EIC
collinear (un)-polarized PDFs and fragmentation functions

, I. Borsa, X. Chu, Ch. van Hulse,
R.Sassot, H. Spiesberger, M. Stratmann,
K. Wichmann, E.C. Aschenauer

Electron Ion Collider

BROOKHAVEN NATIONAL LABORATORY
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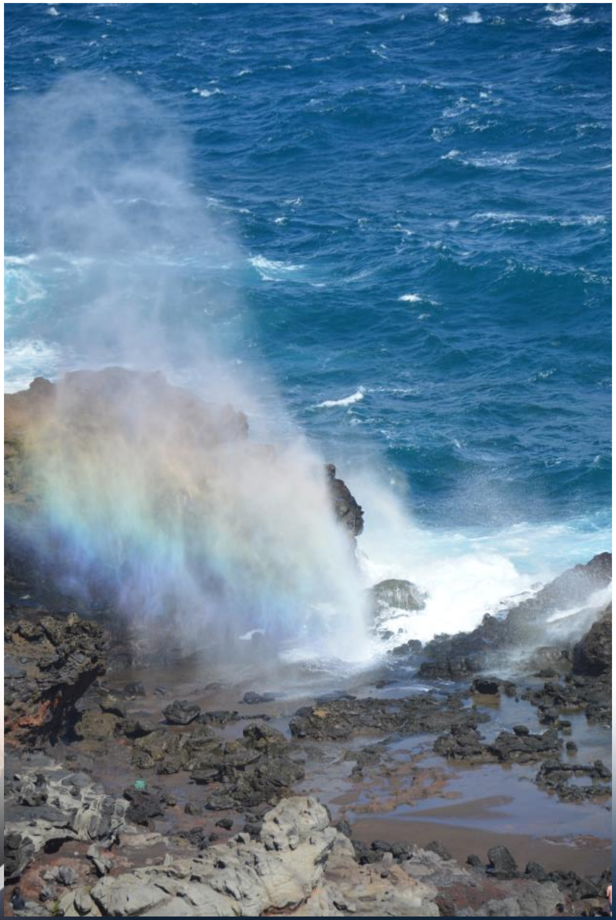
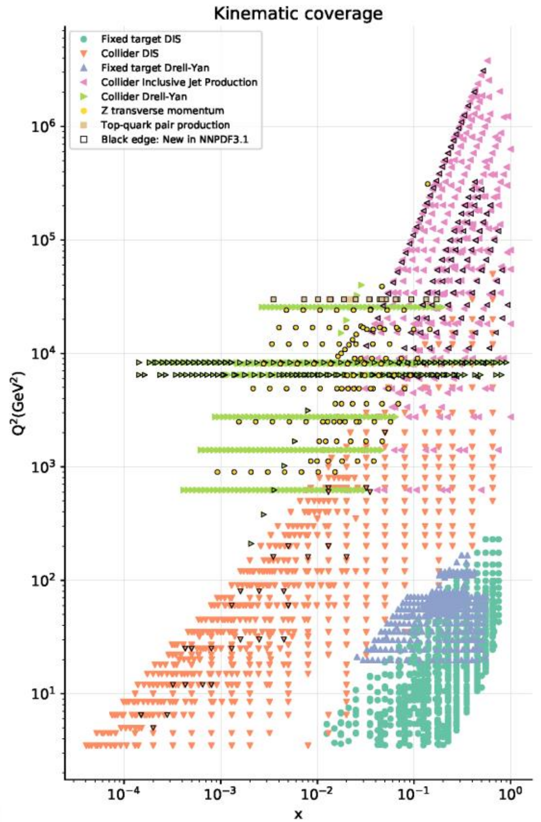
The inner life of hadrons
Parton distribution functions

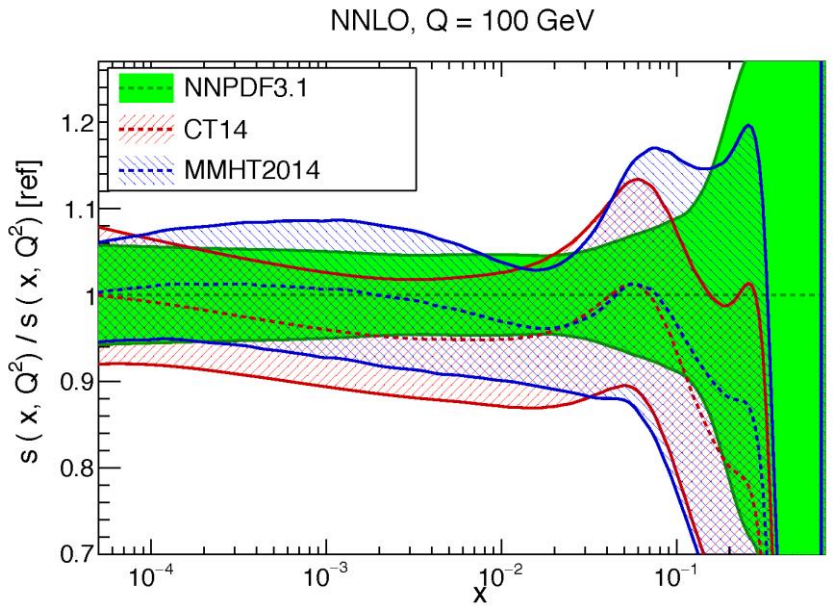


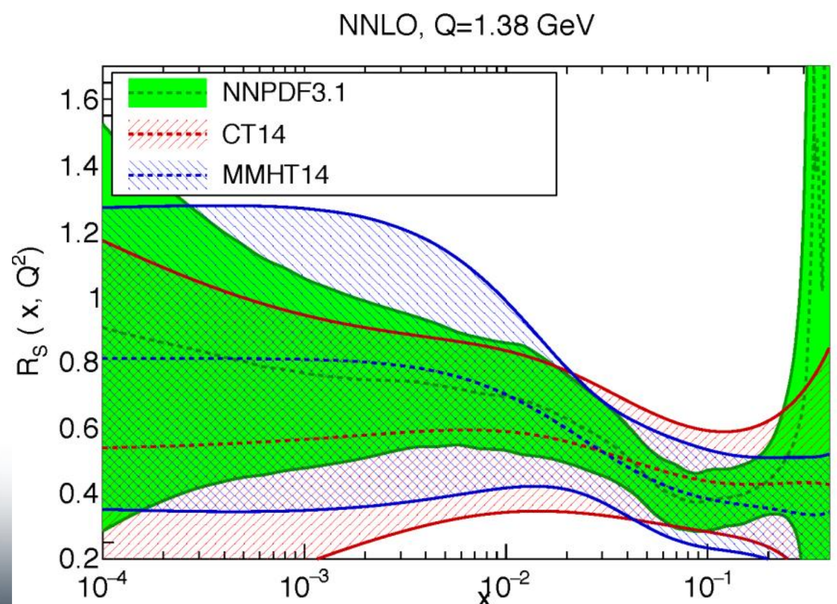
s(x) and sbar(x) where do we stand?

NNPDF 3.1 arXiv:1706.00428



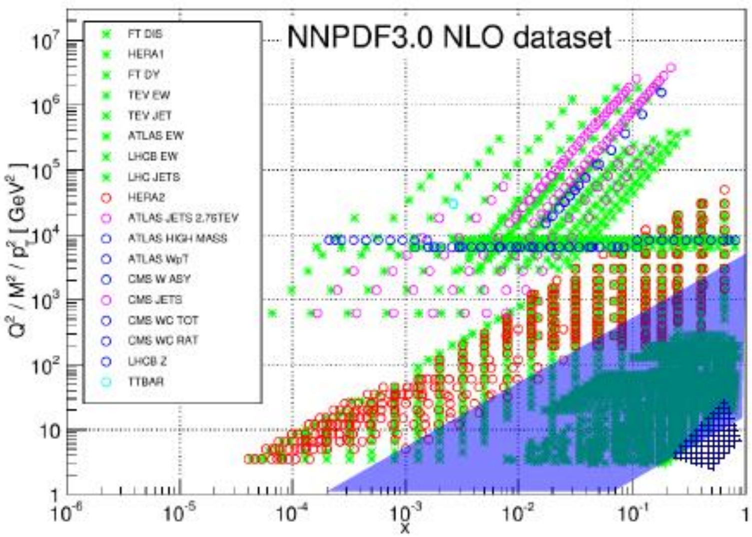
$$r_s(x,Q^2) = \frac{s(x,Q^2)+\bar{s}(x,Q^2)}{\bar{d}(x,Q^2)+\bar{u}(x,Q^2)} .$$



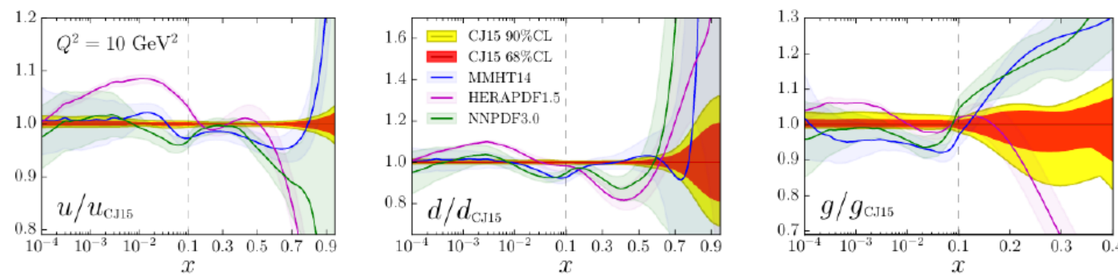


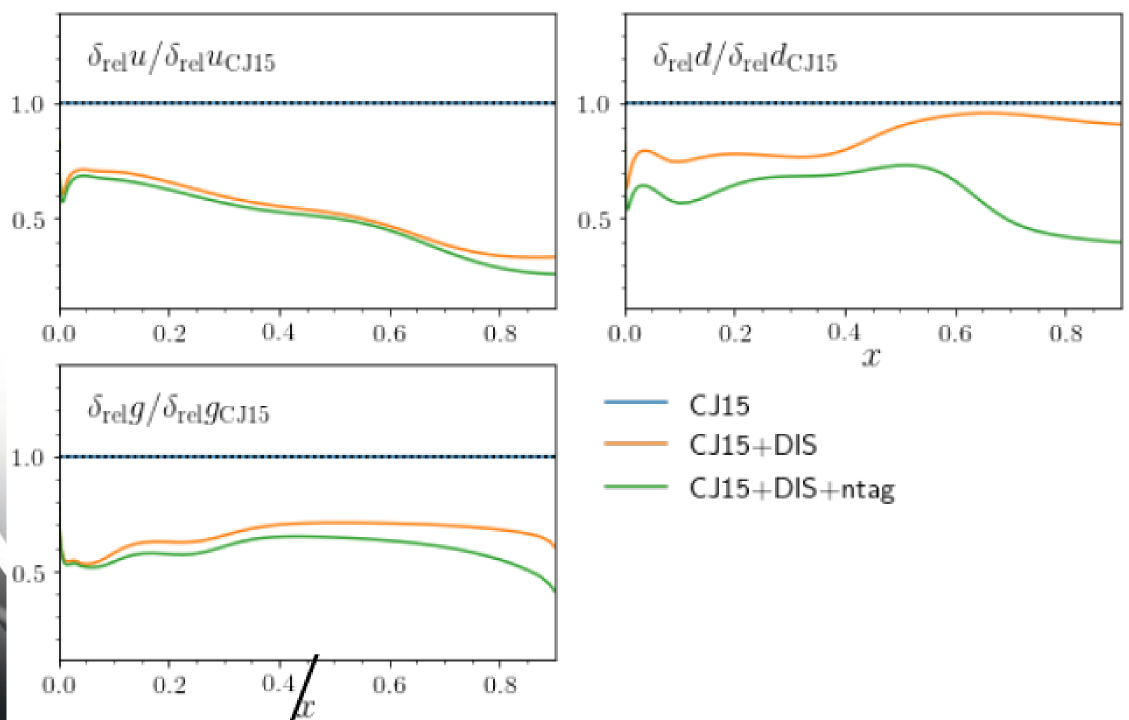
A. Accardi et al.

Proton PDFs at high x



Baseline: CJ-15





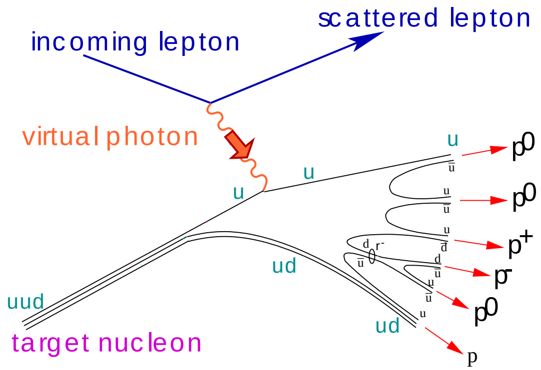
Relative error improvement:

- pseudo-data for 0.01 < x < 0.9
- NC Cross sections on proton target
- F_2^n from deuterium with tagged proton spectator
- 10x100 GeV^2 at 100 fb^{-1},
- energy scan $\sqrt{s}$=57, 49, 28 GeV at 10 fb^{-1}

→ more studies in progress

HOW TO ACCESS SEA QUARKS IN DIS

SIDIS:

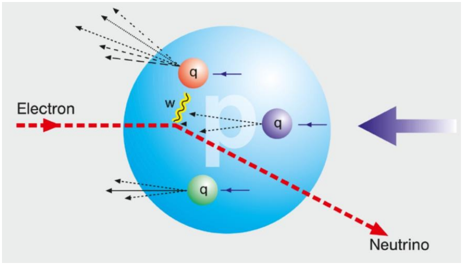


Detect identified hadrons in coincidence to scattered lepton

→ needs fragmentation functions to correlate hadron type with parton

→ Detector: PID over a wide range of η

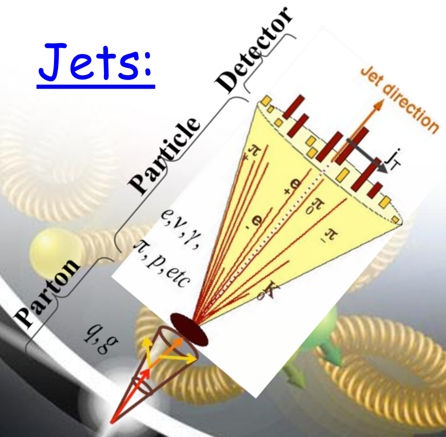
Charge Current:



W-exchange: direct access to the quark flavor no FF – complementary to SIDIS

→ Detector: large rapidity coverage and large √s

Jets:



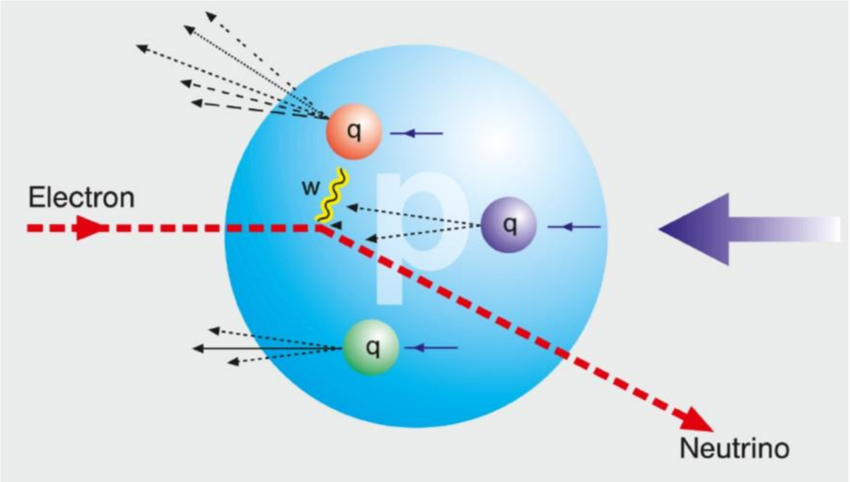
tag sea-quarks through the sub-processes and jet substructure

→ Detector: large rapidity coverage and PID

W-exchange:
direct access to the quark flavor

Ws are maximally parity violating
→ Ws couple only to one parton helicity

$$W^- + p \rightarrow u\bar{d}$$
$$W^- + n \rightarrow d\bar{u}$$



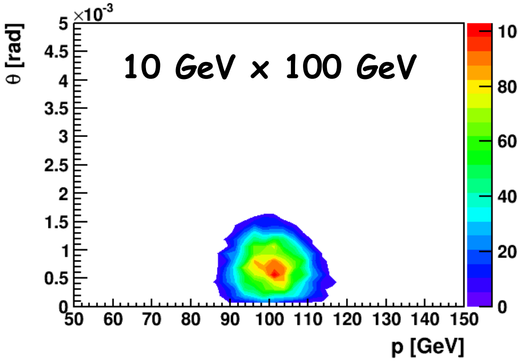
Complementary to SIDIS:

- high Q^2-scale: > 100 GeV^2
- best way to measure at very high x
- extremely clean theoretically
- No Fragmentation function

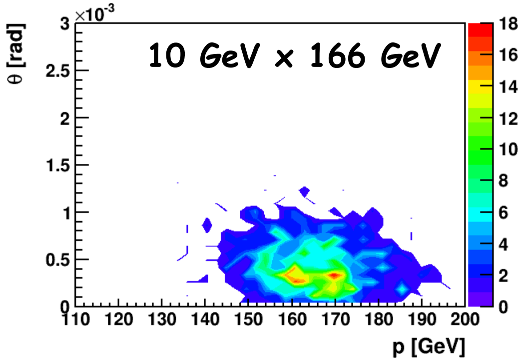
→ stringent test on theory approach for SIDIS
UNIVERSALITY of PDFs

effective neutron target:
(un)polarized Deuterium or /and He-3
through tagging the spectator proton(s)

Deuterium spectator protons:

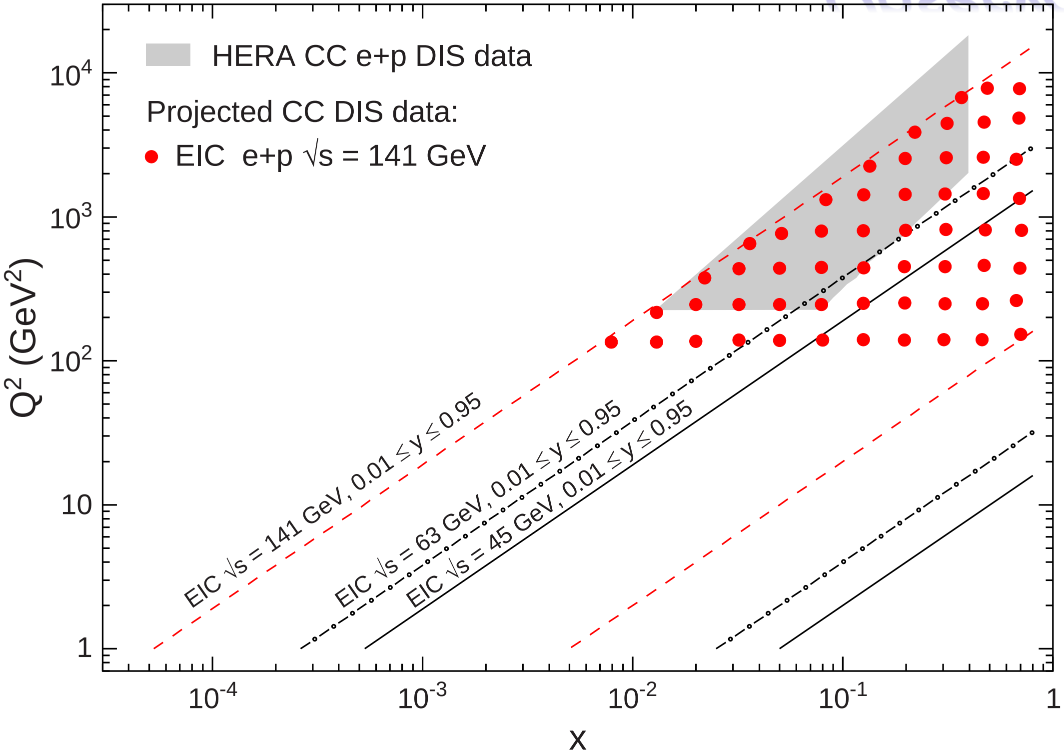


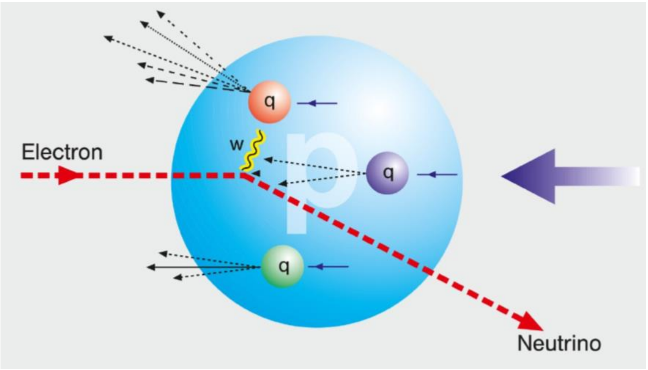
He-3 spectator protons:

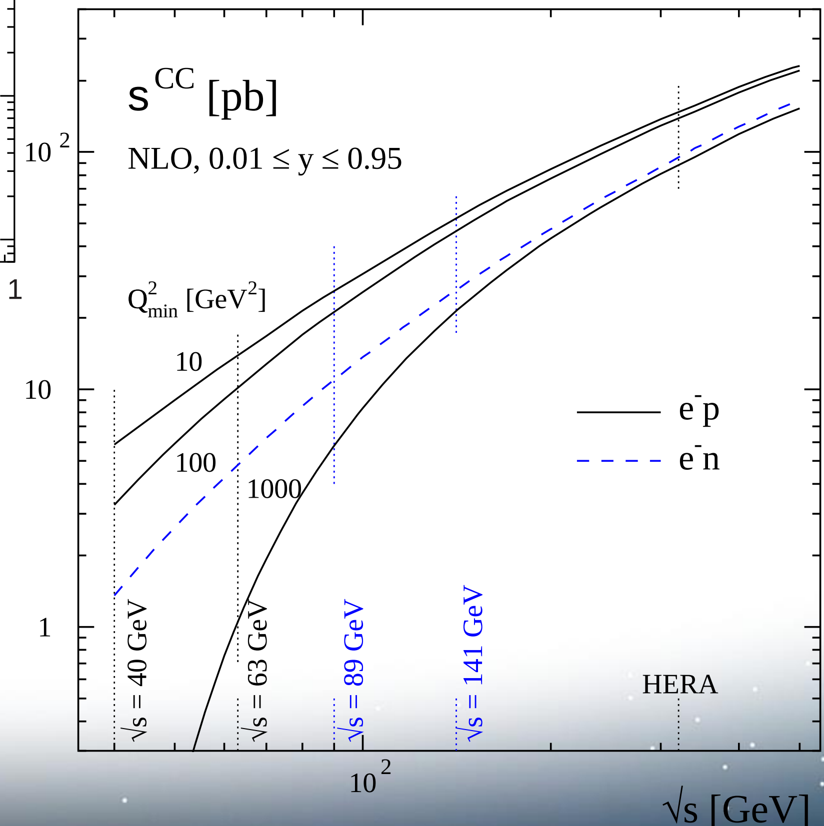


EIC:
first time charge current physics
in polarized ep and eA collisions

Observables: Charge Current in ep







EIC has a large kinematic coverage for charge current events (○)

Observables: Charge Current in ep and eA

Just some of the physics opportunities:

polarized ep/en:

- test models based on helicity retention $\Delta d/d \rightarrow 1$
  (Phys.Rev.Lett. 99 (2007) 082001)
- precision test models assuming charge symmetry violation
- precision test handiness of Ws
- tag charm in coincidence with CC event → Δs

unpolarized ep/en:

- impact on PDFs → high x quark PDFs
  - tag charm in coincidence ot CC event → s
- precision constrain on light quark weak neutral current couplings a_u, v_u, a_d v_d

unpolarized eA:

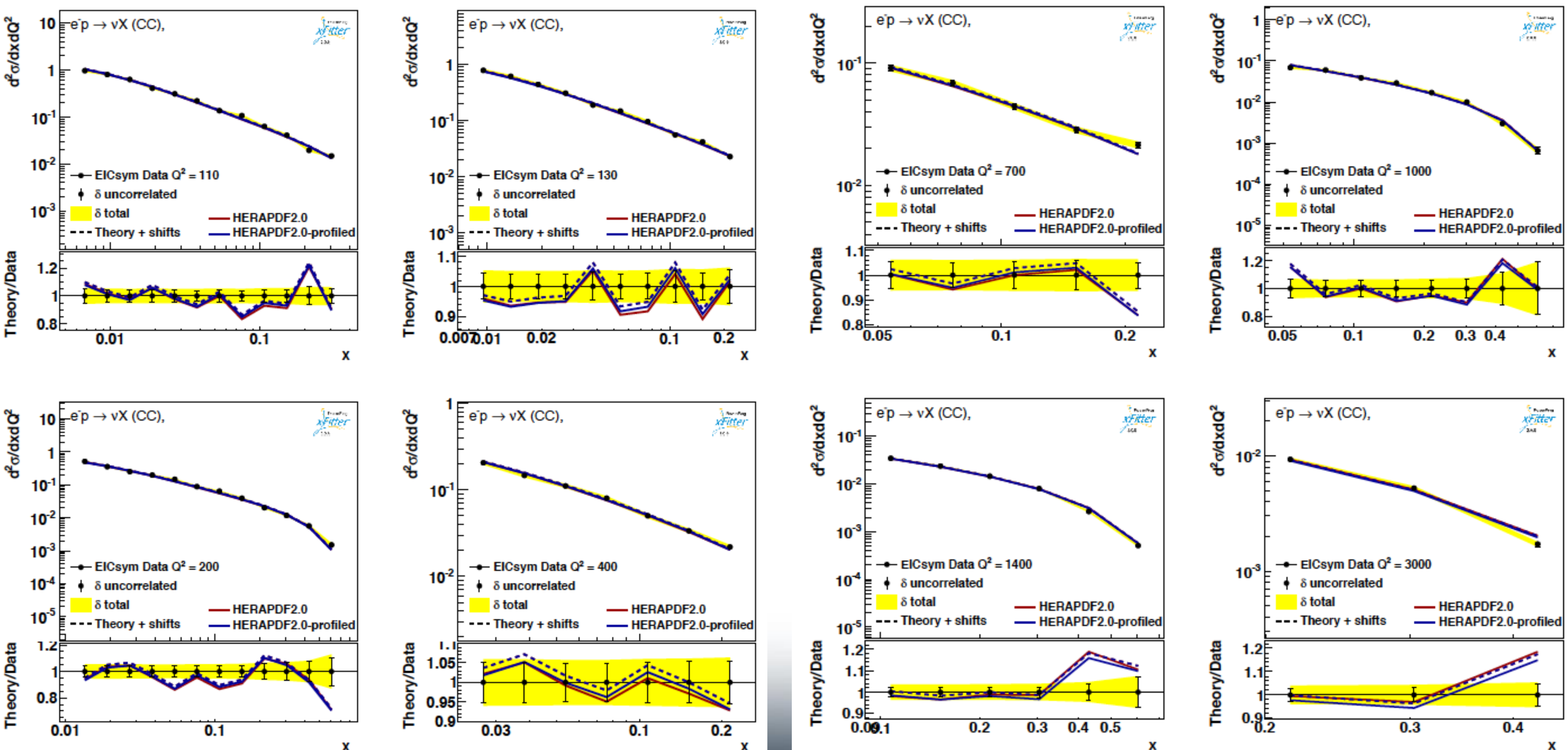
- Test Models for the EMC-effect
  - charge symmetry violation
  - Isovector EMC effect
    (Cloet, Bentz, Thomas et. al., PRL 102 252301)

CC@EIC: Impact on PDFs

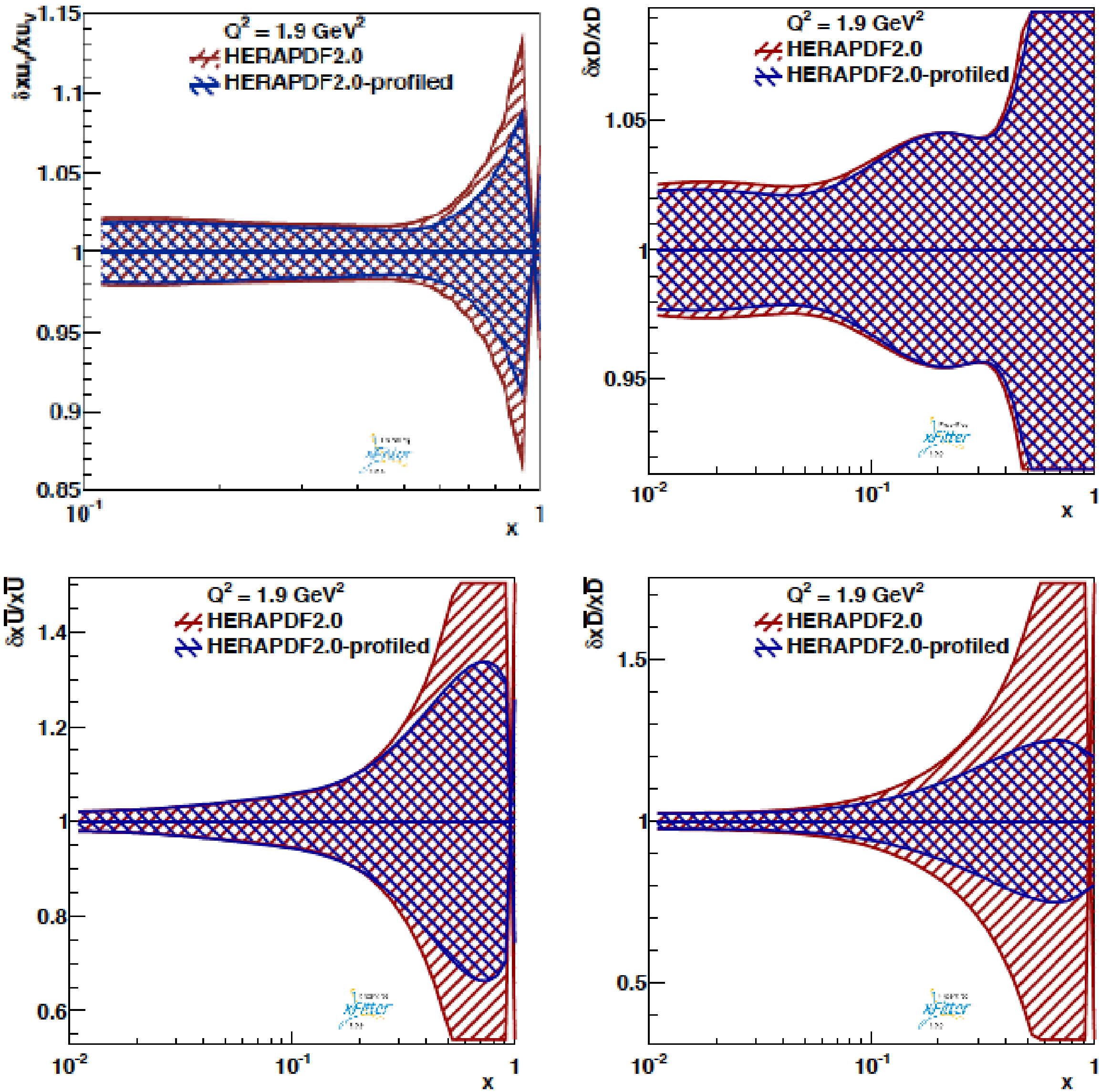
Generated 10 fb^{-1} worth of ep CC events with DJANGOH for 20 GeV x 250 GeV

xFitter is used to get the impact on PDFs

good agreement between pseudo-data and prediction



Impact of CC@EIC to PDFs



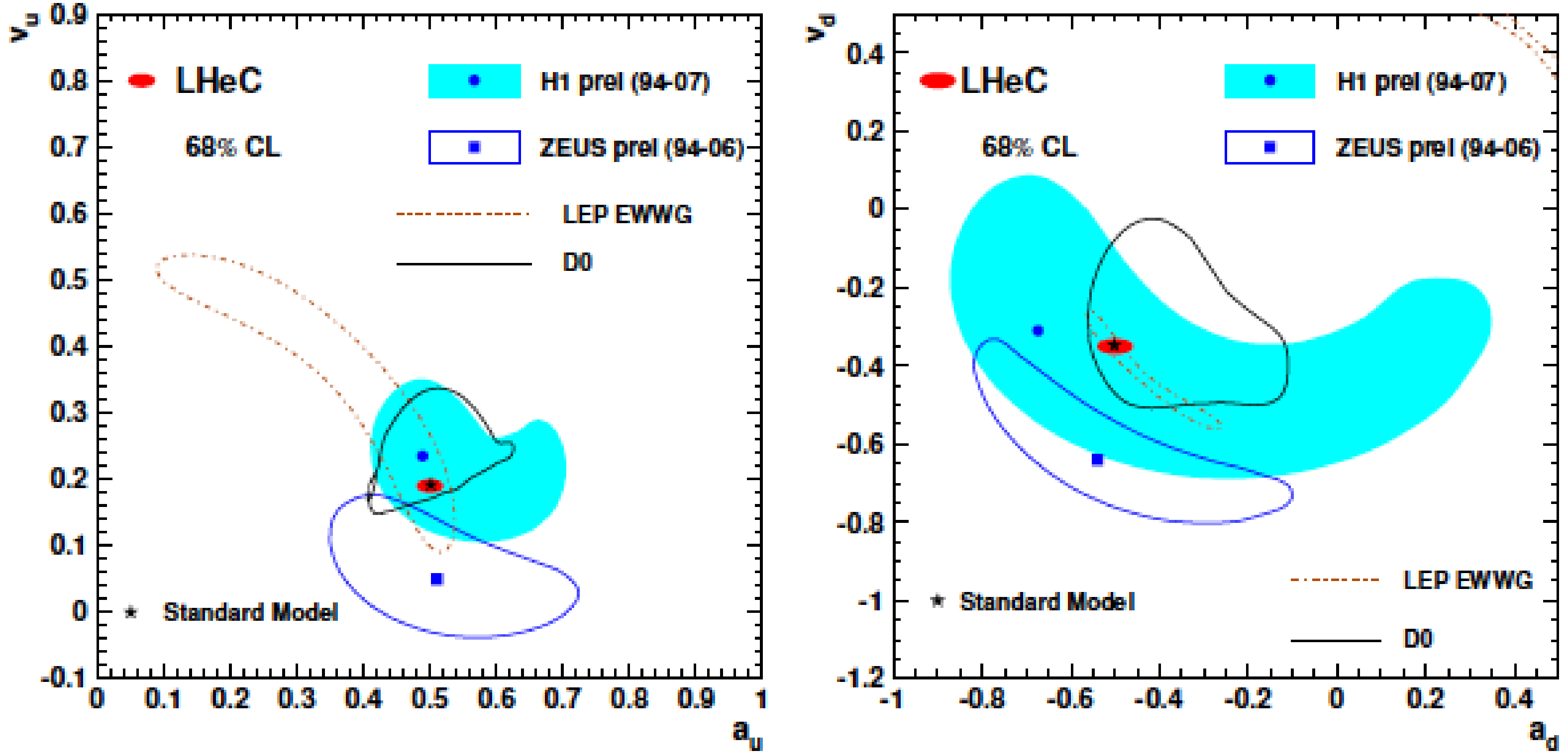
$$xU = xu + xc$$
$$xD = xd + xs$$
$$x\bar{U} = x\bar{u} + x\bar{c}$$
$$x\bar{D} = x\bar{d} + x\bar{s}$$
$$xu_v = xU - x\bar{U}$$
$$xd_v = xD - x\bar{D}$$

Very strong impact on $x\bar{D}$
significant impact on xu_v
Need to still understand in detail why there is impact on $x\bar{U}$

→ very promising first results

What can an EIC Do?

Should study what NC and CC cross sections at EIC can tell us on the vector and axial-vector weak neutral current couplings



Ch.vanHulse, I. Borsa, R. Sassot, ECA

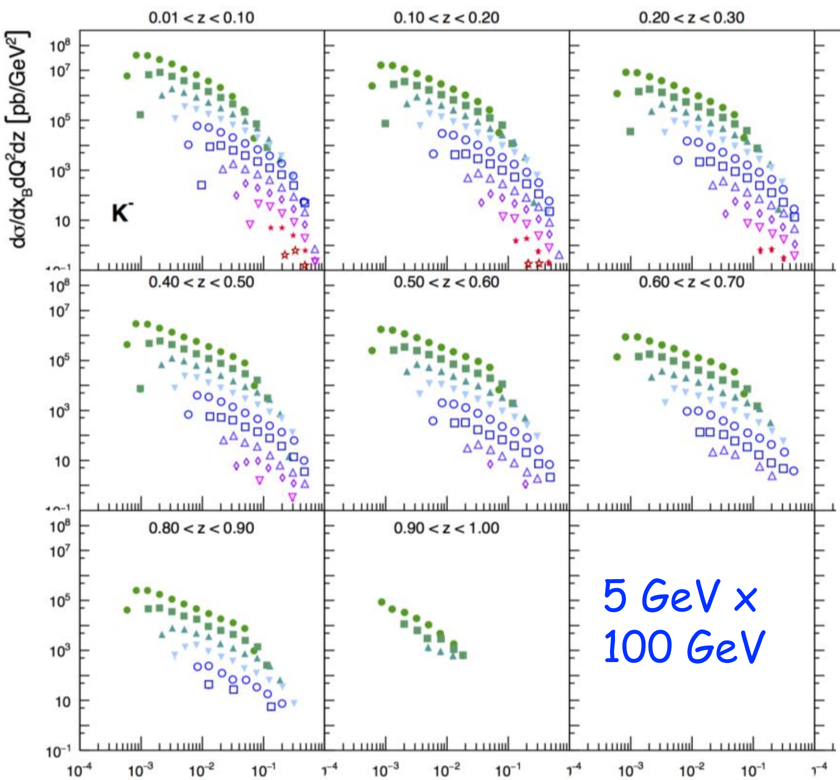
What can SIDIS@EIC Teach us

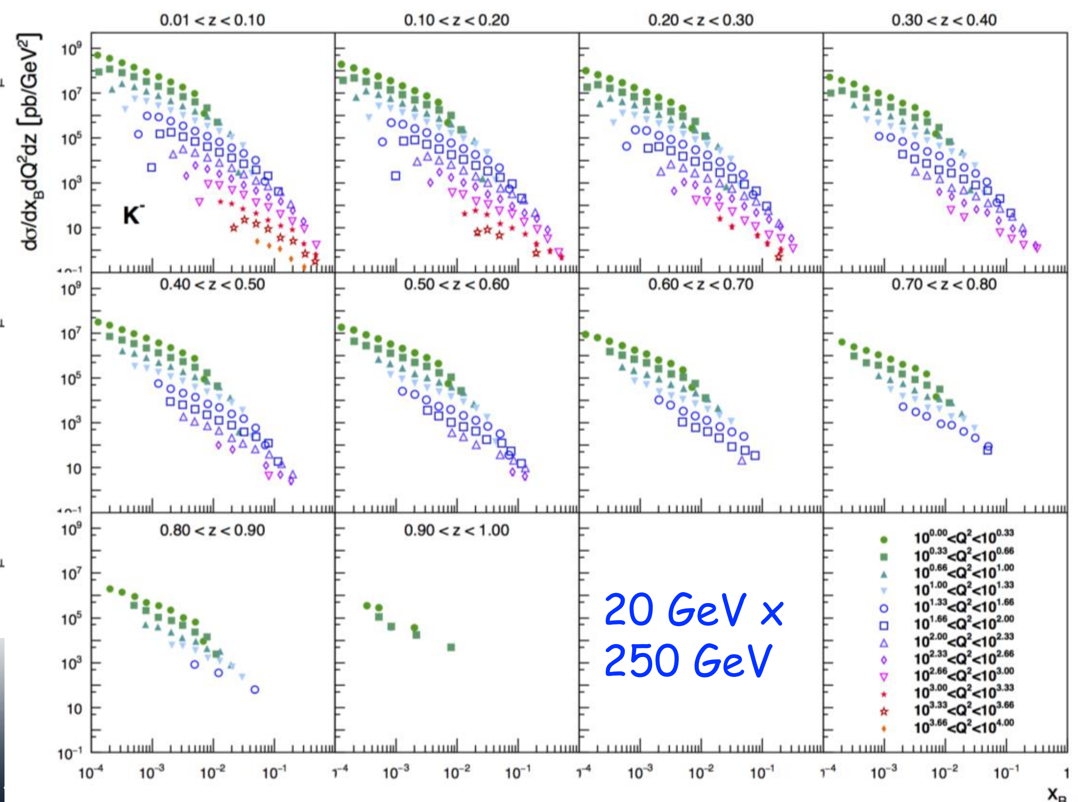
Cuts:

$Q^2 > 1\ GeV^2$ $0.1 < y < 0.95$ $W^2 > 10\ GeV^2$ $p_T > 0.2\ GeV$

PID:

	pi:	K:	p:
-3.5< rapidity< -1 RICH:	0.5 < p < 5 GeV	1.6 < p < 5 GeV	3 < p < 8 GeV
-1.5< rapidity < -1 dE/dx	0.2 < p < 0.6 GeV	0.2 < p < 0.6 GeV	0.2 < p < 1.0 GeV
-1 < rapidity < 1 : dE/dx & DIRC:	0.2 < p < 4 GeV	0.2< p <0.7 & 0.8 < p < 4 GeV	0.2< p <1.1 & 1.5 < p < 4 GeV
1 < rapidity < 3.5 RICH	0.5 < p < 50 GeV	1.6 < p < 50 GeV	3 < p < 50 GeV
1 < rapidity < 1.5 dE/dx	0.2 < p < 0.6 GeV	0.2 < p < 0.6 GeV	0.2 < p < 1.0 GeV





PDFs: flavor separation from SIDIS@EIC

Use reweighting method to define EIC SIDIS data impact on collinear unpolarized PDFs and Fragmentation functions

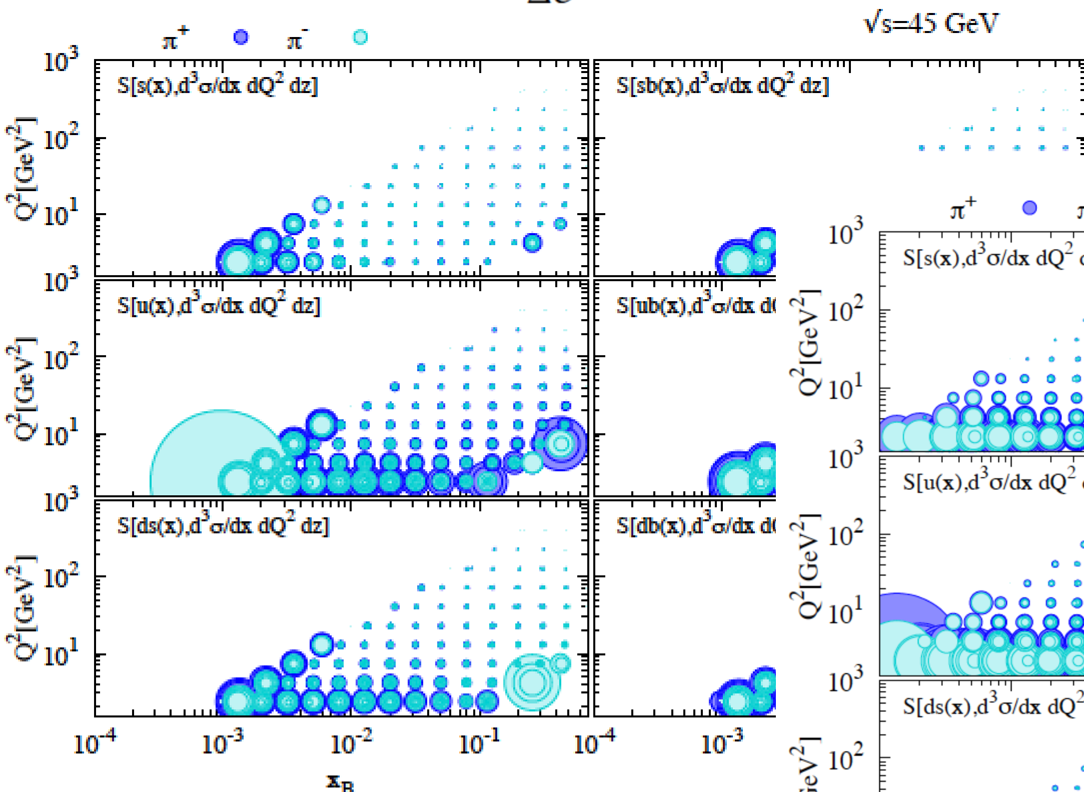
$\delta\mathcal{O}$: exp. uncertainty Observable

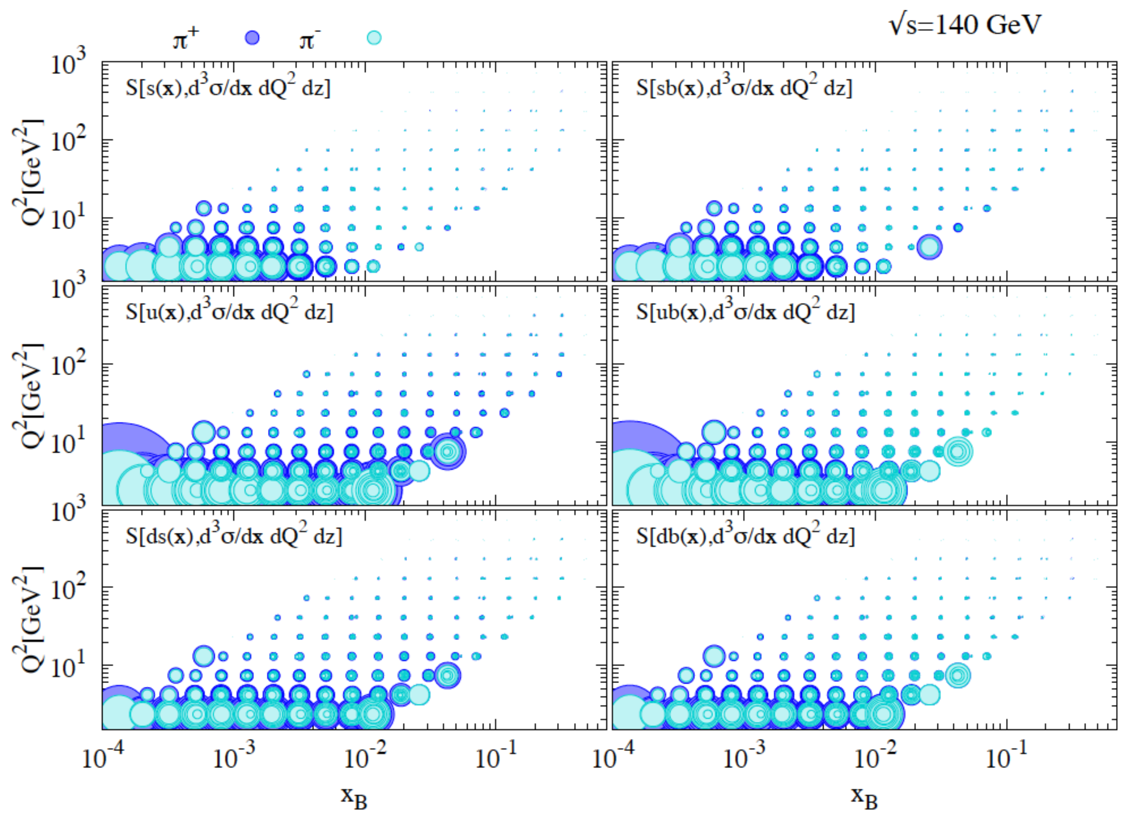
Δ PDF in Observable

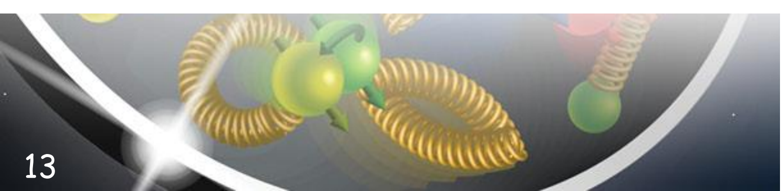
Correlation factor of observable $\mathcal{O}$ to a flavor i

$$\rho\,[f_i, \mathcal{O}] = \frac{\langle \mathcal{O}\cdot f_i\rangle - \langle \mathcal{O}\rangle\langle f_i\rangle}{\Delta\mathcal{O}\Delta f_i}\,, \quad \xrightarrow{\text{account for uncertainties}} \quad S[f_i, \mathcal{O}] = \frac{\langle \mathcal{O}\cdot f_i\rangle - \langle \mathcal{O}\rangle\langle f_i\rangle}{\xi\,\Delta\mathcal{O}\Delta f_i}\,,$$

$$\xi \equiv \frac{\delta\mathcal{O}}{\Delta\mathcal{O}}$$







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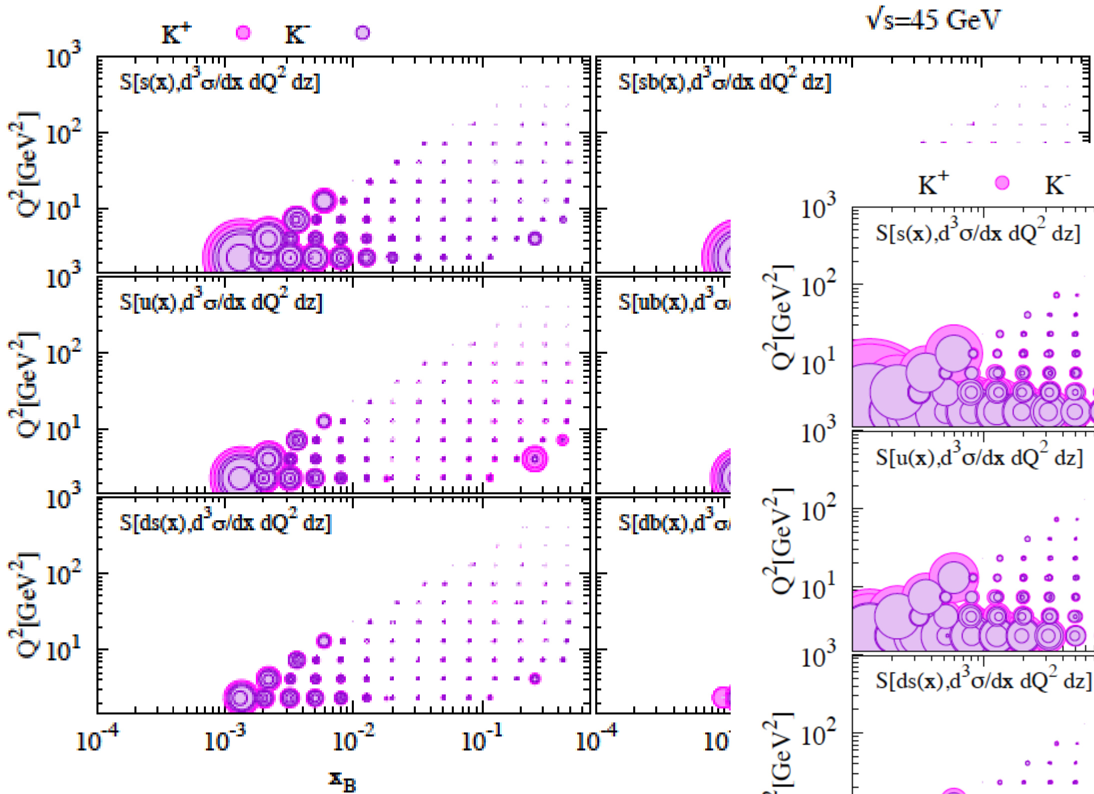
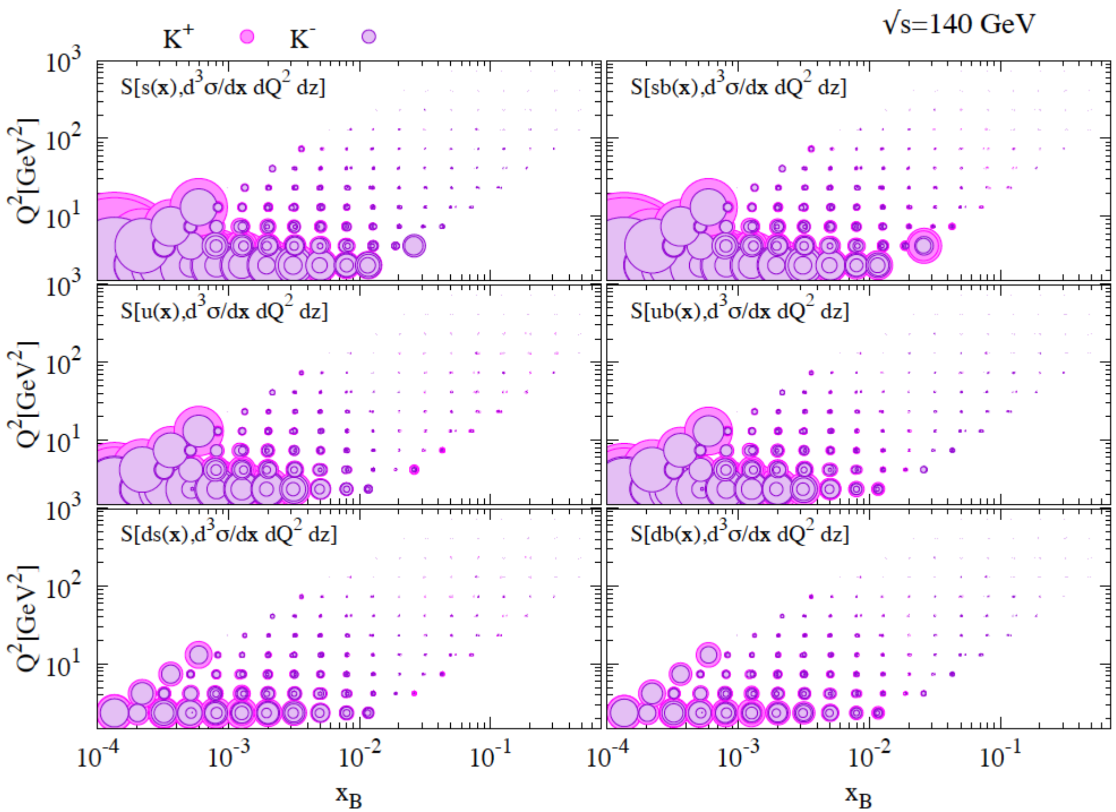
$$\xi \equiv \frac{\delta \mathcal{O}}{\Delta \mathcal{O}}$$

$\delta\mathcal{O}$: exp. uncertainty Observable

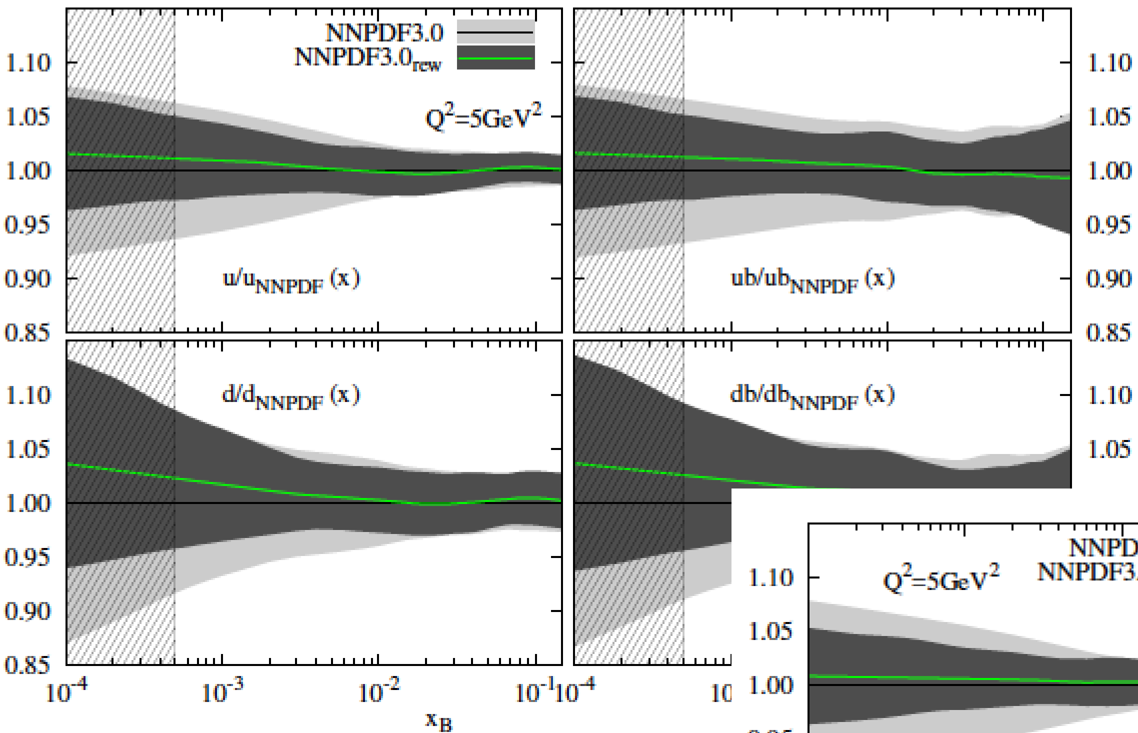
Δ PDF in Observable



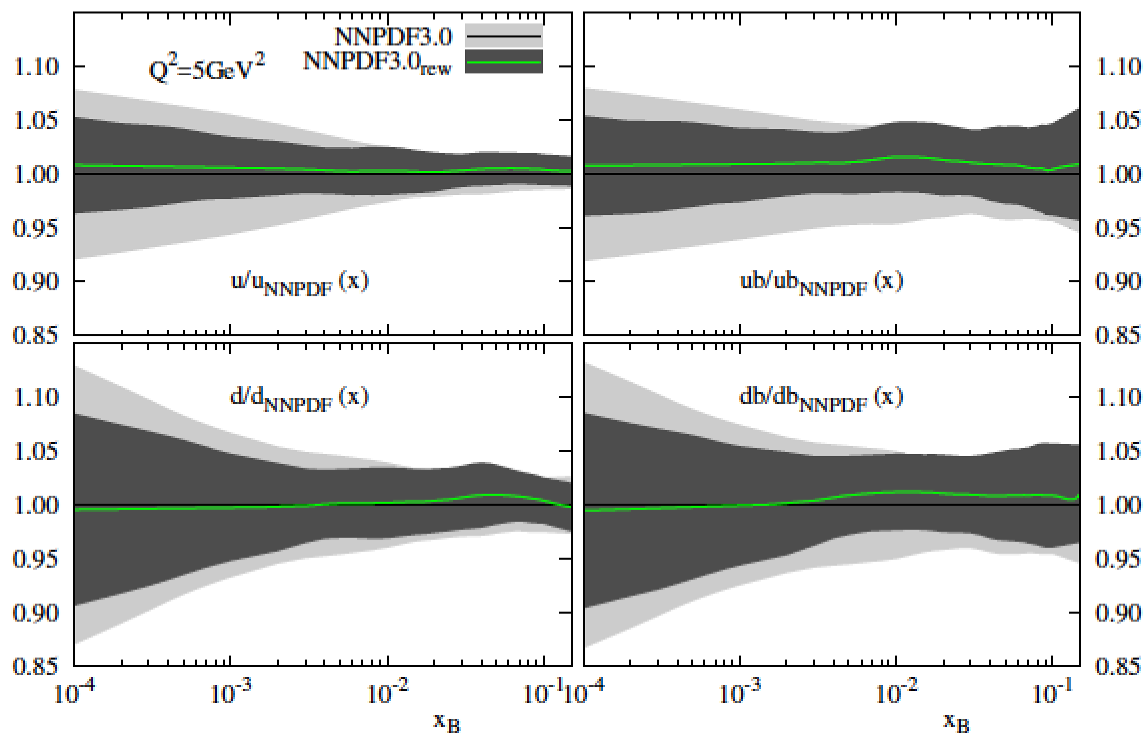


PDF Constrain from SIDIS@EIC

√s=45 GeV



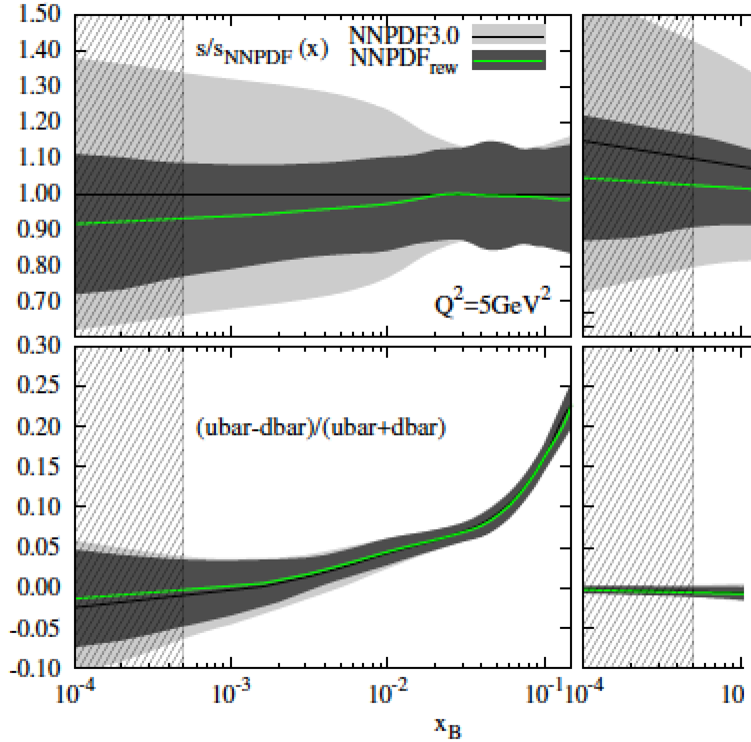
√s=145 GeV



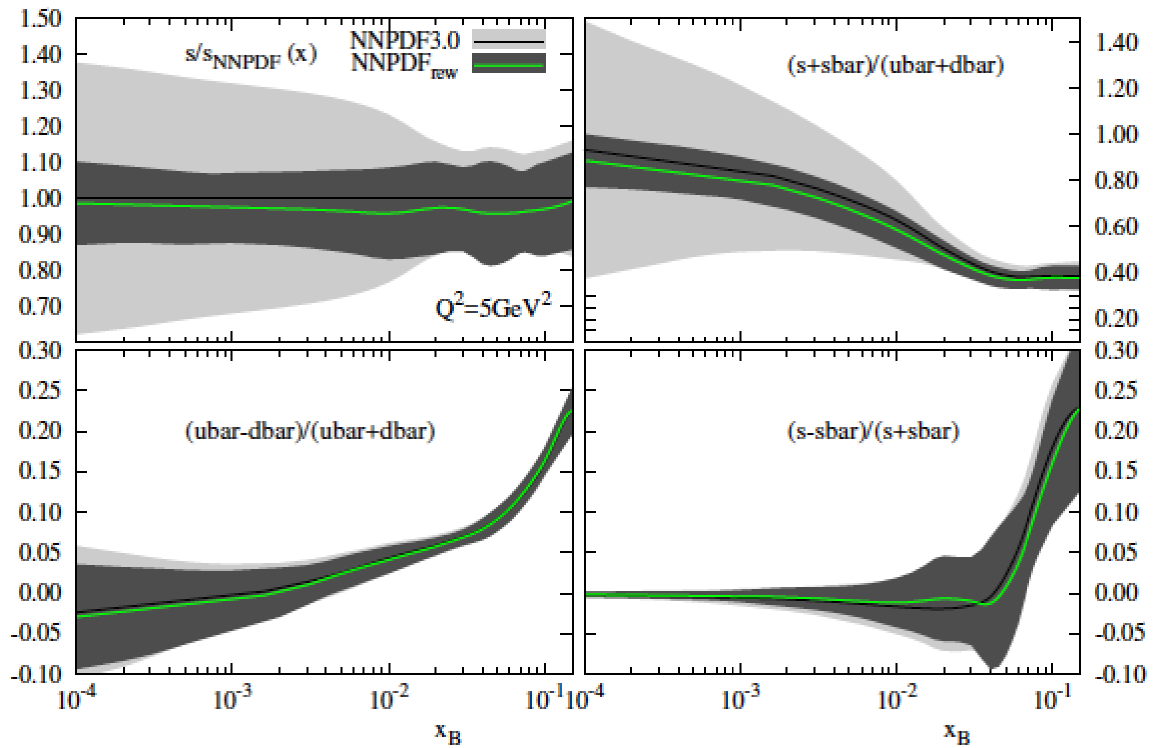
Impressive constrain of
light quarks for x < 0.1
need to investigate x>0.1 more
→ impact grows with √s

PDF Constrain from SIDIS@EIC

√s=45 GeV



√s=145 GeV



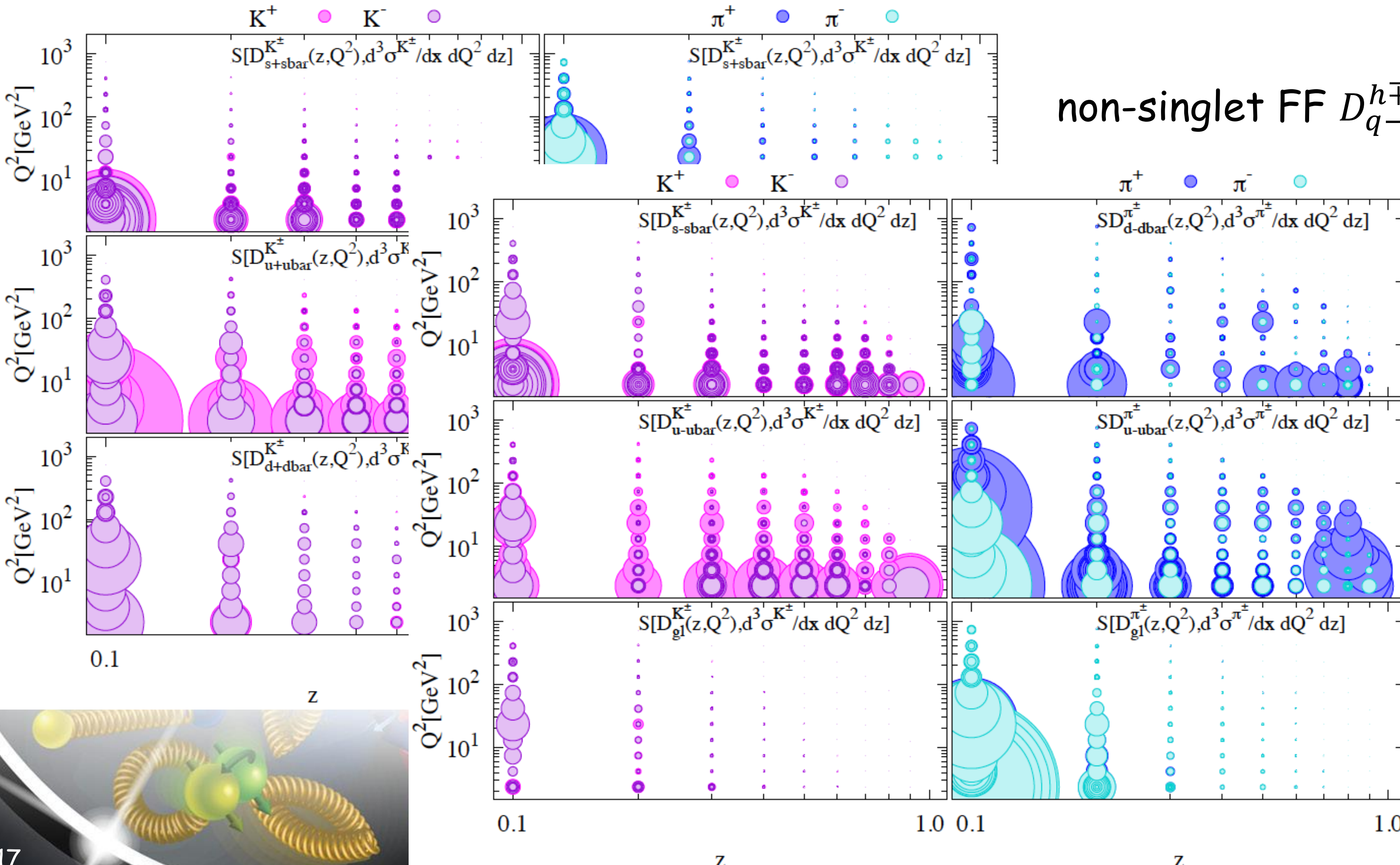
If you want to know
s-PDF ask the EIC
→ impact grows with √s

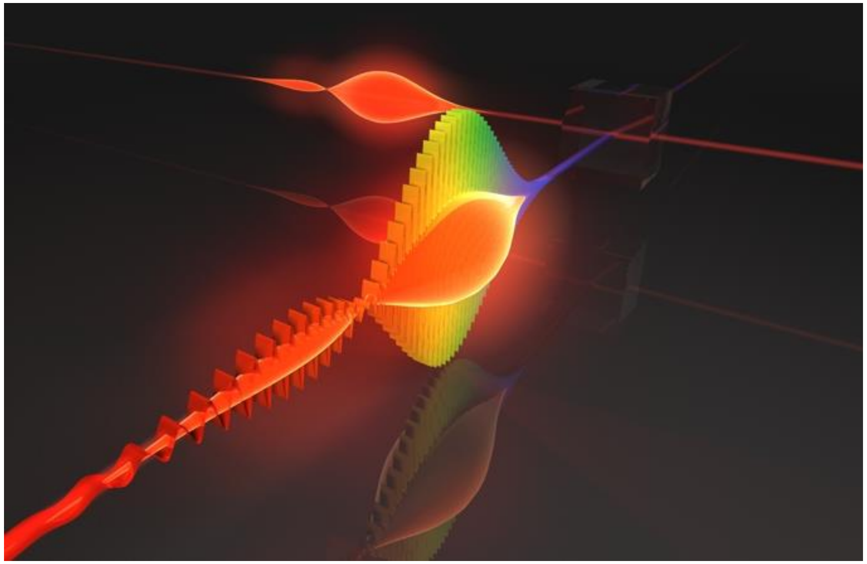
FF Constrain from SIDIS@EIC

Utilize the same method as for PDFs

singlet FF $D^{h\mp}_{q+\bar{q}}$

non-singlet FF $D^{h\mp}_{q-\bar{q}}$





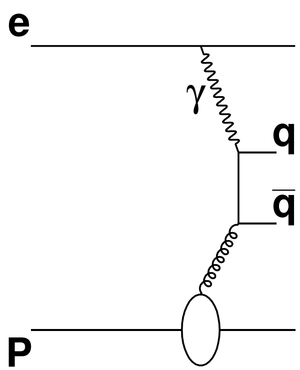
Example for Jet Physics at an EIC:

Unpolarized and polarized photon structure

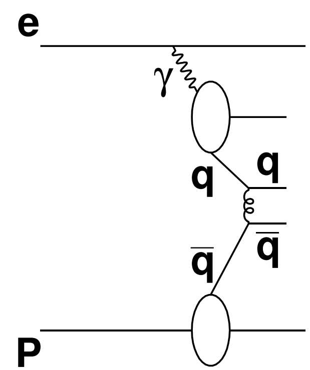
Details: X. Chu, ECA arXiv:1705.08831

Photon Parton Structure

In high energy ep collision, two types of processes lead to the production of di-jets:



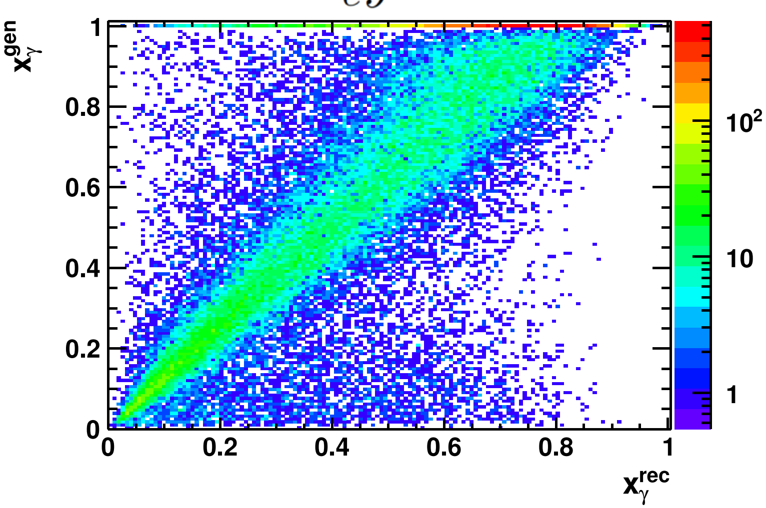
direct: point-like photon

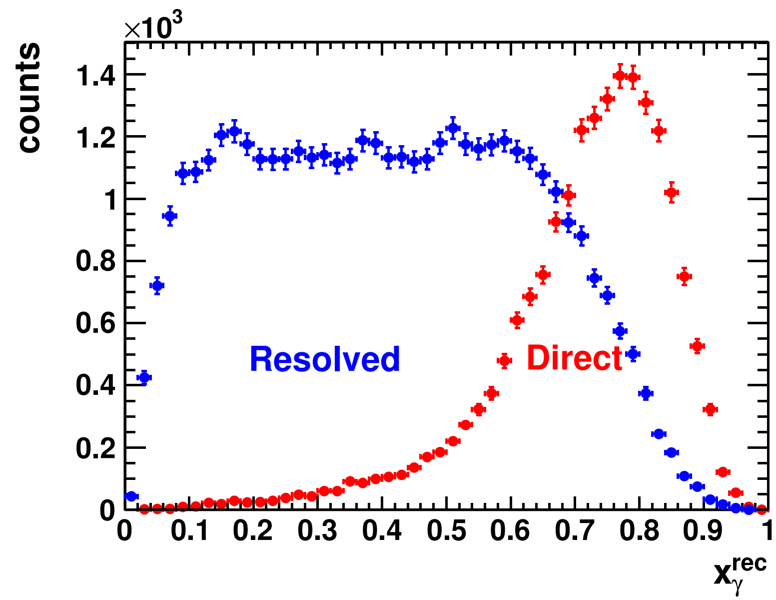


resolved: hadronic photon

- **Di-jets@EIC ideal probe to constrain (un)polarised Photon-PDFs**
  - **Direct/resolved contributions can be separated** reconstructing xγ

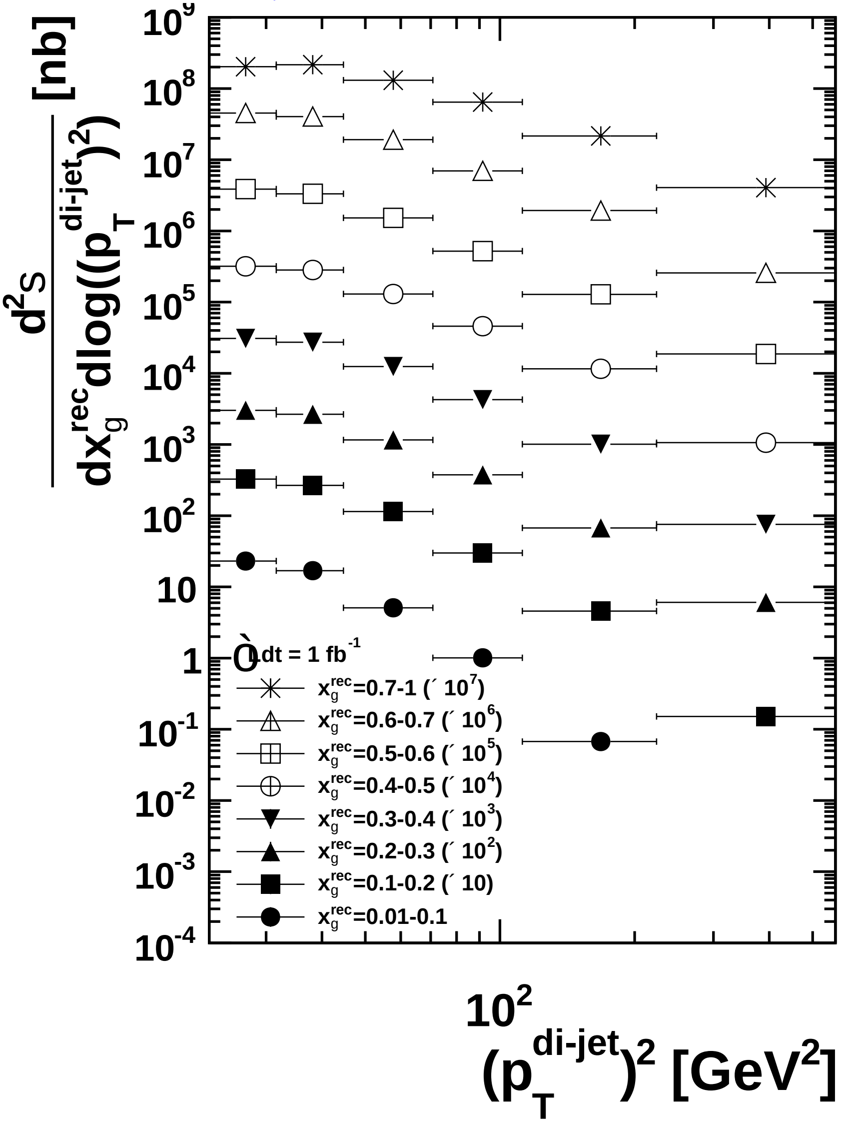
$$x_\gamma^{rec} = \frac{1}{2E_e y}\left(p_{T1}e^{-\eta_1} + p_{T2}e^{-\eta_2}\right)$$



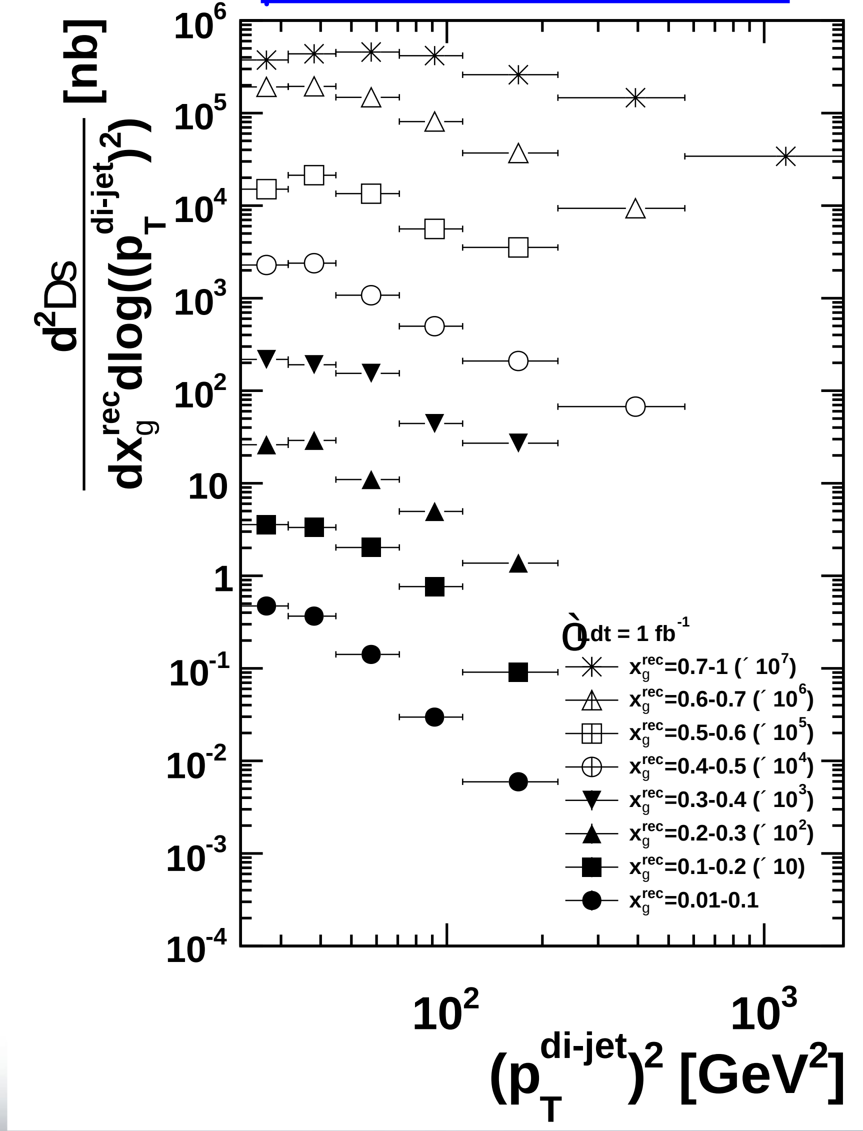


Photon Parton Structure

unpolarized cross section:



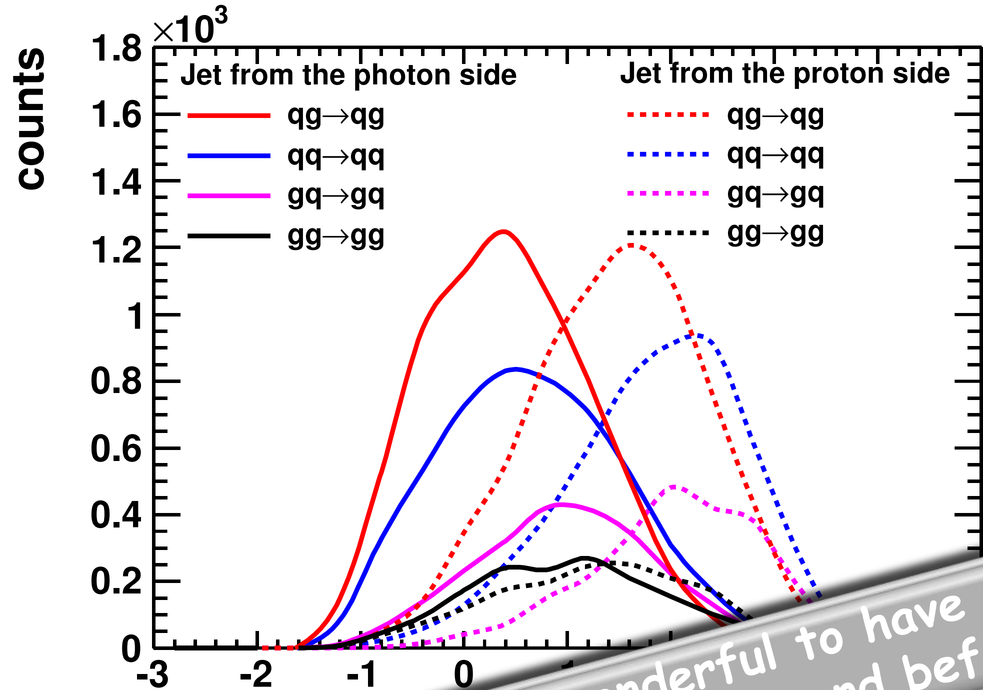
polarized cross section:



Input: proton-CTEQ-5 & γ: SAS

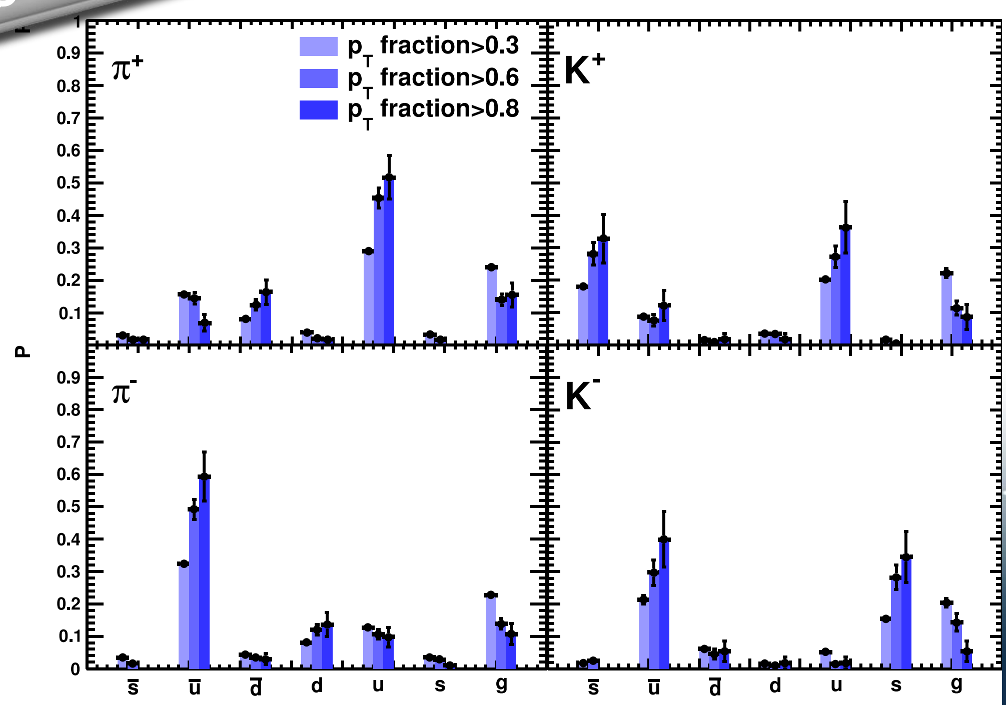
Input: proton-DSSV &
γ: PLB 337 373 (1994)

Photon Parton Structure

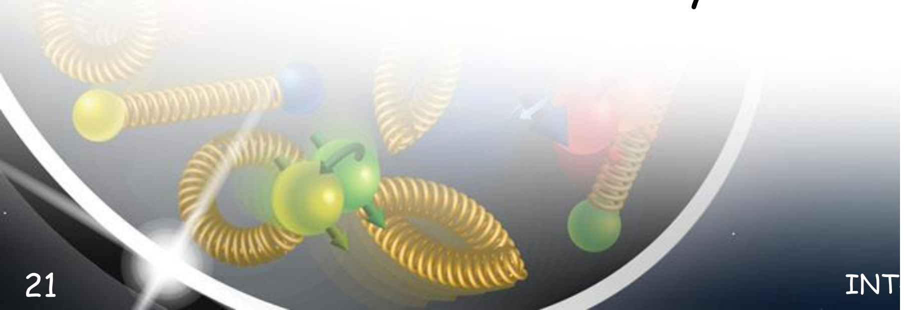


Jets from photon and proton side are well separated in η for quark initiated processes

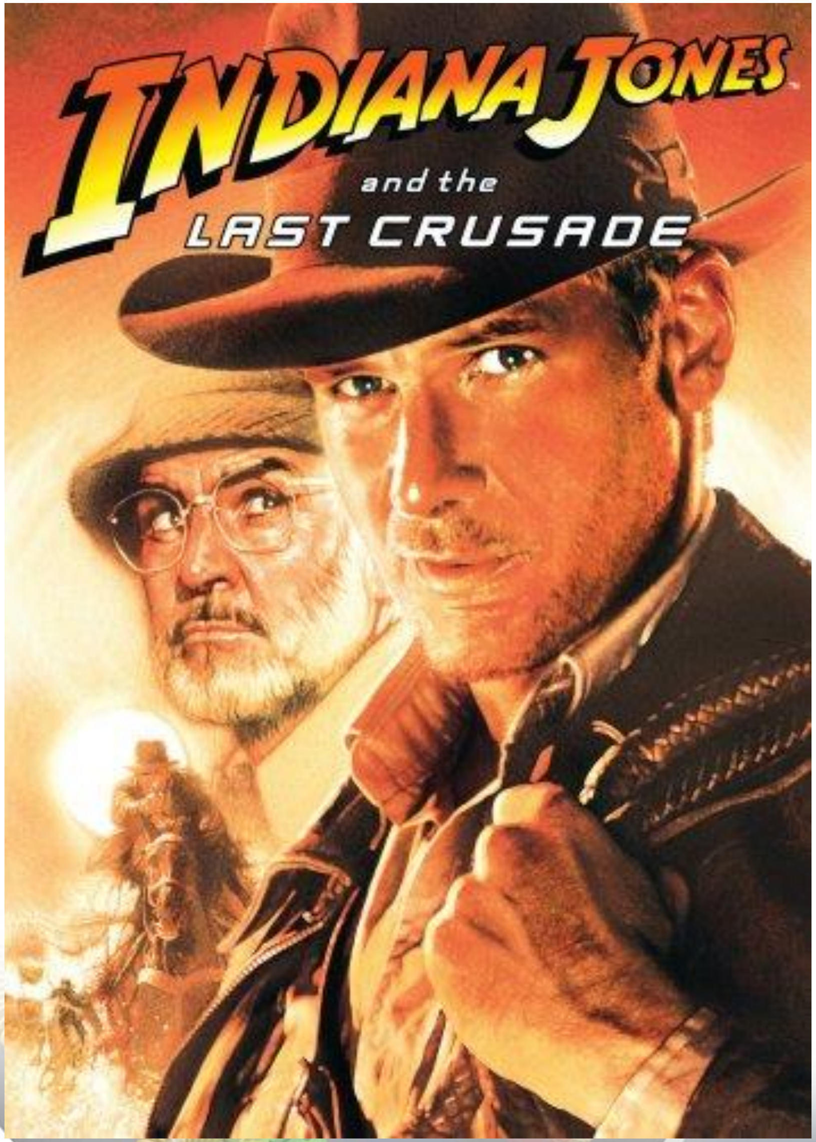
It would be wonderful to have unpolarised photon PDFs with all data (LEP & HERA and before) fitted with uncertainties



identified hadron tagging in jet enhances flavor sensitivity



What else can be done



The Holy Grail

Why should we care?

Spin ideal tool to understand the dynamics of sea quarks and gluons inside the hadron

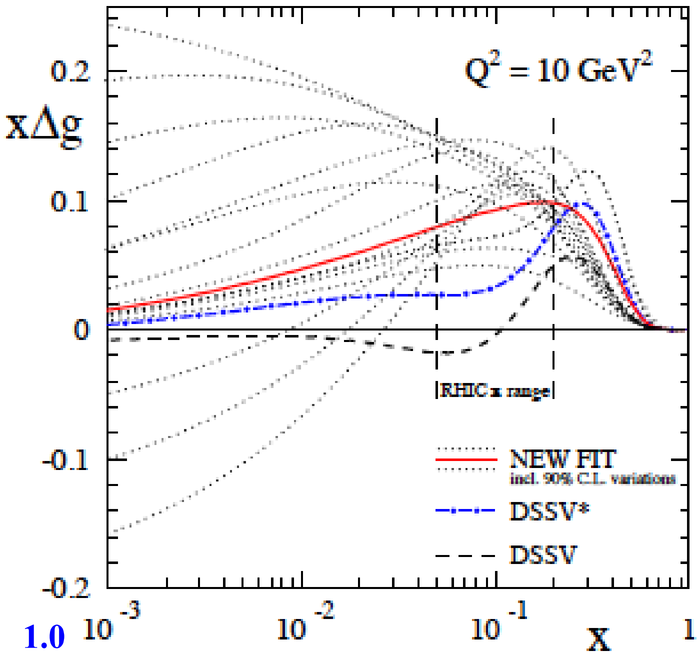
Despite decades of QCD – Spin one of the least understood quantities
→ Consequence very few models, but several physics pictures, which can be tested with high precision data

- the pion/kaon cloud model
  - → rooted in deeper concepts → chiral symmetry
  - → generated q-qbar pairs (sea quarks) at small(ish)-x are predicted to be unpolarized
  - → gluons if generated from sea quarks unpolarised → spatial imaging
  - → a high precision measurement of the flavor separated polarized quark and gluon distributions as fct. of x is a stringent way to test.
- the chiral quark-soliton model
  - → sea quarks are generated from a "Dirac sea" with a rich dynamical structure but excludes gluons at its starting scale
  - → sea quarks are polarized → asymmetry $\Delta\bar{u} \neq \Delta\bar{d}$
  - → a high precision measurement of the flavor separated polarized quark as fct. of x is a stringent way to test
- stringent test of lattice calculations
  - → the relative importance of lattice graphs
  - → probe quark is connected to the proton wave function or is created from the 'gluon soup' inside the proton

What we have now: ∫Δg(x)

DSSV: arXiv: 1404.4293, PRL 113, 012001

DSSV: arXiv:0904.3821
DSSV*: DSSV + all new (SI)DIS
DSSV: DSSV* & RHIC 2009

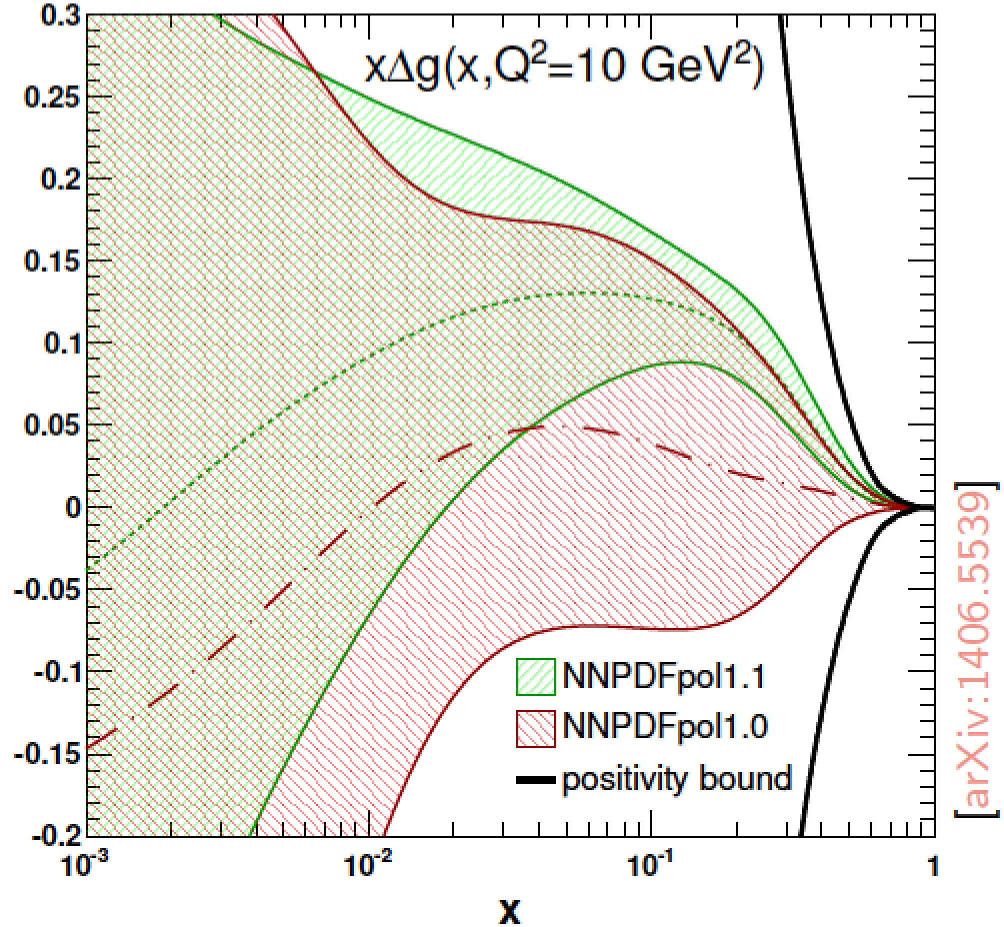


$$\int_{0.05}^{1.0} dx\Delta g \sim 0.2 \pm^{0.06}_{0.07} @\ 10\ \text{GeV}^2$$

First time a significant non-zero Dg(x)

- strong constrain on $\int \Delta g(x)$
- first $\int \Delta g(x) > 0$
- completely consistent with DSSV* in 90% C.L.

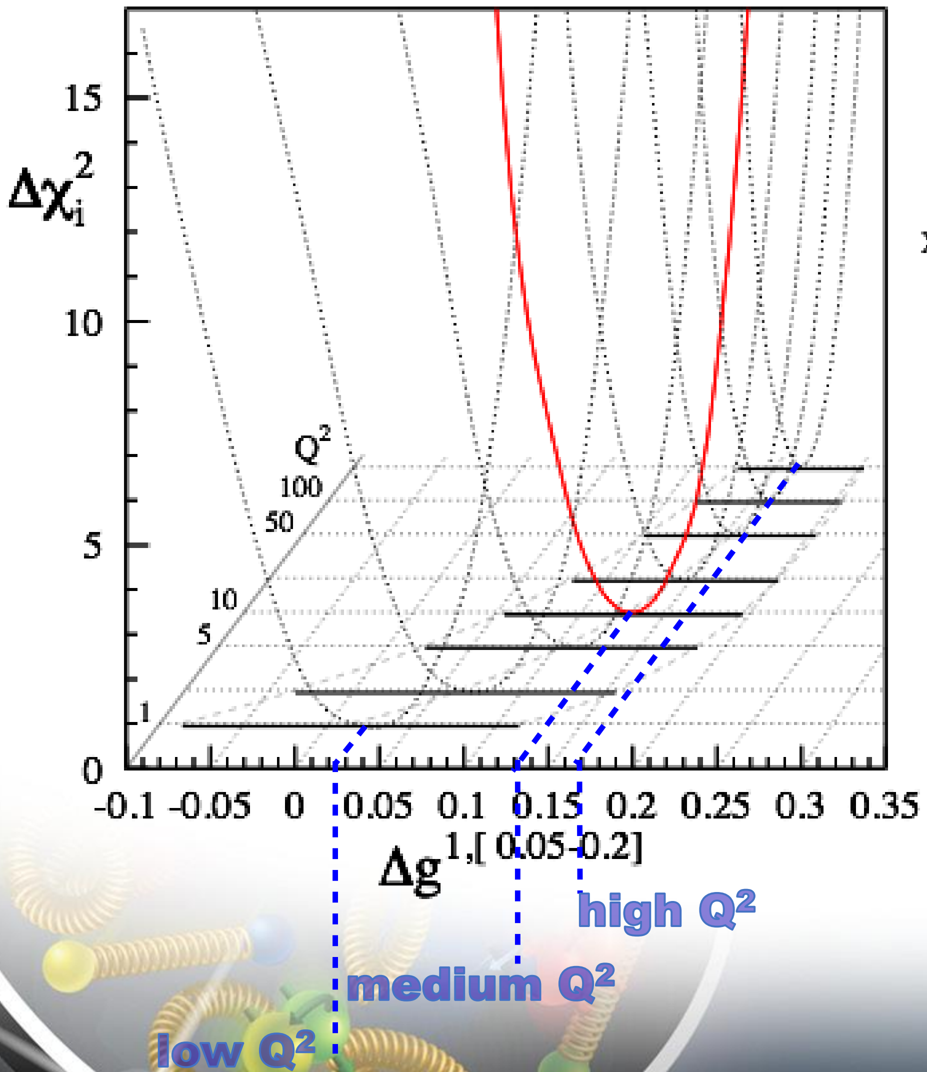
Impact in NNPDF

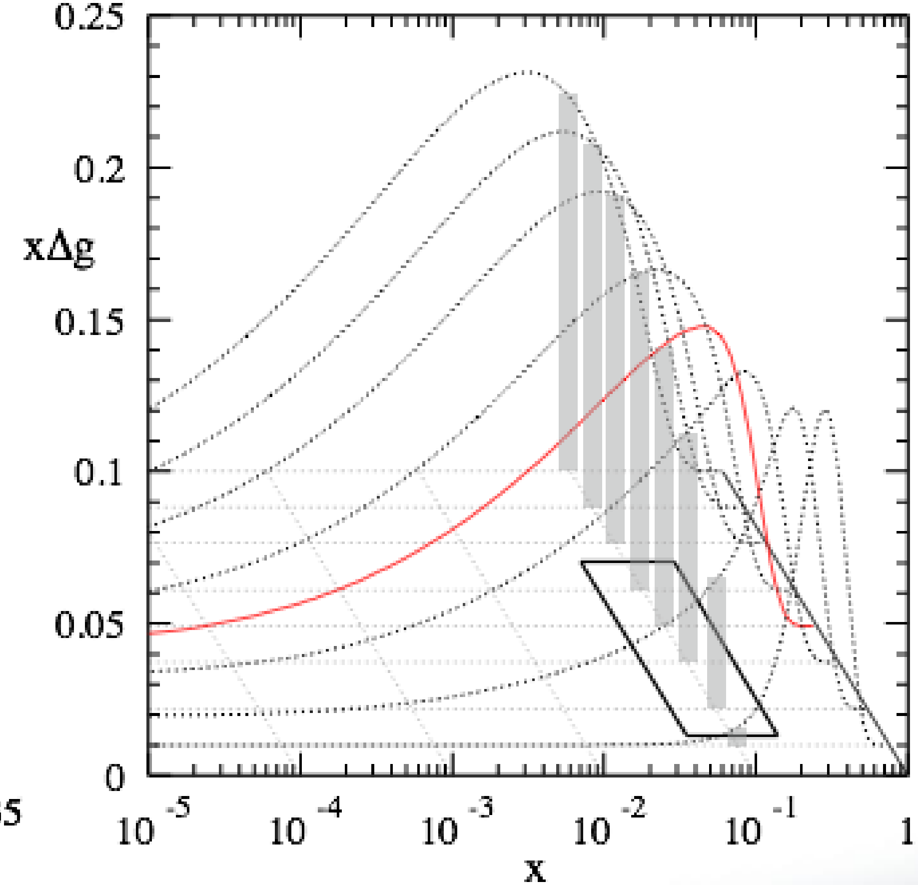


only STAR jets included

Q^2-Dependence

$$\Delta g^{1,[0.05-0.2]}(Q^2) \equiv \int_{0.05}^{0.2} \Delta g(x, Q^2)\, dx$$





very fast evolution
in RHIC kinematics

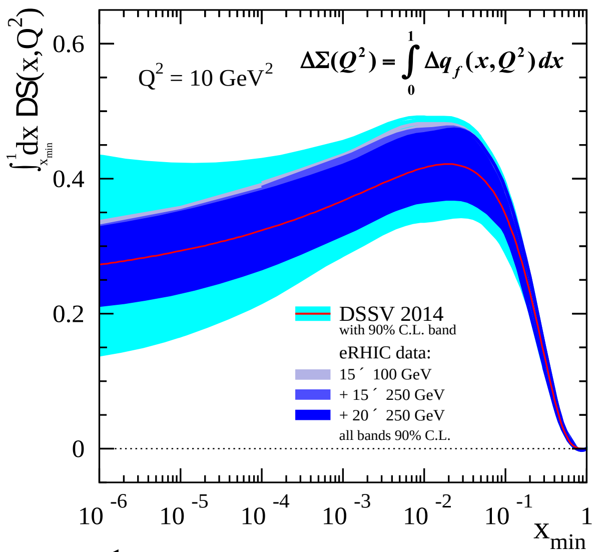
Why is separating quark flavors important?

Why is separating quark flavors important?

- nuclear structure is encoded in parton distribution functions
- understand dynamics of the quark-antiquark fluctuations
- flavor asymmetry in the light quark sea in the proton

  unpolarized: ubar < dbar Helicity: Δubar > Δdbar TMDs: ?????

  - shape of polarized sea-quark PDFs critical for quark contribution to spin

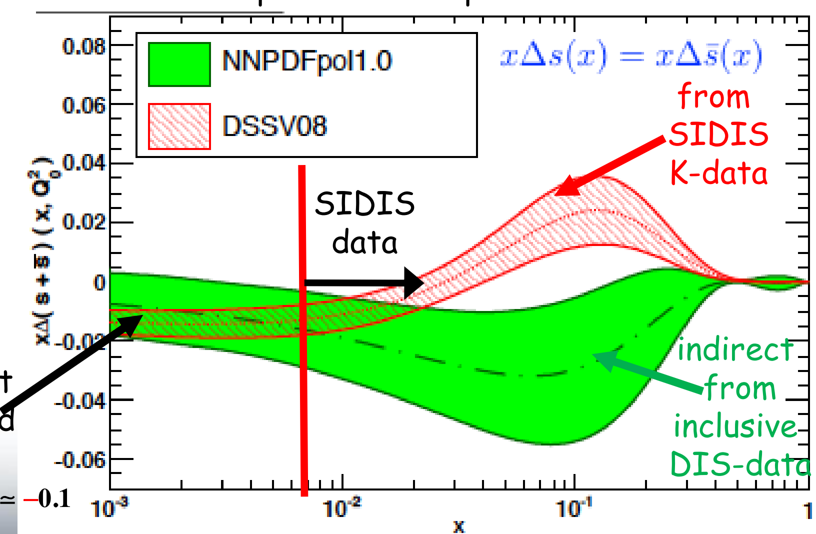


$$\int_{0.001}^{1} dx\Delta\Sigma \sim 0.366 \pm^{0.042}_{0.062} @10GeV^2$$

$$\int_{0}^{1} dx\Delta\Sigma \sim 0.242 @10GeV^2$$

ΔΣ does not converge at low x

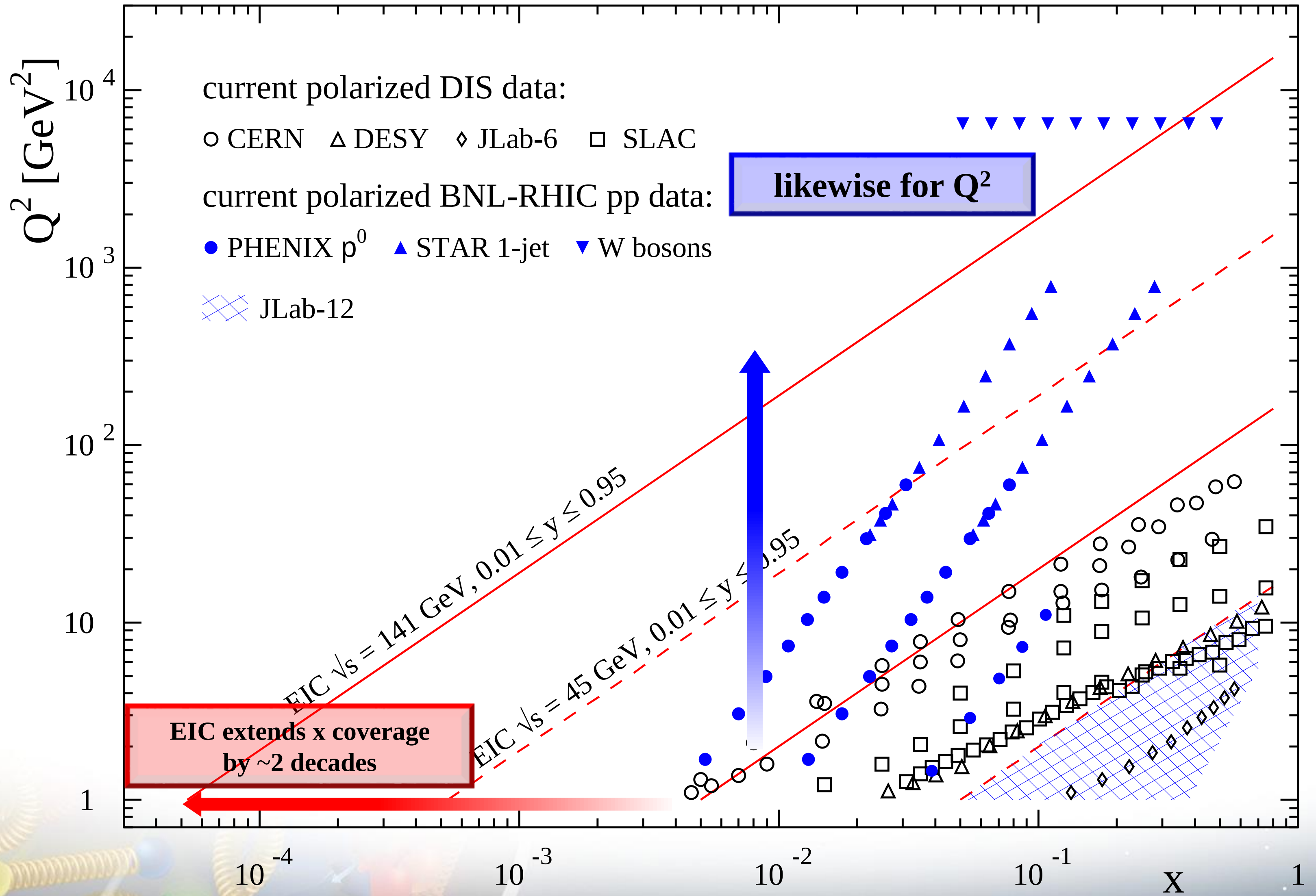
- due to current constrains put in the fits
- strangeness was identified to be one of the least known quantities
  - both unpolarized and polarized



1[st] moment constrained by 3F-D

$\int_0^1 dx\,[\Delta s + \Delta\bar{s}](x) \simeq -0.1$

present vs EIC kinematic coverage



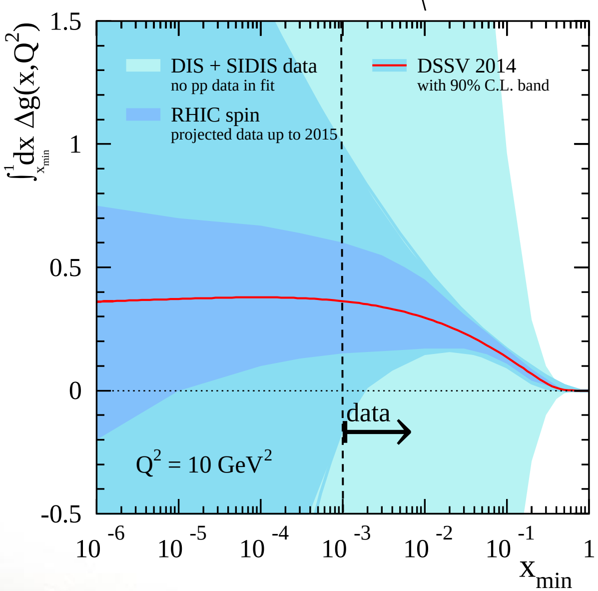
Details: R.Sassot, M. Stratmann, ECA, arXiv:1206.6014, arXiv:1509.06489

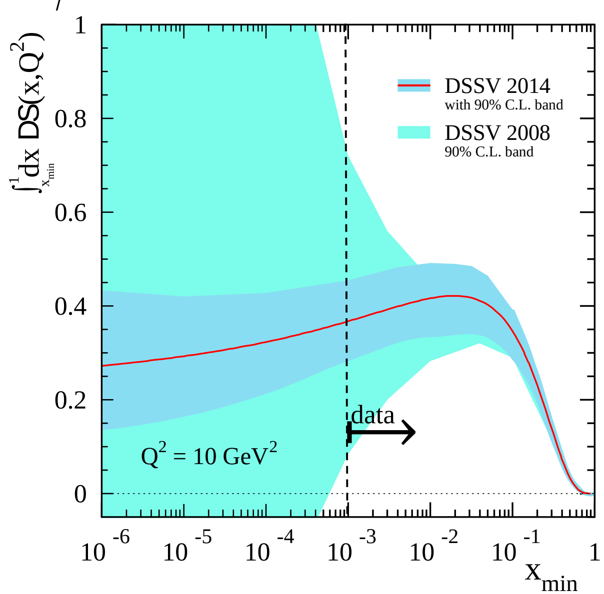
What forms the Spin of the Proton

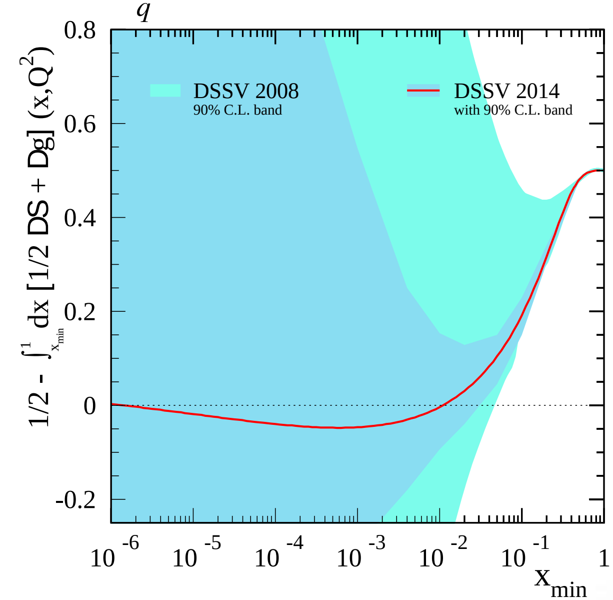
Spin is more than the number $\frac{1}{2}$! It is the interplay between the intrinsic properties and interactions of quarks and gluons

What do we know:

$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2}\,|\,J^z_{QCD}\,|\,P,\frac{1}{2}\right\rangle = \overbrace{\frac{1}{2}\int_0^1 dx\Delta\Sigma(x,Q^2)}^{\text{total quark spin}} + \overbrace{\int_0^1 dx\Delta G(x,Q^2)}^{\text{gluon spin}} + \overbrace{\int_0^1 dx\left(\sum_q L_q^z + L_g^z\right)}^{\text{angular momentum}}$$





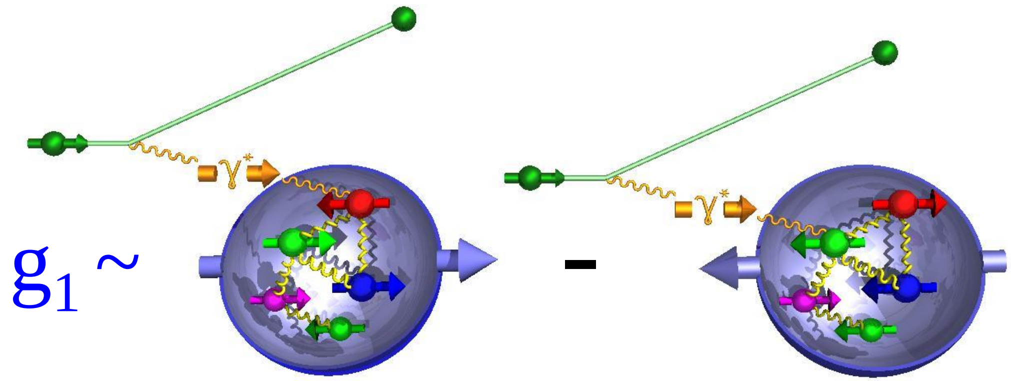


1/2 - Gluon -- Quarks = orbital angular momentum

40% **30%**

How to decompose the Spin of the Proton

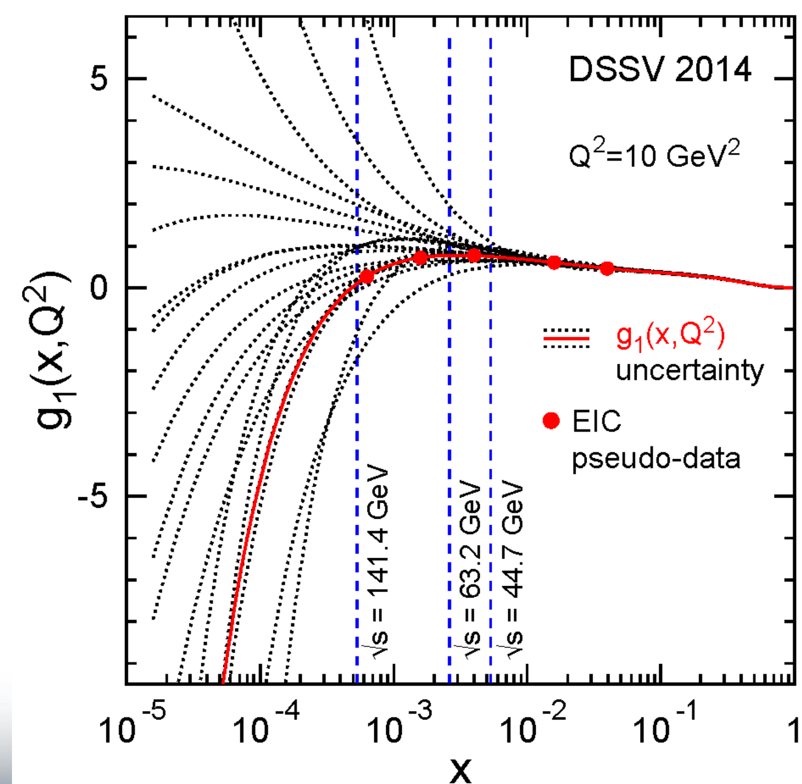
To determine the contribution of quarks and gluons to the spin of the proton, one needs to measure the cross section difference g_1 as function of x and Q^2



quark contribution:
The integral of Δq over x from 0 to 1

gluon contribution:
$dg_1(x,Q^2)/d\ln Q^2 \rightarrow \Delta g(x,Q^2)$

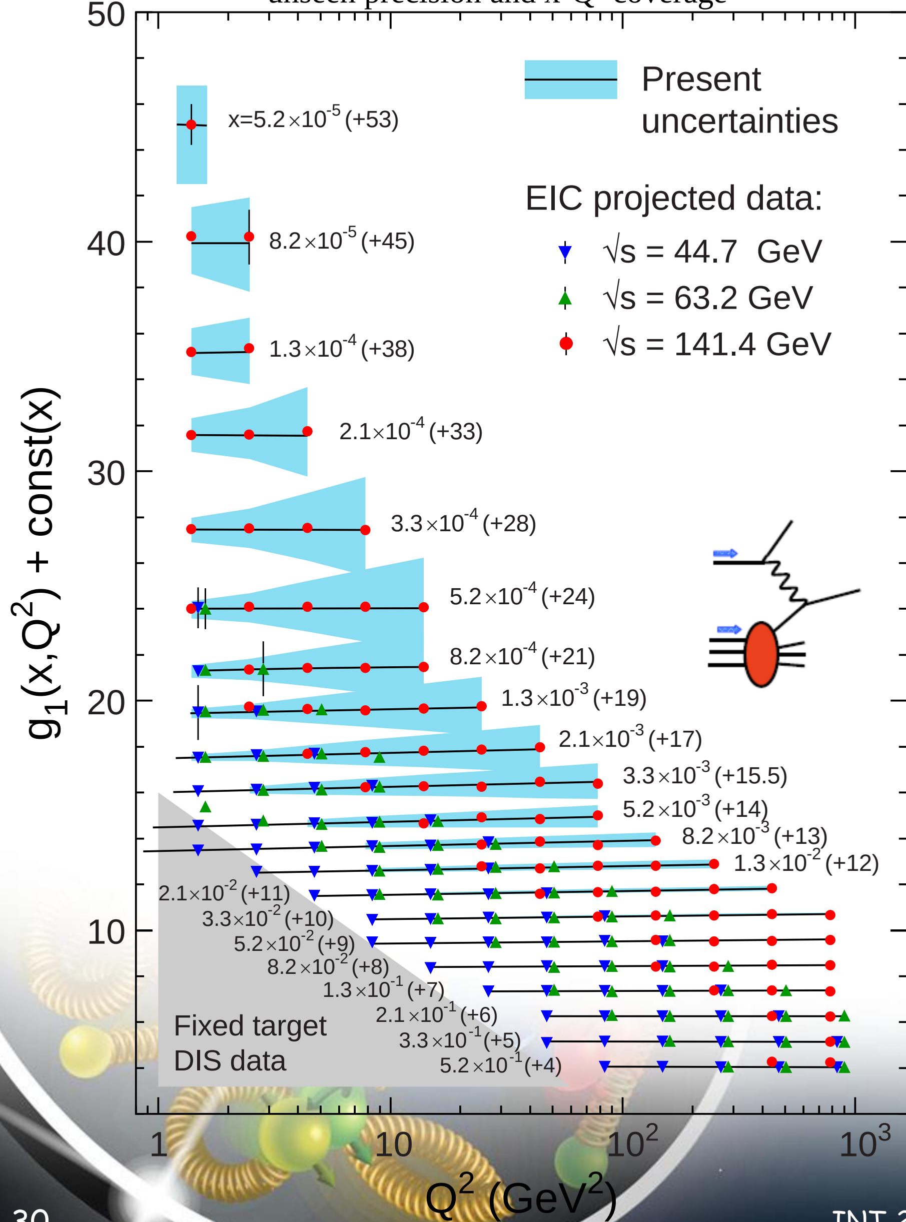
The current knowledge about g_1 as function of x at Q^2=10 GeV^2



g_1^p the way to find the Spin

M.Stratmann, R. Sassot, ECA: arXiv:1206.6014 & 1509.06489

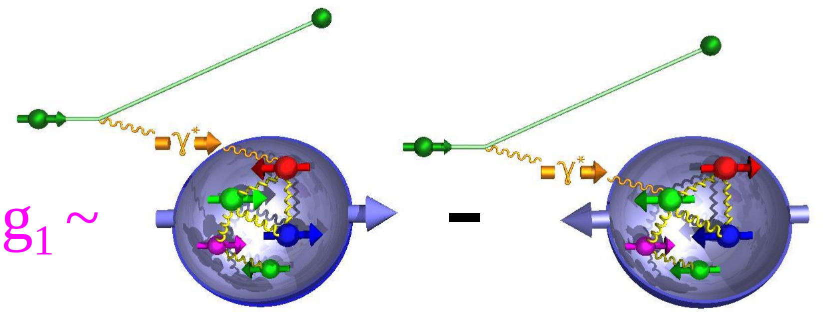
unseen precision and x-Q² coverage



cross section: $\frac{d^2\sigma}{d\Omega dE'} \sim L_{\mu\nu} W^{\mu\nu}$

$$W^{\mu\nu} = -g^{\mu\nu} F_1 - \frac{p^\mu p^\nu}{\nu} F_2 + \frac{i}{\nu}\varepsilon^{\mu\nu\lambda\sigma} q^\lambda s^\sigma g_1 + \frac{i}{\nu^2}\varepsilon^{\mu\nu\lambda\sigma} q^\lambda \left(p \bullet q s^\sigma - s \bullet q p \sigma\right) g_2$$

$g_1 \sim$



pQCD scaling violations

$$\frac{dg_1}{d\log(Q^2)} \sim -\Delta g(x,Q^2)$$

$$\Delta\Sigma(Q^2) = \int_0^1 g_1(x,Q^2)\,dx = \int_0^1 \Delta q_f(x,Q^2)\,dx$$

scaling violations at small x

rough small-x approximation to Q^2-evolution:

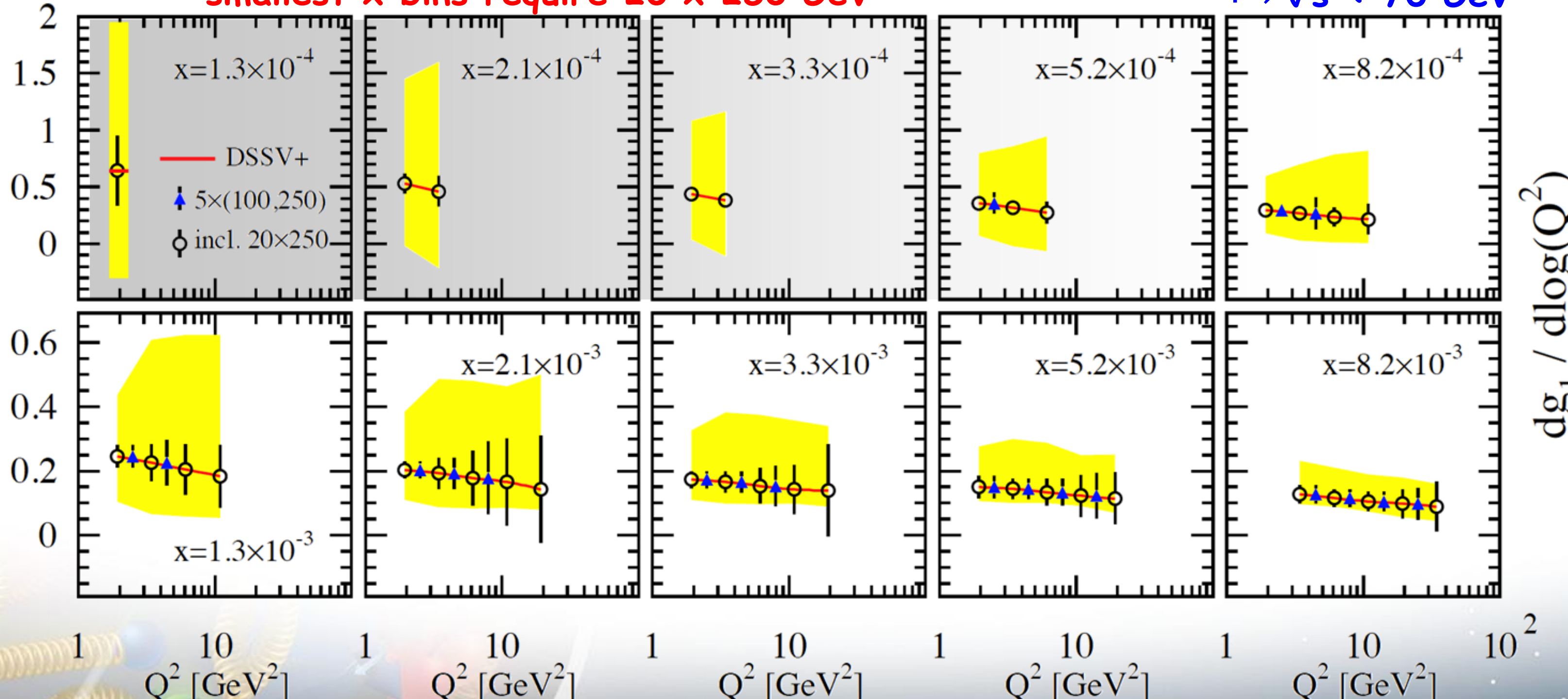
$$\frac{dg_1}{d\log(Q^2)} \propto -\Delta g(x, Q^2)$$

spread in $\Delta g(x,Q^2)$ translates into spread of scaling violations for $g_1(x,Q^2)$

- need x-bins with a least two Q^2 values to compute derivative (limits x reach somewhat)

smallest x bins require 20 x 250 GeV

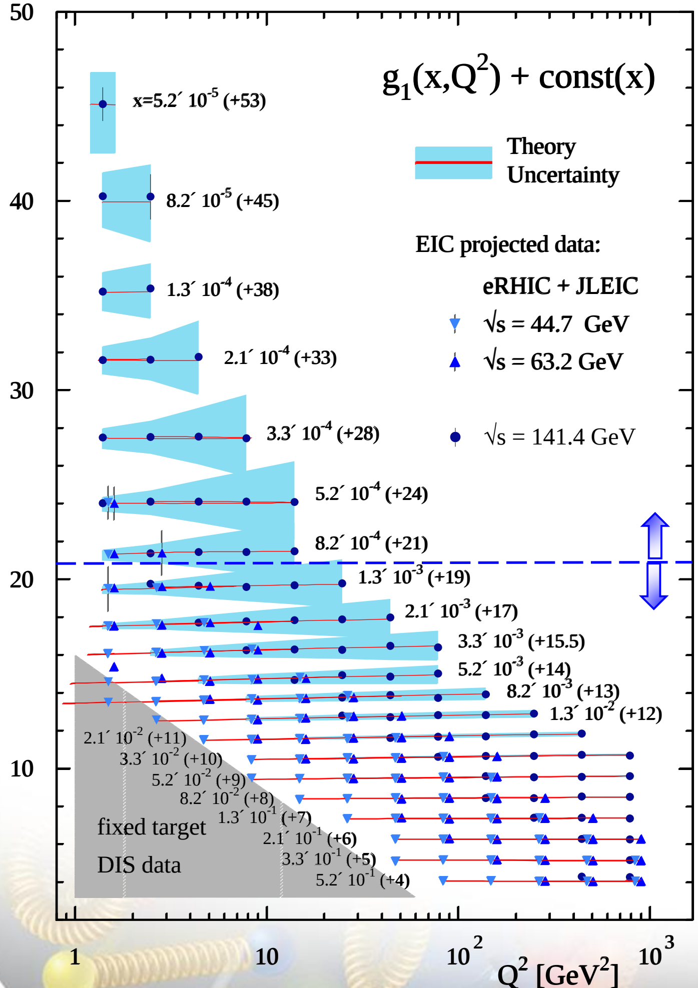
$\mapsto \sqrt{s} < 70$ GeV

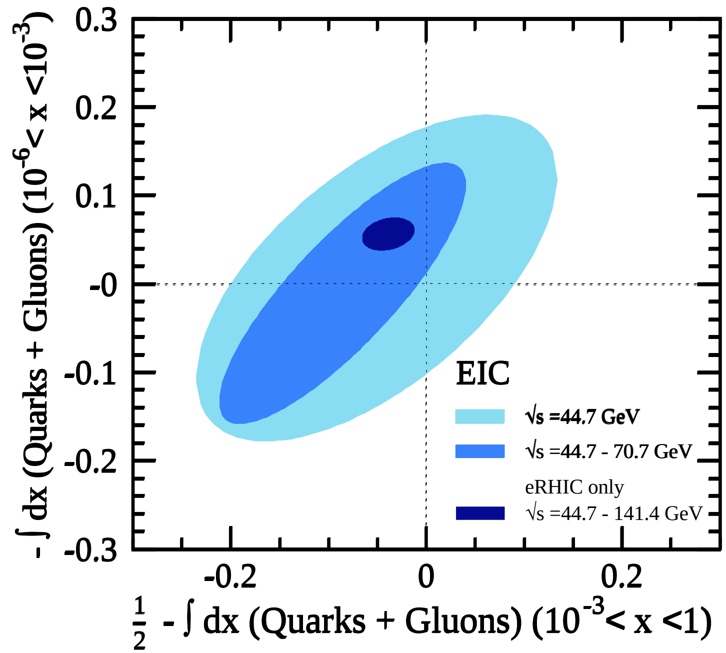


- error bars for moderate $10 fb^{-1}$ per c.m.s. energy; bands parameterize current DSSV+ uncertainties

What forms the Spin of the Proton

The polarized SF $g_1(x,Q^2)$ as measured by EIC for low to high $\sqrt{s}$





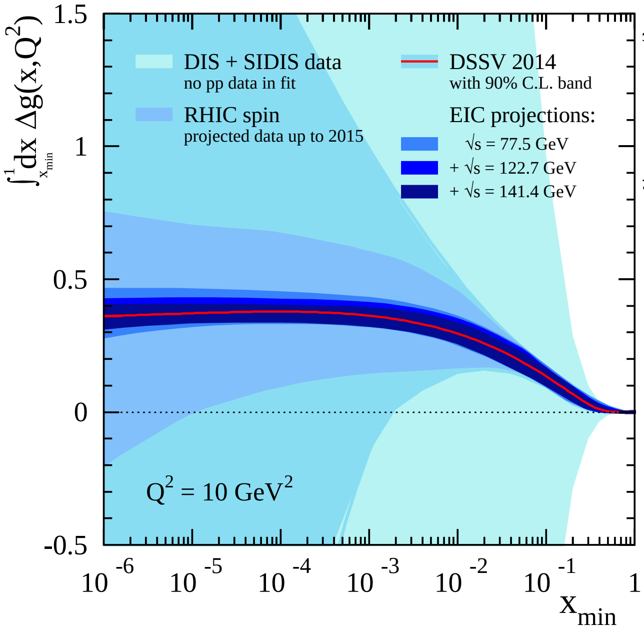
arXiv:1509.06489
PRD 92, 094030

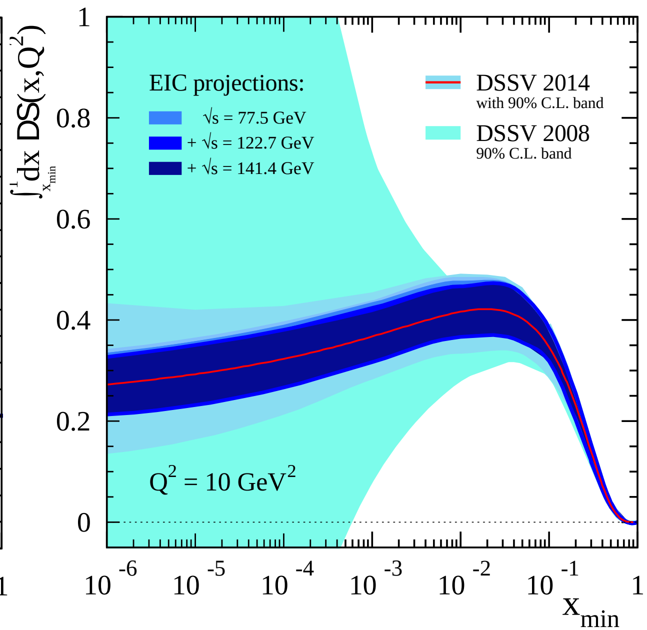
Only with the center-of-mass energies available at EIC the different contributions to the spin of the proton can be disentangled

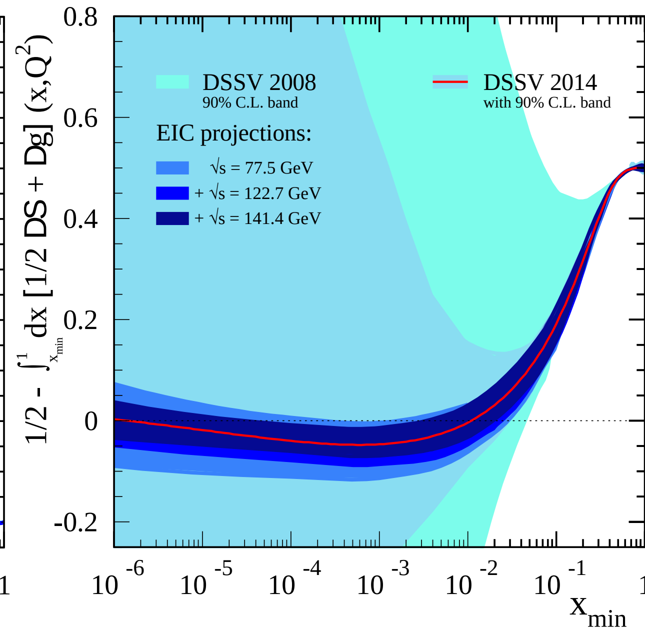
Where does the Spin of the proton hide

"Helicity sum rule:"

$$\frac{1}{2}\hbar = \left\langle P,\frac{1}{2} \middle| J^z_{QCD} \middle| P,\frac{1}{2}\right\rangle = \overbrace{\sum_q \frac{1}{2} S^z_q}^{\text{total quark spin}} + \overbrace{S^z_g}^{\text{gluon spin}} + \overbrace{\sum_q L^z_q + L^z_g}^{\text{angular momentum}}$$



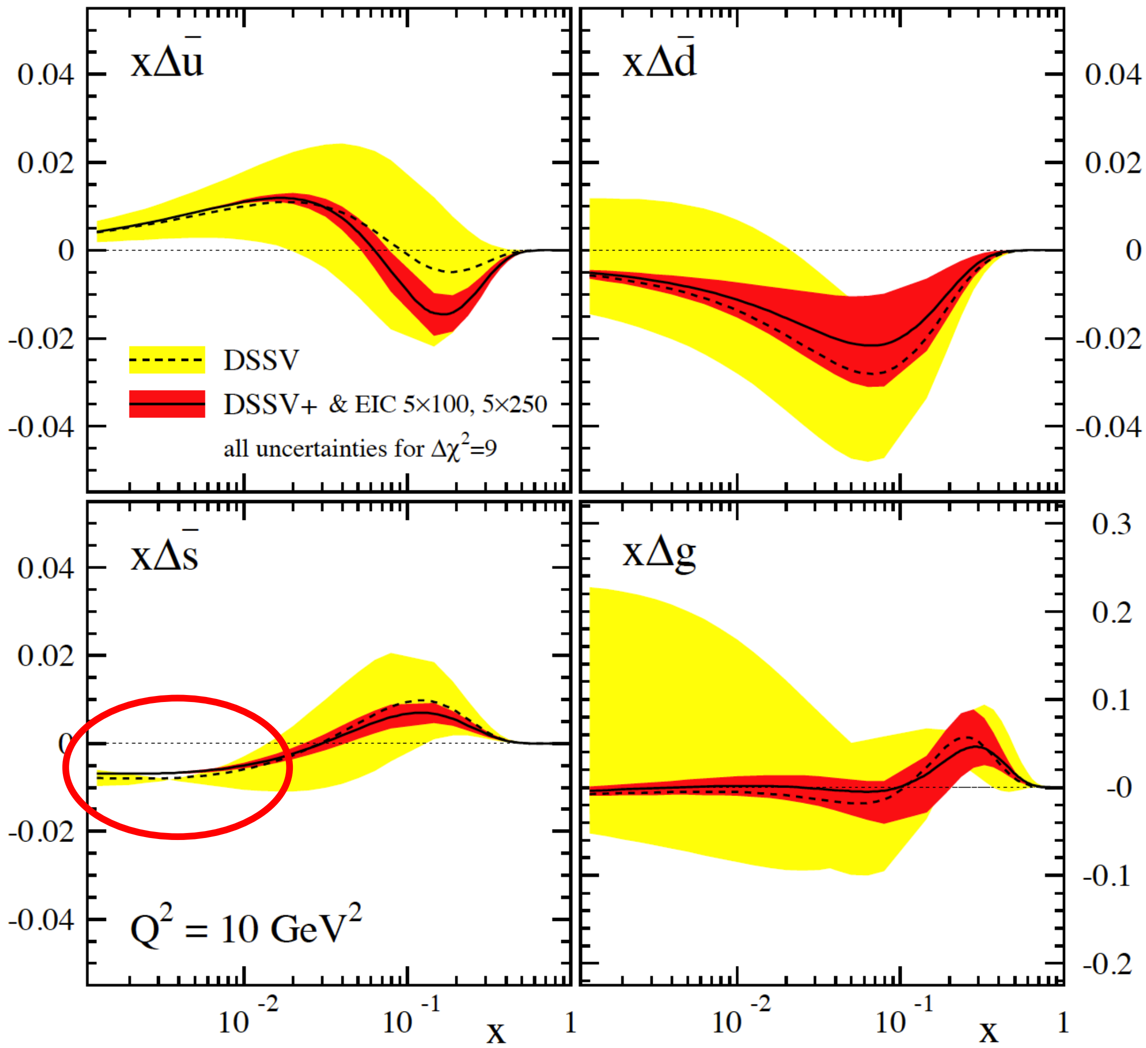




1/2 - Gluon - Quarks = orbital angular momentum

SIDIS@EIC: HELICITY PDFs

Can cover the same kinematics for $g_1^{\pi,K}$ as for g_1
→ will constrain Δq



yet, small x behavior completely unconstrained
→ determines x-integral, which enters proton spin sum

- includes data for $\sqrt{s}$=45 GeV & 70 GeV
- can be pushed to x=10^{-4} with $\sqrt{s}$=140 GeV data
- Lox x-behavior for Δs is artificial due to constrains put in the fits 3F-D
  → EIC can remove all constrains

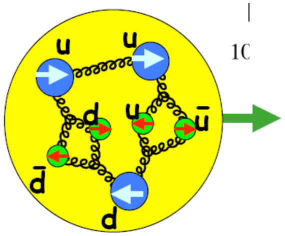
"issues":

- (SI)DIS @ EIC limited by **systematic uncertainties**
  need to control rel. lumi, polarimetry, PID performance, … very well

probing a possible asymmetry in the polarized sea

- current SIDIS data not sensitive to $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ (known to be sizable for unpol. PDFs)
- many models predict sizable asymmetry [large N_C, chiral quark soliton, meson cloud, Pauli blocking]

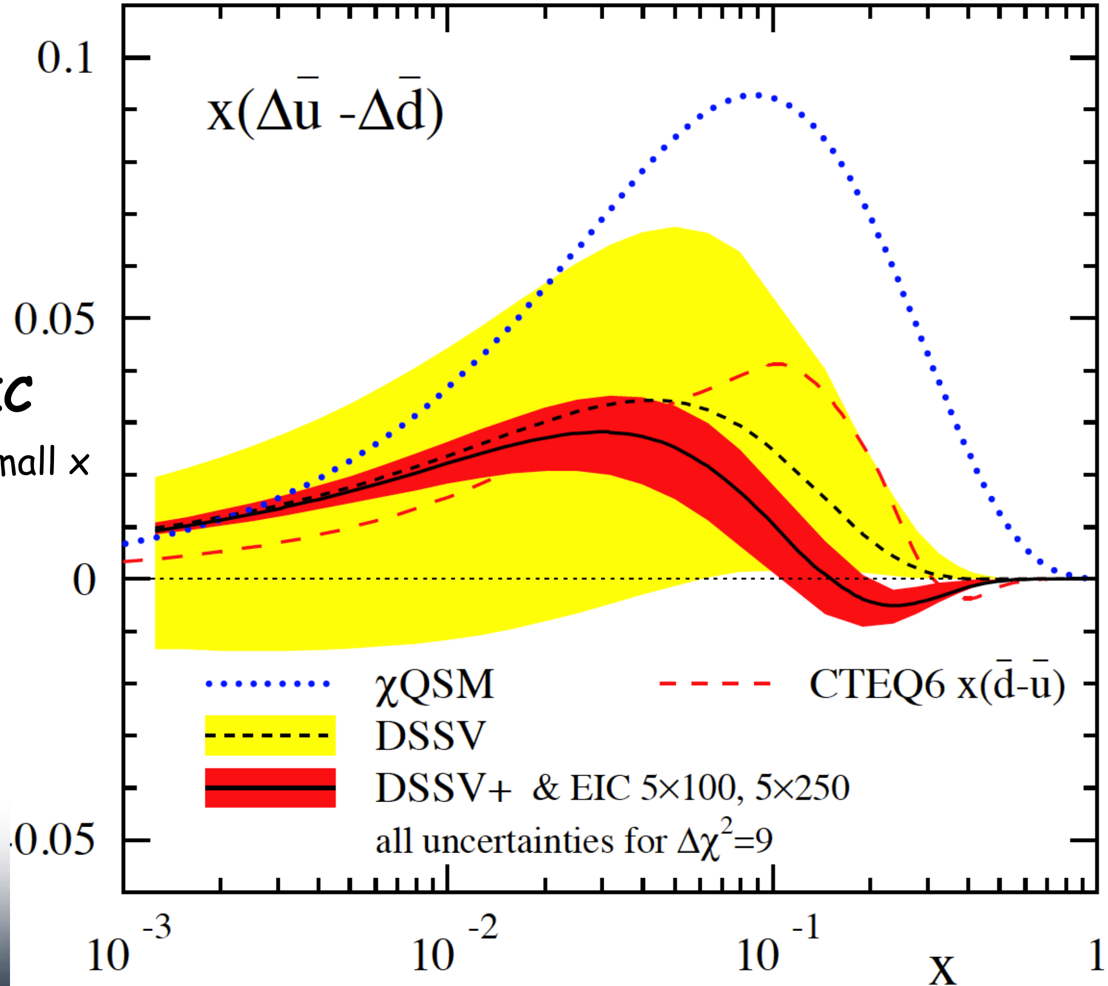
Thomas, Signal, Cao; Holtmann, Speth, Fassler;
Diakonov, Polyakov, Weiss; Schafer, Fries; Kumano;
Wakamatsu; Gluck, Reya; Bourrely, Soffer, ...



- **can be easily studied at an EIC**

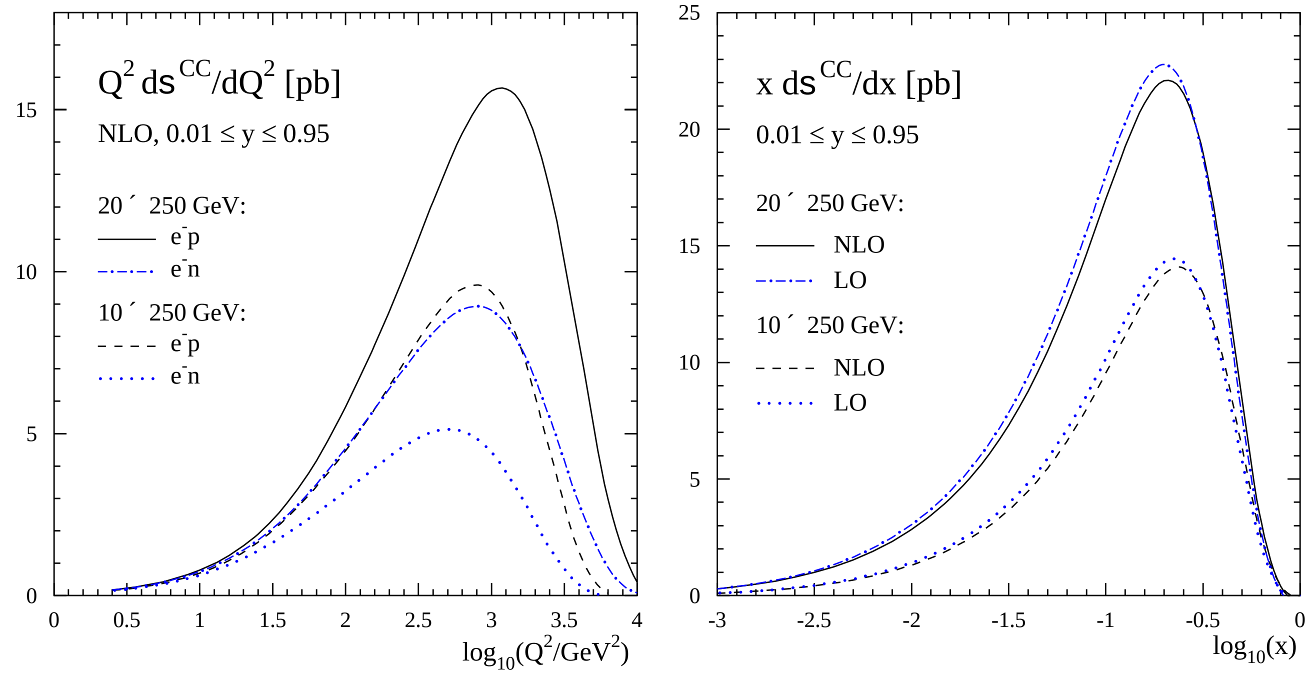
  main effect expected to be at not too small x
  → can test x dependence

- can try to look into a possible $\Delta s(x) - \Delta\bar{s}(x)$ with $K^{+/-}$ SIDIS data



Observables: Charge Current in polarized ep

Polarized CC cross section



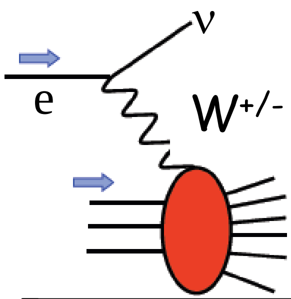
Approximate behavior of the LO single spin asymmetry

	y → 0	y = 1/2	y → 1
$A_L^{W^-,p}$	$\frac{\Delta u(x)-\Delta\bar{d}(x)}{u(x)+\bar{d}(x)}$	$\frac{4\Delta u(x)-\Delta\bar{d}(x)}{4u(x)+\bar{d}(x)}$	$\frac{\Delta u(x)}{u(x)}$
$A_L^{W^-,n}$	$\frac{\Delta d(x)-\Delta\bar{u}(x)}{d(x)+\bar{u}(x)}$	$\frac{4\Delta d(x)-\Delta\bar{u}(x)}{4d(x)+\bar{u}(x)}$	$\frac{\Delta d(x)}{d(x)}$

similar to what is seen in W production in polarized pp

Details: Th. Burton, T. Martini, H. Spiesberger, M. Stratmann, ECA, arXiv:13095327 PRD 88 (2013) 114025

Polarized EW PHYSICS

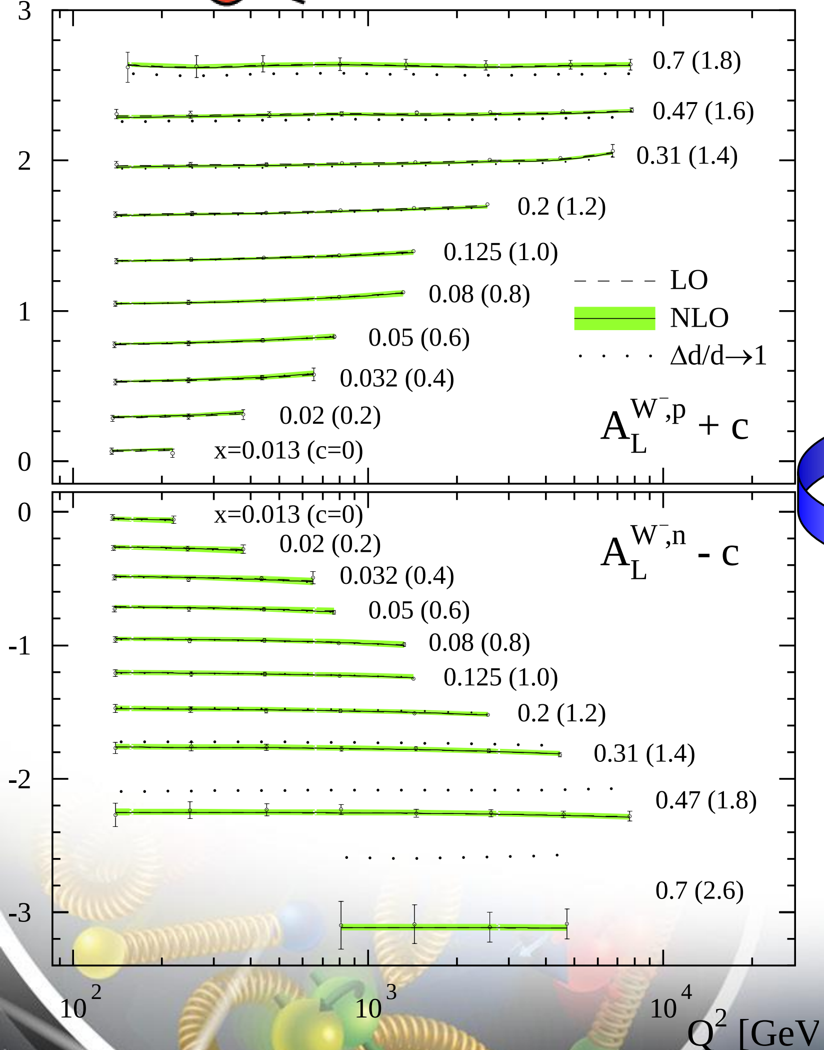


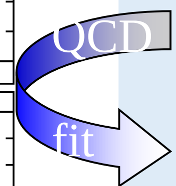
$$A_L^{W^-,N} = \frac{d^2\Delta\sigma^{W^-,N}/dxdy}{d^2\sigma^{W^-,N}/dxdy}$$

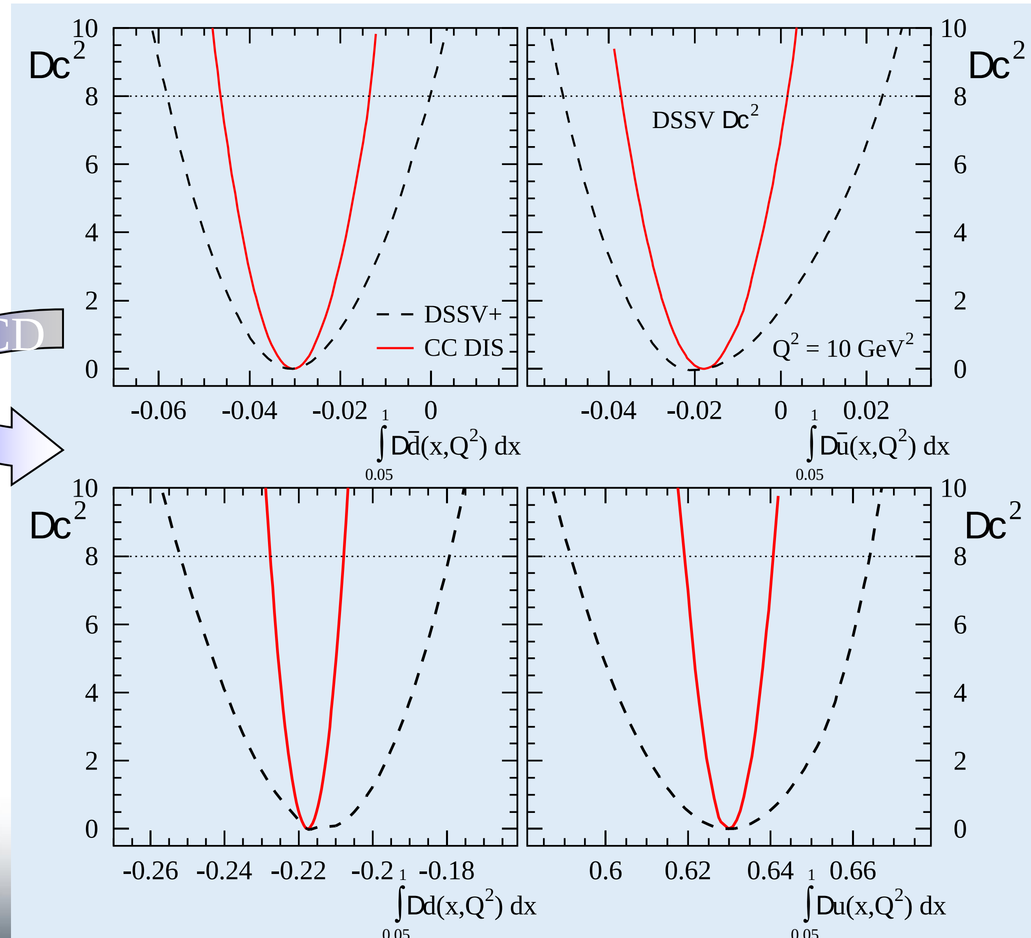
$$g_1^{W^-,p}(x) = \Delta u(x) + \Delta\bar{d}(x) + \Delta c(x) + \Delta\bar{s}(x)$$

$$g_1^{W^-,n}(x) = \Delta d(x) + \Delta\bar{u}(x) + \Delta c(x) + \Delta\bar{s}(x)$$

More Details: arXiv:1309.5327







Summary

- More work to be done on unpolarized PDF and FF constrains
  - but EIC will be critical for PDF and FF constrains
  - did not discuss inclusive DIS and F_2^c→ but coverage better then for eA arXiv:1708.05654
- EIC at high √s the only machine to unravel the different components to the spin of the proton
  - critical for low-x behaviour
- CC important observable for flavor separation and testing limitations of SIDIS

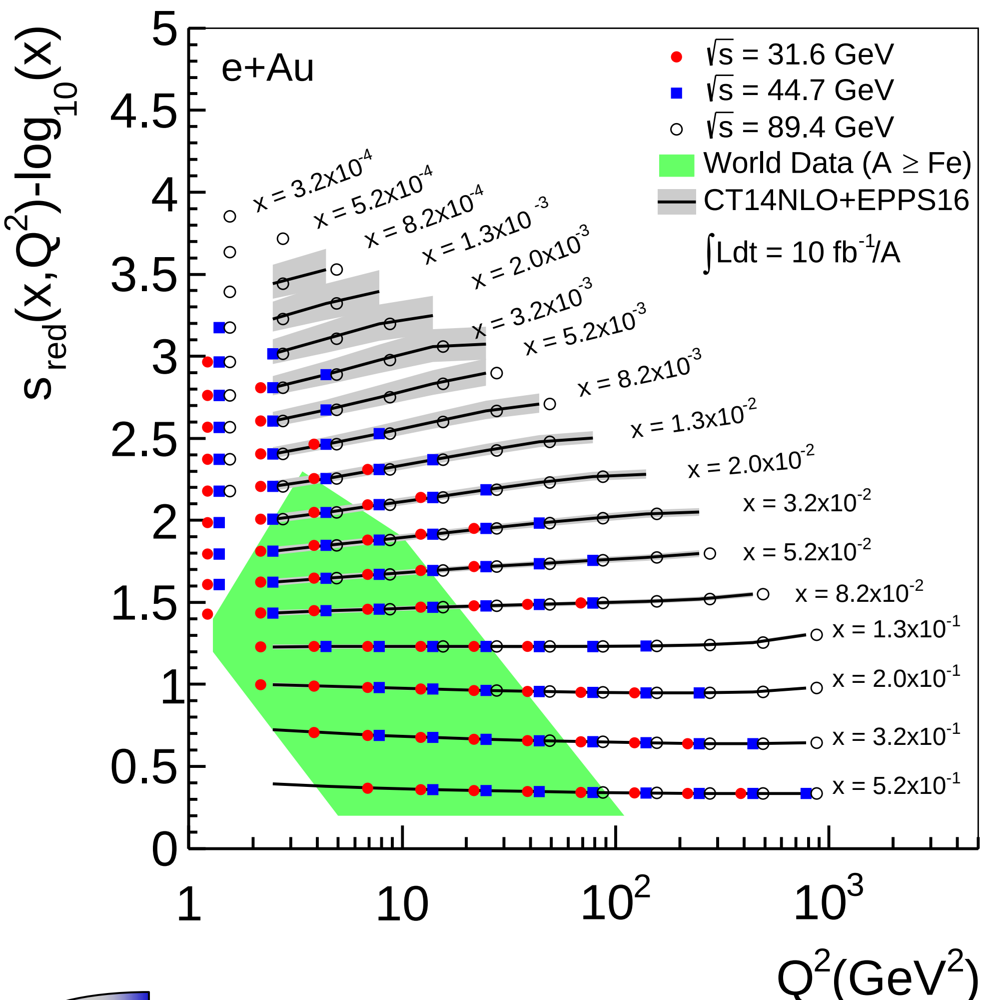
Questions to be answered before an EIC

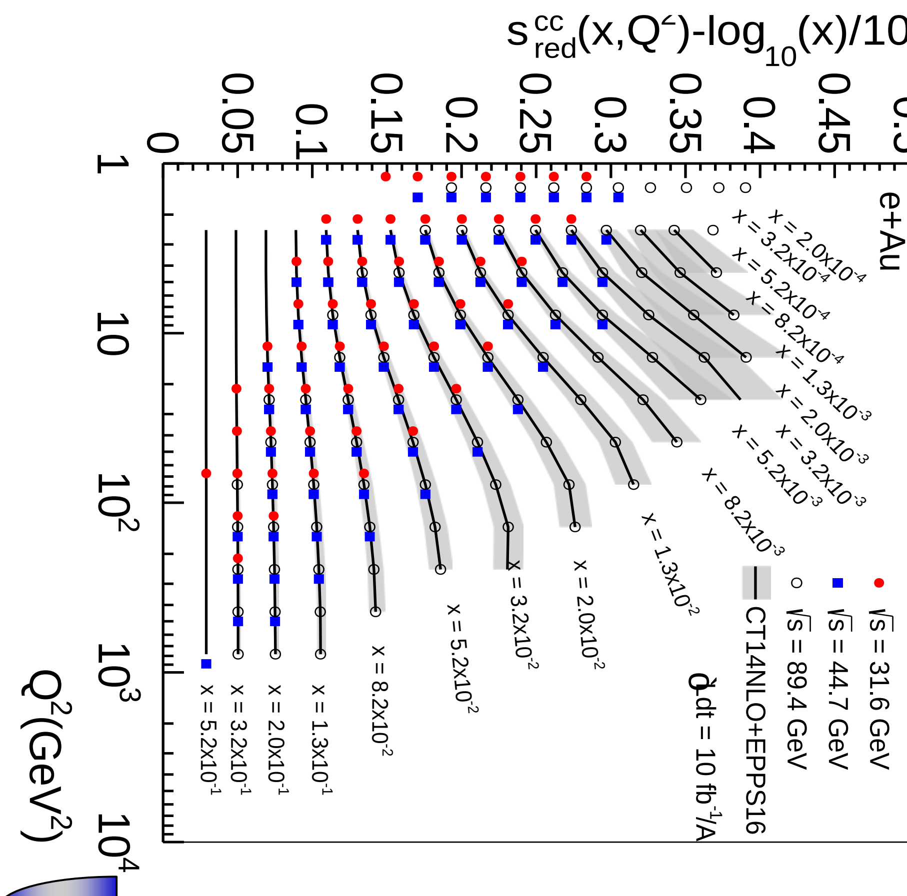
- effective neutron target: √s Deuterium: 100 GeV Helium-3: 166 GeV
  - He-3 larger x coverage proton equivalent √s: 250 GeV
  - what is the better choice with respect to nuclear effects
- What are the limiting theoretical factors to determine high-x PDFs?
  - what is the golden observable to constrain $g(x,Q^2)$ at high x
- How can we measure *Lq* and *Lg* from Jaffe-Manohar
- What are the golden observables to learn about hadronization
  - Correlations between different rapidity ranges and distributions inside jets?


BACK UP

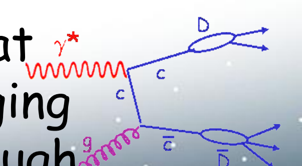
Inclusive Cross-Sections in eA

arXiv:1708.05654





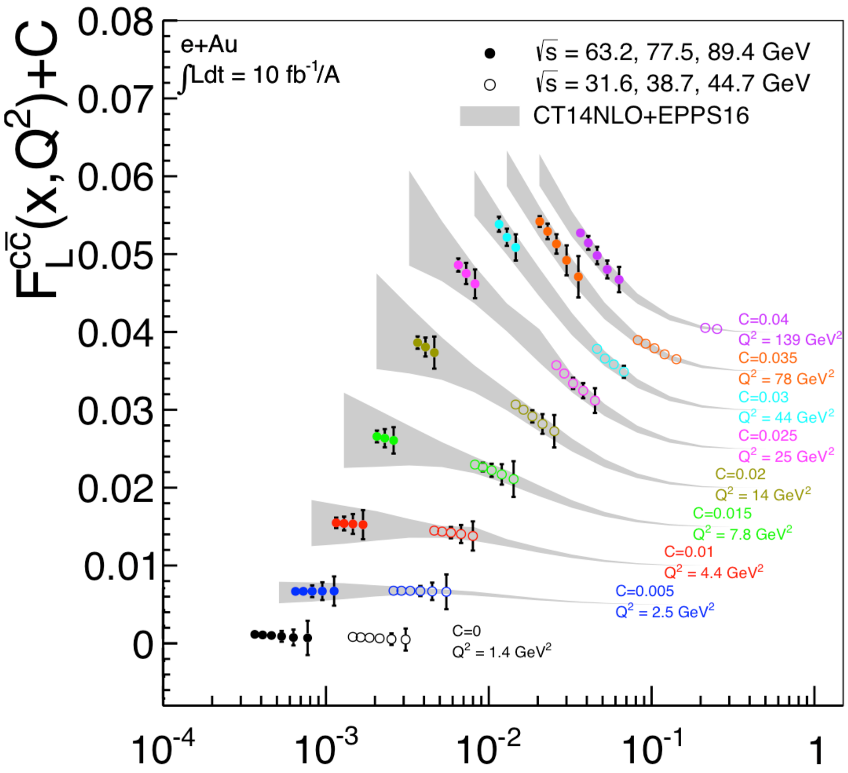
Direct Access to gluons at medium to high x by tagging photon-gluon fusion through charm events

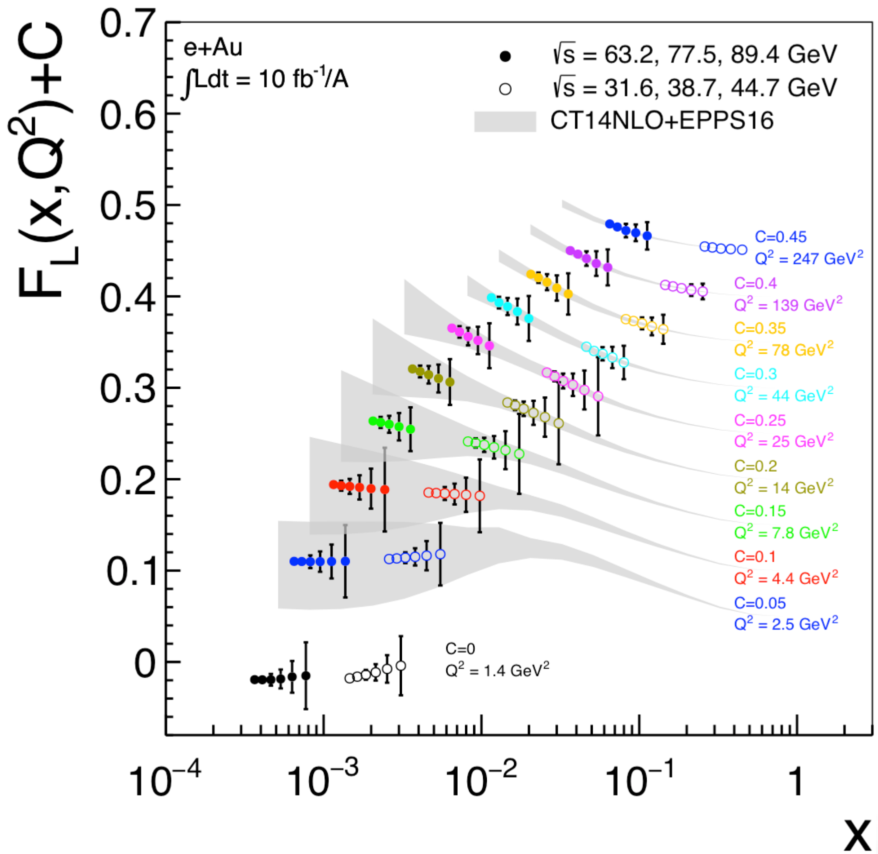


Gluon distribution ~ $d\sigma(x,Q^2)/d\ln Q^2$

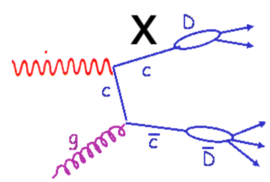
Direct Access to Gluons in eA

For Details: arXiv:1708.05654





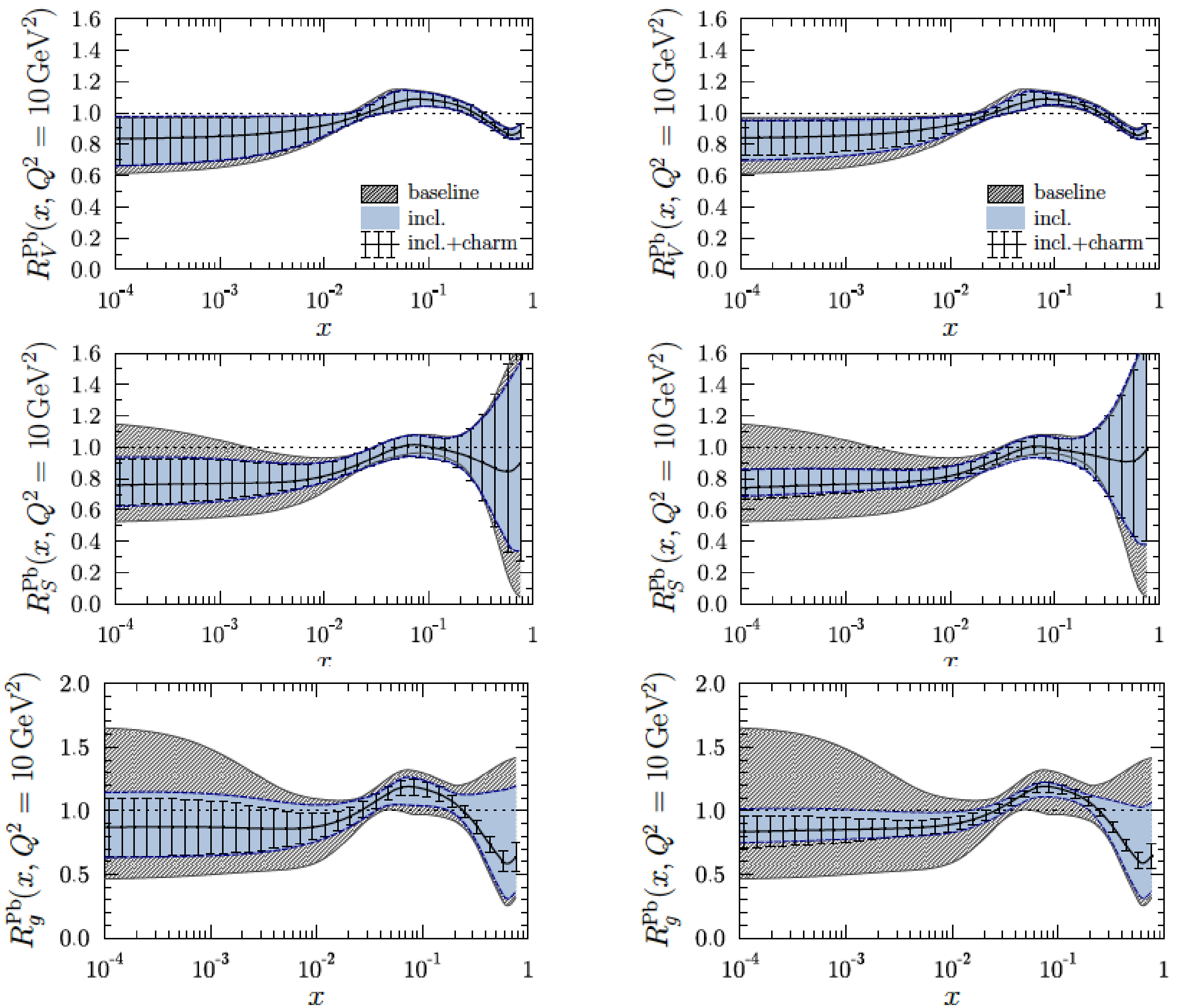
Direct Access to gluons at medium to high x by tagging photon-gluon fusion through charm events



high precision F_L^{charm} will offer an opportunity to benchmark different GM-VFNS schemes with an unprecedented precision.

EIC: Impact on the Knowledge of 1D Nuclear PDFs

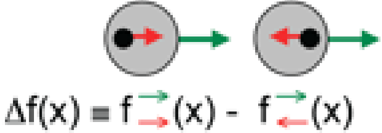
√s < 45 GeV   √s < 90 GeV

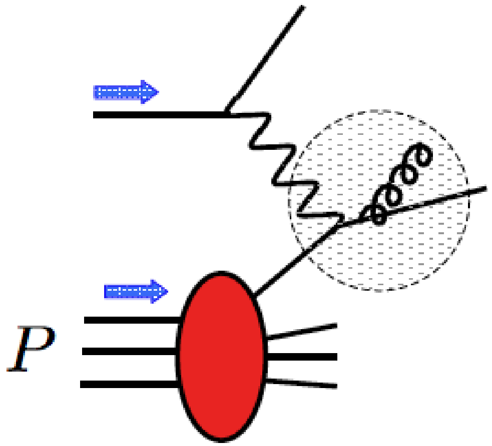


Ratio of PDF of Pb over Proton

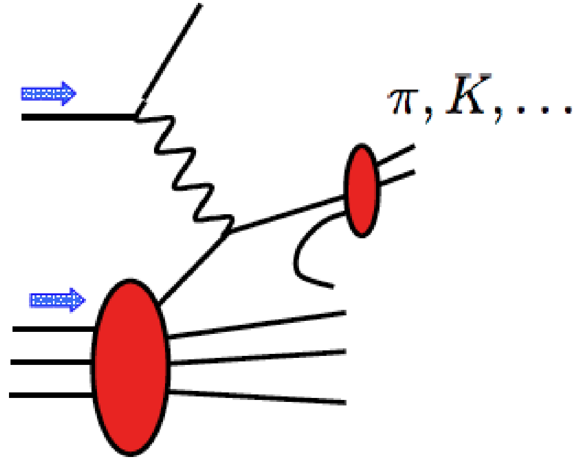
- Without EIC, large uncertainties
  → With EIC significantly reduced uncertainties
- Complementary to RHIC and LHC pA data. Provides information on initial state for heavy ion collisions.
- Does the nucleus behave like a proton at low-x?
  → relevant to very high-energy cosmic ray studies
  → critical input to AA
- submitted to PRD arXiv:1708.05654

probes of nucleon helicity structure

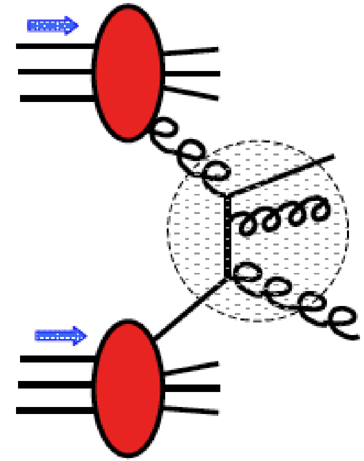




DIS



SIDIS



pp

DIS	SIDIS		pp	
$\Delta q + \Delta \bar{q}$	$\Delta q, \Delta \bar{q}$	pions, kaons	Δg	1-jet, 1-hadron
	Δg	charm, 2-hadrons	$\Delta q, \Delta \bar{q}$	$W^{+/-}$ bosons

guiding principle: **factorization**

e.g. **DIS**

$$d\Delta\sigma = \sum_{f=q,\bar{q},g} \int dx \, \Delta f(x, Q^2) \, d\Delta\hat{\sigma}_{\gamma^* f}(xP, \alpha_s(Q^2))$$

essential: QCD corrections $d\Delta\hat{\sigma} = d\Delta\hat{\sigma}^{\mathrm{LO}} + \alpha_s \, d\Delta\hat{\sigma}^{\mathrm{NLO}} + \ldots$

need DIS + SIDIS + pp to constrain all aspects of PDFs (a way to test factorization)