Heavy flavor hadron polarization and nonperturbative QCD in spin-directed momentum transfer



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## Outline

- $\Lambda_{s,c,b}$  polarization Puzzles and Uses
- I. Large polarization in hadron processes
- II. Leptoproduction of  $\Lambda_s \& \Sigma_s$

Large double correlations at small  $Q^{\rm 2}$ 

- I. Analysis more tractable
- II. Which formalism is most useful? TMDs, GPDs, Generalized Fracture Functions?

## Outline (cont'd)

#### I. Large polarization in hadron processes

II. Leptoproduction of  $\Lambda_s \& \Sigma_s$ 

#### III. Tool to get into transversity –

- I. Chen, GG, Jaffe, Ji ( $e^+e^- \rightarrow \Lambda_s \text{ anti} \Lambda_s X$ )
- II. "off-diagonal" SIDIS via Transversity odd distributions (intrinsic charm?)
- III. Target fragmentation: GPDs, Fragmentation functions, Fracture Functions (many authors: D.Boer; M. Anselmino. et al.; A. Kotzinian; . . .)
- IV. Collider production target or central region (e.g. D. Sivers)

#### IV. TMDs, GPDs, Generalized Fracture Functions

- I. Why GPDs? Phases and transversity - -
- II. Preliminary results & relations

## Single Spin Asymmetries & Target Fragmentation

- $e p \rightarrow e' meson + p'$
- Current and target fragments are correlated



#### Some SSA papers

- Experiment & models
  - Sichtermann Hyperons in Polarized Proton-Proton Collisions at RHIC (Vs=200-500 GeV )

Indiana-Illinois Workshop on Fragmentation Functions Dec.12-14, 2013

- $p \Rightarrow + p \rightarrow \Lambda \Rightarrow + X$  measures  $D_{LL}$  also anti- $\Lambda$
- $p \Rightarrow + p \Rightarrow \rightarrow \Lambda + X$  measures  $A_{LL}$  also anti- $\Lambda$
- D<sub>LL</sub> Small, but non-zero –
- Models: Artru, et al., COMPASS
- Ceccopieri & Mancusi QCD analysis of Lambda hyperon production in DIS target-fragmentation region – arXiv:1211.3333 & EPJ C73, 2435 (2013) – Weak production of unpolarized Lambdas – some data
- CLAS PRL90, 131804 (2003) First Measurement of Transferred Polarization in the Exclusive e⇒ p → e K<sup>+</sup> Λ ⇒ Reaction

Low energy 2.6 GeV in resonance region - but big effect

## Important recent papers (cont'd)

- Donghee Kang COMPASS thesis Longitudinal  $\Lambda$  and anti $\Lambda$  polarization mu + p  $\rightarrow \Lambda$  +X Large spin transfer
- HERMES PRD74, 072004 (2006) Small D<sub>LL</sub> at large z SIDIS
- J. Rosner  $\Lambda_{\rm b}$  & anti  $\Lambda_{\rm b}$  asymmetry at FNAL and LHC polzn at pi+p but not ATLAS !!
- Anselmino, Barone, Kotzinian (PLB699, etc.):
- Pitonyak (Spin2016\_Pitonyak-1.pdf) mostly  $A_N$  but ref to  $e^+e^- \rightarrow \Lambda \uparrow \pi X$
- Metz (QCD-N\_metz.pdf) nice summary of twist 3 in A<sub>N</sub> in many cases ....
- \*\*. Is large  $\Lambda$  polarization in hadronic reactions purely a higher twist target fragmentation phenomenon?

## Polarized hyperon production in single-inclusive electron-positron # annihilation at next-to-leading order

Leonard Gamberg (Penn State U., Berks-Lehigh Valley), Zhong-Bo Kang (UCLA and Los Alamos), Daniel Pitonyak (Penn State U., Berks-Lehigh Valley and Lebanon Valley Coll. and Old Dominion U.), Marc Schlegel (New Mexico State U.), Shinsuke Yoshida (Los Alamos) (Oct 19, 2018) Published in: *JHEP* 01 (2019) 111 • e-Print: 1810.08645 [hep-ph]

## Issues to consider

- Kinematics to distinguish target fragmentation region from current fragmentation region in semi-inclusive leptoproduction -
- Quark transversity involves chiral odd maybe also higher twist for exclusive channels
- Are SIDIS data from CLAS, HERMES, COMPASS at all overlapping & compatible?
- Basic questions: do Λ and Σ<sup>+</sup> get their polarization from fragmentation or from quark + diquark initial state and/or final state interactions?
- Evidence from Inclusive hadronic production and/or from inclusive leptoproduction and/or from e<sup>+</sup>e<sup>-</sup> annihilation

## History: Large polarization in hadron+hadron



compiled by K.Heller (1997) Systematic behavior Curves Dharmaratna & GG

Ramberg, et al., (FNAL) PLB338, 403 (1994)

POLARIZATION (%)

Fig. 4. Lambda polarization versus production transverse momentum  $(p_T)$ . For comparison, data for 400 GeV production (Ref. 10) are also shown.

## LHC $\Lambda$ polarization ATLAS at 7 TeV (Phys.Rev.D91,032004 (2015)) very small $x_F$ $P(x_F, p_T, s)$



Spin: Problem of Polarization of Hyperons and Charmed Baryons in **pp collisions** Helicity amps  $\rightarrow f_{a,b,c,d}(x, t, ...)$ 

density matrices  $\rightarrow \Sigma_{a,b,c} f_{a b, c d} f^*_{a b, c d'} \sim \rho_{d d'}$ 

Probability for spin of particle  $\textbf{\textit{d}}$  to be polarized ~  $\Sigma\,\rho_{d\,d'}\,(\sigma_{n})_{d'd}$ 

with <  $|\sigma_n|$  > where **n** direction from  $p_a X p_d$  has to involve transverse momenta – "spin directed transverse momenta"

$$< \ldots j |\sigma_{Y}| \ldots k > \sim (\sigma_{Y})_{jk} \sim +/-i => beyond tree level$$

#### interference effect



Spin degrees of freedom in pp scattering

Set of all data compiled by K. Heller

#### Transverse $\Lambda$ polarization in unpolarized scattering

Large asymmetries have been observed in  $p + p \rightarrow \Lambda^{\uparrow} + X$ G. Bunce *et al.*, PRL 36 (1976) 1113



## Ideas about Source of **A** Polarization in Hadrons

- Semi-classical: Lund; Thomas precession; SU(6); Soffer, et al.
- DeGrand & Miettinen (1981): q+0 or1diquark  $\rightarrow \Sigma^+ /\Lambda \simeq 2/3$  ?
- Q Field Th: Single polarization requires interference =>Real x Im part & helicity flip
- Kane, Pumplin, Repko: PQCD (PRL41,1689(1978) $\rightarrow P_{\Lambda} \sim \alpha(\hat{s})m_q / \sqrt{\hat{s}}$
- Complete order  $\alpha_s$  calculation of quark, antiquark, gluon 2-body scattering  $\rightarrow s_{\uparrow} + s_{f}$  imbedded in hadron+hadron pdf's (but small  $m_s$ ) (Dharmaratna & GG 1990,1996) How does s  $\uparrow$  get translated to  $\Lambda \uparrow \&$  enhanced?
- NPQCD must play a significant role in our understanding of orbital angular momentum & hadron formation - confinement.



#### P<sub>quark</sub> vs. flavor from gluon fusion grows with flavor

Does this give larger P<sub>hadron</sub> for heavier flavor?

What sets scales? quark "mass" or hyperon mass

Top quark most polarized!





#### Model of hyperon polarization

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POLARIZATION

Dharmaratna & GRG (1990,96,99)

1.  $p+p \rightarrow A+X$  has large negative  $P_A$  with flat s dependence & growth with  $p_T$  (see Heller . . .)

2. Clues: K<sup>-</sup> p  $\rightarrow$ **/**+X at 176 GeV/c or  $\sqrt{s}$ =18GeV Polzn even larger - need *s*-quark?

3. Simple factorization expectation Kane, Pumplin, Repko  $P_A \sim \alpha(\hat{s}) m_q / \sqrt{\hat{s}}$ 

helicity flip ~  $m_q$ /hard energy scale Soft phenomenon?

Dharmaratna & GRG: 1. Gluon fusion dominant mechanism for producing polarized

massive quark pair

- 2. Low  $\boldsymbol{p}_{T}$  phenomenon
- 3. Acceleration mechanism



 $p+p\rightarrow A+X Polzn(A)$ 

compiled by K.Heller (1997)



#### **Charmed Hyperon Polarization**





 $P(\Lambda_c)$  vs.  $p_T(GeV)$  for several  $x_F$  values)

E.M. Aitala, et al. (E791 Collaboration) "Multidimensional Resonance Analysis of  $\Lambda_c + \rightarrow pK - \pi + "$ , Fermilab 1999.

Theory Curves: GG, hep-ph/9907573

 $P(\Lambda_c)$  does not fall off with  $p_T$ Important Trend to be tested?

## <sup>3</sup>P<sub>0</sub> mechanism





To produce a net hyperon transverse spin the quark orbital angular momentum between the initial and final states must differ by one unit of h

## Evolving Ideas about Source of $\Lambda$ Polarization in Hadrons

- Semi-classical: Lund; Thomas precession; SU(6)
- Q Field Th: Single polarization requires interference =>Real x Im part & helicity flip
- Kane, Pumplin, Repko: PQCD $\rightarrow P_{\Lambda} \sim \alpha(\hat{s})m_a / \sqrt{\hat{s}}$
- Complete order  $\alpha_s$  calculation of quark, antiquark, gluon 2-body scattering  $\rightarrow s$  +sbar imbedded in hadron+hadron pdf's (Dharmaratna & GG 1990,1996)
- How does s figet translated to  $\Lambda$  ?
- LUND model and <sup>3</sup>P<sub>0</sub> mechanism gluonic Flux tube between quarks breaks
  - Andersson, et al.
- Consider electroproduction of  $\Lambda$ 's. Prelude to hadron production. QCD more under control.
  - Soft matrix elements from TMDs & SIDIS or GPDs &/or Fracture Functions

Electroproduction & hyperons vs. hadroproduction perturbatively

• reduced subset of diagrams  $\rightarrow$  heavy quark pair



• vs. gluon+gluon  $\rightarrow$  gluon  $\rightarrow$  quark+antiquark



#### Electroproduction of $\boldsymbol{\Lambda}$

Simple tree level model for extended fracture function (Trentadue & Veneziano) + D Sivers with spin => BM, etc. Diquark spectator & fragmentation "do" squares & sums over X states with anti-s flavor Diquark $\rightarrow \Lambda$ +s-bar simple vertex z,p<sub>T</sub>



 $z=E_{\Lambda}/(1-x)E_{\gamma P CM}$  for target fragment or  $P_{\Lambda}^+=z(1-x)P^+$ 

#### **Double Spectator Model**

$$\begin{split} f_{\Lambda_{H}\Lambda_{\gamma},\Lambda} &= \sum_{\lambda} g_{\lambda}^{\Lambda_{\gamma}} \otimes \mathcal{F}_{\Lambda\lambda}^{\Lambda_{H}}(P,k) & \text{Fracture function} \\ \\ \mathcal{F}_{\Lambda,\lambda}^{\Lambda_{H}}(x,k_{T},z,p_{T},Q^{2}) = A_{\lambda,\Lambda} \sum_{\Lambda_{X}} B_{\Lambda_{X}}^{\Lambda_{H}} \\ A_{\Lambda,\lambda_{q}} &= \mid \phi_{\lambda_{q},\Lambda}(k,p) \mid^{2} & B_{\Lambda_{X}}^{\Lambda_{B}} = \tilde{\phi}_{\Lambda_{X},\Lambda_{B}}^{*}(p_{X},p_{B}) \tilde{\phi}_{\Lambda_{X},\Lambda_{B}}(p_{X},p_{B}) \\ \phi_{\Lambda,\lambda_{q}}(k,p) &= \Gamma(k) \frac{\bar{u}(k,\lambda_{q})U(p,\Lambda)}{(k^{2}-m^{2})((p-k)^{2}-M_{qq}^{2})} \end{split}$$

#### Modeling the <sup>3</sup>P<sub>0</sub> mechanism: Double Spectator Model



#### **Double Spectator Model**

Fracture Functions represent a joint probability for current quark (or antiquark or gluon) at  $x_B$ ,  $k_T$  and target hadron at fraction of target momentum z,  $p_T$ .





Dipole form factors dampen  $P \rightarrow u + diq vertex \Lambda$ , diquark, struck quark all on shell

$$k^{2} = xM^{2} - \frac{\vec{k}_{T}^{2}}{(1-x)} - \frac{x}{(1-x)}(P-k)^{2} \qquad \delta((k+q)^{2}) \rightarrow x = x_{Bj}$$

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#### diquark model extended fracture function

$$(P-k)^{2} = m_{s}^{2} + \frac{M_{\Lambda}^{2}}{z} + \frac{1-z}{z} \left( \vec{P}_{\Lambda T} - \frac{z}{1-z} \vec{P}_{XT} \right)^{2}$$
$$k^{2} = xM^{2} - \frac{\vec{k}_{T}^{2}}{(1-x)} - \frac{x}{(1-x)} (P-k)^{2}$$

$$\mathcal{F}_{\Lambda_N,\Lambda_\Lambda}^{\lambda_q}(x,k_T,z,p_T,Q^2) = \sum_{\Lambda_X} \int \frac{d^3 P_X}{(2\pi)^3 2E_X} \int \frac{d^4 \xi}{(2\pi)^4} e^{ik \cdot \xi} \langle P \mid \bar{\psi}(\xi) \mid P_h;X \rangle \langle P_h;X \mid \psi(0) \mid P \rangle.$$

quark correlator for Extended Fracture Functions helicity labels  $\langle P, \Lambda_N | \& | P_h, \Lambda_A; X \rangle$ For unpolarized d $\sigma$ , sum over all helicity labels. For polarized  $\Lambda$ , keep floating

#### diquark model extended fracture function

In the spectator model

$$\mathcal{F}_{\lambda_q,\Lambda_N}^{\Lambda_\Lambda,\Lambda'_\Lambda}(x,k_T,z,p_T,Q^2) = A_{\Lambda_N,\lambda_q} \sum_{\Lambda_X} B_{\Lambda_X}^{\Lambda_\Lambda,\Lambda'_\Lambda}$$

where

$$A_{\Lambda_N,\lambda_q} = |\phi_{\lambda,\Lambda}(k,P)|^2,$$

with

$$\phi_{\Lambda,\lambda}(k,P) = \Gamma(k) \frac{\bar{u}(k,\lambda_q)U(P,\Lambda_N)}{k^2 - m^2},$$

and

$$k = P - P_X - P_\Lambda \quad \Rightarrow k^2 = k^2 (x, \mathbf{k}_T, z, \mathbf{p}_T)$$

whereas

$$B^{\Lambda_{\Lambda},\Lambda'_{\Lambda}}_{\Lambda_{X}} = \tilde{\phi}^{*}_{\Lambda_{X},\Lambda'_{\Lambda}}(P_{X},P_{h})\tilde{\phi}_{\Lambda_{X},\Lambda_{\Lambda}}(P_{X},P_{h}),$$

with

$$\tilde{\phi}_{\Lambda_X,\Lambda_\Lambda}(P_X,P_h) = \Gamma(P_X)\bar{v}(P_X,\Lambda_X)U(P_h,\Lambda_\Lambda)$$

$$\sum_{\Lambda_X} B^{\Lambda_\Lambda,\Lambda'_\Lambda}_{\Lambda_X} = (1-x)^2 \left( \left[ -zM_X + (1-z)M_\Lambda \right]^2 + p_T^2 \right) \delta_{\Lambda_\Lambda,\Lambda_\Lambda}$$



Quark-diquark interactions Perturbative & non-perturbative

**Distinctions in SIDIS** 

Beyond ep  $\rightarrow \pi X$ consider target fragmentation Diquark can pick up Heavy quark to form hyperon

(u,d) spin singlet +s quark  $\rightarrow \Lambda$ (u,u) spin triplet + s quark  $\rightarrow \Sigma^+$ . => -1/3 polarization



## Summary & Next Step

- Hyperon polarization is touchstone for understanding transversity & NPQCD
- Several ways to begin to explain phenomena
  - Extended GPDs → Extended Fracture Functions
- These efforts aim to "look" at quarks + diquarks

(& gluons) contributions to spin degrees of freedom of nucleon indirectly. Observables integrate away the unobservable.

- Theoretically GTMDs focus on unintegrated quark & gluon distributions and bridge TMDs & GPDs.
- Can GTMDs be more directly observable?

## Backup slides

## Contributions to order $\alpha_S$ Imaginary Part

(Dharmaratna & GG 1990,1996)





#### Model of hyperon polarization

Dharmaratna & GRG (1990,96,99)

1.p+p → Gluon fusion dominant mechanism for producing polarized massive quark pair P<sub>q</sub> & P<sub>anti-q</sub>
2. Low p<sub>T</sub> phenomenon
3. Recombination needs to <u>enhance by</u>

Thomas precession



# $$\begin{split} \mathcal{F}_{\Lambda;\Lambda'_{h},\Lambda_{h}}^{\lambda_{q}}(x,k_{T},z,p_{T},Q^{2}) = \\ \int \frac{d^{3}P_{X}}{(2\pi)^{3}2E_{X}} \int \frac{d^{4}\xi}{(2\pi)^{4}} e^{ik\cdot\xi} \langle P,\Lambda \mid \bar{\psi}^{\lambda_{q}}(\xi) \mid P_{h},\Lambda'_{h};X \rangle \langle P_{h},\Lambda_{h};X \mid \psi^{\lambda_{q}}(0) \mid P,\Lambda \rangle \end{split}$$