Opportunities in ep Physics at an Electron-Ion Collider

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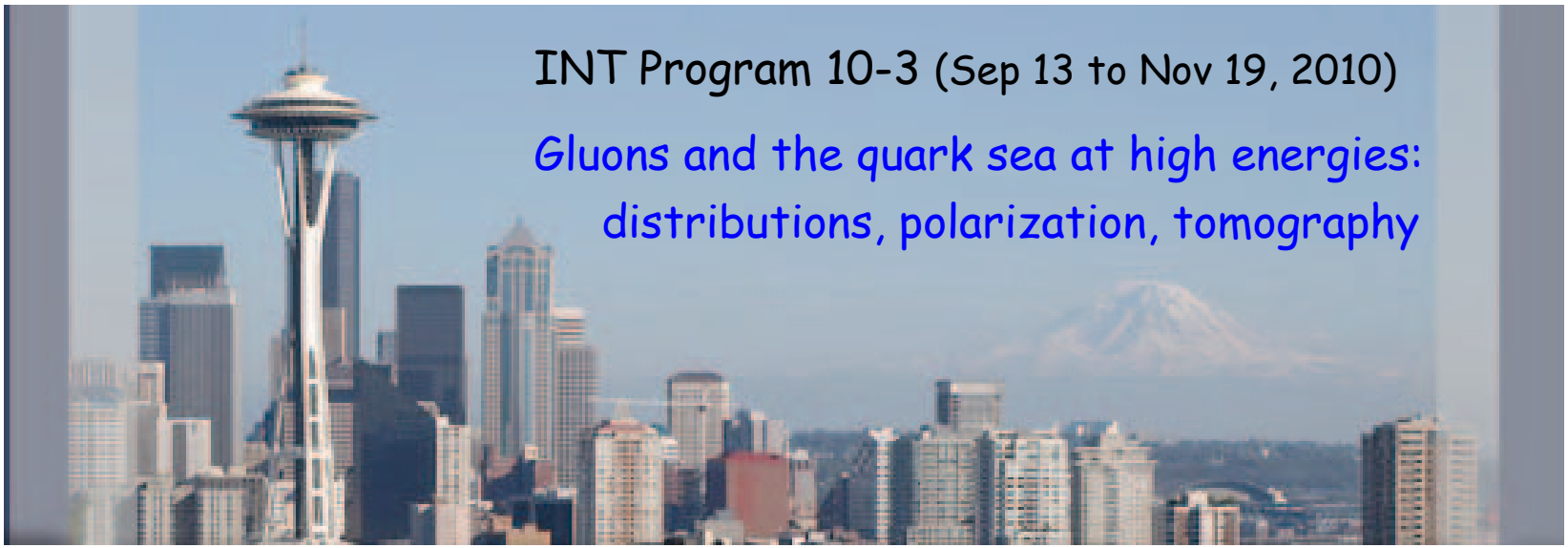
Office of Science
U.S. Department of Energy



organizers: D. Boer, M. Diehl, R. Milner, R. Venugopalan, W. Vogelsang

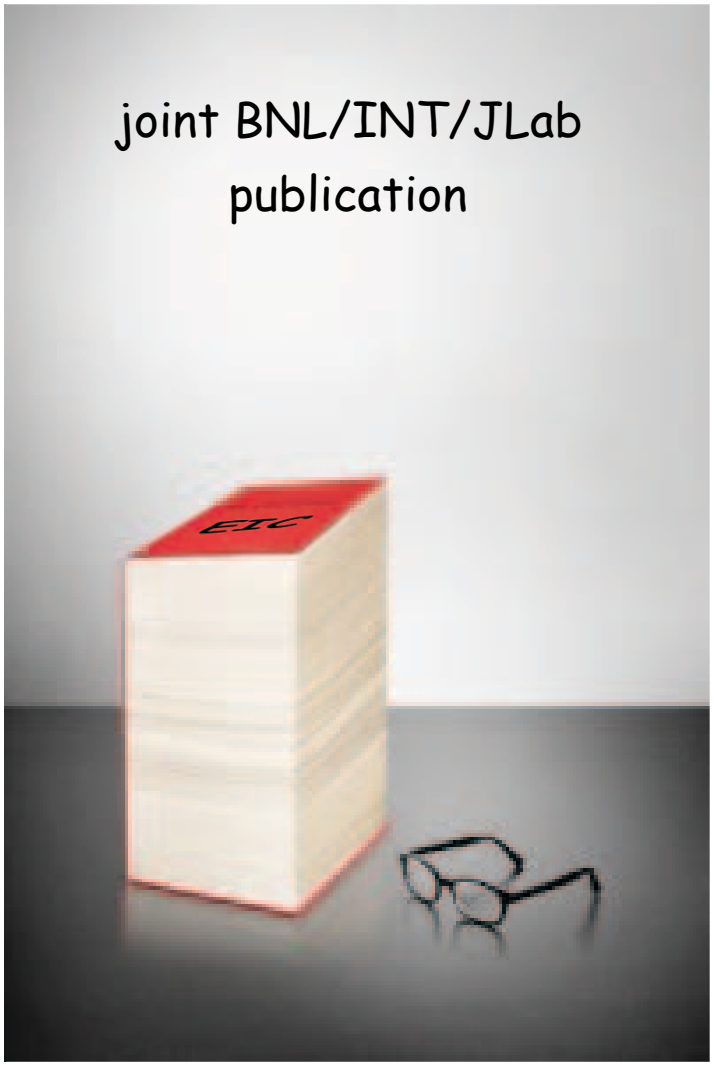
convenors: D. Hasch, M.S., F. Yuan spin, PDFs, TMDs M. Burkardt, V. Guzey, F. Sabatie imaging
A. Accardi, M. Lamont, C. Marquet eA K. Kumar, Y. Li, W. Marciano beyond SM

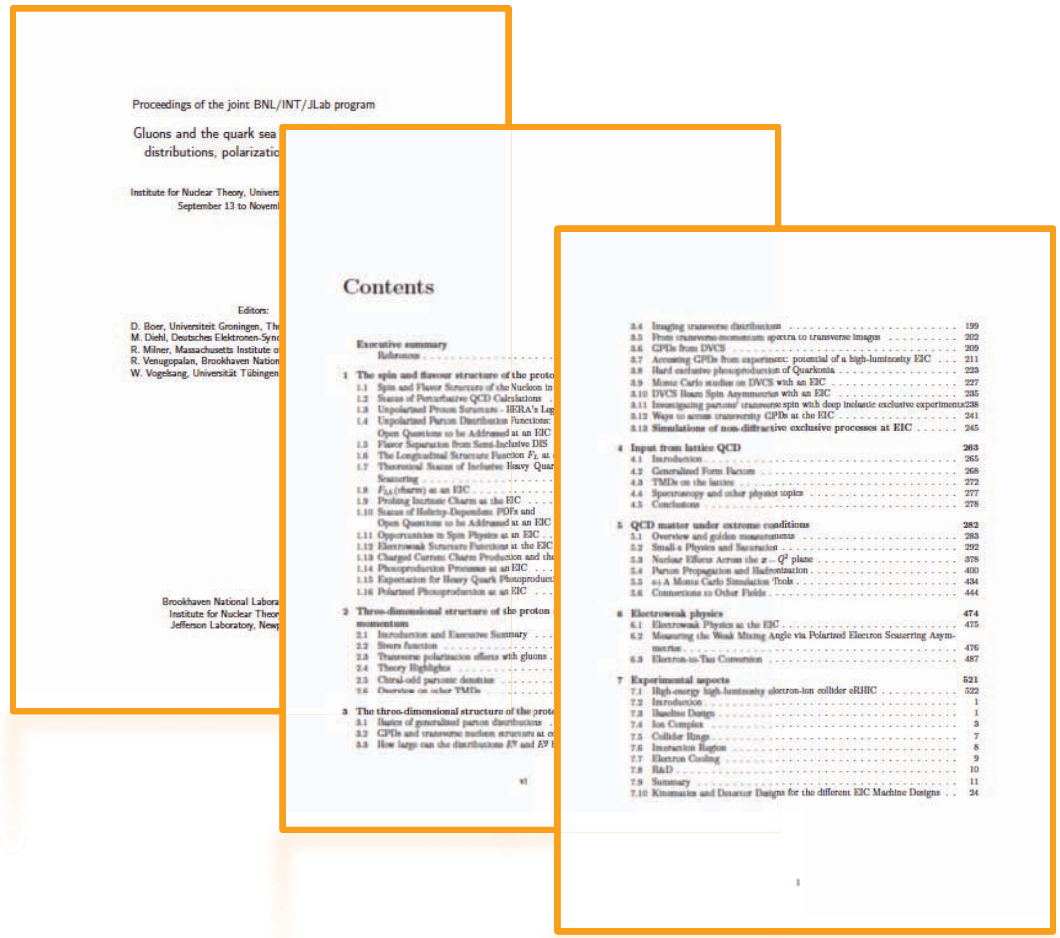
main goal: sharpen the physics case for an EIC for next NSAC long range plan

- identify outstanding open questions in hadronic physics still relevant in 10+ years
- devise key "golden" measurements in ep and eA to address these questions
- quantify experimental needs & requirements and study feasibility

very successful, well attended program; most goals accomplished

detailed 500+ pages write-up is in its finishing stages – to appear on the arXiv soon





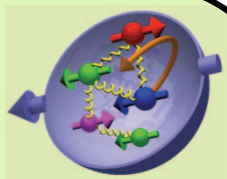
but no time to sit & relax

- studies for identified **"golden measurements"** need to be substantiated & feasibility demonstrated
- input for community wide white paper (draft by end of 2011)

Physics Questions to be addressed at an EIC

most compelling physics questions

spin physics

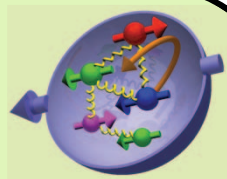


- what is the polarization of gluons at small x where they are most abundant
- what is the flavor decomposition of the polarized sea depending on x

determine quark and gluon contributions to the proton spin at last

most compelling physics questions

spin physics



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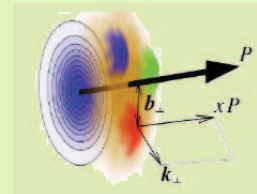
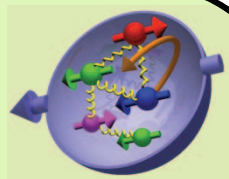


- what is the spatial distribution of quarks and gluons in nucleons/nuclei
- understand deep aspects of gauge theories revealed by k_T dep. distr'n

possible window to orbital angular momentum

most compelling physics questions

spin physics



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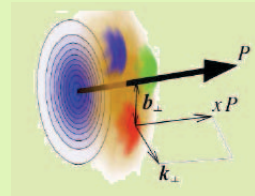

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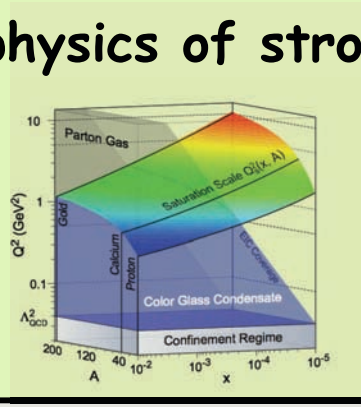
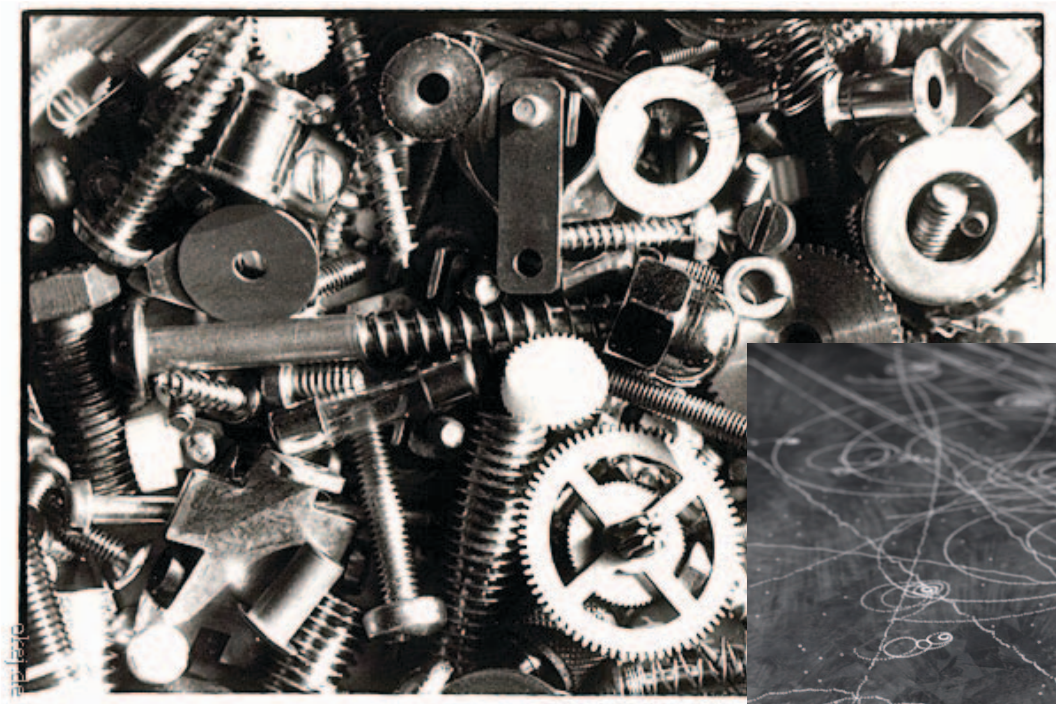
possible window to orbital angular momentum

physics of strong color fields

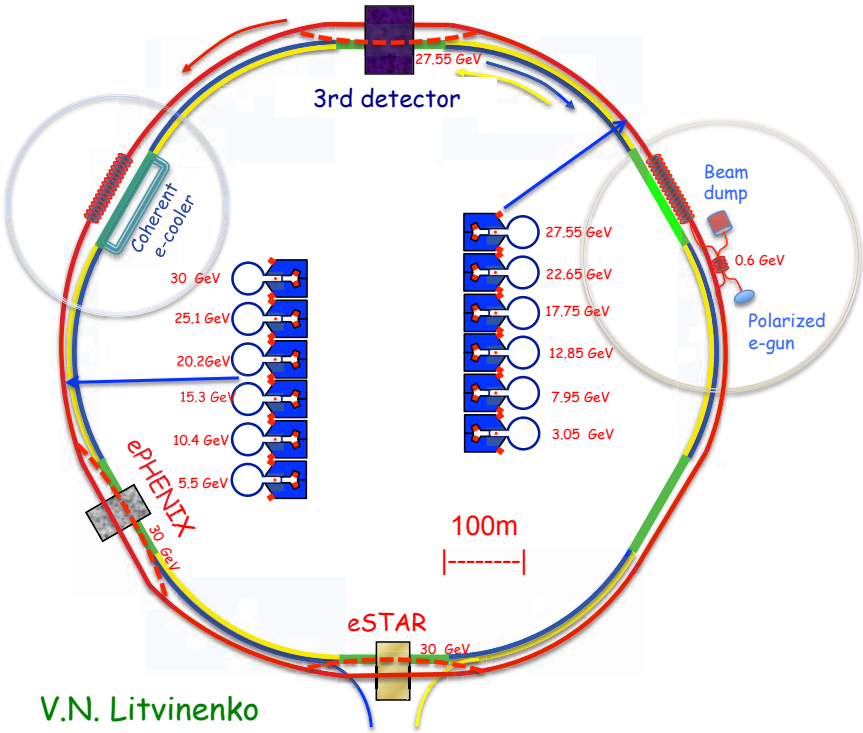
quantitatively probe the universality of strong color fields in AA, pA, and eA



- understand in detail the transition to the non-linear regime of strong gluon fields and the physics of saturation
- how do hard probes in eA interact with the medium



Prerequisites: Machine, Kinematics

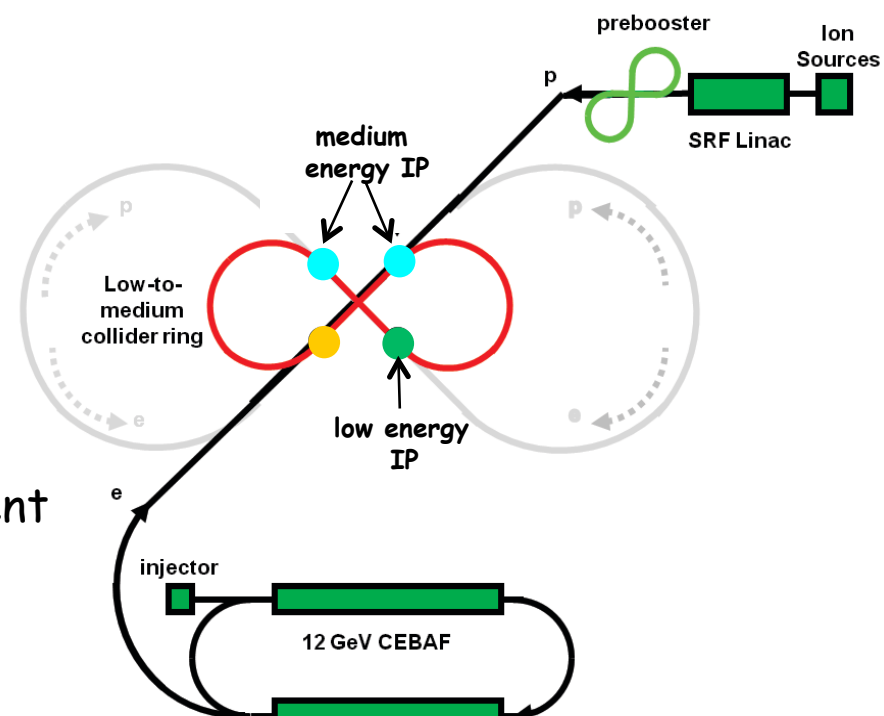


V.N. Litvinenko

- most design parameters converging (likewise for detector concepts)
- both machines have staged approach

eRHIC:
up to 30 GeV electrons (stage-1: 5GeV)
up to 325 GeV protons
up to 130 GeV/u ions

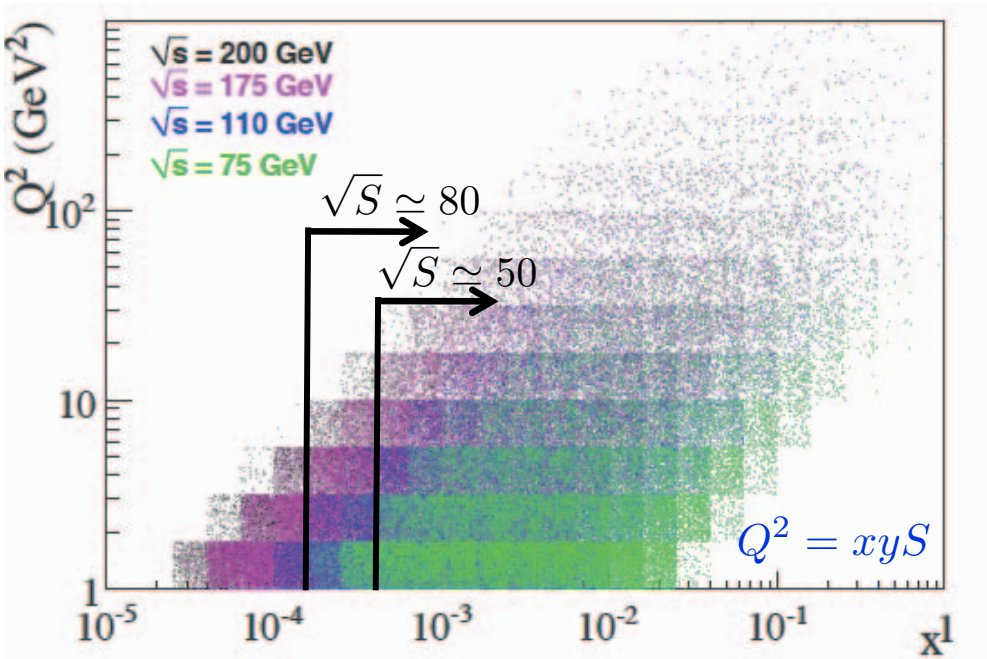
MEIC: (stage-1)
3-11 GeV electrons
20-100 GeV protons (full ELIC: 250GeV)
12-40 GeV/u ions (full ELIC: 100GeV/u)



- luminosities of few × 10^{33} $cm^{-2}s^{-1}$ sufficient to perform most "golden" measurements (often quickly systematics limited)
- **small x reach critical to achieve goals** (saturation regime, spin,...)

V. Morozov @ DIS2011

key to EIC program: large & *variable* kinematic coverage



EIC stage-1 (ep):

$\sqrt{S} = 32$ 45 71 81

$x_{\min} \approx 10^{-3}$ 2×10^{-4} 1.6×10^{-4}

small x pol. DIS

← lever arm for F_L →

eRHIC 5x50, 5x100, …, **5x250**, **5x325**

MEIC 11x60

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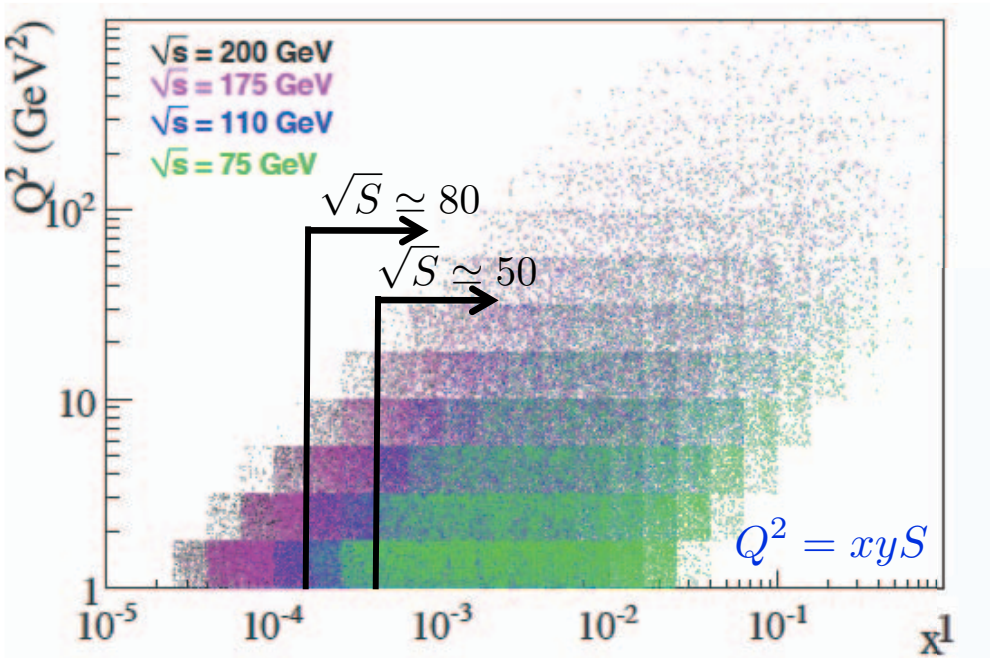

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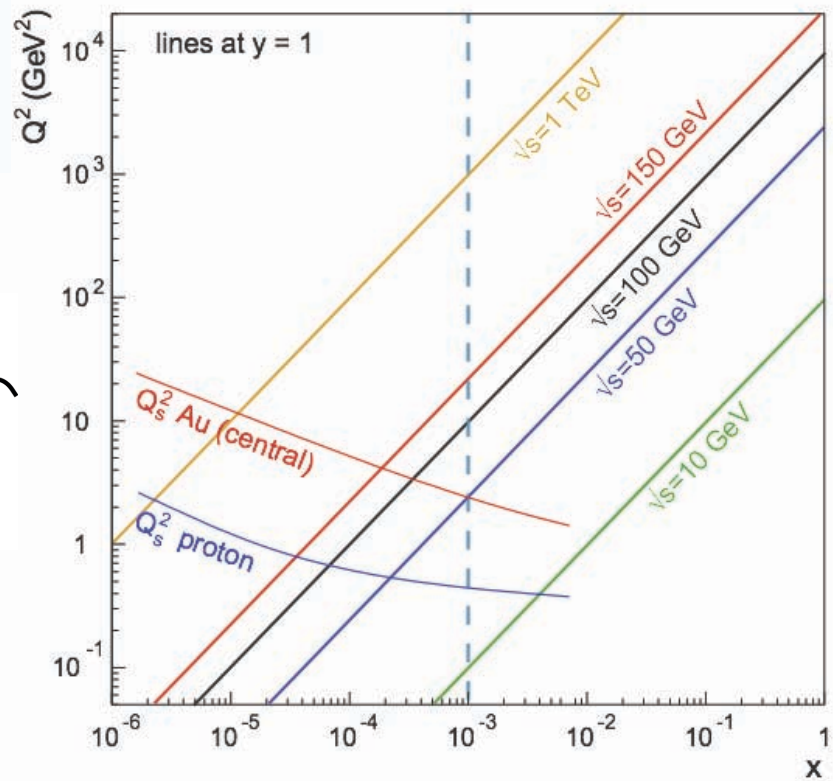
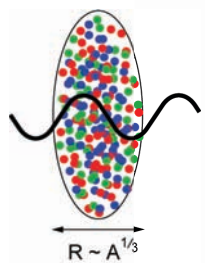


EIC stage-1 (eA): $\sqrt{S} \simeq 50$ sufficient?

benefit from nuclear enhancement factor

$$Q_s^2(eA) \simeq A^{1/3} Q_s^2(ep)$$

Kowalski, Lappi, Venugopalan



to reach saturation regime much earlier in eA

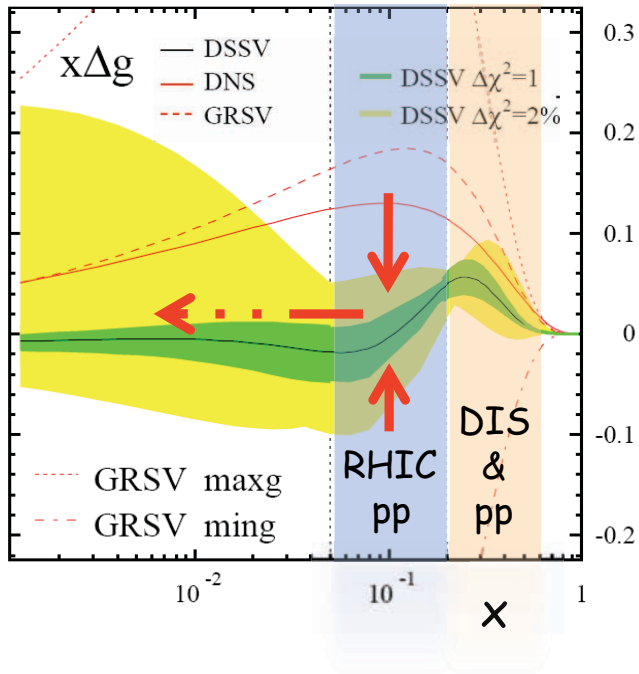
however, little lever-arm at stage-1

full EIC $\sqrt{S} \simeq 120$ will allow us to go "in and out" of saturation regime; F_L^{eA} measurement possible

Some "golden Measurements"

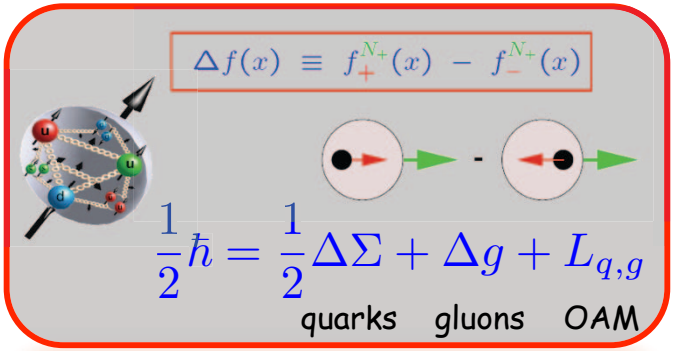
the quest for the spin of the proton: Δg

current status:



DSSV global fit
de Florian, Sassot,
MS, Vogelsang

- low x behavior unconstrained
  significant polarization still possible
- no reliable error estimate
  for 1st moment $\int_0^1 dx\, \Delta g(x, Q^2)$
  (enters spin sum rule)
- RHIC will continue to improve
  our knowledge at medium x



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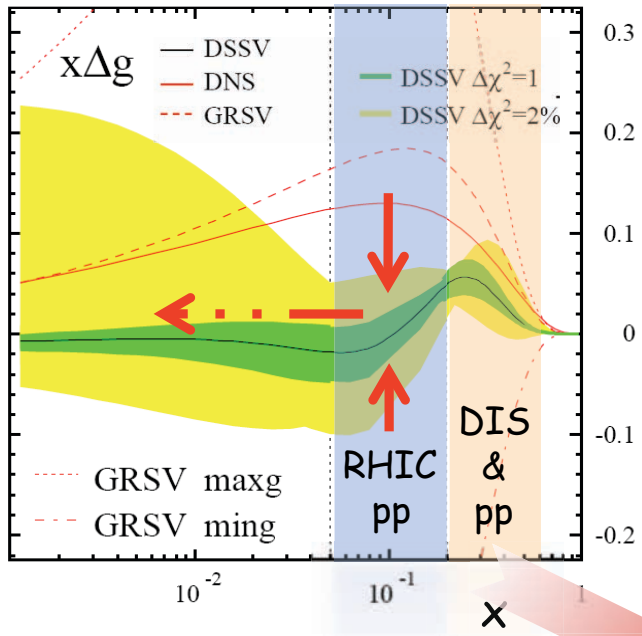

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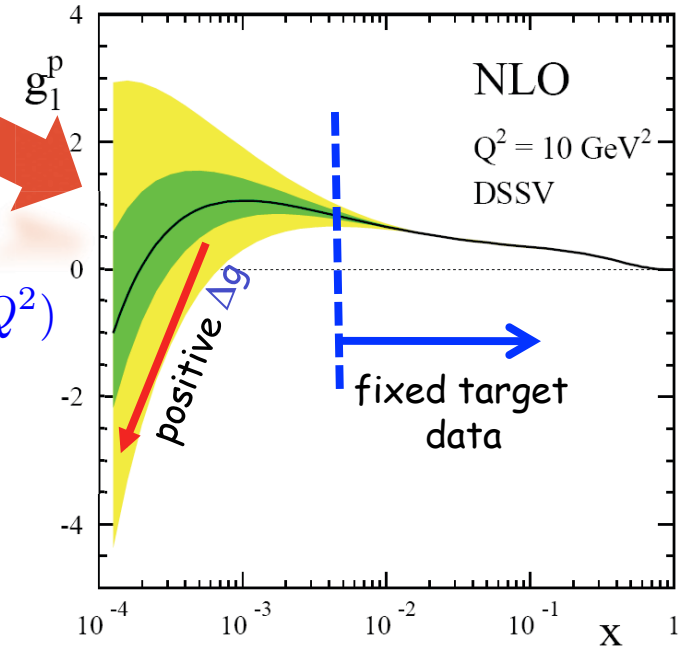
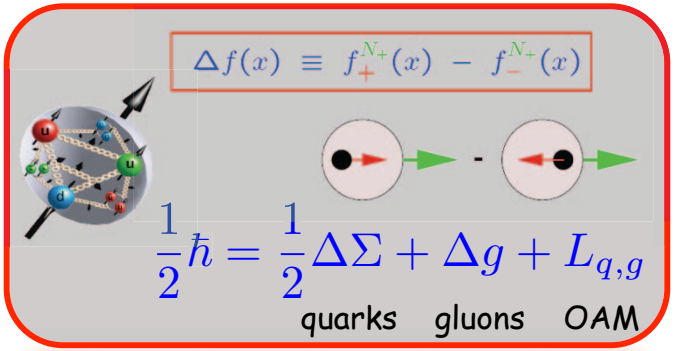
best probe for small x gluons

pQCD scaling violations

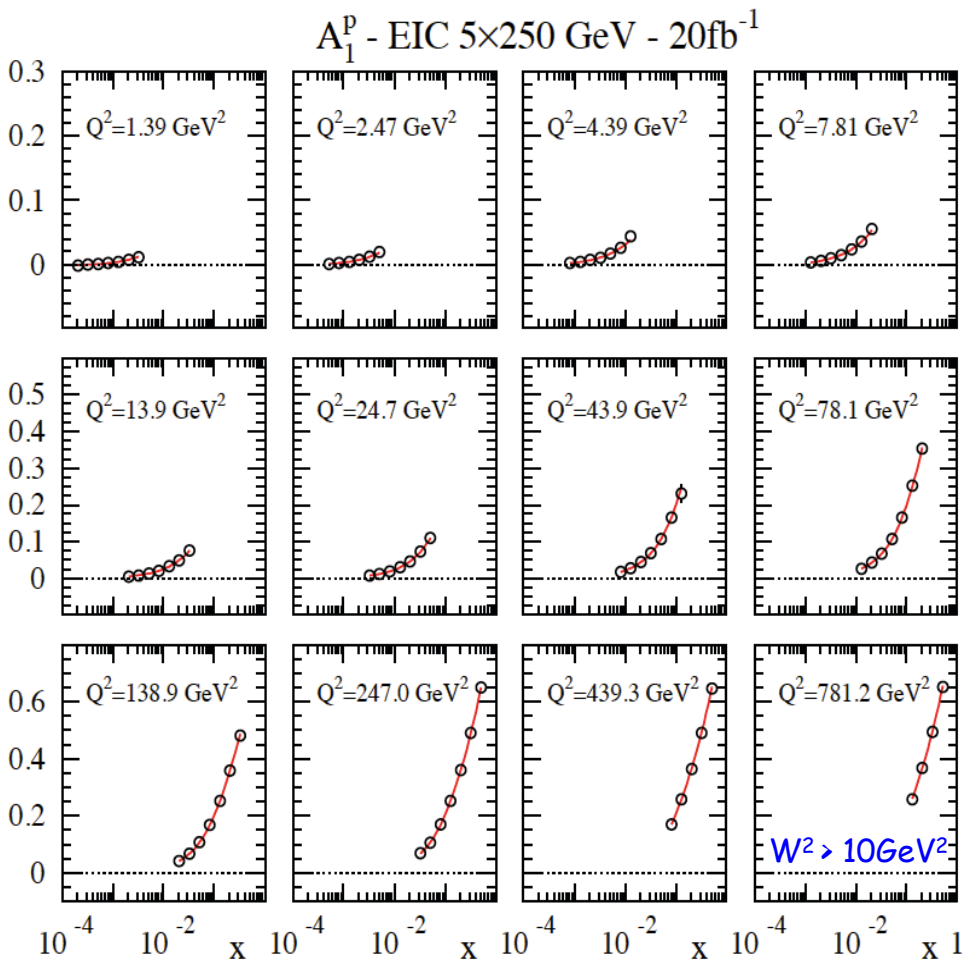
$$\frac{dg_1(x, Q^2)}{d \ln Q^2} \propto -\Delta g(x, Q^2)$$

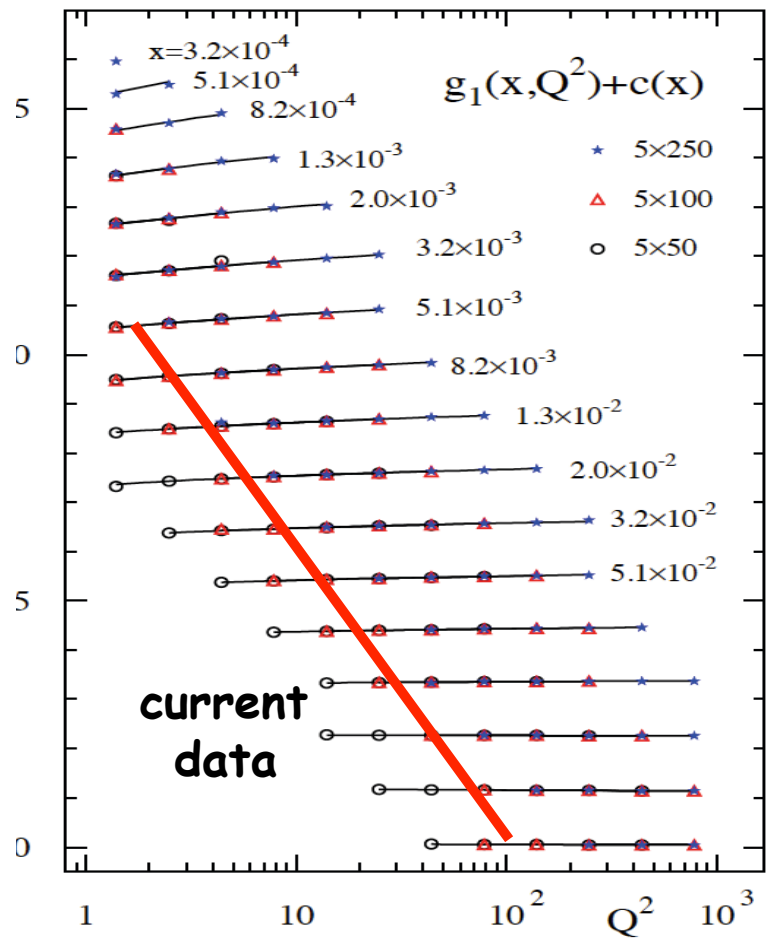




polarized DIS @ EIC and impact on $\Delta g(x,Q^2)$

strategy to quantify impact: global QCD fits with realistic pseudo-data





measurements limited by systematics – need to control them very well

issues: bunch-by-bunch polarimetry, relative luminosity, detector performance, …

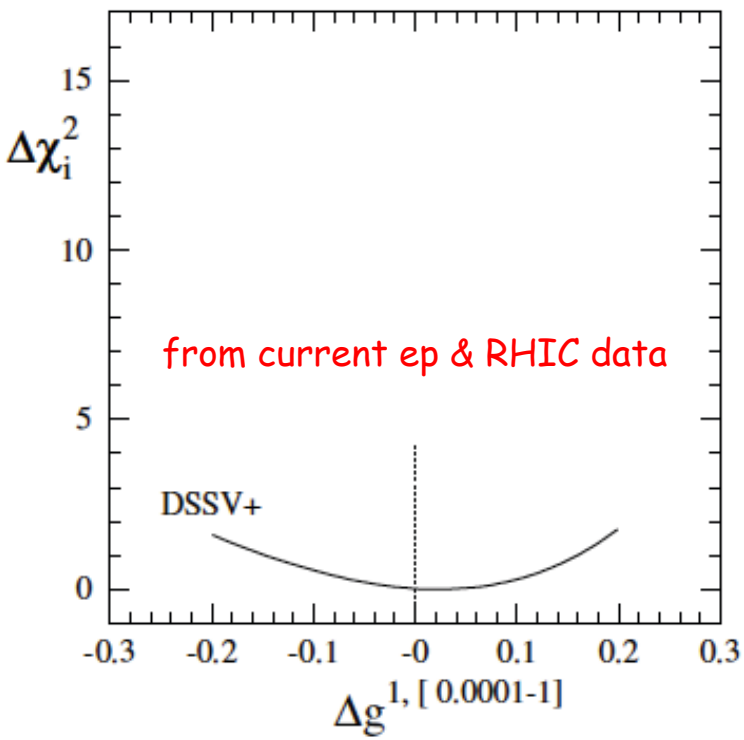
what can be achieved for Δg at an EIC

how effective are scaling violations ?

Sassot, MS

quantitative studies based on simulated data for eRHIC stage-1: 5 x (50, 100, 250, 325) GeV

χ^2 profile for $\int_{10^{-4}}^{1} \Delta g(x, Q^2)\, dx$



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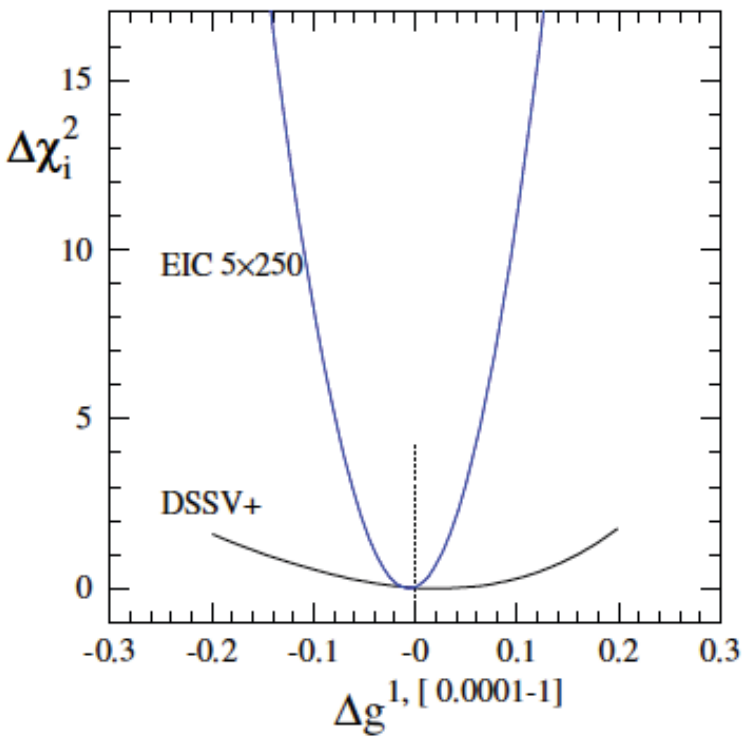

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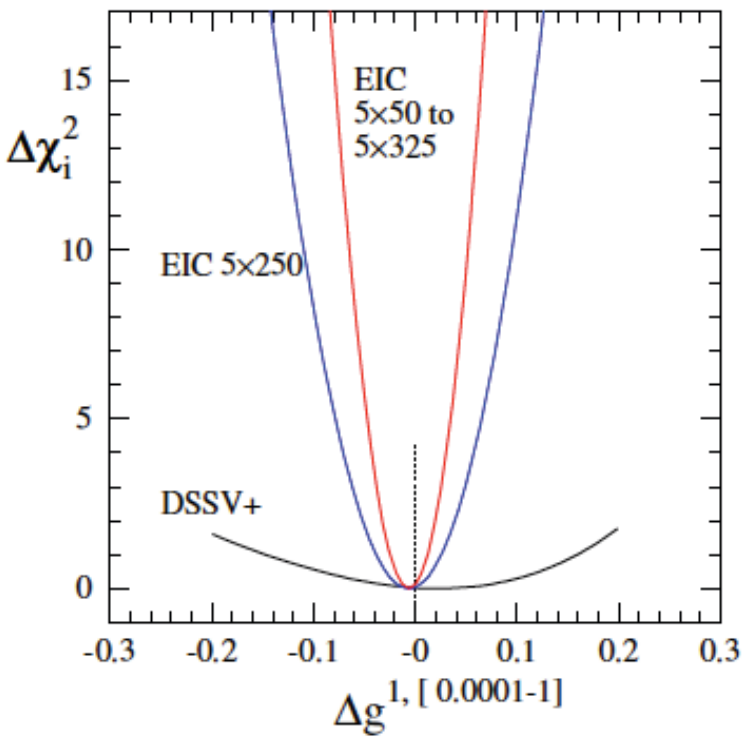

χ^2 profile slims down significantly already for eRHIC stage-1

what can be achieved for Δg at an EIC

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Sassot, MS

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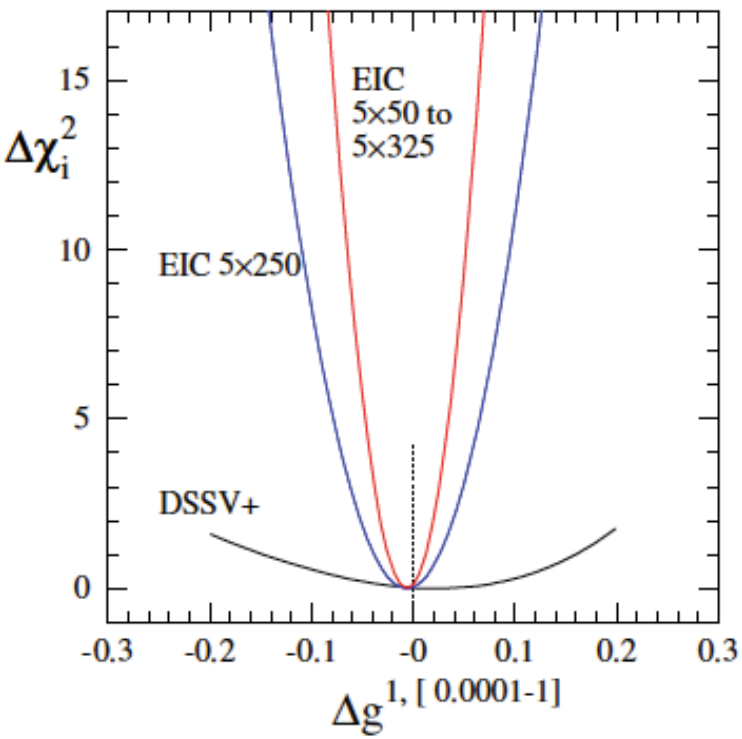
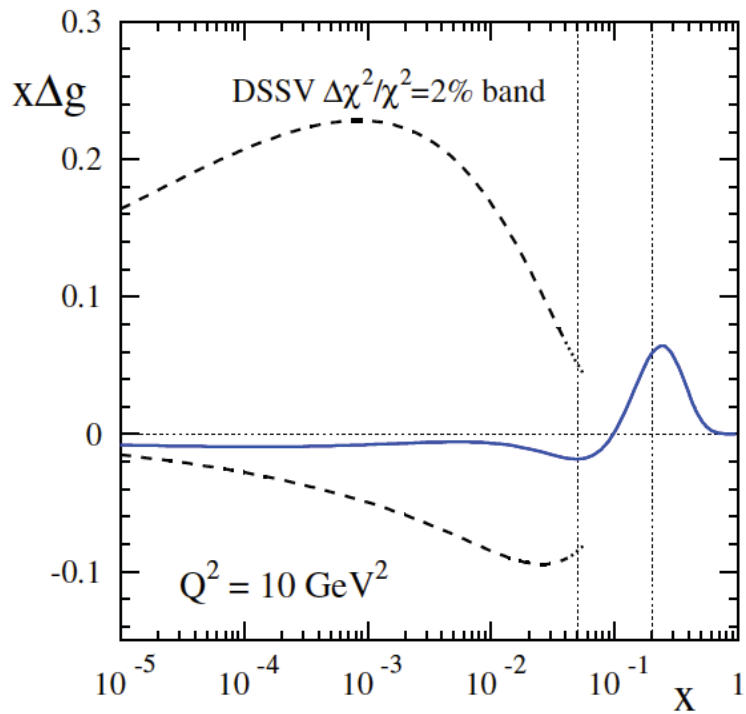


uncertainties on the x-shape of $\Delta g(x, Q^2)$



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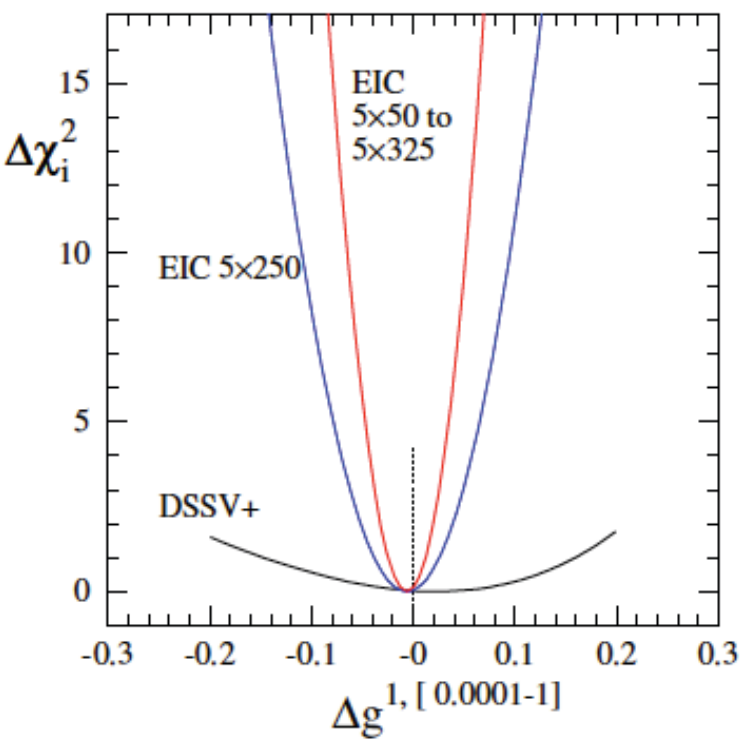

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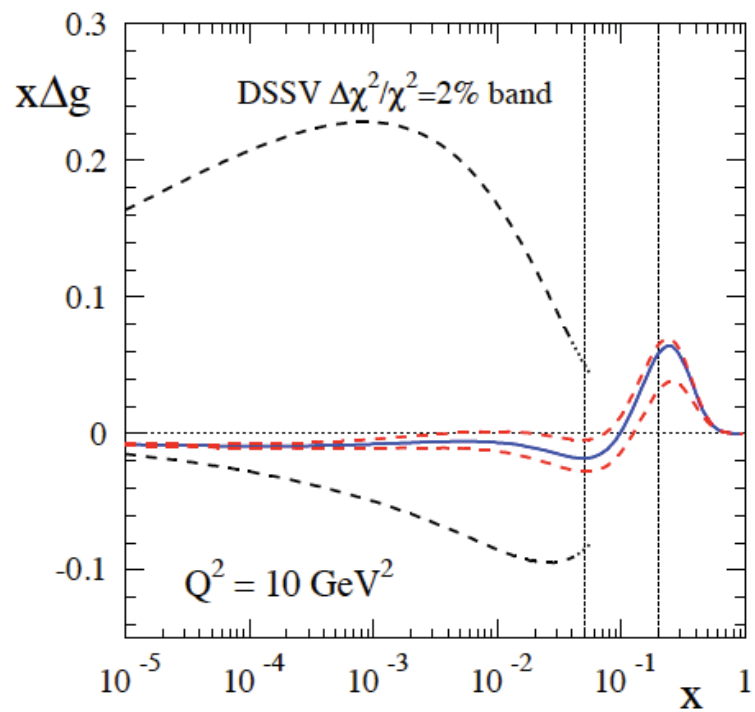

expect to determine $\int_0^1 dx\, \Delta g(x, Q^2)$ at about 10% level (or better – more studies needed)

kinematic reach down to x = 10^{-4} essential to determine integral

what can be achieved for Δg at an EIC

how effective are scaling violations ?

Sassot, MS

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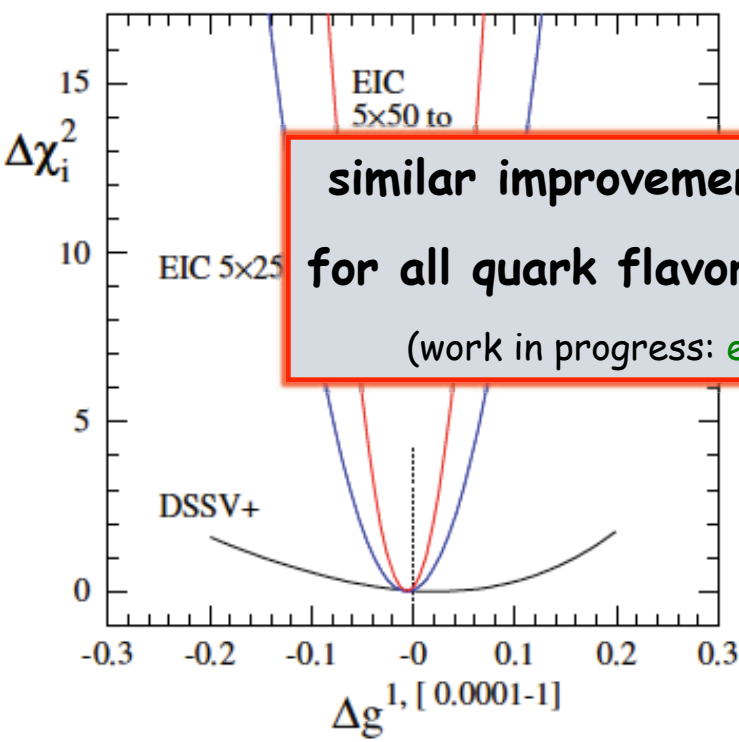
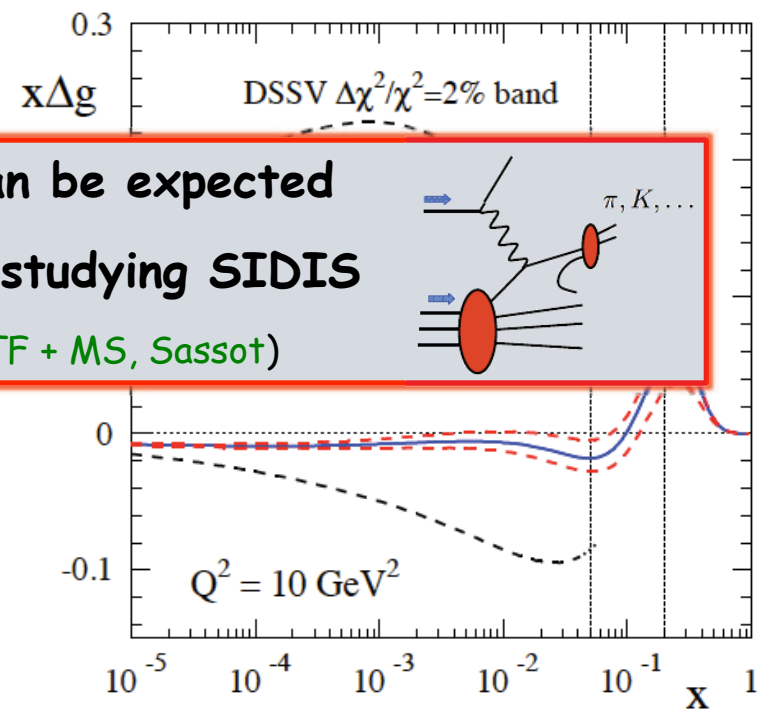




similar improvements can be expected

for all quark flavors by studying SIDIS

(work in progress: eRHIC TF + MS, Sassot)

expect to determine $\int_0^1 dx\, \Delta g(x, Q^2)$ at about 10% level (or better – more studies needed)

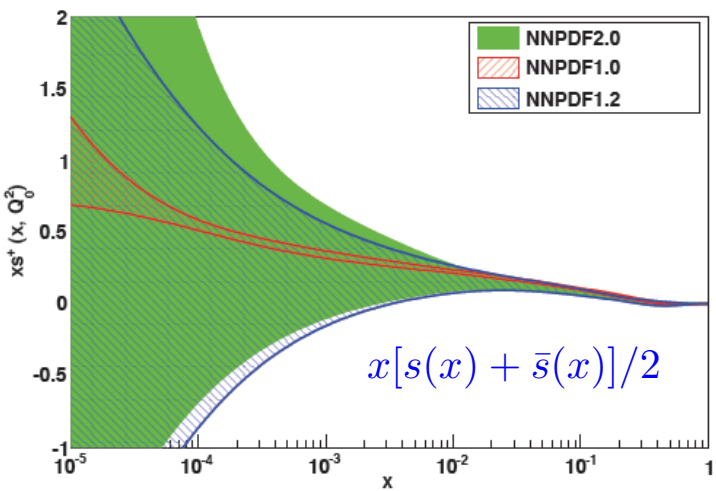
kinematic reach down to x = 10^{-4} essential to determine integral

selected open issues in flavor structure

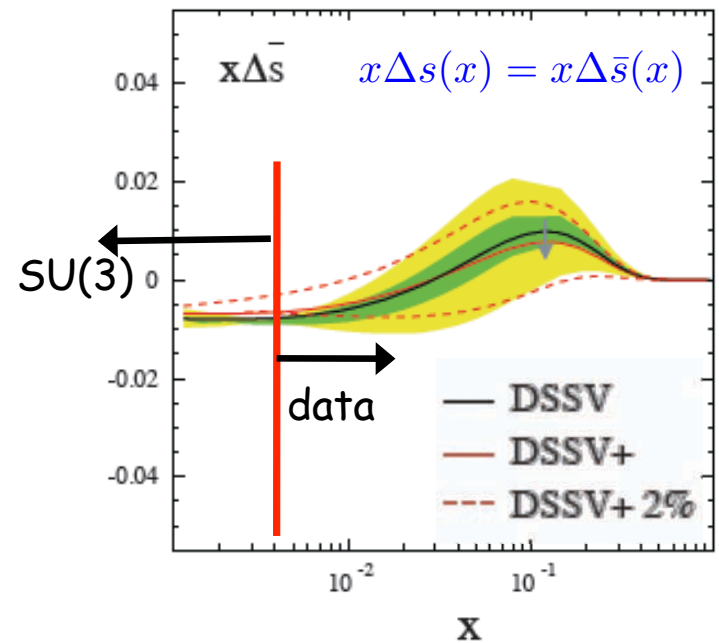
strangeness is one of the least known quantities in hadronic physics

– both unpolarized and polarized – where significant progress is difficult w/o an EIC

NNPDF collaboration



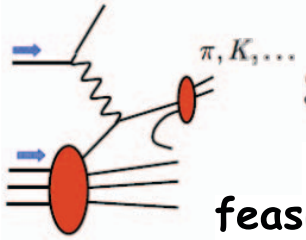
DSSV (incl. latest COMPASS data)



- substantial uncertainties
- known issues with HERMES data at large x
- **hot topic:** $s(x) - \bar{s}(x)$

- **surprise:** Δs small & positive from SIDIS data
- but 1st moment is negative and sizable due to "constraint" from hyperon decays (F,D) (assumed SU(3) symmetry debatable M. Savage)
- drives uncertainties on ΔΣ (spin sum)

we really need to determine it better ! (including their u,d quark colleagues)

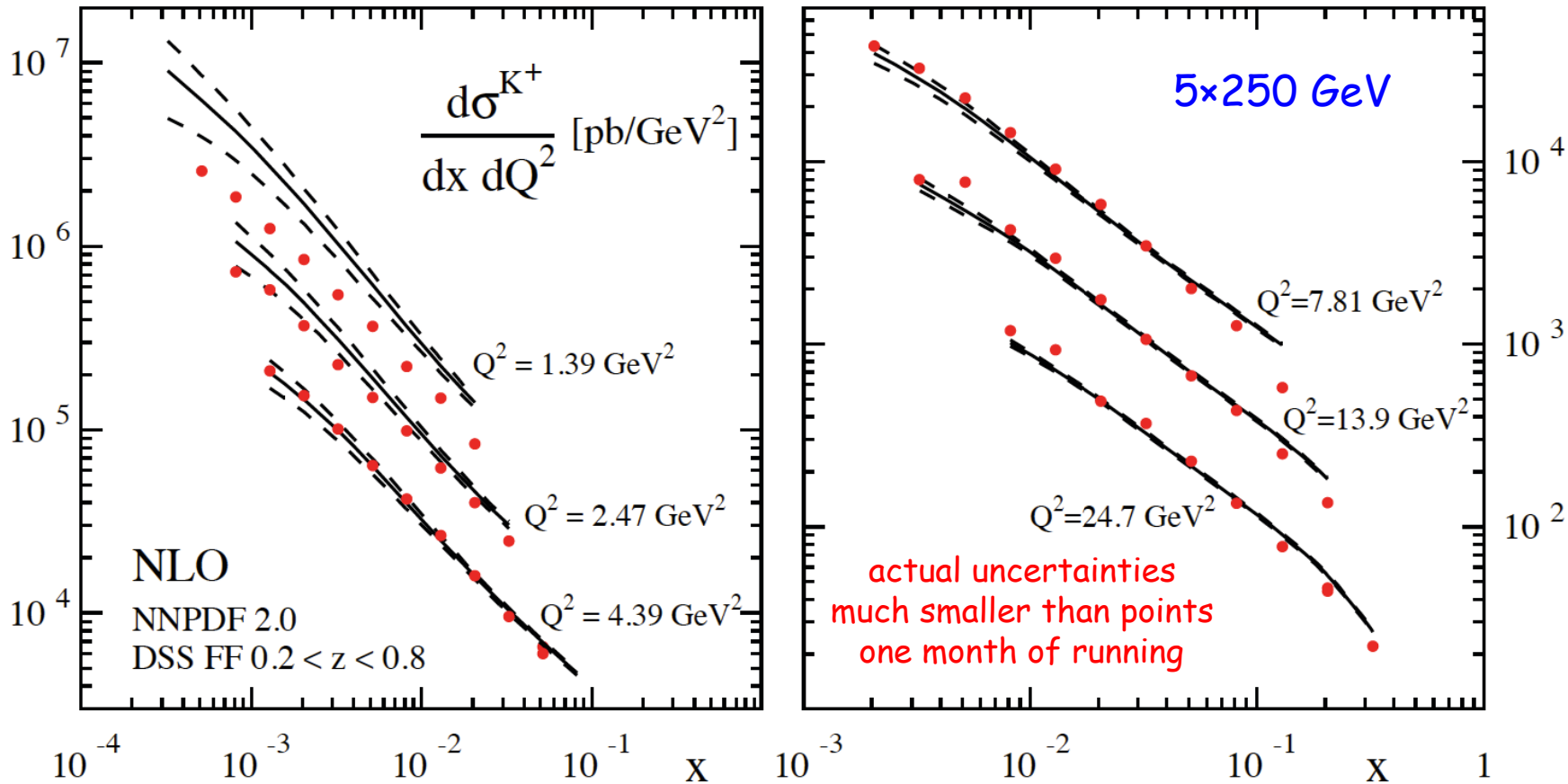


semi-inclusive DIS @ EIC: charged kaons

Aschenauer, MS

feasibility study: K^+ yields in unpol. ep at NLO based on 100 NNPDF replicas

z integrated to minimize FF uncertainties

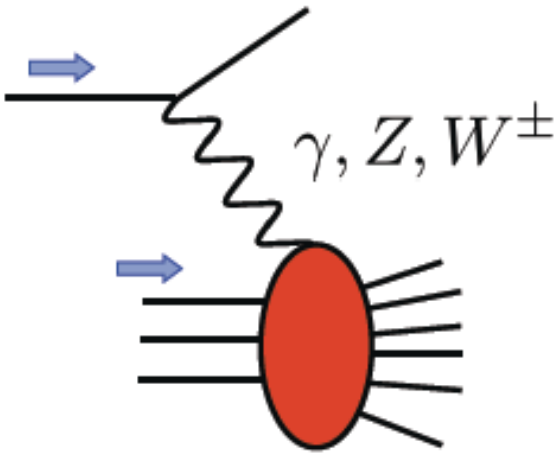


PYTHIA MC points agree well with NLO (despite ***very*** different hadronization model)

work in progress: quantify impact (requires full global analyses); pion yields, SIDIS in polarized ep

large Q^2: novel electroweak probes for Δq's

studies by Deshpande, Kumar, Ringer, Riordan, Taneja, Vogelsang



at high enough Q^2 electroweak probes become relevant

- **neutral currents** (γ, Z exchange, γZ interference)
- **charged currents** (W exchange)

parameterized by new structure functions which probe combinations of PDFs different from photon exchange

--> **flavor decomposition without SIDIS; e-w couplings**

hadron-spin averaged case: studied to some extent at HERA (limited statistics)

hadron-spin difference:

contains e-w propagators and couplings

Wray; Derman; Weber, MS, Vogelsang; Anselmino, Gambino, Kalinowski; Blumlein, Kochelev; Forte, Mangano, Ridolfi; ...

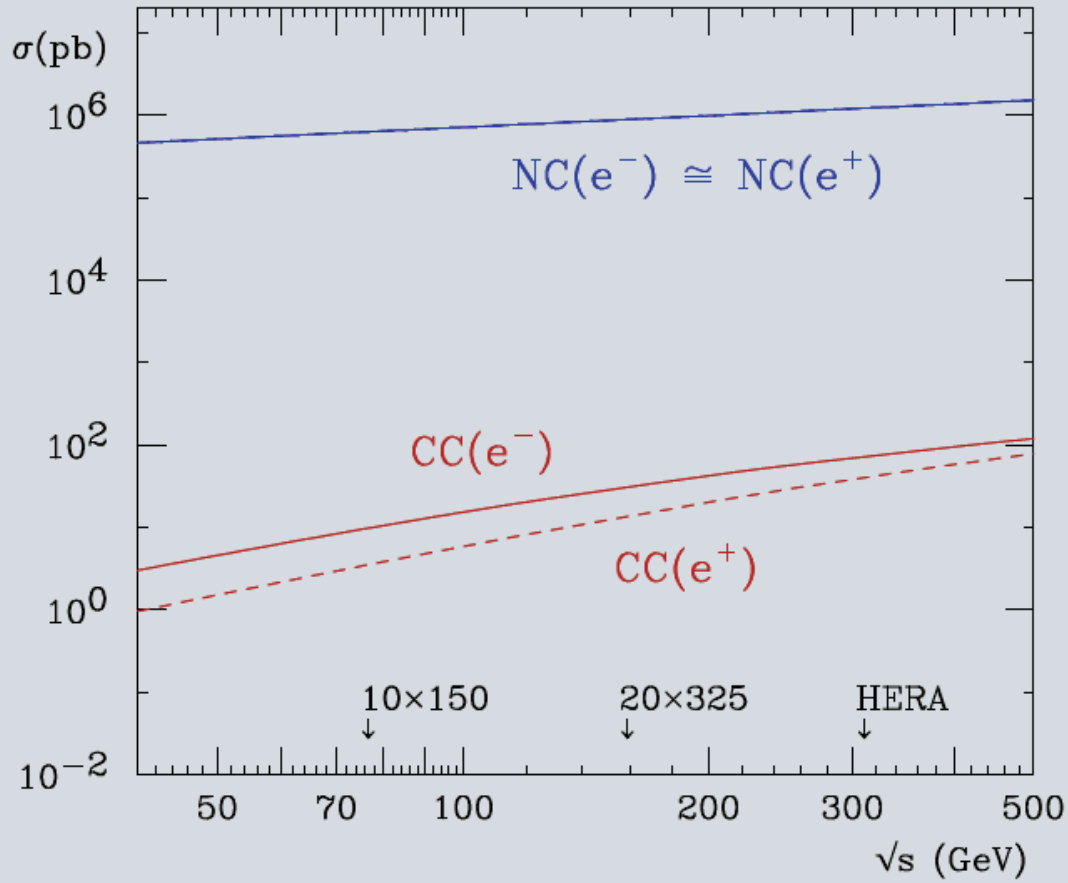
$$\frac{d\Delta\sigma^{e^{\mp},i}}{dxdy} = \frac{4\pi\alpha^2}{xyQ^2}\left[\pm y(2-y)x\hat{g}_1^i - (1-y)\hat{g}_4^i - y^2 x\hat{g}_5^i\right] \quad \mathrm{i} = \mathrm{NC}, \mathrm{CC}$$

unexplored so far – unique opportunity for the EIC

large Q^2: novel electroweak probes for Δq's

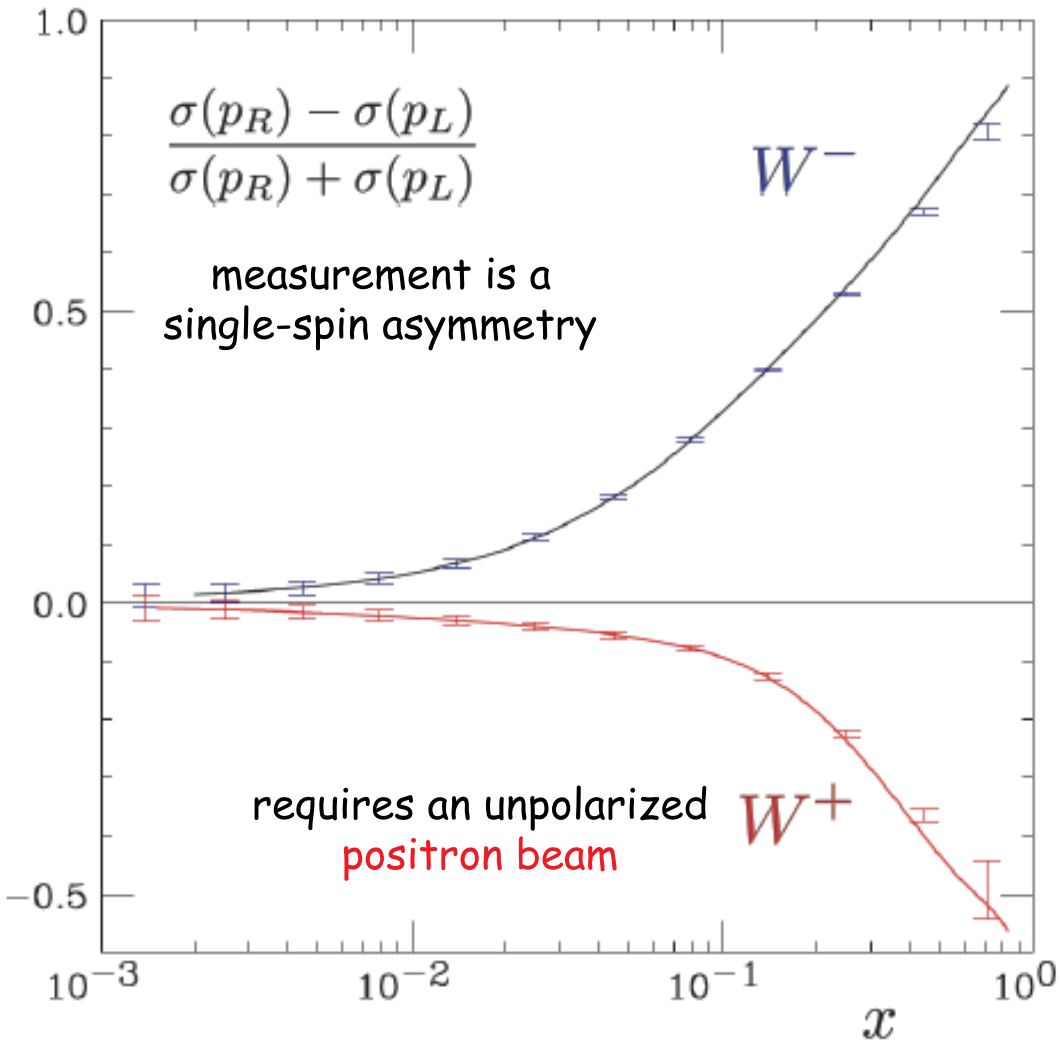
key for e-w measurements at an EIC:

drop in cross section more than compensated by luminosity increase



unexplored so far – unique opportunity for the EIC

most promising: charged current DIS



20 × 250 GeV

DIS cuts

10 fb^{-1}

need to be able to reconstruct x, Q^2 from hadronic final-state

separate up-type and down-type PDF combinations by varying y

$$A^{W^-} = \frac{(\Delta u + \Delta c) - (1-y)^2(\Delta\bar{d} + \Delta\bar{s})}{(u+c) + (1-y)^2(\bar{d} + \bar{s})} \quad A^{W^+} = \frac{(1-y)^2(\Delta d + \Delta s) - (\Delta\bar{u} + \Delta\bar{c})}{(1-y)^2(d+s) + (\bar{u} + \bar{c})}$$

Cabibbo suppressed contributions neglected

DIS structure fct. F_L at an EIC

recall: hard to measure $\sigma_r = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$

$$y = Q^2/xS$$
$$Y_+ = 1 + (1-y)^2$$

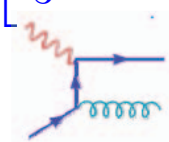
contributes mainly at large y (= lowest x for any given Q^2)

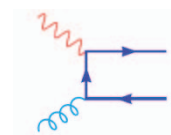
strategy: slope of y^2/Y_+ for different S at fixed x and Q^2 **strength of an EIC**

largely missed at HERA (limited statistics for different E_p)

very relevant: strong sensitivity to gluons -> saturation effects

at LO $$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[\frac{16}{3} F_2(z) + 8 \sum_q e_q^2 \left(1 - \frac{x}{z}\right) z g(z) \right]$$





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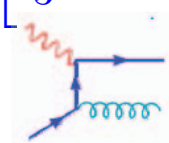
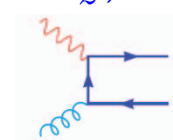
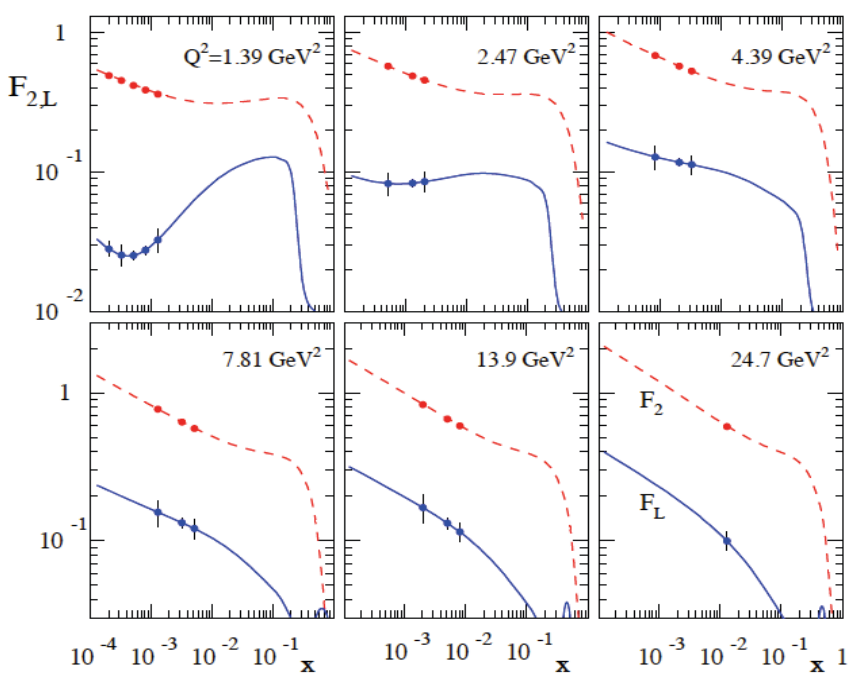






1st feasibility study for ep

Aschenauer, Debbe, MS

5x50 - 5x325
running combined
(about 1 month each)

needs to be refined:

- detector resolution
- systematic uncertainties
- QED radiative corrections
- extend to eA

aside: F_L and saturation – what to expect

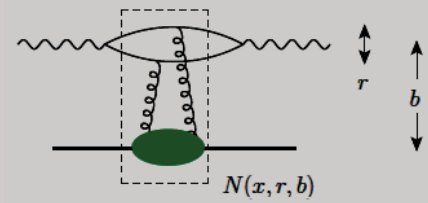
quantitative estimate based on phenomenological successful dipole model description of DIS data

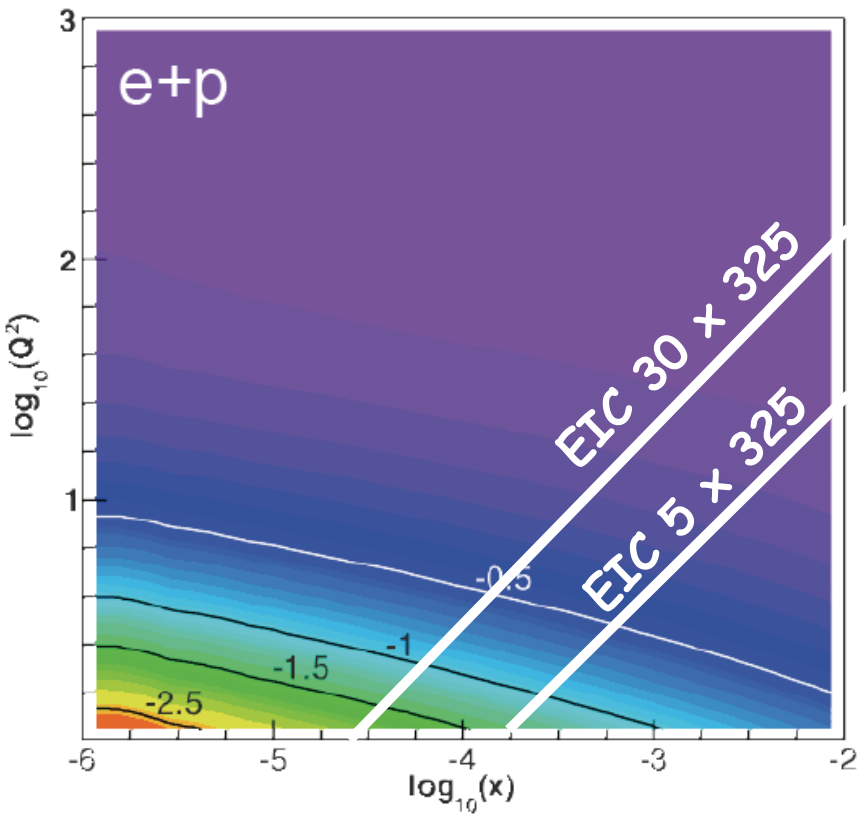
compute non-linear effects in

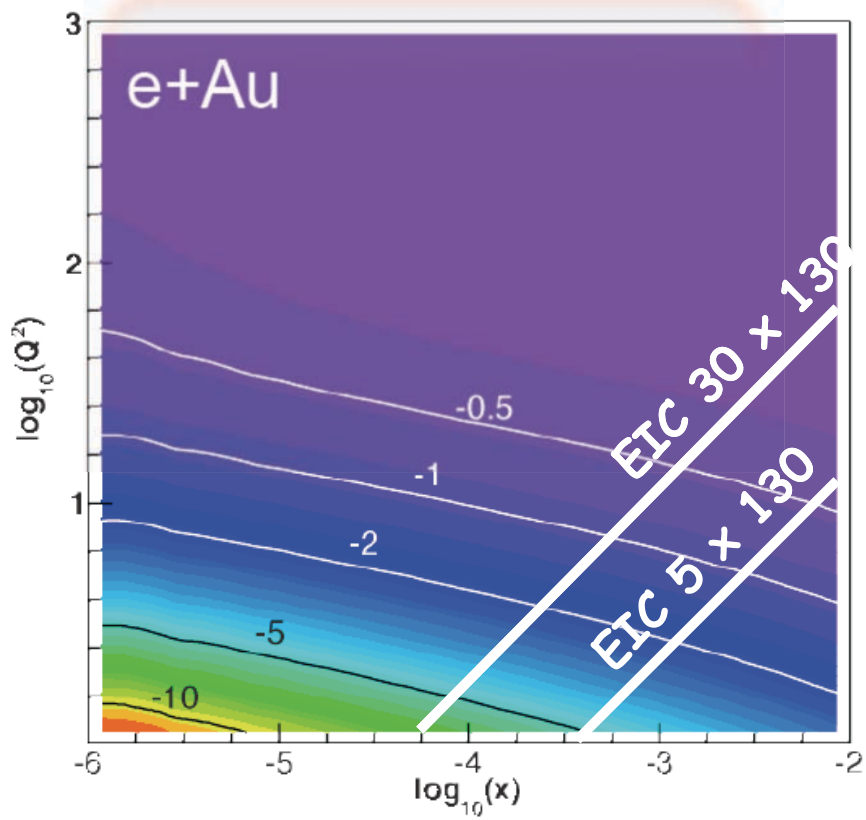
Bartels, Golec-Biernat, Motyka

$$\text{ratio} = \frac{F_L^{\text{tot}} - F_L^{\text{leading twist}}}{F_L^{\text{tot}}}$$

recall: DIS in the proton rest frame: photon splits into a quark-antiquark pair ("**color dipole**") which scatters off the target proton (= "slow" gluon field)







"3D imaging" of nucleons and nuclei

goal: going beyond longitudinal momentum structure & collinear factorization

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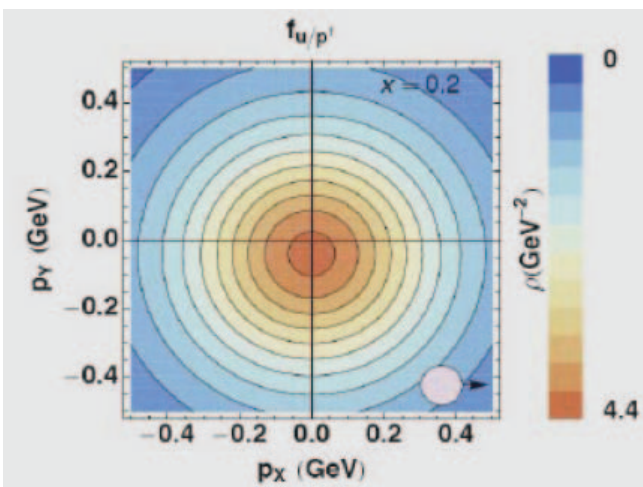
TMDs

2+1 D picture in **momentum space**



Bacchetta, Conti, Radici

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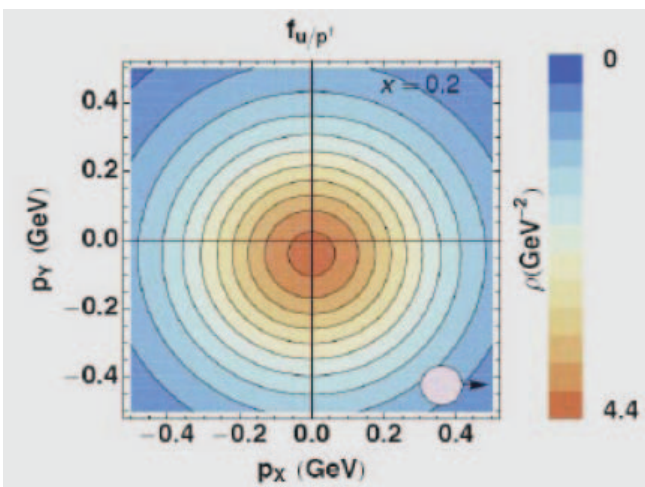
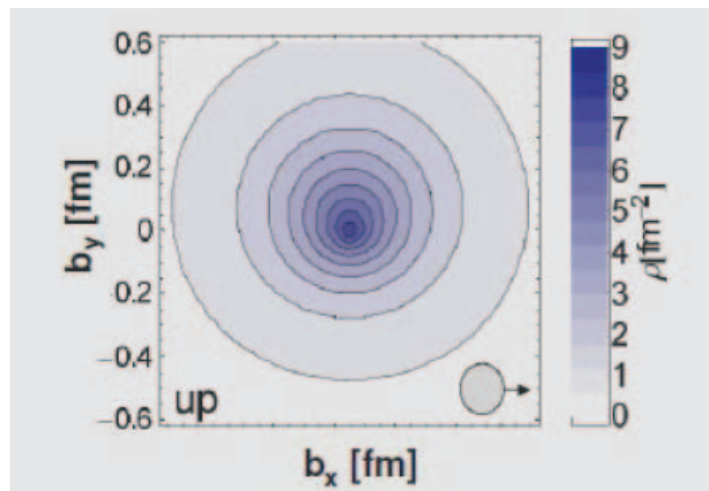


Bacchetta, Conti, Radici

2+1 D picture in **impact-parameter space**



QCDSF collaboration

transverse structure: momentum vs. position

relativistic system/uncertainty principle: can localize only in *two* dimensions

TMDs

- intrinsic transverse motion
- spin-orbit correlations = indicator of OAM
- role of gluons "accompanying" partons (Wilson lines or gauge links)
- non-trivial factorization
- matching between small k_T (TMDs) and large, perturbative k_T (twist-3 parton correl.)
- connected to physics of saturation at small x

GPDs

- collinear but long. momentum transfer
- indicator of OAM; access to Ji's total $J_{q,g}$
- existing factorization proofs
- "dipole model" in small x (large Q^2) limit

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gluon and sea distributions largely unknown -> EIC

no direct, model-indep. connection known between TMDs and GPDs

average transverse mom. and position *not* Fourier conjugates

"high level connection" through Wigner phase space distr. $W(x,k_T, b_T)$

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next talk

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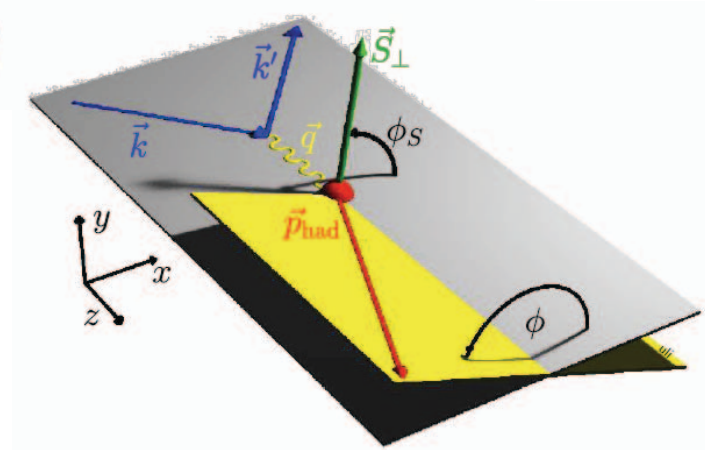

suite of observables accessible in

azimuthal (ϕ) asymmetries in SIDIS

related to entire zoo of TMD functions (PDFs & FFs)

measured at large x by HERMES & COMPASS

focus on unpolarized f_1 and Sivers function to illustrate underlying physics:

$$f_{q/P^\uparrow}(x, \mathbf{k}_\perp, S) = f_1(x, \mathbf{k}_\perp^2) - \frac{\mathbf{S} \cdot (\hat{\mathbf{P}} \times \mathbf{k}_\perp)}{M} f_{1T}^\perp(x, \mathbf{k}_\perp^2)$$

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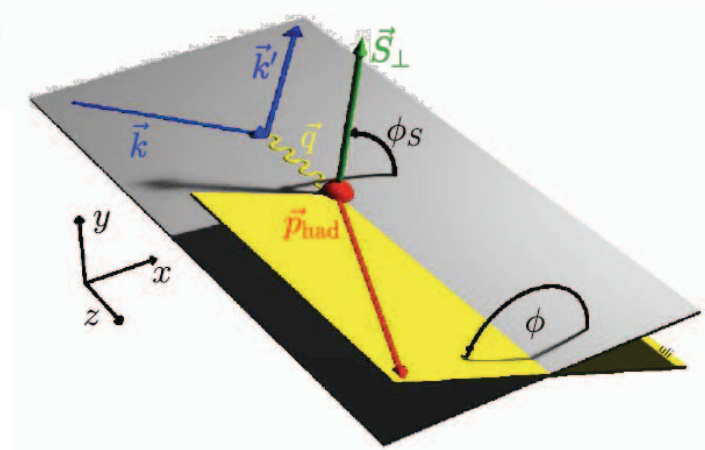

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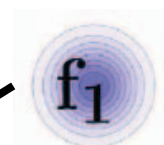
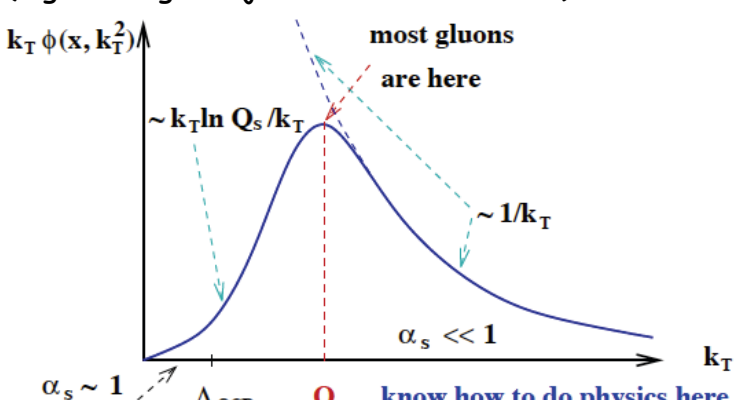


"unintegrated PDFs"

k_T dep. gluon plays prominent role at small x

rather direct access to saturation scale $Q_s(x)$

(e.g. through di-jet correlations in eA)



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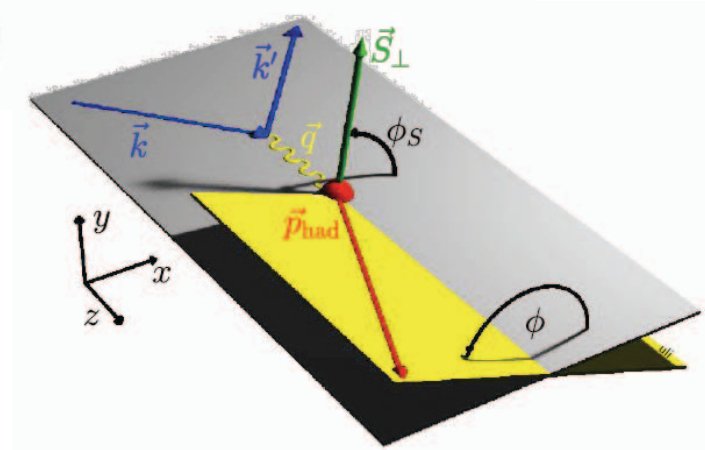

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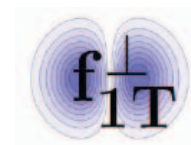

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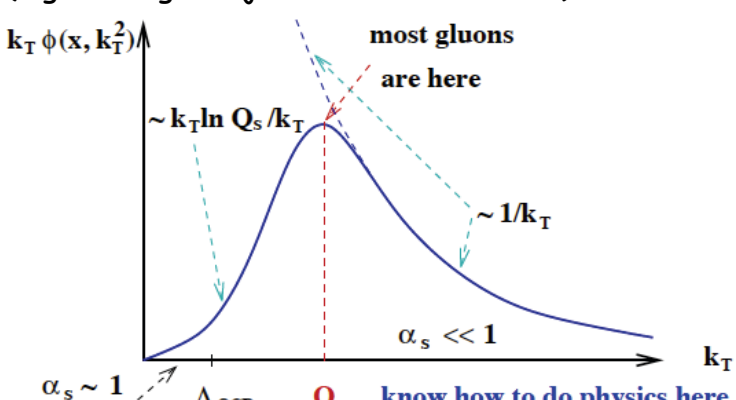
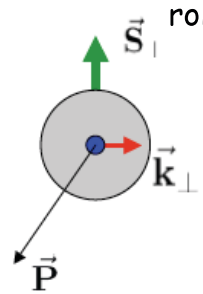


"Sivers effect"

access to 3D imaging in momentum space

non-trivial role of Wilson lines

role of spin-orbit correlations & OAM

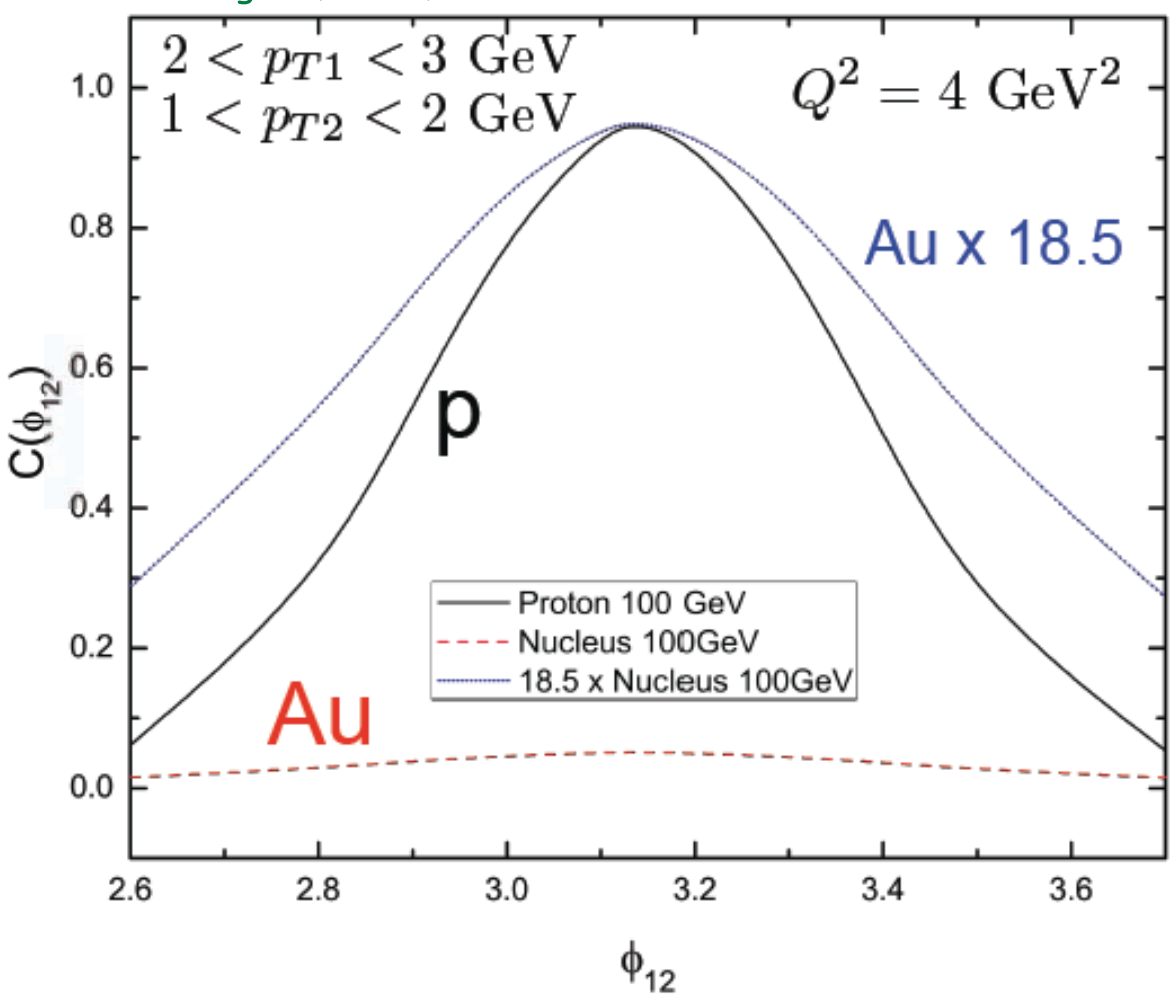


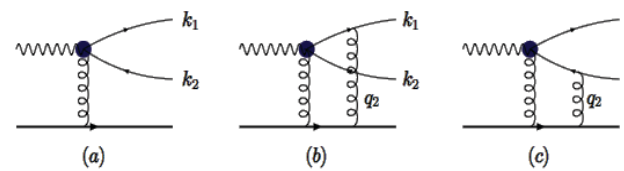
correlation of transverse spin of proton with k_T of unpolarized quark

aside: di-hadron correlations in eA

never been measured before; **excellent signature for saturation in eA**

Dominguez, Xiao, Yuan





systematic depletion of away-side peak with increasing nuclear size/energy

can be also obtained in TMD factorization

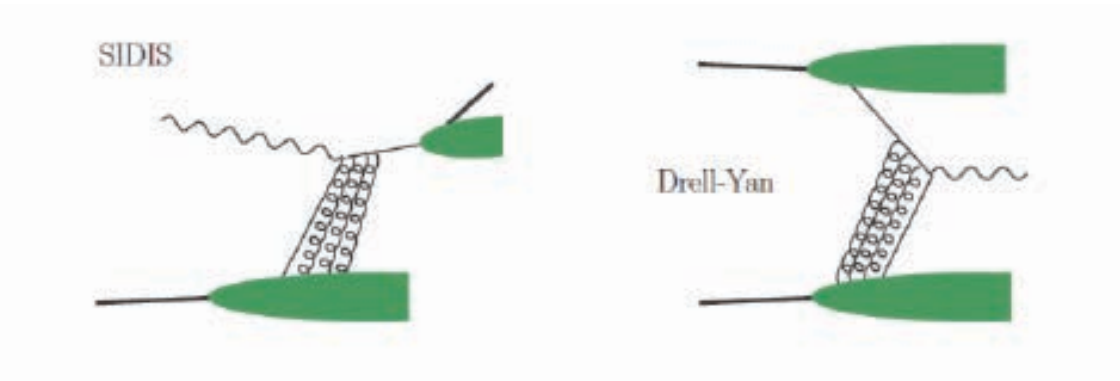
<-> unintegrated gluon at small x

TMDs: physics of Wilson lines

profound consequence of gauge invariance: colored partons "surrounded" by gluons

(technically realized by Wilson lines; also leads to issues with factorization in some pp processes)

Collins; Belitsky, Ji, Ma, Yuan; Boer, Mulders, Pijlman; Mulders, Rogers; Aybat, Rogers; ....



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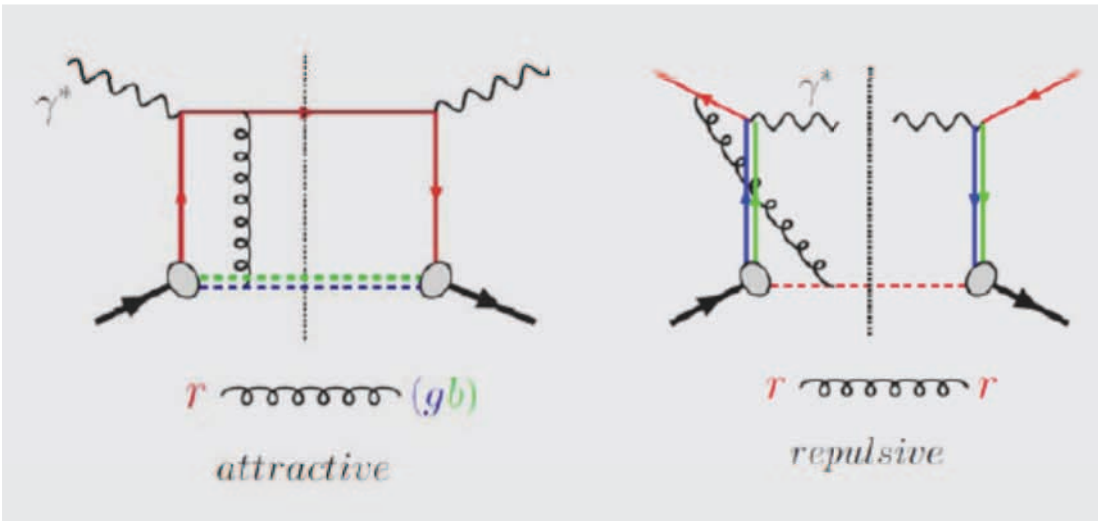

$$f_{1T}^{\perp \mathrm{SIDIS}} = -f_{1T}^{\perp \mathrm{DY}}$$

Sivers fct. has **opposite sign** when gluons couple "after" quark scatters (SIDIS) or "before" quark annihilates (DY)
(and would be zero without gluons)

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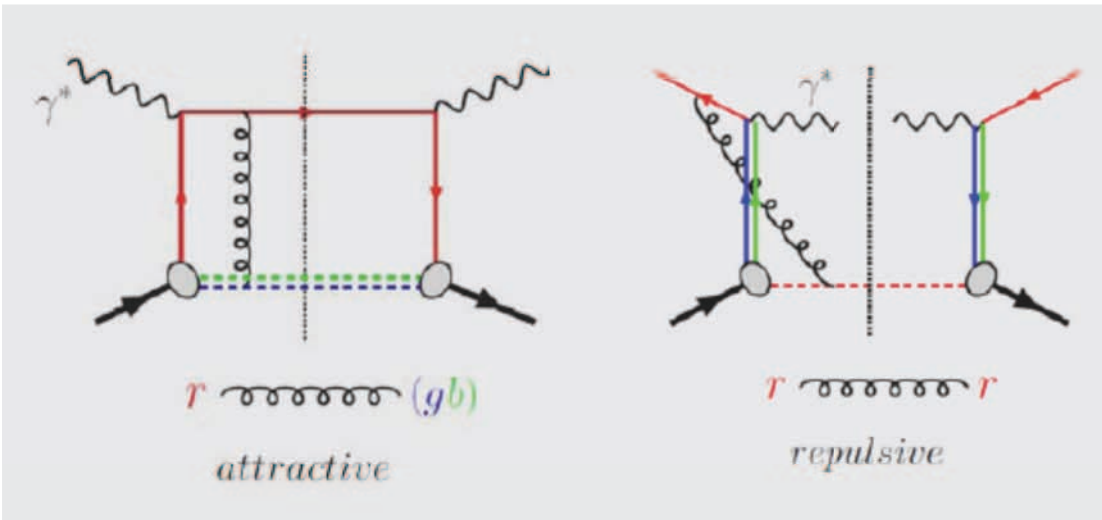

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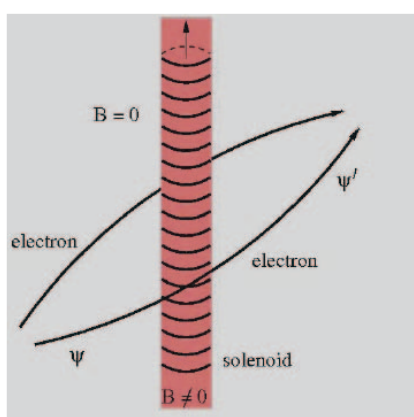
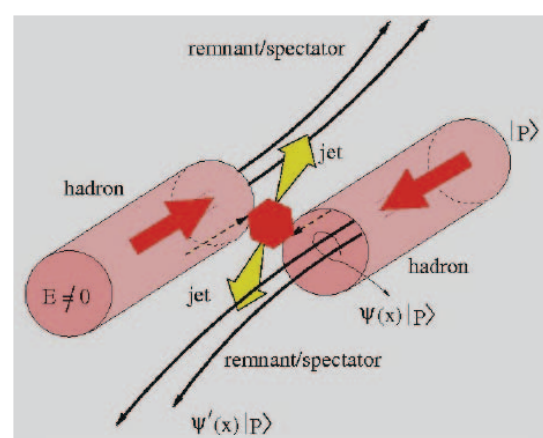
rough analogy:

P. Mulders

importance of phases in physics



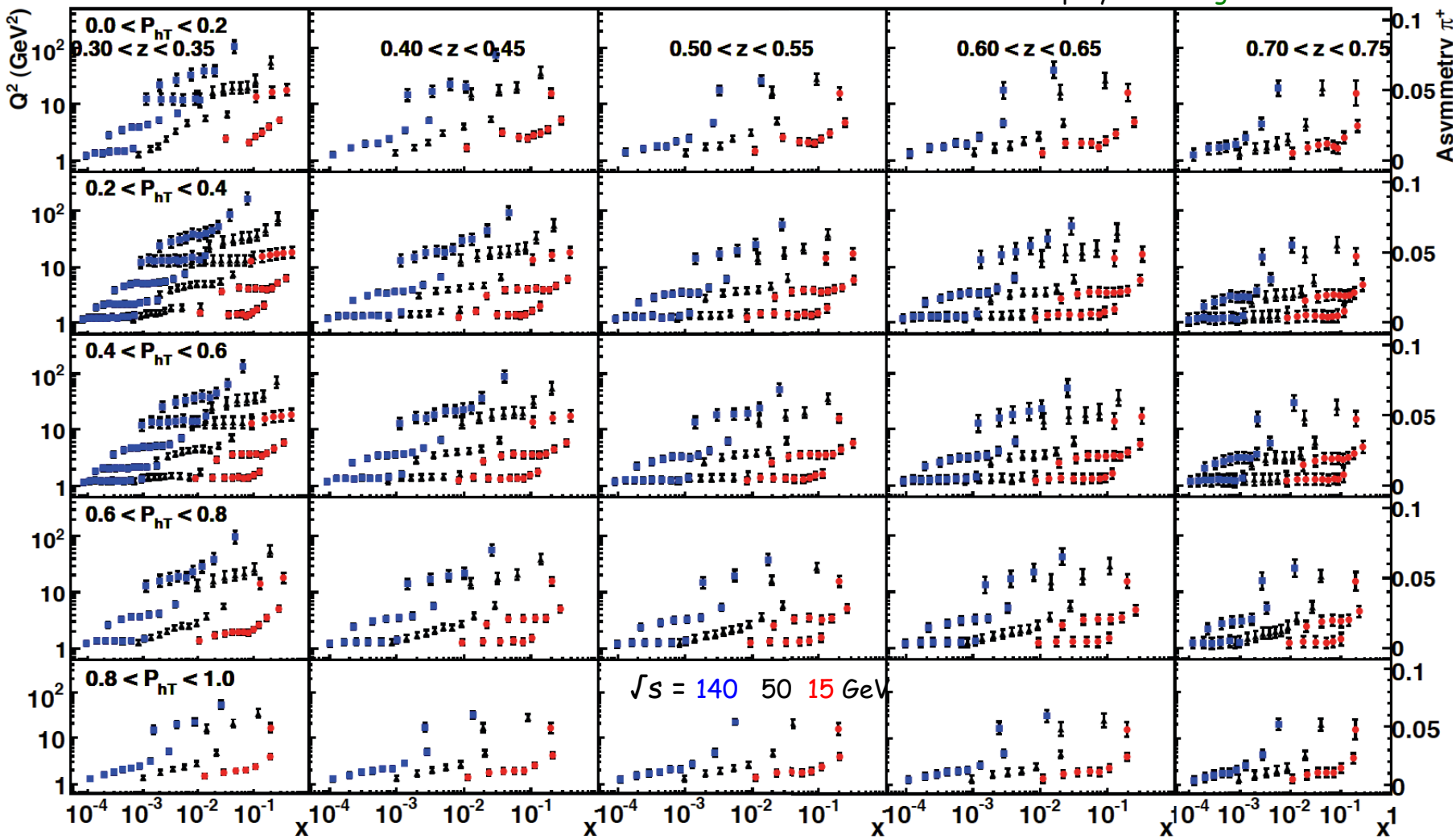
$$\psi' = e^{ie\int ds.A}\psi$$



$$\psi_i(x)|P\rangle = e^{-ig\int_x^{x'} ds_\mu A^\mu}\psi_i(x')|P\rangle$$

Sivers TMD @ EIC: 1st feasibility studies

studies for the INT writeup by M. Huang; T. Burton; …

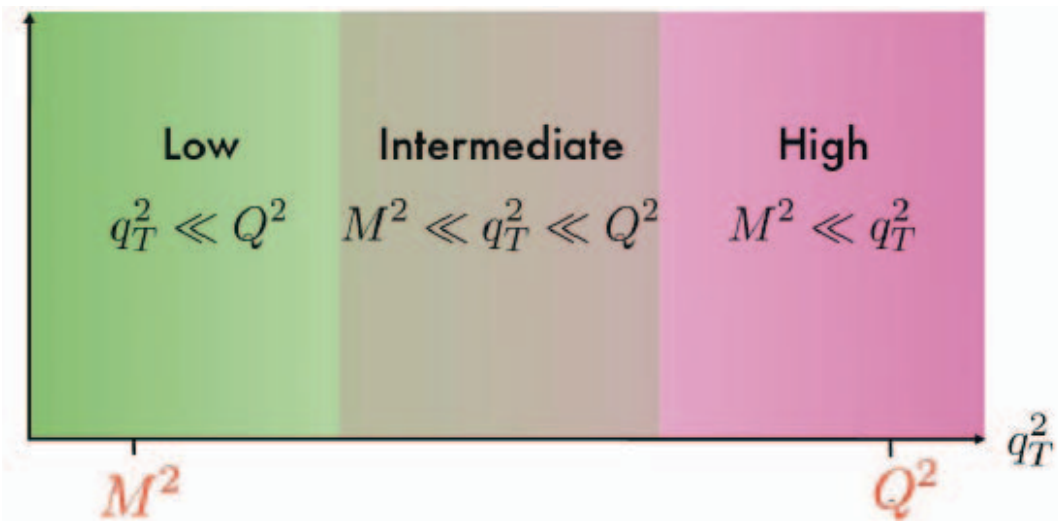


- multi-dim. binning possible (here 30fb^{-1} = few months of running) – similarly for kaons
- pseudo-data being used in global fits of TMDs (work in progress) Prokudin et al

matching low and high p_T physics

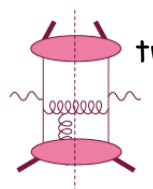
- TMDs encode physics for small transverse momenta (or p_T differences) and $Q \gg p_T$
- if p_T is large, it can be treated perturbatively
- no sharp boundary between "intrinsic" and "radiative" p_T --> **matching region**

example: SIDIS (hadron mass M, $q_T^2 \approx p_{T,H}^2/z$)



TMD factorization

collinear factorization



twist-3 parton-parton correlation

Efremov, Teryaev;
Qiu, Sterman

the leading high-p_T part should match with the p_T tail of the TMD

Collins, Soper, Sterman; Ji, Qiu, Vogelsang, Yuan

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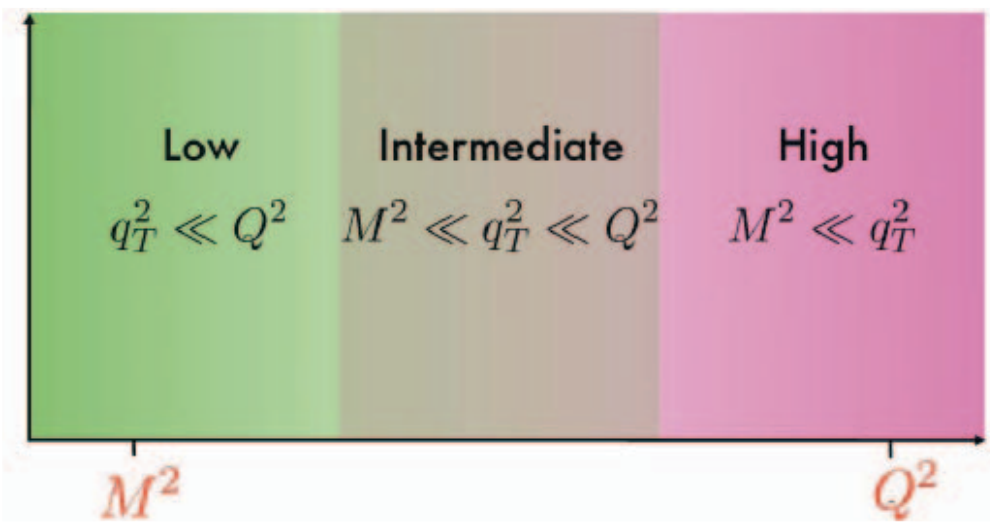

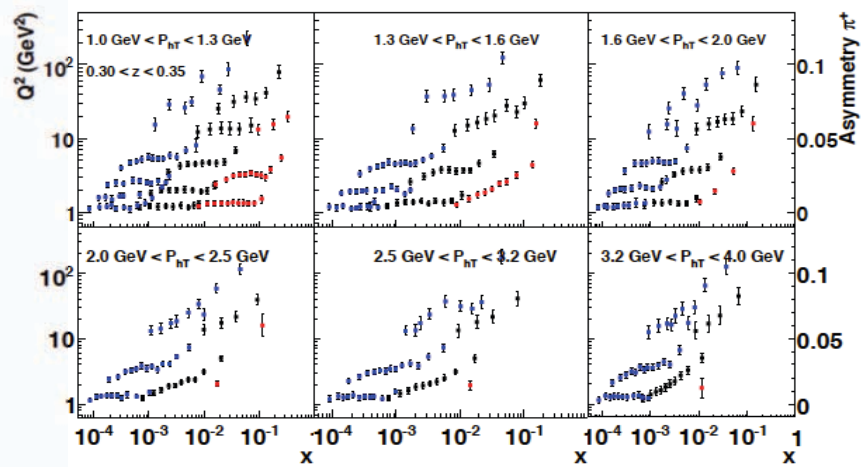

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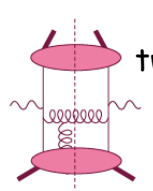


twist-3 parton-parton correlation

Efremov, Teryaev; Qiu, Sterman

can be studied in detail at an EIC

requires about 100fb^{-1}

the leading high-p_T part should match with the p_T tail of the TMD

Collins, Soper, Sterman; Ji, Qiu, Vogelsang, Yuan

TMD vs twist-3 correlations: latest puzzle

- latest twist: "sign mismatch" Kang, Qiu, Vogelsang, Yuan

1st k_T moment of Sivers fct and twist-3 analogue related at operator level

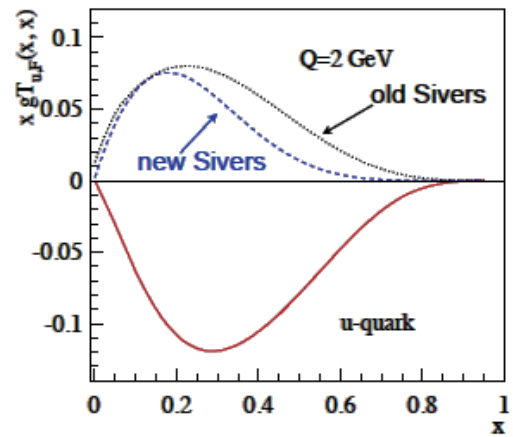
$$g_s T_{q,F}(x,x) = -\int d^2k_T \frac{|k_T|^2}{M} f_{1T}^{\perp}(x,k_T^2)|_{\rm SIDIS}$$

Boer, Mulders, Pijlman;
Ji, Qiu,, Vogelsang, Yuan

both sides have been extracted from data

find: similar magnitude ✓but wrong sign ✖

inconsistency in formalism?



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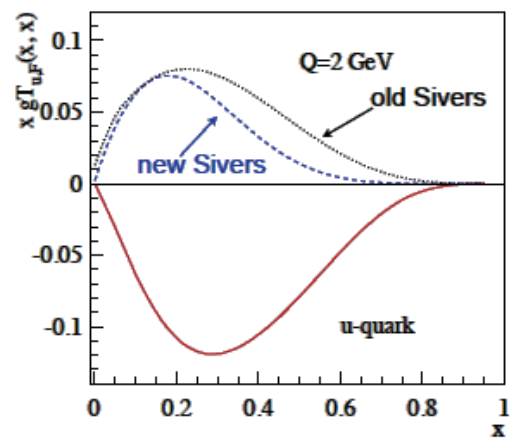


inconsistency in formalism?

possible resolutions: (1) data constrain Sivers fct only at low k_T; function has a node

phenomenological studies with more flexible Sivers fct. under way

Kang, Prokudin

(2) analysis of $T_{q,F}$ neglects possible final-state contributions to A_N

need data for A_N which are insensitive to fragmentation: photons, jets, DY

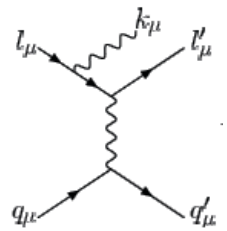
- on the bright side: recent progress on evolution for Sivers fct Kang, Xiao, Yuan

crucial for consistent phenomenology – properly related experiments at different scales

general complication: QED radiative corrections

precision measurements in ep/eA require good understanding of QED corrections

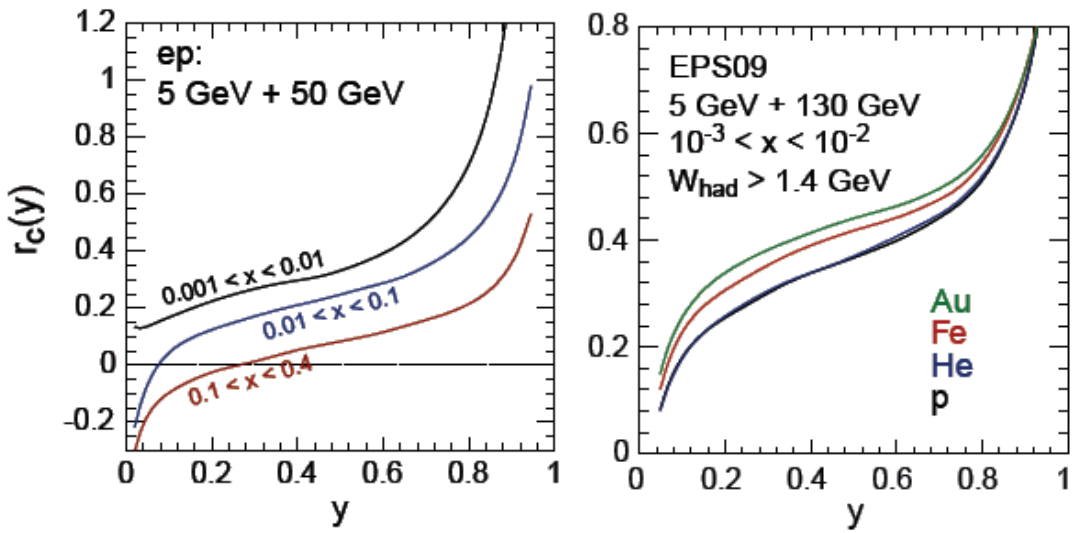
problem:



photon radiation strongly affects exp. determination of kinematics

e.g. $\mathbf{Q^2 = -(l - l')^2 \;\rightarrow\; \tilde{Q}^2 = -(l - l' - k)^2}$

effects are large but we can benefit from HERA experience



"correction factor"

$$\mathbf{r_c(y) = \frac{d\sigma/dy|_{\mathcal{O}(\alpha)}}{d\sigma/dy|_{Born}} - 1}$$

H. Spiesberger

extraction of "true" structure functions requires unfolding procedure:

$$\mathbf{F_i^{obs}(x, Q^2) = \int d\tilde{x} d\tilde{Q}^2 \; R_i(x, Q^2; \tilde{x}, \tilde{Q}^2) \; F_i^{true}(\tilde{x}, \tilde{Q}^2)}$$

"radiator function"
calculable

general complication: QED radiative corrections

precision measurements in ep/eA require good understanding of QED corrections

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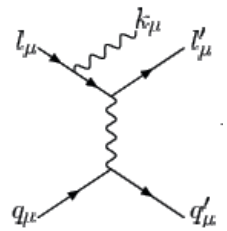

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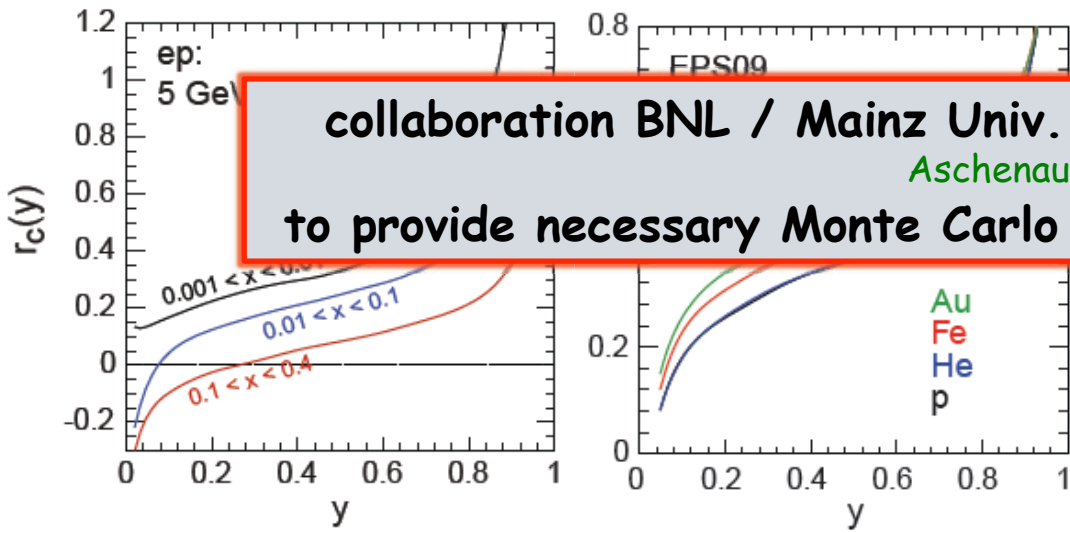

collaboration BNL / Mainz Univ. established

Aschenauer, Spiesberger, MS

to provide necessary Monte Carlo tools & studies

"correction factor"

$$\frac{\mathcal{O}(\alpha)}{\text{Born}} - 1$$

H. Spiesberger

extraction of "true" structure functions requires unfolding procedure:

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"radiator function"
calculable

other opportunities in ep scattering

- watch out for "surprises" at small-x = deviations from polarized DGLAP
  might set in earlier than in unpol. DIS: $[\alpha_s \ln^2(1/x)]^k$ Bartels, Ermolaev, Ryskin; Ermolaev, Greco, Troyan
- tag on g_1^{charm} - irrelevant so far (<< 1%), driven by Δg at small x, NLO in progress Kang, MS
- extract (anti-)strangeness from CC charm production $W^+ s' \to c$ NLO Kretzer, MS
- Bjorken sum rule: $\int_0^1 dx \left[g_1^p(x,Q^2) - g_1^n(x,Q^2)\right] = \frac{1}{6} C_{\rm Bj}\left[\alpha_s(Q^2)\right] \; g_A$ known to $O(\alpha_s^4)$

  Kodaira; Gorishny, Larin; Larin, Vermaseren; Baikov, Chetyrkin, Kühn, ...

  - experimental challenge: effective neutron beam (^{3}He), very precise polarimetry, ...
  - theor. motivation for precision measurement: Crewther relation

$$\text{Adler function } D(Q^2) \text{ in } e^+e^- \xleftrightarrow[\text{deviation from exact conformal symmetry}]{\sim 1 + \frac{\beta(\alpha_s)}{\alpha_s} K(\alpha_s)} \text{Bj sum } C_{\rm Bj}(Q^2) \text{ in DIS}$$

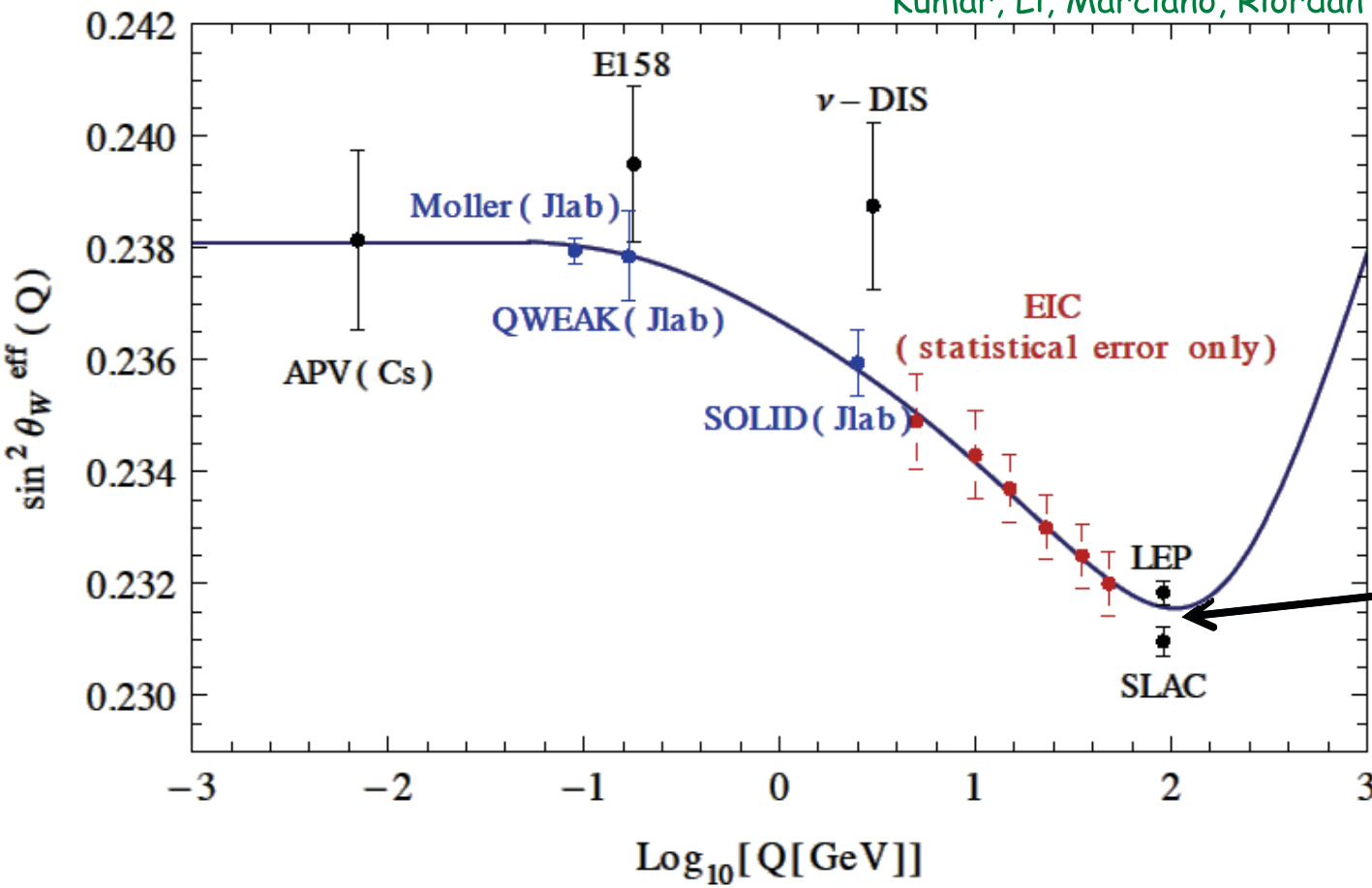
- detailed study of heavy quark production: F_2, F_L, and intrinsic charm ?
- host of photoproducion measurements (access to photon PDFs needed at an ILC)

and many other topics ...

aside: electroweak precision physics at an EIC ?

- goal: measure running of $\sin^2 \Theta_W$ over a wide range of scales Q

Kumar, Li, Marciano, Riordan



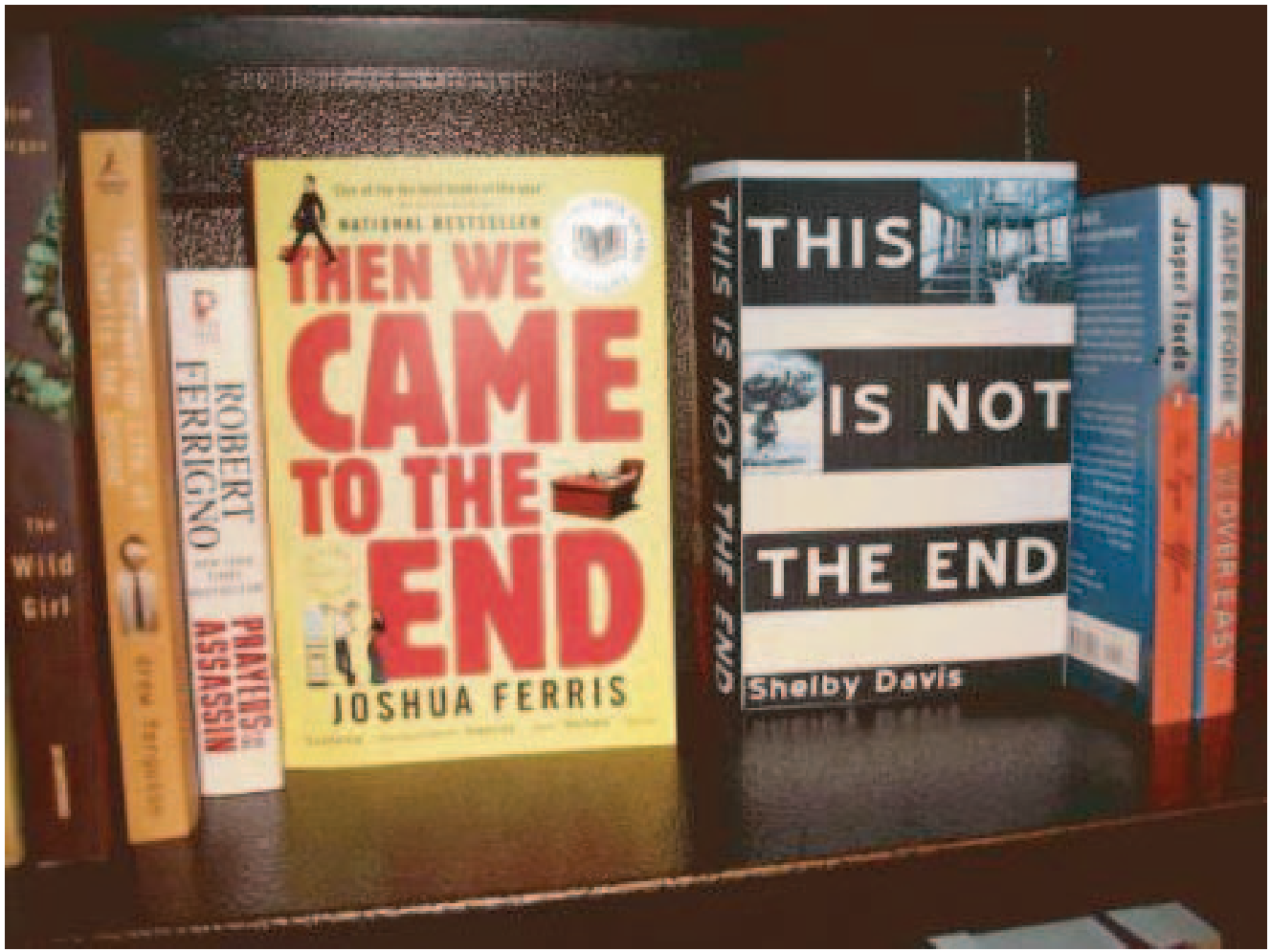
statistical errors only
assumes 200 fb^{-1} at
20 x 250 GeV

apparent discrepancy
at Z pole (3 sigma)

different implications
for new physics

- other avenues pursued: electron-tau conversion

Deshpande, Faroughy, Gonderinger, Kumar, Taneja



Summary & Outlook

overarching theme of an EIC

from testing QCD to a detailed understanding of QCD

- an EIC is the **Über-microscope** for **precision QCD studies**

  can explore the rich science of QCD many-body dynamics of "cold" nuclear matter

  complementary to pp / pA / AA physics

- made quite some headway in identifying the "golden measurements"

  details need to be worked out now (realistic feasibility studies & "impact plots")

- detailed write-up of INT program will appear *very* soon – stay tuned

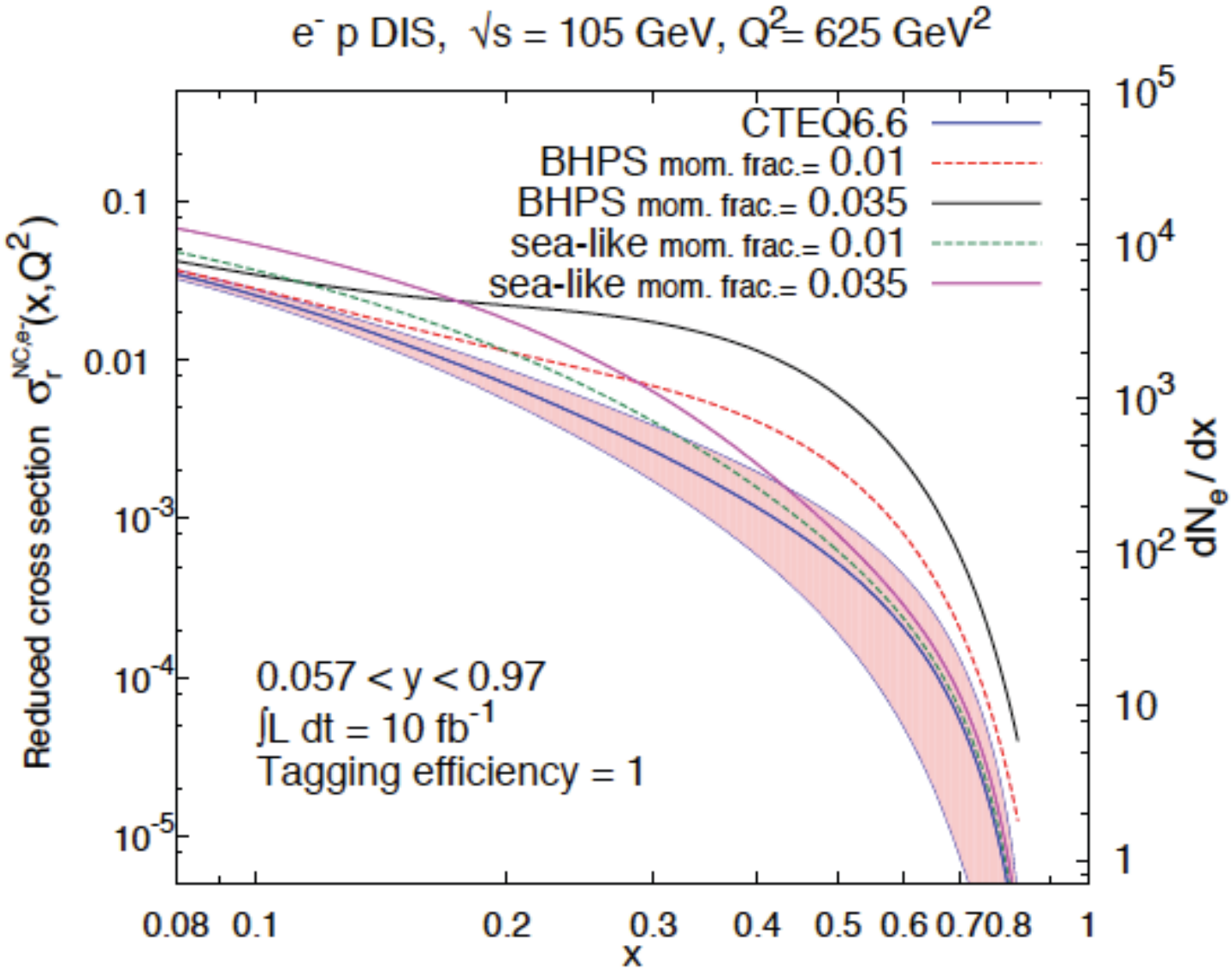
  serves as input to a White Paper anticipated for the end of the year

BACKUP SLIDES

intrinsic charm ?

Brodsky, Hoyer, Peterson, Sakai

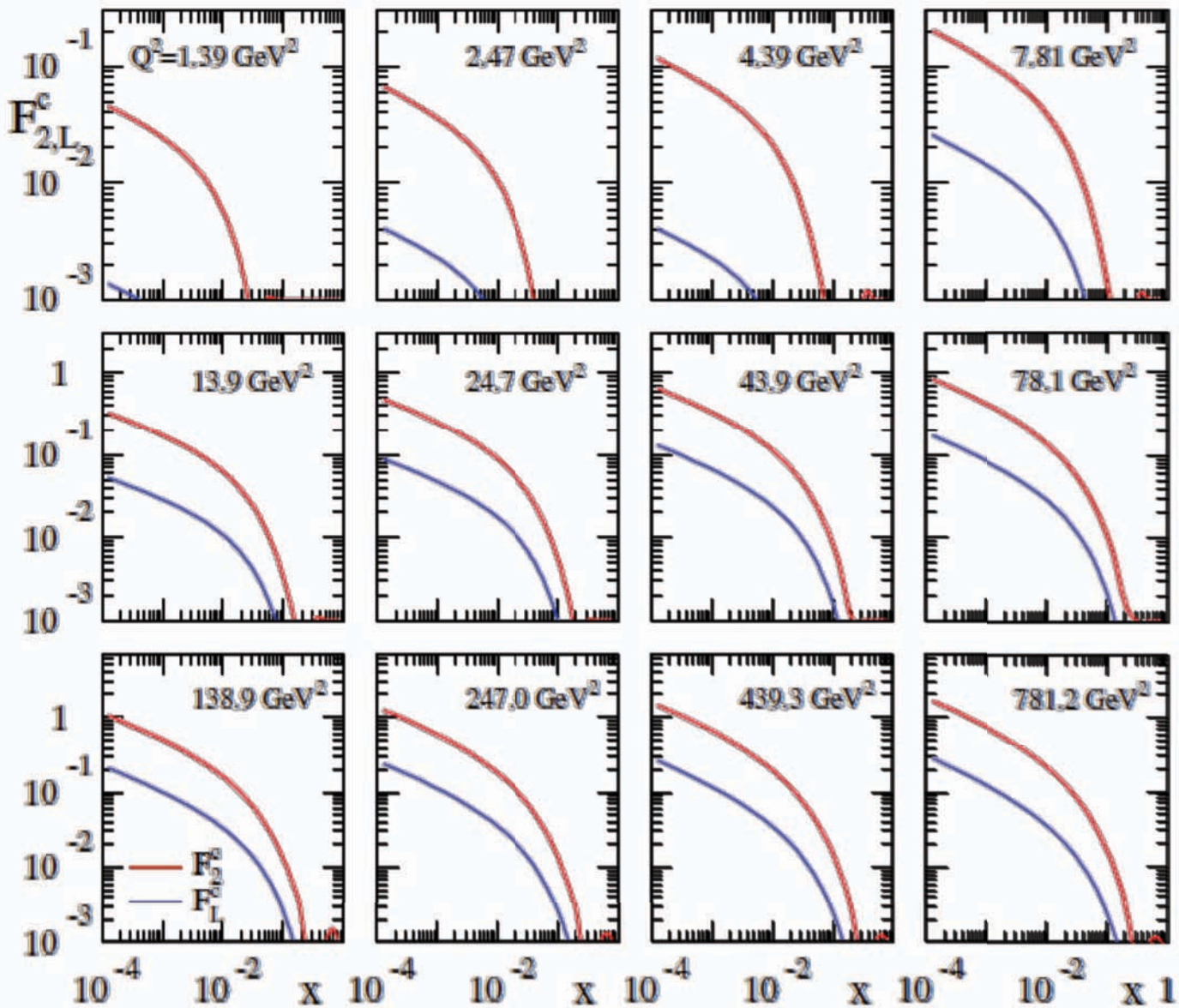
can we finally settle this?



M. Guzzi, P. Nadolsky, F. Olness (work in progress)

expectations for F_2^c and F_L^c

ABKM (S. Alekhin)



- shown:
  F_2^C BMSN
  (close to $m_c \neq 0$)

- F_L^C is not small
  ($m_c \neq 0$)

TO DO:

det. simulations &
optimize extraction
of $F_{2,L}^c$

accessing TMDs in SIDIS

- many observables possible in lp -> lhX if intrinsic k_T included and Φ kept
  e.g. "left-right asymmetries" in the direction of produced hadron
- seen at HERMES and COMPASS (but mainly valence quark region & large uncertainties)

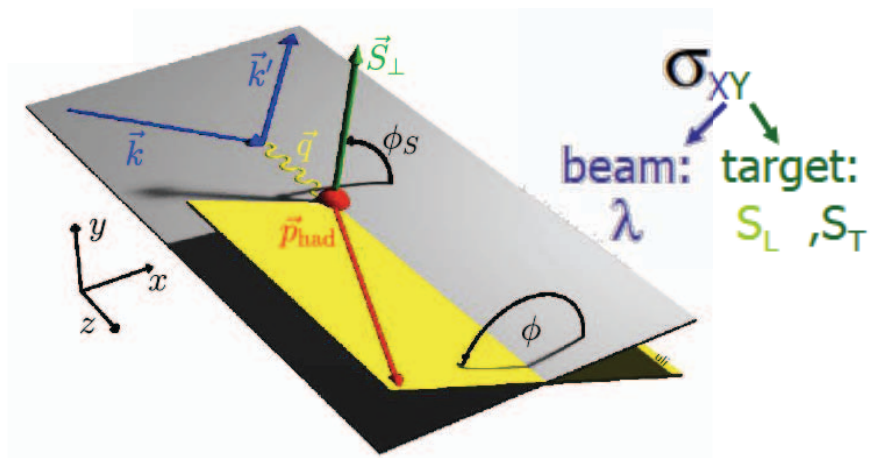
SIDIS cross section:

Kotzinian; Mulders, Tangermann; Boer, Mulders. ...

$$d\sigma^h(x,Q^2,z,P_T^h,\phi,\phi_S,\lambda) = d\sigma_{UU} + \cos 2\phi\, d\sigma_{UU} + S_L \sin 2\phi\, d\sigma_{UL} + \underbrace{\lambda S_L d\sigma_{LL}}_{\Delta q \otimes D}$$

$$+S_T\left[\sin(\phi+\phi_S)d\sigma_{UT} + \underbrace{\sin(\phi-\phi_S)d\sigma_{UT}}_{f_{1T}^{\perp}\otimes D} + \sin(3\phi-\phi_S)d\sigma_{UT}\right]$$

$$+\lambda S_T \cos(\phi-\phi_S)d\sigma_{LT} + \frac{1}{Q}\ldots$$



$f_{1T}^{\perp} \otimes D$ **"Sivers effect"**

correlation of transverse spin of proton with k_T of unpolarized quark