# Experiment: Spin physics I

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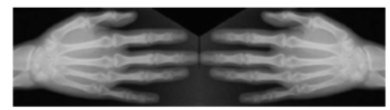
# Spin ½ - most important example

- Longitudinal polarization:

$$n^\mu = \frac{1}{m}(|\vec{p}|, Ep^i/|\vec{p}|) \longrightarrow \Pi = \frac{\vec{J}\cdot\vec{p}}{|\vec{p}|}$$

  – Eignvalue: helicity λ; helicity stats labelled as | p, λ>
  – High energy limit or m ~ 0
    - $\Pi \to \gamma_5$ and $\boxed{\text{helicity = chirality}}$ 
    - helicity becomes Lorentz-invariant

- Transverse polarization: $n^\mu = (0, \vec{n}_\perp, 0)$

- Spin polarization vector: $\vec{P} = \frac{\langle \vec{s} \rangle}{s} = \frac{\langle \vec{s} \rangle}{\hbar/2}$ , $|P| \leq 1$

- Spin density matrix: $\rho = \frac{1}{2}(1 + \vec{P}\cdot\vec{\sigma}),\ \vec{P} = Tr\rho\vec{\sigma}$

  $(\rho = \sum_i P_i |i><i|)$

# Why do we care about SPIN?

- Spin physics studies the spin-dependent quantity.

- Spin, can serve as a “new” window, to study QCD:

  for example, QCD predicts a sign change of Sivers function in semi-inclusive DIS and Drell-Yan process,

  -> fundamental feature of QCD

- Spin phenomena gave us lots of surprises in the past:

  for example, hyperon polarization, single spin asymmetry, proton “spin crisis” –spin structure of nucleon…

  **-> better understanding of QCD and hadron structure**

# Why QCD spin physics?

- Zuotang Liang

## Four types of striking spin effects observed in high energy reactions since 1970s

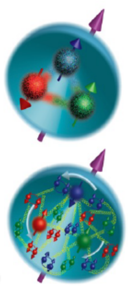
### “Proton spin crisis” 质子自旋危机

**夸克模型**

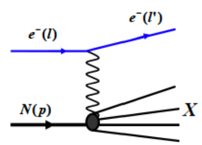
夸克自旋之和Σ
=质子自旋$S_p$

**DIS实验**

89年: Σ~0
目前: Σ~20%$S_p$



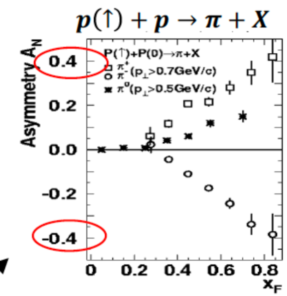
DIS: $e + p \to e + X$

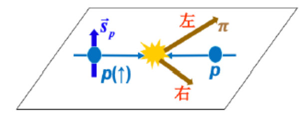



EMC, PLB 206,364 (1988)

### Single spin left-right asymmetry (SSA)

$p(\uparrow) + p \to \pi + X$



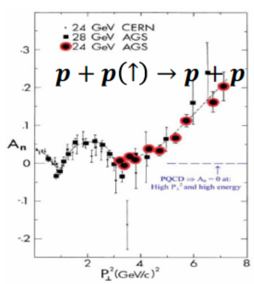



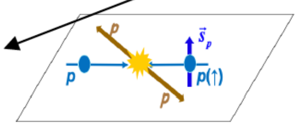

$$A_N \equiv \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

e.g. FNAL E704,
PLB264, 462 (1991)

predictions of pQCD（微扰QCD预言）～ 0

### Spin analyzing power in $pp \to pp$



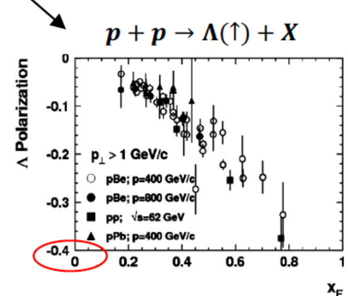



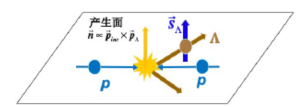

$$A_N \equiv -\frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

e.g. D. Grab *et al.*,
PRL41, 1257 (1978)

### Transverse polarization of $\Lambda$ in $pp \to \Lambda X$

$p + p \to \Lambda(\uparrow) + X$




$$P_\Lambda \equiv \frac{\sigma(\uparrow) - \sigma(\downarrow)}{\sigma(\uparrow) + \sigma(\downarrow)}$$

e.g. S.A. Gourlay *et al.*,
PRL56, 2244 (1986)

**实验与理论严重冲突 ⟹ QCD理论研究突破口 ⟹ QCD自旋物理**

# Spin structure of nucleon

In the naive Quark Model, the nucleon is made of three quarks - p(uud)
The quark spins make up the nucleon spin, since the quarks are in the s-orbit:

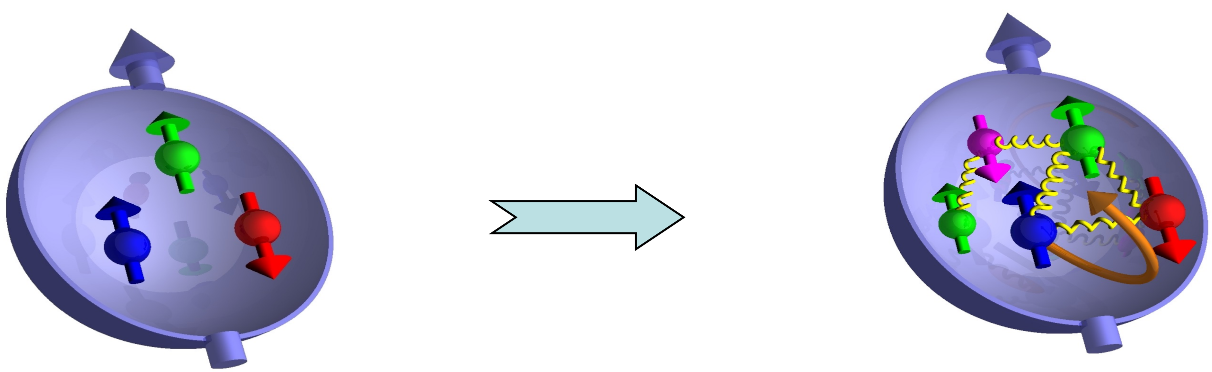
$\Delta\Sigma = 1$

$$\begin{cases} \left|p^{\uparrow}\right\rangle = \sqrt{\tfrac{2}{3}}u^{\uparrow}u^{\uparrow}d^{\downarrow} - \sqrt{\tfrac{1}{3}}\sqrt{\tfrac{1}{2}}(u^{\uparrow}u^{\downarrow} + u^{\downarrow}u^{\uparrow})d^{\uparrow} \\ \Delta U = \dfrac{4}{3},\ \Delta D = -\dfrac{1}{3} \end{cases}$$

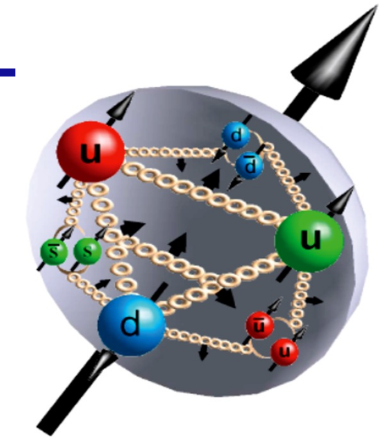
With Parton Model (sea quark, gluon) but assumes $\Delta S=0$:

$\Delta\Sigma \approx 0.6$

1988 - European Muon Collaboration (polarized Deep Inelastic Scattering)
"Spin Crisis"--- proton spin carried by quark spin is rather small: $\Delta\Sigma \sim 0.2$



# Spin structure of nucleon




- Spin sum rule (longitudinal case):

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_{q,g} \rangle$$

**Quark spin,**
**Best known**
**(~30%)-DIS**

**Gluon spin,**
**Poorly known,**
**RHIC**

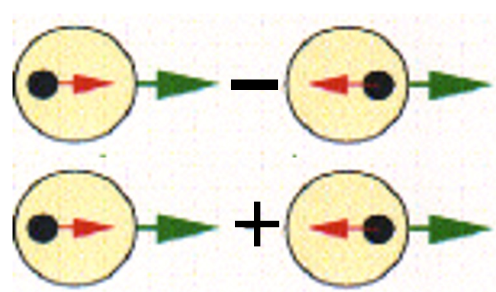
**Orbital Angular Momenta**
**Little known**

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s} \qquad [\Delta q = \int_0^1 \Delta q(x)dx]$$

- Polarized parton densities:

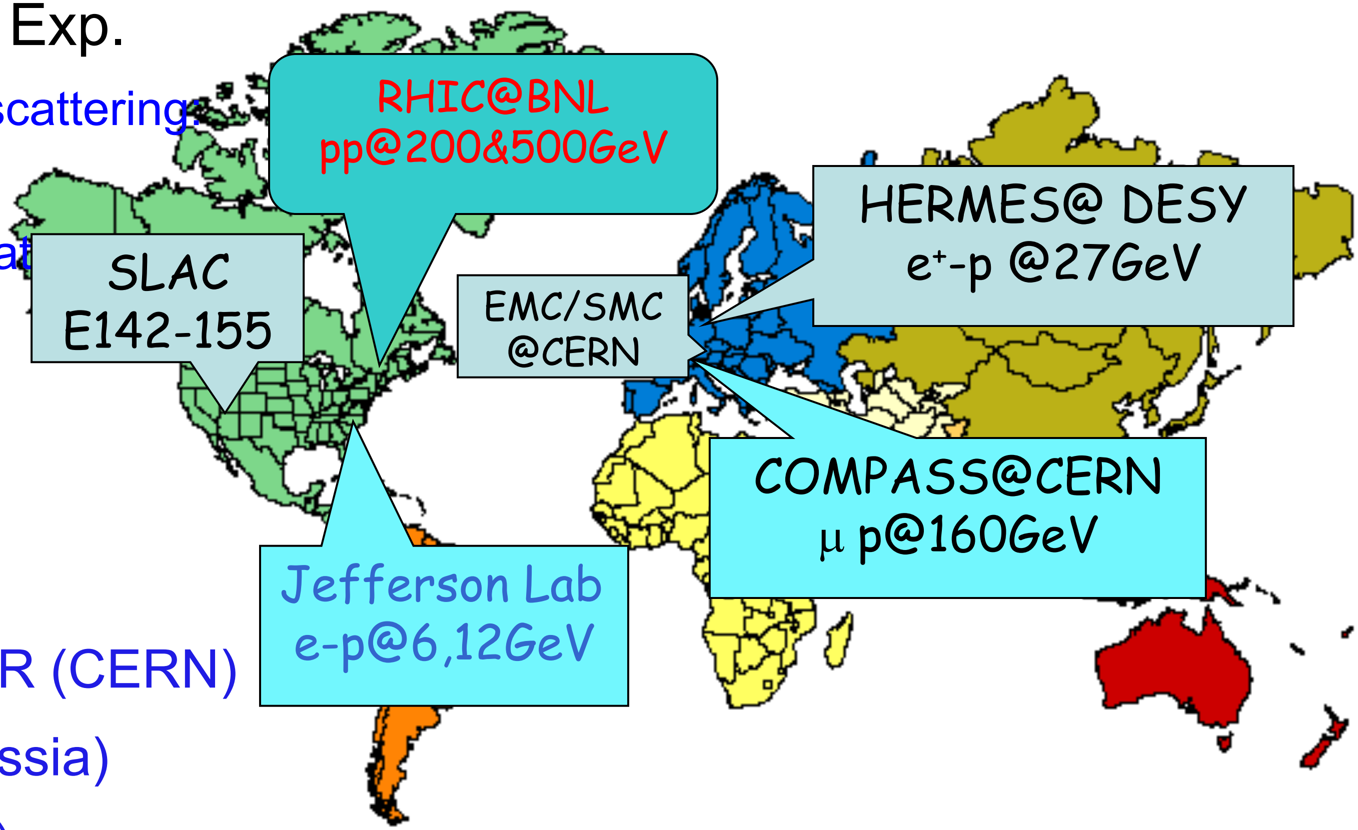
$$\Delta q(x,Q^2) = q^+(x,Q^2) - q^-(x,Q^2)$$

$$q(x,Q^2) = q^+(x,Q^2) + q^-(x,Q^2)$$

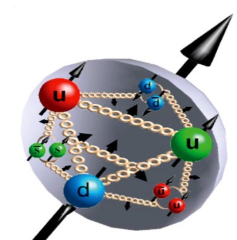


# World efforts for spin physics

- Finished experiments: SLAC, EMC, SMC, HERMES, COMPASS
- Current running Exp.
  - Lepton-nucleon scattering: JLab
  - Proton-proton scat RHIC
- Future facilities
  - EIC (US)
  - EicC (China)
  - LHCspin/AFTER (CERN)
  - NICA-SPD (Russia)
  - JPARC (Japan)
  - GSI-FAIR (Germany)

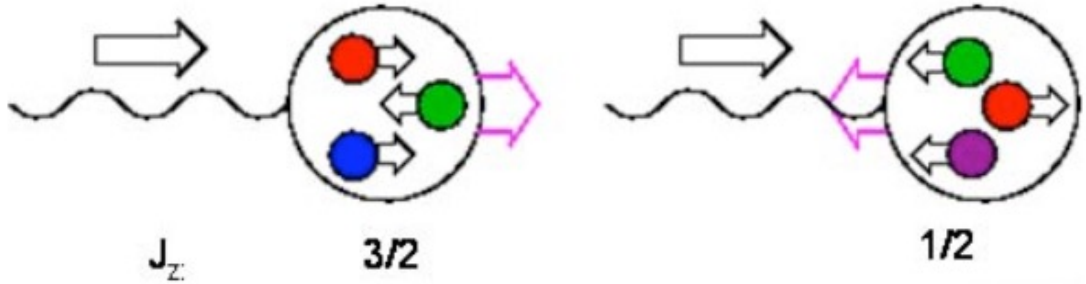



**Goal:**
**Nucleon spin structure**

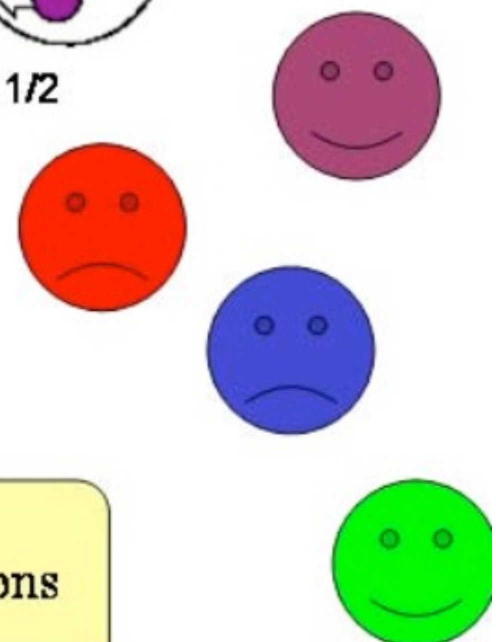


# How to measure ΔΣ ?

- Photoabsorption: (flavours ignored)

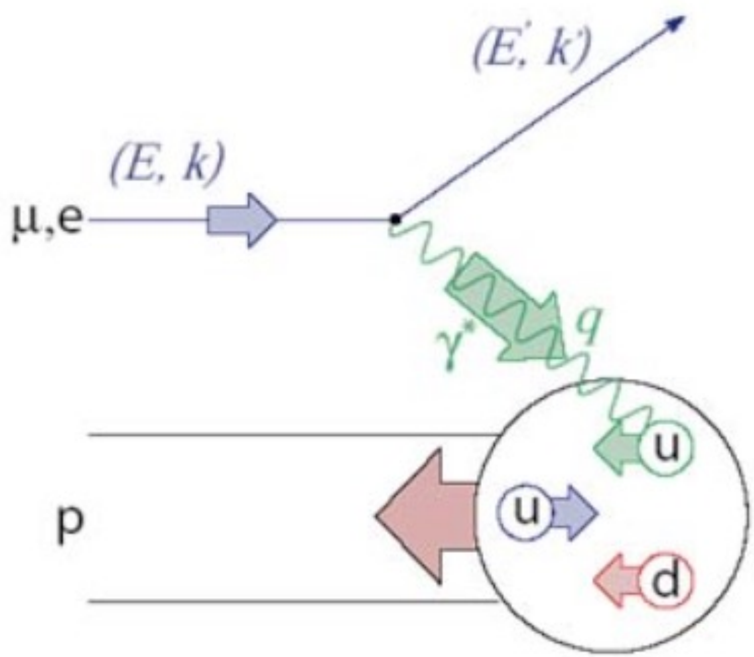



- only quarks with opposite helicity can absorb the polarised photon via spin-flip
- # quarks in direction of nucleon $\dfrac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$



⇒ need polarised photons & nucleons

# Polarized Deep Inelastic Scattering




$$Q^2 = -(k-k')^2 \stackrel{lab}{=} 4EE'\sin^2\frac{\vartheta}{2}$$

$$P\cdot q \stackrel{lab}{=} M\nu = M(E-E')$$

$$P\cdot k \stackrel{lab}{=} ME$$

**Bjorken-x:** fraction of longitudinal momentum carried by struck quark in infinite-momentum frame (Breit)

$$x \stackrel{lab}{=} \frac{Q^2}{2M\nu} = \frac{-q^2}{2P\cdot q}$$

$$y \stackrel{lab}{=} \frac{\nu}{E} = \frac{P\cdot q}{P\cdot k}$$

$Q^2$ corresponds to the "spatial resolution" $\lambda \approx \frac{1}{|\vec{q}\,|}$

# How to measure ΔΣ: lepton-nucleon scattering

- Lepton Nucleon Cross Section

$$\frac{d^3\sigma}{dx\,dy\,d\phi} = \frac{\alpha^2 y}{2Q^4} L_{\mu\nu}(k,q,s,)W^{\mu\nu}(P,q,S)$$

Nucleon spin

Lepton spin

- Lepton tensor $L_{\mu\nu}$ affects the kinematics (QED)
- Hadronic tenosr $W^{\mu\nu}$ has information about the hadron structure

$$W^{\mu\nu}(P,q,S) = -(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2})\underline{F_1(x,Q^2)} + (p^\mu - \frac{P\cdot q}{q^2}q^\mu)(p^\nu - \frac{P\cdot q}{q^2}q^\nu)\frac{1}{P\cdot q}\underline{F_2(x,Q^2)}$$

$$-i\epsilon^{\mu\nu\lambda\sigma}q_\lambda\left[\frac{MS_\sigma}{P\cdot q}(g_1(x,Q^2) + g_2(x,Q^2)) - \frac{M(S\cdot q)P_\sigma}{P\cdot q}g_2(x,Q^2)\right]$$

# Structure Function and parton densities (PDF)

$F_1,\ F_2$ unpolarised structure functions: momentum distributions

$g_1,\ g_2$ polarised structure functions: spin distributions

QPM:

$$F_2(x) = 2xF_1$$ Calan Gross relation

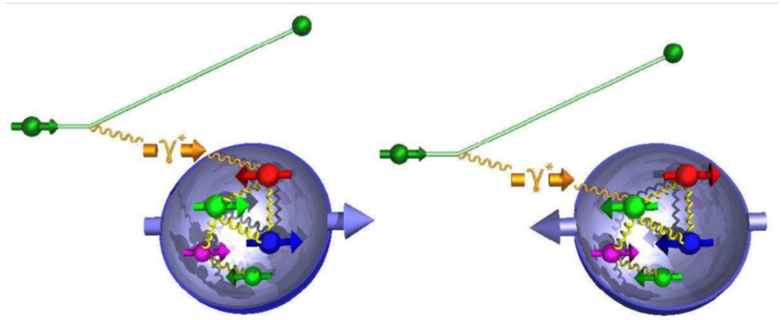
$$g_2 = 0$$ twist-3 quark-qluon correlations

$$F_1(x) = \tfrac{1}{2}\textstyle\sum_f e_f^2 \left\{q_f^+(x) + q_f^-(x)\right\} = \frac{1}{2}\sum_f e_f^2 q_f(x)$$

$$g_1(x) = \tfrac{1}{2}\textstyle\sum_f e_f^2 \left\{q_f^+(x) - q_f^-(x)\right\} = \frac{1}{2}\sum_f e_f^2 \Delta q_f(x)$$

# Experiment with pol. DIS

- Deep Inelastic polarized electron or muon scattering




$$A_{\gamma * p} \propto \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}$$

$$A_{meas} = P_t P_b f A$$

$P_b$, $P_t$ beam and target polarisations,

$f$ target dilution factor = polarisable N/total N

note: linear in error: $f$=1/2 => requires 4 times statistics

$$g_1 \simeq \frac{A_{||}}{D} F_1 \simeq \frac{A_{||}}{D} \frac{F_2}{2x}$$

huge rise of $F_2/2x$ at small $x$

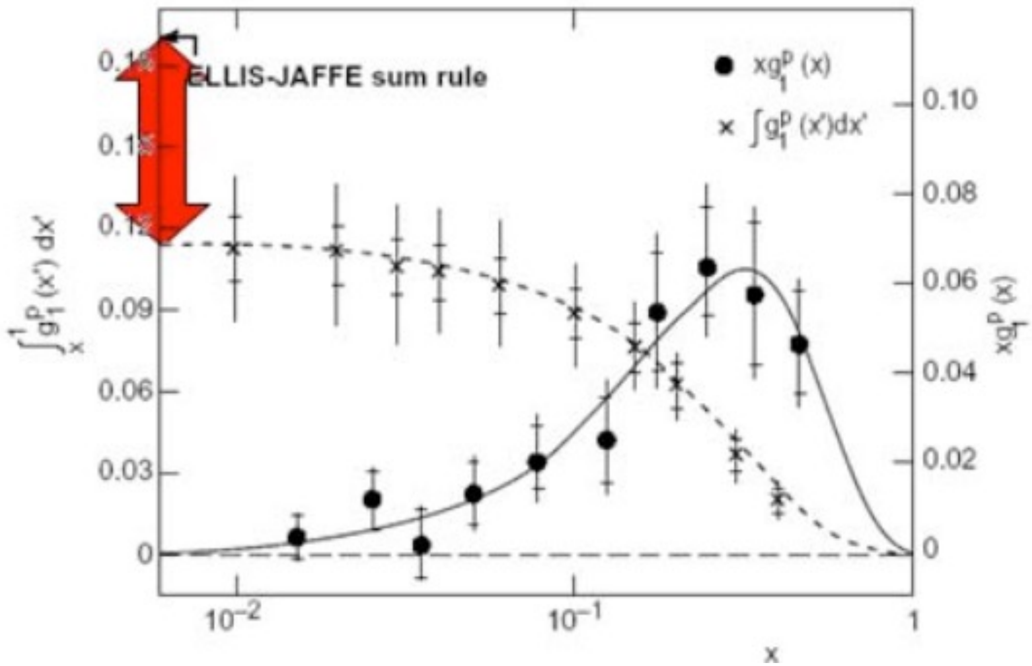
$D$ depolarisation factor, kinematics, polarisation transfer from polarised lepton to photon, $D \approx y$

Even big $g\_1$ at small $x$ means small asymmetries

# The First Moment of $g_1$

- first moment of $g_1$

$$\Gamma_1 = \int_0^1 g_1(x)\mathrm{d}x$$




"Spin crisis"
EMC 1987

# Sum rules

- With

$$\Delta q = \int \Delta q(x) dx$$

$$g_1(x) = \frac{1}{2}\Sigma_f e_f^2 \{q_f^+(x) - q_f^-(x)\} = \frac{1}{2}\Sigma_f e_f^2 \Delta q_f(x)$$

$$\Gamma_1^p = \frac{1}{2}\left[\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right]$$

$$= \frac{1}{12}\underbrace{(\Delta u - \Delta d)}_{a_3 = g_a} + \frac{1}{36}\underbrace{(\Delta u + \Delta d - 2\Delta s)}_{a_8} + \frac{1}{9}\underbrace{(\Delta u + \Delta d + \Delta s)}_{\substack{a_0 \\ \Delta\Sigma}}$$

Neutron decay

(3F-D)/3
Hyperon Decay

$$\Gamma_1^{p,n} = \frac{1}{12}\left[\pm a_3 + \frac{1}{\sqrt{3}} a_8\right] + \frac{1}{9} a_0$$

- Connected to neutron, hyperon β decay data under SU(3) symmetry

$$a_3 = \frac{g_A}{g_V} = F + D = 1.2601 \pm 0.0025$$

$$a_8 = 3F - D \Longrightarrow F/D = 0.575 \pm 0.016$$

# Sum rules

Bjorken sum rule

PR 148 (1966) 1467

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6} g_a$$

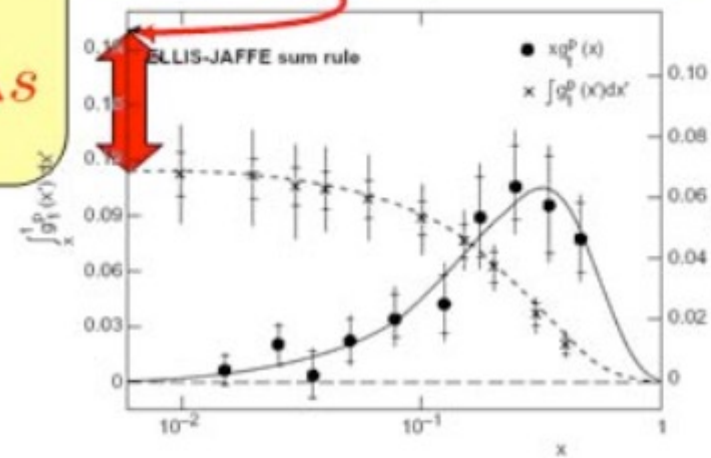
if wrong ⇒ QCD wrong, "worthless equation", needs neutron measurement

Ellis-Jaffe sum rule

PR D9 (1974) 1444

$$\Gamma_1^p = \frac{1}{12} g_a + \frac{5}{36}\sqrt{3} a_8 + \frac{1}{3}\Delta s \Rightarrow \Delta\Sigma \simeq 0.6$$

formulated for $\Delta s=0$, unpolarised strange quarks




Consequences of violation:

$$\begin{aligned} \Delta s &= -0.19 \pm 0.06 \\ \Delta\Sigma &= 0.12 \pm 0.17 \end{aligned}$$

EMC 1987

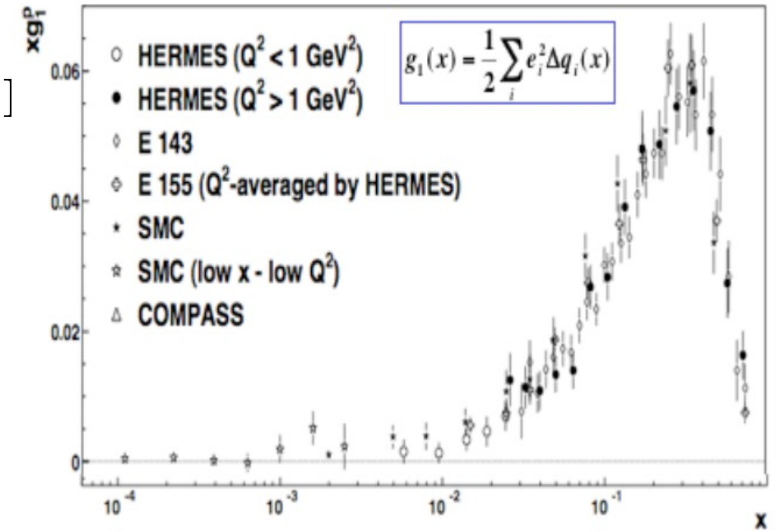
G. Mallot, 2004

# polarized inclusive DIS

- Determination of $\Delta S$ , $\Delta\Sigma$ with polarized inclusive DIS:

$$\Gamma_1^p = \int_0^1 g_1^p(x)dx = \frac{1}{2}\int \sum_i e_i^2 \Delta q_i(x) = \frac{1}{18}[4\Delta U + \Delta D + \Delta S]$$

$$\Delta\Sigma = \underbrace{\Delta u + \Delta\bar{u}}_{\Delta U} + \underbrace{\Delta d + \Delta\bar{d}}_{\Delta D} + \underbrace{\Delta s + \Delta\bar{s}}_{\Delta S}$$




Each flavor's contribution to nucleon spin:

$$\Delta q = \int_0^1 \Delta q(x)dx$$

$\Delta q(x) = q^+(x) - q^-(x)$: helicity distribution function

- Together with neutron, hyperon $\beta$ decay data using SU(3)_f symmetry:

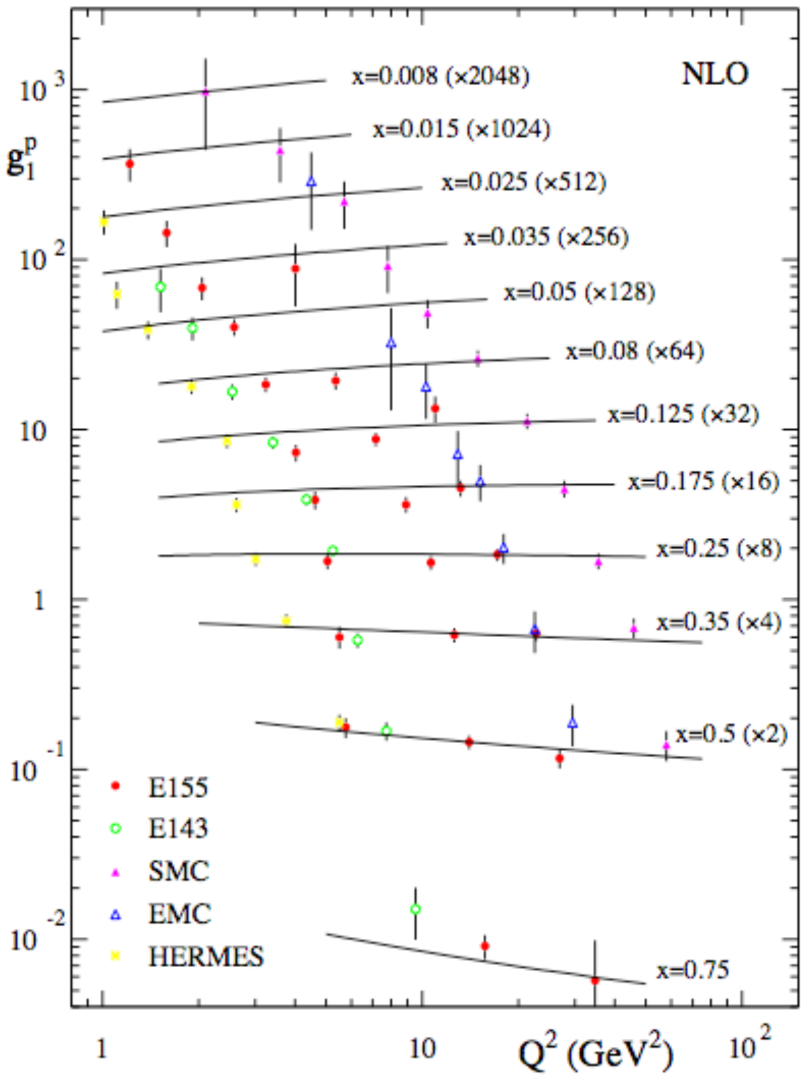
$\Rightarrow \Delta\Sigma = 0.33 \pm 0.03$:

$$\begin{cases} \Delta U \sim 0.8, \\ \Delta D \sim -0.4, \\ \Delta S \sim -0.1 \end{cases}$$ (HERMES, $Q^2$=5 GeV$^2$)

*COMPASS also obtained similar results.

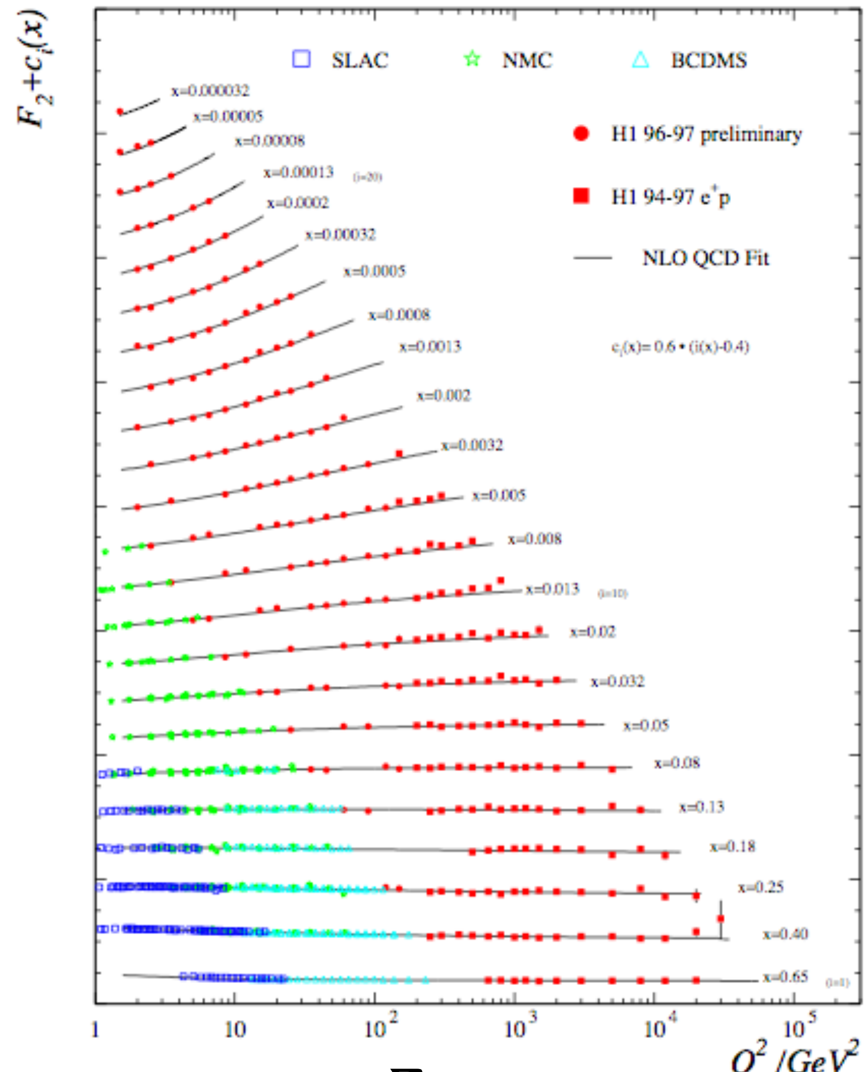
# World data on pol. and unpol. deep-inelastic scattering

polarized



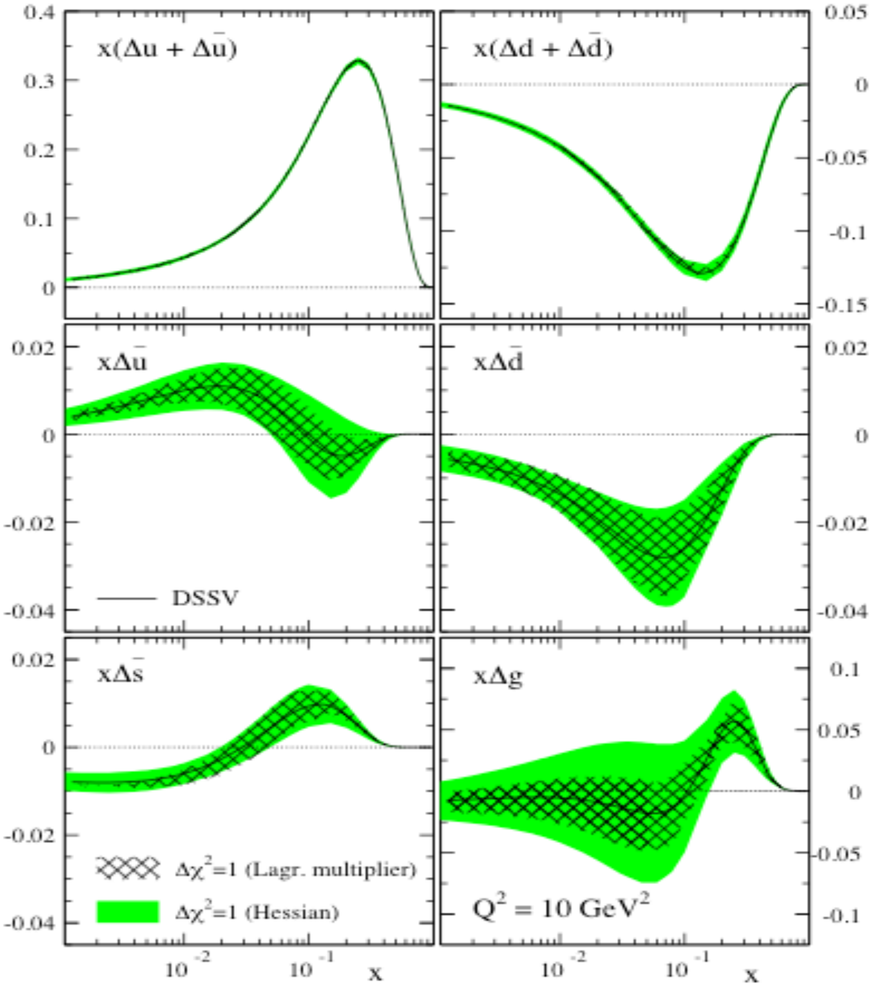

$$g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x)$$

unpolarized

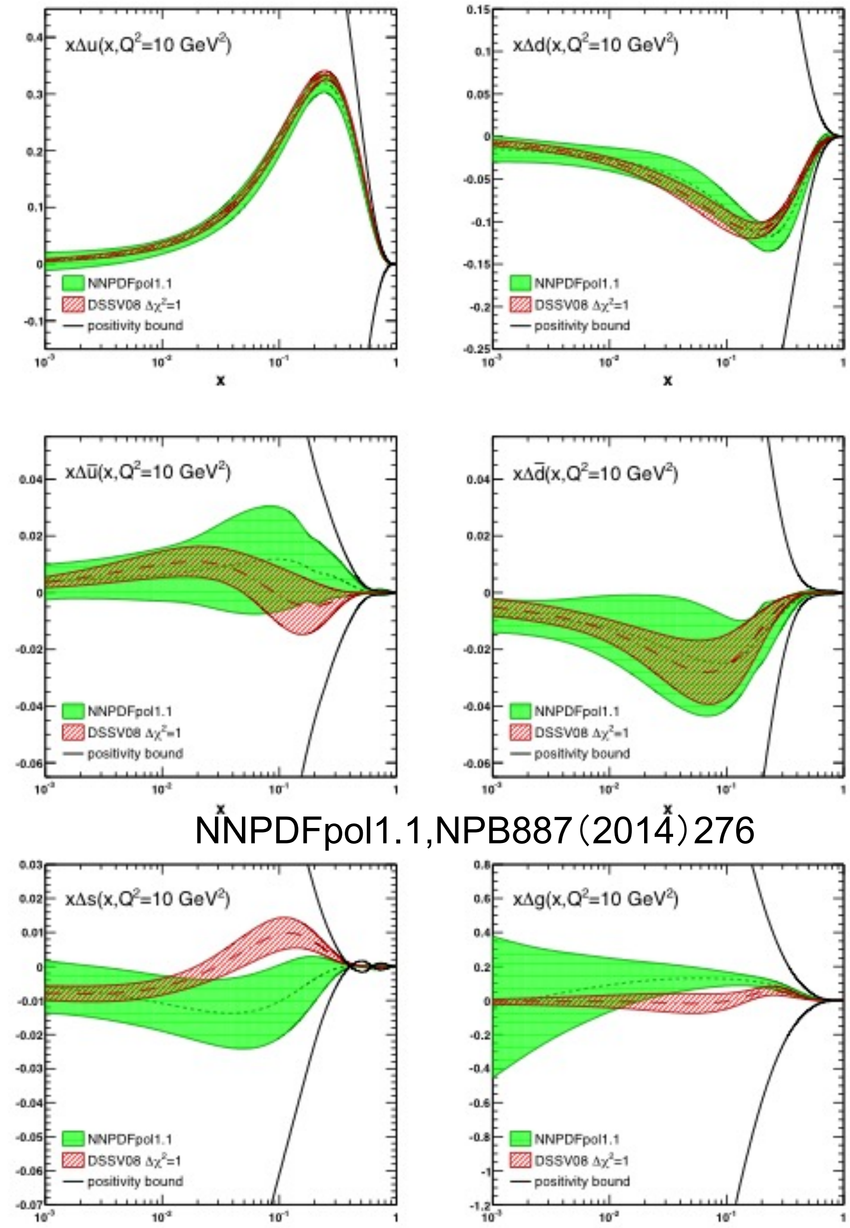



$$F_2(x) = \sum_i e_i^2 x q_i(x)$$

# Detailed knowledge on Δq(x), Δg(x)- global fit using DIS and pp data



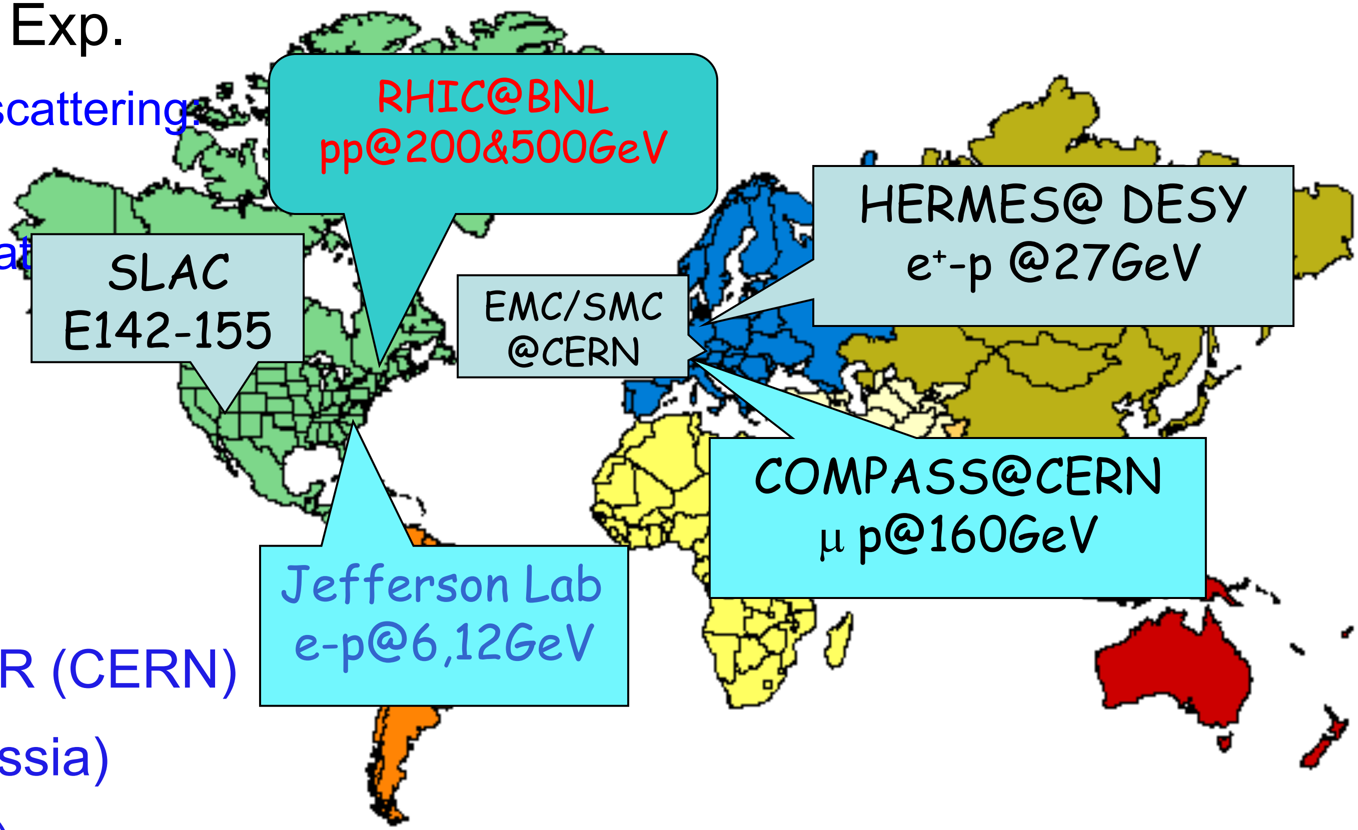

D. De Florian, R. Sassot, M. Stratmann, W. Vogelsang, PRD80(2009)



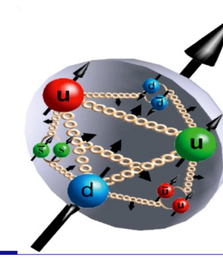

NNPDFpol1.1,NPB887（2014）276

# World efforts for spin physics

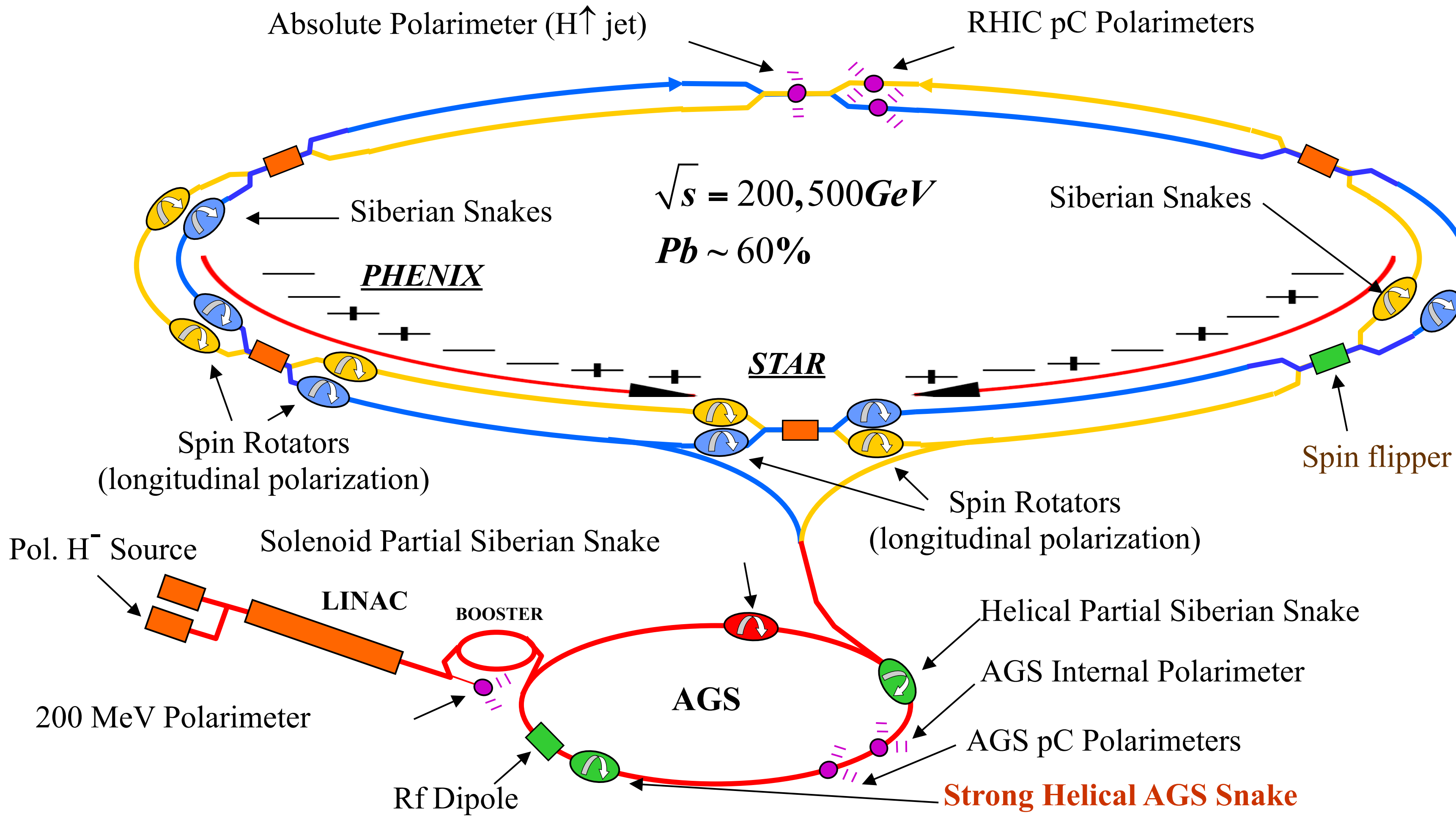
- Finished experiments: SLAC, EMC, SMC, HERMES, COMPASS
- Current running Exp.
  - Lepton-nucleon scattering: JLab
  - Proton-proton scattering: RHIC
- Future facilities
  - EIC (US)
  - EicC (China)
  - LHCspin/AFTER (CERN)
  - NICA-SPD (Russia)
  - JPARC (Japan)
  - GSI-FAIR (Germany)




**Goal:**
**Nucleon spin structure**



# RHIC- 1st polarized proton-proton collider

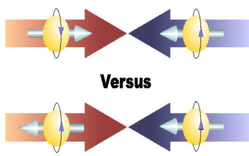



- Polarization direction changes from bunch to bunch
- Spin rotators provide choice of spin orientation

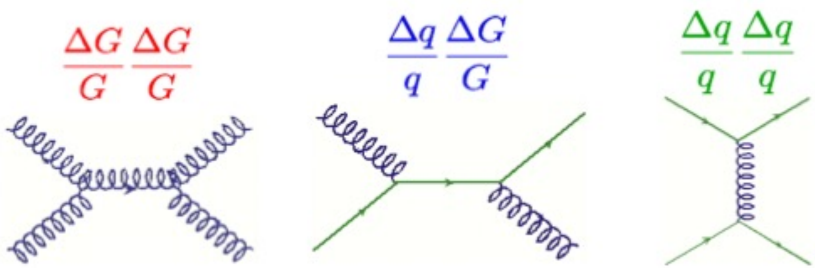
# Accessing $\Delta g(x)$ in pp collision

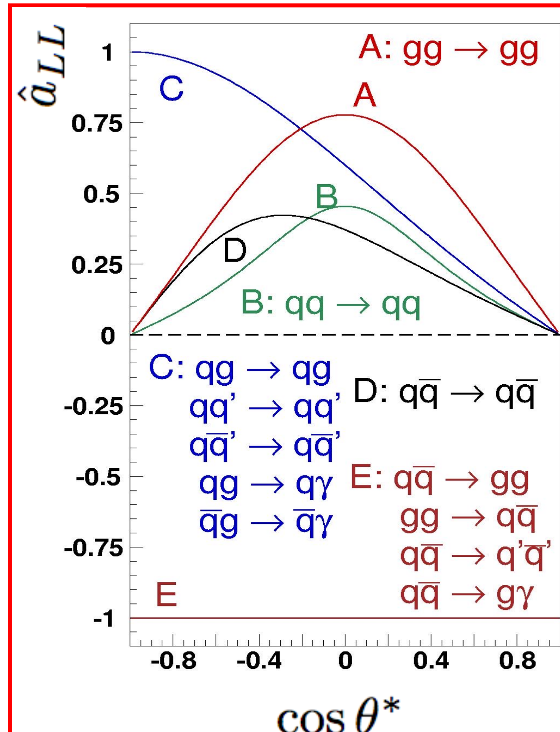
- Longitudinal spin asymmetry:

$\Delta f_1$ $\quad$ $\Delta f_2$ $\quad$ $\hat{a}_{LL} = \frac{d\Delta\hat{\sigma}}{d\hat{\sigma}}$ $\quad$ $D_f^{\pi}$



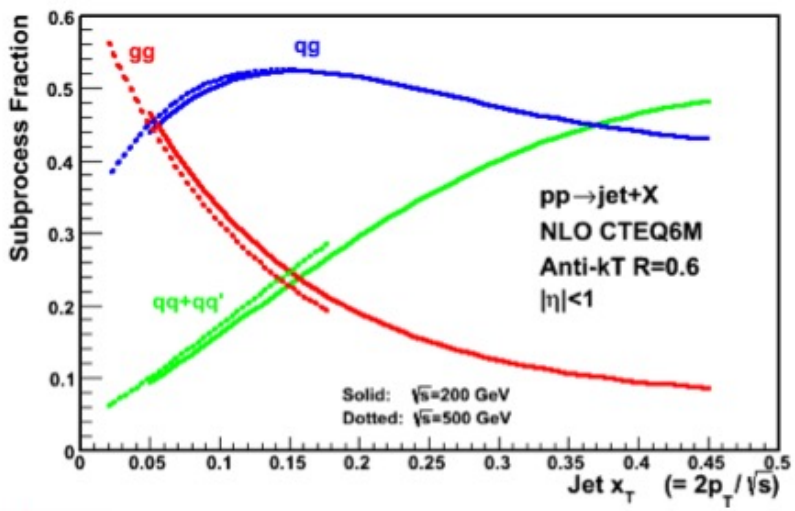

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum_{f_1,f_2} \Delta f_1 \otimes \Delta f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to f X} \cdot \hat{a}_{LL}^{f_1 f_2 \to f X} \otimes D_f^{\pi}}{\sum_{f_1,f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to f X} \otimes D_f^{\pi}}$$



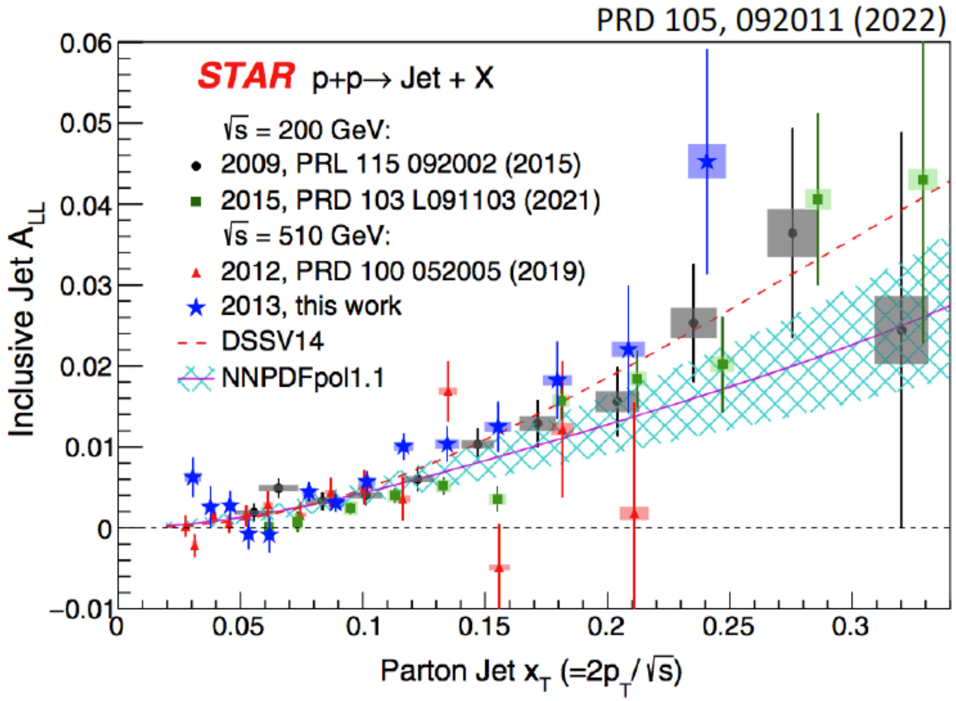

G. Bunce et al, Annu. Rev. Nucl. Part. Sci. 50, 525(2000)

- Partonic fraction for jet/$\pi^0$ production:



# $A_{LL}$ results on jet/$\pi^0$ at 510 GeV from RHIC

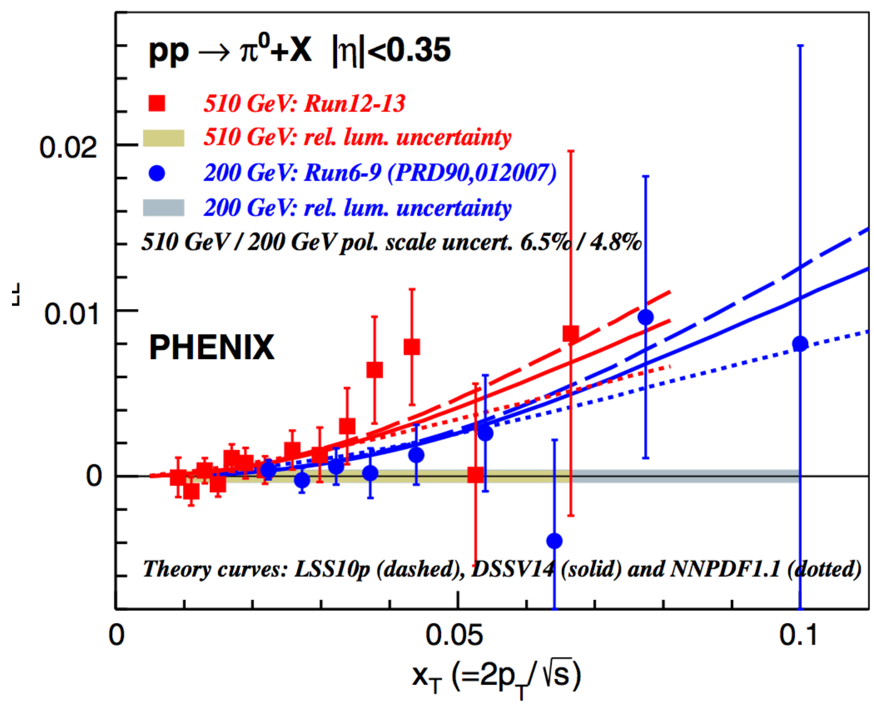
- Further measurements to improve our knowledge on $\Delta g(x)$




STAR, PRD103,91103(2021)

STAR, PRD105,92011(2022)

- ➢ STAR jet $A_{LL}$ at 510 GeV, access small x region down to x~0.015.
- ➢ Most precision $A_{LL}$ results at 200GeV from STAR 2015.



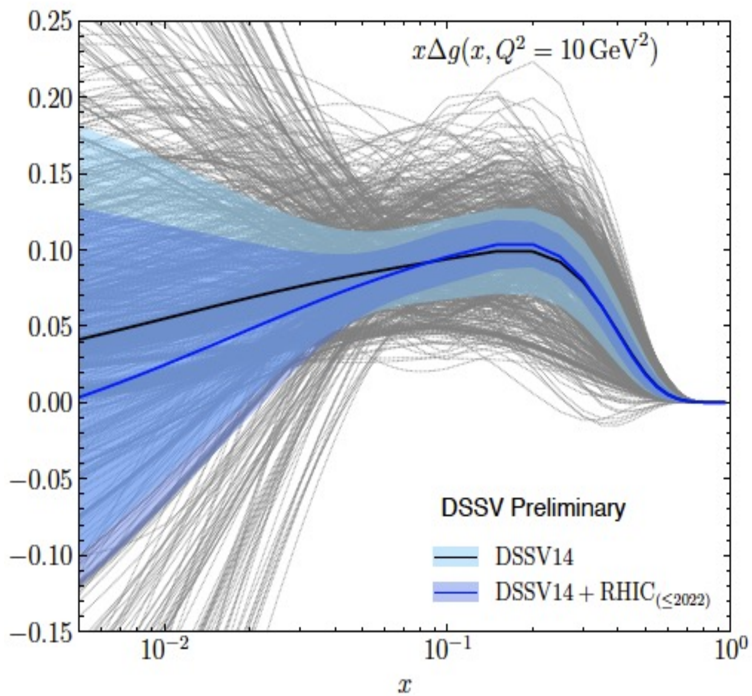

PHENIX, PRD 93, 011501 (2016)

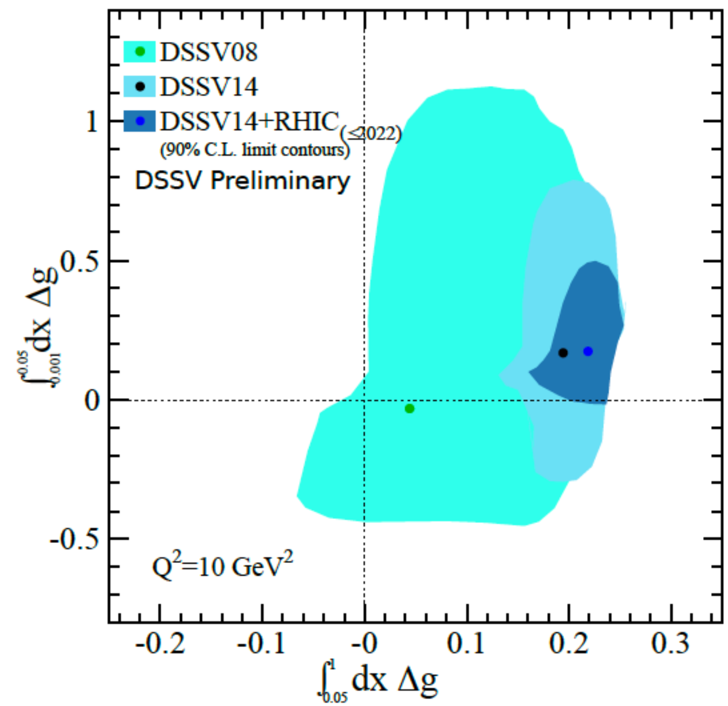
- ➢ PHENIX $\pi^0$ $A_{LL}$ at 510 GeV, which is also sensitive to $\Delta g$ in small x region

# Most recent updates from DSSV group on Δg

- The impact of RHIC 2014+ data in constraining gluon polarization Δg :

RHIC Cold QCD White paper, arXiv2302.00605




➢ 1st Lattice calculation:

$$\int_0^1 dx \Delta g(x) = 0.251 \pm 0.047(\text{stat.}) \pm 0.016(\text{syst.})$$

χQCD, PRL118,102001(2017)

$$\int_{0.05}^{1} \Delta g(x, Q^2) dx = 0.218 \pm 0.027$$

**~40% of proton spin with 8σ**

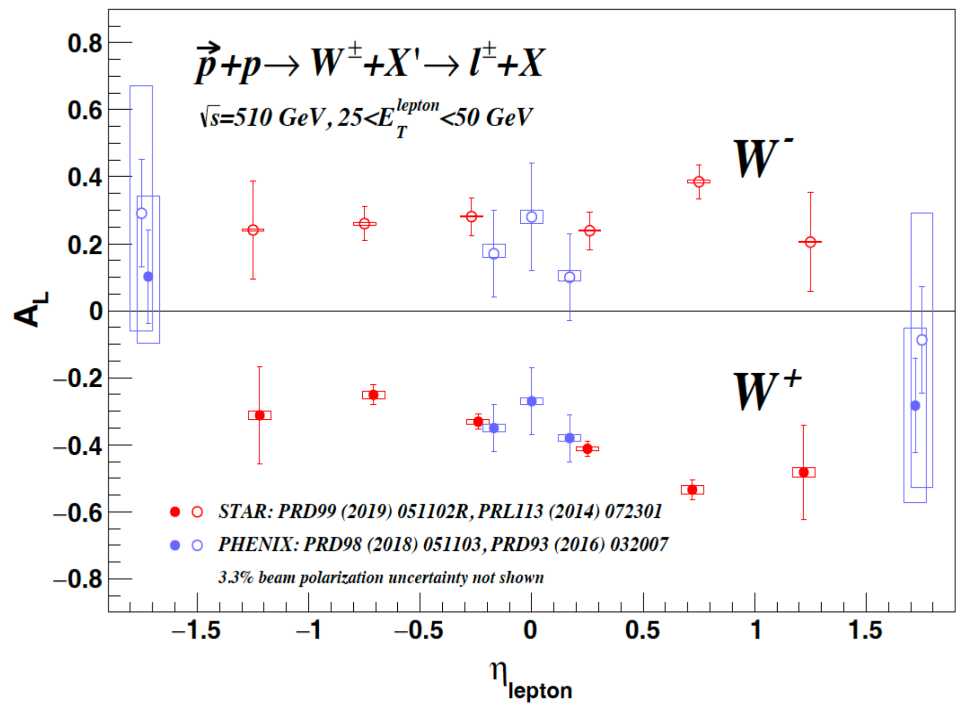
# Probing sea quark polarization via W production

- Unique quark polarimetry with W-bosons at RHIC:

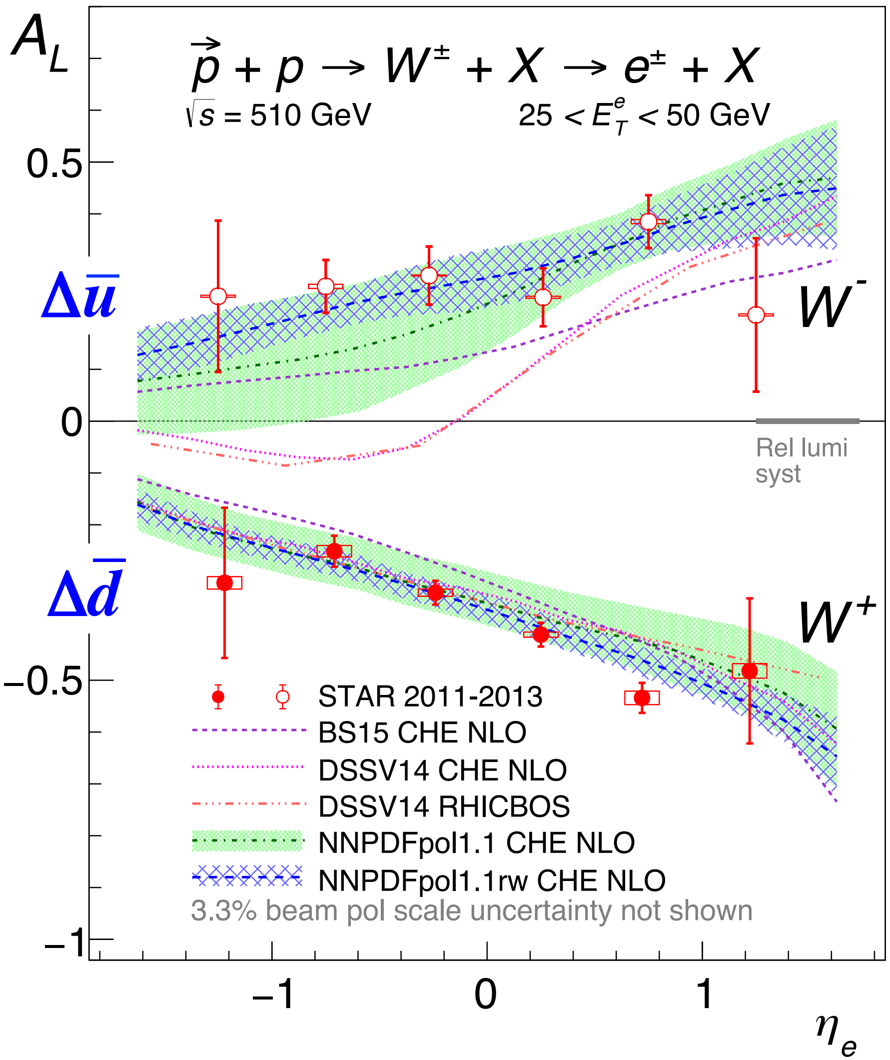
$$A_L^{W^+} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} \sim \begin{cases} -\dfrac{\Delta u(x_1)}{u(x_1)}, & y_{W^+} >> 0 \\ \dfrac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}, & y_{W^+} << 0 \end{cases}$$

$$A_L^{W^-} \sim \begin{cases} -\dfrac{\Delta d(x_1)}{d(x_1)}, & y_{W^-} >> 0 \\ \dfrac{\Delta\bar{u}(x_1)}{\bar{u}(x_1)}, & y_{W^-} << 0 \end{cases}$$

- Dedicated 500GeV p+p run at RHIC during 2011-2013
  - ➢ W-detection through high $p_T$ lepton
  - ➢ $A_L$ measurements at PHENIX and STAR



# W $A_L$ results – STAR 2013



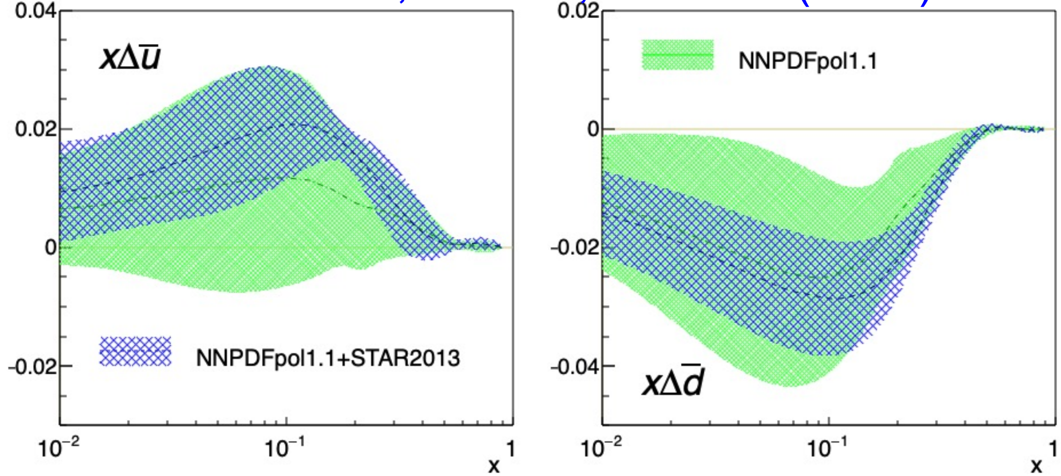

STAR, PRD99, 051102R(2019)

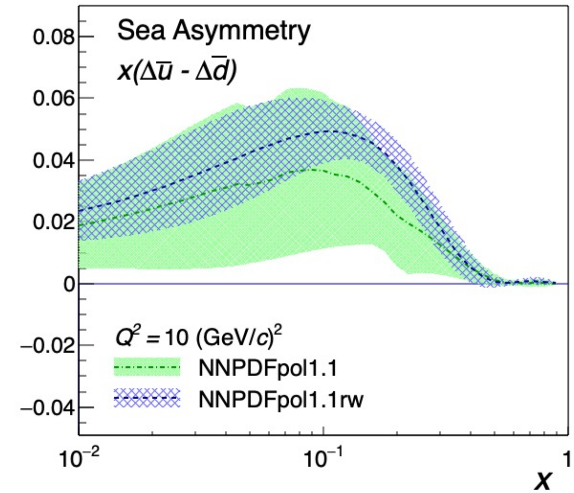
- Combined STAR 2011-2013 results in comparison with theoretical predications
- $A_L$ of $W^-$ shows indication that data are larger than the DSSV predictions
- $A_L$ of $W^+$ is consistent with theoretical predictions using global fits based on DIS data -> universality

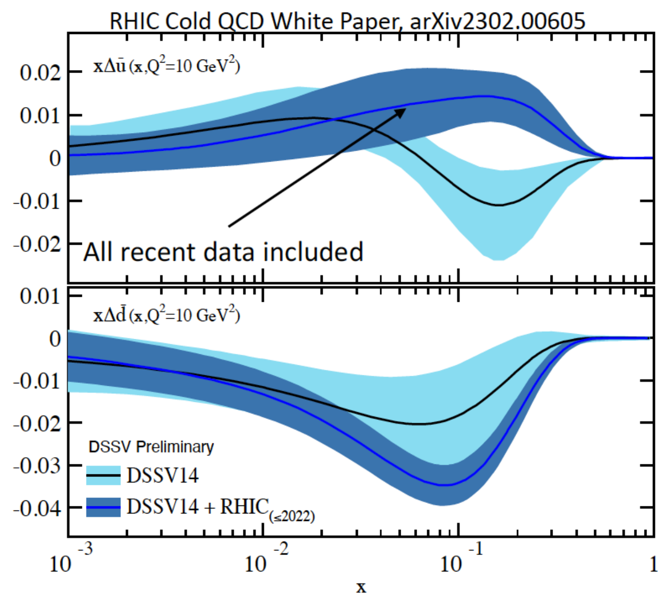
# Impact of STAR 2013 W $A_L$ results

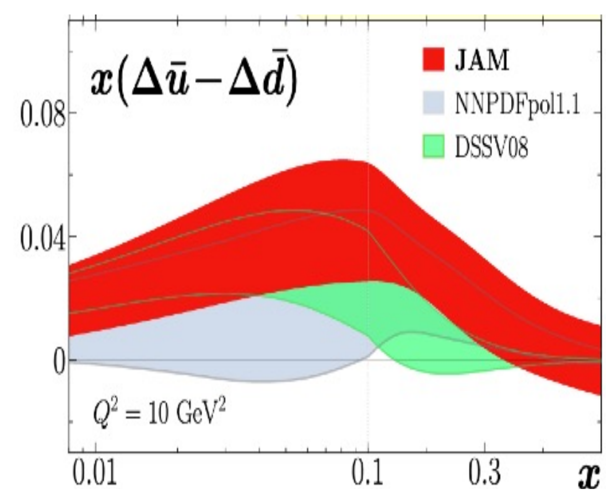
- SU(2) flavor asymmetry observed in the polarized sea quark distribution, confirmed by JAM and reweighting NNPDF, DSSV:

STAR, PRD99, 051102R(2019)




JAM, PRD106, 031502(2022)

# Impact of STAR 2013 W $A_L$ results

- SU(2) flavor asymmetry observed in the polarized sea quark distribution, confirmed by JAM and reweighting NNPDF, DSSV:

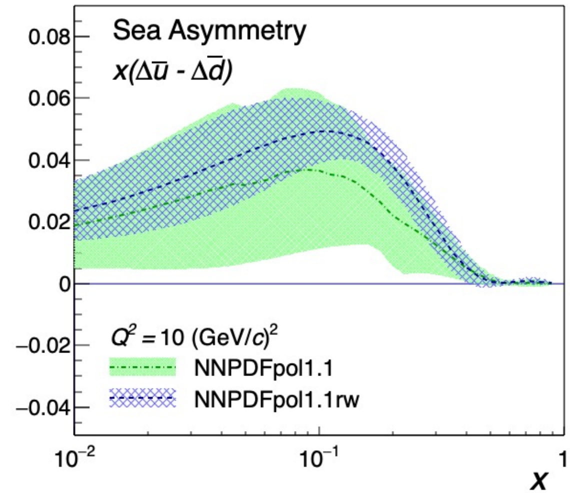
$$\Delta\bar{u} > 0 > \Delta\bar{d},\ |\Delta\bar{d}| > |\Delta\bar{u}|$$

$$\Delta_s = \Delta\bar{u} - \Delta\bar{d}$$

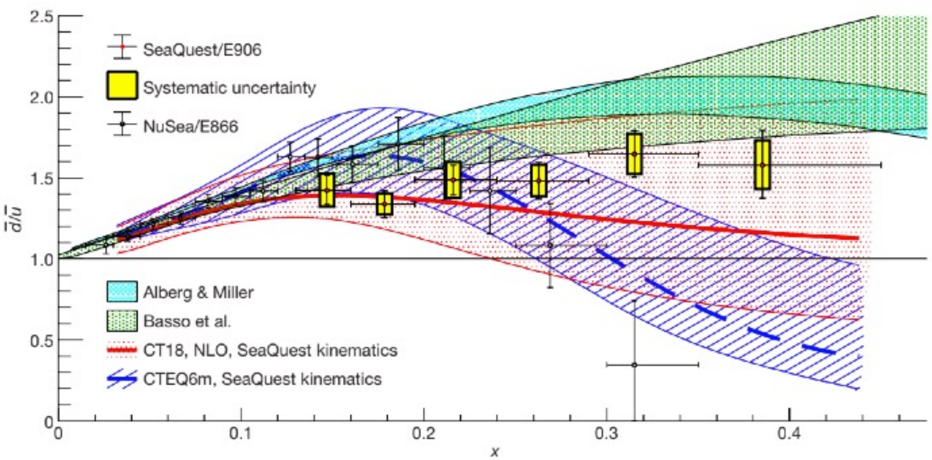
$$\int_{0.04}^{0.4} dx\, \Delta_s(x, Q^2 = 10\,\mathrm{GeV}^2) = +0.06 \pm 0.03$$

- E. Nocera @ Hadron2019

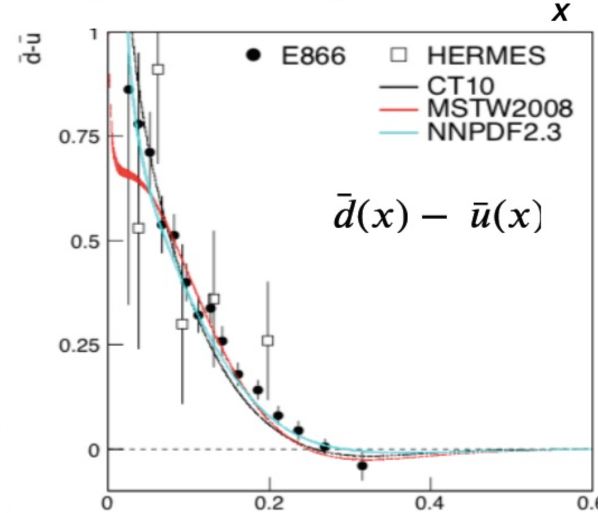
$$\rightarrow +0.07 \pm 0.01$$




- The polarized flavor asymmetry is opposite to the unpolarized case !




- SeaQuest, Nature 590, 561(2021)




- E866, PRD64, 052002(2001)
- NNPDF2.3, NPB867, 244(2013)

# Spin physics with unpolarized source ?

- Yes!  Two examples:
  - Lambda spontaneous polarization in hadron collisions
  - Global polarization in heavy ion collisions

# Self analyzing Λ polarization via weak decay

- Λ polarization can be measured in experiment via weak decay:

$\Lambda \to p\pi^-$(Br64%), $\Lambda \to n\pi^0$(Br36%) ,

-T.D.Lee, C.N.Yang(1957)

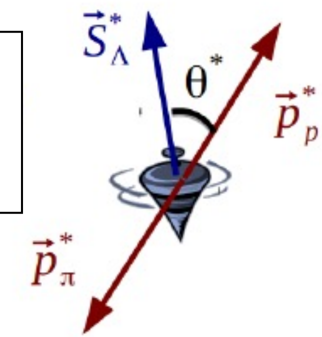
$$\frac{dN}{d\Omega} \propto 1 + \alpha\,(\vec{P}_\Lambda \cdot \hat{p}^*_p)$$

decay parameter

0.752

Λ polarization vector

Unit vector along proton momentum in Λ's rest frame.




$\Lambda \to p + \pi^+$

(BR: 63.9%, c$\tau$~7.9 cm)

- Λ's contain a strange constitute quark, whose spin is expected to carry most of the Λ spin: $|\Lambda^\uparrow\rangle = (ud)_{00}\, s^\uparrow$

- Λ polarization can serve as a powerful tool in spin physics of different field.

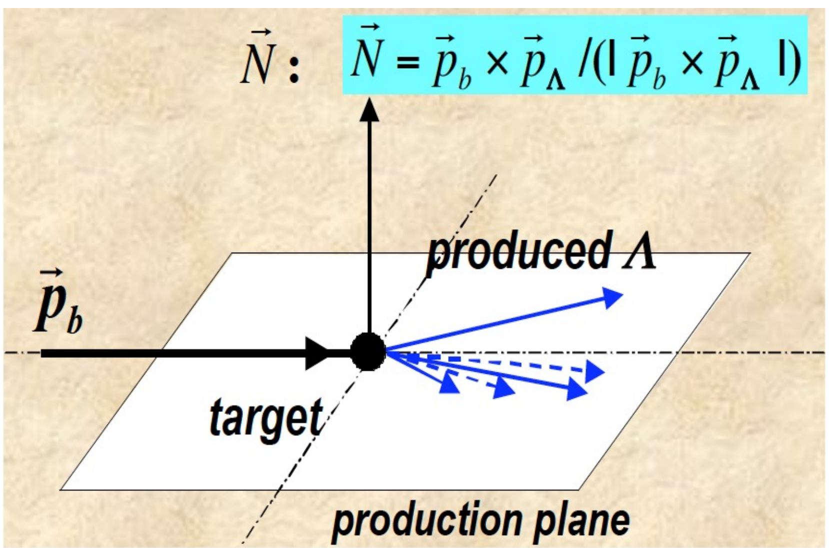
# Induced transverse Λ polarization

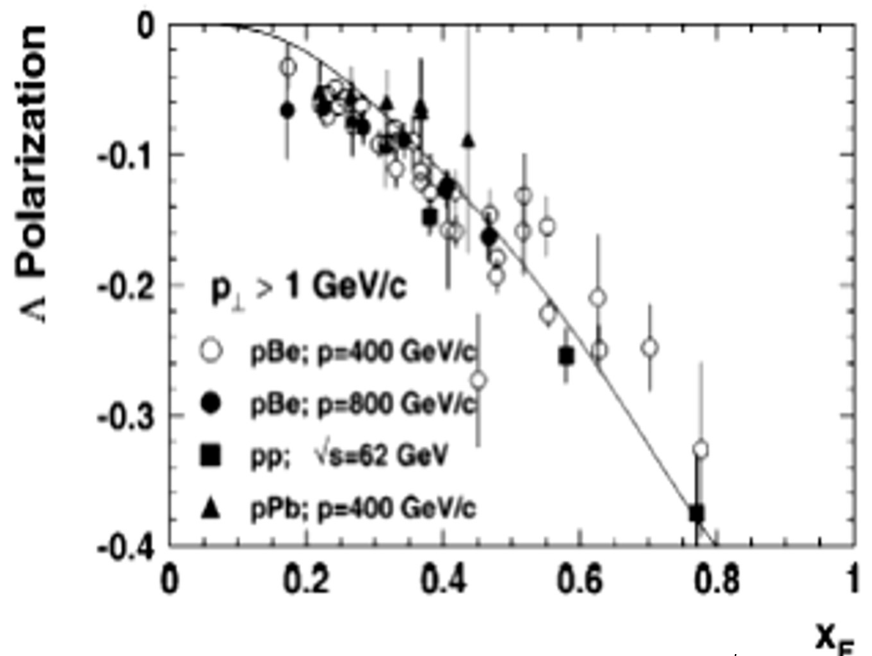
- Large polarization with unpolarized beam $p + p \to \Lambda^{\uparrow} + X$, observed in different experiments.

  -G.Bunce *et al* PRL36,1113,(1976) -583 citations, followed by 50+ measurements

- pQCD calculation ~0 ($\propto m_q$).

  Kane, Pumplin & Repko, PRL41,1689(1978).

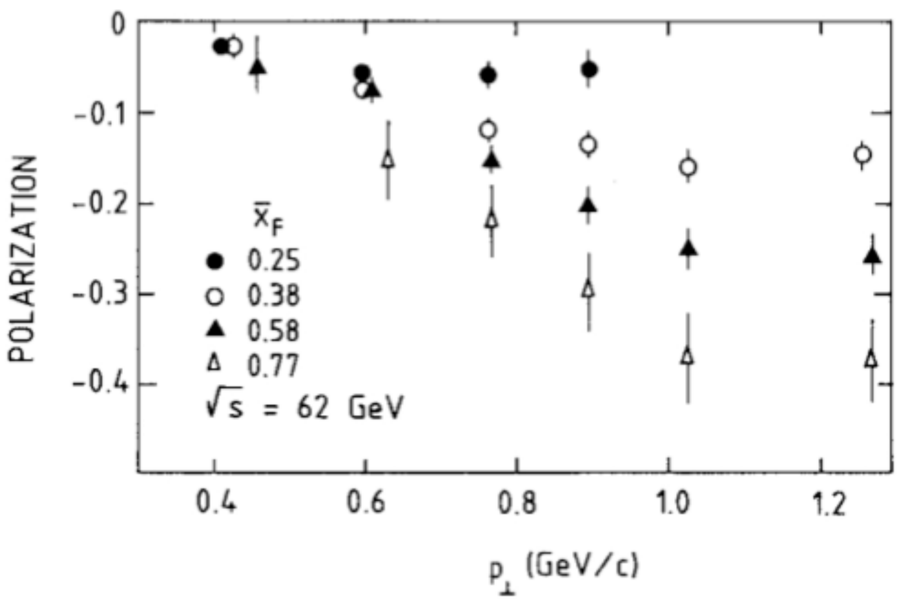


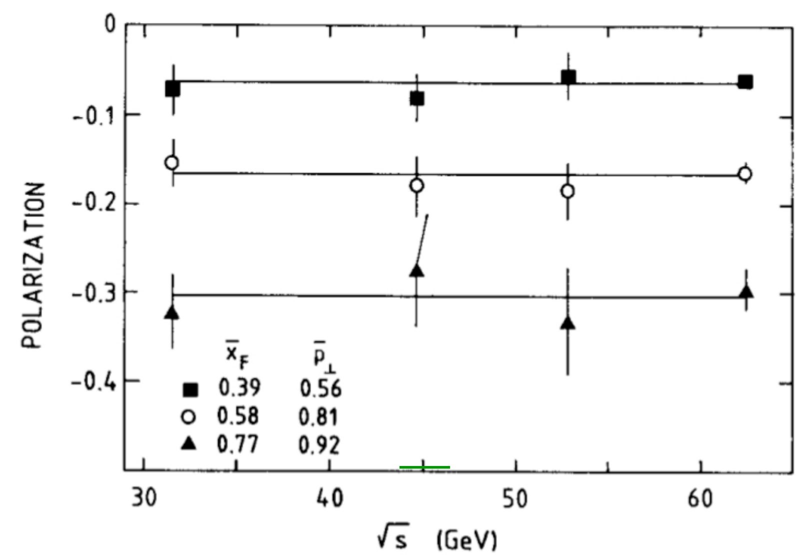




( $x_F = 2p_L/\sqrt{s}$)

# What did the data tell us?

- Polarization increase linearly with $x_{F,}$ ~40% at large $x_F$ !
- Polarization  increase with $p_\perp < 1$ GeV and saturates at  $p_\perp > 1$ GeV
- Small energy dependence ($P_b \rightarrow$12-2000 GeV)
- Anti-Lambda polarization much smaller, ~0
- Extended to Xi, Sigma polarization



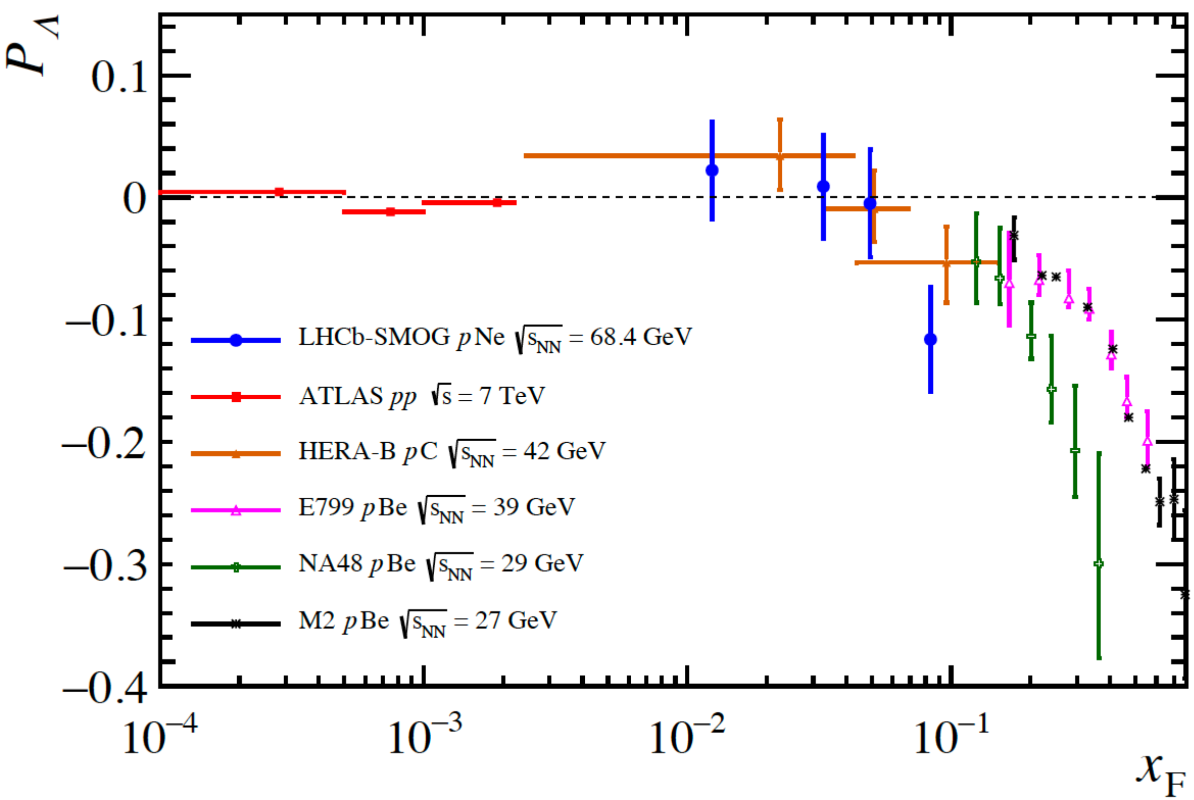



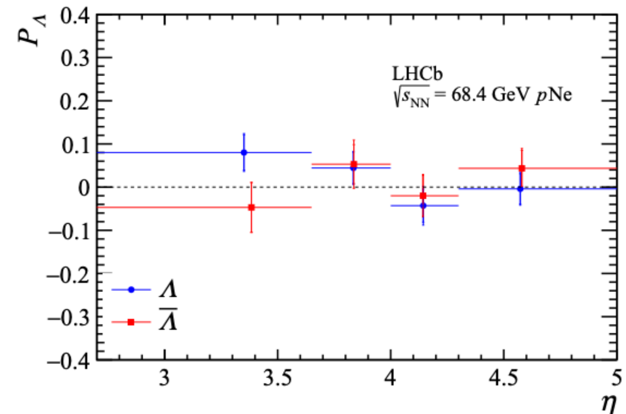

-- Data review, i.e., A.D. Panagiotou, Int.J.Mod.Phys.A 5, 1197,(1990)

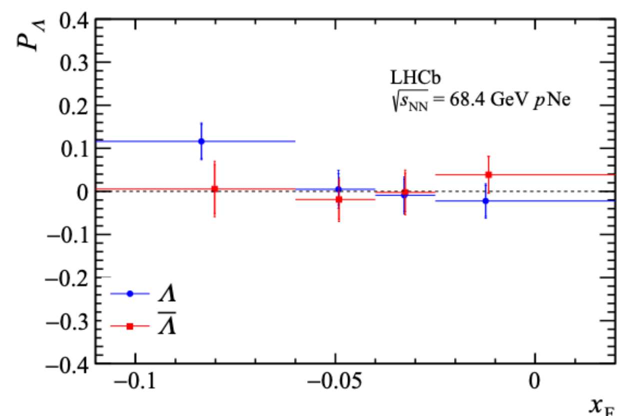
➢ More recent measurements at LHC, Belle, RHIC, JLab …

# Transverse polarization measurement of $\Lambda$ hyperons in $p$Ne collisions at $\sqrt{s_{NN}} = 68.4\,\text{GeV}$ with the LHCb detector

LHCb, JHEP09, 082 (2024)



# Theoretical understanding - history

- pQCD calculation leads to P~ 0 ($\propto \alpha_s m_q$) at parton level
- Available Models (mostly based on recombination of a $ud$ diquark from the proton and a $s$ quark from the sea):
  - ✓ Lund string fragmentation (B.Andersson et al, 1979)
  - ✓ De Grand-Mietinnen precession model (1981)
  - ✓ Angular momentum of valence quarks (Boros, Meng, Liang,1993)

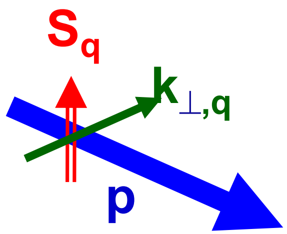
- Most models give qualitative descriptions for data with $p_T$<1GeV.
- No coherent description of all pheonomena!

-review of models by J. Felix, Mod.Phys.Lett.A 14 (1999) 827

# Theoretical understanding – QCD framework

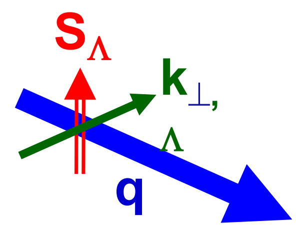
- Within QCD framework:
  - polarization originates from non-perturbative processes->

**Polarizing distribution function**




$$\leftarrow \vec{S}\cdot(\vec{p}\times\vec{k}_\perp) \rightarrow$$

**Polarizing fragmentation function**




-Boer-Mulders function : pol. parton in unpol. hadron

- Chiral odd contribution
- Boer-Mulders function

  D. Boer, P. J. Mulders,
  PRD 57, 5780303 (1998),

-pFF: unpol. parton fragment into pol. hadron

- Fit of data: M. Anselmino *et al*,
  PRD63 (2001) 054029;
- Predictions of pol. within a jet:

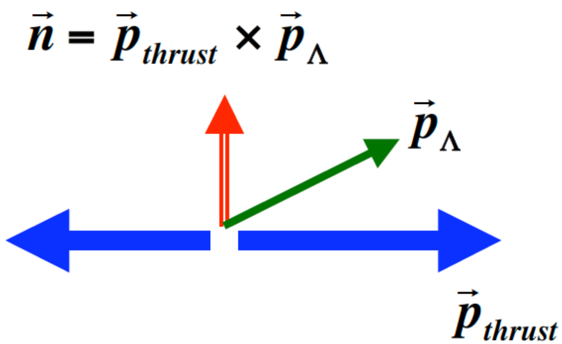
  D.Boer *et al*, PLB 659 (2008) 127.

  Z.B. Kang *et al*, PLB 809, 135756 (2020).

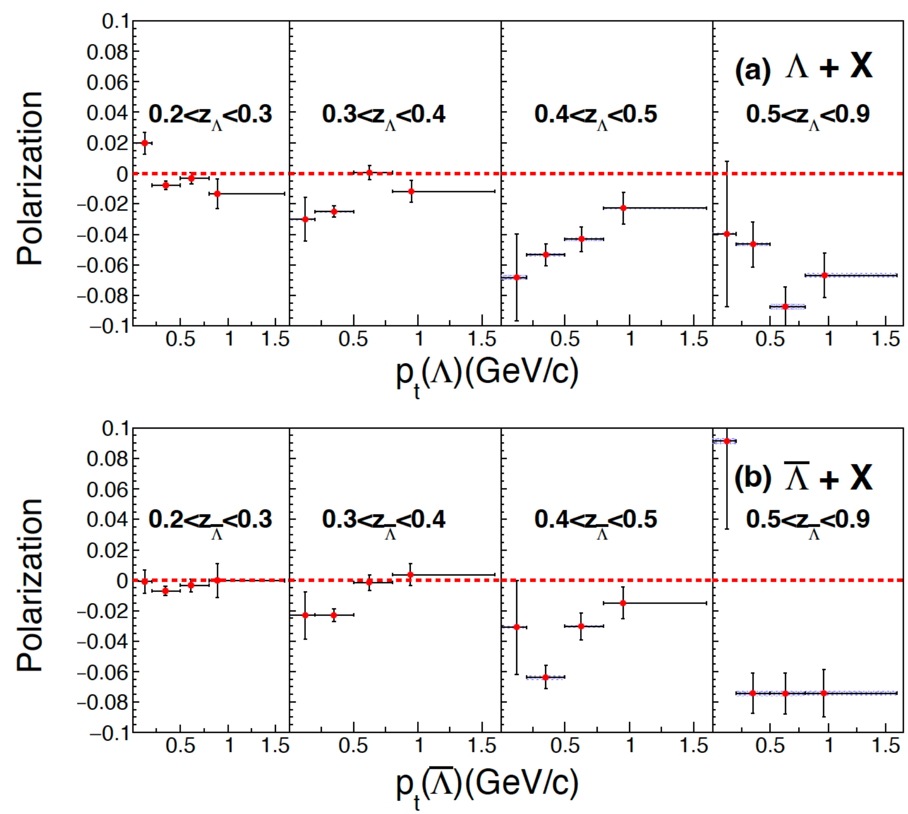
- High twist framework: high twist correlation, high twist fragmentation
  - Y. Kanazawa & Y. Koike, PRD 64, 034019 (2001).
  - J.Zhou, F.Yuan, Z.Liang, PRD78 (2008)114008;

# $\Lambda$ polarization in $e^+e^-$– study of pFF

- Belle experiment observed significant polarization of $\Lambda/\overline{\Lambda}$ transverse to $\Lambda/\overline{\Lambda}$ - thrust axis plane in unpolarized $e^+e^-$ annihilation ($\sqrt{s} = 10.6\ GeV$)




**Belle, PRL 122(2019) 042001**




**Extraction/modelling of pFF:**

U. D'Alesio, F. Murgia, M. Zaccheddu, Phys. Rev. D 102 (5) (2020) 054001

D. Callos, Z.B. Kang, J. Terry, Phys. Rev. D 102 (9) (2020) 096007

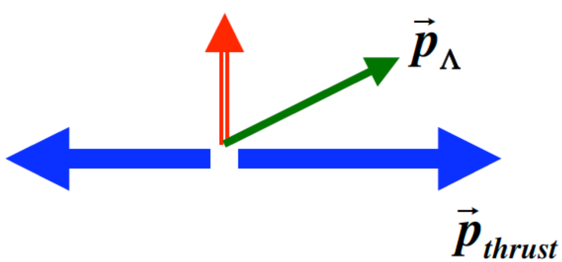
K.B. Chen, Z.T. Liang, Y.L. Pan, Y.K. Song, S.Y. Wei, Phys. Lett. B 816 (2021) 136217

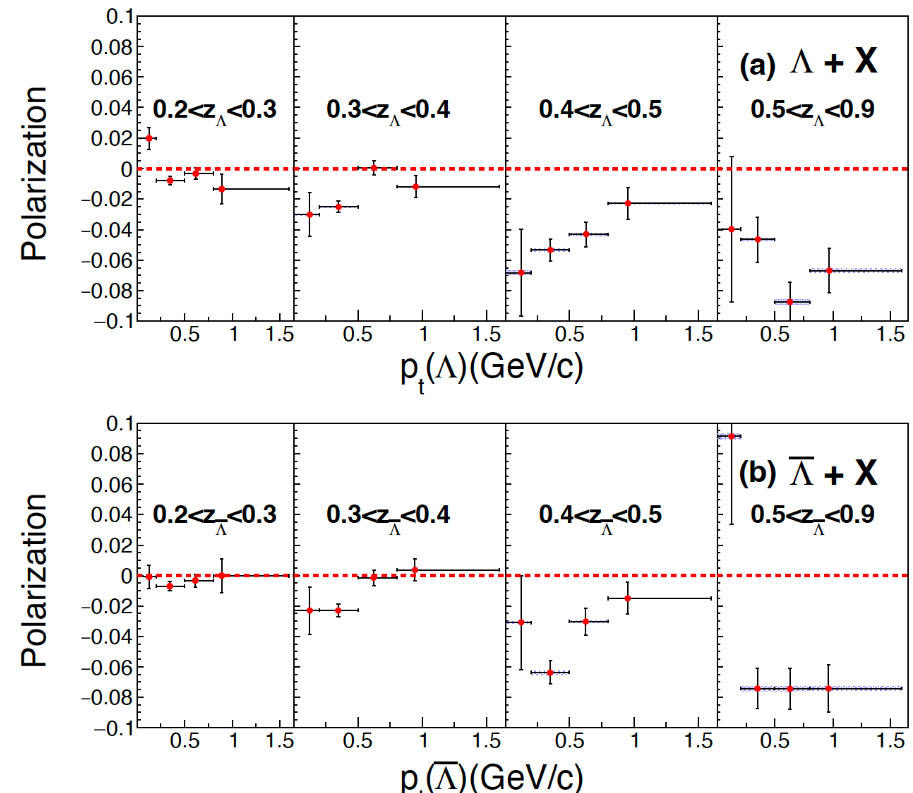
# $\Lambda$ polarization in $e^+e^-$ – study of pFF

- Belle experiment observed significant polarization of $\Lambda/\bar{\Lambda}$ transverse to $\Lambda/\bar{\Lambda}$ - thrust axis plane in unpolarized $e^+e^-$ annihilation ($\sqrt{s} = 10.6\ GeV$)

**Belle, PRL 122(2019) 042001**

$$\vec{n} = \vec{p}_{thrust} \times \vec{p}_{\Lambda}$$




- No polarization at LEP ?!

$$P_T^{\Lambda} = 0.019 \pm 0.014$$
$$P_T^{\bar{\Lambda}} = 0.015 \pm 0.014$$
(OPAL)

$$P_T^{\Lambda+\bar{\Lambda}} = 0.016 \pm 0.007$$
(ALEPH)

-ALEPH, Phys. Lett. B374, 319 (1996)

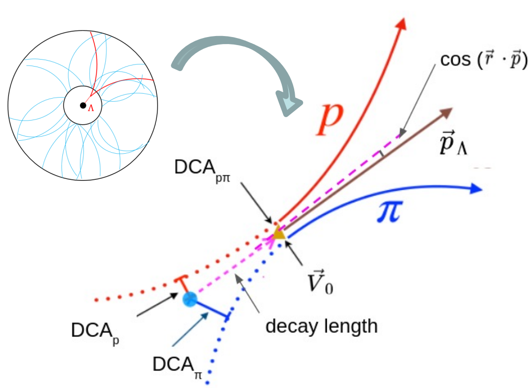
-OPAL, Eur. Phys. J. C2, 49 (1998)

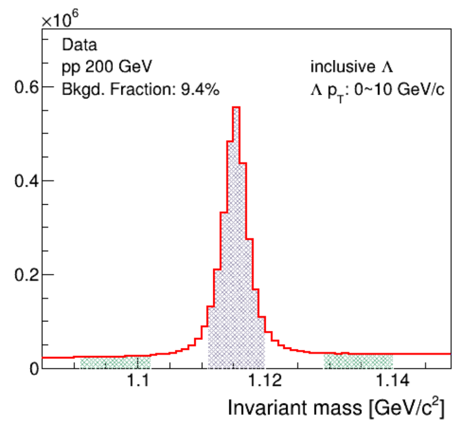
➢ Jet energy evolution effect ? $\Lambda$ pol. in jet in pp at higher jet energy at RHIC?

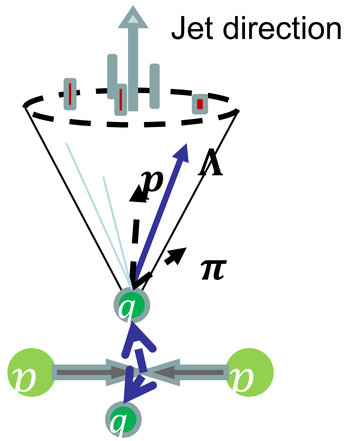
# $\Lambda$ and jet reconstruction

- $\Lambda$ reconstruction:
  - ✓ $\Lambda \rightarrow p + \pi^-$ ; $\bar{\Lambda} \rightarrow \bar{p} + \pi^+$
  - ✓ Track reconstruction and particle identification by TPC
  - ✓ Topological criteria

- Jet reconstruction
  - ✓ Anti-$k_T$ with $\mathrm{R} = 0.6$
  - ✓ Reconstructed $\Lambda, \bar{\Lambda}$ as inputs
  - ✓ Including tracks and tower energies



# Acceptance correction & polarization extraction

## Mixed events

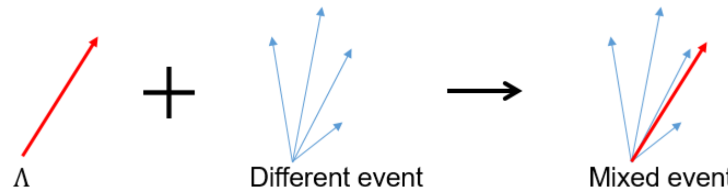
- Mixed $\Lambda$ with jet from different event
- Difference of $V_z$: $|\Delta V_z| \leq 5$ cm
- The same trigger

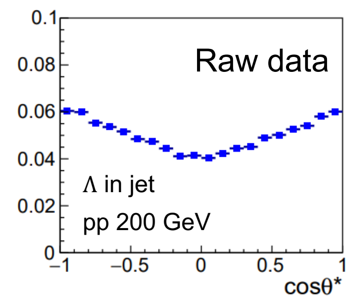
## Acceptance correction

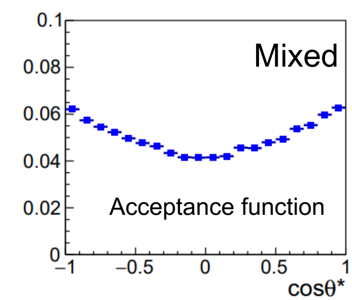
- Reweighting 3D distribution of $\Delta\eta, \Delta\phi$ between $\Lambda$ and jet, and $\eta_{\text{jet}}$
- Correction $\dfrac{N(cos\theta^*)_{Data}}{N(cos\theta^*)_{Mixed}}$

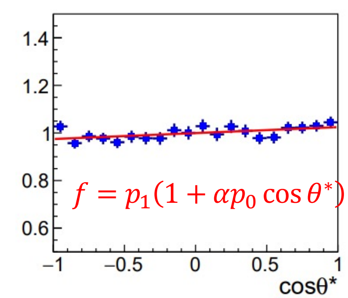
## Polarization extraction

$$\frac{dN}{d\cos\theta^*} \propto (1 + \alpha P \cos\theta^*)$$



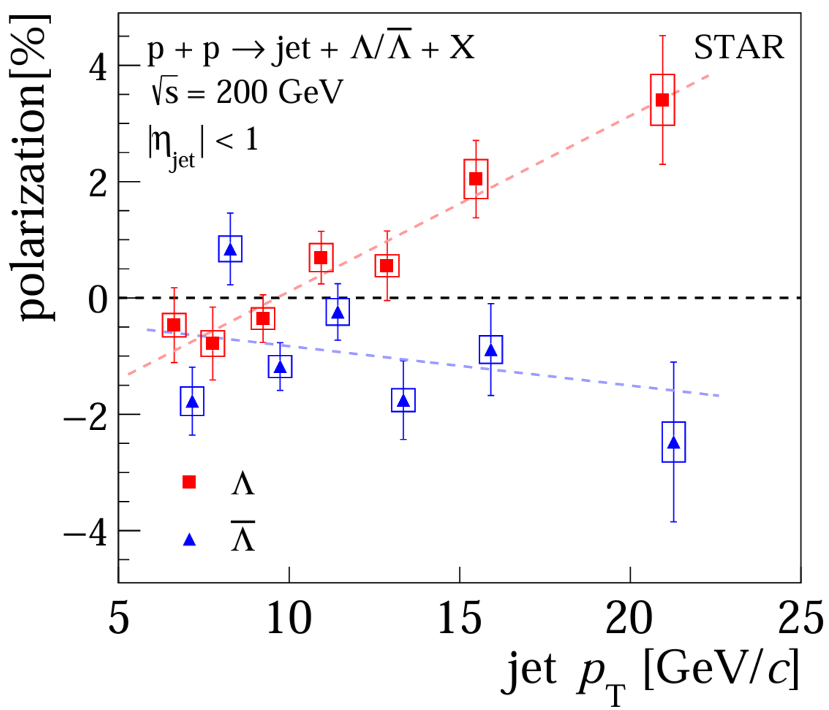



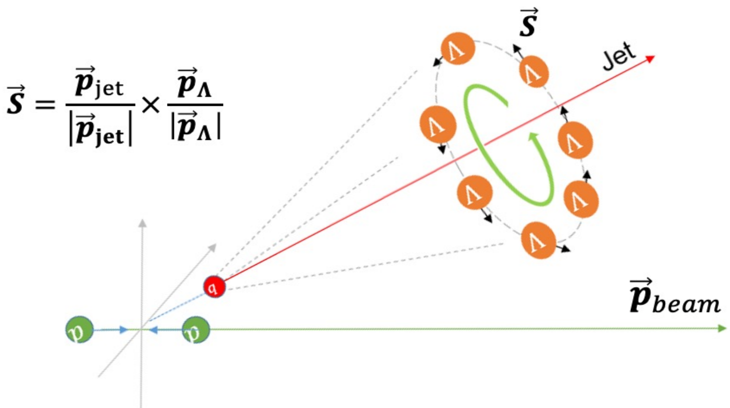



# $\Lambda$ polarization within jet in unpolarized pp collision

- $\Lambda$ polarization in jet -> polarizing fragmentation function at STAR:

*STAR,arXiv:2509.17487*




- First measurement of $\Lambda$ polarization in jet in $pp$ collisions
  - ✓ Clear jet $p_T$ dependence of $\Lambda$ polarization, indication of sign change from low to high jet $p_T$
  - ✓ $\overline{\Lambda}$ polarization mostly remains negative
  - ✓ First constraints on gluon PFF

# Comparison of 200 and 510GeV

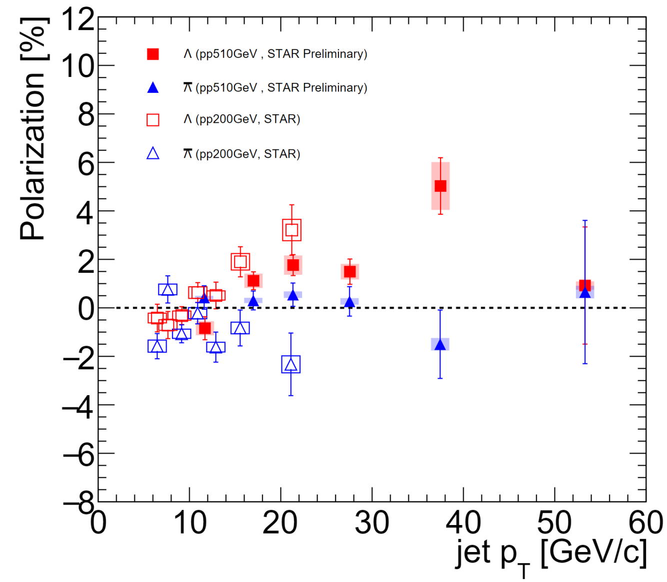
- $\Lambda$ polarization at 510 GeV consistent with the trend at $\sqrt{s}$ = 200 GeV

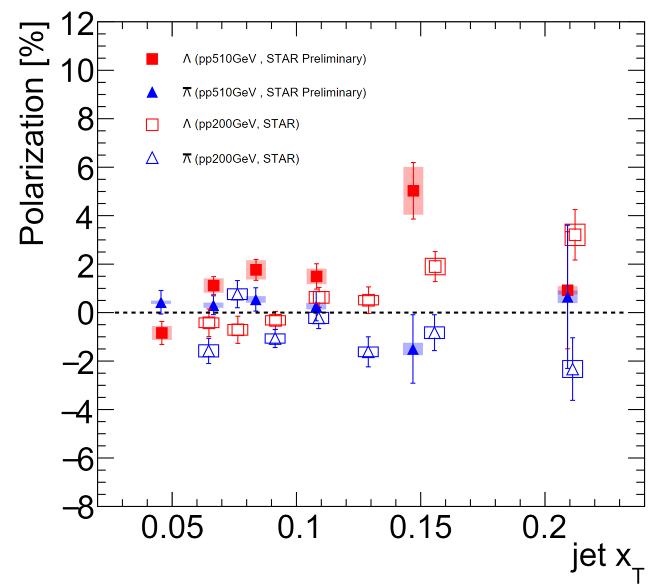
- Relative contribution from different partons is different between $\sqrt{s}$= 200 GeV and 510 GeV at same jet $p_T$

$$x_T = \frac{2p_T^{\mathbf{jet}}}{\sqrt{s}}$$

- $x_T$ approximate to the momentum fractions of scattering partons at $\sqrt{s}$ = 200 and 510 GeV

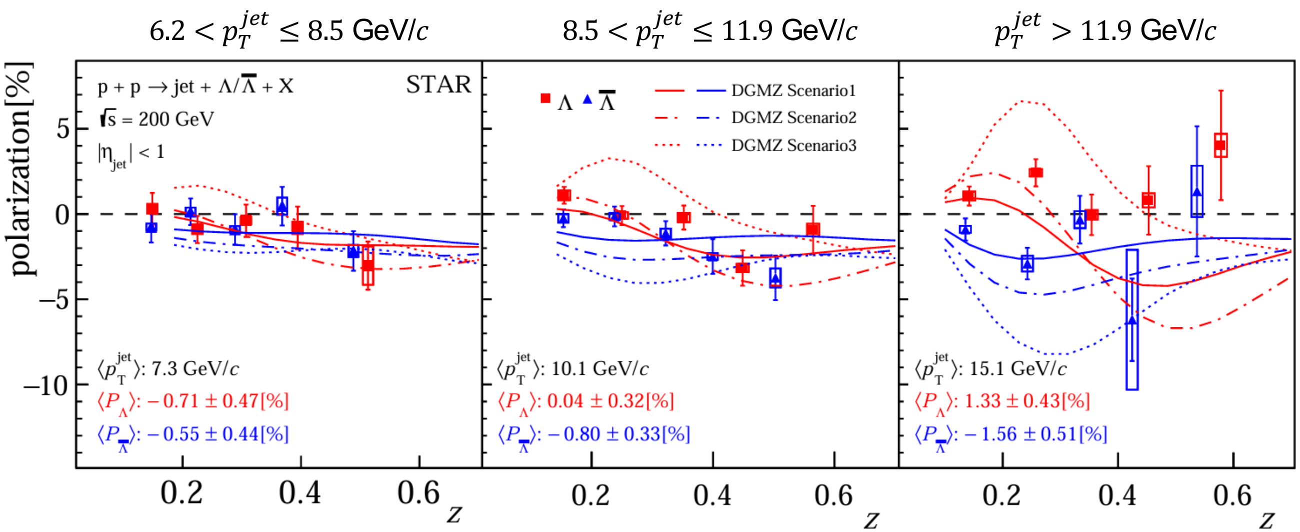
- The comparison between $\sqrt{s}$ = 200 GeV and 510GeV at same $x_T$, then reflects the scale dependence; with a factor of 2.55 difference



# Results as function of $z$

STAR,arXiv:2509.17487




## DGMZ model:

*D'Alesio, Gamberg, Murgia, Zaccheddu, Phys. Lett. B 851 (2024) 138552*

Scenario 1: Different PFF for u, d, s and their antiquarks

Scenario 2: Same as in Sc. 1 including charm in unpolarized x-section

Scenario 3: Including $SU(2)$ isospin symmetry based on Sc. 2

$z$: jet longitudinal momentum fraction carried by $\Lambda$

- Provide the first experimental constraints for PFF from $pp$ collisions
- Possible $z$ dependences are observed at different jet $p_T$ ranges
- Sizeable agreement between data and model, untill high jet $p_T$ range

# Electron-Ion Collider (EIC)

- **EIC Project Design Goals:**

✓ High Luminosity: L= $10^{33}$ – $10^{34}$ $cm^{-2}s^{-1}$, 10～100 $fb^{-1}$/year

✓ Highly Polarized Beams: 70%

✓ Large Center of Mass Energy Range: $E_{cm}$ = 20 – 140 GeV

✓ Large Ion Species Range: protons – Uranium

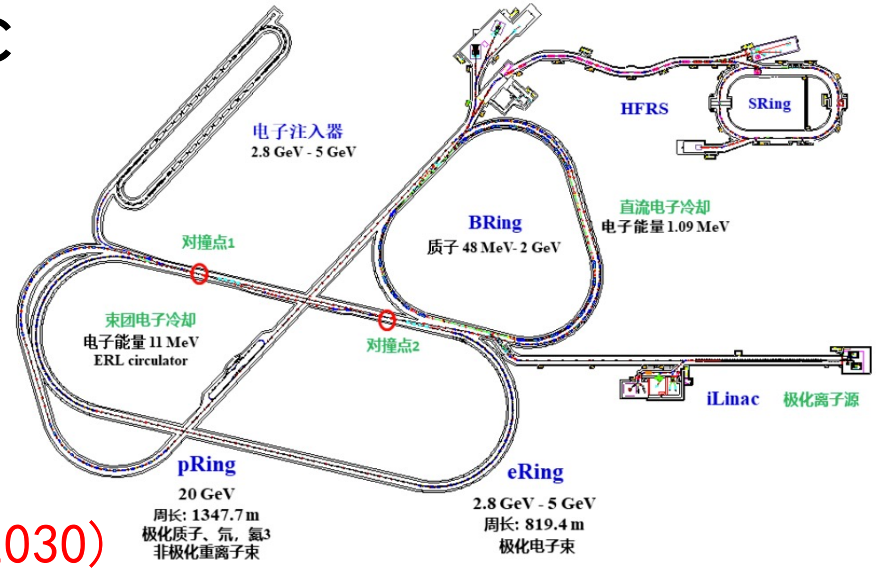
✓ Large Detector Acceptance

✓ Accommodate a Second Interaction Region (IR)


- EIC will be built at Brookhaven National Laboratory in ～2030+

# Electron-ion collider China(EicC)

- **中国的电子-离子对撞机计划EicC**
  - ✓ 电子能量2.8～5GeV
  - ✓ 质子/核能量～20GeV
  - ✓ 中等能区、高亮度
  - ✓ 与美国EIC物理互补
  - ✓ 中英文白皮书已发布
  - ✓ 基于兰州所HIAF装置(惠州,～2030)



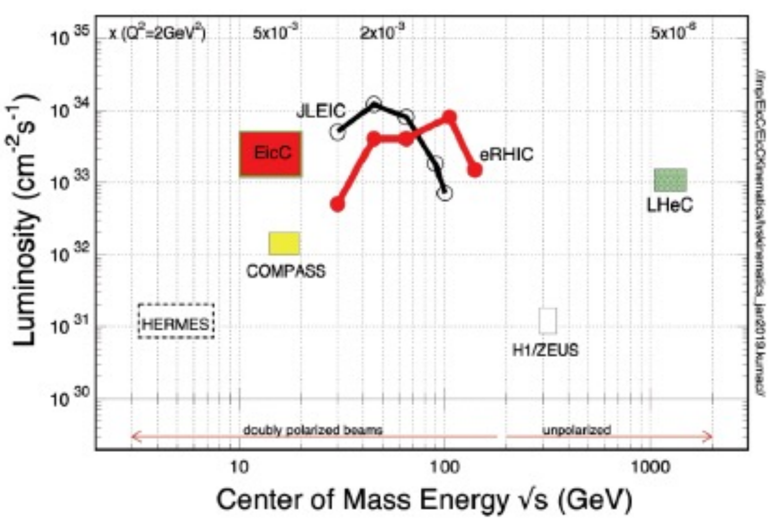
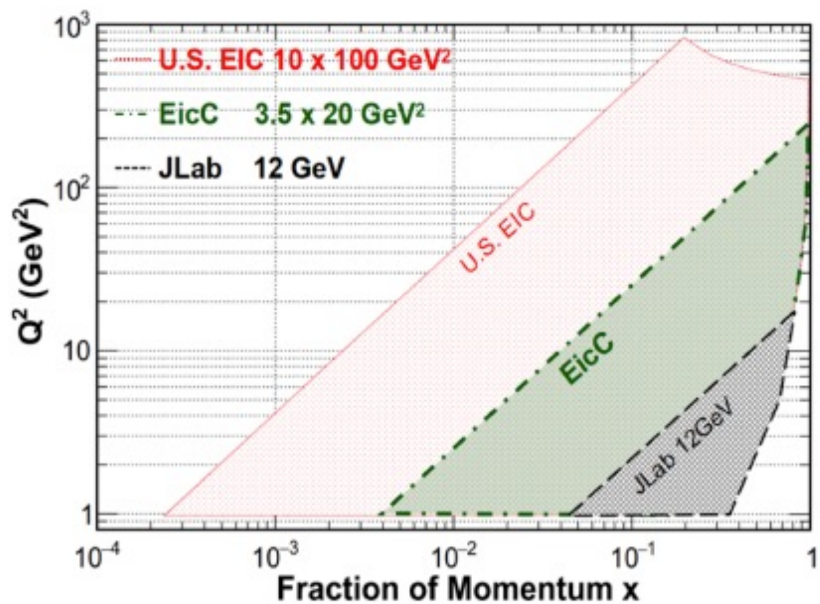




图 1.4: 国际上电子离子装置（包括拟建）亮度和质心系能量比较。



# Summary -I

- Concept of spin
- Spin structure of nucleon – fundamental question in QCD
- Polarized deep inelastic scattering
- Studying nucleon spin structure at RHIC
- Hyperon polarization in unpolarized hadron-hadron collision