

Workshop on the Physics Program with High Luminosity Facilities
JLAB, 07/10/2026

Polarizing Pythia hadronization

Albi Kerbizi

Lund University
INFN Trieste



Funded by the
European Union

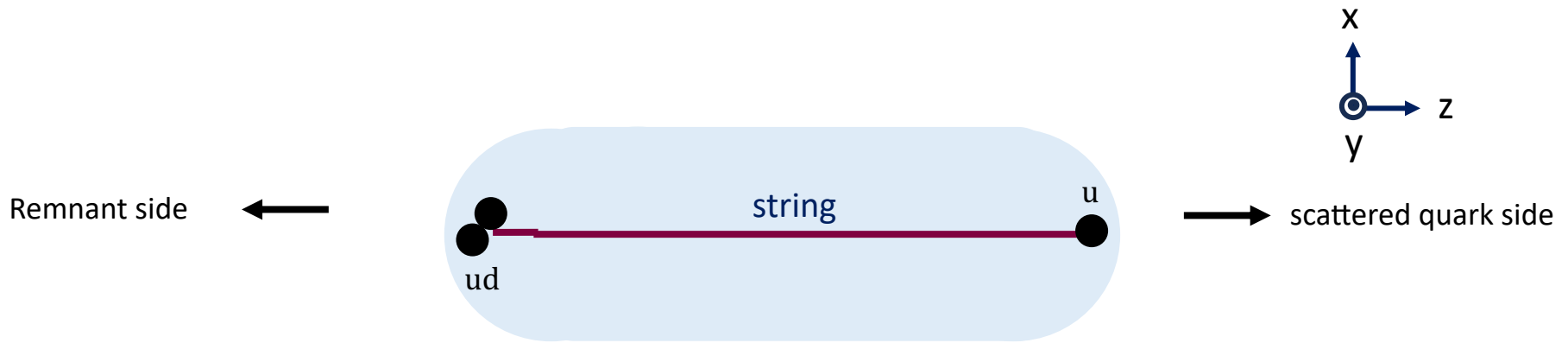


A model of hadronization with spin effects: string+ $^3P_0$

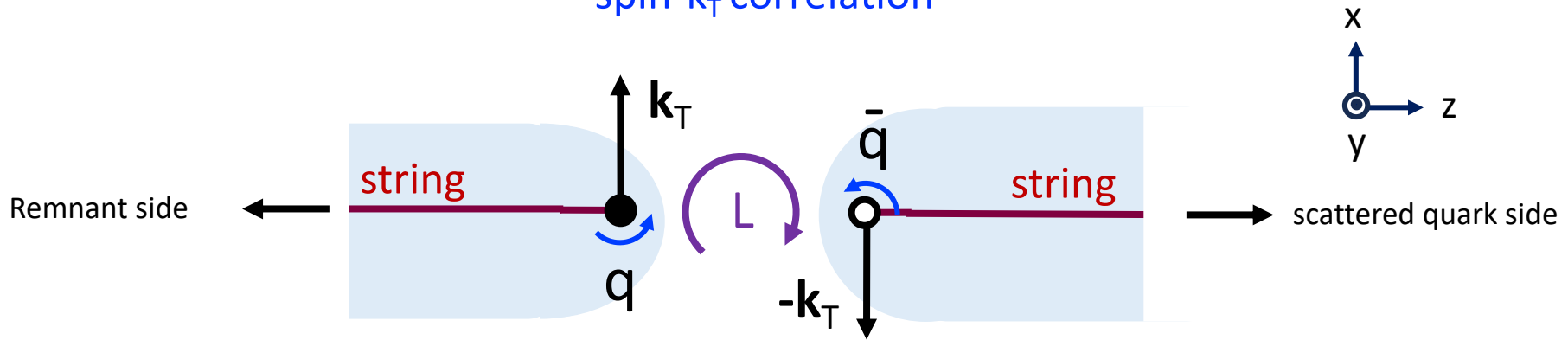
- ❑ Lund string Model $\otimes$ spin
initially proposed by X. Artru [Dubna-Spin 2009, arXiv:1001.1061]
- ❑ Interfaced to Pythia 8: **StringSpinner** AK, Lönnblad, CPC **292** (2023) 108886;
now v. 2.0 handles DIS and $e^+e^- \rightarrow \text{hadrons}$ AK, Lönnblad, arXiv:2606.27162
- ❑ Reproduces the Collins effect, 2h asymmetries,..., long. spin effects
- ❑ Applied to strings without gluons: parton showers off
AK, Artru, PRD 110 (2024) 7, 074029
- ❑ Includes meson production (PM, VM) AK, Artru, Martin, PRD 104, 114038 (2021)
more recently also spin-1/2 baryons
AK, Artru, PRD 113 (2026) 3, 034007



String breaking:



String breaking: spin- k_T correlation



The pair is produced at a distance d

$$\vec{L} = \vec{d} \times \vec{k}_T \neq \vec{0}$$

Local conservation of angular momentum

$$\vec{S} = \vec{S}_q + \vec{S}_{\bar{q}} \neq \vec{0}$$

therefore

$$\vec{J} = \vec{L} + \vec{S} = \vec{0}$$

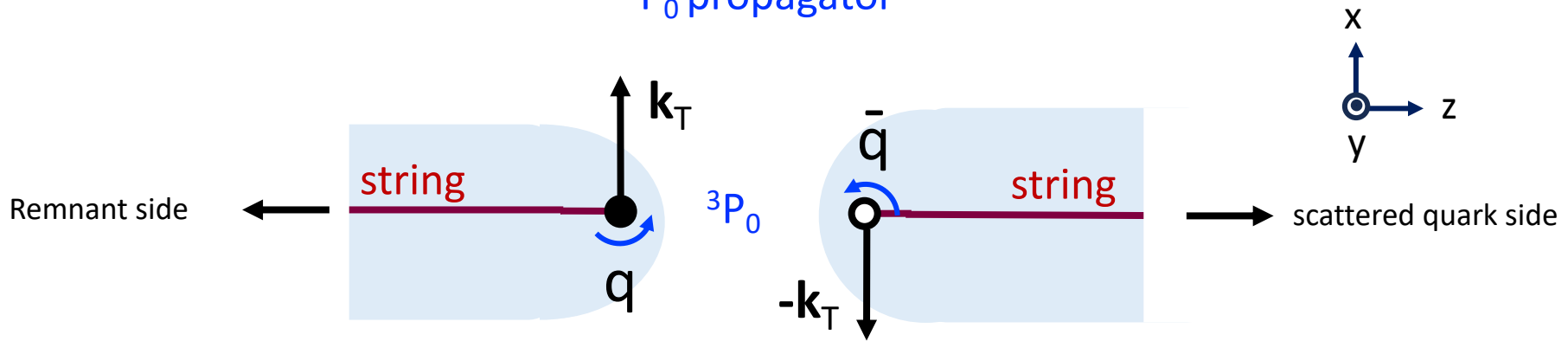
$$L=1, S=1$$

relative
 $^3P_0$ state

Andersson, Gustafson, Ingelman, PRL 85, 417 (1979)
Artru, Czyzewski, Yabuki, Z.Phys.C 73 (1997) 527-534
Artru [Dubna-Spin 2009], arXiv: 1001.1061



String breaking: ${}^3P_0$ propagator



“quark propagator” (2x2)

$$\Delta_q = \mu + \sigma_z \boldsymbol{\sigma}_T \cdot \mathbf{k}_T$$

“complex mass” μ

2 free parameters

$\text{Im}(\mu)$	Transverse spin effects (Collins, dihadron ...)
$\text{Re}(\mu)$	Longitudinal spin effects (beam spin asymm ...)

Artru [Dubna-Spin 2009], arXiv: 1001.1061

AK, Artru, Belghobsi, Bradamante, Martin, PRD 97 (2018) 7, 074010

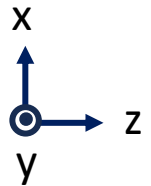
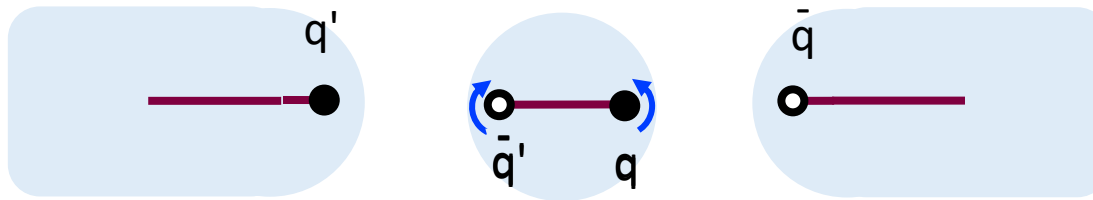
AK, X. Artru, Z. Belghobsi, A. Martin, PRD 100 (2019) 1, 014003



Meson production: coupling matrix

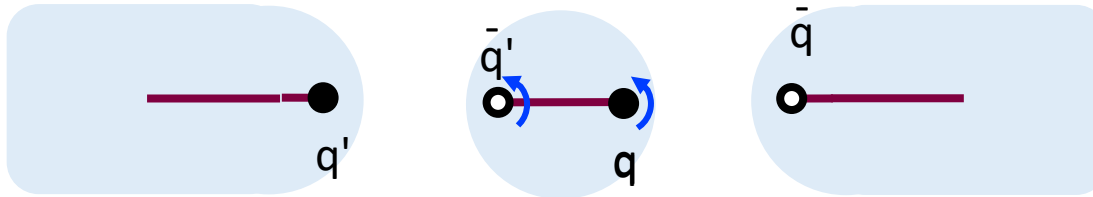
Pseudoscalar meson (PM)

$$\Gamma_{h=PM} = \sigma_z$$



Vector meson (VM)

$$\Gamma_{h=VM} = G_T \vec{\sigma}_T \sigma_z \cdot \vec{V}_T^* + G_L 1 V_L^*$$



VM/PM suppression

Longitudinal Polarization

Interference L/T polarizations

$$2|G_T|^2 + |G_L|^2$$

$$f_L = \frac{|G_L|^2}{|G_T|^2} / [2 + \frac{|G_L|^2}{|G_T|^2}]$$

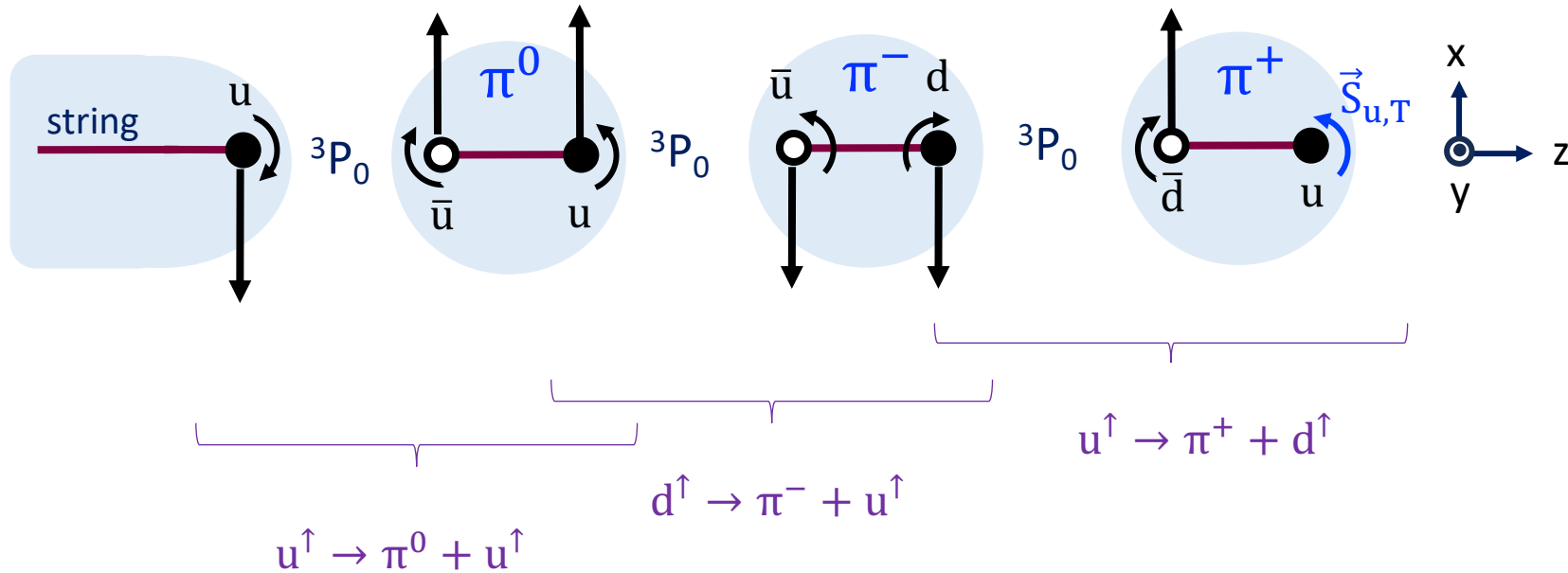
$$\theta_{LT} = \arg G_L / G_T$$

2 free parameters

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



Spin correlations in hadronization



polarized string fragmentation $\leftrightarrow$ recursive polarized splittings

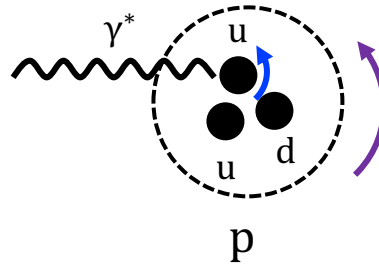
$$q \rightarrow h + q'$$

described at amplitude level by 2x2 splitting matrix $T_{q',h,q}$



Initial condition for spin

Deep Inelastic Scattering
transversely polarized target



transversely polarized struck quark

parametrization

transversity PDF

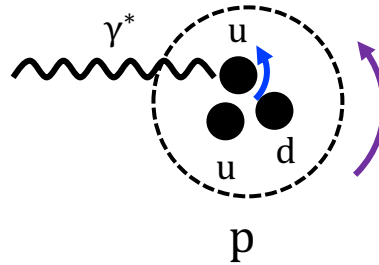
$$\vec{S}_q = \frac{h_1^q}{f_1^q} \vec{S}_T$$

$$\rho(q) = (1 + \vec{\sigma} \cdot \vec{S}_q)/2$$



Initial condition for spin

Deep Inelastic Scattering
transversely polarized target



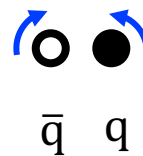
transversely polarized struck quark

parametrization
transversity PDF

$$\vec{S}_q = \frac{h_1^q}{f_1^q} \vec{S}_T$$

$$\rho(q) = (1 + \vec{\sigma} \cdot \vec{S}_q)/2$$

e^+e^- annihilation



spin of q and $\bar{q}$ correlated

γ^* exchange
appropriate at BELLE/BABAR

$$\rho(q, \bar{q}) \propto 1_q \otimes 1_{\bar{q}} - \sigma_q^z \otimes \sigma_{\bar{q}}^z + \hat{a}_{NN}(\hat{\theta}) [\sigma_q^x \otimes \sigma_{\bar{q}}^x + \sigma_q^y \otimes \sigma_{\bar{q}}^y]$$

$$\hat{a}_{NN}(\hat{\theta}) = \frac{\sin^2 \theta}{1 + \cos^2 \theta}$$

recipe for fragmentation of a string stretched between entangled quarks

→ AK, Artru, PRD 110 (2024) 7, 074029

Results from Pythia + StringSpinner

- string+ $^3P_0$ parameters tuned to e^+e^- data from BELLE and BABAR data using Professor 2

BELLE

PRD 78, 032011 (2008)



$$A_0^{\text{UL(UC)}}(z_1, z_2)$$

$\pi\pi$

BABAR

PRD 90, 052003 (2014)



PRD 92, 111101(R) (2015)

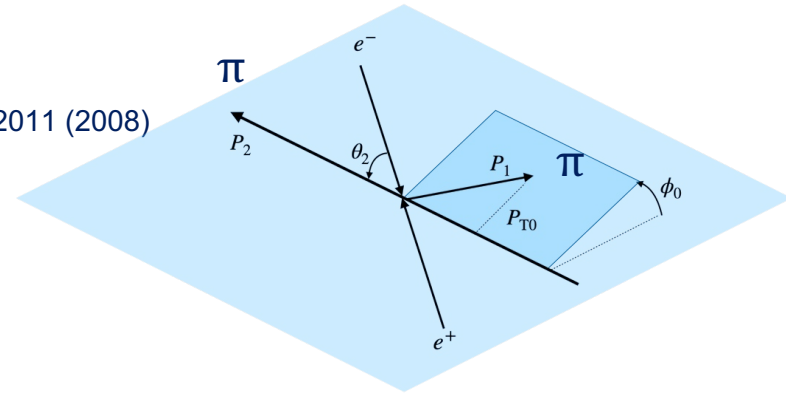
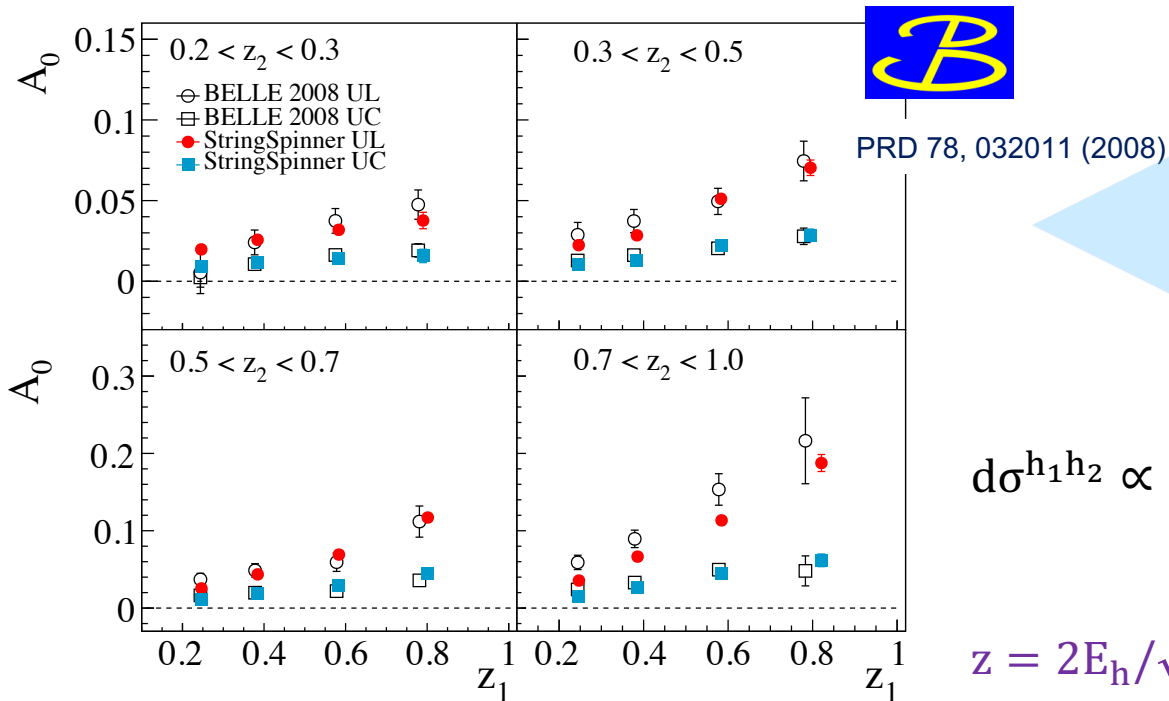
$$A_0^{\text{UL(UC)}}(P_{T0}) \quad A_0^{\text{UL(UC)}}(z_1, z_2)$$

$\pi\pi, \pi K, KK$

*more in a forthcoming paper with
A. Buckley, C. Gutsche, L. Lönnblad*



A_0 for $\pi\pi$: BELLE



$$d\sigma^{h_1 h_2} \propto 1 + \hat{a}_{NN}(\theta_2) A_0 \cos(2\phi_0) + \dots$$

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

$$A_0^{UL} \simeq A_0^U - A_0^L$$

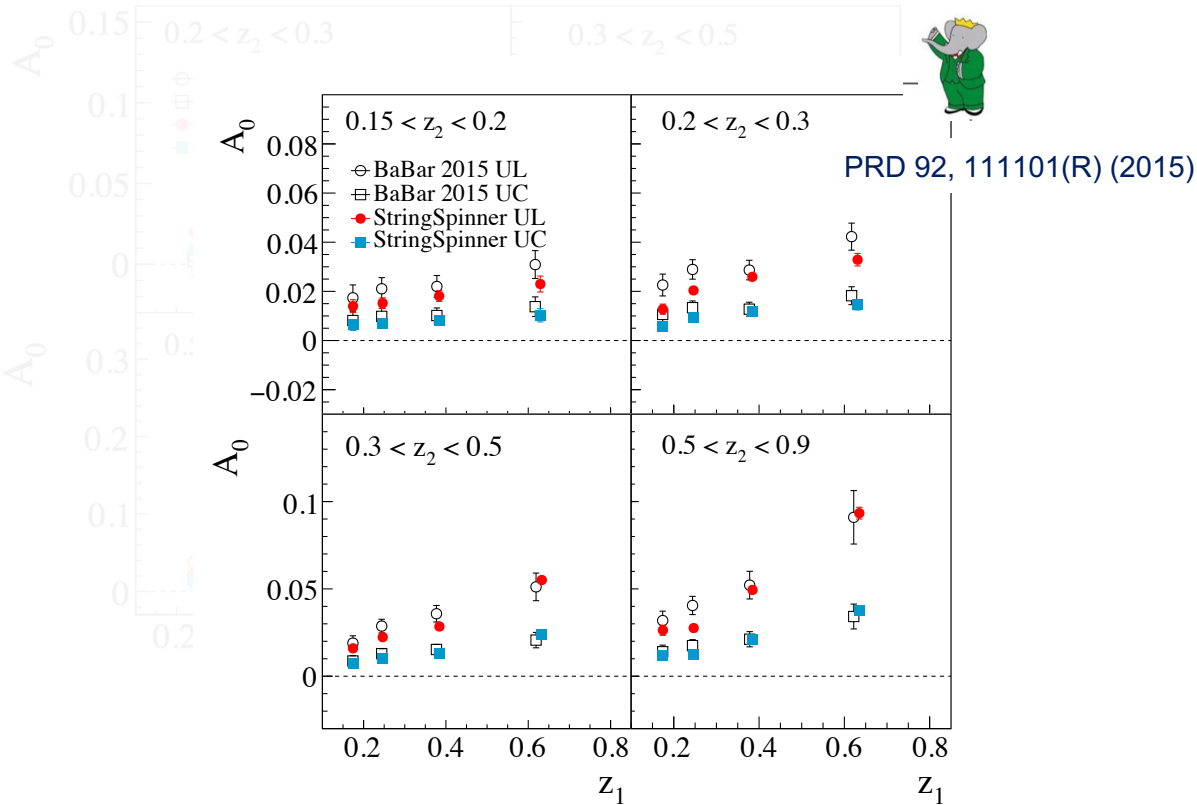
$$A_0^{UC} \simeq A_0^U - A_0^C$$

$$U \rightarrow \pi^+\pi^- + \pi^-\pi^+$$

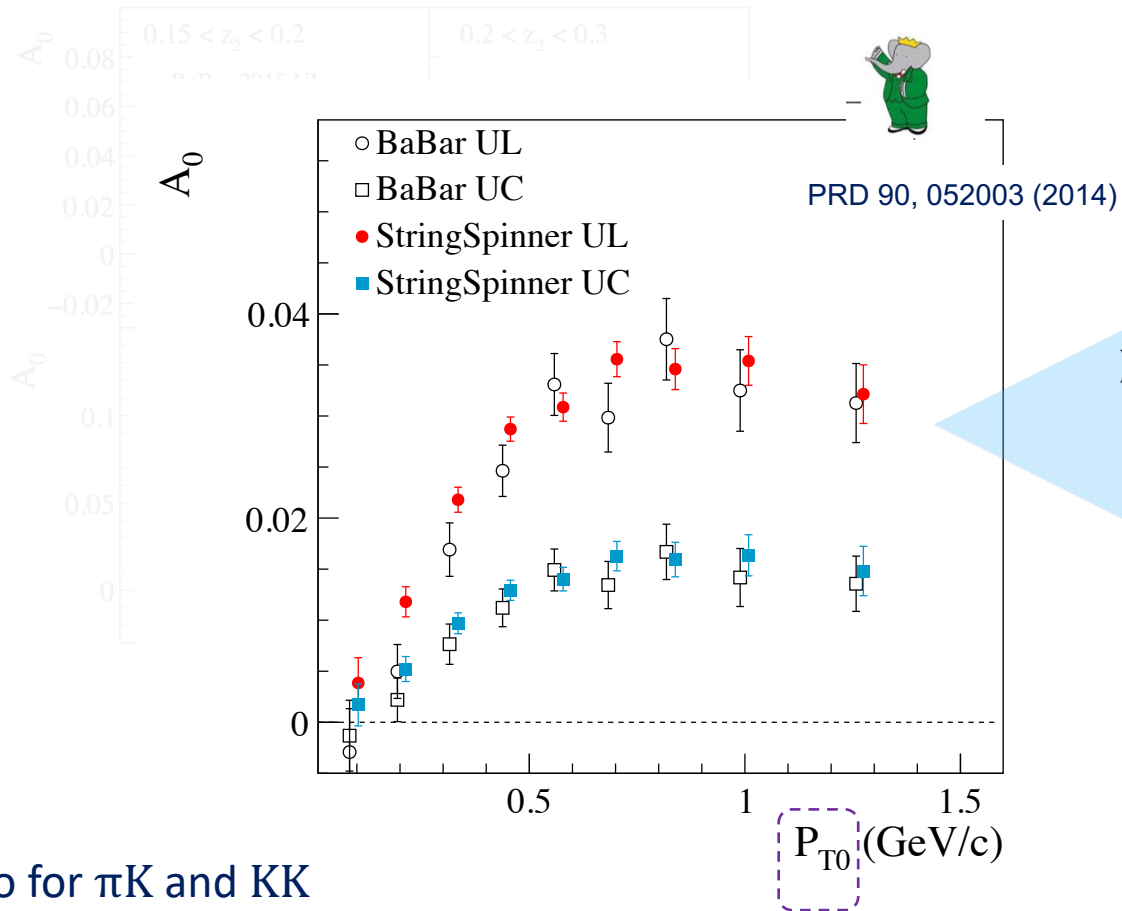
$$L \rightarrow \pi^+\pi^+ + \pi^-\pi^-$$

$$C \rightarrow \pi^+\pi^- + \pi^-\pi^+ + \pi^+\pi^+ + \pi^-\pi^-$$

A_0 for $\pi\pi$: BABAR

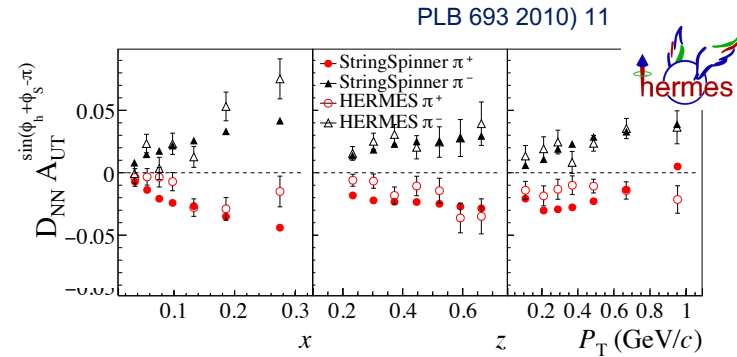
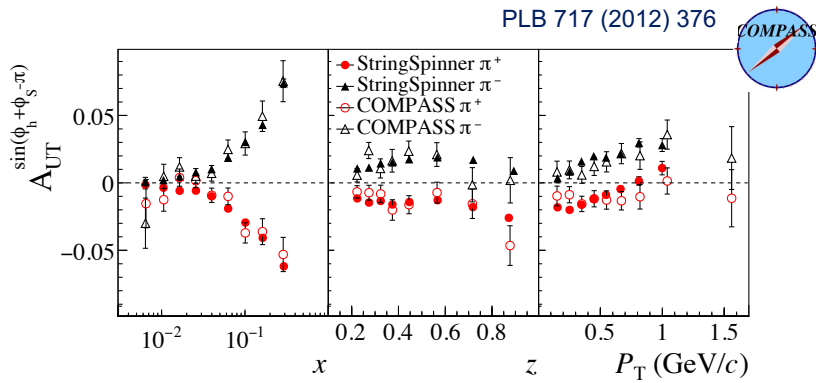


A_0 for $\pi\pi$: BABAR

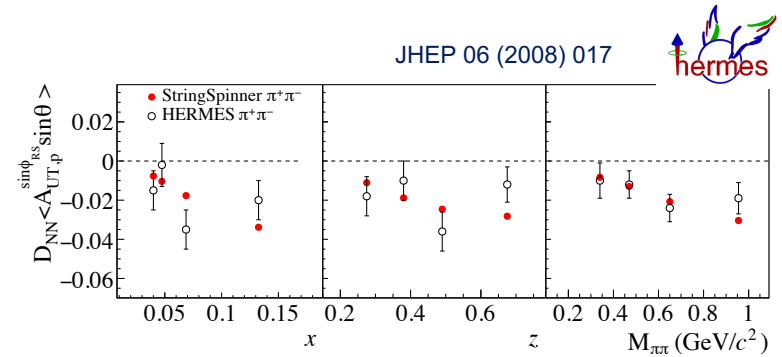
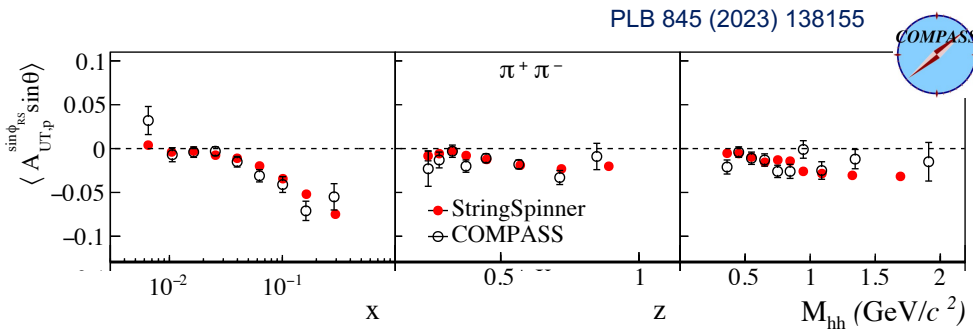


Transverse spin asymmetries in SIDIS

Collins asymmetries



2h asymmetries

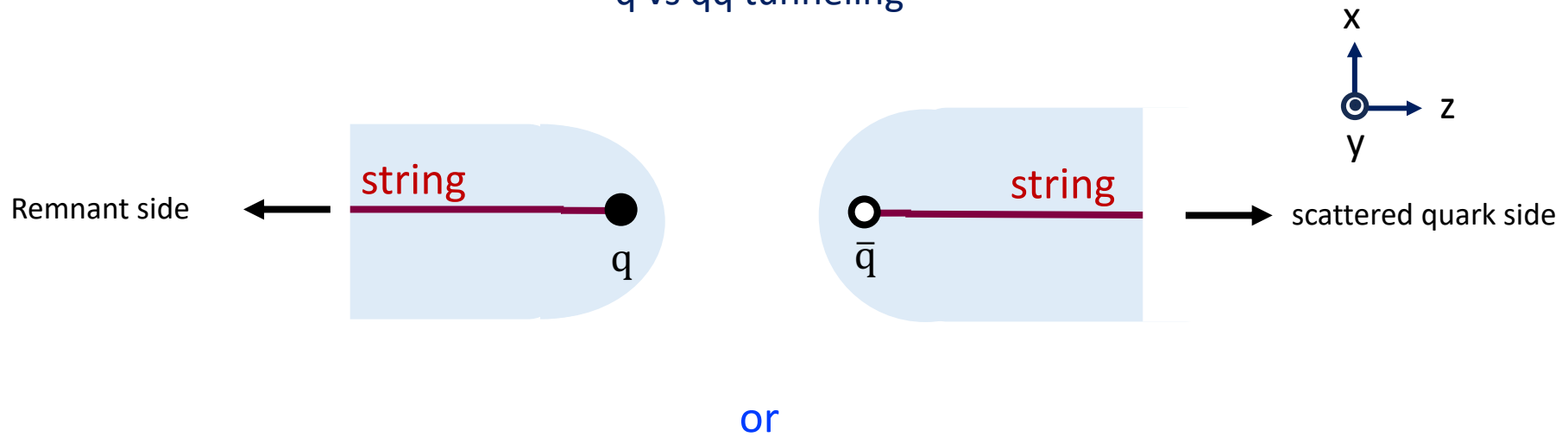


spin-1/2 baryons

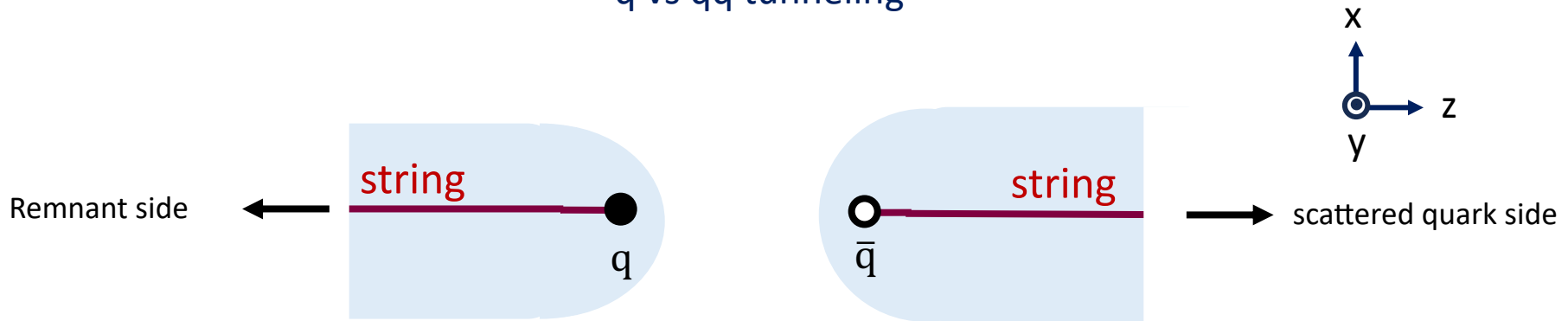
AK, X. Artru, Phys.Rev.D 113 (2026) 3, 034007



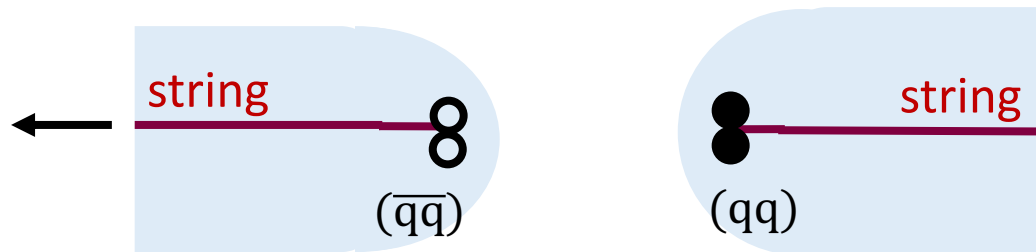
String breaking q vs qq tunneling



String breaking q vs qq tunneling



or



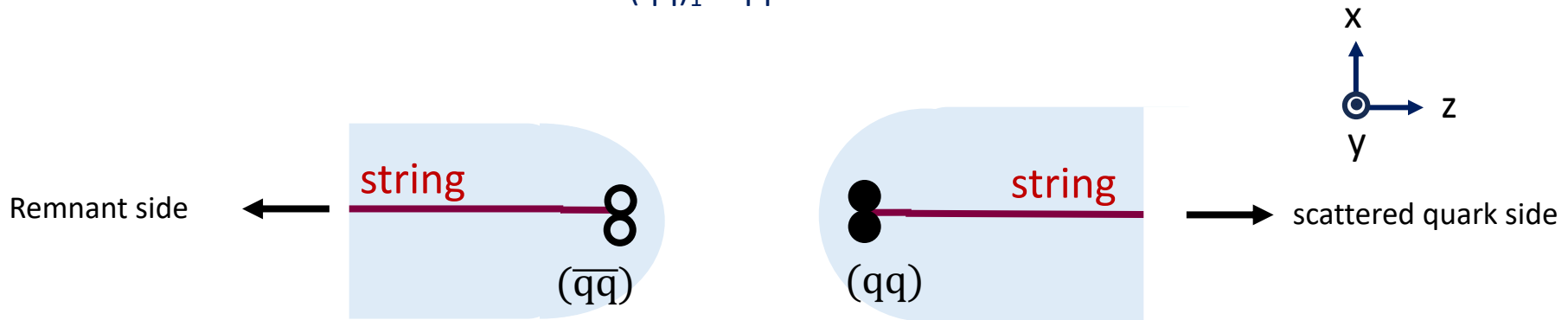
diquark tunneling suppressed w.r.t quark tunneling

$$\frac{P_{qq}}{P_q} \approx 0.1$$

Pythia 8
[tunable]



String breaking (qq)₁ suppression



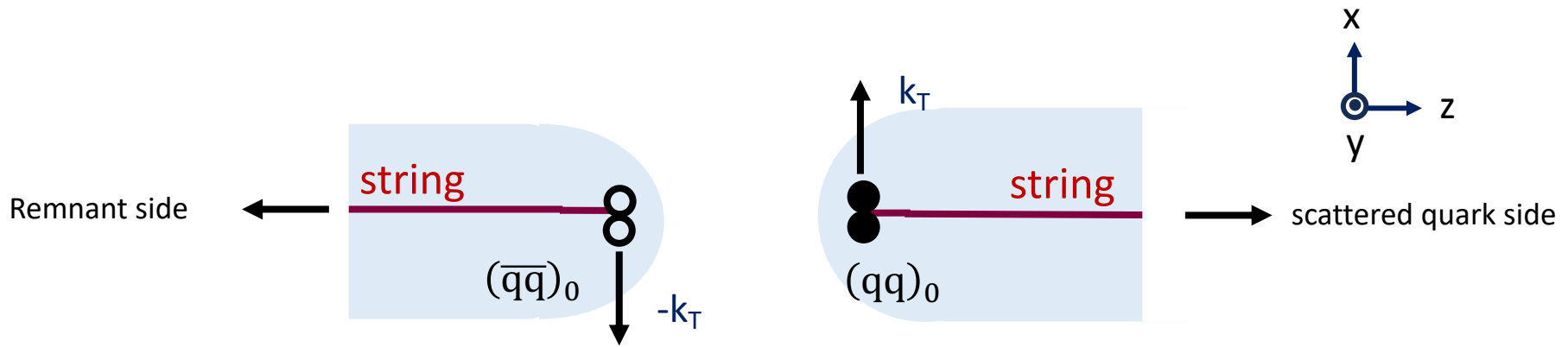
Suppression of spin-1 diquarks

$$\frac{P_{(qq)_1}}{P_{(qq)_0}} \approx 0.03$$

Pythia 8
[tunable]

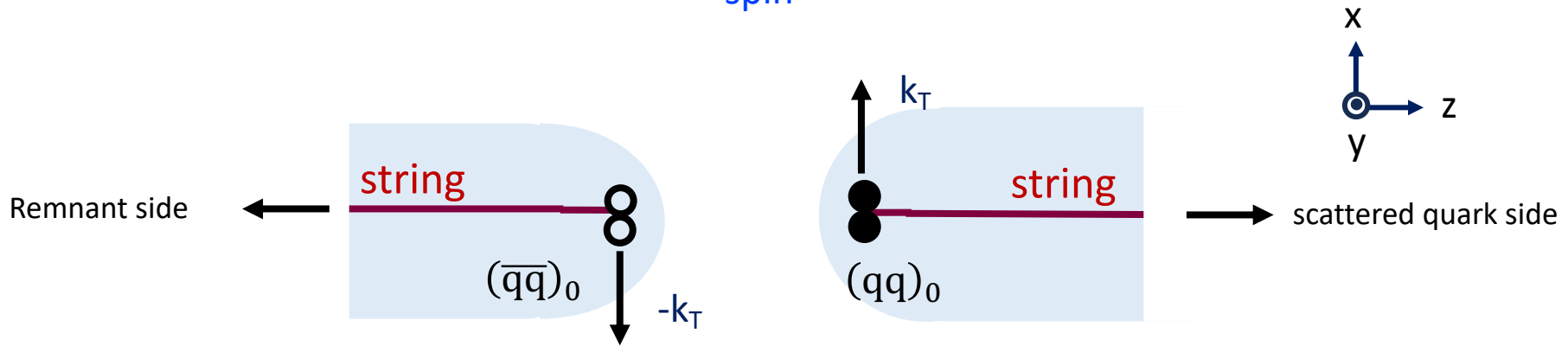


String breaking

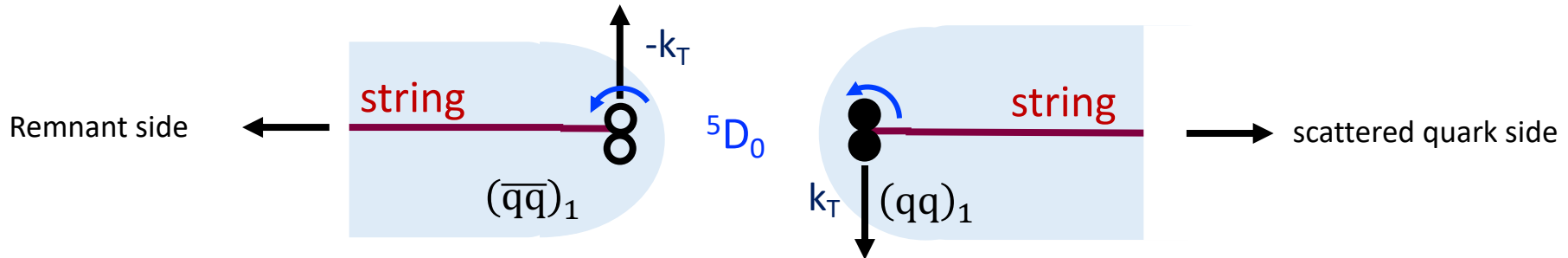


Local conservation of k_T for $(qq)_0$

String breaking: spin



Local conservation of k_T for $(qq)_0$



Local conservation of angular momentum for $(qq)_1$

${}^5D_0$ mechanism

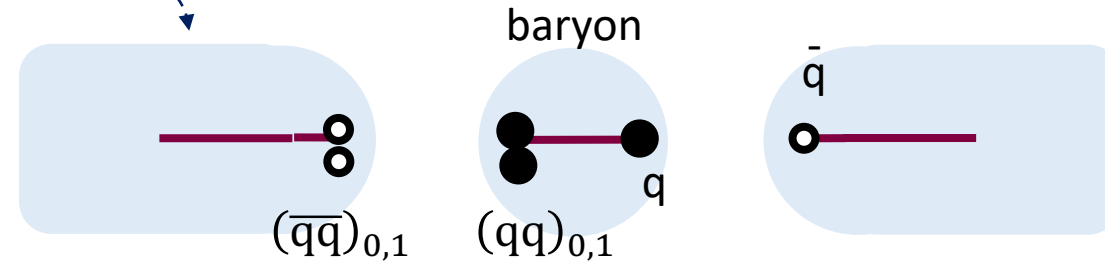
3x3 propagator model

more in AK, X. Artru, PRD 113 (2026) 3, 034007



Baryon production: coupling matrix

Anti-baryon
will form here



Coupling with $(qq)_0$
 $\Gamma_B = 1$

Coupling with [polarization vector of] $(qq)_1$
 $\Gamma_B = \boldsymbol{\sigma} \cdot \mathbf{V}_{qq}$

No additional free parameters

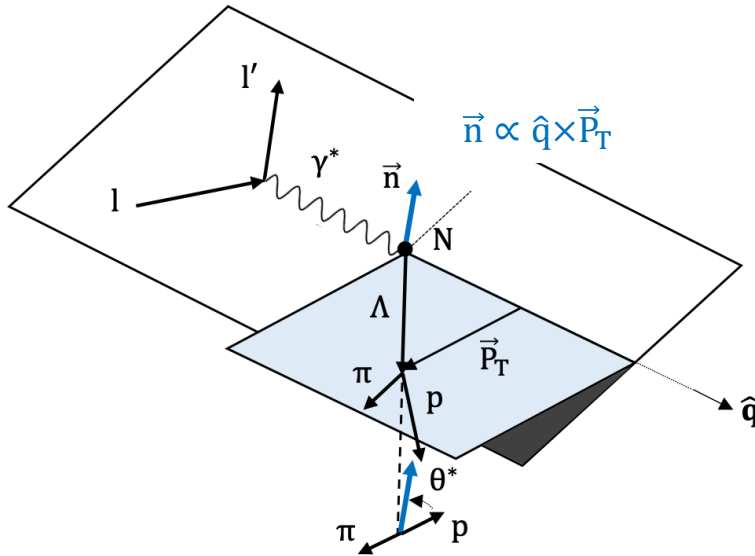


Spontaneous polarization of Λ and $\bar{\Lambda}$ in DIS

AK [DIS2026], arXiv:2609.15656

Mulders, Tangerman, NPB 484, 538-540 (1997)

Anselmino et al., PRD 63 054029 (2001)



Polarizing Fragmentation Function (pFF)

$$\text{CFR} \quad P_n^\Lambda \sim \frac{D_{1T}^\perp}{D_1}$$

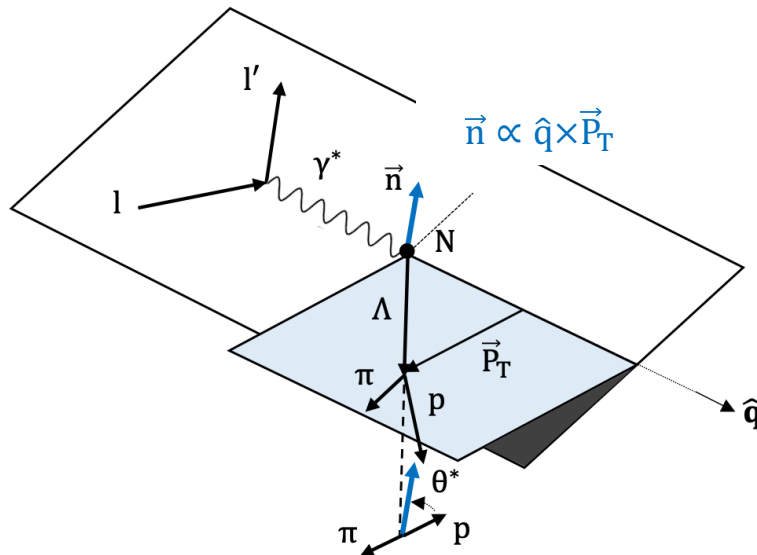
«Polarizing» Fracture Function

$$\text{TFR} \quad P_n^\Lambda \sim \frac{\Delta_T \hat{M}}{\hat{M}}$$

Anselmino, Barone, Kotzinian, PLB
699 (2011), 108-118

Spontaneous polarization of Λ and $\bar{\Lambda}$ in DIS

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Mulders, Tangeman, NPB 484, 538-540 (1997)
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Polarizing Fragmentation Function (pFF)

CFR $P_n^\Lambda \sim \frac{D_{1T}^\perp}{D_1}$

«Polarizing» Fracture Function

TFR $P_n^\Lambda \sim \frac{\Delta_T \hat{M}}{\hat{M}}$

Anselmino, Barone, Kotzinian, PLB 699 (2011), 108-118

Not measured in DIS

only quasi-real photoproduction

HERMES [PRD 90, 072007 (2014)]

COMPASS prel. [B. Grube, PhD thesis (Münich Uni), CERN-THESIS-2006-114]

recent measurement by BELLE in e^+e^-
followed by intense phenomenology
on pFF extraction

PRL 122, 042001 (2019)

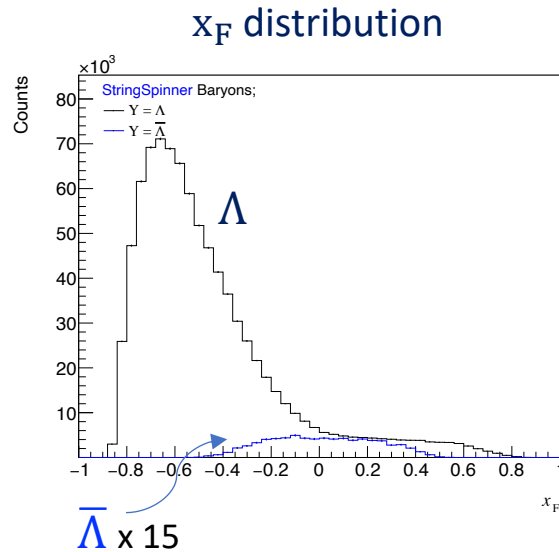
D'Alesio et al., PRD 102, 054001 (2020); JHEP12 (2022) 074;
PRD 108, 094004 (2023); PLB 851 (2024) 138552
Kang et al., PRD 105, 094303 (2022)

- Can be measured from the angular distribution of decay products,
e.g. the proton in $\Lambda \rightarrow p + \pi$

$$N_p^\Lambda \propto 1 + \alpha_\Lambda P_n^\Lambda \cos \theta^*$$

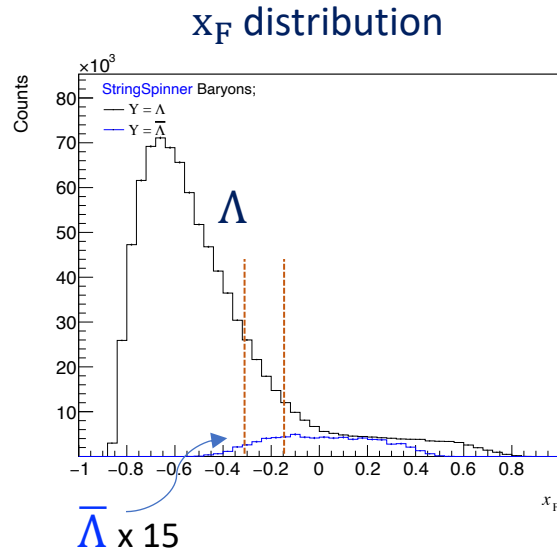


Preliminary results @ JLAB kinematics
spontaneous polarization of $\Lambda, \bar{\Lambda}$

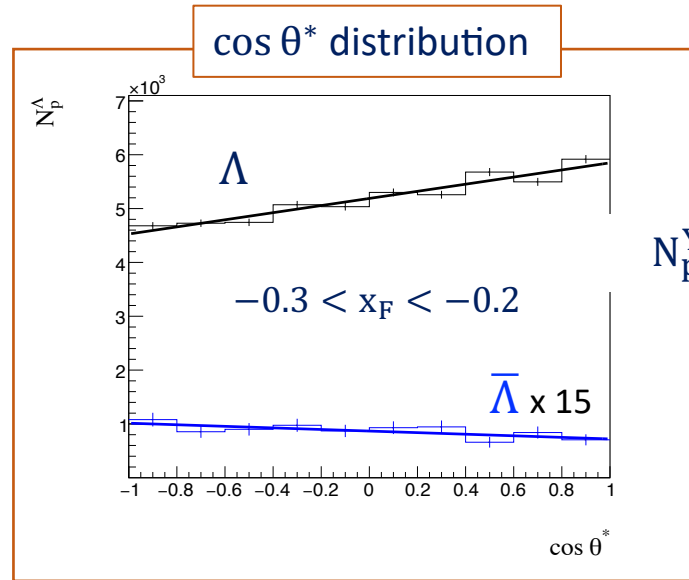


Λ s mainly from TFR
 $\bar{\Lambda}$ production suppressed

Preliminary results @ JLAB kinematics
spontaneous polarization of $\Lambda, \bar{\Lambda}$



Λ s mainly from TFR
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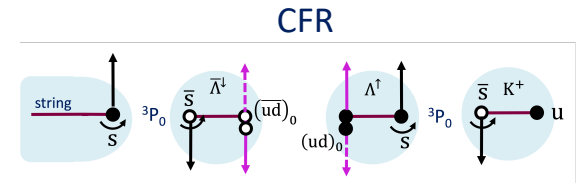
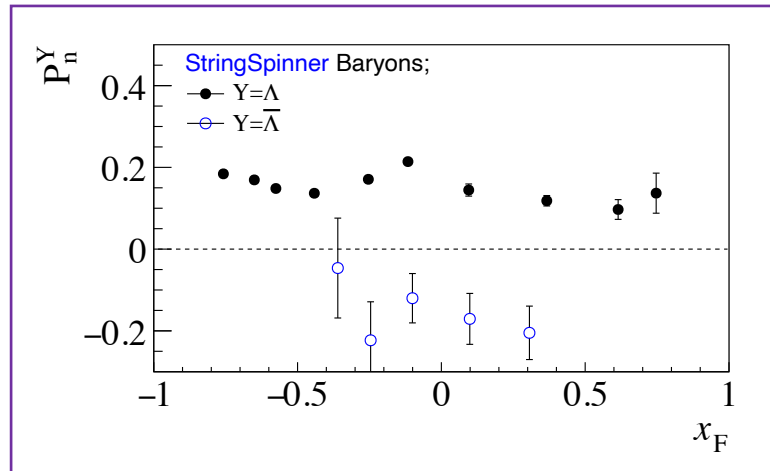
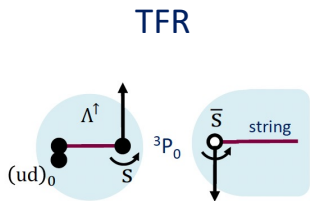
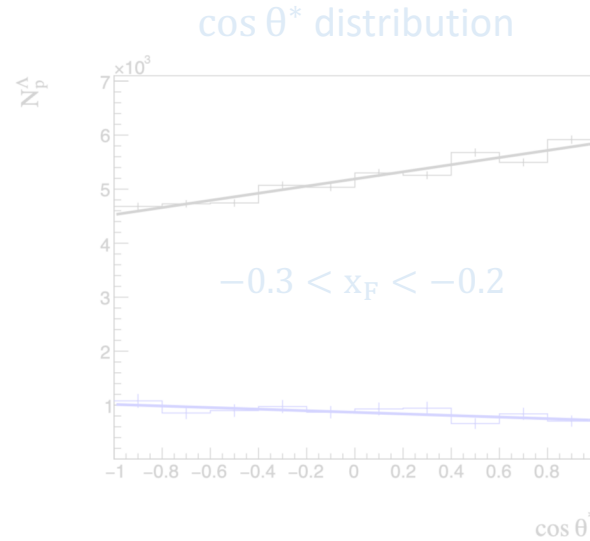
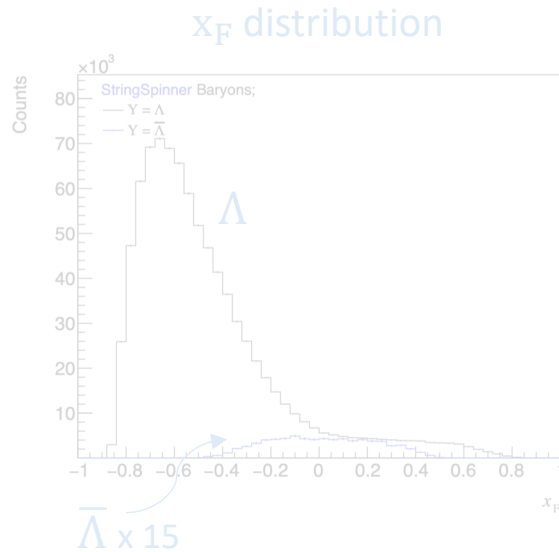


$$N_p^Y \propto 1 + \alpha_Y P_n^Y \cos \theta^*$$

$$Y = \Lambda, \bar{\Lambda}$$



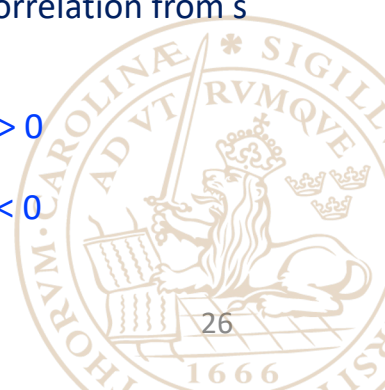
Preliminary results @ JLAB kinematics spontaneous polarization of $\Lambda, \bar{\Lambda}$



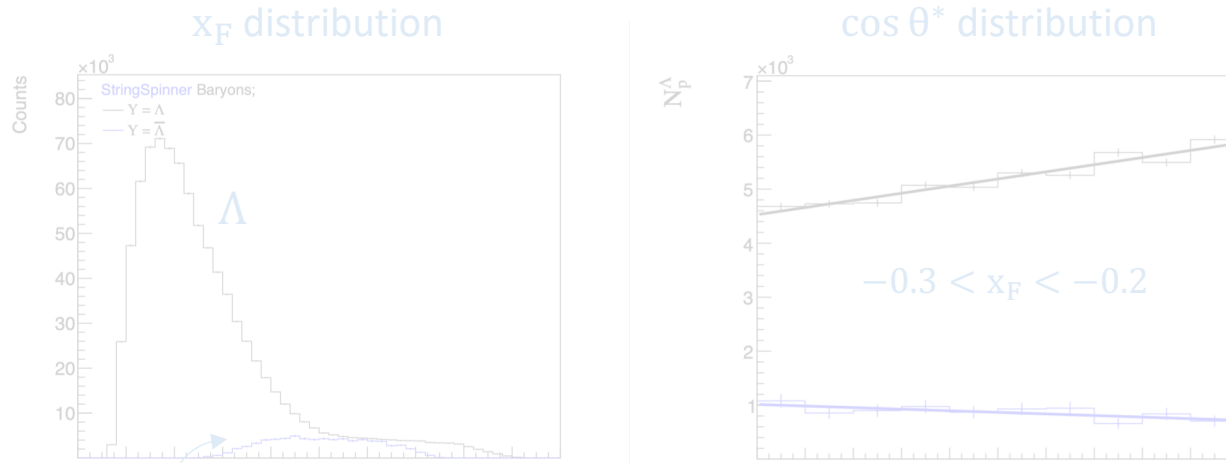
Λ inherits spin-kT correlation from s

$$\langle \vec{S}_\Lambda \cdot (\hat{z} \times \vec{p}_{\Lambda,T}) \rangle > 0$$

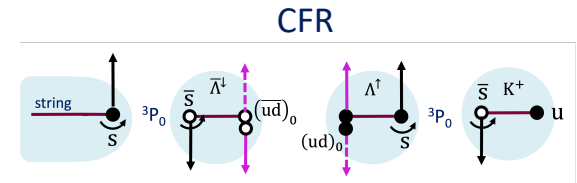
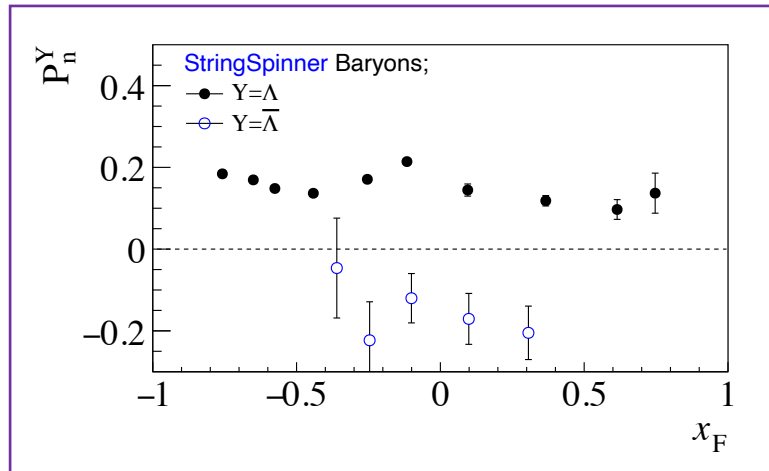
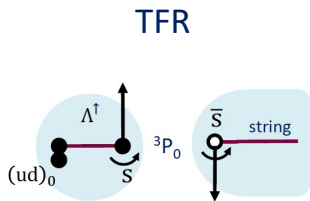
$$\langle \vec{S}_{\bar{\Lambda}} \cdot (\hat{z} \times \vec{p}_{\bar{\Lambda},T}) \rangle < 0$$



Preliminary results @ JLAB kinematics spontaneous polarization of $\Lambda, \bar{\Lambda}$



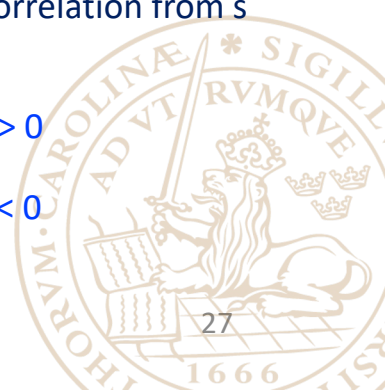
more experimental input needed for spin-dependent hadronization
JLAB @ high lumi can contribute!



Λ inherits spin-kT
correlation from s

$$\langle \vec{S}_\Lambda \cdot (\hat{z} \times \vec{p}_{\Lambda,T}) \rangle > 0$$

$$\langle \vec{S}_{\bar{\Lambda}} \cdot (\hat{z} \times \vec{p}_{\bar{\Lambda},T}) \rangle < 0$$



Conclusions

- ❑ We are building a model of hadronization with spin (string+ $^3P_0$)
- ❑ It is used for the implementation of spin effects in Pythia by StringSpinner
- ❑ Promising results so far, further developments foreseen
more experimental input needed to shed light on spin-effects in hadronization,
JLAB @ high lumi can certainly help!

