October 1, 2024
Yerevan

Polarized hadronization in Pythia

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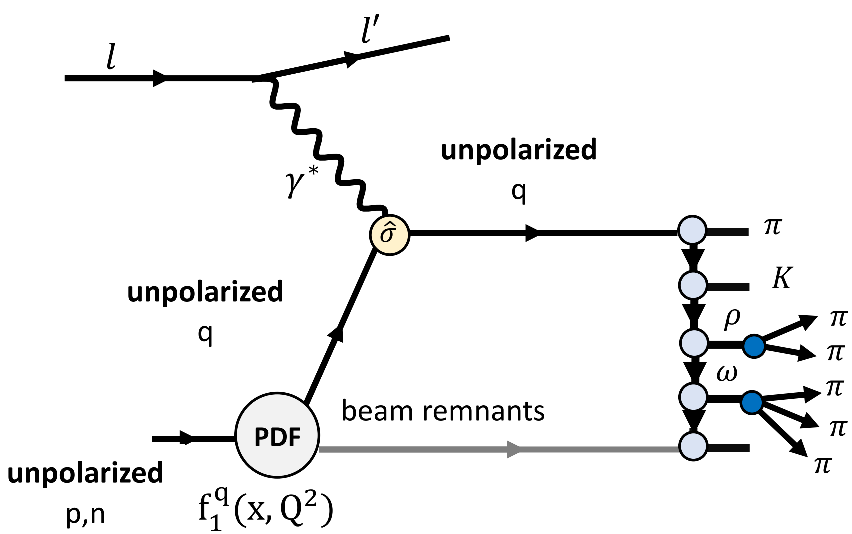
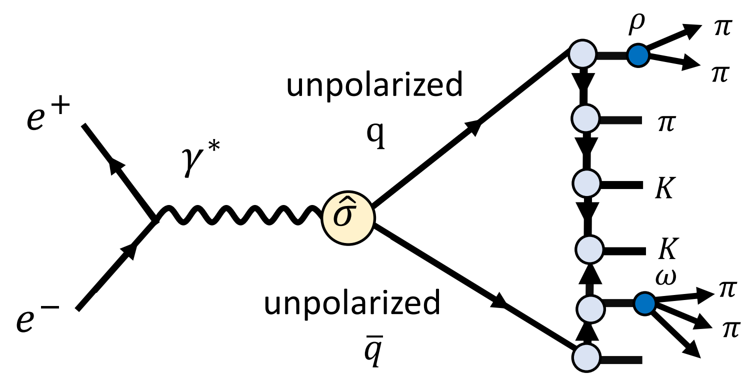
StringSpinner: spin in the Pythia generator

PYTHIA 8 standard tool in particle physics,
capable of simulating several processes: DIS, e+e-, pp, pA, ..
without spin effects





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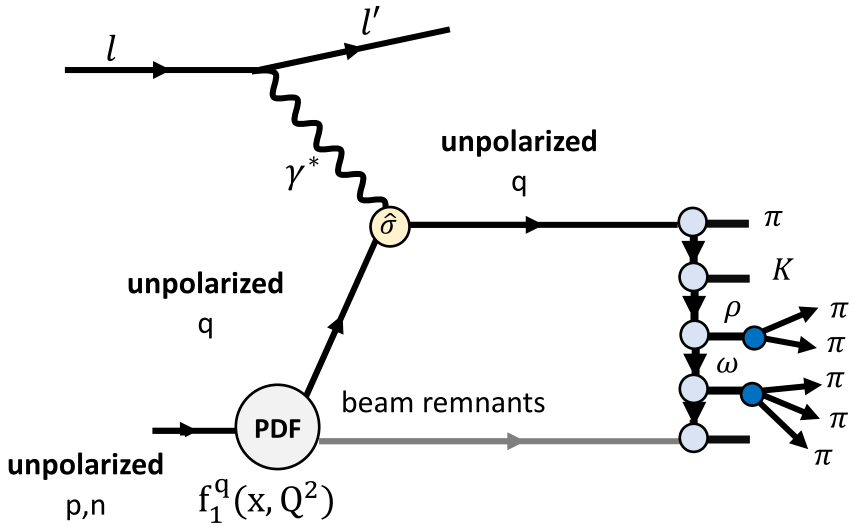
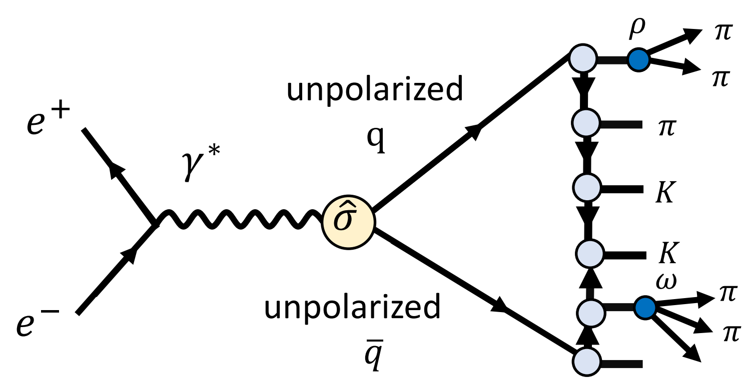
→ implemented in Pythia for DIS and e^+e^- by StringSpinner





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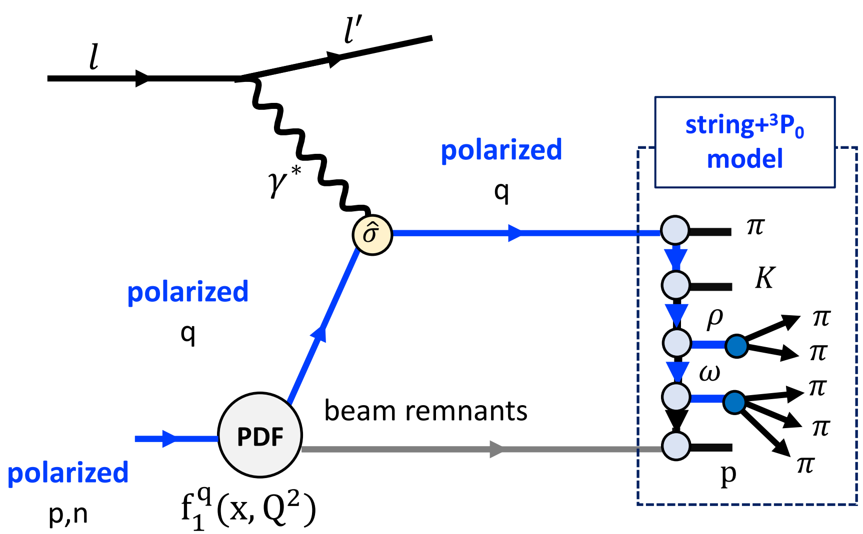

Transversity $h_1^q(x)$ [*valence quarks,*
sea quarks unpol.]
or arbitrary polarization of quarks

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

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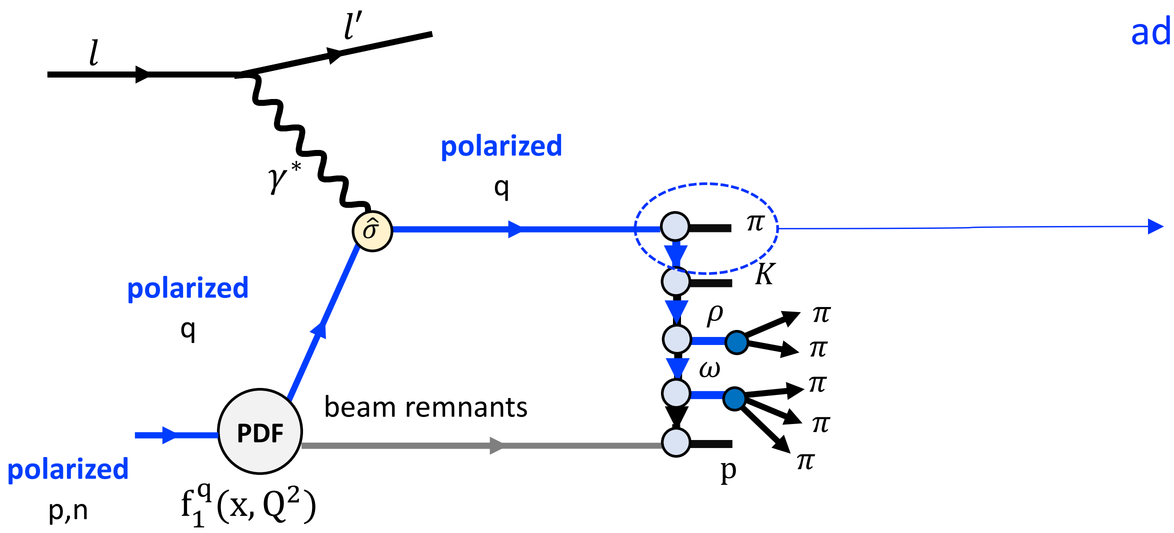
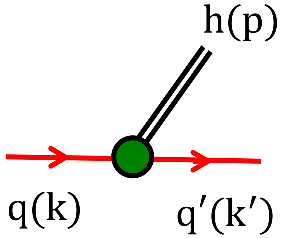
AK, Artru, Martin, PRD 104, 114038 (2021)

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





Elementary quark splitting

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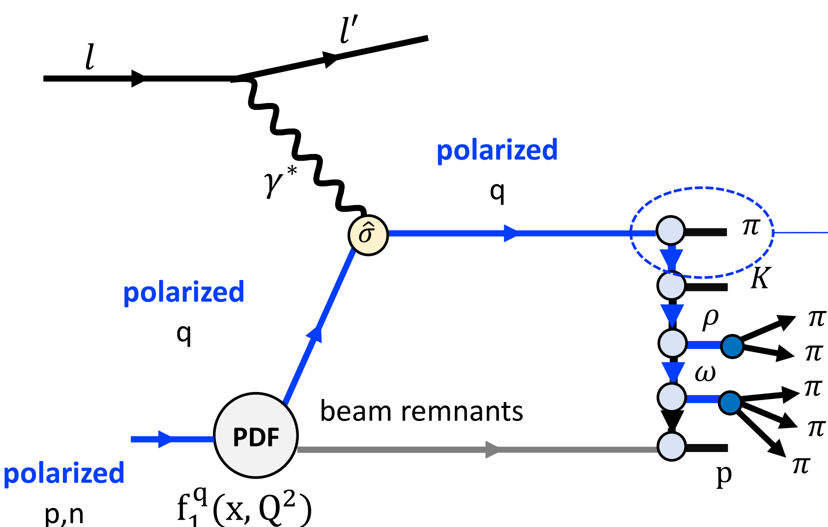
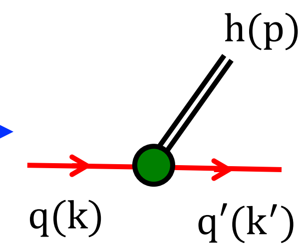
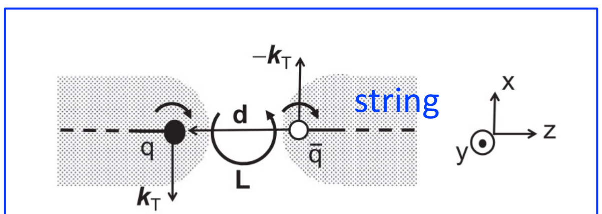




Elementary quark splitting

Splitting amplitude

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



$^3P_0$ mechanism
μ complex mass paramter

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

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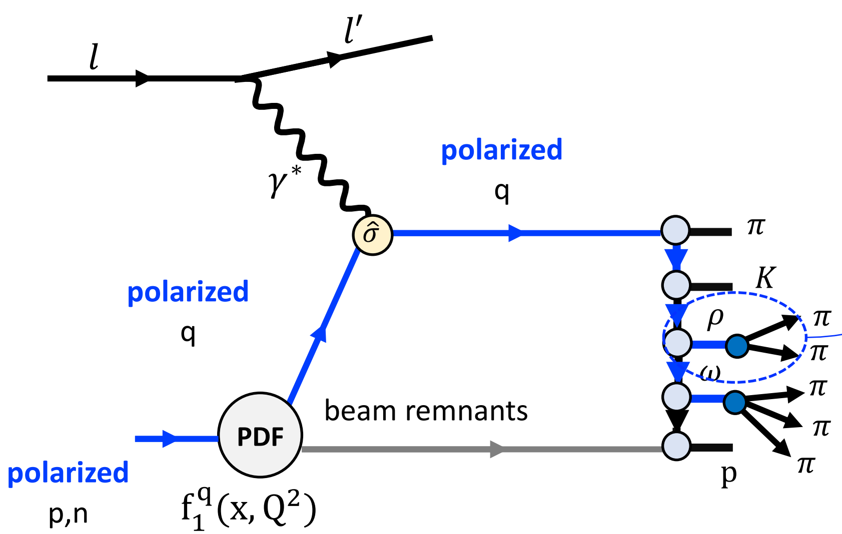

→ Coupling of quarks with VMs

f_L
fraction of L pol. VMs

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

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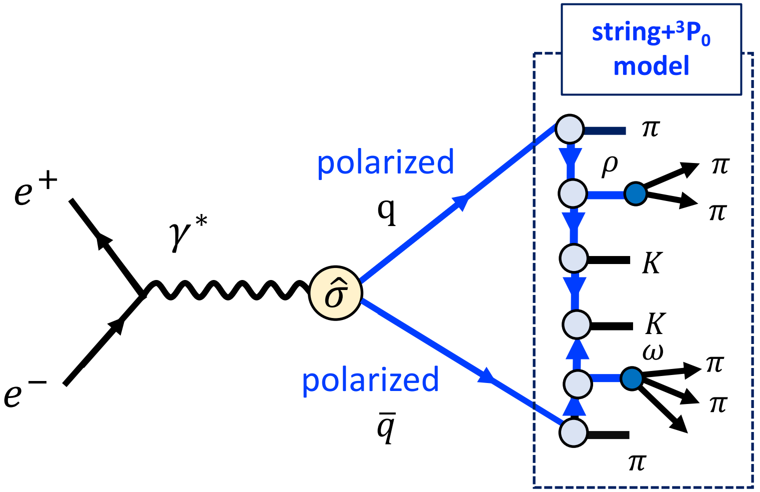
For e^+e^- splittings from q and $\bar{q}$

Antiquark splitting amplitude similar to the quark one



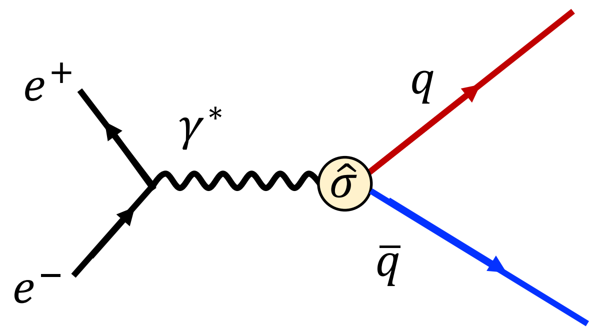
Joint spin density matrix $\rho(q, \bar{q})$
correlations between the spin states of q and $\bar{q}$

AK, Artru, PRD 109 (2024) 5, 054029
AK, Lönnblad, Martin, arXiv: 2407.07706

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

AK, X. Artru, PRD 109 (2024) 5, 054029

Recursive recipe for $\mathrm{e}^+\mathrm{e}^-$

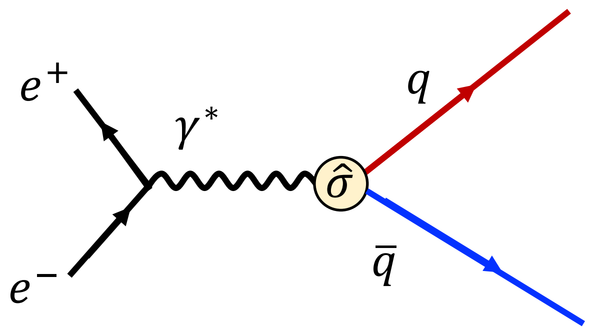


Steps:

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

[AK, X. Artru, PRD 109 (2024) 5, 054029]

Recursive recipe for e^+e^-



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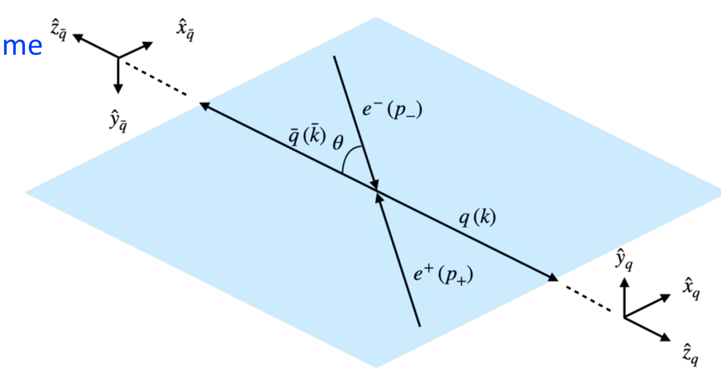
[AK, X. Artru, PRD 109 (2024) 5, 054029]

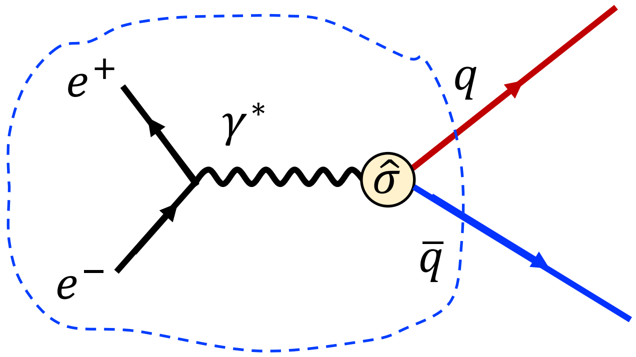
Set up the scattering $e^+e^- \rightarrow q\bar{q}$ in the c.m.s
generate the quark flavors and kinematics using differential cross section

antiquark helicity frame
(AHF)



quark helicity frame
(QHF)

Recursive recipe for e^+e^-



$\rho(q,\bar{q})$

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

[AK, X. Artru, PRD 109 (2024) 5, 054029]

- ❑ 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

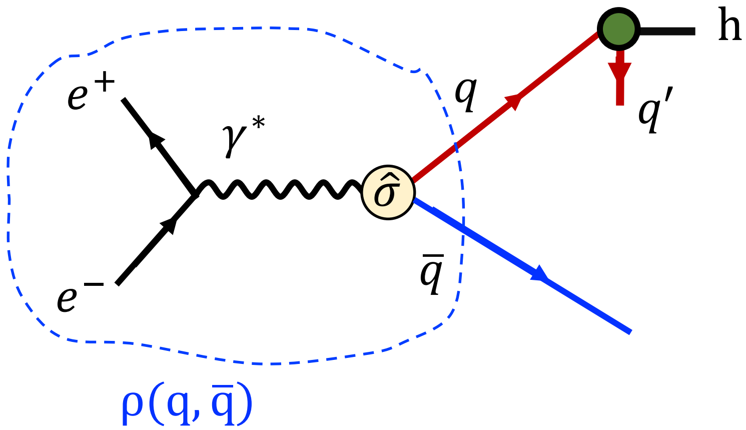
$\alpha = 0, x_q, y_q, z_q$

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

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

[AK, X. Artru, PRD 109 (2024) 5, 054029]

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

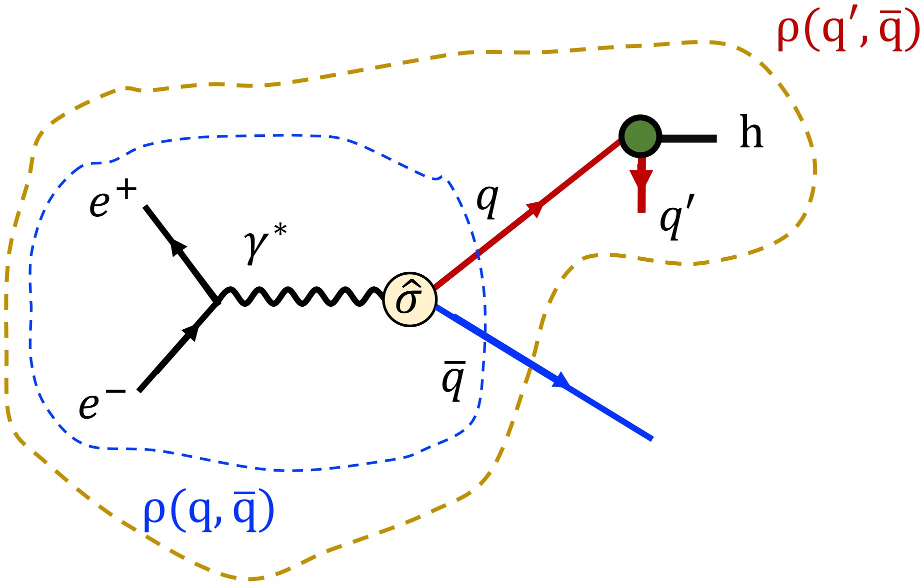
$$\frac{dP(q \to h + q'; q\bar{q})}{dZ_+ Z_+^{-1} d^2p_T} = \mathrm{Tr}_{q'\bar{q}} \mathbf{T}_{q',h,q}\, \rho(q,\bar{q})\, \mathbf{T}^\dagger_{q',h,q} = F_{q',h,q}(Z_+, \mathbf{p}_T; \mathbf{k}_T, C^{q\bar{q}})$$

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

in the QHF

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

Recursive recipe for e^+e^-



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

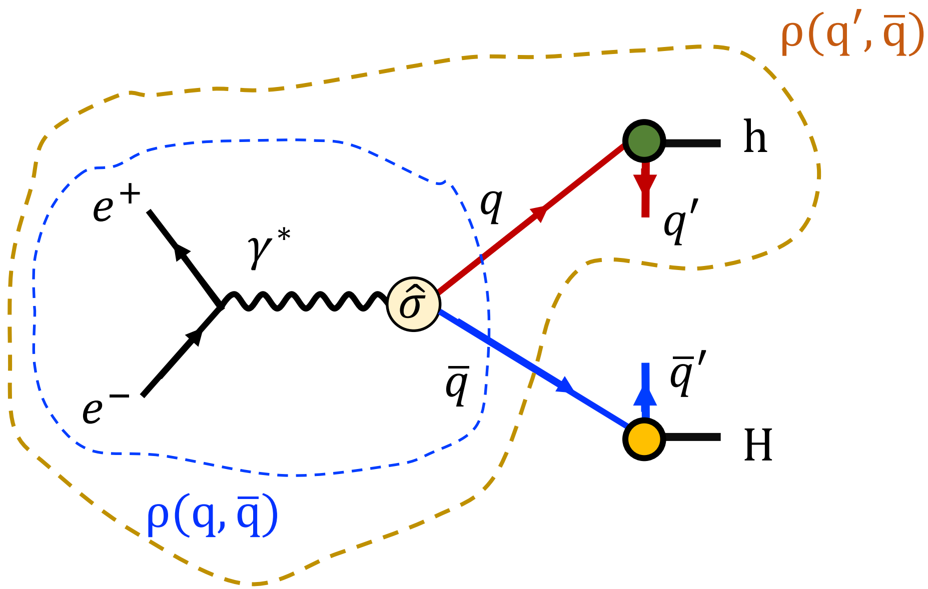
[AK, X. Artru, PRD 109 (2024) 5, 054029]

- ❑ 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:
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3. Hadron emission from q
4. Update density matrix
5. **Hadron emission from $\bar{q}$**
6. Exit condition

[AK, X. Artru, PRD 109 (2024) 5, 054029]

Depend on the azimuthal angle h

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

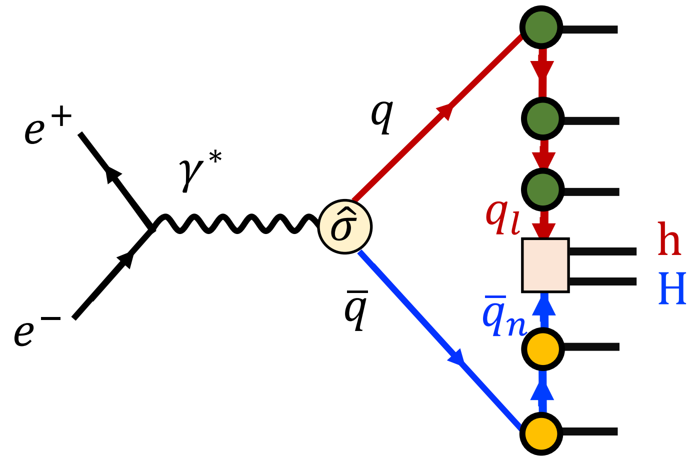
$$\frac{dP(\bar{q}\to H+\bar{q}';q'\bar{q})}{dZ_-Z_-^{-1}d^2P_T} = \mathrm{Tr}_{q'\bar{q}'}\mathbf{T}_{\bar{q}',H,\bar{q}}\,\rho(q',\bar{q})\,\mathbf{T}^\dagger_{\bar{q}',H,\bar{q}} = F_{\bar{q}',H,\bar{q}}(Z_-,P_T;\bar{k}_T,C^{q'\bar{q}})$$

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
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5. Hadron emission from $\bar{q}$
6. **Exit condition**

[AK, X. Artru, PRD 109 (2024) 5, 054029]

- 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

- $\sqrt{s} = 10.6$ 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

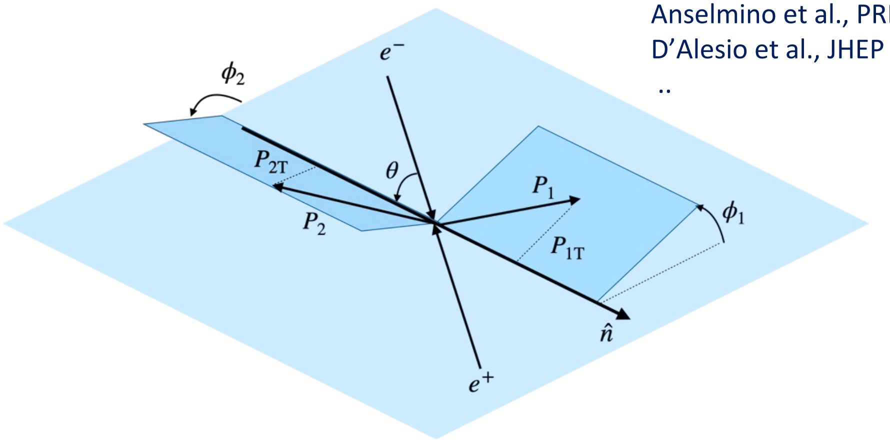
  found to give a satisfactory agreement with e^+e^- data,
  ok also for SIDIS

- **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**

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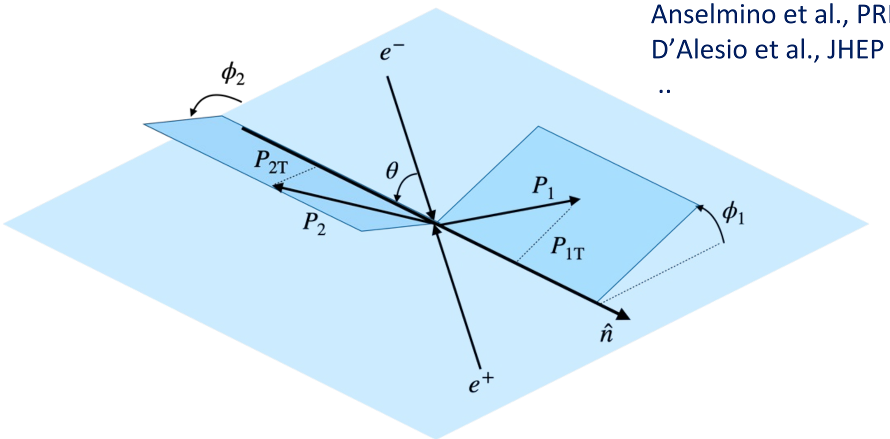
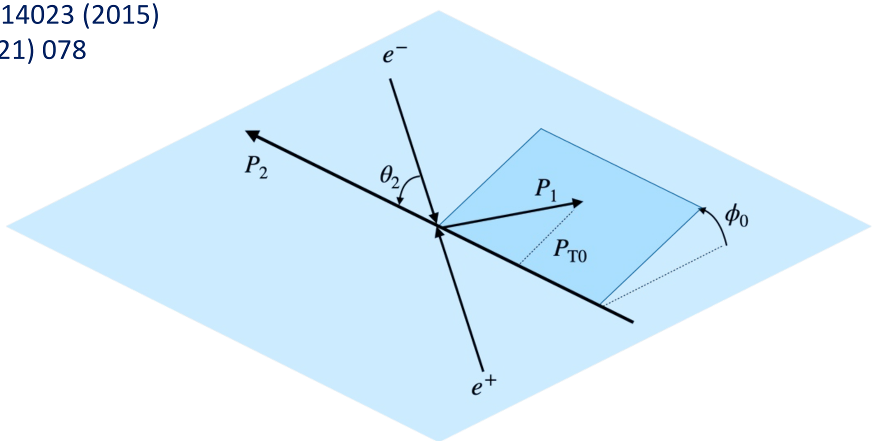
- **Hadronic plane method**





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

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

Collins asymmetry

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

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

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

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

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

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❑ Thrust axis method

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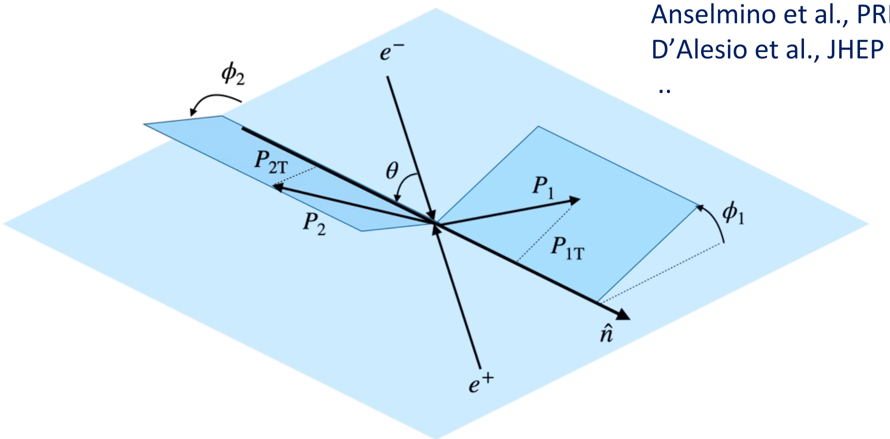

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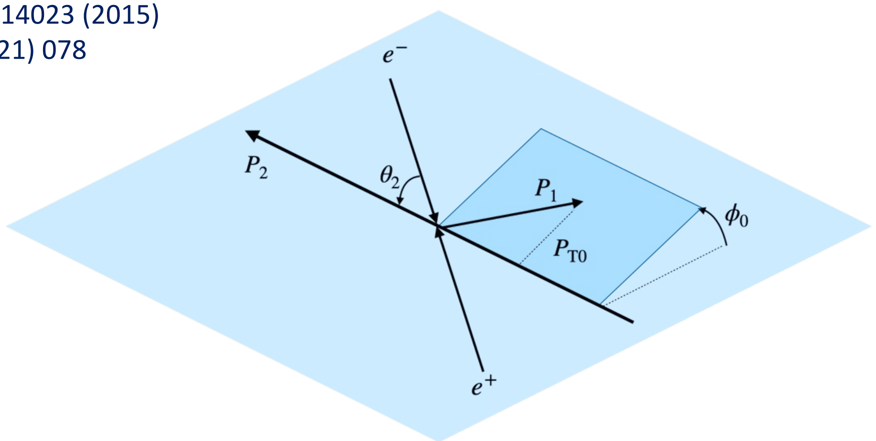

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Collins asymmetry

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Measured by	BELLE	2006 ($\pi\pi$), 2008 ($\pi\pi$), 2019 ($\pi\pi, \pi^0\pi, \eta\pi$)
	BABAR	2014 ($\pi\pi$), 2015 ($\pi\pi, \pi K, KK$)
	BESIII	2016 ($\pi\pi$)

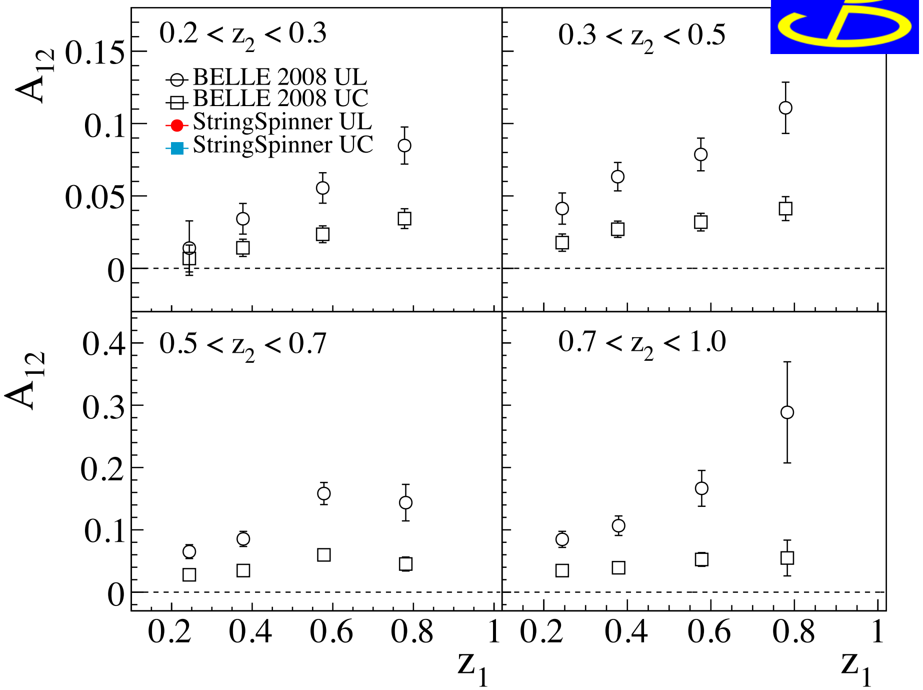
Used in many phenomenological fits to extract h_1 and H_1, here only the model results

Comparison with the A_{12} asymmetry

AK, L. Lönnblad, A. Martin, arXiv: 2407.07706 (accepted by PRD)

A_{12} asymmetry for charged π π pairs

PRD 78, 032011 (2008)



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

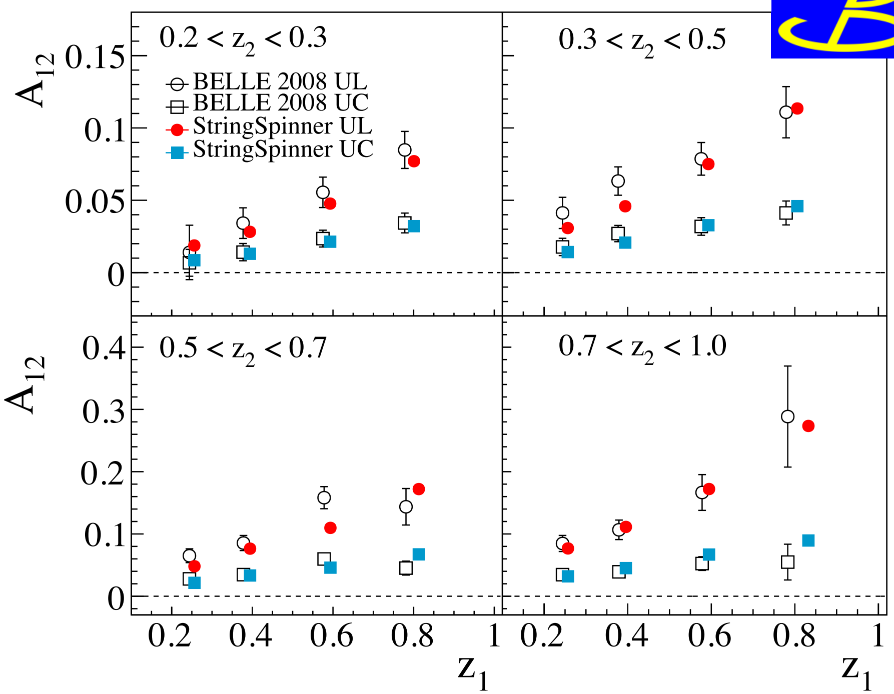
Belle asymmetries corrected for thrust smearing

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)



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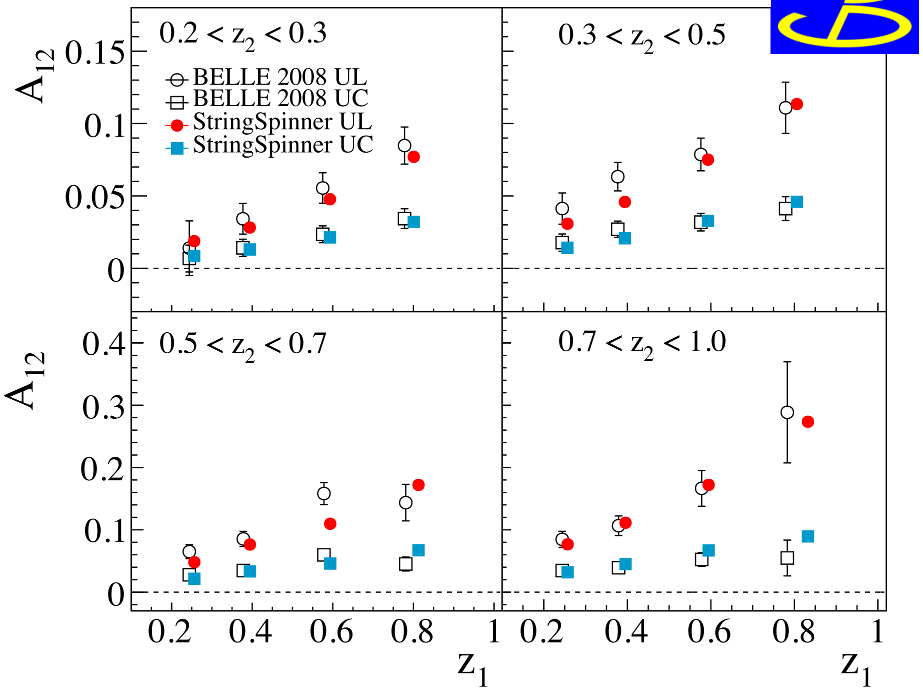
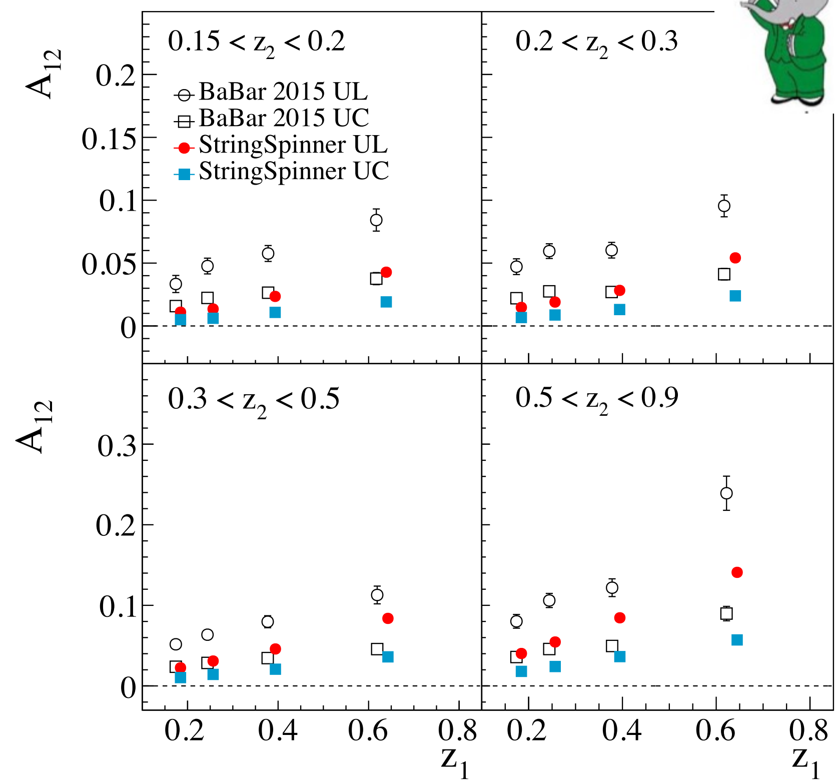
StringSpinner reproduces trend and size

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

PRD 78, 032011 (2008)



PRD 92, 111101(R) (2015)



Belle asymmetries corrected for thrust smearing

Cuts:

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

BaBar asymmetries corrected for thrust smearing

Cuts:

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

StringSpinner lower than BABAR

BABAR and BELLE data different, unlike StringSpinner

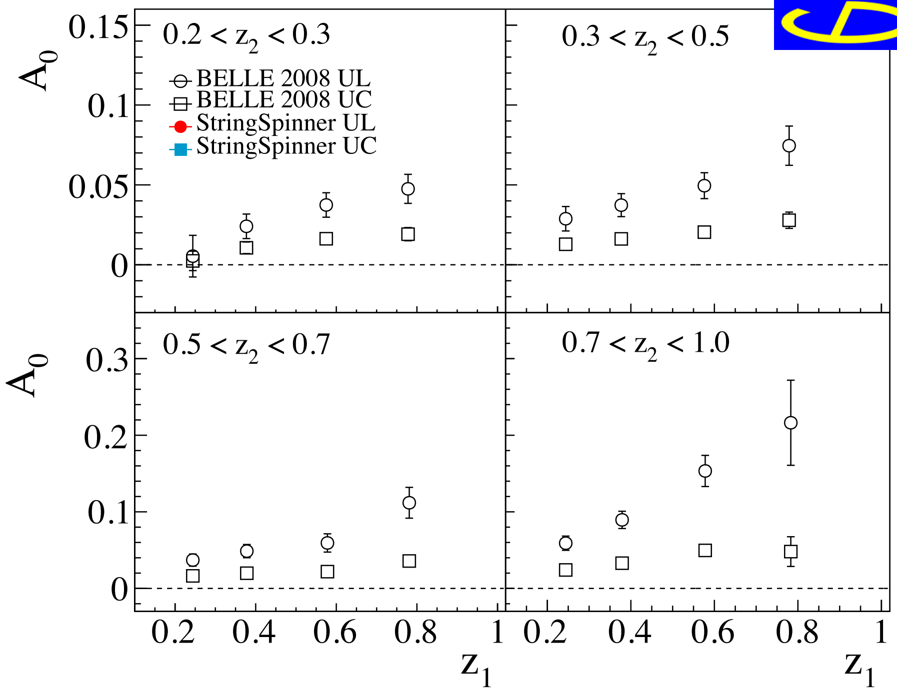
PRD 90, 052003 (2014)

Comparison with the A_0 asymmetry

AK, L. Lönnblad, A. Martin, arXiv: 2407.07706 (accepted by PRD)

A_0 asymmetry for π π pairs:

PRD 78, 032011 (2008)



Cuts:

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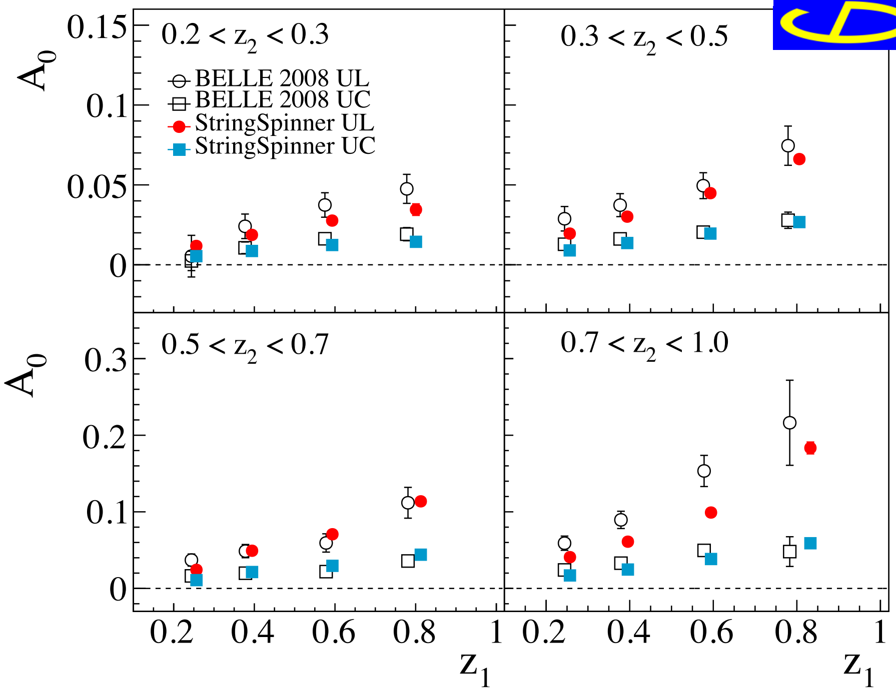
A_0 asymmetry for π π pairs:

PRD 78, 032011 (2008)



Cuts:

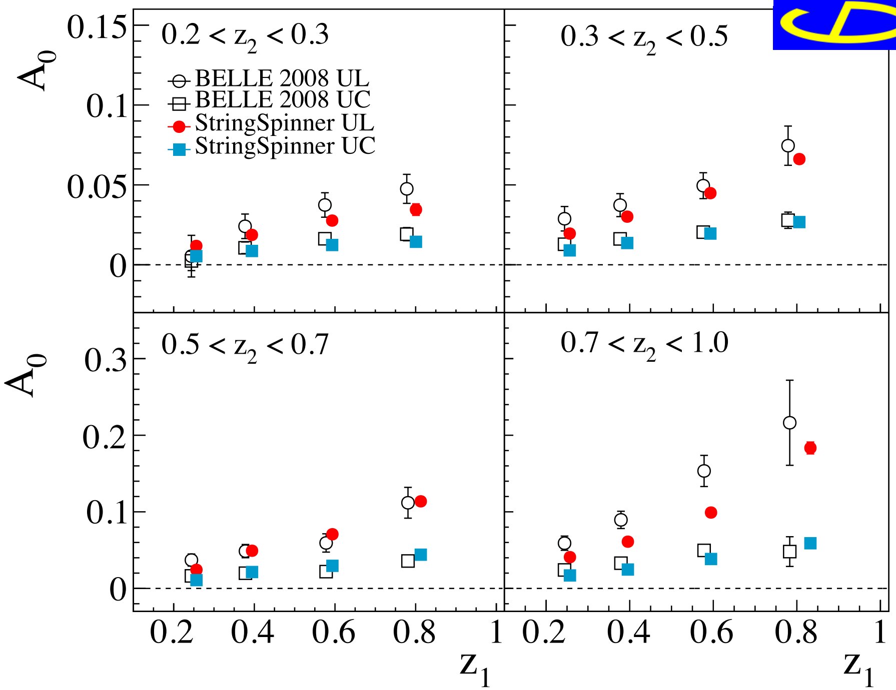
$$T > 0.8, z > 0.2, Q_T < 3.5\text{GeV}$$

Trend reproduced by string+$^3P_0$

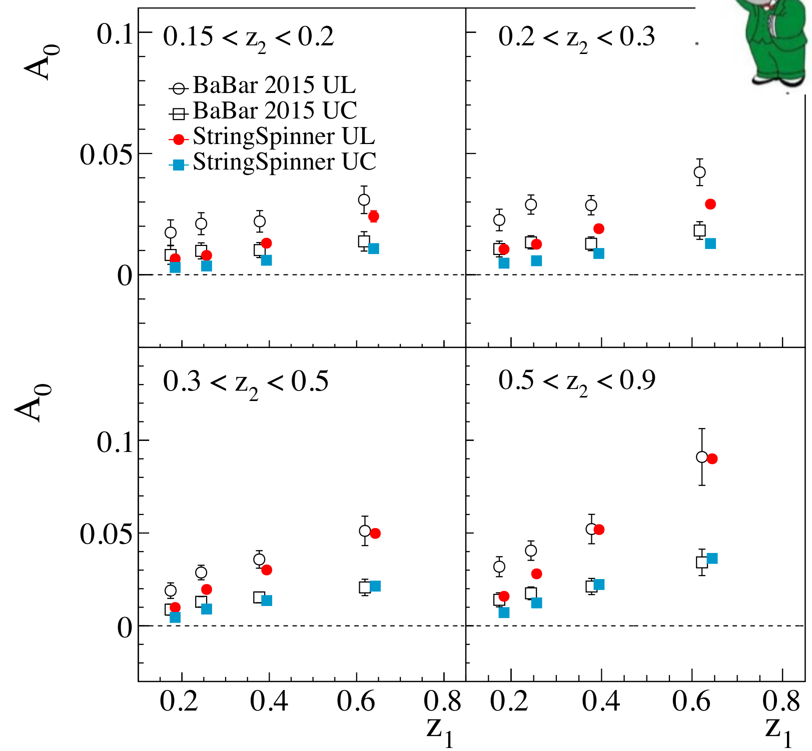
somewhat lower values in the last z_2 bin

A_0 asymmetry for π π pairs:

PRD 78, 032011 (2008)



PRD 92, 111101(R) (2015)



Cuts:

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

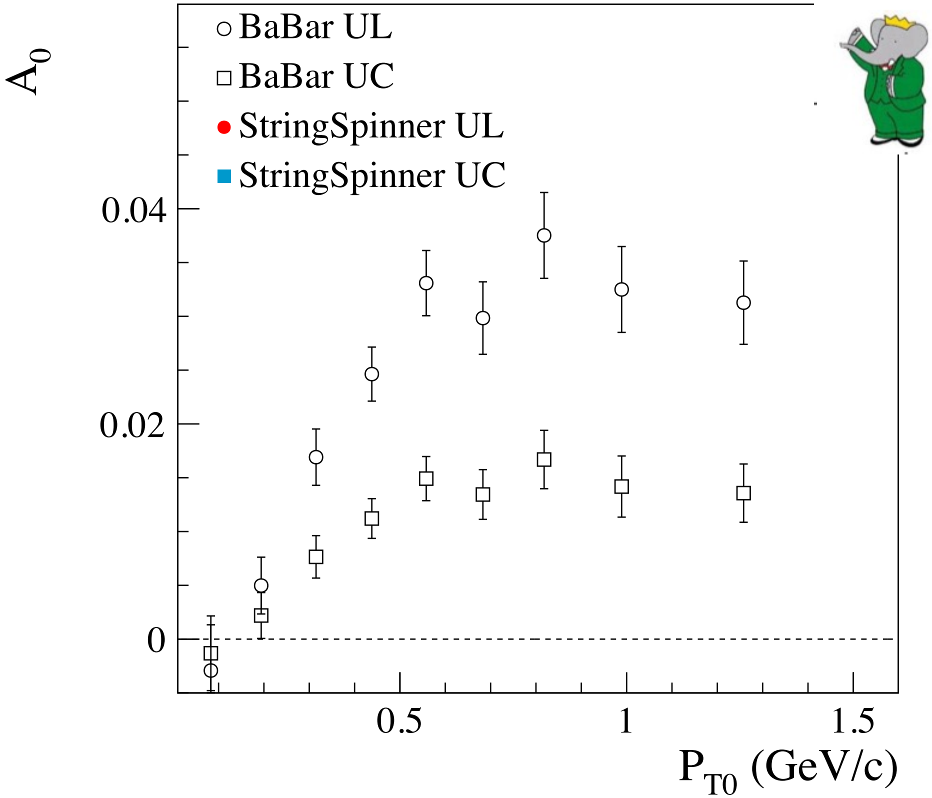
Trend reproduced by string+$^3P_0$

somewhat lower values in the last z_2 bin

BABAR asymmetries also ok

A_0 asymmetry for $\pi\,\pi$ pairs: P_{T0} dependence

PRD 90, 052003 (2014)

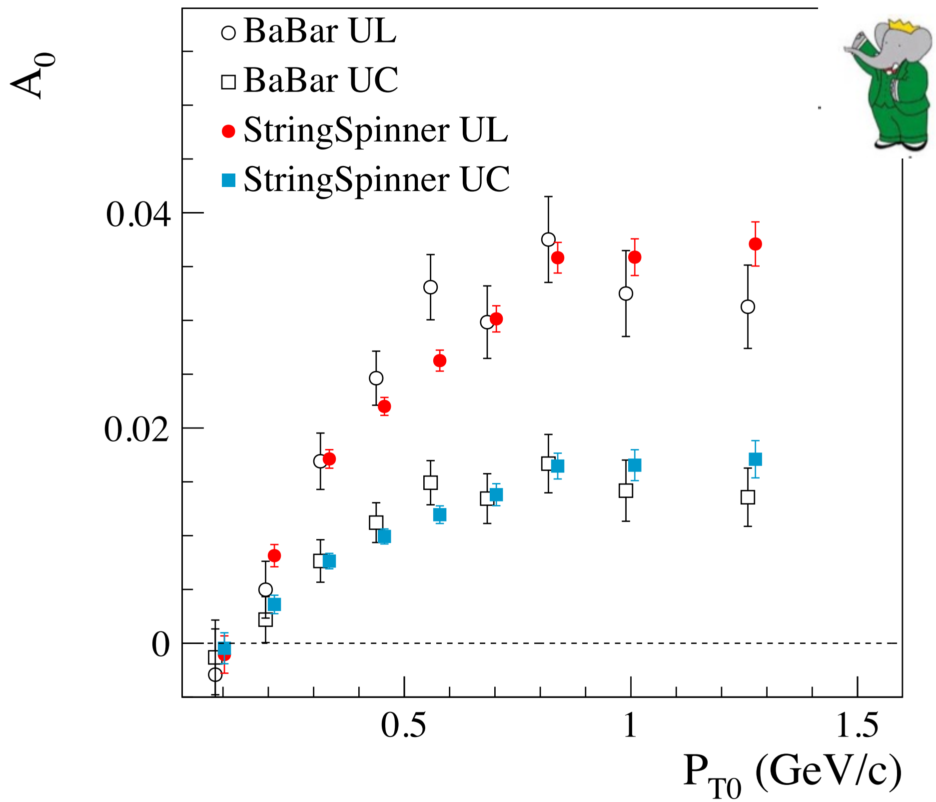


Cuts:

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

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

PRD 90, 052003 (2014)



Cuts:

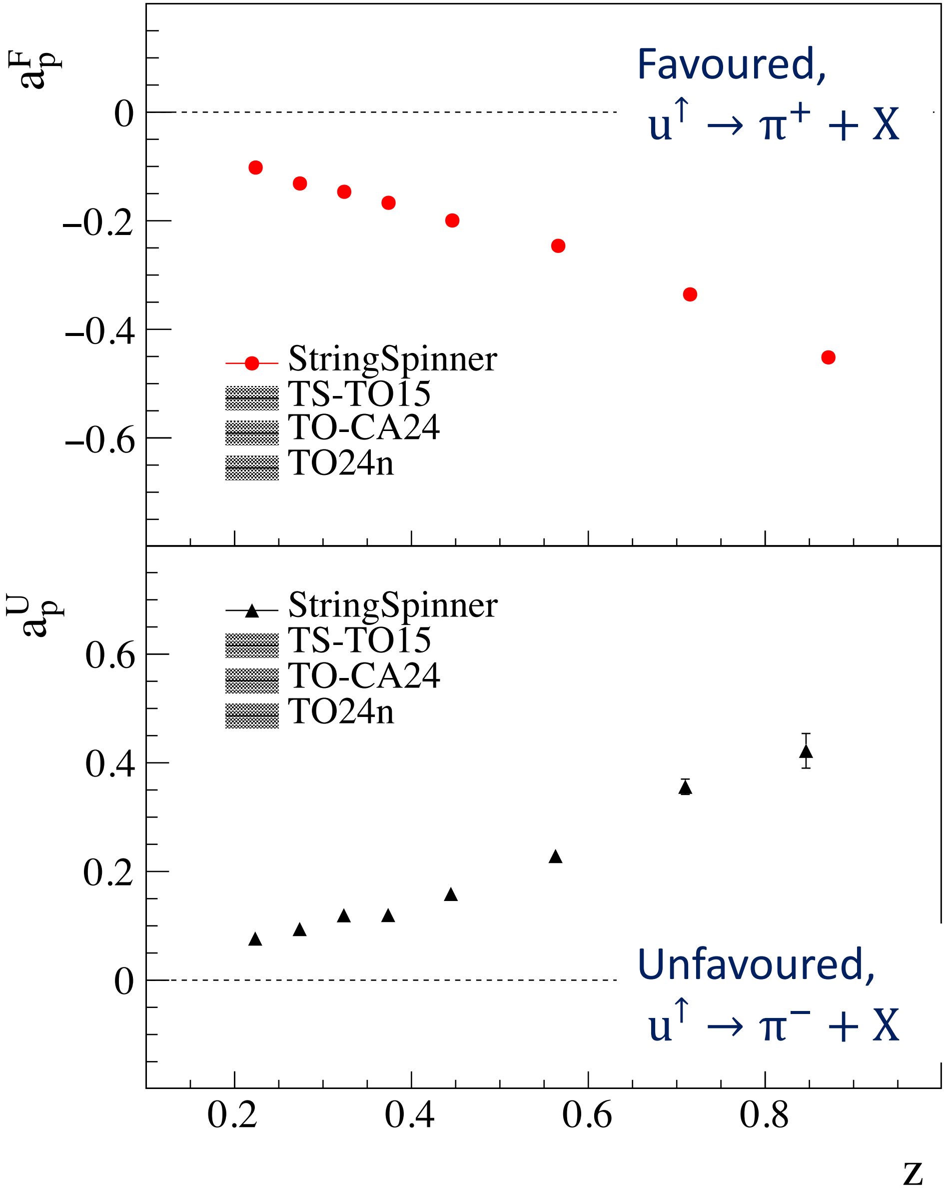
$T > 0.8, z > 0.15, Q_T < 3.5\mathrm{GeV}$

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

Comparison with phenomenology

AK, L. Lönnblad, A. Martin, arXiv: 2407.07706 (accepted by PRD)

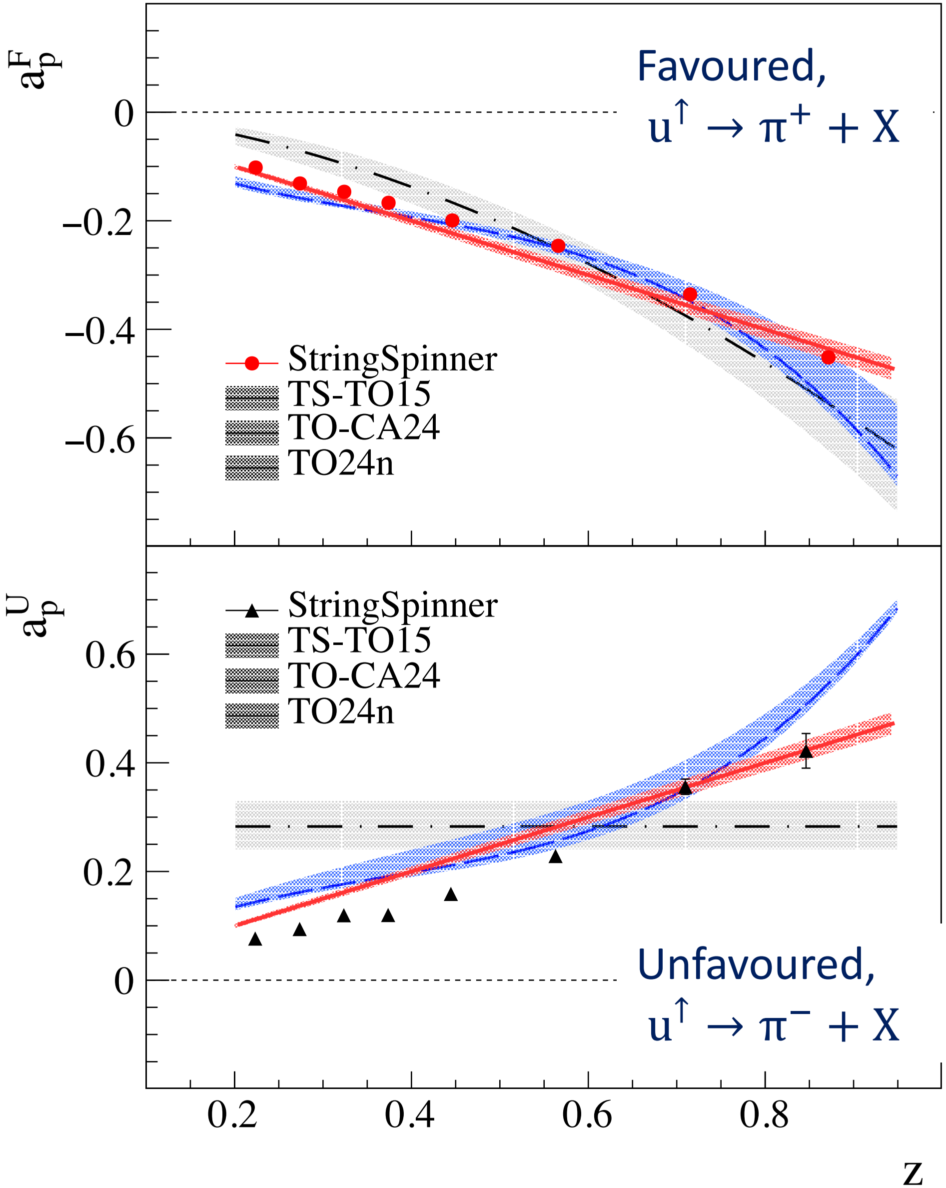
Comparison with phenomenology



Collins analysing power

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

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

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 public soon for e^+e^-

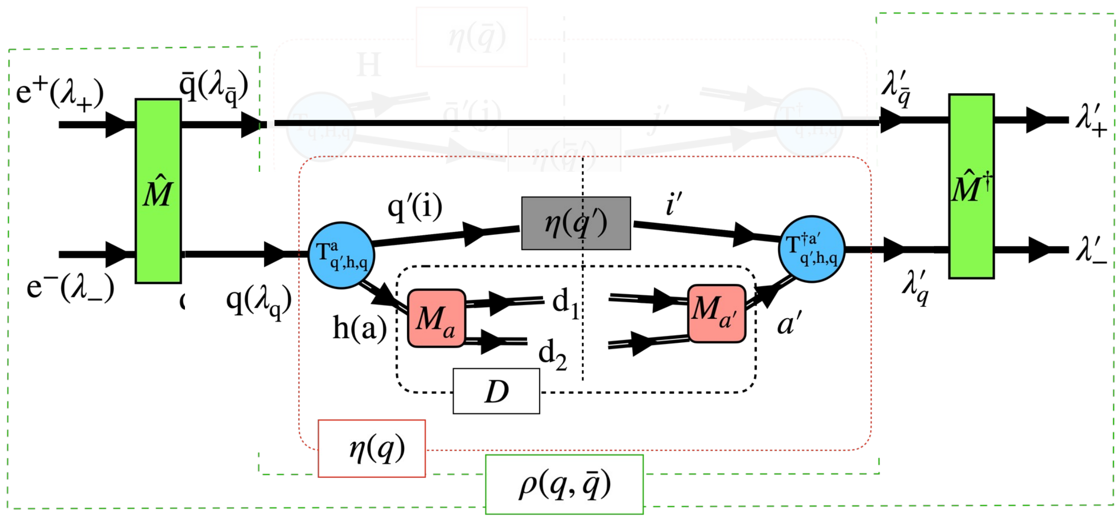
- Encouraging results on Collins asymmetries in e^+e^-
  the predicted Collins effect can be used to guide parametrizations
  in phenomenological extractions

- More developments of the string+$^3P_0$ model possible and foreseen
  baryon production, pQCD effects, inclusion of TMDs in DIS, ..

- Several steps towards an event generator systematically implementing spin effects done!

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. $D_{a'a} = \delta_{a'a}$)

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

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

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

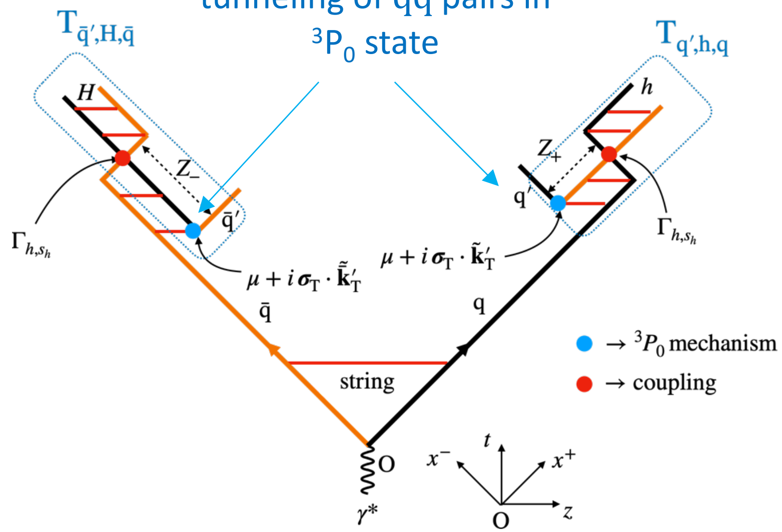
iii) Decay the meson $p \rightarrow p_1\, p_2 ..$

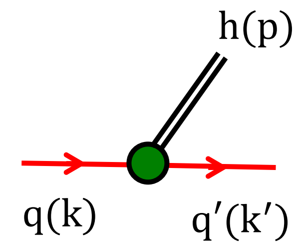
$$dN(p_1, p_2..)/d\Omega \propto M^{a}_{dec.}(p \rightarrow p_1 p_2..)\ \rho_{aa'}(h) M^{\dagger a'}_{dec.}(p \rightarrow p_1 p_2..)$$

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

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

string breaking by tunneling of $q\bar{q}$ pairs in $^3P_0$ state





quark splitting $q \to h + q'$

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

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

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

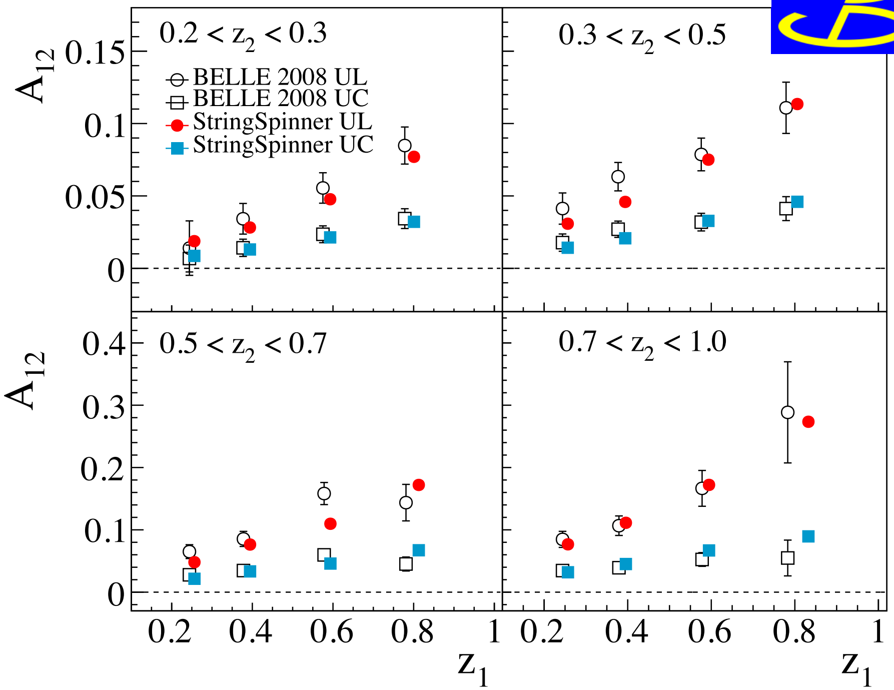
Free param. Lund

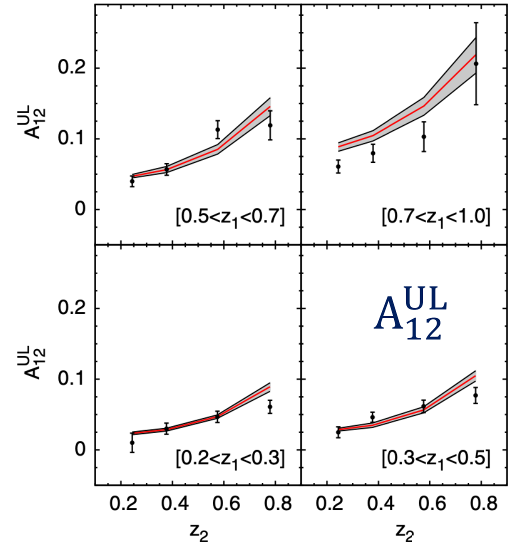
Free param. string+$^3P_0$

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

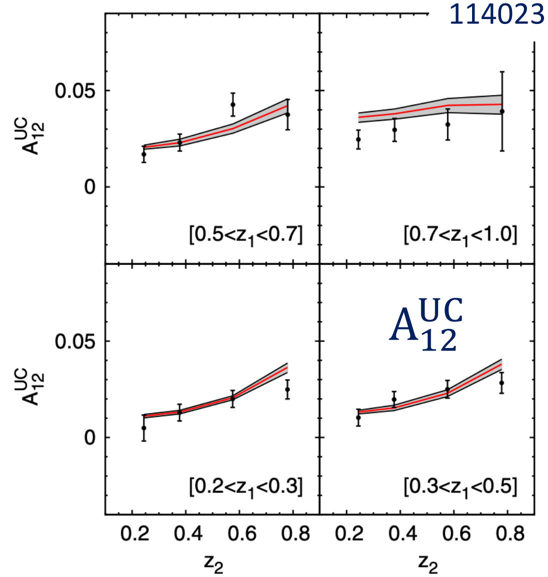
A_{12} asymmetry for charged π π pairs

PRD 78, 032011 (2008)





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



Belle asymmetries corrected for thrust smearing

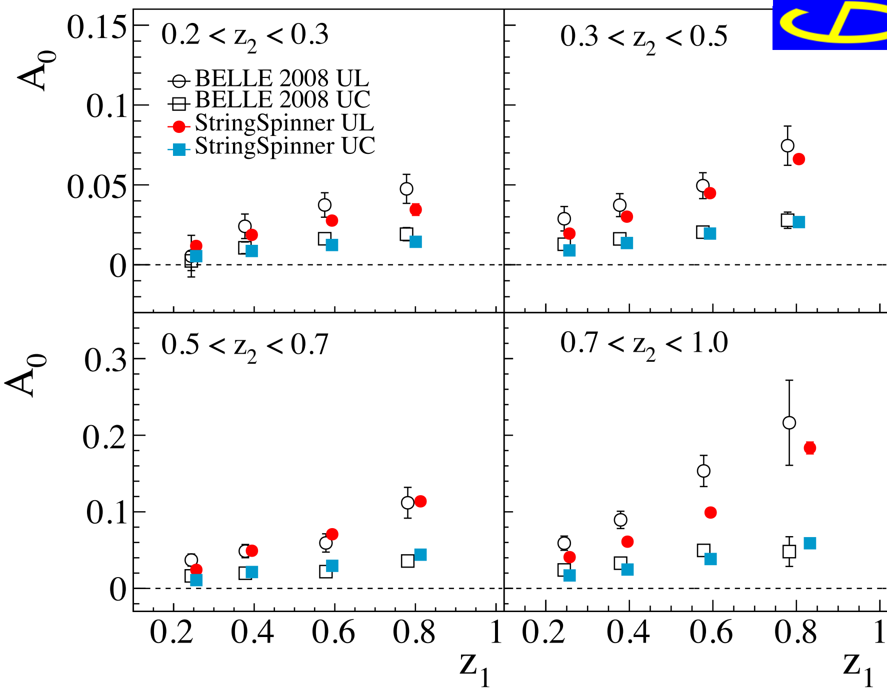
Cuts:

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

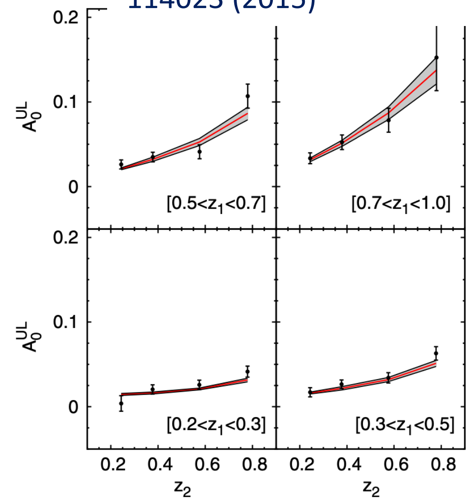
StringSpinner reproduces trend and size

A_0 asymmetry for charged pions

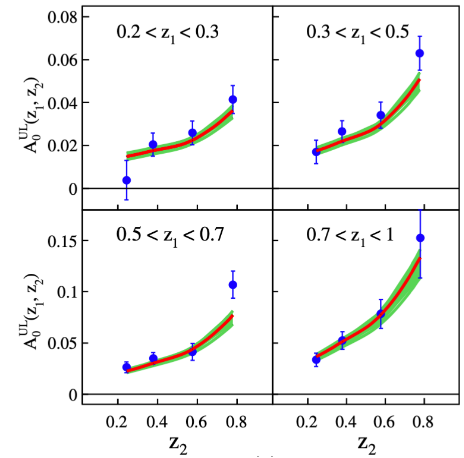
PRD 78, 032011 (2008)



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



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

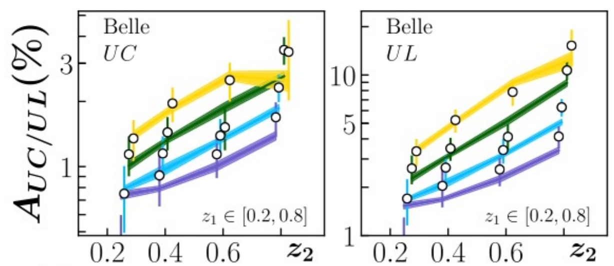


Cuts:

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

Trend reproduced by string+$^3P_0$

somewhat lower values in the last z_2 bin

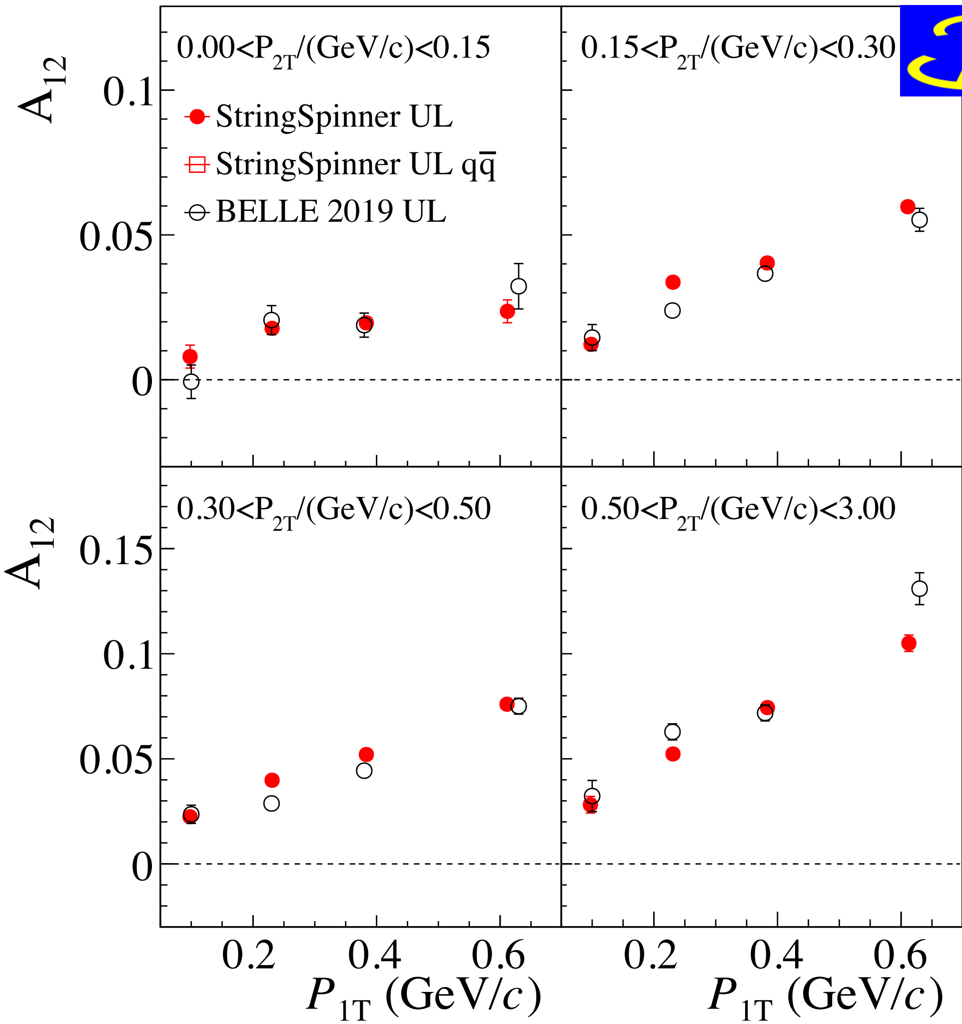


JAM, PRD 102, 054002 (2020)

A_0 asymmetry essential observable included in phenomenological fits

A_{12}^{UL} asymmetry for charged $\pi\ \pi$ pairs

$P_{T1} \times P_{T2}$ - dependence w.r.t thrust



PRD 100, 092008 (2019)

Asymmetries using thrust axis,
not corrected for thrust smearing

$T > 0.8$

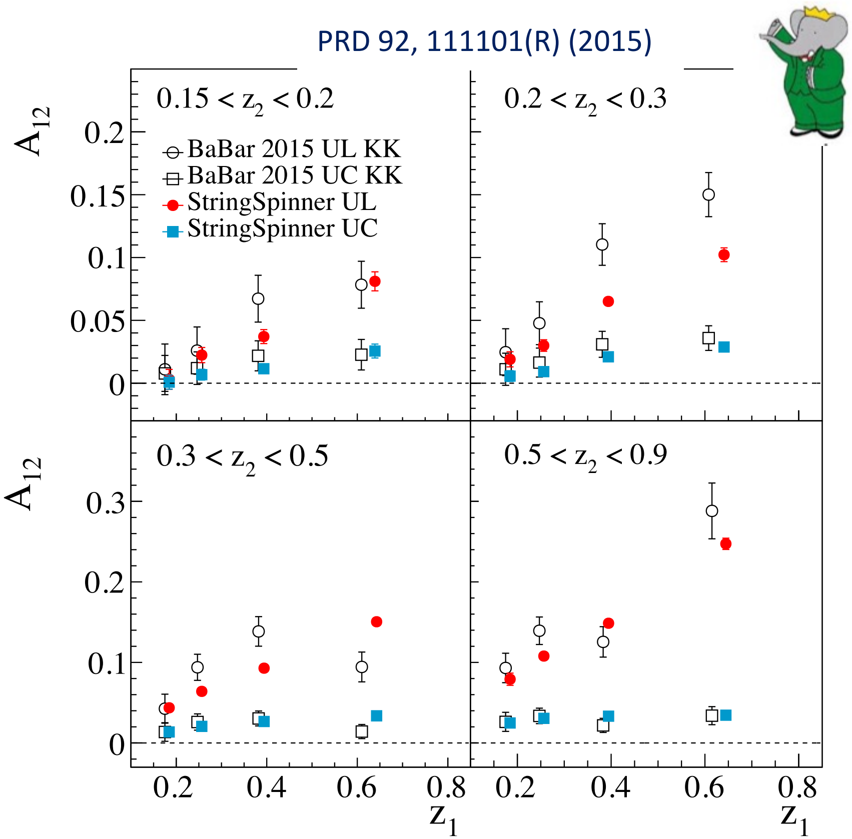
$z > 0.2, P_T < 3.0$ GeV/c

$\alpha_O < 0.3$ rad

StringSpinner reproduces the nearly linear trend observed by BELLE

A_{12} asymmetry for charged KK pairs

PRD 92, 111101(R) (2015)



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+$^3P_0$