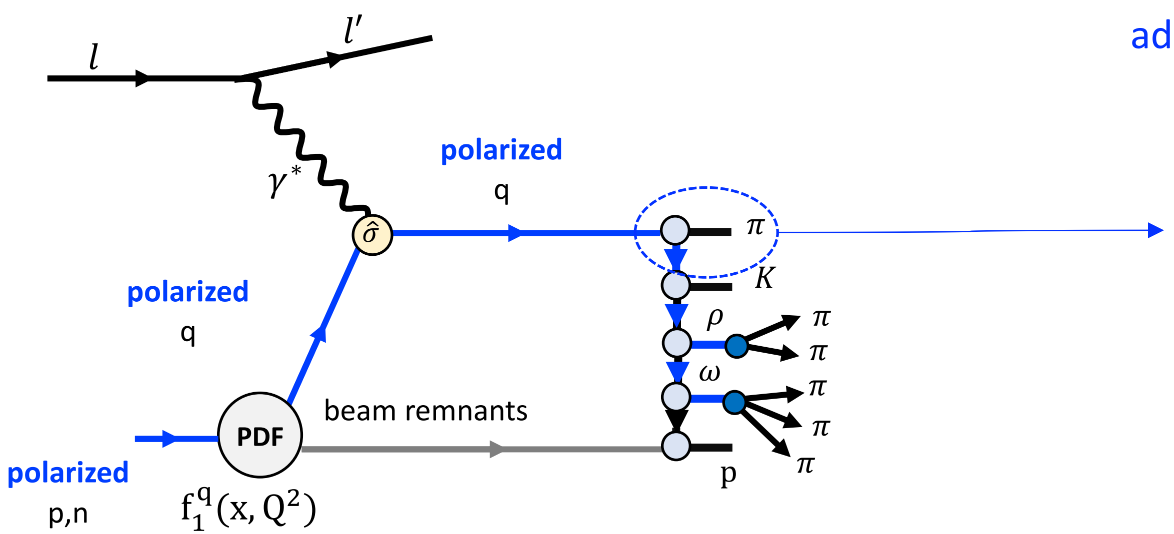
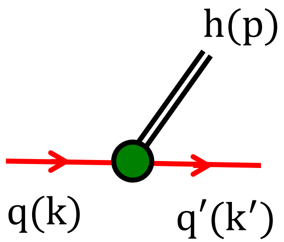


AK, Artru, Martin, PRD 104, 114038 (2021)

string+$^3P_0$ model:
adds spin to the Lund string model



Elementary quark splitting

Spin in Pythia for DIS

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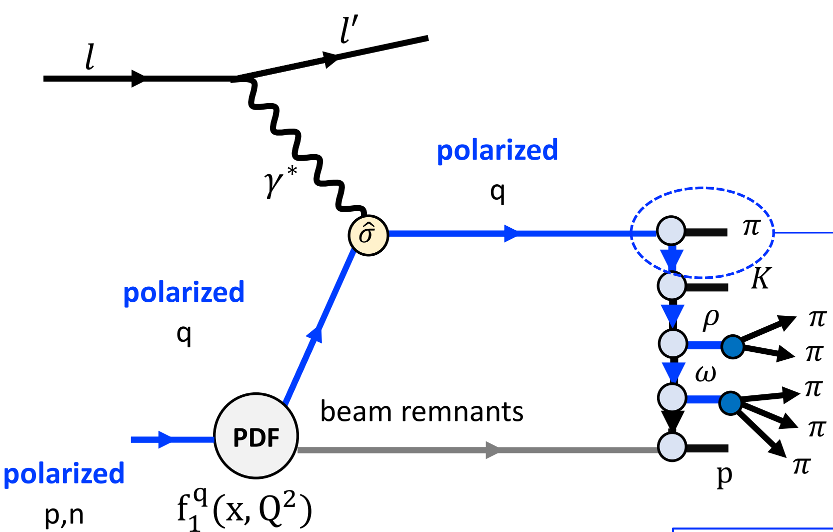
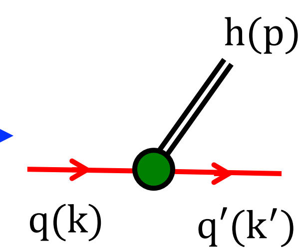
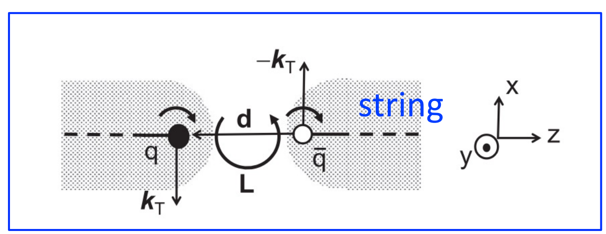




Elementary quark splitting

Splitting matrix

$$T_{q',h,q} \propto \left[F^{\rm Lund}_{q',h,q}\right]^{1/2} \left[\mu + \sigma_z \boldsymbol{\sigma}_T \cdot \mathbf{k}'_T\right] \; \Gamma_{h,s_h}$$



$^3P_0$ mechanism
μ complex mass paramter

Coupling
e.g.
$\Gamma_{h=PS} = \sigma_z$

Spin in Pythia for DIS

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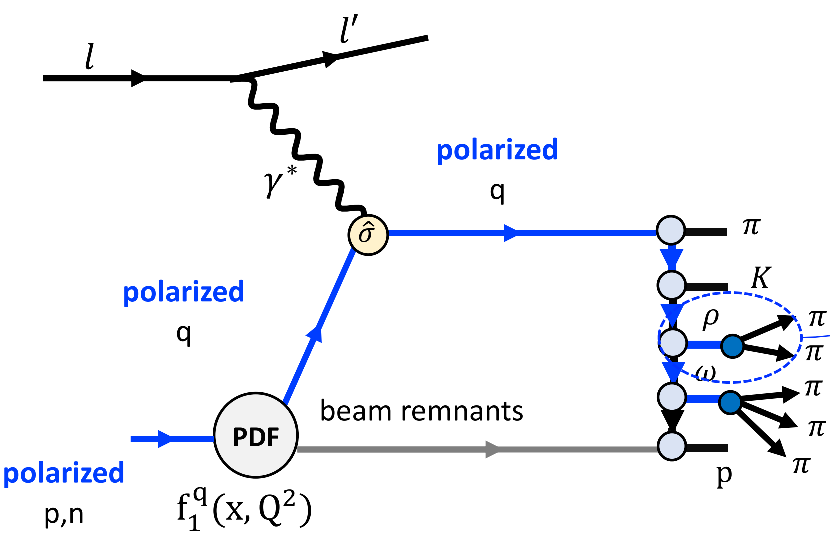
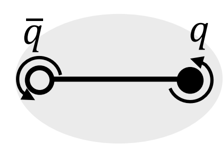
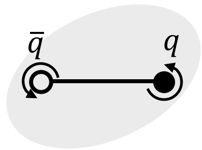


Coupling of quarks with VMs

f_L
fraction of L pol. VMs



θ_{LT}
oblique polarization (L/T interference)



Spin in Pythia for DIS

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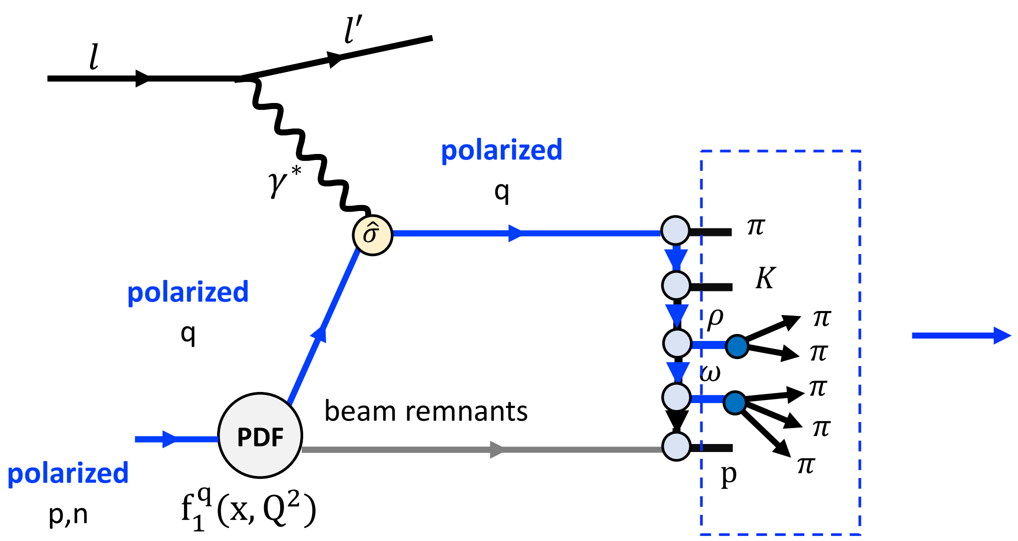
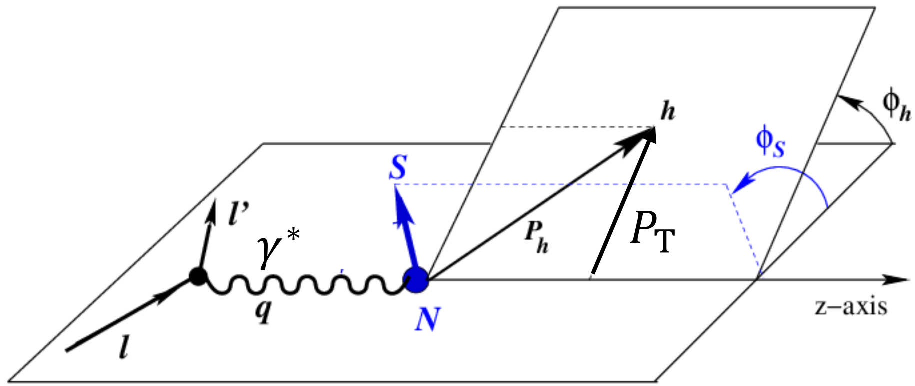


Produced hadrons accessible from the standard Pythia event record

Analyze → Collins asymmetry
Dihadron asymmetry
Beam spin asymmetry
etc.

Results from simulations of SIDIS
@ COMPASS and HERMES kinematics



Pythia parameters

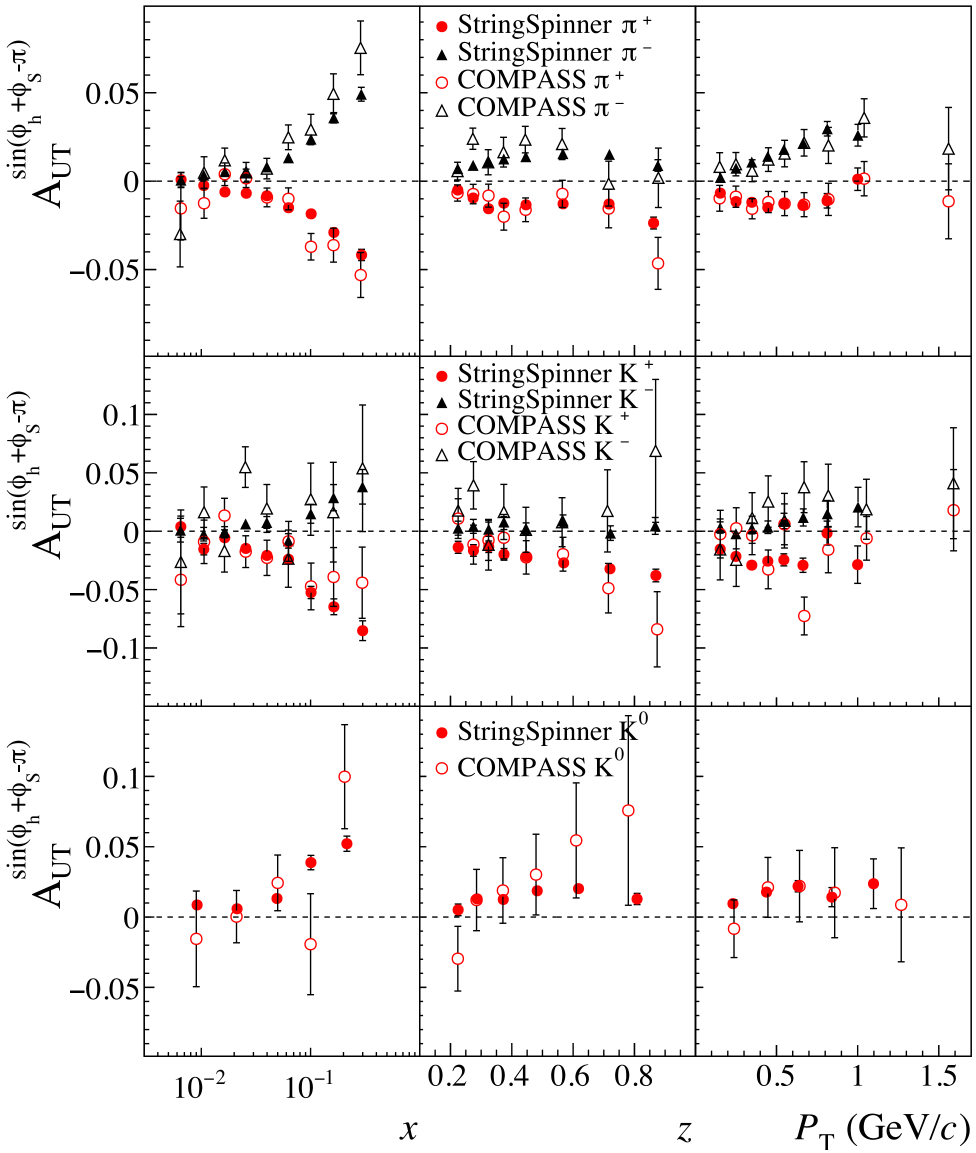
StringZ:aLund	default (0.68)
StringZ:bLund	default (0.98)
StringPT:sigma	default (0.335 GeV)
StringPT:enhancedFraction	0.0
StringPT:enhancedWidth	0.0 GeV/c
StringFlav:probStoUD	default (0.217)
StringFlav:mesonUDvector	default (0.5)
StringFlav:mesonSvector	default (0.55)

String+$^3P_0$ parameters   CPC **292** (2023) 108886

$\mathrm{Re}(\mu)$	0.42	GeV/c^2
$\mathrm{Im}(\mu)$	0.76	GeV/c^2
f_L	0.93	L pol. VM → large Collins effect
θ_{LT}	0.0	

e^+e^- annihilation requires small f_L (T pol VMs) and $\theta_{LT} \neq 0$

Transverse spin effects: Collins asymmetries

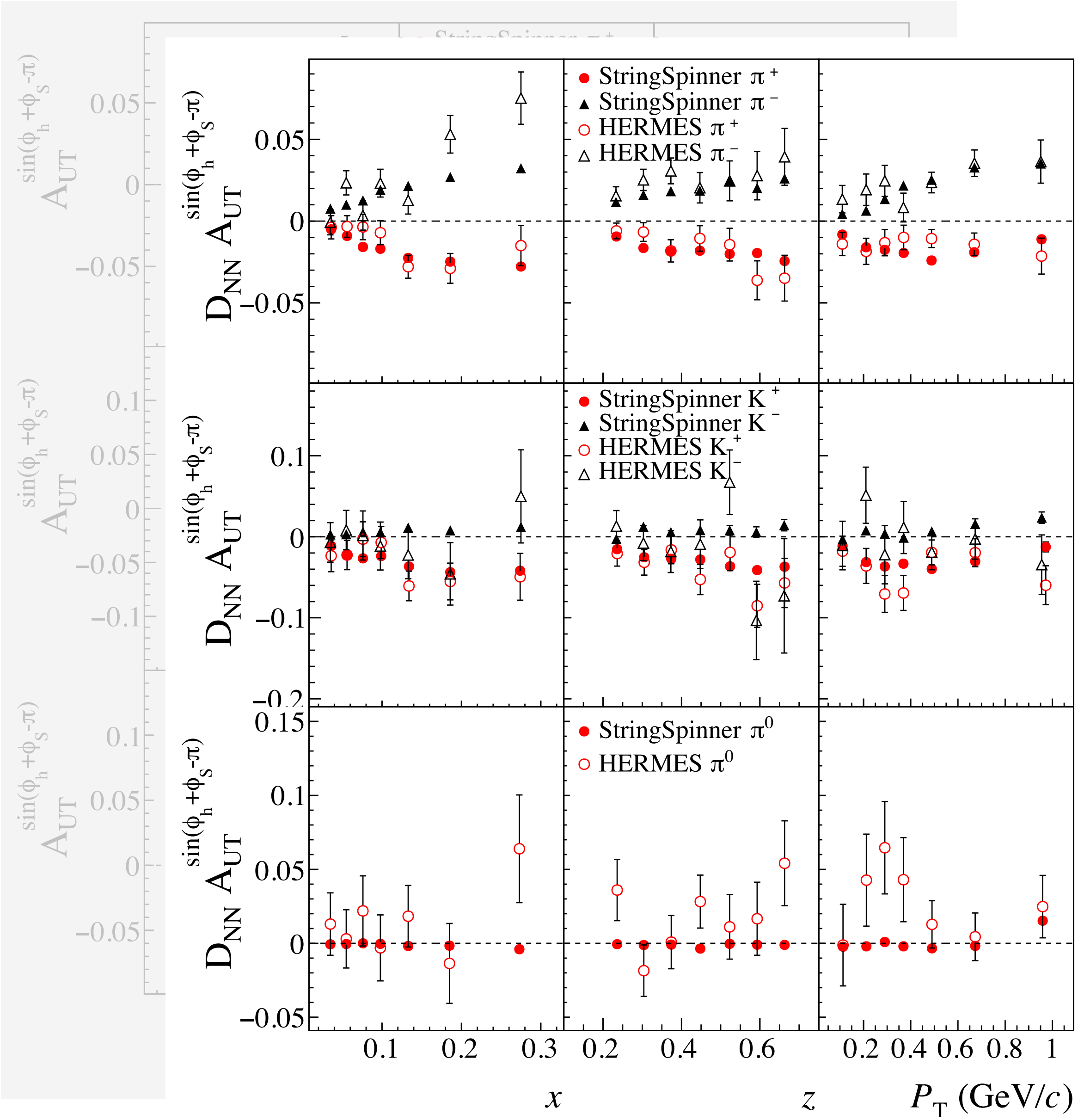


PLB 717 (2012) 376

Comparison with COMPASS
160 GeV muons off protons

AK, L. Lönnblad, CPC **292** (2023) 108886

Transverse spin effects: Collins asymmetries



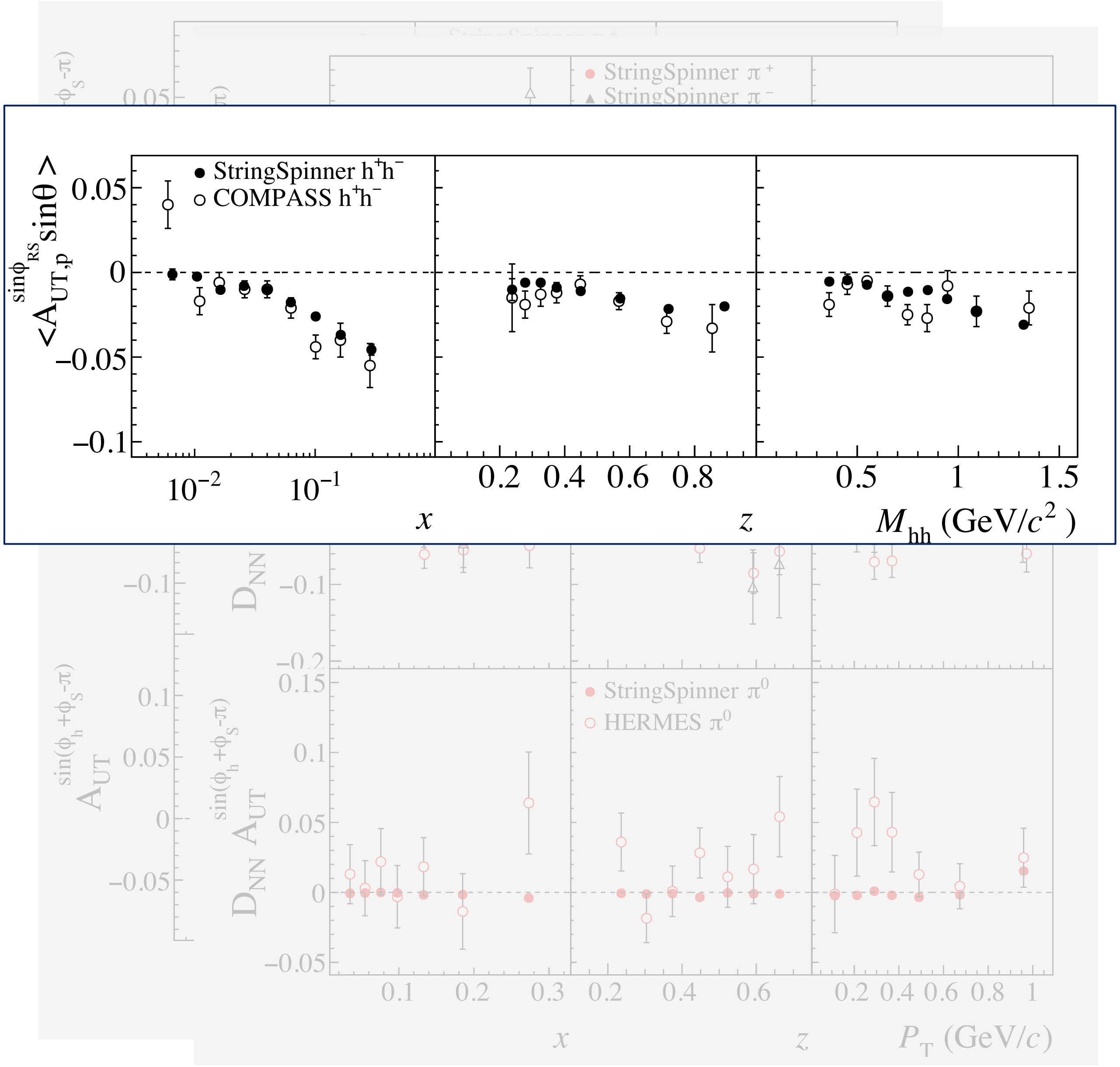
PLB693 (2010) 11

Comparison with HERMES

27 GeV electrons off protons

AK, L. Lönnblad, CPC **292** (2023) 108886

Transverse spin effects: dihadron asymmetries



PLB 736 (2014) 124

Comparison with COMPASS

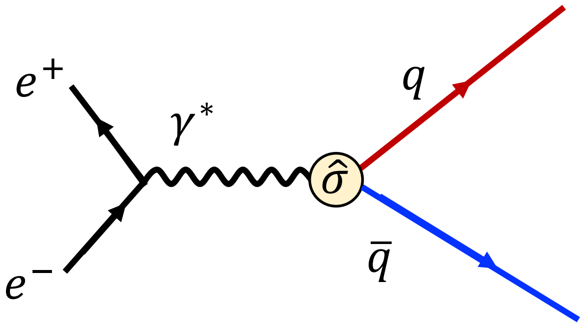
160 GeV muons off protons

AK, L. Lönnblad, CPC **292** (2023) 108886

Recipe for the simulation of e^+e^- annihilation

AK, X. Artru, PRD 109 (2024) 5, 05402

Recursive recipe for e^+e^-



Steps:

1. Hard scattering
2. Joint spin density matrix
3. Hadron emission from q
4. Update density matrix
5. Hadron emission from $\bar{q}$
6. Exit condition

Recursive recipe for e^+e^-

Steps:

1. Hard scattering

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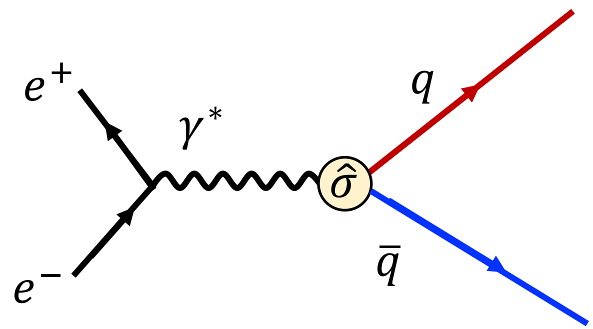
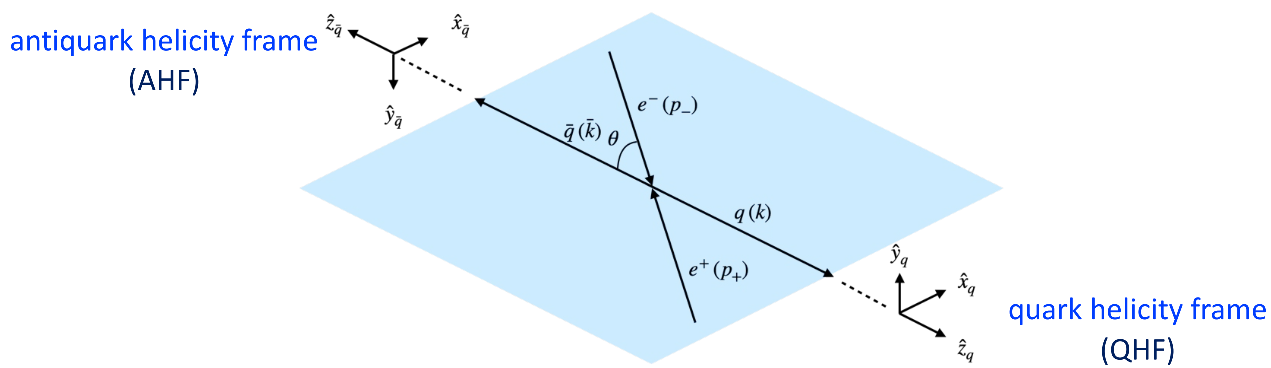
6. Exit condition



Set up the scattering $e^+e^- \to q\bar{q}$ in the c.m.s

generate the quark flavors and kinematics using differential cross section



Recursive recipe for e^+e^-

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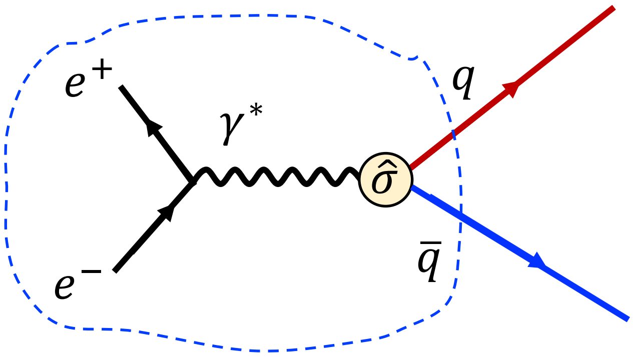


- Set up the joint spin density matrix of the $q\bar{q}$ pair

$$\rho(q, \bar{q}) = C^{q\bar{q}}_{\alpha\beta} \quad \sigma^{\alpha}_{q} \otimes \sigma^{\beta}_{\bar{q}}$$

correlation coefficients

Pauli matrices along QHF and AHF

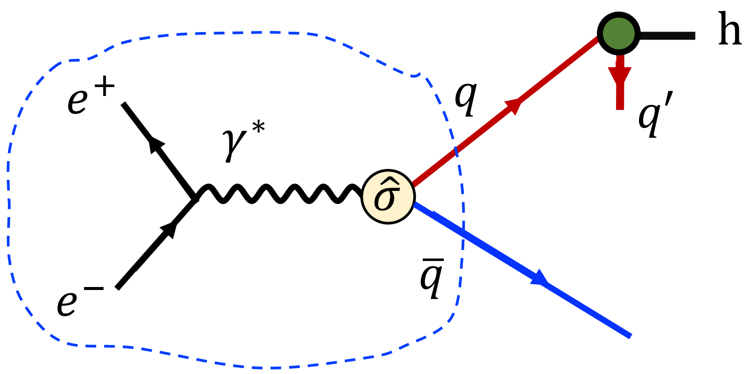
$\alpha = 0, x_q, y_q, z_q$

$\beta = 0, x_{\bar{q}}, y_{\bar{q}}, z_{\bar{q}}$

For γ^* exchange

$$\rho(q, \bar{q}) \propto 1_q \otimes 1_{\bar{q}} - \sigma^z_q \otimes \sigma^z_{\bar{q}} + \frac{\sin^2\theta}{1+\cos^2\theta} \left[\sigma^x_q \otimes \sigma^x_{\bar{q}} + \sigma^y_q \otimes \sigma^y_{\bar{q}}\right]$$

Recursive recipe for e^+e^-



Steps:
1. Hard scattering
2. Joint spin density matrix
3. **Hadron emission from *q***
4. Update density matrix
5. Hadron emission from $\bar{q}$
6. Exit condition

- ❑ Emit the first hadron using the splitting function (emission probability density)

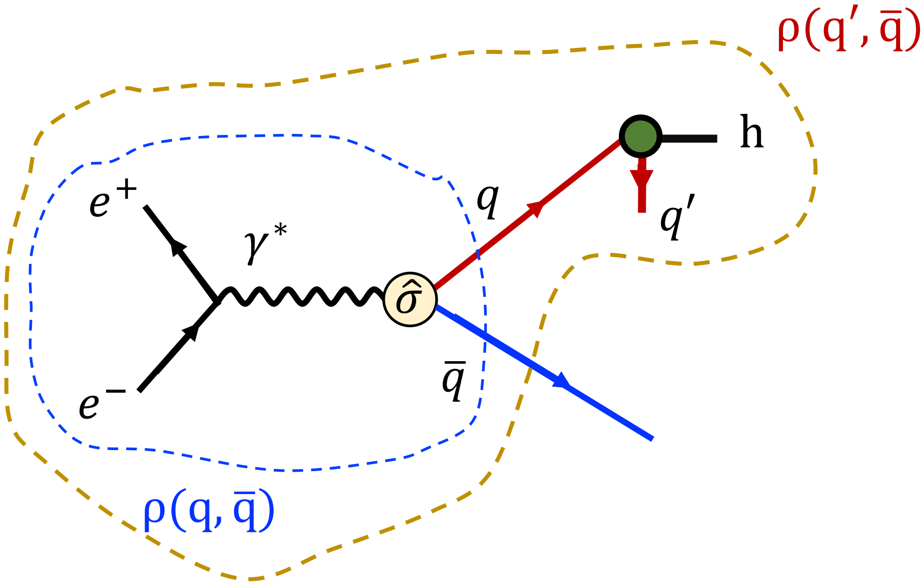
$$\frac{dP(q \to h + q'; q\bar{q})}{dZ_+ Z_+^{-1} d^2 p_T} = \mathrm{Tr}_{q'\bar{q}} \mathbf{T}_{q',h,q}\, \rho(q,\bar{q})\, \mathbf{T}^{\dagger}_{q',h,q} = F_{q',h,q}(Z_+, \mathbf{p}_T; \mathbf{k}_T, C^{q\bar{q}})$$

$$\mathbf{T}_{q',h,q} \equiv T_{q',h,q} \otimes 1_{\bar{q}}$$

in the QHF

- ❑ For VM emission need also to handle the polarized decay → backup

Recursive recipe for e^+e^-



Steps:

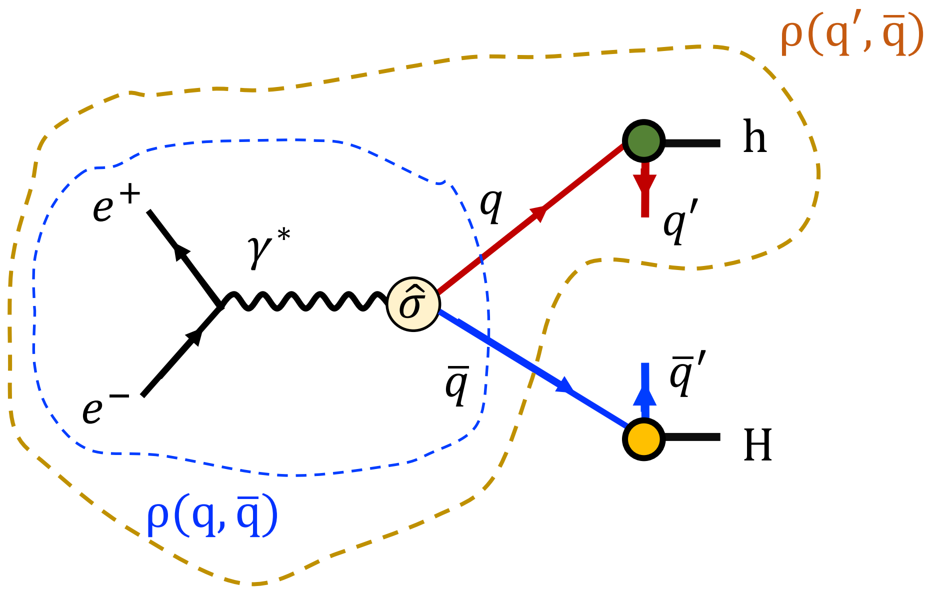
1. Hard scattering
2. Joint spin density matrix
3. Hadron emission from q
4. **Update density matrix**
5. Hadron emission from $\bar{q}$
6. Exit condition

- Evaluate the spin density matrix $\rho(q'\bar{q})$

$$\rho(q',\bar{q}) = \mathbf{T}_{q',h,q} \ \ \rho(q,\bar{q}) \ \ \mathbf{T}^{\dagger}_{q',h,q}$$

includes the information on the emission of h

Recursive recipe for e^+e^-



Steps:
1. Hard scattering
2. Joint spin density matrix
3. Hadron emission from q
4. Update density matrix
5. **Hadron emission from $\bar{q}$**
6. Exit condition

- Emit a hadron from the $\bar{q}$ side using the splitting function

Depend on the azimuthal angle h

$$\frac{dP(\bar{q} \to H + \bar{q}'; q'\bar{q})}{dZ_- Z_-^{-1} d^2 P_T} = \mathrm{Tr}_{q'\bar{q}'} \mathbf{T}_{\bar{q}',H,\bar{q}}\, \rho(q', \bar{q})\, \mathbf{T}^{\dagger}_{\bar{q}',H,\bar{q}} = F_{\bar{q}',H,\bar{q}}(Z_-, P_T; \bar{k}_T, C^{q'\bar{q}})$$

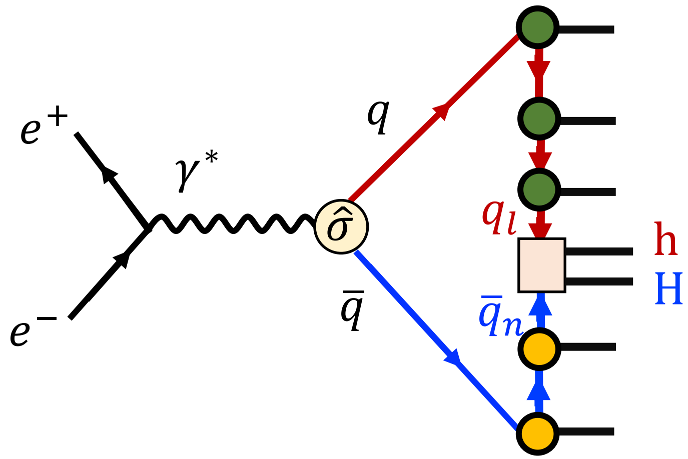
Expressed in the AHF

conditional probability of emitting H, having emitted h

→ correlations between the transverse momenta

[Collins NPB, 304:794–804, 1988, Knowles NPB, 310:571–588, 1988]

Recursive recipe for e^+e^-



Steps:

1. Hard scattering
2. Joint spin density matrix
3. Hadron emission from q
4. Update density matrix
5. Hadron emission from $\bar{q}$
6. **Exit condition**

- Iterate until the exit condition is called and the last quark pair is hadronized
  more details in PRD 109 (2024) 5, 054029

Simulations of e^+e^- annihilation with spin effects

using Pythia 8.3 + StringSpinner

AK, L. Lönnblad, A. Martin, Phys. Rev. D 110 (2024) 7, 074029

- $\sqrt{s} = 10.6$ GeV, γ^* exchange, quarks produced u, d, s consistent with BELLE and BABAR data

- Free parameters

spin-less hadronization	as in standard Pythia 8.3
complex mass μ	as in AK, Lonnblad, CPC 292 (2023) 108886
$f_L = 0.12$	~ T pol. VMs
$\theta_{LT} = -0.65$	interference between T and L pol. of VMs

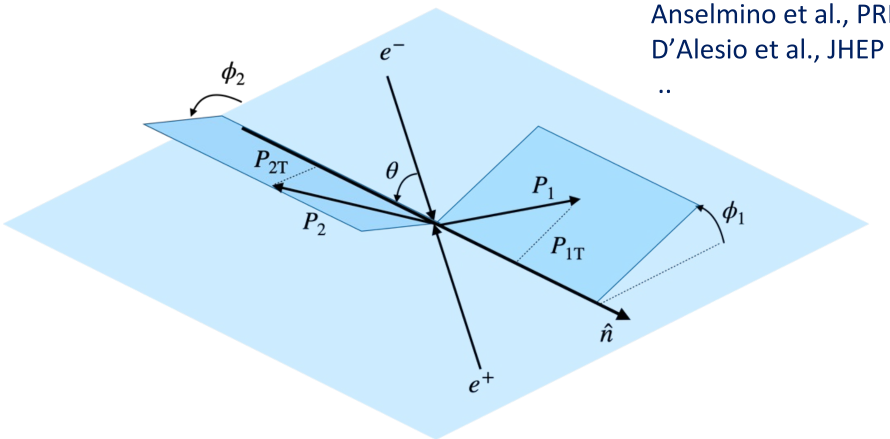
found to give a satisfactory agreement with e^+e^- data,
ok also for SIDIS

- **Compare with Collins asymmetries**

The Collins asymmetries in e^+e^- for back-to-back h_1h_2

- **Thrust axis method**

Boer et al., NPB504, 345 (1997).
Boer, NPB, 806:23–67, 2009
Anselmino et al., PRD 92, 114023 (2015)
D'Alesio et al., JHEP 10 (2021) 078
..



$$N_{h_1h_2} \propto 1 + \frac{\langle \sin^2\theta \rangle}{\langle 1+\cos^2\theta \rangle} A_{12} \cos(\phi_1 + \phi_2)$$

Collins asymmetry

$$A_{12} = \frac{\sum_q e_q^2\ H_{1q}^{\perp h_1}\ H_{1\bar{q}}^{\perp h_2}}{\sum_q e_q^2\ D_{1q}^{h_1}\ D_{1\bar{q}}^{h_2}}$$

- Measured asymmetry

$$A_{12}^{UL(UC)} \simeq A_{12}^{U} - A_{12}^{L(C)}$$

U unlike sign pair e.g. $\pi^+\pi^- + \pi^-\pi^+$
L like sign pair e.g. $\pi^+\pi^+ + \pi^-\pi^-$
C charged pair e.g. $\pi^+\pi^- + \pi^-\pi^+ + \pi^+\pi^+ + \pi^-\pi^-$

The Collins asymmetries in e^+e^- for back-to-back h_1h_2

- **Thrust axis method**

Boer et al., NPB504, 345 (1997).
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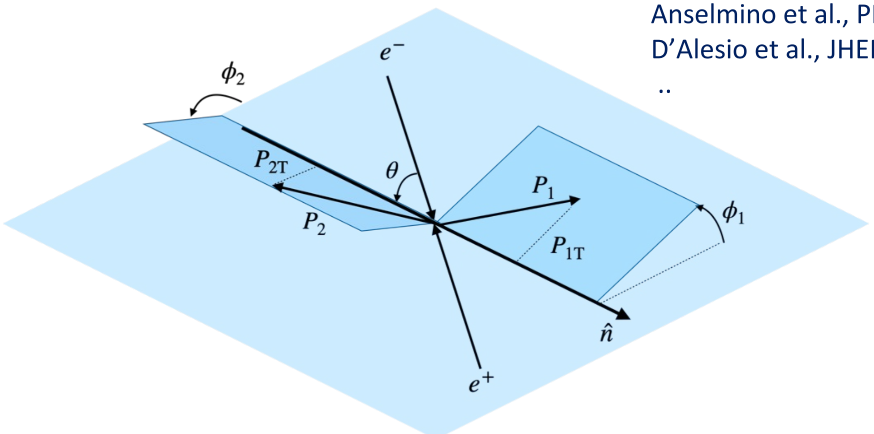


$$N_{h_1h_2} \propto 1 + \frac{\langle \sin^2\theta\rangle}{\langle 1+\cos^2\theta\rangle} A_{12}\cos(\phi_1+\phi_2)$$

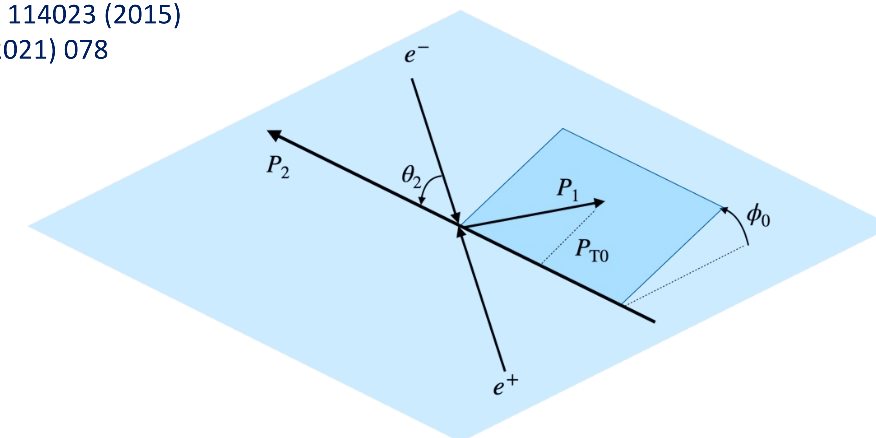
Collins asymmetry

$$A_{12} = \frac{\sum_q e_q^2\; H_{1q}^{\perp h_1}\; H_{1\bar{q}}^{\perp h_2}}{\sum_q e_q^2\; D_{1q}^{h_1}\; D_{1\bar{q}}^{h_2}}$$

- Measured asymmetry

$$A_{12}^{UL(UC)} \simeq A_{12}^{U} - A_{12}^{L(C)}$$

- **Hadronic plane method**



$$N_{h_1h_2} \propto 1 + \frac{\langle \sin^2\theta_2\rangle}{\langle 1+\cos^2\theta_2\rangle} A_0\cos(2\phi_0)$$

Collins asymmetry

$$A_0 = \frac{\sum_q e_q^2\; wH_{1q}^{\perp h_1} \otimes H_{1\bar{q}}^{\perp h_2}}{\sum_q e_q^2\; D_{1q}^{h_1} \otimes D_{1\bar{q}}^{h_2}}$$

- Measured asymmetry

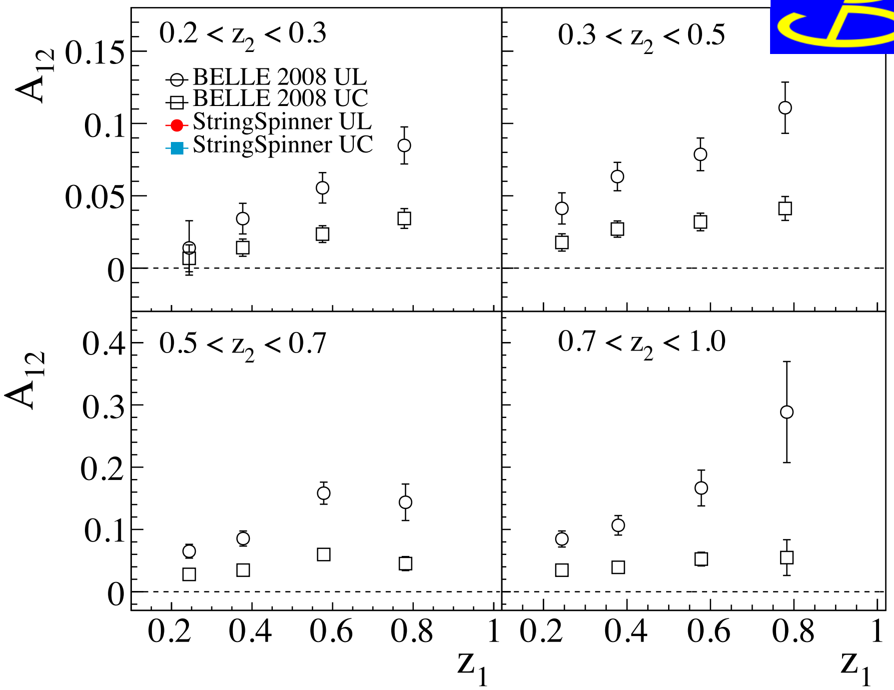
$$A_{0}^{UL(UC)} \simeq A_{0}^{U} - A_{0}^{L(C)}$$

U unlike sign pair e.g. $\pi^+\pi^- + \pi^-\pi^+$
L like sign pair e.g. $\pi^+\pi^+ + \pi^-\pi^-$
C charged pair e.g. $\pi^+\pi^- + \pi^-\pi^+ + \pi^+\pi^+ + \pi^-\pi^-$

Comparison with the A_{12} asymmetry

A_{12} asymmetry for charged π π pairs

PRD 78, 032011 (2008)



$$z_i = \frac{2E_{h_i}}{\sqrt{s}}$$

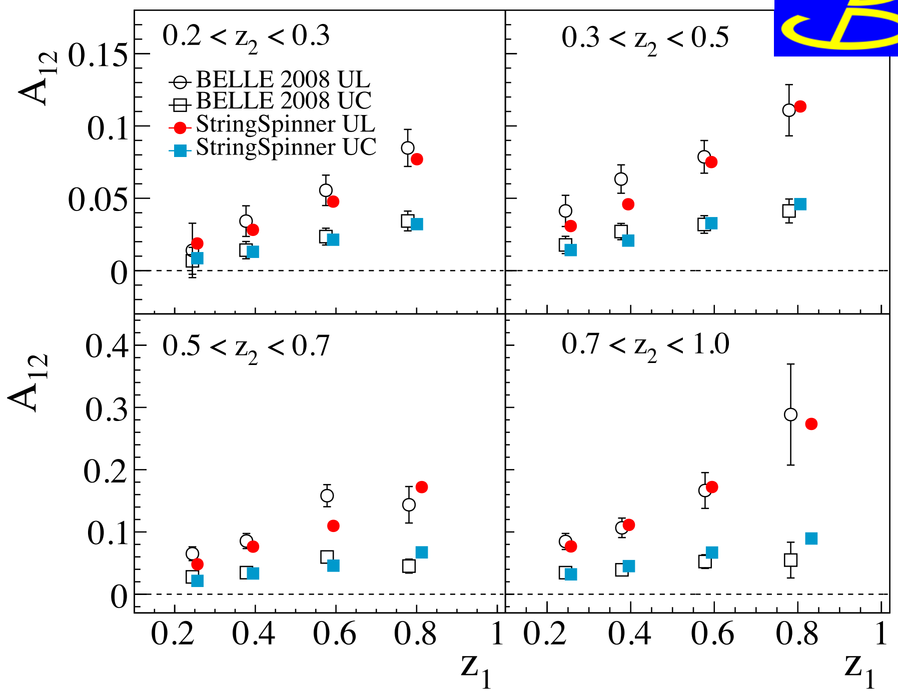
Belle asymmetries corrected for thrust smearing

Cuts:

$$T > 0.8, z > 0.2, Q_T < 3.5 \text{ GeV}$$

A_{12} asymmetry for charged π π pairs

PRD 78, 032011 (2008)



$$z_i = \frac{2E_{h_i}}{\sqrt{s}}$$

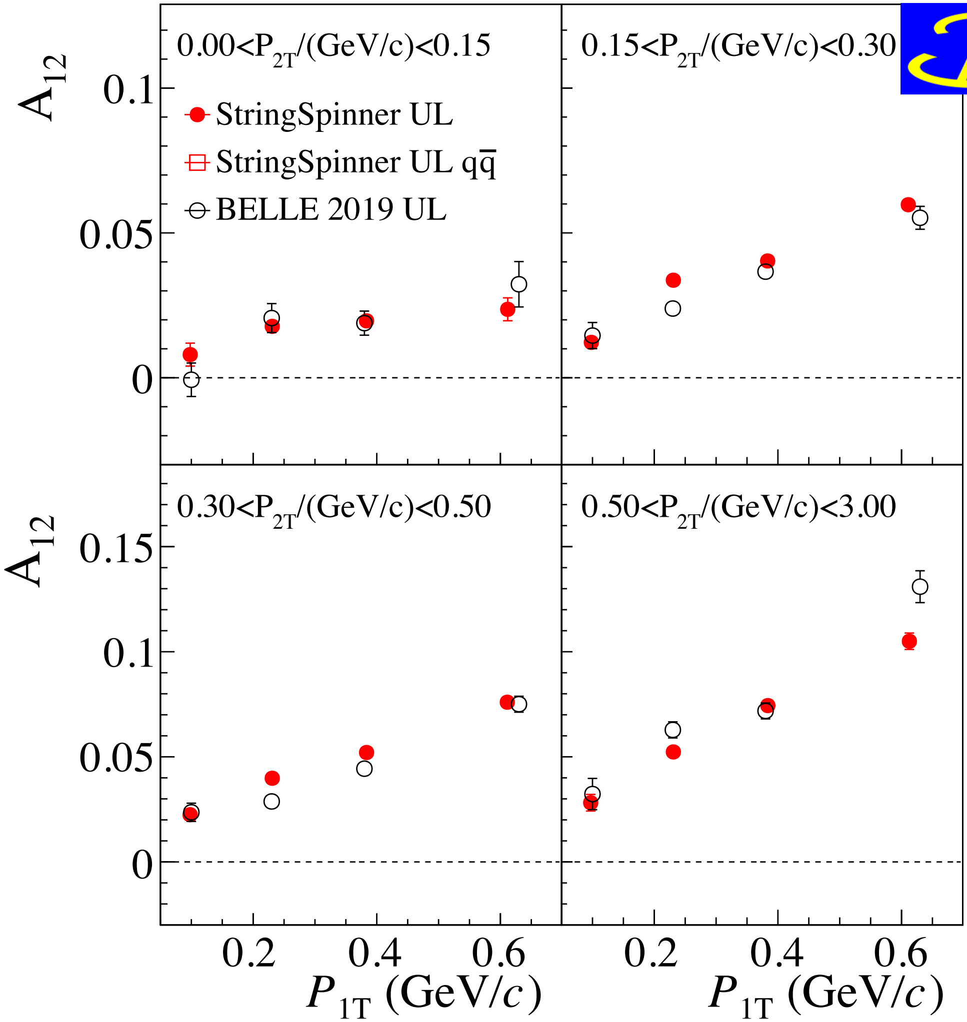
Belle asymmetries corrected for thrust smearing

Cuts:

$$T > 0.8, z > 0.2, Q_T < 3.5 \text{ GeV}$$

StringSpinner reproduces trend and size

A_{12}^{UL} asymmetry for charged π π pairs
$P_{T1} \times P_{T2}$ - dependence w.r.t thrust



PRD 100, 092008 (2019)

Asymmetries using thrust axis,
not corrected for thrust smearing

$T > 0.8$

$z > 0.2, P_T < 3.0$ GeV/c

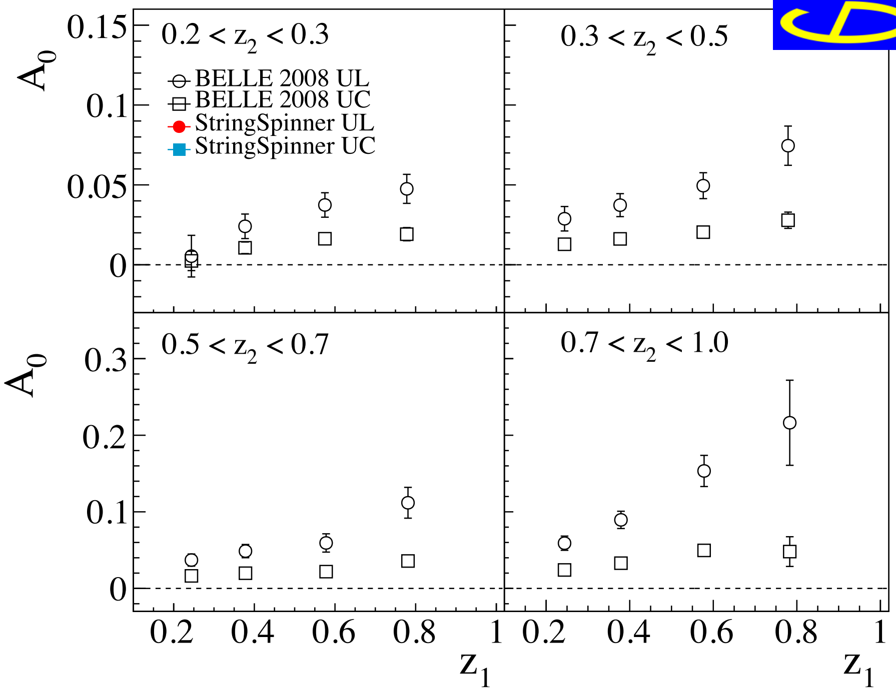
$\alpha_O < 0.3$ rad

StringSpinner reproduces the nearly linear trend observed by BELLE

Comparison with the A_0 asymmetry

A_0 asymmetry for π π pairs:

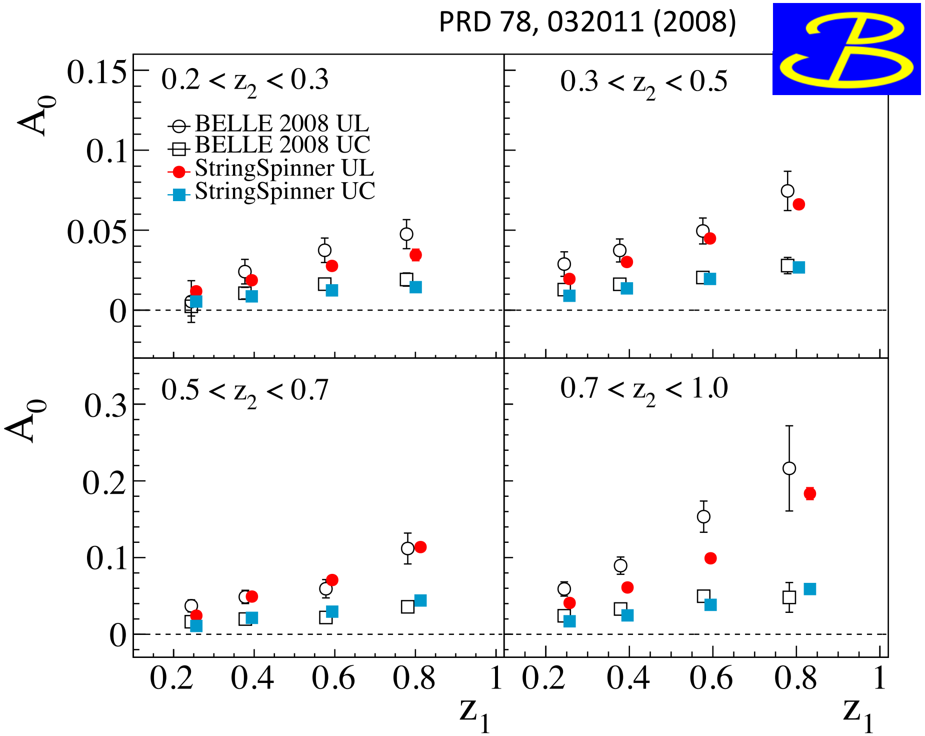
PRD 78, 032011 (2008)



Cuts:

$$T > 0.8, z > 0.2, Q_T < 3.5\text{GeV}$$

A_0 asymmetry for π π pairs:



Cuts:

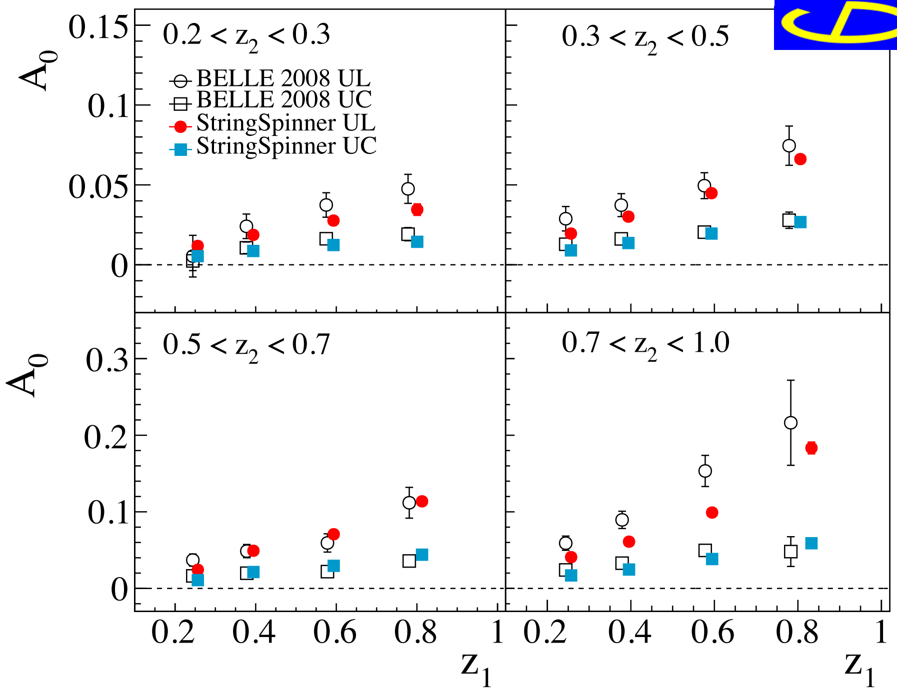
$$T > 0.8, z > 0.2, Q_T < 3.5\text{GeV}$$

Trend reproduced by string+$^3P_0$

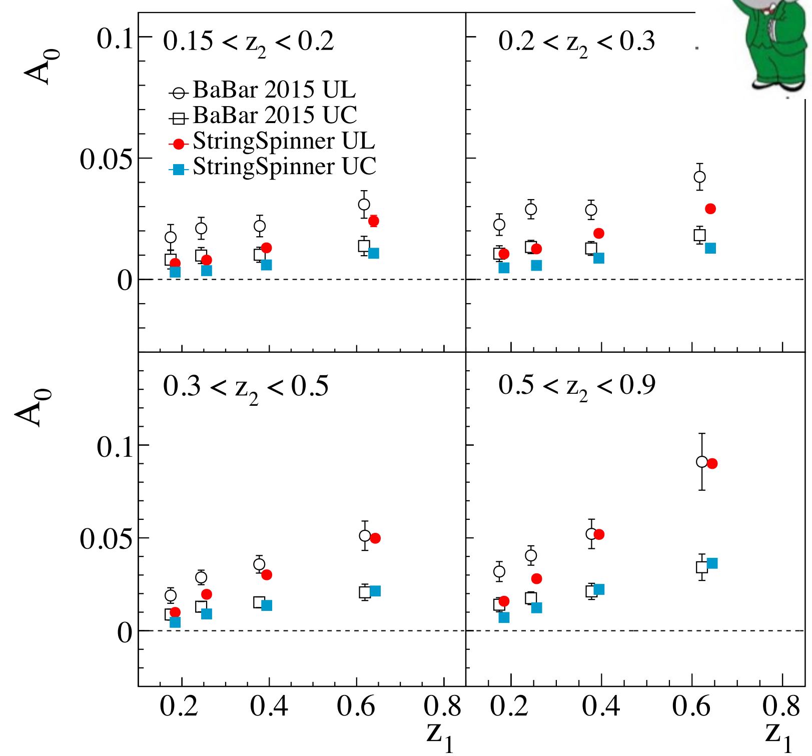
somewhat lower values in the last z_2 bin

A_0 asymmetry for π π pairs:

PRD 78, 032011 (2008)



PRD 92, 111101(R) (2015)



Cuts:

$$T > 0.8, z > 0.2, Q_T < 3.5\text{GeV}$$

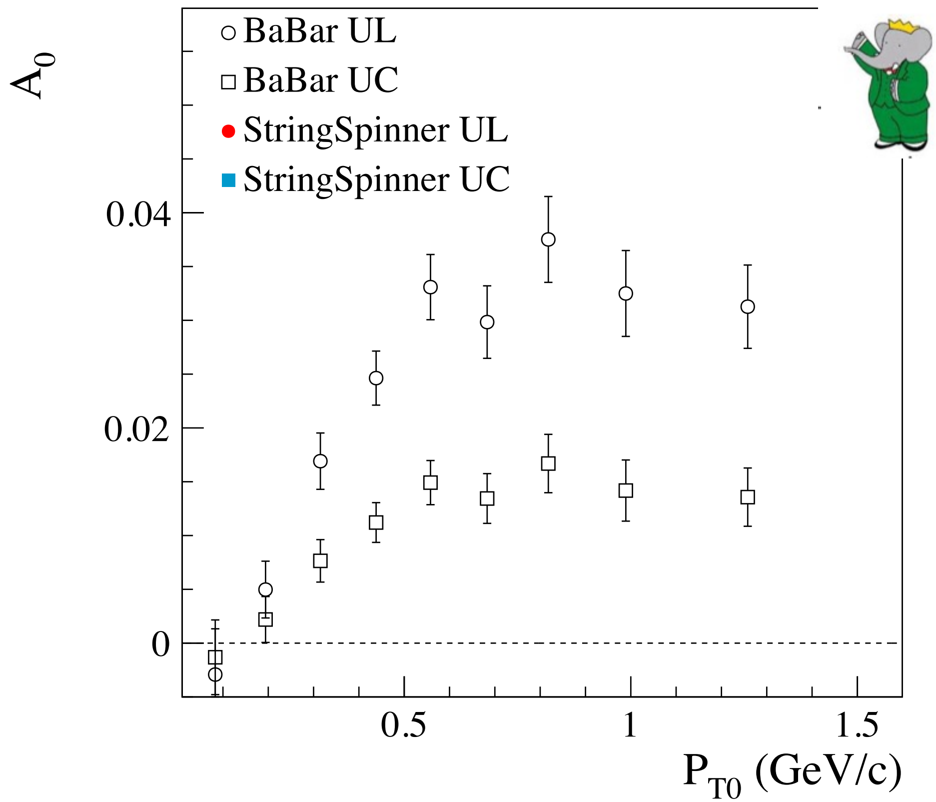
BABAR asymmetries also ok

Trend reproduced by string+$^3P_0$

somewhat lower values in the last z_2 bin

A_0 asymmetry for π π pairs: P_{T0} dependence

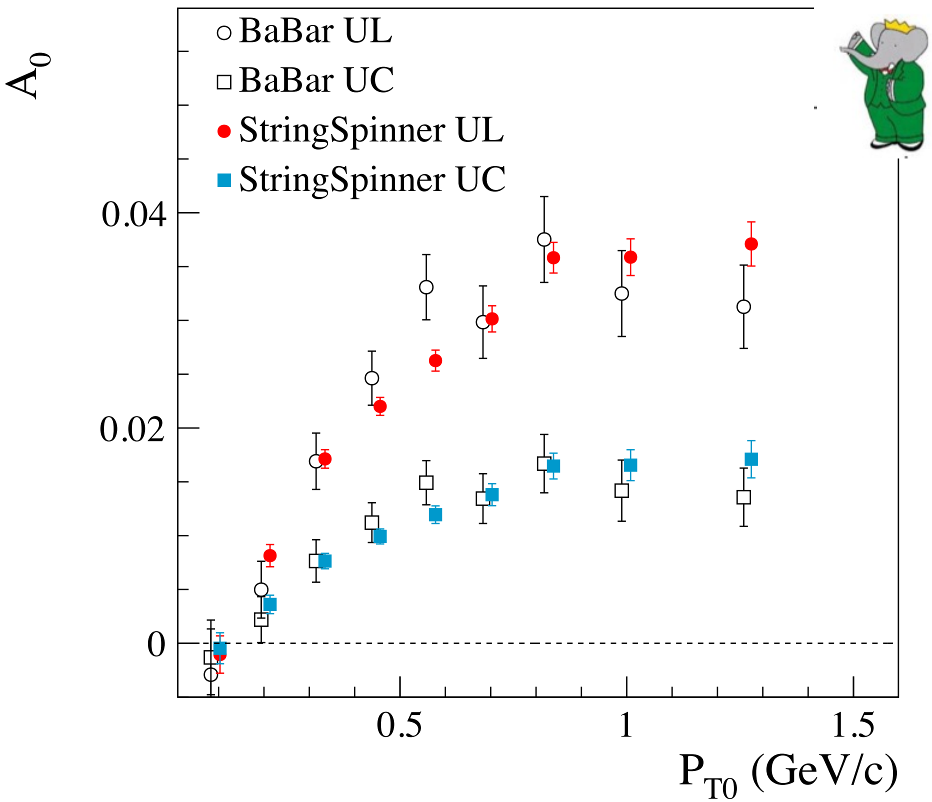
PRD 90, 052003 (2014)



Cuts:
$T > 0.8, z > 0.15, Q_T < 3.5 GeV$

A_0 asymmetry for π π pairs: P_{T0} dependence

PRD 90, 052003 (2014)



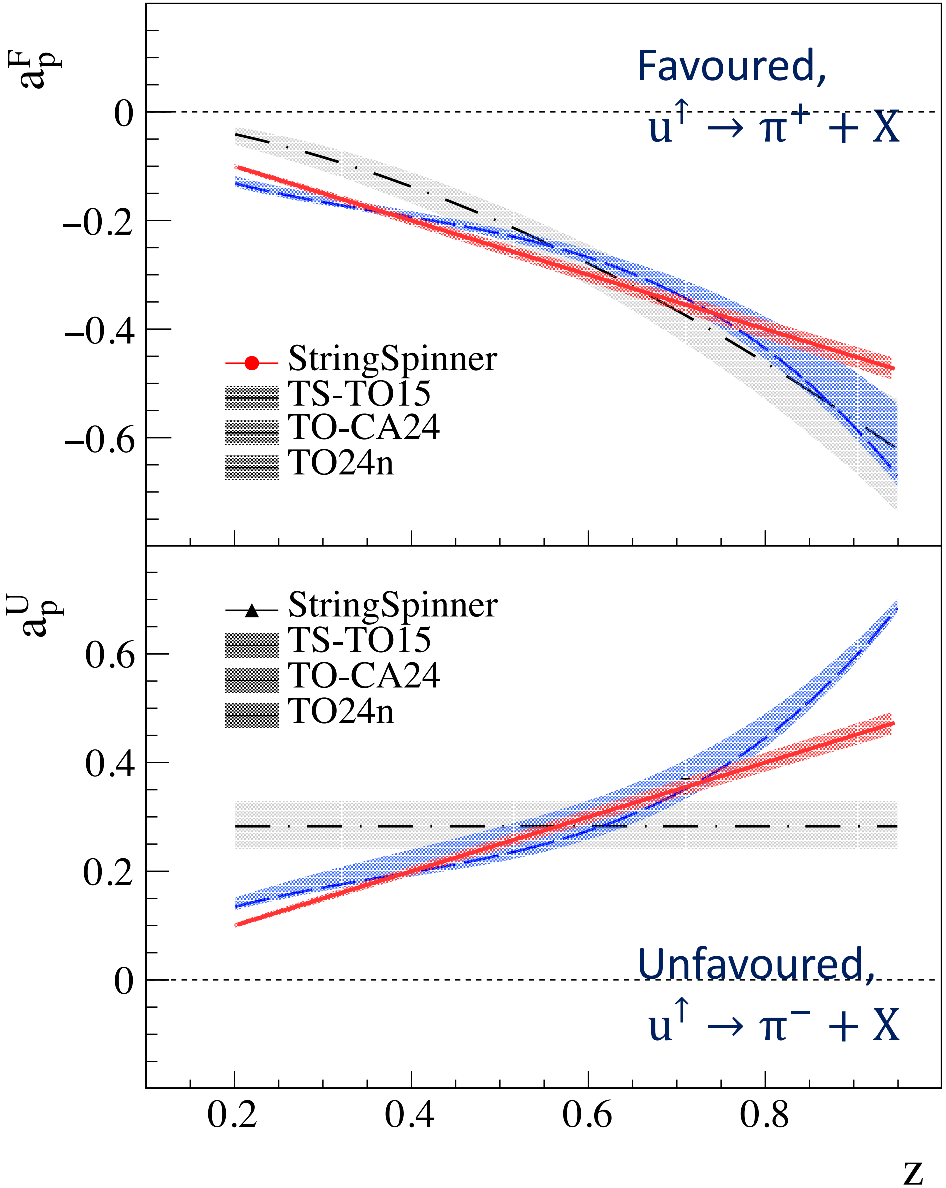
Cuts:

$T > 0.8, z > 0.15, Q_T < 3.5\mathrm{GeV}$

Transverse-momentum dependence reproduced by string+$^3P_0$!

Comparison with phenomenology

Comparison with phenomenology



Collins analysing power

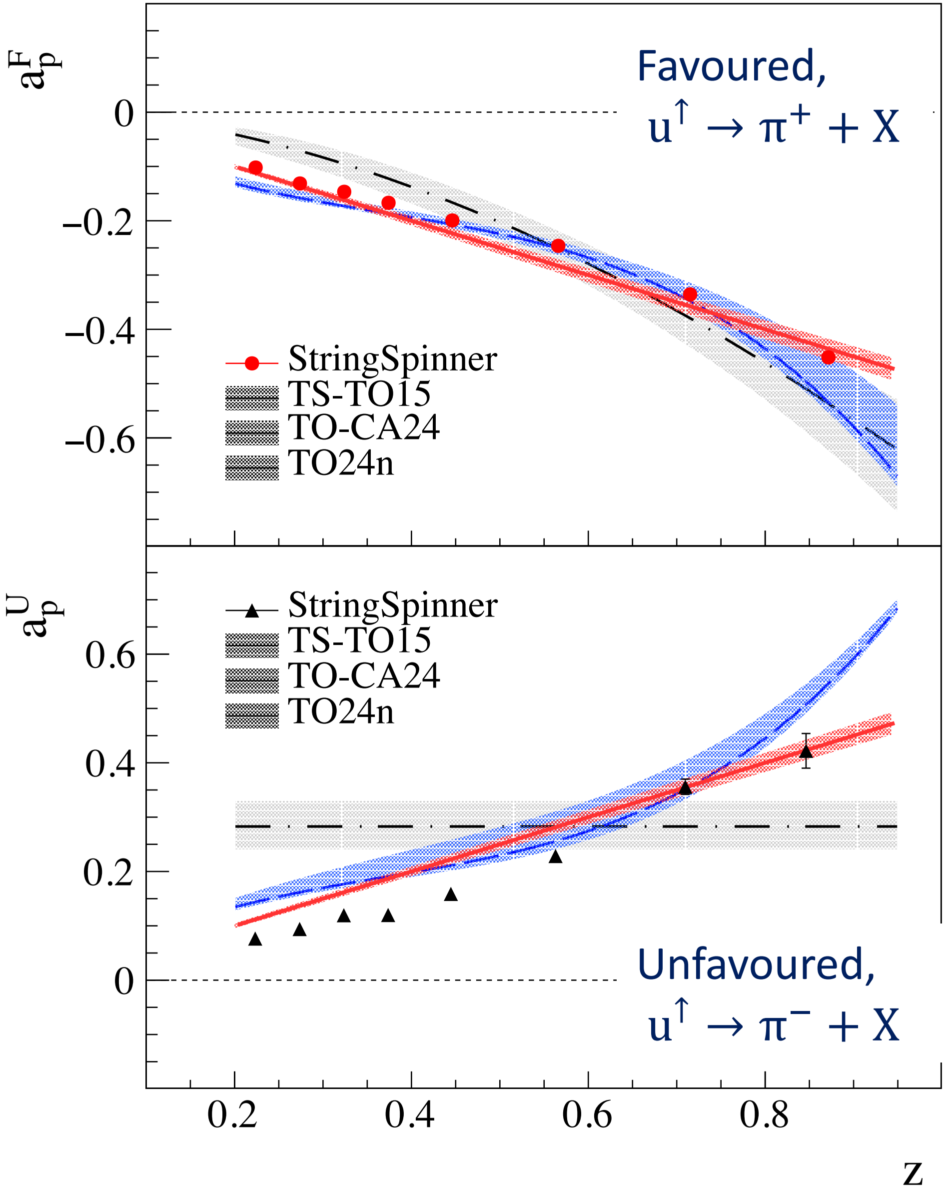
$$a_p = -\frac{p_\perp}{zM_h}\frac{H_{1q}^{h\perp}}{D_{1q}^h}$$

TS-TO15 Martin, Bradamante, Barone
PRD 91 (2015) 1, 014034
point-by-point extraction from Belle A_{12}^{UL}

TO-CA24 Boglione et al., PLB 854 (2024) 138712
fit of SIDIS, e^+e^- and pp

TO24n Boglione, Flore (2024, private comm.)
like in TO-CA24 + Collins asymm. COMPASS 2022 data on d

Comparison with phenomenology



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like in TO-CA24 + Collins asymm. COMPASS 2022 data on d

string+$^3P_0$ → rising trend with z for fav. and unfav.

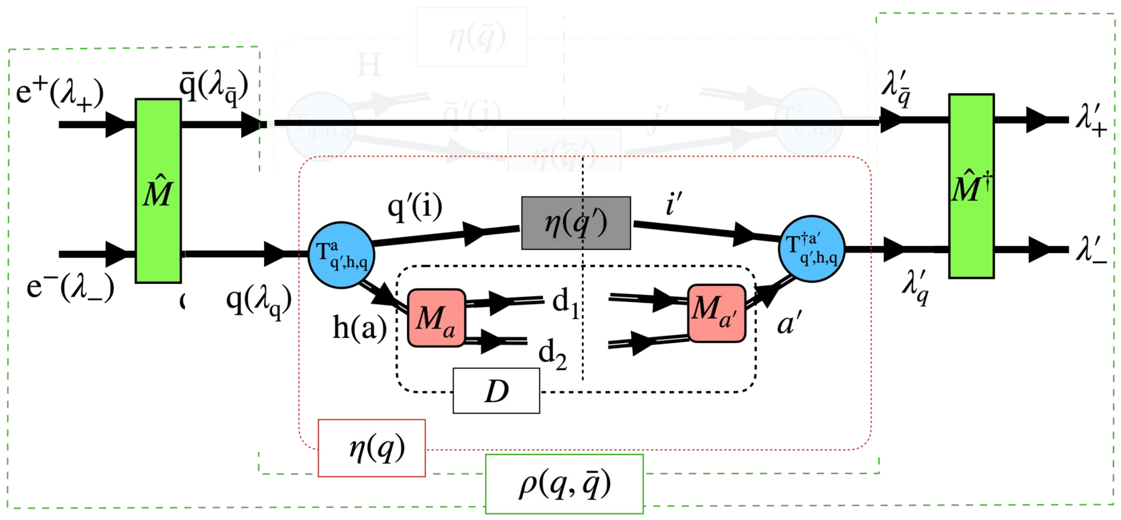
A guide for the choice of the parametrizations of Collins FFs used in phenomenology?

Conclusions

- Spin effects implemented in Pythia 8.3 for DIS and e^+e^-
  - StringSpinner → string+$^3P_0$ in Pythia
- Encouraging results on transverse spin effects
- More developments of the string+$^3P_0$ model foreseen
  - baryon production, parton-showers, ..
- The work on the systematic implementing spin effects relevant for the Electron Ion Collider

Backup

The recursive recipe for simulating e^+e^- annihilation: VM emission



For a vector meson h=VM

$$\rightarrow \eta(q) = \mathbf{T}^{a'\dagger}_{q',h=VM,q}\, \eta(q')\, \mathbf{T}^{a}_{q',h=VM,q} D_{a'a},\quad \eta(q') = 1_{q'} \text{ and } \eta(\bar{q}) = 1_{\bar{q}}$$

Steps:

i) Emission probability density (summing over decay information, i.e. $D_{a'a} = \delta_{a'a}$)

$$\frac{dP(q \rightarrow h = VM + q'; q\bar{q})}{dM^2 dZ_+ Z_+^{-1} d^2 p_T} = \mathrm{Tr}_{q'\bar{q}}\, \mathbf{T}^{a}_{q',h,q}\, \rho(q,\bar{q})\, \mathbf{T}^{a\dagger}_{q',h,q} = F_{q',h,q}(M^2, Z_+, p_T; k_T, C^{q\bar{q}})$$

ii) Calculate the spin density matrix of h=VM, and decay the meson

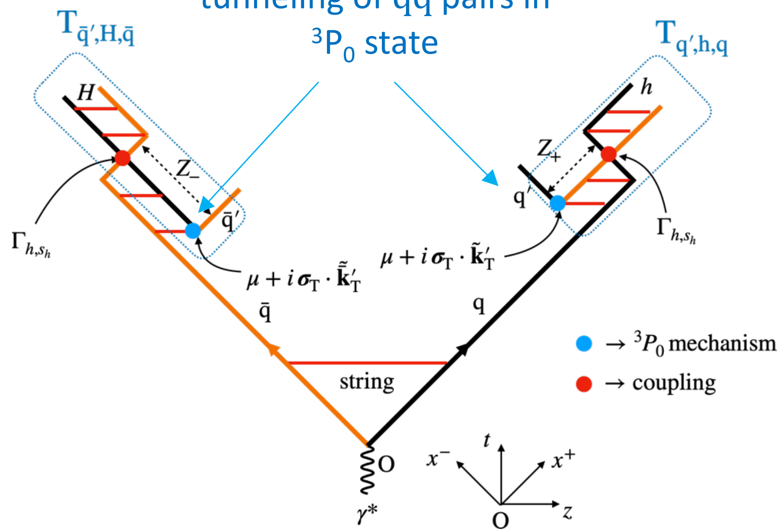
$$\rho_{aa'}(h) = \mathrm{Tr}_{q'\bar{q}}\, \mathbf{T}^{a}_{q',h,q}\, \rho(q,\bar{q})\, \mathbf{T}^{a'\dagger}_{q',h,q}$$

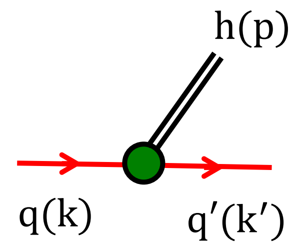
iii) Decay the meson $p \rightarrow p_1\, p_2 ..$

$$dN(p_1, p_2..)/d\Omega \propto M^{a}_{dec.}(p \rightarrow p_1 p_2..)\, \rho_{aa'}(h) M^{\dagger a'}_{dec.}(p \rightarrow p_1 p_2..)$$

iv) Build the decay matrix $D_{a'a}(p_1, p_2, ..) = M^{\dagger a'}_{dec.}(p \rightarrow p_1 p_2..)\, M^{a}_{dec.}(p \rightarrow p_1 p_2..)$

The hadronization model: **string+$^3P_0$**





quark splitting $q \rightarrow h + q'$

Relevant variables:
$\mathbf{k}_T = \mathbf{p}_T + \mathbf{k}'_T$
$Z_+ = p^+/k^+$
$\varepsilon_h^2 = M^2 + p_T^2$

Transverse vectors defined w.r.t. string axis

Quark splitting amplitude in the string+$^3P_0$ model

$$T_{q',h,q} \propto C_{q',h,q}\ D_h(M^2) \left(\frac{1-Z_+}{\varepsilon_h^2}\right)^{\frac{a}{2}} \exp\left[-\frac{b_L \varepsilon_h^2}{2Z_+}\right] N_a^{-\frac{1}{2}}(\varepsilon_h^2)\ e^{-\frac{b_T k'^2_T}{2}}\ [\mu + \sigma_z \boldsymbol{\sigma}_T \cdot \mathbf{k}'_T]\ \ \Gamma_{h,s_h}$$

flavor — mass — longitudinal momentum — transverse momentum (w.r.t string axis) — $^3P_0$ mechanism [μ complex mass paramter] — Coupling e.g. $\Gamma_{h=PS} = \sigma_z$

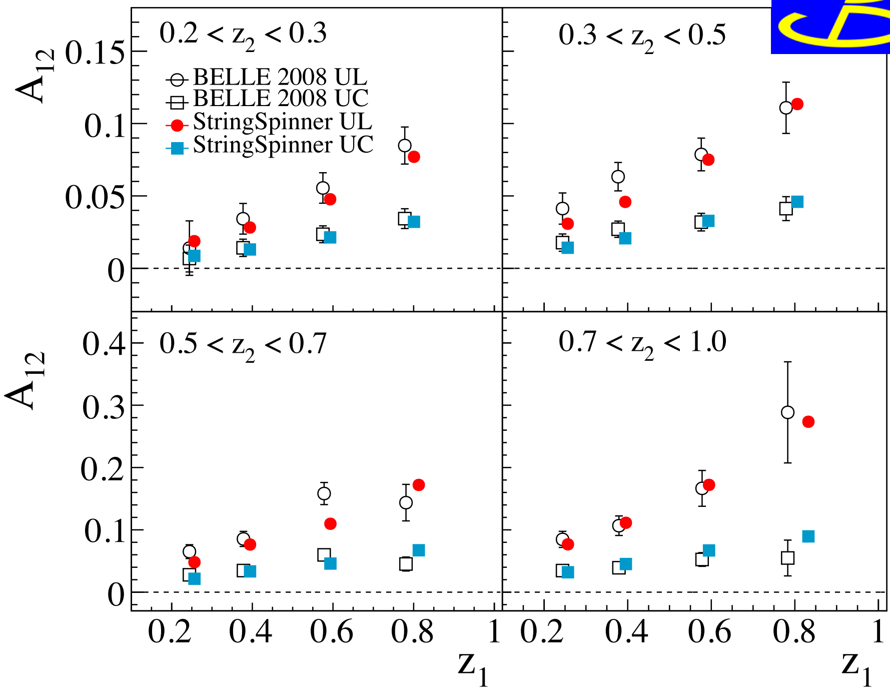
Free param. Lund

Free param. string+$^3P_0$

AK, X. Artru, PRD 109 (2024) 5, 05402

A_{12} asymmetry for charged π π pairs

PRD 78, 032011 (2008)

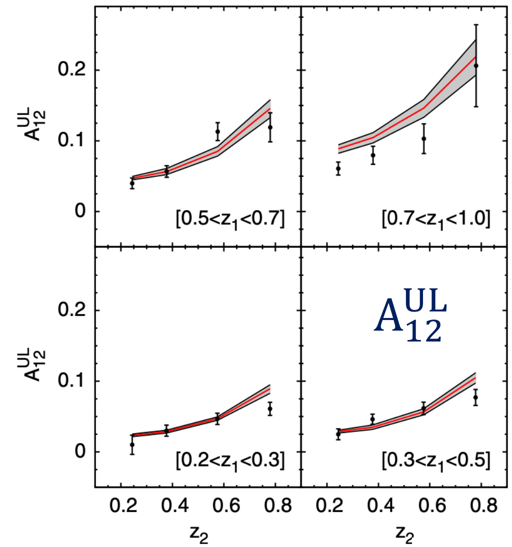


Belle asymmetries corrected for thrust smearing

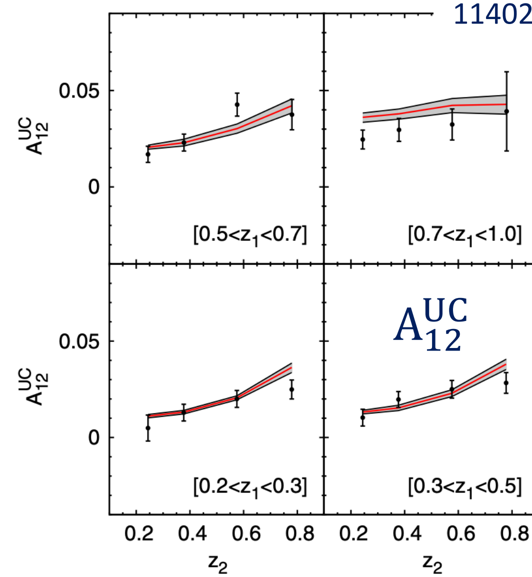
Cuts:

$$T > 0.8, z > 0.2, Q_T < 3.5\ \text{GeV}$$

StringSpinner reproduces trend and size

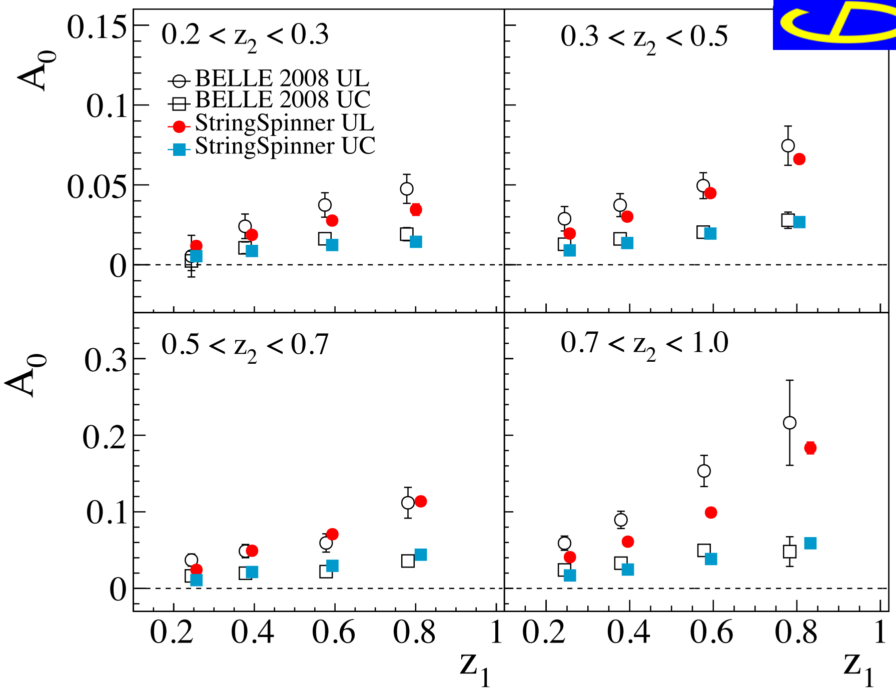


Anselmino et al., PRD 92, 114023 (2015)

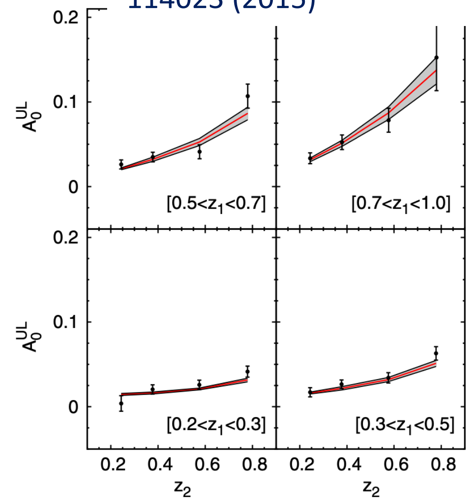


A_0 asymmetry for charged pions

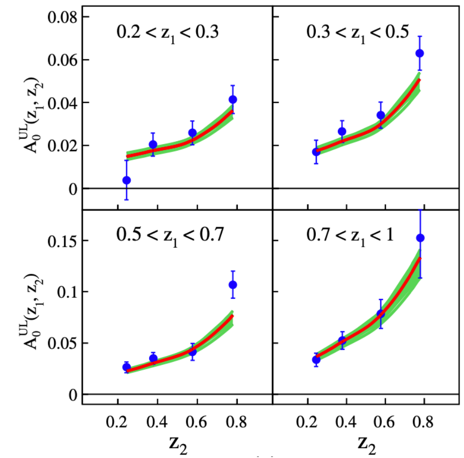
PRD 78, 032011 (2008)

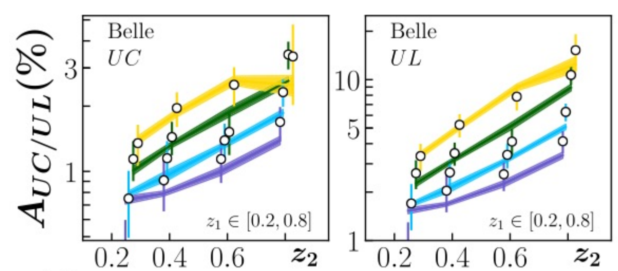


Anselmino et al., PRD 92, 114023 (2015)



Kang et al., PRD 93, 014009 (2016)





JAM, PRD 102, 054002 (2020)

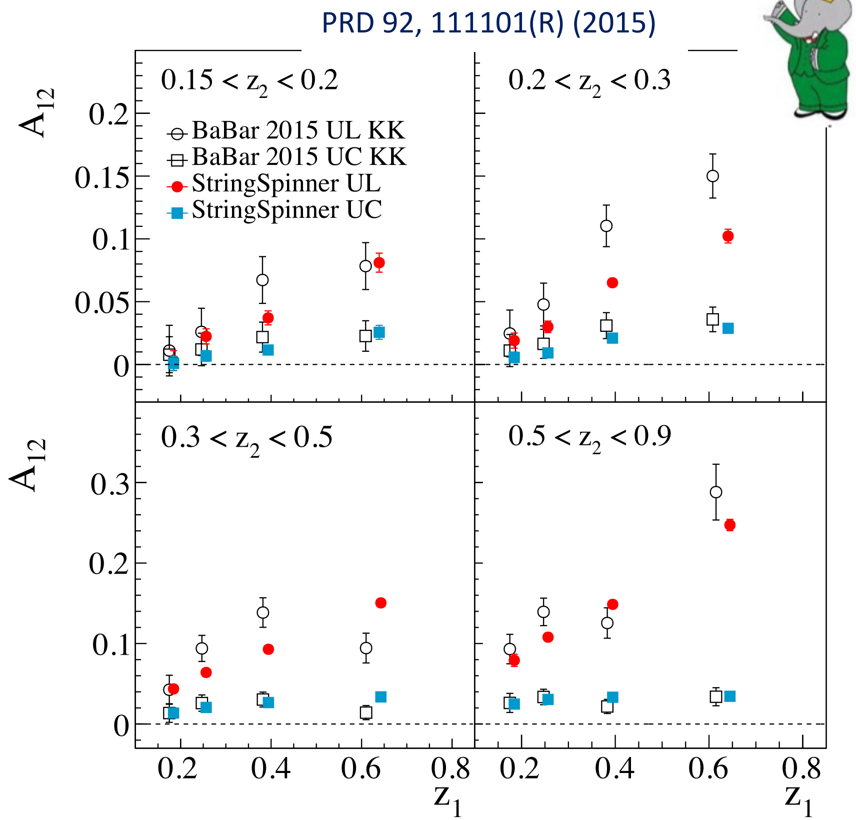
Cuts:

$$T > 0.8, z > 0.2, Q_T < 3.5\text{GeV}$$

Trend reproduced by string+$^3P_0$
somewhat lower values in the last z_2 bin

A_0 asymmetry essential observable included in phenomenological fits

A_{12} asymmetry for charged KK pairs



Corrected for thrust smearing

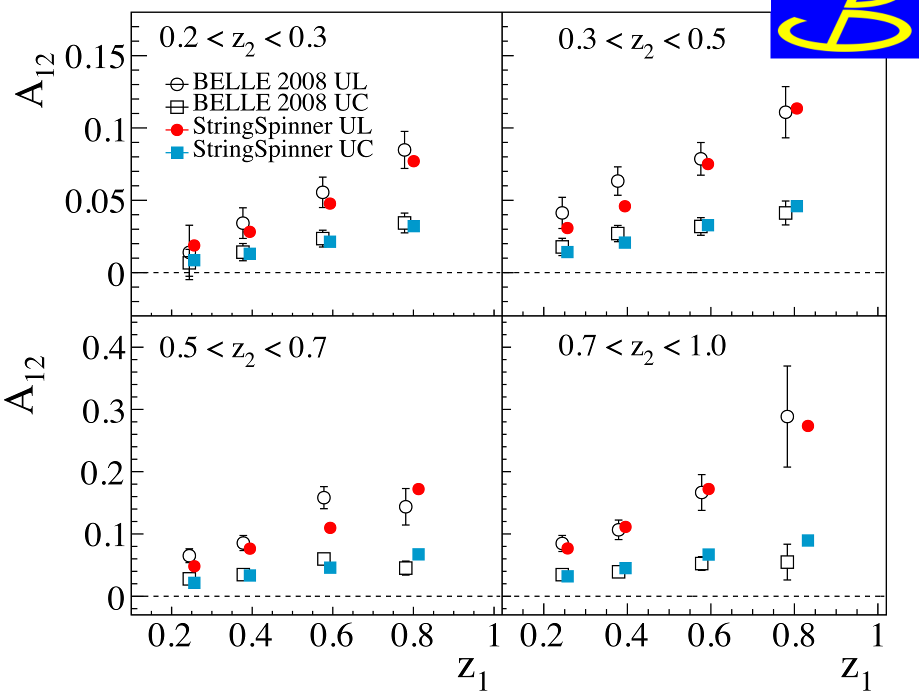
Cuts

$T > 0.8, z > 0.15, Q_T < 3.5\ \text{GeV}, \alpha_O < \pi/4$

A_{12}^{UC} much smaller than A_{12}^{UL} at large z reproduced by string+$^3P_0$

A_{12} asymmetry for charged $\pi\,\pi$ pairs

PRD 78, 032011 (2008)

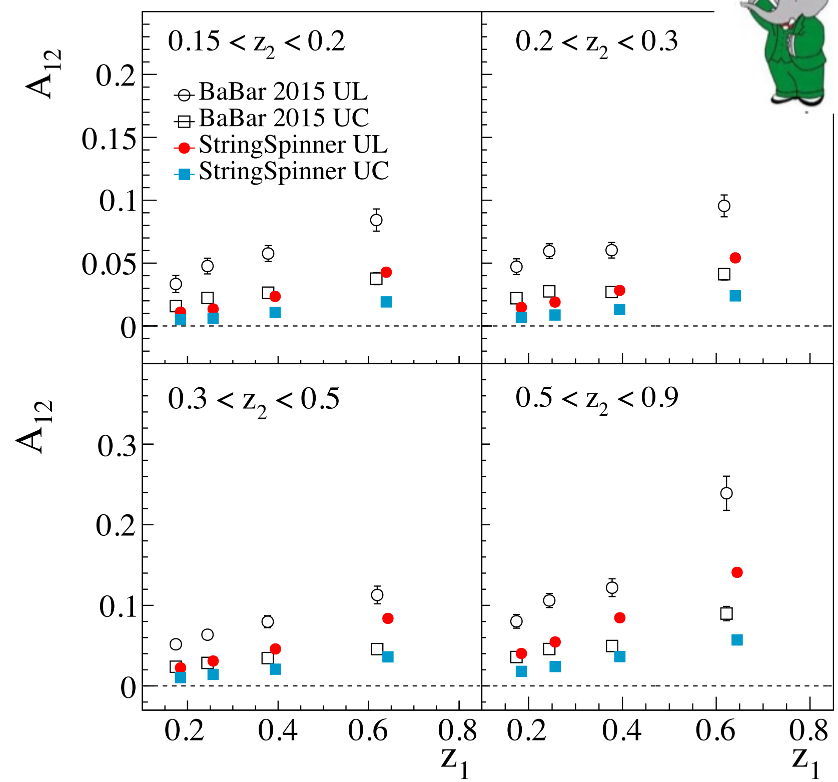


Belle asymmetries corrected for thrust smearing

Cuts:

$$T > 0.8, z > 0.2, Q_T < 3.5\ \mathrm{GeV}$$

PRD 92, 111101(R) (2015)



BaBar asymmetries corrected for thrust smearing

Cuts:

$$T > 0.8, z > 0.15, Q_T < 3.5\ \mathrm{GeV}, \alpha_0 < \pi/4$$

StringSpinner lower than BABAR

BABAR and BELLE data different, unlike StringSpinner

PRD 90, 052003 (2014)