EIC Yellow Report
Chapter 7 - The EIC Measurements and Studies

Section 7.1
Global Properties and Parton Structure of Hadrons

Barbara Pasquini
Università di Pavia & INFN (Italy)

Based on the work of Inclusive Reactions WG
Diffractive & Tagging WG
Jet, Heavy Quarks WG
Semi-inclusive Reactions WG
Exclusive Reactions WG

7.1.1 Unpolarized parton structure of the proton and neutron

-Inclusive NC and CC DIS

-Positron beam

-Parity violating DIS

-Tagged DIS

-Sea quark PDFs via SIDIS measurements

-Non perturbative charm

-Charm jets

7.1.2 Spin structure of the proton and neutron

-Inclusive A_{LL}

-Helicity and small x dipole formalism

-Neutron spin structure from inclusive and tagged DIS with polarized ^3He and ^2H

-Orbital angular momentum contribution to nucleon spin

-Parity violating DIS

-Sea quark helicities via SIDIS

-ΔG from dijet A_{LL}

7.1.3 Parton structure of mesons

-Sullivan process

-Theoretical background in extracting the data

-Kinematic of interest to address specific theory questions

-Meson structure functions projections

-Impact on global QCD analysis

-Complementarity with other facilities

-Synergy with continuum and lattice QCD

7.1.4 Origin of the hadron mass

7.1.5 Multiparton correlations

-$g_T(x)$ from inclusive DIS

-e(x) from semi-inclusive DIS

7.1.6 Inclusive and hard diffractions

-Inclusive diffraction

-Diffractive dijets

-Large |t| diffractive production of vector mesons

7.1.7 Global event shapes and the strong coupling constant

-Theoretical methods

-Predictions

-Fitting for α_S

-Experimental projections

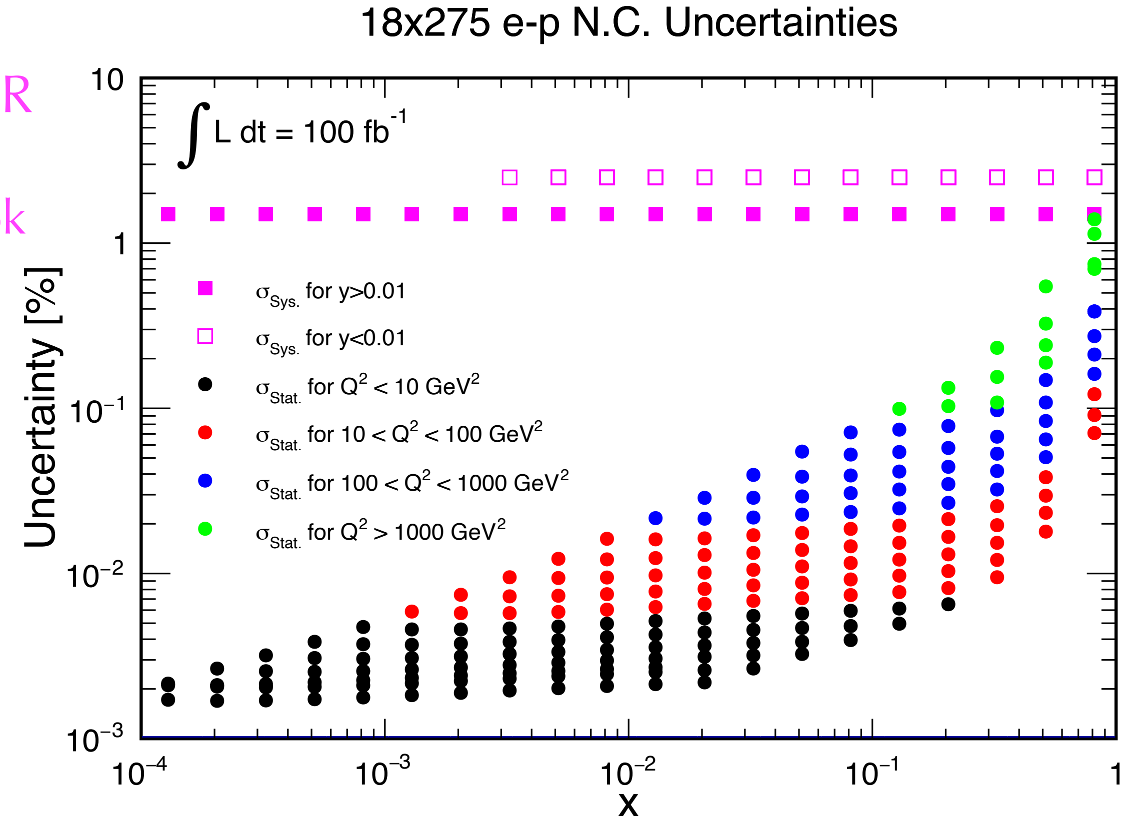
-Jet measurement performance

- τ_1^a measurement performance

-Systematic uncertainties and unfolding

Systematic uncertainties: see sect. 8.1 of YR

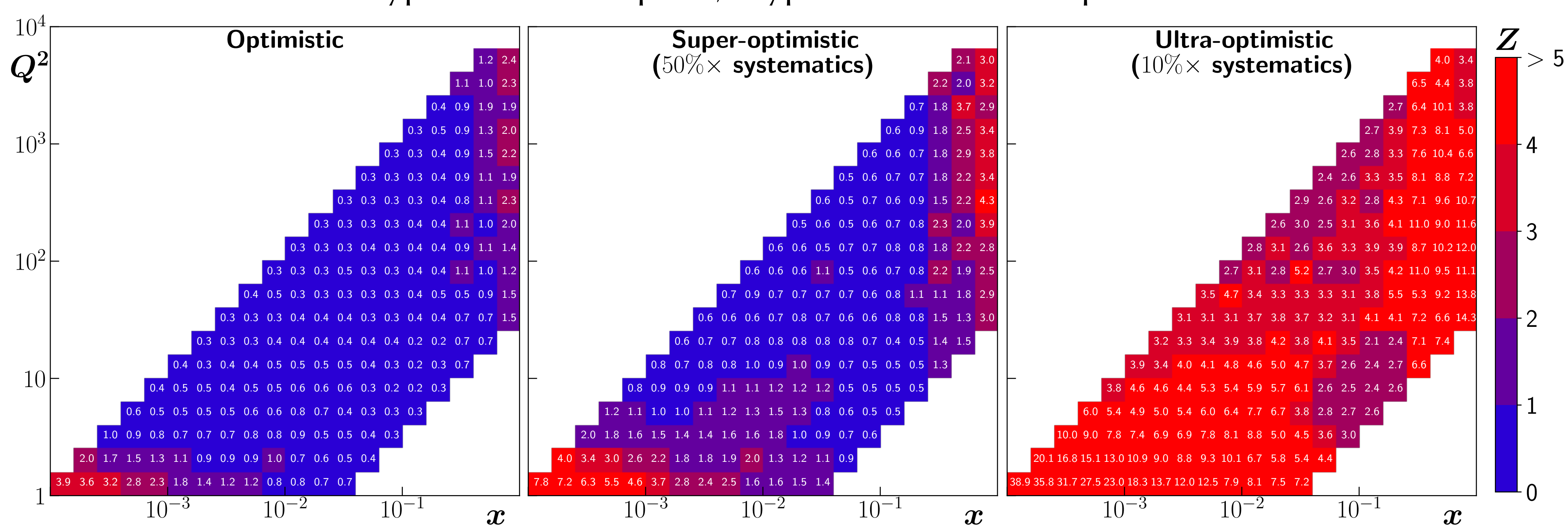
based on simulation studies with EIC Handbook Detector and current EIC detector matrix



Z-score: statistical separation in units of σ between two-hypothesis of cross sections

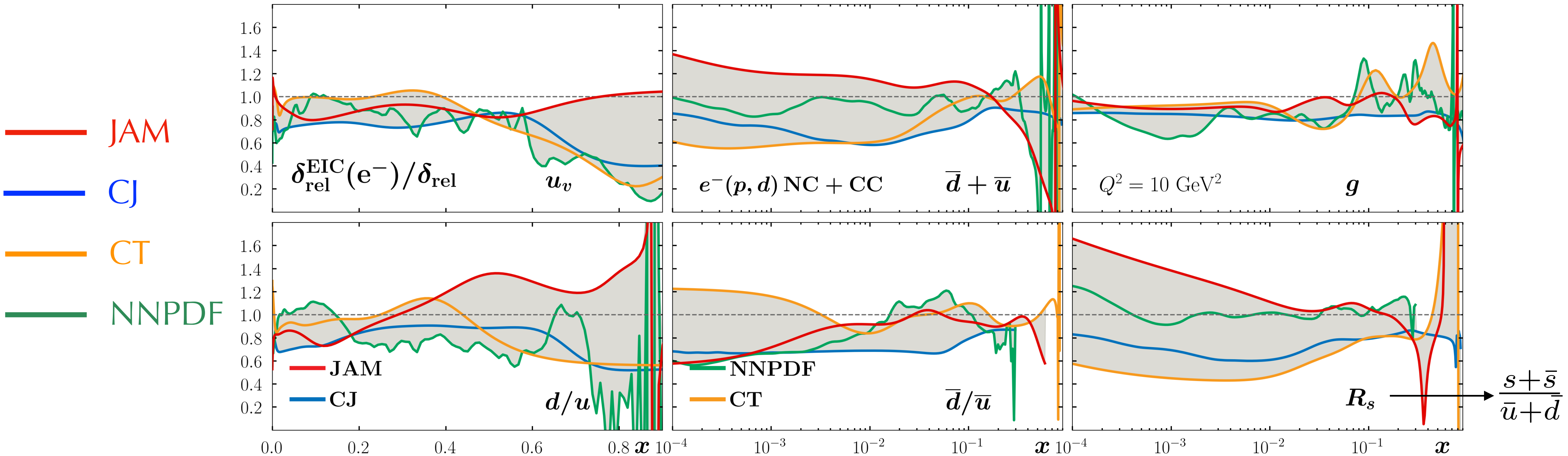
Based on NNPDF3.1PDF set :

hyp. 1: central replica; hyp 2: non-central replica



Flavor separation of x f(x)

relative uncertainties after EIC / relative uncertainties pre EIC (only e- p data sets)



e- p: $\sqrt{s}$ = 28.6, 44.7, 63.3, 140.7 GeV for NC and 140.7 for CC; proton beam $\mathcal{L}$=100 fb^{-1}

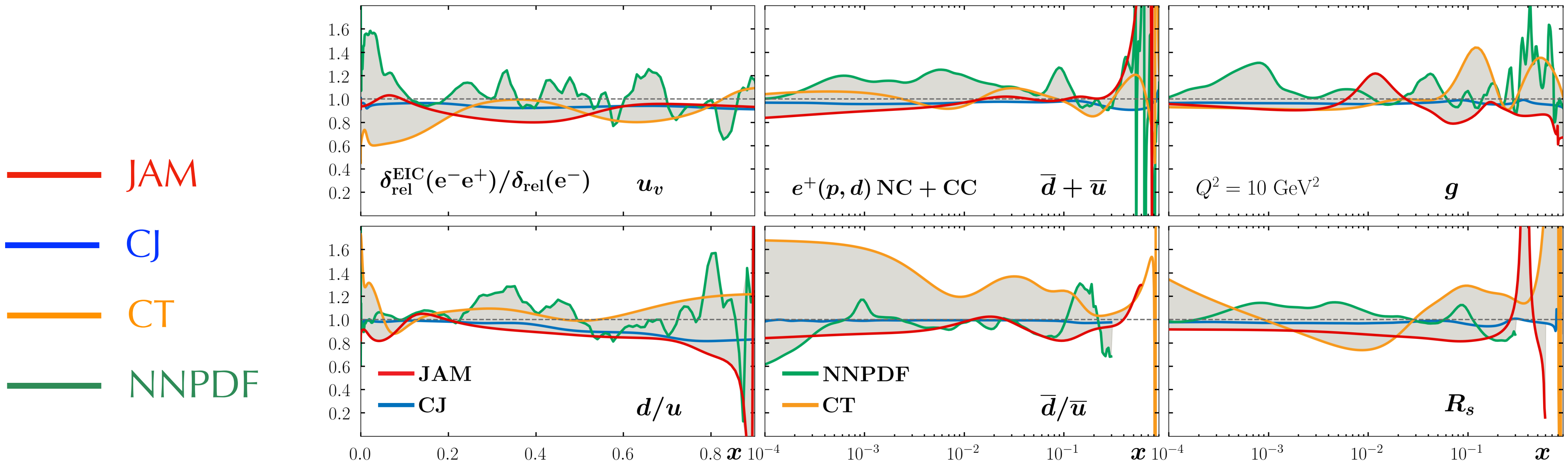
e- d: $\sqrt{s}$ = 28.6, 63.3, 89.0 GeV for NC only ; deuteron beam $\mathcal{L}$=10 fb^{-1}

Strong impact (80%) on the valence sector and d/u ratio at large x

Good impact (50%) on the sea sector at low x

Positron Beam: complementary to ep for flavor structure

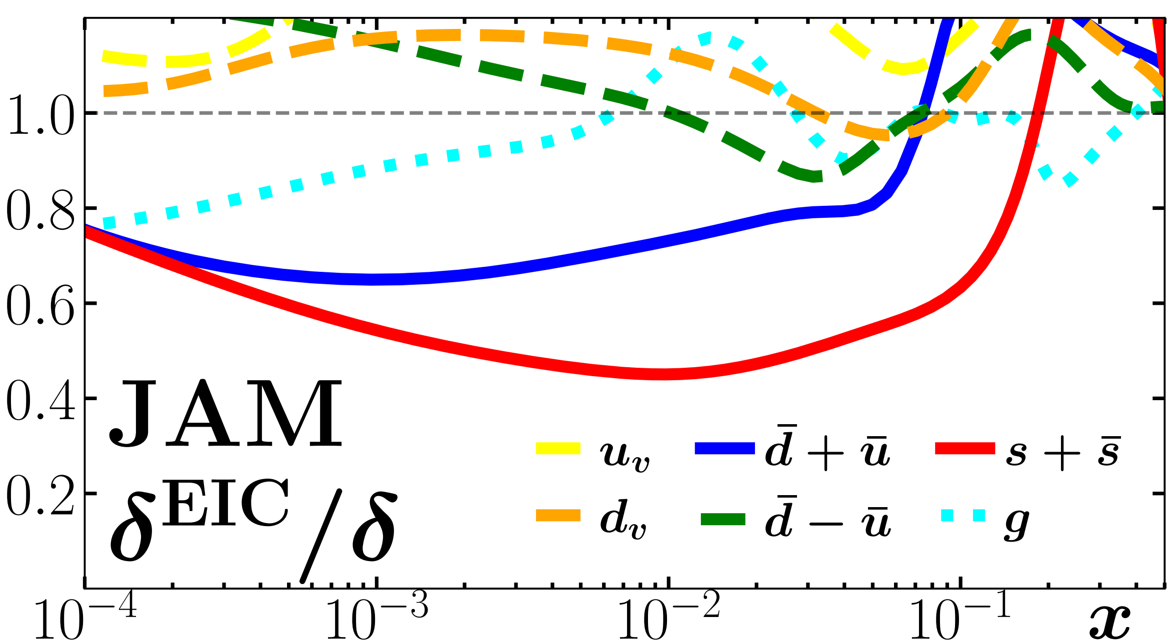
relative uncertainties after EIC (e^- + e^+ at EIC) / relative uncertainties pre EIC (e^- data set)



additional constraints on the d-type PDFs

Parity Violating

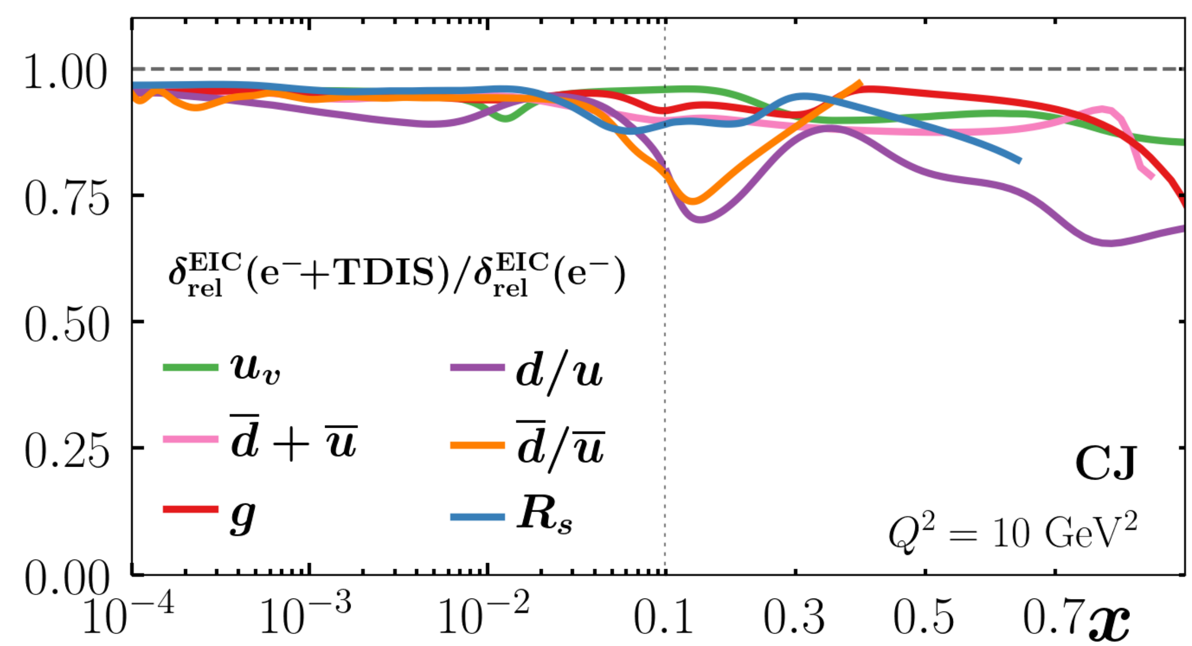
$\delta^{\rm EIC}$ with A_{PV} data / δ no EIC data



Tagged DIS

e + D ⟶ e′ + p +X

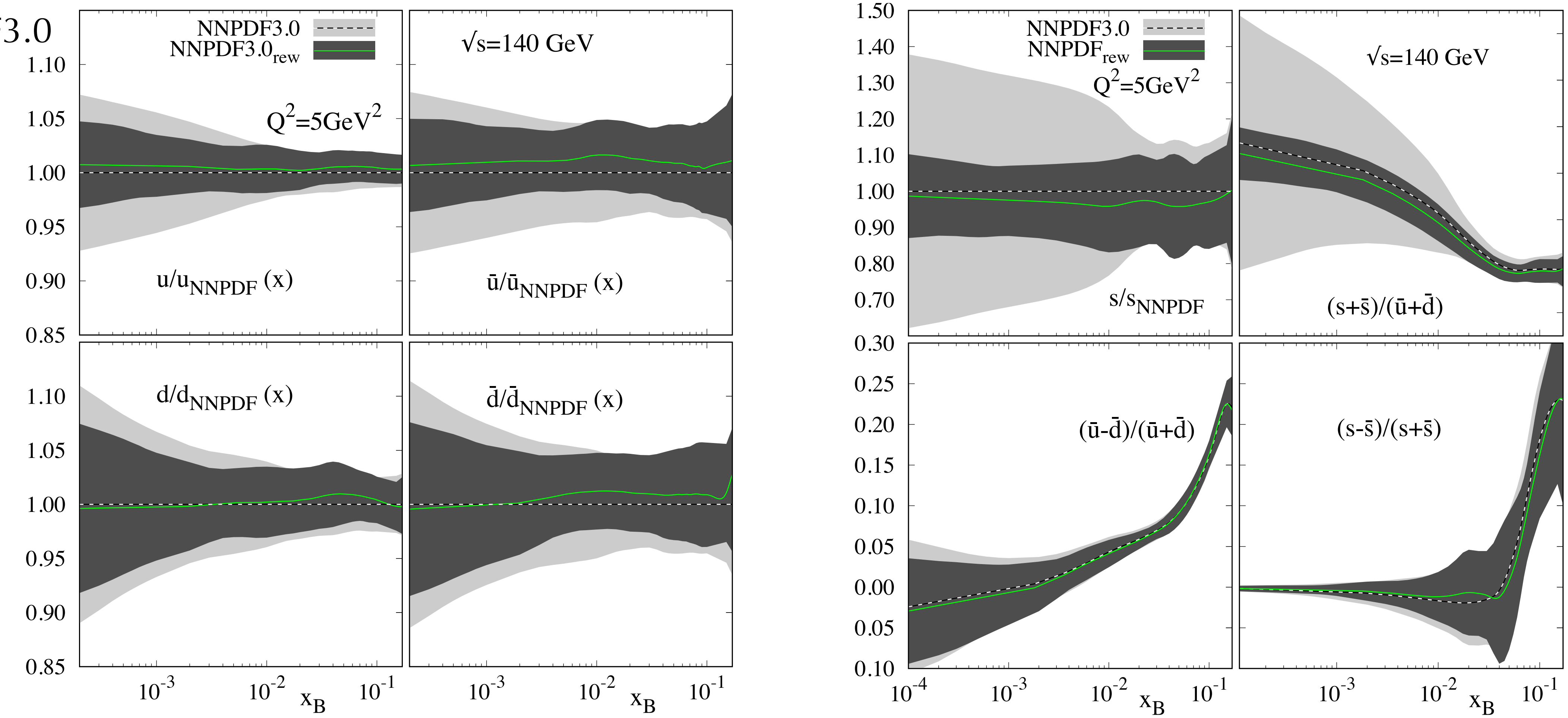
$\delta^{\rm EIC}$ (e^- p+ TDIS) / $\delta^{\rm EIC}$ (e^- p)



Sea quark PDF via SIDIS e+p ⟶ e+H+X measurements

$\int L\, dt = 10\ fb^{-1}$ - charged pion and kaon identification in the main EIC detector

baseline NNPDF3.0



Strongest impact in the strange sector:

substantial reduction of uncertainty for s(x) distribution: up to 75% at low $x<10^{-2}$

constraint on the x dependence of the strange ratio

Aschenauer, Borsa, Sassot, Van Hulse, PRD99 (2019)

Charmed-jet production in CC DIS

Constraints on $R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$ —> SU(3) symmetry breaking in the light-quark sea

Demands high-luminosity and specific requirements for the detector

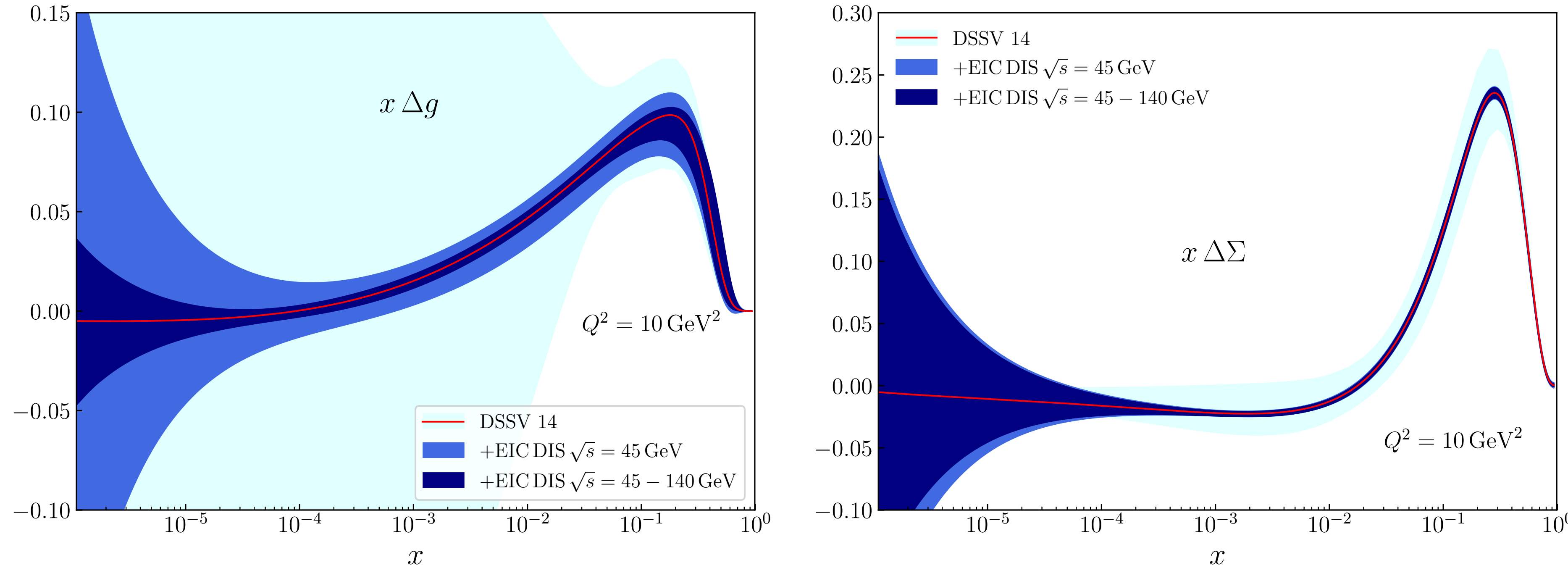
Arratia, Furletova, Hobbs, Olness, Sekula, arXiv:2006.12520

Spin structure of the proton and neutron

Present kinematical coverage $x \gtrsim 0.01$ At EIC $x \sim 10^{-4}$ At low x: $\partial g_1(x,Q^2)/\partial \ln Q^2 \approx -\Delta g(x,Q^2)$

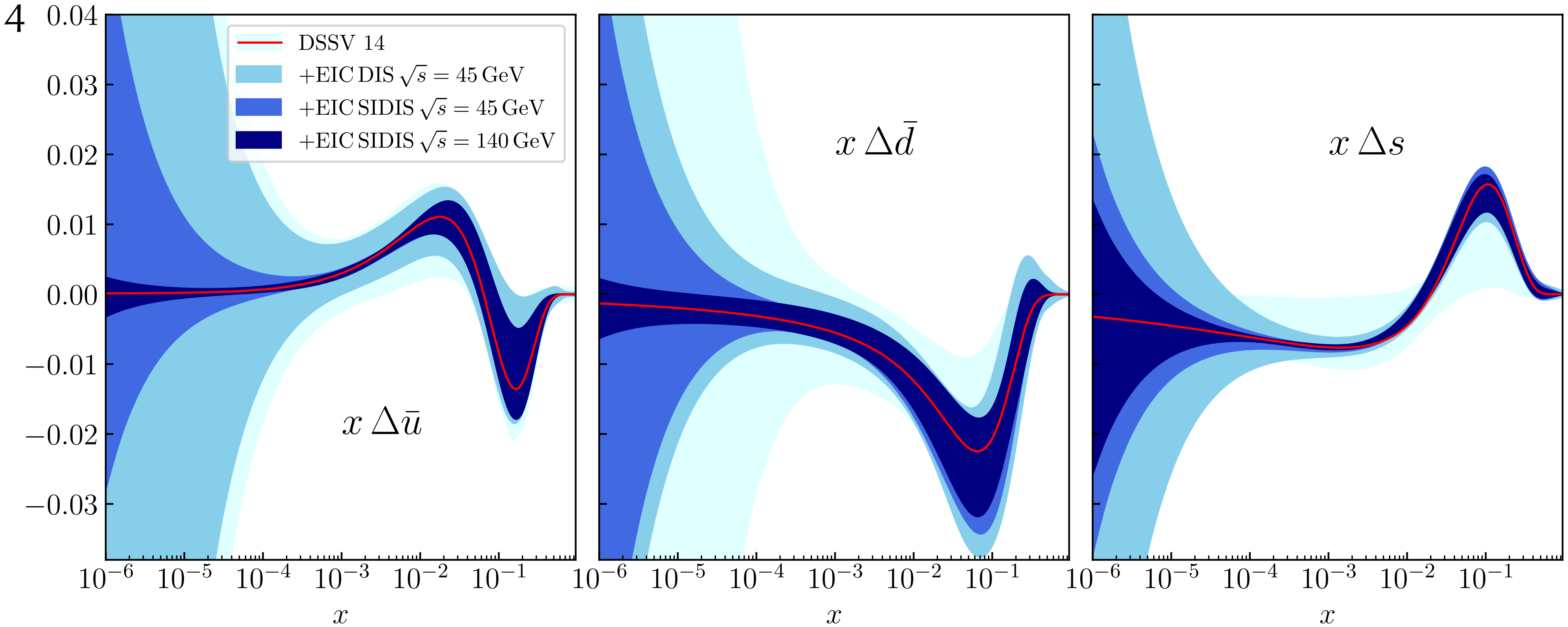
Inclusive A_{LL} - $\int L\, dt = 10\ fb^{-1}$

baseline DSSV14



SIDIS data (charged pion and kaon) to constrain the sea quark polarization

baseline DSSV14

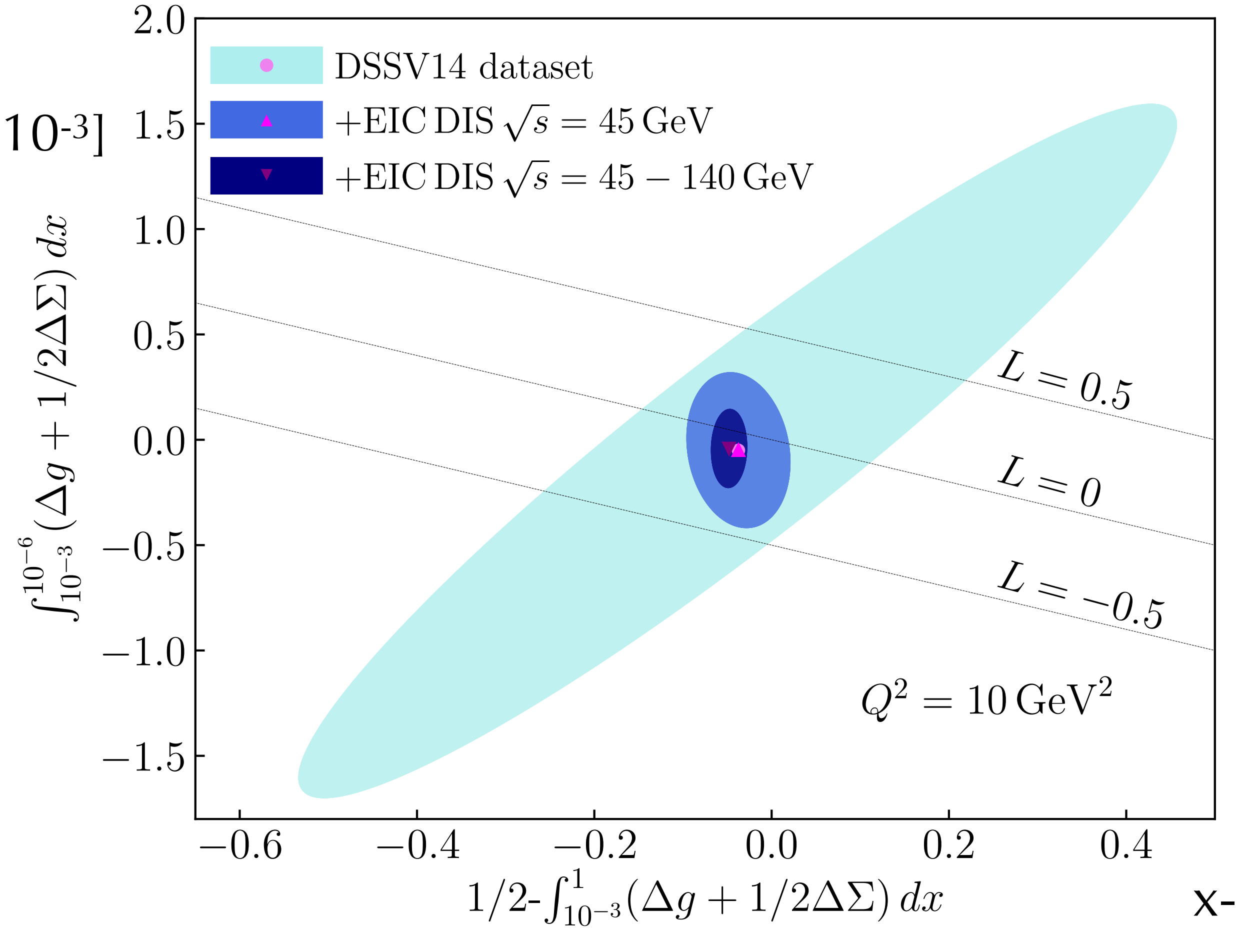


Borsa, Lucero, Sassot, Aschenauer, Nunes, arXiv:2007.08300

Orbital angular momentum contribution to nucleon spin

Spin Sum Rule: $\frac{1}{2} = \int_{-1}^{1} dx(\Delta g + \frac{1}{2}\Delta\Sigma) + L$

x-integration:[10^{-6}, 10^{-3}]



x-integration:[10^{-3}, 1]

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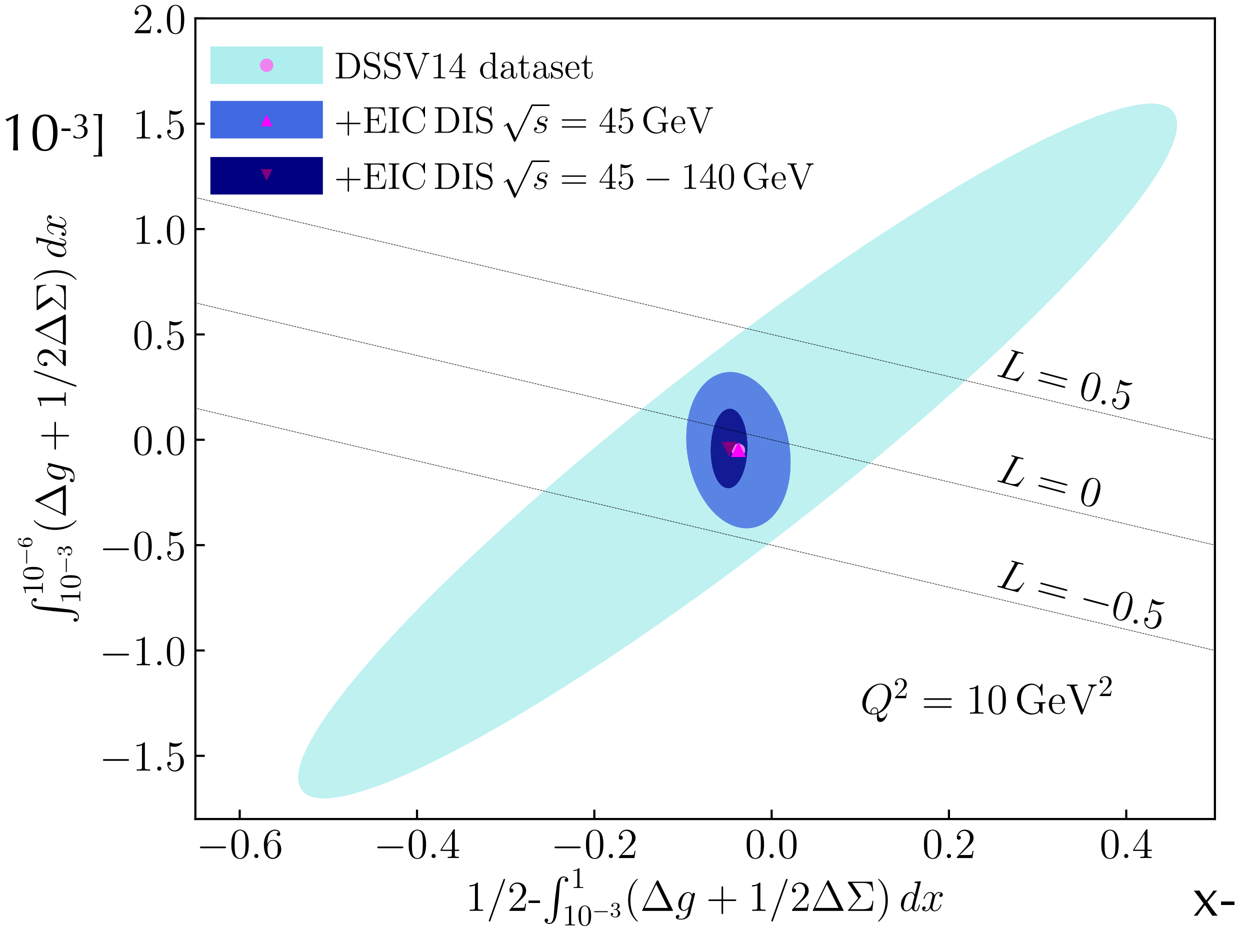
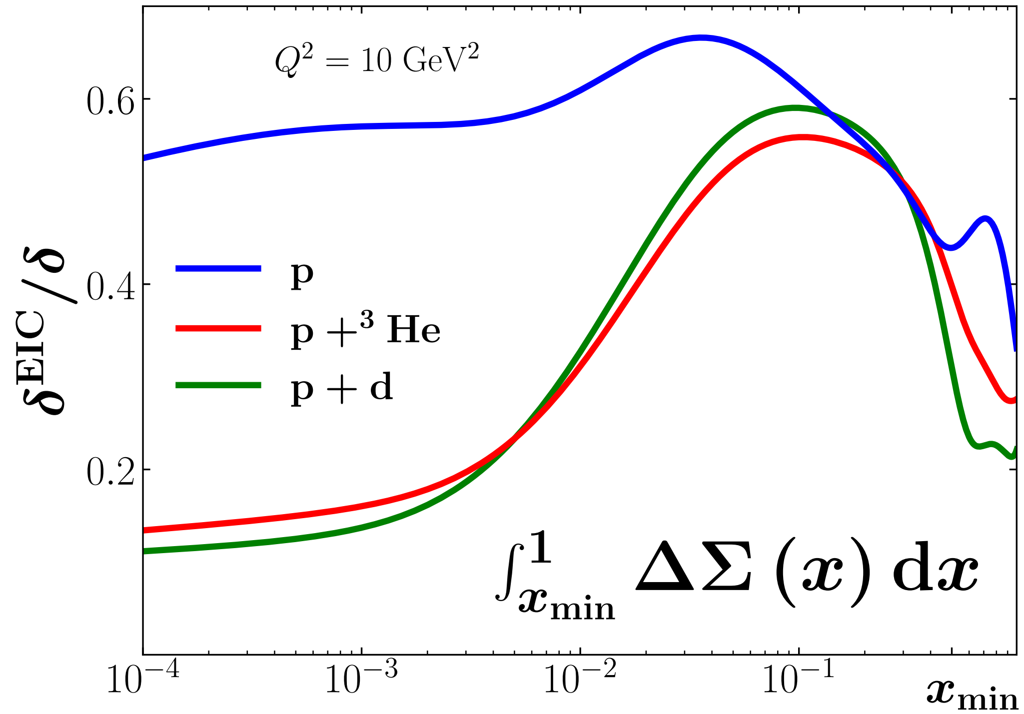


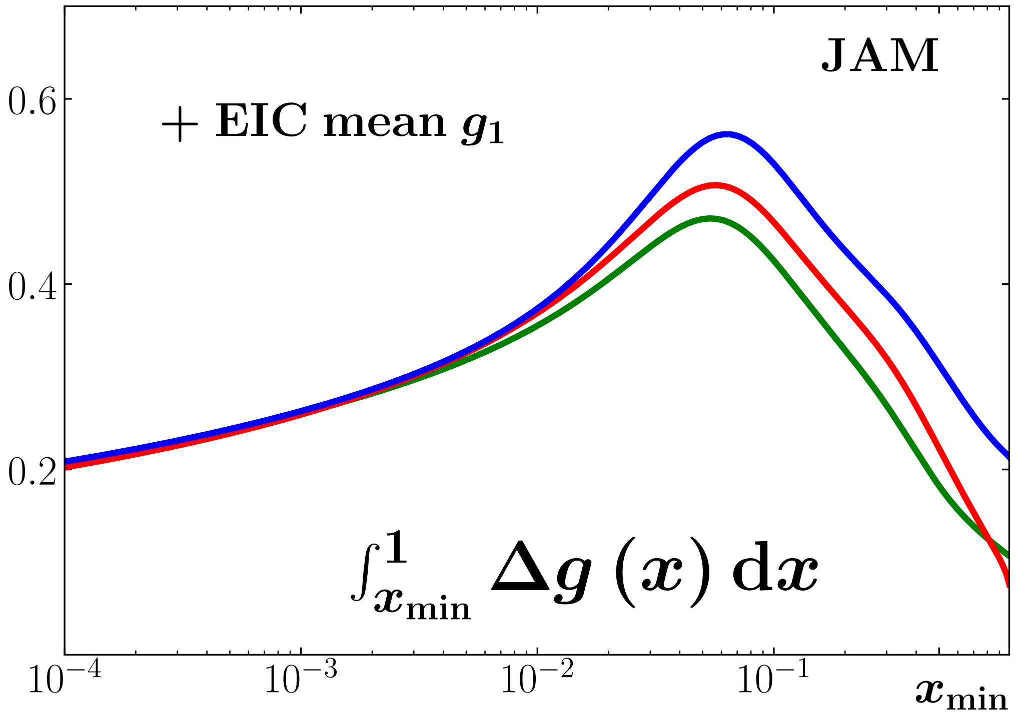
x-integration:[10^{-3}, 1]

$$L = L^Q + L^G$$

Individual contributions only from GPDs or Wigner distributions
(see talk of A. Vossen)

Inclusive A_{LL} - $\int L\,dt = 10\ \text{fb}^{-1}$





reduction of uncertainty by a factor 3-4
after including EIC data with ^{3}He and D
(baseline g1 from JAM17)

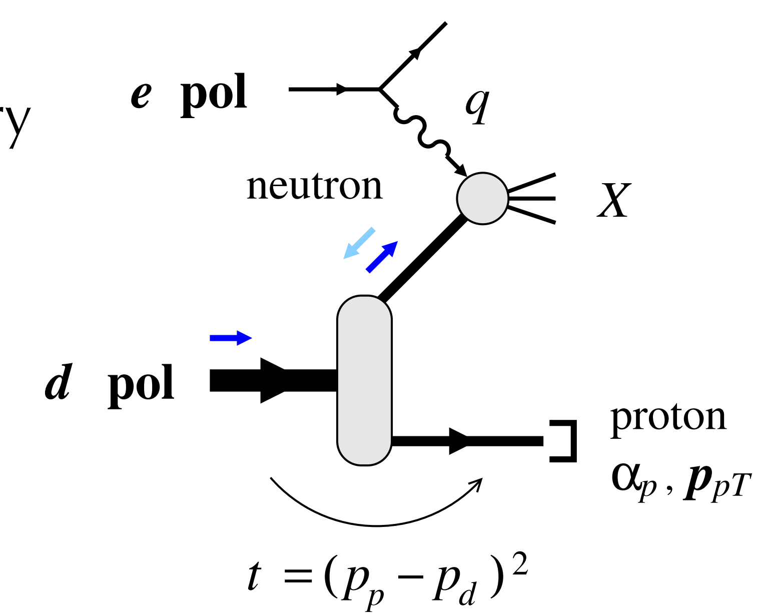
Ethier, Sato, Melnitchouk, PRL119, 2017: (JAM17)

not significant improvement
after including EIC data with ^{3}He and D

Zhou, Sato, Ethier, Melnitchouk, in preparation

Neutron spin structure from tagged DIS on ^{2}H

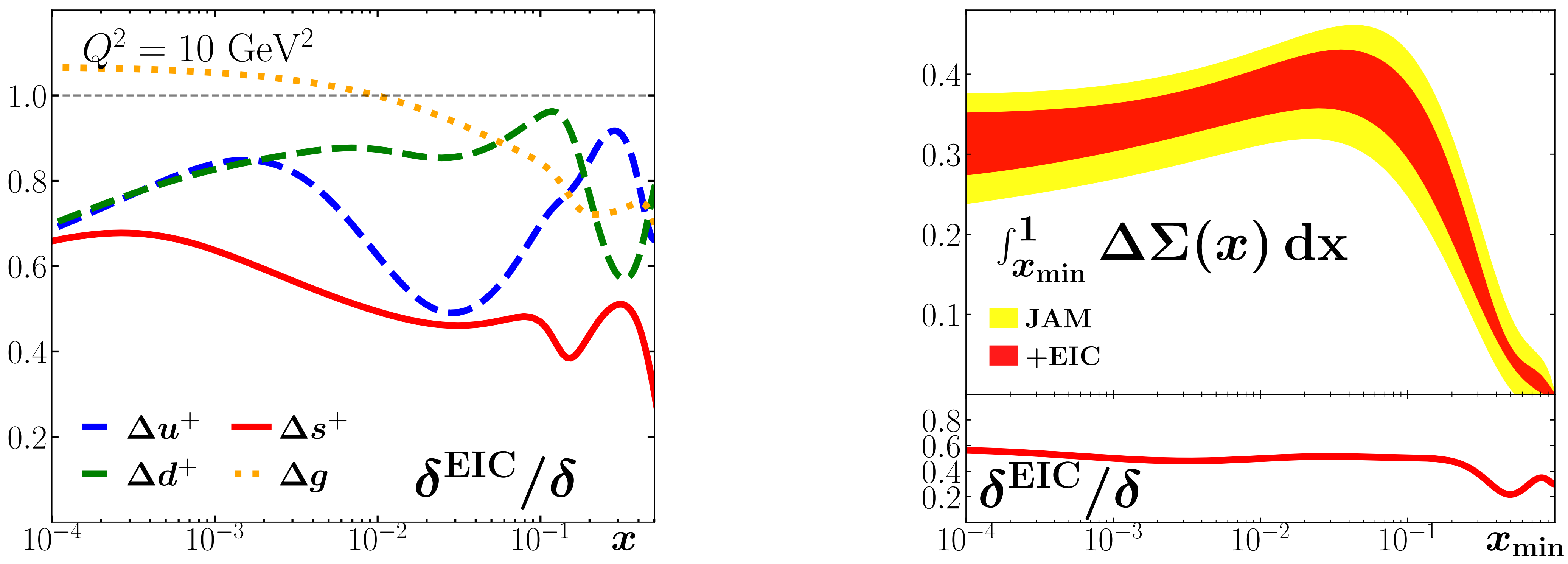
On-shell extrapolation $(M_N^2 - t) \to 0$ gives free-neutron double spin asymmetry
Complementary to measurements with ^{3}He
Better controls of nuclear effects



Cosyn, Weiss, PLB799, 2019; Cosyn, Weiss, arXiv: 2006.03033

Parity violating DIS

asymmetry with unpolarized electron and polarized proton with ∫L dt=10 fb-1



Analysis with JAM17 (Zhou, Sato, Ethier, Melnitchouk, in preparation)

50% impact on Δs, 20% impact on valence quarks, no impact on Δg

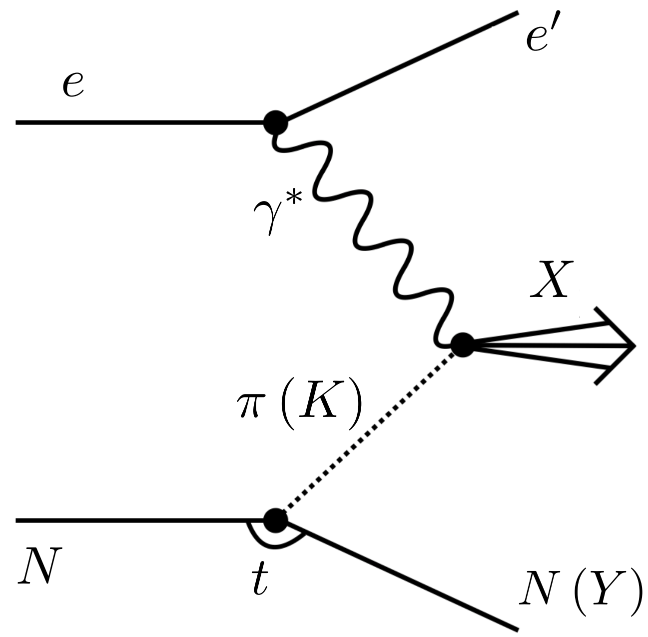
50% impact on ∫ΔΣ(x) dx

Structure of mesons: key experimental efforts at the EIC

Science Question	Key Measurement[1]	Key Requirements[2]
What are the quark and gluon energy contributions to the pion mass?	Pion structure function data over a range of x and Q^2.	• Need to uniquely determine $e+p \rightarrow e' + X + n$ (low $-t$) • CM energy range ~10-100 GeV • Charged and neutral currents desirable
Is the pion full or empty of gluons as viewed at large Q^2?	Pion structure function data at large Q^2.	• CM energy ~100 GeV • Inclusive and open-charm detection
What are the quark and gluon energy contributions to the kaon mass?	Kaon structure function data over a range of x and Q^2.	• Need to uniquely determine $e+p \rightarrow e' + X + \Lambda/\Sigma^0$ (low $-t$) • CM energy range ~10-100 GeV
Are there more or less gluons in kaons than in pions as viewed at large Q^2?	Kaon structure function data at large Q^2.	• CM energy ~100 GeV • Inclusive and open-charm detection
Can we get quantitative guidance on the emergent pion mass mechanism?	Pion form factor data for Q^2 = 10-40 (GeV/c)^2.	• Need to uniquely determine exclusive process $e+p \rightarrow e' + \pi^+ + n$ (low $-t$) • $e+p$ and $e+d$ at similar energies • CM energy ~10-75 GeV
What is the size and range of interference between emergent-mass and the Higgs-mass mechanism?	Kaon form factor data for Q^2 = 10-20 (GeV/c)^2.	• Need to uniquely determine exclusive process $e+p \rightarrow e' + K + \Lambda$ (low $-t$) • L/T separation at CM energy ~10-20 GeV • Λ/Σ^0 ratios at CM energy ~10-50 GeV
What is the difference between the impacts of emergent- and Higgs-mass mechanisms on light-quark behavior?	Behavior of (valence) up quarks in pion and kaon at large x	• CM energy ~20 GeV (lowest CM energy to access large-x region) • Higher CM energy for range in Q^2 desirable
What is the relationship between dynamically chiral symmetry breaking and confinement?	Transverse-momentum dependent Fragmentation Functions of quarks into pions and kaons	• Collider kinematics desirable (as compared to fixed-target kinematics) • CM energy range ~20-140 GeV

Parton Structure of Mesons

$$e + p \to e' + X + (N \,\text{or}\, Y)$$



Tagged inclusive reaction dominated by the Sullivan process at low -t:
-t<0.6 GeV^2 (pion exchange); -t<0.9 GeV^2 (kaon exchange)

c.s. integrated over t: $\frac{\mathrm{d}^3\sigma(ep\to eNX)}{\mathrm{d}x\mathrm{d}Q^2\mathrm{d}z} \propto F_2^{LP(3)}(x, Q^2, E'/E_p)$

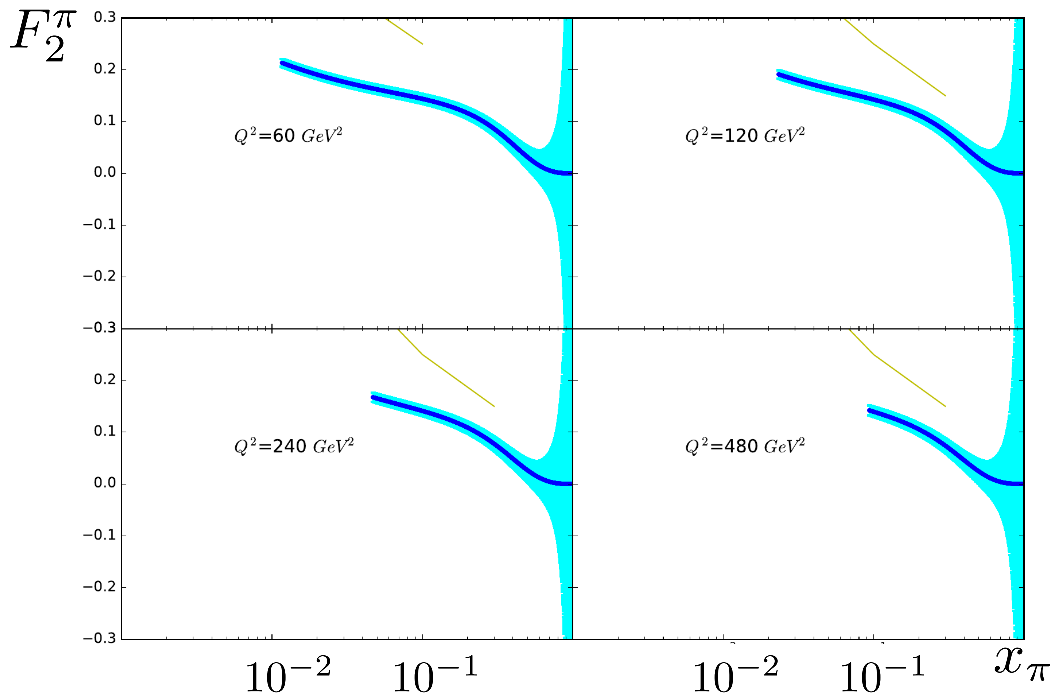
Regge model: $F_2^{LP(3)} = \sum_{i=\pi,\rho,\ldots} \left[\int_{t_0}^{t_{\min}} f_i(z,t)\right] F_2^i(x_i, Q^2)$

Model uncertainties: overall systematic th. uncertainty ~ 25%

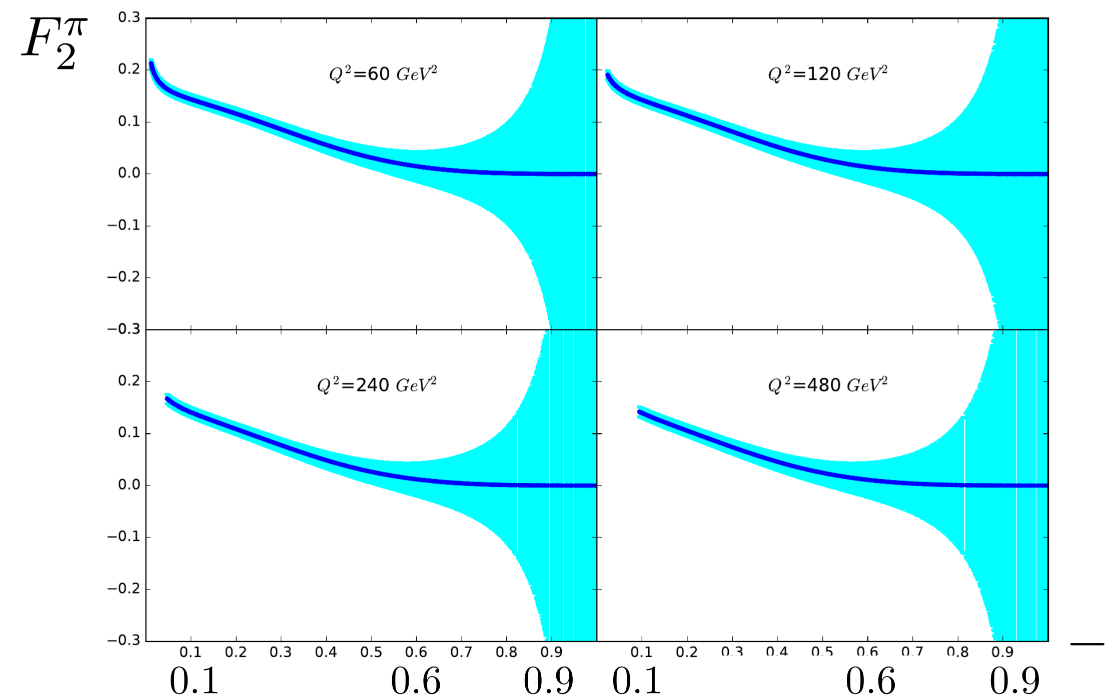
- corrections to the Sullivan process (non pion-pole, nucleon resonances contributions,…)
- lack of knowledge of pion flux

blue regions: statistical uncertainty with ∫L dt=10 fb^{-1} ; beam energies 10X135 GeV

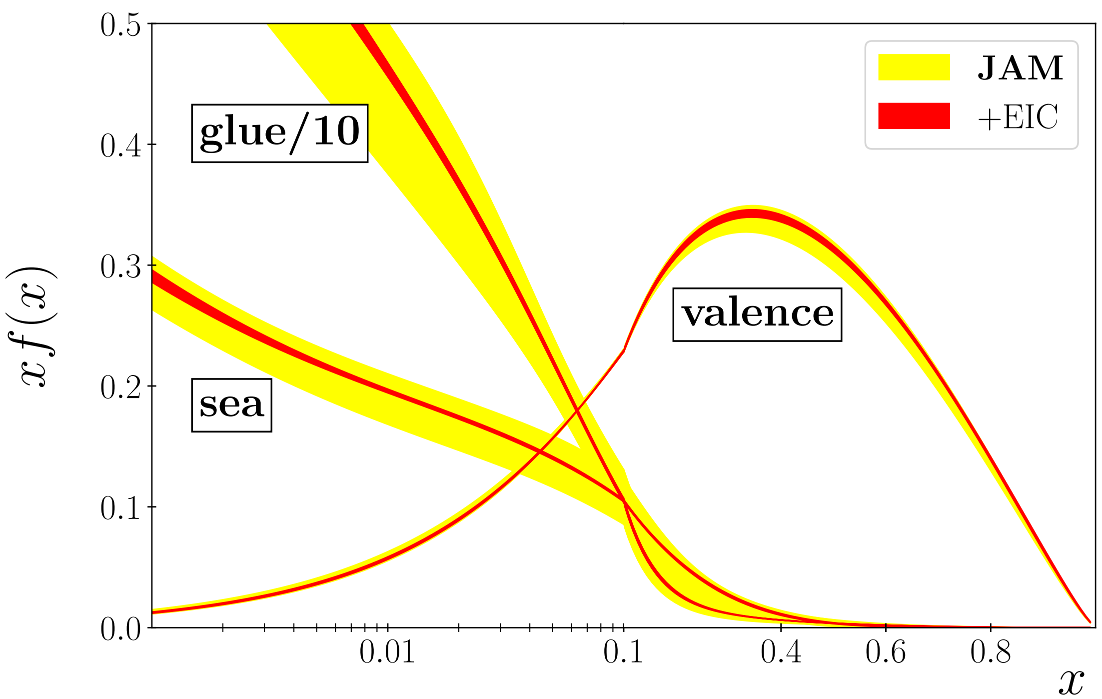
reach in x_π

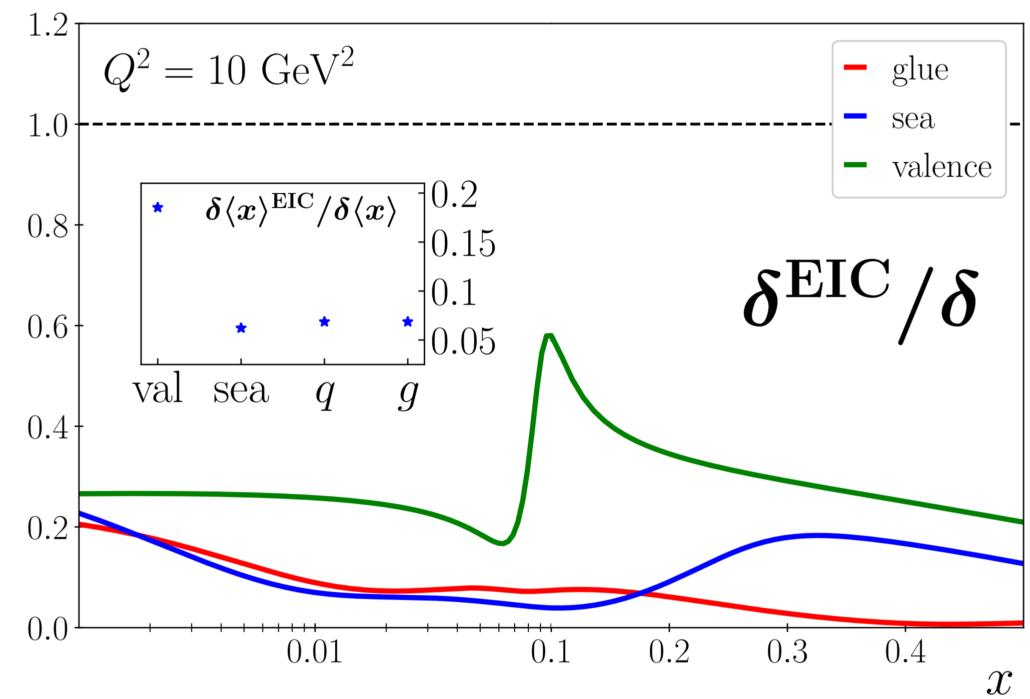


reach in t: 10 times more statistics than at HERA



∫L dt=100 fb^{-1}; 1.2% systematic unc.; $\sqrt{s}$=63.25 GeV





uncertainty reduced by a factor 5~10 for gluon and sea PDFs x<0.1; a factor~3 for valence PDF

uncertainty reduced by a factor ~15 for first moment of total quark and gluon PDF

uncertainties from the model dependence of the pion flux (~10-20%) are not included

Origin of the hadron mass

$$T^{\mu\nu} = \overline{\psi}\gamma^{\mu}\,\frac{i}{2}\overleftrightarrow{D}^{\nu}\psi - G^{a\mu\lambda}G^{a\nu}{}_{\lambda} + \frac{1}{4}\,g^{\mu\nu}G^{2}$$

$$\langle P|T^{\mu\nu}_{q,G}(0)|P\rangle = 2P^{\mu}P^{\nu}A_{q,G}(0) + 2M^{2}g^{\mu\nu}\bar{C}_{q,G}(0)$$

$A_q(0) + A_G(0) = 1$

$\bar{C}_q(0) + \bar{C}_G(0) = 0$

Origin of the hadron mass

$$T^{\mu\nu} = \overline{\psi}\gamma^{\mu}\,\tfrac{i}{2}\overset{\leftrightarrow}{D}{}^{\nu}\psi - G^{a\mu\lambda}G^{a\nu}{}_{\lambda} + \tfrac{1}{4}\,g^{\mu\nu}G^{2}$$

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$$A_q(0) + A_G(0) = 1 \qquad\qquad \bar{C}_q(0) + \bar{C}_G(0) = 0$$

$$\langle T^{\mu\nu}\rangle \equiv \tfrac{1}{2M}\langle P|T^{\mu\nu}|P\rangle|_{P=0}$$

Energy decomposition

$$M = U_q + U_G$$

$$U_{q,G} \equiv \langle T^{00}_{q,G}\rangle = \left[A_{q,G}(0) + \bar{C}_{q,G}(0)\right] M$$

Trace decomposition

$$M = I_q + I_G$$

$$I_{q,G} \equiv g_{\mu\nu}\langle T^{\mu\nu}_{q,G}\rangle = \left[A_{q,G}(0) + 4\bar{C}_{q,G}(0)\right] M$$

Origin of the hadron mass

$$T^{\mu\nu} = \overline{\psi}\gamma^\mu \, \tfrac{i}{2}\overset{\leftrightarrow}{D}{}^\nu \psi - G^{a\mu\lambda}G^{a\nu}{}_\lambda + \tfrac{1}{4}\, g^{\mu\nu} G^2$$

$$\langle P | T^{\mu\nu}_{q,G}(0) | P\rangle = 2P^\mu P^\nu A_{q,G}(0) + 2M^2 g^{\mu\nu} \bar{C}_{q,G}(0)$$

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$$I_{q,G} \equiv g_{\mu\nu}\langle T^{\mu\nu}_{q,G}\rangle = \left[A_{q,G}(0) + 4\bar{C}_{q,G}(0)\right] M$$

$$A_{q,G}(0) = \int \mathrm{d}x \, x \, f_1^{q,G}(x)$$

from DIS

$$\bar{C}_q \sim \sigma = \langle \overline{\psi} m \psi \rangle$$

πN scattering

$$\bar{C}_G \sim \langle \tfrac{\beta}{2g} G^2 + \gamma_m \overline{\psi} m \psi \rangle$$

??

Origin of the hadron mass

$$T^{\mu\nu} = \overline{\psi}\gamma^{\mu}\,\tfrac{i}{2}\overleftrightarrow{D}^{\nu}\psi - G^{a\mu\lambda}G^{a\nu}{}_{\lambda} + \tfrac{1}{4}\,g^{\mu\nu}G^{2}$$

$$\langle P|T^{\mu\nu}_{q,G}(0)|P\rangle = 2P^{\mu}P^{\nu}A_{q,G}(0) + 2M^{2}g^{\mu\nu}\bar{C}_{q,G}(0)$$

$$A_q(0) + A_G(0) = 1 \qquad \bar{C}_q(0) + \bar{C}_G(0) = 0$$

$$\langle T^{\mu\nu}\rangle \equiv \tfrac{1}{2M}\langle P|T^{\mu\nu}|P\rangle|_{P=0}$$

Energy decomposition

$$M = U_q + U_G$$

$$U_{q,G} \equiv \langle T^{00}_{q,G}\rangle = \left[A_{q,G}(0) + \bar{C}_{q,G}(0)\right] M$$

Trace decomposition

$$M = I_q + I_G$$

$$I_{q,G} \equiv g_{\mu\nu}\langle T^{\mu\nu}_{q,G}\rangle = \left[A_{q,G}(0) + 4\bar{C}_{q,G}(0)\right] M$$

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πN scattering

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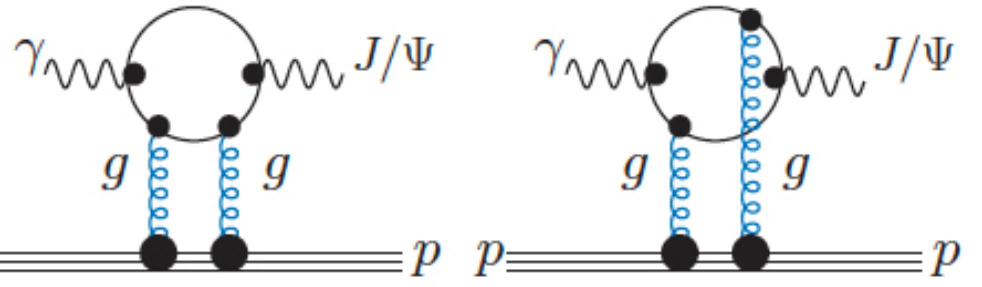
??

Gluon trace anomaly

heavy quarkonium photo- and electro-production at threshold



- measurements at JLab (GlueX and SoLID) for J/Ψ
- at EIC: J/Ψ and Υ photo- and electro-production (see chapter 8)

heavy quarkonium lepto-production at threshold with large photon virtuality $Q^2 >> M^2$

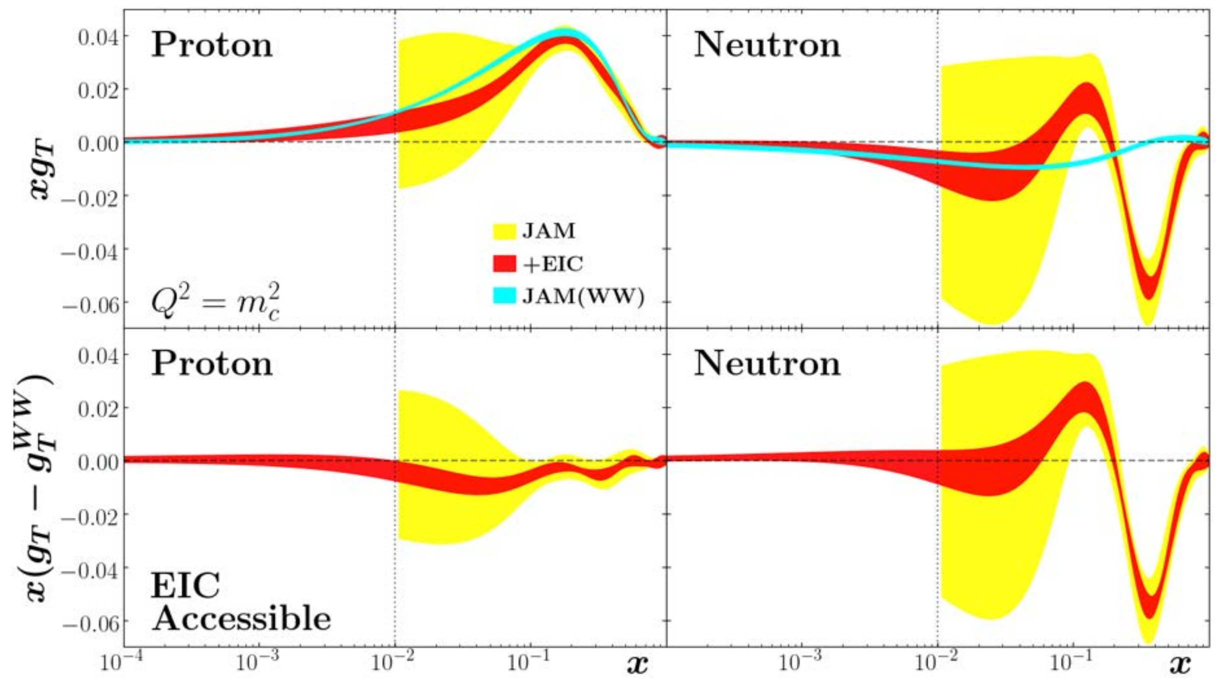
- also sensitive to gluon D-term

- requires high luminosity and large leverage in Q^2 (simulations at EIC not yet available)

Multiparton correlations - twist-3 PDFs

Measurement of double-spin asymmetry A_{LT} in $\vec{e}p^{\uparrow} \to e'X$

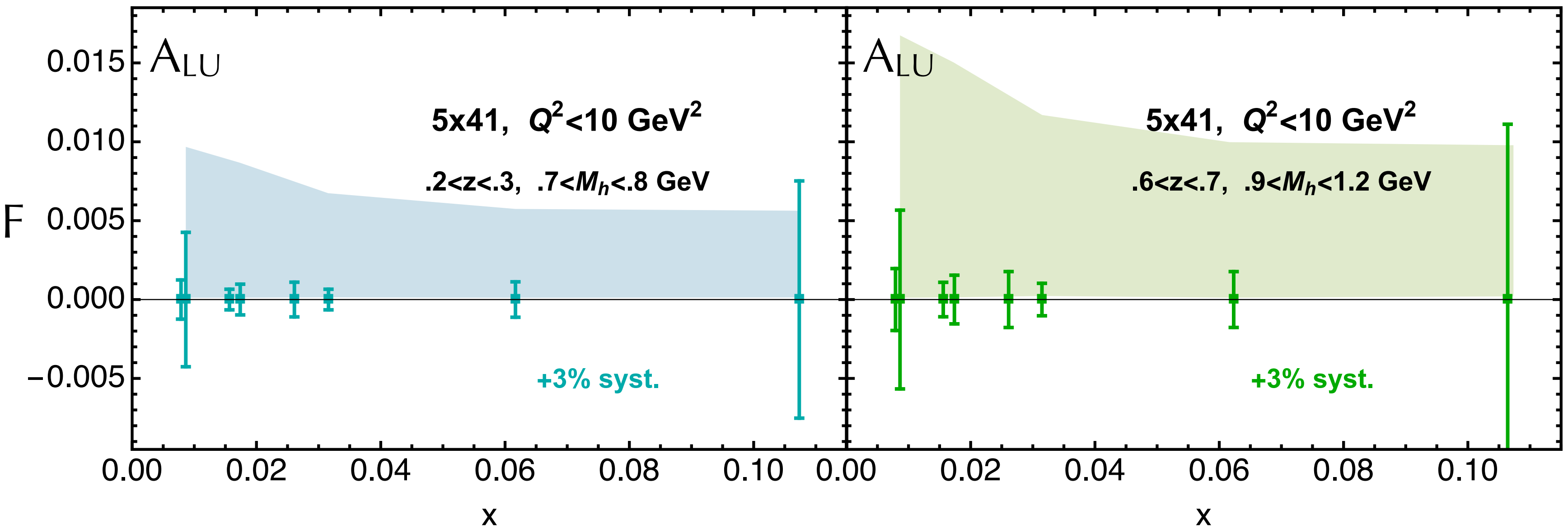
proton, deuteron, ^{3}He with $\int L\, dt = 100\ fb^{-1}$; 1.6% point by point uncorrelated syst. uncertainties



baseline g_1 and g_T from JAM: Sato, Melnitchouk, Kuhn, Ethier, Accardi, PRD93 (2016)

Measurement of beam spin asymmetry A_{LU} in semi-inclusive dihadron production

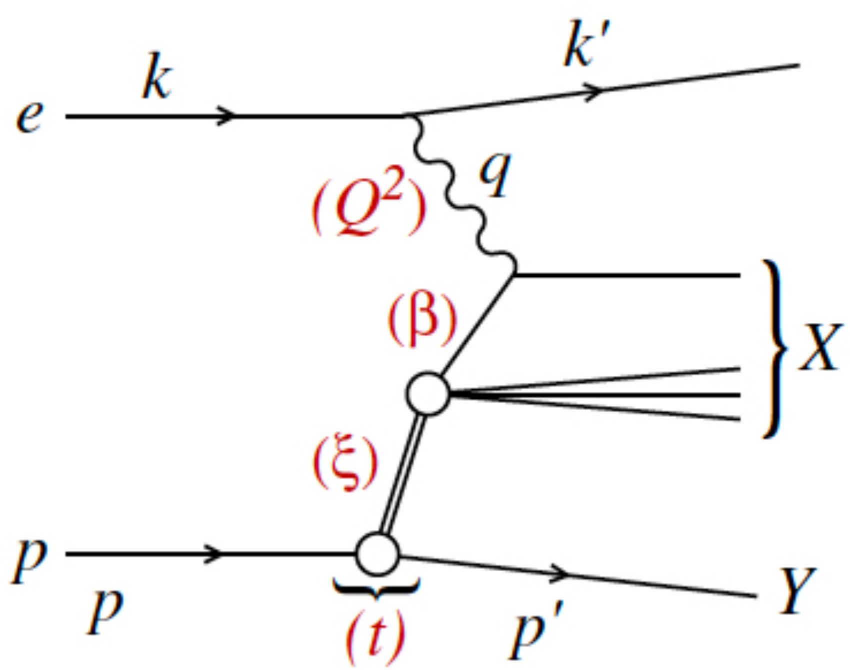
dashed areas: uncertainty from DiFF and model for e(x)



sensitive to chiral-odd twist-3 PDF e(x) coupled with interference two-hadron fragmentation function

contribution from twist-2 PDF coupled to twist-3 DiFF is neglected

Inclusive Diffraction $e + p \to e' + X + Y$



$$\xi \equiv x_{\mathbb{P}} = \frac{Q^2+M_X^2-t}{Q^2+W^2}$$

momentum fraction
of the diffractive exchange
w.r.t. hadron

$$t = (p - p')^2$$

momentum transferred
at the proton vertex

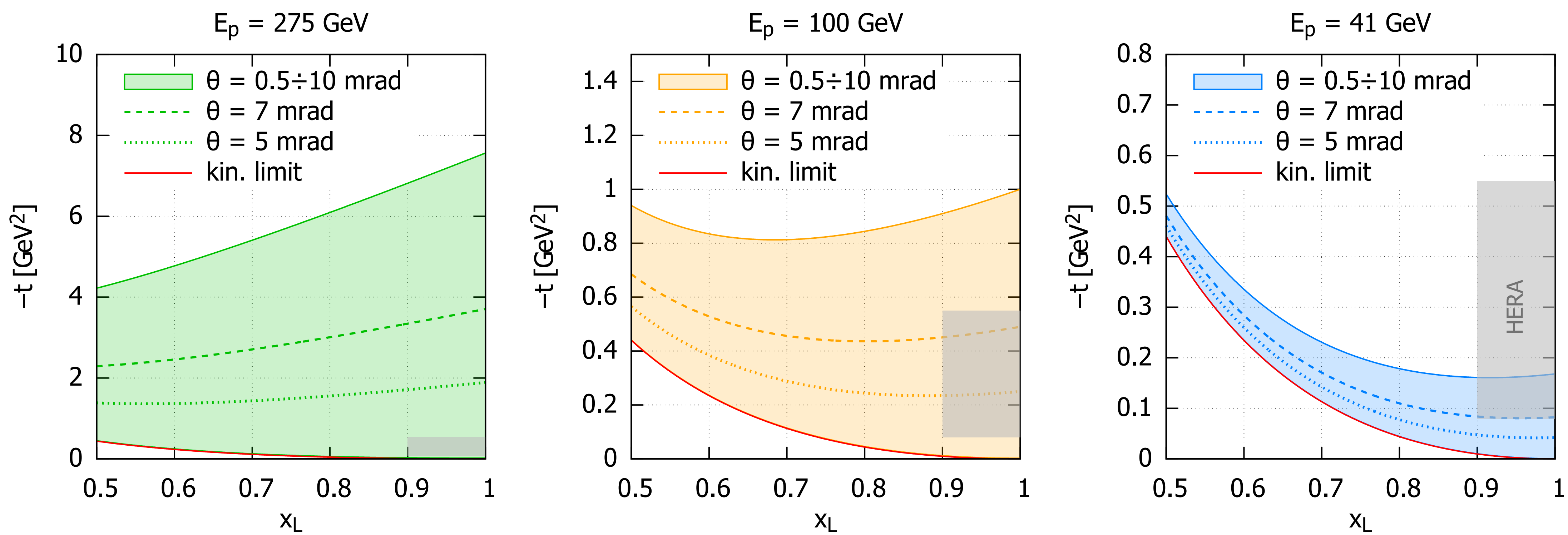
$$\beta = \frac{Q^2}{Q^2+M_X^2-t}$$

momentum fraction of the
parton w.r.t. the diffractive exchange

$$x = \beta\xi$$

Bjorken variable

Kinematics range of t and x_L



$x_L = p'^+/p^+$

HERA range

$$\sigma_r^{D(3)} = F_2^{D(3)}(\beta, \xi, Q^2) - \frac{y^2}{Y_+} F_L^{D(3)}(\beta, \xi, Q^2)$$

Diffractive Structure Functions

$$F_{2/L}^{D(3)}(\beta, \xi, Q^2) = \sum_i \int_\beta^1 \frac{dz}{z} C_{2/l,i}\left(\frac{\beta}{z}\right) f_i^{D(3)}(z, \xi, Q^2)$$

Diffractive PDF (DPDF): two-component model

$$f_i^{D(3)}(z, \xi, Q^2) = \phi_{\mathbb{P}}^p(\xi) f_i^{\mathbb{P}}(z, Q^2) + \phi_{\mathbb{R}}^p(\xi) f_i^{\mathbb{R}}(z, Q^2)$$

$$\sigma_r^{D(3)} = F_2^{D(3)}(\beta,\xi,Q^2) - \frac{y^2}{Y_+} F_L^{D(3)}(\beta,\xi,Q^2)$$

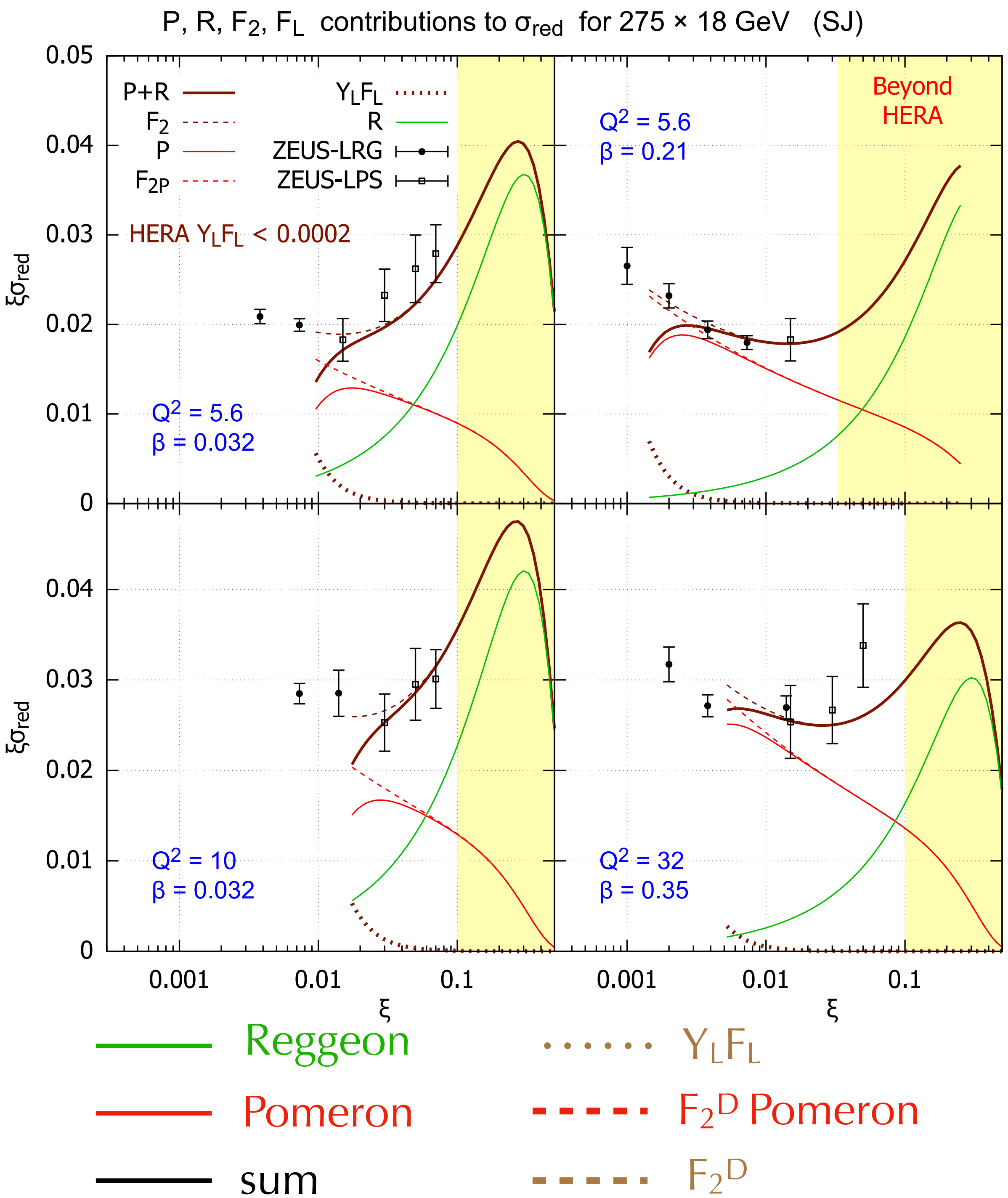
Diffractive Structure Functions

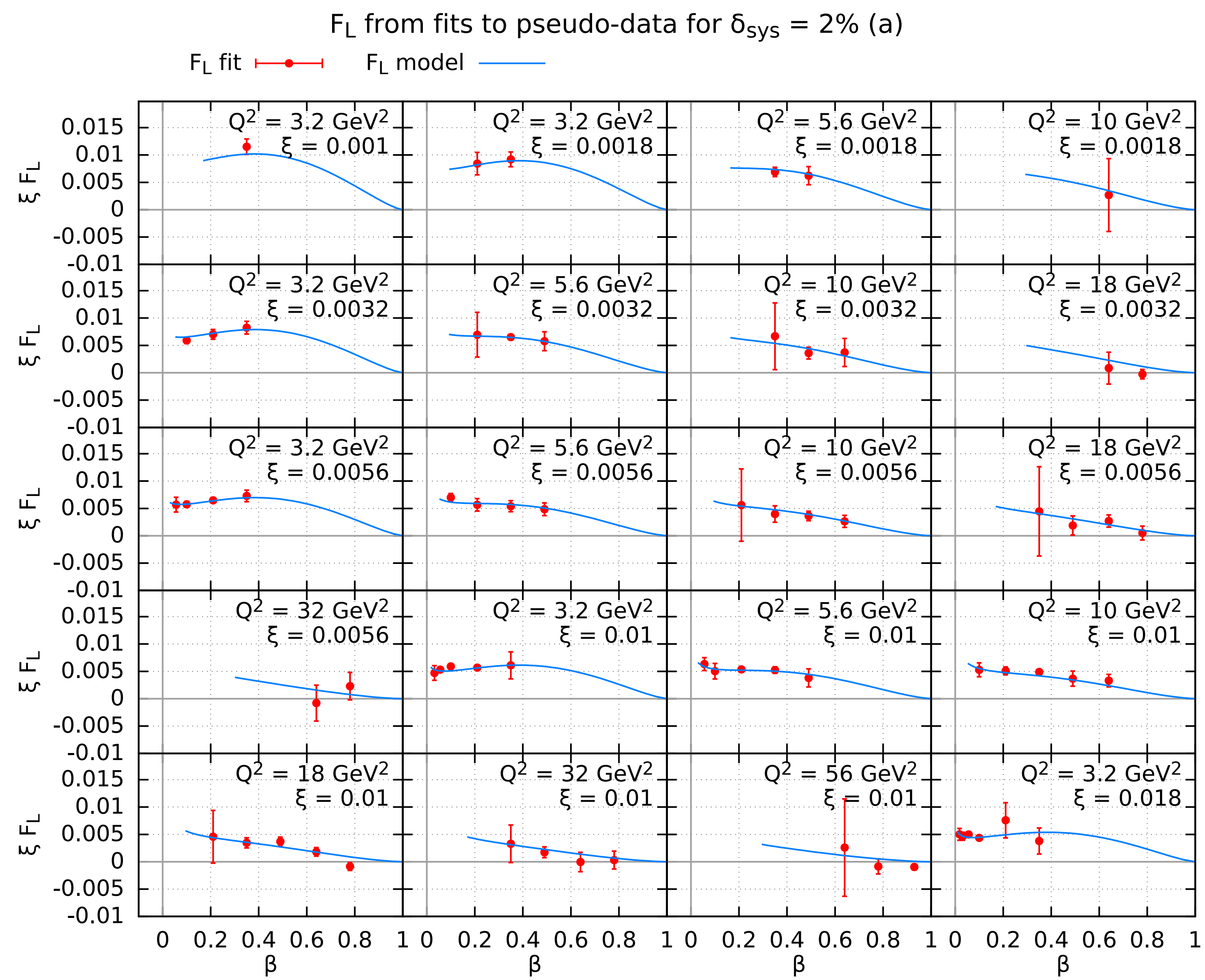
$$F_{2/L}^{D(3)}(\beta,\xi,Q^2) = \sum_i \int_\beta^1 \frac{dz}{z} C_{2/l,i}\left(\frac{\beta}{z}\right) f_i^{D(3)}(z,\xi,Q^2)$$

Diffractive PDF (DPDF): two-component model

$$f_i^{D(3)}(z,\xi,Q^2) = \phi_{\mathbb{P}}^p(\xi) f_i^{\mathbb{P}}(z,Q^2) + \phi_{\mathbb{R}}^p(\xi) f_i^{\mathbb{R}}(z,Q^2)$$

At EIC: potential to separate the Reggeon and Pomeron components; potential for extraction of F_L^D and DPDF



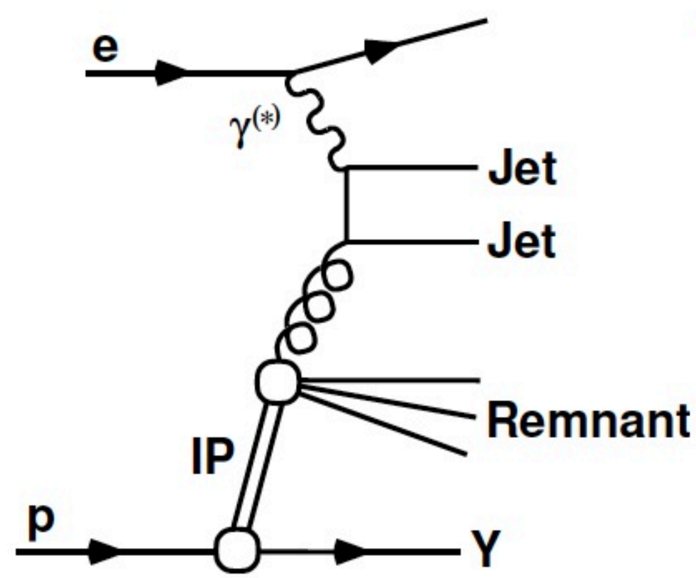


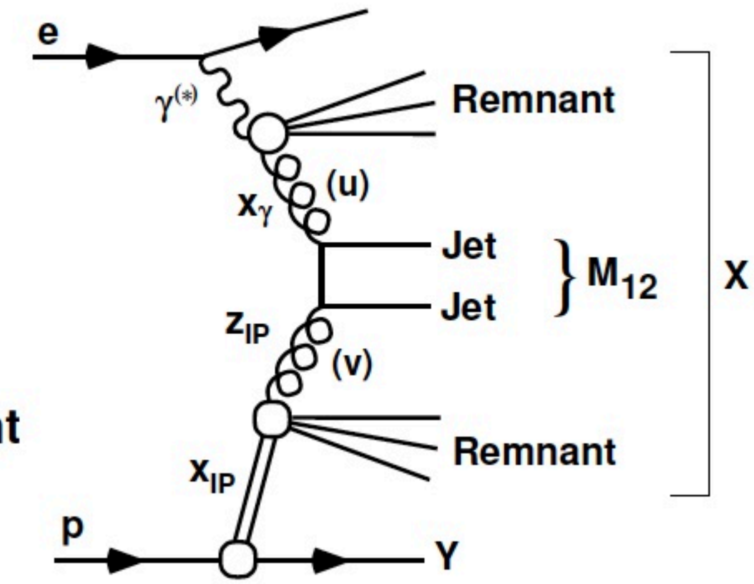
18 beam setups (5,10,18)X(41,100,120,165,180,275)

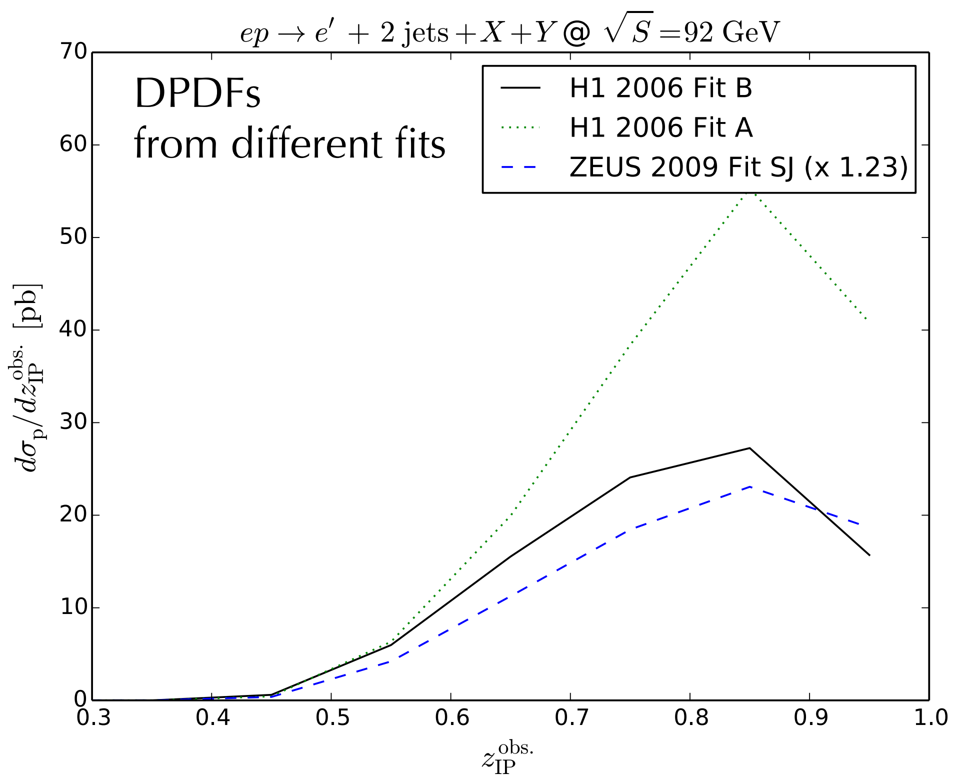
Cuts at $Q^2 > 3$ GeV^2 and $M_X > 2$ GeV

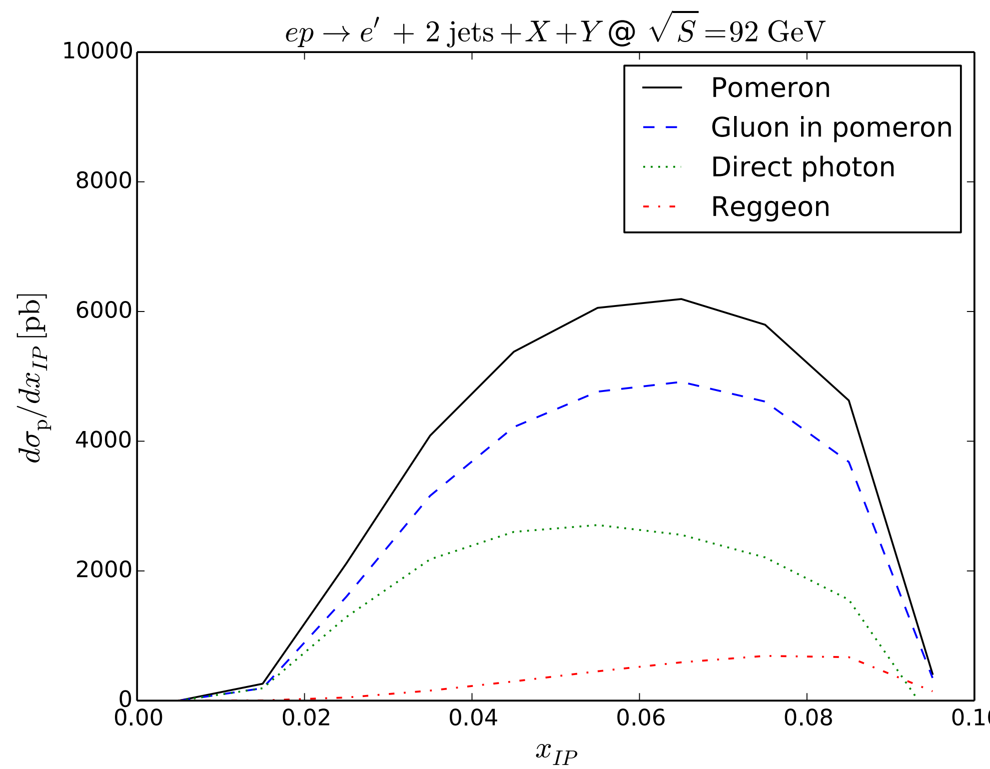
Diffractive dijets

$$e + p \to e + 2\,\text{jets} + Y + X$$









Extending the average p_T from 8 to 14 GeV:
to enhance contribution from resolved photon;
to access to larger range of $x_{\mathbb{P}}$ and check factorisation breaking at NLO

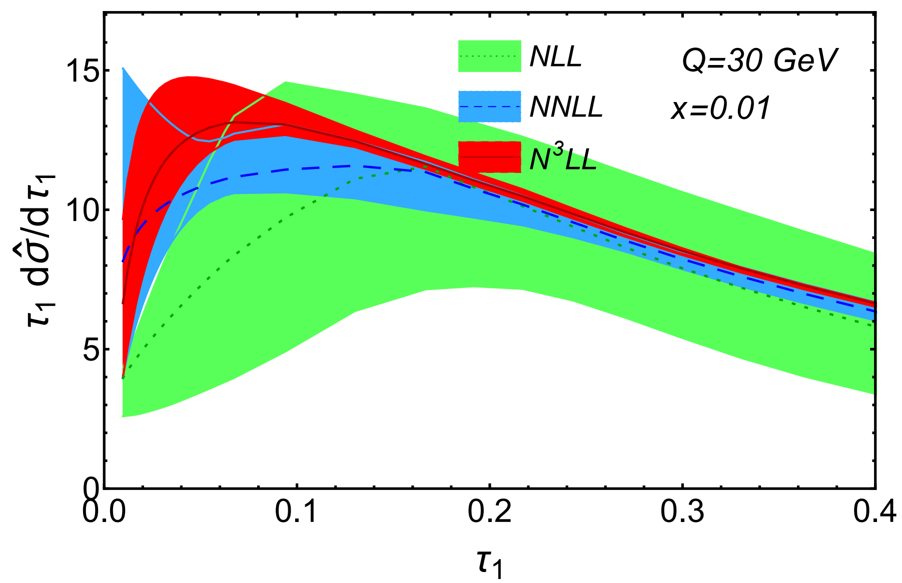
Guzey, Klasen, JHEP05 (2020) 074

Global event shape and the strong coupling constant

Inclusive production of a single jet in ep scattering: $e + p \to J + X$

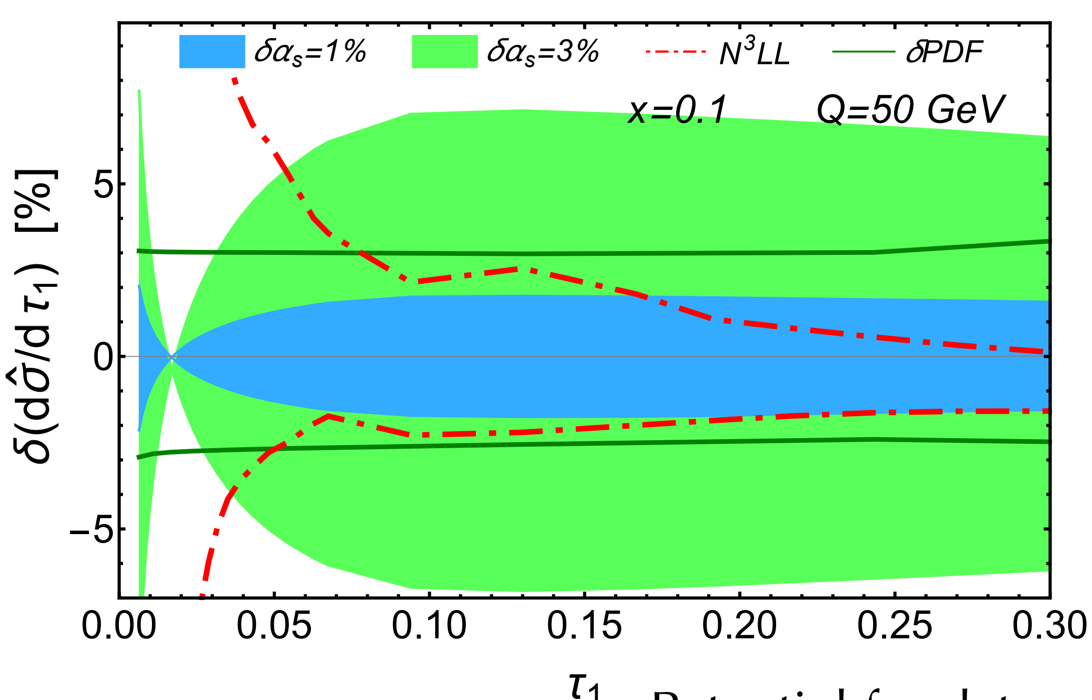
$$\tau_1^b \equiv \frac{2}{Q^2} \sum_{i \in X} \min\{q_B^b \cdot p_i \, , q_J^b \cdot p_i\} = \tau_Q$$

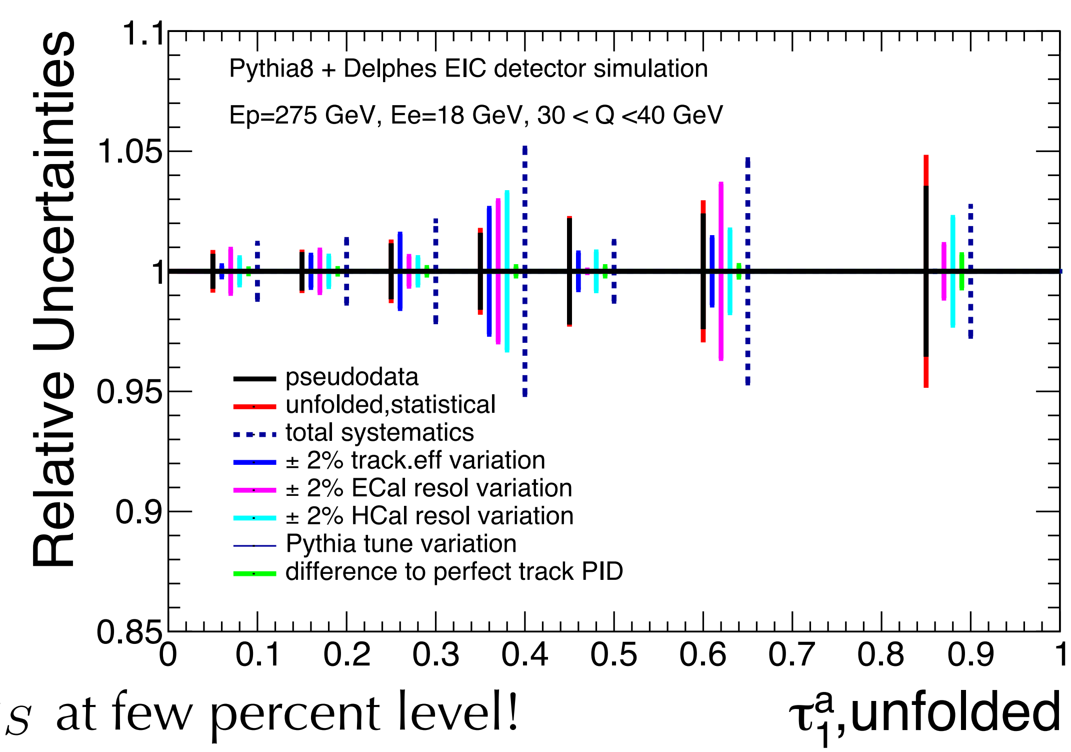
1-jettiness (corresponding to DIS thrust) measures the jet broadening w.r.t the tree-level expectation, where the jet corresponds to the scattered quark



Th. error bands:
accuracy of α_S,
uncertainties in PDF,
nonperturbative corrections due to hadronization

th. uncert. at N^3LL — variation in PDF sets — $\delta\alpha_S = 1\%$ — $\delta\alpha_S = 3\%$





Potential for determination of α_S at few percent level!

Impressive amount of new work!

~15 new publications in the last months

A lot of new impact studies yet to be published

New ideas and new processes to be further investigated

Thanks to all!