EW physics with positrons at the EIC

Wally Melnitchouk

— Jefferson Lab —

Overview

- Availability of positron beams (also with polarization) would open up an entire new frontier for hadron structure & BSM studies at EIC.

Interference Physics
- Two-photon physics
- Generalized parton distributions

Structure Functions
- Neutral and charged currents DIS
- Charm production
- Pion and kaon structure

Standard Model Tests
- Charge conjugation violation
- Right-handed W-bosons
- Dark photon search
- Leptoquarks, leptogluons

Overview

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- In this talk will focus on 2 applications:

  $\longrightarrow$ multi-photon physics in exclusive reactions

  $\longrightarrow$ flavor separation in inclusive (NC and CC) DIS

Overview

- Availability of positron beams (also with polarization) would open up an entire new frontier for hadron structure & BSM studies at EIC.

- In this talk will focus on 2 applications:

  → multi-photon physics in exclusive reactions

  → flavor separation in inclusive (NC and CC) DIS

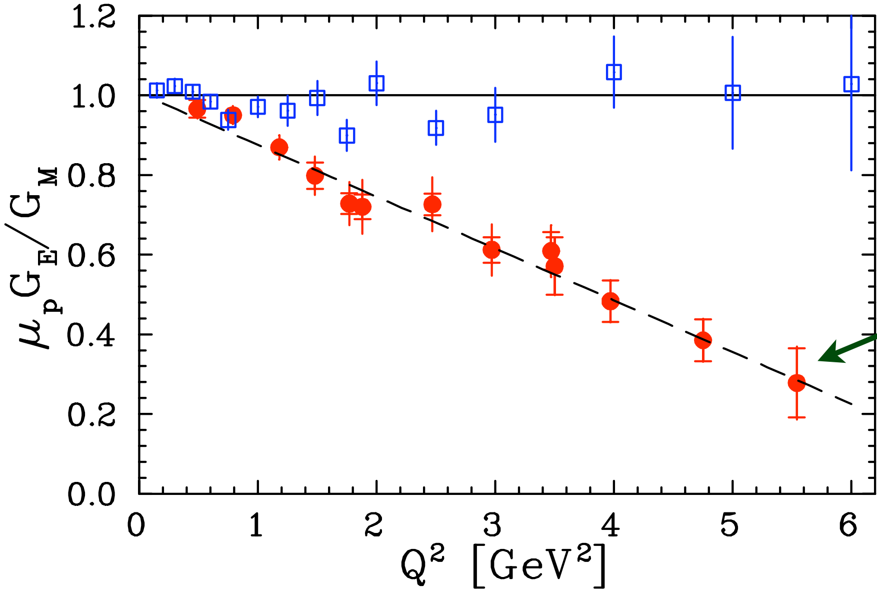
- A lot of material from earlier positron (JLab) workshops:

https://www.jlab.org/conferences/JPOS09/

https://www.jlab.org/conferences/JPOS17/

Multi-photon physics with e^+ and e^-

Proton G_E/G_M ratio



Rosenbluth (Longitudinal-Transverse) Separation

Polarization Transfer

$$\tau = Q^2/4M^2$$

$$\varepsilon = [1 + 2(1+\tau)\tan^2(\theta/2)]^{-1}$$

LT method

$$\sigma_R = G_M^2(Q^2) + \frac{\varepsilon}{\tau} G_E^2(Q^2)$$

$\longrightarrow$ G_E from slope in ε plot

$\longrightarrow$ suppressed at large Q^2

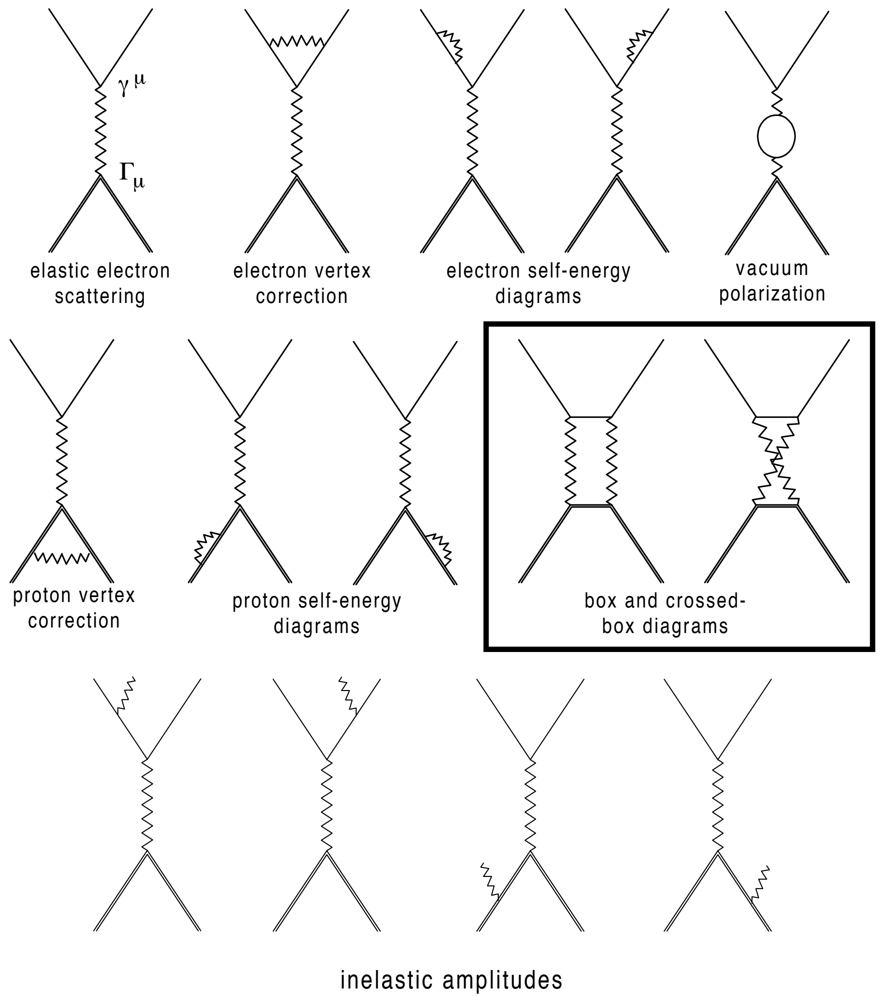
PT method

$$\frac{G_E}{G_M} = -\sqrt{\frac{\tau(1+\varepsilon)}{2\varepsilon}}\frac{P_T}{P_L}$$

$\longrightarrow$ $P_{T,L}$ recoil proton polarization in $\vec{e}\, p \to e\, \vec{p}$

QED radiative corrections

- Cross section modified by 1γ loop effects



Born

TPE

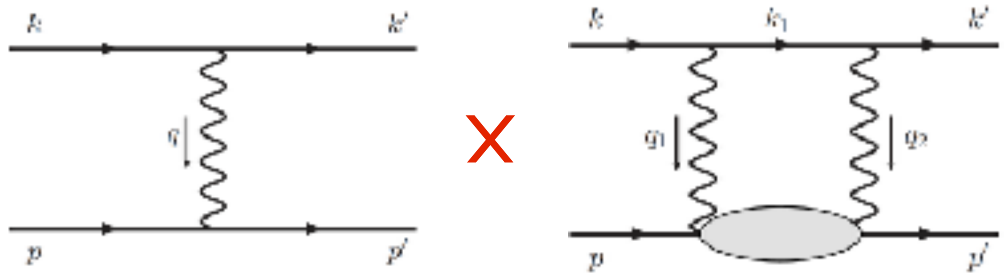
$$d\sigma = d\sigma_0\,(1+\delta)$$

δ contains additional ε dependence, mostly from box diagrams

(most difficult to calculate)

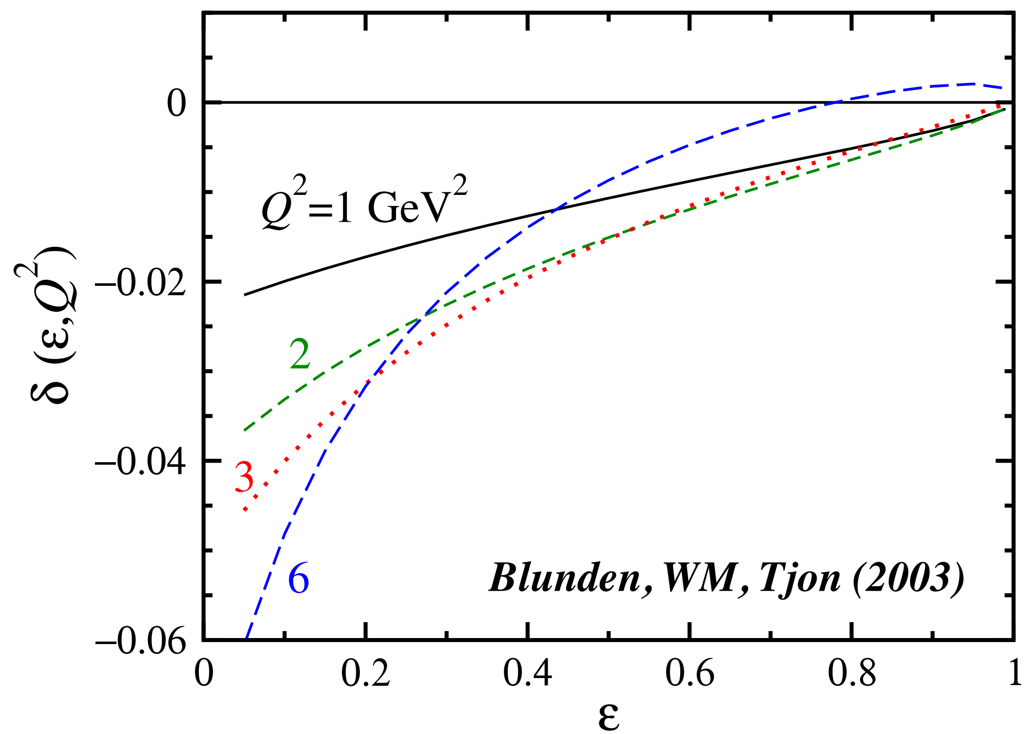
Two-photon exchange

- Interference between Born and TPE amplitudes

$\mathcal{M}_0$  $\mathcal{M}_{\gamma\gamma}$

- Correction to cross section

$$\delta^{(2\gamma)} = \frac{2\mathcal{R}e\left\{\mathcal{M}_0^\dagger\ \mathcal{M}_{\gamma\gamma}\right\}}{|\mathcal{M}_0|^2}$$

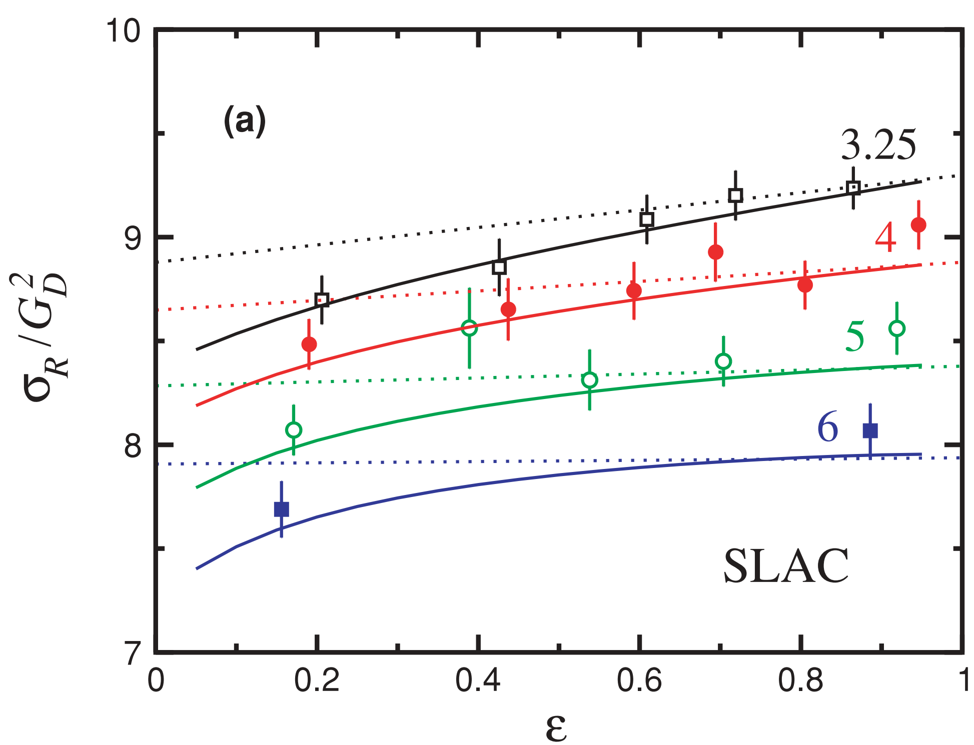


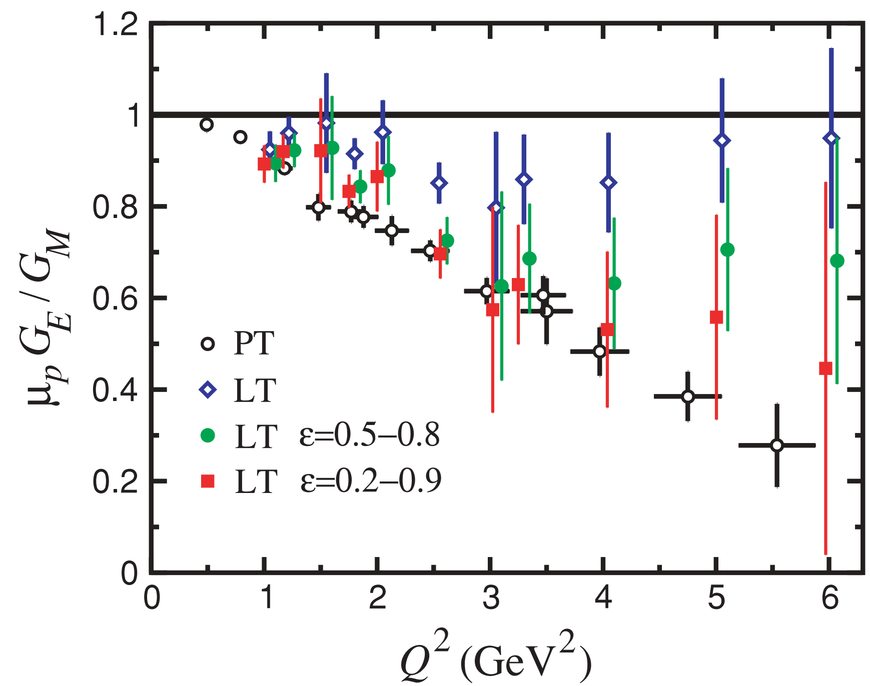
→ positive slope will reduce Rosenbluth ratio

→ nonlinearity grows with Q^2

Two-photon exchange

- TPE improves agreement with reduced cross sections





Blunden, WM, Tjon (2005)

- Resolves most of the discrepancy between LT and PT data

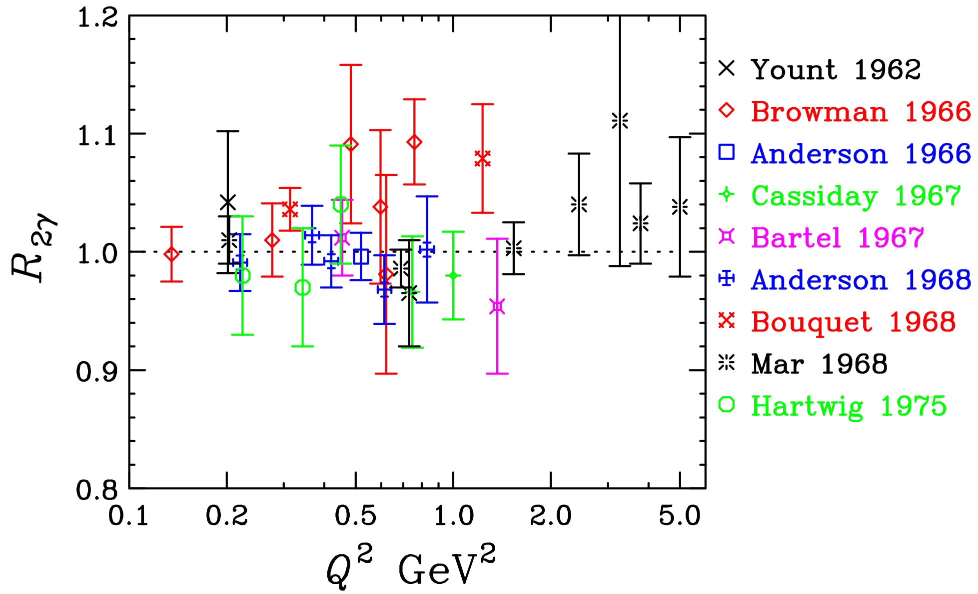
- Is there more direct evidence for relevance of TPE?

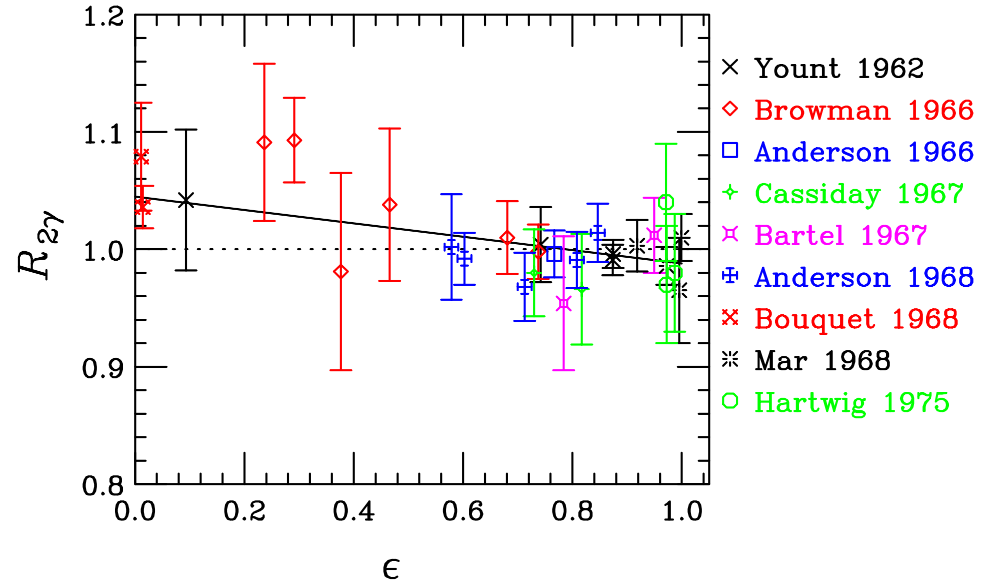
TPE in e^+p to e^-p ratio

- TPE interference changes sign for positrons vs electrons

$$R_{2\gamma} = \frac{\sigma^{e^+}}{\sigma^{e^-}} \approx 1 - 2\delta_{\gamma\gamma}$$

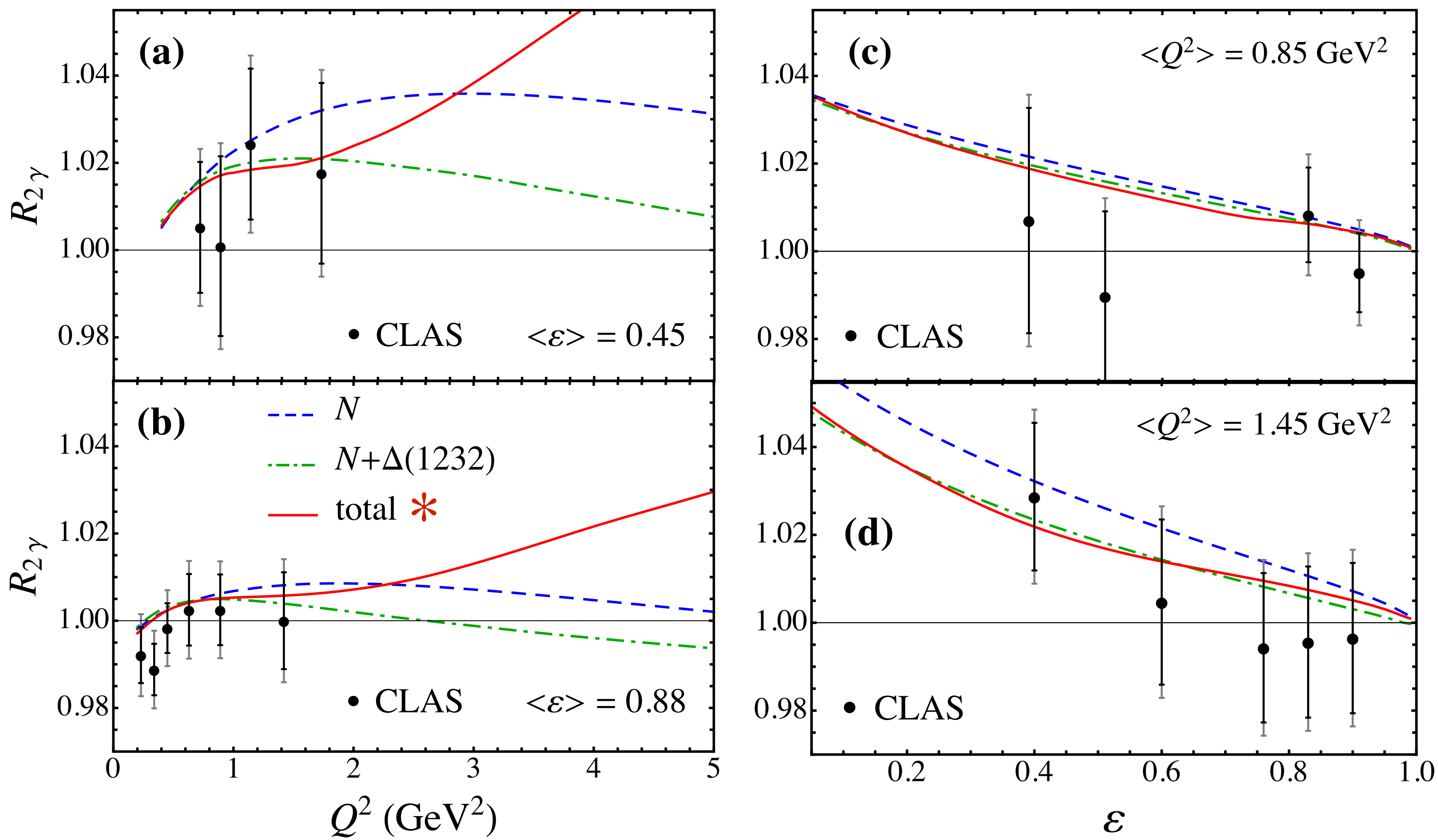
Old data from 1960-1970's





TPE in e^+p to e^-p ratio

- More recent measurements from CLAS at JLab

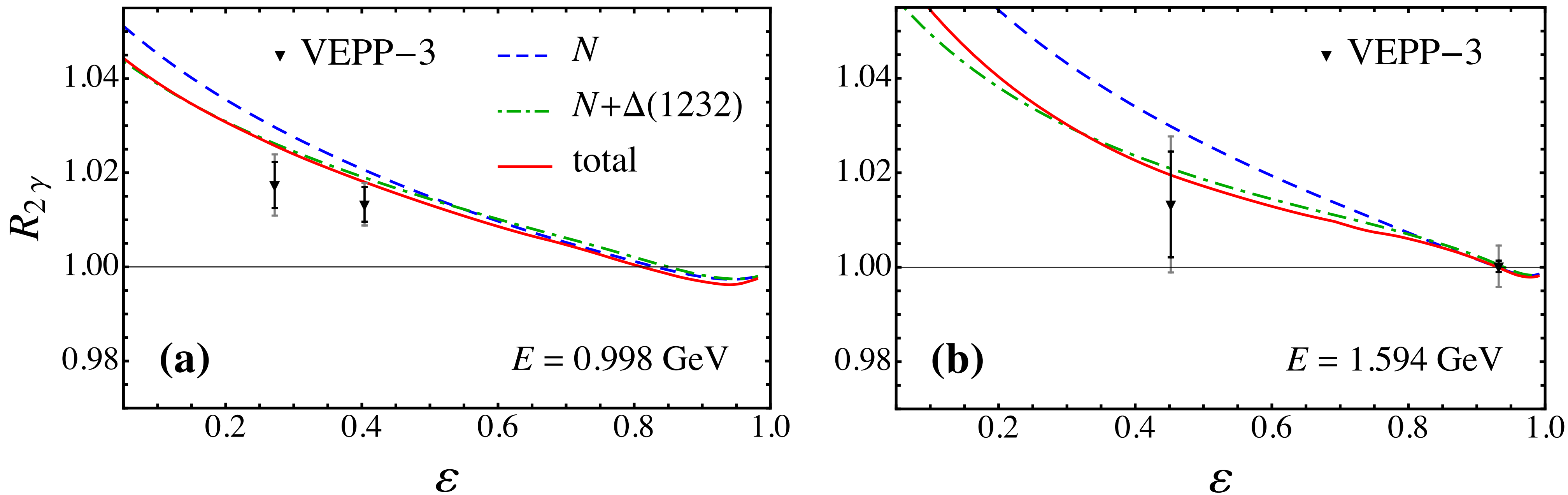


Ahmed, Blunden, WM (2020)

* dispersive calculation with all major N^* resonances in intermediate state

TPE in e^+p to e^-p ratio

- More recent measurements from VEPP-3 at Novosibirsk

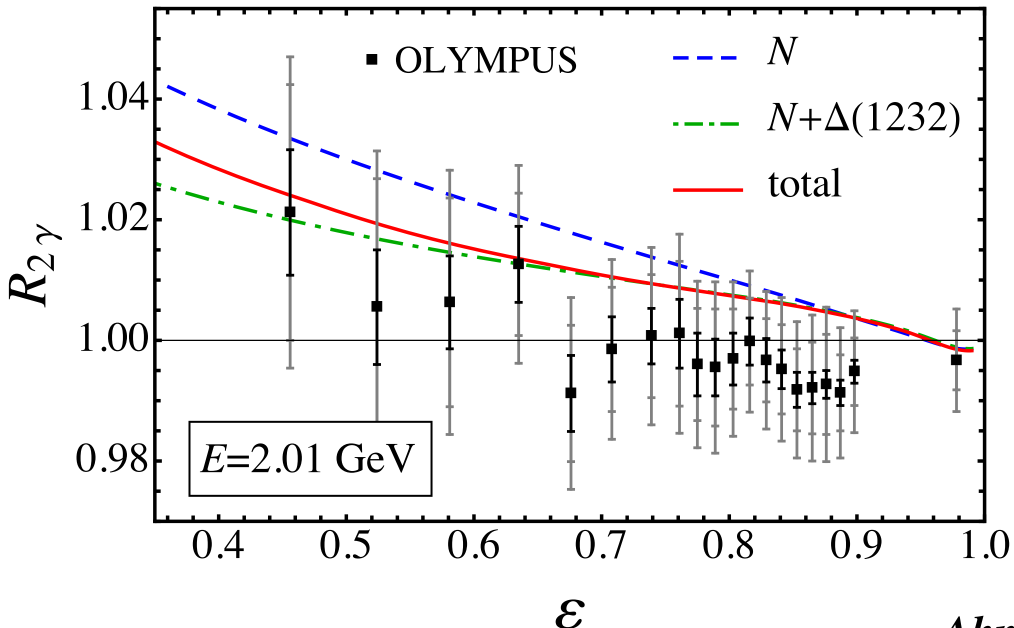


Ahmed, Blunden, WM (2020)

→ indication from data of 1–2% TPE effect at backward angles

TPE in e^+p to e^-p ratio

- More recent measurements from OLYMPUS at DESY



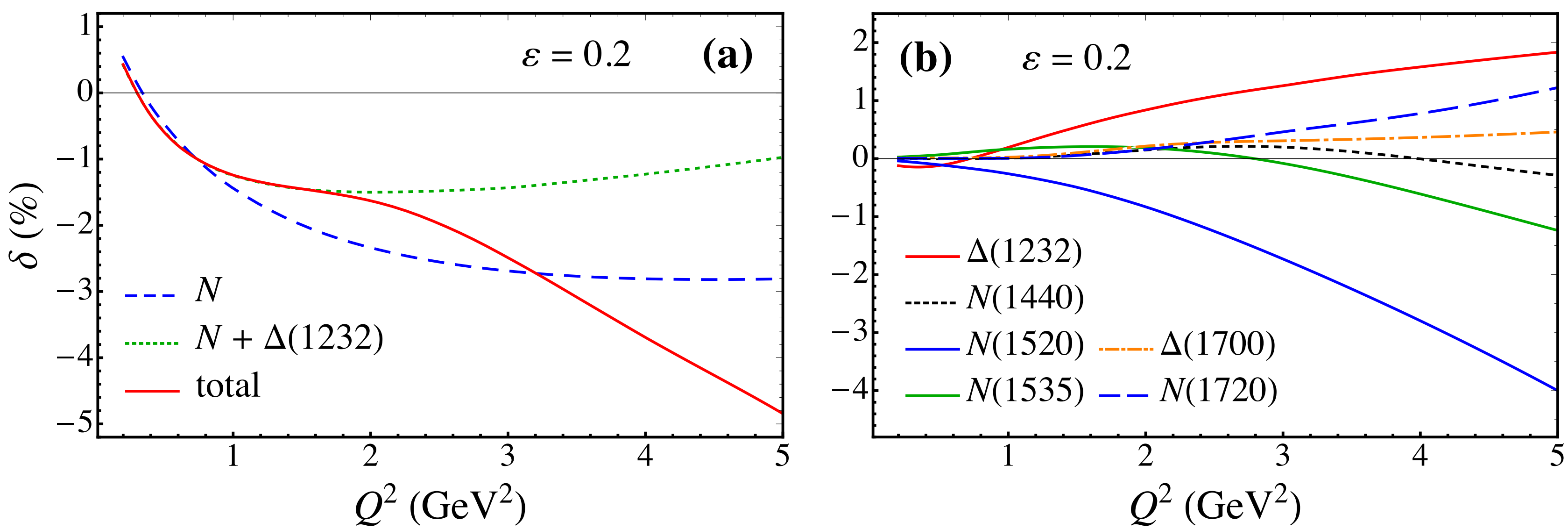
Ahmed, Blunden, WM (2020)

→ curious behavior at forward angles, difficult to reproduce in quantitative TPE calculations
(but still consistent within total uncertainties)

TPE in e^+p to e^-p ratio

- Most measurements have been at large ε and low Q^2 where TPE are somewhat suppressed

- Optimal sensitivity at small ε ("backward angles") and $Q^2 \gtrsim (3-4)\,\mathrm{GeV}^2$



Ahmed, Blunden, WM (2020)

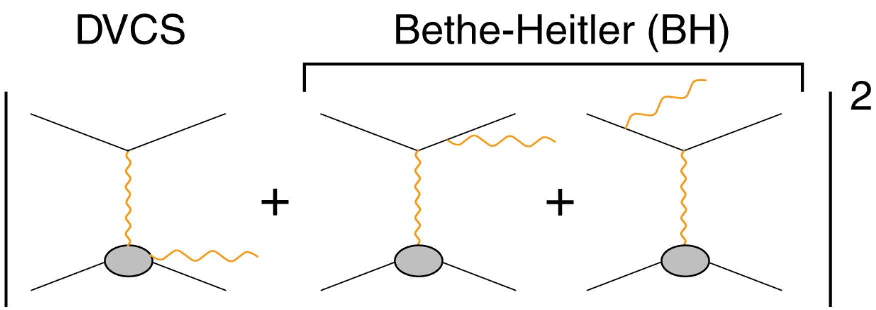
Exclusive photon production

Eric Voutier
Irène Joliot-Curie

N(e,e'γN) Differential Cross Section

M. Diehl at the CLAS12 European Workshop, Genova, February 25-28, 2009

$\sigma(eN \longrightarrow eN\gamma) =$



$$\sigma^{e}_{P0} = \sigma_{BH} + \sigma_{DVCS} + P_l\,\tilde{\sigma}_{DVCS} + e_l\left(\sigma_{INT} + P_l\,\tilde{\sigma}_{INT}\right)$$

Electron observables

$$\sigma^{-}_{00} = \sigma_{BH} + \sigma_{DVCS} - \sigma_{INT}$$
$$\sigma^{-}_{+0} - \sigma^{-}_{-0} = 2\,\tilde{\sigma}_{DVCS} - 2\,\tilde{\sigma}_{INT}$$

Electron & positron observables

$$\sigma^{+}_{00} - \sigma^{-}_{00} = 2\,\sigma_{INT}$$
$$\left[\sigma^{+}_{+0} - \sigma^{+}_{-0}\right] - \left[\sigma^{-}_{+0} - \sigma^{-}_{-0}\right] = \left[\sigma^{+}_{+0} - \sigma^{-}_{+0}\right] - \left[\sigma^{+}_{-0} - \sigma^{-}_{-0}\right] = 4\,\tilde{\sigma}_{INT}$$

Polarized electrons and positrons allow to separate the unknown amplitudes of the cross section for electro-production of photons.

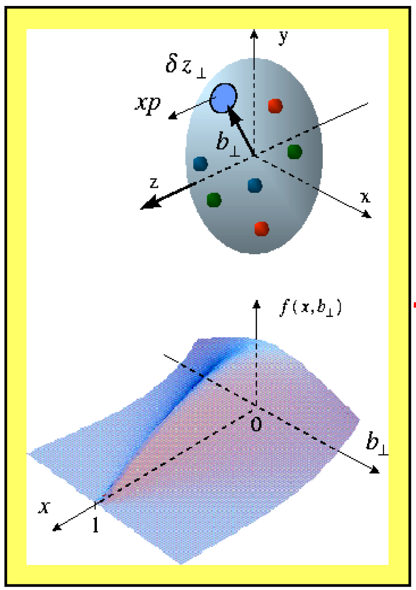
Exclusive photon production

Eric Voutier

Parton Imaging

D. Müller, D. Robaschik, B. Geyer, F.M. Dittes, J. Horejsi, FP 42 (1994) 101 X. Ji, PRD 55 (1997) 7114 A. Radyushkin, PRD 56 (1997) 5524

- GPDs parameterize the partonic structure of hadrons and offer the unprecedented possibility to access the spatial distribution of partons.



M. Burkardt, PRD 62 (2000) 071503 M.Diehl, EPJC 25 (2002) 223

GPDs encode the correlations between partons and contain information about the dynamics of the system like the angular momentum or the distribution of the strong forces experienced by quarks and gluons inside hadrons.

X. Ji, PRL 78 (1997) 610 M. Polyakov, PL B555 (2003) 57

GPDs can be interpreted as a distribution in the transverse plane of partons carrying some fraction of the longitudinal momentum of the nucleon.

A new light on hadron structure

Exclusive photon production

Eric Voutier
IJCLab Irène Joliot-Curie

Nucleon Internal Pressure

V. Burkert, L. Elouadrhiri, F.-X. Girod, Nature 557 (2018) 396 M.V. Polyakov, P. Schweitzer, Int. J. Mod. Phys. A33 (2018) 1830025
K. Kumerički, Nature 570 (2019) E1

$$\int_{-1}^{1} x\, H(x,\xi,t)\, dx = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$$

The 2nd order **Mellin moment** of GPDs allow to access the pressure distribution inside hadrons through the **skewness dependency** of GPDs… (**DDVCS**).

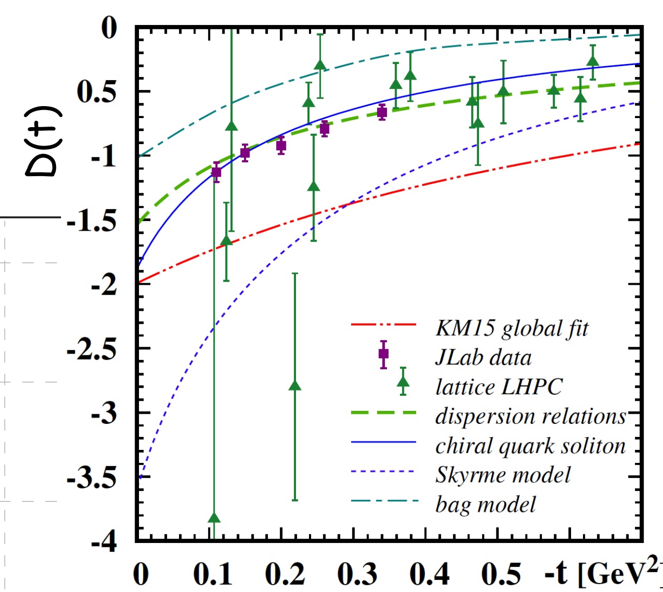
CFF $$\boxed{\mathcal{H}(\xi,t) = \int_{-1}^{1}\left[\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right] H(x,\xi,t)\, dx}$$

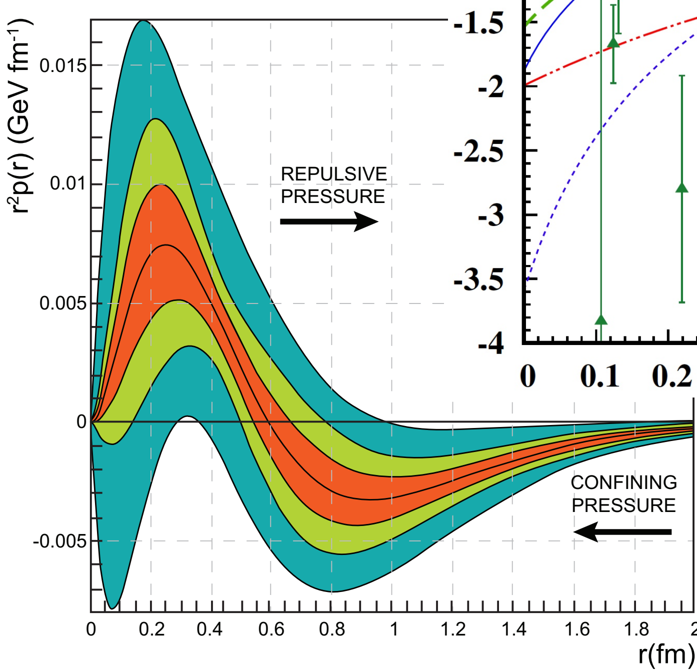
$$\Re\mathrm{e}[\mathcal{H}(\xi,t)] \overset{\mathrm{LO}}{=} D(t) + \mathcal{P}\left\{\int_{-1}^{1}\left[\frac{1}{\xi - x} - \frac{1}{\xi + x}\right]\Im\mathrm{m}[\mathcal{H}(x,t)]\, dx\right\}$$

$$D(t) = \frac{1}{2}\int_{-1}^{1}\frac{D(z,t)}{1-z}\, dz$$

$$D(z,t) = (1-z^2)\left[d_1(t)\, C_1^{3/2}(z) + \ldots\right]$$

Real part of Compton form factors (σ_{INT})





Exclusive photon production

Eric Voutier

Beam Charge Asymmetries

Using polarized electron and positron beams, we are proposing to measure

- The unpolarized beam charge asymmetry A^C_{UU}, which is sensitive to the **CFF real part**
- The polarized beam charge asymmetry A^C_{LU}, which is sensitive to the **CFF imaginary part**
- The charge averaged beam spin asymmetry A^0_{LU}, which is sensitive to **higher twist effects**

New GPD Observables

$$A^C_{UU} = \frac{(Y^+_+ + Y^+_-) - (Y^-_+ + Y^-_-)}{Y^+_+ + Y^+_- + Y^-_+ + Y^-_-} = \frac{\sigma_{INT}}{\sigma_{BH} + \sigma_{DVCS}}$$

$$A^C_{LU} = \frac{(Y^+_+ - Y^+_-) - (Y^-_+ - Y^-_-)}{Y^+_+ + Y^+_- + Y^-_+ + Y^-_-} = \frac{\tilde{\sigma}_{INT}}{\sigma_{BH} + \sigma_{DVCS}}$$

$$A^0_{LU} = \frac{(Y^+_+ + Y^-_+) - (Y^+_- + Y^-_-)}{Y^+_+ + Y^+_- + Y^-_+ + Y^-_-} = \frac{\tilde{\sigma}_{DVCS}}{\sigma_{BH} + \sigma_{DVCS}}$$

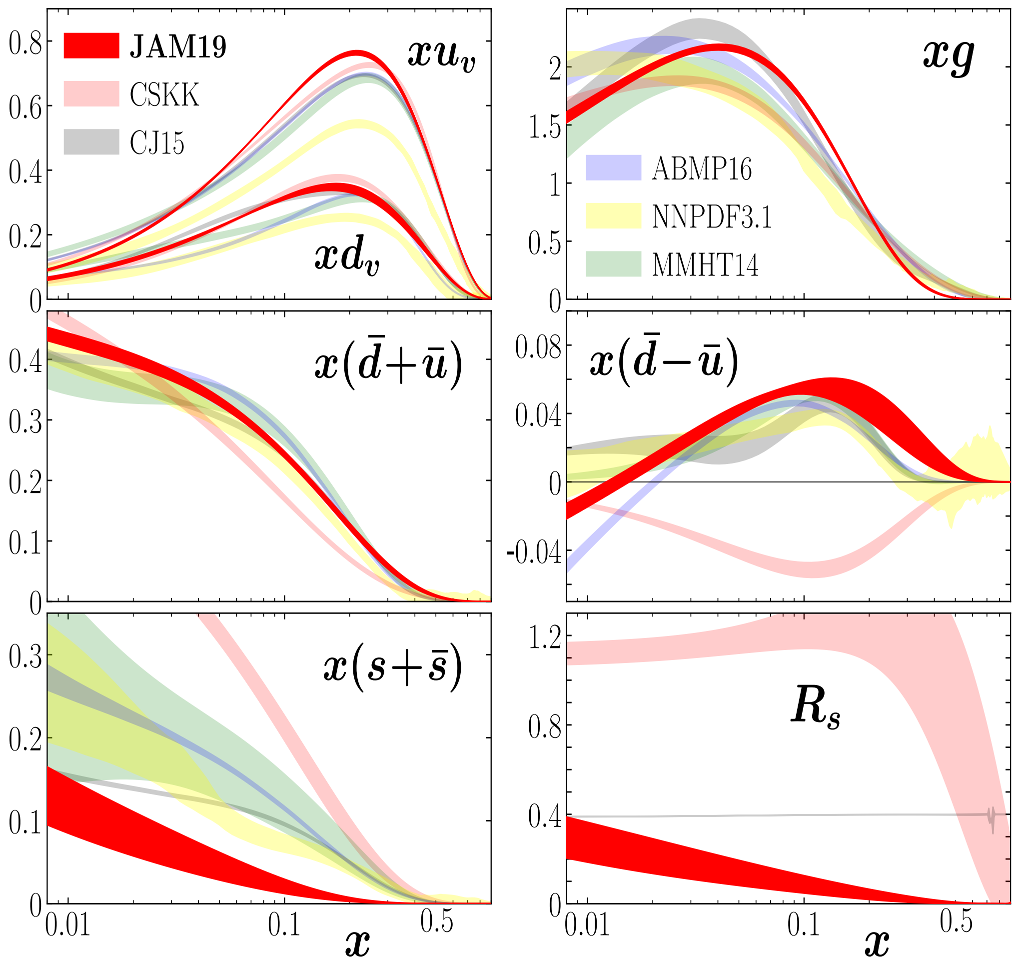
$$A^C_{LU} \neq A^{\pm}_{LU} = \frac{\tilde{\sigma}_{DVCS} \pm \tilde{\sigma}_{INT}}{\sigma_{BH} + \sigma_{INT} + \sigma_{DVCS}}$$

$Y^{e^\pm}_{\pm P^\pm} = \frac{N^\pm_\pm}{Q^\pm_\pm P^\pm}$ *is the beam polarization and accumulated charge normalized yield.*

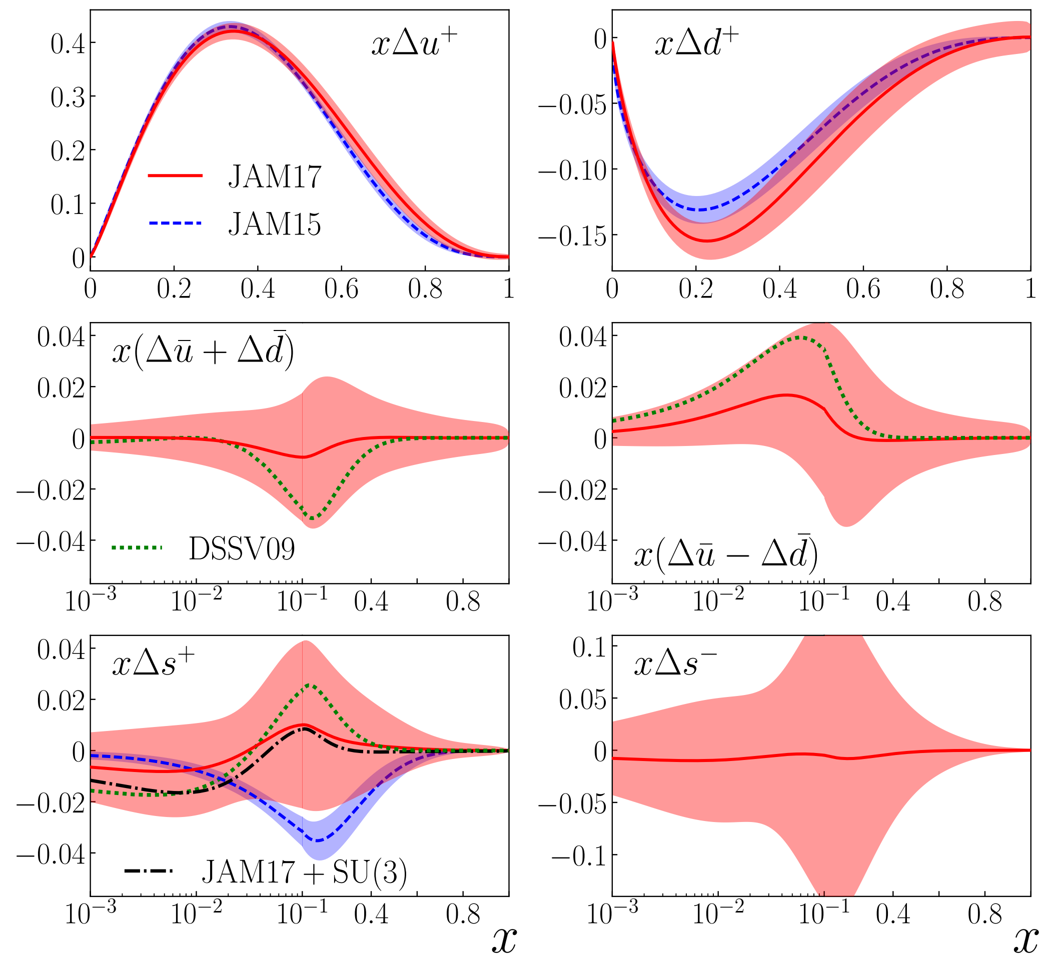
Flavor separation with e^+ and e^- DIS

Current status of PDFs

Spin-averaged



Spin-dependent



- PDFs in the EIC era — Monte Carlo methods (multiple solutions)
  — simultaneous extraction of PDFs, FFs

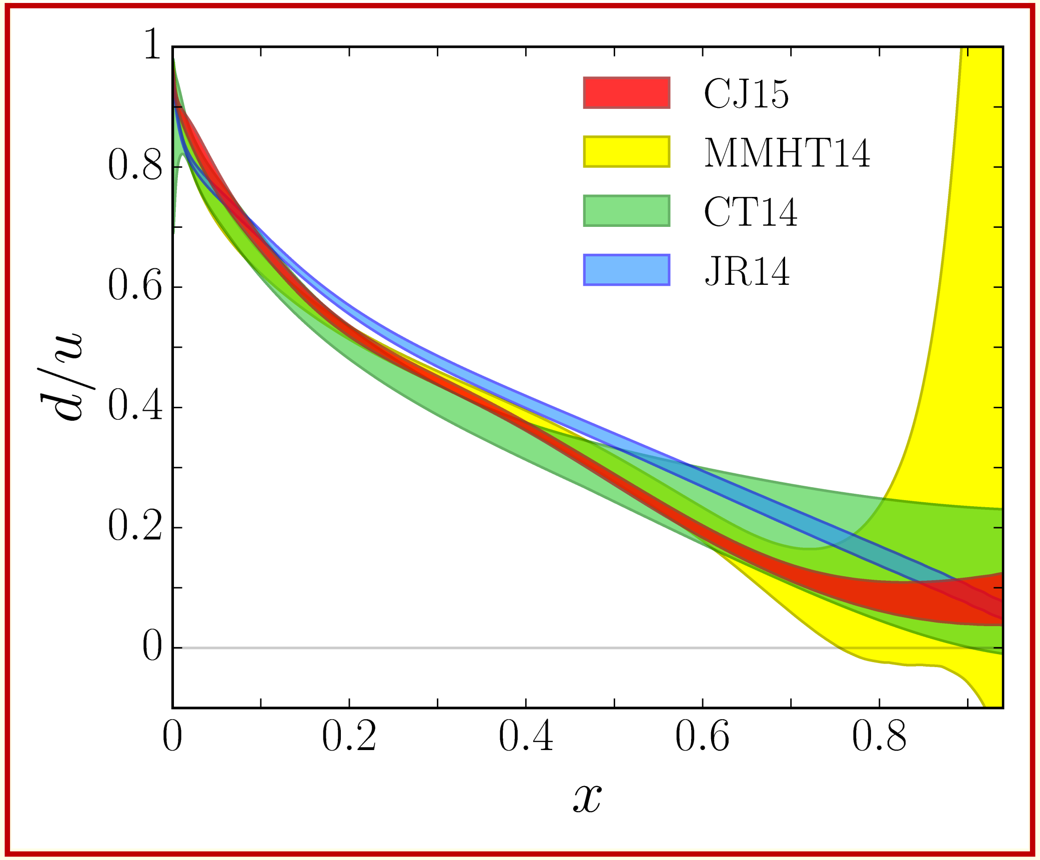
Current status of PDFs

What are some issues of current interest in PDFs?

In a phrase - *flavor separation*

1. d/u behavior at large values of x
2. Determination of the $s \pm \bar{s}$ PDFs
3. Constraints on the gluon PDF

d/u ratio shows significant variations between various PDF sets



- Some is due to parametrization bias
- Some is due to Q and W cuts that effectively limit x to $x \sim 0.7$ so the large x region is an extrapolation
- Some is due to different treatments of nuclear corrections

d/u ratio

Need a way to constrain the d PDF in the absence of nuclear corrections

Classic solution is to use neutrino DIS. Again, at lowest order at large values of x

$$F_2^{\nu p} = 2x(d + s + \bar{u} + \bar{d}) \xrightarrow[x \to 1]{} 2xd$$

and

$$F_2^{\bar{\nu} p} = 2x(u + c + \bar{d} + \bar{s}) \xrightarrow[x \to 1]{} 2xu$$

so that at large values of x

$$F_2^{\nu p} / F_2^{\bar{\nu} p} = d/u$$

d/u ratio

However

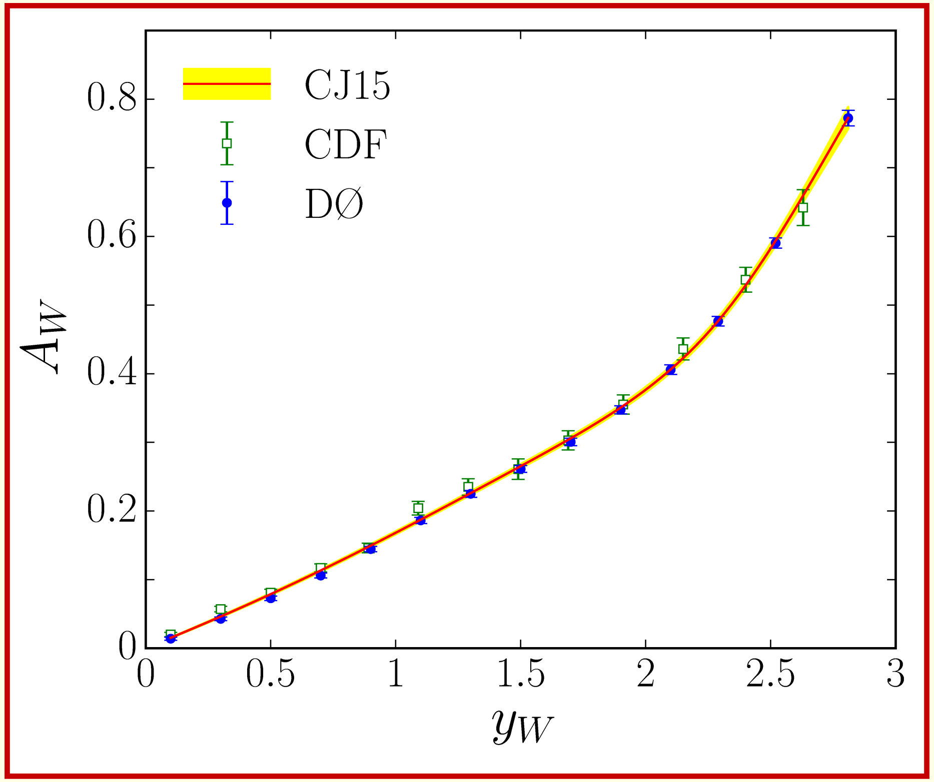
- Data on proton targets from early bubble chamber experiments had low statistics and provided little constraint on d/u at large values of x
- High statistics experiments used nuclear targets
  - Results give information on *nuclear* PDFs
  - Need to account for nuclear model dependent corrections to extract d/u for the proton
  - Highly unlikely to get data from a hydrogen target using modern high intensity neutrino beams due to safety concerns

One solution is to use the charged current interaction in the form of W production from the Tevatron

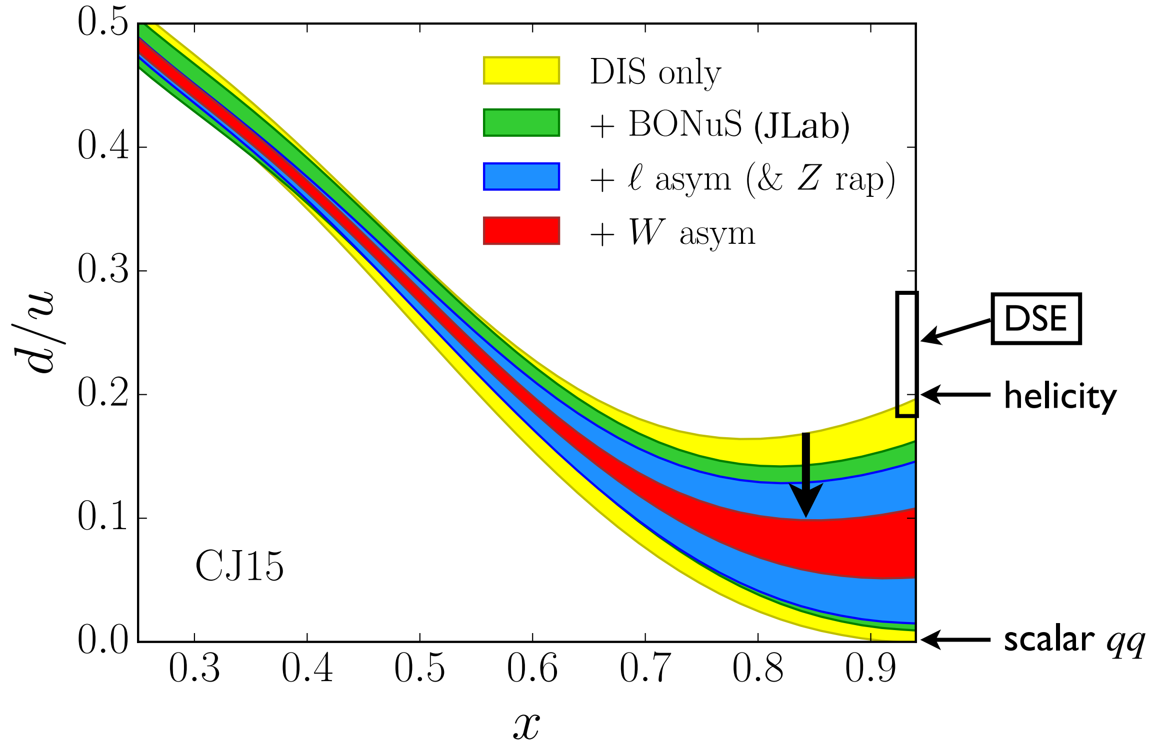
The charged W asymmetry

$$A(y) = \frac{\sigma(W^+) - \sigma(W^-)}{\sigma(W^+) + \sigma(W^-)} \approx \frac{1 - d/u(x_1)}{1 + d/u(x_1)} \quad \text{with} \quad x_1 \approx \frac{M_W}{\sqrt(s)} e^{\eta_W}$$

at large W rapidity is sensitive to the d/u ratio



Accardi, Brady, WM, Owens, Sato (2016)



$\longrightarrow$ extrapolated ratio at $x = 1$

$d/u \;\rightarrow\; 0.09 \pm 0.03$

$\longrightarrow$ does not match any model…

- Can see the effect of adding various data sets to a series of fits
- Can see the decrease in the d/u error bands
- No nuclear corrections needed
- Can help select amongst the various treatments of nuclear corrections

d/u ratio

- W asymmetry has more constraining power than the W-lepton asymmetry
- Leptonic $V - A$ decay limits the reach in rapidity $\Rightarrow$ less constraint on the d PDF
- On the other hand, the W asymmetry extraction is model dependent

d/u ratio

Another solution - use the line-reversed DIS processes, again for large x

$$e^+p \to \bar{\nu} + X \qquad \boxed{F_2^{e^+p,cc}(x,Q) \propto xd}$$

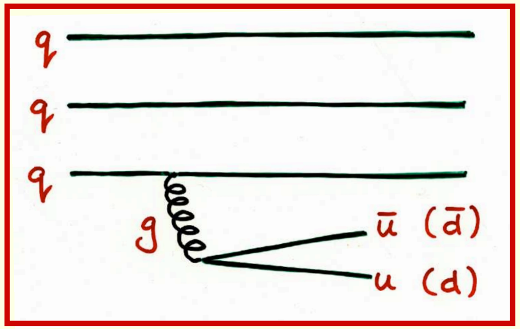
and

$$e^-p \to \nu + X \qquad \boxed{F_2^{e^-p,cc}(x,Q) \propto xu}$$

- Allows direct extraction of d/u at large values of x
- These processes have been measured at HERA out to $x \simeq 0.4$
- Need good statistics at larger x values if one wants to extract d/u directly

Light quark sea asymmetry

- From perturbative QCD expect symmetric $q\bar{q}$ sea generated by gluon radiation into $q\bar{q}$ pairs (if quark masses are the same)

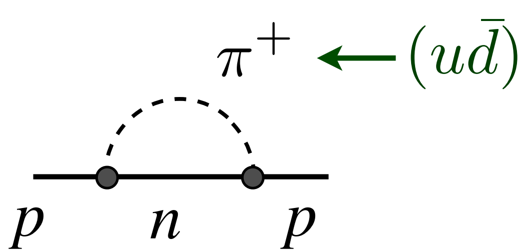


$\longrightarrow$ since u and d quarks nearly degenerate, expect flavor-symmetric light-quark sea

$$\bar{d} \approx \bar{u}$$

- From chiral symmetry of QCD (important at low energies) should have consequences for antiquark PDFs in the nucleon (at high energies)

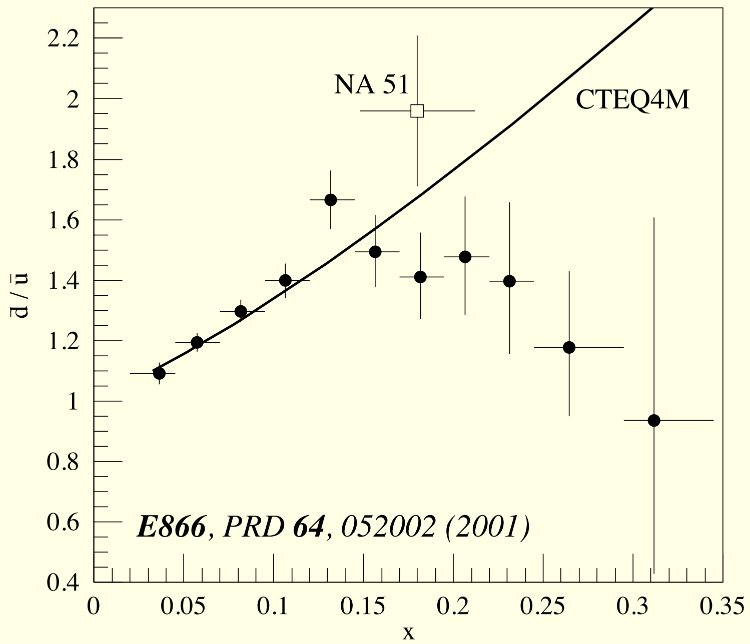
A. Thomas (1984)

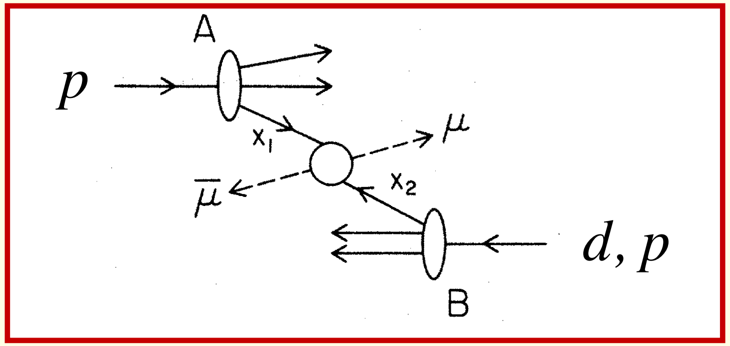


$\longrightarrow$ $\boxed{\bar{d} > \bar{u}}$

Light quark sea asymmetry

- Asymmetry spectacularly confirmed in high-precision DIS and Drell-Yan experiments





$$\frac{d\sigma}{dx_1 dx_2} \sim \sum_q e_q^2\, q(x_1)\, \bar{q}(x_2) \; + \; (x_1 \leftrightarrow x_2)$$

$$\frac{\sigma^{pd}}{\sigma^{pp}} \approx 1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)} \quad \text{for } x_1 \gg x_2$$

$\longrightarrow$ strongly suggested role of chiral symmetry and pion cloud as central to understanding of nucleon's quark structure

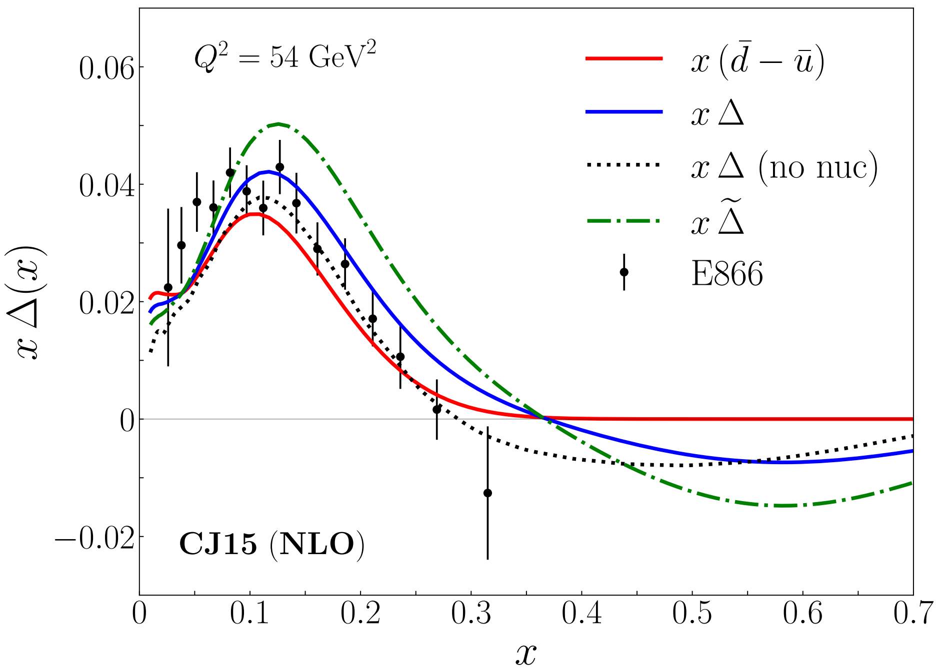
$$(\bar{d} - \bar{u})(x) = (f_\pi \otimes \bar{q}_\pi)\,(x)$$

pion distribution in nucleon

pion PDF

Light quark sea asymmetry

- Intriguing suggestion of sign change in $\bar{d} - \bar{u}$ at high x



Accardi, Keppel, S.Li, WM, Niculescu (x2), Owens (2020)

$$\Delta \equiv \frac{1}{2}(u_v - d_v) - \frac{3}{2x}(F_2^p - F_2^n)$$

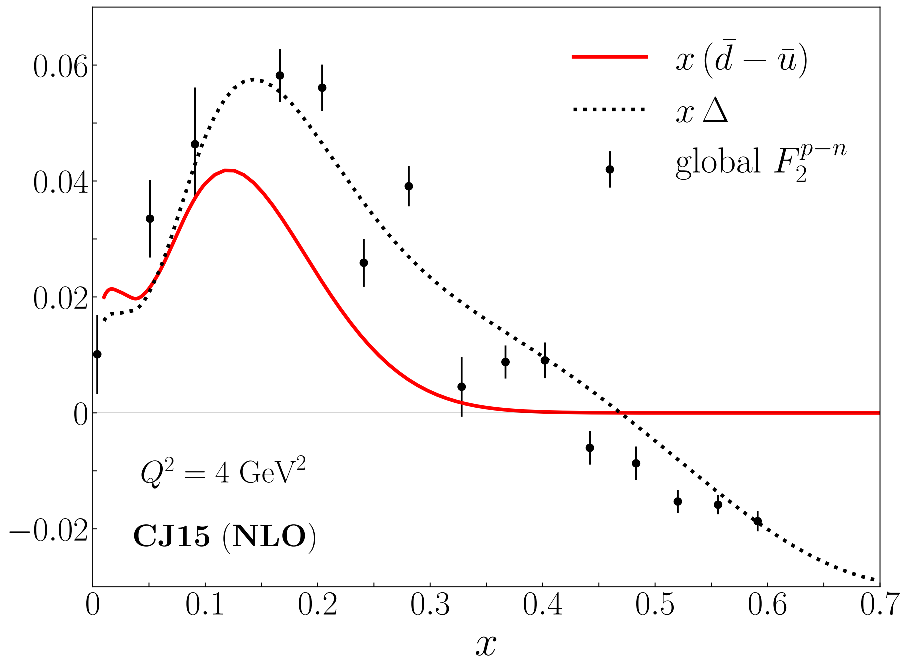
$$\xrightarrow{\text{LO}} \bar{d} - \bar{u}$$

alternative definition (equivalent at LO)

$$\widetilde{\Delta} \equiv u - d - \frac{3}{x}(F_2^p - F_2^n)$$

Light quark sea asymmetry

- Intriguing suggestion of sign change in $\bar{d} - \bar{u}$ at high x



$$\Delta \equiv \frac{1}{2}(u_v - d_v) - \frac{3}{2x}(F_2^p - F_2^n)$$

$$\xrightarrow{\text{LO}} \bar{d} - \bar{u}$$

suggestion that $F_2^p - F_2^n$ data supports sign-change hypothesis

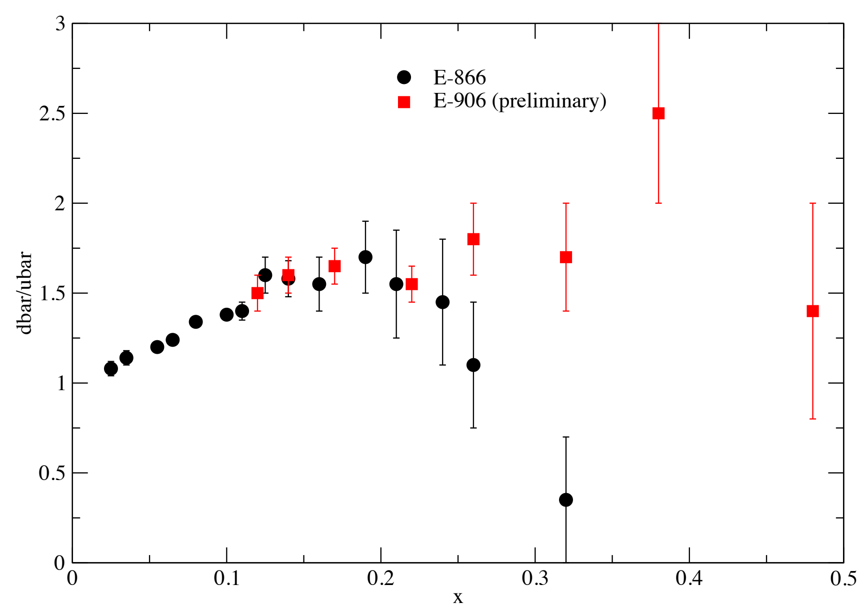
Peng et al. (2014)

$\longrightarrow$ global analysis shows that $F_2^p - F_2^n$ data can be well described with <u>no sign change</u> in $\bar{d} - \bar{u}$

$\longrightarrow$ apparent effect is due to higher-order (NLO) α_S corrections!

Light quark sea asymmetry

- New experiment E-906 (SeaQuest) at Fermilab will have improved statistics and kinematic coverage
- Preliminary data suggests $\bar{d} > \bar{u}$ out to at least $x \approx 0.5$
- Additional data being taken, acceptance and efficiency corrections being finalized.



Light quark sea asymmetry

Again, consider the charged current structure functions in lowest order

$$F_2^{e^+p,cc}(x,Q) = \boxed{2x(d+s+\bar{u}+\bar{c})}$$

and

$$F_2^{e^-p,cc}(x,Q) = \boxed{2x(u+c+\bar{d}+\bar{s})}$$

- If $xF_3^{e^-p,cc} = 2(\underline{u-\bar{d}-\bar{s}+c})$ and $xF_3^{e^+p,cc} = 2(\underline{d-\bar{u}-\bar{c}+s})$ can be extracted, one can separate the quark and antiquark PDFs
- If the charm PDF is perturbative, *i.e.* there is no intrinsic charm, then $c = \bar{c}$
- Can get information on $\bar{d}/\bar{u}$

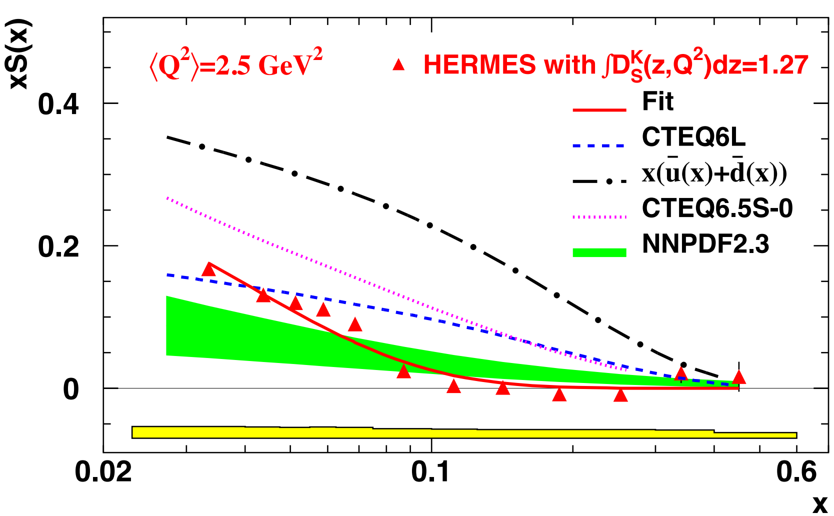
Strange quarks

- Strange quark PDFs more difficult to constrain, since fewer observables directly sensitive to it
- Traditionally s-quark PDF extracted from dimuon production in (anti)neutrino-nucleus DIS $(W^+ s \to c \;/\; W^- \bar{s} \to \bar{c})$

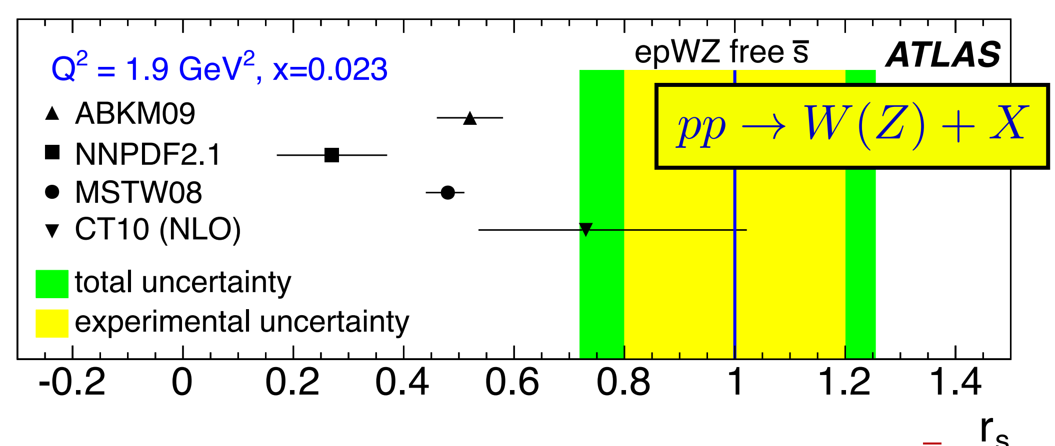
⟶ CCFR/NuTeV give strange/nonstrange ratio $R_s = \dfrac{s + \bar{s}}{\bar{u} + \bar{d}} \sim 0.4$

⟶ but significant uncertainty from nuclear corrections, semileptonic branching ratio uncertainty

⟶ tensions with HERMES K-production & ATLAS W-production data?



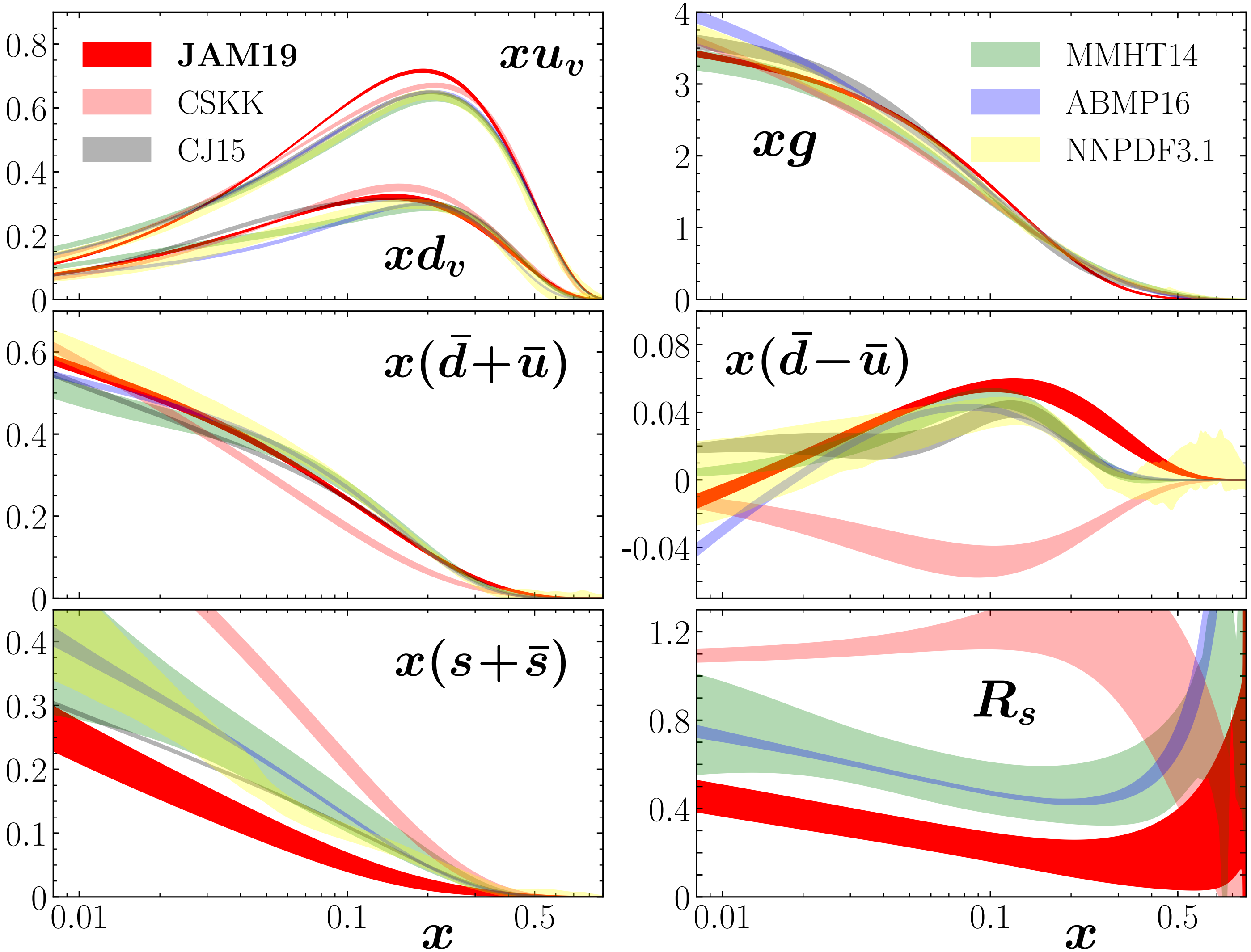
PRD 89 (2014) 097101



PRL 109 (2012) 012001

$$r_s = (s + \bar{s})/2\bar{d} = 1.00^{+0.25}_{-0.28}$$

JAM 2019 simultaneous analysis



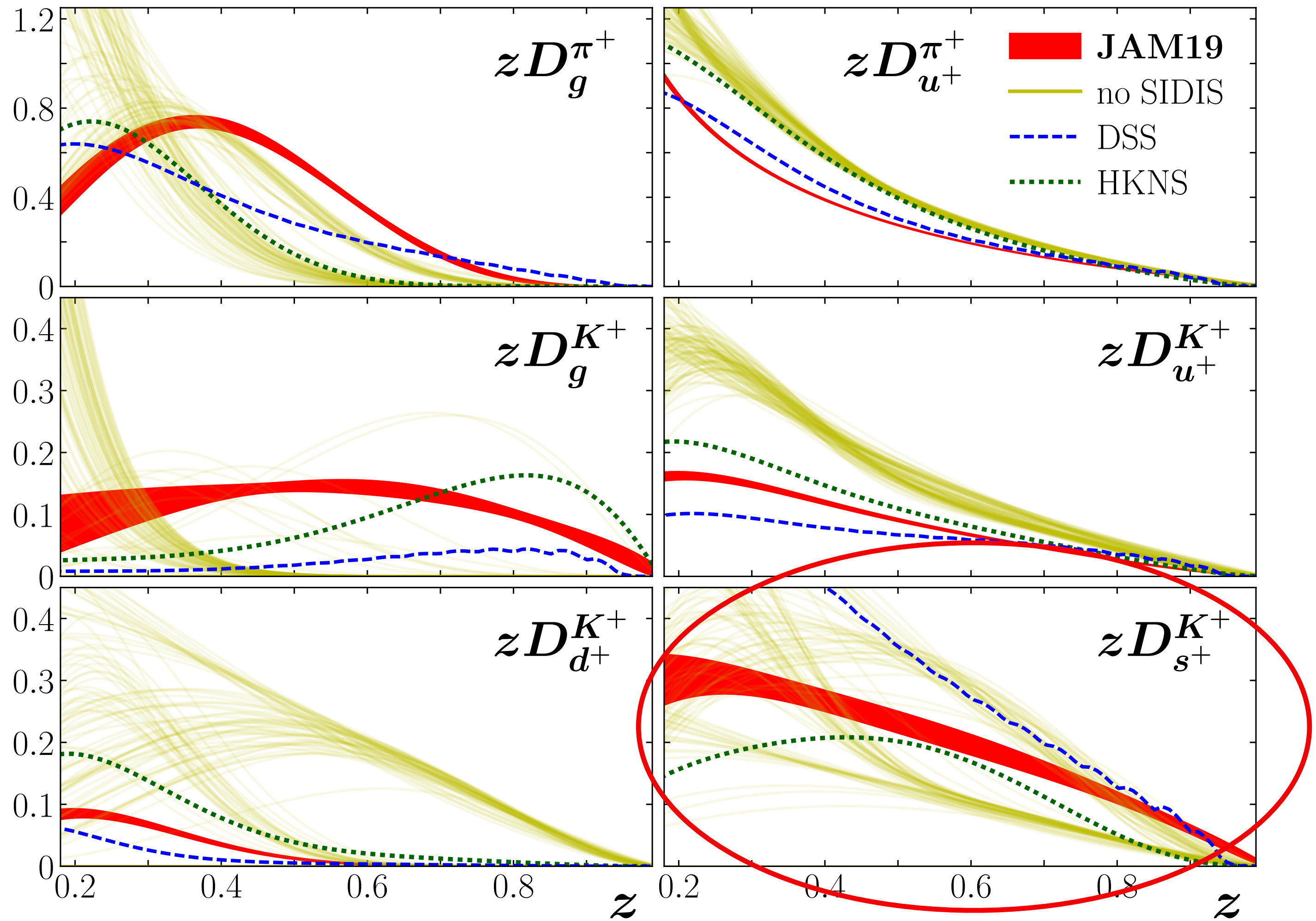
Global analysis of DIS, DY, SIDIS, SIA

Sato, Andres, Ethier, WM (2020)

⟶ valence & light sea quark broadly in agreement with other groups

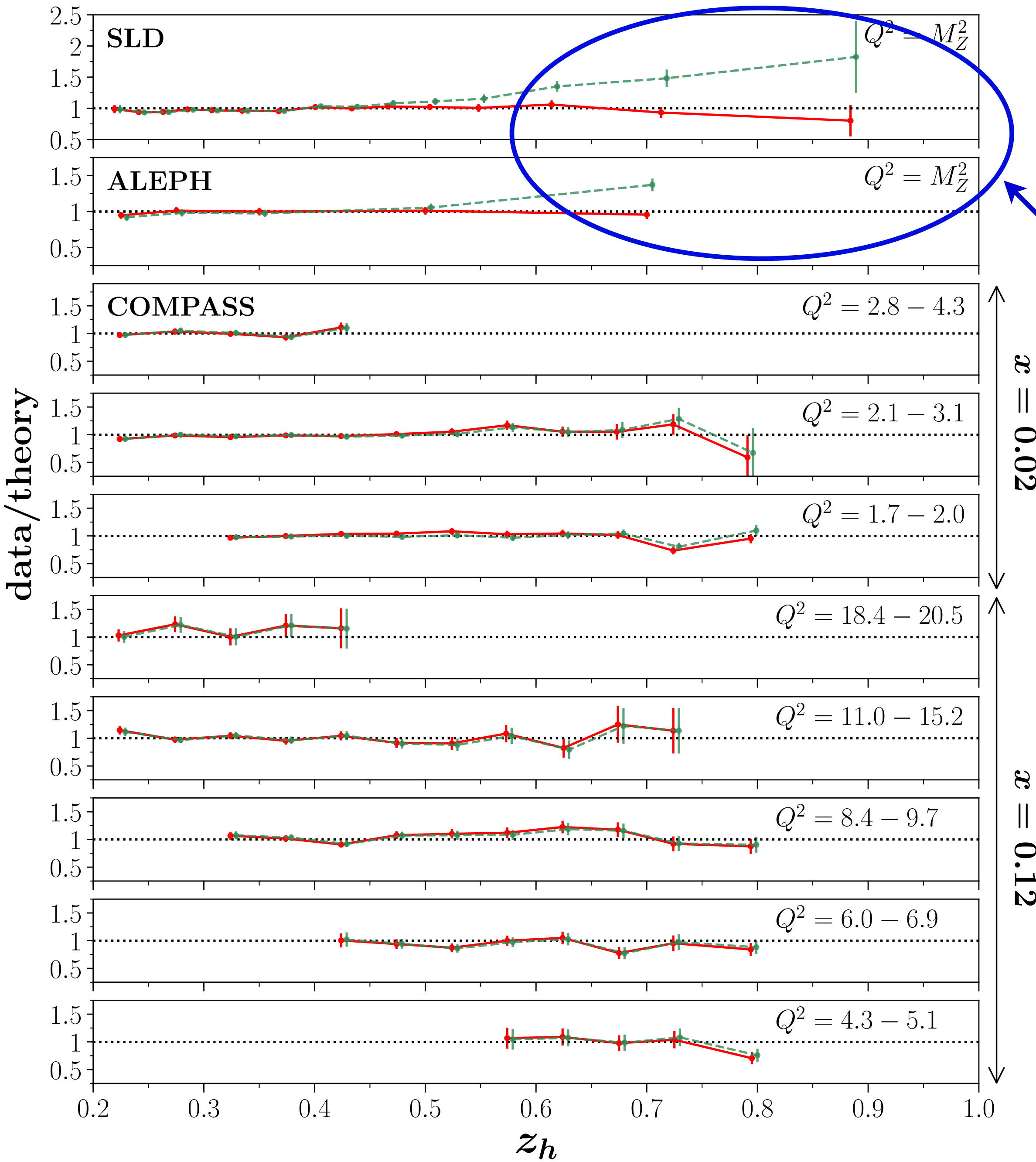
⟶ <u>suppression of strange</u> PDF compared to other extraction

JAM 2019 simultaneous analysis



→ SIDIS + SIA data force strange to kaon FF to be larger

JAM 2019 simultaneous analysis



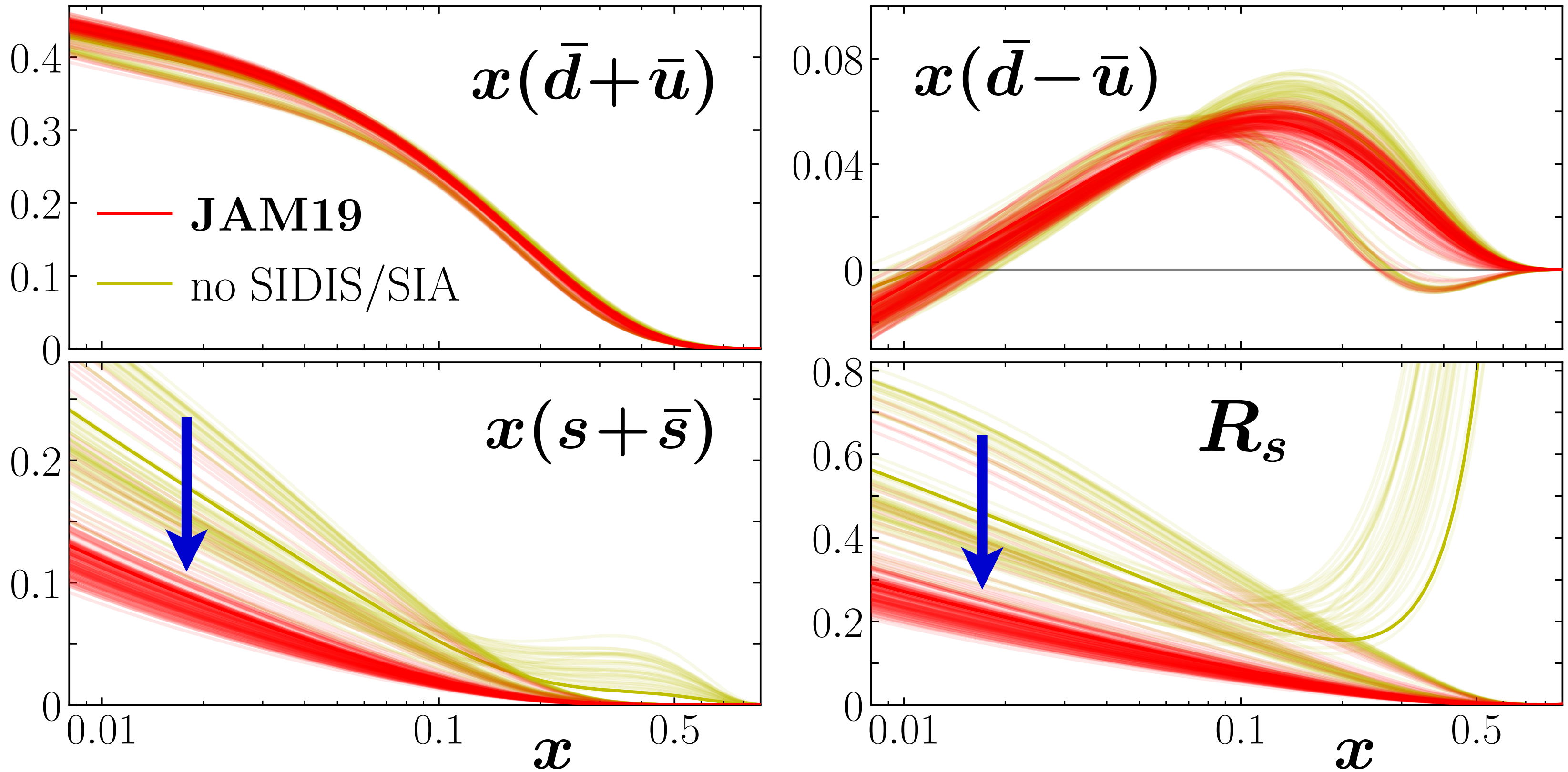
solutions with large $s(x)$

fully constrained solutions

SIA data at large z strongly <u>disfavor</u> <u>small strange → K FF</u>

larger strange → K FF then requires strange PDF to be smaller

JAM 2019 simultaneous analysis



→ vital role played by SIDIS + SIA data in constraining strange PDF

→ could not have seen this without simultaneous MC analysis

Strange quarks

Measure charged current cross sections with a muon tag to select charm final states

$$e^+ s \to \bar{\nu} c \quad \text{followed by} \quad c \to s \mu^+ \nu_\mu$$

and

$$e^- \bar{s} \to \nu \bar{c} \quad \text{followed by} \quad \bar{c} \to \bar{s} \mu^- \bar{\nu}_\mu$$

- Note that the sign of the muon is the same as the sign of initial state lepton
- Potentially capable of separating s from $\bar{s}$

Charged current measurements in $e^{\pm}p$ DIS are potentially capable of improving our knowledge of PDFs by providing:

- Better constraints on d/u in the large x region
- Additional constraints on $\bar{d}/\bar{u}$ to complement information from lepton pair production
- Constraints on $\frac{s+\bar{s}}{\bar{u}+\bar{d}}$ without the need for nuclear corrections

$\longrightarrow$ spin structure functions with positrons: Yuxiang Zhao

Outlook

- Positrons can provide crucial complementary information for mapping of full 3-d structure of the nucleon

Interference Physics
- Two-photon physics
- Generalized parton distributions

Structure Functions
- Neutral and charged currents DIS
- Charm production
- Pion and kaon structure

Standard Model Tests
- Charge conjugation violation
- Right-handed W-bosons
- Dark photon search
- Leptoquarks, leptogluons

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