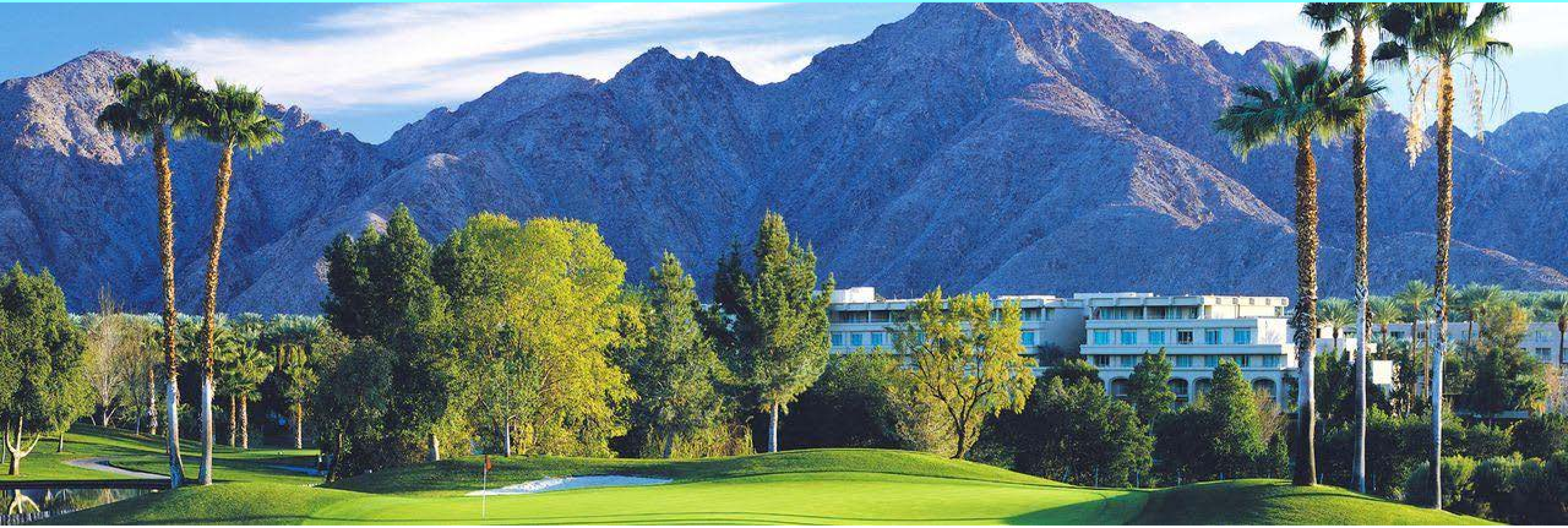
The Structure of the Nucleon



CIPANP 2018, Palm Springs

M. Grosse Perdekamp, University of Illinois

Overview

- The Atomic Hypothesis and the Nucleon

  How do fundamental building blocs of matter, quarks and gluons, form complex composite matter: the nucleon?

- Quark and Gluon Structure of the Proton

  Momentum distributions
  Spin (helicity) distributions

- 3-D Structure and Tomography

  Coordinate space: Generalized Parton Distributions
  Momentum space: Transverse Momentum Dependent Parton Distributions

Richard Feynman on the Atomic Hypothesis

Feynman Lectures, Volume I; Lecture 1, "Atoms in Motion"; Section 1-2, "Matter is made of atoms"; p. 1-2

If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words?

I believe it is the *atomic hypothesis* that *all things are made of atoms — little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another.*

In that one sentence, you will see, there is an *enormous* amount of information about the world, if just a little imagination and thinking are applied.

From an Ancient Hypothesis to Modern Science
How do Atoms Form Complex Matter?

First ideas by Greek philosophers:

Leukip and Demokrit formulated the atomic hypothesis:

There are small particles, atoms, of which all matter is made and which cannot be divided in smaller parts.

After 80 generations, some 2400 years later:

Our experimental tools may have identified the atoms of nature and lead us to quantitative answers how these form the complex visible matter!

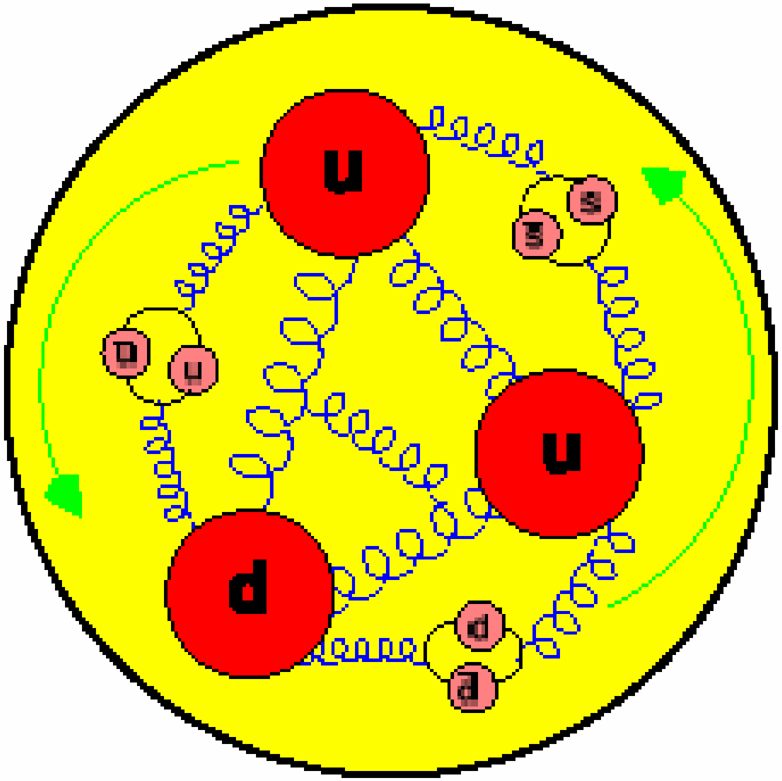
At the Intersection of Particle and Nuclear Physics

The proton is the fundamental bound state of QCD. Quarks and gluons are the constituents:

Can we understand the wave function of the proton from first principles QCD ?

Present (modest) status:

Description of proton in hard scattering processes with parton distribution functions.

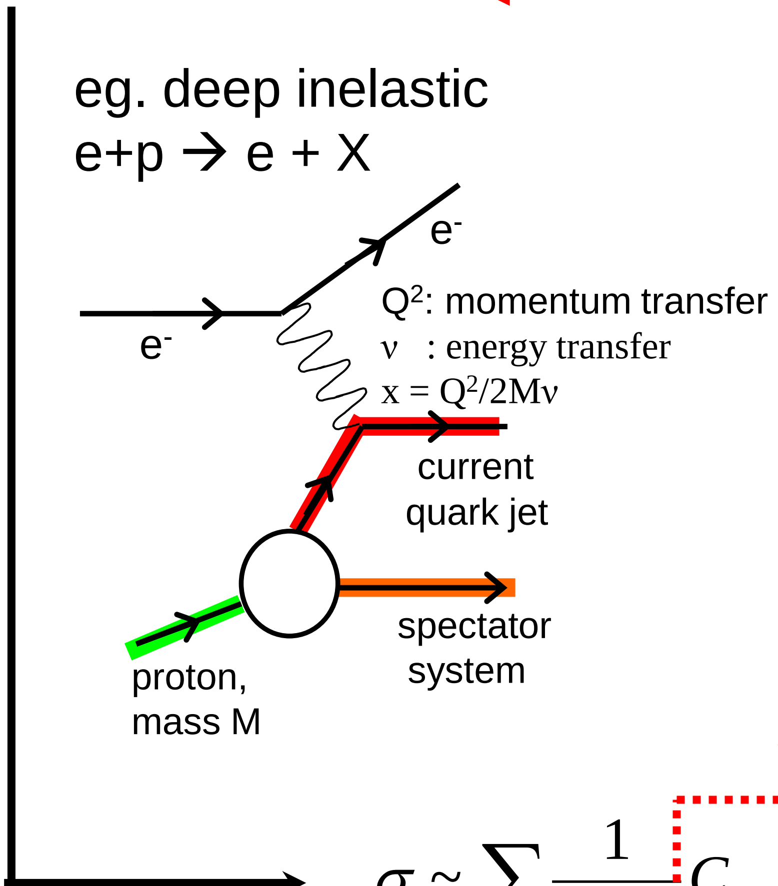


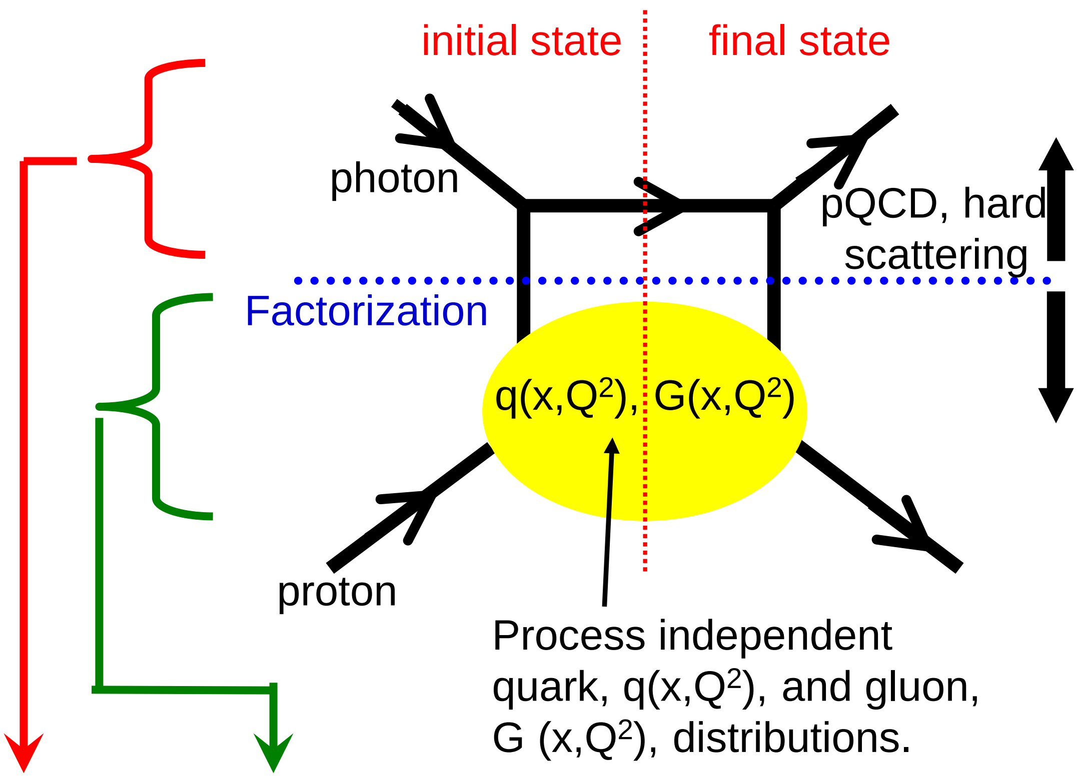
Quark and Gluon Structure from Scattering Experiments with High Energy Probes

Measure:
Cross Section

Optical Theorem

Analyze:
Forward Elastic Scattering Amplitude





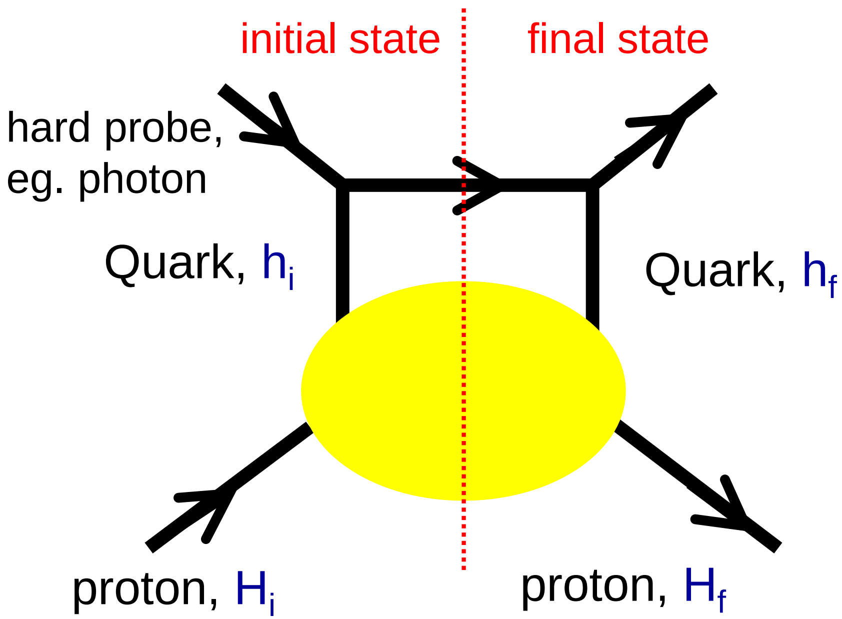
$$\sigma \sim \sum_{\mu\ldots\nu} \frac{1}{Q^{-t/2}} C_{t=d-n_{\mu\ldots\nu}}(Q^2)\langle p \,|\, O^{\mu\ldots\nu} \,|\, p\rangle$$

Operator product expansion in twist parameter t, $t=d-n_{u..v}$

Wilson coefficients — Operator matrix element

Helicity Amplitudes for k_T Integrated Cross Section are Related to Quark Momentum Distributions

Forward Scattering Amplitude



h: quark helicity
H: proton helicity

} In initial and final state

H_i	h_i		H_f	h_f	
$\frac{1}{2}$	$\frac{1}{2}$	$\rightarrow$	$\frac{1}{2}$	$\frac{1}{2}$	Helicity is conserved
$\frac{1}{2}$	$-\frac{1}{2}$	$\rightarrow$	$\frac{1}{2}$	$-\frac{1}{2}$	

$\Rightarrow q(x,Q^2)\,,\,F_{1,2}(x,Q^2)$ helicity average

$\Delta q(x,Q^2),\, g_1\,(x,Q^2)$ helicity difference

H_i	h_i		H_f	h_f	
$\frac{1}{2}$	$-\frac{1}{2}$	$\rightarrow$	$-\frac{1}{2}$	$\frac{1}{2}$	helicity flip

$\Rightarrow \delta q(x,Q^2)$ transverse spin distributions for quarks: transversity

Hard Scattering Data Sets Used to Constrain Nucleon Quark and Gluon Distributions

low-x → high-x

HERA inclusive NC and CC data

Backbone of all PDF fits
Low-x resummation

HERA c,b data

New data for DIS2018
Low-x gluon, flavour schemes, c, b quark masses

HERA jets

H1 jets NNLO analysis
Low/medium-x gluon, α_s

LHC c+Z,c+γ

New ATLAS+CMS results
Fits with “intrinsic” charm

pp jets

ATLAS jets 8&13 TeV
CMS jets 8 TeV
RHIC 0.5 TeV
High-x valence and gluon

LHC ttbar

ATLAS, CMS, LHCb at various √s
High-x gluon

flavour separation

LHC W+charm

New CMS data: strangeness

Collider W,Z,DY

New W,Z LHC
u,d,s flavour separation

Fixed target DY

SeaQuest 2017 run
u(bar)-d(bar)

Fixed target DIS

Quark flavours at high-x
JLAB prospects

Nuclear PDFs

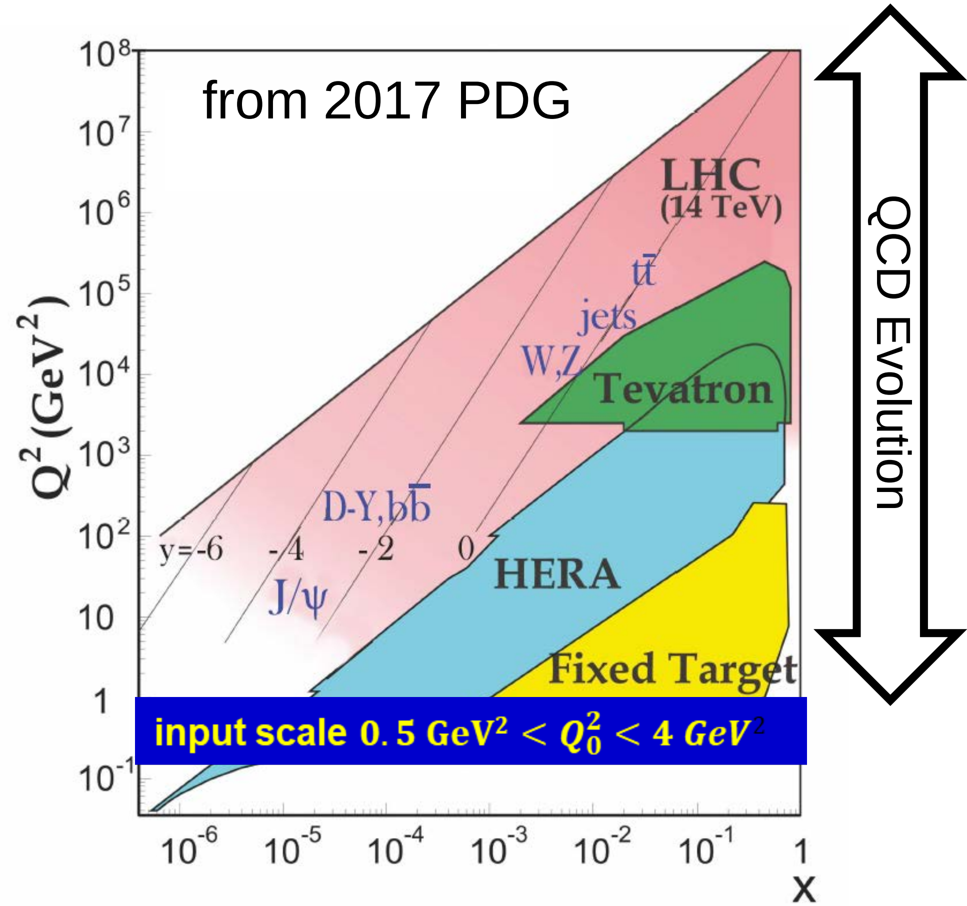
pA and AA data

Z,W in pA,AA
Jets, charm in pA, AA

from Stefan Schmitt, DIS 2018 in Kobe, Japan

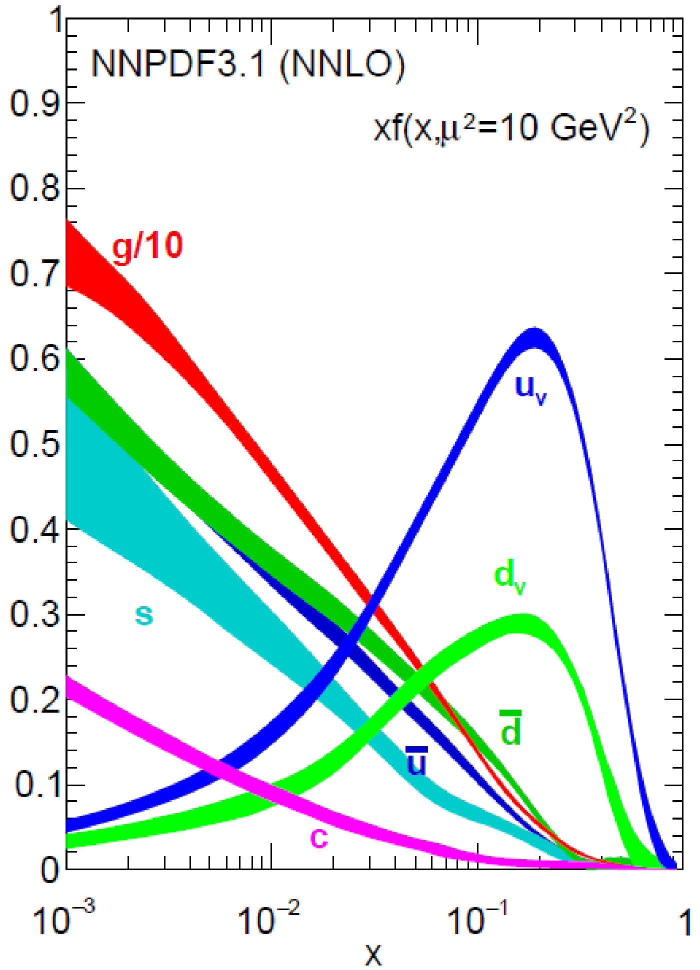
Extraction of Quark and Gluon Momentum Distributions from Hard Scattering Data

- o choose parton distributions, PDFs, at input scale, Q_0^2 :
  $u(x), \bar{u}(x), d(x), \bar{d}(x), s(x), G(x)$, ...
- o evolve pdfs to Q^2 of experimental data sets using pQCD at LO, NLO or NNLO
- o compute cross section, compare to data, compute χ^2
- o vary PDFs to minimize χ^2



Recent global fits by 6 groups
MNHT, NNPDF, CTEQ, HERA PDF, ABMP, JR

NNPDF Results for Parton Distributions



NNPDF3.1: EPJ C77 (2017) 663

Deep Inelastic Scattering

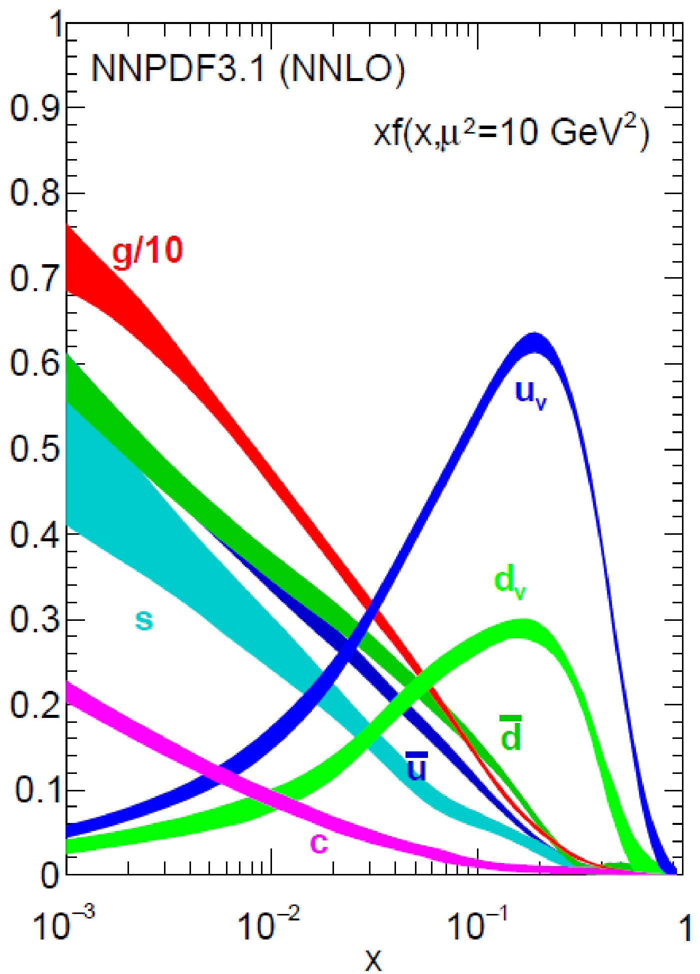
Experiment	Obs.	Ref.	$N_{\rm dat}$
NMC	F_2^d/F_2^p	[28]	260 (121/121)
	$\sigma^{\rm NC,p}$	[29]	292 (204/204)
SLAC	F_2^p	[32]	211 (33/33)
	F_2^d	[32]	211 (34/34)
BCDMS	F_2^p	[30]	351 (333/333)
	F_2^d	[31]	254 (248/248)
CHORUS	$\sigma^{CC,\nu}$	[39]	607 (416/416)
	$\sigma^{CC,\bar{\nu}}$	[39]	607 (416/416)
NuTeV	σ_{ν}^{cc}	[40, 41]	45 (39/39)
	$\sigma_{\bar{\nu}}^{cc}$	[40, 41]	45 (37/37)
HERA	$\sigma_{\rm NC,CC}^p$ (*)	[9]	1306 (1145/1145)
	$\sigma_{\rm NC}^c$	[38]	52 (47/37)
	F_2^b (*)	[67, 68]	29 (29/29)
EMC	[F_2^c] (*)	[69]	21 (16/16)

Tevatron + FNAL fixed target

Exp.	Obs.	Ref.	$N_{\rm dat}$
E866	$\sigma_{\rm DY}^d/\sigma_{\rm DY}^p$	[48]	15 (15/15)
	$\sigma_{\rm DY}^p$	[46, 47]	184 (89/89)
E605	$\sigma_{\rm DY}^p$	[45]	119 (85/85)
CDF	$d\sigma_Z/dy_Z$	[42]	29 (29/29)
	k_t incl jets	[87]	76 (76/76)
D0	$d\sigma_Z/dy_Z$	[43]	28 (28/28)
	W electron asy (*)	[14]	13 (13/8)
	W muon asy (*)	[13]	10 (10/9)

NNPDF Results for Parton Distributions

Precise Collider Data ➔ good sensitivity for PDFs



NNPDF3.1: EPJ C77 (2017) 663

LHC experiments

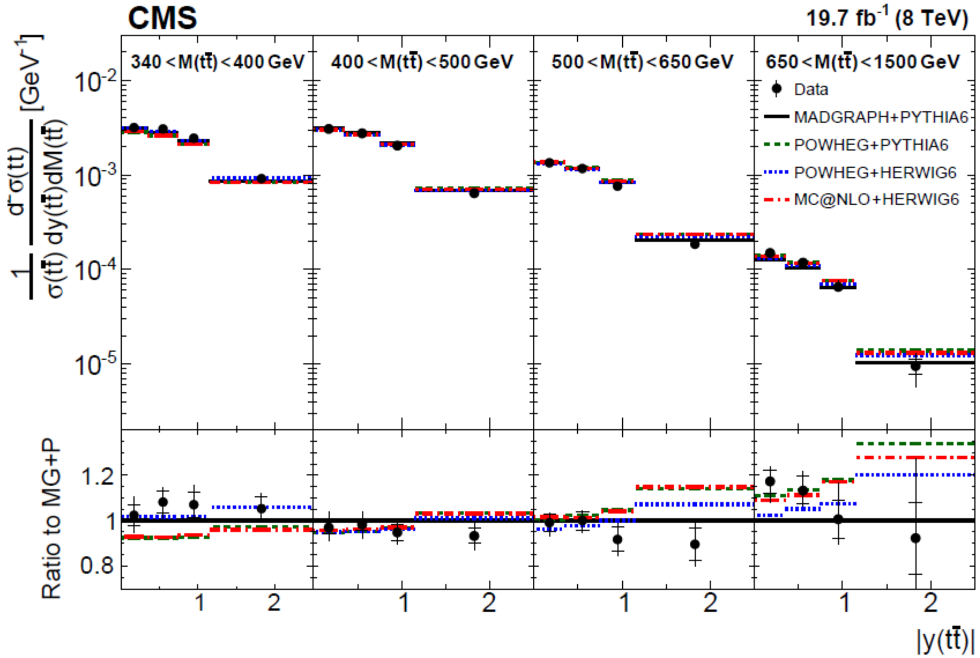
Exp.	Obs.	Ref.	$N_{\rm dat}$
ATLAS	W, Z 2010	[49]	30 (30/30)
	W, Z 2011 (*)	[72]	34 (34/34)
	high-mass DY 2011	[50]	11 (5/5)
	low-mass DY 2011 (*)	[77]	6 (4/6)
	[Z p_T 7 TeV (p_T^Z, y_Z)] (*)	[78]	64 (39/39)
	Z p_T 8 TeV (p_T^Z, M_{ll}) (*)	[71]	64 (44/44)
	Z p_T 8 TeV (p_T^Z, y_Z) (*)	[71]	120 (48/48)
	7 TeV jets 2010	[57]	90 (90/90)
	2.76 TeV jets	[58]	59 (59/59)
	7 TeV jets 2011 (*)	[76]	140 (31/31)
	$\sigma_{\rm tot}(t\bar{t})$	[74, 75]	3 (3/3)
	$(1/\sigma_{t\bar{t}})d\sigma(t\bar{t})/y_t$ (*)	[73]	10 (10/10)
CMS	W electron asy	[52]	11 (11/11)
	W muon asy	[53]	11 (11/11)
	$W + c$ total	[60]	5 (5/0)
	$W + c$ ratio	[60]	5 (5/0)
	2D DY 2011 7 TeV	[54]	124 (88/110)
	[2D DY 2012 8 TeV]	[84]	124 (108/108)
	$W^{\pm}$ rap 8 TeV (*)	[79]	22 (22/22)
	Z p_T 8 TeV (*)	[83]	50 (28/28)
	7 TeV jets 2011	[59]	133 (133/133)
	2.76 TeV jets (*)	[80]	81 (81/81)
	$\sigma_{\rm tot}(t\bar{t})$	[82, 88]	3 (3/3)
	$(1/\sigma_{t\bar{t}})d\sigma(t\bar{t})/y_{t\bar{t}}$ (*)	[81]	10 (10/10)
LHCb	Z rapidity 940 pb	[55]	9 (9/9)
	$Z \to ee$ rapidity 2 fb	[56]	17 (17/17)
	$W, Z \to \mu$ 7 TeV (*)	[85]	33 (33/29)
	$W, Z \to \mu$ 8 TeV (*)	[86]	34 (34/30)

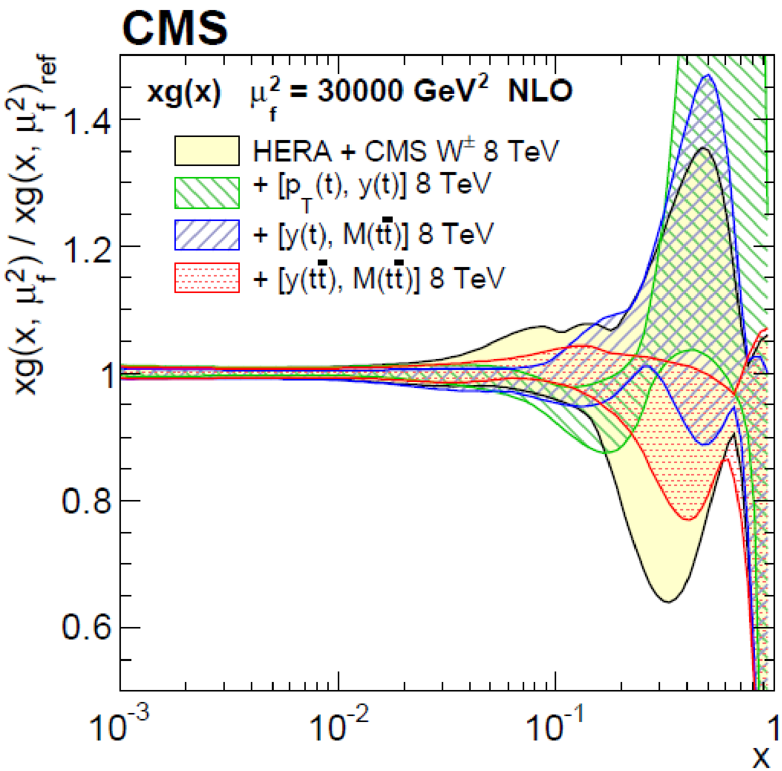
CMS, EPJ C77 (2017) 459
Double Differential $t\bar{t}$ Production Constrains G(x)

Example: $\frac{1}{\sigma(t\bar{t})}\frac{d^2\sigma(t\bar{t})}{dy(t\bar{t})dM(t\bar{t})}$

Additional cross section in CMS QCD analysis:

$[p_T(t), y(t)], [y(t), M(tt)], [y(tt), M(tt)]$

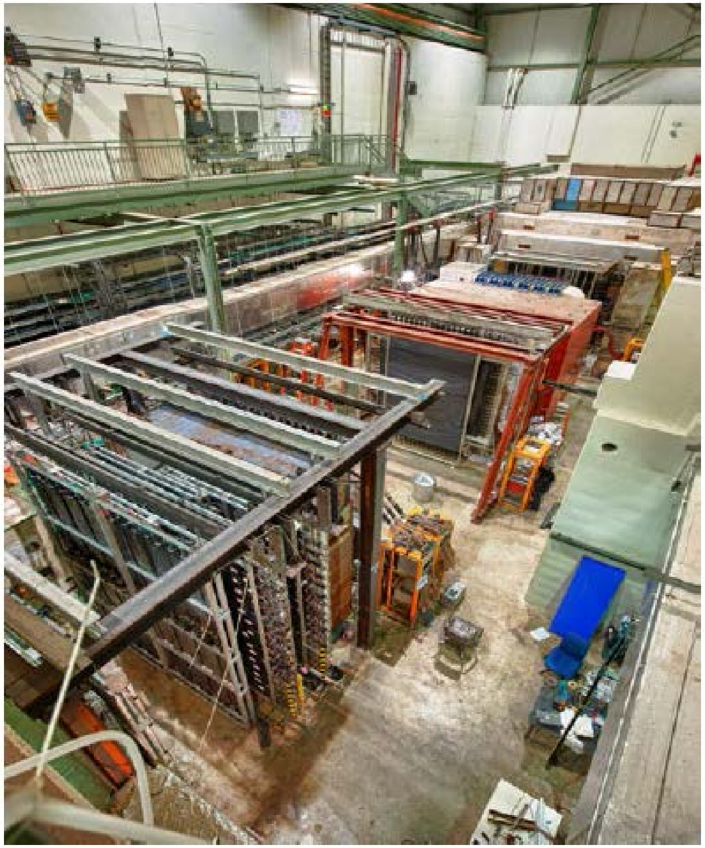


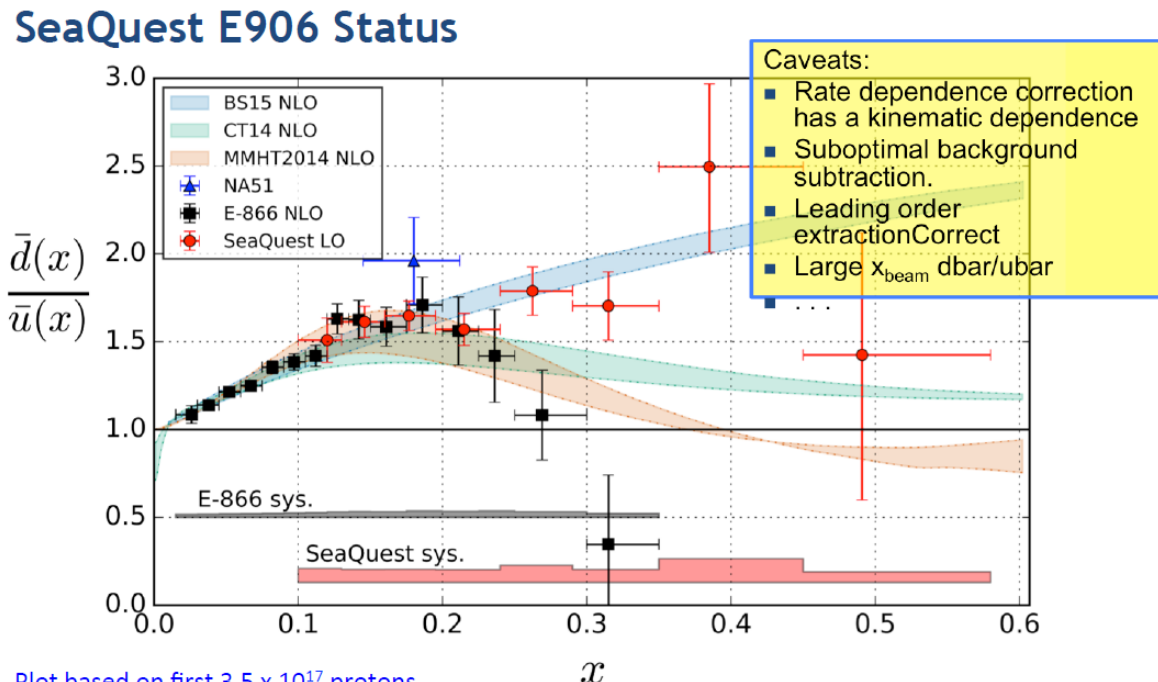


$t\bar{t}$ data constrain $G(x,\mu_f^2)$ for $x>0.05$

FNAL Drell-Yan, SeaQuest: $\frac{\bar{d}(x)}{\bar{u}(x)} > 1$ at large x!

- o Fixed-target proton induced Drell-Yan with hydrogen and deuterium targets
- o extending sea-quark measurements to larger x by using 120 GeV protons from Fermilab Main Injector.





Plot based on first 3.5 x 10^{17} protons

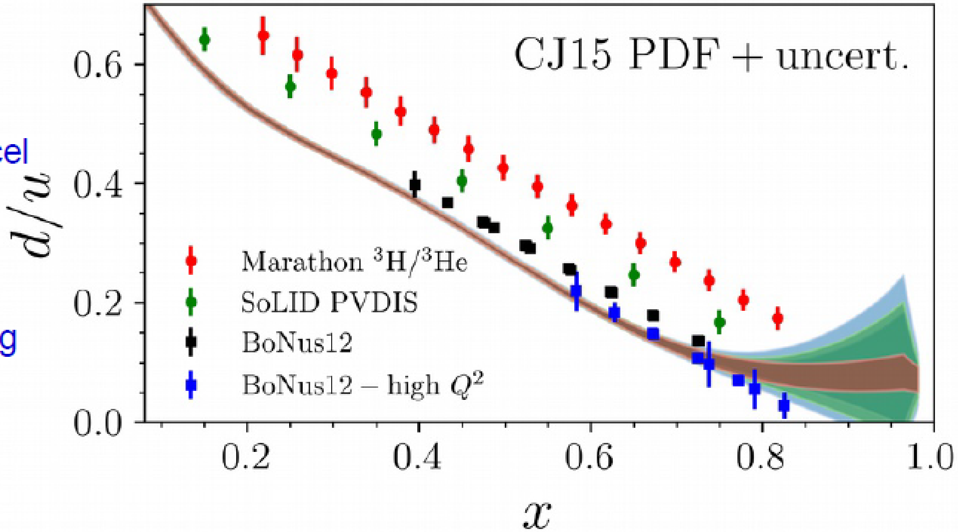
Acceptance improvements so later protons are “worth” more

25% of total expected beam current

Jefferson Laboratory: *d(x)/u(x)* at high x in DIS

- JLAB 12 GeV program includes dedicated experiments to improve structure functions and d/u ratio at high x
  - Hall C: precision F_2 for ep and ed scattering
  - MARATHON: ^3H and ^3He, nuclear corrections cancel in ratio
  - BONuS12: effective free neutron target in ed scattering with proton tag
  - SoLID PVDIS: u/d from parity-violating ep scattering
- Fitting group CJ at JLAB, focussing on the use of high-x data in PDFs

Projected precision on u/d from future 12 GeV JLAB experiments

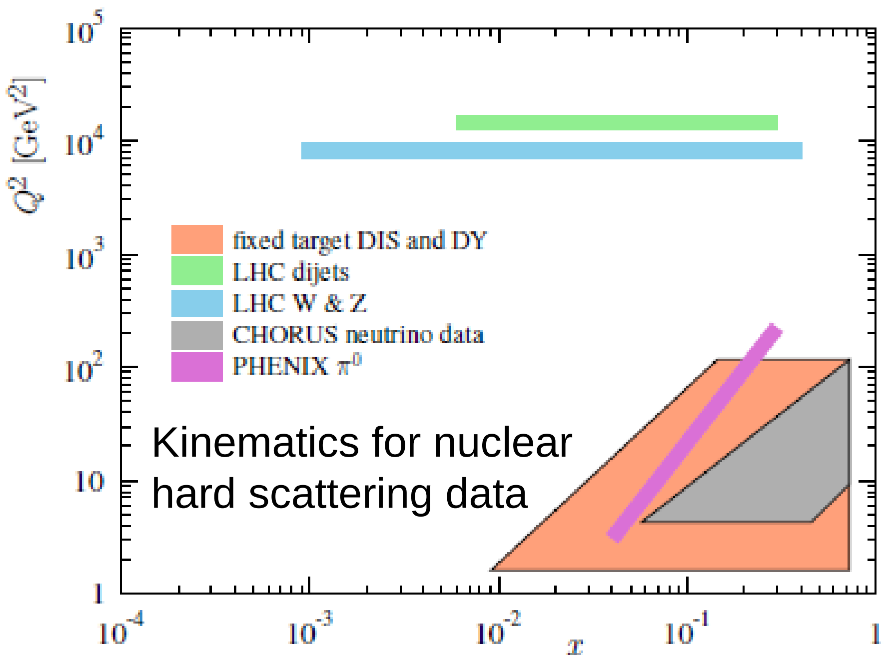


CJ15 PDFs: Phys.Rev. D93 (2016) 114017 [arXiv:1602.03154]
BONuS 5 GeV: Phys.Rev. C89 (2014) 045206, add: Phys.Rev. C90 (2014) 059901[arXiv:1402.2477]
MARATHON: https://www.jlab.org/exp_prog/proposals/10/PR12-10-103.pdf
SoLID PVDIS: https://www.jlab.org/exp_prog/proposals/10/PR12-10-007.pdf
Hall C precision F2: https://www.jlab.org/exp_prog/proposals/10/PR12-10-002.pdf

Parallel session talks:
BONuS12: WG7(261) 18.4. 10:24
JLAB 12GeV: WG7(255) 18.4. 16:54

from Stefan Schmitt, DIS 2018 in Kobe, Japan

Modification of Nucleon Structure in Nuclei



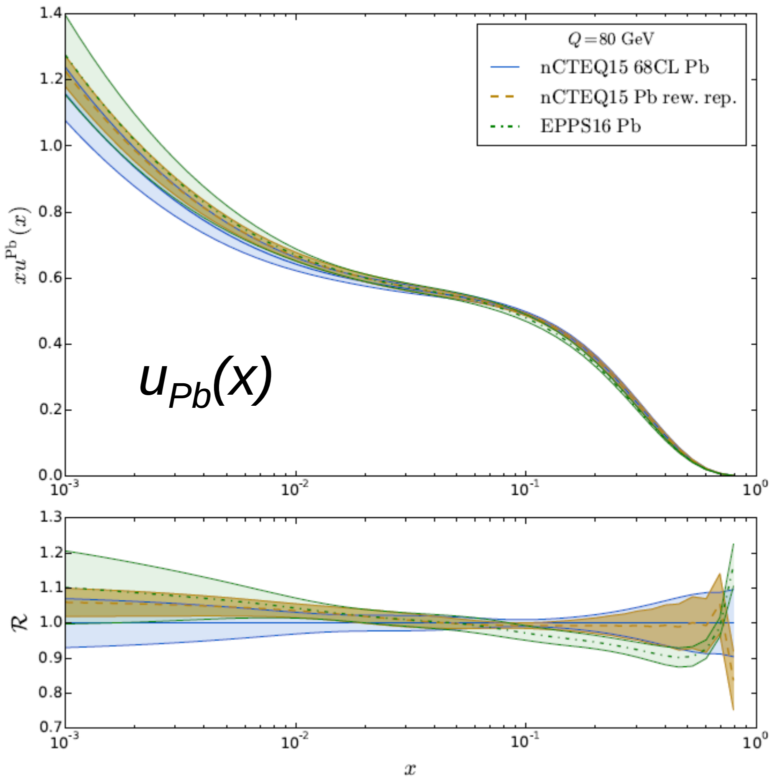
LHC pPb and PbPb data

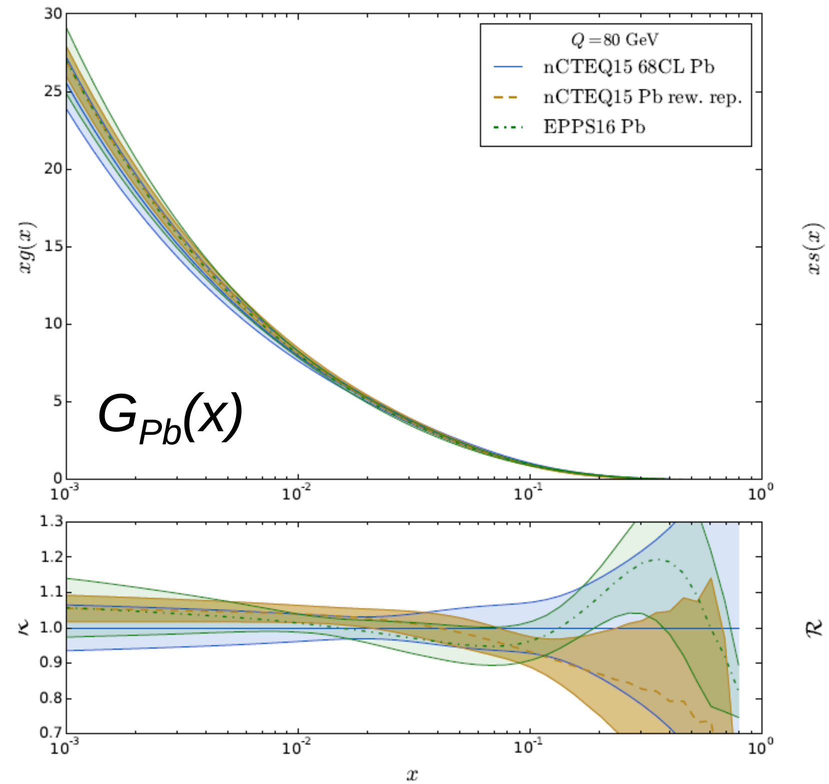
		Observable
pPb	ATLAS	$d\sigma(Z \to \ell^+\ell^-)/dy_Z$ [1]
		$d\sigma(W^+ \to \ell^+\nu)/dy_{\ell^+}$ [2]
		$d\sigma(W^- \to \ell^-\bar{\nu})/dy_{\ell^-}$ [2]
	CMS	$d\sigma(Z \to \ell^+\ell^-)/dy_Z$ [3]
		$d\sigma(W^+ \to \ell^+\nu)/dy_{\ell^+}$ [4]
		$d\sigma(W^- \to \ell^-\bar{\nu})/dy_{\ell^-}$ [4]
	LHCb	$\sigma(Z \to \ell^+\ell^-)$ [5]
	ALICE	$\sigma(W^+ \to \ell^+\nu)$ [6]
		$\sigma(W^- \to \ell^-\bar{\nu})$ [6]
PbPb	ATLAS	$1/\sigma_{tot} d\sigma/dy_Z$ [7]
		A_ℓ [8]
	CMS	$1/\sigma_{tot} d\sigma/dy_Z$ [9]
		A_ℓ [10]

Recent nuclear PDF fits:

nCTEQ: Phys.Rev. D93 (2016) 085037
EPPS16: EPJ C77 (2017) 163 [arXiv:1612.05741]

Impact of LHC *pPb* and *PbPb* data on $u_{Pb}(x)$ and $G_{Pb}(x)$: nCETQ vs EPPS16

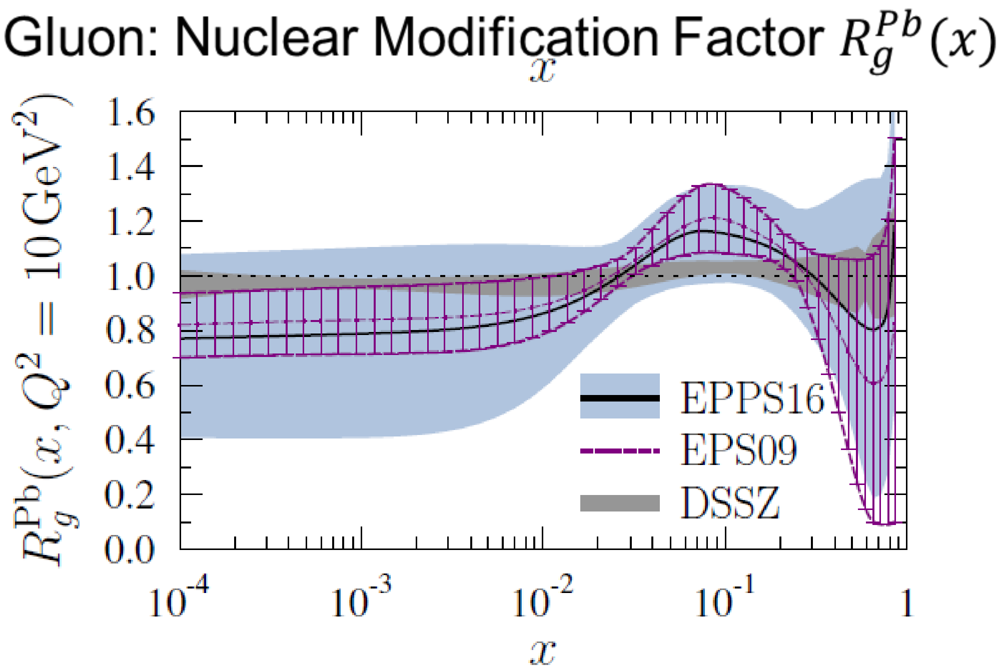




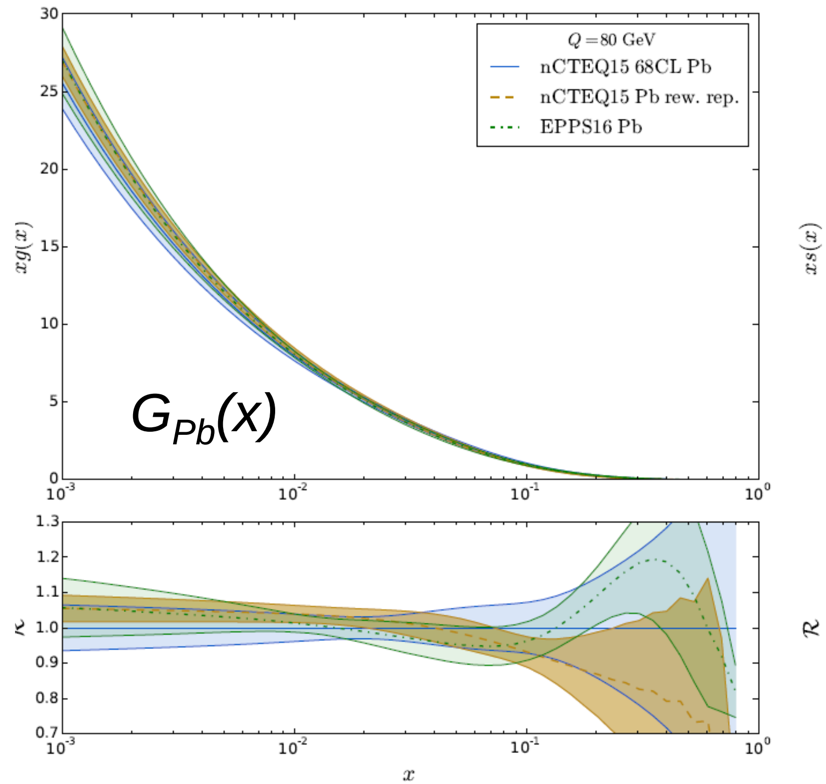
nCTEQ: Phys.Rev. D93 (2016) 085037
EPPS16: EPJ C77 (2017) 163 [arXiv:1612.05741]

LHC data in agreement with fixed target and RHIC data. More HI data taking to come …

Impact of LHC *pPb* and *PbPb* data on $u_{Pb}(x)$ and $G_{Pb}(x)$: nCETQ vs EPPS16



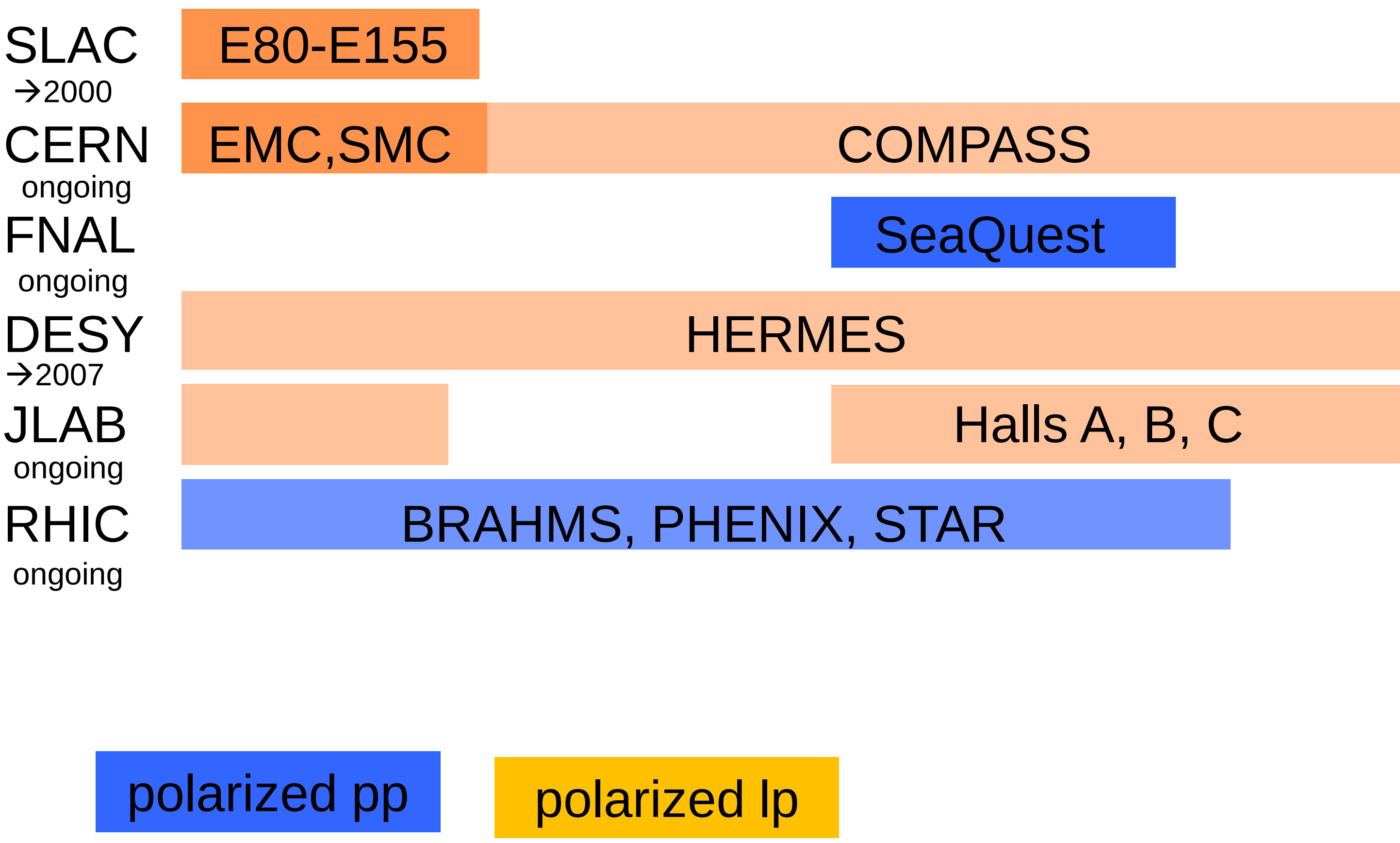
nCTEQ: Phys.Rev. D93 (2016) 085037
EPPS16: EPJ C77 (2017) 163 [arXiv:1612.05741]



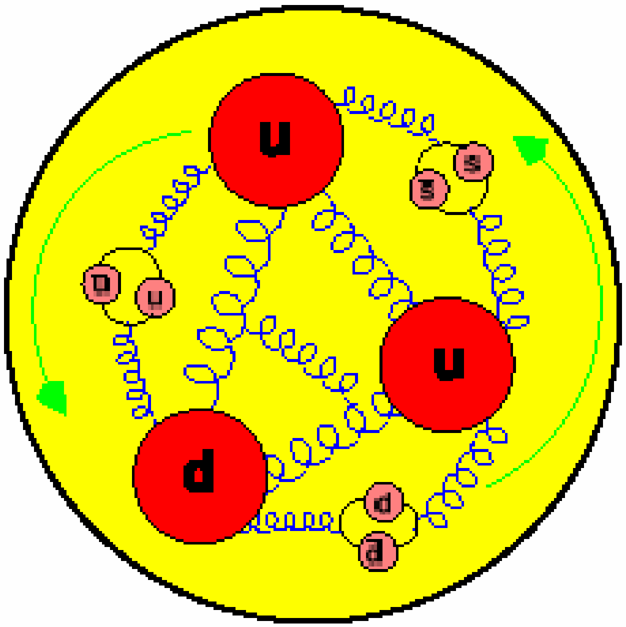
LHC data in agreement with fixed target and RHIC data. More HI data taking to come …

Nucleon Spin Structure: 40 Years of Experiment

Quark Spin – Gluon Spin – Transverse Spin – GPDs



Proton Structure: Spin (Helicity) Distributions



Constituents:

quarks = u, d, s and gluons

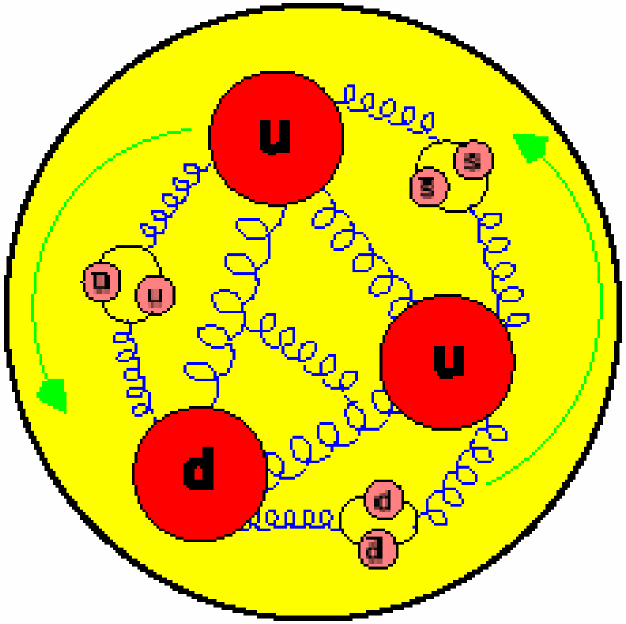
$\Rightarrow$ Total Quark Spin :

$$\Delta\Sigma = \sum_{q,\bar{q}} \int_{x=0}^{x=1} \Delta q(x)$$

$\Rightarrow$ Total Gluon Spin :

$$\Delta G = \int_{x=0}^{x=1} \Delta G(x)$$

Proton Structure: Helicity Sumrule



De-composition of the Proton Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

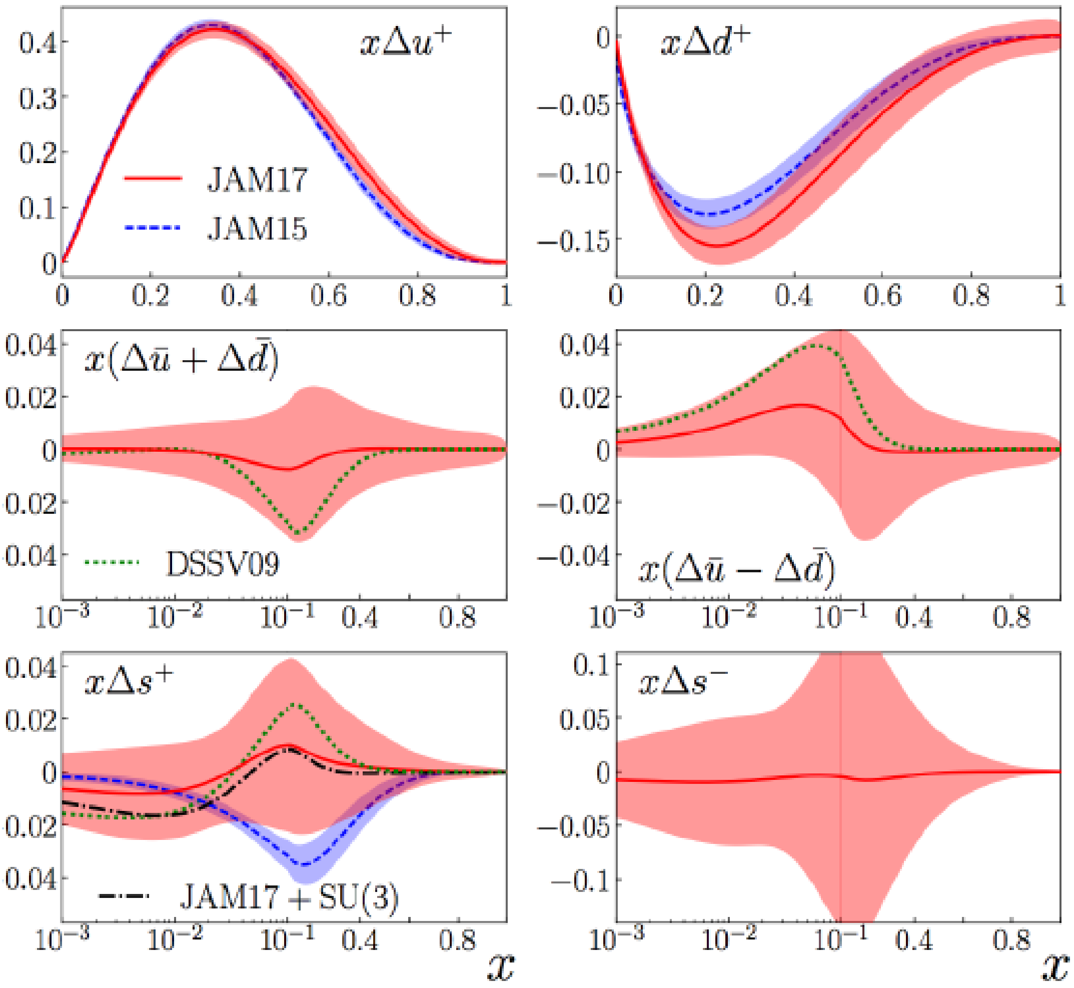
Quark Spin

Gluon Spin

Orbital Angular momentum

Quark and Gluon Helicity Distributions from •NNPDF

J.J. Ethier *et al.* (JAM Collaboration), PRL 119, 132001 (2017)



Up and down quark helicity distributions are known.

Large uncertainties for sea-quarks.

Quark Spin

$\Delta\Sigma = 0.36 \mp 0.09$

$\Delta s = -0.03 \mp 0.1$

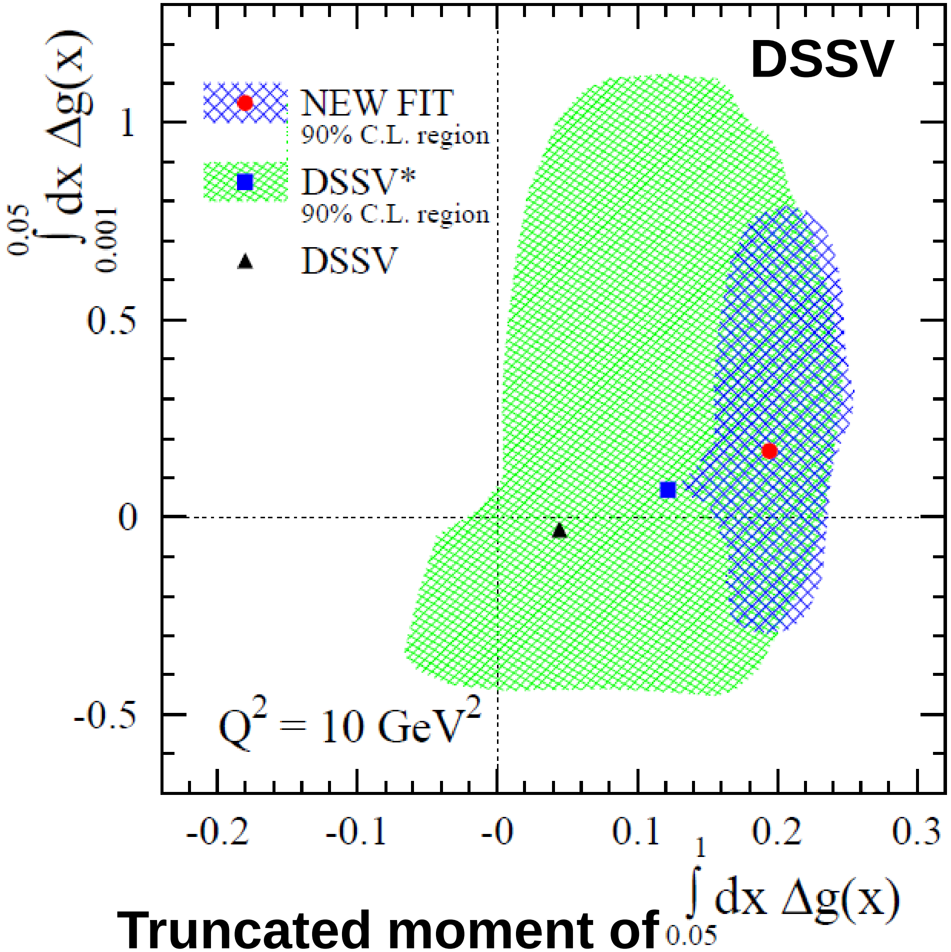
$Q^2 = 1\ GeV^2$

DIS and SIDIS at Jlab 12 GeV!

Knowledge of Truncated Moments of ΔG and ΔΣ(Q²)in Valence- and Sea-Regions

Phys.Rev.Lett. 113 (2014) 012001

Truncated moment of ΔG(x) for sea between 0.001 < x < 0.05



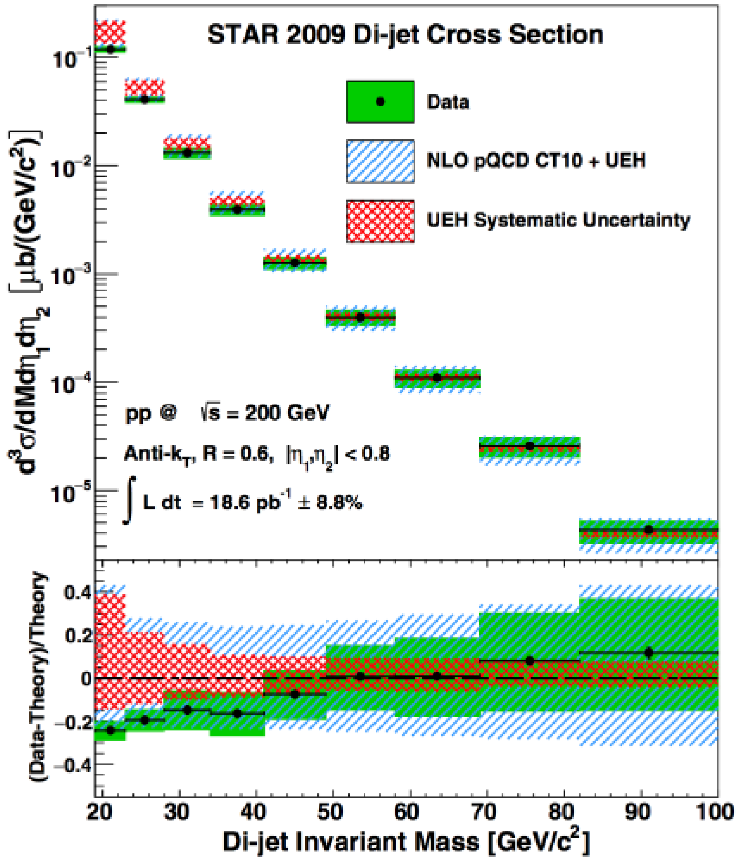
Truncated moment of ΔG(x) for valence region 0.05 < x < 1

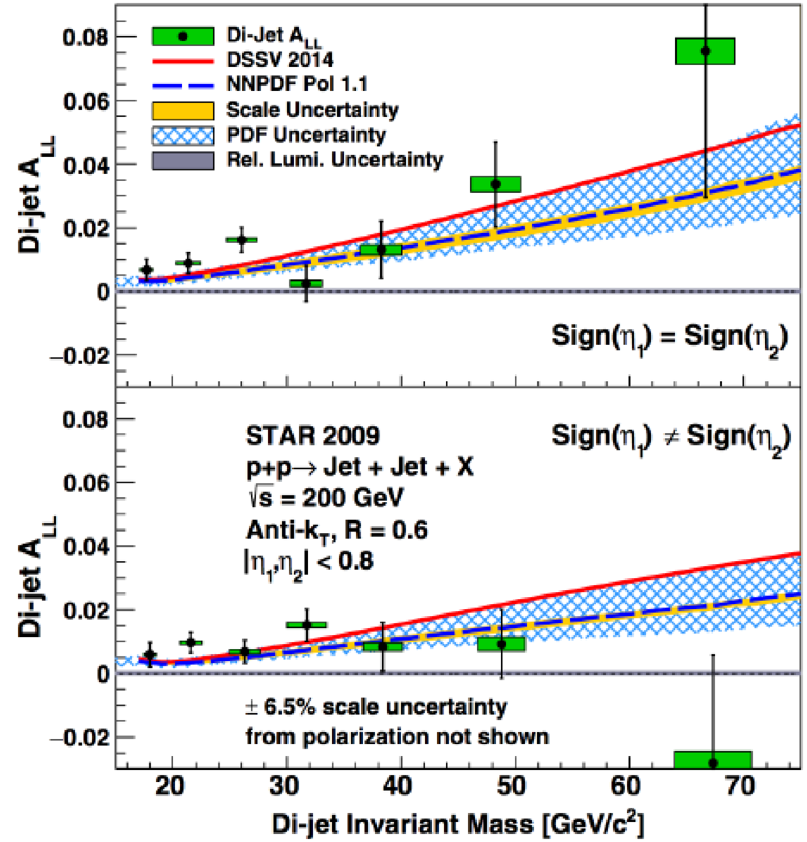
Within errors large gluon spin contributions possible at low x!

$$\int_{0.05}^{1} \Delta G(x) \approx 0.2 \mp 0.05℃$$

$$\int_{0.001}^{0.05} \Delta G(x) \approx 0.13 + 1.1 - 0.3$$

Constraining $\Delta G(x)$: First $A_{LL}^{jet}(M_{jet})$





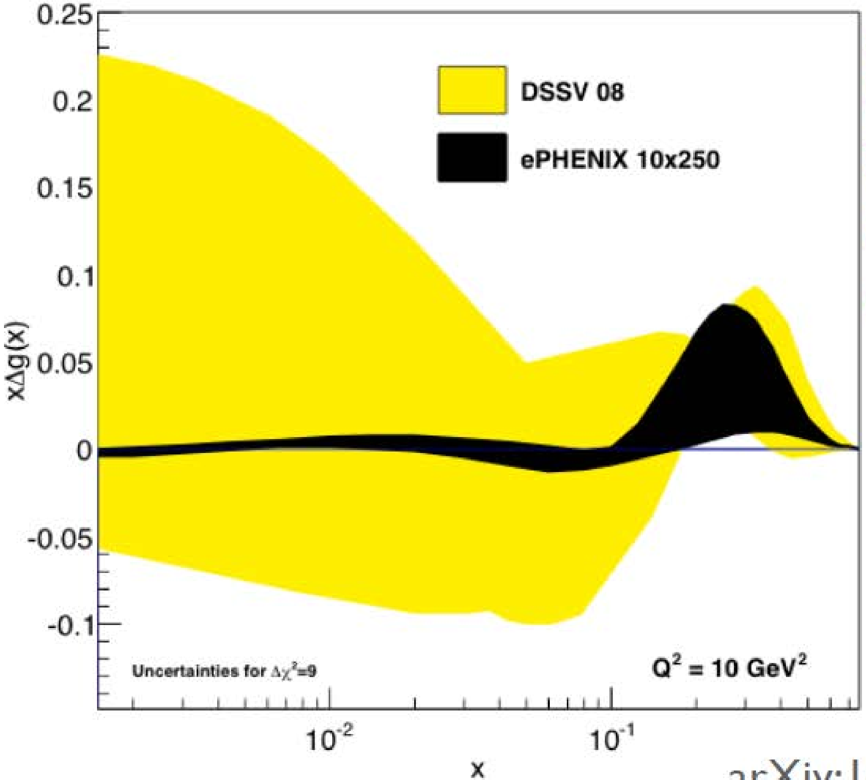
Consistent with analyses that find $\int_{0.05}^{1} \Delta G(x) \approx 0.2$ for x>0.05

L. Adamczyk *et al.*, STAR, Phys. Rev. D 95, 071103 (2017).

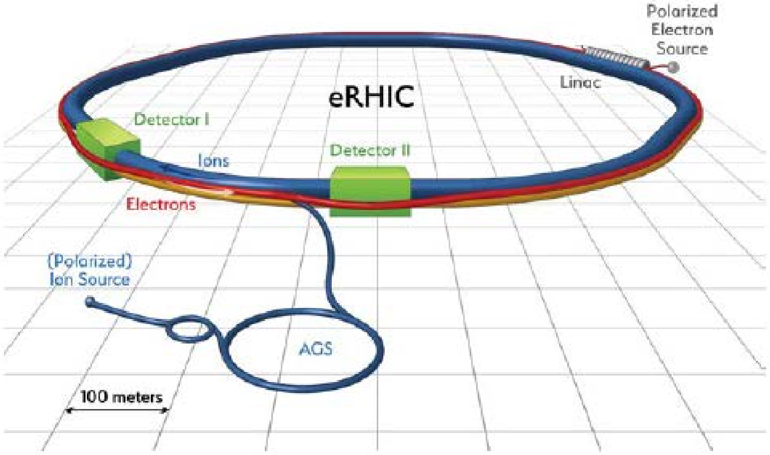
EIC – Impact on low x Extrapolation for $\Delta G(x)$

Future Electron-Ion Collider

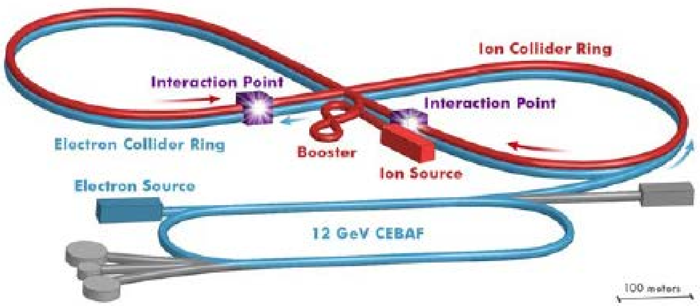
$\Delta G(x)$ **reduction of uncertainties**



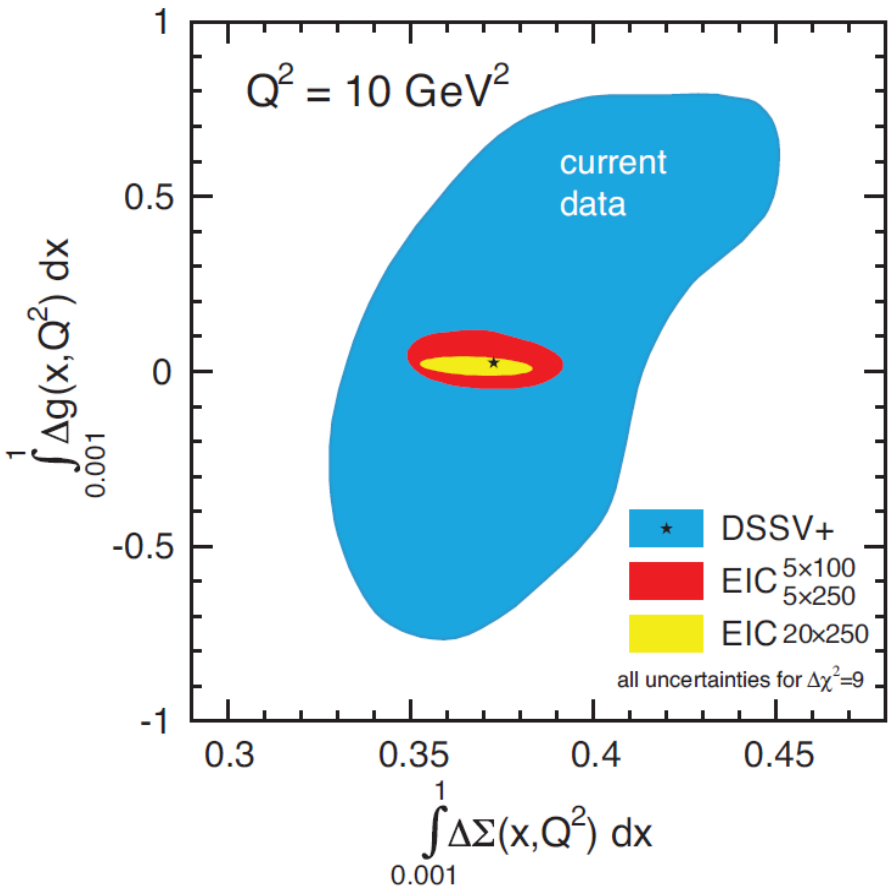
arXiv:I



Not to scale



Impact of EIC on Gluon- and Quark-Spin Contributions.

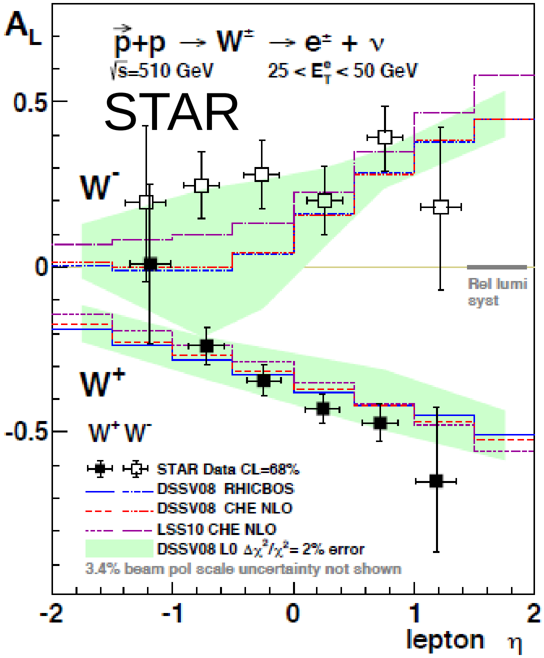


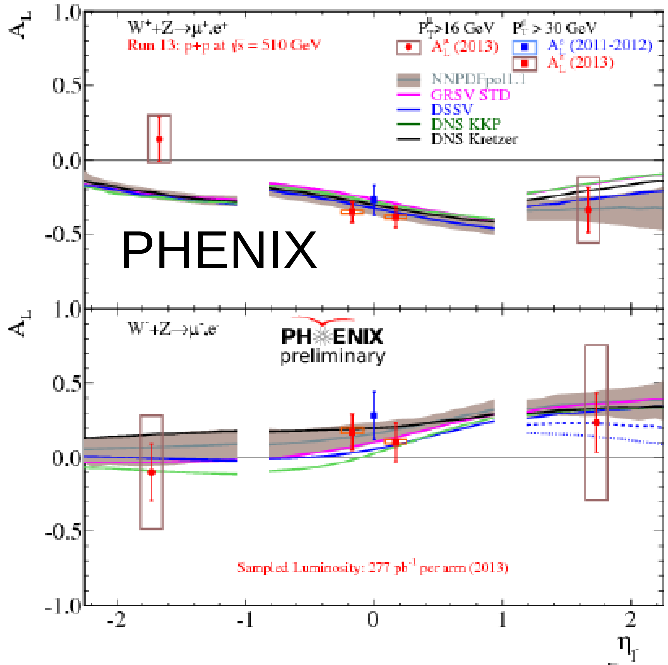
Will constrain orbital contribution:

$$L_Z = \frac{1}{2} - \frac{1}{2}\Delta\Sigma - \Delta G$$

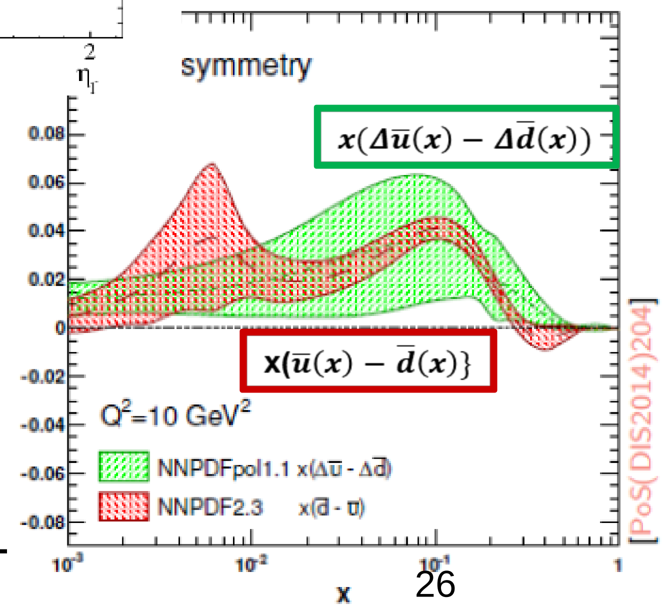
$\Delta\bar{u}(x) - \Delta\bar{d}(x)$ from $A_L^{W\rightarrow l\nu_l}$ in polarized p-p at RHIC

Aschenauer et al. arXiv:1602.0392



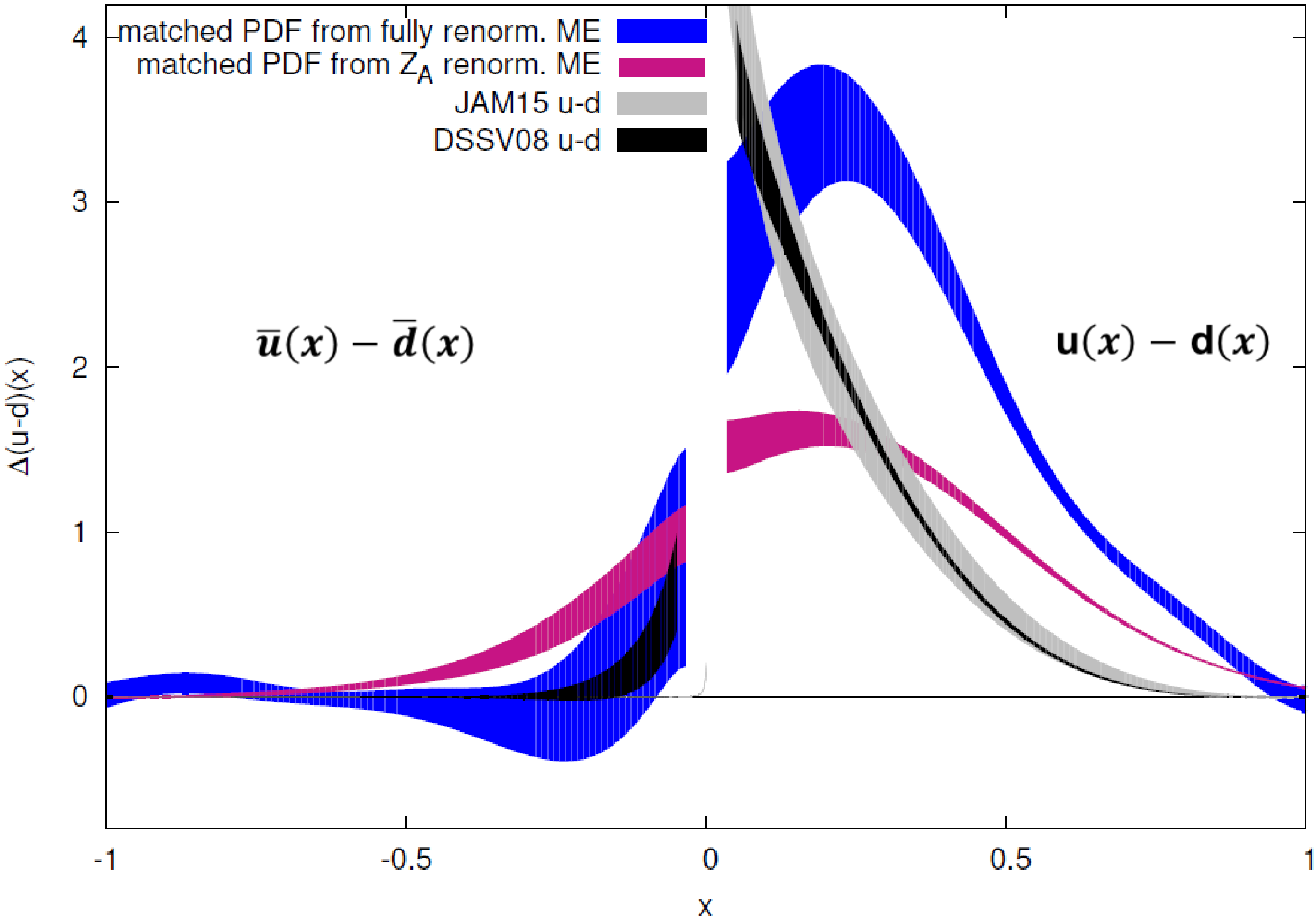


Global Analysis of SIDS + $A_L^{W\rightarrow e\nu_e}$ from STAR



A non-perturbative renormalization prescription for quasi-PDFs from the Lattice

C. Alexandroua et al.
Nucl.Phys. B923 (2017) 394-415



Parton distributions and lattice QCD calculations: a community white paper

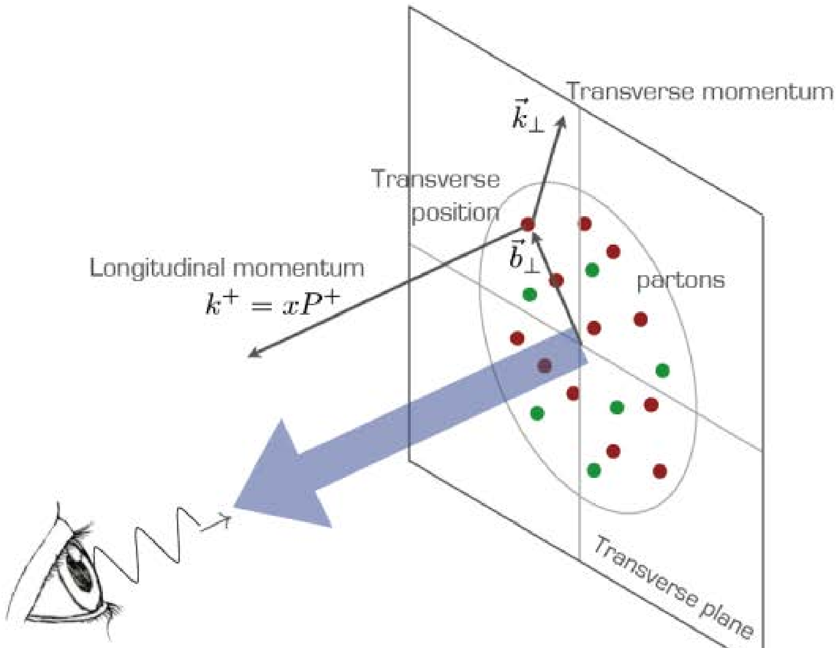
Huey-Wen Lin, et al. Prog.Part. Nucl.Phys. 100 (2018) 107-160

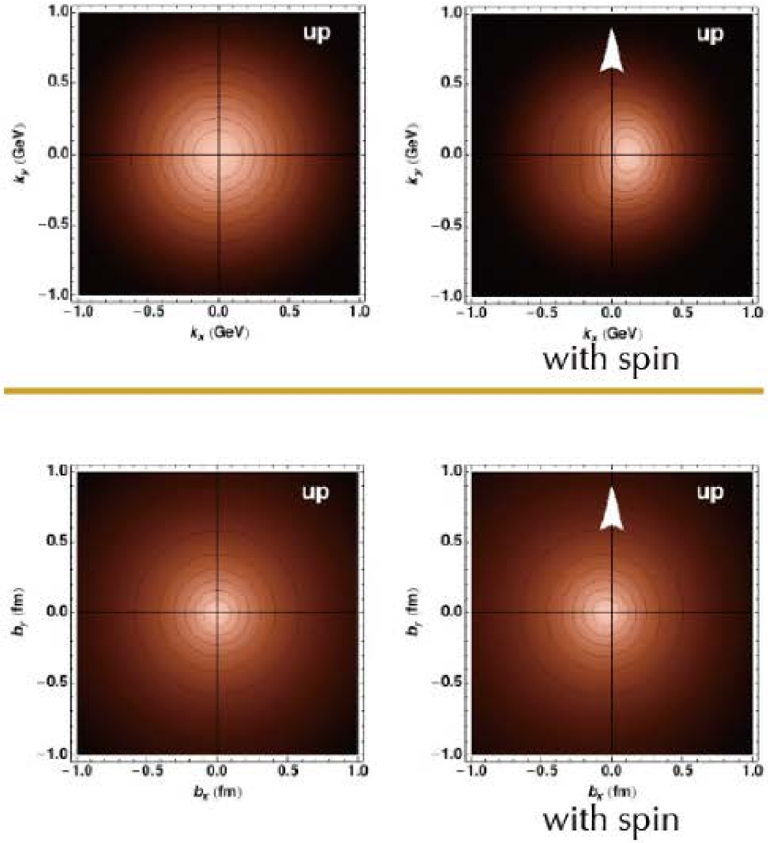
Abstract In the framework of quantum chromodynamics (QCD), parton distribution functions (PDFs) quantify how the momentum and spin of a hadron are divided among its quark and gluon constituents. Two main approaches exist to determine PDFs. The first approach, based on QCD factorization theorems, realizes a QCD analysis of a suitable set of hard-scattering measurements, often using a variety of hadronic observables. The second approach, based on first-principle operator definitions of PDFs, uses lattice QCD to compute directly some PDF-related quantities, such as their moments.

Motivated by recent progress in both approaches, in this document we present an overview of lattice-QCD and global-analysis techniques used to determine unpolarized and polarized proton PDFs and their moments. We provide benchmark numbers to validate present and future lattice-QCD calculations and we illustrate how they could be used to reduce the PDF uncertainties in current unpolarized and polarized global analyses. This document represents a first step towards establishing a common language between the two communities, to foster dialogue and to further improve our knowledge of PDFs.

Consider Orbital Motion in the Nucleon: 1D → 3D

from Alessandro Bacchetta





Generalized parton distribution (GPD)
Transverse momentum dependent parton distribution (TMD)

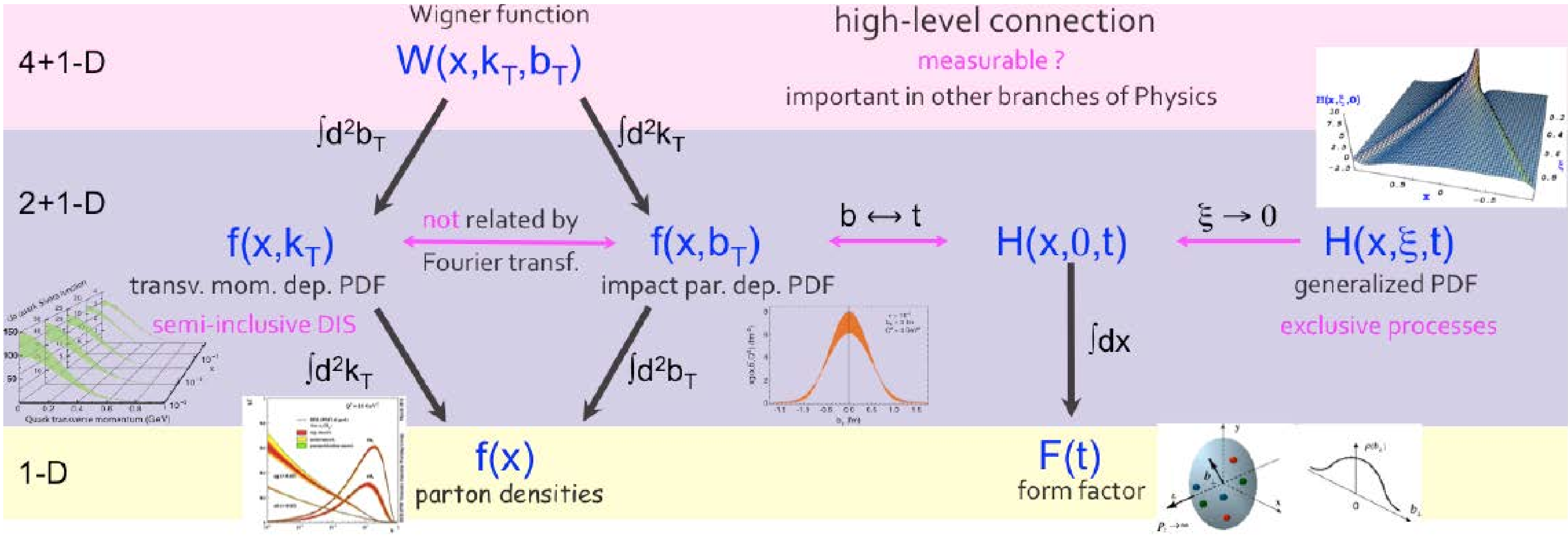
Unified View of Nucleon Structure

Wigner Functions (x,k_T,b_T)

Transverse Momentum Dependent Distributions, TMDs (x,k_T)

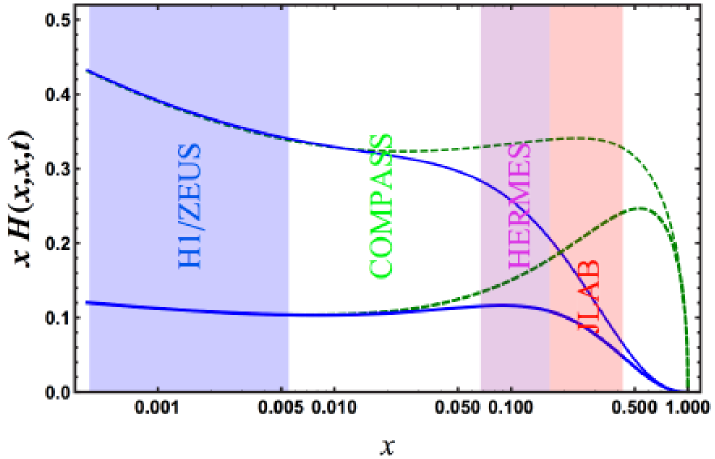
Generalized Parton Distributions, GPDs (x,ξ,t)

Parton Distribution Functions, PDFs(x)

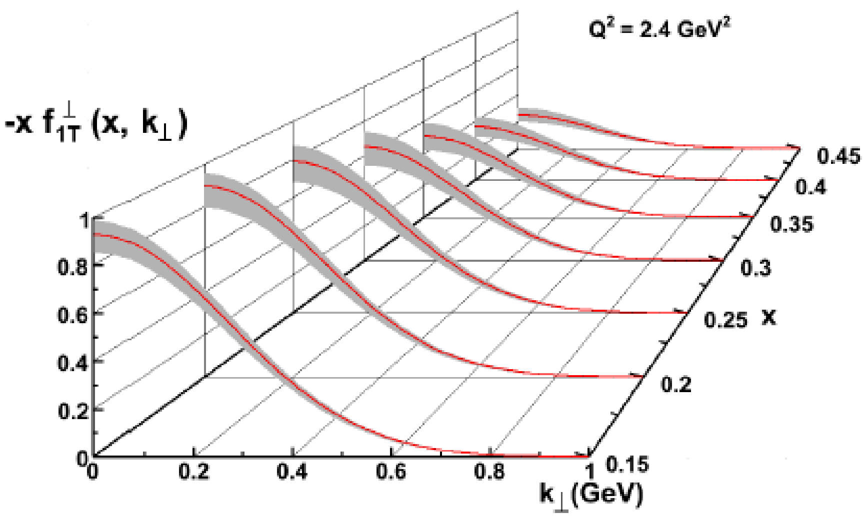


Precision Measurements of GPDs: Jlab 12 GeV and later Upgrades, eg. SoLID

Gloal analysis of HERA, COMPASS and Jlab data

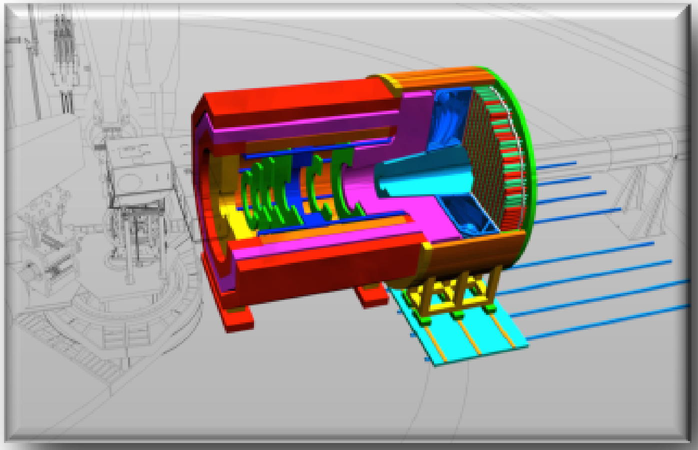


Kumerički and Müller NP B841, 1(2010)



SoLID provides unique capability:

- ✓ high luminosity (10^{37-39})
- ✓ large acceptance with full ϕ coverage

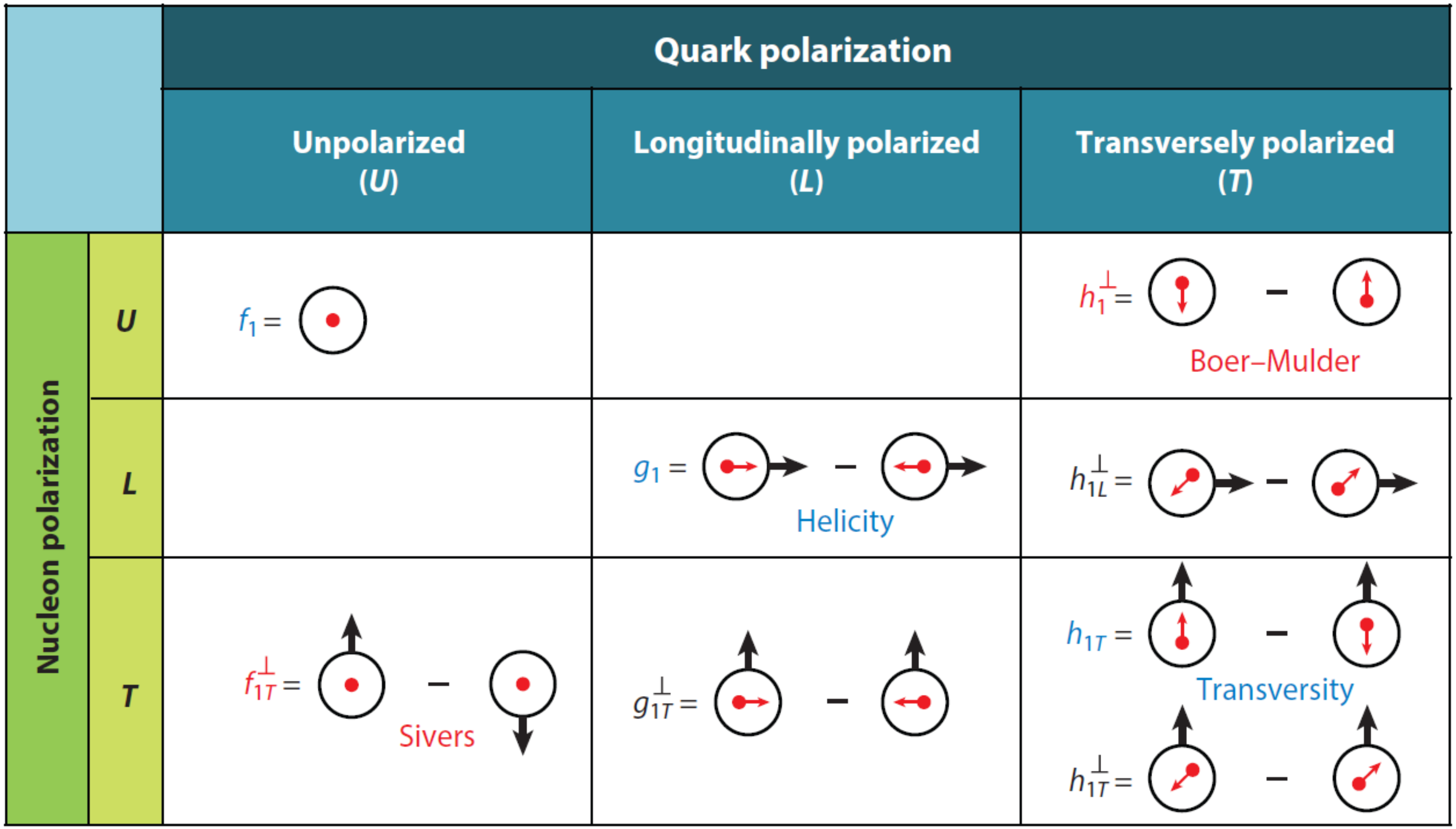


→ multi-purpose program to maximize the 12-GeV science potential

Ji's sum rule: access to L^q

$$J^q = \frac{1}{2}\int_{-1}^{1} dx\, x[H^q(x,\xi,t)+E^q(x,\xi,t)] = \frac{1}{2}\Delta\Sigma + L^q$$

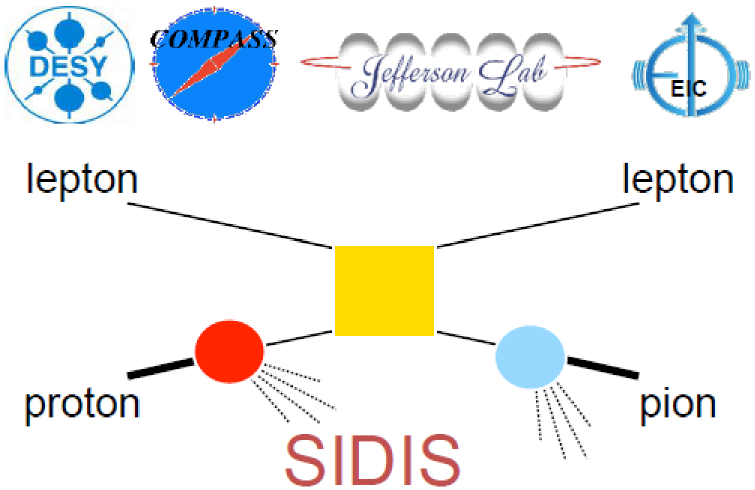
Distributions to Parameterize TMD Hard Scattering Cross Section at Leading Twist

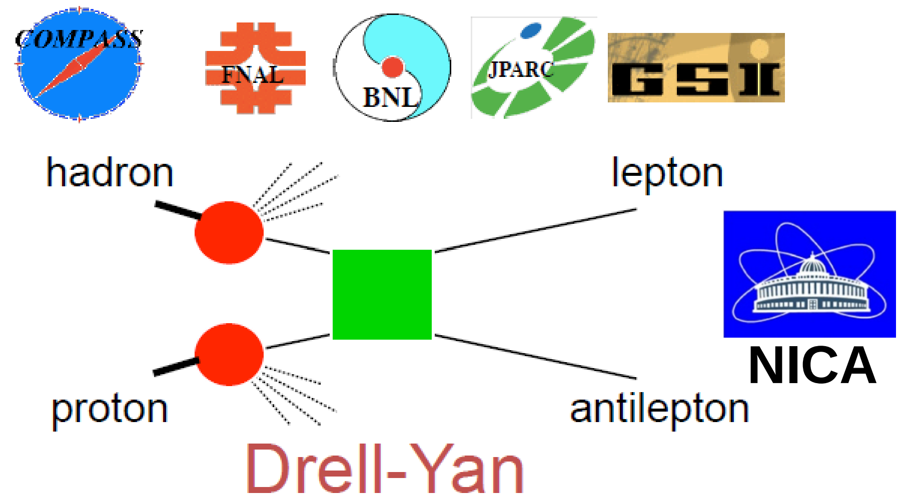


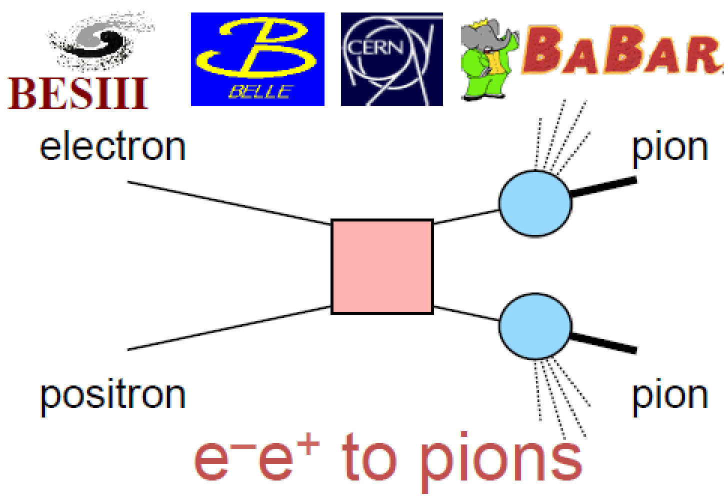
Transverse Momentum Dependent (TMD)

TMD independent

Experimental Facilities used to measure TMDs







- Partonic scattering amplitude
- Fragmentation amplitude
- Distribution amplitude

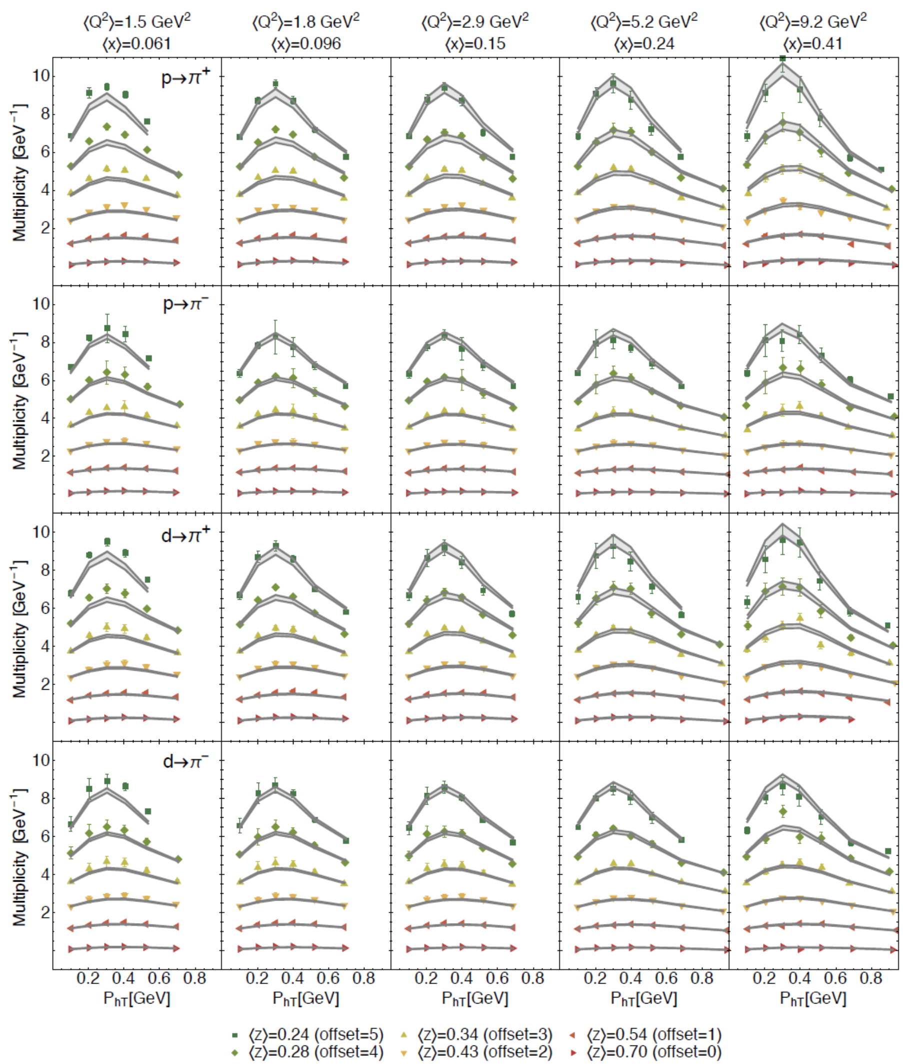
Global Analysis of **Unpolarized TMD Multiplicities** in SIDIS, DY and Z-Boson Production

Bacchetta, Delcarro, Pisano, Radici, Signori
JHEP 1706 (2017) 081

HERMES & COMPASS SIDIS
Multiplicities vs p_T

E288 and E605
DY cross sections vs q_T

D0 and CDF
Z-Boson cross sections vs q_T



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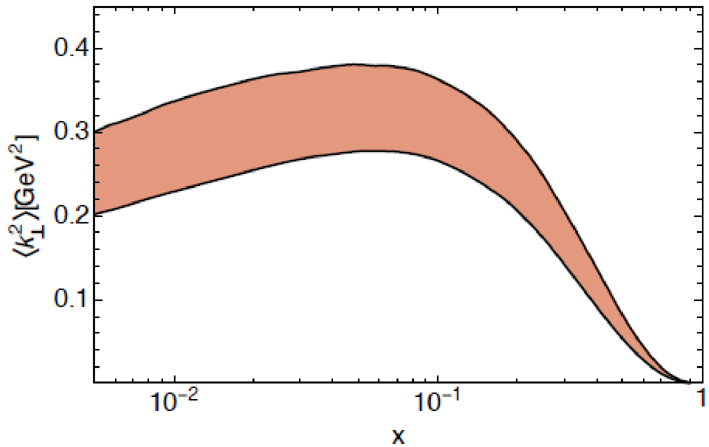
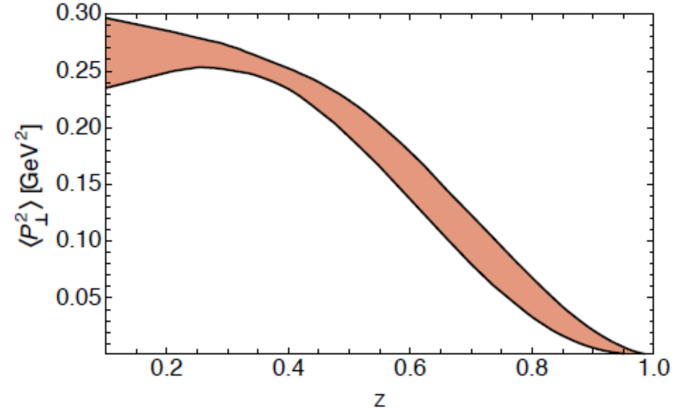
Average parton $k^2_\perp$



Average $P^2_\perp$ picked up in fragmentation

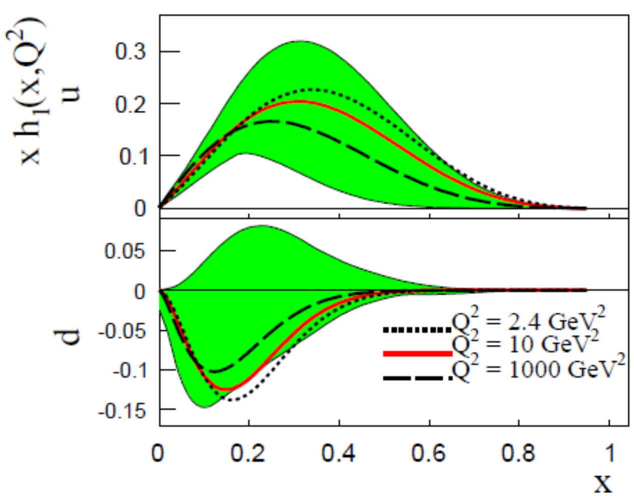


Transversity Quark Distributions and the Tensor Charge Extracted Using TMD Evolution

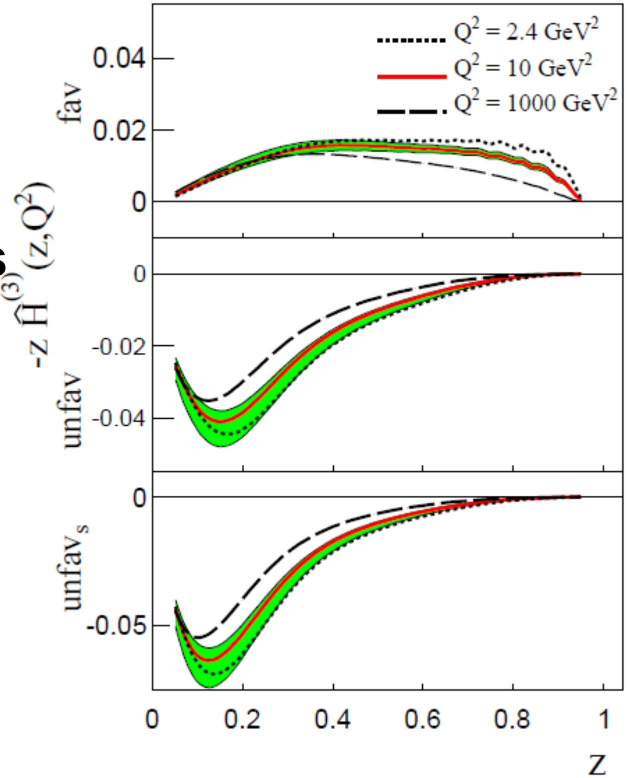
Z.-B. Kang., A. Prokudin, P. Sun, F. Yuan - Phys.Rev. D93 (2016) 1, 014009

Results given at
Q^2=2.4, 10 and 1000 GeV^2

up and down
transversity distributions



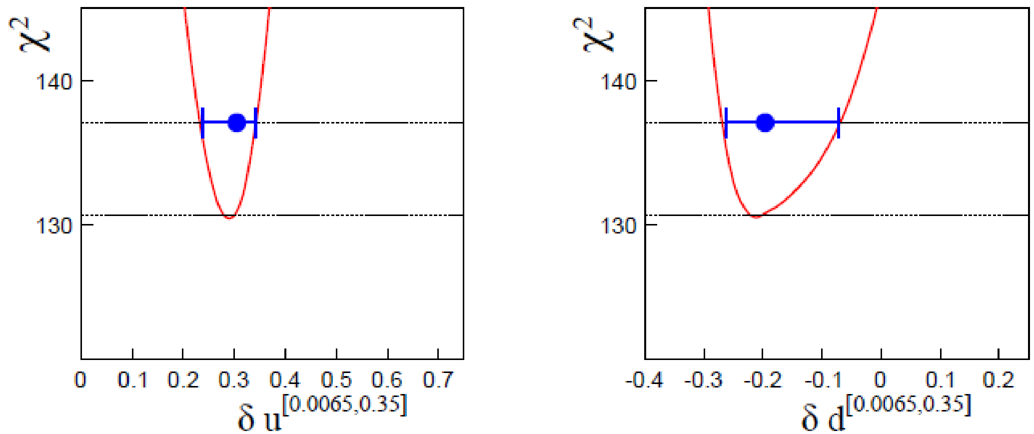
Favored and unfavored
Collins FF



Transversity and the **Tensor Charge** Extracted Using TMD Evolution and Recent Data Sets

Z.-B. Kang., A. Prokudin, P. Sun, F. Yuan - Phys.Rev. D93 (2016) 1, 014009

up and down contributions to tensor charge



Integrals in data region

$$\delta u^{[0.0065,0.35]} = +0.30^{+0.04}_{-0.07}$$
$$\delta d^{[0.0065,0.35]} = -0.20^{+0.12}_{-0.07}$$

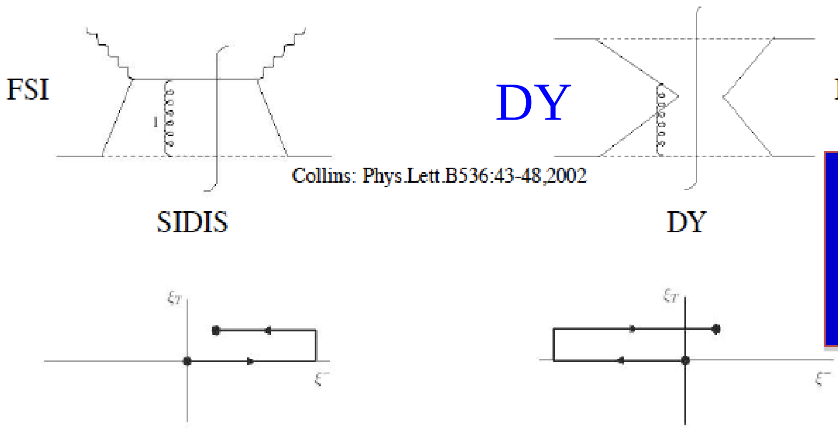
Integrals in [0,1]

$$\delta u^{[0,1]} = +0.39^{+0.07}_{-0.11}$$
$$\delta d^{[0,1]} = -0.22^{+0.14}_{-0.08}$$

Evolution has significant effect
Need higher precision SIDIS data: Jlab 12 GeV
Need to extend data range to high and low x

Sign Change of Sivers- and Boer-Mulders Functions Between SIDIS and DY

SIDIS



Direction of the gauge-link integrals of k_T dep. pdfs is process-dependent and changes its sign between SIDIS and DY

Sivers $$f_{1T}^{\perp}(x,\mathbf{k}_T)\Big|_{SIDIS} = -f_{1T}^{\perp}(x,\mathbf{k}_T)\Big|_{DY}$$

Boer-Mulders $$h_1^{\perp}(x,\mathbf{k}_T)\Big|_{SIDIS} = -h_1^{\perp}(x,\mathbf{k}_T)\Big|_{DY}$$

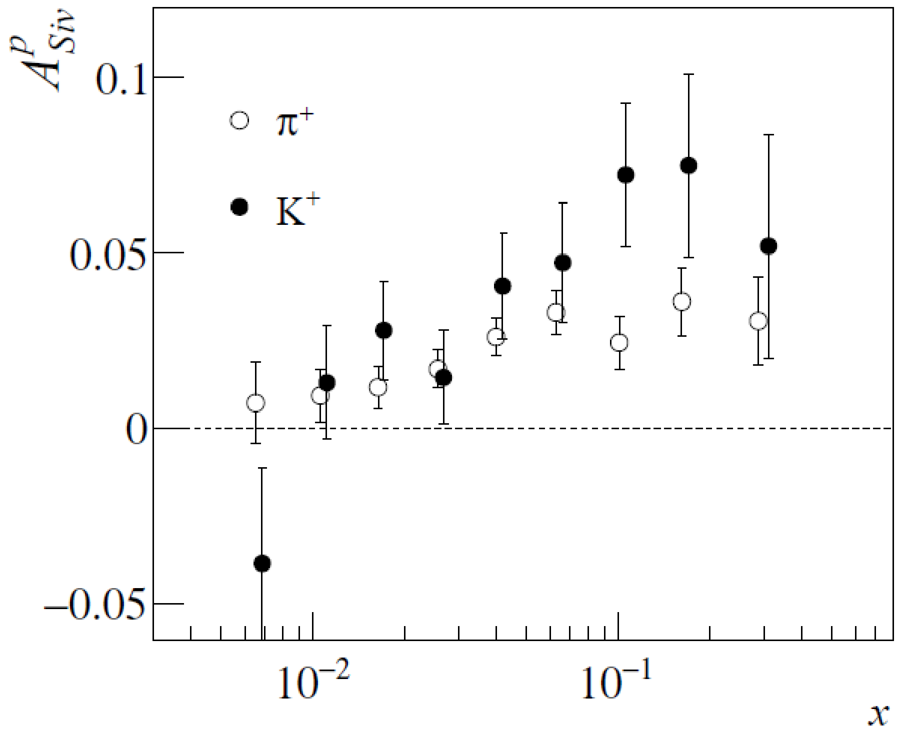
Need to confirm sign reversal in polarized Drell-Yan!

NSAC performance Milestone HP13 for 2015

TEST “modified” universality of TMD pdfs!

Sivers Asymmetries for π$^+$ vs K$^+$

COMPASS Phys.Lett. B744:250(2015)

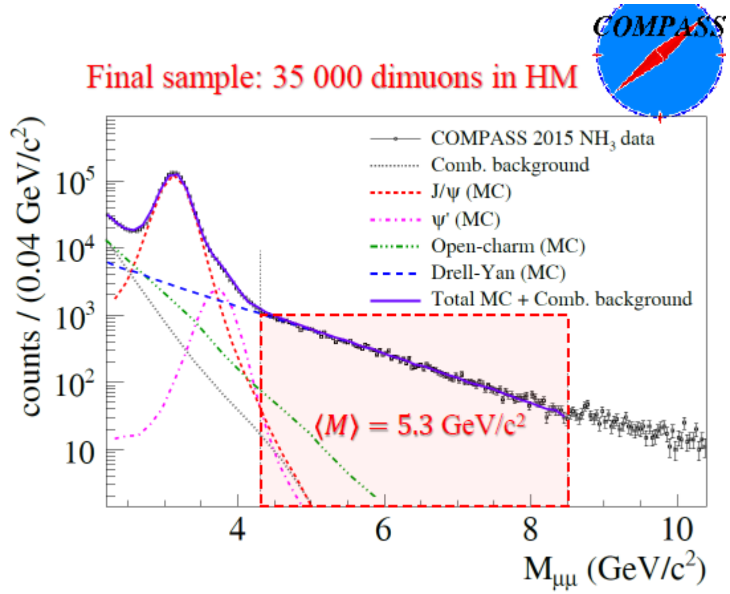


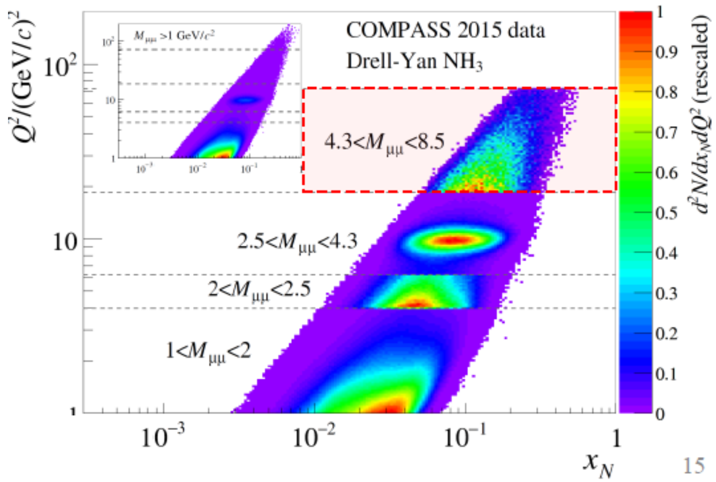
Kaon asymmetries slightly larger Compared to pion? Evidence for sea contribution?

Combined 2007 and 2010 proton data samples analyzed.

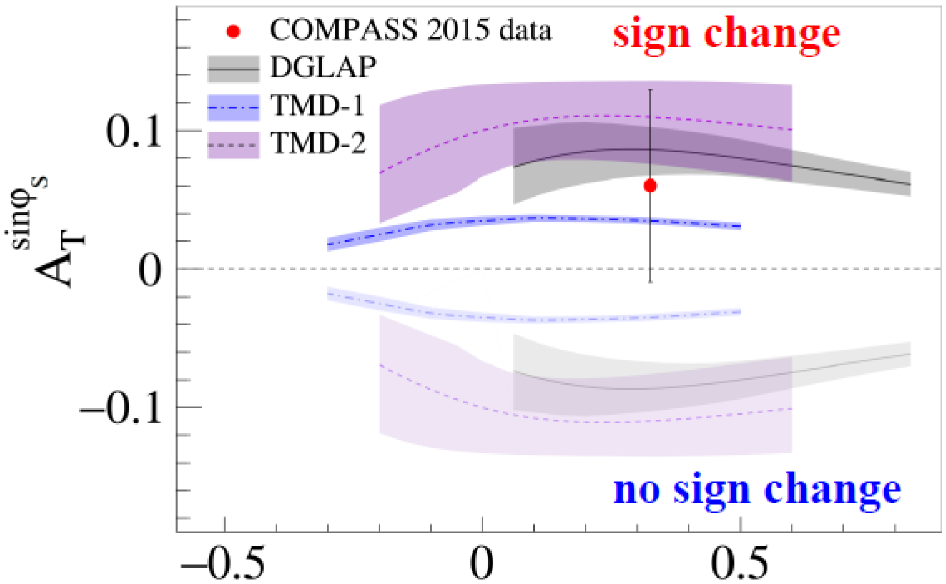
First COMPASS Result show 2 Sigma Preference for Sign Change

Final sample: 35 000 dimuons in HM





New! **03 April 2017**
COMPASS
[CERN-EP-2017-059]
[arXiv:1704.00488[hep-ex]]



Nucleon Structure Summary

- Good Knowledge of Parton Momentum Distributions further improving with incoming precise LHC data
- New data from HI collisions at LHC to constrain nuclear PDFs. Significantly more statistics will be needed. Will require eA at EIC.
- Helicity Distributions: quark helicity distributions well known. Nonzero gluon spin contribution observed. Large uncertainties from low extrapolation. Orbital angular momentum can be constraint if low x extrapolation uncertainty will be reduced
  ➔ EIC!
- Lattice QCD on track to compute x-dependent PDFs?!
- TMD and GPD have been solidly established. Require precision of Jlab 12 GeV and kinematic reach + precision of EIC