EMMI RRTF: Impact of Vector Mesons on the Studies
of the 3D Structure of the Nucleon
CERN
15/06/2026

Modeling vector meson production within the StringSpinner framework

Albi Kerbizi

Lund University
INFN Trieste

Funded by the European Union

MARIE CURIE ACTIONS
SPINFRAG

LUND UNIVERSITY

INFN
Istituto Nazionale di Fisica Nucleare

StringSpinner

https://gitlab.com/albikerbizi/stringspinner

- Enables spin effects in Pythia 8

  deep inelastic scattering — AK, Leif Lönnblad CPC 2023
  e^+e^- annihilation to hadrons — AK, Leif Lönnblad, arXivXXYYZZ

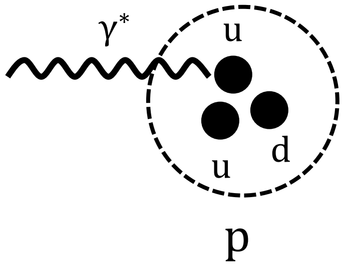
- Employs the string+$^3P_0$ model of hadronization

  ✓ PM, VM — AK, Xavier Artru, Anna Martin, PRD 104, 114038 (2021)
  X *spin-1/2 baryons* — AK, Xavier Artru, PRD 113 (2026) 3, 034007
  (only preliminary implementation for DIS)

- Parton showers off

  study of the connection with parton showers ongoing

String breaking



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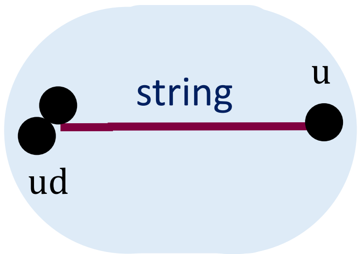
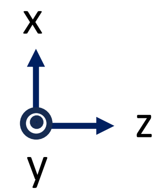
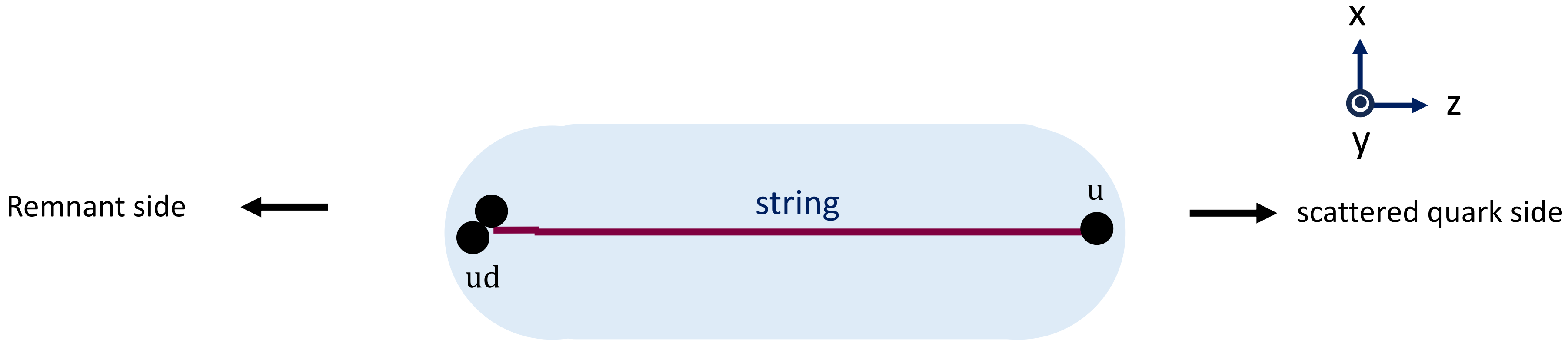
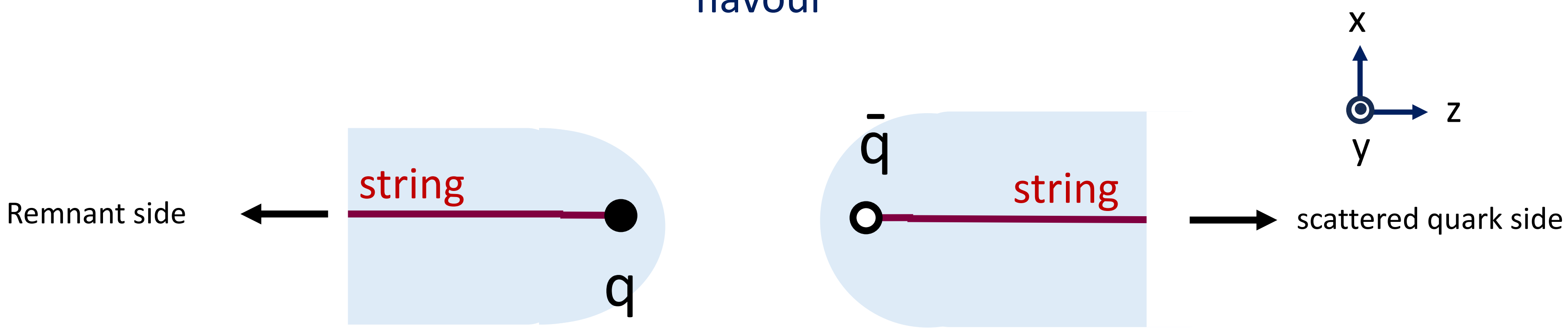




String breaking



String breaking
flavour



String breaking via $q\bar{q}$ tunneling

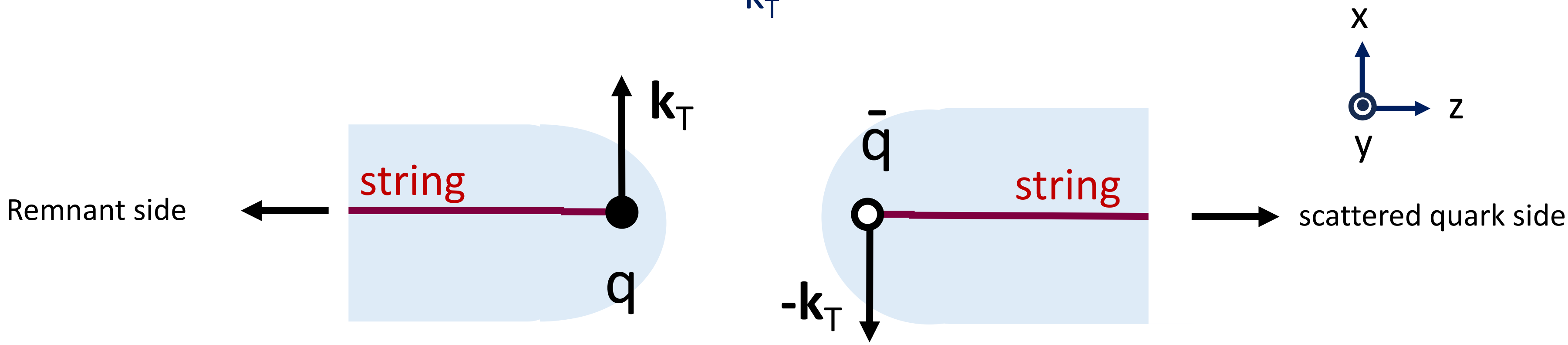
suppression of s quarks

u : d : s = 1 : 1 : γ_s

$\gamma_s \approx 0.2$

Pythia 8

String breaking
k_T



Local conservation of transverse momentum

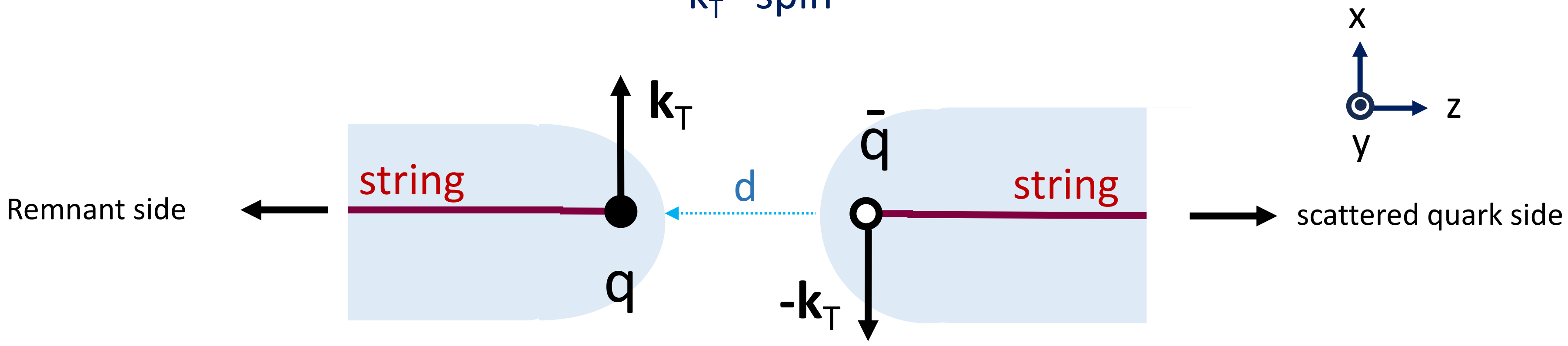
k_T damping [Schwinger mechanism]

$$\left|f_T(k_T^2)\right|^2 \propto \exp(-b_T k_T^2)$$

$$b_T^{-1} \approx 0.67\ \mathrm{GeV}^{-2}$$

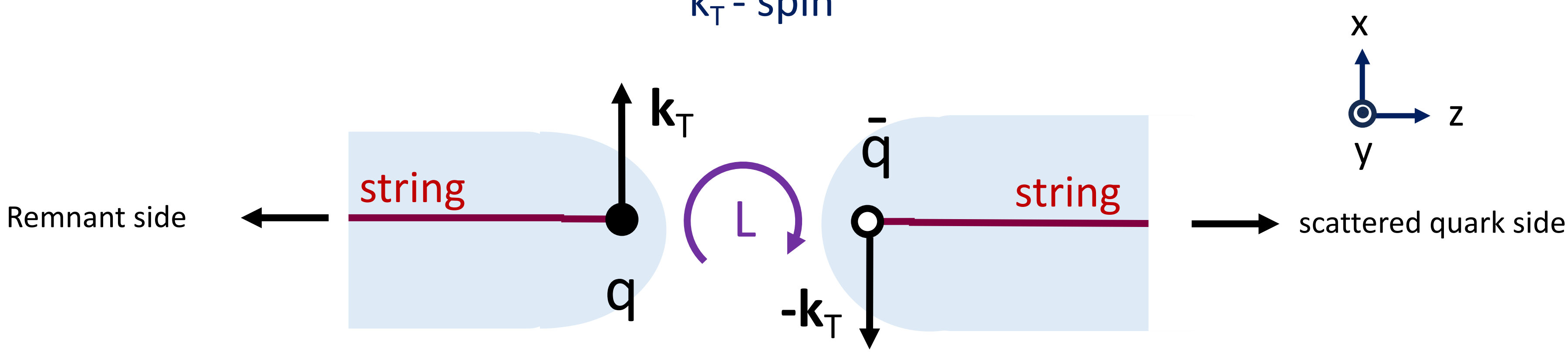
Pythia 8

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

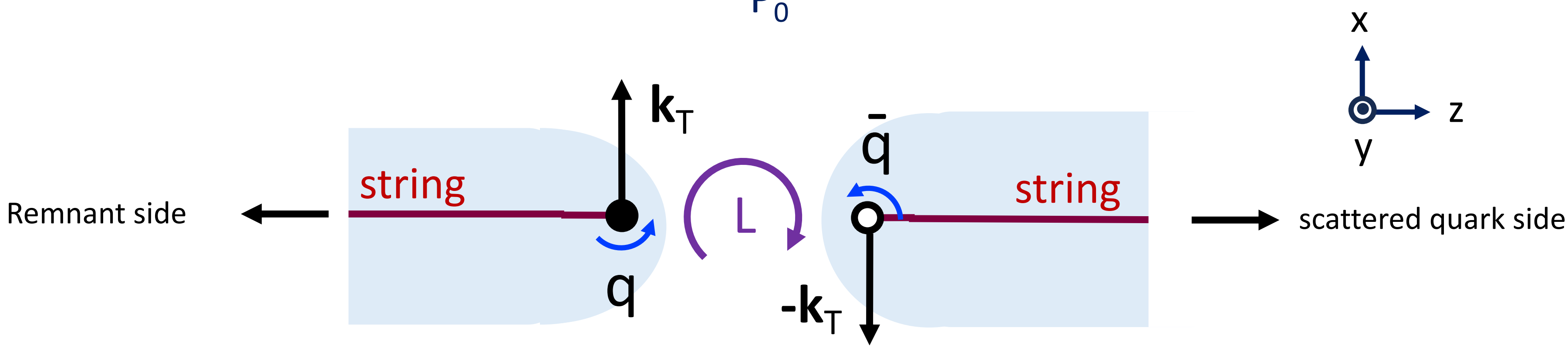
$$\vec{L} = \vec{d} \times \vec{k}_T \neq \vec{0}$$

Local conservation of angular momentum

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

String breaking

$^3P_0$



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Local conservation of angular momentum

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

therefore

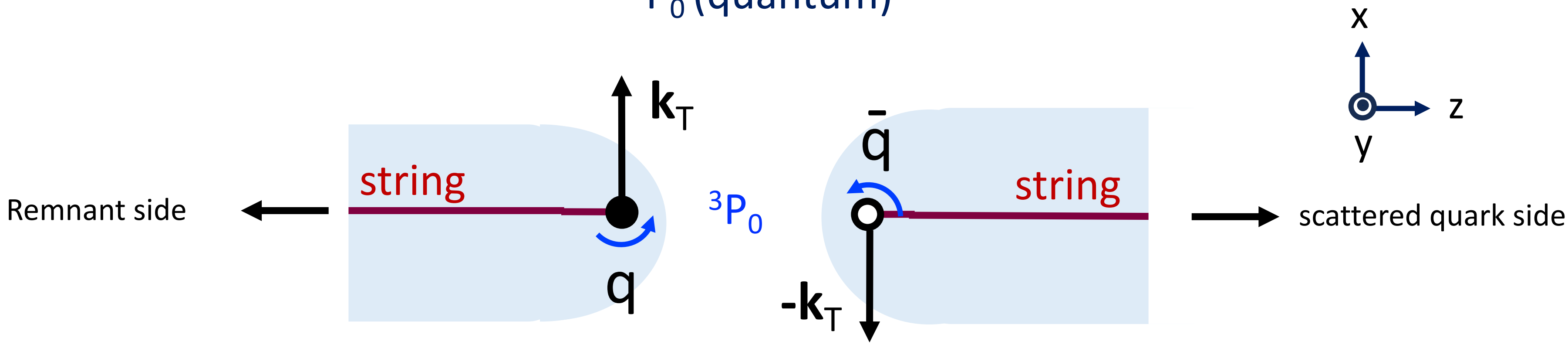
$$\vec{J} = \vec{L} + \vec{S} = \vec{0}$$

$L=1$, $S=1$

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

spin!

String breaking
$^3P_0$ (quantum)



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

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

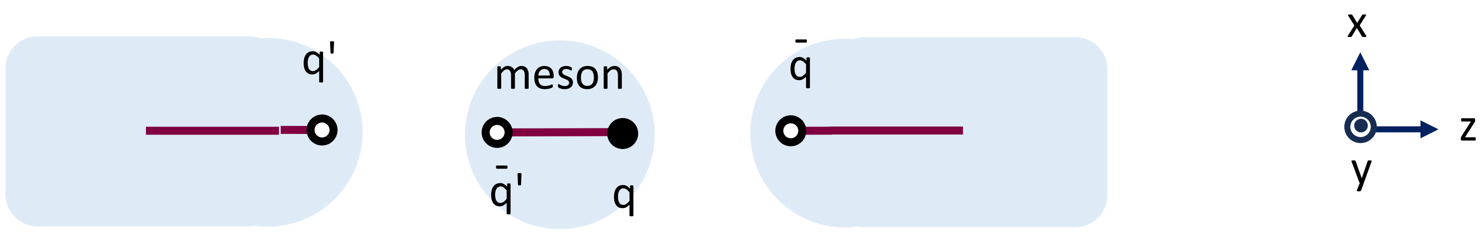
"complex mass" μ

2 free parameters

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

$\mathrm{Re}(\mu)$ responsible for L spin effects (beam spin asymm ...)

Meson production

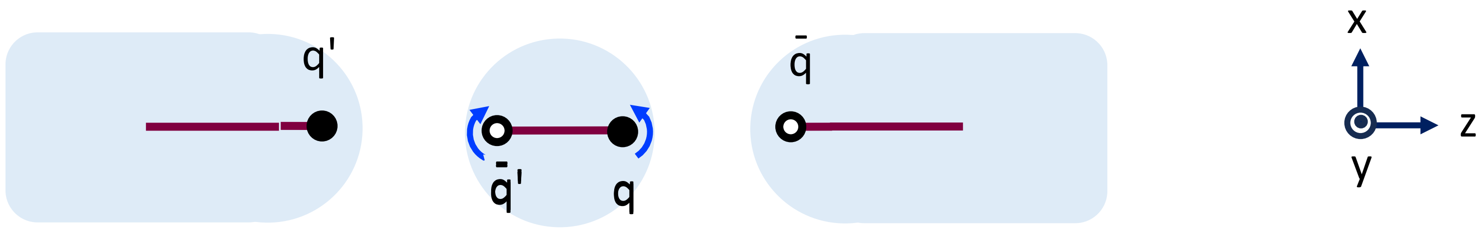


Pseudoscalar meson (PM) or vector meson (VM) with probability

$$f_{VM} = \frac{P_{q\bar{q}' \to VM}}{P_{q\bar{q}' \to PM}} = \begin{cases} 0.5 & \text{Light mesons} \\ 0.55 & \text{Strange mesons} \\ \ldots & \end{cases}$$

Pythia 8

Meson production
PM (quantum)



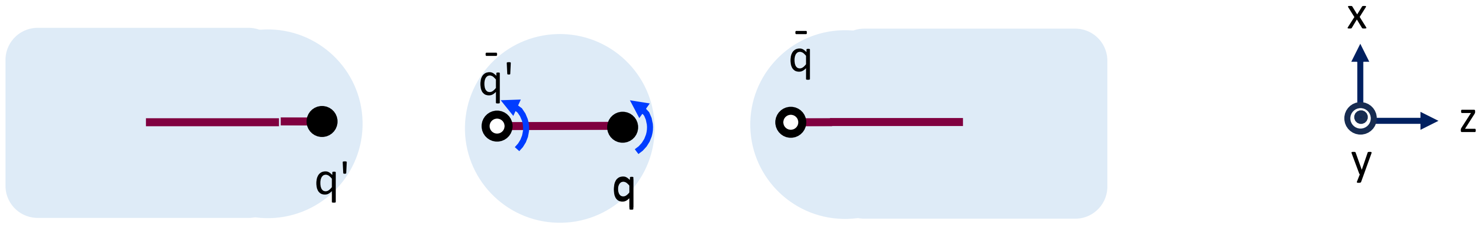
Pseudoscalar meson (PM) or vector meson (VM)

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)

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

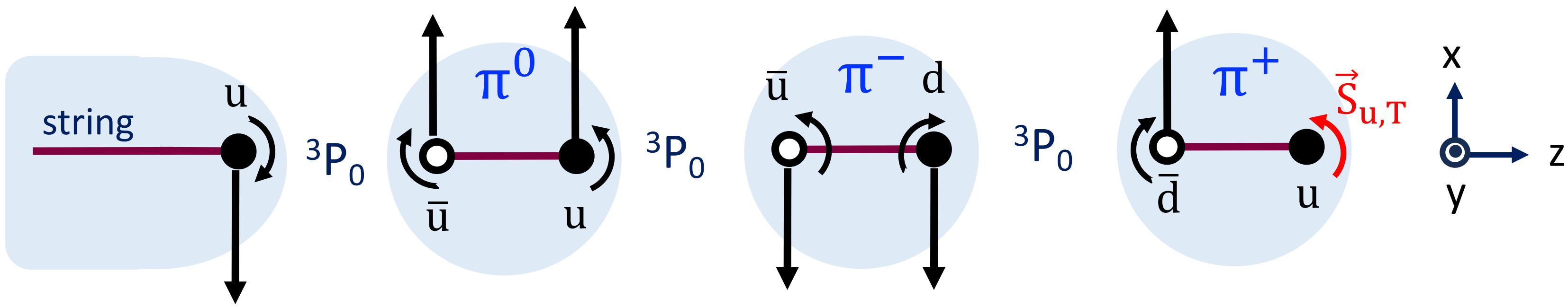
2 free parameters

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

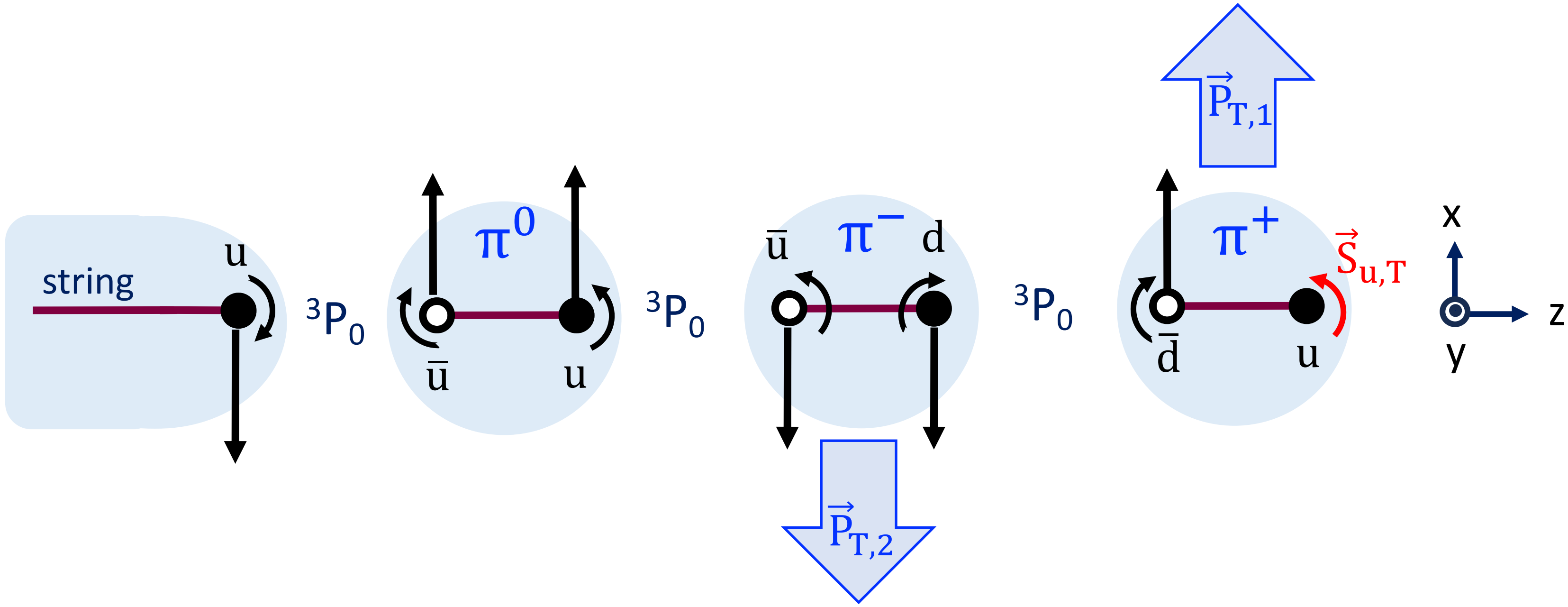
Interference between L and T polarizations $\quad \theta_{LT} = \arg G_L/G_T$

Detailed description in
AK, Artru, Martin, PRD 104, 114038 (2021)

Spin correlations in hadronization

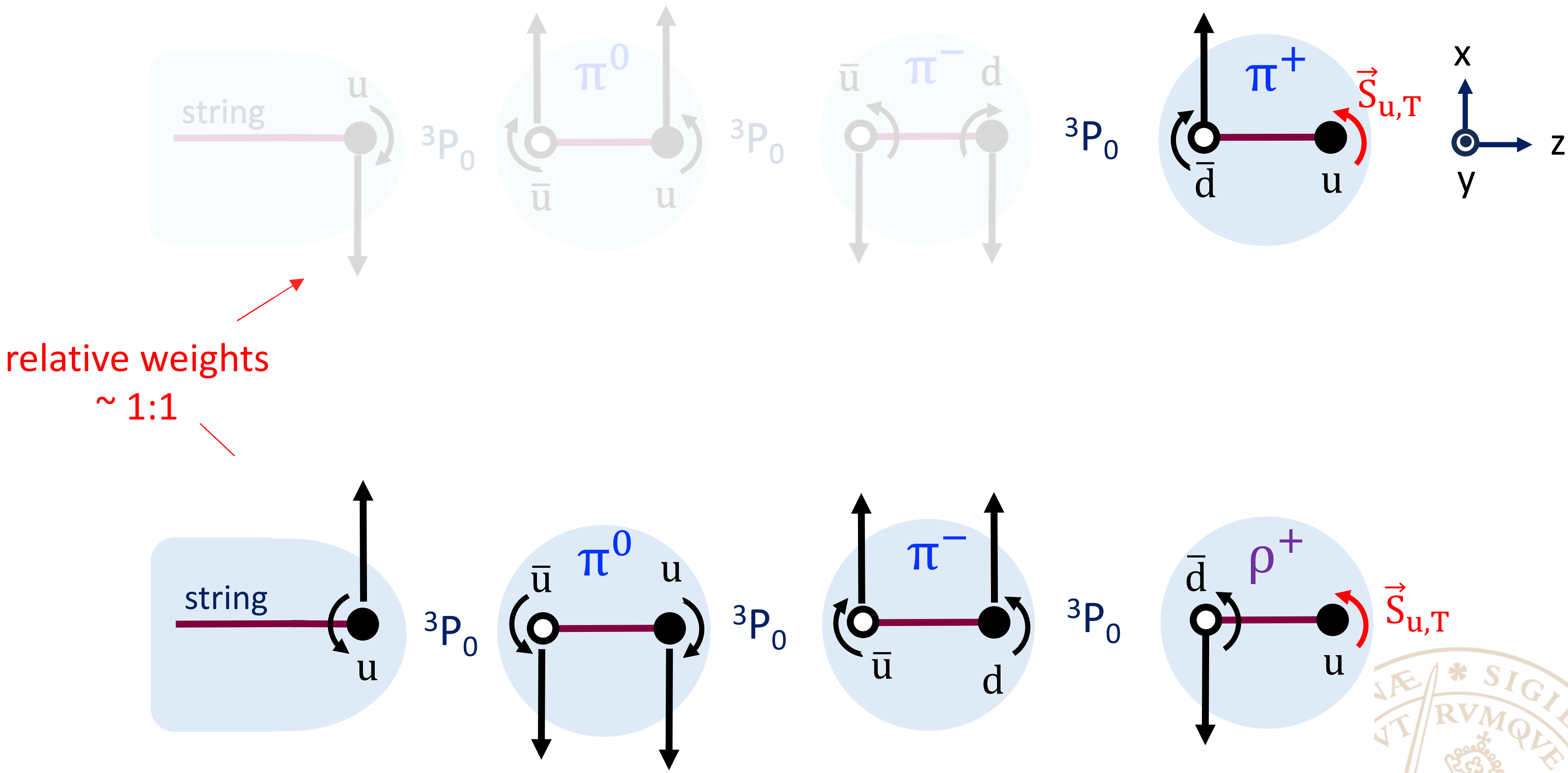


Spin correlations in hadronization

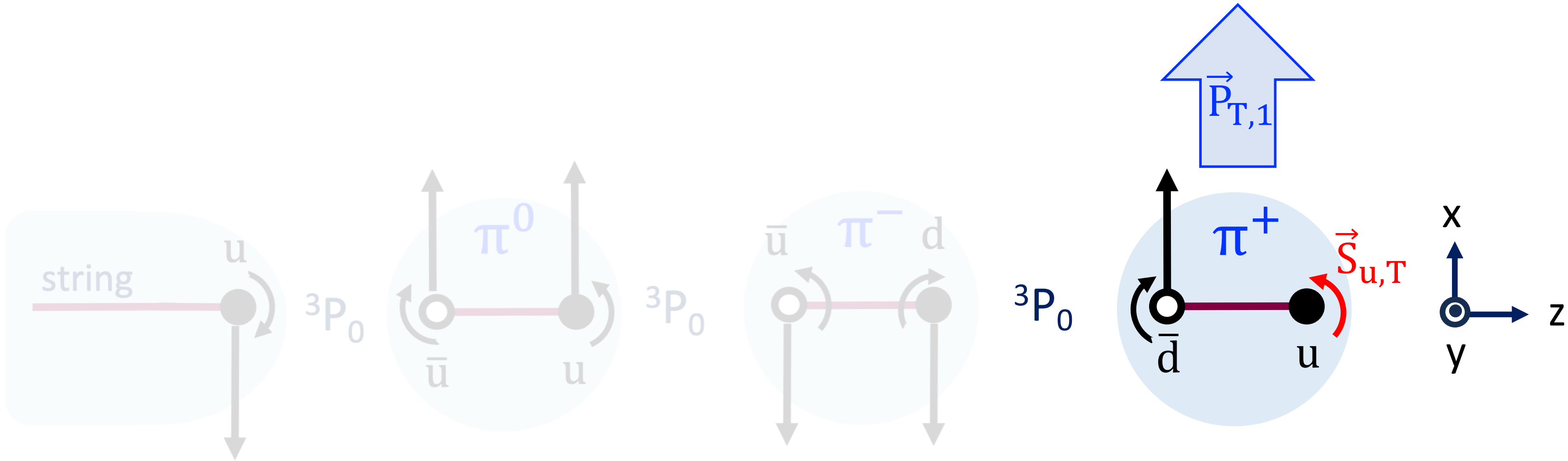


Collins effect of opposite sign for π^+ and π^-

Spin correlations in hadronization

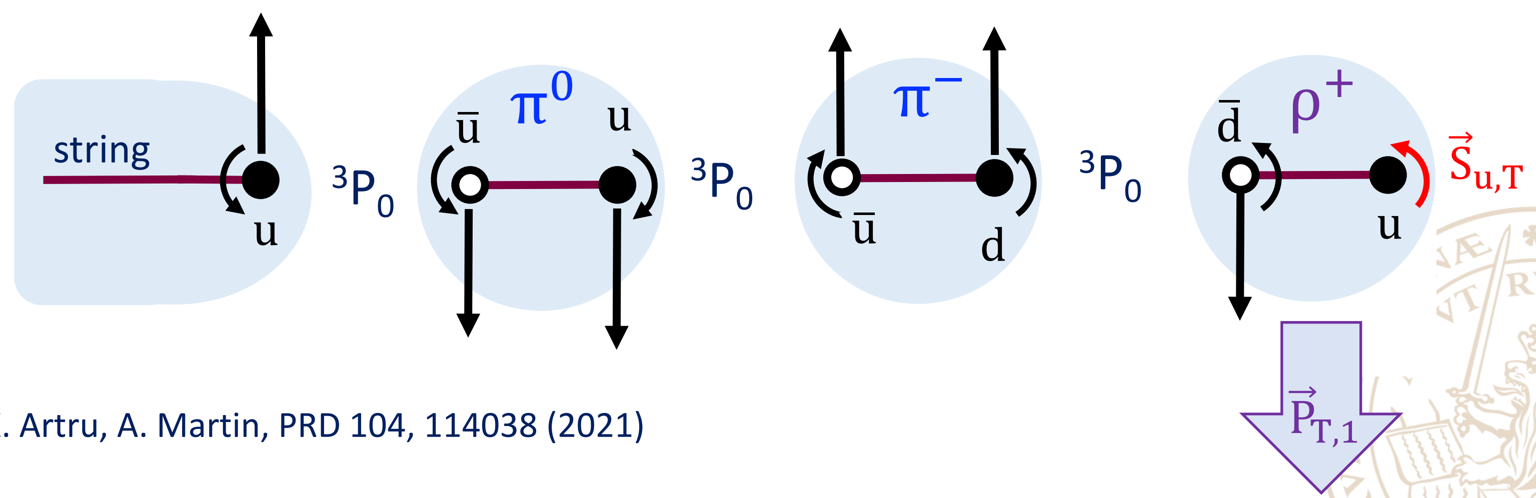


Spin correlations in hadronization



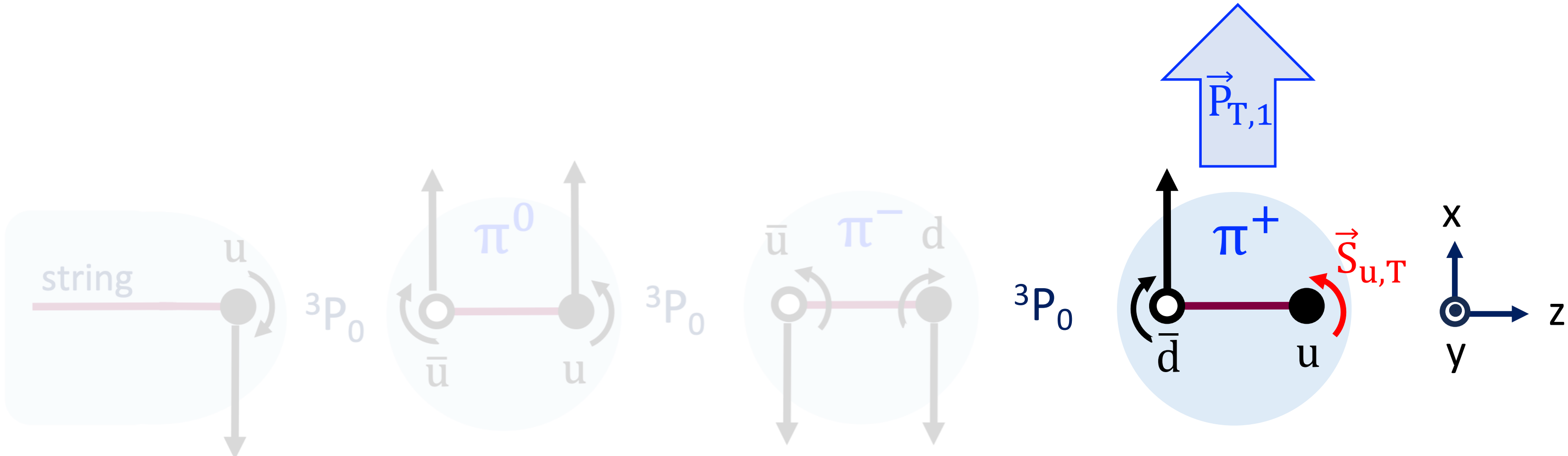
relative weights
~ 1:1

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



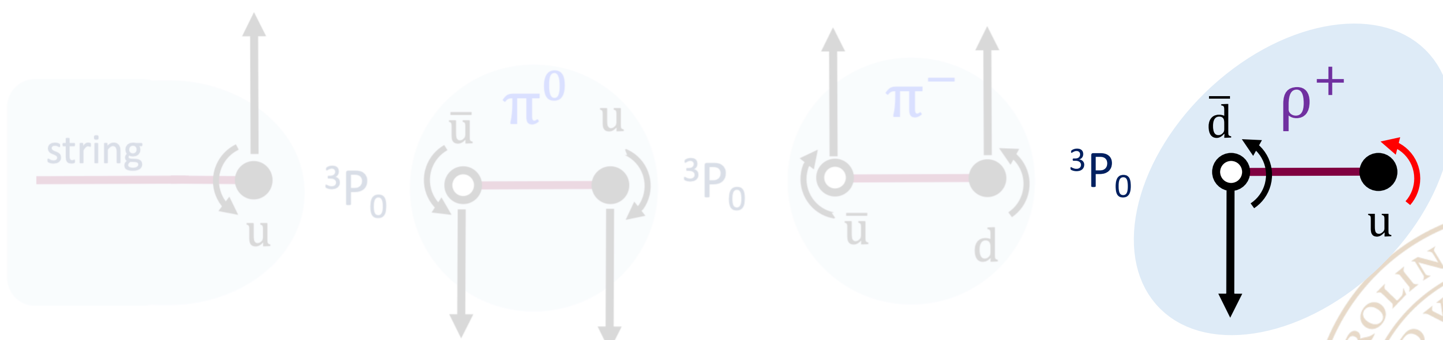
AK, X. Artru, A. Martin, PRD 104, 114038 (2021)

Spin correlations in hadronization



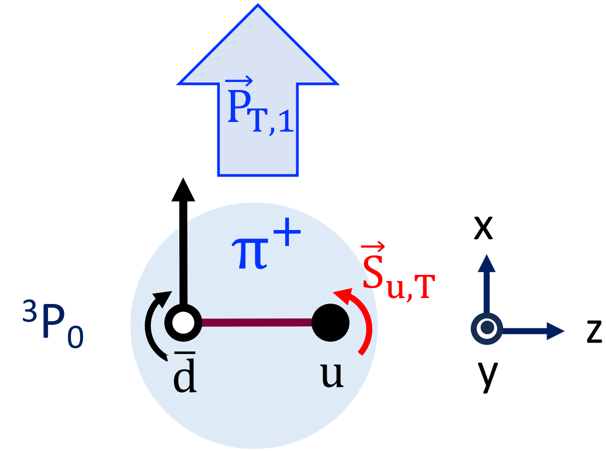
Oblique polarization

$\theta_{LT} < 0$



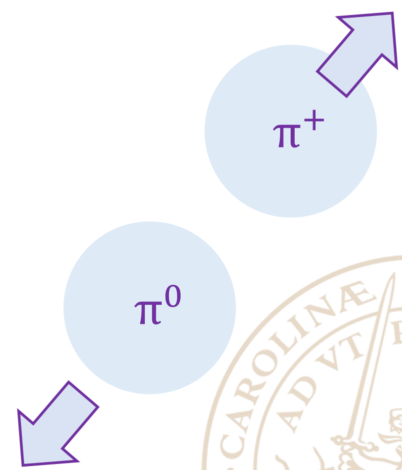
AK, X. Artru, A. Martin, PRD 104, 114038 (2021)

Spin correlations in hadronization



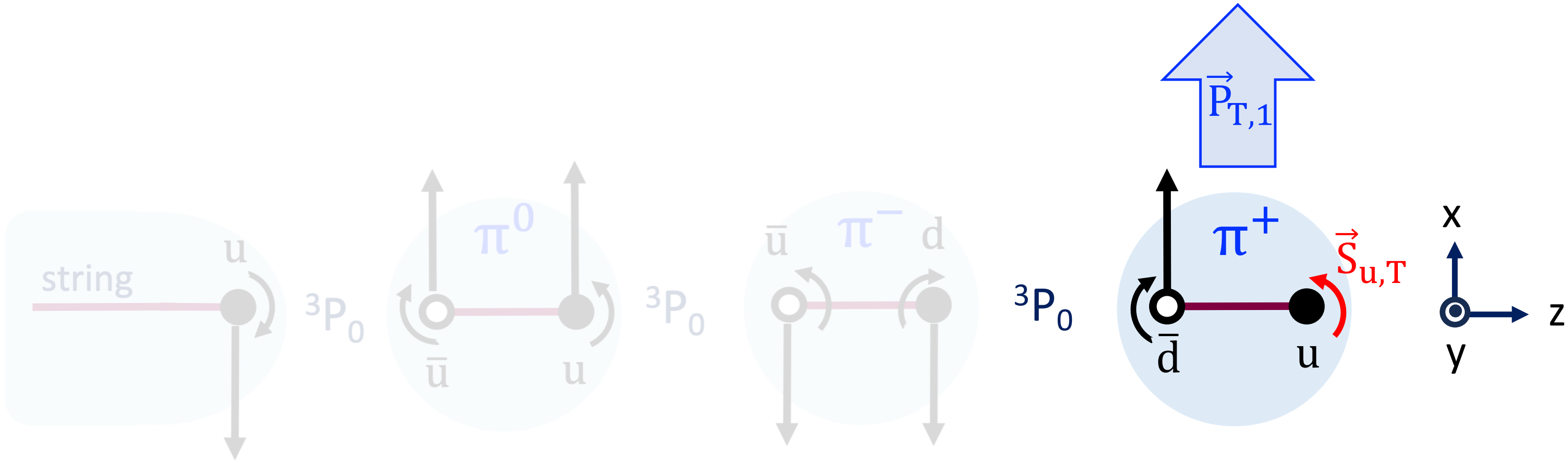
Oblique polarization

Enhancement of Collins effect for π^+



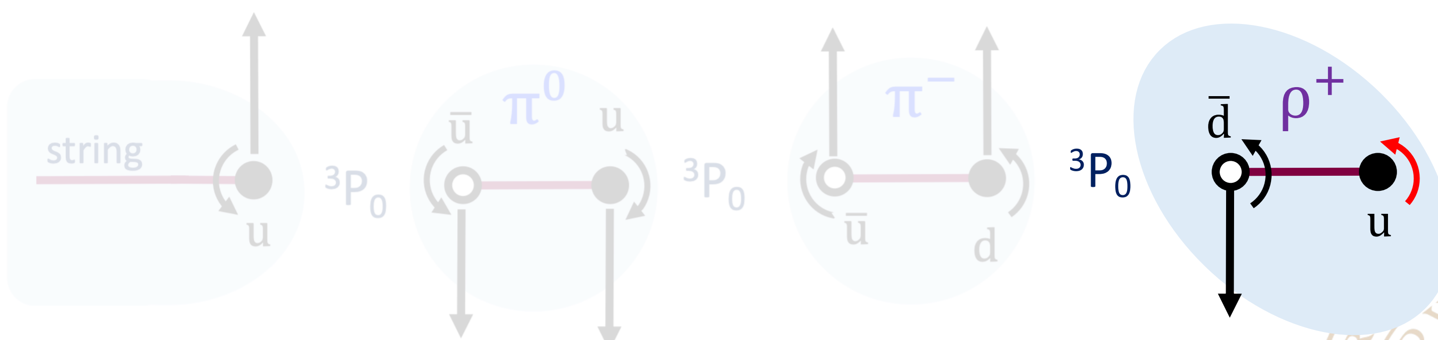
AK, X. Artru, A. Martin, PRD 104, 114038 (2021)

Spin correlations in hadronization



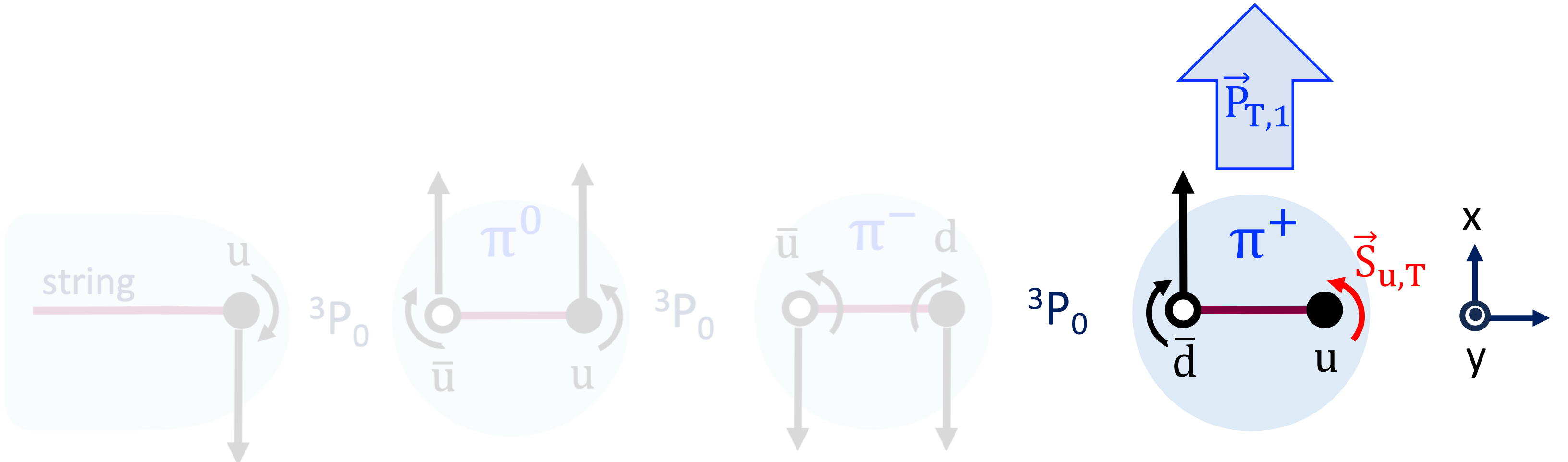
Oblique polarization

$\theta_{LT} > 0$



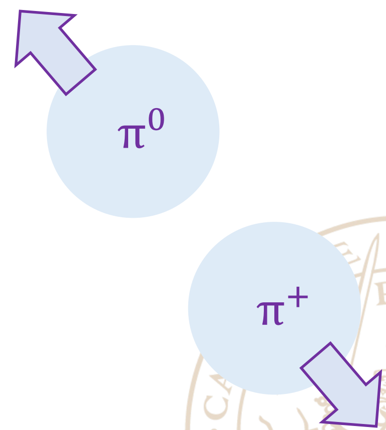
AK, X. Artru, A. Martin, PRD 104, 114038 (2021)

Spin correlations in hadronization



Oblique polarization

Decrease of Collins effect for π^+



AK, X. Artru, A. Martin, PRD 104, 114038 (2021)

Tuning of StringSpinner (ongoing work)

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

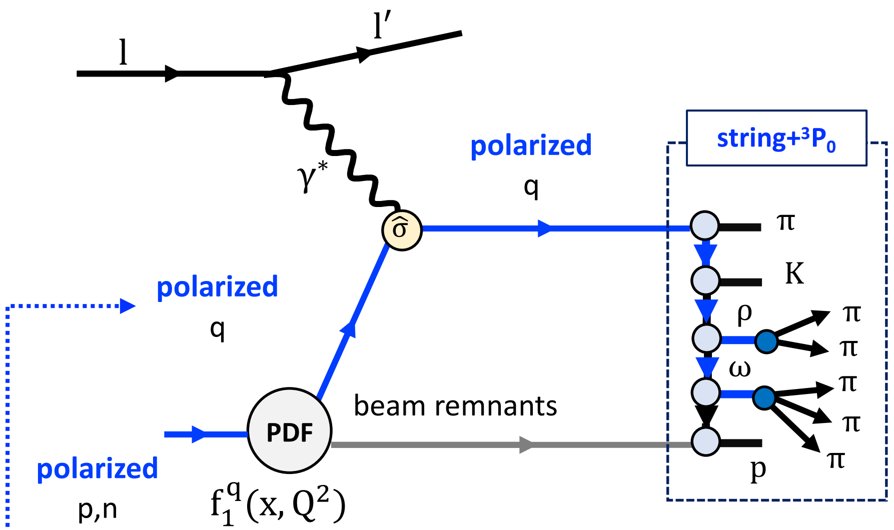
4 parameters for spin

+ spin-independent Pythia hadronization parameters, set to default

Implementation in Pythia by StringSpinner

(polarized) Deep Inelastic Scattering

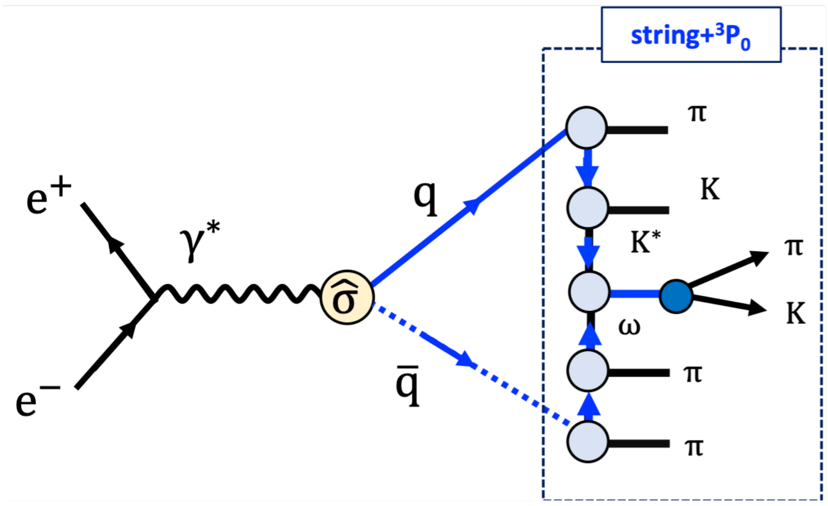
AK, L. Lönnblad, CPC **272** (2022) 108234;CPC **292** (2023) 108886



Initial condition: spin density matrix of q
→ parametrization of transversity
$h_1^q(x)$ for valence quarks

e^+e^- annihilation to hadrons

AK, X. Artru, PRD 109 (2024) 5, 05402
AK, L. Lönnblad, A. Martin, PRD 110 (2024) 7, 074029



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

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

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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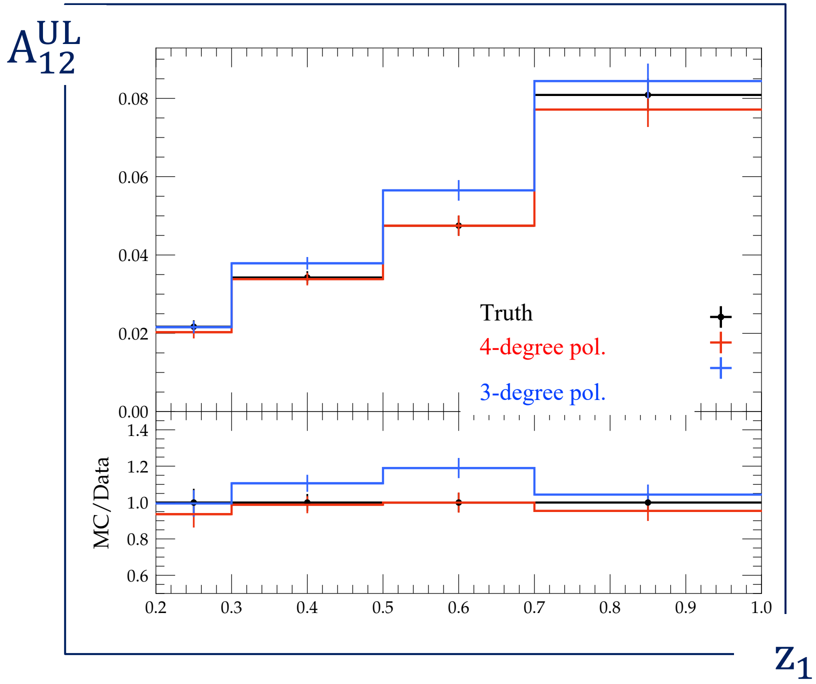

Example of polynomial interpolation

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

Tuning of StringSpinner: procedure

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  - 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

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

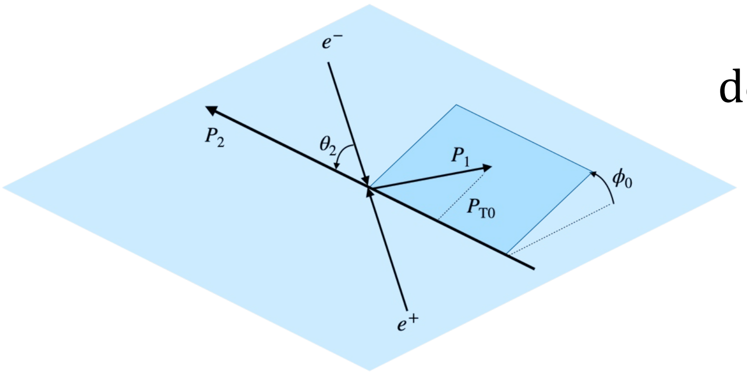
- Obtain $\vec{p}_{tune}$

PROFESSOR 2

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

Tuning of StringSpinner: data

Collins asymmetry A_0 from e^+e^-



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

Collins FF

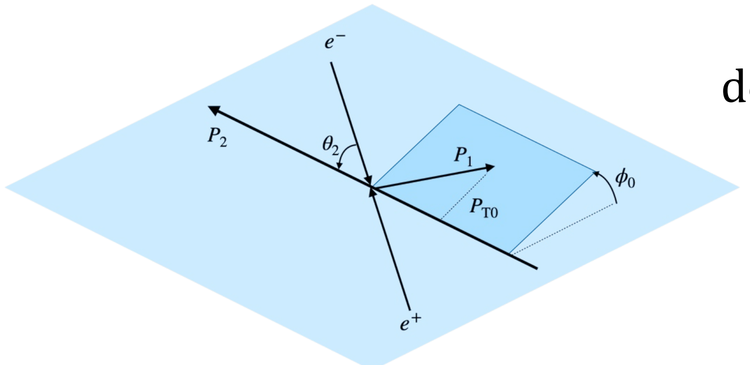
$$A_0 \simeq \frac{\sum_q e_q^2\, \mathcal{C}[w\, H_{1q}^{\perp h_1} \times H_{1q}^{\perp h_2}]}{\sum_q e_q^2\, \mathcal{C}[D_{1q}^{h_1} \times D_{1q}^{h_2}]}$$

Spin-averaged FF

Same observable as in QCD analyses of transversity

Tuning of StringSpinner: data

Collins asymmetry A_0 from e^+e^-



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Spin-averaged FF

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

Tuning of StringSpinner: results

- **Tune**

$$\frac{X^2}{\text{ndf}} = \frac{138.1}{138} \simeq 1.0$$

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

VM produced with T pol.
No oblique pol.

Tuning of StringSpinner: results

❑ Tune

$$\frac{X^2}{\text{ndf}} = \frac{138.1}{138} \simeq 1.0$$

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$f_L = 0.12 \pm 0.05$
$\theta_{LT} = -0.05 \pm 0.15$

VM produced with T pol.
No oblique pol.

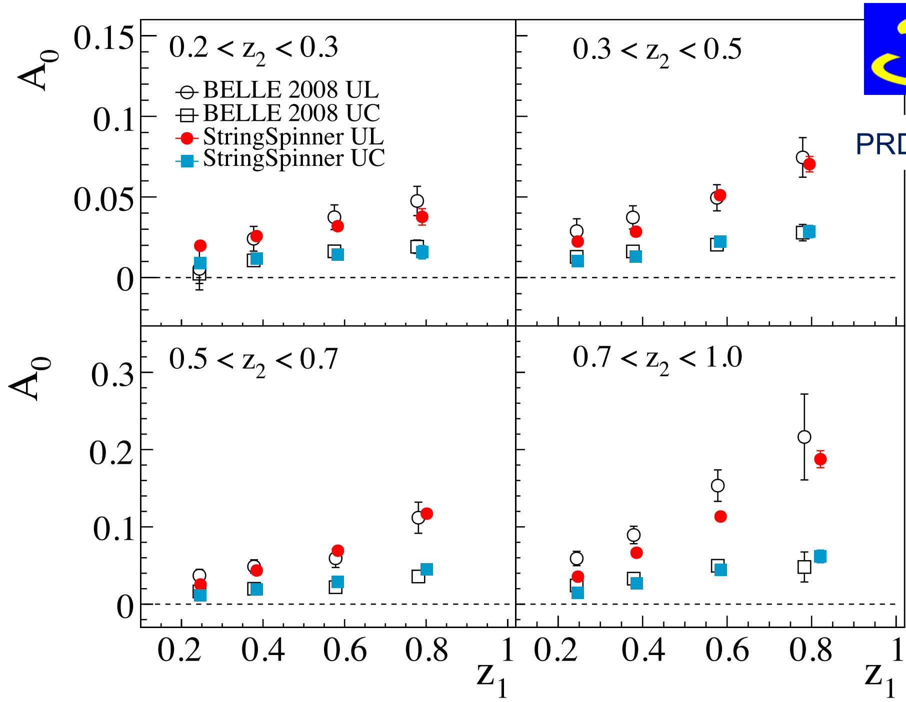
❑ The other minimum

$$\frac{X^2}{\text{ndf}} = \frac{182}{138} \simeq 1.3$$

$\mathrm{Re}(\mu) = 0.24 \pm 0.02$
$\mathrm{Im}(\mu) = 0.38 \pm 0.02$
$f_L = 0.38 \pm 0.04$
$\theta_{LT} = 2.57 \pm 0.13$

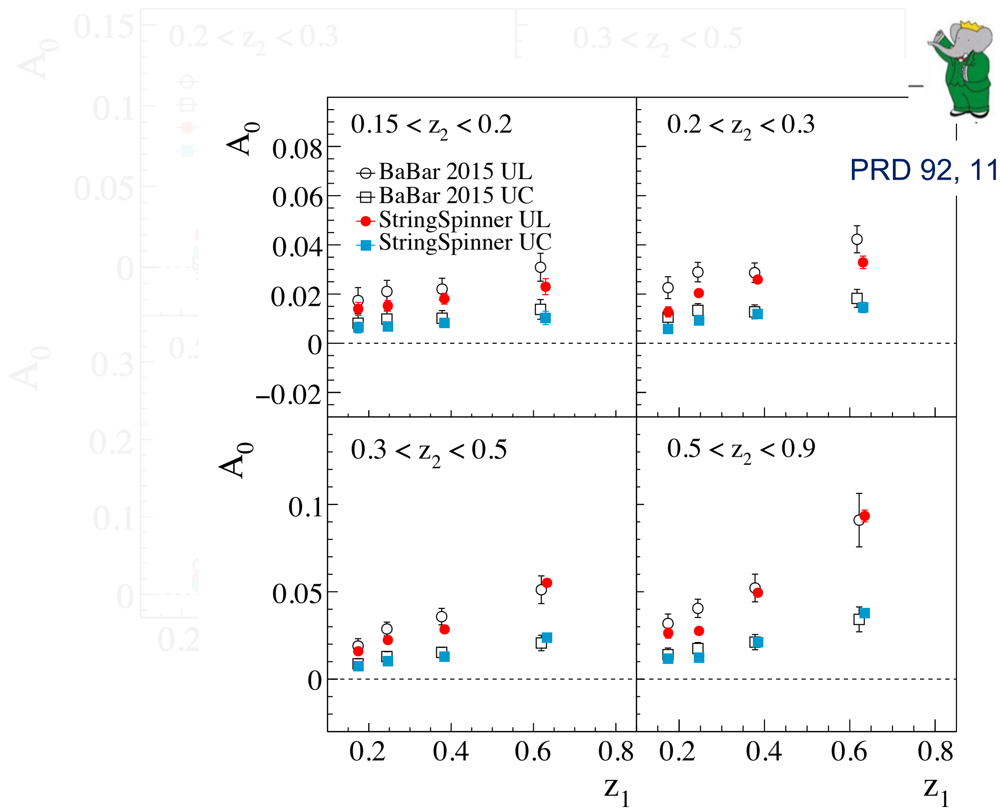
VM with T and L pol. equally produced
Oblique pol.

A_0 for ππ: BELLE



PRD 78, 032011 (2008)

A_0 for ππ: BABAR

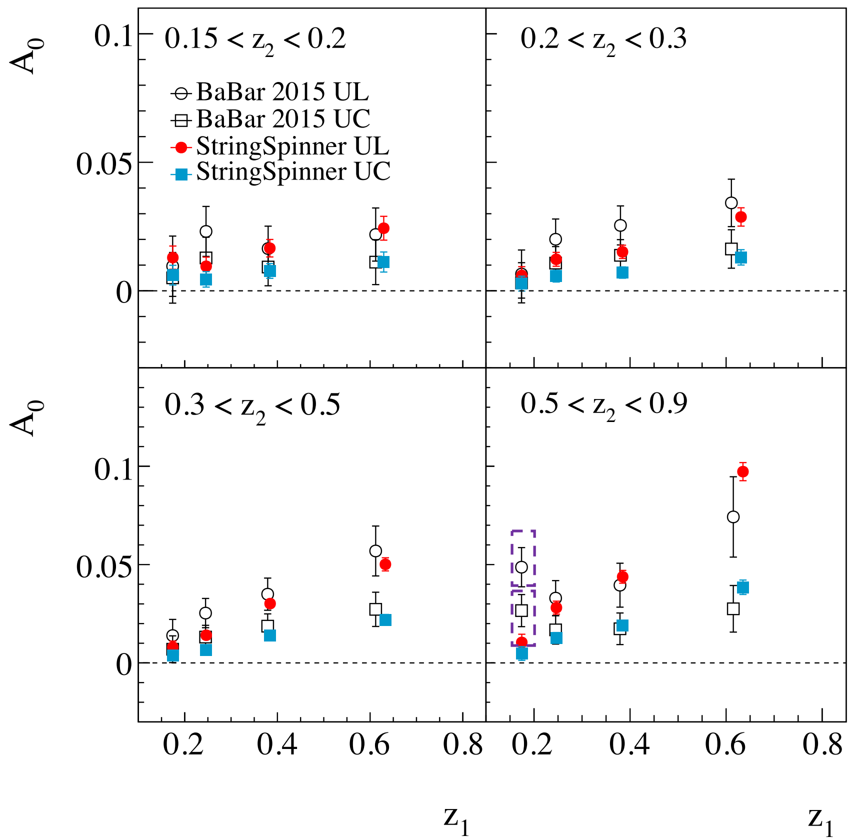


PRD 92, 111101(R) (2015)

A_0 for πK: BABAR

PRD 92, 111101(R) (2015)

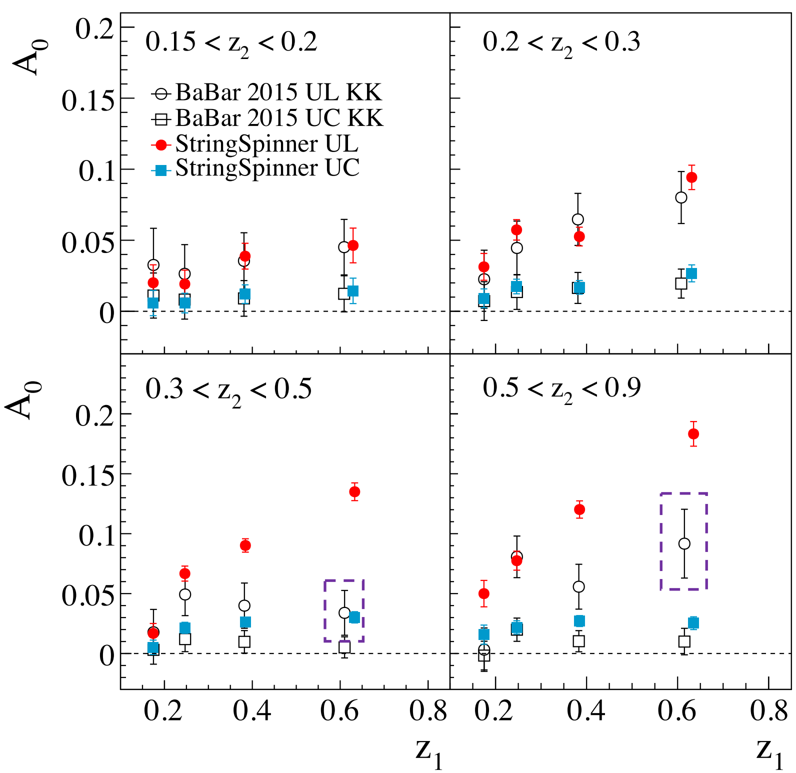
excluded from tuning



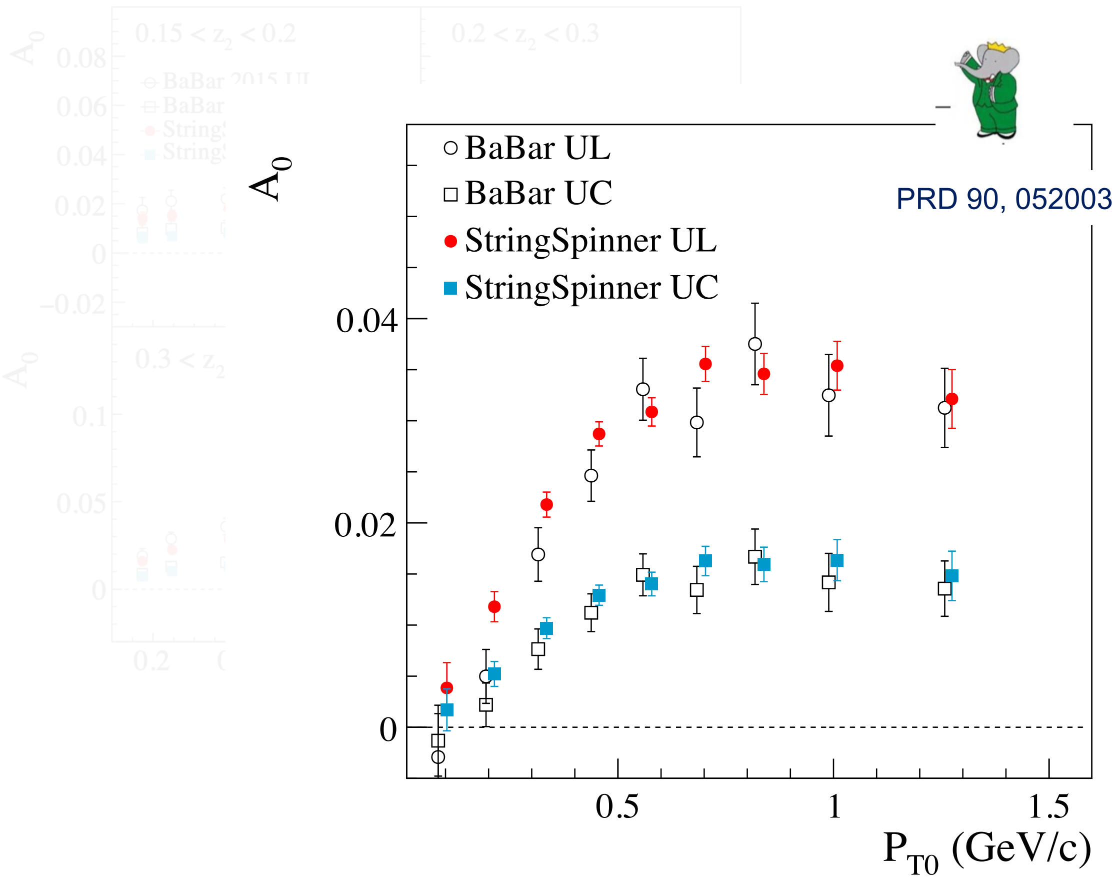
A_0 for KK: BABAR

PRD 92, 111101(R) (2015)

excluded from tuning



A_0 for ππ: BABAR



PRD 90, 052003 (2014)

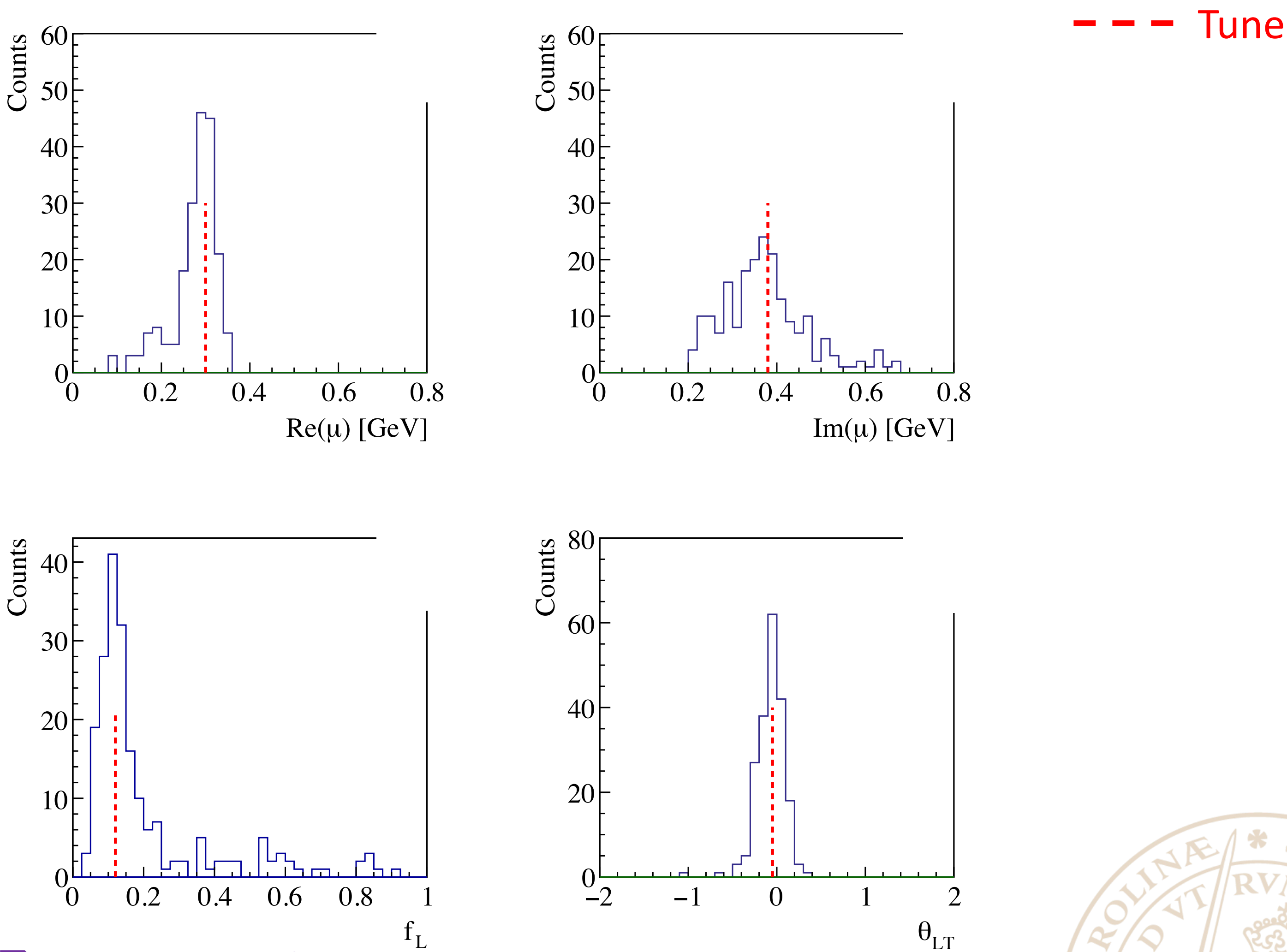
Tuning of StringSpinner (ongoing work)

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

How well do we know the parameters?

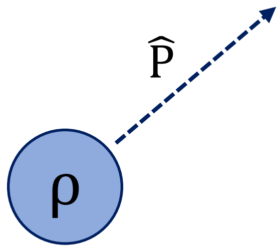
200 replica of each measured asymmetry
same tuning procedure for each replica

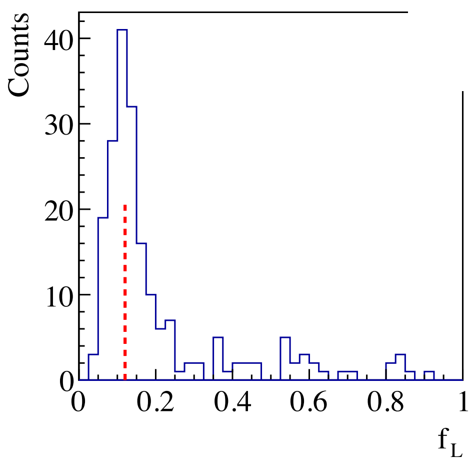
Distribution of free parameters from replica

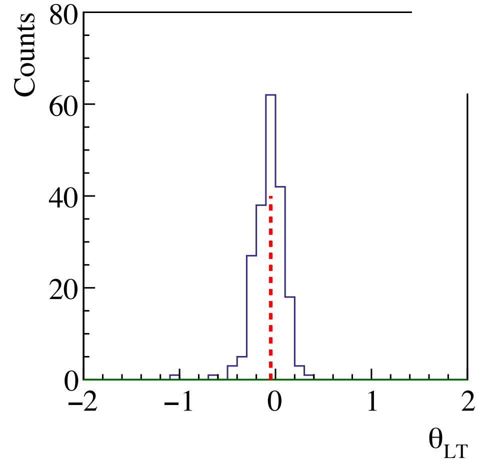


- ❑ Agreement with tune
- ❑ Tail in f_L?

Distribution of free parameters from replica







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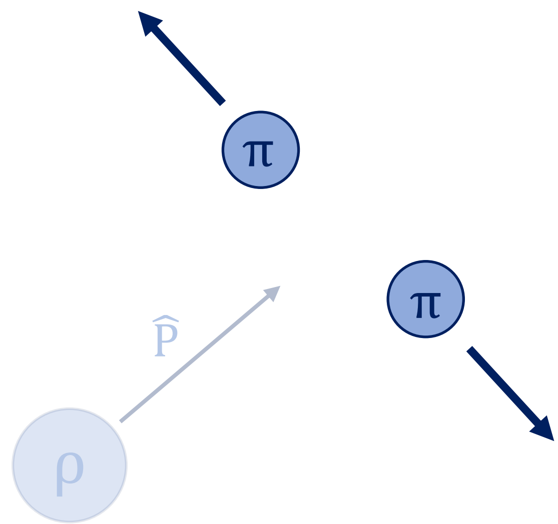
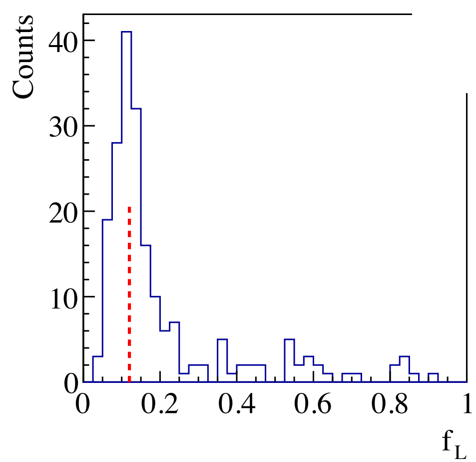
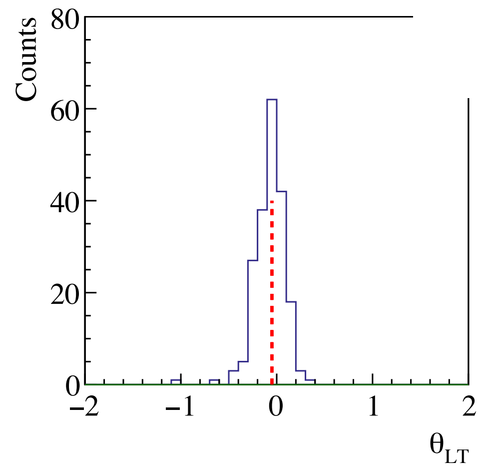
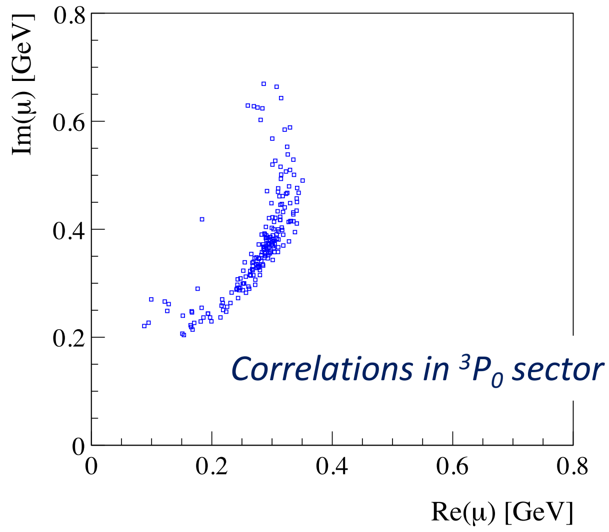




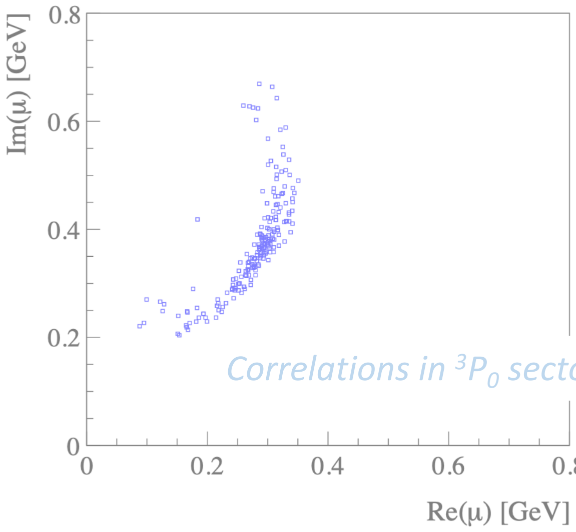


Correlations between free parameters from replica

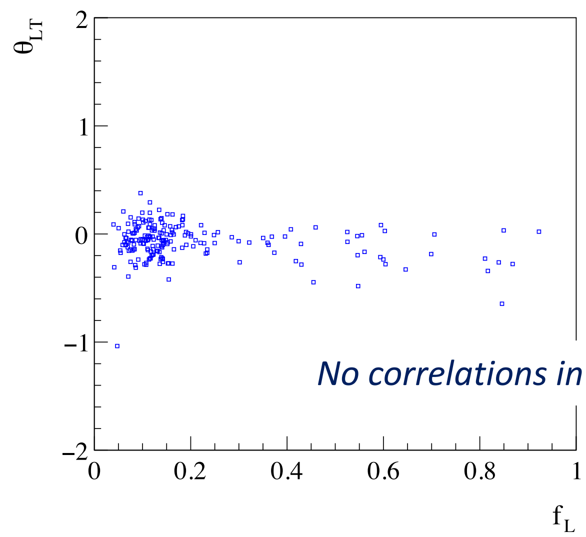


Correlations in $^3P_0$ sector

Correlations between free parameters from replica

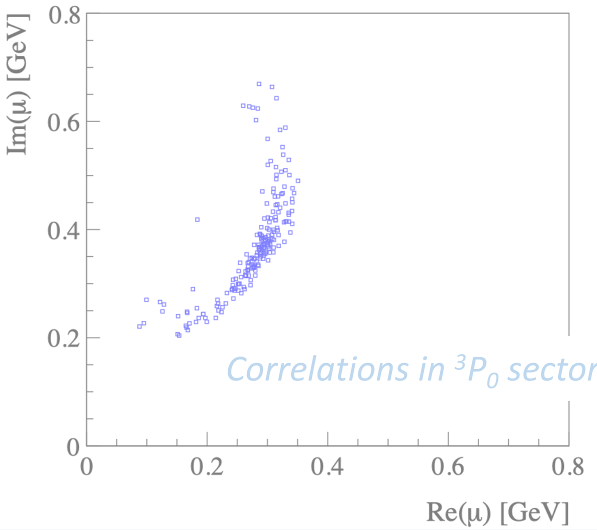


Correlations in $^3P_0$ sector

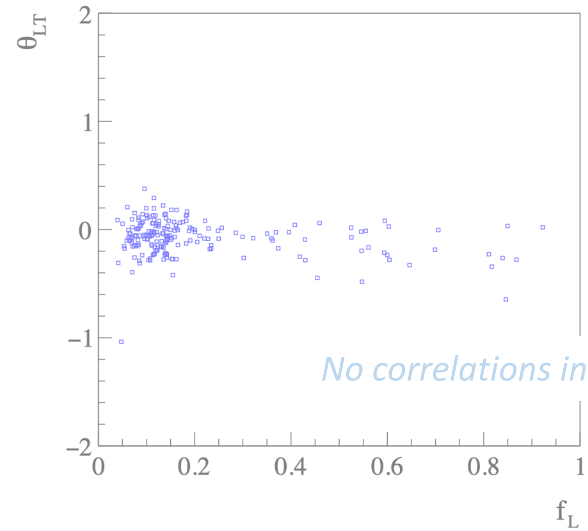


No correlations in VM sector

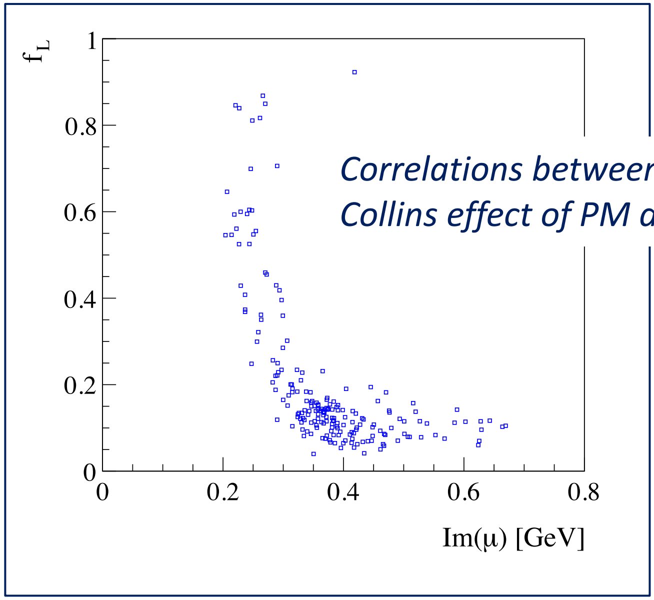
Correlations between free parameters from replica



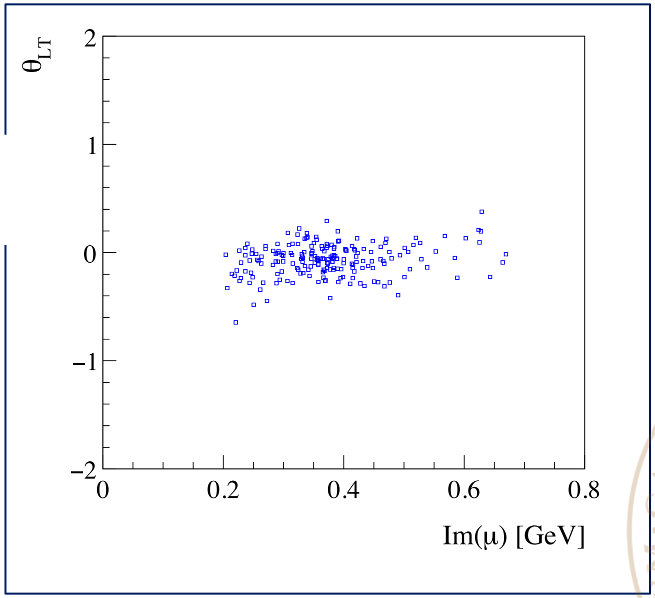
Correlations in $^3P_0$ sector



No correlations in VM sector



Correlations between
Collins effect of PM and VM



Conclusions

- VM production is a key aspect of MC generators, in particular for spin
  sizeable contribution to the final state hadronic sample

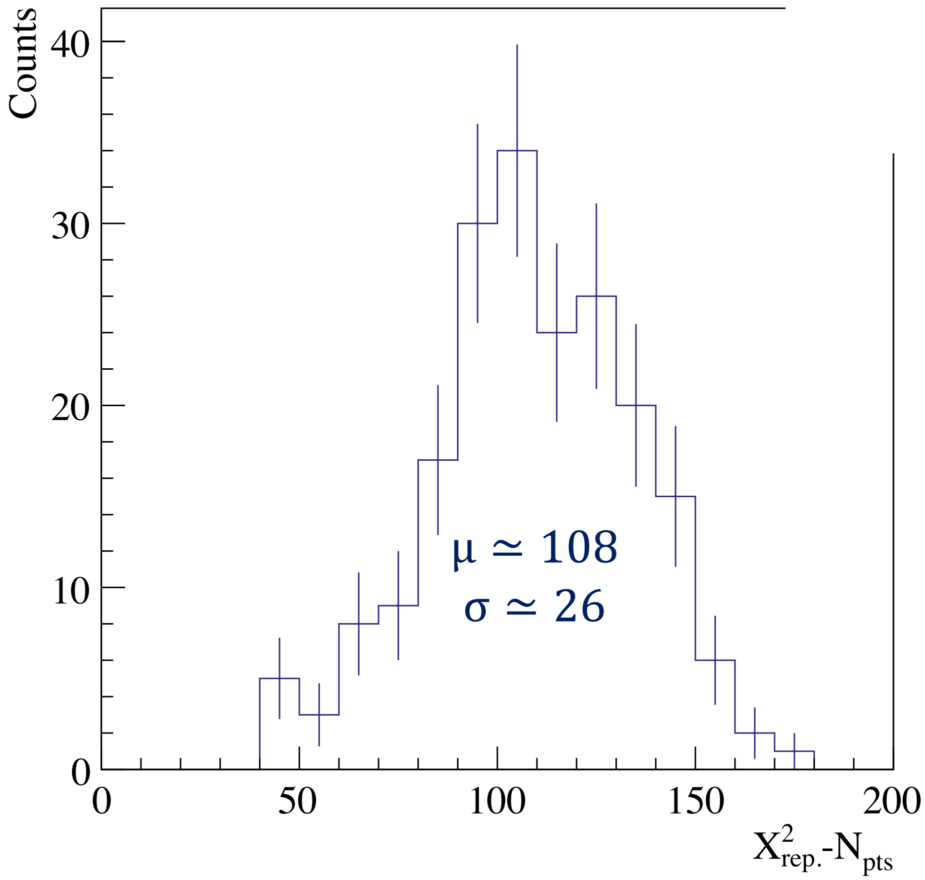
- First systematic tuning of StringSpinner using Collins effect in e^+e^-
  insights into VM production and decay in hadronization
  tune consistent with SIDIS data (more in the upcoming paper)

- Correlations between parameters seen through the replica method
  expected $\rightarrow$ data is sensitive only to the sum of contributions from primary hadrons and feed-down Collins effect

- Quite fun!
  more fun if: Collins asymmetry for VMs (ρ, K^*, ...)
  alignment of VMs (data from LEP available)
  ...

Backup

Distribution of X2 of replica



The X2 evaluated on the replica is shifted roughly by Npts …