Self-similarity of proton spin

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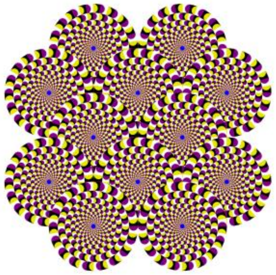
*JINR, Dubna, Russia
**NPI, Řež, Czech Republic



Contents

Principles & Symmetries

"Fundamental symmetry principles dictate the basic laws of physics, control the structure of matter and define the fundamental forces in nature."

Leon M. Lederman

"…for every conservation law there must be a continuous symmetry...."

Emmy Nöether

Discrete (C,P,T,..) and continuous symmetries correspond to fundamental principles (gauge, special, general and scale relativity, …) and conservation laws (charge,….) and vice versa.

- Principles are reflected as regularities in measurable observables and can be usually expressed as scaling in a suitable representation of data.
- z-Scaling of differential cross sections of inclusive particle production in p+p, p+A and A+A is used as a tool to search for and study of principles and symmetries that reflect properties of hadron interactions at constituent level.
- z-Scaling is based on the principles of *self-similarity*, *fractality*, *and locality*.

There exists a symmetry inherent to them:

Symmetry with respect to structural degrees of freedom - structural relativity.

Motivation & Goals

Development of z-scaling approach for description of processes with polarized particles in inclusive reactions to understand the spin origin.

Analysis of double spin asymmetry of π meson and jet production and coefficient of polarization transfer for Λ hyperon production in p+p collisions to determine spin-dependent fractal dimensions

It concerns

- Properties of sub-structure of the colliding objects, interactions of their constituents, and fragmentation process at small scales.
- Fractal properties of flavor (u,d,s,c,b,t)
- Fundamental principles (self-similarity, scale relativity, fractality, Lorentz invariance,…)
- Origin of mass, spin, charge,…, fractal topology of space-time,…

Self-similarity: z-scaling in p+p

z is similarity parameter, ψ(z) is dimensionless function

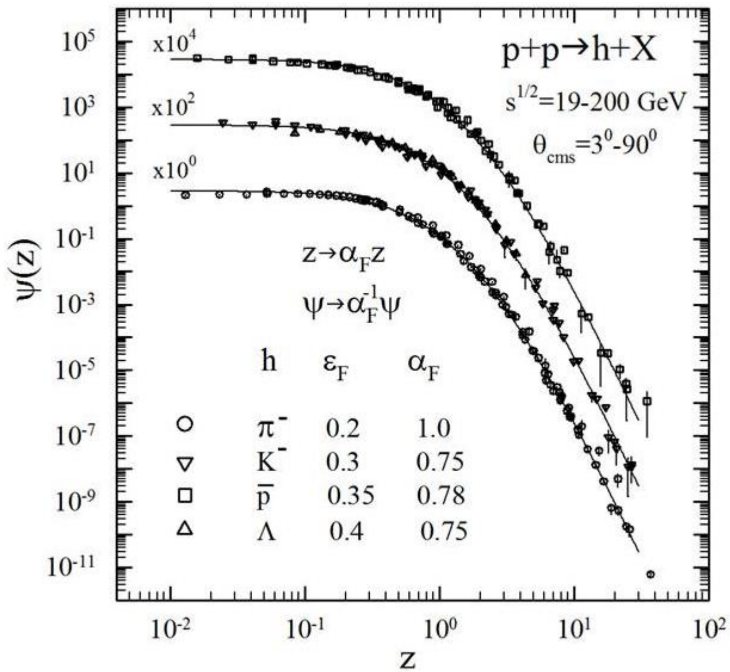
Inclusive cross sections of π^-, K^-, $\bar{p}$, Λ in pp collisions

FNAL:
PRD 75 (1979) 764

ISR:
NPB 100 (1975) 237
PLB 64 (1976) 111
NPB 116 (1976) 77
(low p_T)
NPB 56 (1973) 333
(small angles)

STAR:
PLB 616 (2005) 8
PLB 637 (2006) 161
PRC 75 (2007) 064901

Saturation at low z



Power law at high z

Energy scan of spectra
at U70, ISR, Sp̄pS, SPS, HERA, FNAL(fixed target), Tevatron, RHIC, LHC

MT & I.Zborovsky
T.Dedovich
Phys.Rev.D75,094008(2007)
Int.J.Mod.Phys.A24,1417(2009)
J. Phys.G: Nucl.Part.Phys. 37,085008(2010)
Int.J.Mod.Phys.A27,1250115(2012)
J.Mod.Phys.3,815(2012)

- Energy & angular independence
- Flavor independence (π, K, $\bar{p}$, Λ)
- Saturation for $z < 0.1$
- Power law $\Psi(z) \sim z^{-\beta}$ for high $z > 4$

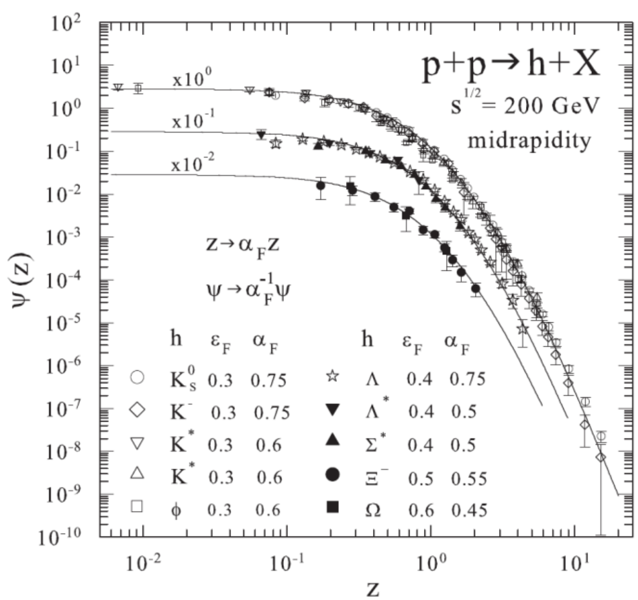
Scaling – “collapse” of data points onto a single curve.

z-Scaling of strange hadrons in p+p at RHIC

"Collapse" of data points onto a single curve

$K_S^0, K^-, K^*, \phi, \Lambda, \Xi, \Omega, \Sigma^*, \Lambda^*$

MT & I.Zborovsky
Int. J. Mod. Phys.
A 32, 1750029 (2017)



- Energy independence
- Flavor independence
- Saturation for $z < 0.1$
- Power law $\Psi(z) \sim z^{-\beta}$ for high $z > 4$
- Fractal dimensions $\delta = 0.5$, $\varepsilon_F \equiv \varepsilon_a = \varepsilon_b$
- "Specific heat" $c = 0.25$

STAR
PRL 97 (2006) 132301
PLB 612 (2005) 181
PRC 71 (2005) 064902
PRC 75 (2007) 064901
PRL 108 (2012) 072302
PLB 616 (2005) 8
PLB 637 (2006) 161

PHENIX
PRD 83 (2011) 052004
PRC 90 (2014) 054905

FNAL & ISR
PRD 19 (1979) 764
NPB 100 (1975) 237
NPB 106 (1976) 1
PLB 64 (1976) 111
NPB 116 (1976) 77
NPB 56 (1973) 333
PRD 40 (1989) 2777

Properties of $\Psi(z)$ in pp & $p\bar{p}$ collisions

- Energy independence of $\Psi(z)$ ($s^{1/2} > 20$ GeV)
- Angular independence of $\Psi(z)$ ($\theta_{cms}=3^0$-90^0)
- Multiplicity independence of $\Psi(z)$ ($dN_{ch}/d\eta=1.5$-26)
- Power law, $\Psi(z) \sim z^{-\beta}$, at high z ($z > 4$)
- Flavor independence of $\Psi(z)$ (π,K,φ,Λ,..,D,J/ψ,B,Υ,…, top)
- Saturation of $\Psi(z)$ at low z ($z < 0.1$)

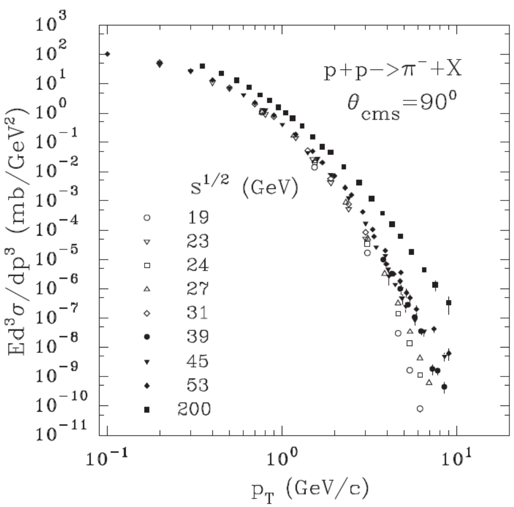
These properties reflect self-similarity, locality, and fractality
of the hadron interaction at a constituent level.
It concerns the structure of the colliding objects, interactions
of their constituents, and fragmentation process.

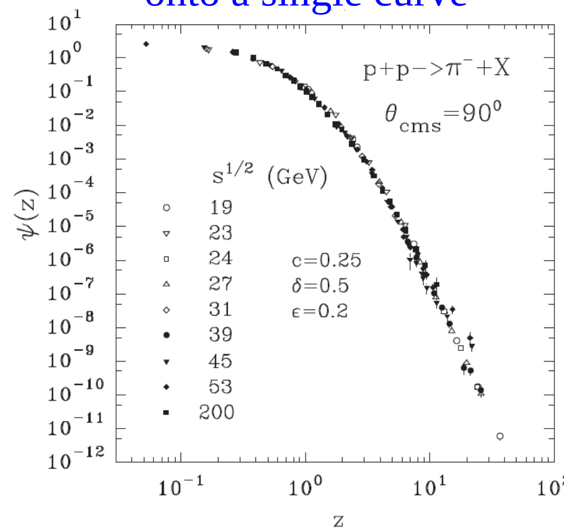
M.T. & I.Zborovskỳ
Phys. At. Nucl. 70,1294(2007)
Phys. Rev. D75,094008(2007)
Int. J. Mod. Phys. A24,1417(2009)
J. Phys. G: Nucl. Part. Phys. 37,085008(2010)
Int. J. Mod. Phys. A27,1250115(2012)
Int. J. Mod. Phys. A 32, 1750029 (2017)

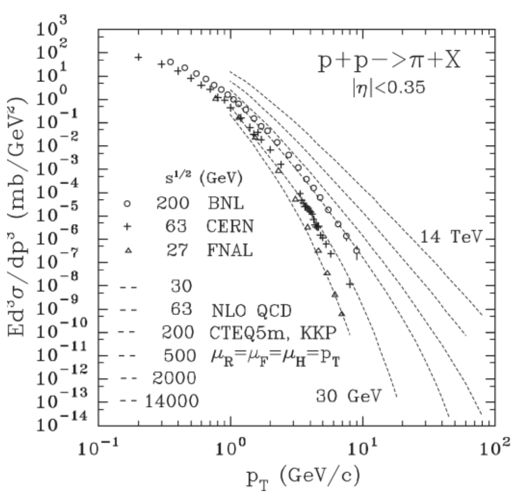
High-p_T spectra and the asymptotics of $\psi(z)$

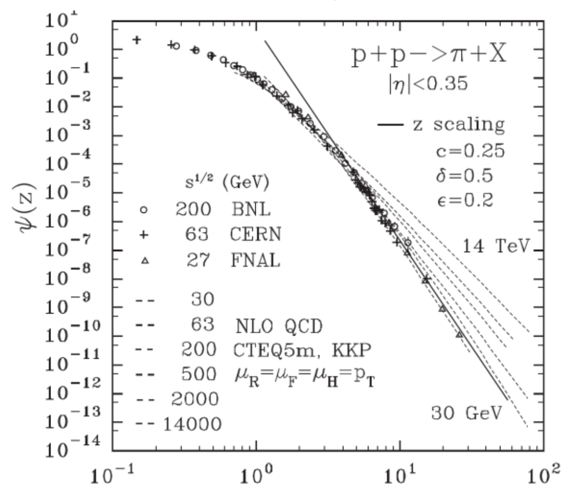
Phys.Rev.D75 (2007) 094008

"Collapse" of data points onto a single curve









Spectra vs. p_T

- Exponential law
- Power law
- Strong dependence on $\sqrt{s}$ at high p_T

Scaling function vs. z

- Scaling
- Power law at low z
- Power law at high z

High-p_T spectra & QCD

- PDFs
- FFs
- μ_F, μ_R, μ_H
- Q^2- evolution

Constraints on evolution of PDFs, FFs

Data on inclusive spectra obtained
at U70, ISR, SPS, Sp̄pS, RHIC, Tevatron, LHC
are consistent with z-scaling
for unpolarized processes

What about z-scaling hypothesis
for processes with polarized protons ?

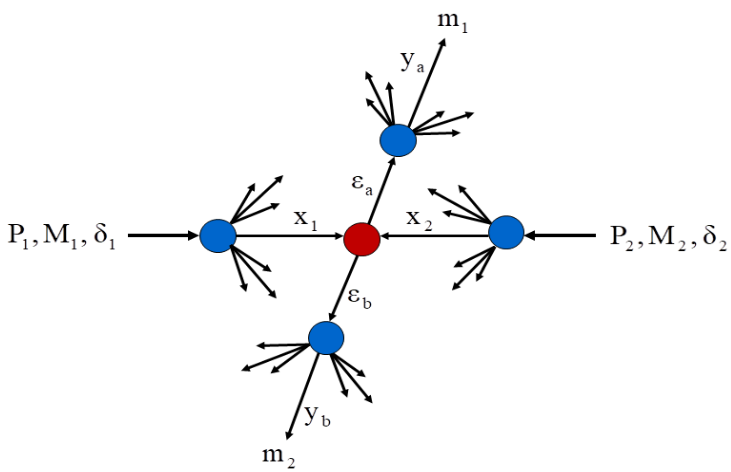
F.Lehar

Self-similarity of spin structure

Hypothesis of z-scaling for processes with polarized particles

Inclusive spin-dependent particle distributions
can be described in terms of constituent sub-processes and
parameters characterizing bulk properties of the system.

$s^{1/2}$, p_T, θ_{cms}
spin



spin-dependent fractions

x_1, x_2, y_a, y_b

spin-dependent dimensions

$\delta_1, \delta_2, \varepsilon_a, \varepsilon_b$

spin-dependent cross section

$Ed^3\sigma/dp^3$

Scaled spin-dependent inclusive cross section
of particle production depends in a self-similar
way on a single spin-dependent scaling variable z.

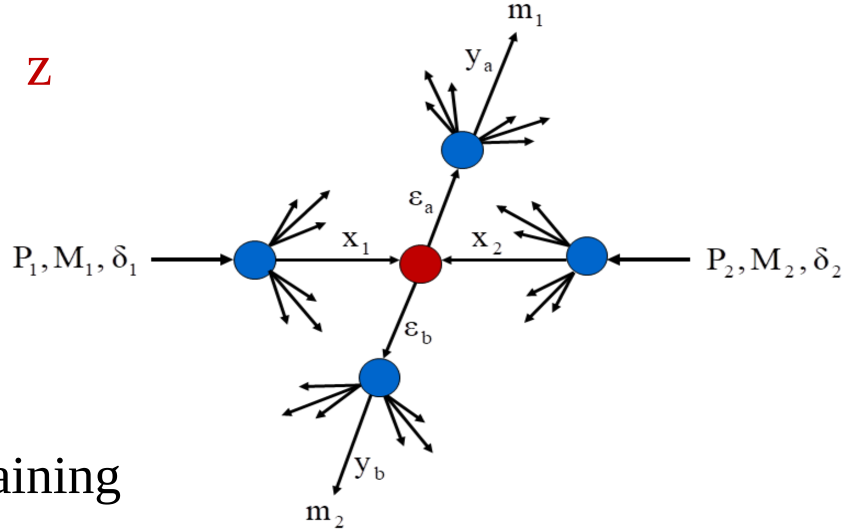
spin-dependent
z & Ψ

Universality of the shapes of $\Psi(z)$ for spin-dependent procesess

Phys. Part. Nucl. Lett., 12 (2015) 81
Phys. Part. Nucl. Lett., 12 (2015) 214

Spin-dependent fractal measure z

Fractality is reflected in the definition of z



$$z = z_0 \cdot \Omega^{-1}$$

$$\Omega = (1-x_1)^{\delta_1}(1-x_2)^{\delta_2}(1-y_a)^{\varepsilon_a}(1-y_b)^{\varepsilon_b}$$

Ω is relative number of configurations containing a sub-process with spin-dependent fractions x_1, x_2, y_a, y_b of the corresponding 4-momenta

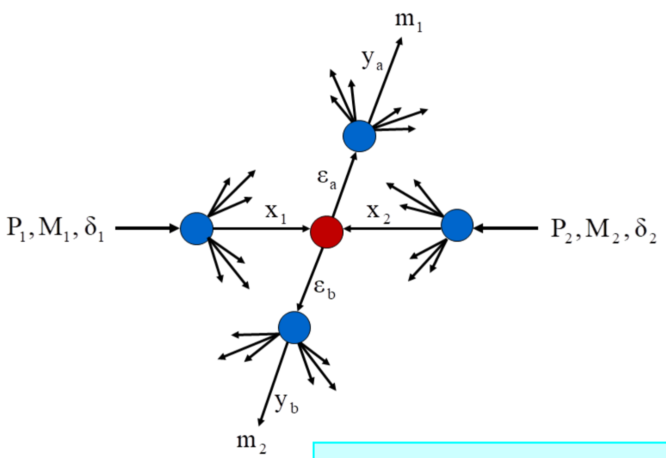
$\delta_1, \delta_2, \varepsilon_a, \varepsilon_b$ are parameters characterizing spin-dependent structure of the colliding objects and fragmentation process, respectively

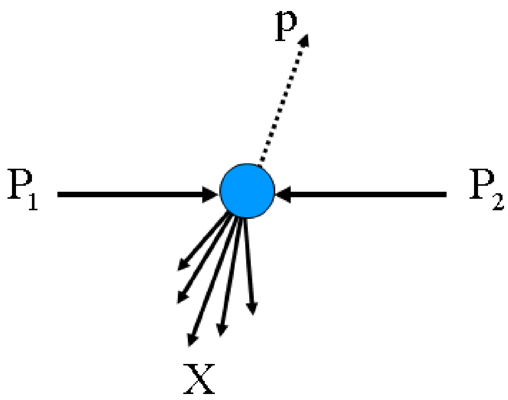
$\Omega^{-1}(x_1, x_2, y_a, y_b)$ characterizes spin-dependent resolution at which a constituent sub-process can be singled out of the inclusive reaction

$$z(\Omega)|_{\Omega^{-1}\to\infty} \to \infty$$

Spin-dependent fractal measure z diverges as the resolution Ω^{-1} increases.

Spin-dependent z & Ψ





spin-dependent
z & Ψ

$$\Psi = \frac{\pi}{(dN/d\eta)\cdot\sigma_{inel}} \cdot J^{-1} \cdot E\frac{d^3\sigma}{dp^3}$$

spin-dependent
cross section σ

- σ_{in} - total inelastic cross section
- N - average multiplicity
- $dN/d\eta$ - pseudorapidity multiplicity density
- $J(z,\eta;p_T^2,y)$ - spin-dependent Jacobian
- $Ed^3\sigma/dp^3$ - spin-dependent inclusive cross section

$Ed^3\sigma/dp^3 \equiv \sigma$

spin-independent: σ, Ψ, z

spin-dependent: $\sigma_{+-}, \Psi_{+-}, z_{+-}$

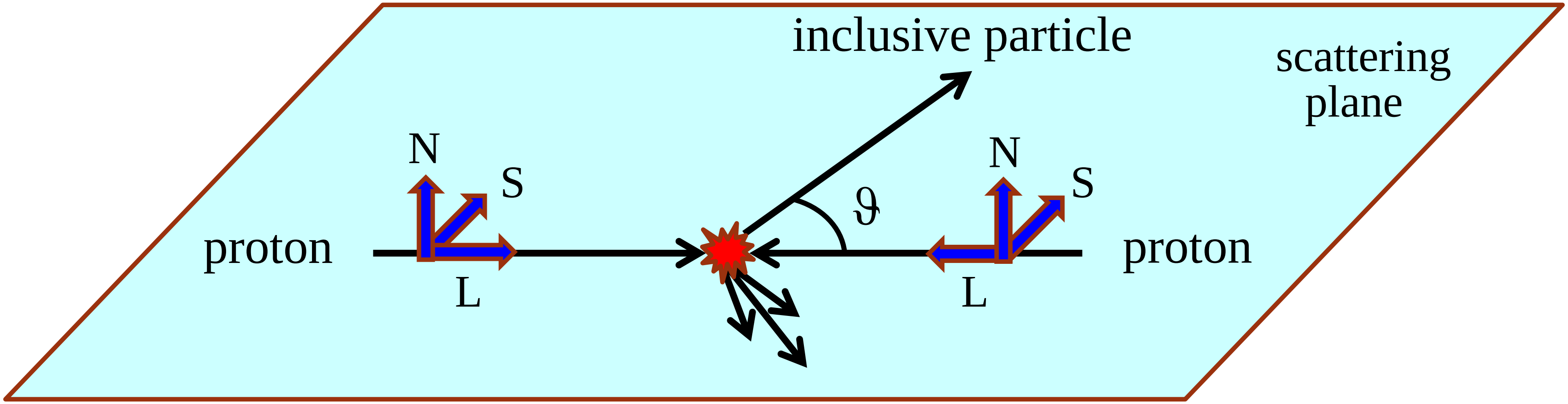
Self-similarity in processes with polarized protons

New hypothesis:

- Self-similarity of spin structure
- Fractality of proton spin
- Spin-dependent fractal dimensions

L, N, S represent the unit vectors along spin directions of initial particles

L is along the incident momentum
N is along the normal to the scattering plane
S is along N×L



Double spin asymmetry

$p^{\uparrow} + p^{\downarrow} \to h + X$ A_{NN}

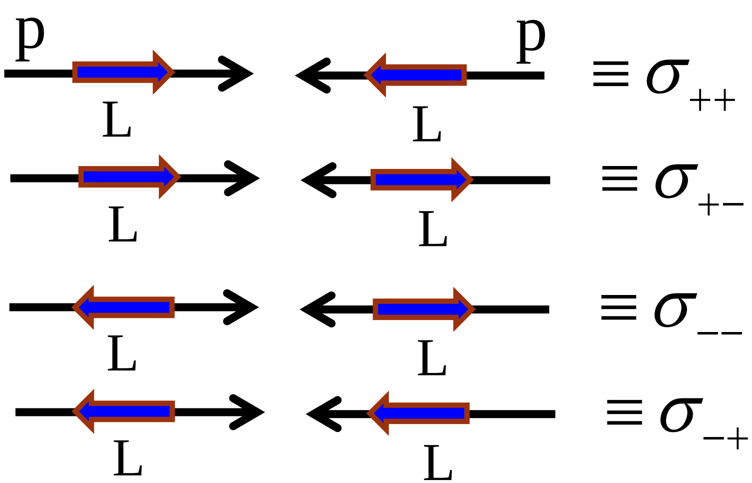
$p^{\rightarrow} + p^{\leftarrow} \to h + X$ A_{LL}

$p^{\rightarrow} + p^{\uparrow} \to h + X$ A_{LN}

Double spin asymmetry of pion production in pp

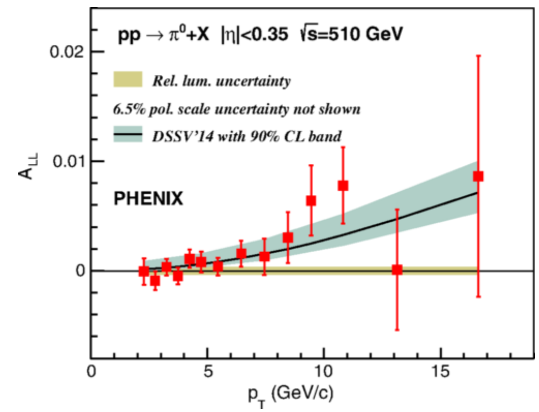
$$\vec{p} + \vec{p} \to \pi + X$$

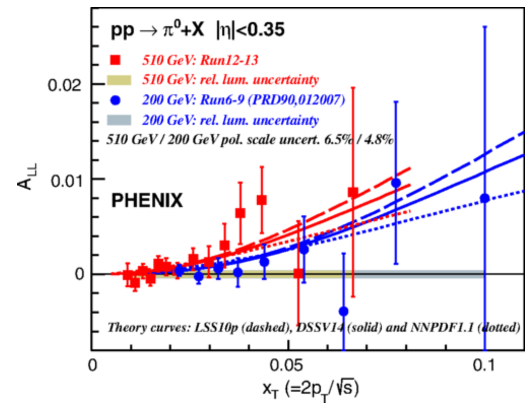
$$A_{LL} = \frac{\sigma_{++} + \sigma_{--} - \sigma_{+-} - \sigma_{-+}}{\sigma_{++} + \sigma_{--} + \sigma_{+-} + \sigma_{-+}}$$



$$\sigma_{++} + \sigma_{--} + \sigma_{+-} + \sigma_{-+} = 4\sigma_{00}$$

STAR & PHENIX at RHIC





PHENIX Collaborartion

Adare A. et al. Phys. Rev. D 90 (2014) 012007

Adare A. et al. Phys. Rev. D 93 (2016) 011501

RHIC SPIN Collaboration

Arschenauer E.C. et al. nucl-ex:1304.0079

Self-similarity of spin-dependent process

Spin-independence of $\Psi(z)$

$$\Psi_{++} \overset{\text{def}}{=} \Psi(z_{++}),\ \Psi_{+-} \overset{\text{def}}{=} \Psi(z_{+-}),\ \Psi_{00} \overset{\text{def}}{=} \Psi(z_{00})$$

$$z_{++} = z_0 \cdot \Omega^{-1}_{++00}\ ,\ldots$$

$$\Omega = (1-x_1)^{\delta_1}(1-x_2)^{\delta_2}(1-y_a)^{\varepsilon_F}(1-y_b)^{\varepsilon_F}$$

$$\Omega_{0000} =: \{\delta, \delta, \varepsilon_F, \varepsilon_F\}$$

$$\Omega_{++00} =: \{\delta - \Delta\delta/2, \delta - \Delta\delta/2, \varepsilon_F, \varepsilon_F\}$$

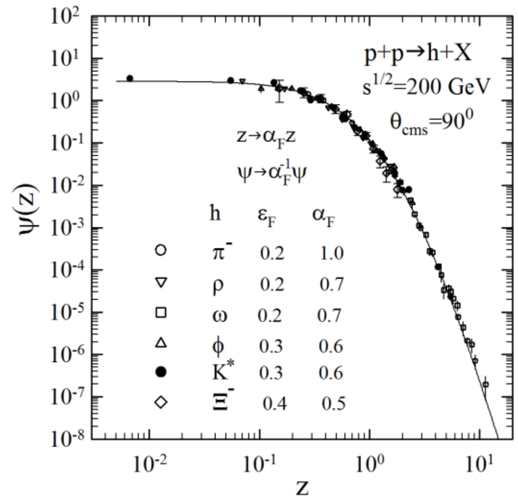
$$\Omega_{--00} =: \{\delta - \Delta\delta/2, \delta - \Delta\delta/2, \varepsilon_F, \varepsilon_F\}$$

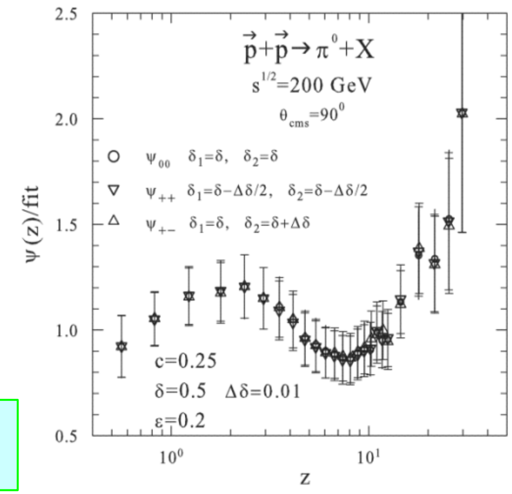
$$\Omega_{-+00} =: \{\delta + \Delta\delta, \delta, \varepsilon_F, \varepsilon_F\}$$

$$\Omega_{+-00} =: \{\delta, \delta + \Delta\delta, \varepsilon_F, \varepsilon_F\}$$

Spin correction to fractal dimension: δ, $\Delta\delta$

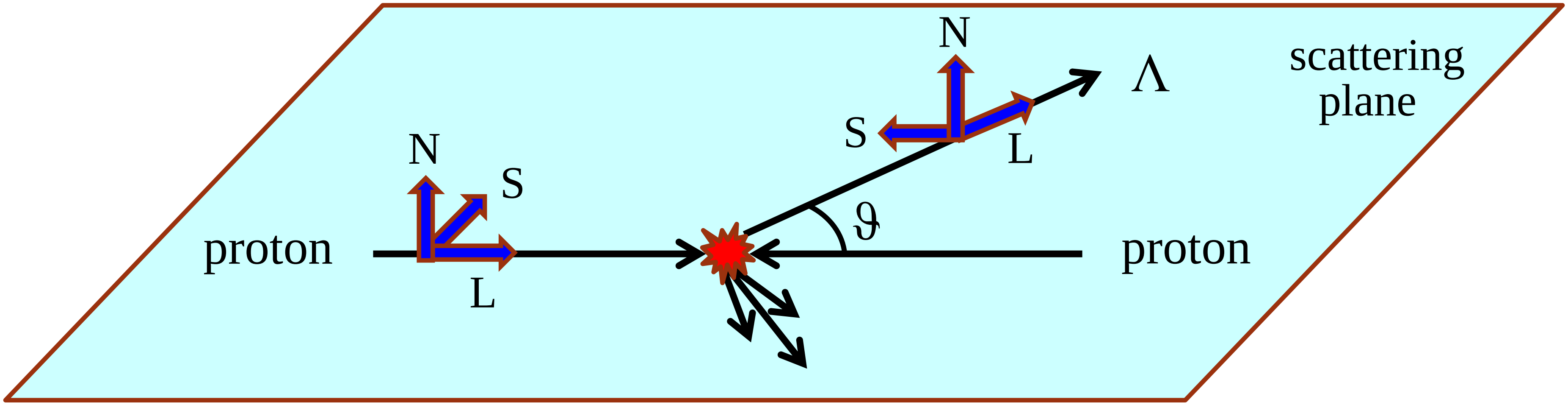
$$\vec{p} + \vec{p} \rightarrow \pi + X$$





Self-similarity in processes with polarized Λ

- Self-similarity of spin structure
- Fractality of proton spin
- Spin-dependent fractal dimensions
- Self-similarity of spin-dependent fragmentation



Spin transfer coefficient

$p^{\uparrow} + p \rightarrow \Lambda^{\uparrow} + X$ D_{NN}

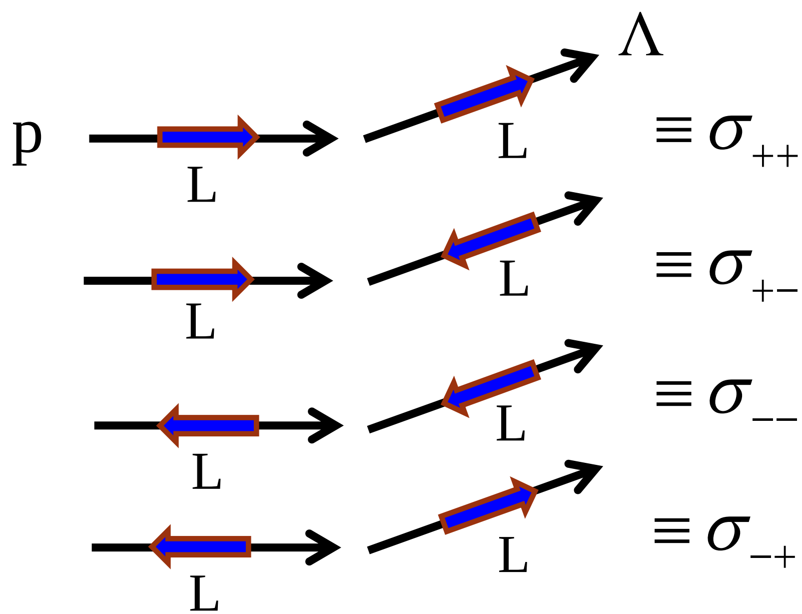
$p^{\rightarrow} + p \rightarrow \Lambda^{\rightarrow} + X$ D_{LL}

$p^{\rightarrow} + p \rightarrow \Lambda^{\uparrow} + X$ D_{LN}

Longitudinal spin transfer coefficient D_{LL}

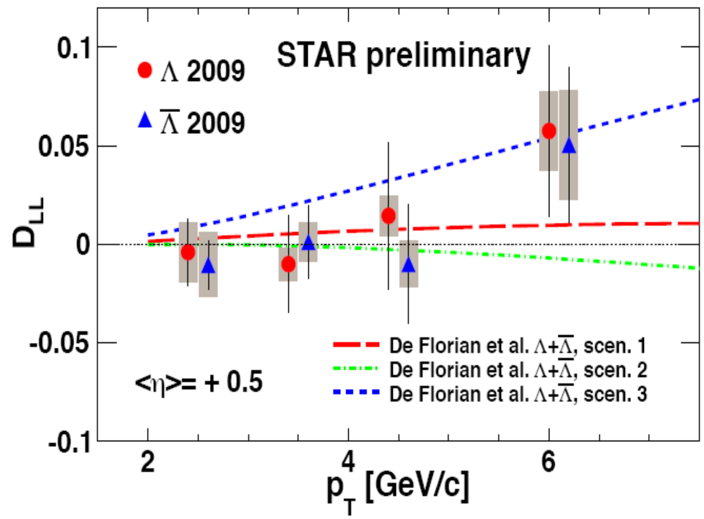
$$\vec{p} + p \to \vec{\Lambda} + X$$

$$D_{LL} = \frac{\sigma_{++} + \sigma_{--} - \sigma_{+-} - \sigma_{-+}}{\sigma_{++} + \sigma_{--} + \sigma_{+-} + \sigma_{-+}}$$



$$\sigma_{++} + \sigma_{--} + \sigma_{+-} + \sigma_{-+} = 4\sigma_{00}$$

STAR at RHIC



Xu Q. STAR Collaboration,
DSPIN2013, Dubna, Russia,
8-12 October, 2013

Self-similarity of spin-dependent process with Λ

$$\vec{p} + p \to \vec{\Lambda} + X$$

Spin-independence of $\Psi(z)$

$$\Psi_{++} \stackrel{def}{=} \Psi(z_{++}),\ \Psi_{+-} \stackrel{def}{=} \Psi(z_{+-}),\ \Psi_{00} \stackrel{def}{=} \Psi(z_{00})$$

$$z_{++} = z_0 \cdot \Omega^{-1}_{++00}\ ,\ldots$$

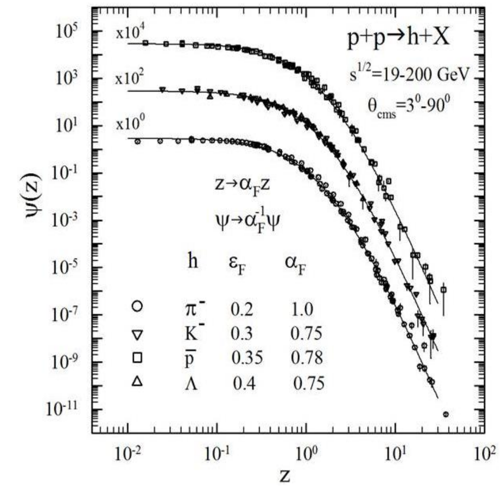
$$\Omega_{0000} =: \{\delta, \delta, \varepsilon_F, \varepsilon_F\}$$

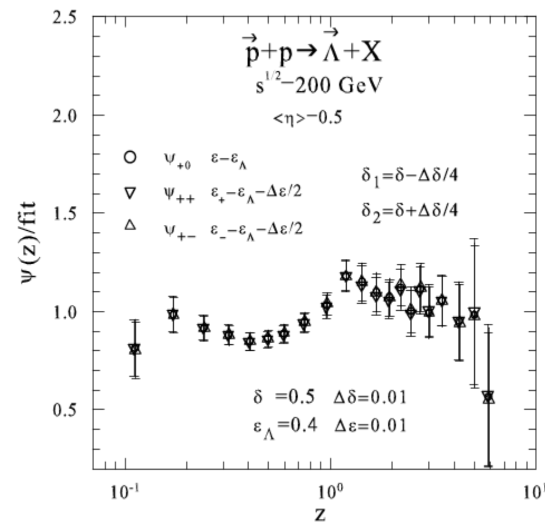
$$\Omega_{+0+0} =: \{\delta - \Delta\delta/4, \delta + \Delta\delta/4, \varepsilon_F - \Delta\varepsilon_F/2, \varepsilon_F\}$$

$$\Omega_{+0-0} =: \{\delta - \Delta\delta/4, \delta + \Delta\delta/4, \varepsilon_F + \Delta\varepsilon_F/2, \varepsilon_F\}$$

Spin correction to proton fractal dimension: δ, $\Delta\delta$

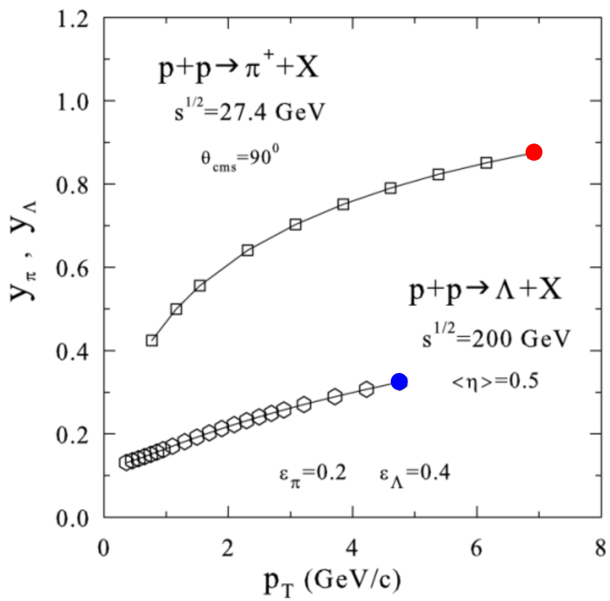
Spin correction to fragmentation fractal dimension: ε_F ,$\Delta\varepsilon_F$





Spin-dependent energy loss

Energy loss $\Delta E/E \sim (1-y_a)$

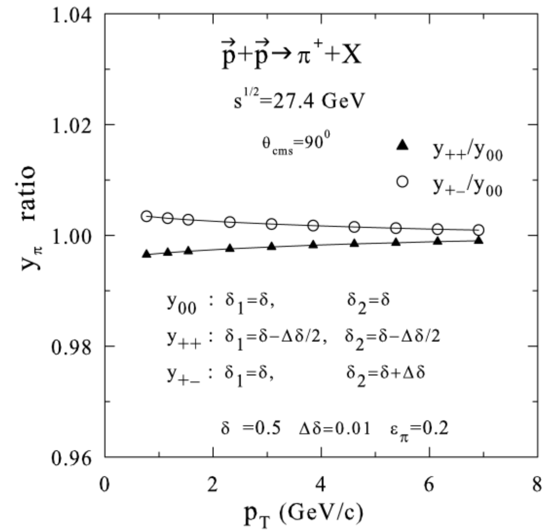


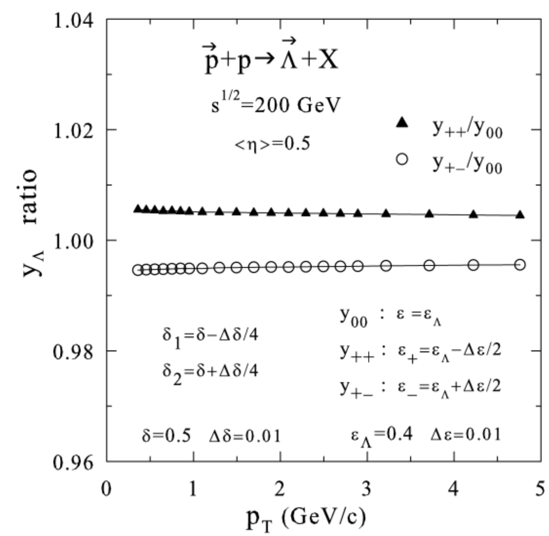
$p_T \approx 7$ GeV/c

π
10% energy loss
$q \approx 7.8$ GeV/c

$p_T \approx 5$ GeV/c

Λ
70% energy loss
$q \approx 16.7$ GeV/c





- Energy loss is smaller for opposite helicities than for the same ones ($y_{+-} > y_{++}$) for A_{LL}
- Energy loss is smaller for same helicities than for opposite ones ($y_{++} > y_{+-}$) for D_{LL}

Phys. Part. Nucl. Lett. 12 (2015) 81

Self-similarity in polarized processes with jets

New hypothesis:

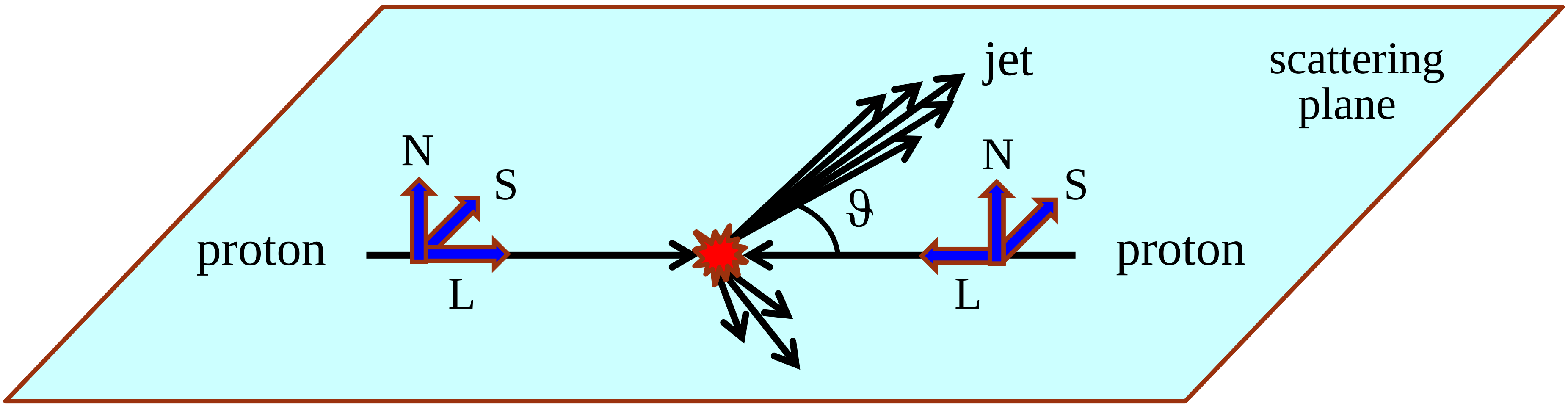
- Self-similarity of spin structure
- Fractality of proton spin
- Spin-dependent fractal dimensions

L, N, S represent the unit vectors along spin directions of initial particles

L is along the incident momentum

N is along the normal to the scattering plane

S is along N×L



Double spin asymmetry

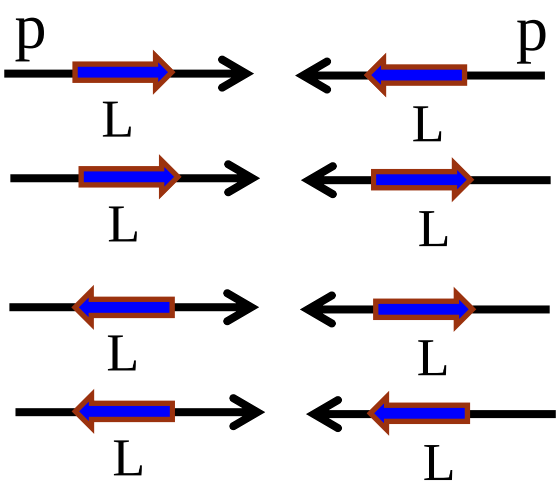
$$p^{\uparrow} + p^{\downarrow} \rightarrow jet + X \qquad p^{\rightarrow} + p^{\leftarrow} \rightarrow jet + X \qquad p^{\rightarrow} + p^{\uparrow} \rightarrow jet + X$$

A_{NN} A_{LL} A_{LN}

Double spin asymmetry of jet production in pp

$$\vec{p} + \vec{p} \to jet + X$$

$$A_{LL} = \frac{\sigma_{++} + \sigma_{--} - \sigma_{+-} - \sigma_{-+}}{\sigma_{++} + \sigma_{--} + \sigma_{+-} + \sigma_{-+}}$$



$$\equiv \sigma_{++}$$

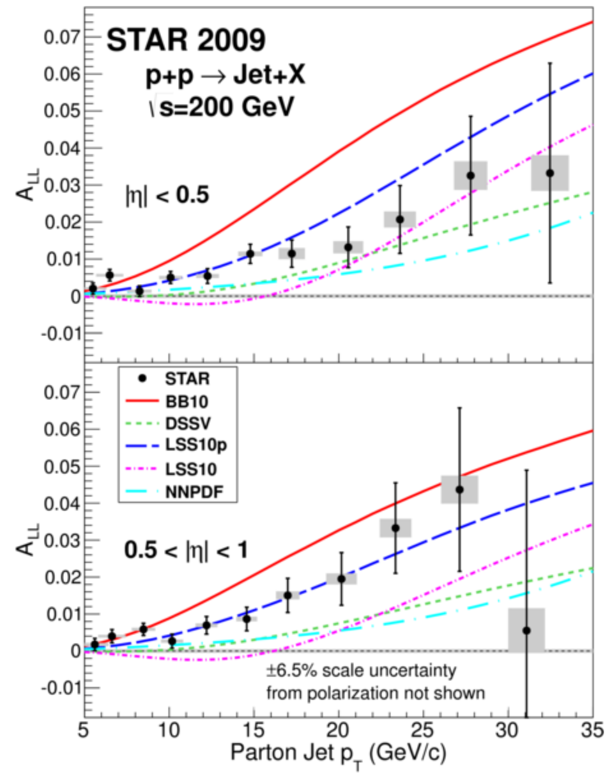
$$\equiv \sigma_{+-}$$

$$\equiv \sigma_{--}$$

$$\equiv \sigma_{-+}$$

$$\sigma_{++} + \sigma_{--} + \sigma_{+-} + \sigma_{-+} = 4\sigma_{00}$$

STAR at RHIC



STAR Collaboration,
L.Adamczyk et al.
Phys. Rev. Lett. 115, 092002 (2015)

Self-similarity of spin-dependent process: $\vec{p} + \vec{p} \to jet + X$

Spin-independence of $\Psi(z)$

$$\Psi_{++} \overset{\text{def}}{=} \Psi(z_{++}),\ \Psi_{+-} \overset{\text{def}}{=} \Psi(z_{+-}),\ \Psi_{00} \overset{\text{def}}{=} \Psi(z_{00})$$

$$z_{++} = z_0 \cdot \Omega^{-1}_{++00}\ ,...$$

$$\Omega = (1-x_1)^{\delta_1}(1-x_2)^{\delta_2}(1-y_a)^{\varepsilon_F}(1-y_b)^{\varepsilon_F}$$

$$\Omega_{0000} =: \{\delta, \delta, \varepsilon_F, \varepsilon_F\}$$

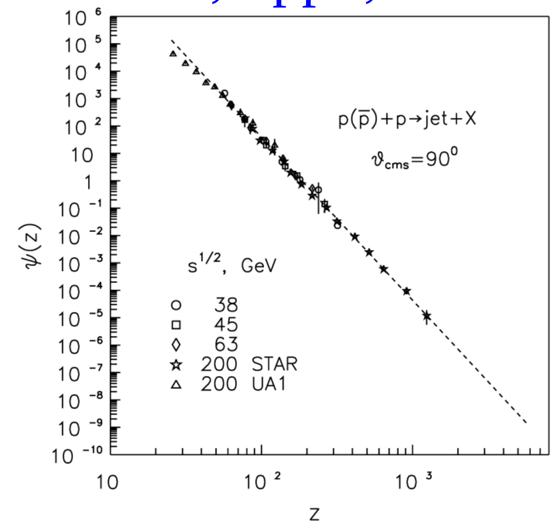
$$\Omega_{++00} =: \{\delta - \Delta\delta/2, \delta - \Delta\delta/2, \varepsilon_F, \varepsilon_F\}$$

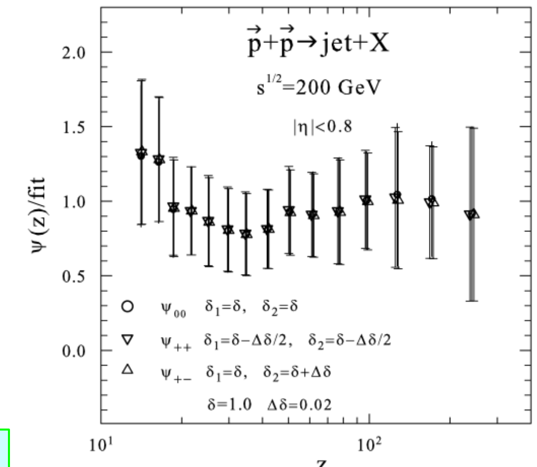
$$\Omega_{--00} =: \{\delta - \Delta\delta/2, \delta - \Delta\delta/2, \varepsilon_F, \varepsilon_F\}$$

$$\Omega_{-+00} =: \{\delta + \Delta\delta, \delta, \varepsilon_F, \varepsilon_F\}$$

$$\Omega_{+-00} =: \{\delta, \delta + \Delta\delta, \varepsilon_F, \varepsilon_F\}$$

ISR, Sp$\bar{p}$S, RHIC





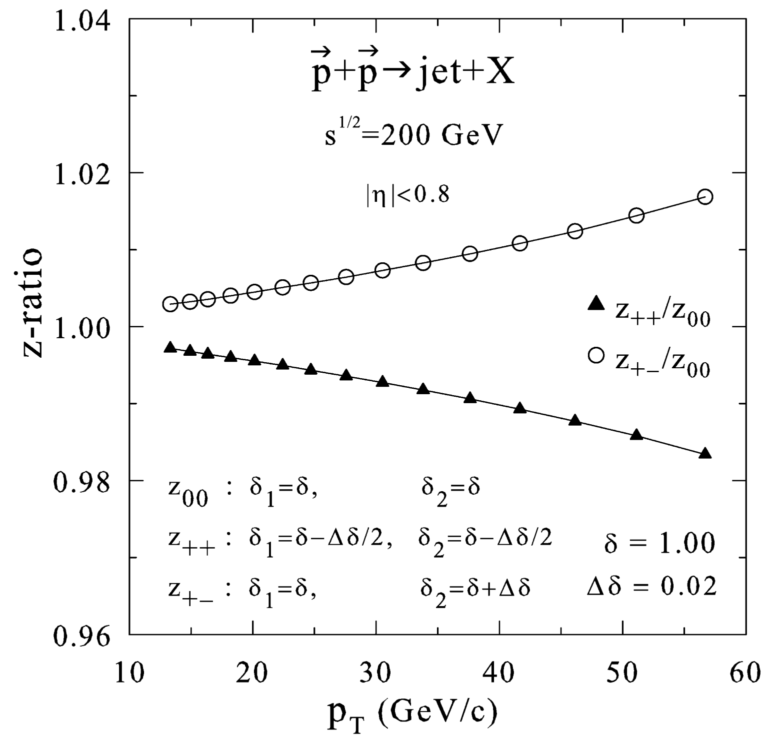
Spin correction to fractal dimension: $\delta, \Delta\delta$

Resolution of proton spin structure

$$\vec{p} + \vec{p} \rightarrow jet + X$$

Energy loss $\Delta E/E \sim (1-y_a)$

- Fragmentation dimension for jets is small, $\varepsilon_F \approx 0$
- Energy loss is negligible in that case
- Spin-independent dimension $\delta \approx 1.00$
- Spin-dependent correction $\Delta\delta \approx 0.02$



Hypothesis of self-similarity

⇓

Spin–independence of $\Psi(z)$

⇓

The spin structure can be probed with higher resolution ($z_{+-} > z_{++}$) for opposite helicities than for the same ones.

Conclusions

- A hypothesis of self-similarity of proton spin was formulated.
- Method of data analysis based on z-scaling for description of processes with polarized protons was justified.
- Results of analysis of longitudinal double spin asymmetry A_{LL} of π and jet production and longitudinal spin transfer coefficient D_{LL} of Λ production in pp collisions in z-scaling approach were presented.
- Spin correction to fractal dimensions of proton structure and fragmentation process to Λ hyperon were estimated.
- Spin-dependent constituent energy loss were estimated.

Proposal for Experiment

"Spin Physics Experiments at NICA-SPD with polarized proton and deuteron beams" in Dubna

Measurements: Inclusive cross sections and asymmetries of particle production in p-p collisions with polarized protons

Kinematic region: $\sqrt{s}$=10-30 GeV, high p_T , central rapidity range
Particles: π,.., J/ψ, Λ,…, γ, $l^+ l^-$,…

New characteristics of hadron production:
Spin-dependent fractal dimensions
Spin-dependent energy loss

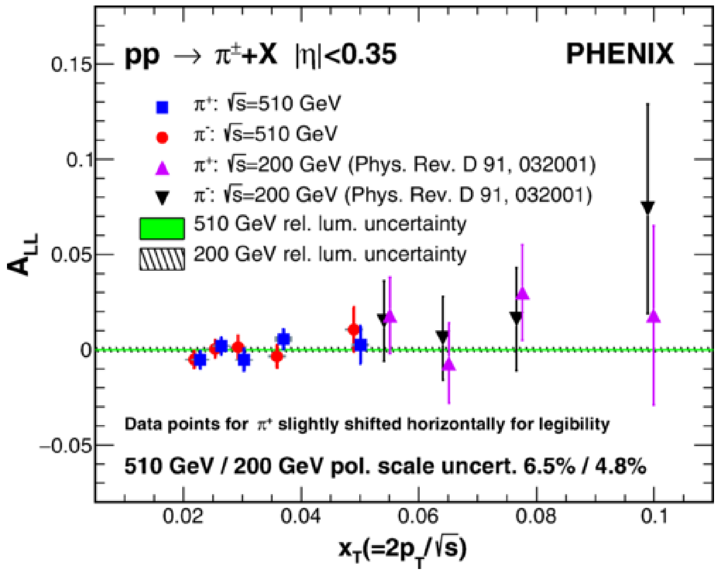
M.T. & I.Zborovsky
A.Aparin
Part. Nucl. Lett.,
12 (2015) 81

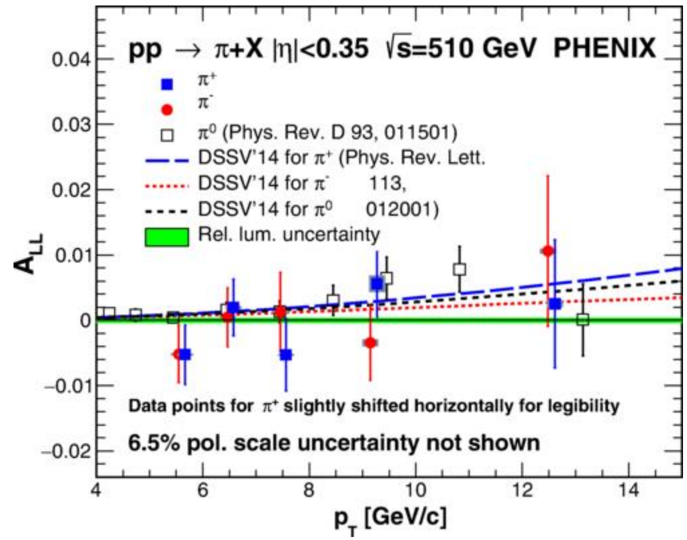
New properties of spin origin:
Self-similarity of spin structure
Fractality of proton spin

Thank You For Your Attention !

Back-up slides

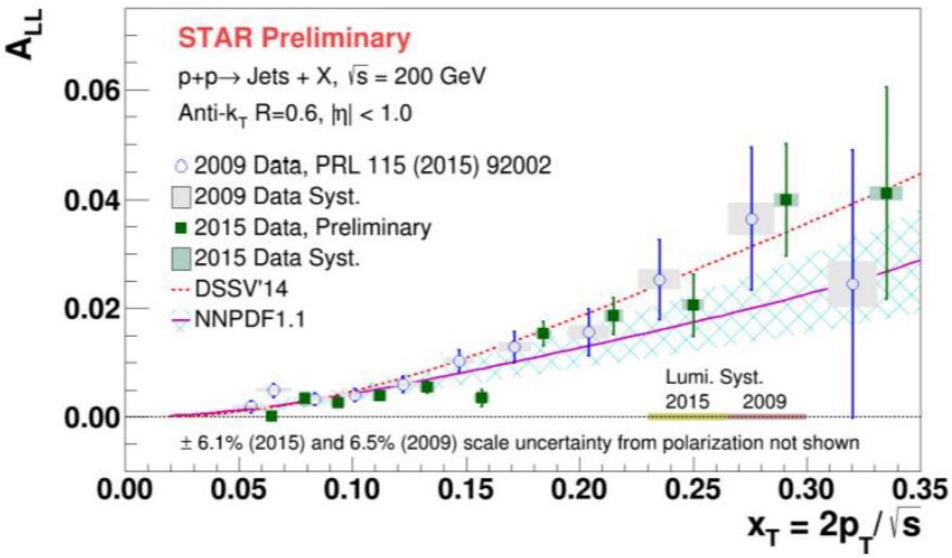
Double spin meson asymmetry at midrapidity in longitudinally polarized p+p collisions at √s=510 GeV





PHENIX Collaboration
U. Acharya *et al.*
Phys. Rev. D 102 (2020) 032001

Double spin jet asymmetry at midrapidity in longitudinally polarized p+p collisions at √s=510 GeV



STAR Collaboration

Oleg Eyser "Gluon polarization at RHIC",
Workshop "Gluon Content of Proton and Deuteron with the Spin Physics Detector at NICA",
September 30, 2020, JINR, Dubna, Russsia