


# Beam-spin induced polarization of $\Lambda$ and $\bar{\Lambda}$ hyperons in semi-inclusive DIS at HERMES

G. Schnell

ikerbasque Basque Foundation for Science
EUSKO JAURLARITZA GOBIERNO VASCO
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DESY.
eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea
EHU QC
EHU Quantum Center

# Single-hadron TMD*) fragmentation functions

*) TMD … transverse-momentum dependent

| hadron pol. \ quark pol. | U | L | T |
|---|---|---|---|
| U | $D_1$ | | $H_1^\perp$ |
| L | | $G_1$ | $H_{1L}^\perp$ |
| T | $D_{1T}^\perp$ | $G_{1T}^\perp$ | $H_1\, H_{1T}^\perp$ |

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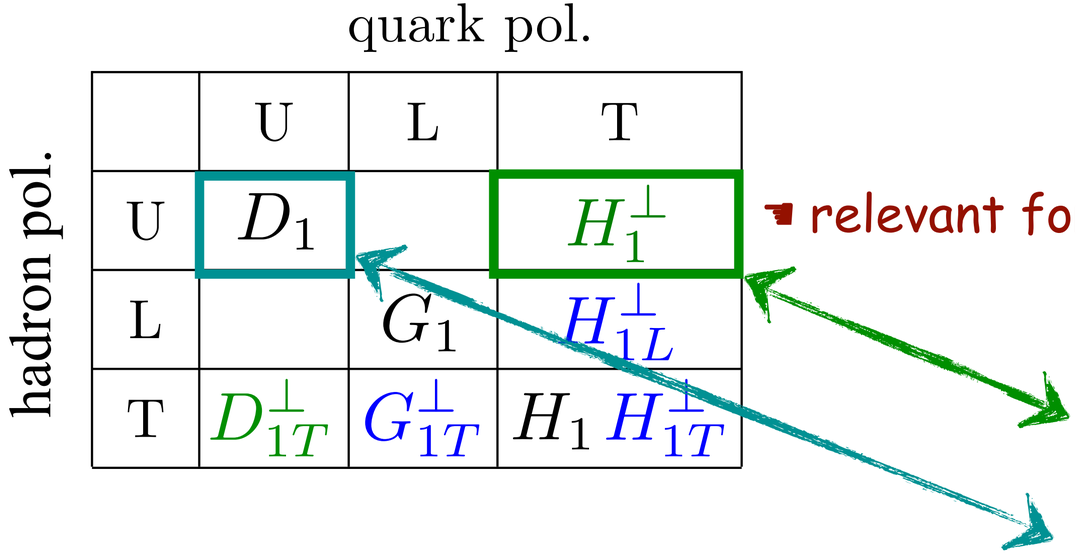
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☚ relevant for unpolarized final state

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Collins FF: $H_1^{\perp,q\to h}$

ordinary FF: $D_1^{q\to h}$

FF … fragmentation function

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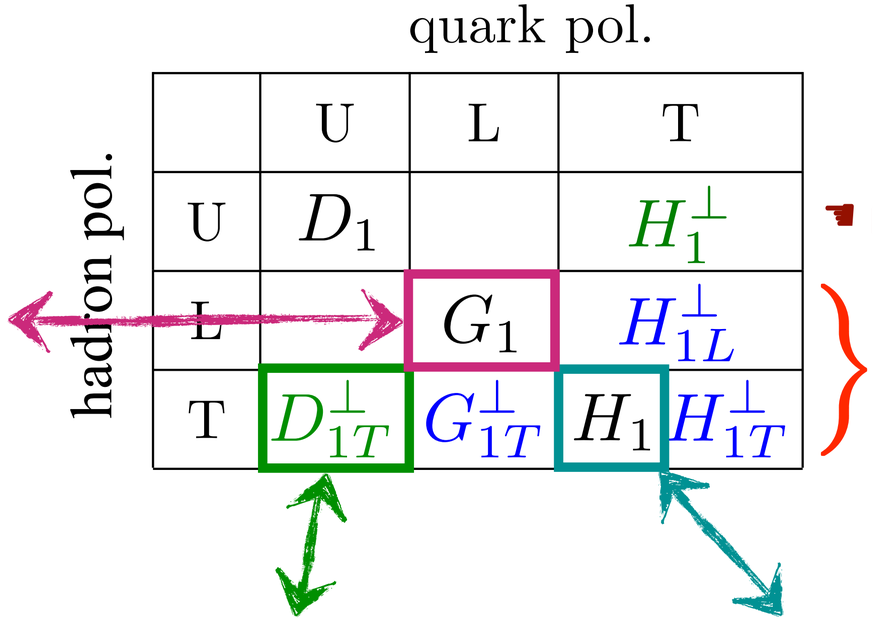
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} polarized final-state hadrons

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helicity FF (longitudinal spin transfer)

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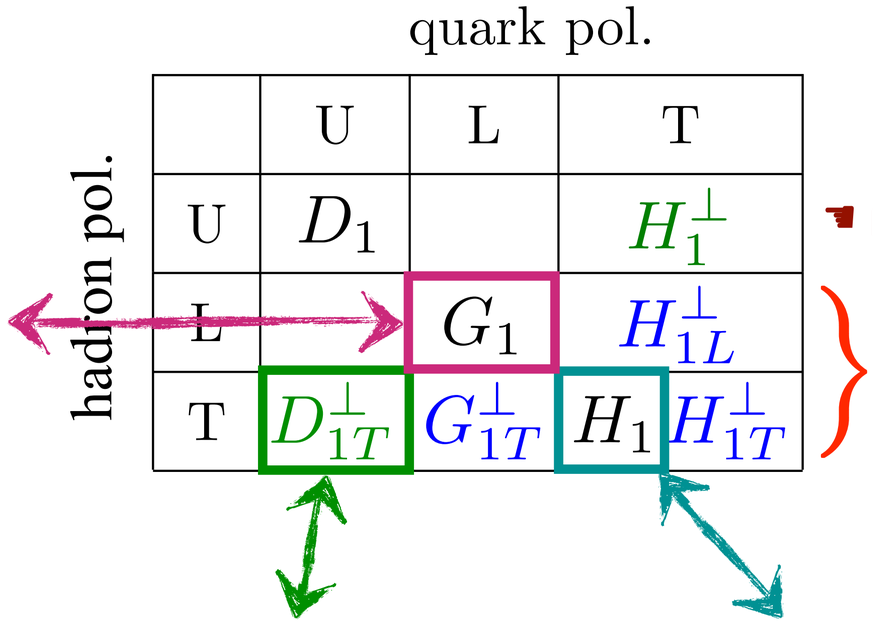
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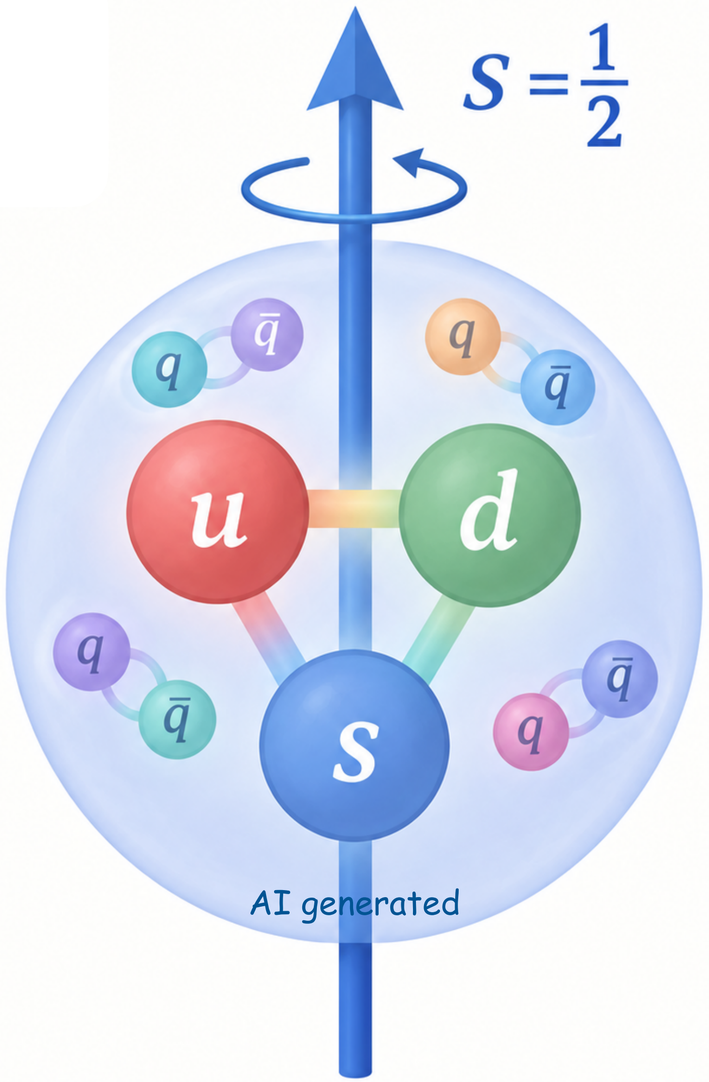
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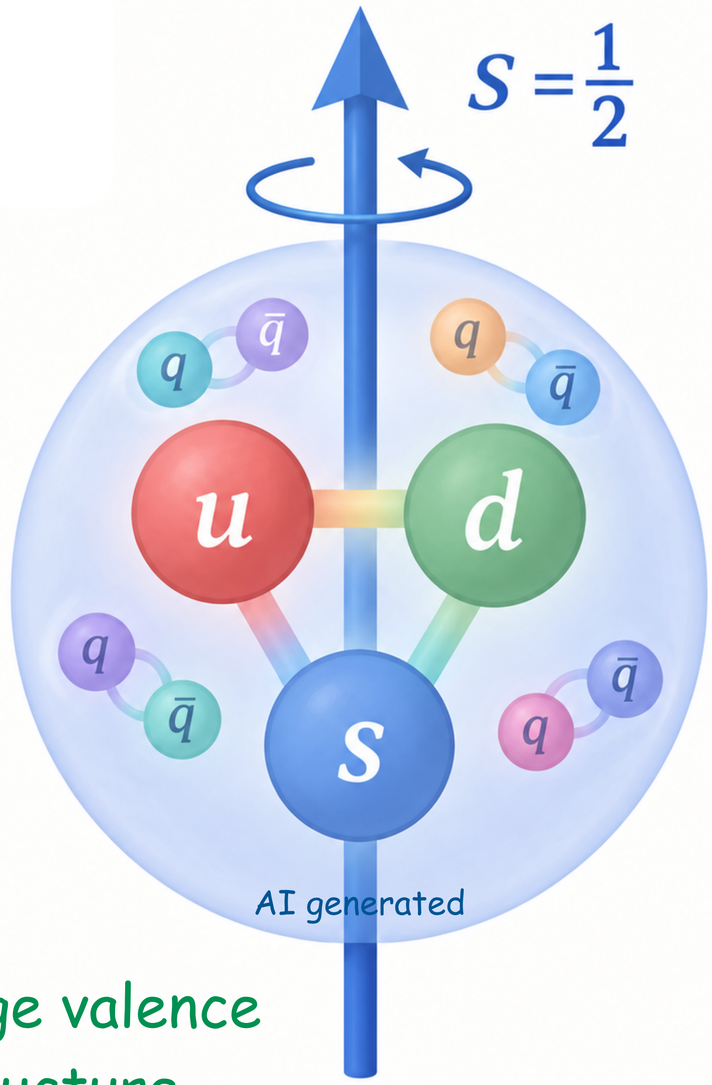
➠ FFs act as quark flavor-tagger and polarimeter

FF … fragmentation function

# Why Lambda?

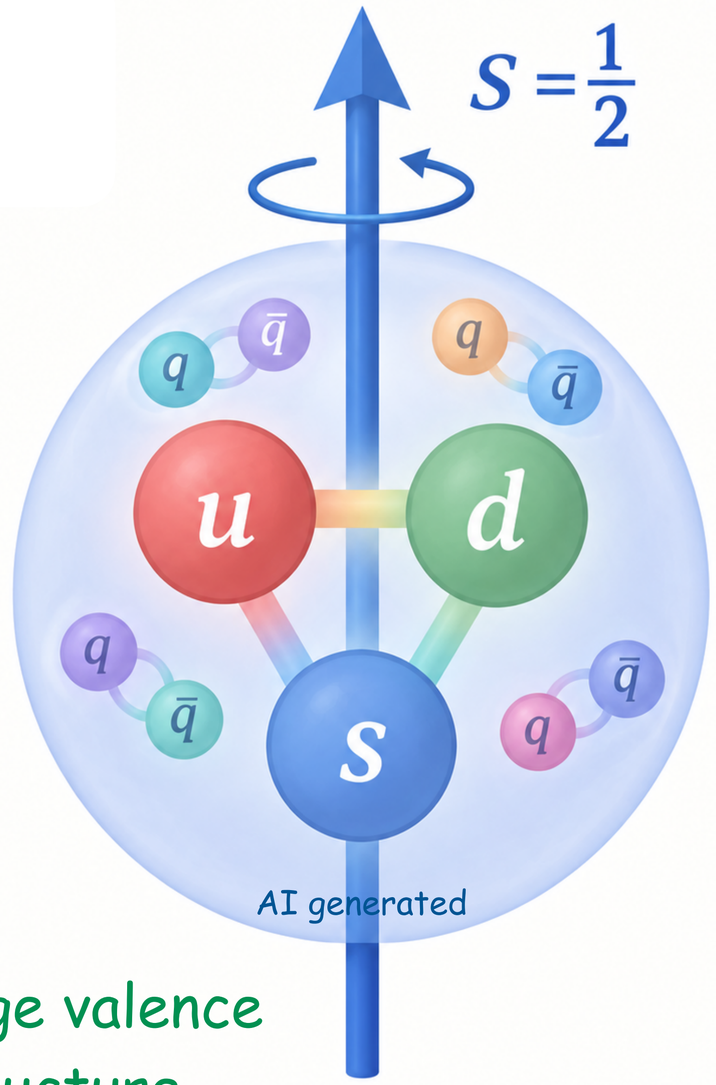


# Why Lambda?




strange valence structure

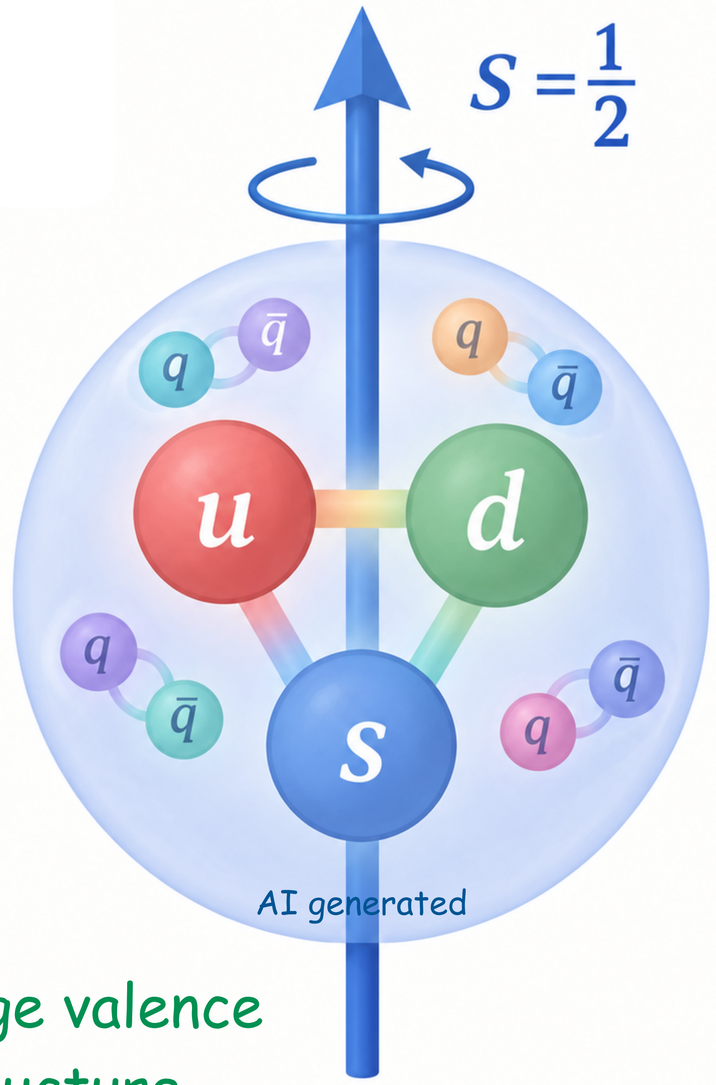
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sensitive to spin-dependent fragmentation

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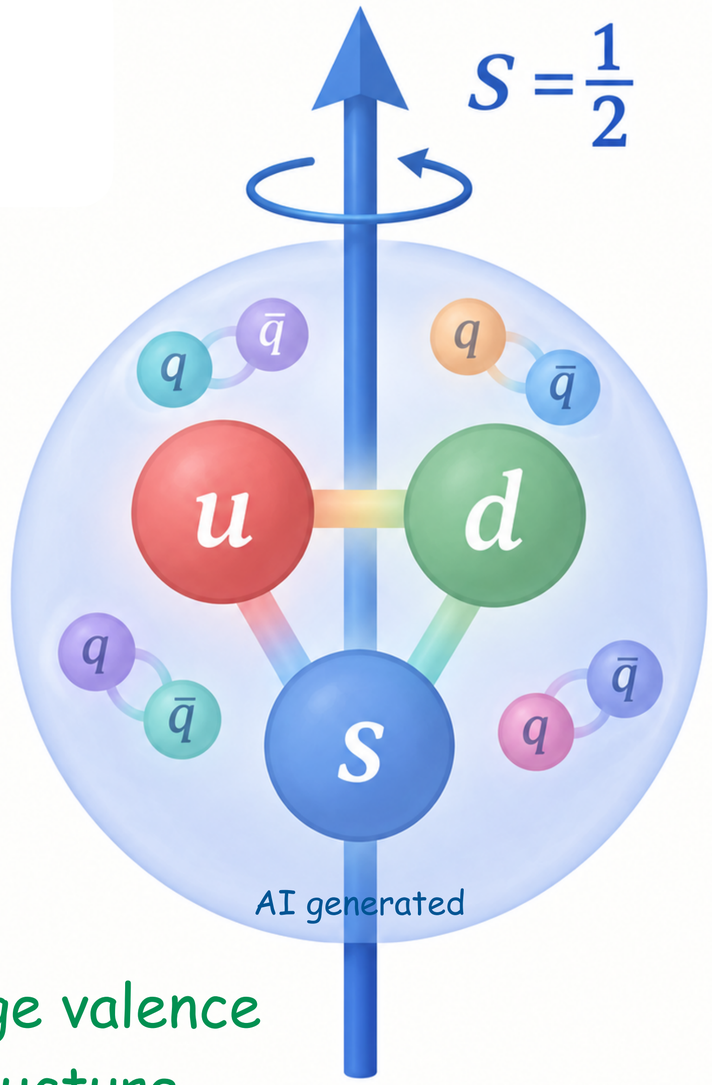

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strange valence structure

quark models: spin carried by s quark; ud unpolarized

# Why Lambda?

its weak decay:
easy-to-use polarimeter



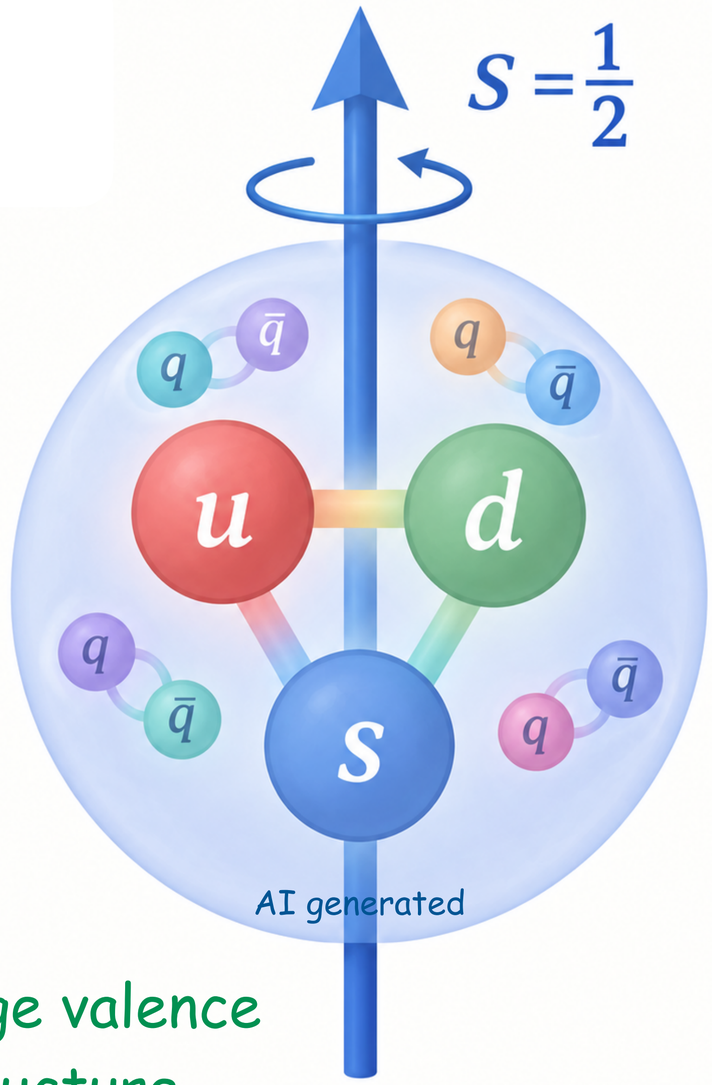

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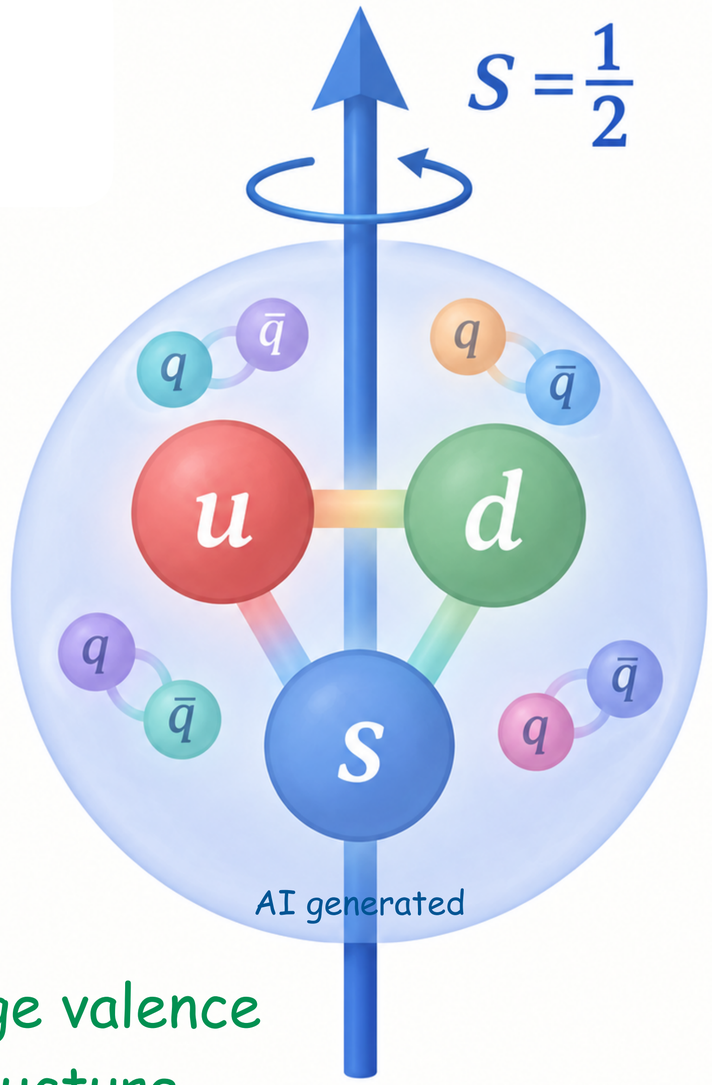
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# Why Lambda?

its weak decay:
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sensitive to
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fragmentation




relatively low yield
compared to light
mesons

lowest-mass hyperon:
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# Lambda fragmentation – a window to strangeness

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## First next-to-next-to-leading-order extraction of fragmentation functions for $\Lambda$ hyperons

**Valerio Bertone**,[a] **Alessia Bongallino**,[b] **Amedeo Chiefa**,[c] **Miguel G. Echevarría**[b] **and Gunar Schnell**[b,d]

[a] *Université Paris-Saclay, CEA, IRFU, 91191 Gif-sur-Yvette, France*
[b] *Department of Physics & EHU Quantum Center, University of the Basque Country (EHU), P.O. Box 644, 48080 Bilbao, Spain*
[c] *The Higgs Centre for Theoretical Physics, University of Edinburgh, JCMB, KB, Mayfield Rd, Edinburgh EH9 3JZ, Scotland*
[d] *IKERBASQUE, Basque Foundation for Science, Plaza Euskadi 5, 48009 Bilbao, Spain*

*E-mail:* valerio.bertone@cea.fr, alessia.bongallino@ehu.eus, amedeo.chiefa@ed.ac.uk, miguel.garciae@ehu.eus, gunar.schnell@desy.de

Abstract: We present `MAPFF1.0_Lambda`, the first global analysis at next-to-next-to-leading order in perturbative QCD of the collinear unpolarised fragmentation functions of $\Lambda$ hyperons. The fit is based on data from single-inclusive electron-positron annihilation, and from both neutral-current and — for the first time — charged-current semi-inclusive deep-inelastic scattering. We have adopted a statistical framework based on Monte Carlo sampling and parametrised fragmentation functions in terms of a neural network. The fragmentation function set comprises a total of seven independent parton flavours, allowing for the first independent determination of valence-quark distributions. Our analysis offers new insights into the hadronisation mechanism of strange baryons and establishes a baseline for future phenomenological and experimental investigations.

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# Lambda fragmentation – a window to strangeness

## Motivation

Improving the determination of FFs by focusing on a less extensively explored hadron:
the $\Lambda$ hyperon, the lightest among the strange baryons

### State of the art of $\Lambda$ collinear unpolarised fits

| Collaboration | Data | Flavour separation | Accuracy | Extracted particle |
|---|---|---|---|---|
| **DSV** (1998) Phys. Rev. D 57, 5811 | SIA | $u = d = s$ | NLO | $\Lambda + \bar{\Lambda}$ |
| **AKK** (2006) Nucl. Phys. B, 734 | SIA | ✓ | | |
| (2008) Nucl. Phys. B 803 | SIA, pp collisions | ✓ | | |
| **NPC23** (2025) Phys. Rev. D 112, 054045 | SIA, SIDIS, pp collisions | $u = d$ | | |
| **MAPFF1.0_Λ** (2026) | SIA, SIDIS (NC and CC) | ✓ | NNLO | $\Lambda, \bar{\Lambda}$ |

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Inclusion of all available SIDIS neutral-and – for the first time – **charged-current** data

First independent determination of valence-quark distribution for the $\Lambda$, i.e., for $u$, $d$, $s$

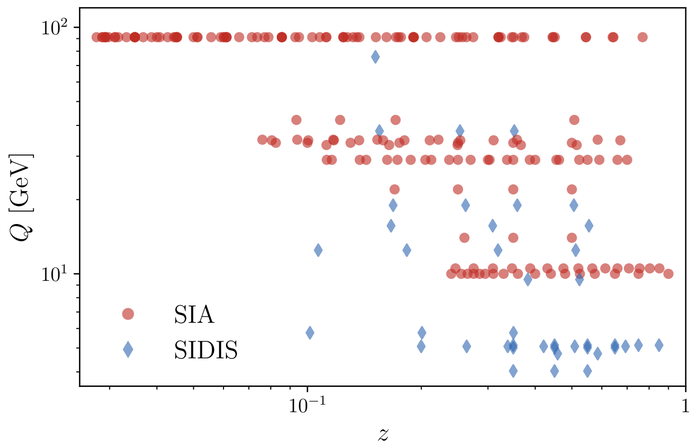
SIDIS data allow to reliably extract for the first time FFs for $\Lambda$ and $\bar{\Lambda}$ **separately**

[JHEP10(2026)089]

# Lambda fragmentation – a window to strangeness

## Experimental data

| Experiment | $\sqrt{s}$ [GeV] | $N_{\text{dat}}^{\Lambda+\bar{\Lambda}}$ |
|---|---|---|
| SIA | | |
| ARGUS | 10.0 | 16 |
| Belle | 10.52 | 15 |
| TASSO14 | 14.0 | 3 |
| TASSO22 | 22.0 | 4 |
| TASSO33.3 | 33.3 | 5 |
| TASSO34 | 34.0 | 7 |
| TASSO34.8 | 34.8 | 10 |
| TASSO42.1 | 42.1 | 4 |
| CELLO | 35.0 | 7 |
| MARK II | 29.0 | 13 |
| HRS | 29.0 | 12 |
| SLD | 91.2 | 15 |
| | 91.2 | 8 |
| | 91.2 | 8 |
| | 91.2 | 8 |
| ALEPH | 91.2 | 25 |
| DELPHI91 | 91.2 | 10 |
| OPAL | 91.2 | 15 |
| Experiment | $\sqrt{s}$ [GeV] | $N_{\text{dat}}^{\Lambda} + N_{\text{dat}}^{\bar{\Lambda}}$ |
| Neutral-Current SIDIS | | |
| CHIO | 20.6 | 3 + 4 |
| EMC | 23.5 | 4 + 3 |
| E665 | 30.3 | 3 + 3 |
| H1 1996 | 300 | 2 |
| ZEUS 10−40 | 319 | 1 |
| ZEUS 40−160 | 319 | 2 |
| ZEUS 160−640 | 319 | 4 |
| ZEUS 640−2560 | 319 | 3 |
| ZEUS 2560−10240 | 319 | 1 |
| Charged-Current SIDIS | | |
| WA59 | 9.2 | 6 + 0 |
| NOMAD | 9.3 | 6 + 7 |
| ABCMO | 23.5 | 4 + 0 |
| Total | | 241 |




SIA Range in $\sqrt{s}$ spans from $10\,\text{GeV}$ to $M_Z$

Datasets delivered as the sum of $\Lambda$ and $\bar{\Lambda}$

SIDIS Measurements for neutral- and charged-current

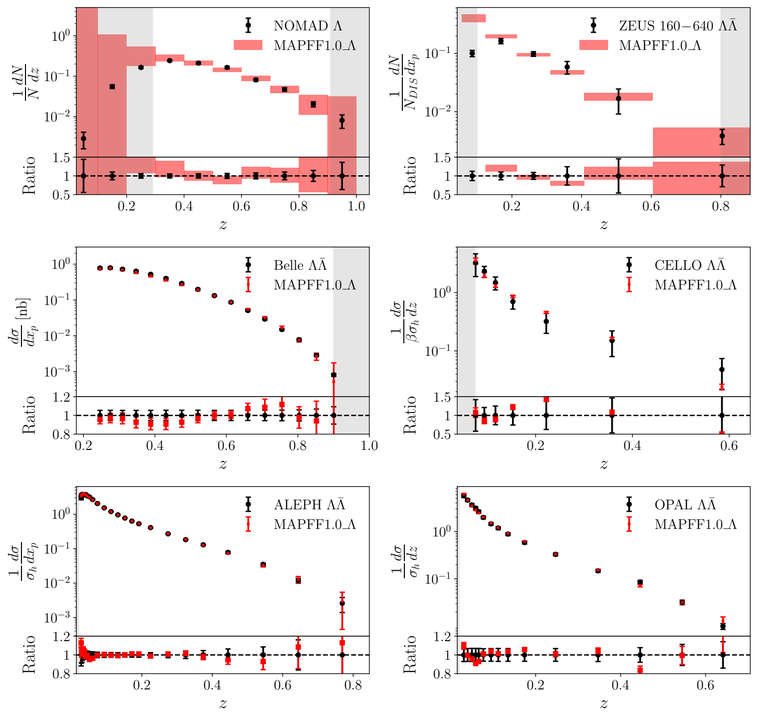
Data provided separately for $\Lambda$ and $\bar{\Lambda}$

[JHEP10(2026)089]

# Lambda fragmentation – a window to strangeness

## Fit quality

| Experiment | $N_{\rm dat}$ | $\chi^2/N_{\rm dat}$ NLO | $\chi^2/N_{\rm dat}$ NNLO |
|---|---|---|---|
| CHIO $\Lambda$ | 3 | 0.56 | 0.55 |
| CHIO $\bar{\Lambda}$ | 4 | 1.11 | 1.03 |
| EMC $\Lambda$ | 4 | 1.19 | 0.83 |
| EMC $\bar{\Lambda}$ | 3 | 0.12 | 0.47 |
| E665 $\Lambda$ | 3 | 0.50 | 0.48 |
| E665 $\bar{\Lambda}$ | 3 | 1.00 | 1.27 |
| H1 $\Lambda\bar{\Lambda}$ | 2 | 1.18 | 1.01 |
| ZEUS $\Lambda\bar{\Lambda}$ 10-40 | 1 | $< 0.01$ | $< 0.01$ |
| ZEUS $\Lambda\bar{\Lambda}$ 40-160 | 2 | 0.61 | 0.75 |
| ZEUS $\Lambda\bar{\Lambda}$ 160-640 | 4 | 1.07 | 0.81 |
| ZEUS $\Lambda\bar{\Lambda}$ 640-2560 | 3 | 0.46 | 0.37 |
| ZEUS $\Lambda\bar{\Lambda}$ 2560-10240 | 1 | 0.03 | 0.03 |
| WA59 $\Lambda$ | 6 | 0.34 | 0.33 |
| NOMAD $\Lambda$ | 6 | 1.36 | 1.85 |
| NOMAD $\bar{\Lambda}$ | 7 | 0.14 | 0.18 |
| ABCMO $\Lambda$ | 4 | 4.05 | 3.05 |
| ARGUS | 16 | 1.49 | 1.55 |
| Belle | 15 | 1.13 | 1.26 |
| TASSO 14 | 3 | 0.23 | 0.23 |
| TASSO 22 | 4 | 0.48 | 0.49 |
| TASSO 33 | 5 | 0.78 | 0.78 |
| TASSO 34 | 7 | 0.57 | 0.56 |
| TASSO 34.8 | 10 | 2.79 | 2.75 |
| TASSO 42.1 | 4 | 1.13 | 1.12 |
| HRS | 12 | 0.82 | 0.82 |
| MARK II | 13 | 1.47 | 1.47 |
| CELLO | 7 | 0.52 | 0.51 |
| ALEPH | 25 | 0.48 | 0.44 |
| DELPHI 91.2 | 10 | 2.62 | 2.58 |
| OPAL | 15 | 1.04 | 1.04 |
| SLD | 15 | 0.24 | 0.25 |
| SLD UDS | 8 | 2.30 | 2.02 |
| SLD C | 8 | 2.31 | 2.19 |
| SLD B | 8 | 0.50 | 0.80 |
| Total | 241 | 1.10 | 1.09 |



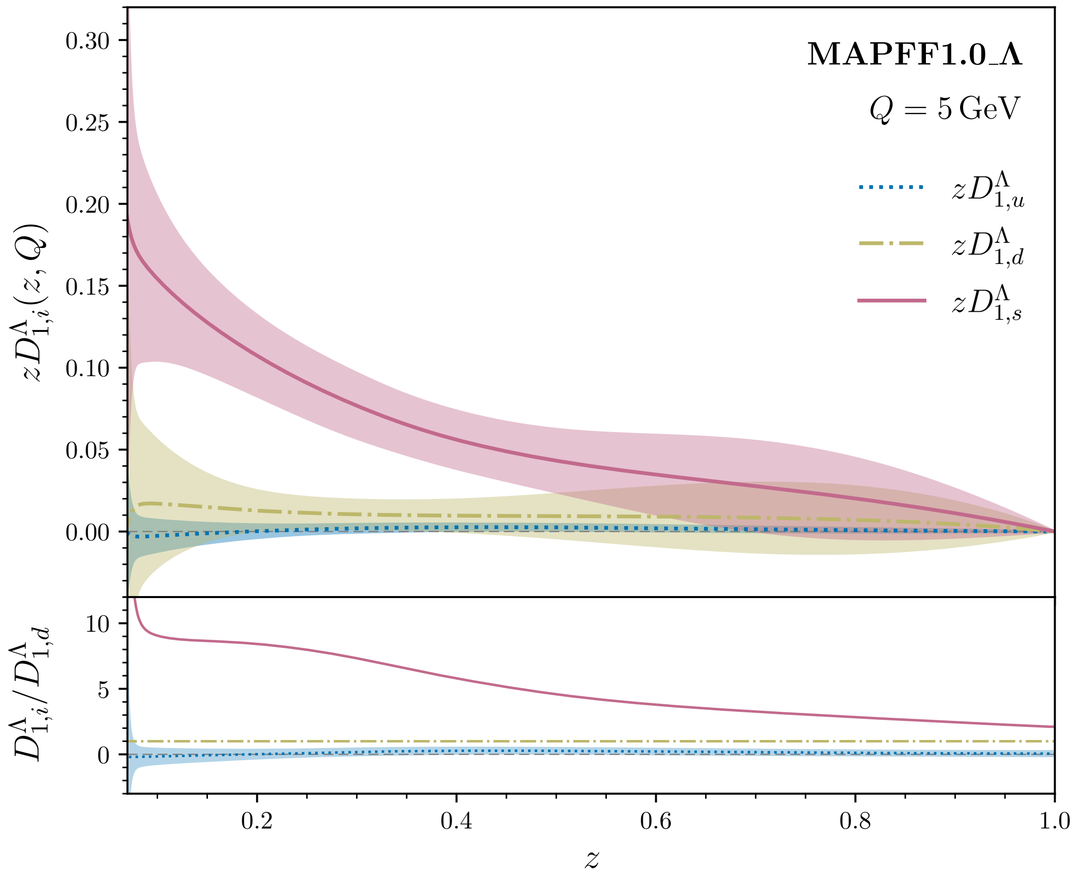

$\chi^2 = 1.10$ at NLO, $\chi^2 = 1.09$ at NNLO

Quality of the fit stable when going at NNLO
Slight improvement for the majority of the datasets

[JHEP10(2026)089]

# Lambda fragmentation – a window to strangeness

## Valence quarks

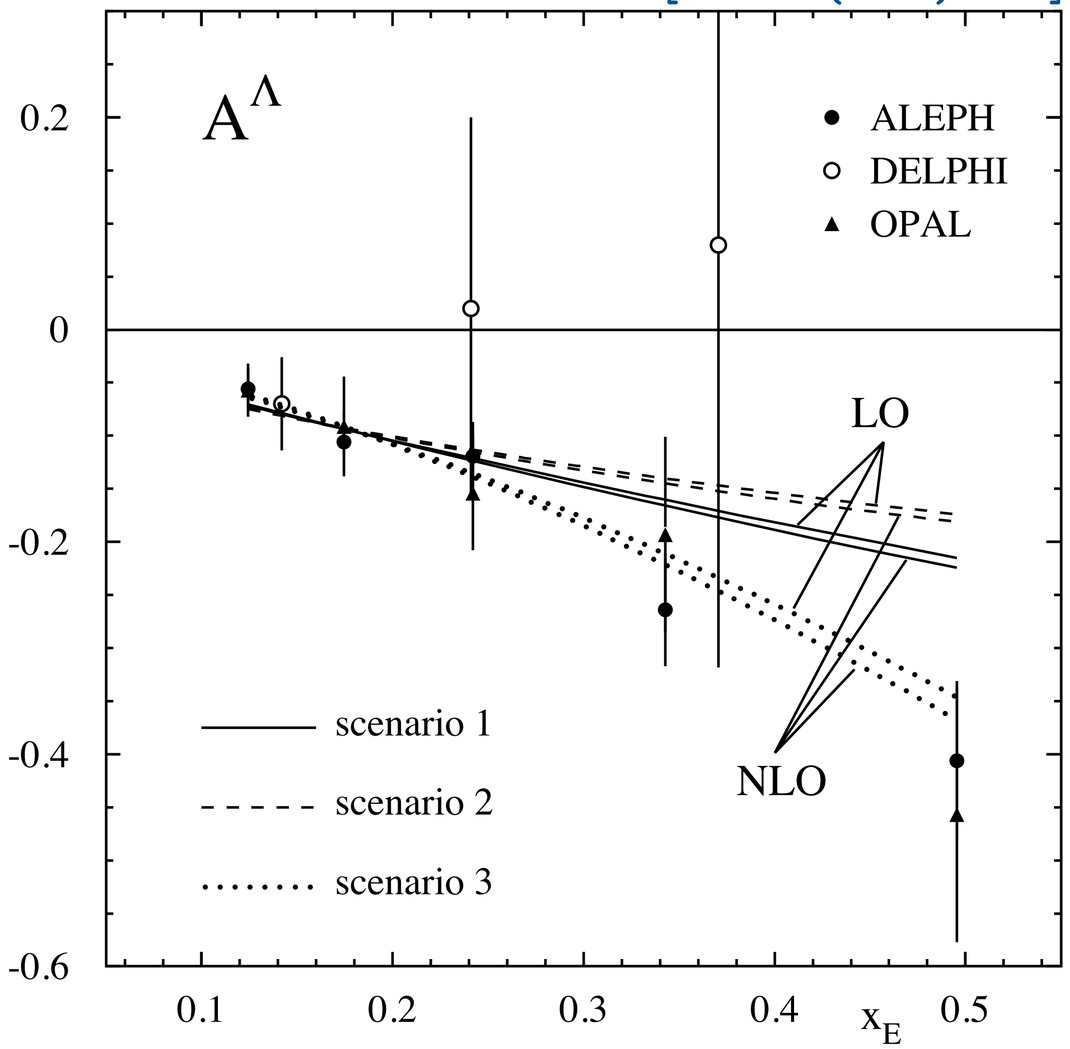



- **Dominance** of the strange quark over the entire $z$ range: consistency with the quark composition of the $\Lambda$
- Fragmentation of $u$ or $d$ into $\Lambda$ is less pronounced compared to $s$-quark fragmentation, the distributions show a similar shape

[JHEP10(2026)089]

# Longitudinal polarization in fragmentation?

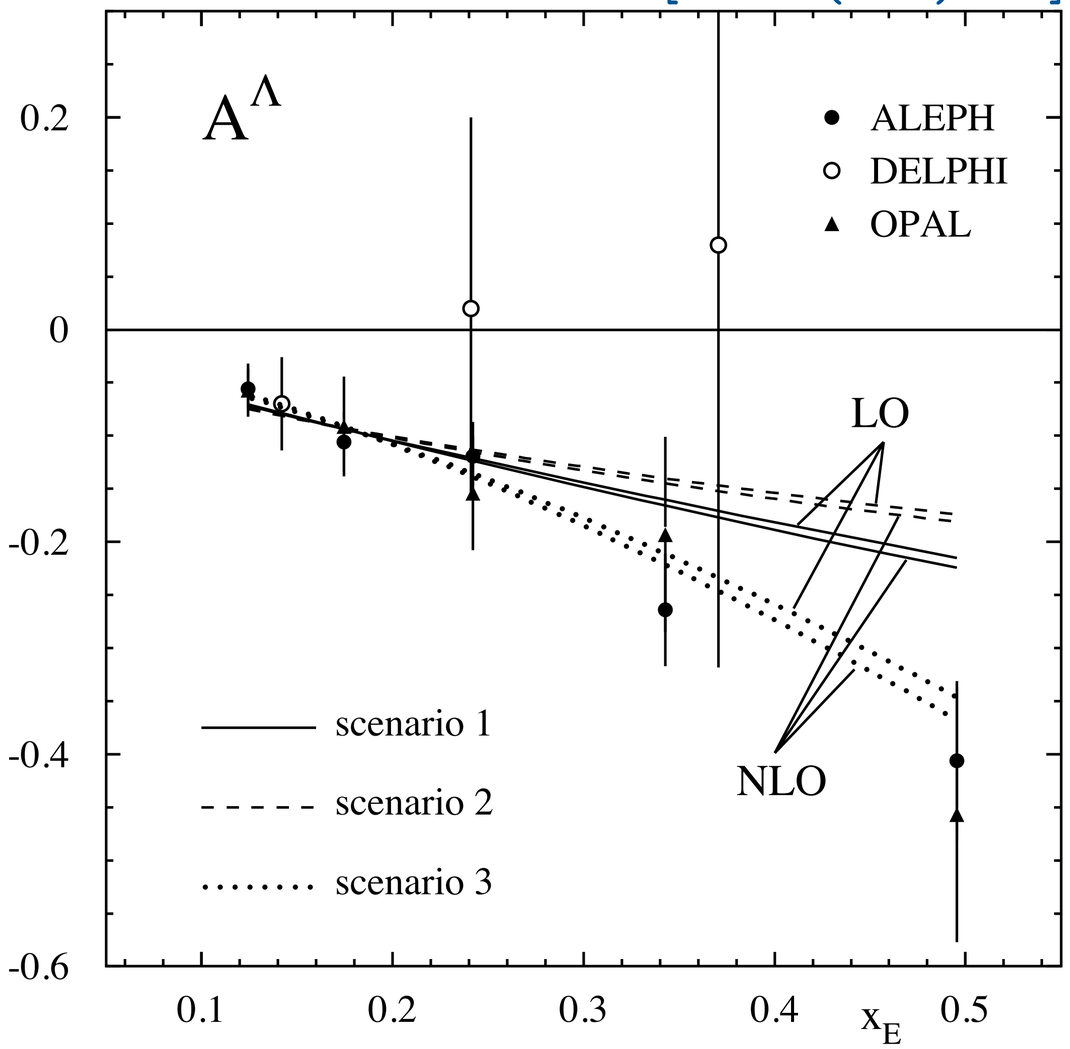
[PRD 57 (1998) 5811]




- large longitudinal polarization in $e^+e^-$ at LEP
  ➥ $G_1 \neq 0$

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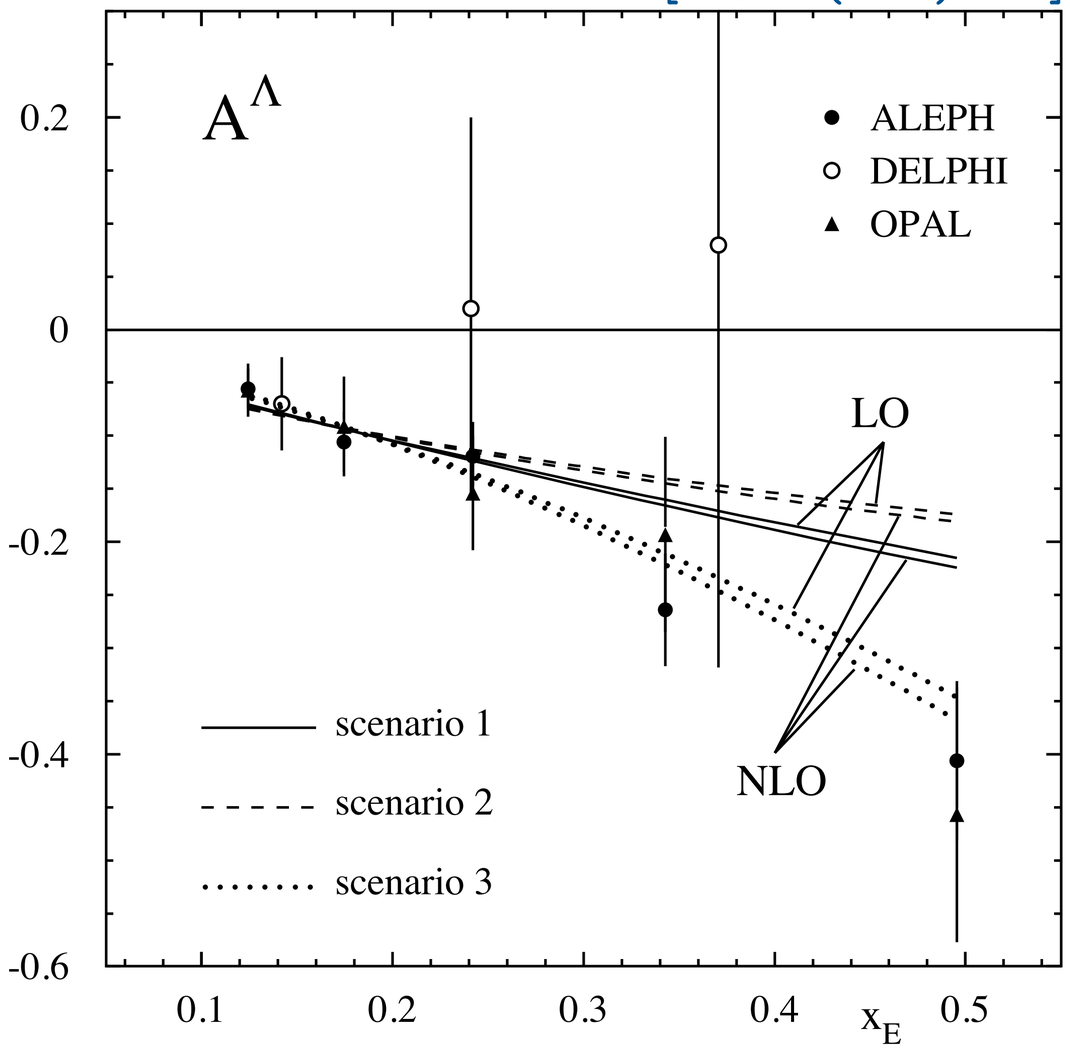
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- $Z^0$ decay produces pairs of highly polarized strange (anti)quarks
- in simple quark models, the $\Lambda$ spin is carried by strange quarks; the ud pair has zero spin.
  - suggests strong spin transfer from a polarized strange quark to $\Lambda$

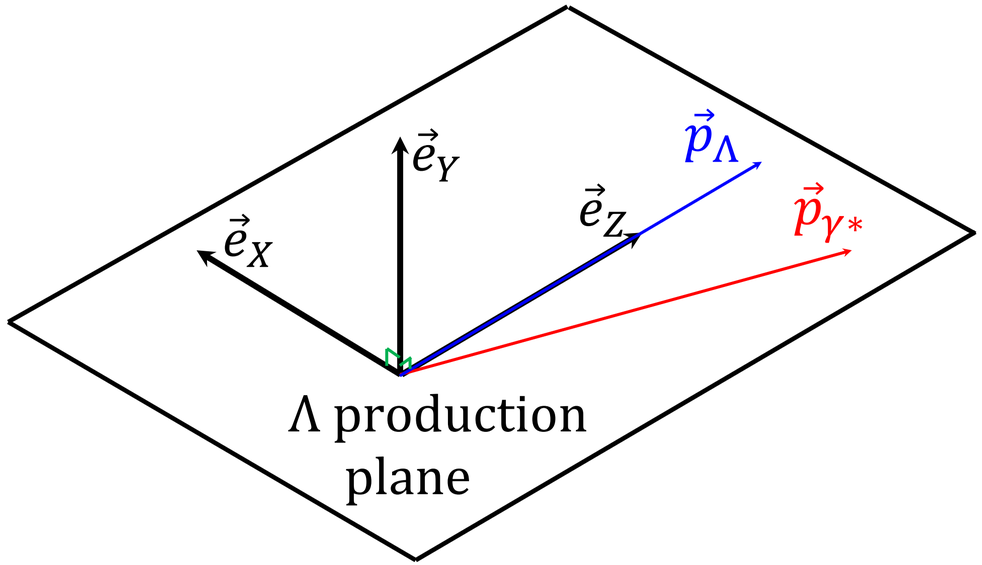
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- in DIS, mainly scattering off u (and d) quarks

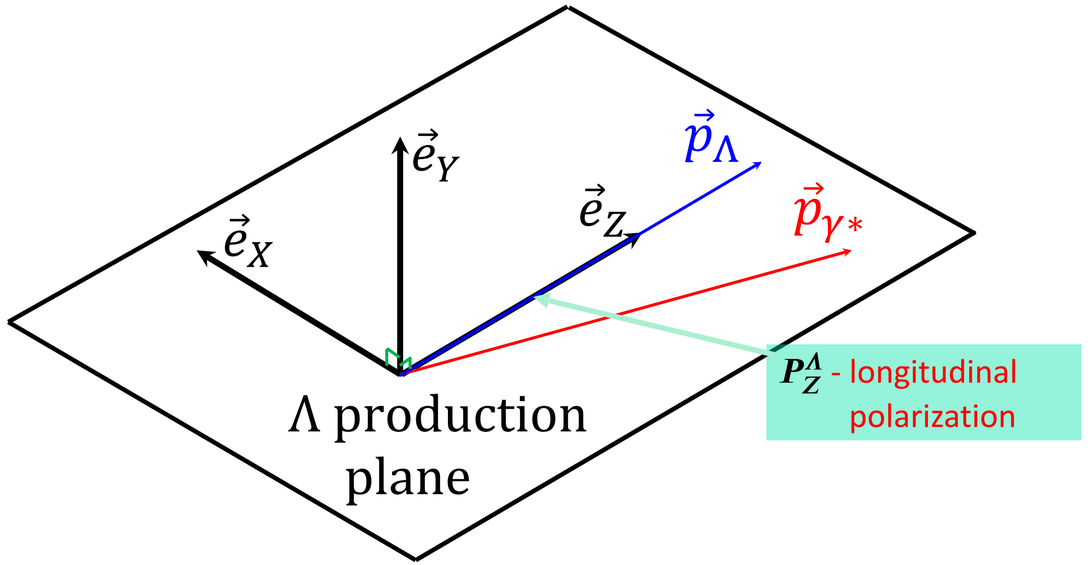
# Lambda production in DIS



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Mulders &Tangerman, Nucl. Phys. B 461 (1996) 197; unpolarized target:

$$P_Z^\Lambda = P_B D_Z(y) \frac{\sum_q e_q^2 x_B f_1^q(x_B) G_1^q(z)}{\sum_q e_q^2 x_B f_1^q(x_B) D_1^q(z)}$$

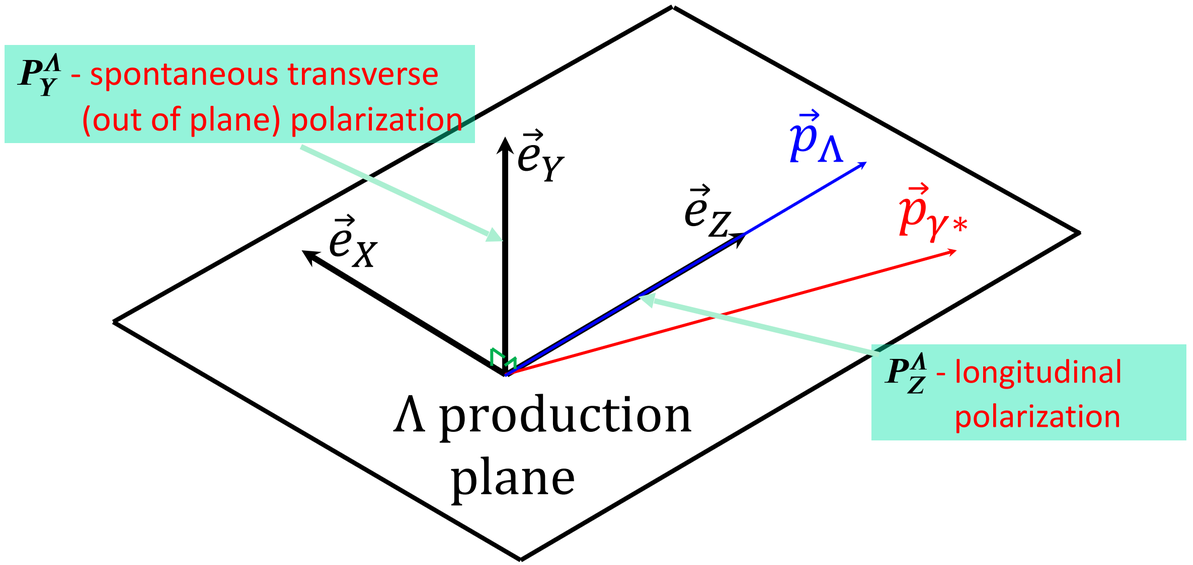


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$$P_Y^\Lambda = D_Y(y)\frac{M}{Q}\frac{\sum_q e_q^2 x_B f_1^q(x_B) D_{1T}^{\perp(1)q}(z)}{\sum_q e_q^2 x_B f_1^q(x_B) D_1^q(z)}$$

$$P_Z^\Lambda = P_B D_Z(y)\frac{\sum_q e_q^2 x_B f_1^q(x_B) G_1^q(z)}{\sum_q e_q^2 x_B f_1^q(x_B) D_1^q(z)}$$



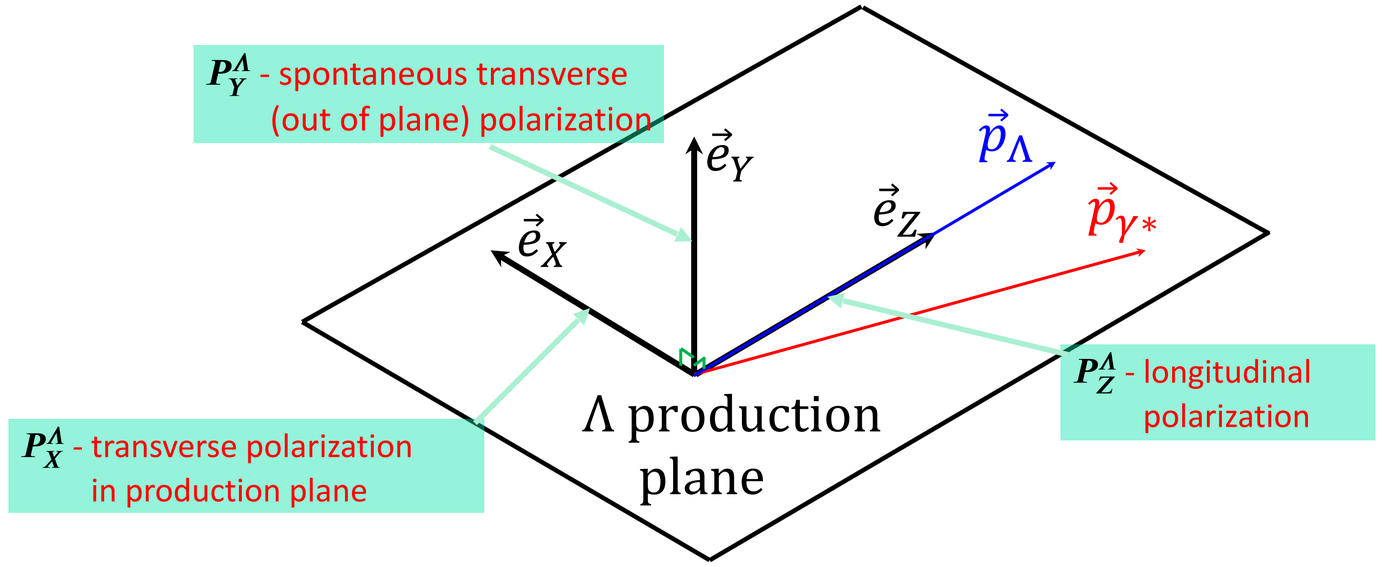
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$$P_X^\Lambda = -P_B D_X(y) \left\{ \frac{M}{Q} \frac{\sum_q e_q^2 x_B e^q(x_B) H_1^q(z)}{\sum_q e_q^2 x_B f_1^q(x_B) D_1^q(z)} + \frac{M^\Lambda}{Q} \frac{\sum_q e_q^2 x_B f_1^q(x_B) \tilde{G}_T^q(z)}{\sum_q e_q^2 x_B f_1^q(x_B) D_1^q(z)} \right\}$$

$$P_Y^\Lambda = D_Y(y) \frac{M}{Q} \frac{\sum_q e_q^2 x_B f_1^q(x_B) D_{1T}^{\perp(1)q}(z)}{\sum_q e_q^2 x_B f_1^q(x_B) D_1^q(z)}$$

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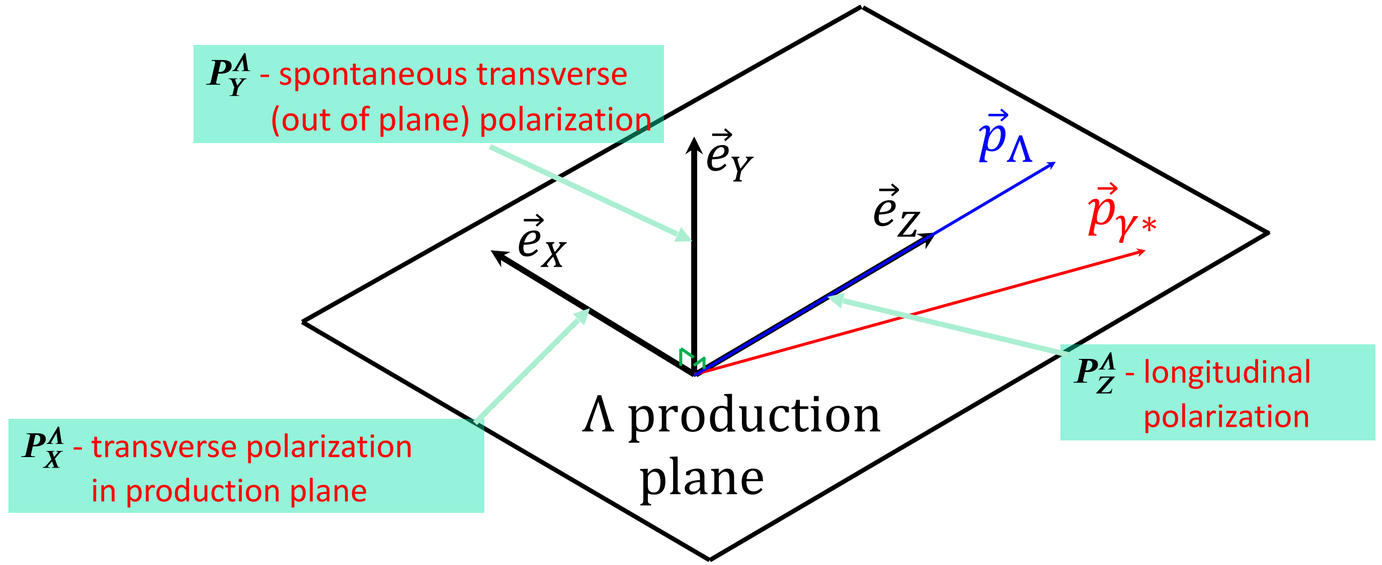
# Lambda production in DIS

Mulders &Tangerman, Nucl. Phys. B 461 (1996) 197; unpolarized target:

$$P_X^\Lambda = -P_B D_X(y) \left\{ \frac{M}{Q} \frac{\sum_q e_q^2 x_B e^q(x_B) H_1^q(z)}{\sum_q e_q^2 x_B f_1^q(x_B) D_1^q(z)} + \frac{M^\Lambda}{Q} \frac{\sum_q e_q^2 x_B f_1^q(x_B) \tilde{G}_T^q(z)}{\sum_q e_q^2 x_B f_1^q(x_B) D_1^q(z)} \right\}$$

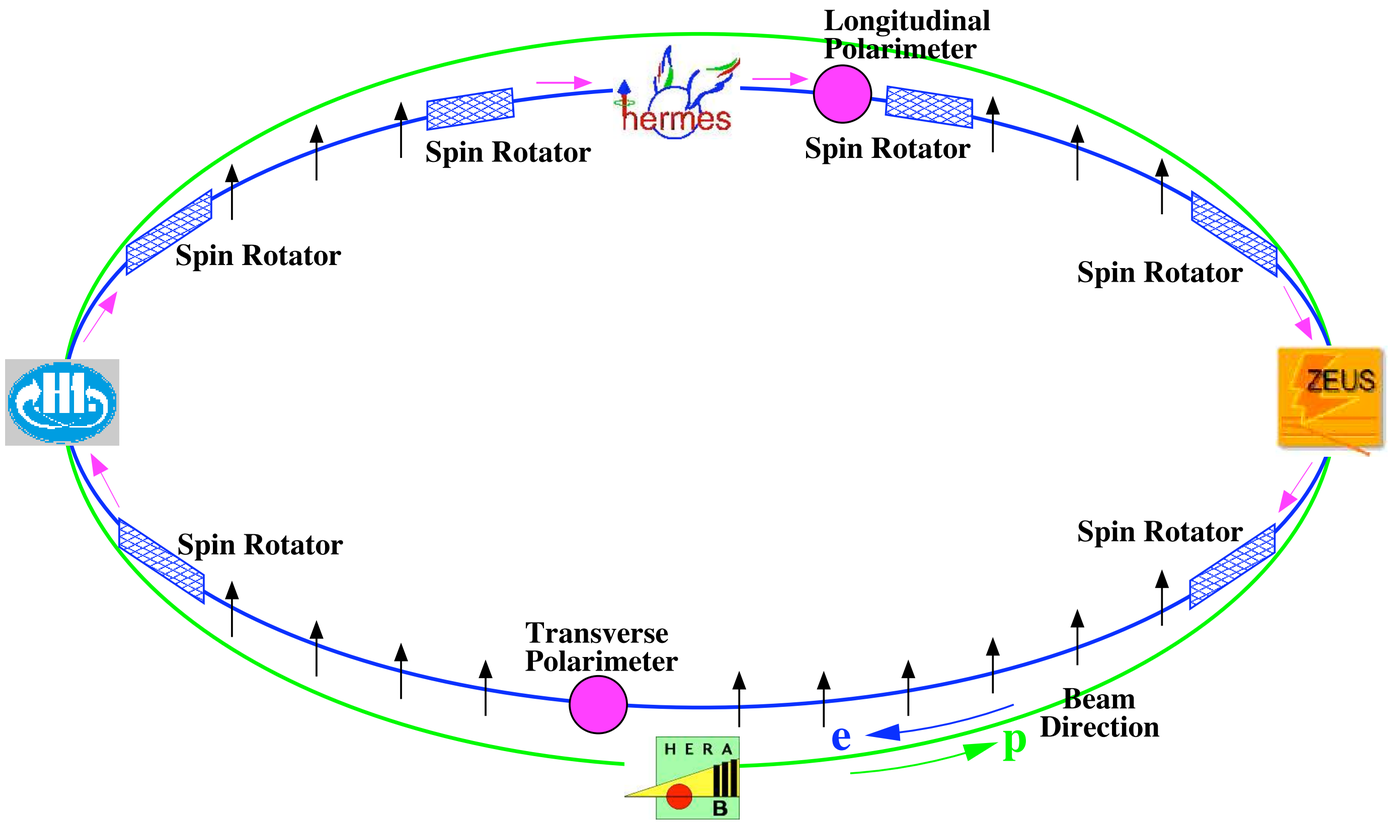
$$P_Y^\Lambda = D_Y(y) \frac{M}{Q} \frac{\sum_q e_q^2 x_B f_1^q(x_B) D_{1T}^{\perp(1)q}(z)}{\sum_q e_q^2 x_B f_1^q(x_B) D_1^q(z)}$$

$$P_Z^\Lambda = P_B D_Z(y) \frac{\sum_q e_q^2 x_B f_1^q(x_B) G_1^q(z)}{\sum_q e_q^2 x_B f_1^q(x_B) D_1^q(z)}$$

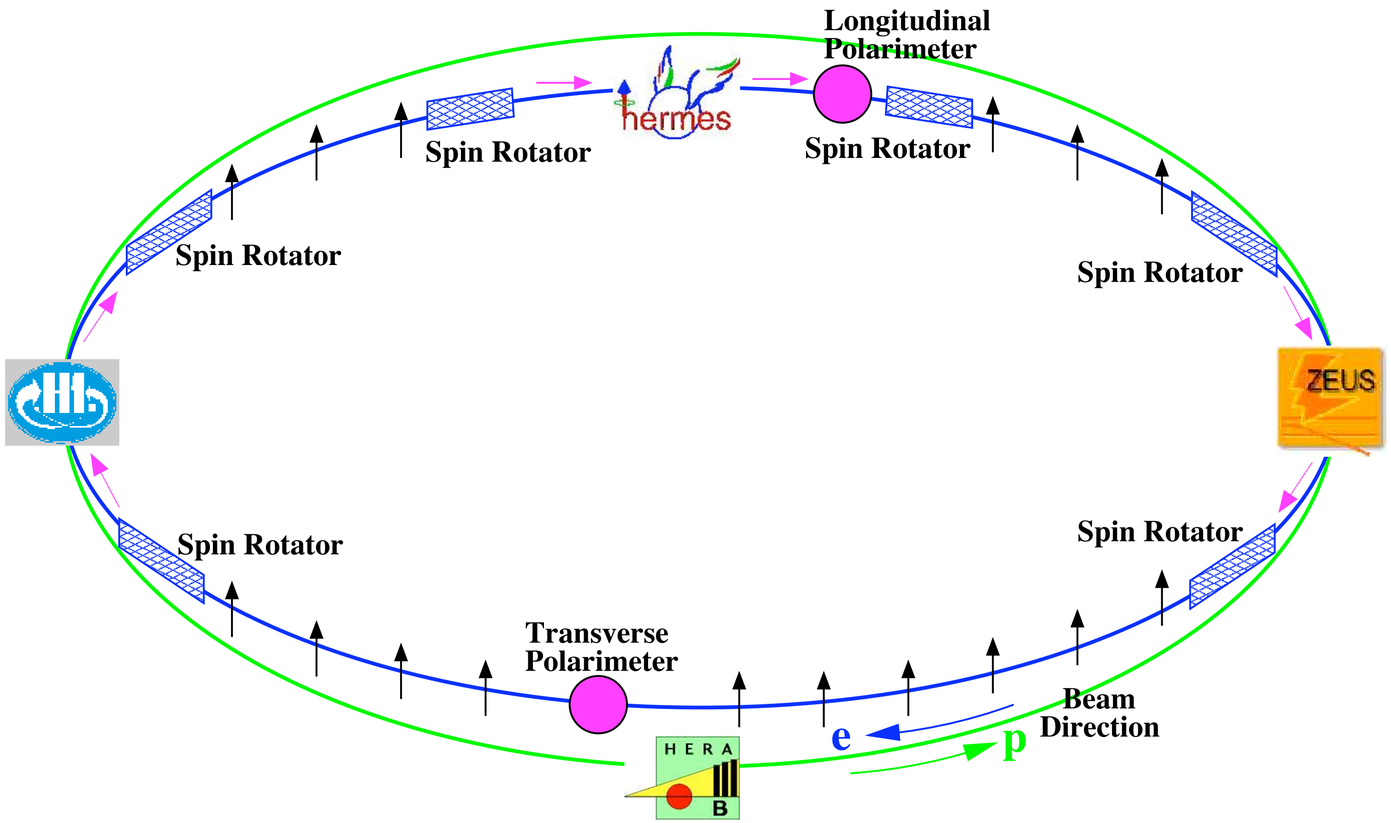


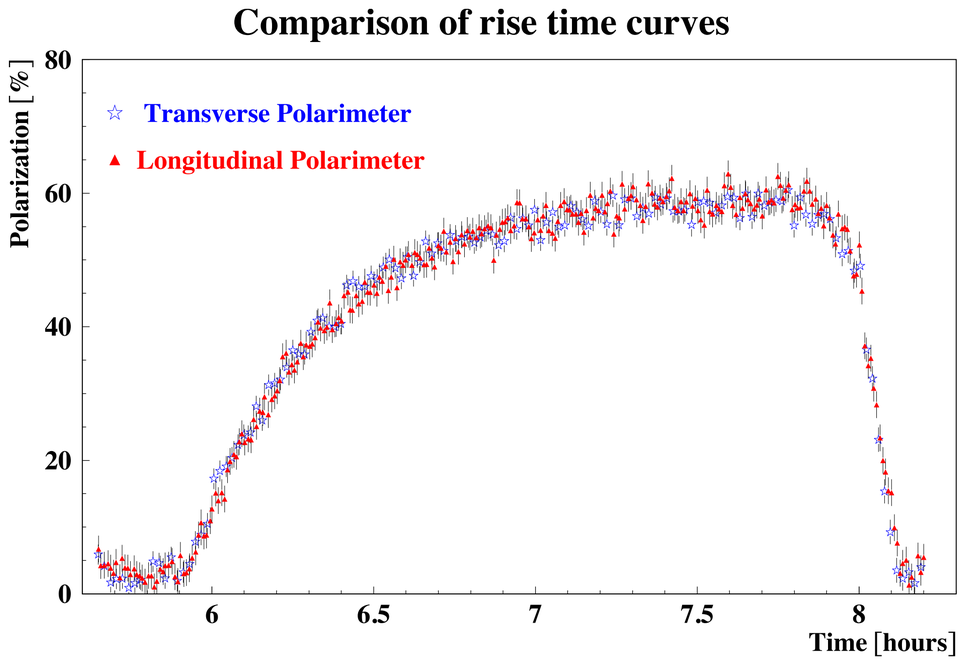

- access to several novel spin-dependent FFs
- Y-component of polarization ("self-polarization") not correlated with beam polarization $P_B$
  - ➥ drops out in beam-spin asymmetries
- concentrate on longitudinal-to-longitudinal and longitudinal-to-transverse spin transfer

# HERMES (1995-2007) @ HERA (DESY)



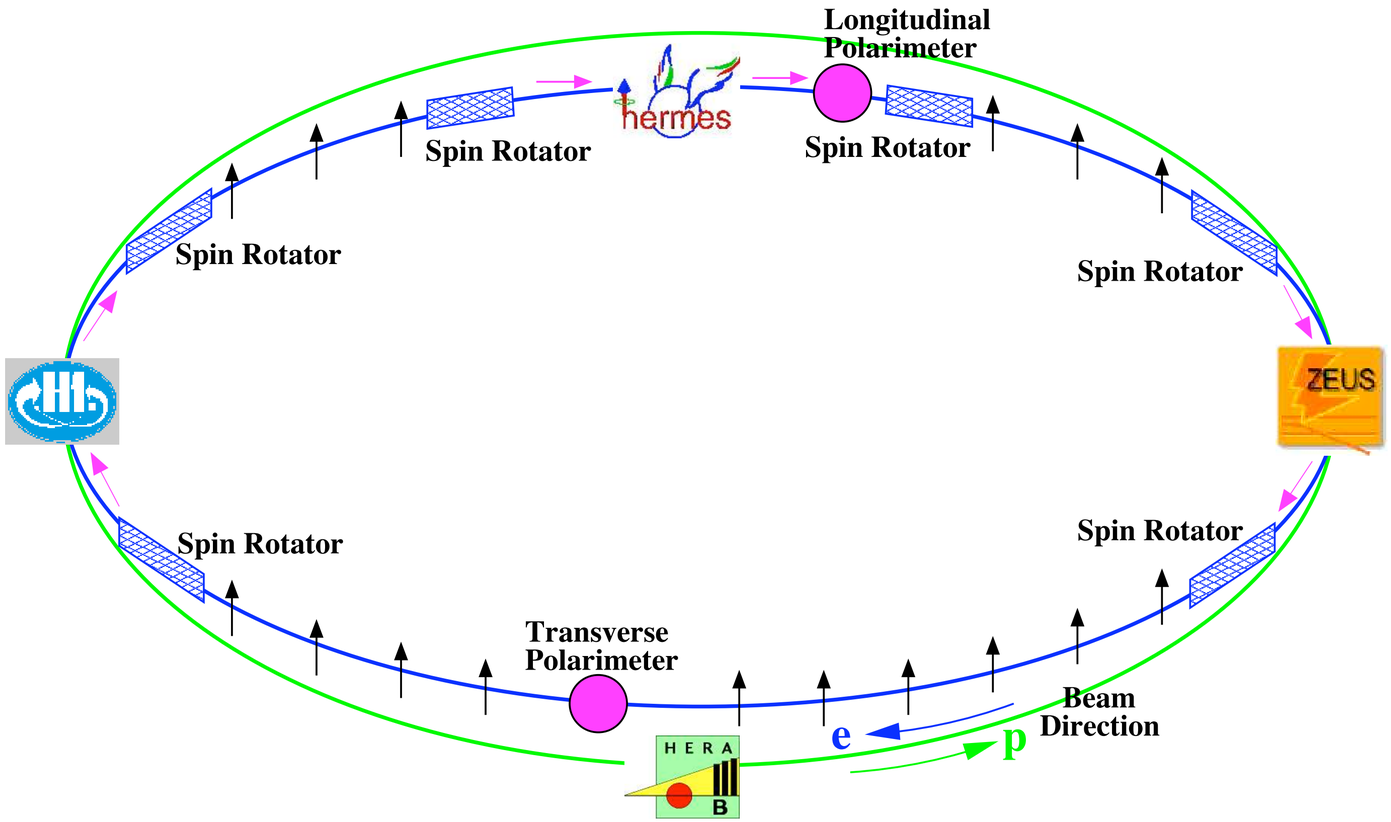
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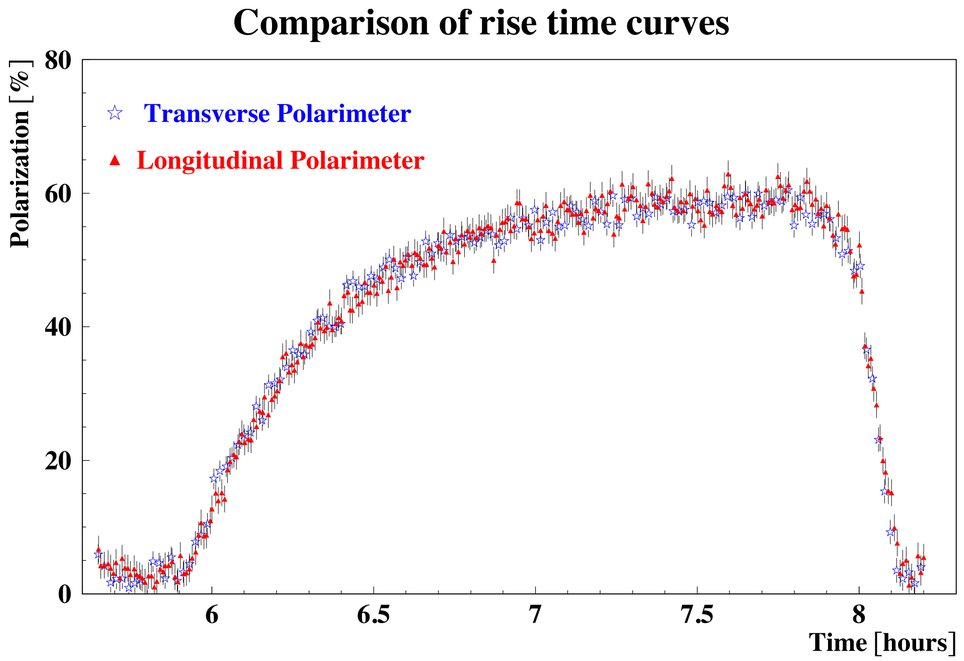



- ☑ beam polarization measured independently by two polarimeters
  - ☑ excellent agreement

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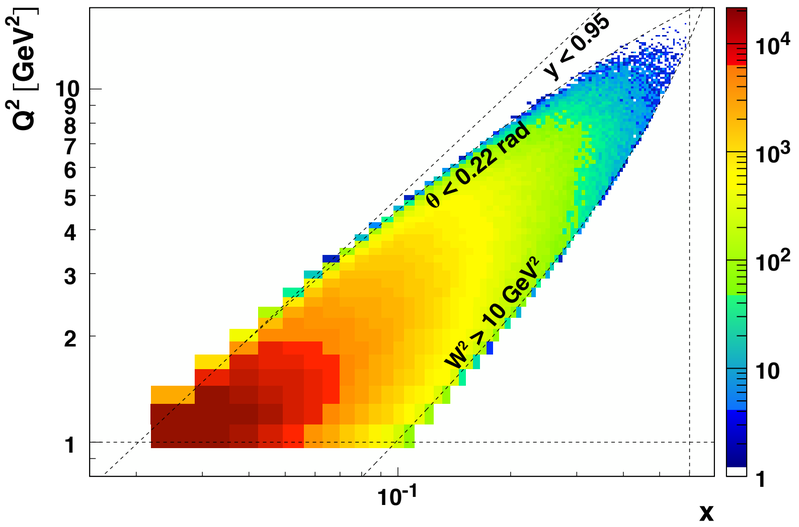


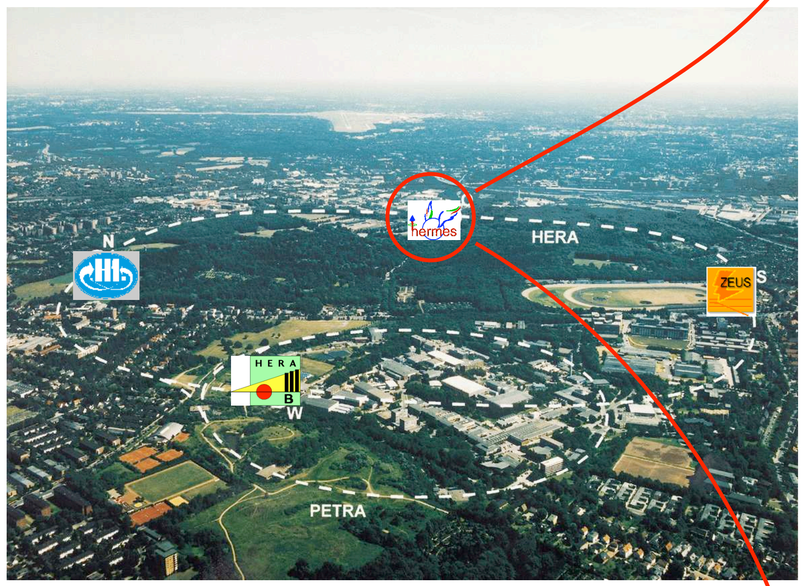



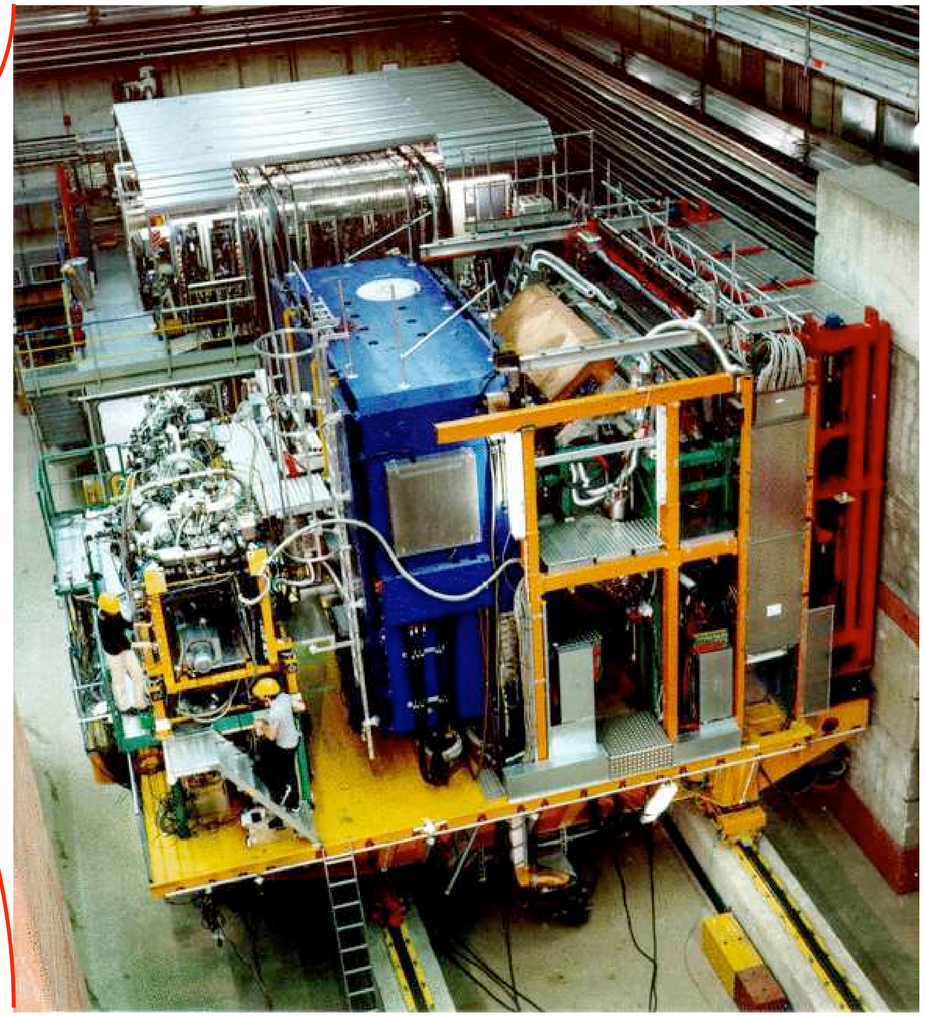

- ☑ beam polarization measured independently by two polarimeters
  - ☑ excellent agreement
- ☑ polarization up to 60% during HERA I

# HERMES (1995-2007) @ HERA (DESY)

27.6 GeV polarized $e^+/e^-$ beam scattered off …



- ☑ unpolarized (H, D, He,…, Xe) as well as
- ☑ transversely (H) or longitudinally (H, D, He) polarized **pure gas targets**
- ☑ particle ID (incl. dual-radiator RICH) for efficient **e/pi/K/p separation**

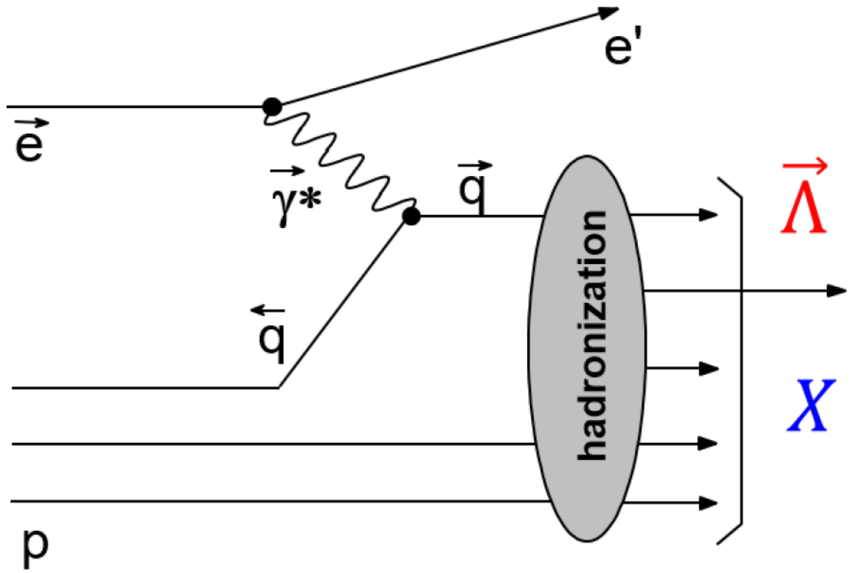
# Polarization measurement

$$\vec{\gamma}^{*} + p \rightarrow \vec{\Lambda} + X$$
$$\hookrightarrow p\pi^{-}$$

$$\frac{dN}{d\Omega_p} = \frac{dN_0}{d\Omega_p}\left(1 + \alpha\, P_{L'}^{\Lambda} \cos\theta_{pL'}\right)$$

unpolarised (uniform) distribution

angle between proton momentum and $\Lambda$ spin in $\Lambda$ rest frame




- "self-analyzing" particle due to its parity-violating decay
- polarization can be extracted by "simply" measuring angular distribution of decay protons
  - in praxis distorted by instrumental effects

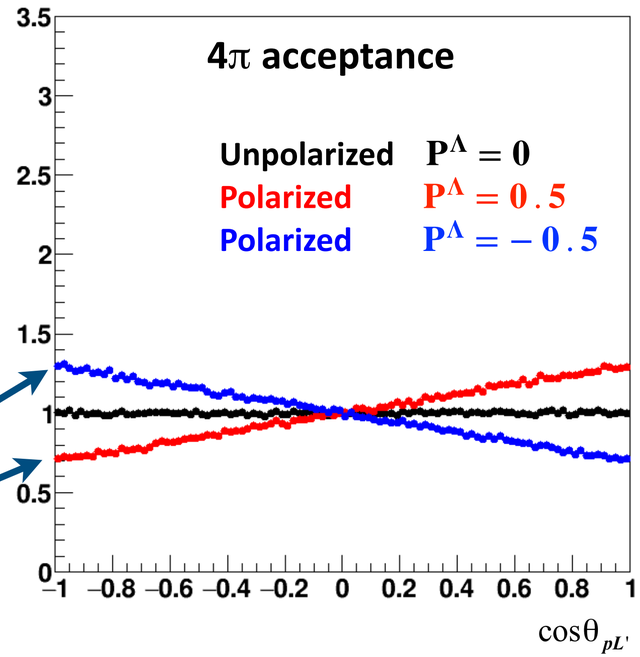
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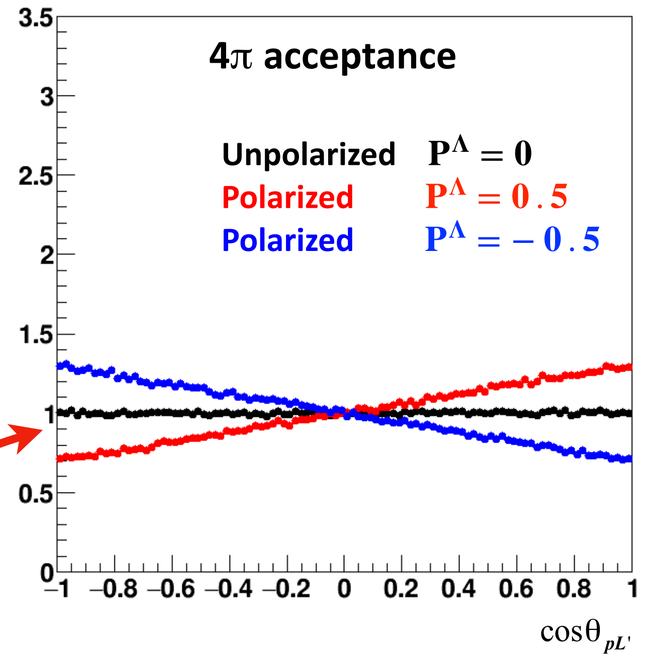
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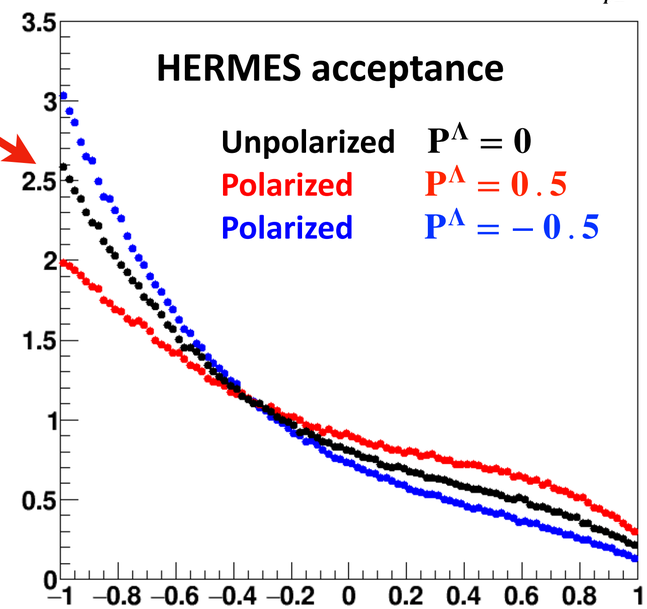
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unpolarised (uniform) distribution

tilts the uniform distribution




- acceptance **ε** distorts distribution
  - heavy use of Monte Carlo to correct for acceptance
  - major source of systematic uncertainty

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- NOMAD: basically $4\pi$ acceptance

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- COMPASS: **MC simulation** of acceptance

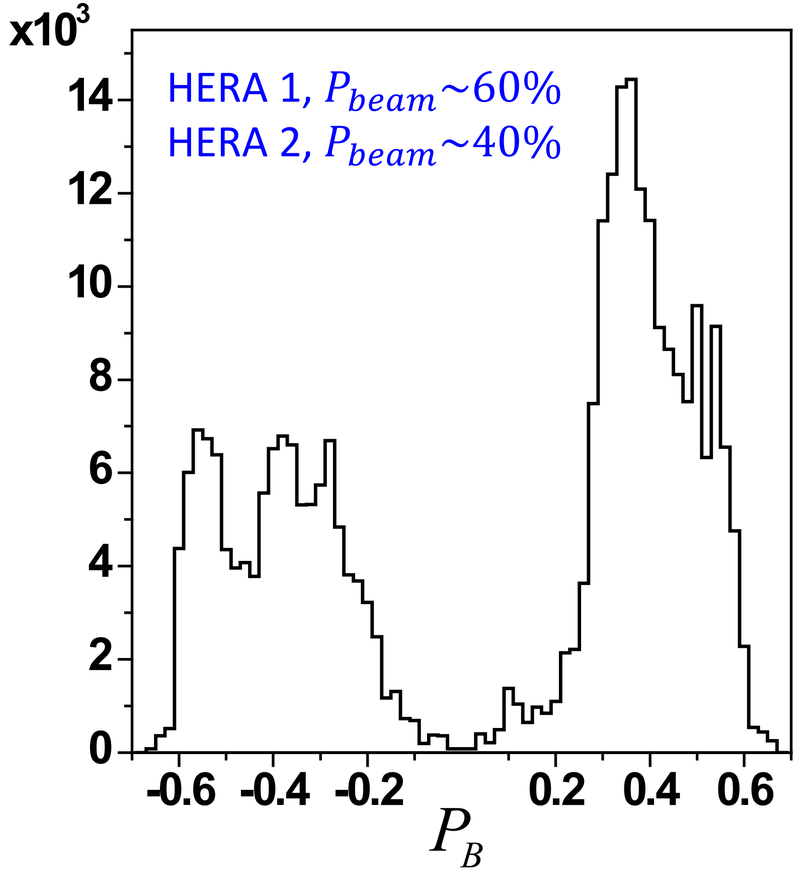
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- HERMES: **cancel** acceptance effect using two beam helicity states (basically measures spin asymmetry)

# Polarization measurement

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2. in simple 1D case and helicity-balanced data sample: $[\![P_B]\!] \equiv \frac{1}{\mathscr{L}^{tot}} \int P_B \, d\mathscr{L} = 0$

$$\langle P_B \cos\theta_{pL'} \rangle = \frac{[\![P_B]\!] \langle \cos\theta_{pL'} \rangle_0 + \alpha D_{LL'} [\![P_B^2]\!] \langle \cos^2\theta_{pL'} \rangle_0}{1 + \alpha D_{LL'} [\![P_B]\!] \langle \cos\theta_{pL'} \rangle_0} \overset{[\![P_B]\!]=0}{=} \alpha D_{LL'} [\![P_B^2]\!] \langle \cos^2\theta_{pL'} \rangle_0$$

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- slightly more complicated iteration procedure used in case of unbalanced $P_B$
- extended to 3D case

# Polarization measurement

## Extraction of spin transfer in 3D and unbalanced case:

$$\sum_{k=x,z} D_{Lk} \left\langle \frac{D_k(y) D_i(y) \cos\theta_k \cos\theta_i}{1 + \alpha [\![P_B]\!] \sum_{j=x,z} D_j(y) D_{Lj} \cos\theta_j} \right\rangle = \frac{1}{\alpha} \frac{\left\langle P_B D_i(y) \cos\theta_i \right\rangle - [\![P_B]\!] \left\langle D_i(y) \cos\theta_i \right\rangle}{[\![P_B^2]\!] - [\![P_B]\!]^2}$$

- system of "linear" equations

$$\sum_k D_{Lk} a_{ik} = c_i$$

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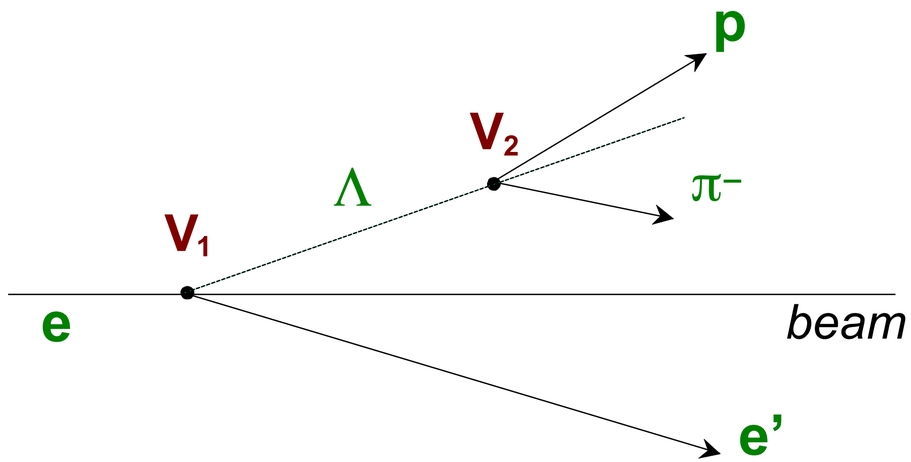
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- 3 steps are sufficient to converge due to $\alpha [\![P_B]\!] \sum_{j=x,z} D_j(y) D_{Lj} \cos\theta_j \sim 0$

# (anti-)Lambda yields at HERMES

- HERA-I data of 1999-2000
- HERA-II data of 2003-2007
- DIS cuts
  - $W^2 > 10\ GeV^2$
  - $0.2 < y < 0.85$
  - $0.8\ GeV^2 < Q^2 < 24\ GeV^2$




**Background suppression**

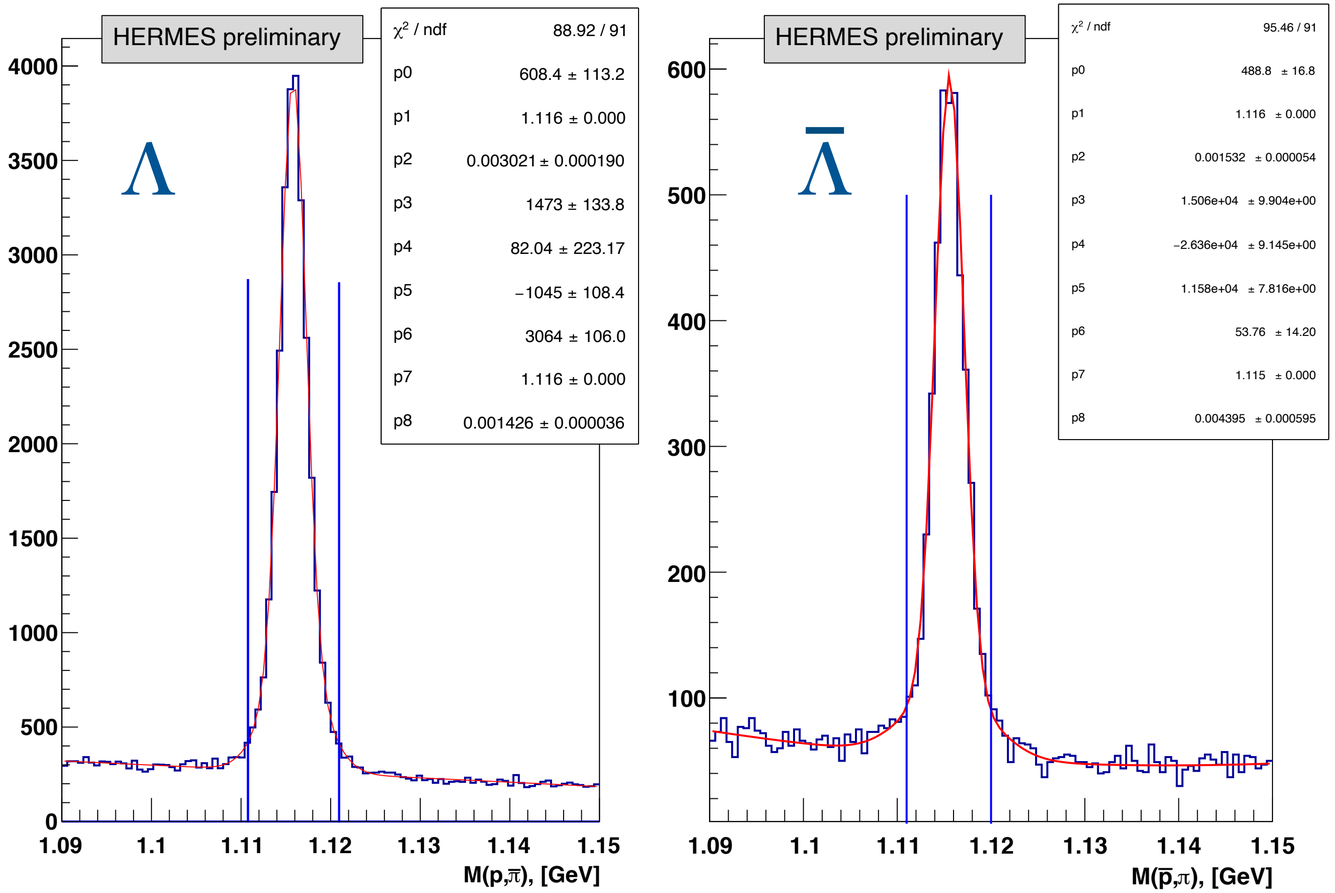
- leading $\pi$ rejection
  (in HERMES kinematics proton is always leading):
- $h^+h^-$ pair background (coming from $V_1$) rejection,
  vertex separation:
  - $d(V_1,V_2) > 6$ cm for $\Lambda$
  - $d(V_1,V_2) > 10$ cm for $\bar{\Lambda}$

$$x = \frac{Q^2}{2M\nu},\ y = \frac{\nu}{E_e} = \frac{E_e - E'_e}{E_e},\ z = \frac{E^\Lambda}{\nu}$$ [fixed-taregt frame]

$$x_F = \frac{p_\parallel^\Lambda}{p_{max}^\Lambda}$$ [photon-nucleon c.m. frame]

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- total number of (anti)$\Lambda$ is about **40k (6k)**



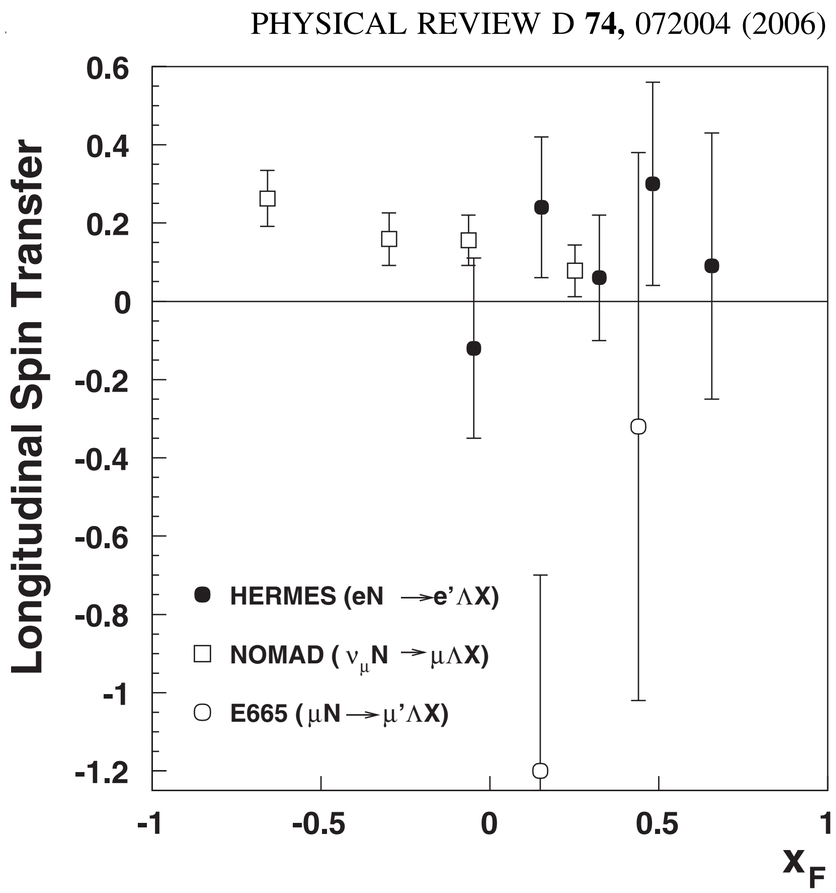

[one data-taking period]

$$x = \frac{Q^2}{2M\nu},\ y = \frac{\nu}{E_e} = \frac{E_e - E_e'}{E_e},\ z = \frac{E^\Lambda}{\nu}$$ [fixed-taregt frame]

$$x_F = \frac{p_\parallel^\Lambda}{p_{max}^\Lambda}$$ [photon-nucleon c.m. frame]

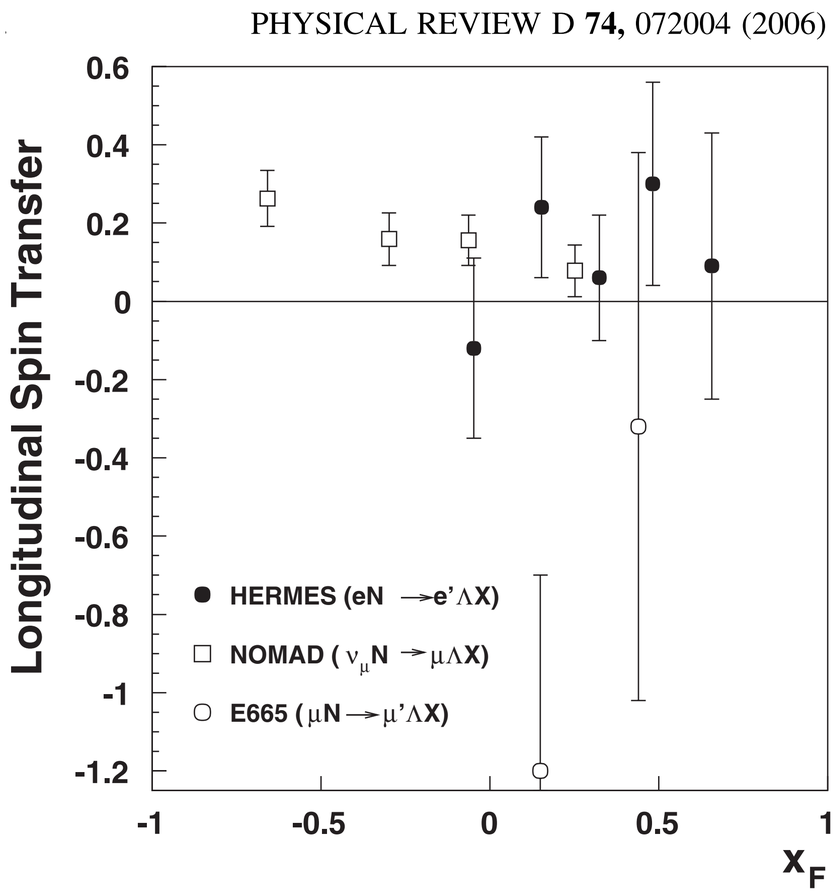
$$D_{LZ} \propto \frac{f_1^q \otimes G_1^q}{f_1^q \otimes D_1^q}$$

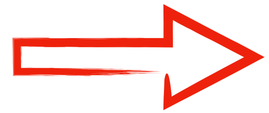
# Improvements from previous publication

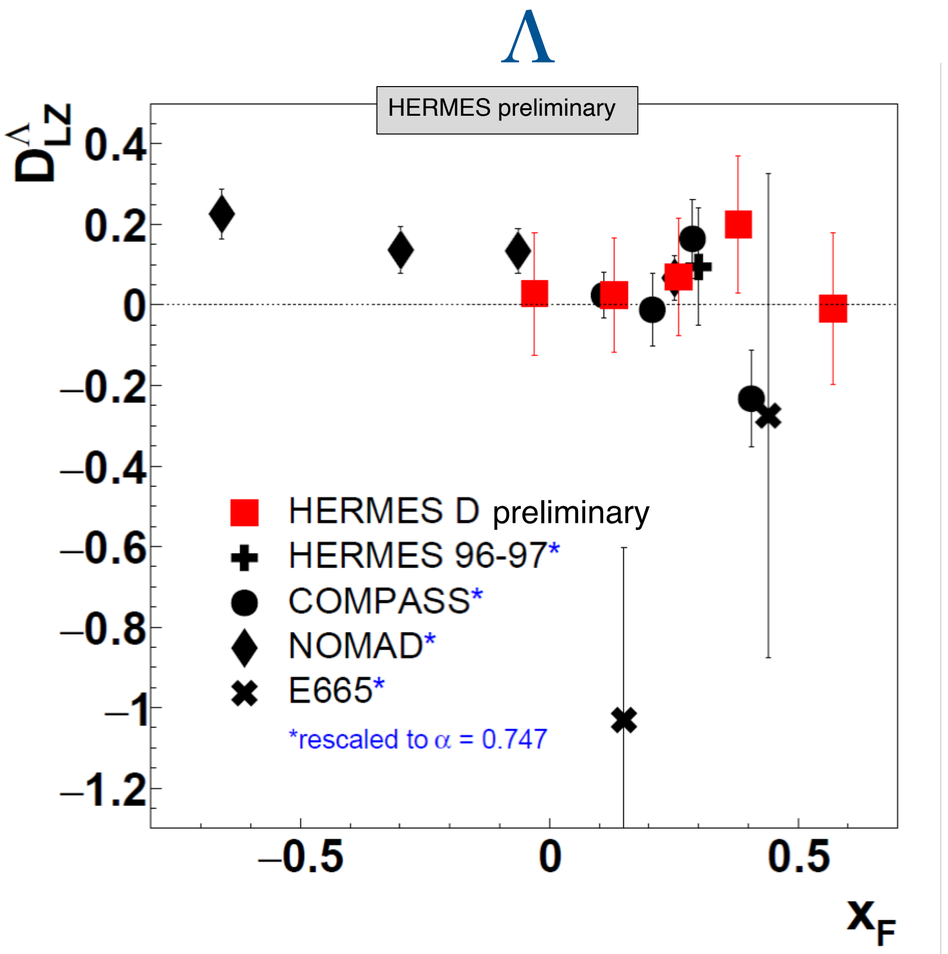


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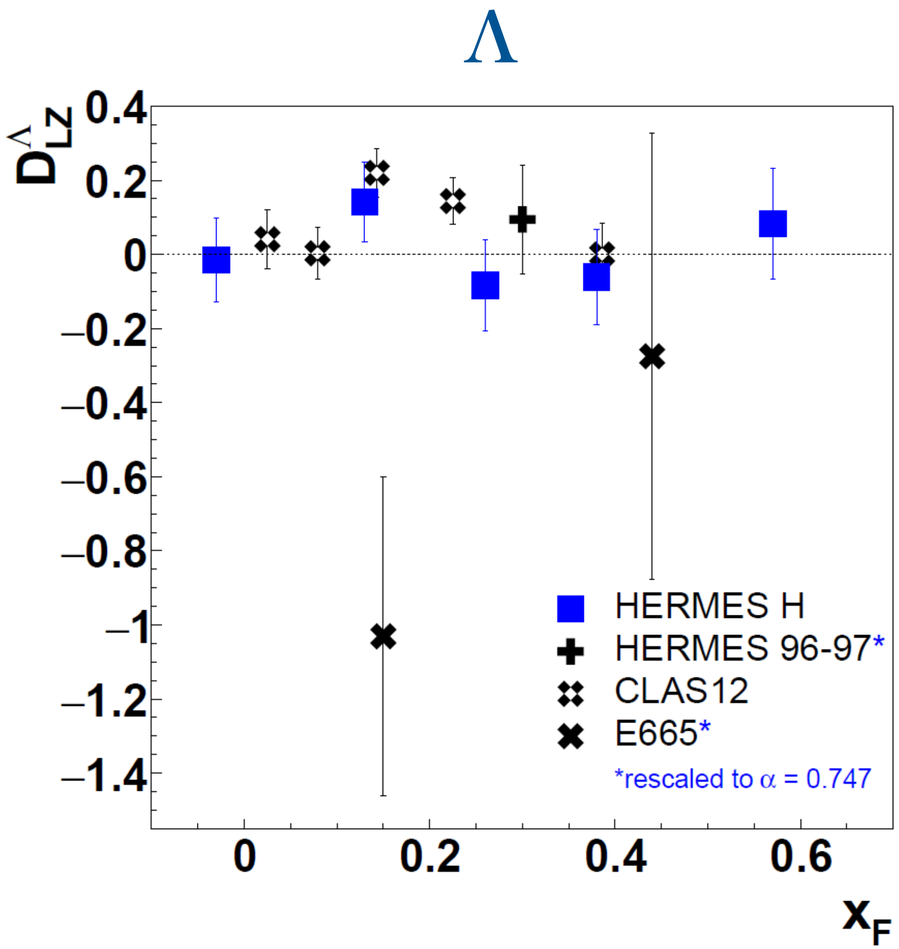



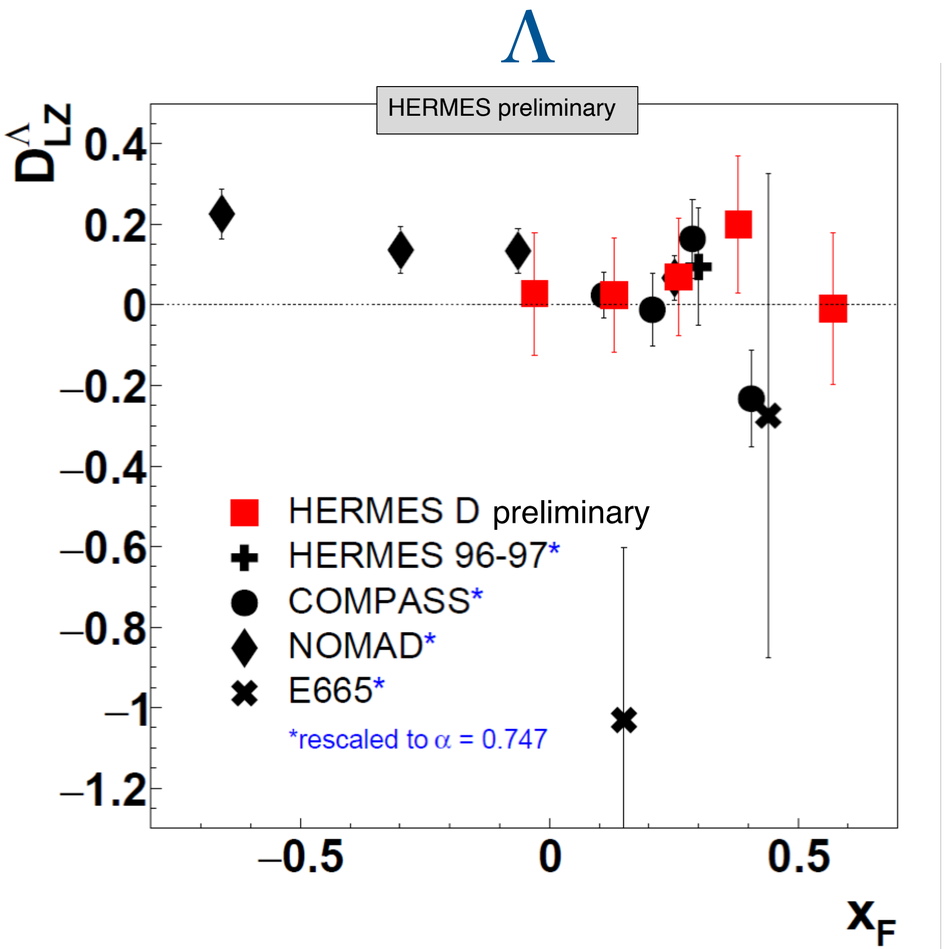



- PDG updated values of asymmetry parameter ➠ rescaled older results that used previous ±0.642

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# Improvements from previous publication



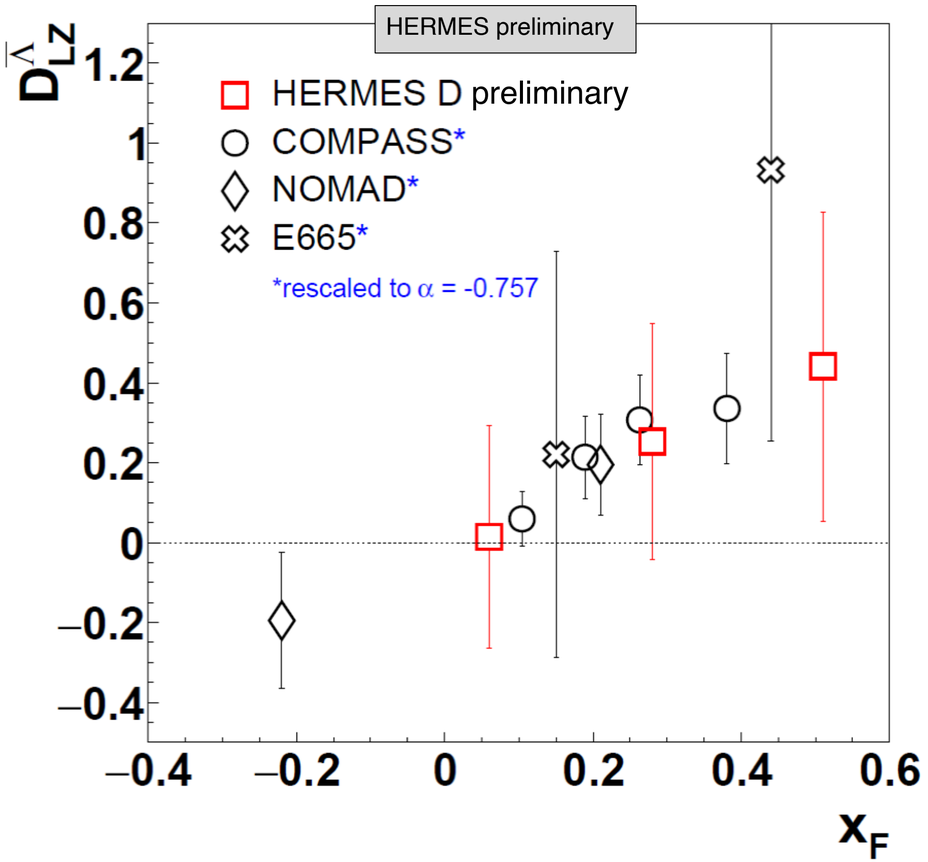




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- separate results for **H** and **D** targets

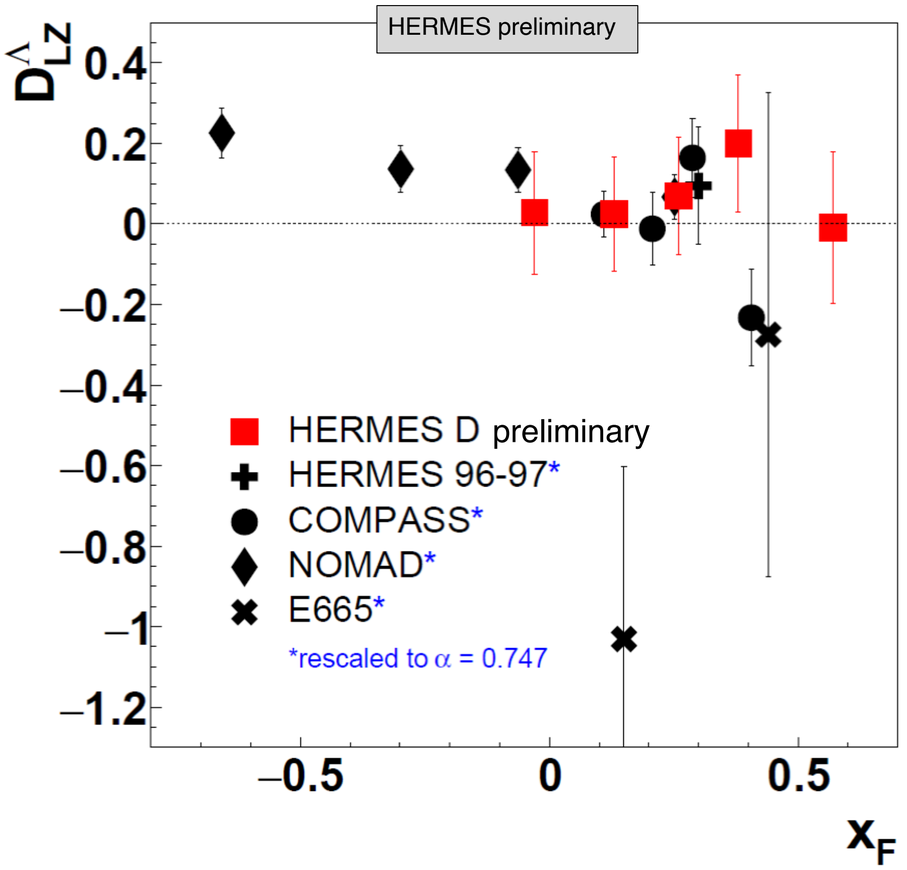
$$D_{LZ} \propto \frac{f_1^q \otimes G_1^q}{f_1^q \otimes D_1^q}$$

# Improvements from previous publication

$\bar{\Lambda}$



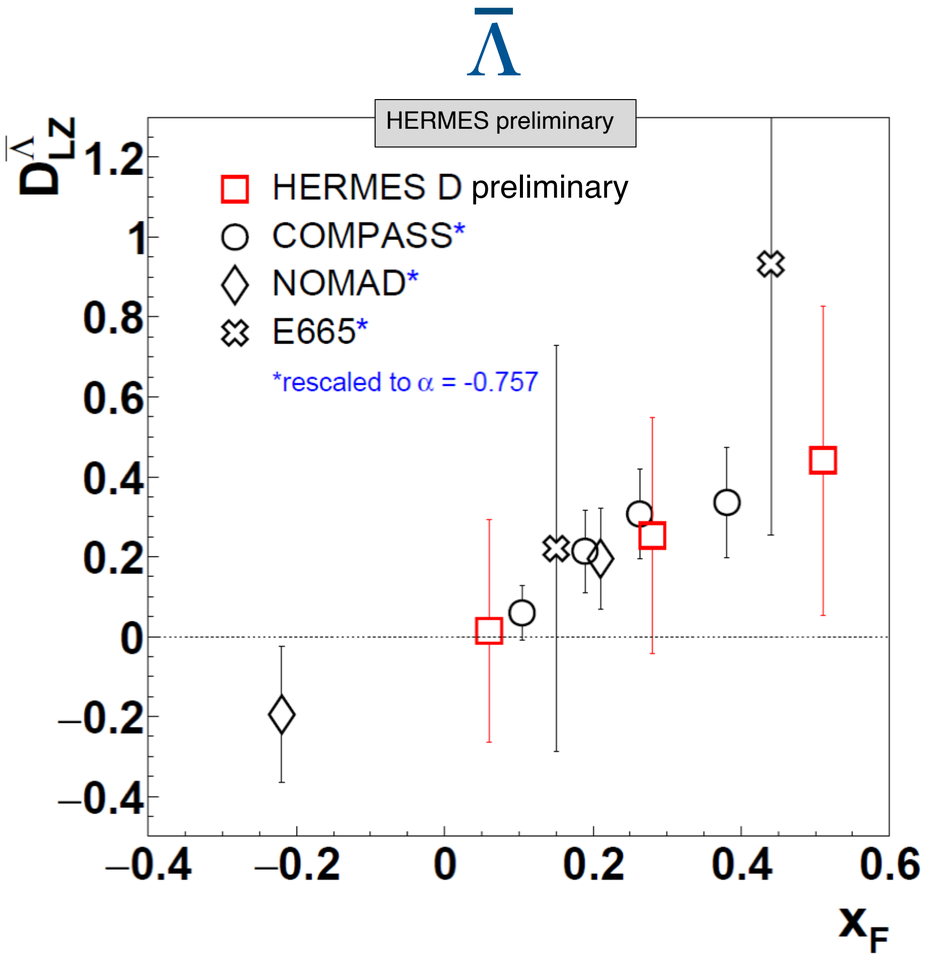

$\Lambda$




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- results for **anti-Λ**

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# Improvements from previous publication



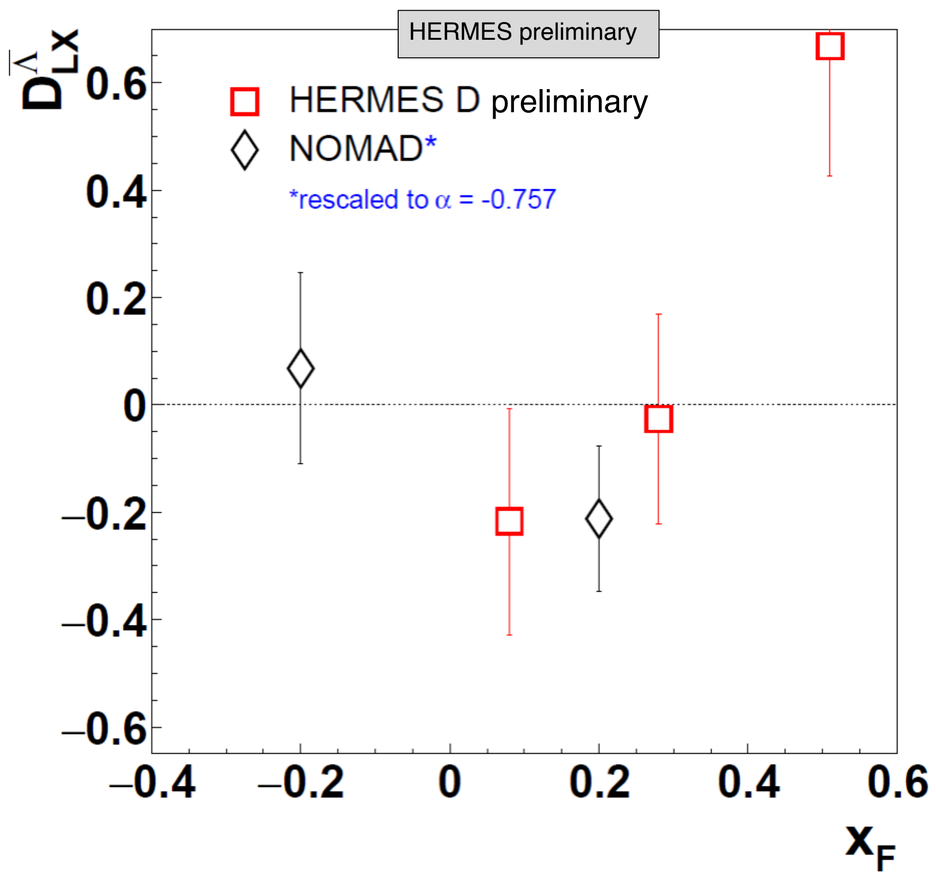

Clear rise of spin transfer:
result of less suppressed anti-s contribution
to anti-Lambda production in SIDIS?

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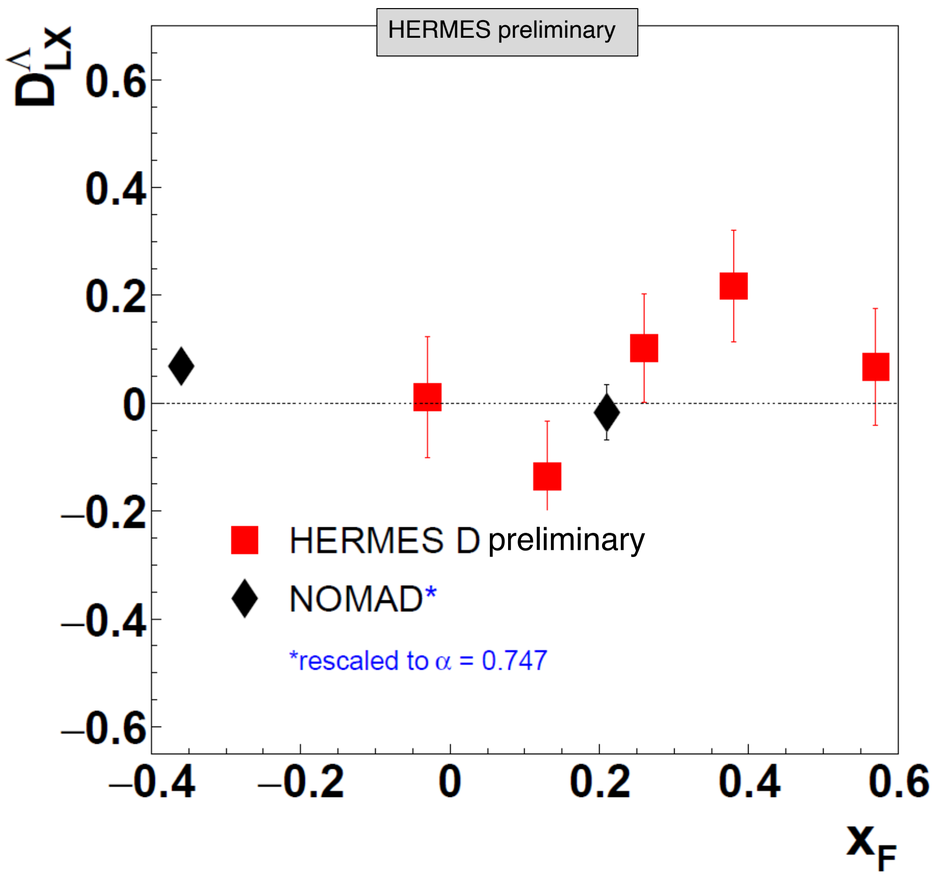
$$D_{LX} \propto \frac{e^q \otimes H_1^q}{f_1^q \otimes D_1^q} + \frac{f_1^q \otimes \tilde{G}_1^q}{f_1^q \otimes D_1^q}$$

# Improvements from previous publication

$\bar{\Lambda}$




$\Lambda$




first more detailed exploration of current fragmentation region for

**longitudinal-to-transverse** spin transfer

e.g., sensitivity to twist-3 e(x) and transversity FF $H_1(z)$

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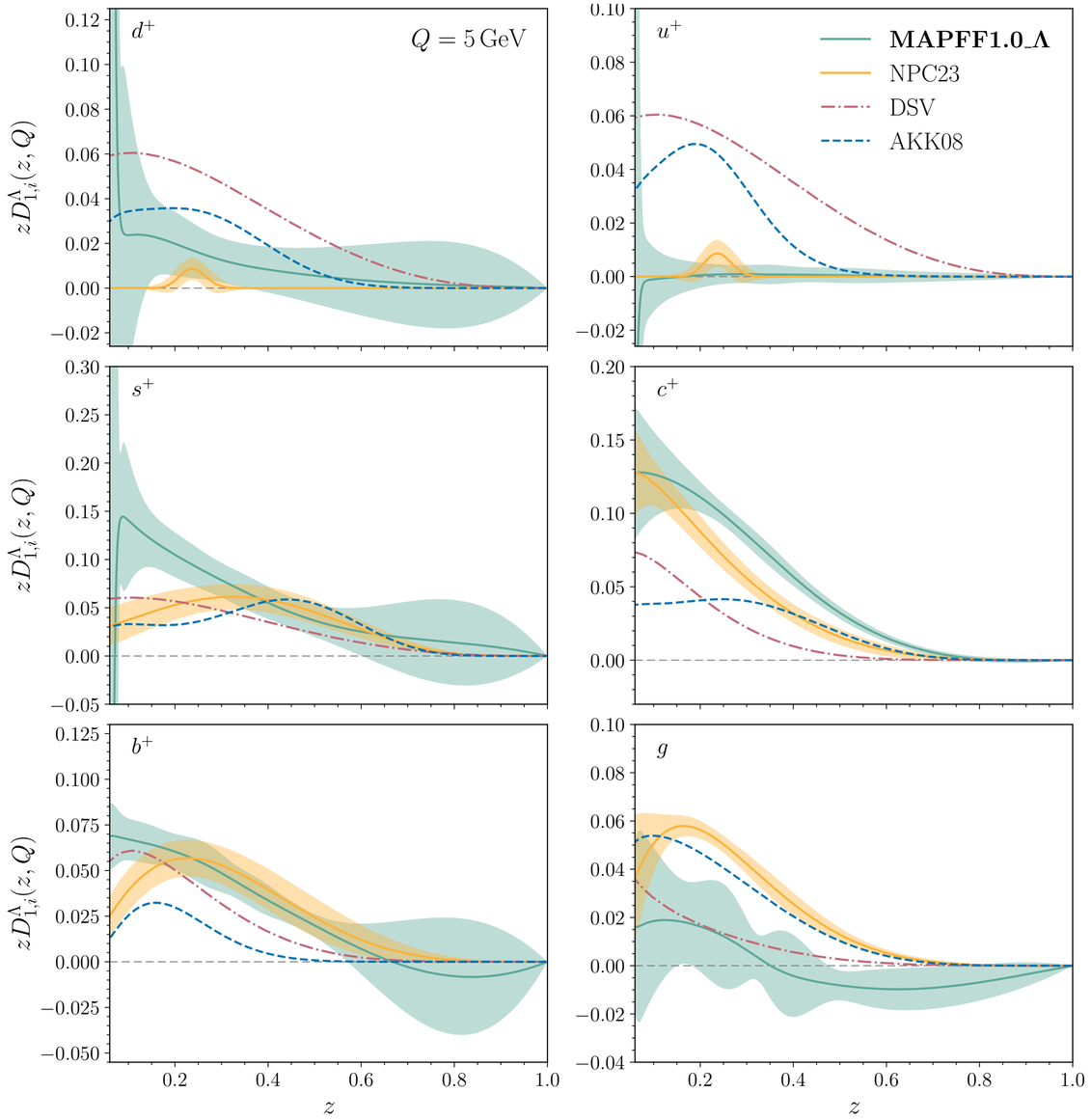
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- HERMES in good position to measure beam-spin dependent hyperon polarization due to frequent reversal of beam helicity
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- preliminary results from 1999-2007 data on longitudinal and longitudinal-to-transverse spin transfer to Lambda and anti-Lambda shows no significantly non-zero spin transfer coefficients
  - potentially consequence of up-quark dominance in contrast to strange-quark dominance at LEP (where large longitudinal polarization was observed)
  - global trend of rise with $x_F$ for anti-Lambda suggestive for substantial strange $G_1$

# Thank you!

# back-up

# Lambda fragmentation – a window to strangeness




[arXiv: 2605.05314]