The Deep Exclusive Meson Production as a probe of the Λ^0 polarization at the EIC

Kong Tu, BNL

EIC 2nd detector workshop, July 2023

Zhoudunming (Kong) Tu (2023), manuscript in preparation

A big question and a longtime puzzle

- Discovered in the mid 1970s, **Λ-hyperon polarization** was observed in unpolarized proton-Beryllium collisions.
- ~ A 50-year problem that still not fully understood.
- Despite the mystery, **Λ**-hyperon's self-analyzing weak decay became an excellent experimental probe of spin observables.

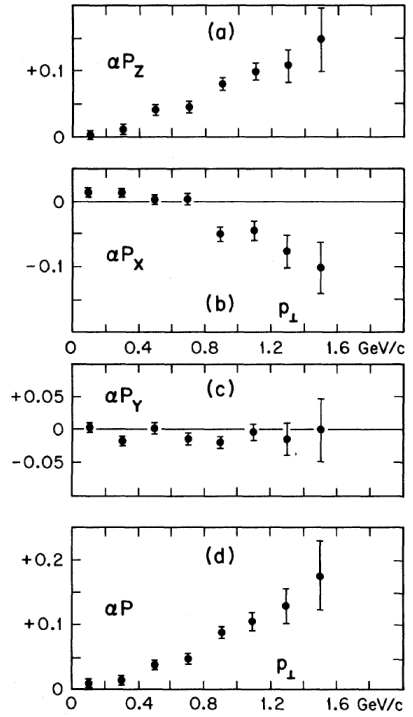


FIG. 3. Three components and magnitude of the $\Lambda^0 \to p + \pi^-$ asymmetry as a function of Λ^0 transverse momentum.

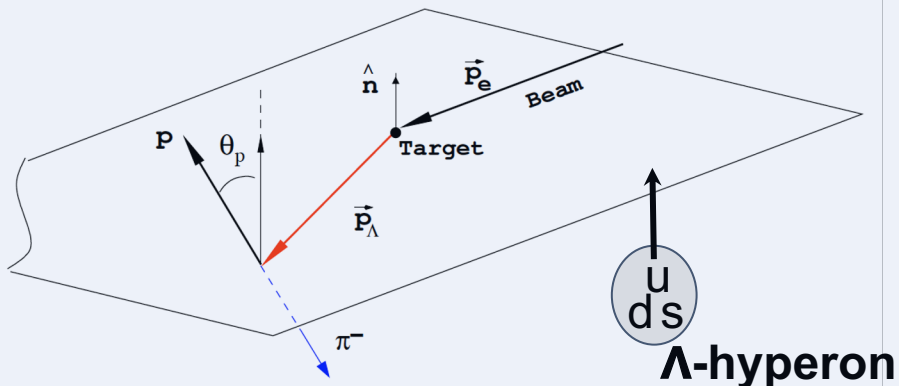
Phys. Rev. Lett. 36, 1113 (1976)

This was the beginning of the `spin physics` in high energy scatterings.

Λ^0 polarization `puzzle`

Production plane

Example: HERMES experiment of ep deep inelastic scattering (DIS).



Λ-hyperon

Λ^0-polarization has been observed in p+p, NC/CC DIS, e+e, p+A, and AA* collisions.

* only in heavy-ion AA collisions, people think it's of different origin.

Λ^0 polarization `puzzle`

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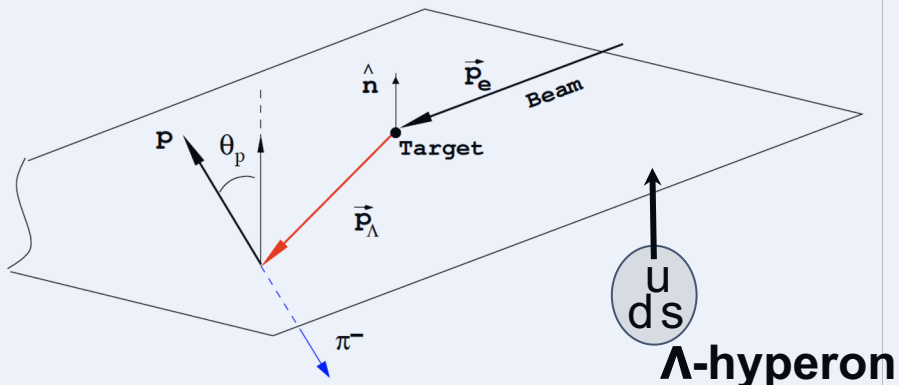

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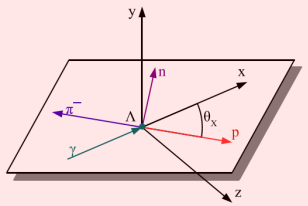
Parton spin direction

Example: COMPASS experiment of mu+p deep inelastic scattering (DIS)



In Λ rest frame:

$$\frac{dN}{d\Omega} = \frac{N_{tot}}{4\pi}\left(1 + \alpha \vec{P}\vec{k}\right)$$

$\alpha = +(-)0.642 \pm 0.013$ – Λ ($\bar{\Lambda}$) decay parameter, $\vec{P}$ – polarization vector, $\vec{k}$ – unit vector along the proton momentum, x-axis align with the virtual photon direction.

Λ^0 polarization is to measure the longitudinal spin transfer from lepton/photon or nucleon to quark.

No signal has been observed.

Λ^0 polarization `puzzle`

Production plane

- TMD polarizing FFs seem to explain the e+e- data (*Gamberg et al 2021*).
- Thomas presession mechanism (*Degrand and Miettinen 1981*): valance quarks and k_T of the strange quark via recombination.
- Other models, including single-pion exchange (*Tornqvist and Sofer 1991*), resonance model with interference (*Jeseph and Sofer 1980)*, etc.

Final-state effects: polarization generated by hadronisation

Λ^0 polarization `puzzle`

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Parton spin direction

Measurement ~ helicity ⊗ partonic scattering cross section ⊗ pFFs

$$d\Delta\sigma^{\Lambda} = \sum \int dx_a dx_b dz \Delta f_a(x_a) f_b(x_b) \otimes \Delta\sigma(ab \to cd) \otimes \Delta D^{\Lambda}(z)$$

helicity distribution — pQCD calculable — polarized FF

- Some argued: polarized FF is too small, so no signal is observed. Similar for transversity.
- …
- Some argued: Feed-down dilution.

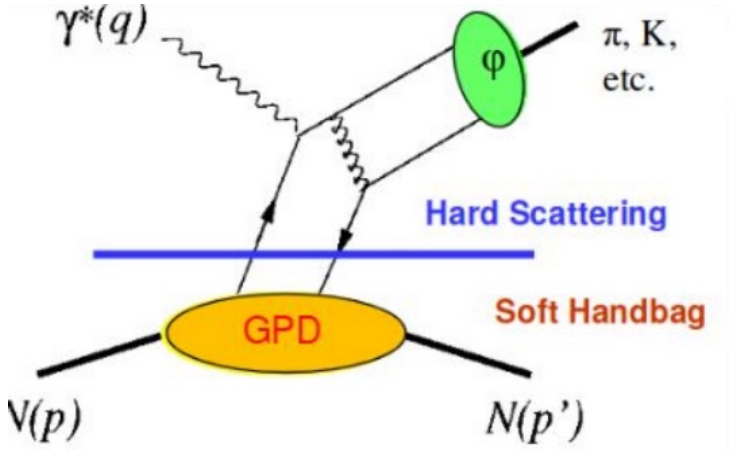
Final-state effects: polarization NOT seen due to hadronisation

Deep Exclusive Meson Production (DEMP)

An exclusive reaction channel to study the meson structure and GPDs.

- Sensitive to the QCD confinement.
- Complementary to the Form Factor measurements.
- Three-dimensional structures, e.g., orbital angular momentum, of the Pion and Kaon.

See [T. Horn 2017] and [G. Huber's talk]



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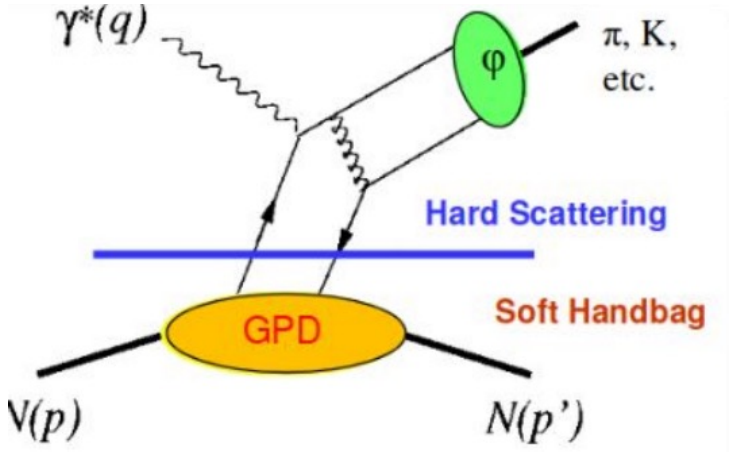
This talk, I focus on:

$$e+p \rightarrow e' + K^{+} + \Lambda^{0}$$

with polarization observables.

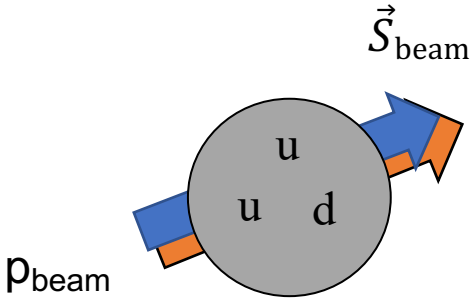


DEMP in $e\vec{p}$

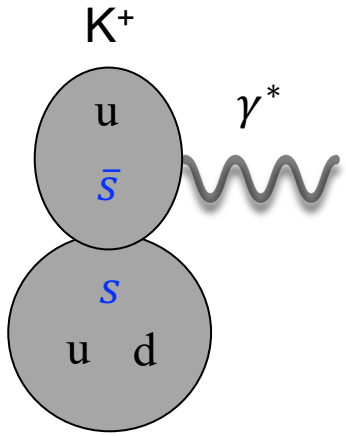
Final states with decay

DEMP process

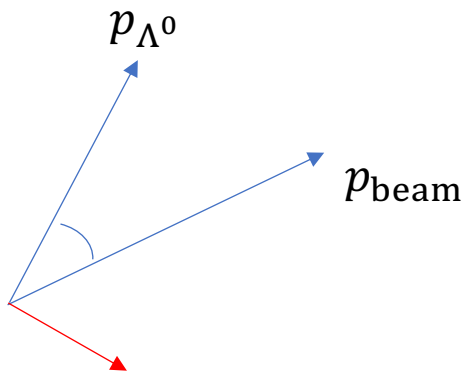
Pre collision < t_0

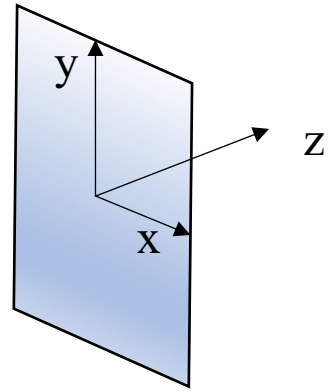


Proton with spin up (70% polarization)



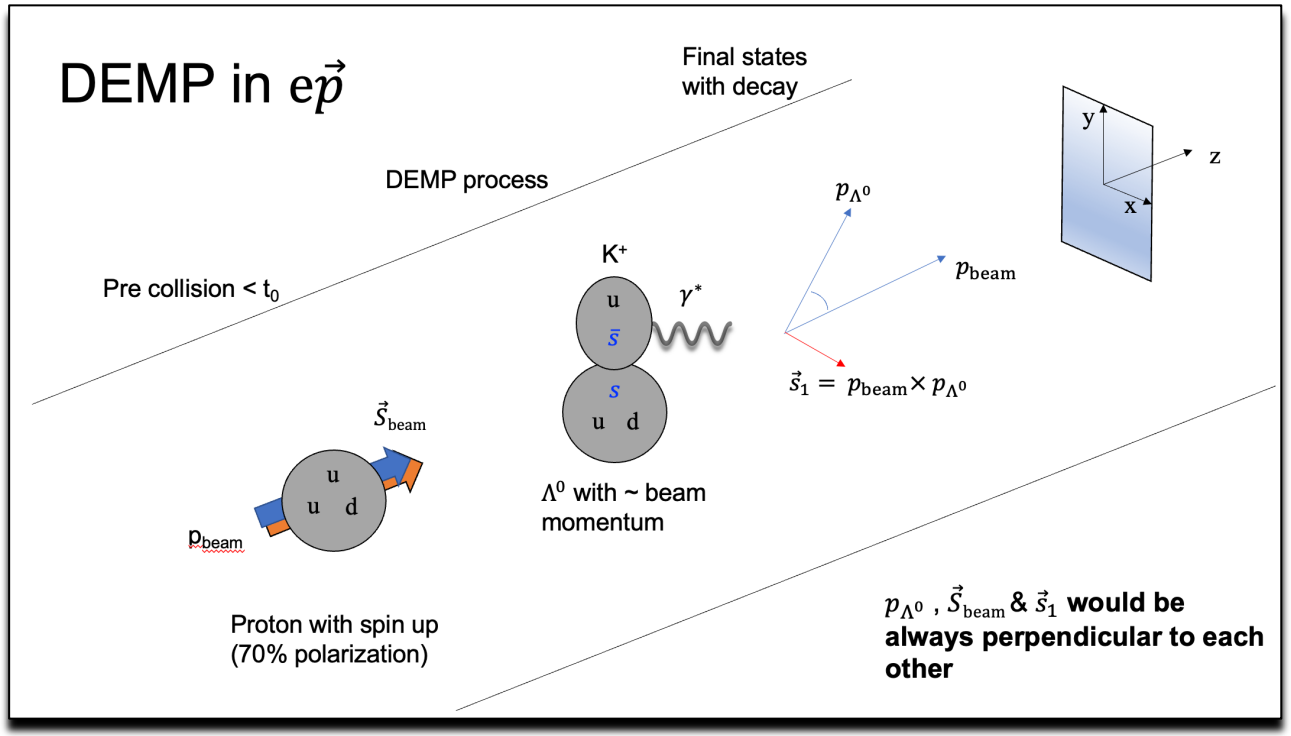
Λ^0 with ~ beam momentum





p_{Λ^0} , $\vec{S}_{\text{beam}}$ & $\vec{s}_1$ would be always perpendicular to each other

Why DEMP?



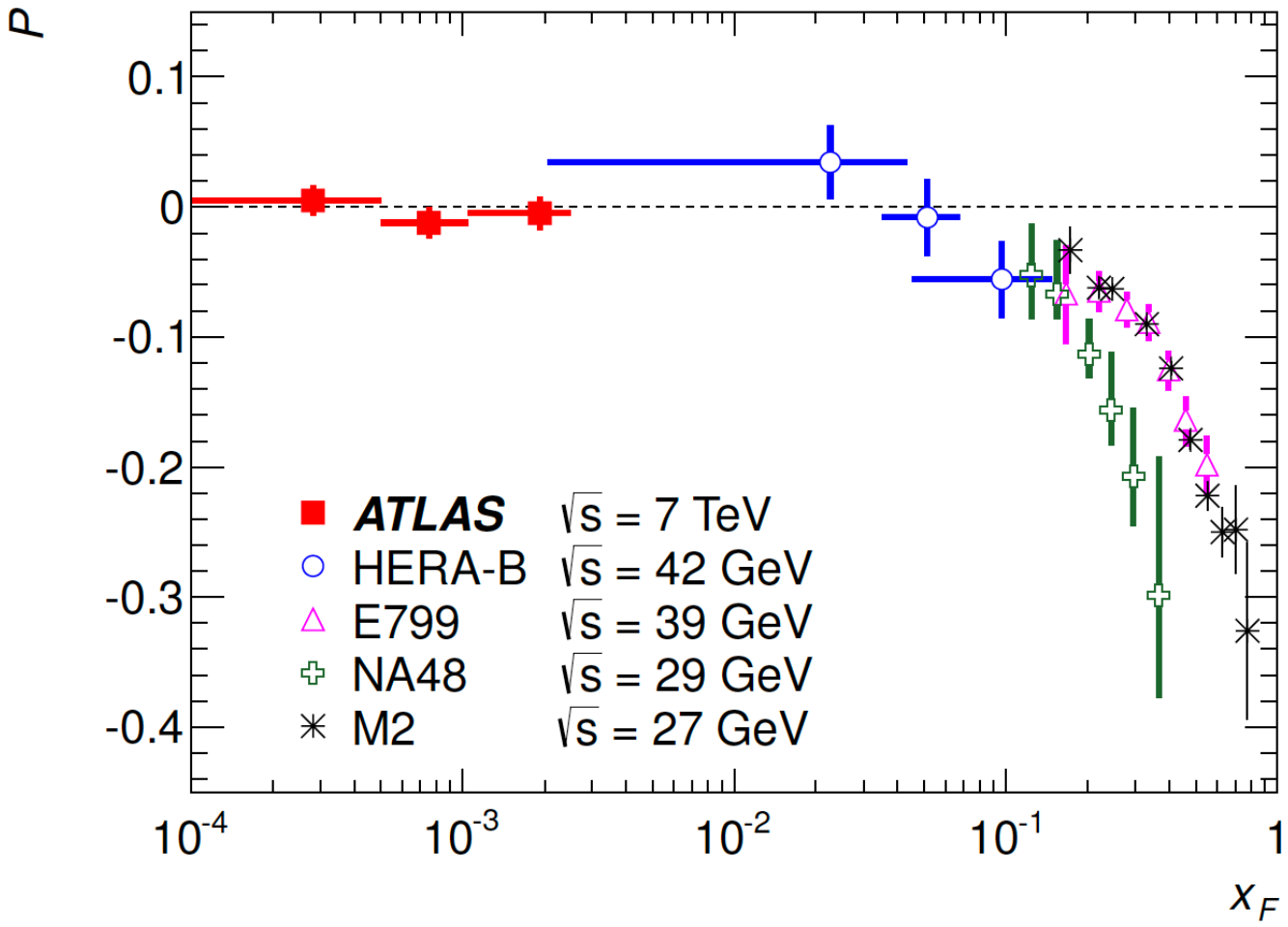
This measurement tests an extreme case:

1. x_F ~ 1.0
2. Exclusive final-states, spin can be counted.
3. ~ No FFs involved.

Which direction Λ^0 would be polarized? $\vec{s}_1$ or $\vec{S}_{\text{beam}}$?

we force $\vec{s}_1 \cdot \vec{S}_{\text{beam}} = 0$ (perpendicular)

Expectation 1 – large P_Λ w.r.t production plane



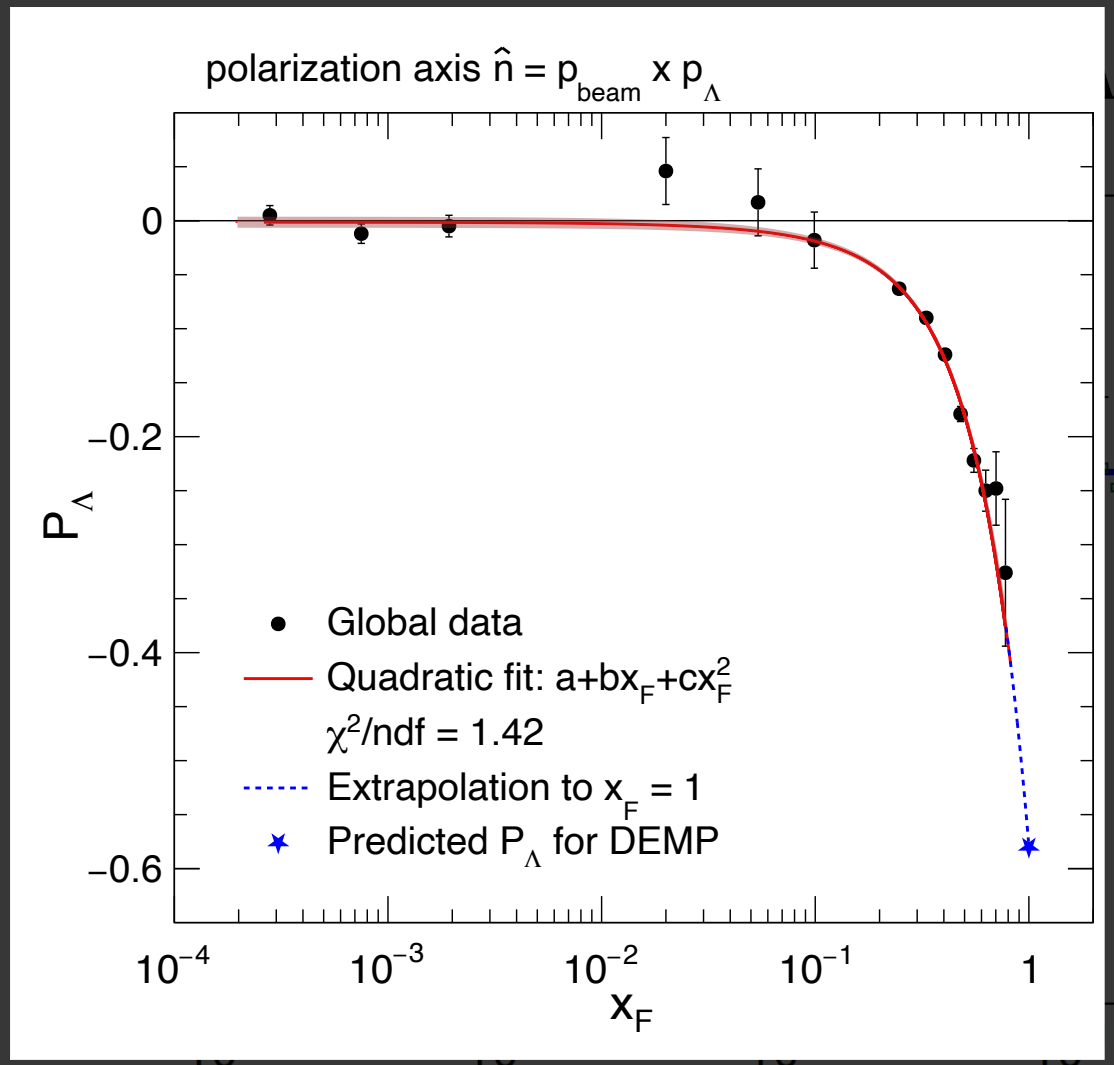
Simply based on data extrapolation:

At large $x_F \sim 1$, polarization prediction is negative and less than -40% w.r.t $\vec{s}_1$ direction

$$\omega_T = a \times v$$

Thomas presession mechanism can still explain this expectation.

*Sign of polarization depends on definition of plane. For all fixed target, it is `beam X lambda` and it matters if it is proton or photon projectile.



w.r.t production plane

Quadratic fit works very well.

Linear fit works too, but with a smaller polarization at $x_F \sim 1$ (-40%)

Simply based on data extrapolation:

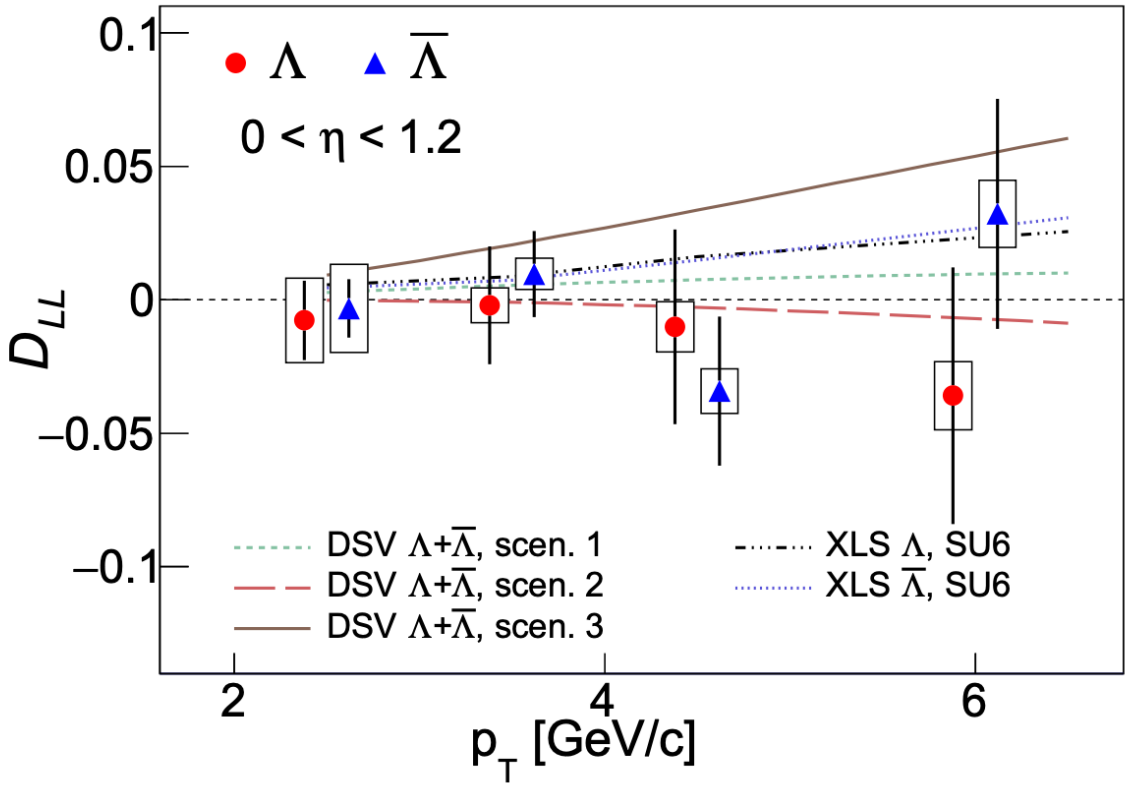
At large $x_F \sim 1$, polarization prediction is negative and less than -40% w.r.t $\vec{s}_1$ direction

- No feed-downs
- No FFs
- Large x_F with large acceleration of strange quark

Thomas presession mechanism can still explain this expectation.

*Sign of polarization depends on definition of plane. For all fixed target, it is `beam X lambda` and it matters if it is proton or photon projectile.

Expectation 2: What to expect for P_Λ w.r.t $\vec{S}_{\text{beam}}$?

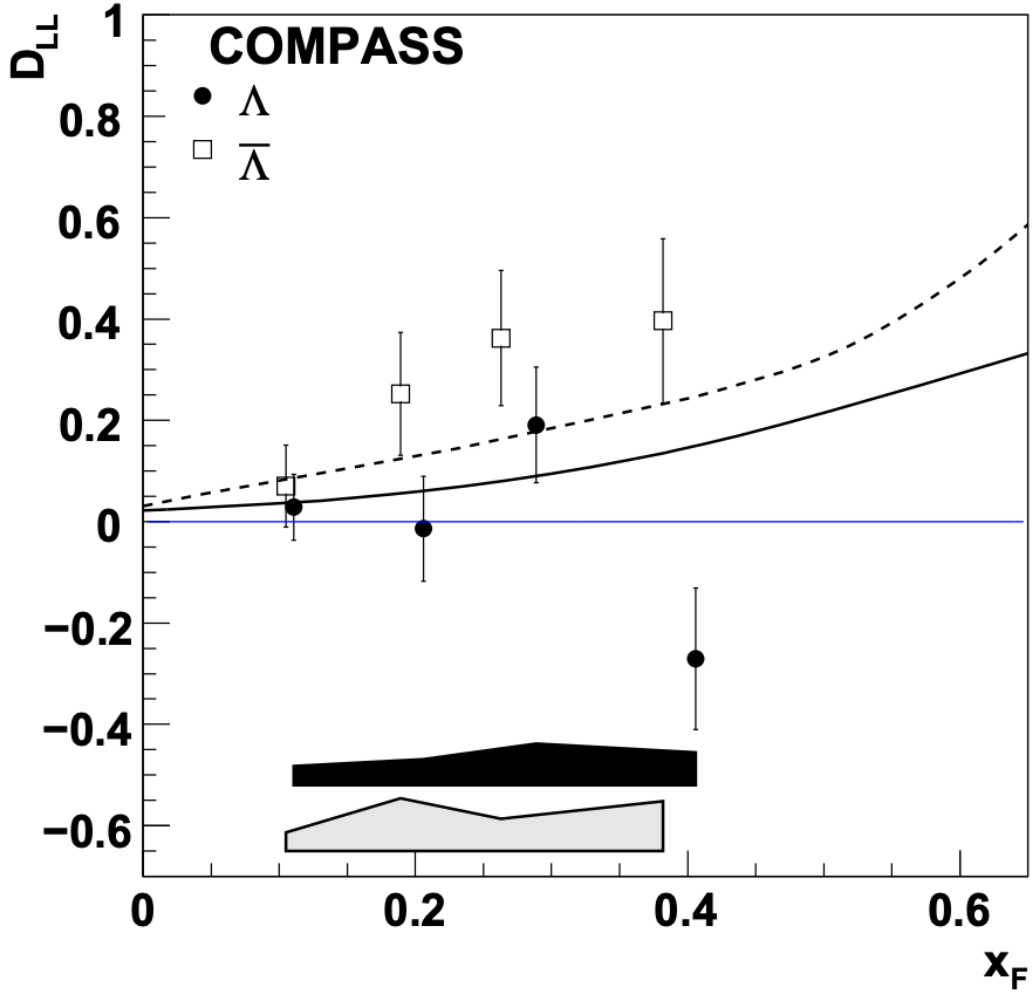


STAR data on proton target;
similar for transverse spin transfer

Despite expectation of a positive P_Λ signal, it has never been observed.

1. We don't know how much **s quark** (could) carries the spin of Λ. (some say 100%, some 60%, and some 0%)
2. In DIS or pp, **feed-down** from heavier particles could dilute signal, if there's any.
3. **Fragmentation** seems to be playing an important role.

Measurement ~ helicity ⊗ partonic scattering cross section ⊗ pFFs



ect for P_Λ w.r.t $\vec{S}_{beam}$?

Similarly found by COMPASS, but to make things `worse`, signal for anti-lambda showed up.

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similar for transverse spin transfer

Eur.Phys.J.C64:171–179,2009

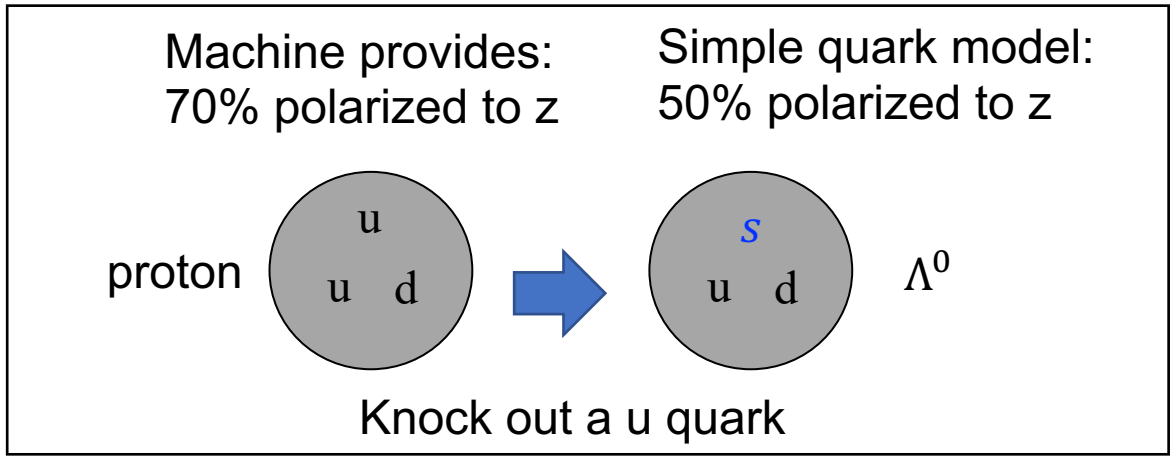
Expectation 2: large P_Λ w.r.t $\vec{S}_{\text{beam}}$

TABLE VIII: First and second moments of various helicity distributions in the measured range at a scale of $Q_0^2 = 2.5\ \text{GeV}^2$.

	Moments in measured range
Δu	$0.601 \pm 0.039 \pm 0.049$
$\Delta \bar{u}$	$-0.002 \pm 0.036 \pm 0.023$
Δd	$-0.226 \pm 0.039 \pm 0.050$
$\Delta \bar{d}$	$-0.054 \pm 0.033 \pm 0.011$
Δs	$0.028 \pm 0.033 \pm 0.009$
$\Delta u + \Delta \bar{u}$	$0.599 \pm 0.022 \pm 0.065$
$\Delta d + \Delta \bar{d}$	$-0.280 \pm 0.026 \pm 0.057$
Δu_v	$0.603 \pm 0.071 \pm 0.040$
Δd_v	$-0.172 \pm 0.068 \pm 0.045$
$\Delta \bar{u} - \Delta \bar{d}$	$0.048 \pm 0.057 \pm 0.028$
$\Delta\Sigma$	$0.347 \pm 0.024 \pm 0.066$
Δq_3	$0.880 \pm 0.045 \pm 0.107$
Δq_8	$0.262 \pm 0.078 \pm 0.045$

HERMES data
(Phys.Rev.D71:012003,2005)

- Up quarks in proton accounts for 60% of the total spin. (down quark accounts negatively, so total 30% - $\Delta\Sigma$)
- Knocking out one up quark is naively expected to be half of it. So 30% of the total spin.
- If the proton is longitudinally polarized ~ 70%, then the remaining polarization (the Λ^0) is expected to be 70%*70% ~ 50% w.r.t the beam polarization direction.



Expectations with $\vec{s}_1 \cdot \vec{S}_{\text{beam}} = 0$:

- Expectation 1: large polarization w.r.t production plane $\vec{s}_1$ [*final-state effect*]
- Expectation 2: large polarization w.r.t Λ^0 momentum or $\vec{S}_{\text{beam}}$ [*initial-state effect*]

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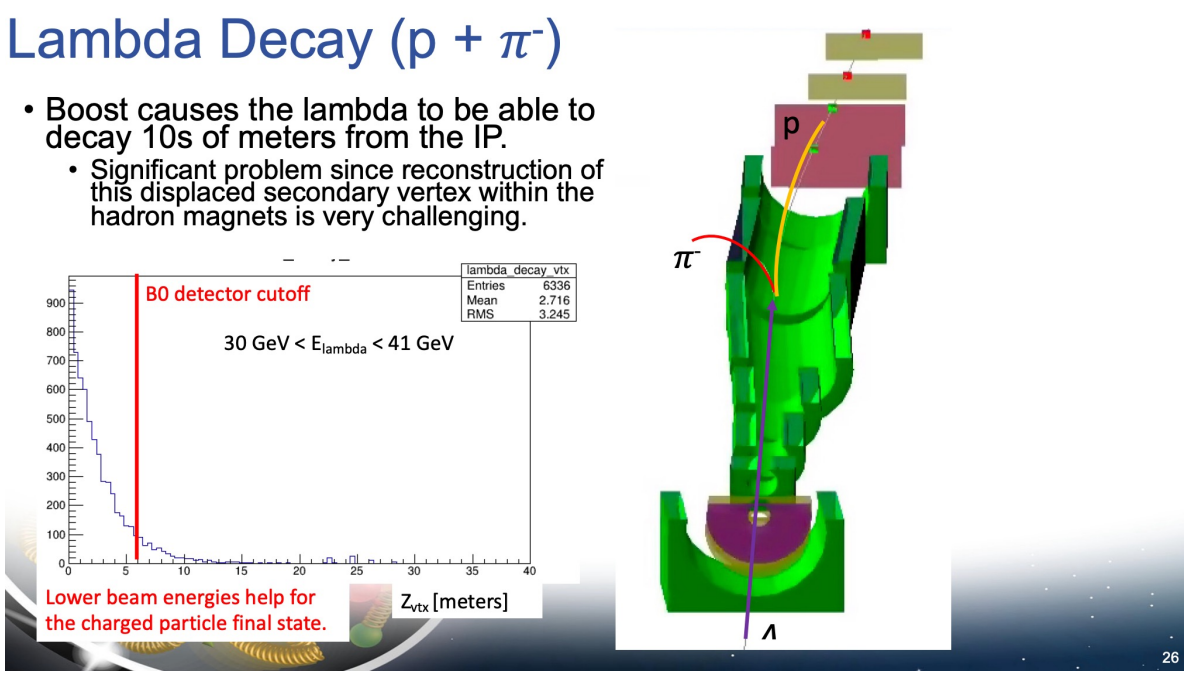
Further questions:

Energy & (Q^2,x) dependence?

- Does the energy of the beam change the picture / result?
- How about (Q^2,x)?
- Low-x strange quark vs high-x?

ePIC detector



(A. Jentsch, BNL)

An interesting channel that we need to detect exactly a Pion, Kaon, and Proton in the forward region, where momentum and position resolution needs to be good for proton – this is not easy

- Lowest energy (41 GeV/c) seems possible
- Highest energy (275 GeV/c) seems very difficult.
- **Can second detector at the EIC focus more on forward direction with higher energy Λ^0 ?**
- Resolution of proton daughter reconstruction, beam effects, etc. are important.

Summary

- The DEMP has been proposed to be a probe to study the spin transfer at the EIC and might shine new lights on the 50 years of Λ^0 polarization puzzle.
  - Expectation 1: large Λ^0 polarization w.r.t production plane;
  - Expectation 2: large Λ^0 polarization w.r.t beam (parton) polarization;

- ePIC detector can only do low proton energy. 2nd EIC detector would be helpful and focus on forward region with higher energy Lambda.
- **EIC is unique because Jlab can only use the missing mass without tagging the Lambda.**

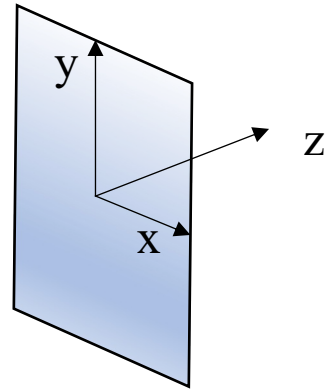
Backup

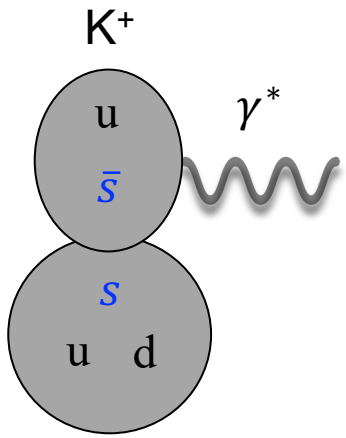
Similarly, for transverse spin

Final states with decay

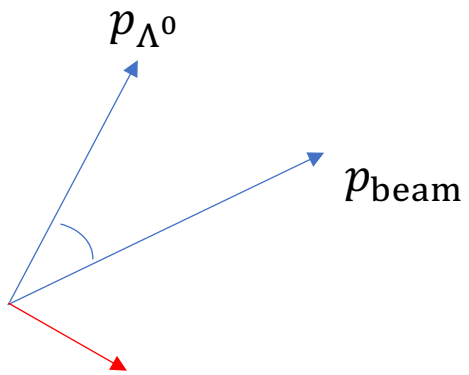
DEMP process

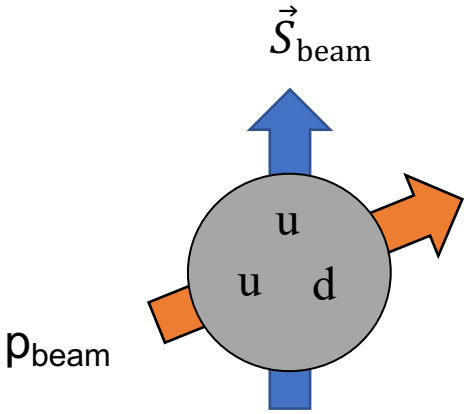
Pre collision < t_0





Λ^0 with ~ beam momentum

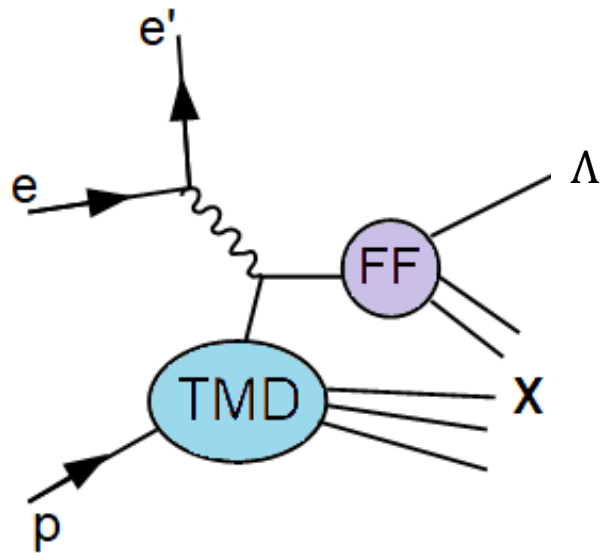




Proton with spin up (70% polarization)

Observable:
The Λ^0 polarization with respect to i) $\vec{S}_{\text{beam}}$ or ii) $\vec{s}_1$, where $\vec{s}_1$ can go full azimuthal angle.

Let’s take a look at the picture



(a)

SIDIS looks at one (leading) parton and the idea is:

- Polarization of nucleon (transfer →) polarization of parton, e.g., u/d/s quark.
- Strange (or u/d) quark carries (some of) the spin and fragment/hadronize.
- Measure the final-state hadron, Λ.

What we understood based on the data is: **this process needs to undergo fragmentation, which by itself is complicated.**

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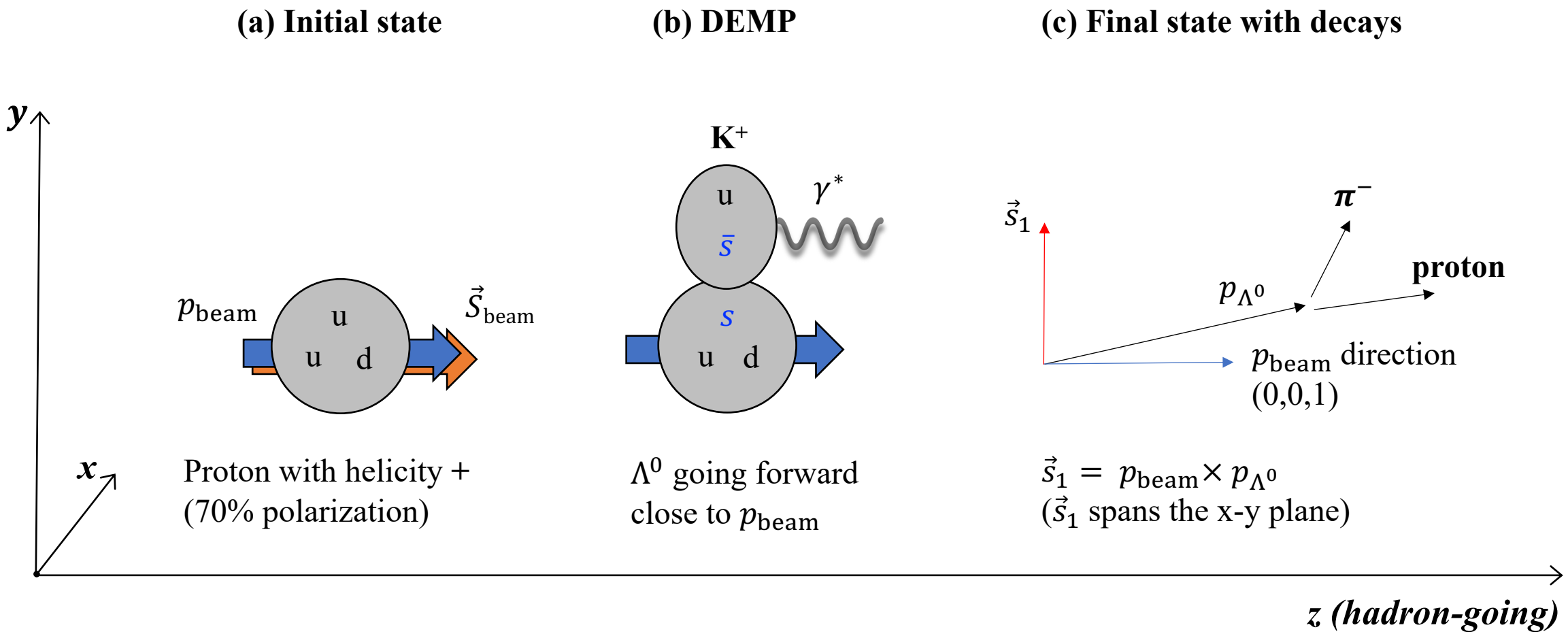
(a) Initial state
(b) DEMP
(c) Final state with decays
y
x
z (hadron-going)
p_{beam}
u
u d
$\vec{S}_{\text{beam}}$
Proton with helicity +
(70% polarization)
K+
u
$\bar{s}$
γ^*
s
u d
Λ^0 going forward
close to p_{beam}
$\vec{s}_1$
π^-
proton
p_{Λ^0}
p_{beam} direction
(0,0,1)
$\vec{s}_1 = p_{\text{beam}} \times p_{\Lambda^0}$
($\vec{s}_1$ spans the x-y plane)