WG6: Spin and 3D structure
Summary

Yoshitaka Hatta, Kenichi Nakano, Sanghwa Park

Apologies for omissions and inaccuracies…

WG6: Scope

Spin
- Longitudinal spin – sum rules, gluon helicity
- Transverse spin – transversity, single spin asymmetry

3D structure
- TMD – sign flip, linearly polarized gluon, fragmentation function
- GPD – Ji sum rule, twist three

18 theory talks, 15 experimental talks,
two joint sessions (with WG1 and WG7)

Longitudinal spin

The proton spin problem

Jaffe-Manohar decomposition

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L^q + L^g$$

Quarks' helicity

Gluons' helicity

Orbital angular Momentum

Quark helicity reasonably constrained $\Delta\Sigma = 0.25 \sim 0.3$

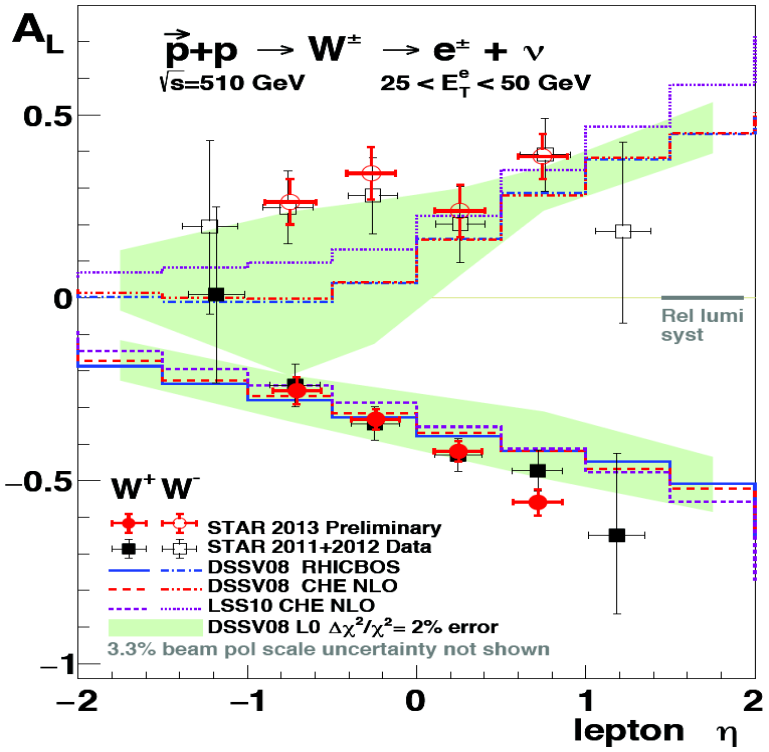
Gluon helicity nonzero!
But the uncertainty in the small-x is huge, need more effort

Little is known about orbital angular momentum

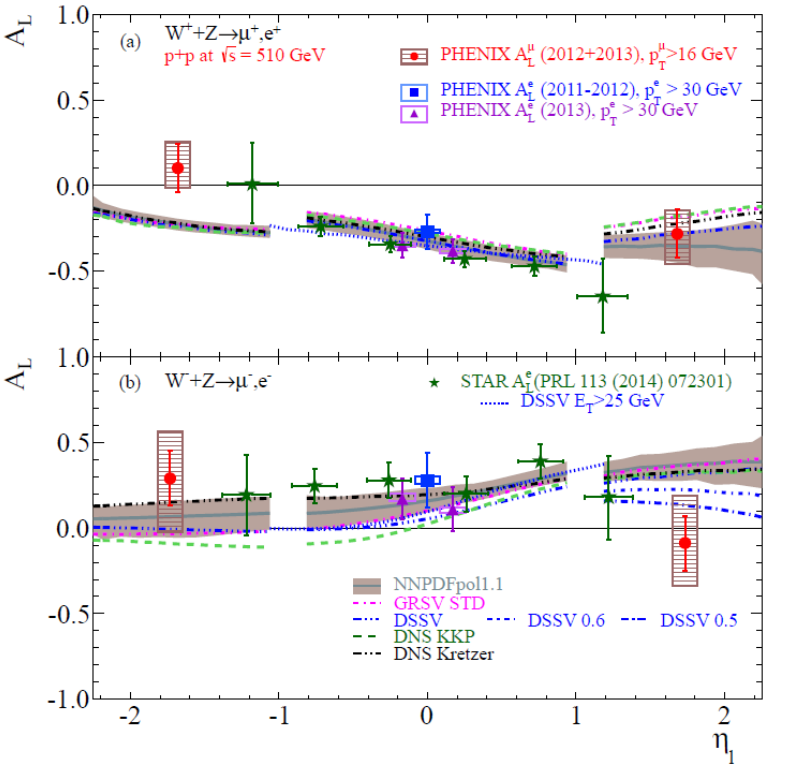
Longitudinal Single-Spin Asymmetry of W in pp at RHIC

Determination of $\Delta\bar{d}$ $\Delta\bar{u}$

B. Surrow



C. Kim

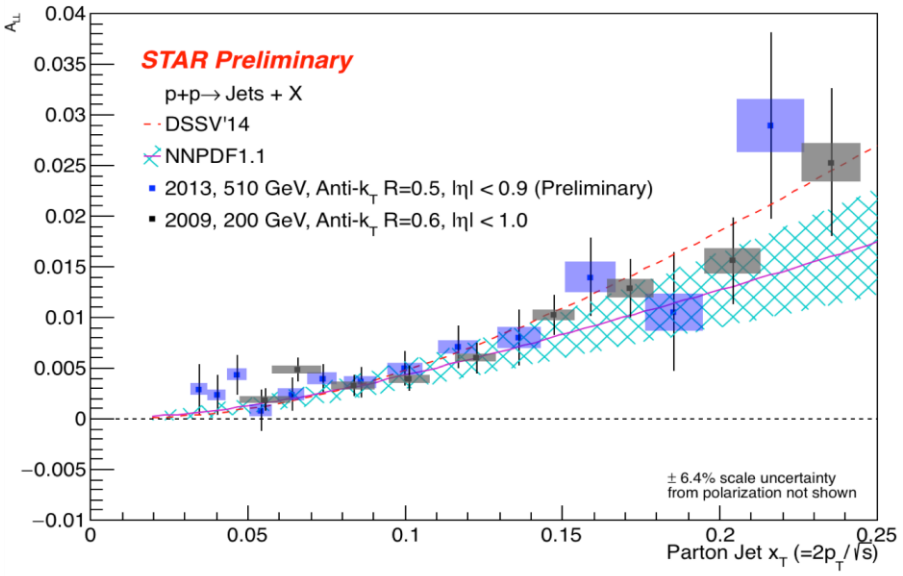


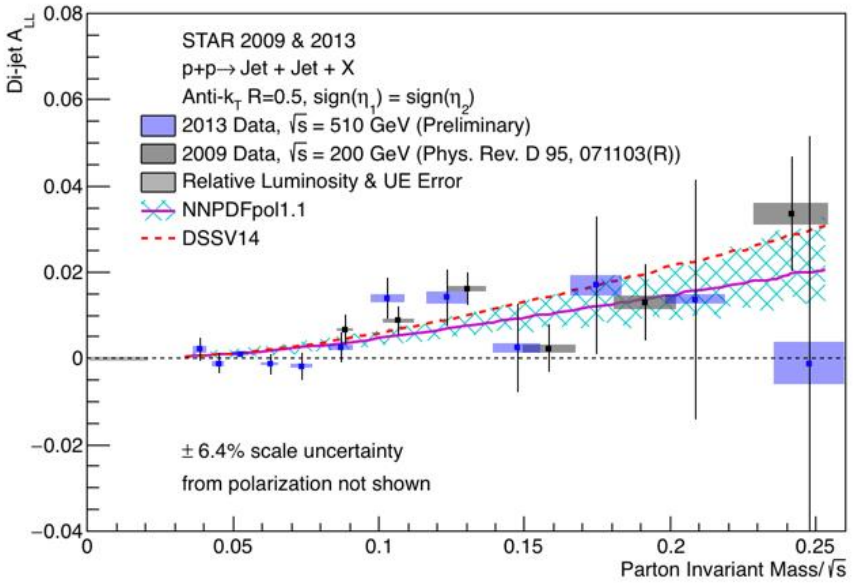
Improved accuracy with latest datasets & better W identification.
Also the ratio $\bar{d}/\bar{u}$ can be determined from STAR measurement of W^+/W^- ratio.

Gluon Polarization via Jets in pp at RHIC

Double helicity asymmetry A_{LL} of inclusive jets & di-jets at 200 & 510 GeV by STAR & PHENIX

A. Quintero
Z. Chang
M. Patel





Improved accuracy with latest datasets & better jet reconstruction.
Inclusive hadron (e.g. pion) productions were measured also.

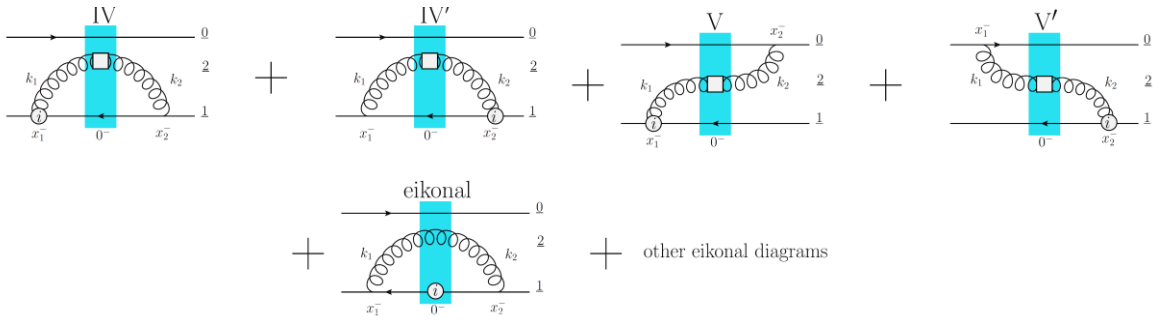
Helicity evolution at small-x

M. Sievert

Small-x evolution of the polarized dipole

$$G(x_{10}^2,z)=G^{(0)}(x_{10}^2,z)+\frac{\alpha_s N_c}{2\pi}\int\limits_{\frac{1}{x_{10}^2 s}}^{z}\frac{dz'}{z'}\int\limits_{\frac{1}{z's}}^{x_{10}^2}\frac{dx_{21}^2}{x_{21}^2}\left[\Gamma(x_{10}^2,x_{21}^2,z')+3G(x_{21}^2,z')\right]$$

$$\Gamma(x_{10}^2,x_{21}^2,z')=G^{(0)}(x_{10}^2,z')+\frac{\alpha_s N_c}{2\pi}\int\limits_{\frac{1}{x_{10}^2 s}}^{z'}\frac{dz''}{z''}\int\limits_{\frac{1}{z''s}}^{\min[x_{10}^2,x_{21}^2\frac{z'}{z''}]}\frac{dx_{32}^2}{x_{32}^2}\left[\Gamma(x_{10}^2,x_{32}^2,z'')+3G(x_{32}^2,z'')\right]$$



Resumption of double logarithms $\alpha_s \ln^2 \frac{1}{x}$ ➡ $\Delta f(x) \sim \left(\frac{1}{x}\right)^{\alpha_h}$

$$\alpha_h^{q,S}=\frac{4}{\sqrt{3}}\sqrt{\frac{\alpha_s N_c}{2\pi}}$$

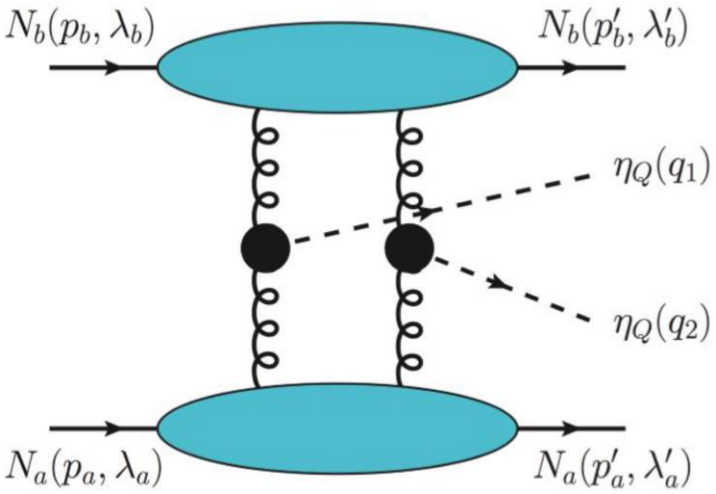
$$\alpha_h^{q,NS}=\sqrt{2}\sqrt{\frac{\alpha_s N_c}{2\pi}}$$

$$\alpha_h^{G}=\frac{13}{4\sqrt{3}}\sqrt{\frac{\alpha_s N_c}{2\pi}}$$

Parton orbital angular momentum

Double η_c - production in pp

S. Bhattacharya



$$\frac{1}{2}(\tau_{XY} - \tau_{YX})$$

$$\approx \quad 2\,\mathrm{Re}\left\{ -\frac{1}{M^2}\left(\varepsilon_\perp^{ij}\Delta q_\perp^i \Delta_{a\perp}^j\right) C\left[\vec{\beta}_\perp \cdot \vec{k}_{a\perp} F_{1,4}\right.\right.$$

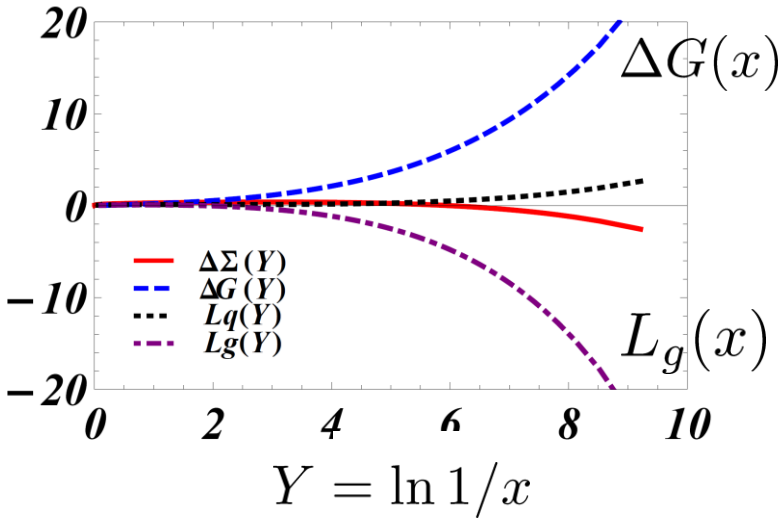
Moment of $F_{1,4}$

→ Gluon orbital angular momentum

Y. Hatta

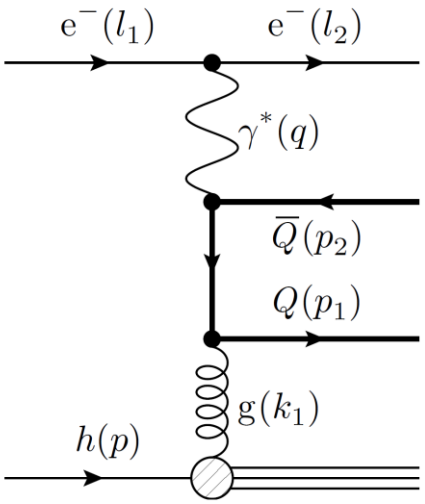
`DGLAP' evolution of OAM density $L_g(x)$

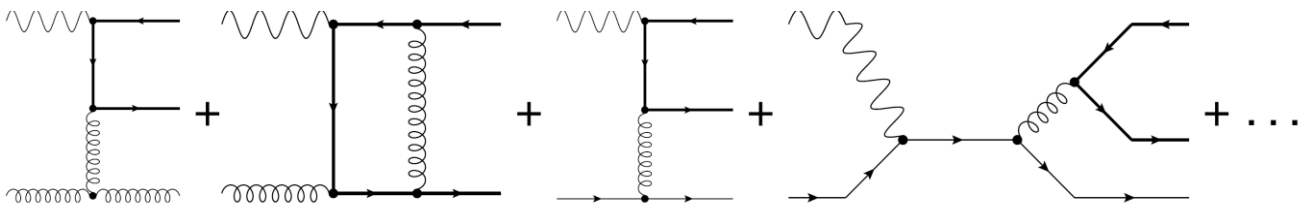
$L_g(x) \approx -\Delta G(x)$ at small-x



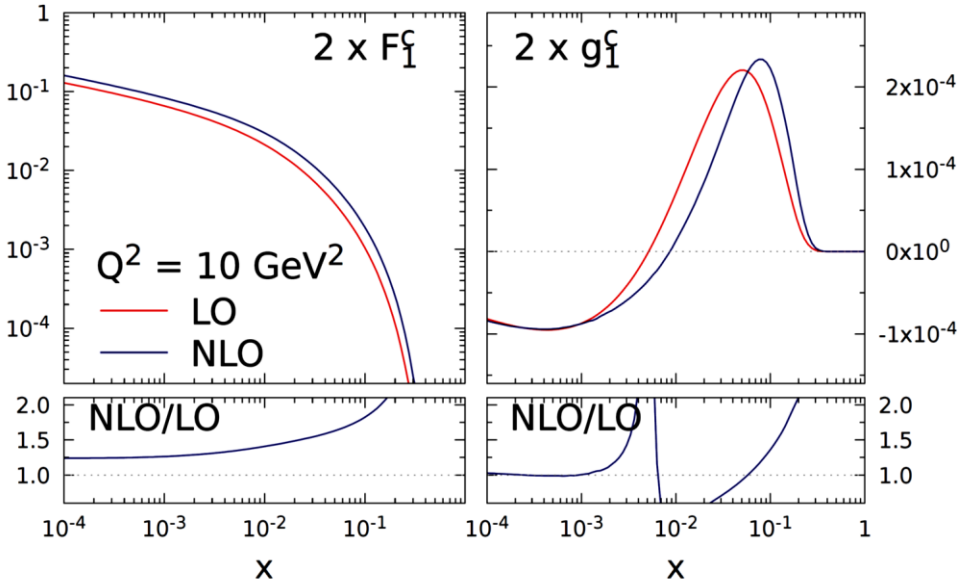
NLO heavy-flavor production in polarized DIS

F. Hekhorn





Full NLO analytical calculation.
NLO corrections large, both for unpolarized/polarized

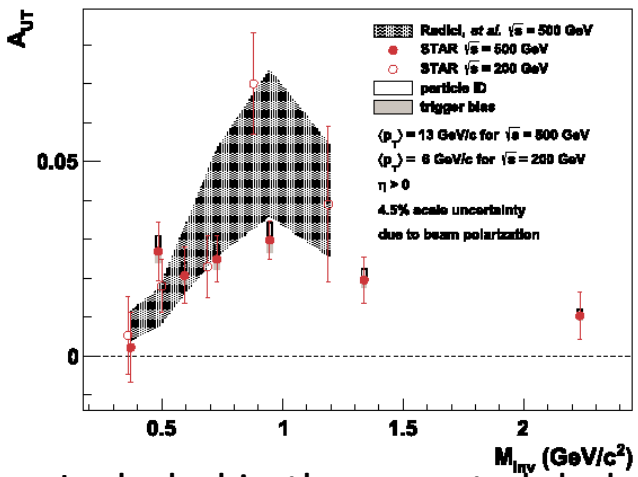


Transverse spin

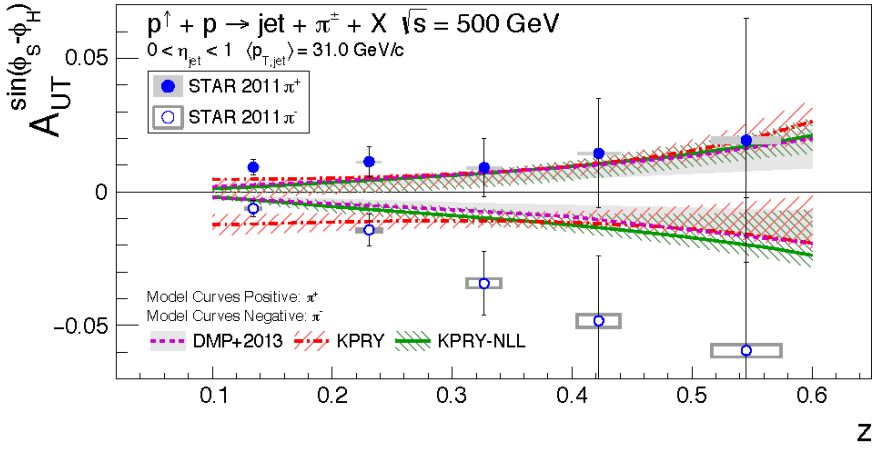
Transversity

C. Gagliardi

- STAR: Transversity via IFF and Collins FF



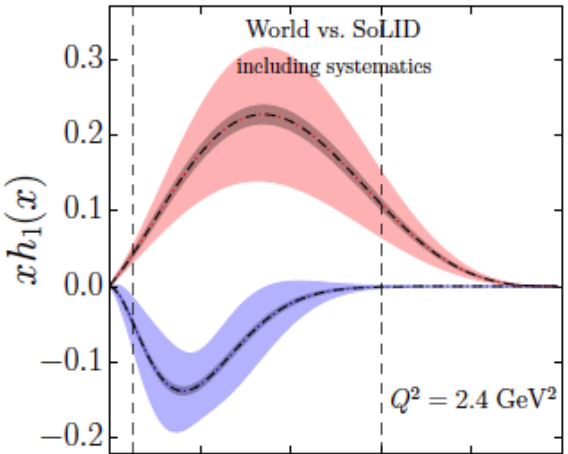
Included in the recent global analysis (Radici and Bacchetta)



First Collins effect measurements in pp collisions
- Universality test of Collins FF
- TMD evolution effects appear to be small

- HERMES, COMPASS and JLab 6 GeV SIDIS data
- JLab 12 GeV upgrade and beyond

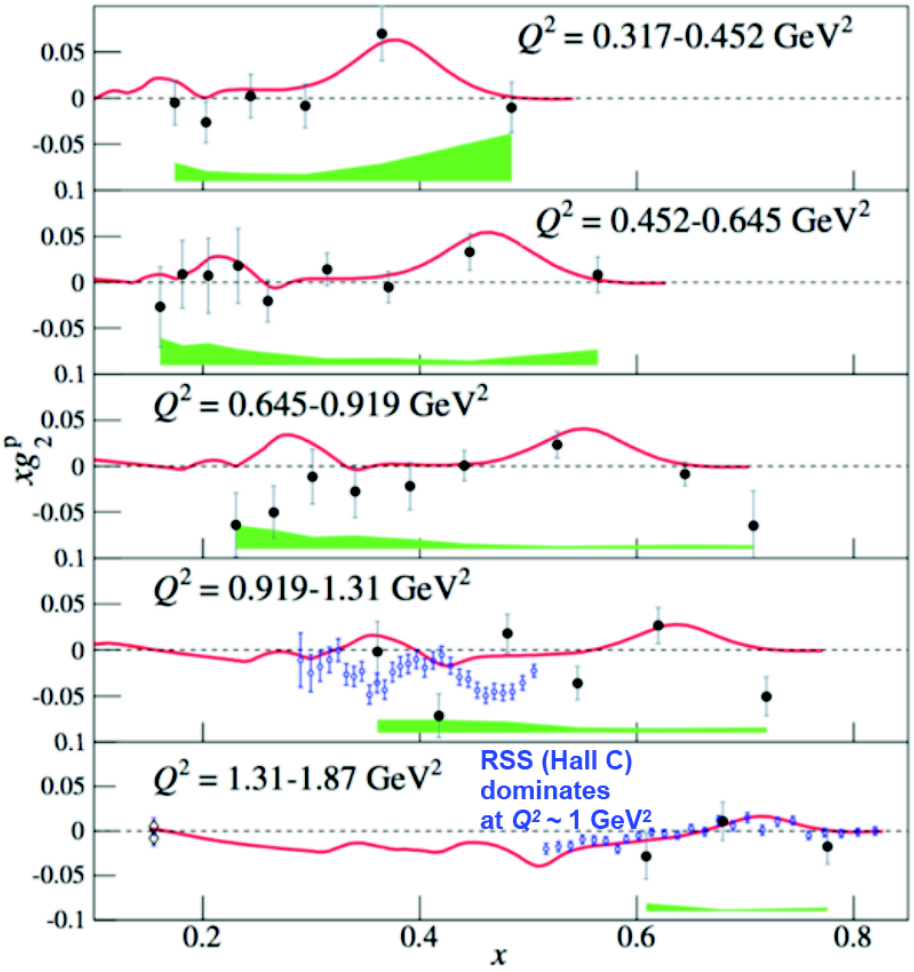
H. Gao



Measurement of $g_2(x)$ by CLAS

First extraction of g2 from EG1 experiment.

R. Fersch

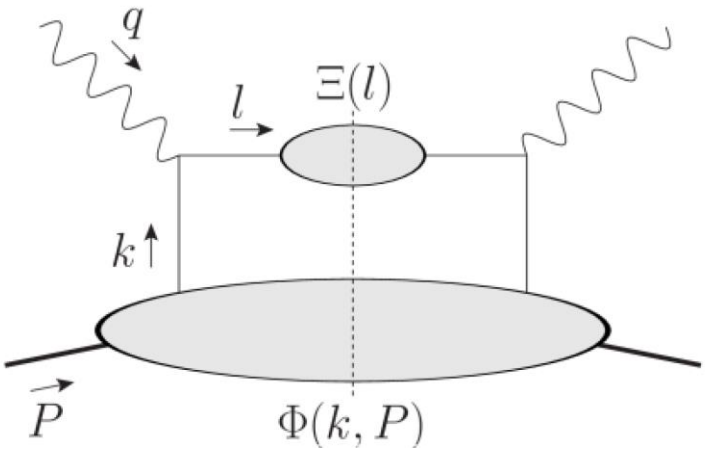


Little world data available!

Useful for extracting higher-twist matrix elements.

New contribution to $g_2(x)$

A. Accardi



Jet correlators

$$\Xi_{ij}(l, n_+) = F.T.\langle 0|\,\mathcal{U}^{n_+}_{(+\infty,\eta)}\,\psi_i(\eta)\bar{\psi}_j(0)\,\mathcal{U}^{n_+}_{(0,+\infty)}\,|0\rangle$$

$$g_2(x_B) - g_2^{WW}(x_B) \equiv g_2^{quark} \qquad \equiv g_2^{jet}$$

$$= \frac{1}{2}\sum_a e_a^2 \left(g_2^{q,\mathrm{tw3}}(x_B) + \frac{m_q}{M}\left(\frac{h_1^q}{x}\right)^{\star}(x_B) + \frac{M_q - m_q}{M}\frac{h_1^q(x_B)}{x_B} \right)$$

Color force distribution

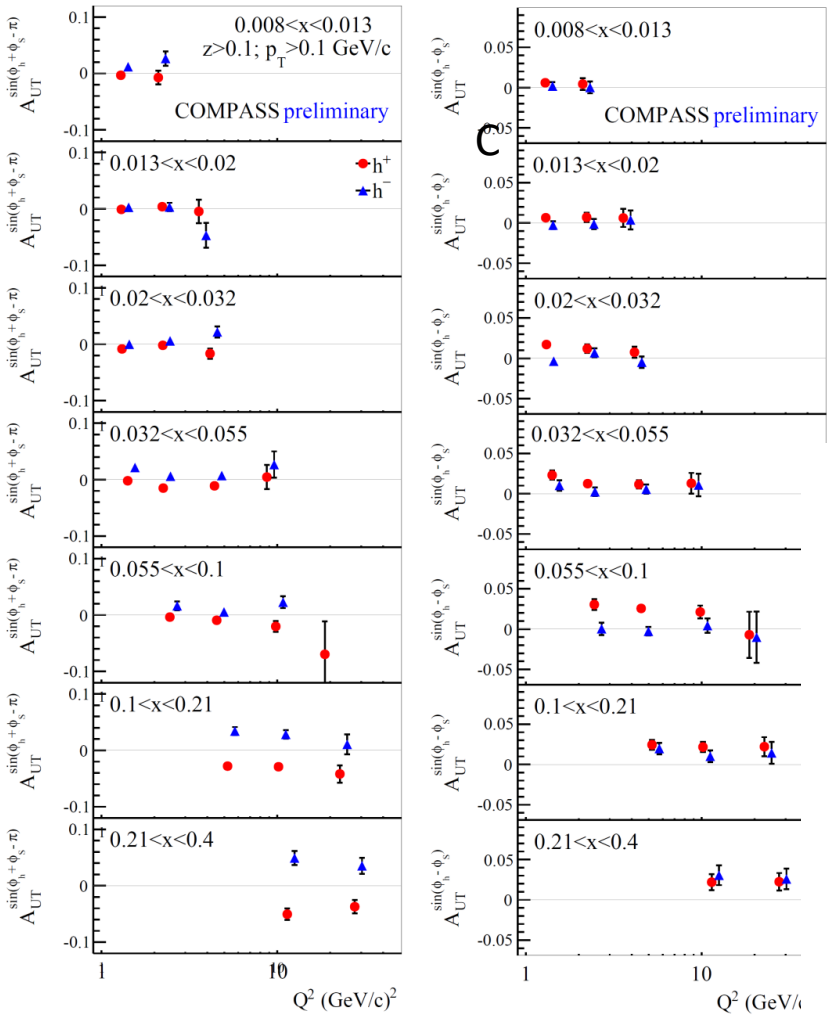
Transversity in inclusive DIS!

Burkardt-Cottingham

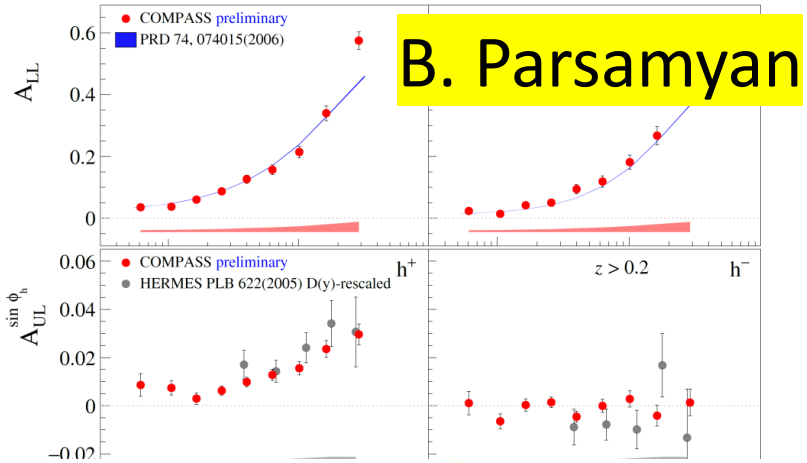
$$\int_0^1 g_2(x) = M_{\text{“jet”}} \int_0^1 dx\, \frac{h_1(x)}{x}$$

→ Broken by quark vacuum fluctuations!

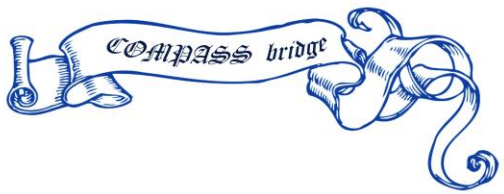
Compass SIDIS Single Spin Asymmetries

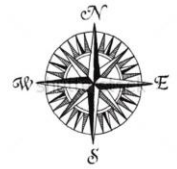


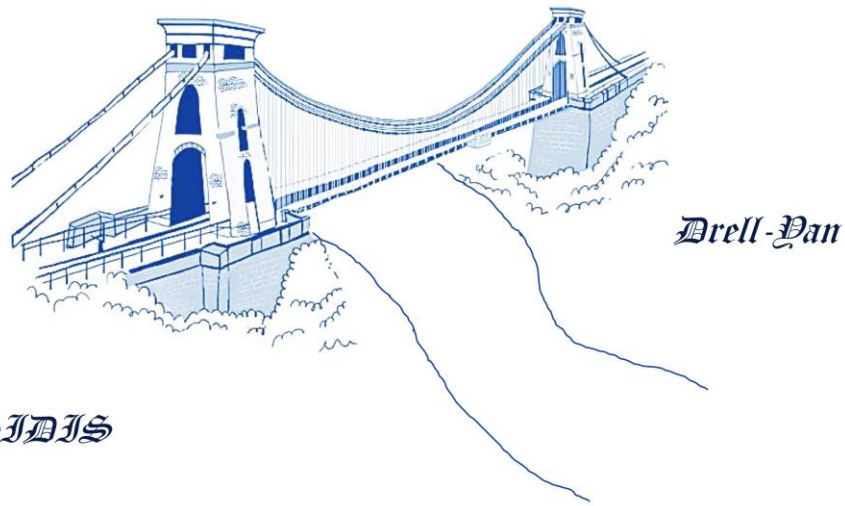
C



B. Parsamyan





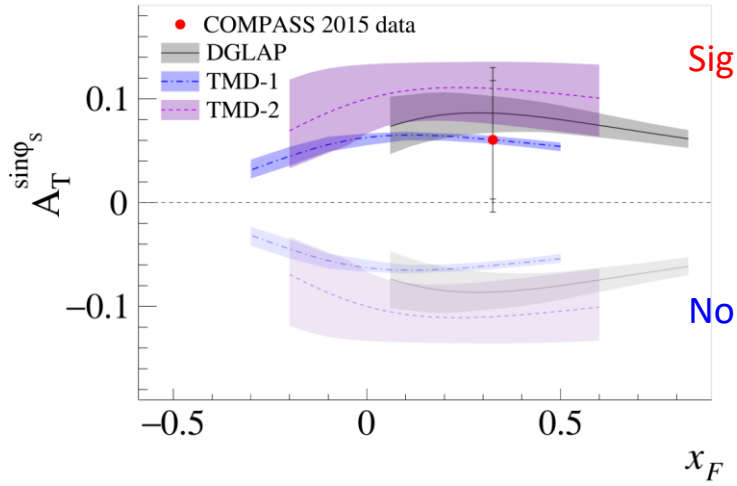


Multidimensional analysis of SIDIS proton SSAs

No hints for significant Q^2-dependences of Sivers and Collins TSAs

Sign change of Sivers function

- COMPASS DY Measurement



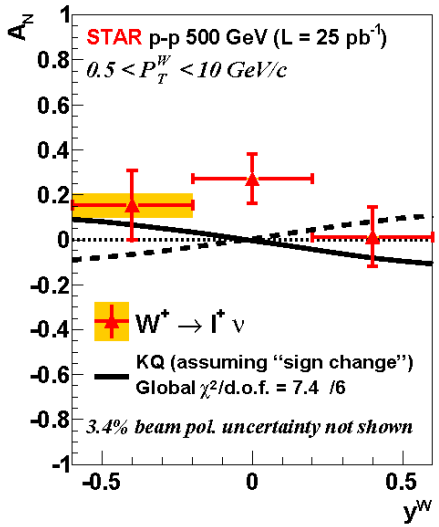
Sign change

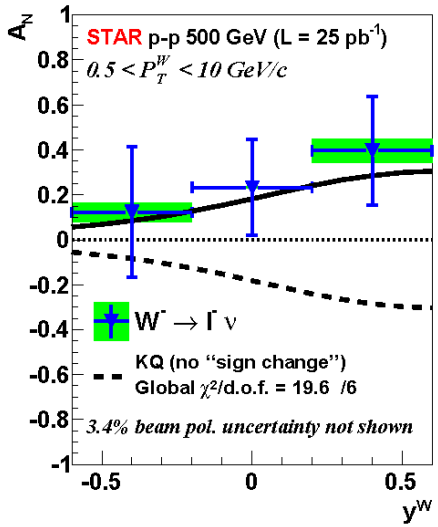
No sign change

M. Chiosso

More data coming! - 2018 second year of polarized DY data taking

- W, Z and DY measurement from STAR





C. Gagliardi

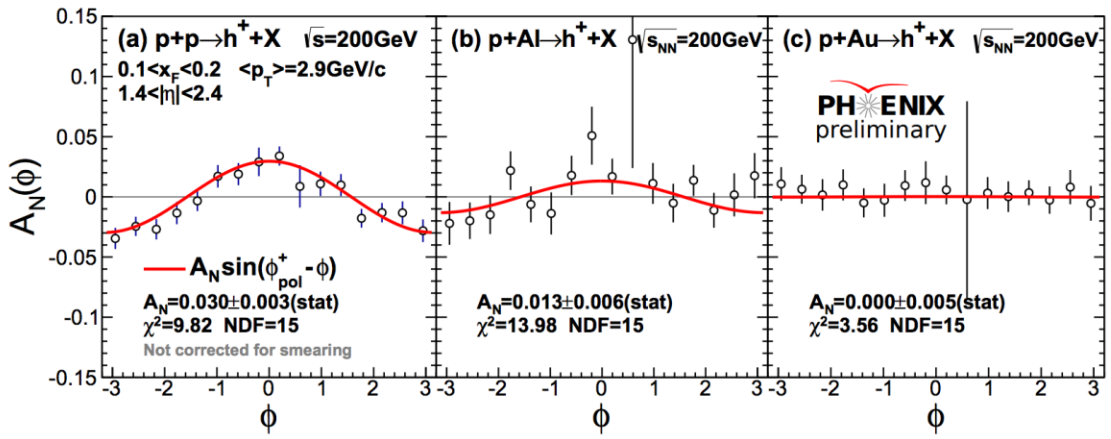
STAR data favors sign change if evolution effects are modest

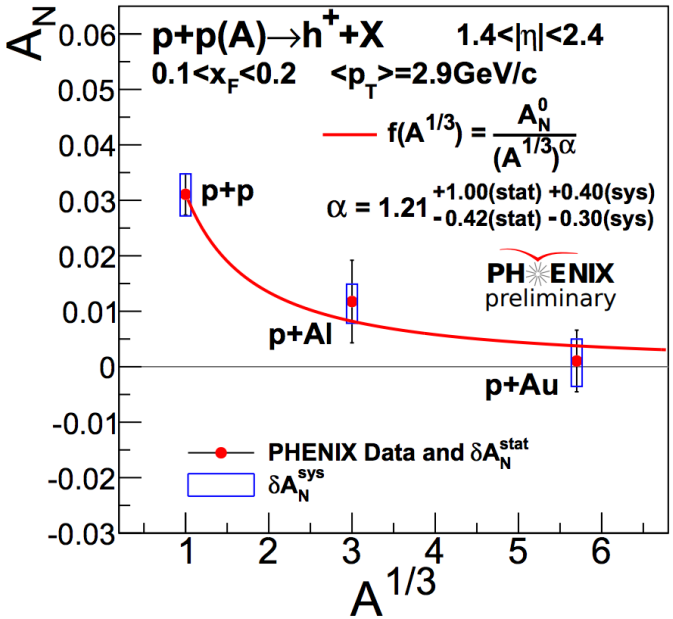
High precision data from 2017 RHIC run under analysis

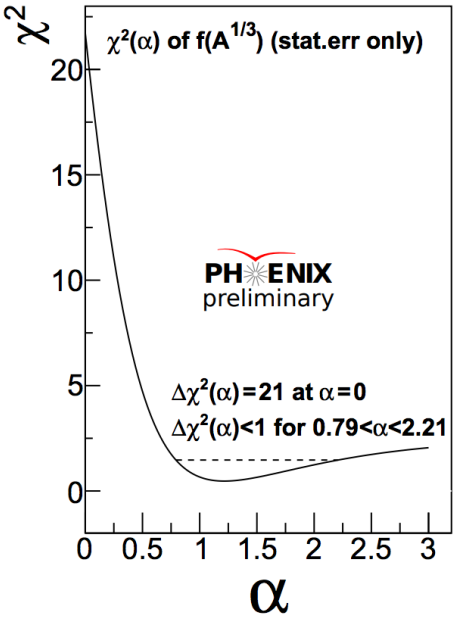
Nuclear dependence A_N

J. Bok

- PHENIX charged hadron A_N in polarized pA







A_N of charged pion and kaon mixture

Non-zero AN observed for positively charged hadrons in p+p

Clear suppression in p+Au

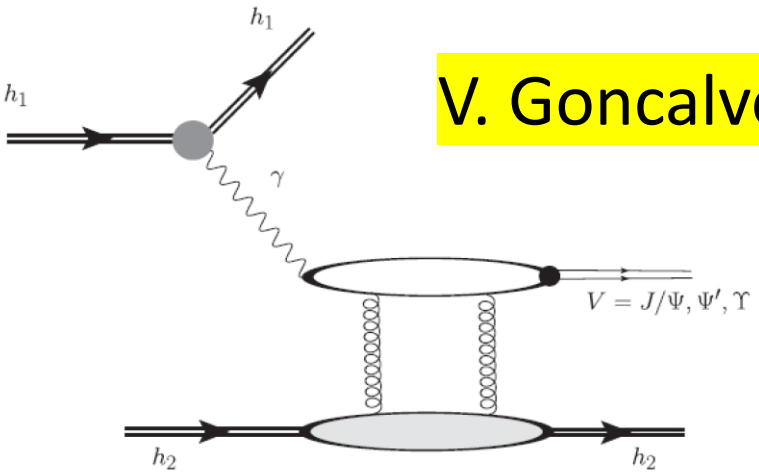
$A^{1/3}$ suppression by gluon saturation is expected

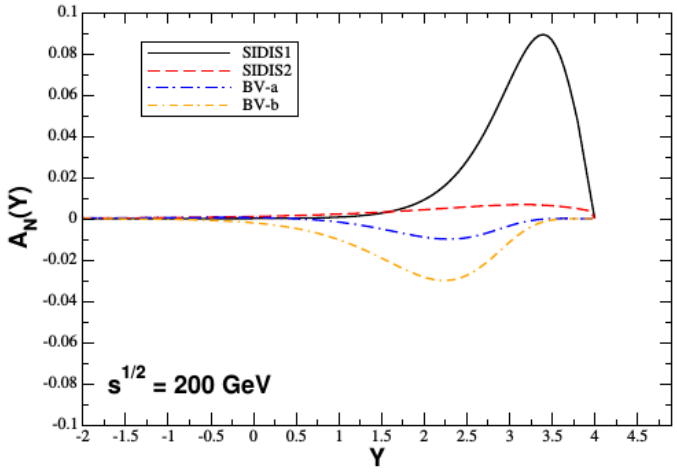
Data favors an A-dependence: $\Delta\chi 2$=21 at α=0 (NO A-dep), out of 4sigma

Single and Double Spin Asymmetry theory

A_N of J/ψ in UPC

V. Goncalves

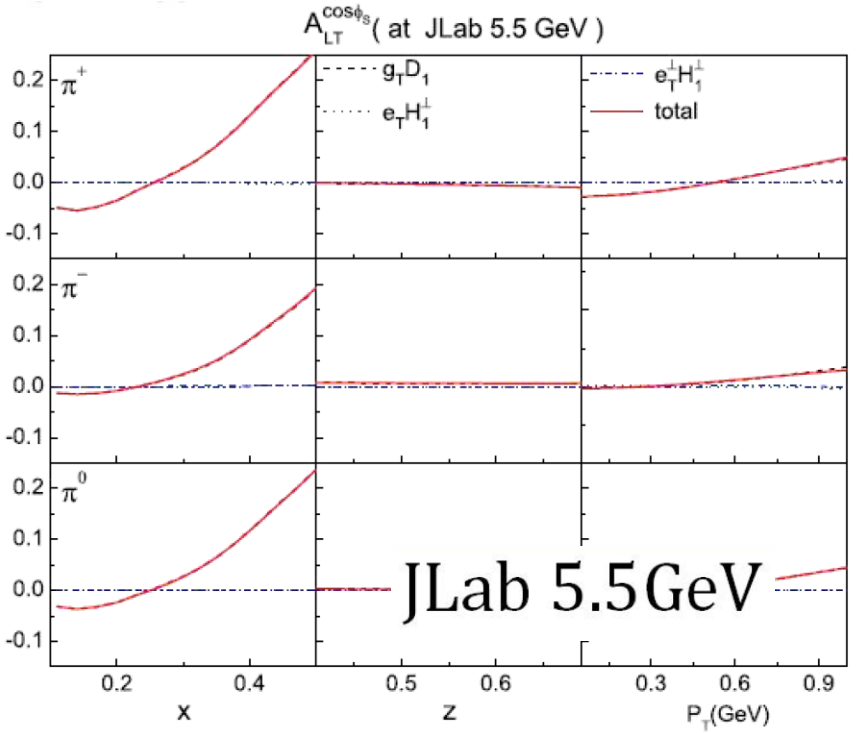




sensitive to gluon Sivers

A_{LT} in SIDIS in the collinear twist-three framework

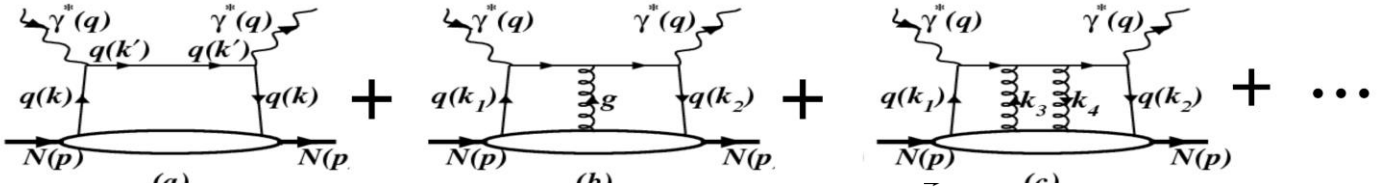
W. Mao



TMD

SIDIS theory

Z.-T. Liang



Complete results for structure functions up to twist-4

$$\kappa_M \equiv \frac{M}{Q}, \quad \bar{k}_\perp \equiv \frac{|\vec{k}_\perp|}{M}$$

$$W_{UU,T} = xf_1 + 4x^2\kappa_M^2 f_{+3dd}, \quad W_{UU,L} = 8x^3\kappa_M^2 f_3$$

$$W_{UU}^{\cos 2\phi} = -2x^2\kappa_M^2 \bar{k}_\perp^2 f_{-3d}^\perp$$

$$W_{UL}^{\sin 2\phi} = 2x^2\kappa_M^2 \bar{k}_\perp^2 f_{+3dL}^\perp$$

$$W_{LL} = xg_{1L} + 4x^2\kappa_M^2 f_{+3ddL}$$

$$W_{UT,T}^{\sin(\phi-\phi_S)} = \bar{k}_\perp(xf_{1T}^\perp + 4x^2\kappa_M^2 f_{+3ddT}), \quad W_{UT,L}^{\sin(\phi-\phi_S)} = 8x^3\kappa_M^2 \bar{k}_\perp f_{3T}^\perp$$

$$W_{UU}^{\cos\phi} = -2x^2\kappa_M \bar{k}_\perp f^\perp$$

$$W_{UL}^{\sin\phi} = -2x^2\kappa_M \bar{k}_\perp f_L^\perp$$

$$W_{LU}^{\sin\phi} = 2x^2\kappa_M \bar{k}_\perp g^\perp$$

$$W_{LL}^{\cos\phi} = -2x^2\kappa_M \bar{k}_\perp g_L^\perp$$

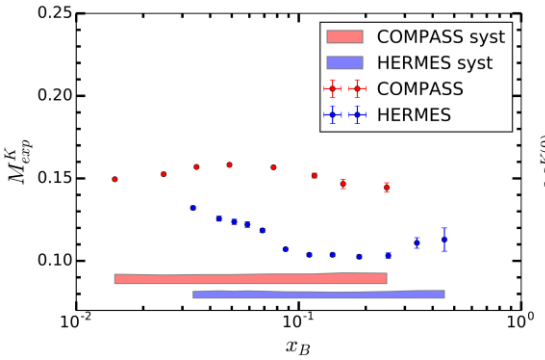
$$W_{UT}^{\sin\phi_S} = -2x^2\kappa_M f_T$$

J. Guerrero

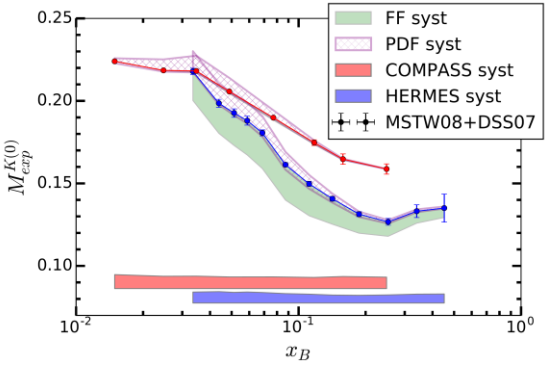
Kaon production in SIDIS,
sensitive to s-quark distribution

Tension between COMPASS ad HERMES
Partly reconciled by hadron mass effects

Experimental Data



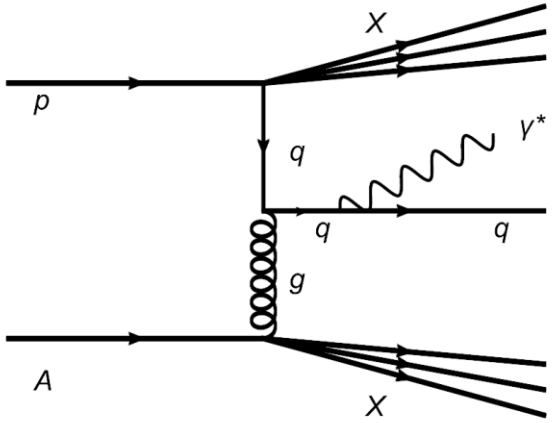
"Massless data" at same Q^2



Linearly polarized gluon distribution

$$\Phi_g^{\mu\nu}(x,\boldsymbol{k}_T,\zeta,\mu) = -\frac{1}{2x}\left\{g_T^{\mu\nu} f_1^g(x,k_T,\mu) - \left(\frac{k_T^\mu k_T^\nu}{M_p^2} + g_T^{\mu\nu}\frac{\boldsymbol{k}_T^2}{2M_p^2}\right) h_1^{\perp g}(x,k_T,\mu)\right\}$$

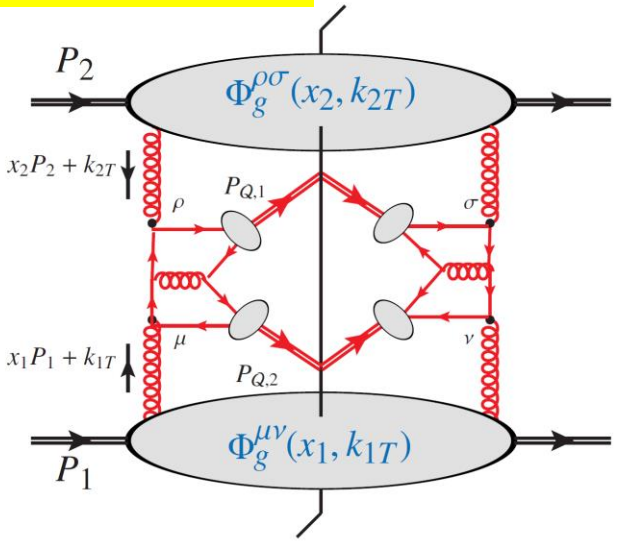
Y. Zhou



$\cos(2\phi)$ asymmetry for $pA \to \gamma^* \; jet \; X$

TMD evolution effects significant

J. Lansberg



$\langle \cos 4\phi_{\rm CS} \rangle$ in double J/ψ production

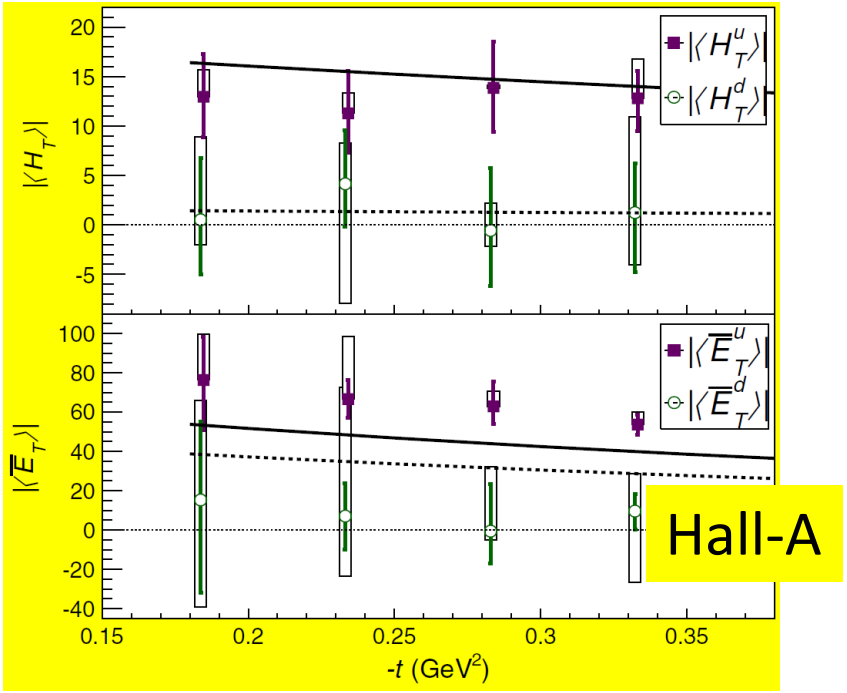
largest values ever predicted ! (up to 40 %)

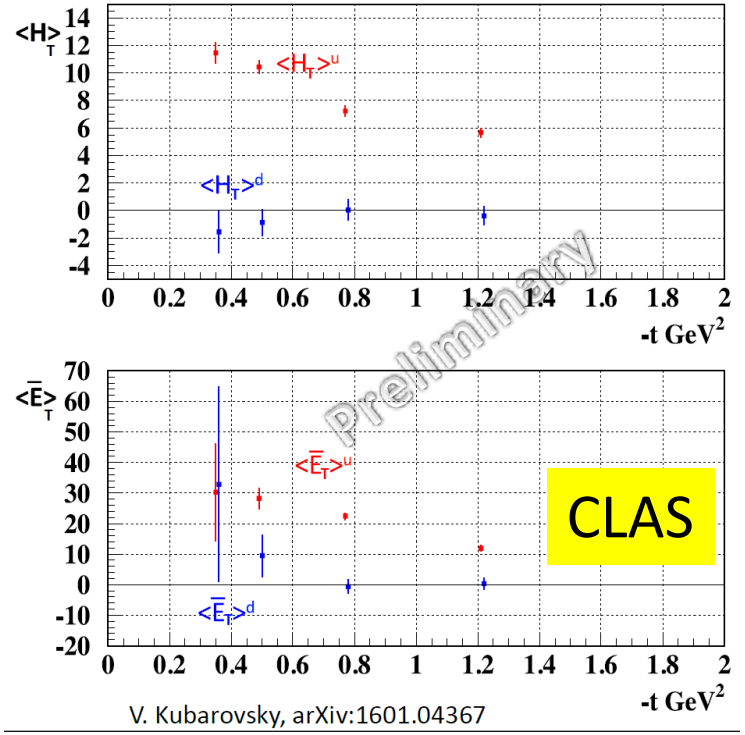
GPD

GPD at JLab @ 6 GeV

C. Hyde
A. Kim

Measurement of transversity GPD (chiral odd) from DVMP $D(e,e'\pi^0)pn$ $H(e,e'\pi^0)p$. First attempt at flavor separation



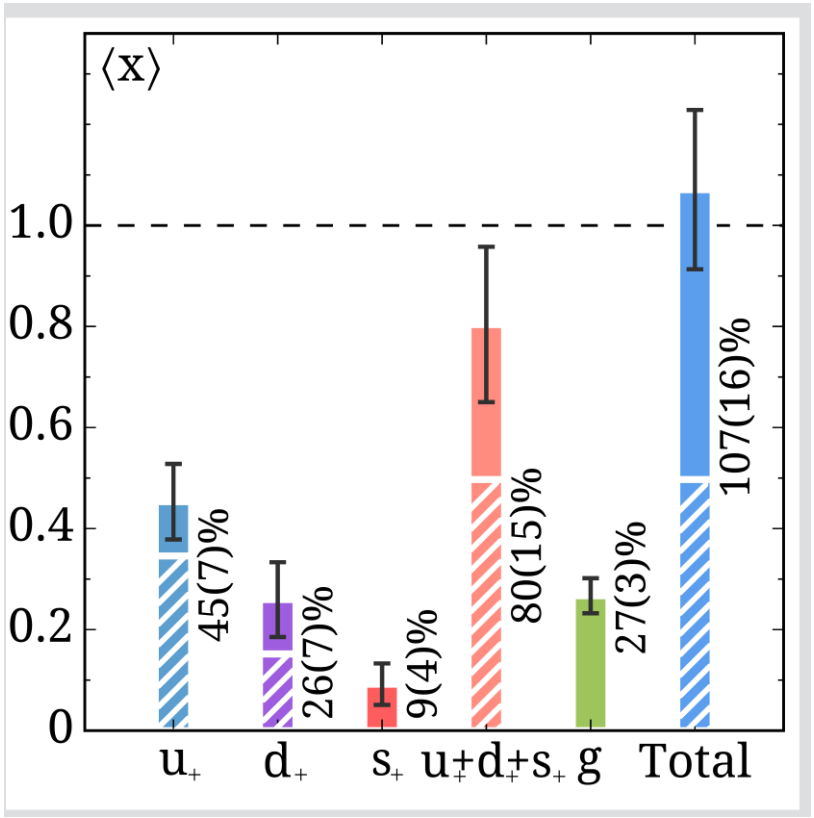


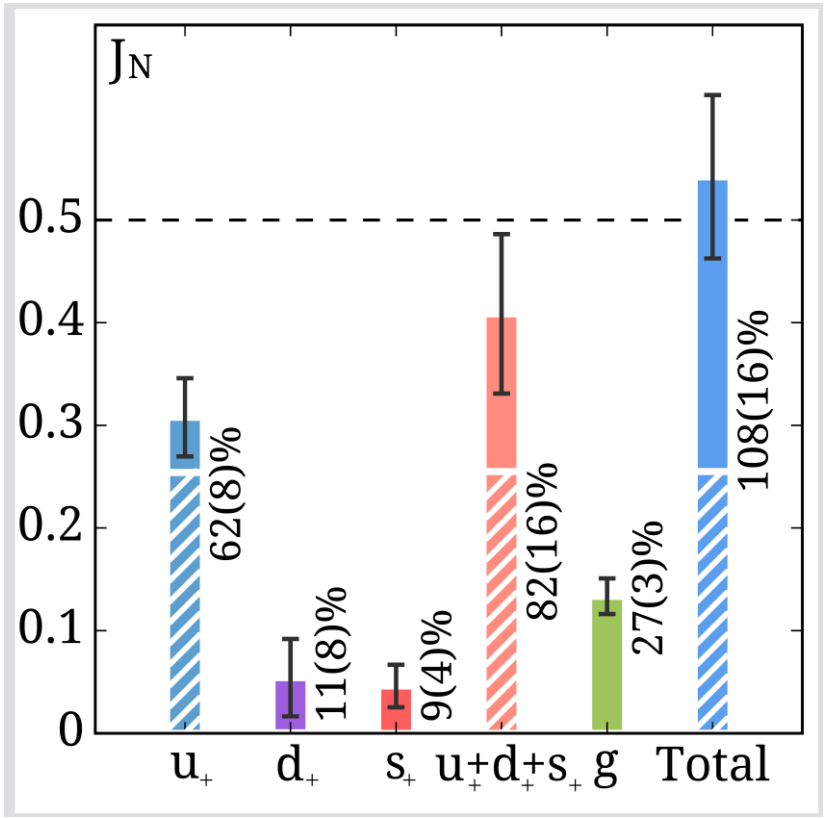
- My prediction: In 10 years, we will be confident in value of $J_{u,d}$

Lattice test of Ji sum rule

Simulations at the physical point!

K. Hadjiyiannakou





$$J^N_{u_+ + d_+ + s_+ + g} = 0.541(62)(49)$$

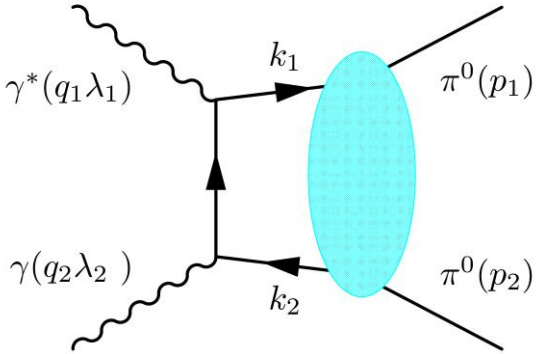
GPD theory developments

M. Burkardt

Twist-2 GPDs → 3D imaging

Twist-3 GPDs → Color Lorentz force (matrix element of $\bar{q}F^{+i}q$)

GPDs not just for the study of imaging but also for color force!

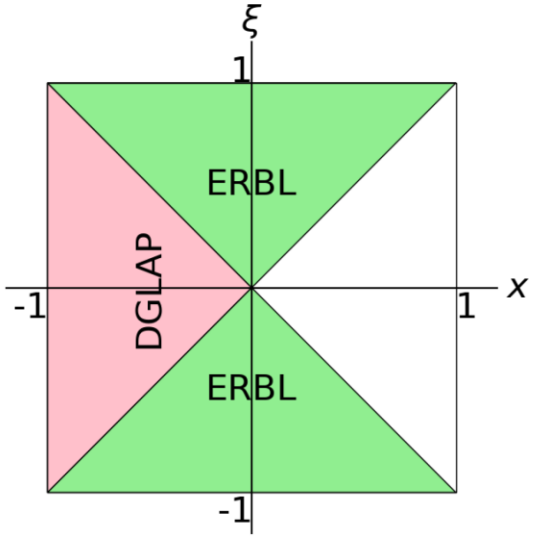


Q.-T. Song

Generalized distribution amplitude (GDA)

Extraction from Belle data $\gamma^*\gamma \to \pi^0\pi^0$.

→ Mass radius of pion



N. Chouika

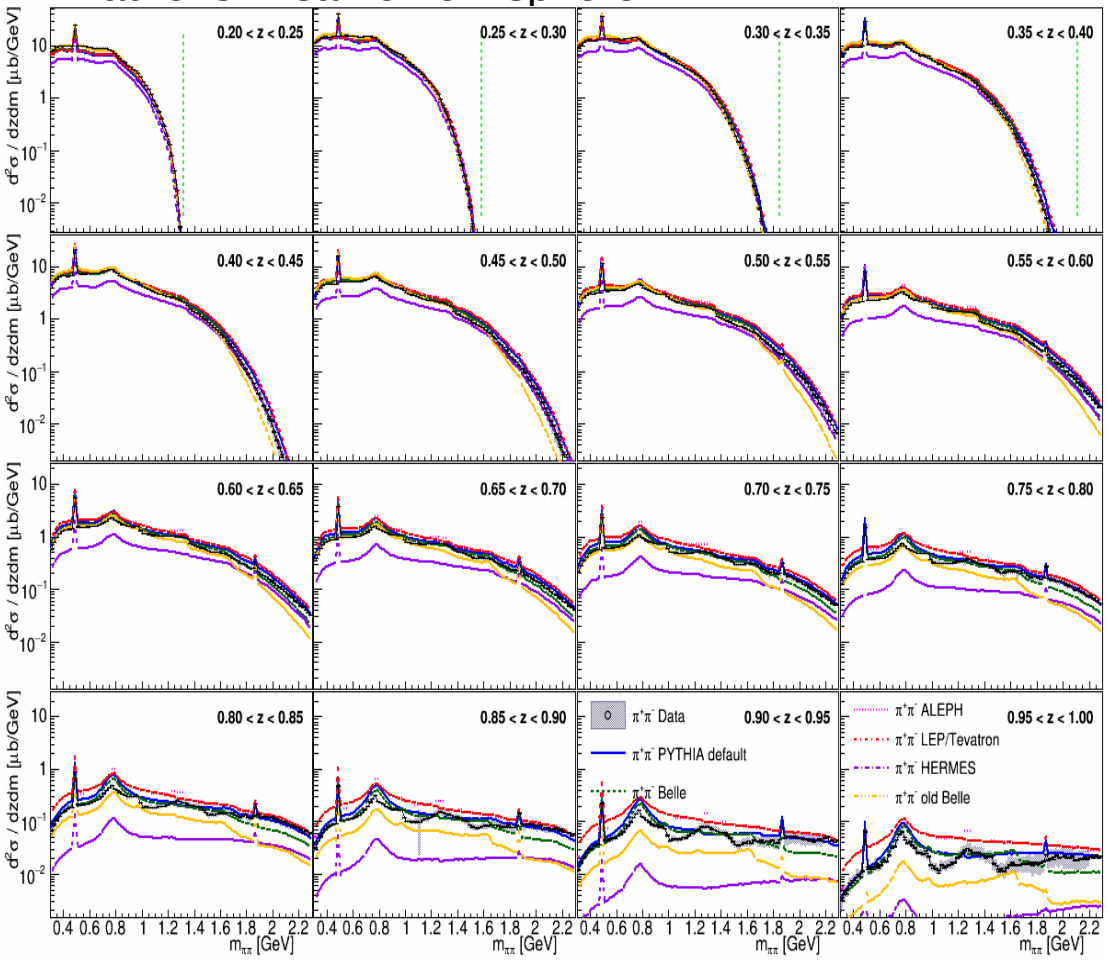
Knowledge of GPD $f(x,\xi,\Delta)$ in the DGLAP region $|x| > |\xi|$

→ Reconstruct the full GPD

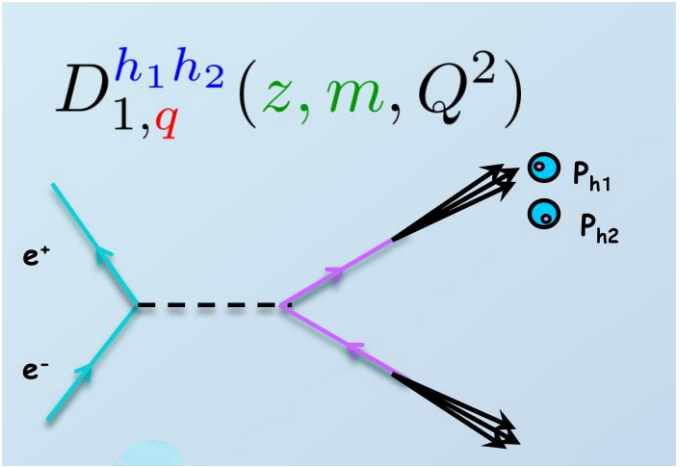
TMD fragmentation function

Fragmentation Functions from e^+e^- at Belle

Di-hadrons in same hemisphere



R. Seidl



Important input for transversity, tensor charge extraction

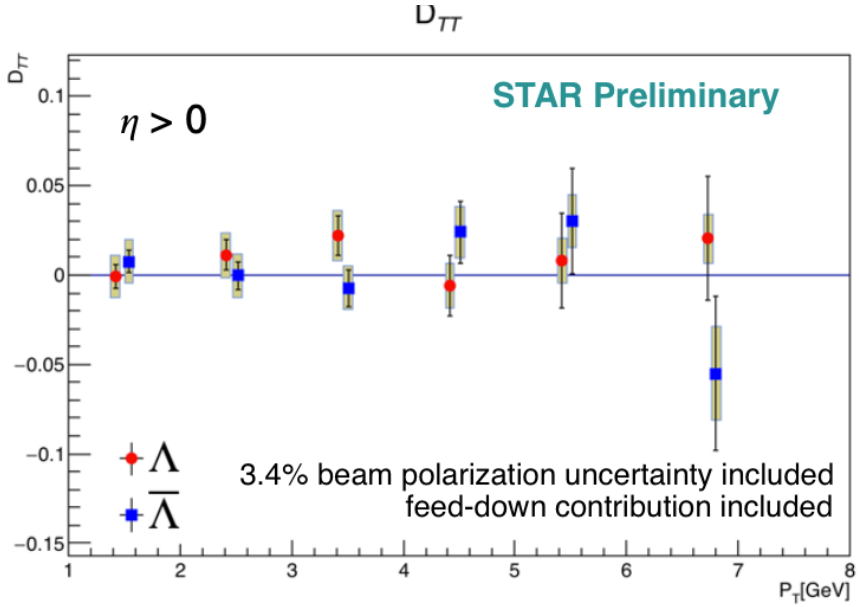
Various types (single hadron & di-hadron) of FFs (and more) were measured.

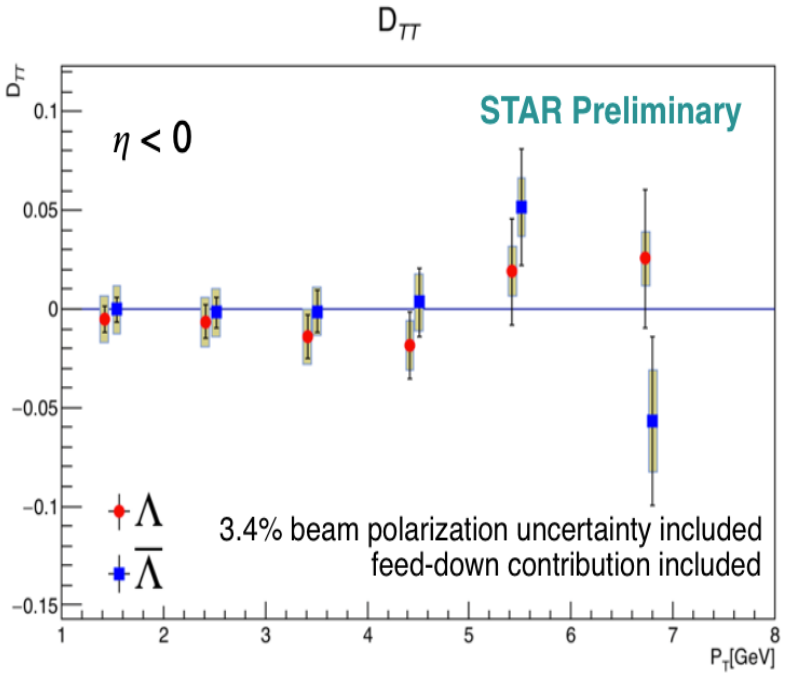
Transverse-Spin Transfer $p \to \Lambda$ in pp

$$D_{TT} \equiv \frac{d\sigma^{(p^{\uparrow}p \to H^{\uparrow}X)} - d\sigma^{(p^{\uparrow}p \to H^{\downarrow}X)}}{d\sigma^{(p^{\uparrow}p \to H^{\uparrow}X)} + d\sigma^{(p^{\uparrow}p \to H^{\downarrow}X)}}$$

measured by STAR at RHIC

Q. Xu

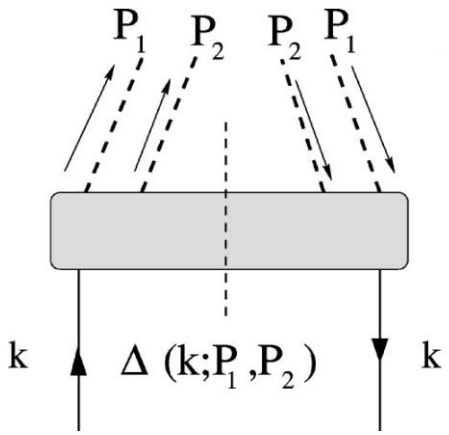




Λ spin ~ *s* quark's spin

Sensitive to strangeness transversity and transversely polarized fragmentation function.
To be improved in statistics and systematics.

Fragmentation function theory developments



H. Matevosyan

$$\Delta_{ij}(k;P_1,P_2) = \sum \int d^4\zeta e^{ik\cdot\zeta}\langle 0|\psi_i(\zeta)|P_1P_2,X\rangle\langle P_1P_2,X|\bar{\psi}_j(0)|0\rangle$$

related to "jet handedness"

$$\Delta^{[\gamma^-\gamma_5]} = \frac{\epsilon_T^{ij} R_{Ti} k_{Tj}}{M_h^2} G_1^\perp(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)$$

New observable to access DiFFs in e+e-

→ ***q_T-weighted asymmetry***

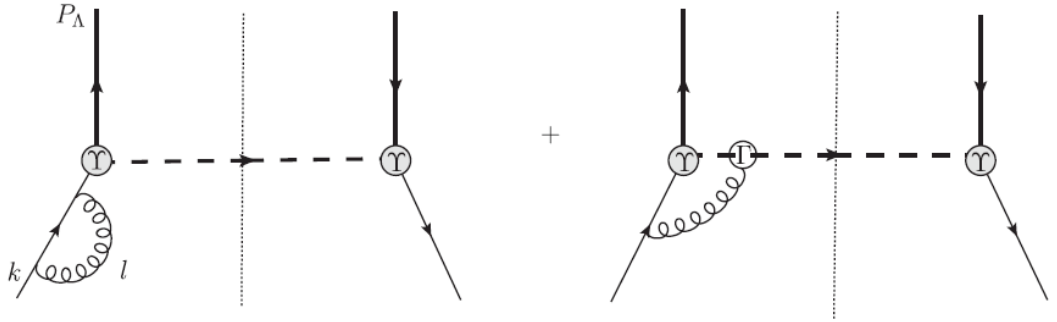
$$\left\langle \frac{q_T^2\left(3\sin(\varphi_q-\varphi_R)\sin(\varphi_q-\varphi_{\bar{R}})+\cos(\varphi_q-\varphi_R)\cos(\varphi_q-\varphi_{\bar{R}})\right)}{M_h\bar{M}_h}\right\rangle$$

Y. Yang

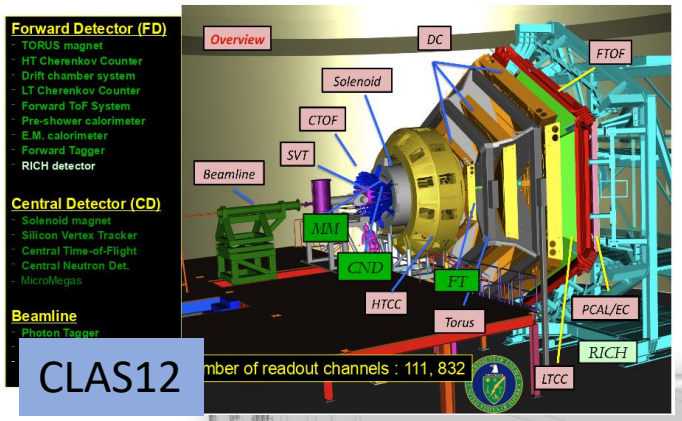
Unpolarized quark → transversely polarized Λ

T-odd. Need final state interaction (loop corrections)

Calculated in the diquark model



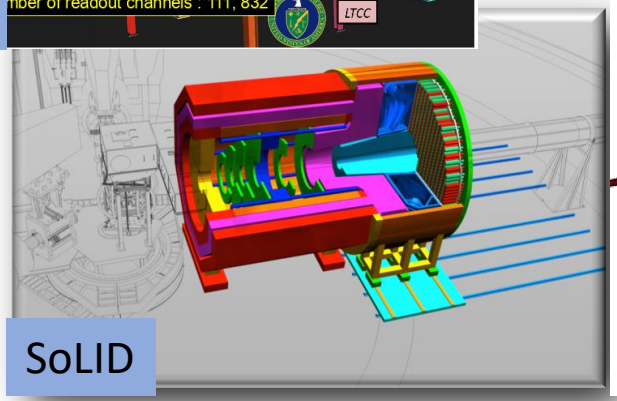
Future experiments



CLAS12

A. Kim

H. Gao



SoLID

- **JLab 12 GeV**

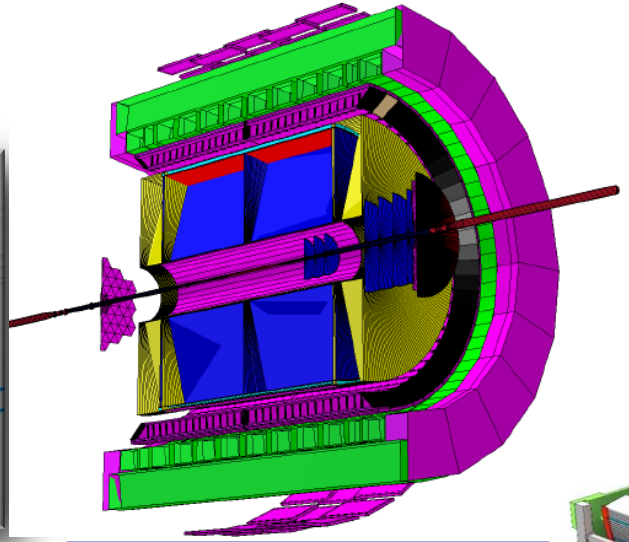
Hall A, Hall C, CLAS12, SBS, SoLID, ..

Rich TMD and GPD program

- **RHIC Cold QCD program**

Jets at forward rapidity

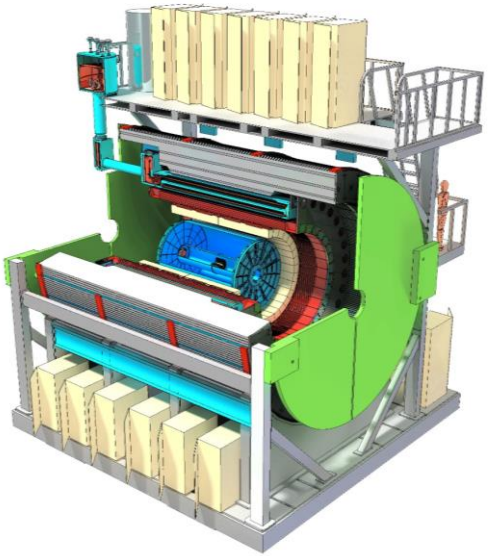
Precision DY measurements



STAR forward upgrade

E. Aschenauer

fsPHENIX



- **Future COMPASS**

SIDIS measurements with transversely polarized deuteron target in 2021