Session 2: Nucleon Helicity Structure

Brian Page
Theory and pp Experiment

Fabienne Kunne
DIS/SIDIS Experiment

Non existence of proton spin crisis

It has long been understood that there is no proton spin crisis…

E.Leader's talk

There was an over naive interpretation of the EMC measurement:

$$\Gamma_1^p \equiv \int_0^1 g_1^p(x)dx$$

$$\Gamma_1^p(Q^2) = \frac{1}{12}\Big[\Big(a_3 + \frac{1}{3}a_8\Big)\Delta C_{NS}^{\overline{MS}} + \frac{4}{3}a_0(Q^2)\Delta C_S^{\overline{MS}}\Big]$$

EMC gave a_0~0, later confirmed as ~0.3,.
Giving rise to the spin crisis in the *(naive)* parton model.

A non naive interpretation should include **gluons** and **the OAM of constituents**
But non so trivial: controversy as to which operator should be used for the OAM.

$$\frac{1}{2} = \frac{1}{2}a_0 + \Delta G + \langle\langle \hat{L}^q_{can,z}\rangle\rangle + \langle\langle \hat{L}^G_{can,z}\rangle\rangle.$$

where each term depends on Q^2, but not the sum.

The non-existence of the spin crisis, cont'd

E. Leader's talk

- The proton ''spin crisis'' in the parton model 30 years ago, was due to misinterpretation of EMC results
- Failure to distinguish constituent quarks and partonic quarks.
- Partonic quarks as well as gluons, certainly process OAM.

Lattice: Spin dependent PDFs

F.Steffens's talk

Proton spin decomposition was presented at the physical pion mass. Spin and momentum sum rules are satisfied;

We have also shown an *ab initio* computation of the x dependence of the iso-vector PDF at the physical point;

No input nor any assumption on their functional dependence, this was unthinkable of just few years ago;

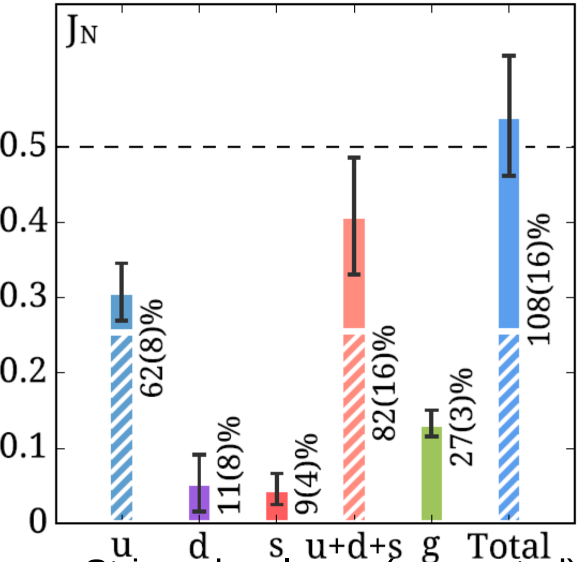
Enormous progress over the last couple of years:

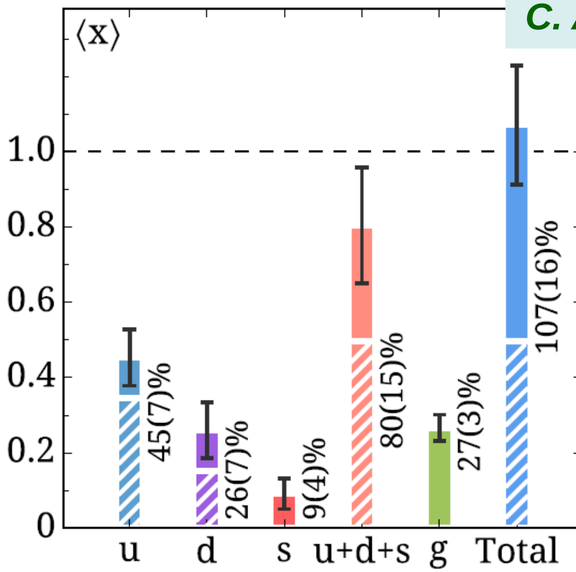
- a complete non-perturbative prescription for the ME has emerged
- the matching equations relating the qPDFs to the light-cone PDFs have been improved

Lattice. Nucleon spin and momentum decomposition

C. Alexandrou et al., ArXiv 1706.02973v3

F.Steffens's talk





Stripped: valence (connected),
Full: sea/gluons (disconnected)

- First ever results at the physical point;
- Spin sum rule satisfied;
- Momentum sum rule satisfied;
- Slightly negative polarized strangeness

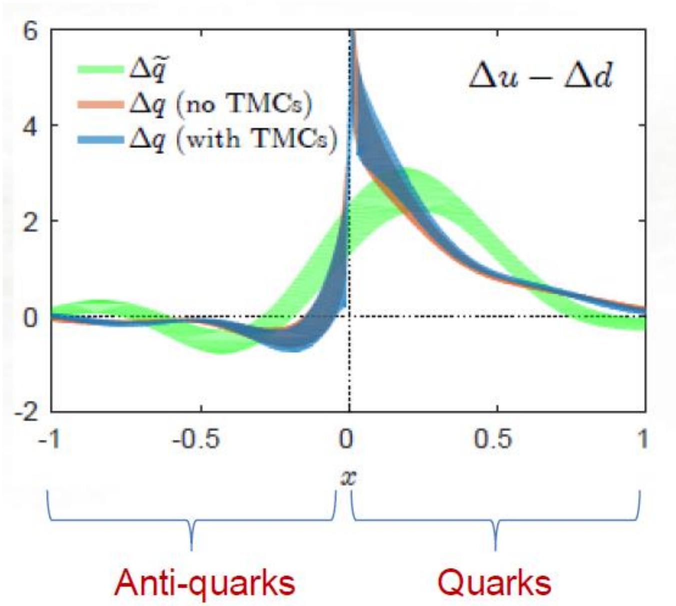
	$\frac{1}{2}\Delta\Sigma$	J	L	$\langle x \rangle$
u	0.415(13)(2)	0.308(30)(24)	-0.107(32)(24)	0.453(57)(48)
d	-0.193(8)(3)	0.054(29)(24)	0.247(30)(24)	0.259(57)(47)
s	-0.021(5)(1)	0.046(21)(0)	0.067(21)(1)	0.092(41)(0)
g	-	0.133(11)(14)	-	0.267(22)(27)
tot.	0.201(17)(5)	0.541(62)(49)	0.207(64)(45)	1.07(12)(10)

Still, we need to go beyond the moments to a deeper understanding of the parton dynamics

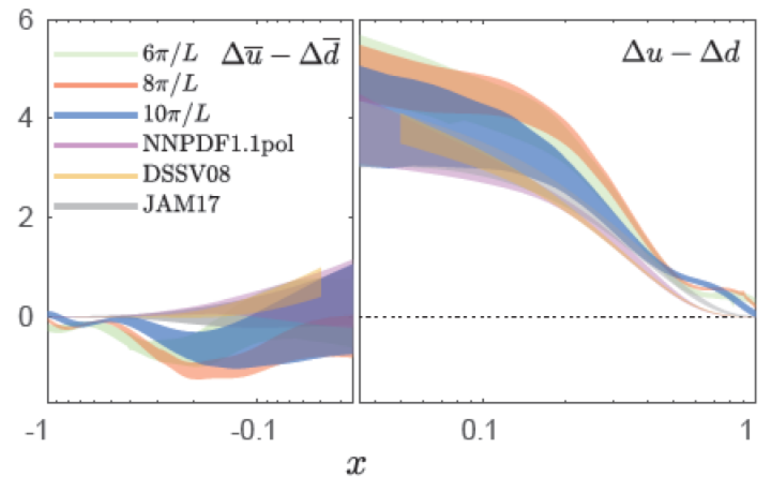
Lattice PDFs

F.Steffens's talk

Helicity iso-vector quark distribution



Helicity iso-vector quark distribution



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JAM Global Analysis

Combined analysis of polarized and unpolarized PDFs and fragmentation functions

N. Sato's talk

JAM18: Universal analysis (preliminary)

Andres, Ethier, Melnitchouk, NS, Rogers

- **Data sets**
  - + DIS, SIDIS(π, K), DY
  - + ΔDIS, ΔSIDIS(π, K)
  - + $e^+e^-(\pi, K)$
- **Theory setup**
  - + Observables computed at **NLO in pQCD**
  - + DIS structure functions only at **leading twist** $(W^2 > 10\ \mathrm{GeV}^2)$

First **universal** analysis of PDFs, ΔPDF and FFs

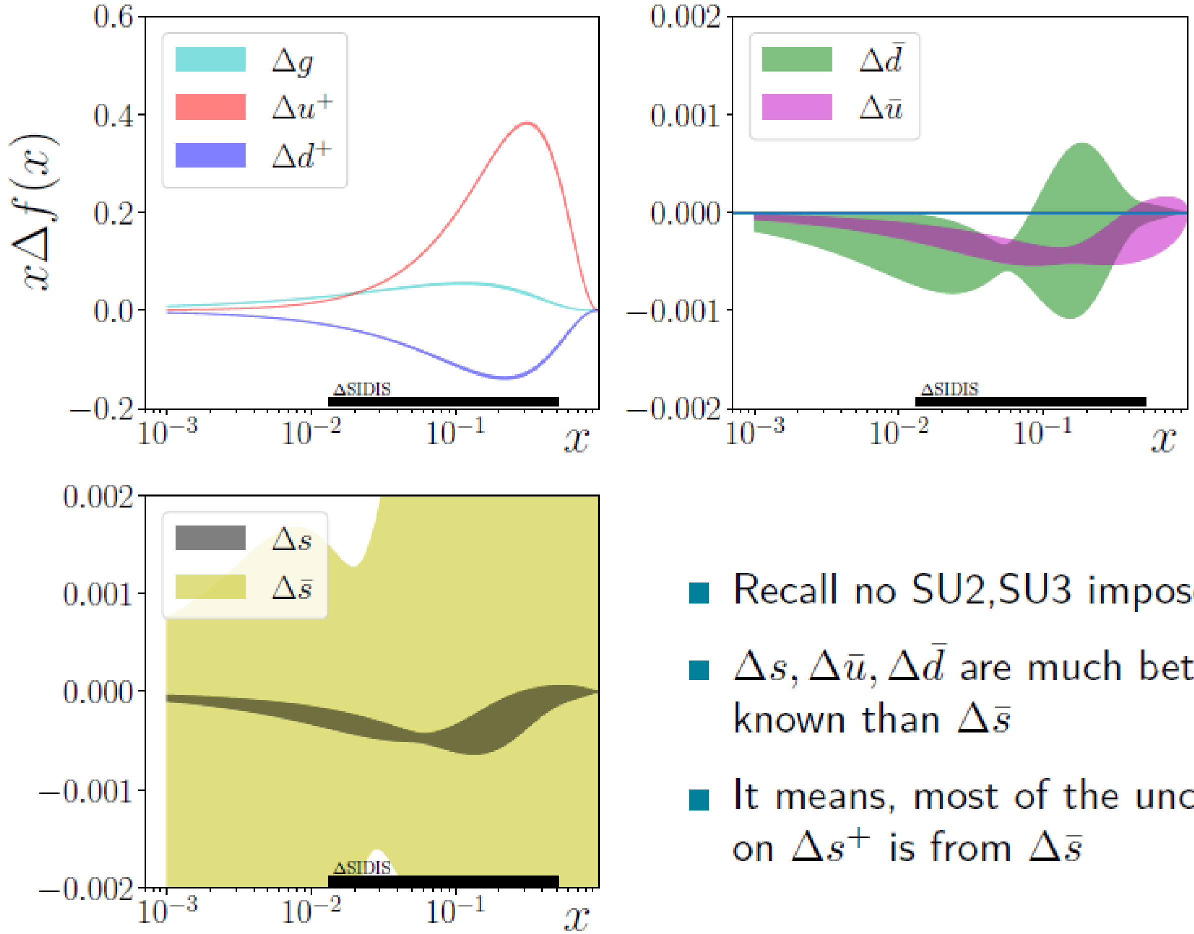
+ New insights on nucleon sea distributions ($s, \bar{s}$ asymmetry)

+ π and K gluon FFs are required by SIDIS to peak at larger z
$\rightarrow$ relevant for TMD physics

JAM18- Polarized PDFs

N. Sato's talk

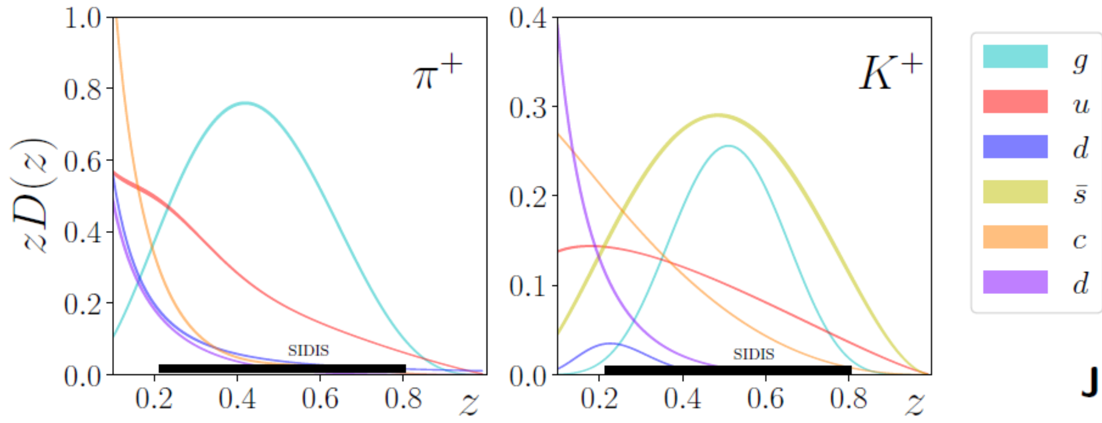
JAM18: ΔPDFs (preliminary)



- Recall no SU2,SU3 imposed
- $\Delta s, \Delta\bar{u}, \Delta\bar{d}$ are much better known than $\Delta\bar{s}$
- It means, most of the uncertainty on Δs^+ is from $\Delta\bar{s}$

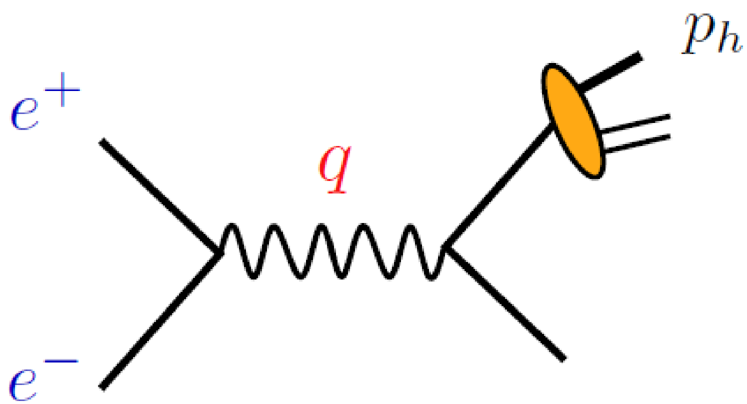
JAM 18 – Fragmentation functions

N. Sato’s talk

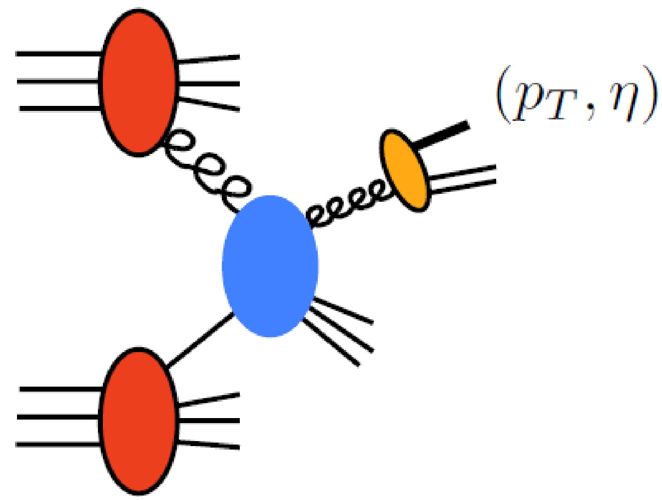


- gluon FFs are significantly affected by SIDIS
- This feature is key for p_T differential SIDIS → see my talk “3D Structure of the Nucleon: TMDs”

W. Vogelsang



pp→πX



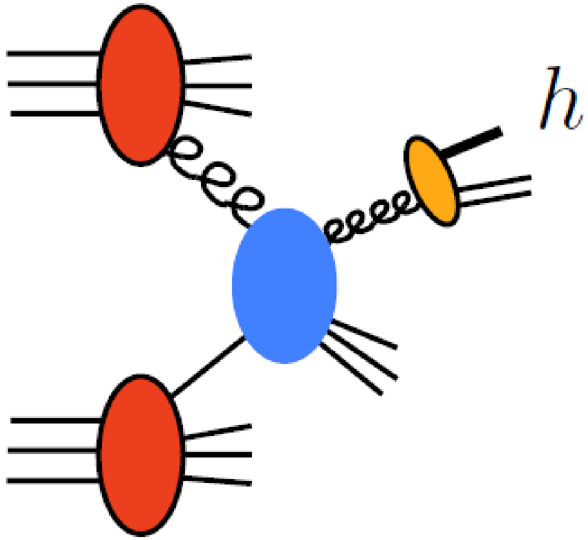
- direct scan of z-dependence: at LO

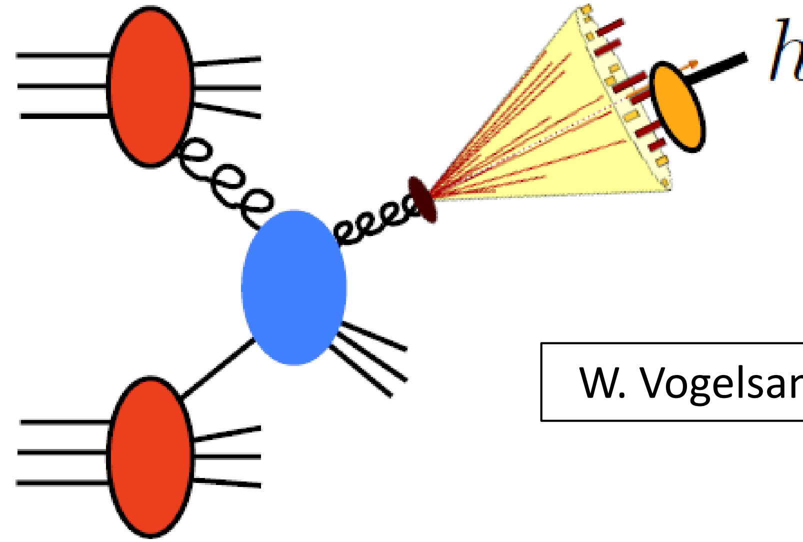
$$\sigma \leftrightarrow D_c(z, q^2)$$

- little sensitivity to gluon FF

- sensitivity to gluon FF

- samples broad range in z_c





W. Vogelsang

$$z_h \equiv \frac{p_T^h}{p_T^{\text{jet}}}$$

LO:

$$\frac{d\sigma^{\text{jet}/h}}{dp_T^{\text{jet}}\, d\eta^{\text{jet}}\, dz_h} \propto \sum_c \Omega^c(p_T^{\text{jet}}, \eta^{\text{jet}})\, D_c(z_h, \mu)$$

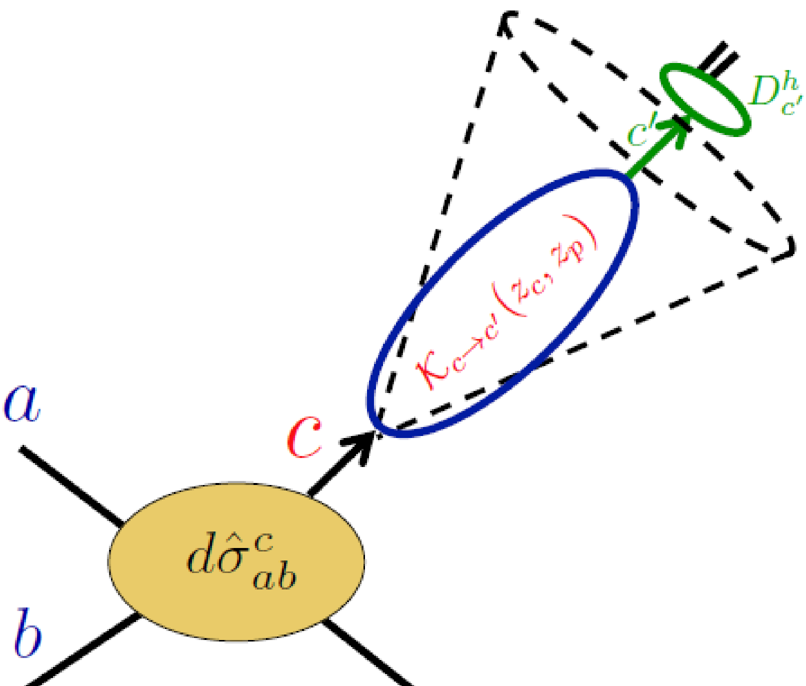
$$\Omega^c = \sum_{a,b} \int dx_a\, f_a(x_a, \mu) \int dx_b\, f_b(x_b, \mu)\, \frac{d\hat{\sigma}^{ab\to c}}{dp_T^{\text{jet}}\, d\eta^{\text{jet}}}$$

NLO result (analytic for “narrow” jets):

W. Vogelsang

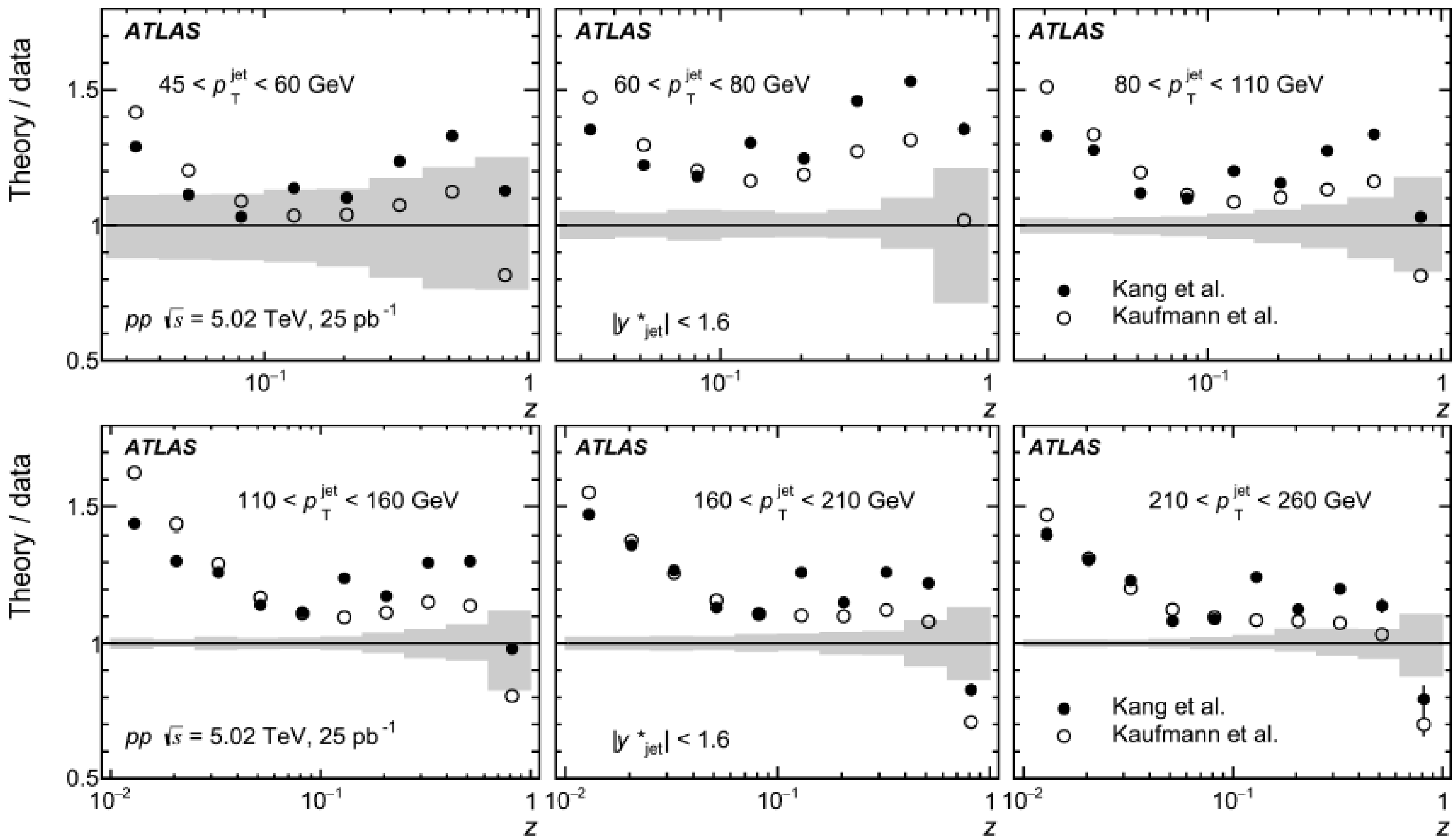
$$\frac{d\sigma^{\mathrm{jet}/h}}{dp_T^{\mathrm{jet}}\, d\eta^{\mathrm{jet}}\, dz_h} = \sum_{a,b,c} \int \frac{dx_a}{x_a} f_a(x_a,\mu) \int \frac{dx_b}{x_b} f_b(x_b,\mu) \int \frac{dz_c}{z_c} \frac{d\hat{\sigma}^{ab\to c}(\hat{s},\hat{p}_T,\hat{\eta},\mu)}{d\hat{p}_T\, d\hat{\eta}}$$

$$\times \sum_{c'} \int_{z_h}^{1} \frac{dz_p}{z_p} \underbrace{\mathcal{K}_{c\to c'}\left(z_c, z_p; \mathcal{R}\, p_T^{\mathrm{jet}}/\mu\right)}_{\text{“fragmenting jet functions”}} D_{c'}\left(\frac{z_h}{z_p},\mu\right)$$

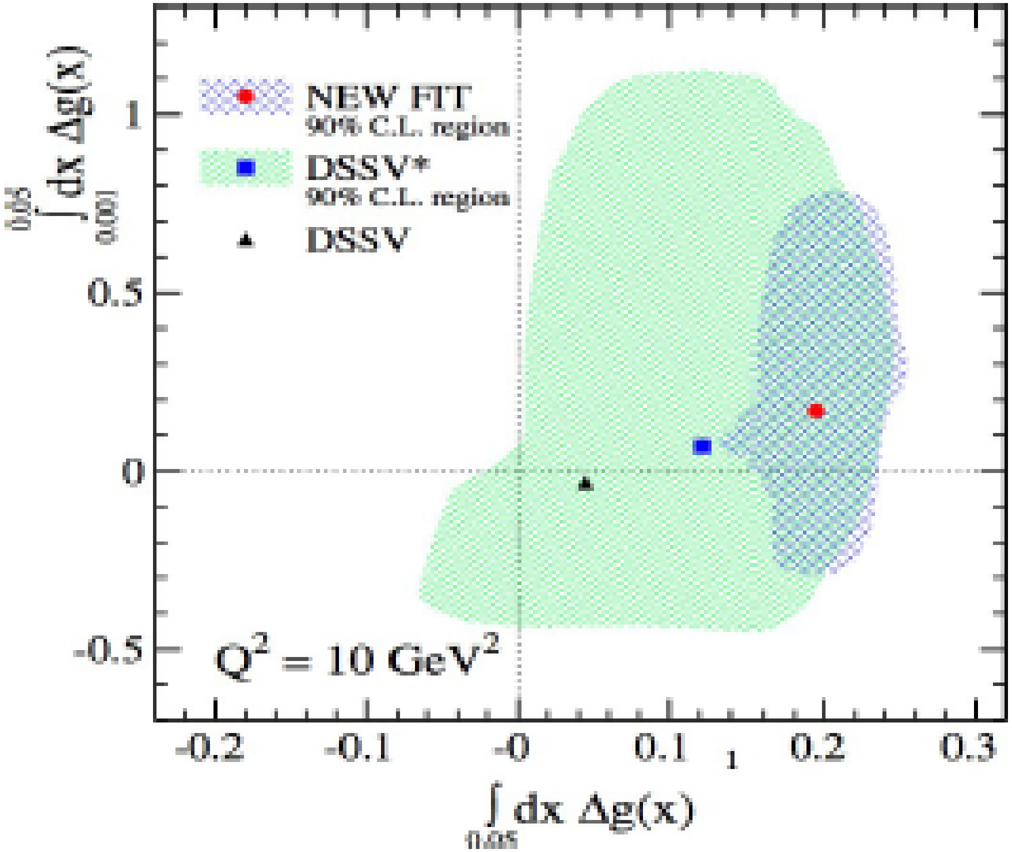


Procura, Waalewijn
Procura, Stewart
Jain, Procura, Waalewijn
Kaufmann, Mukherjee, WV
Thaler et al.
Chien, Kang, Ringer, Vitev, Xing
Arleo, Fontannaz, Guillet, Nguyen

W. Vogelsang


ATLAS
45 < p_T^{jet} < 60 GeV
60 < p_T^{jet} < 80 GeV
80 < p_T^{jet} < 110 GeV
110 < p_T^{jet} < 160 GeV
160 < p_T^{jet} < 210 GeV
210 < p_T^{jet} < 260 GeV
pp $\sqrt{s}$ = 5.02 TeV, 25 pb^{-1}
$|y^*_{jet}|$ < 1.6
Kang et al.
Kaufmann et al.
Theory / data
z

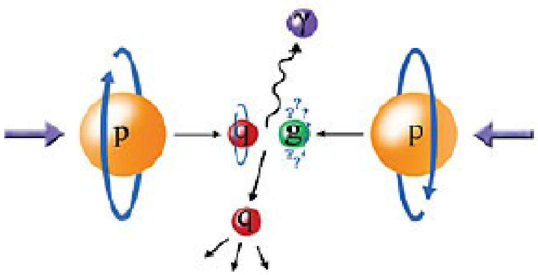
Gluon Polarization at RHIC



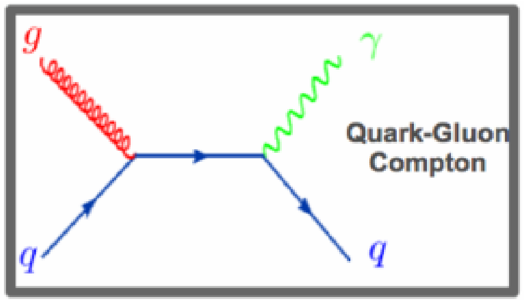
- PHENIX
  - Direct photons – K. Barish
  - Charged Pions – T. Moon
- STAR
  - STAR Overview – C. Dilks
  - Dijets – T. Lin

Direct photon: the golden channel

K. Barish



~85%

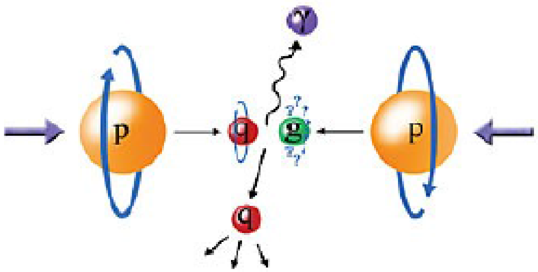


$$A_{LL}^{pp\to\gamma X} \approx \frac{\Delta G(x_g)}{G(x_g)} \cdot \frac{\Delta q(x_q)}{q(x_q)} \cdot a_{LL}^{qg\to\gamma q}$$

- Leading order for gluon polarization: jet, hadron and direct photon in $\vec{p}+\vec{p}$.
- Fragmentation in hadron and jet.
- No hadronizaion in direct photon: "cleanest" channel.
- Dominant process $q+g\to\gamma+q$: probe the sign of the gluon polarization.
- First measure direct photon cross section to confirm consistency with pQCD.
- Then use pQCD to extract gluon contribution.

Direct photon: the golden channel

K. Barish



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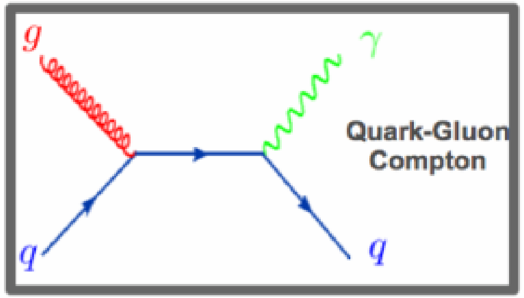

$$A_{LL}^{pp\to\gamma X} \approx \frac{\Delta G(x_g)}{G(x_g)} \cdot \frac{\Delta q(x_q)}{q(x_q)} \cdot a_{LL}^{qg\to\gamma q}$$

- Leading orde … ct photon in $\vec{p}+\vec{p}$.
- Fragmentatic …
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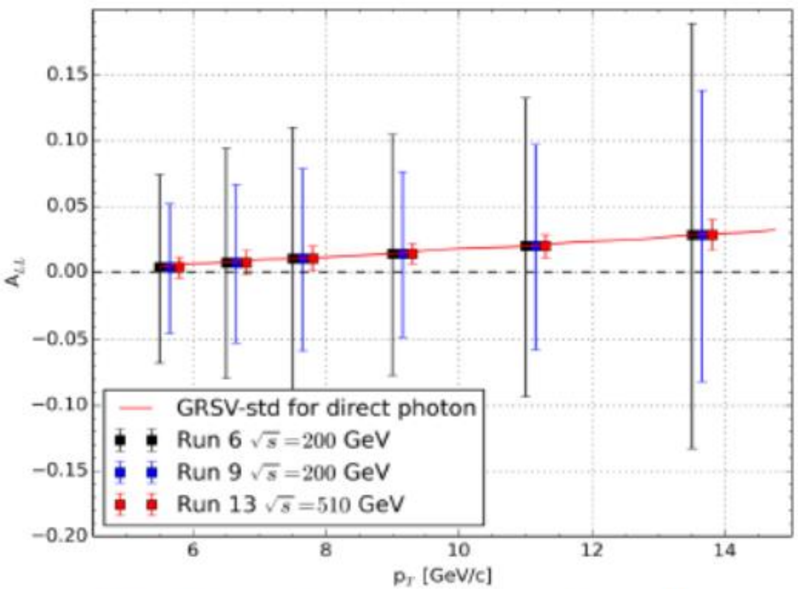
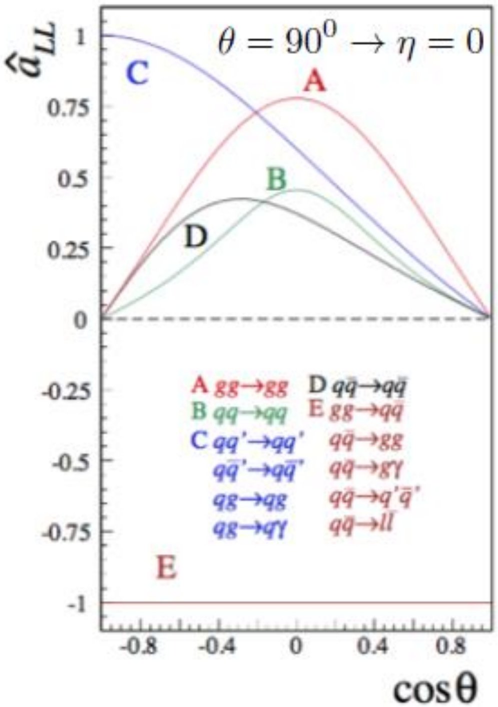


Projected uncertainty for direct photon A_{LL} measurement.

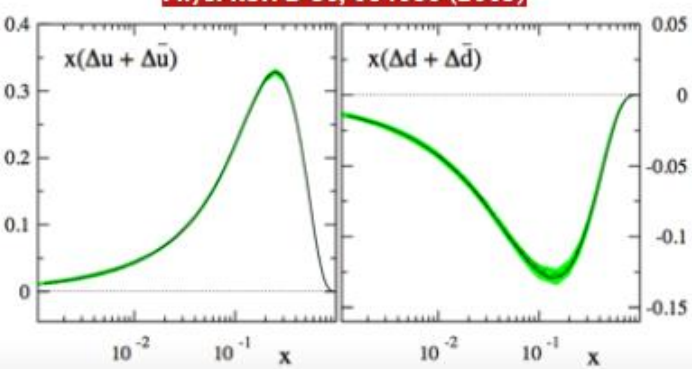
Motivation: "Directly" access the sign of ΔG

T. Moon

PRL 113, 012001 (2014)



Phys. Rev. D 80, 034030 (2009)



- q-g scattering starts to dominate at RHIC p_T above ~5GeV/c.
- Preferential fragmentation of u to π^+ and d to π^-.

$$A_{LL}^{\pi^+} \approx a_{gg}\Delta g \Delta g + \underbrace{a_{ug}}_{>0}\underbrace{\Delta u}_{>0}\Delta g$$

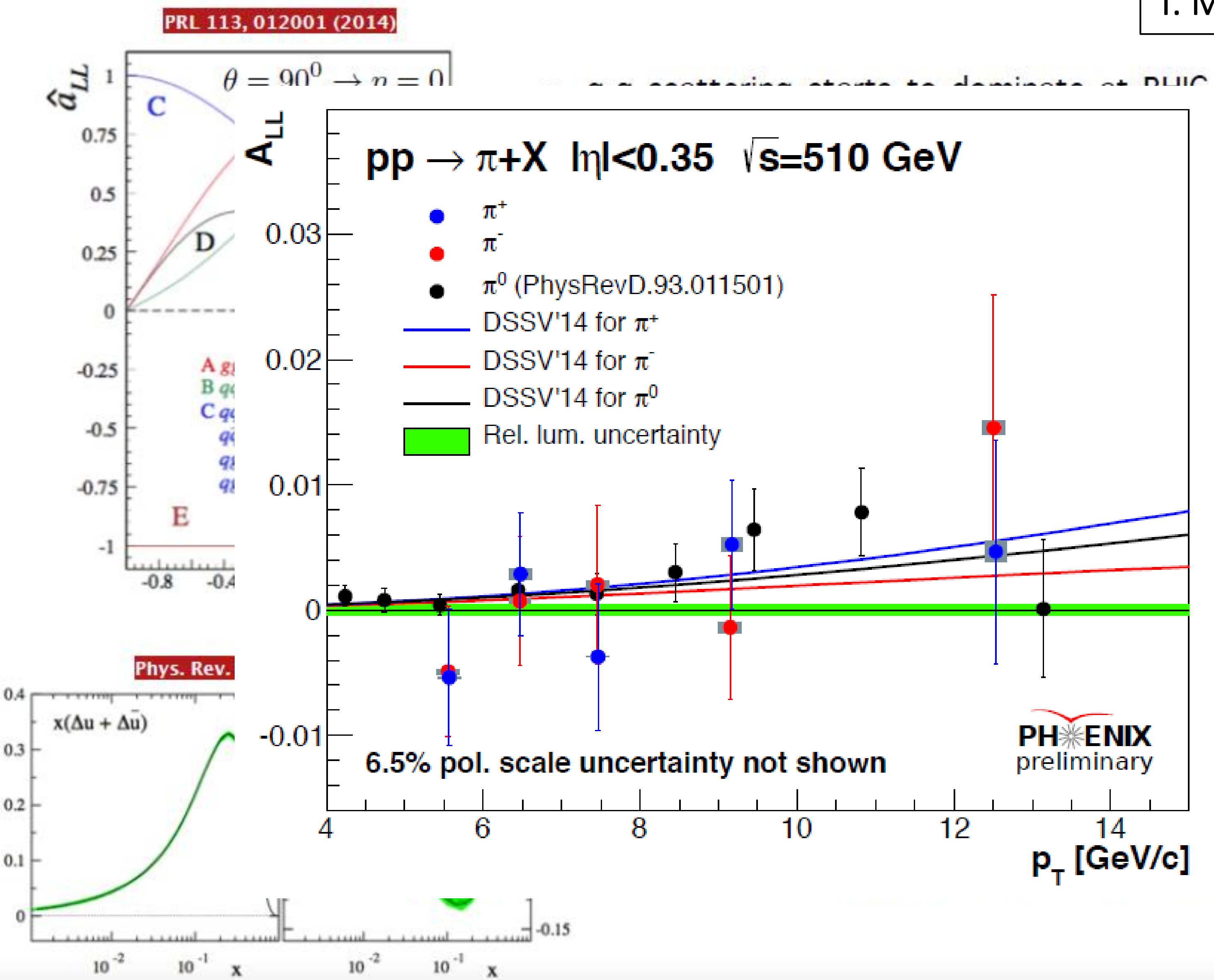
$$A_{LL}^{\pi^-} \approx a_{gg}\Delta g \Delta g + \underbrace{a_{dg}}_{>0}\underbrace{\Delta d}_{<0}\Delta g$$

$$\Delta g > 0 \rightarrow A_{LL}^{\pi^+} > A_{LL}^{\pi^-}$$

and vice versa

Motivation: "Directly" access the sign of ΔG

T. Moon



... p_T above ~5GeV/c.

d to π.

$\Delta u \Delta g$ >0

$\Delta d \Delta g$ <0

$A_{LL}^{\pi^-}$

Summary: Recent A_{LL} Measurements

STAR

√s (GeV)	RHIC Run	Central Jets	Central Dijets	Interm. Dijets	Interm. Pions	Forward Pions	Forward Dijets
200	2006	Published* x>0.05			Published x>0.01		n/a
200	2009	Published x>0.05	Published x>0.05	Published x>0.01			n/a
200	2015	Underway x>0.05	Underway x>0.05			Underway x>0.0025	n/a
510	2012	Preliminary x>0.02	Preliminary x>0.02	Underway x>0.004	Underway x>0.004	Published x>0.001	n/a
510	2013	Preliminary x>0.02	Preliminary x>0.02	Underway x>0.004	Underway x>0.004	Published x>0.001	n/a
200 & 510	2021+						Future x>0.001

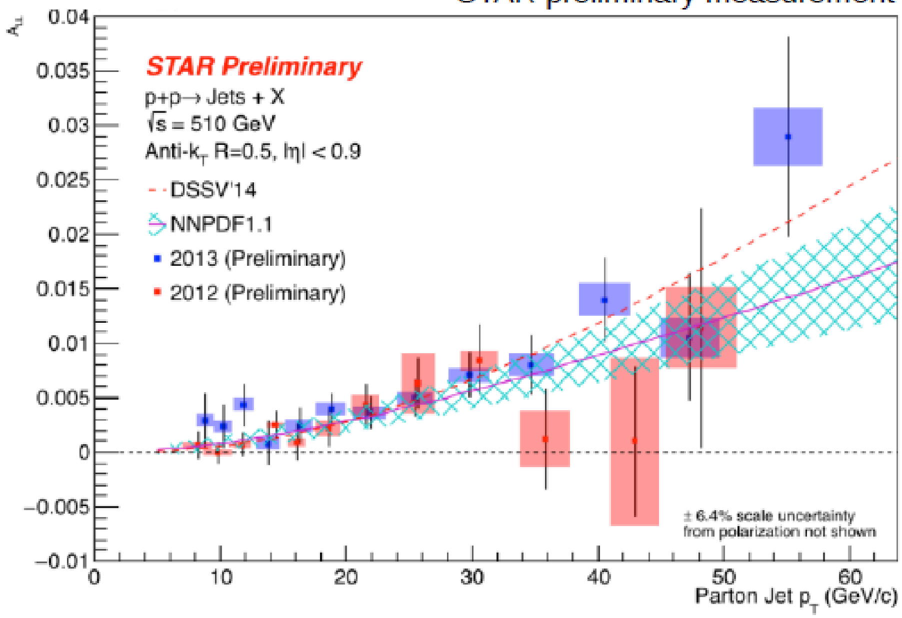
* not presented

C. Dilks

easurements

2013 Data (compared to 2012)

STAR preliminary measurement



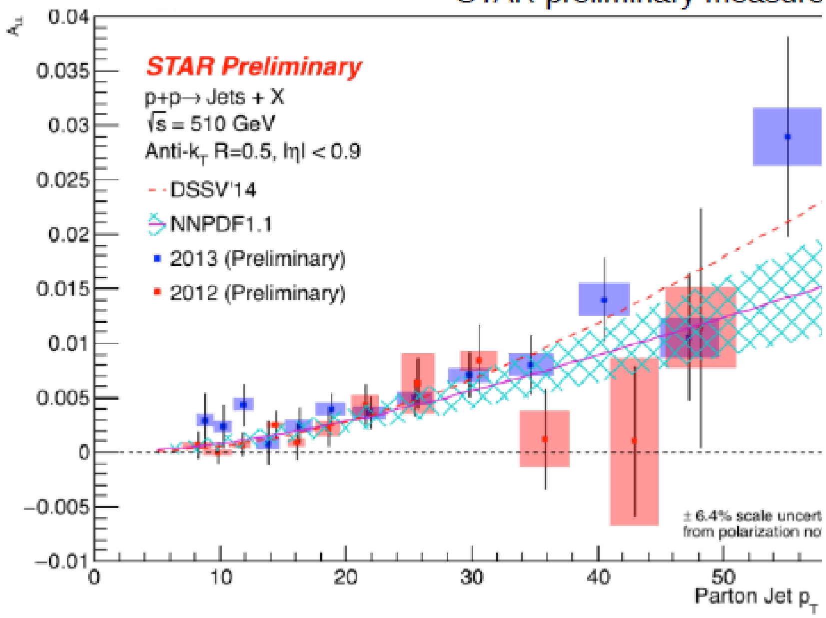
				term. ijets	Interm. Pions	Forward Pions	Forward Dijets
					Published x>0.01		n/a
				lished >0.01			n/a
						Underway x>0.0025	n/a
510	2012	Preliminary x>0.02	Preliminary x>0.02	Underway x>0.004	Underway x>0.004	Published x>0.001	n/a
510	2013	Preliminary x>0.02	Preliminary x>0.02	Underway x>0.004	Underway x>0.004	Published x>0.001	n/a
200 & 510	2021+						Future x>0.001

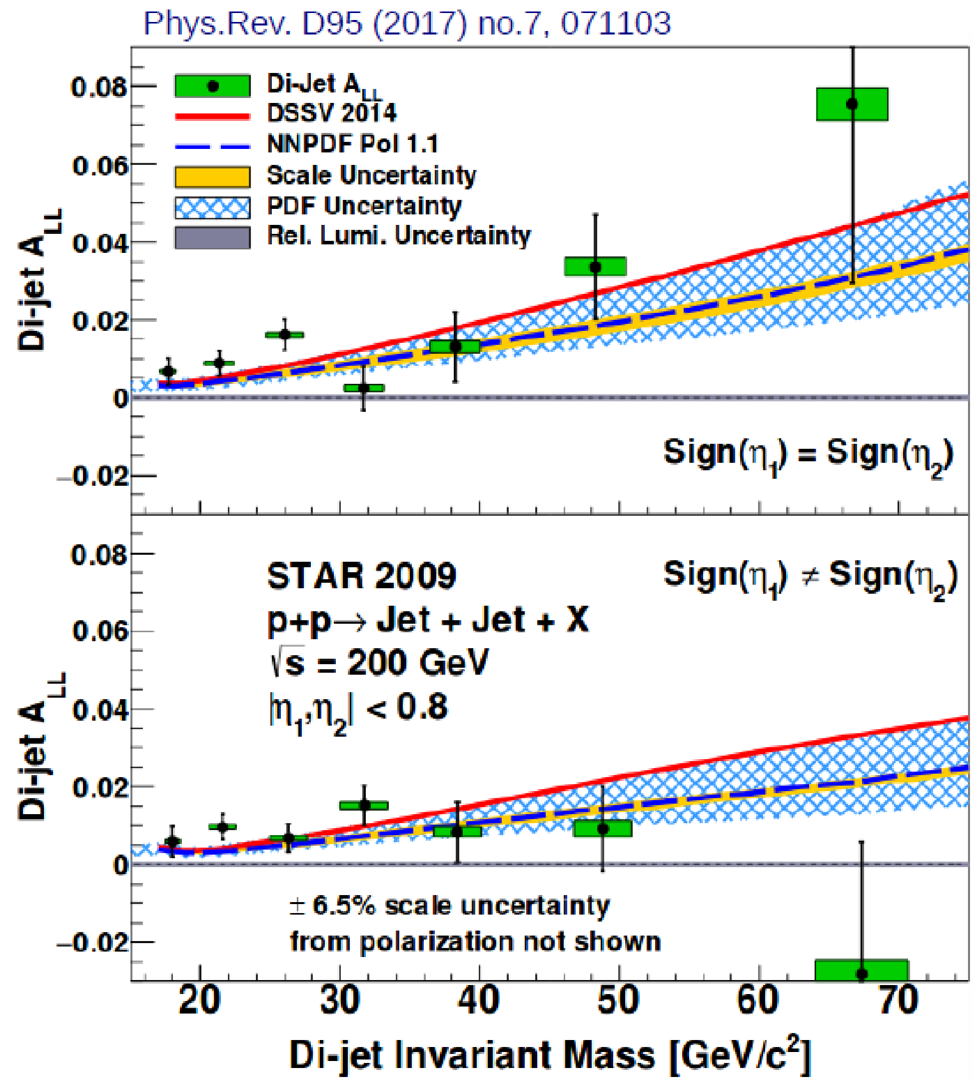
* not presented

C. Dilks

2013 Data (compared to 201

STAR preliminary measure





510	2012	Preliminary x>0.02	Prelimi x>0.
510	2013	Preliminary x>0.02	Prelimi x>0.
200 & 510	2021+		x>0.001

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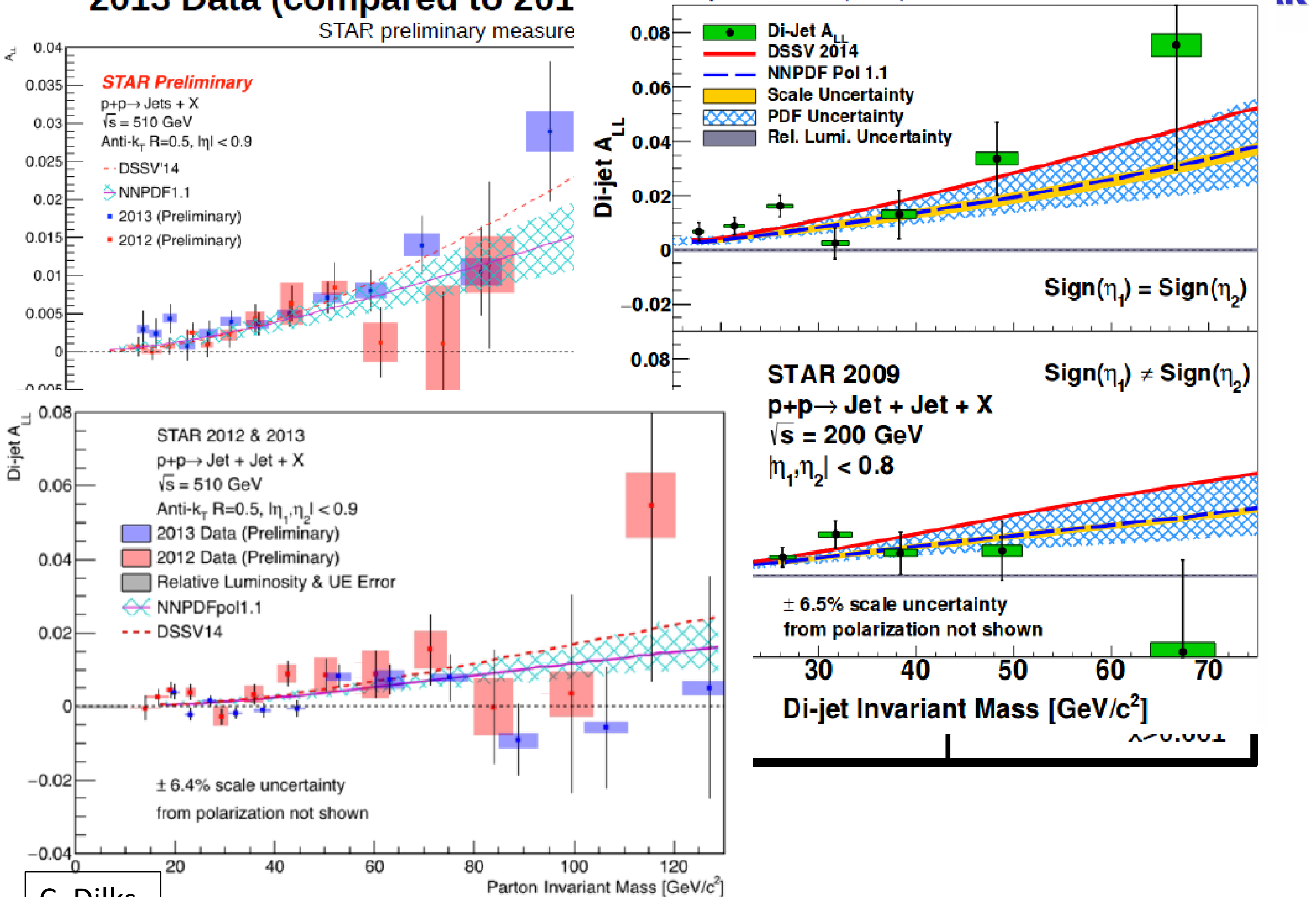
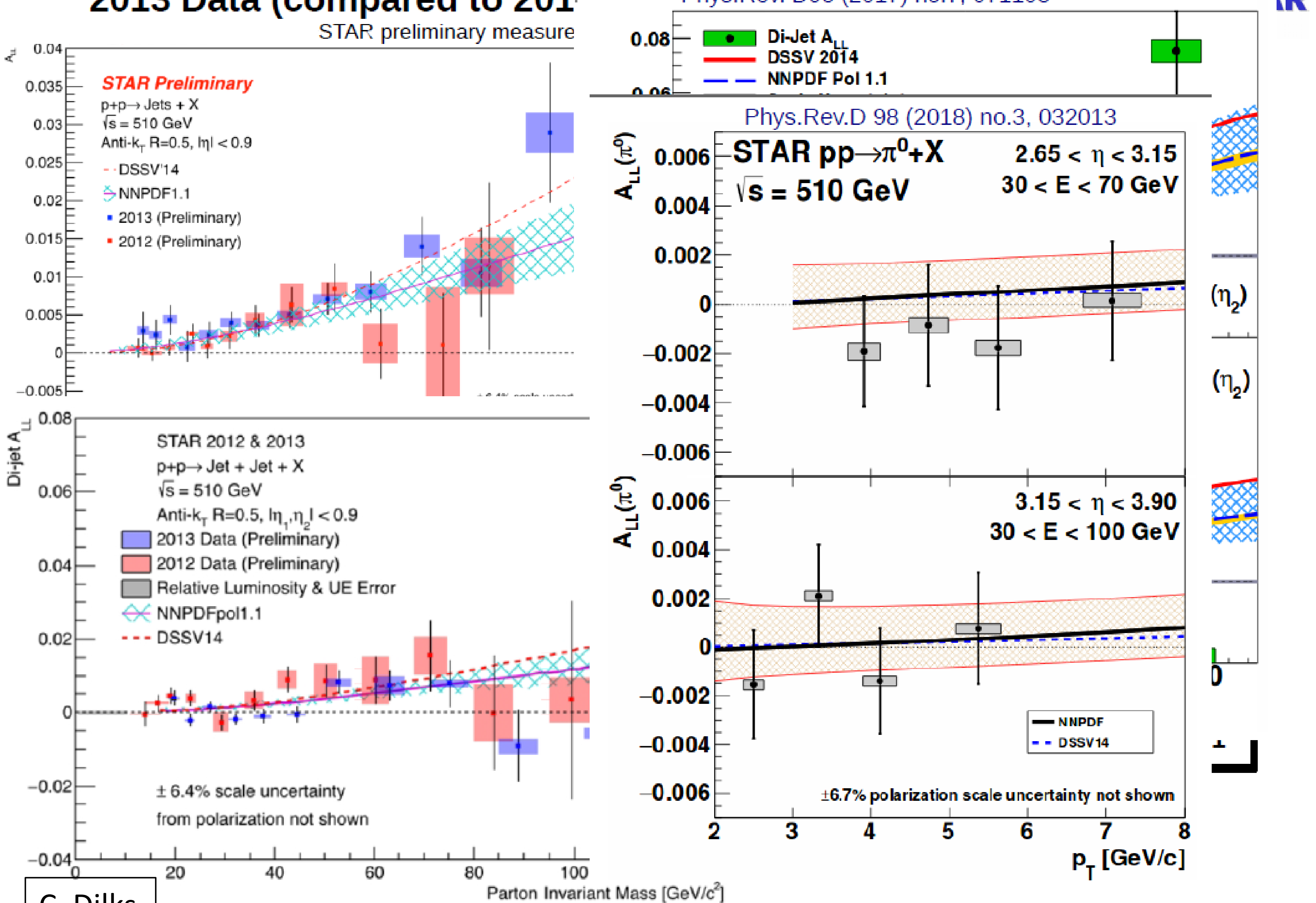
C. Dilks

2013 Data (compared to 201



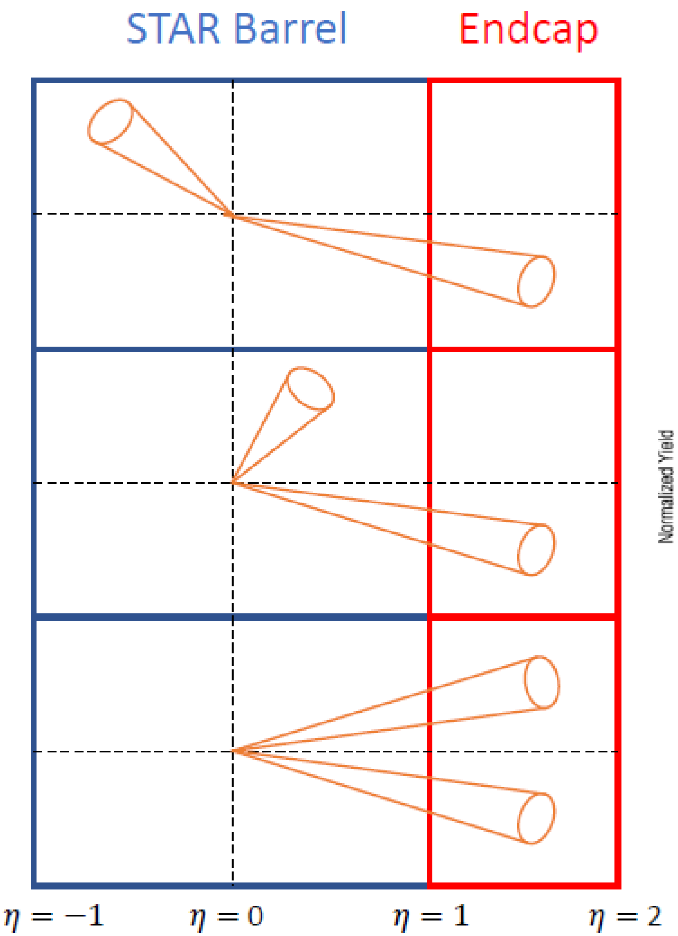
C. Dilks

2013 Data (compared to 201

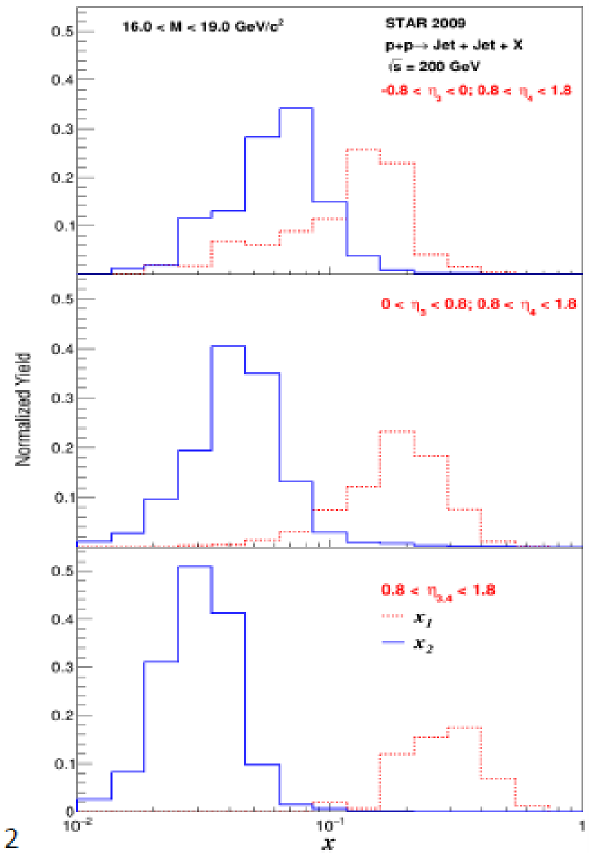


C. Dilks

Forward Rapidity dijet Topology



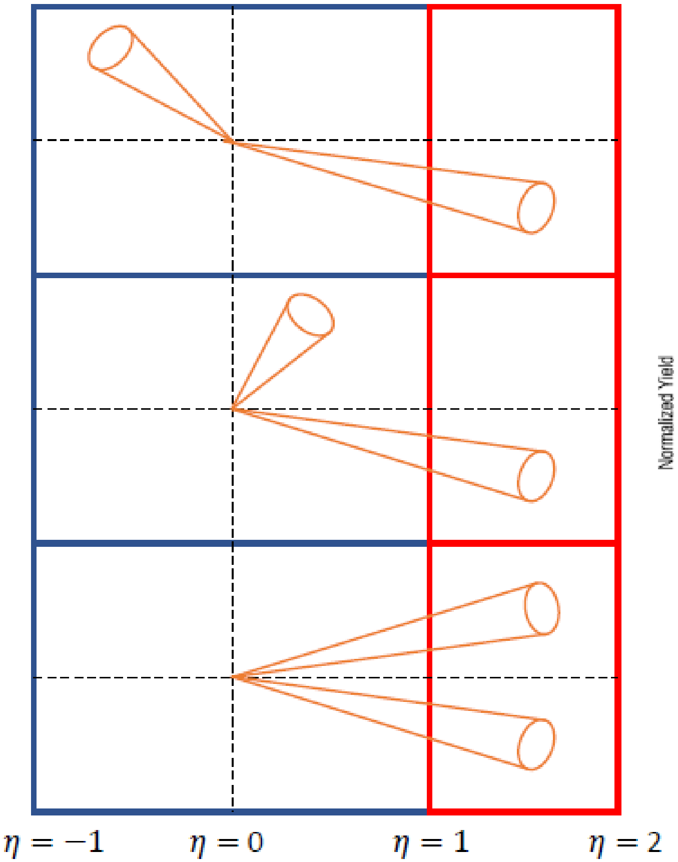
PhysRevD.98.032011

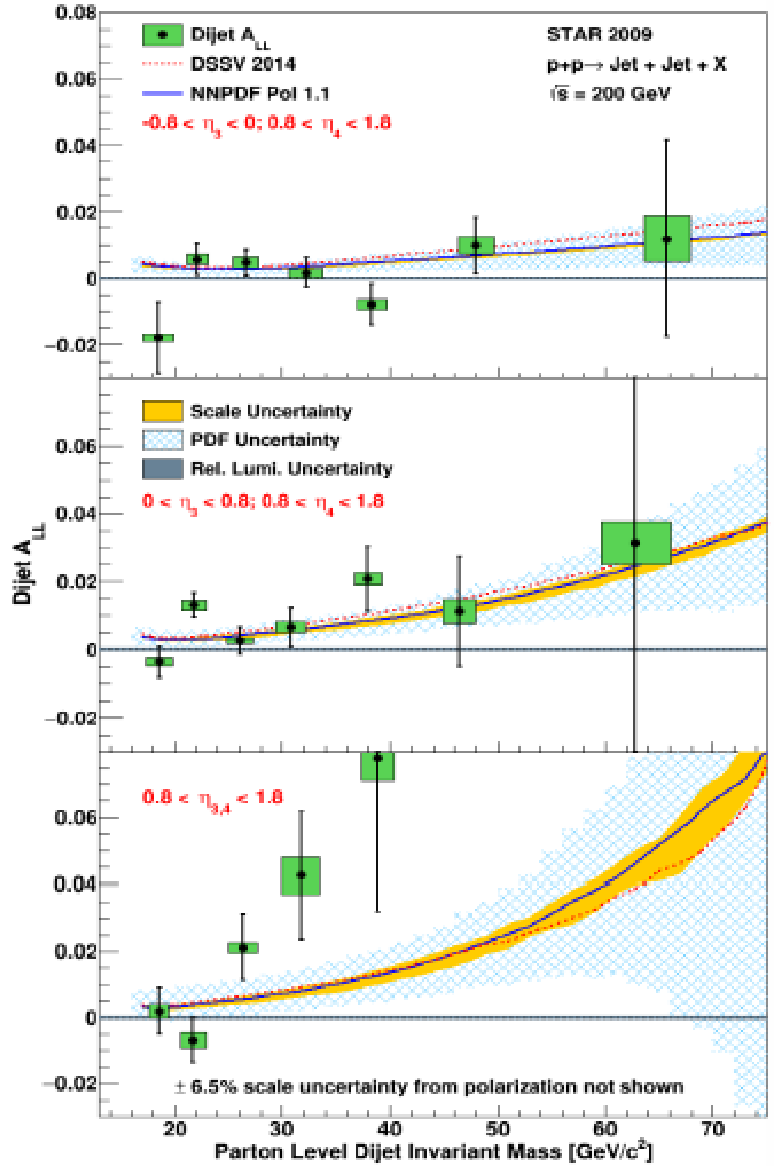


- Adding the Endcap opens up several new dijet topologies
- Forward jets probe lower values of gluon momentum fraction while selecting more asymmetric collisions
- The large imbalance in momentum fractions, coupled with the unpolarized PDF's, suggests that x_2 is dominated by gluons, while x_1 are most often valence quarks

T. Lin

Forward Rapi





Endcap opens up
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t often valence

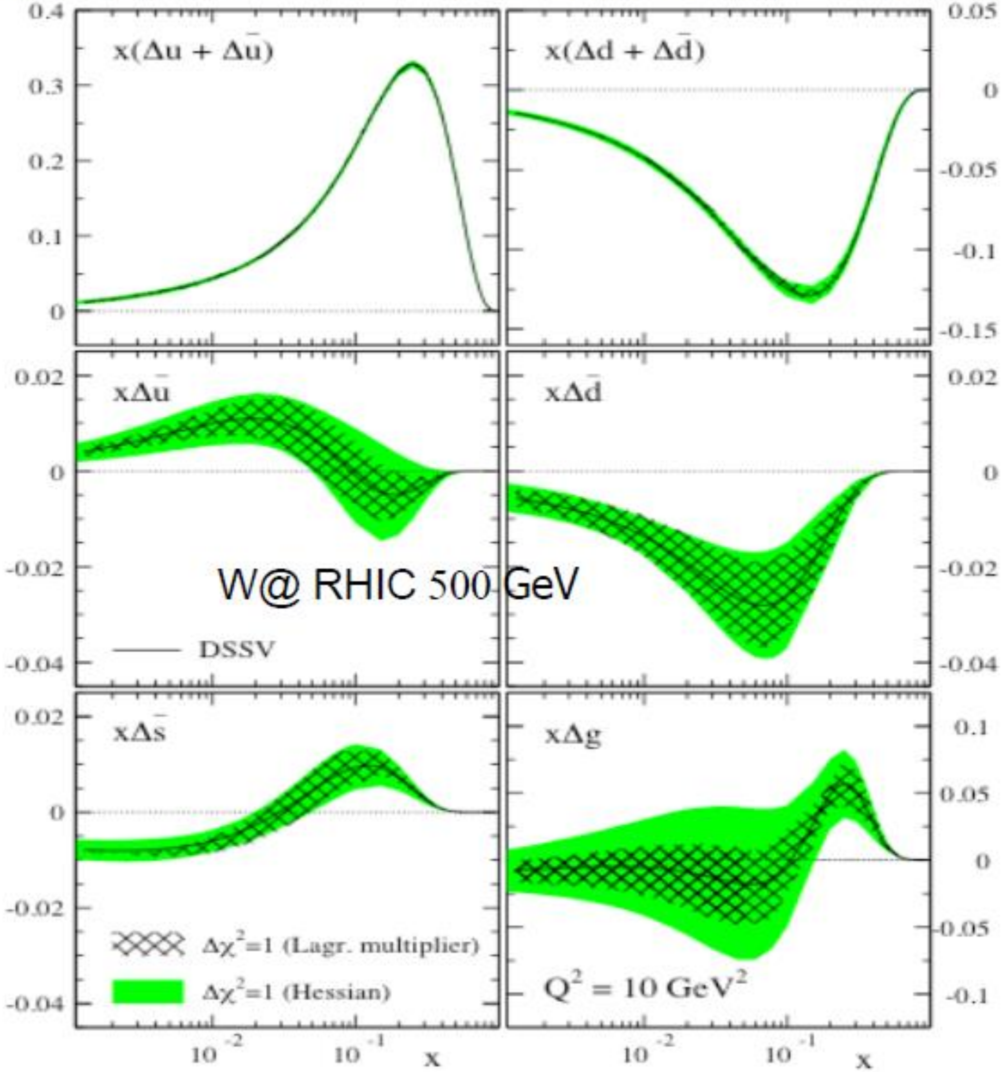
T. Lin

Flavor separation of nucleon spin

- Sea quark polarization not well constrained by DIS data yet:

STAR: Q. Xu

PHENIX: S. Park

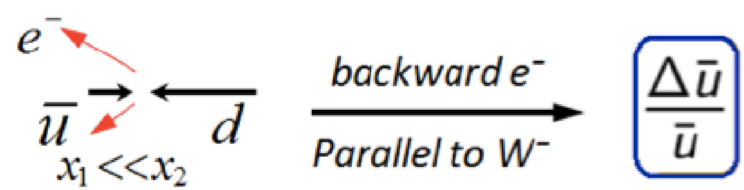


D. de Florian, R. Sassot, M. Stratmann, W. Vogelsang, PRD80 (2009)034030

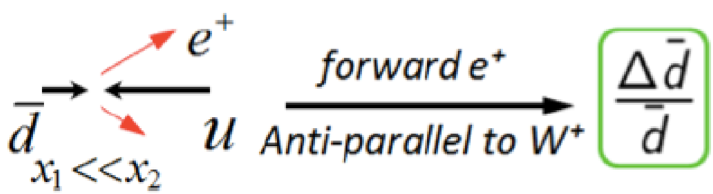
Expectation of W A_L at RHIC

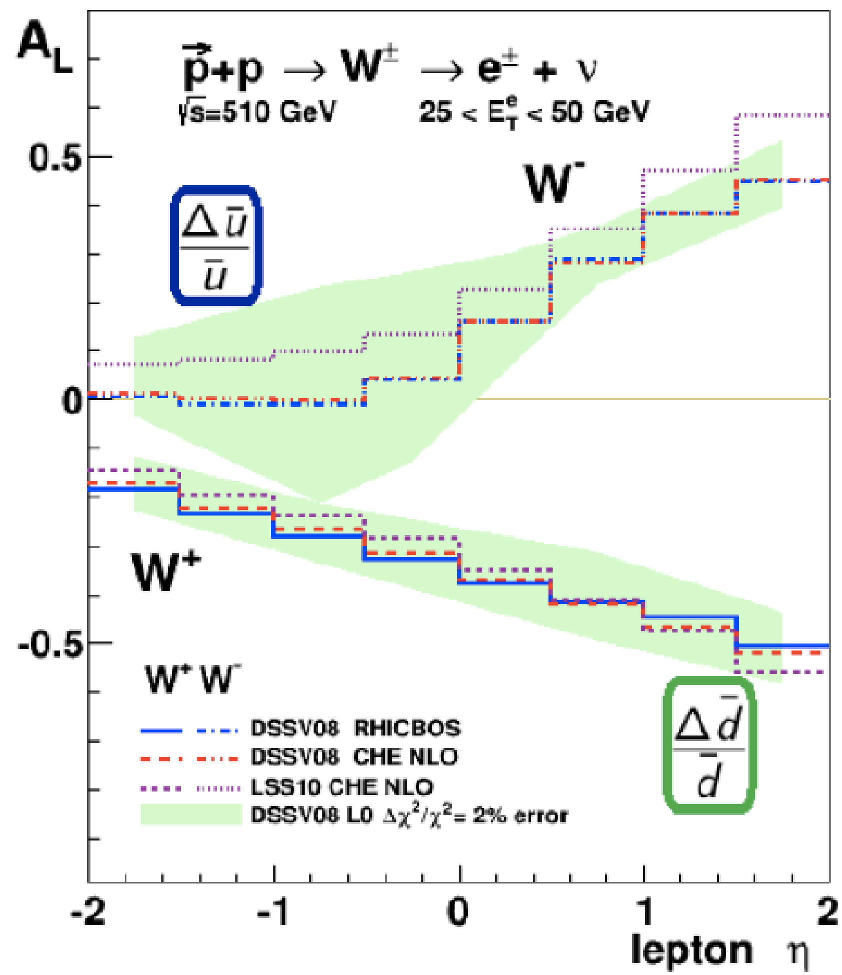
- Large parity-violating asymmetries expected.
- Simplified interpretation at forward and backward rapidity:

$$A_L^{W^-} \propto \frac{-\Delta d(x_1)\bar{u}(x_2)+\Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2)+\bar{u}(x_1)d(x_2)}$$



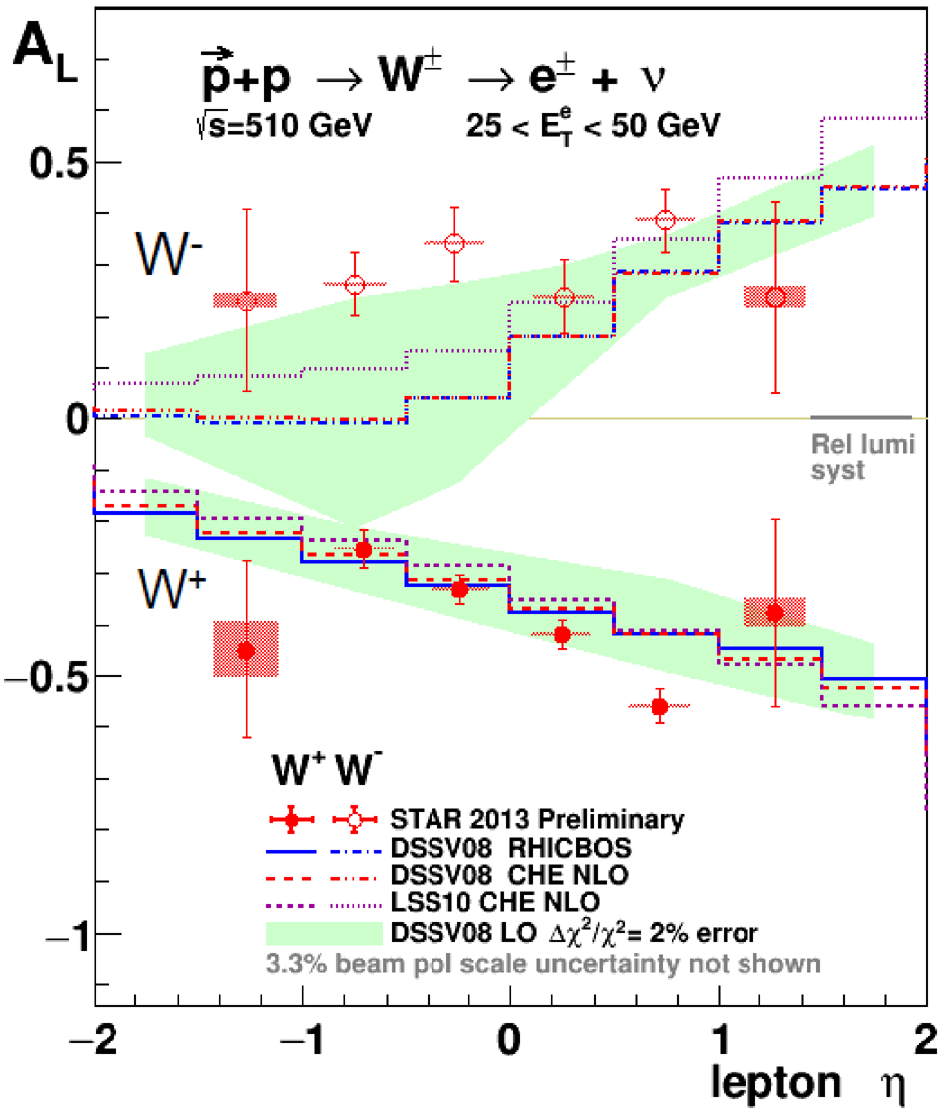
$$A_L^{W^+} \propto \frac{-\Delta u(x_1)\bar{d}(x_2)+\Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2)+\bar{d}(x_1)u(x_2)}$$





Q. Xu

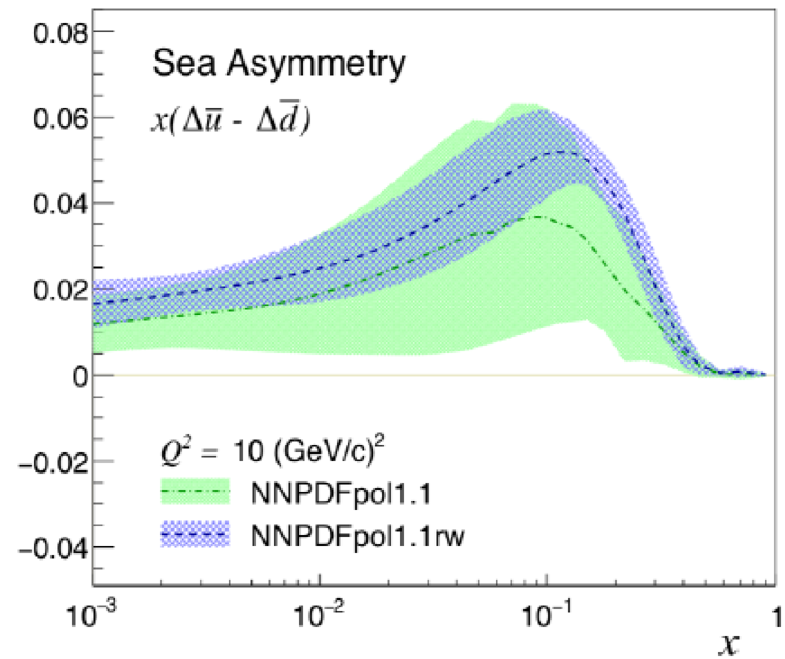
W A_L results – STAR 2013



Q. Xu

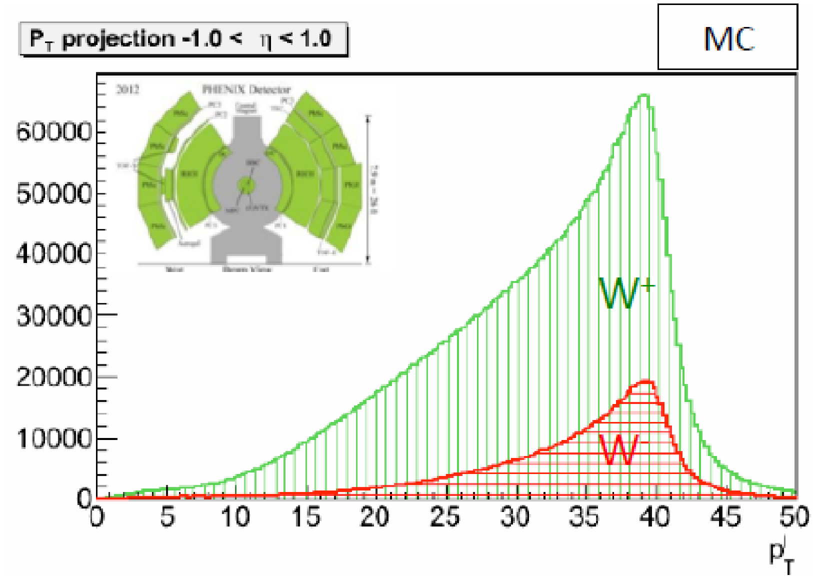
- A_L results at near-forward rapidity added.
- Further confirmed the polarized sea asymmetry:

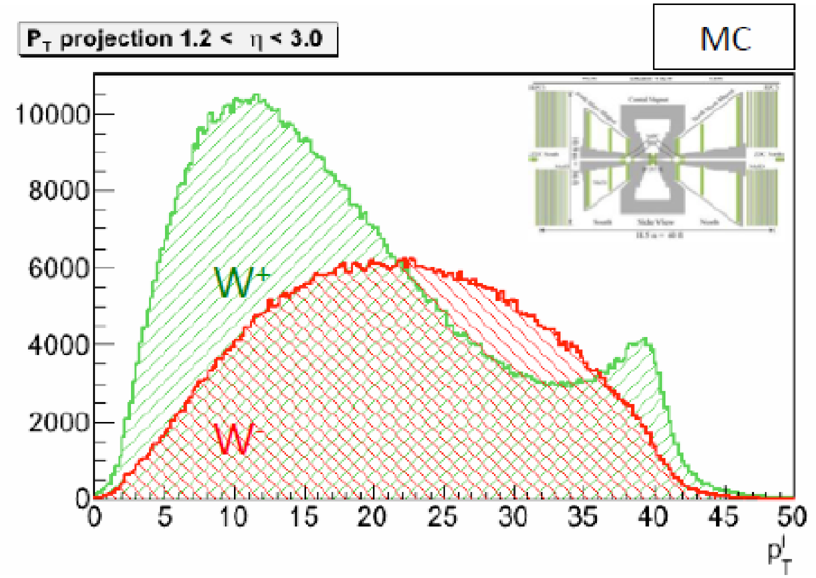
$$\Delta\bar{u} > \Delta\bar{d}$$



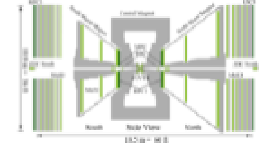
S. Park

$W^{\pm} \rightarrow \ell^{\pm}$ Kinematics





- Different kinematics at mid-rapidity and forward rapidity
- Jacobian peak at mid-rapidity
- Suppressed/no Jacobian peak at forward rapididity
- Access via two decay channels: electrons at mid-rapidity and muons at forward rapidity
- Different analyses to identify W signals in mid- and forward rapidities



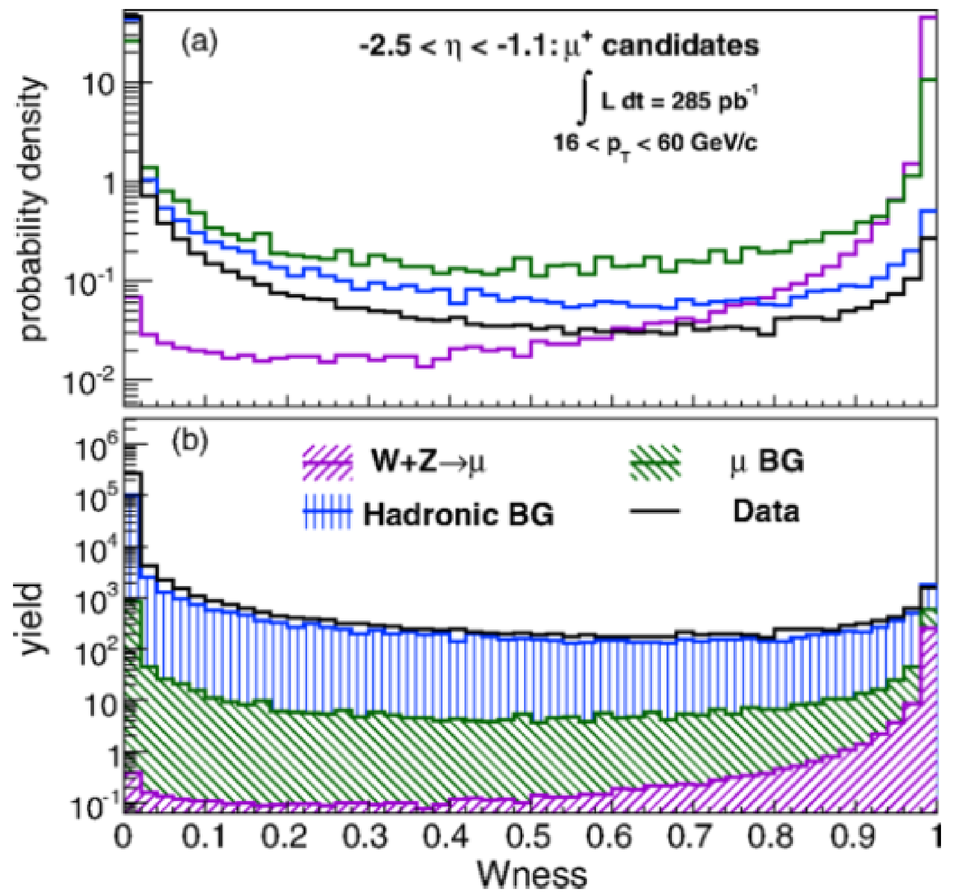
S. Park

Forward measurement

- Reducing BG by likelihood based pre-selection
- Multivariate analysis: 5-9 signal/BG sensitive kinematic variables
- Define likelihood ratio (Wness) based on signal (MC) and BG shapes (data)

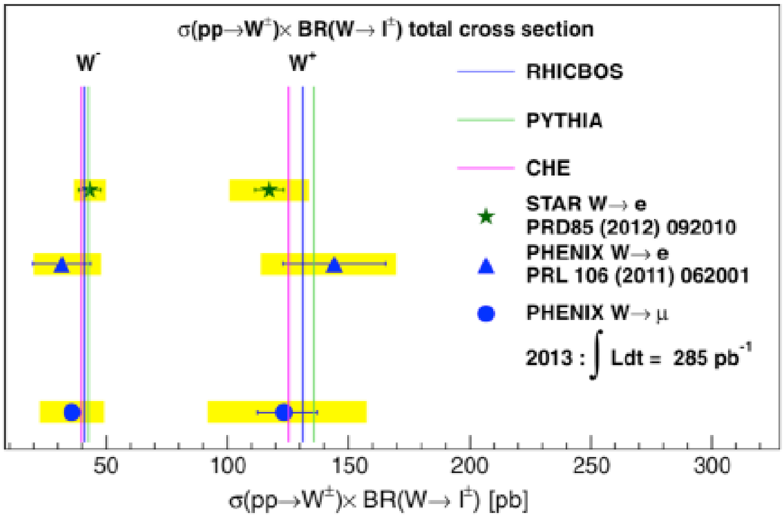
$$\mathrm{Wness} \equiv \frac{\lambda_{\mathrm{sig}}(\mathrm{x})}{\lambda_{\mathrm{sig}}(\mathrm{x}) + \lambda_{\mathrm{BGs}}(\mathrm{x})}$$

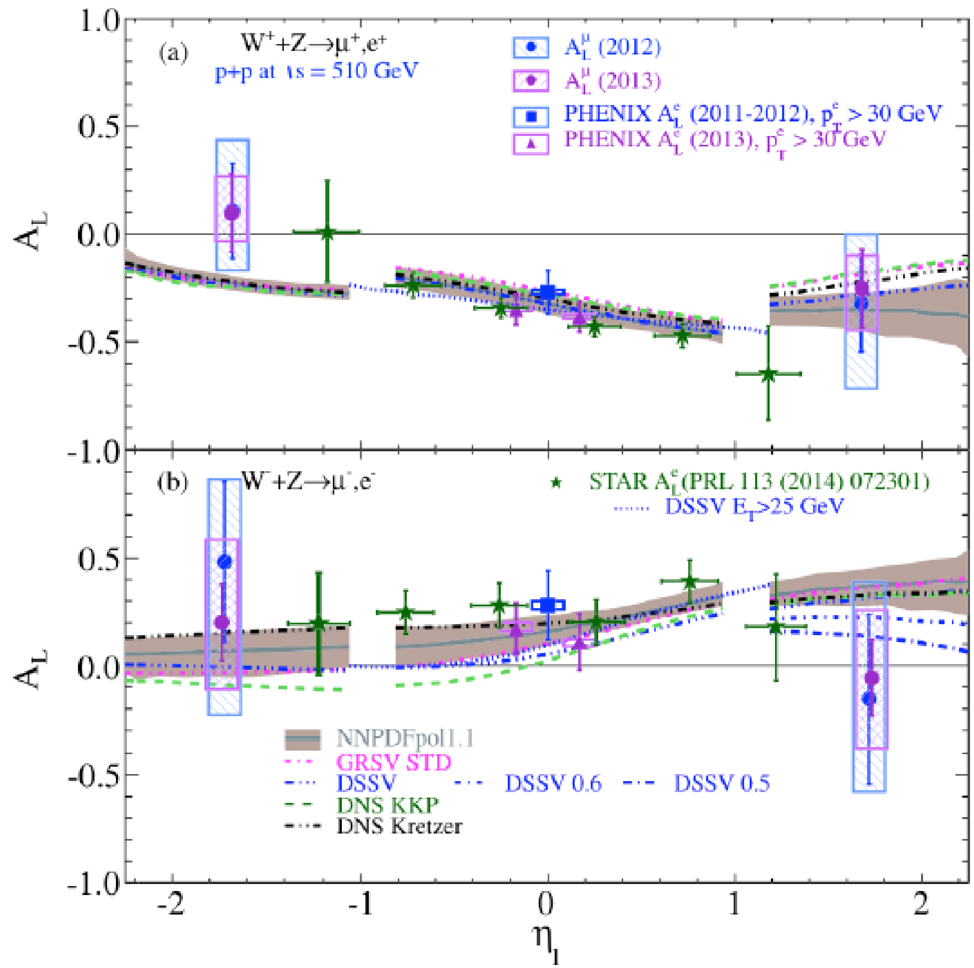
Wness
- Wness → 1: signal-like event
- Wness → 0: background-like event



Forward measurement

S. Park





- First results from muon decay channel published
- Cross sections consistent with previous measurements and theoretical calculations within uncertainties

Phys. Rev. D 98, 032007 (2018)

HERMES SIDIS e^{+-} on p and D targets

P. Kravchenko talk

Recent analyses complement existing publications on longit. spin

- Provides **3D** binning **(x, z, p_{hT})**, first time.

e.g. A_1 for K:

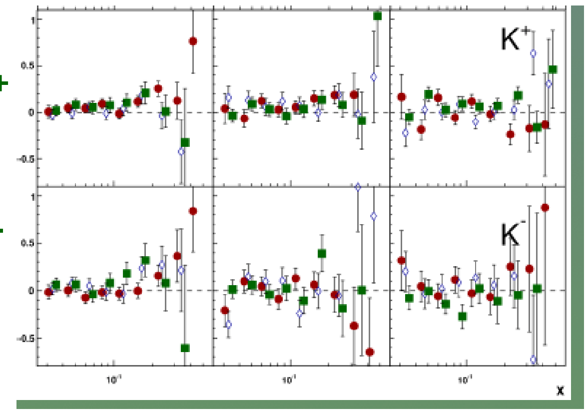
Also done for π

No significant p_T nor z dependence.

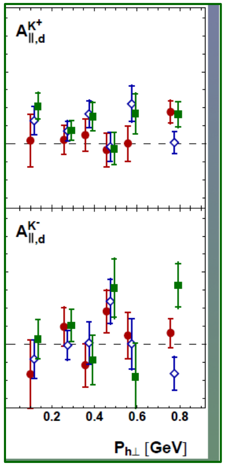
vs x in 3 z bins

K+

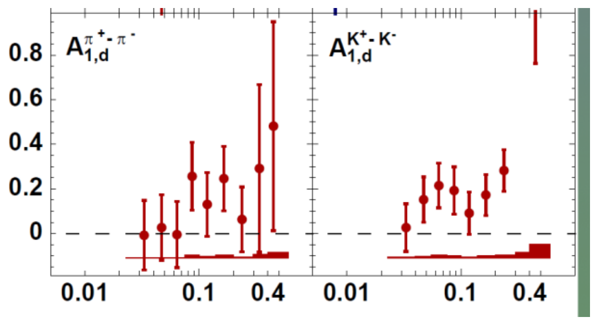
K-

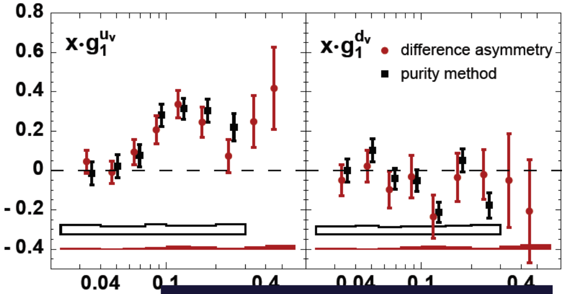


vs p_T



- Asymmetry for charge h difference $A_1^{h^+-h^-}$





A. Airapetian et al., PRD 75 (2007)

Using p and D targets, valence distributions: $g_1 u_v$ and $g1d_V$,

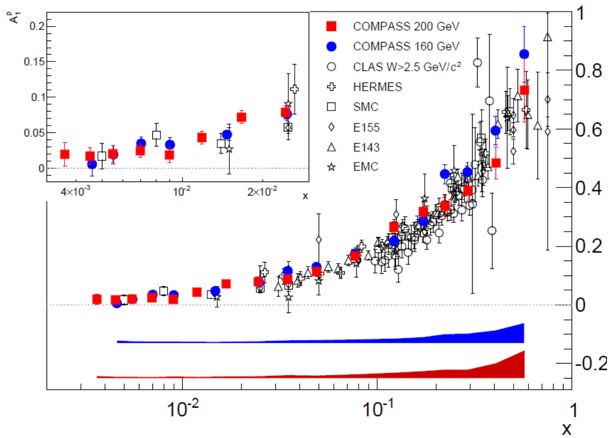
Fragmentation functions cancel, not needed.

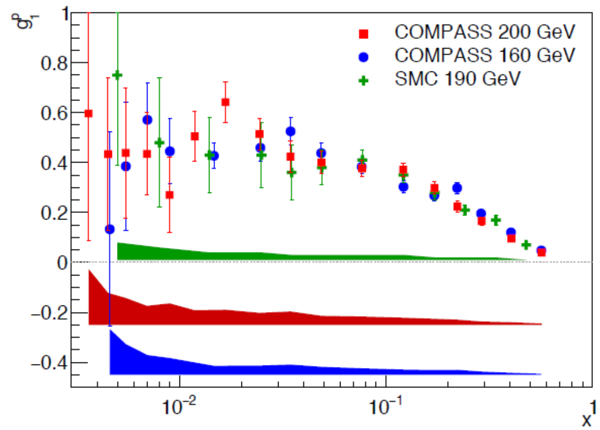
COMPASS legacy on nucleon helicity measurements

200 GeV *PLB 752 (22016) 18*
160 GeV *PLB 690 (2010) 466*

Y. Bedfer's talk

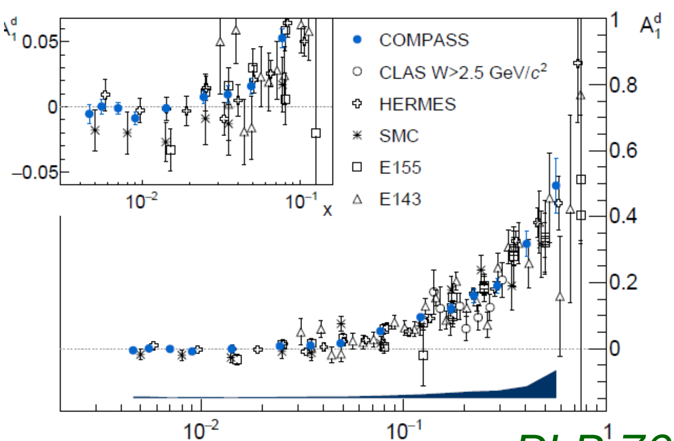
proton

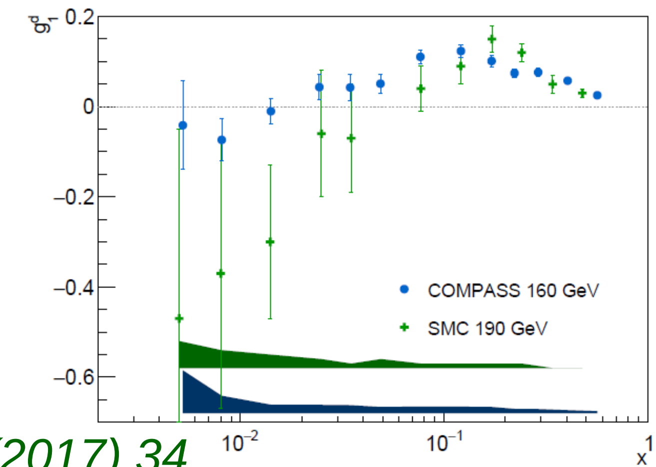




- down to x= 0.003
- g_1^p clearly positive

deuteron





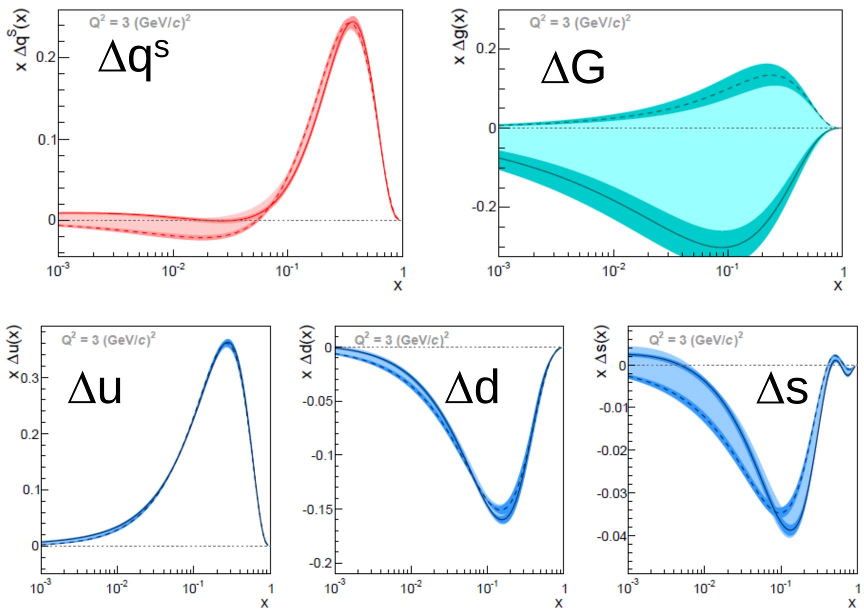
PLB 769 (2017) 34

g_1^d compatible with zero at low x, contrary to hints from SMC

COMPASS cont'd

Y. Bedfer's talk

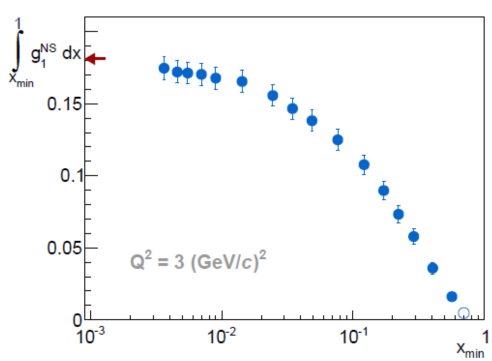
NLO QCD fit to world data
Polarized PDFs:



$$0.26 < \Delta\Sigma < 0.36$$

Large uncertainty due to poor knowledge of ΔG shape.

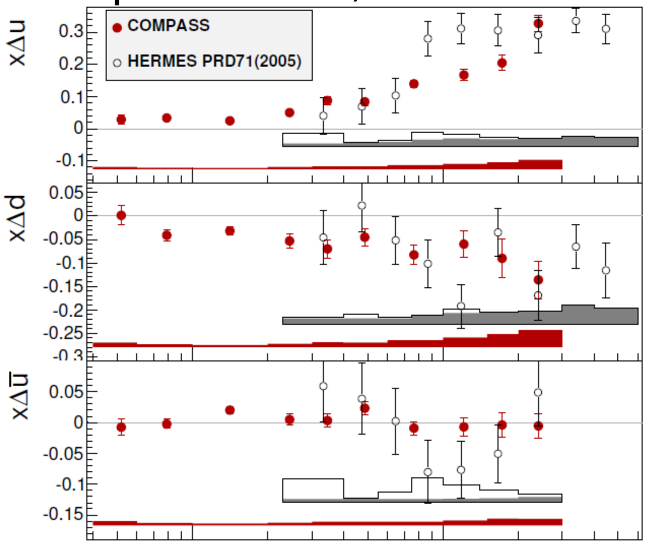
ΔG poorly constrained by g_1 only.

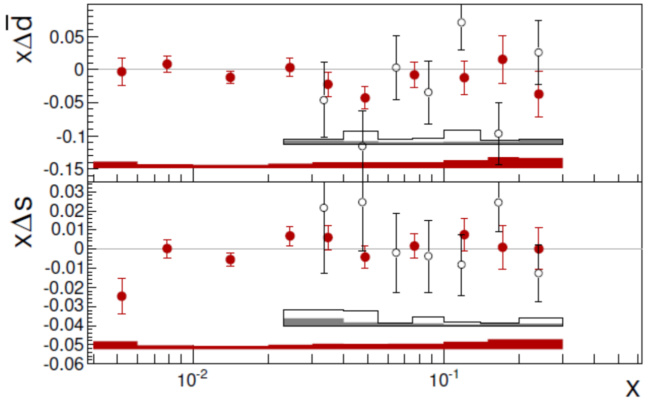


Bjorken sum rule validated to 9% accuracy.

COMPASS cont'd.

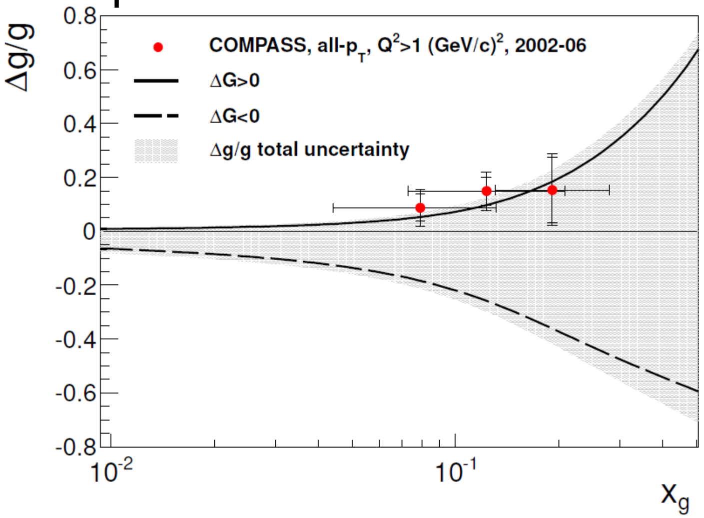
Polarized quark PDFs, from SIDIS down to x=0.003, assuming DSS07 FF.



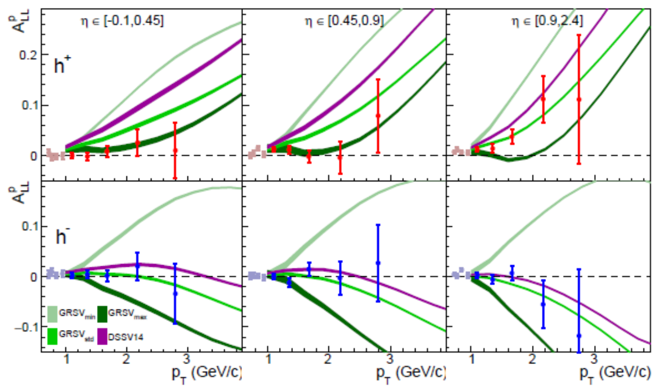


PLB ***693*** *(2010)*

ΔG, direct extraction at LO, compared to NLO fits



ΔG, from incl. hadron at low Q2, compared to NLO fits. *EPJC44 (2005)*



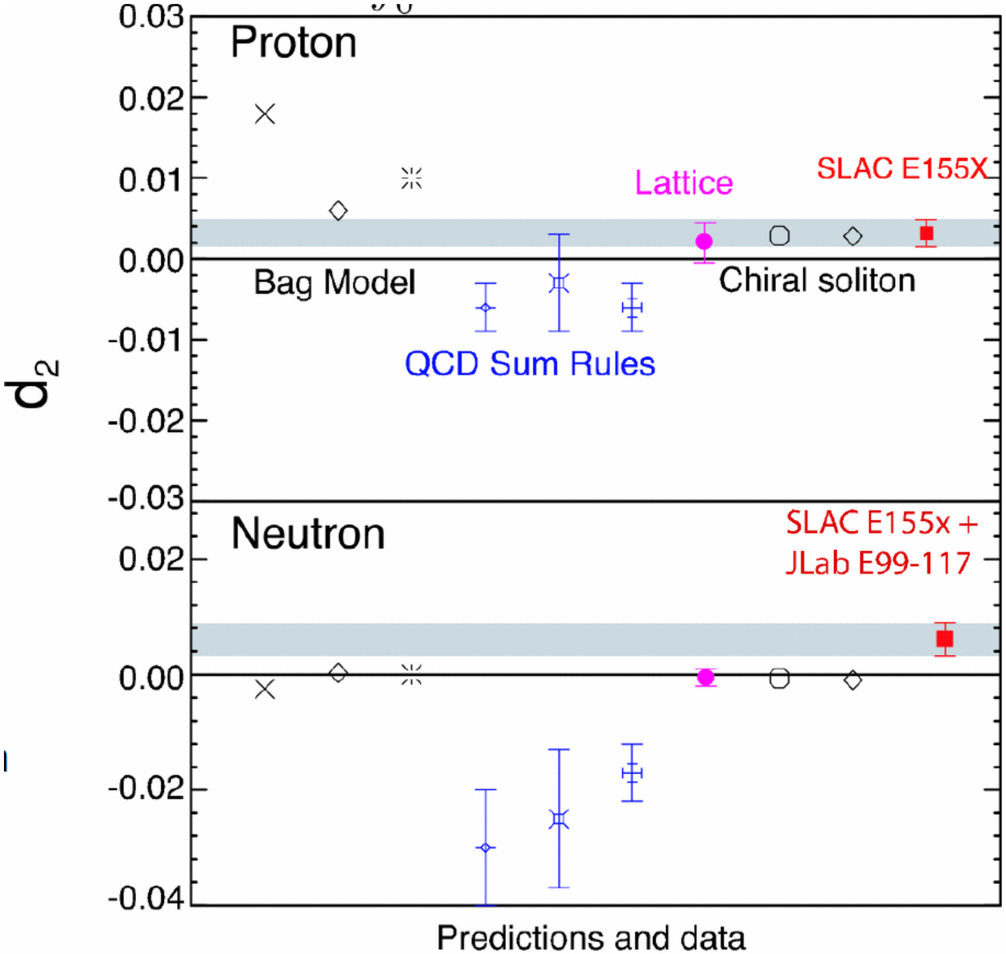
New calc. with large log resummation . Agrees with pol PDFs.

Spin Structure Functions at JLab

d_2: A clean probe of quark-gluon correlations

B. Savatsky talk

$$d_2(Q^2) = \int_0^1 x^2[2g_1(x,Q^2) + 3g_2(x,Q^2)]dx = 3\int_0^1 x^2\overline{g_2}(x,Q^2)dx$$

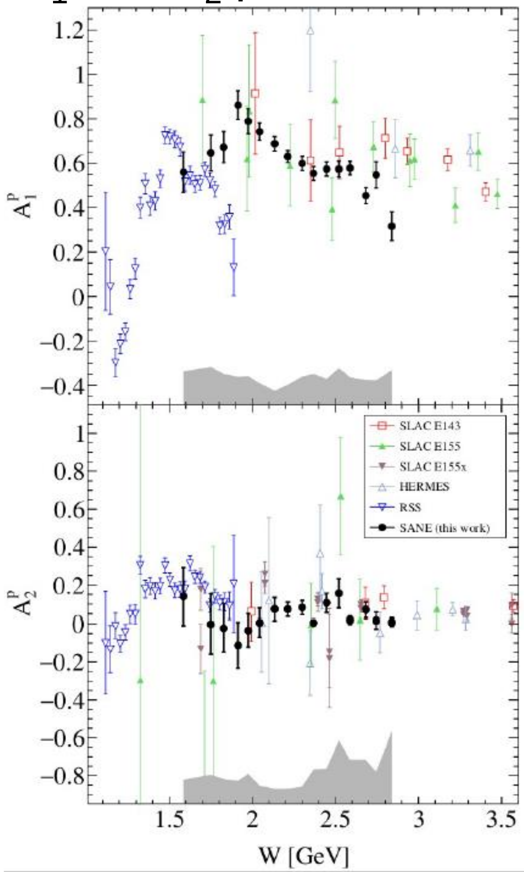


- d_2 is a clean probe of quark-gluon correlations / higher twist effects
  - → d_2 is the 3rd moment of a sum of the spin structure functions
  - → matrix element in the Operator Product Expansion
    - » *it is cleanly computable using Lattice QCD*
- Connected to the *color Lorentz force* acting on the struck quark (Burkardt)
  - → same underlying physics as in SIDIS $k_\perp$ studies

A_1, A_2, d_2 : significant progress

B. Savatsky talk

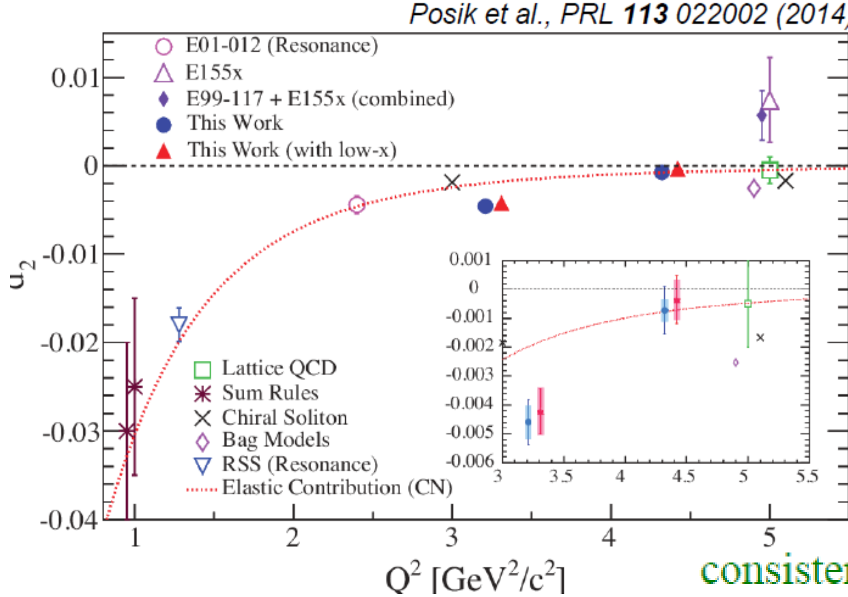
A_1 and A_2 proton from SANE



- $A1$ is roughly linear vs. ln(W)
  → minimal Q^2 dependence
- $A2$ is consistent with E143 even though E143 has much greater Q^2
  → minimal/weak Q^2 dependence for A2?

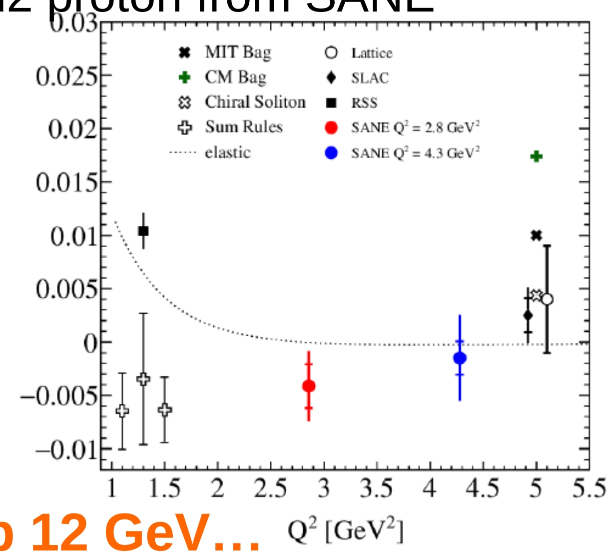
d2 neutron from 'd2n' E06-14

*Posik et al., PRL **113** 022002 (2014)*



consistent with Lattice QCD prediction

d2 proton from SANE

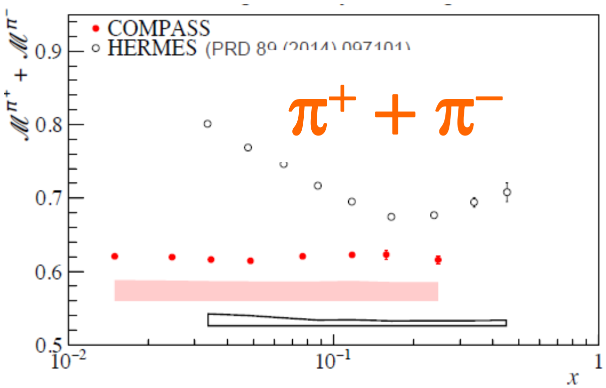


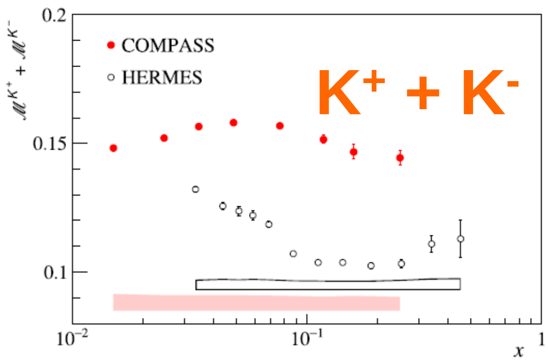
Hint of a negative d_2^p, negative twist-3 at moderate $Q^2 \sim 3$ GeV^2?

And a lot to come from Jlab 12 GeV…

Pion and Kaon multiplicities - COMPASS

F.Kunne talk





>1200 points available for fits to fragmentation functions

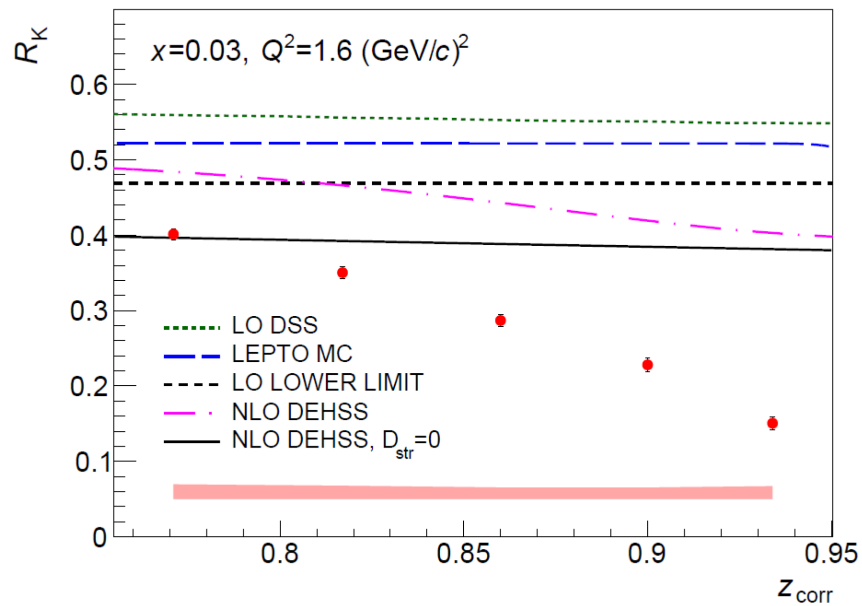
- Hints to explain discrepancies Compass/Hermes:Target mass corrections and W dependence
- Global fits point to smaller value of FF D_s^K / D_u^K

with impact on Δs extraction from polarized SIDIS (more compatible with Δs from inclusive DIS+SU3)

Ratio M(K-)/ M(K+):

First time data at high z.

Disagree with present theory calculations, especially for low ν



hep-ex/1802.00584

Tensor-pololarized SF of deuteron

QT.Song
talk

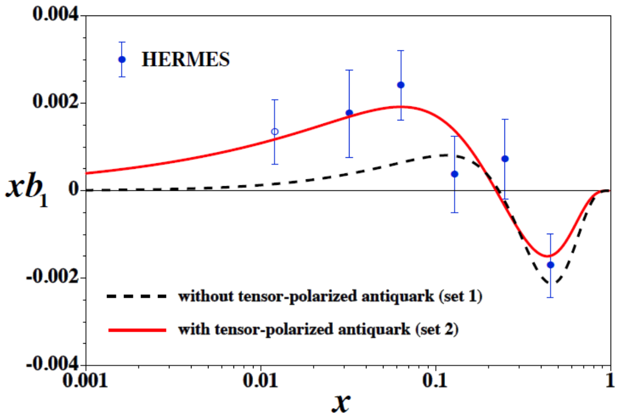
Deuteron, S-D wave Mix. → **b_1 SF**

b_1 small in old predictions (xb1 ~10 $^{-4}$), 10 times larger in Hermes data- 2005

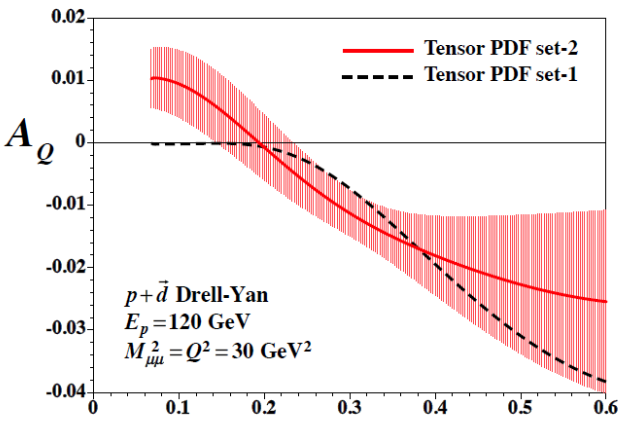
Possible explanations: 6 quarks config,
or shadowing effects in nucleus

Tensor structure of Deuteron can be investigated
- in DIS Jlab (Slifer), b1
- in Drell-Yan at Fermilab E13-09, A_Q

QT.Song talk



Finite tensor-polarized anti-quark needed to fit Hermes data



Based on that, make prediction for Fermilab experiment A_{Q} ~few %

Proton beam 120 GeV on (tensor) polarized D

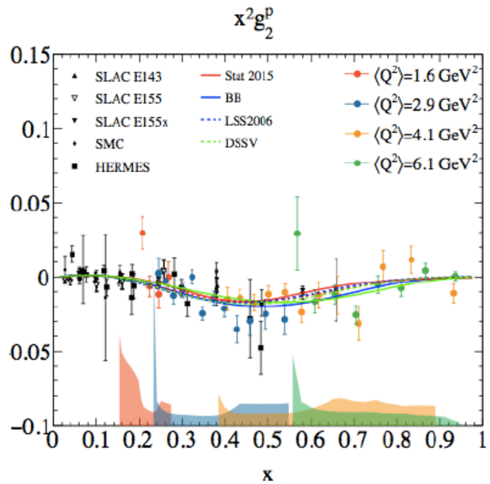
A_{UQ0} at large x_F reflects antiquark tensor-polarized distribution.

Spin structure at low Q^2

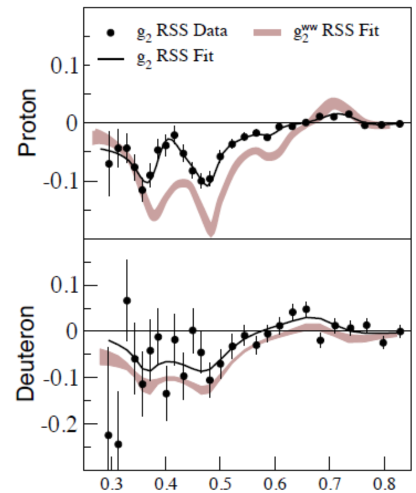
K. Slifer talk

- Measuring **g_2** for higher twist, sum rules GDH, BC, polarisabilities…
- Also a tensor/program target, to measure **b_1**.
- With polarized target hardware developments

SANE g2 p

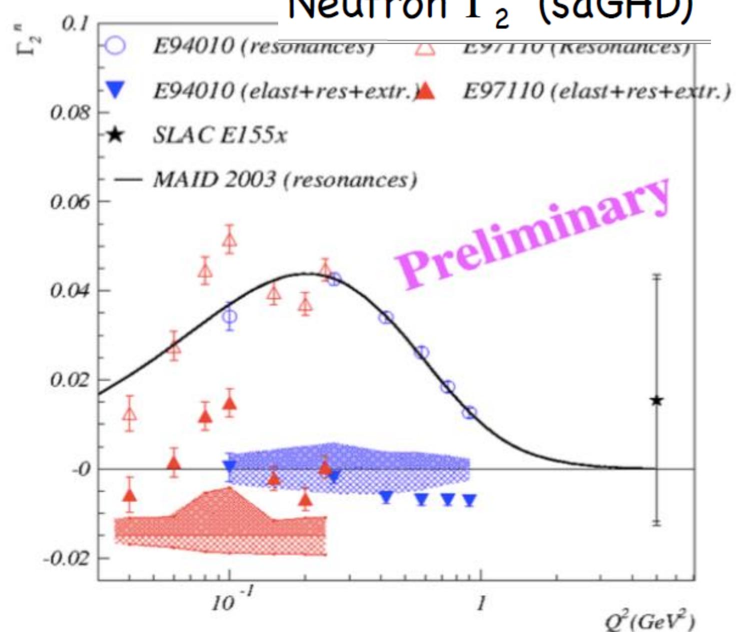


RSS g_2 p and d



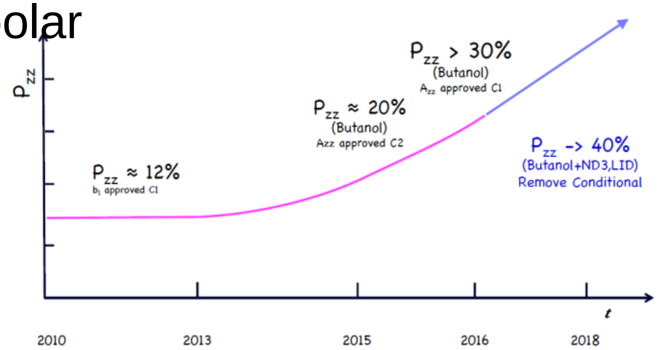
=>Significant HT at low x needed to satisfy Neutron BC sum rule.

Neutron Γ_2 (saGHD)



Jlab expts **g2p (NH3)** and **saGDH (3He),** Impressive sets of very precise preliminary data, large kin. coverage

Tensor polar



year

Transversity and Λ polarization

A. Moretti talk

Goal: access Transversity $h_1^q(x)$ via Λ hyperon polarization P
Λ self analyzing
Struck quark inheriting target transverse polar

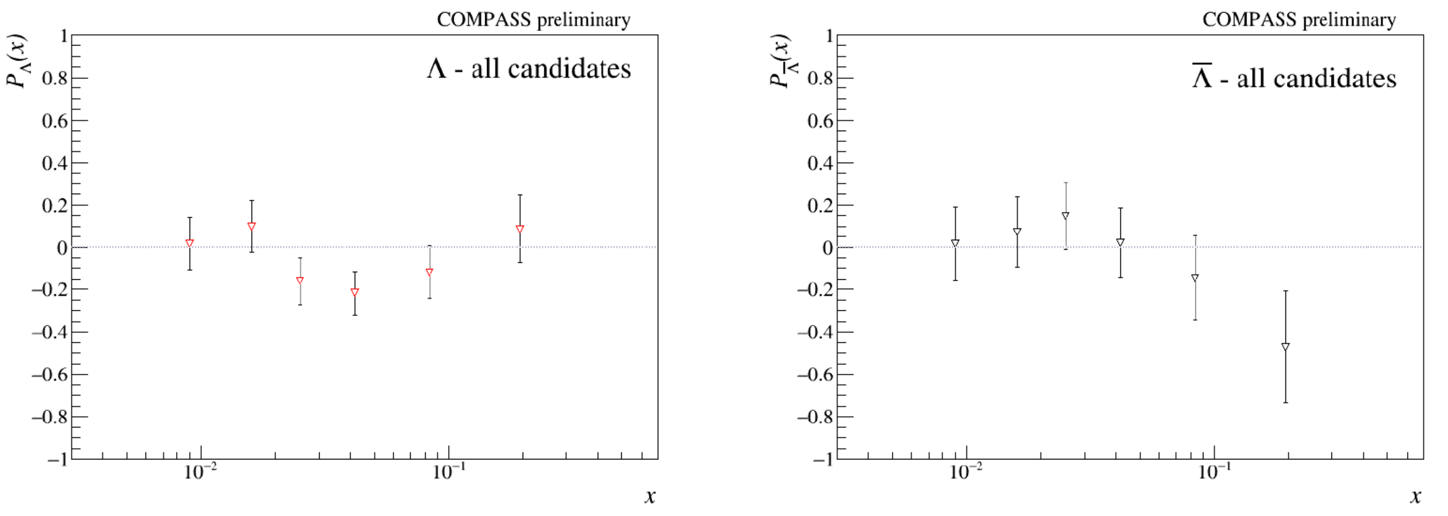
Transversity already measured from Collins asymmetry.
If P not zero, can infer transversity of s quark.

Mu beam, transversely polarized p or d target

Transversity and Λ polarization

A.Moretti

$P_{\Lambda(\bar{\Lambda})}(x)$



Also measured as function of z and p_T; and in 7 kinematic ranges.
In general found compatible with zero

- Three main hypothesis to interpret the results:

1. the first (transversity a valence object) gives the integrated ratio of the fragmentation functions $H_1^{\Lambda,u}(z)$ and $D_1^{\Lambda,u}(z)$, compatible with zero;
2. the second (only s quark counts) allows for an extraction of $xh_1^s(x)$ dependent on the parameter $c_1 = D_1^{\Lambda,s}(z)/D_1^{\Lambda,u}(z)$;
3. the third (quark-diquark model) again gives $xh_1^s(x)$ without assumptions on the fragmentation functions.

Even if definite conclusions cannot be drawn, mainly due to the statistical uncertainty, this is a contribution to a longstanding issue

Ratios of fragmentation functions are extracted here for the first time

Final Thoughts

- Study of the helicity structure of the nucleons being carried out enthusiastically both theoretically and experimentally
- New developments in global analyses will help to better interpret data and lattice calculations are starting to provide first principle calculations to compare to
- Experimental effort is large and varied, spanning collision energies from 500 to a few GeV, utilizing lepton and hadron probes as well as a wide range of different targets
- Future is bright with more analyses coming from RHIC and JLAB 12 GeV data starting to appear

Thanks to all the speakers!