Pythia Week 2026
Jyväskylä
20/08/2026

Spin-dependent hadronization

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Funded by the European Union

MARIE CURIE ACTIONS
SPINFRAG

LUND UNIVERSITY

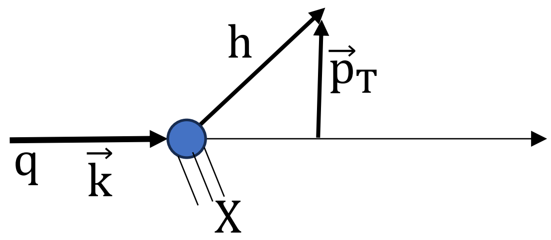
INFN Istituto Nazionale di Fisica Nucleare

Motivation: Collins effect

- **Collins effect** in the fragmentation of transversely polarized quarks

$$z = p^+/k^+$$

Collins, NPB 396, 161 (1993)



$$D_{q^\uparrow \to h+X}(z, \vec{p}_T) = D_{1q}^h(z, p_T^2)$$

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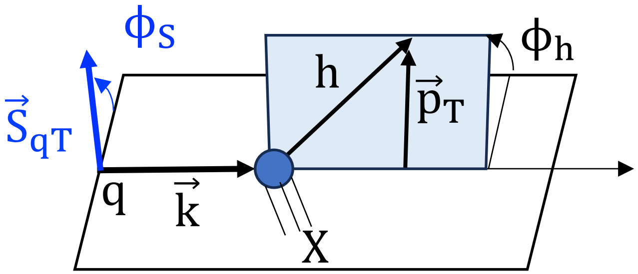


Collins FF

$$D_{q^\uparrow \to h+X}(z, \vec{p}_T) = D^h_{1q}(z, p_T^2) + \frac{H^{h\perp}_{1q}(z, p_T^2)}{zM_h} \vec{S}_{qT} \cdot \hat{k} \times \vec{p}_T$$

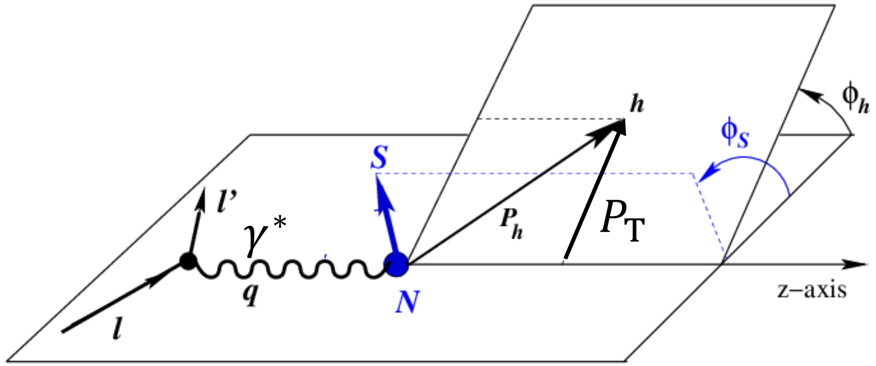
$$\propto 1 - \frac{H^{h\perp}_{1q}}{zM_h D^h_{1q}} |\vec{S}_{qT}||\vec{p}_T| \sin(\phi_h - \phi_{S_{qT}})$$

- Asymmetric azimuthal distribution
  sensitive to the quark transverse polarization → quark polarimetry!

- Appears in: semi-inclusive DIS (SIDIS)
  $e^+e^- \to$ hadrons
  $pp^\uparrow \to hX$

Collins asymmetry in SIDIS

- Asymmetry in the azimuthal distribution of the observed hadrons in DIS



$$\phi_{Coll} = \phi_h + \phi_S - \pi$$

$$d\sigma^h \propto 1 + D_{NN}\,|\vec{S}_T|A_{Coll}\sin\phi_{Coll} + \cdots$$

$$A_{Coll} \simeq \frac{\sum_q e_q^2 h_1^q \otimes H_{1q}^{\perp h}}{\sum_q e_q^2 f_1^q \otimes D_{1q}^h}$$

Transversity PDF h_1^q → transverse spin of quarks in a transversely polarized nucleon

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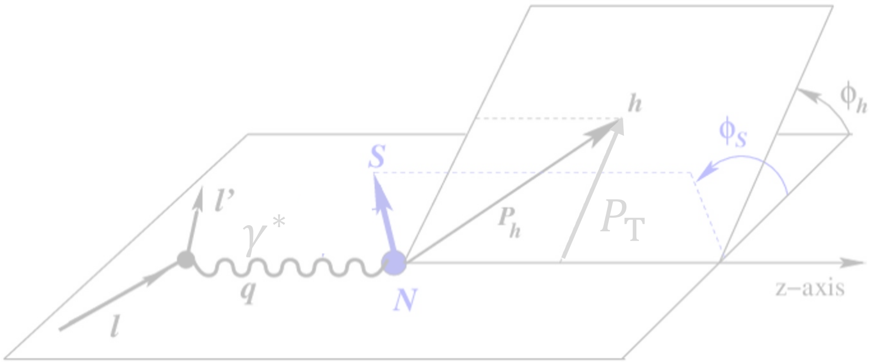

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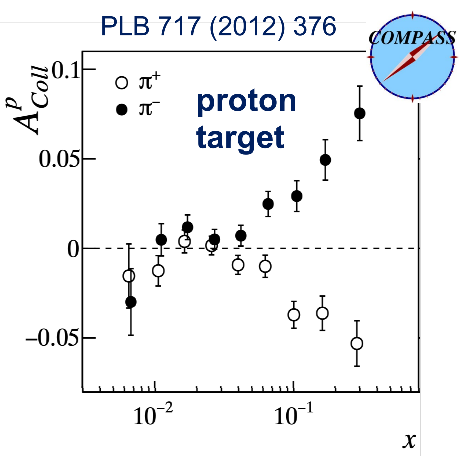
Transversity PDF $h_1^q \rightarrow$ transverse spin of quarks in a transversely polarized nucleon

- A_{Coll} measured by HERMES (DESY), COMPASS (CERN) and at JLAB



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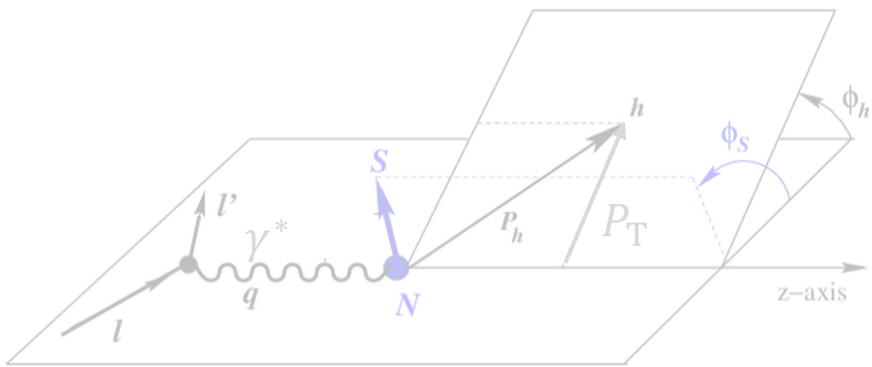

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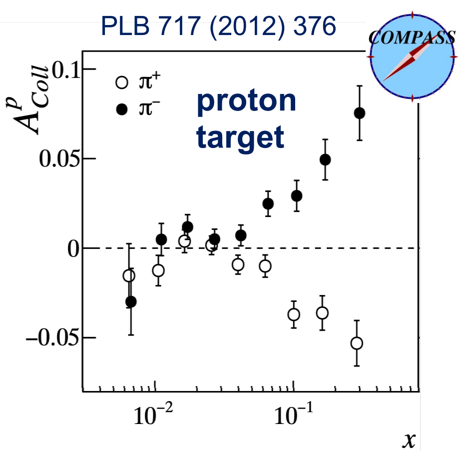
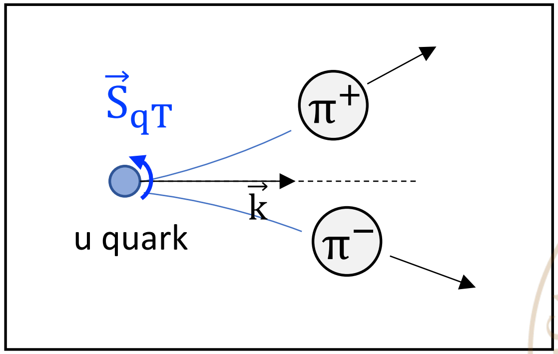
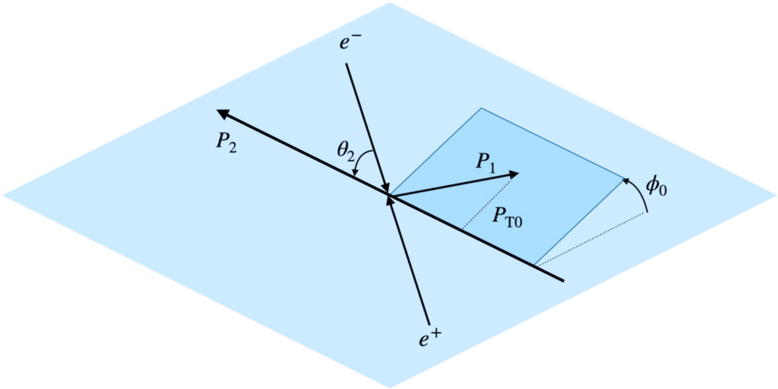


$$A^p_{\rm Coll}(x) \simeq \frac{h_1^u}{f_1^u} \times \frac{H_{1q}^{\perp h}}{D_{1q}^h}$$



Collins asymmetry in e^+e^-

- Azimuthal anisotropy in the azimuthal distribution of back-to-back hadrons in e^+e^-



$$d\sigma^{h_1h_2} \propto 1 + \hat{a}_{NN}(\theta_2)\, A_0 \cos(2\phi_0) + \cdots$$

Collins FF

$$A_0 \simeq \frac{\sum_q e_q^2\, w\, H_{1q}^{\perp h_1} \otimes H_{1q}^{\perp h_2}}{\sum_q e_q^2\, D_{1q}^{h_1} \otimes D_{1q}^{h_2}}$$

spin-averaged FF

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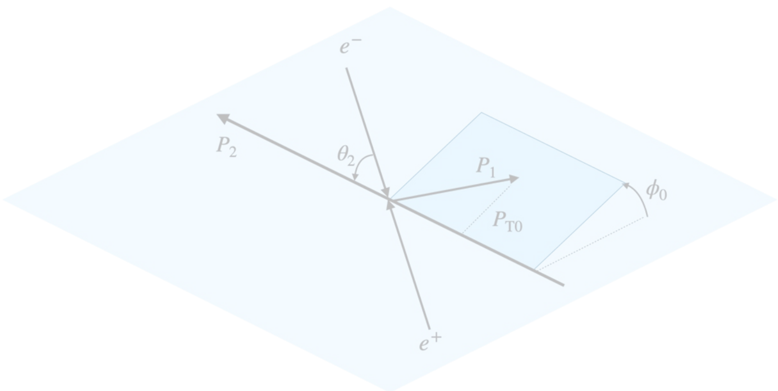

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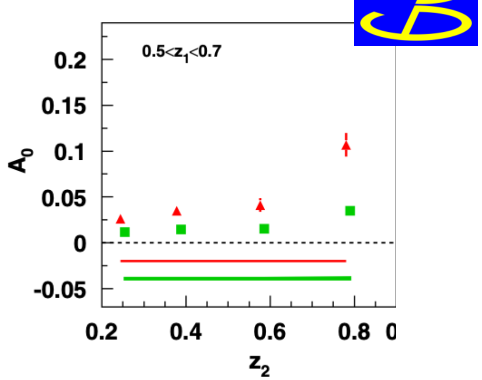
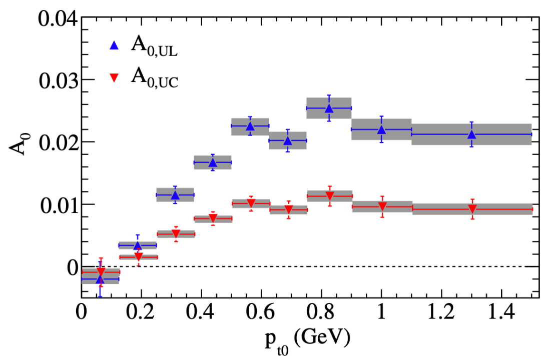
spin-averaged FF

- Measured by BELLE, BABAR, BESIII

PRD 78, 032011 (2008)



PRD 90, 052003 (2014)



- Independent confirmation that Collins FF $\neq 0$!
- Source of information on Collins FF

Connection between hadronization and nucleon structure

Parametrizations of
h_1^q and $H_{1q}^{\perp h}$

Data on
Collins asymmetries in SIDIS

Data on
Collins asymmetries in e+e-

Parametrizations of
$H_{1q}^{\perp h}$

$$A_{\mathrm{Coll}}^{\mathrm{SIDIS}} \simeq \frac{\sum_q e_q^2 h_1^q \otimes H_{1q}^{\perp h}}{\sum_q e_q^2 f_1^q \otimes D_{1q}^h}$$

$$A_0^{e^+e^-} \simeq \frac{\sum_q e_q^2 C[w H_{1q}^{\perp h_1} \times H_{1q}^{\perp h_2}]}{\sum_q e_q^2 C[D_{1q}^{h_1} \times D_{1q}^{h_2}]}$$

Fit
χ^2 min, etc.

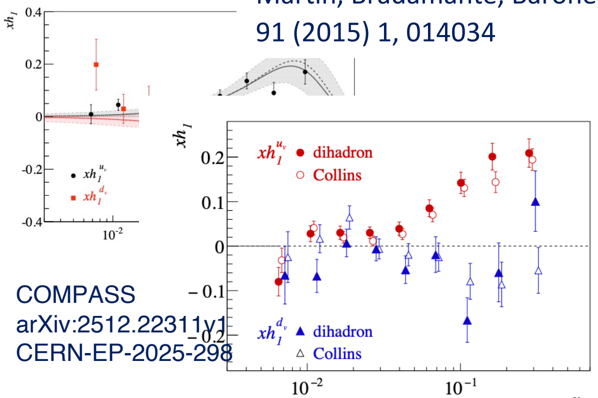
Extracted h_1^q

Extracted $H_{1q}^{\perp h}$

Connection between hadronization and nucleon structure

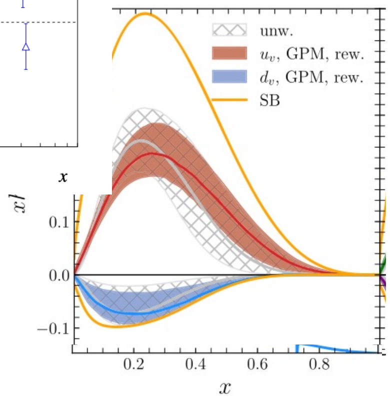
Extracted transversity PDFs h_1^q

Martin, Bradamante, Barone, PRD 91 (2015) 1, 014034

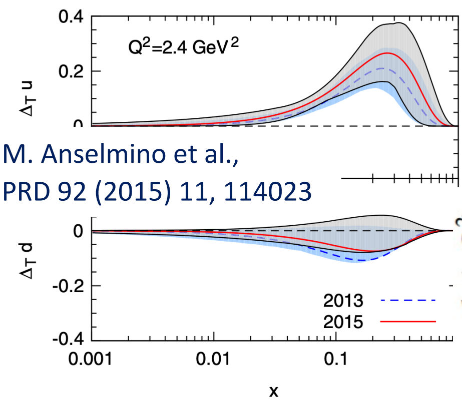


COMPASS
arXiv:2512.22311v1
CERN-EP-2025-298

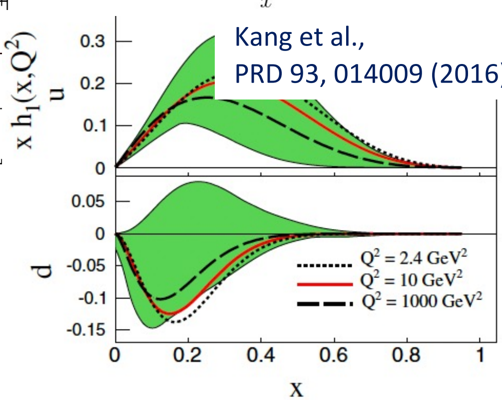
Boglione et al., PLB 854 (2024) 138712



M. Anselmino et al.,
PRD 92 (2015) 11, 114023



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



Non-zero for u-valence
d-valence large uncer.
Compatible with zero for sea

Extracted Collins FFs $H_{1q}^{\perp h}$

Connection between hadronization and nucleon structure

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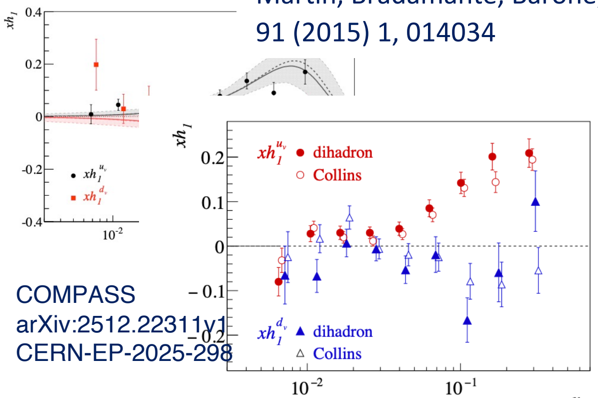

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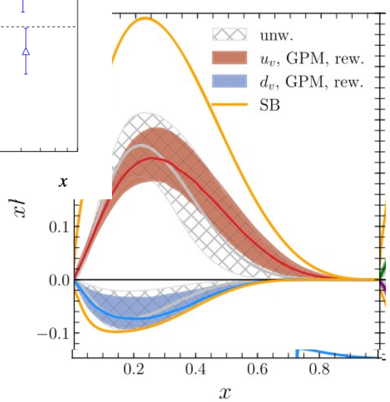
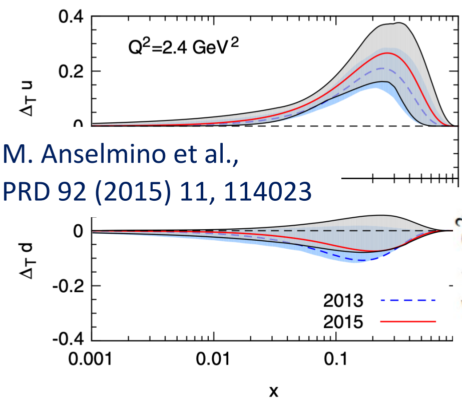
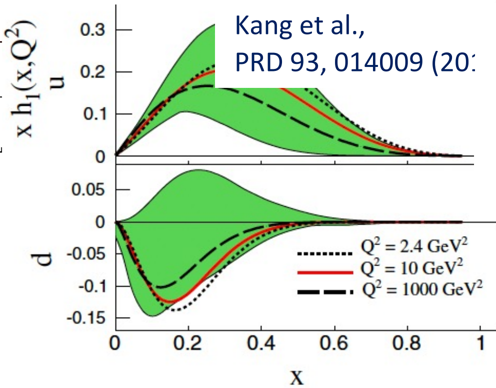




M. Anselmino et al.,
PRD 92 (2015) 11, 114023

Kang et al.,
PRD 93, 014009 (20



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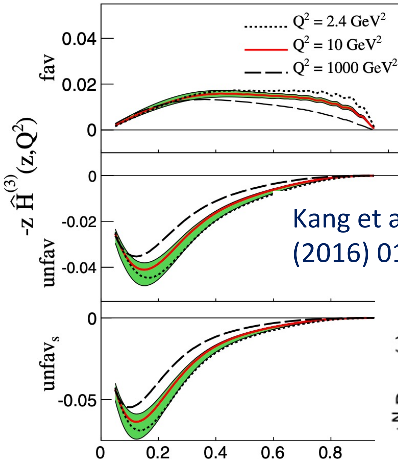

Kang et al., PRD 93 (1) (2016) 014009

Anselmino et al.,
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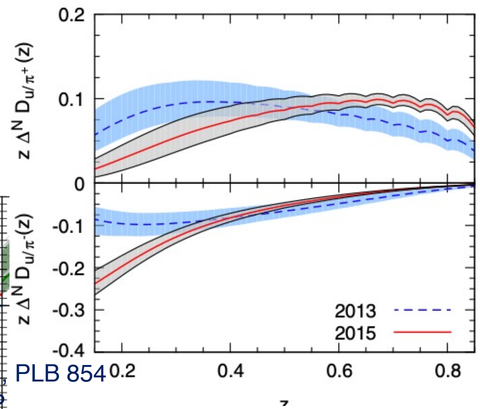

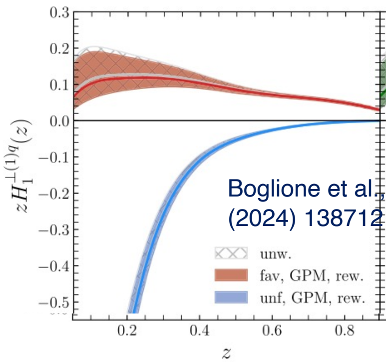

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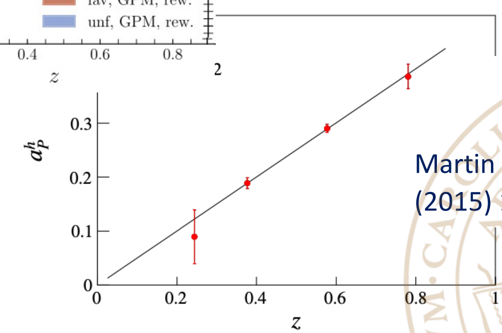

$H_{1q}^{\perp h}/D_{1q}^h$

Martin et al, PRD 91 (2015) 1, 014034

Connection between hadronization and nucleon structure

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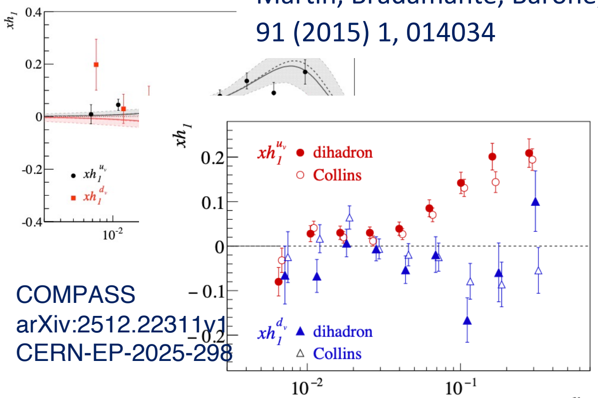

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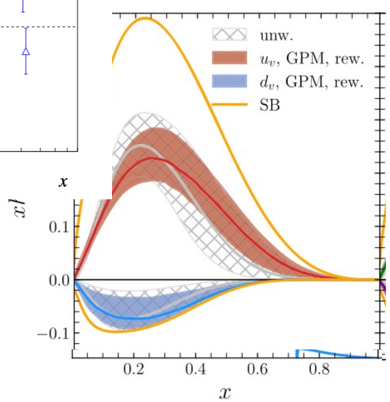

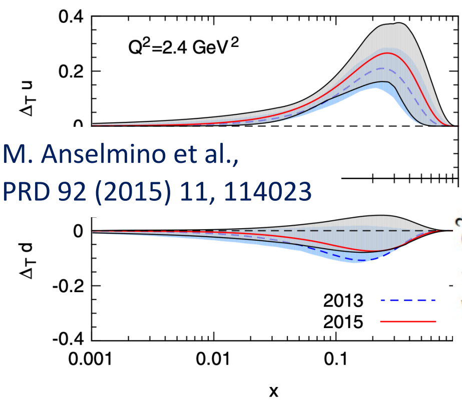

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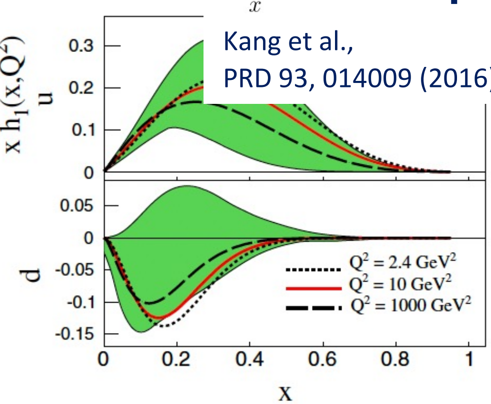

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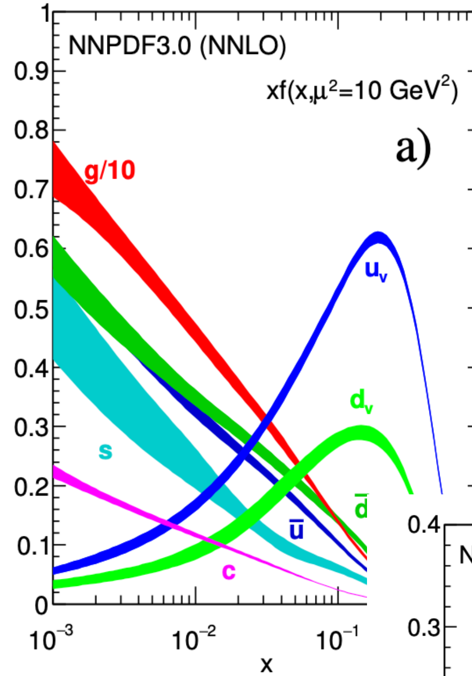
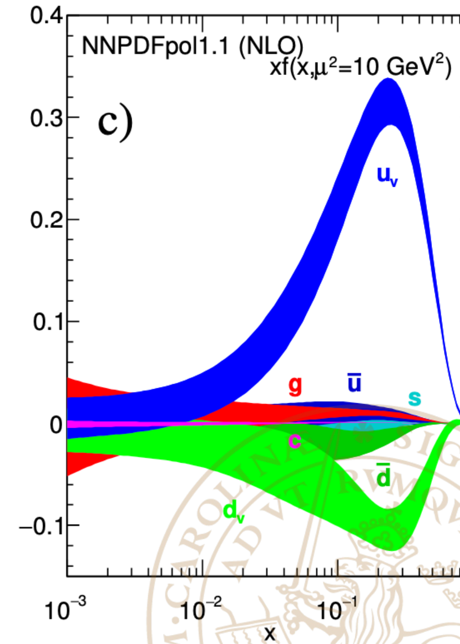
Spin-averaged f_1^q



from PDG

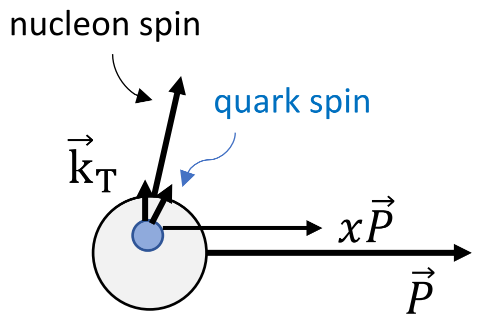
helicity g_1^q



There is more than transversity in the nucleon!

Leading order transverse-momentum-dependent (TMD) PDFs

Quark polarization	Nucleon polarization: Unpolarized (U)	Nucleon polarization: Longitudinal (L)	Nucleon polarization: Transverse (T)
U	$f_1(x,k_T^2)$ (unpolarized)		$f_{1T}(x,k_T^2)$ (Sivers)
L		$g_1(x,k_T^2)$ (helicity)	$g_{1T}(x,k_T^2)$ (worm-gear T)
T	$h_1^{\perp}(x,k_T^2)$ (Boer-Mulders)	$h_{1L}^{\perp}(x,k_T^2)$ (worm-gear L)	$h_1(x,k_T^2)$ (transversity) $h_{1T}^{\perp}(x,k_T^2)$ (pretzelosity)



possible «spin-orbit» correlations

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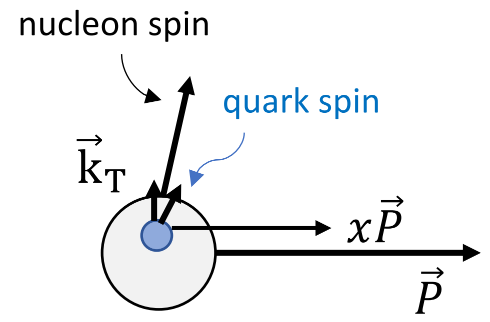

possible «spin-orbit» correlations

many TMD PDFs largerly unknown!

all accessible in polarized DIS

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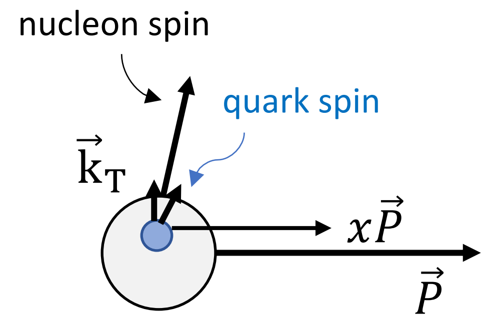


possible «spin-orbit» correlations

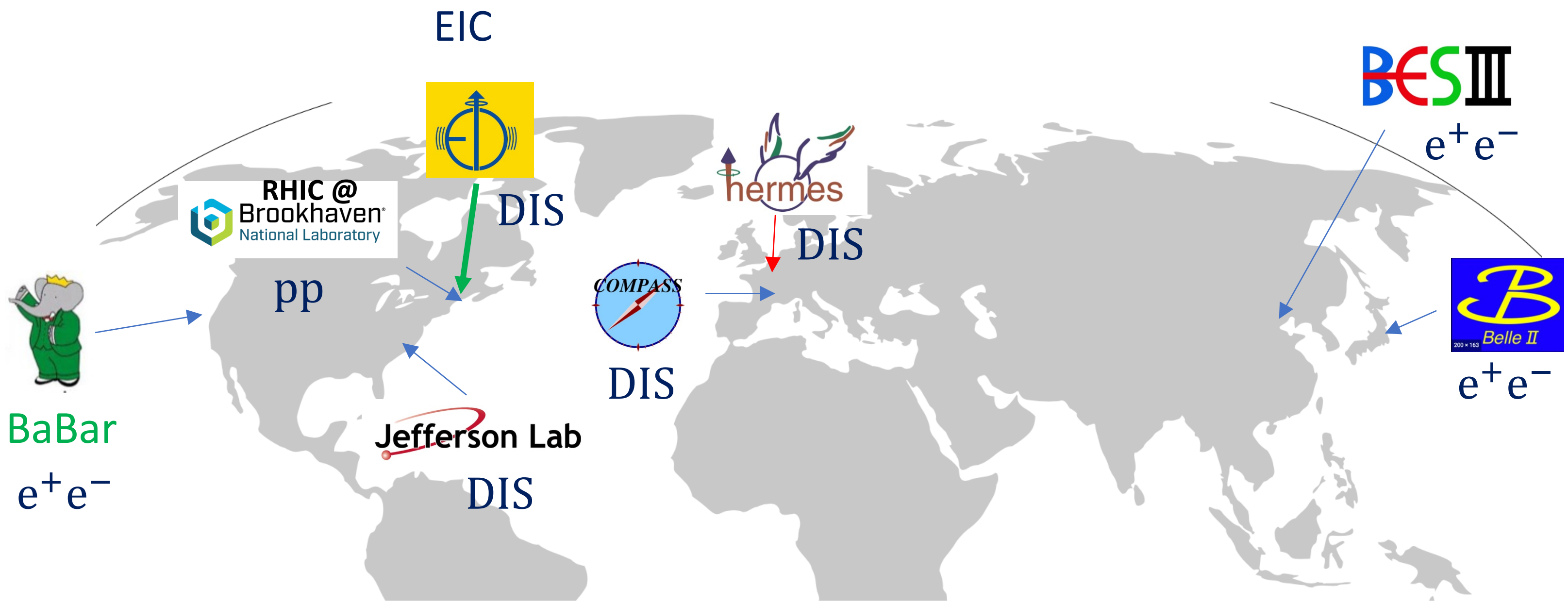
many TMD PDFs largely unknown!

all accessible in polarized DIS

Need a T spin analyzer, e.g. the Collins effect

Landscape of experiments

where spin (will) matter



A MC generator with spin is needed

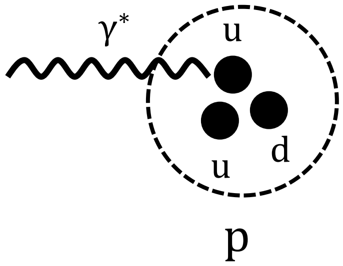
main challenge: hadronization

a model for hadronization with spin

string+$^3P_0$

Alternative model
Matevosyan, Kotzinian, Thomas, PRD 95 (2017) 1, 014021

String breaking



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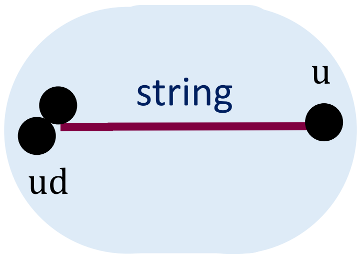

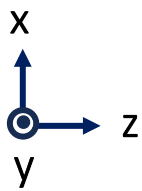

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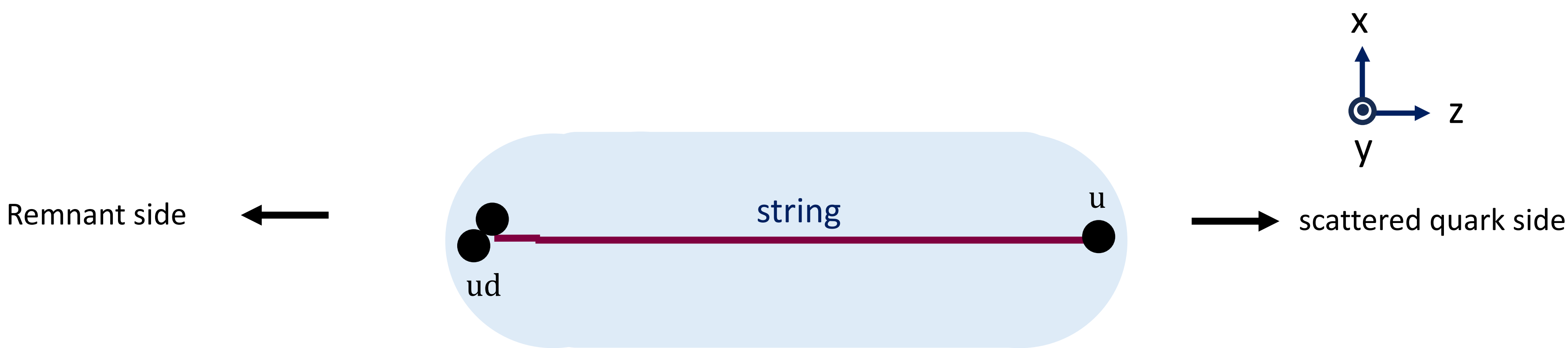
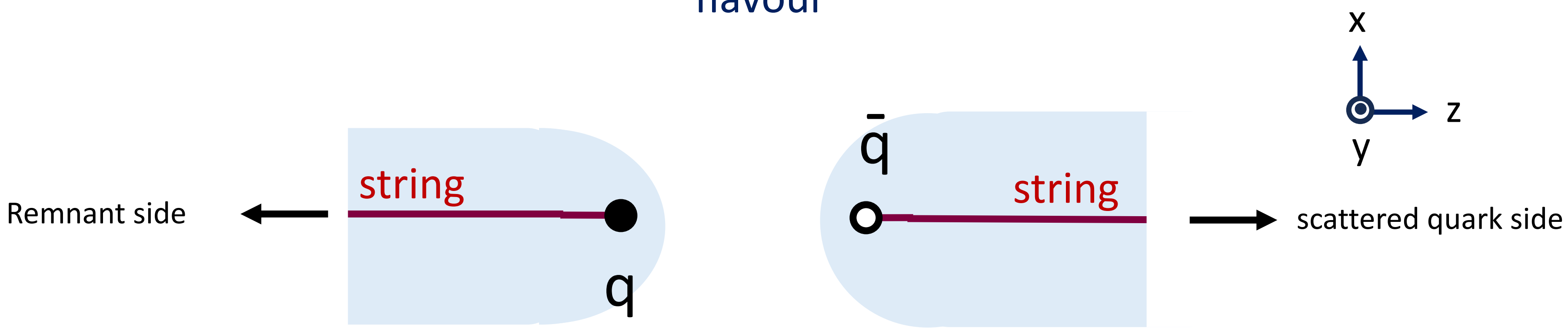
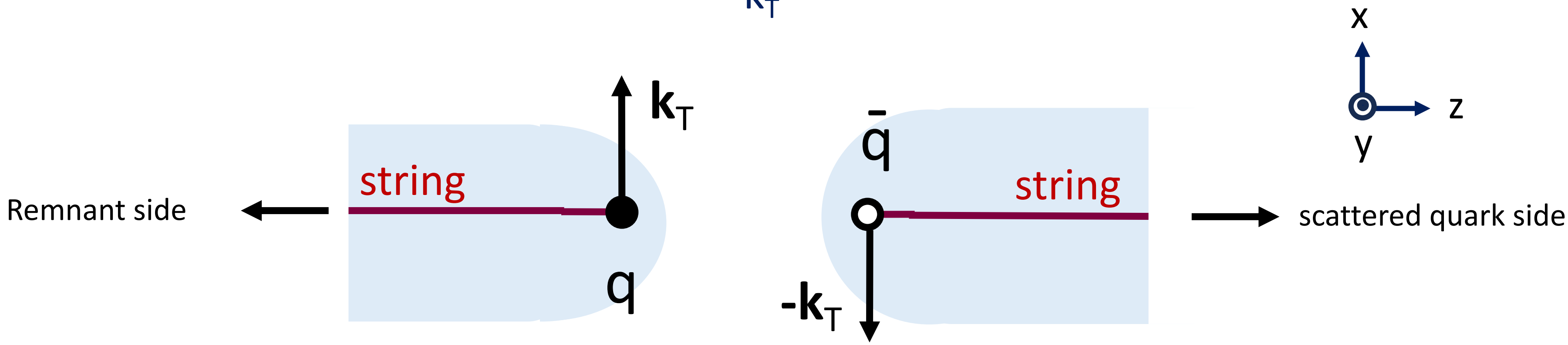


String breaking
flavour



String breaking via $q\bar{q}$ tunneling
[Schwinger mechanism]
suppression of s quarks

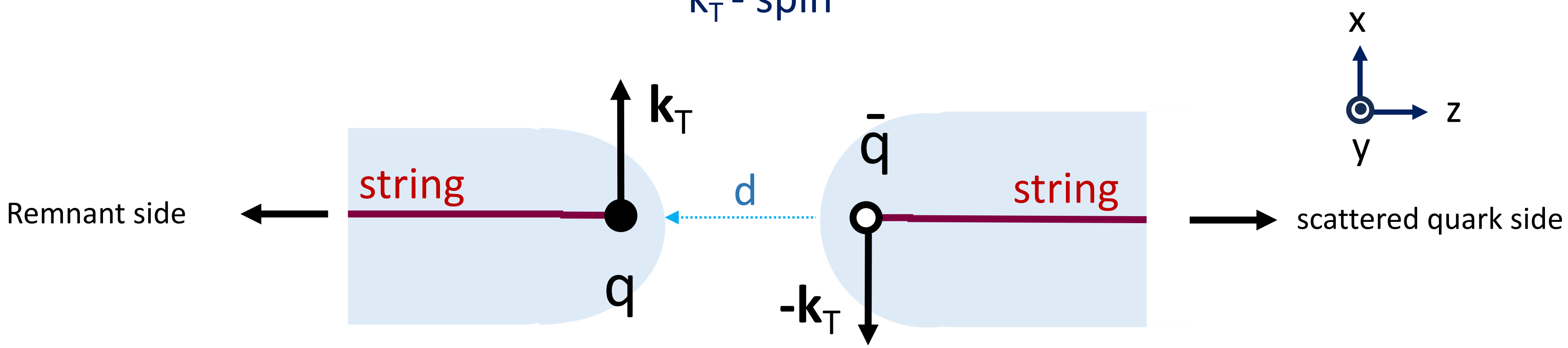
String breaking
k_T



Local conservation of transverse momentum

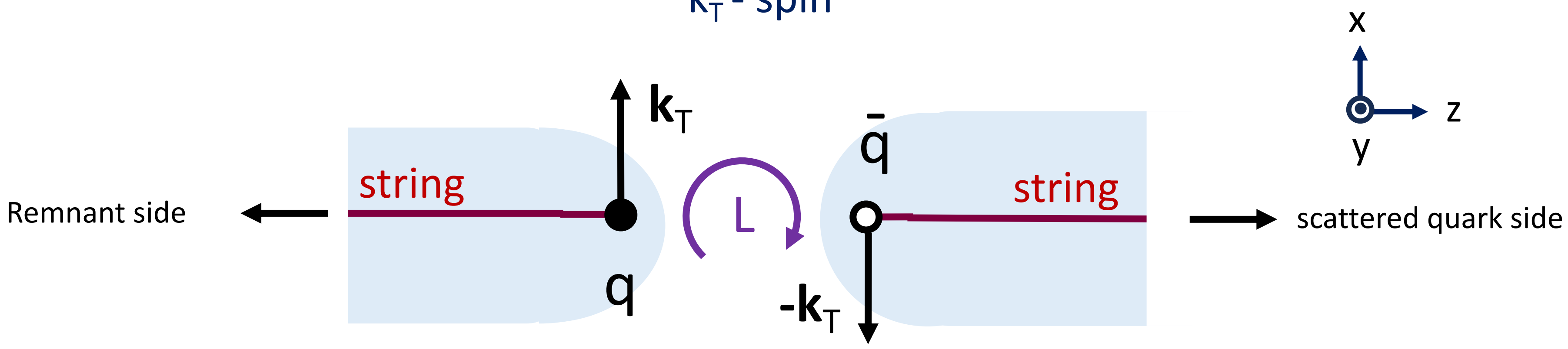
k_T damping [Schwinger mechanism]

String breaking
k_T - spin



The pair is produced at a distance d

String breaking
k_T - spin



The pair is produced at a distance d

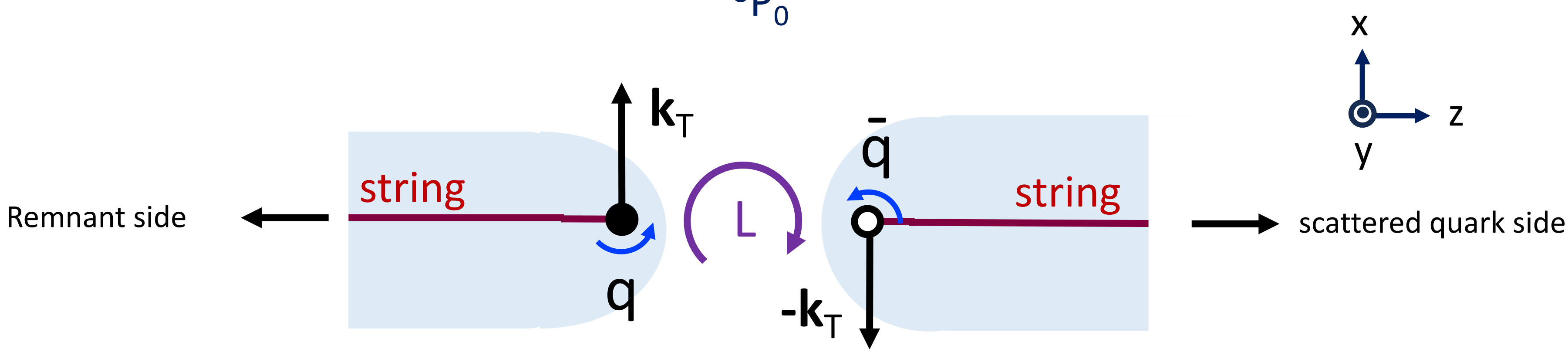
$$\vec{L} = \vec{d} \times \vec{k}_T \neq \vec{0}$$

Local conservation of angular momentum

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

String breaking

$^3P_0$



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

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

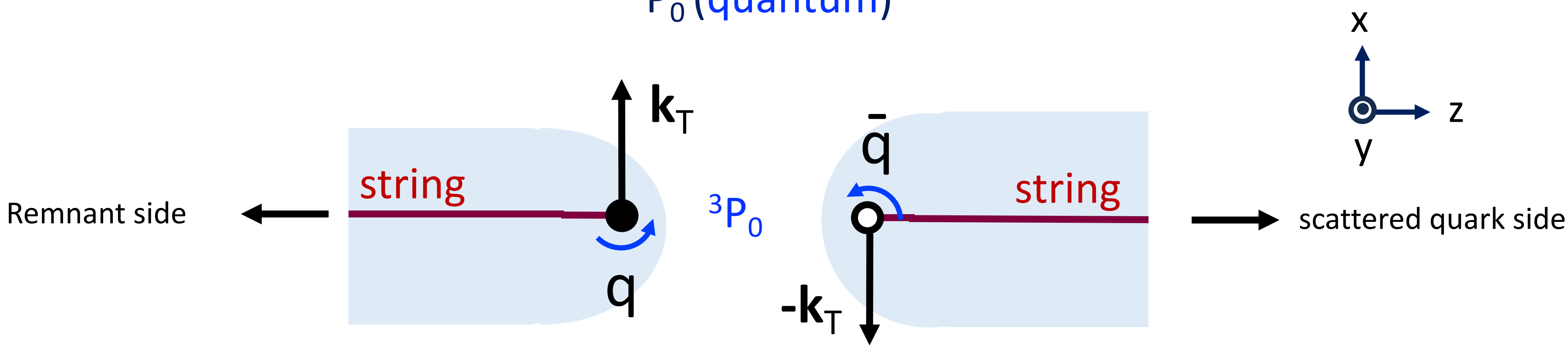
$L=1, S=1$

$q\bar{q}$ in the relative $^3P_0$ state

spin!

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
$^3P_0$ (quantum)



spin-k_T correlation described by "propagator" (2x2)

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

"complex mass" μ

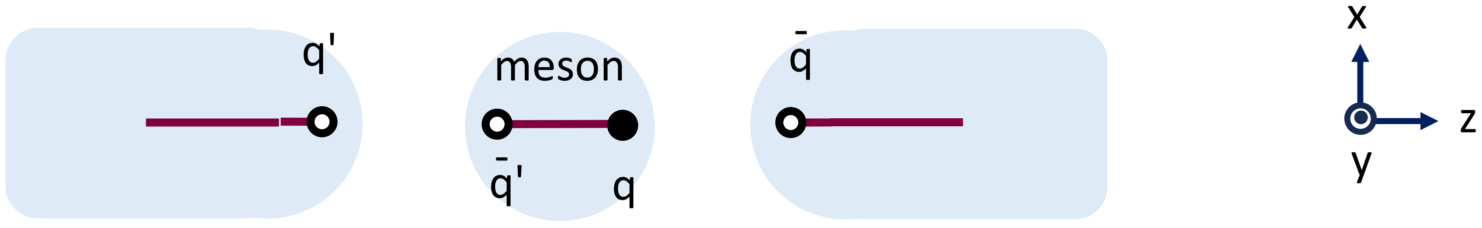
2 free parameters

$\mathrm{Im}(\mu)$ responsible for T spin effects (Collins, dihadron ...)

$\mathrm{Re}(\mu)$ responsible for L 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

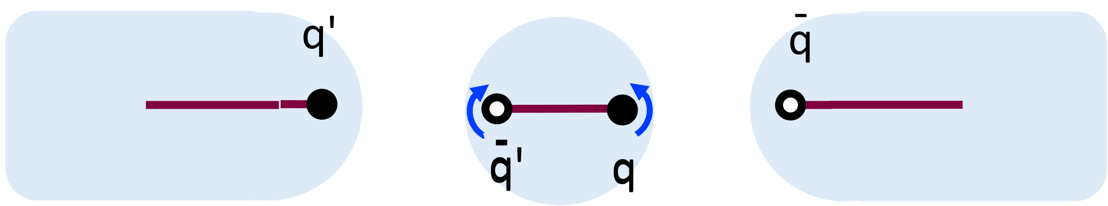
Meson production

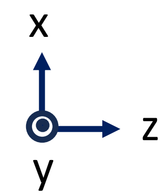


Pseudoscalar meson (PM) or vector meson (VM)

VM/PM $\approx 0.5..$

Meson production
PM (quantum)





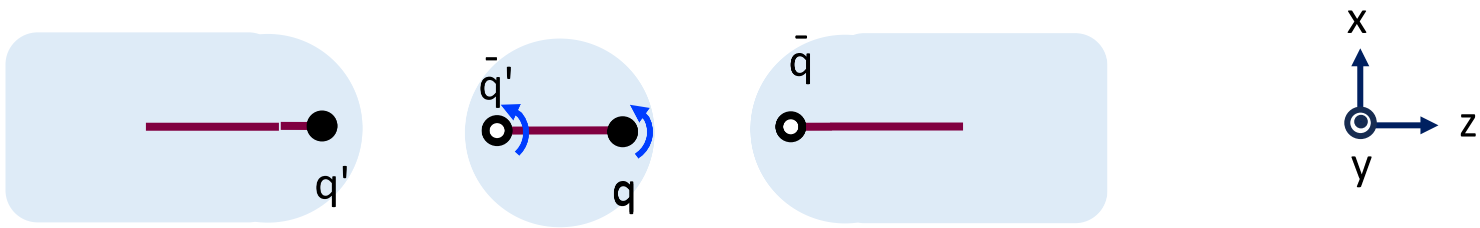
Pseudoscalar meson (PM) or vector meson (VM)

spin given by coupling (2x2)

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

no new free parameters

Meson production
VM (quantum)



Pseudoscalar meson (PM) or vector meson (VM)

spin given by coupling (2x2)

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

VM/PM suppression $2|G_T|^2 + |G_L|^2$

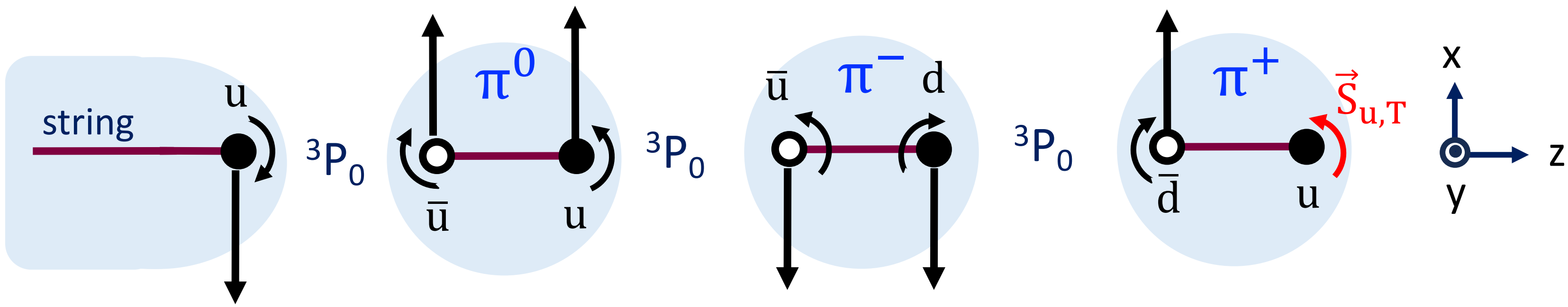
Probability VM has Longitudinal Polarization $f_L = \left|\frac{G_L}{G_T}\right|^2 / [2 + \left|\frac{G_L}{G_T}\right|^2]$

Interference between L and T polarizations $\theta_{LT} = \arg G_L/G_T$

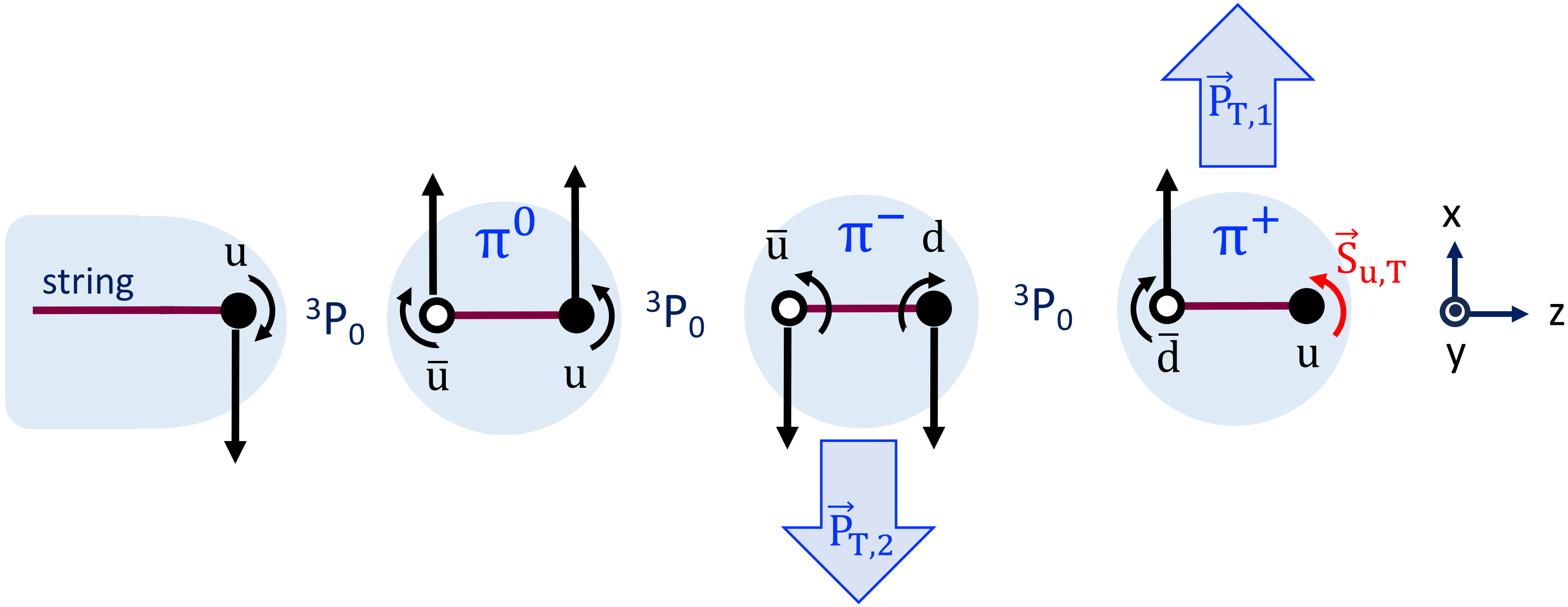
2 free spin parameters

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

Spin correlations in hadronization

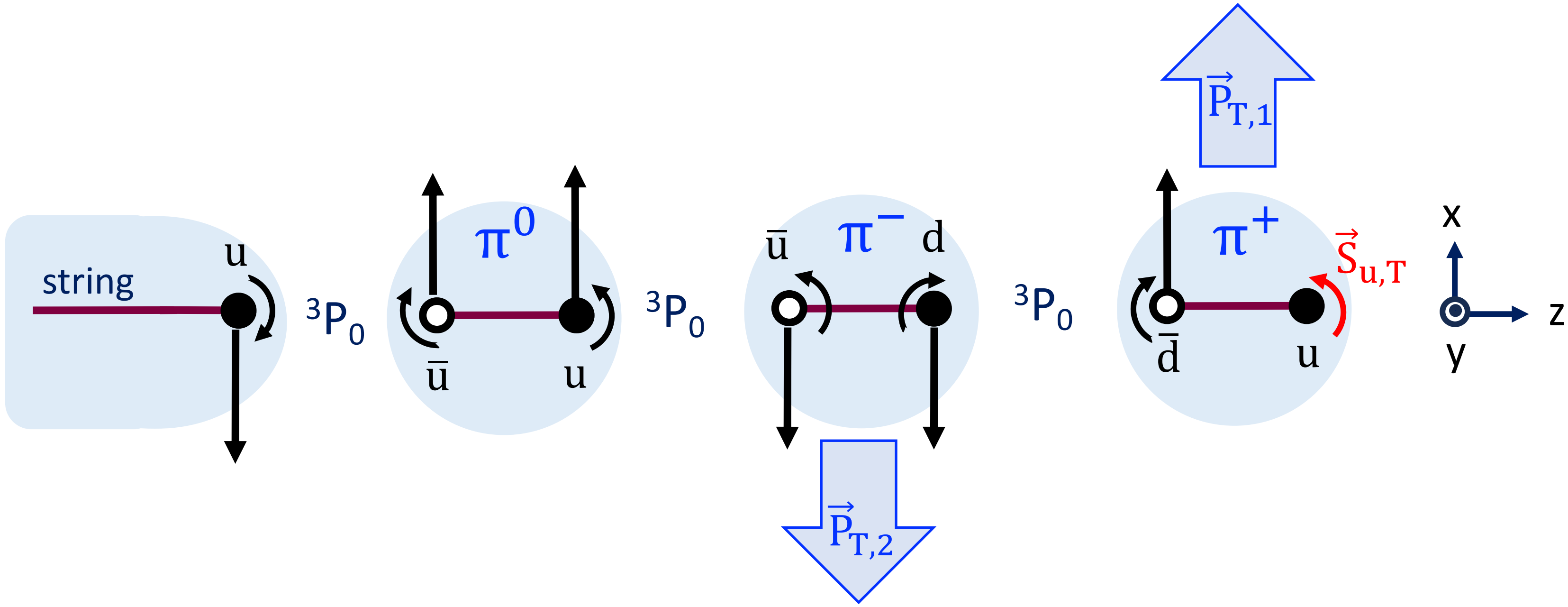


Spin correlations in hadronization



Collins effect of opposite sign for π^+ and π^-

Spin correlations in hadronization



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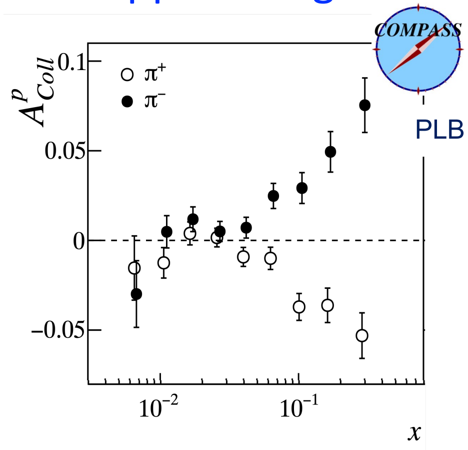
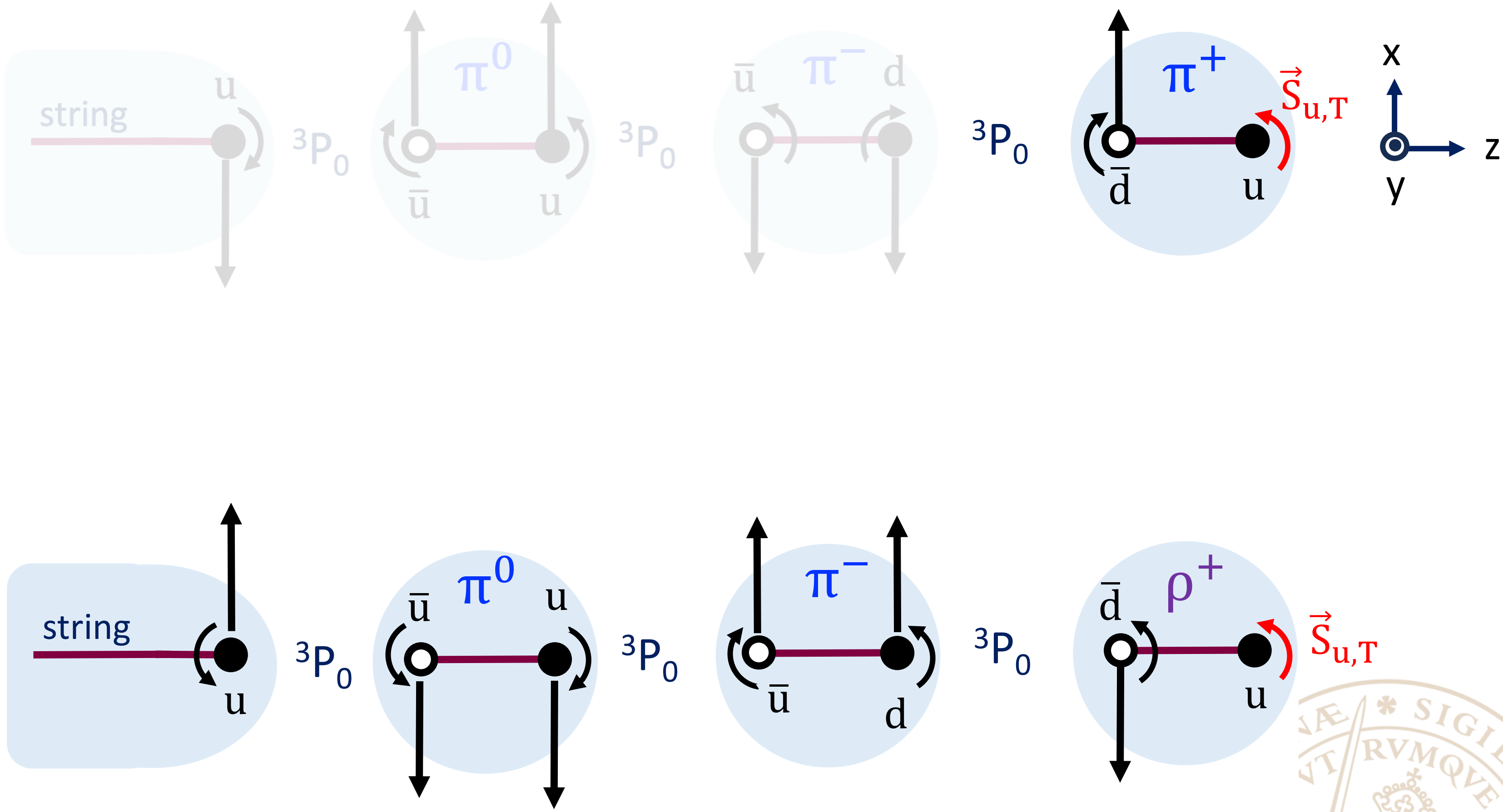
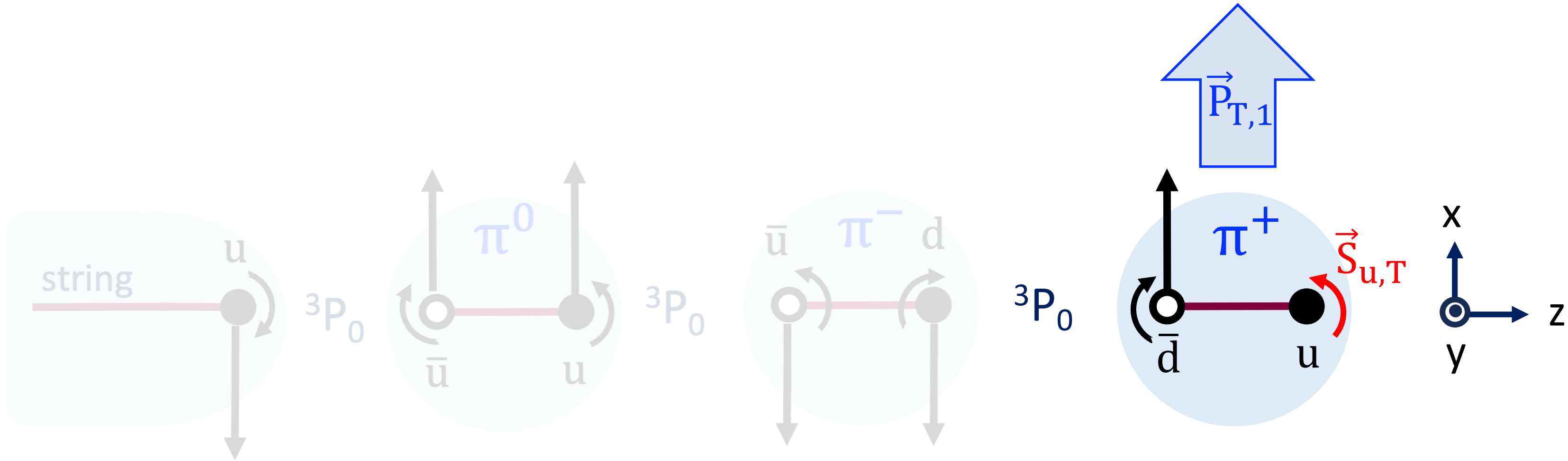


PLB 717 (2012) 376

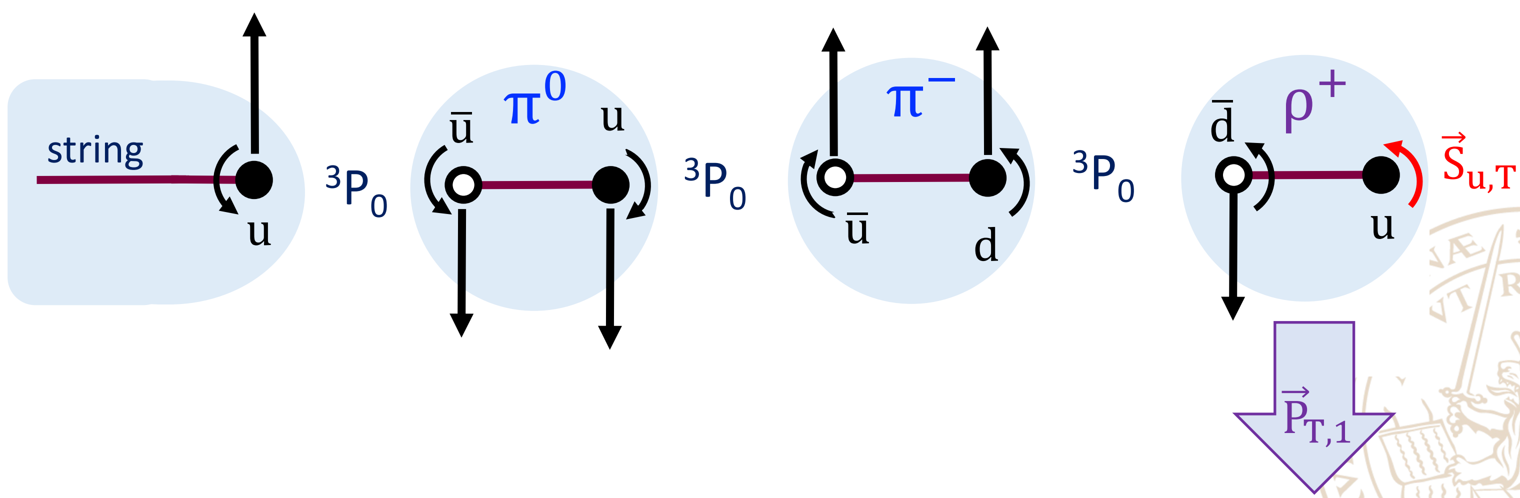
Spin correlations in hadronization



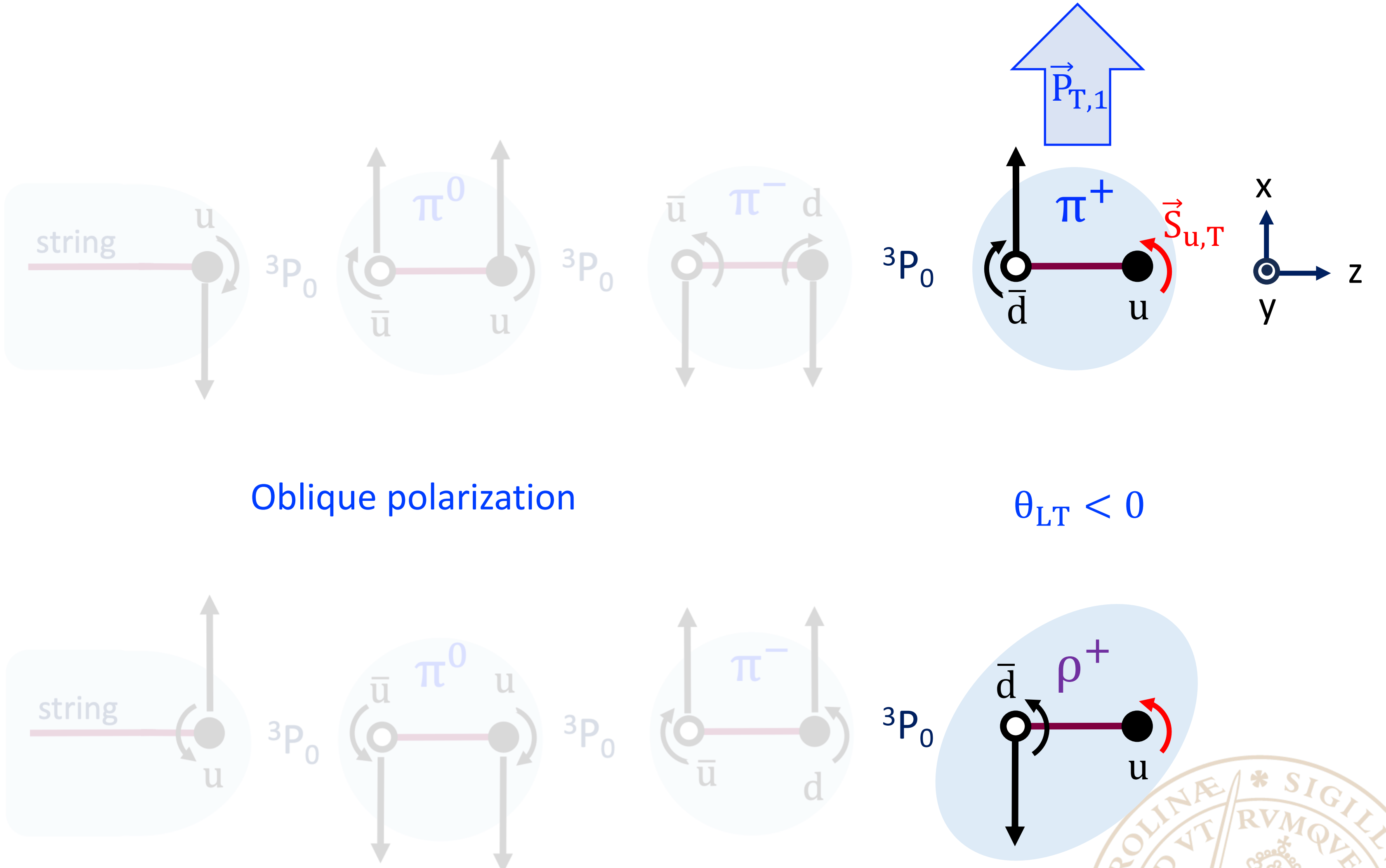
Spin correlations in hadronization



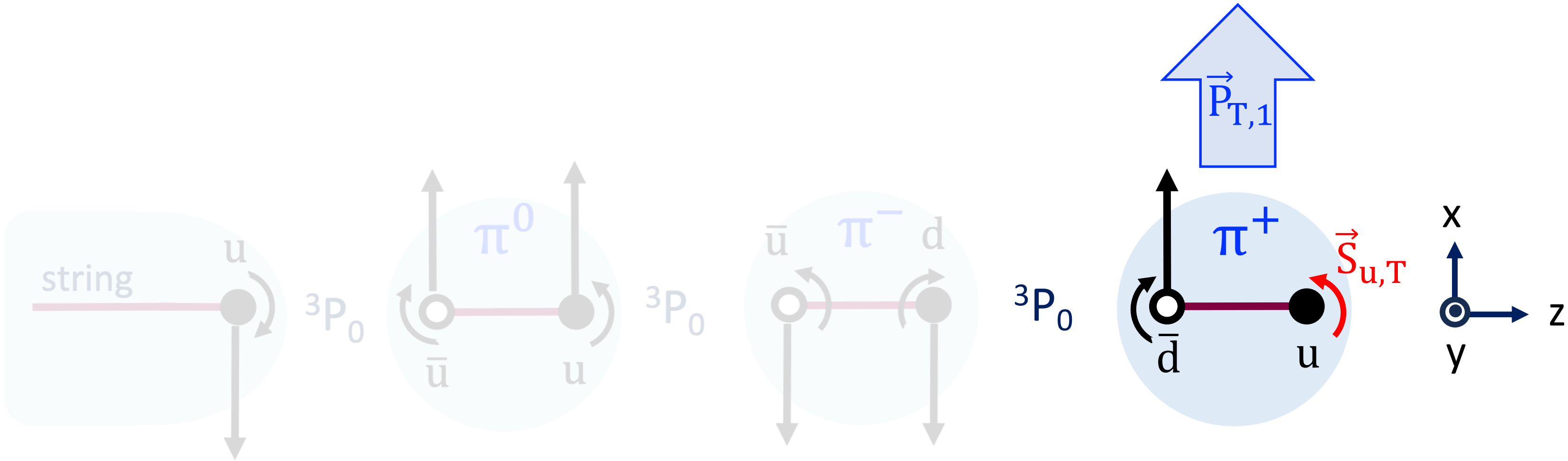
Collins effects for ρ^+ opposite to π^+ governed by f_L



Spin correlations in hadronization

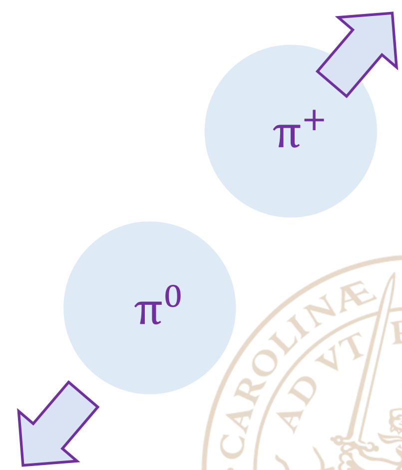


Spin correlations in hadronization

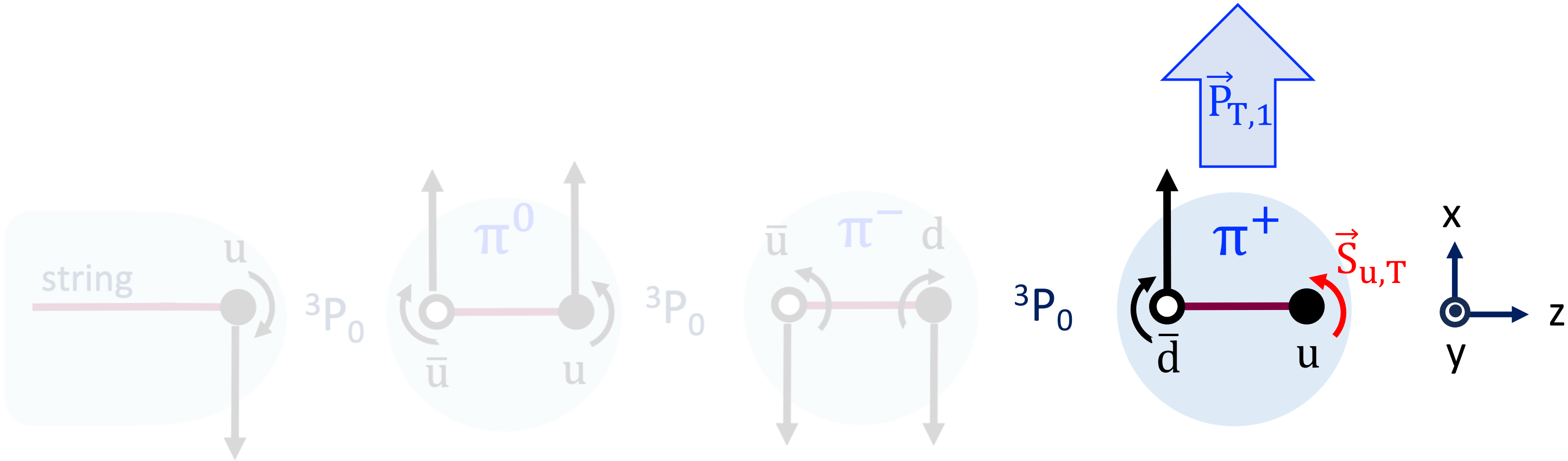


Oblique polarization

Enhancement of Collins effect for π^+

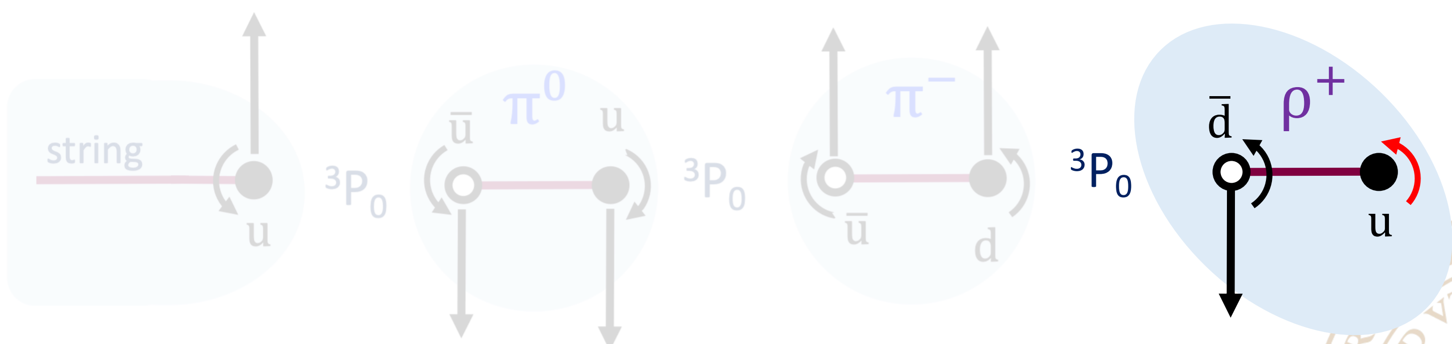


Spin correlations in hadronization

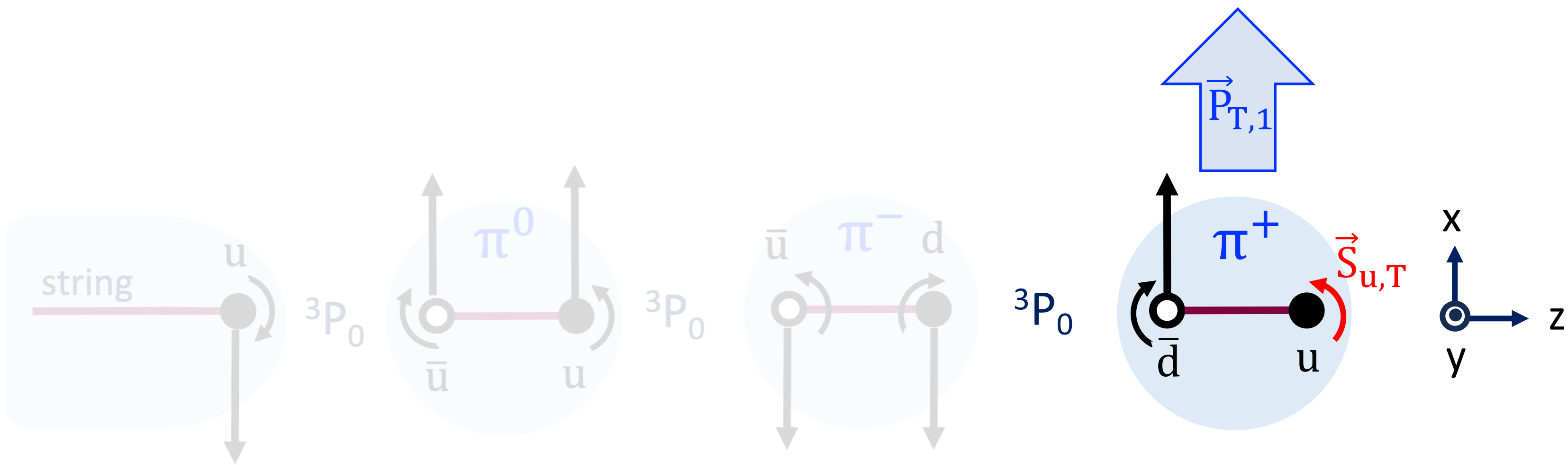


Oblique polarization

$\theta_{LT} > 0$

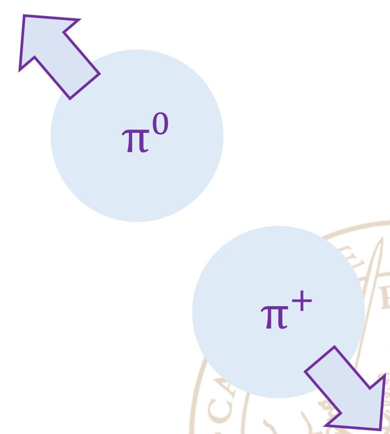


Spin correlations in hadronization



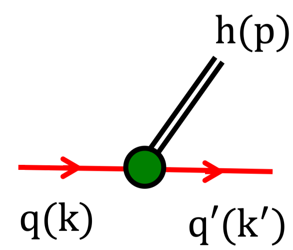
Oblique polarization

Decrease of Collins effect for π^+



"quantum" string + $^3P_0$

- String fragmentation = recursive $q \to h + q'$ splittings
- Quark splitting matrix (2x2): Lund string fragmentation $\otimes$ spin



Pythia

$$T_{q',h,q} \propto \boxed{C_{q',h,q}\; D_h(M^2) \left(\frac{1-Z}{\varepsilon_h^2}\right)^{\frac{a}{2}} \exp\left[-\frac{b_L \varepsilon_h^2}{2Z}\right] N_a^{-\frac{1}{2}}(\varepsilon_h^2)\, e^{-\frac{b_T k'^2_T}{2}}}$$

$$\otimes\; [\mu + \sigma_z \boldsymbol{\sigma}_T \cdot \mathbf{k'}_T] \qquad \Gamma_{h,s_h}$$

$^3P_0$ q-h-q’ coupling

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

"quantum" string + $^3P_0$

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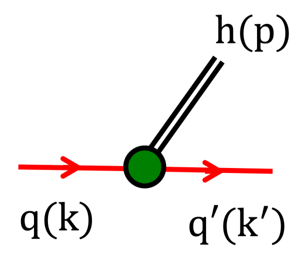

Pythia

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$$\otimes\ [\mu + \sigma_z \boldsymbol{\sigma}_T \cdot \mathbf{k'}_T] \qquad \Gamma_{h,s_h}$$

$^3P_0$ q-h-q’ coupling

- Spin state of q $\quad \rho(q) = [1 + \sigma \cdot \mathbf{S}_q]/2$
- Emission probability $\quad dP(q \to h + q') \propto \mathrm{Tr}\, T_{q',h,q}\, \rho(q)\, T^\dagger_{q',h,q} \quad dZ Z^{-1} d^2\mathbf{p}_T$
- Spin propagation after PM emission $\quad \rho(q') = T_{q',h,q}\, \rho(q)\, T^\dagger_{q',h,q}$

see backup for VM emission

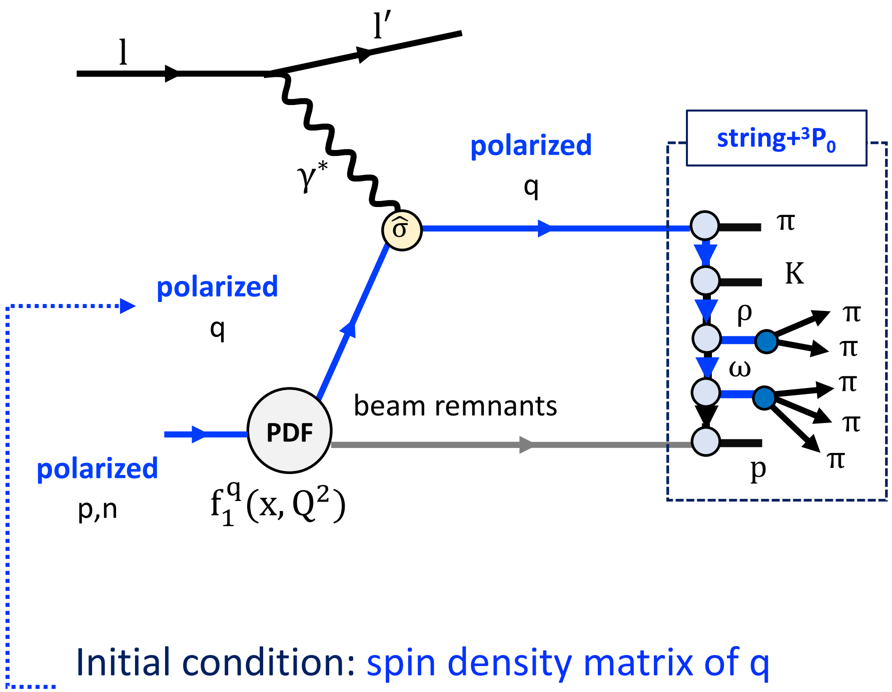
AK, Artru, Martin, PRD 104, 114038 (2021)

Implementation in Pythia by StringSpinner

Implementation in Pythia by StringSpinner

(polarized) Deep Inelastic Scattering

AK, L. Lönnblad, CPC **272** (2021) 108234;CPC **292** (2023) 108886



Initial condition: spin density matrix of q

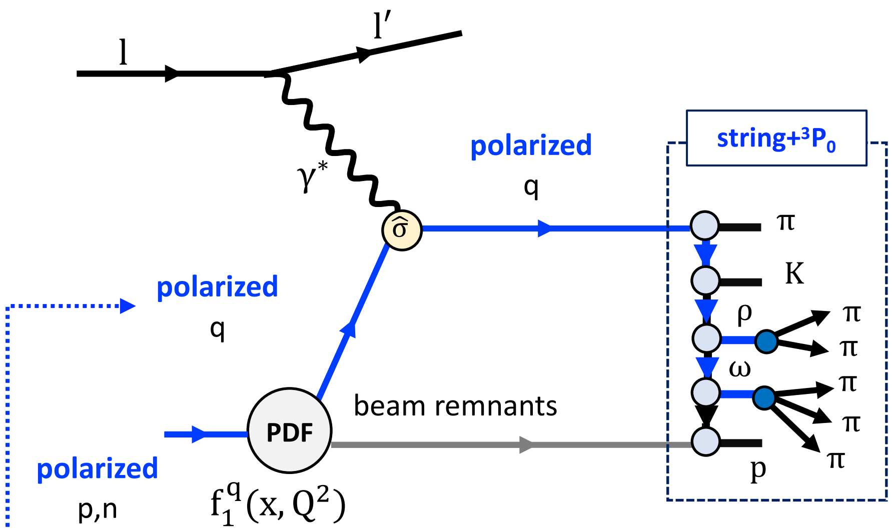
→ parametrization of transversity

$h_1^q(x)$ for valence quarks

Implementation in Pythia by StringSpinner

(polarized) Deep Inelastic Scattering

AK, L. Lönnblad, CPC **272** (2021) 108234;CPC **292** (2023) 108886

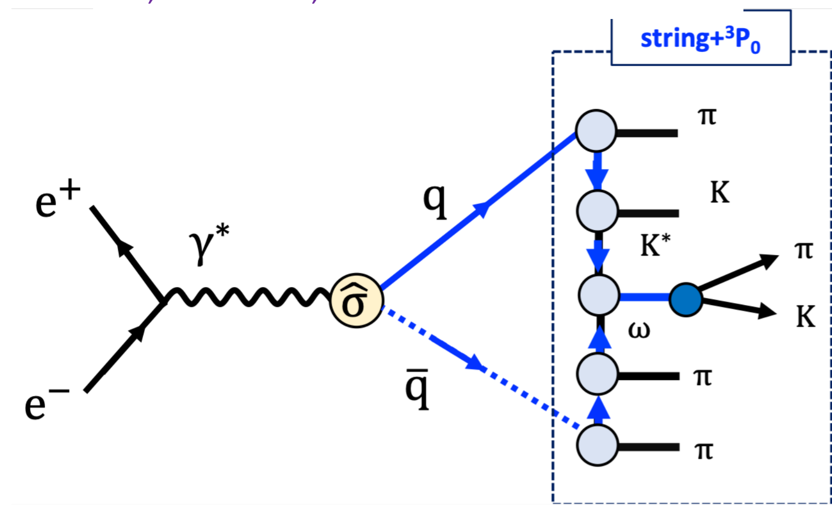


e^+e^- annihilation to hadrons

AK, X. Artru, PRD 110 (2024) 7, 074029

AK, L. Lönnblad, A. Martin, PRD 110 (2024) 7, 074029

AK, L. Lönnblad, arXiv:2606.27162



Initial condition: spin density matrix of q

→ parametrization of transversity

$h_1^q(x)$ for valence quarks

Initial condition: joint spin density matrix of $q\bar{q}$

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

No parton showers!

Tuning of StringSpinner (ongoing work)

with A. Buckley, C. Gutschow, L. Lönnblad

4 parameters for spin

Tuning of StringSpinner: procedure

- Sample $\vec{p}_i = (\mathrm{Re}(\mu), \mathrm{Im}(\mu), f_L, \theta_{LT})_i$ (100 times)

  - for each $\vec{p}_i$
    run Pythia+StringSpinner
    calculate observables O_1, O_2 ... (Collins, 2h asymmetries)

- Parametrize $O_b^{MC}(\vec{p})$ as function of $\vec{p}$ for each bin b

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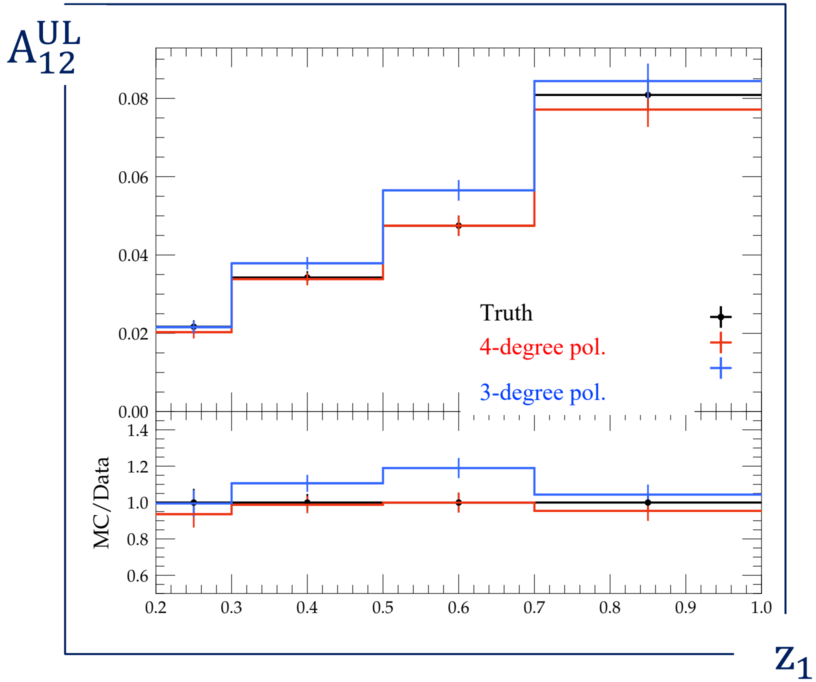


Example of polynomial interpolation

$$A_{12}^{UL}(z_1)$$
$$0.2 < z_2 < 0.3$$

Tuning of StringSpinner: procedure

- Sample $\vec{p}_i = (\mathrm{Re}(\mu), \mathrm{Im}(\mu), f_L, \theta_{LT})_i$ (100 times)

  - for each $\vec{p}_i$
    run Pythia+StringSpinner
    calculate observables O_1, O_2 ... (Collins, 2h asymmetries)

- Parametrize $O_b^{MC}(\vec{p})$ as function of $\vec{p}$ for each bin b
- Minimize

$$X^2 = \sum_O \sum_b \frac{\left(O_b^{MC}(\vec{p}) - O_b^D\right)^2}{\sigma^2_{O_b^{MC}} + \sigma^2_{O_b^D}}$$

- Obtain $\vec{p}_{tune}$

PROFESSOR 2

A. Buckley et al., EPJ C 65 (2010) 331-357

Tuning of StringSpinner

- BELLE and BABAR data

BELLE

PRD 78, 032011 (2008)

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

$\pi\pi$

32 pts

BABAR

PRD 90, 052003 (2014)

PRD 92, 111101(R) (2015)

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

$\pi\pi$, πK, KK

110 pts

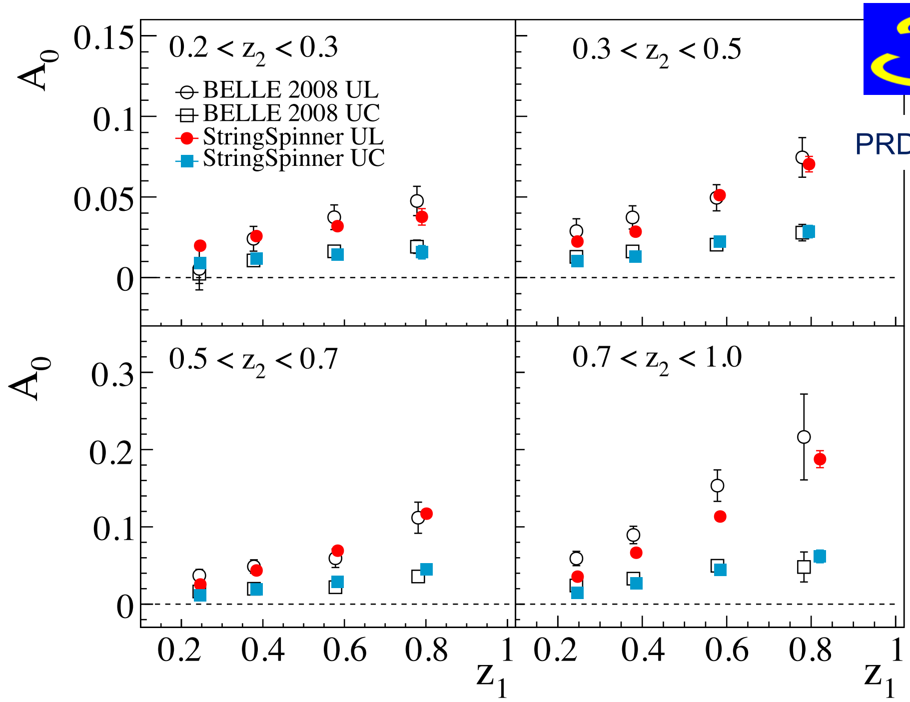
Total pts 142

- **Tune**

$\mathrm{Re}(\mu) = 0.30$ +/- 0.03
$\mathrm{Im}(\mu) = 0.38$ +/- 0.06
$f_L = 0.12$ +/- 0.05
$\theta_{LT} = -0.05$ +/- 0.15

T pol. for VMs
No L/T interference

A_0 for ππ: BELLE



PRD 78, 032011 (2008)

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

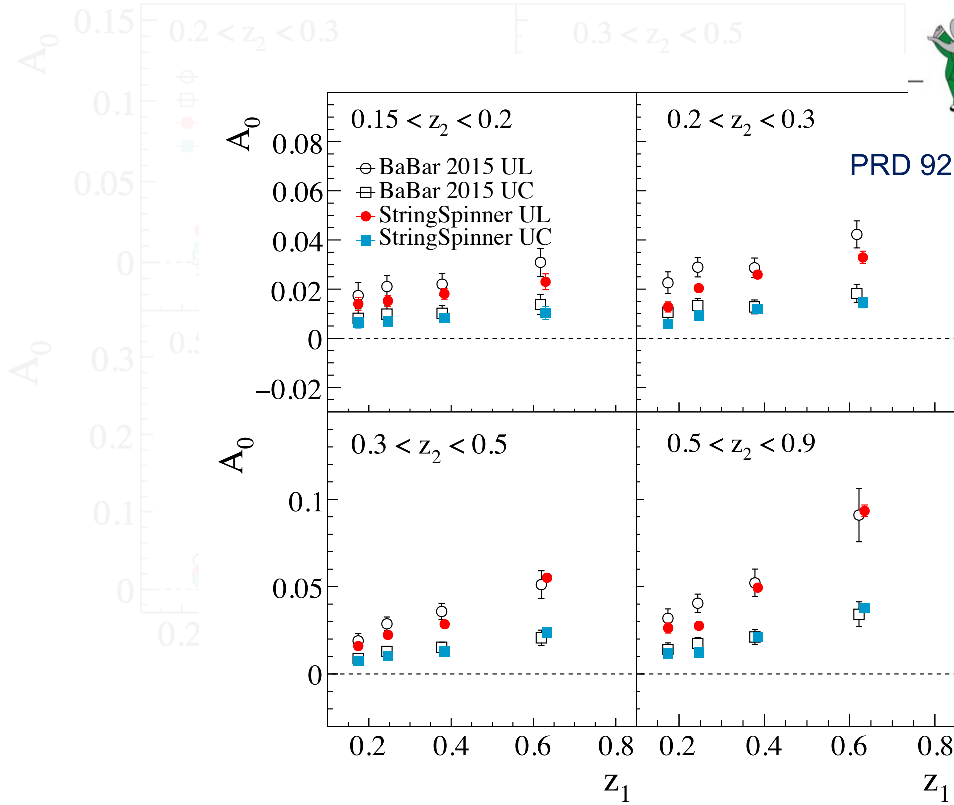
$$A_0^{UC} \simeq A_0^{U} - A_0^{C}$$

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

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

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

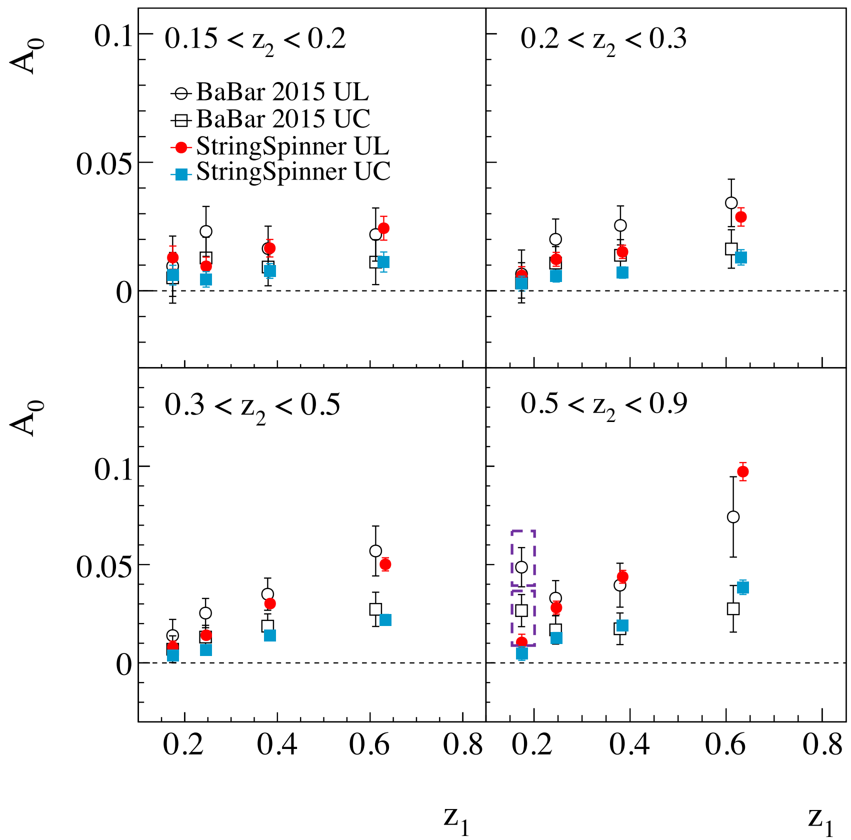
A_0 for ππ: BABAR



PRD 92, 111101(R) (2015)

A_0 for πK: BABAR

PRD 92, 111101(R) (2015)

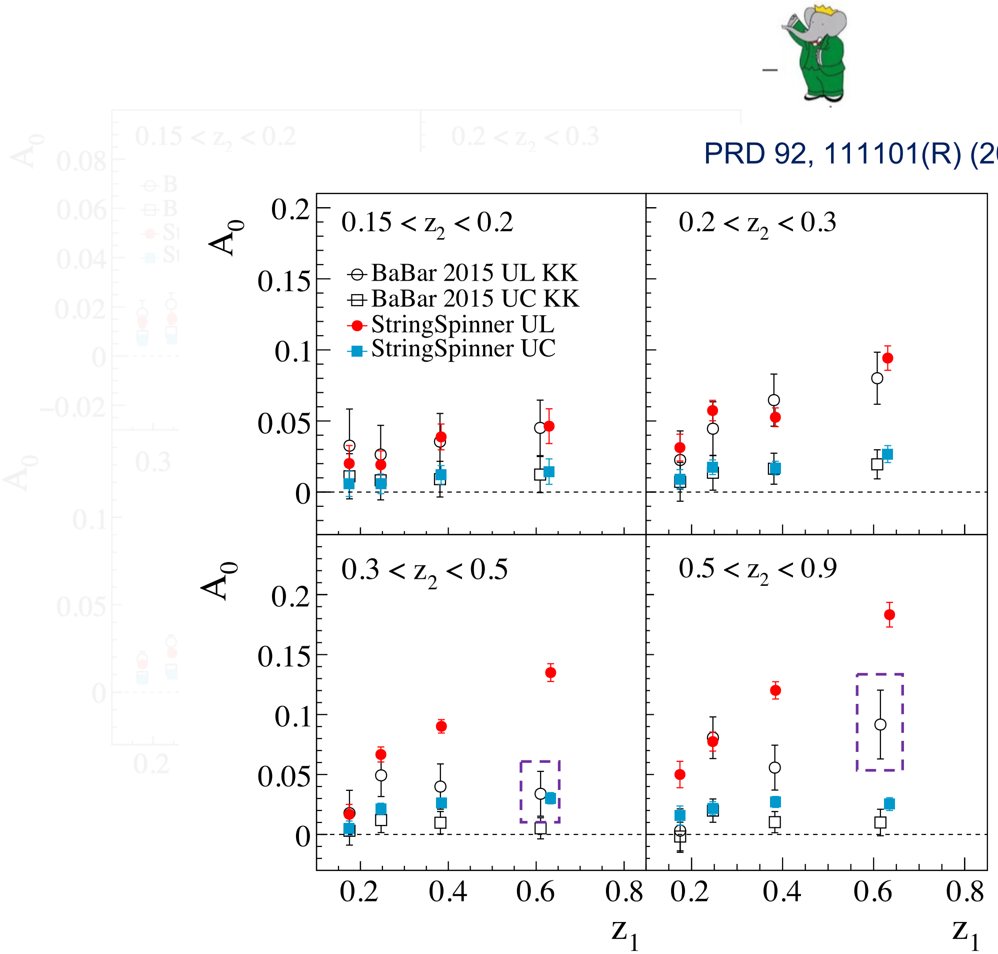


excluded from tuning

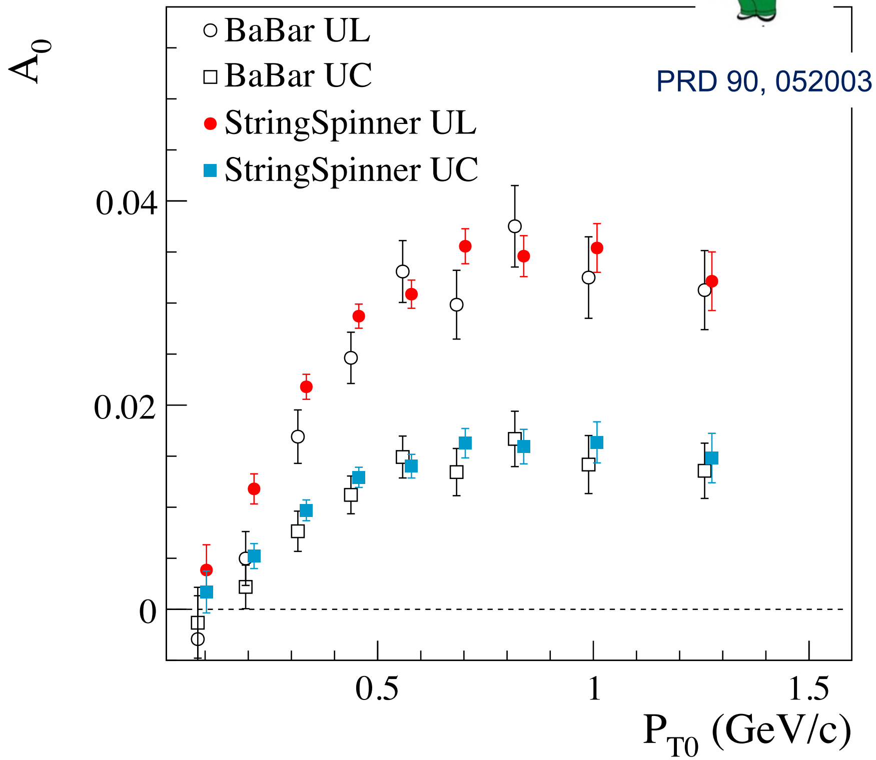
A_0 for KK: BABAR

PRD 92, 111101(R) (2015)

excluded from tuning

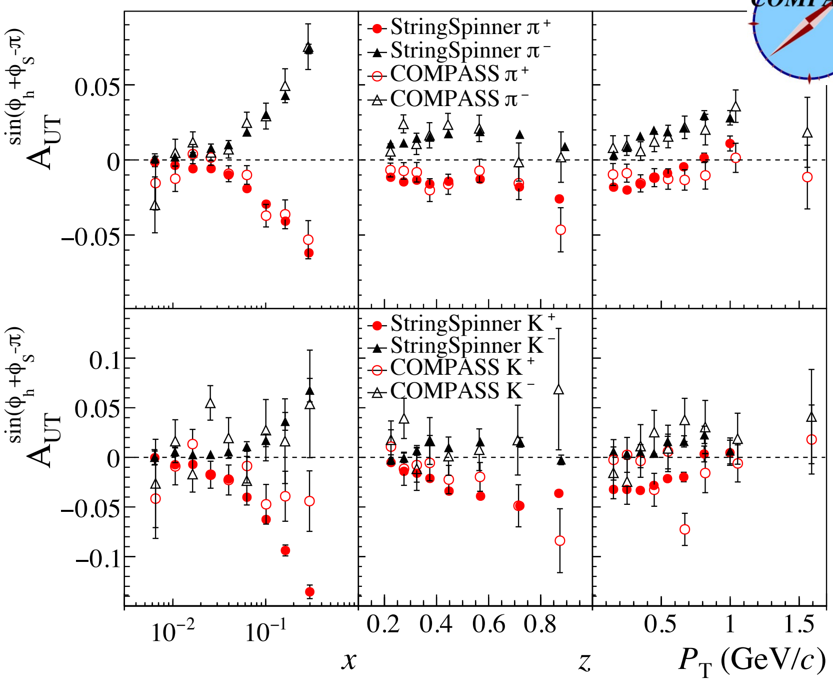


A_0 for ππ: BABAR



PRD 90, 052003 (2014)

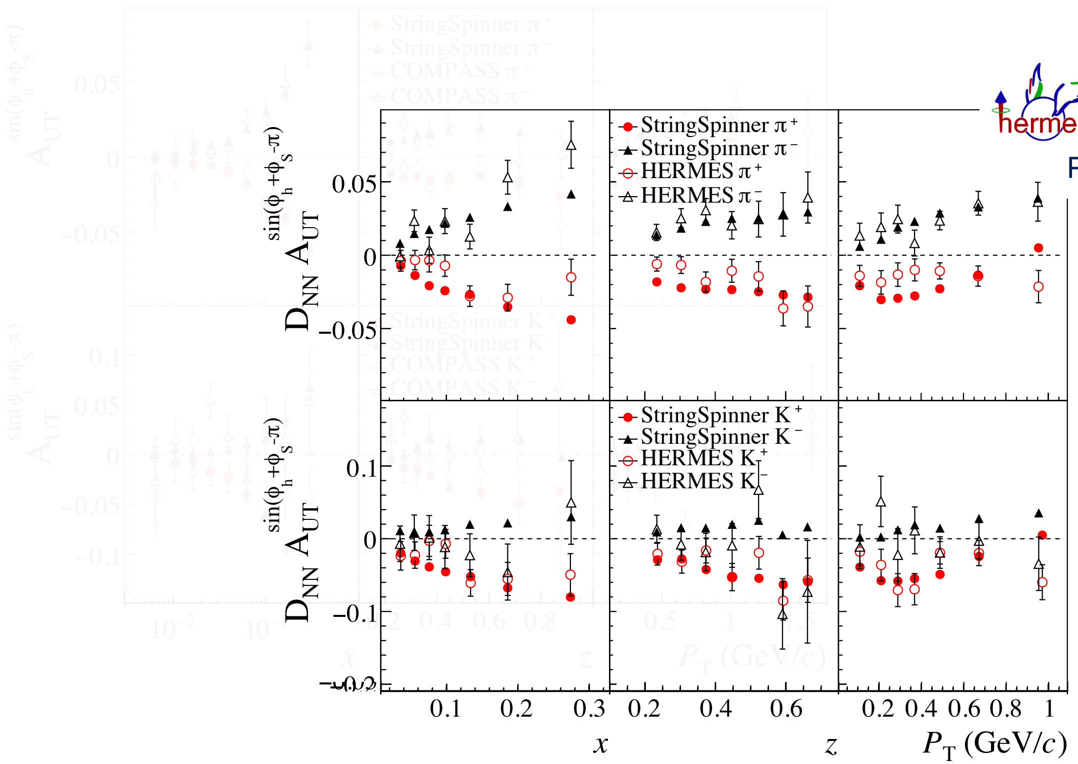
Collins asymmetry in SIDIS: COMPASS



PLB 717 (2012) 376

Collins asymmetry @ COMPASS

Collins asymmetry in SIDIS: HERMES



PLB 693 2010) 11

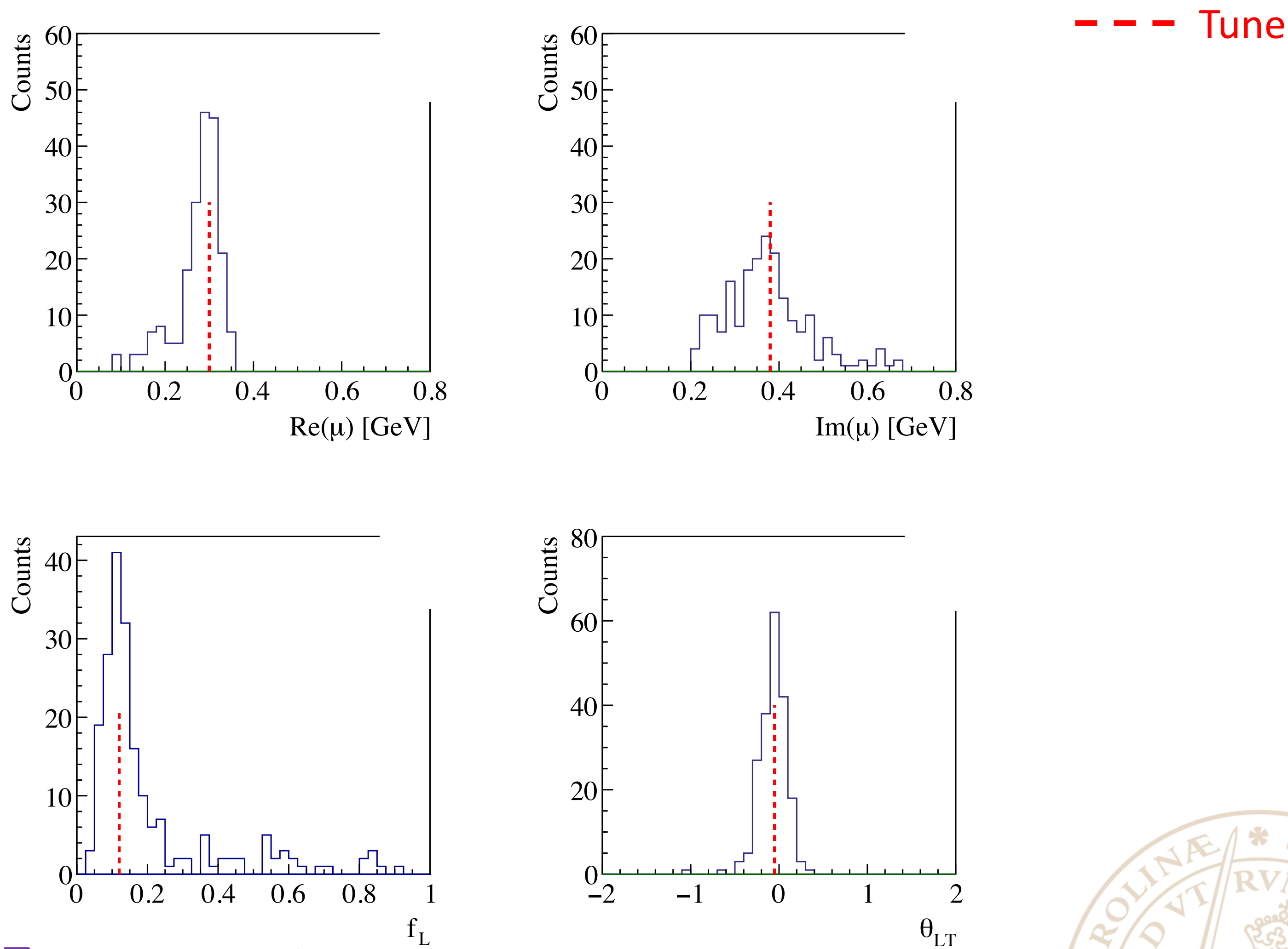
Collins asymmetry @ HERMES

Tuning of StringSpinner (ongoing work)
with A. Buckley, C. Gutschow, L. Lönnblad

How well do we know the parameters?

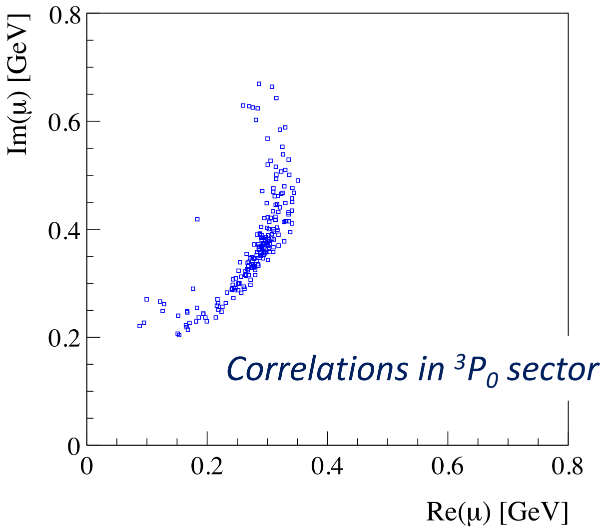
200 replica of each measured asymmetry
same tuning procedure for each replica

Distribution of free parameters from replica



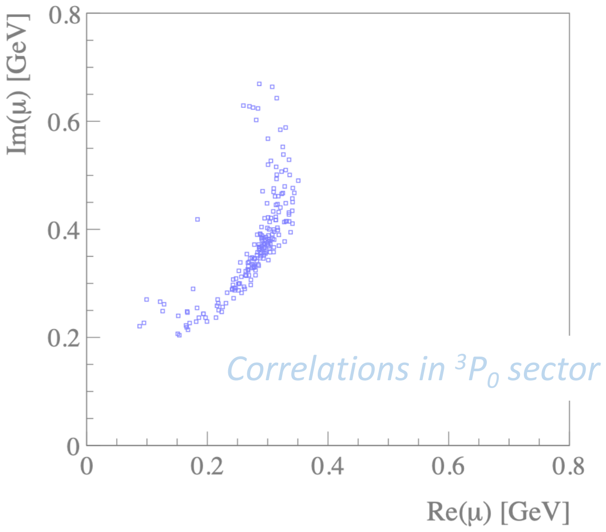
- Agreement with tune
- Tail in f_L?

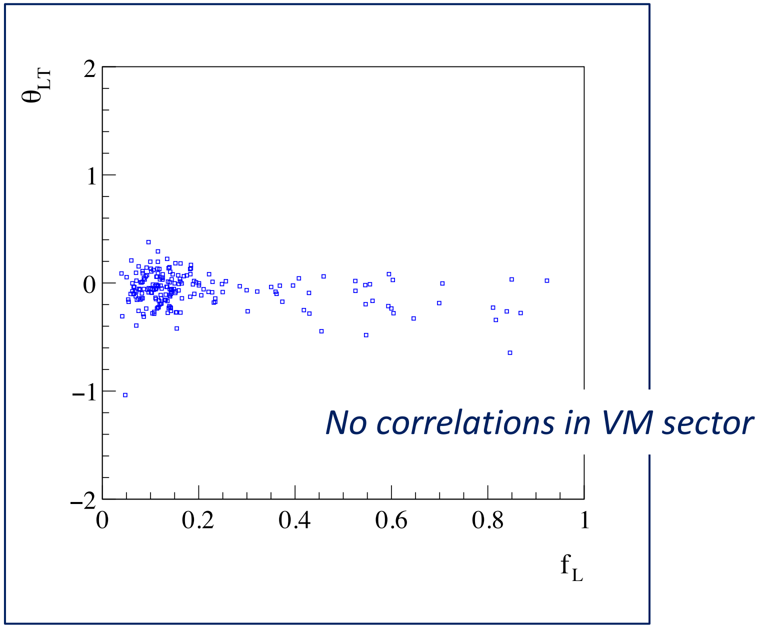
Correlations between free parameters from replica



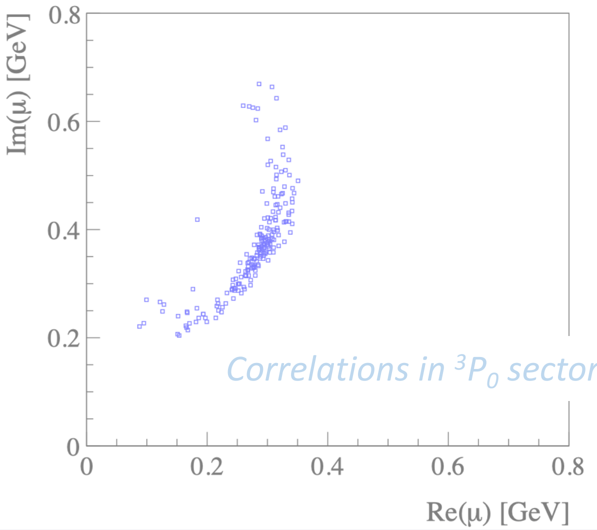
Correlations in $^3P_0$ sector

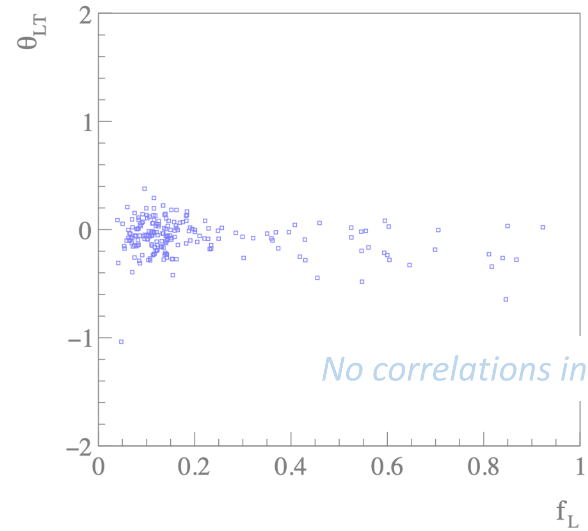
Correlations between free parameters from replica

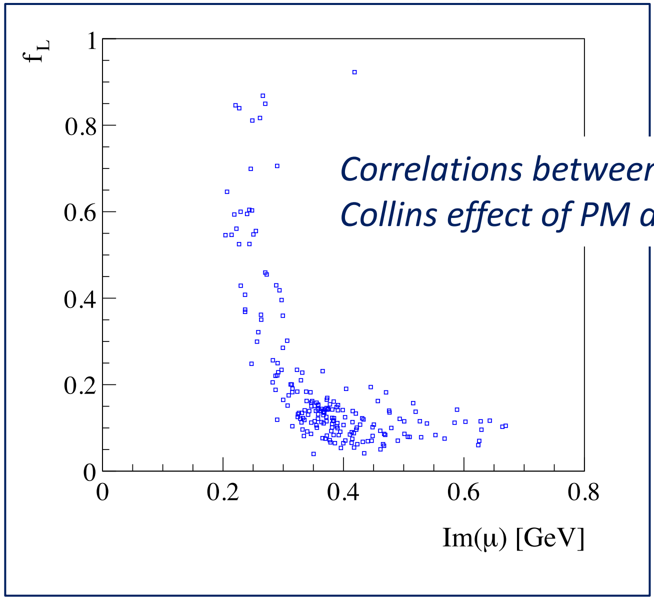




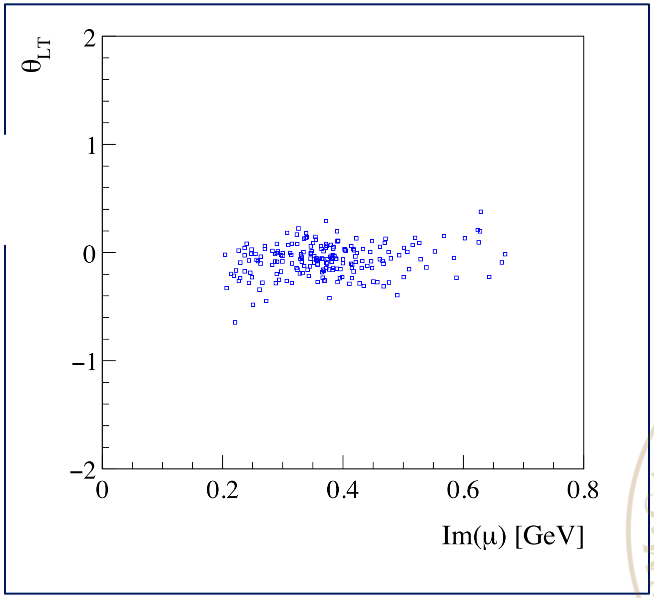
Correlations between free parameters from replica







Correlations between Collins effect of PM and VM



Other spin effect

FFs: $q \rightarrow h + X$

Hadron Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	D_1		$H_1^\perp$ -

Collins FF

Collins, NPB 396, 161 (1993)

Other spin effect

FFs: $q \rightarrow h + X$

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U	D_1		$H_1^{\perp}$ -

Collins FF

Collins, NPB 396, 161 (1993)

Dihadron FFs: $q \rightarrow h_1 h_2 + X$

Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
D_1	$G_1^{\perp}$	$H_1^{\perp}, H_1^{\sphericalangle}$

→ Beam spin asymmetries in SIDIS

«interference» FF

→ used for extractions of transversity

Collins et al., NPB 420 (1994) 565–582

Jaffe et al., PRL 80 (1998) 1166–1169

Bianconi et al., PRD 62 (2000) 034008

Pitonyak et al., PRL 132, 011902 (2024)

Other spin effect

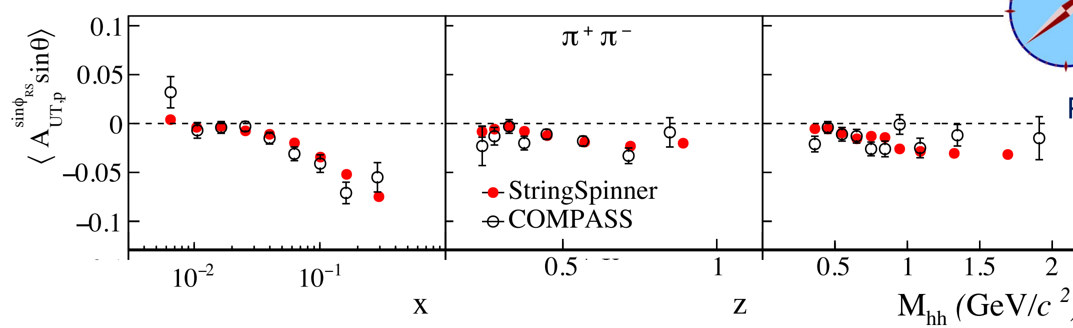
FFs: $q \to h + X$

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Hadron Polarization	U	D_1		$H_1^\perp$

Collins FF

Collins, NPB 396, 161 (1993)

Dihadron asymmetry



PLB 845 (202

reproduced by string+$^3P_0$

Dihadron FFs: $q \to h_1 h_2 + X$

Quark polarization		
Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
D_1	$G_1^\perp$	$H_1^\perp, H_1^\sphericalangle$

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Pitonyak et al., PRL 132, 011902 (2024)

Other spin effect

FFs: $q \rightarrow h + X$

Hadron Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	D_1		$H_1^{\perp}$ -
L		G_{1L} -	$H_{1L}^{\perp}$ -
T	$D_{1T}^{\perp}$ -	G_{1T} -	H_1 - $H_{1T}^{\perp}$ -

"helicity" FF

Collins FF

Collins, NPB 396, 161 (1993)

"transversity" FF

initially proposed as analyzer for transversity

Polarizing FF → hyperon spont. polarization

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

Other spin effect

FFs: $q \rightarrow h + X$

Hadron Polarization	Quark polarization: Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	D_1		$H_1^\perp$ -
L		G_{1L} -	$H_{1L}^\perp$ -
T	$D_{1T}^\perp$ -	G_{1T} -	H_1 - $H_{1T}^\perp$ -

Collins FF

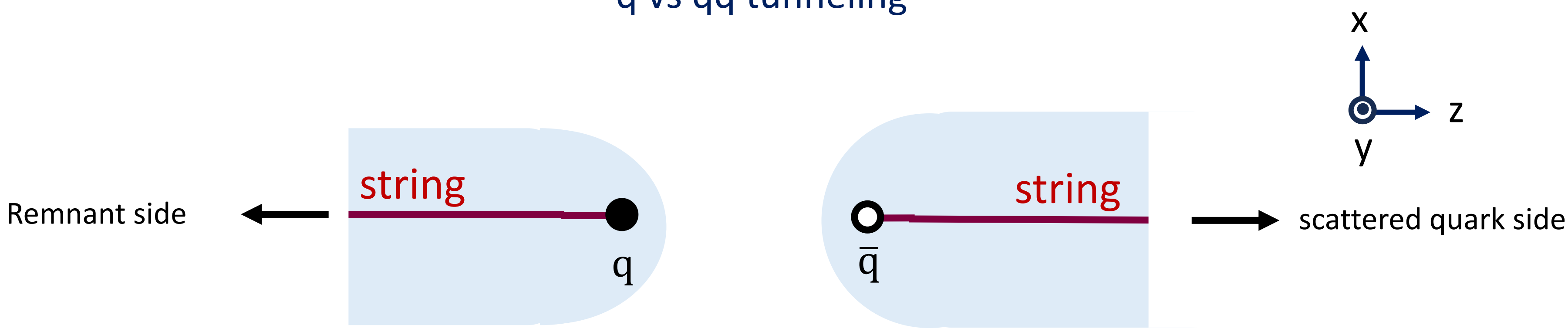
Collins, NPB 396, 161 (1993)

Requires a model for baryon production!

spin-1/2 baryons

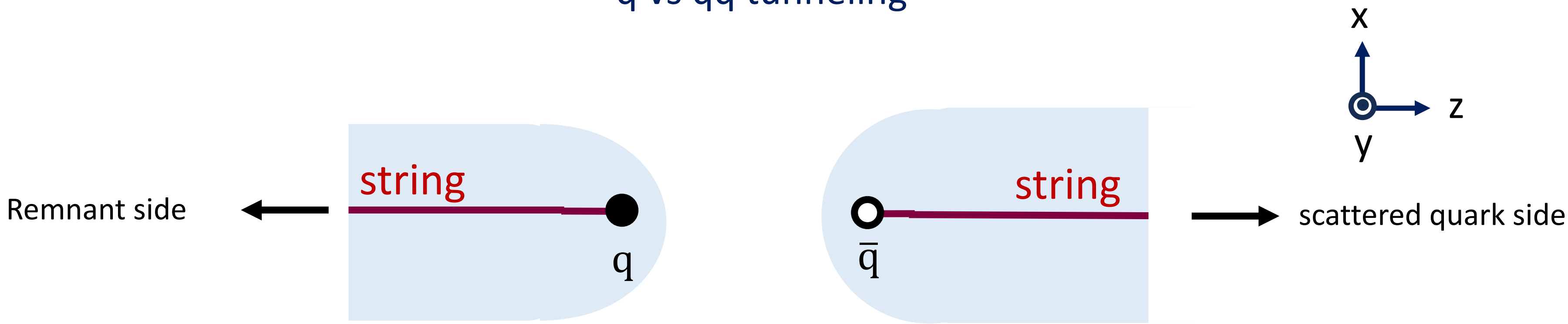
AK, X. Artru, Phys.Rev.D 113 (2026) 3, 034007

String breaking
q vs qq tunneling

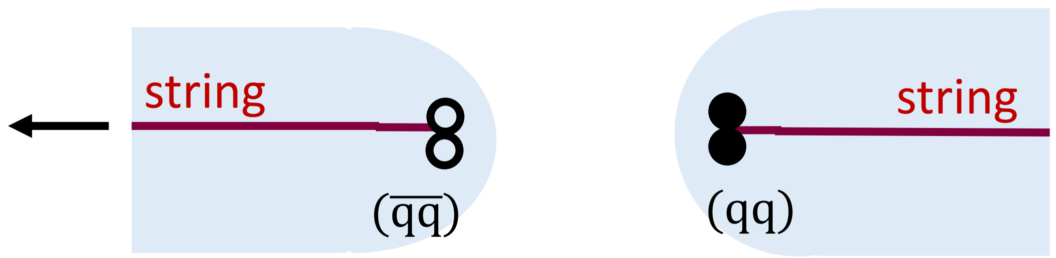


or

String breaking
q vs qq tunneling



or



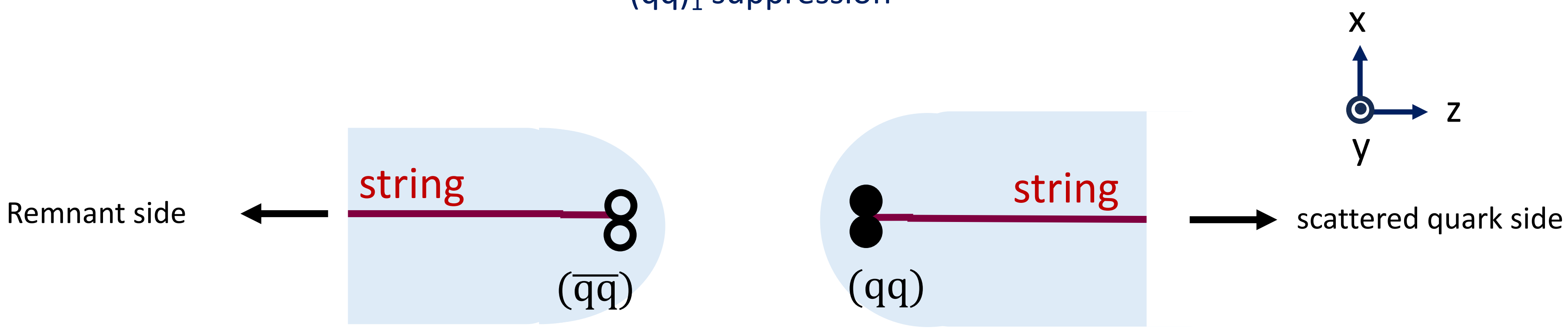
diquark tunneling suppressed w.r.t quark tunneling

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

Pythia 8

String breaking

$(qq)_1$ suppression



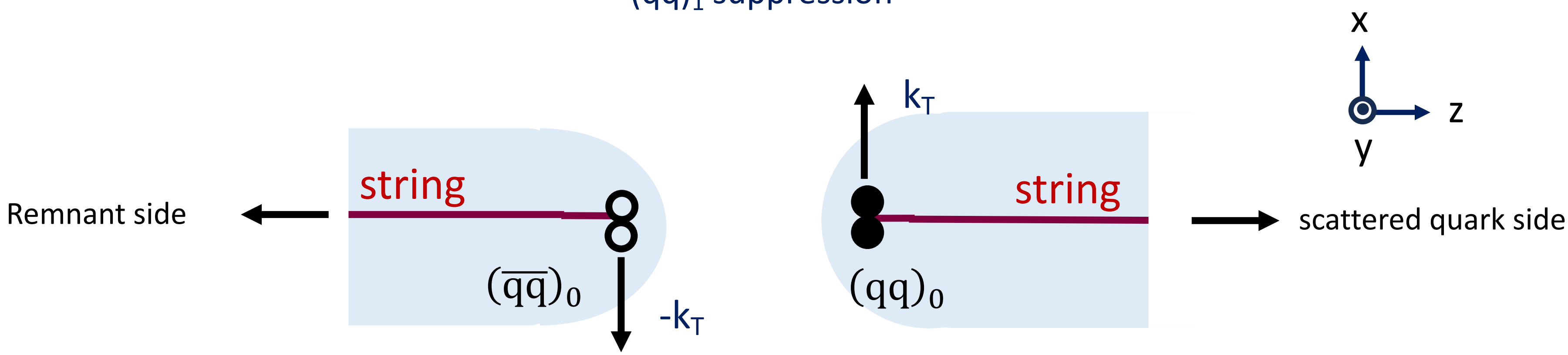
Suppression of spin-1 diquarks

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

Pythia 8

String breaking

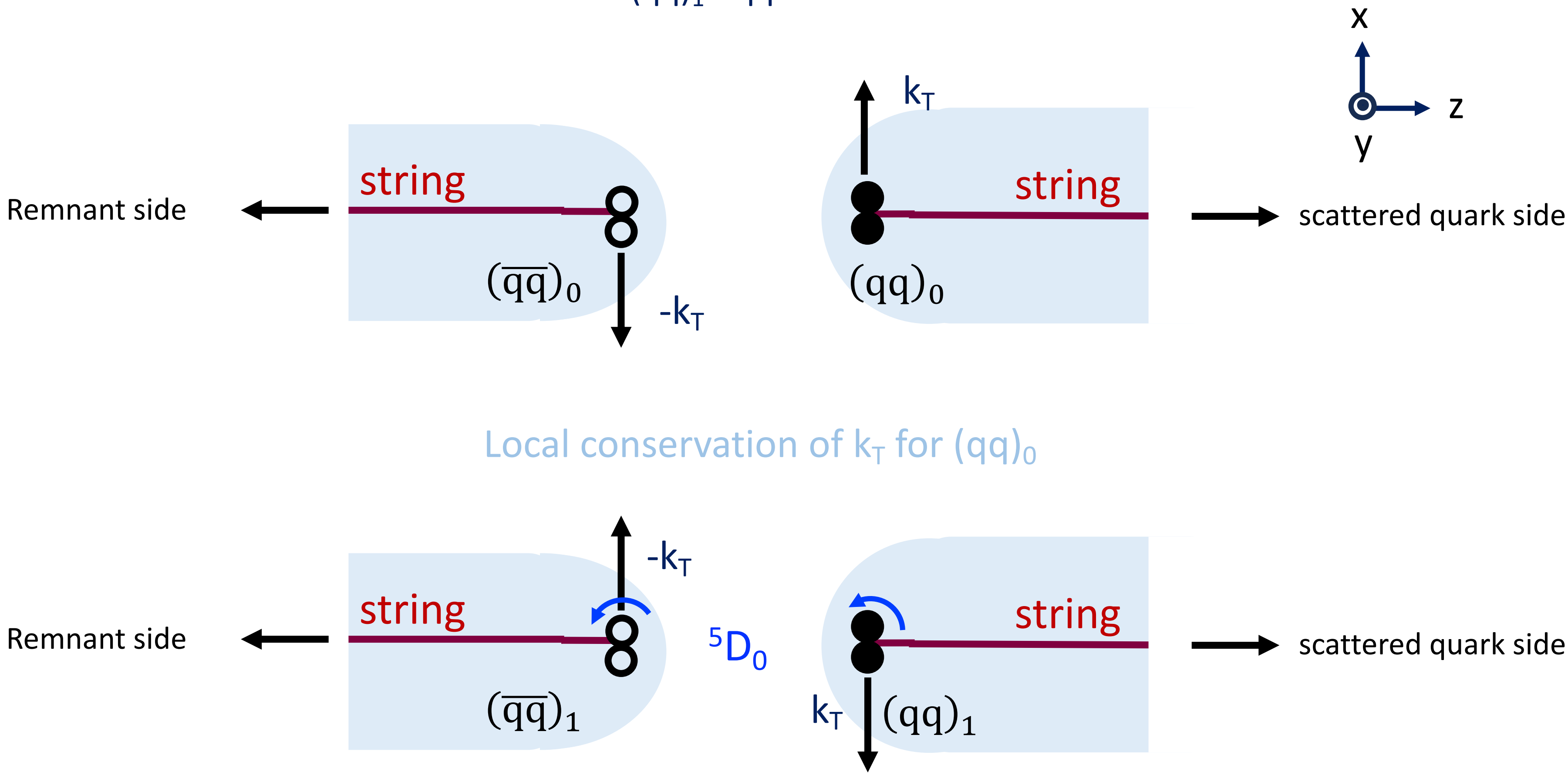
$(qq)_1$ suppression



Local conservation of k_T for $(qq)_0$

String breaking

$(qq)_1$ suppression



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

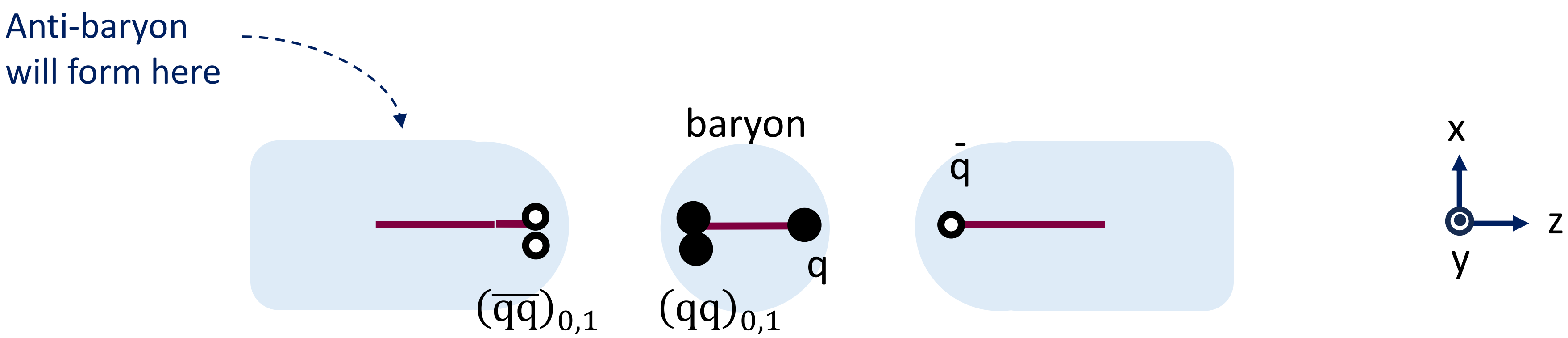
$^5D_0$ mechanism

3x3 propagator depending on complex mass μ_{qq}

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

Baryon production

two successive string breakings



Coupling with $(qq)_0$

$$\Gamma_B = 1$$

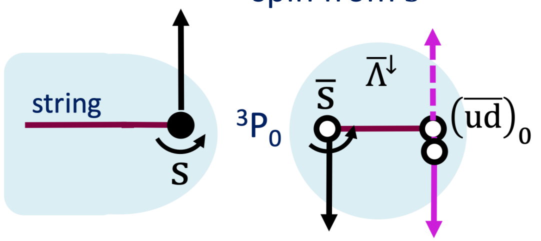
Coupling with [polarization vector of] $(qq)_1$

$$\Gamma_B = \boldsymbol{\sigma} \cdot \mathbf{V}_{qq}$$

No new free parameters

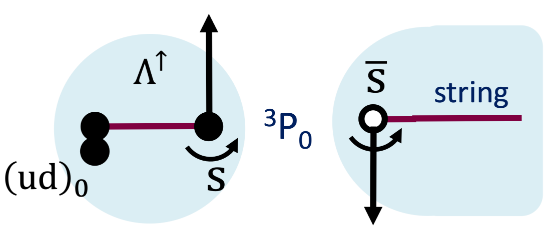
Hyperon production

$\overline{\Lambda}$ inherits transverse spin from $\bar{s}$



Λ inherits transverse spin from s

~large x_F
CFR



Λ inherits transverse spin from s

~negative x_F
TFR

Hyperon production

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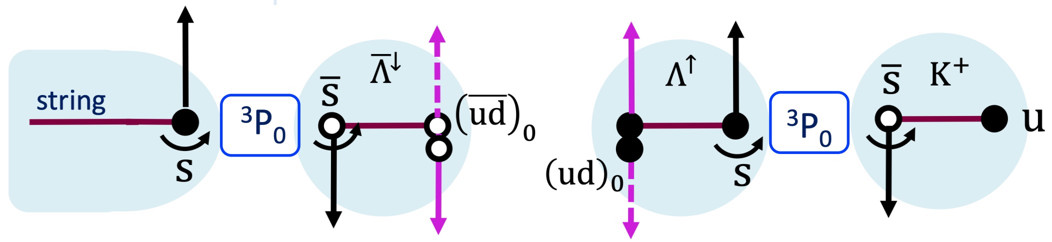

~large x_F
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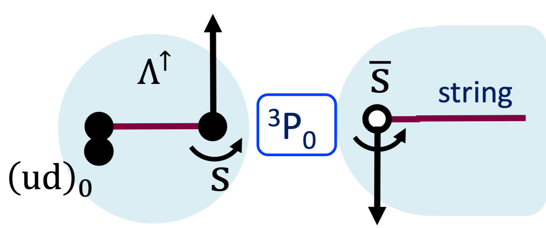
Λ inherits transverse spin from s



~negative x_F
TFR

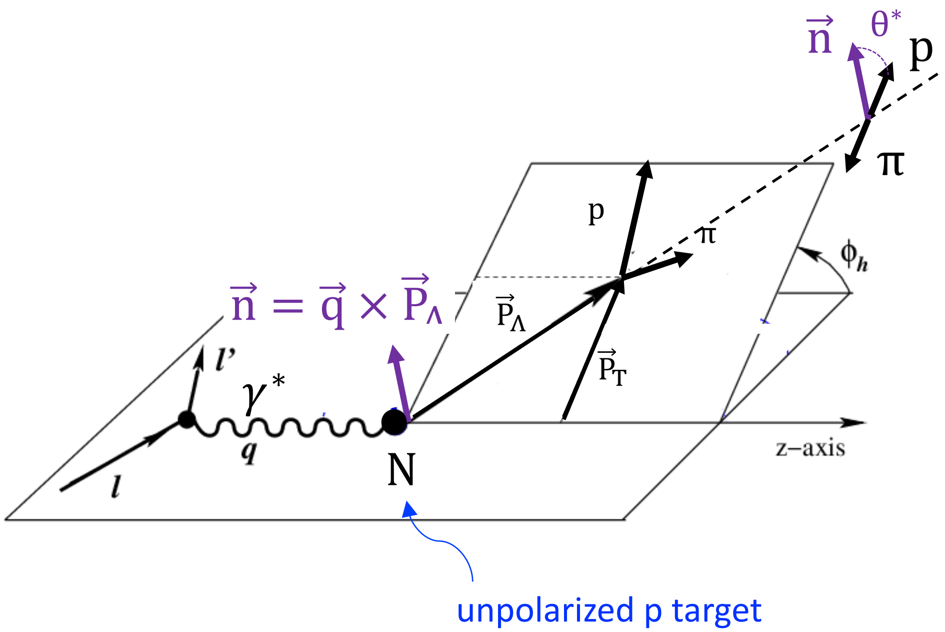
Λ inherits transverse spin from s

$^3P_0$ breakings → spin parameters fixed from Collins effect!

All this implemented in StringSpinner for DIS… (not public yet)

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

with G. Gustafson and L. Lönnblad

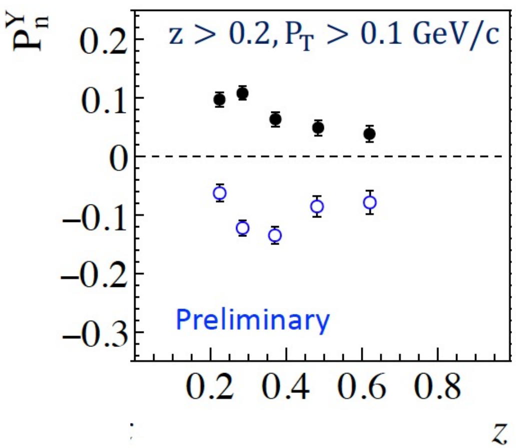


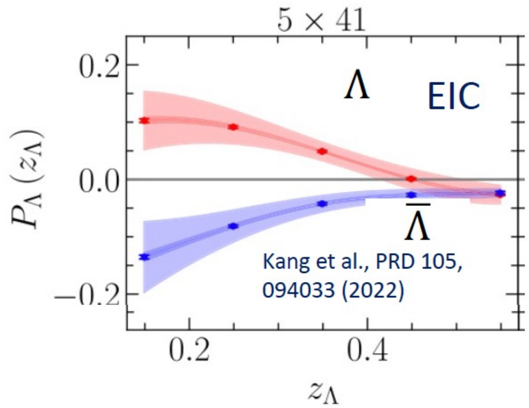
Extracted from the angular distribution of the decay proton in the Λ rest frame

$$\frac{dN_p}{d\cos\theta^*} \propto 1 + \alpha_\Lambda P_n^\Lambda \cos\theta^*$$

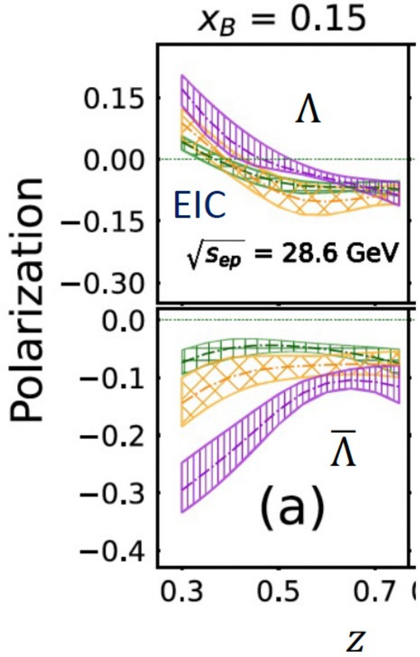
Spontaneous polarization of $\Lambda, \bar{\Lambda}$

«current fragmentation»





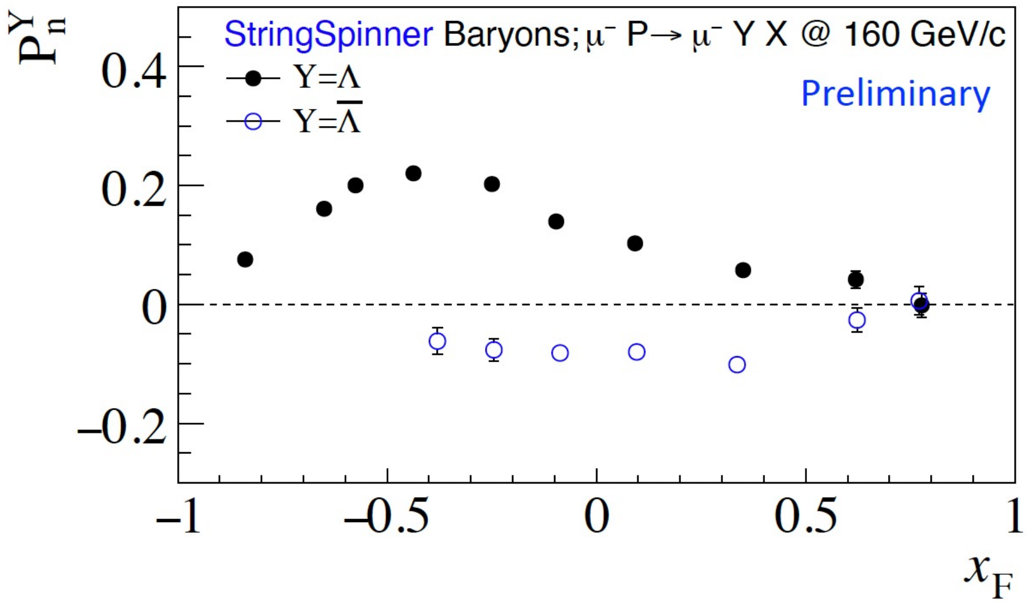
D'Alesio et al.,
PRD 108, 094004 (2023)



Similar values to recent extractions from e^+e^- data

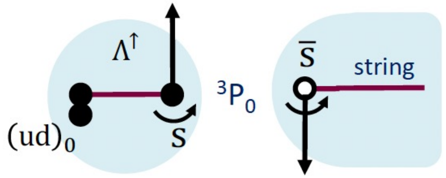
Spontaneous polarization of $\Lambda, \bar{\Lambda}$

«target fragmentation»



Large polarization predicted for Λ in target fragmentation

see also Andersson, Gustafson, Ingelman, PRL 85, 417 (1979)



Large Fracture Function $\widehat{M}_T^h$!

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

Conclusions

- We are building a model of hadronization with spin: string+$^3P_0$
  interfaced to Pythia via StringSpinner

- So far promising
  Collins effect but also
  dihadron asymmetries, beam-spin asymmetries, spontaneous polarization,…

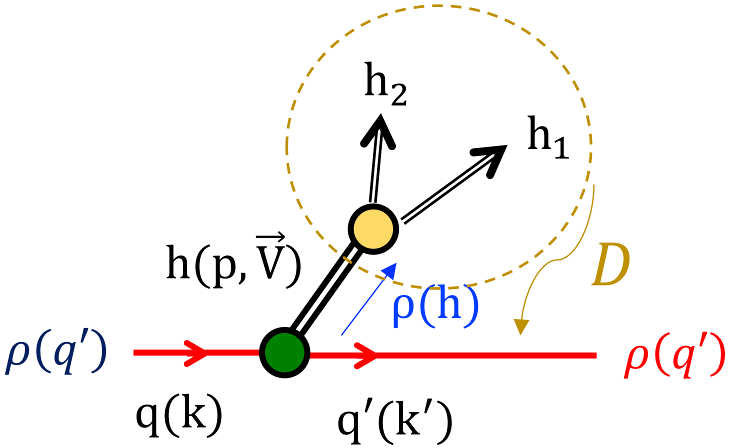
- The model can be used to systematically include spin in Pythia

- Ongoing developments
  implementation of spin effects for baryons
  tuning
  application of string+$^3P_0$ to strings with gluons/connection with the PS

Backup

The rules of the string+ $^3P_0$ model: VM meson emission

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



Emission probability $\quad \mathrm{dP}(\mathrm{q} \to \mathrm{h} + \mathrm{q}') = \mathrm{Tr}\, \sum_{\vec{V}} \mathrm{T}^{\vec{V}}_{q',h,q}\, \rho(q)\, \mathrm{T}^{\vec{V}\dagger}_{q',h,q}\, dZZ^{-1} d^2\boldsymbol{p}_T$

Density matrix of VM $\quad \rho_{ab}(h) = \mathrm{T}^{a}_{q',h,q}\, \rho(q)\, \mathrm{T}^{b\dagger}_{q',h,q}$

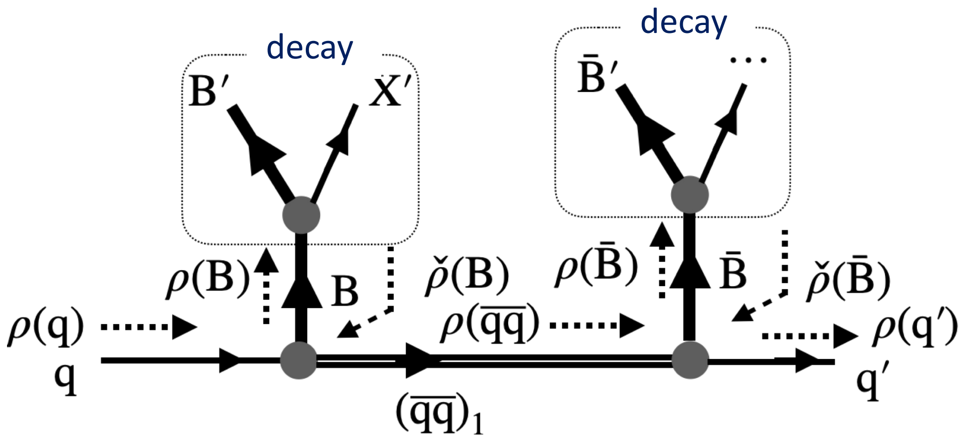
Decay of the VM $\quad dN/d\Omega \propto M_{\mathrm{decay}}(h \to h_1 h_2 ..)\ \rho(h)\ M^{\dagger}_{\mathrm{decay}}(h \to h_1 h_2 ..)$

Decay matrix $\quad D = M_{\mathrm{decay}}(h \to h_1 h_2 ..)\, M^{\dagger}_{\mathrm{decay}}(h \to h_1 h_2 ..)$

Collins '88, Knowles, '88

Propagation of quark spin $\quad \rho(q') = \mathrm{T}^{a}_{q',h,q}\ \ \rho(q)\ \ \mathrm{T}^{b\dagger}_{q',h,q}\ \ \mathrm{D}_{ba}(p_1, p_2, ..)/\ \mathrm{Tr}[..]$

Spin propagation along the fragmentation chain



Recursive algorithm starting e.g. with a quark q

i. chose if to break the string via $q\bar{q}$ or $qq-\overline{qq}$ using P_{qq}/P_q

ii. if qq, decide if $(qq)_1$ or $(qq)_0$ according to $P_{(qq)_1}/P_{(qq)_0}$

iii. draw B according to the splitting function for $q \rightarrow B + (\overline{qq})$

iv. Evaluate $\rho(B)$ and decay B $\rightarrow$ come back with acceptance matrix $\check{\rho}(B)$

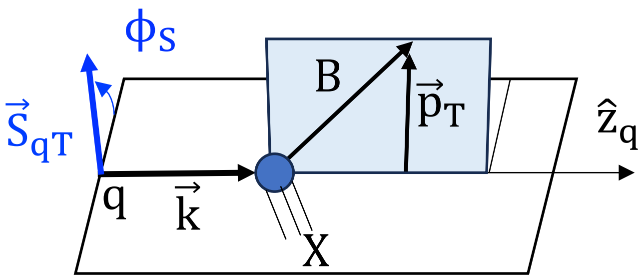
v. Draw $\overline{B}$ according to the splitting function for $\overline{qq} \rightarrow \overline{B} + q'$

vi. Decay $\overline{B}$ etc.

Note: only $B\overline{B}$ configurations, $BM_1..\overline{B}$ for future work
no interference effects

Introduction: spin effects in baryon production

- Production of spin 1/2 baryons, many interesting effects
  - **Collins effect** Collins, NPB 396, 161 (1993)

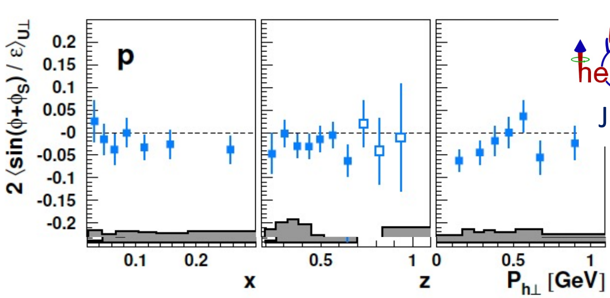


Collins FF

T polarized q
unpolarized B

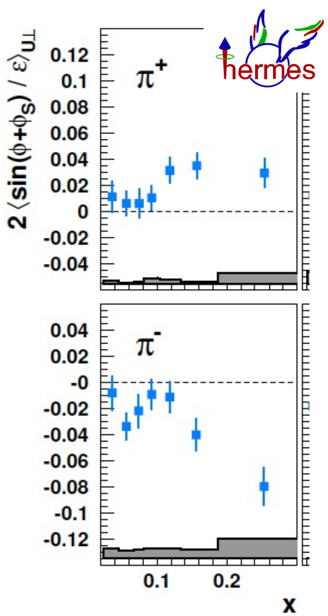
$$z = p^+/k^+$$

$$D_{q^\uparrow \to B+X}(z, \vec{p}_T) = D^B_{1q}(z, p_T^2) + \frac{H^{B\perp}_{1q}(z, p_T^2)}{zM_B} \vec{S}_{qT} \cdot \hat{z}_q \times \vec{p}_T$$

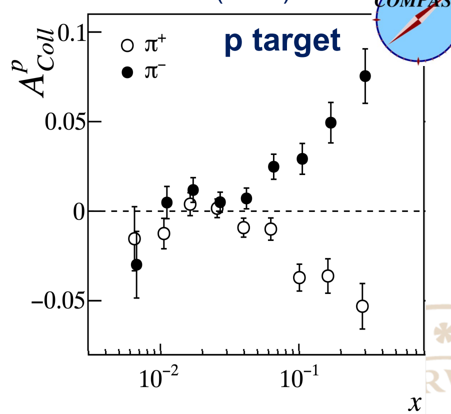


JHEP12 (2020) 010

p target



PLB 717 (2012) 376



pions

- Limited data
- Indication for a small effect (opposite to π^+)?

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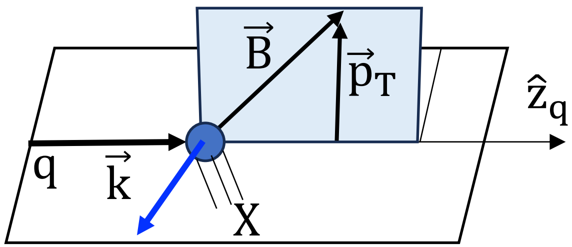
  - **Spontaneous polarization of hyperons**

Mulders, Tangerman, NPB 484, 538-540 (1997)
Anselmino et al., PRD 63 054029 (2001)



$\vec{S}_{BT} \propto \hat{z}_q \times \vec{p}_T$

Polarizing FF

unpolarized q
T polarized B

$$D_{q\to B^{\uparrow}+X}(z,\vec{p}_T) = D_{1q}^{B}(z,p_T^2) + \frac{D_{1q,T}^{B\perp}(z,p_T^2)}{zM_B}\vec{S}_{BT}\cdot\hat{z}_q\times\vec{p}_T$$

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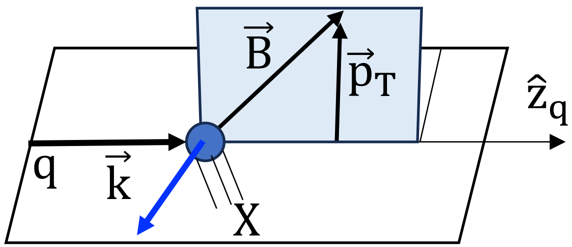

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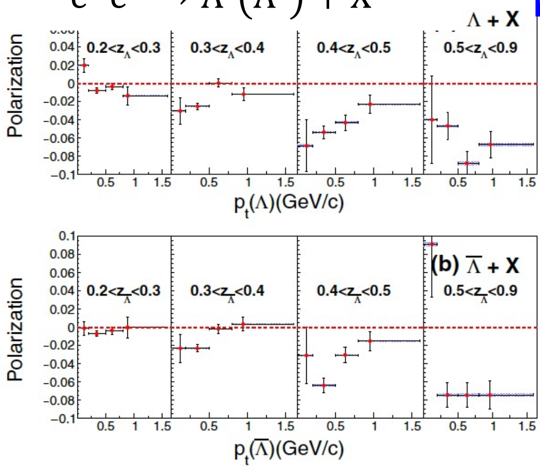
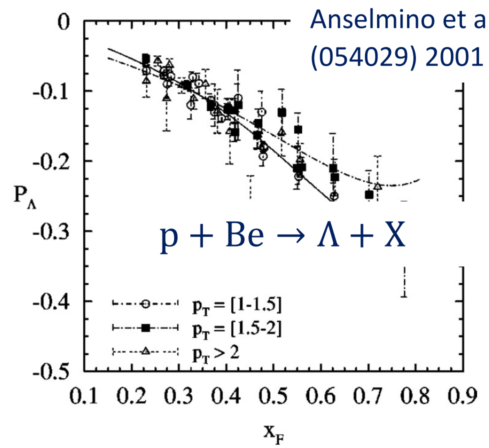
$e^+e^- \to \Lambda^\uparrow(\bar{\Lambda}^\uparrow) + X$

PRL 122, 042001 (2019)



Anselmino et al., PRD63 (054029) 2001



Sizeable effects both in hadronic collisions and e^+e^- annihilation

Many phenomenological studies
- Anselmino et al., PRD63 (054029) 2001
- D'Alesio, Murgia, Zaccheddu, PRD 102, 054001 (2020)
- D'Alesio, Gamberg, Murgia, Zaccheddu, JHEP12 (2022) 074; PRD 108, 094004 (2023); PLB 851 (2024) 138552
- Kang et al., PRD 105, 094303 (2022)

Introduction: spin effects in baryon production

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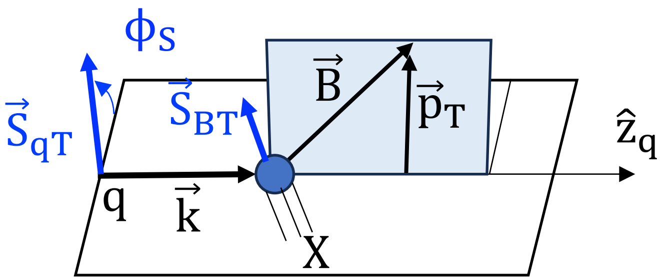
  - Collins effect
  - Spontaneous polarization of hyperons
  - **Transverse spin transfer to hyperons**



«transversity» FF — T polarized q, T polarized B

$$D_{q^\uparrow \to B^\uparrow + X}(z, \vec{p}_T) = D_{1q}^B\left(z, p_T^2\right) + H_{1q,T}^{B\perp}\left(z, p_T^2\right)\, \vec{S}_{BT} \cdot \vec{S}_{qT}$$

Introduction: spin effects in baryon production

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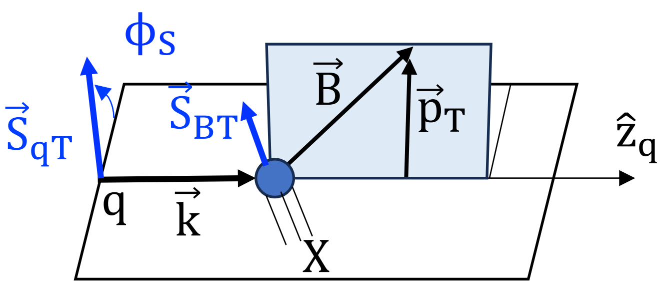
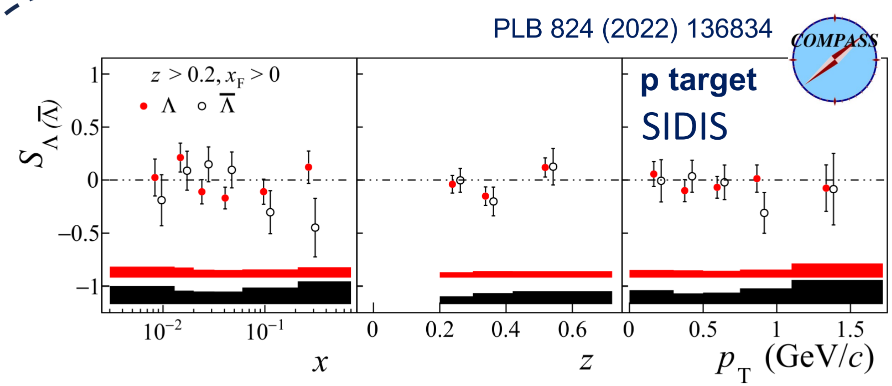


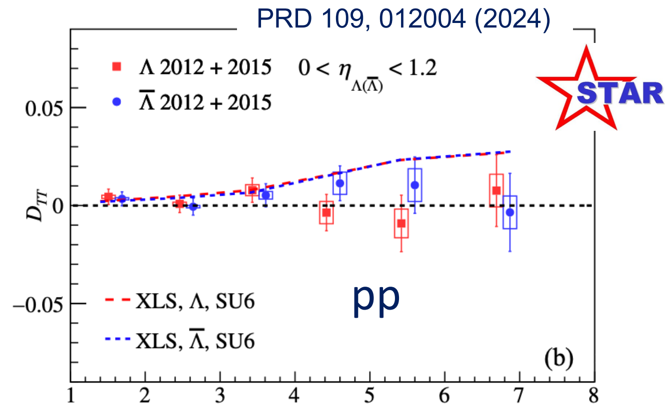
T polarized q
T polarized B
«transversity» FF

$$D_{q^{\uparrow}\to B^{\uparrow}+X}(z,\vec{p}_T) = D^B_{1q}(z,p_T^2) + H^{B\perp}_{1q,T}(z,p_T^2)\,\vec{S}_{BT}\cdot\vec{S}_{qT}$$

PLB 824 (2022) 136834

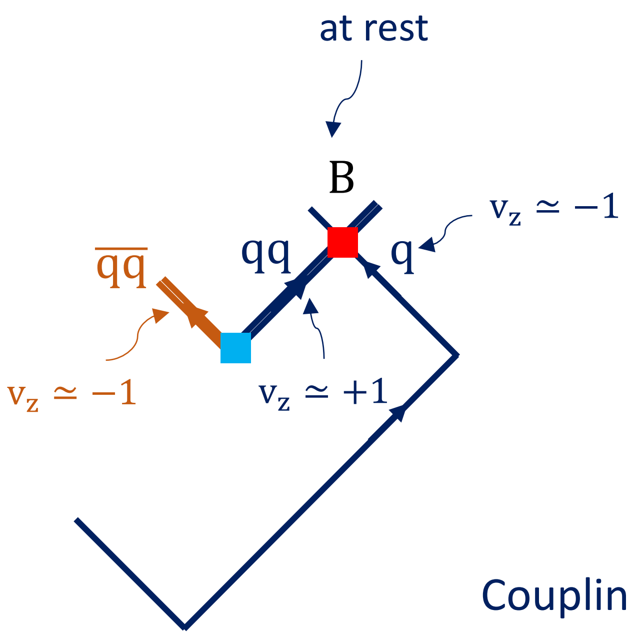


PRD 109, 012004 (2024)



The spin transfer to $\Lambda,\bar{\Lambda}$ is small?

Splitting amplitude for $q \rightarrow B + (\overline{qq})$



- Propagation of PV diquark $(qq)_1$

$$\chi^{\dagger}(\mathbf{S}_B)\, T_{(\overline{qq})_1,B,q}\, \chi(\mathbf{S}_q) = \left[F^{LM}_{(\overline{qq})_1,B,q}\right]^{\frac{1}{2}} \times$$

$$\times\, \phi^{\dagger}_{\overline{qq},a}\, \Delta_{qq,ab}(\mathbf{k}'_T)\;\; \chi^{\dagger}(S_B)\, \Gamma_{B,b}\, \chi(S_q)$$

$$\downarrow$$

$$\sigma_b$$
$$b = x, y, L$$

Coupling for $q \rightarrow B + qq$ from reduction of covariant amplitude

$$\bar{u}(B)\, \gamma_5\gamma^{\mu}\, \varepsilon^{*}_{qq,\mu}\, u(q) \rightarrow \phi^{\dagger}_{qq,b}\, \chi^{\dagger}(S_B)\, \sigma_b\;\, \chi(S_q)$$

Covariant coupling
Bacchetta, Conti, Radici, PRD78, 074010

reduced coupling

$$\phi_{qq} = (\boldsymbol{\varepsilon}_{\mathbf{T}}, \phi_L)$$

reduced qq pol. vector
with $v_z \simeq +1$

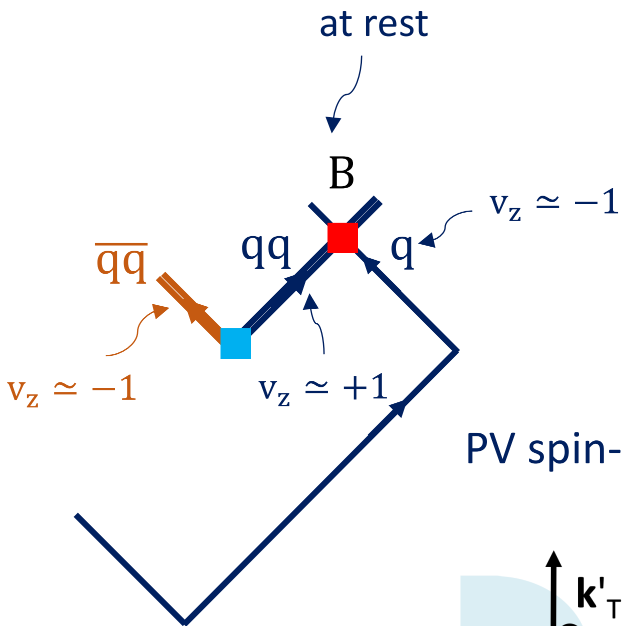
$$\phi_L = 2\varepsilon^{z}_{qq}$$

B at rest with boosts

$$B_T^{-1}(p_T/\varepsilon_B^2)B_L^{-1}(p_z/M_B)$$

required by LR symmetry

Splitting amplitude for $q \to B + (\overline{qq})$



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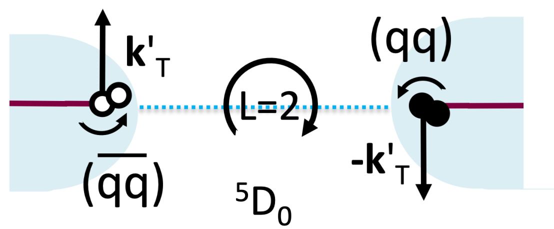
PV spin-1 diquark propagator



Vacuum quantum numbers

$J^{PC} = 0^{++} \to \vec{L} = -(\vec{S}_{qq} + \vec{S}_{\overline{qq}})$

$P = (-)^L, \qquad C = (-)^{L+S}$

Hence

$L = S = 0 \to {}^1S_0$ state

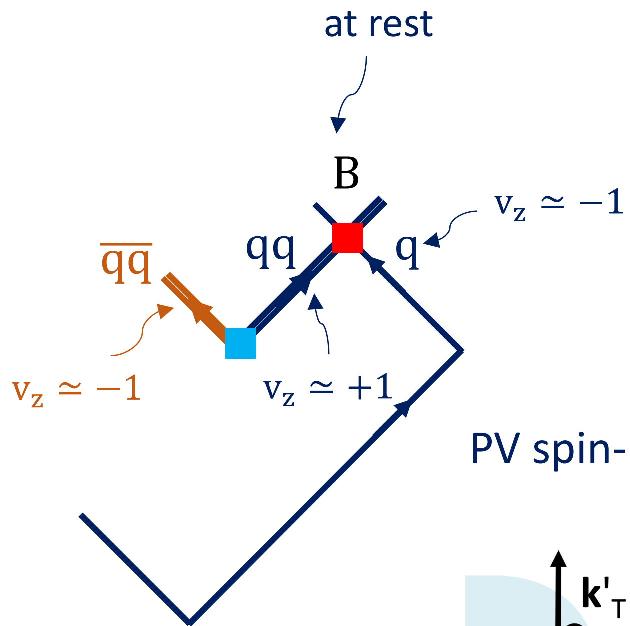
$L = S = 2 \to {}^5D_0$ state

Schwinger mechanism $\langle L \rangle \sim 1.3$

$m_{qq} \simeq 0.5\mathrm{GeV}$

$\to$ mainly $^5D_0$ state

Splitting amplitude for $q \rightarrow B + (\overline{qq})$



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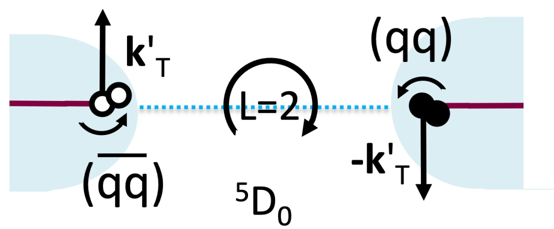
PV spin-1 diquark propagator



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Schwinger mechanism $\langle L \rangle \sim 1.3$

$m_{qq} \simeq 0.5\text{GeV}$

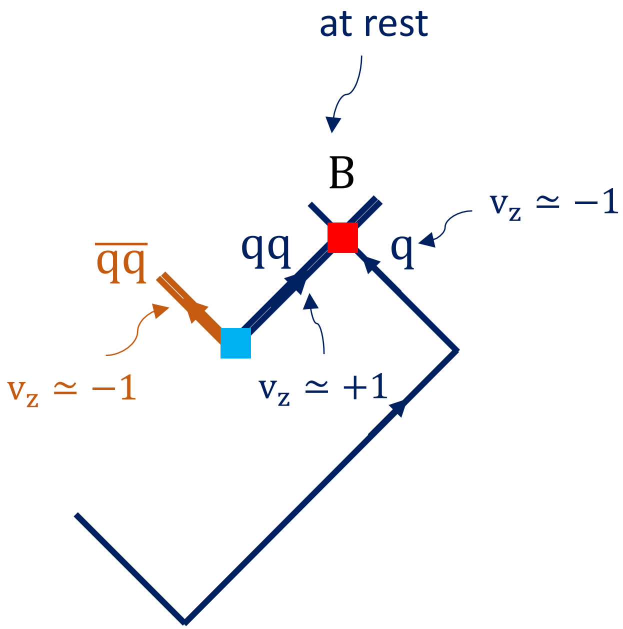
$\rightarrow$ mainly ${}^5D_0$ state

$$\Delta_{qq}(\vec{k}'_T) = \begin{pmatrix} {k'_x}^2 + m^2_{qq}/3 & k'_x k'_y & \kappa_{qq} k'_x \\ k'_x k'_y & {k'_y}^2 + m^2_{qq}/3 & \kappa_{qq} k'_y \\ \kappa_{qq} k'_x & \kappa_{qq} k'_y & \kappa^2_{qq} + m^2_{qq}/3 \end{pmatrix}$$

κ_{qq} new complex parameter
inspired by diquark momentum
during tunneling

$$k_z \simeq i\sqrt{m^2_{qq} + k'^2_T}$$

Splitting amplitude for $q \to B + (\overline{qq})$



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$$\times\, \phi^\dagger_{\overline{qq},a}\, \Delta_{qq,ab}(\mathbf{k}'_T)\ \chi^\dagger(S_B)\, \Gamma_{B,b}\, \chi(S_q)$$

- ❑ Propagation of scalar diquark $(qq)_0$

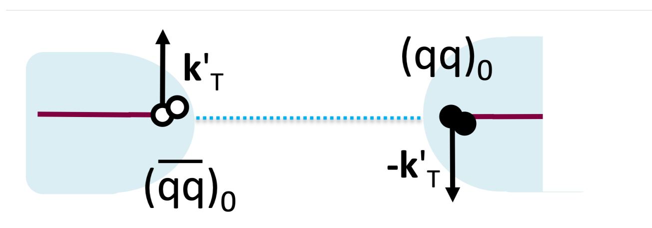
$$\chi^\dagger(\mathbf{S}_B)\, T_{(\overline{qq})_0,B,q}\, \chi(\mathbf{S}_q) = [F^{LM}_{(\overline{qq})_0,B,q}]^{\frac{1}{2}} \times$$

$$\times \phi^\dagger_{(qq)_0}\ \chi^\dagger(S_B)\, \Gamma_{B,0}\, \chi(S_q)$$

c-number

$1_{2\times 2}$

Reduction of the covariant amplitude
$\bar{u}(B)\ 1_{4\times 4}\ u(q)$



no spin-$\mathbf{k}'_T$ correlation at string breaking