Salamanca

HADRON 2017

XVII International Conference on Hadron Spectroscopy and Structure

Update on the Hadron Structure Explored at Current and Future Facilities

Jianwei Qiu

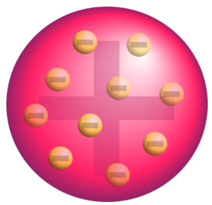
September 25-29, 2017

Salamanca, Spin

Atomic Structure – QED

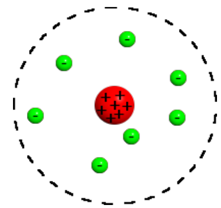
❑ Rutherford's experiment (over 100 years ago):

Atom:



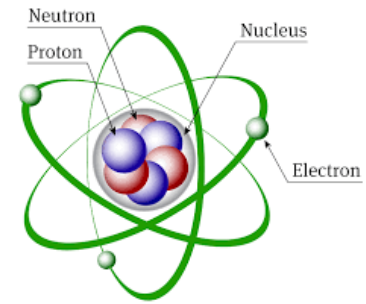
J.J. Thomson's
plum-pudding model

Experiment



Rutherford's
planetary model

Theory



Quantum orbitals

Discovery: ✧ Tiny nucleus - *less than 1 trillionth in volume of an atom*

✧ Quantum probability *- the Quantum World!*

Atomic Structure – QED

- Rutherford's experiment (over 100 years ago):

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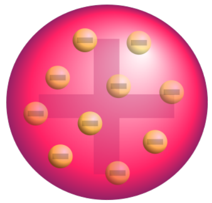

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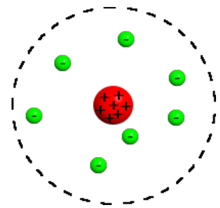

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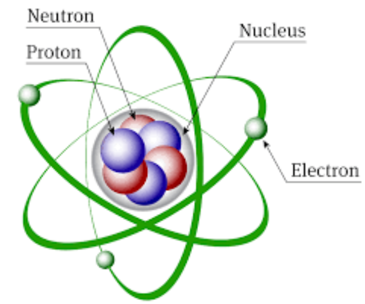
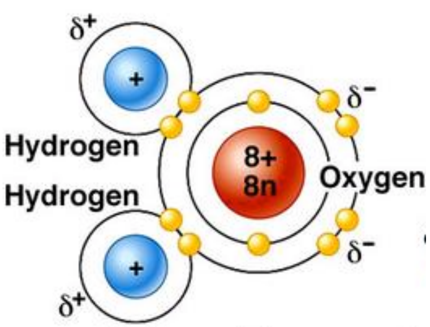


Quantum orbitals

Discovery: ✧ Tiny nucleus - *less than 1 trillionth in volume of an atom*
✧ Quantum probability - *the Quantum World!*

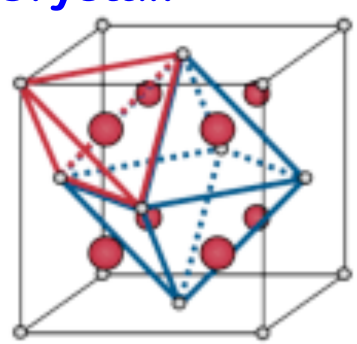
- Localized mass and charge centers – vast "open" space:

Molecule:



"Water"

Crystal:



Rare-Earth metal

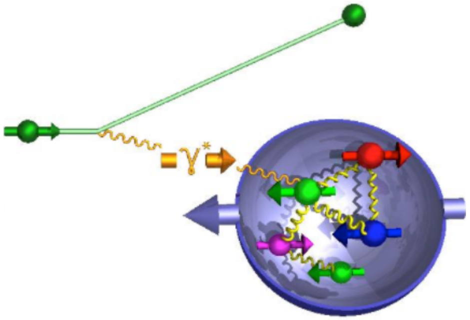
Nanomaterial:

Carbon-based

➡ *Infinite opportunities to create & improve … !*

Hadronic Structure – QCD

- **Modern Rutherford experiment – SLAC (about 50 years ago):**

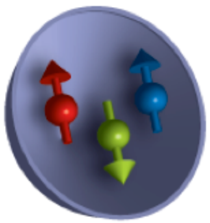


DIS

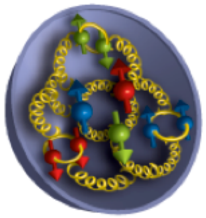
SIDIS

EDIS

Quark-Model



QCD



Nucleon: Strongly interacting, relativistic bound state of quarks & gluons

Hadronic Structure – QCD

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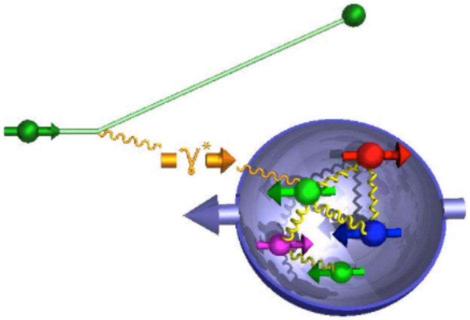

DIS
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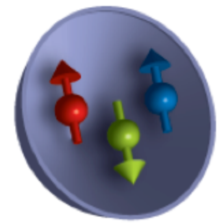
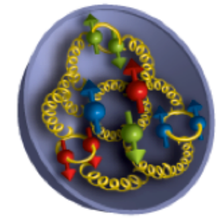


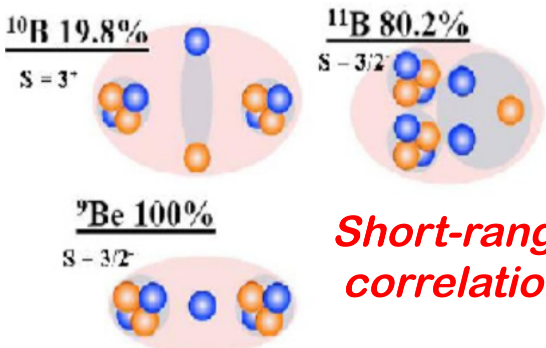
QCD



Nucleon: Strongly interacting, relativistic bound state of quarks & gluons

- NO localized mass and charge centers – "Strong fluctuation":

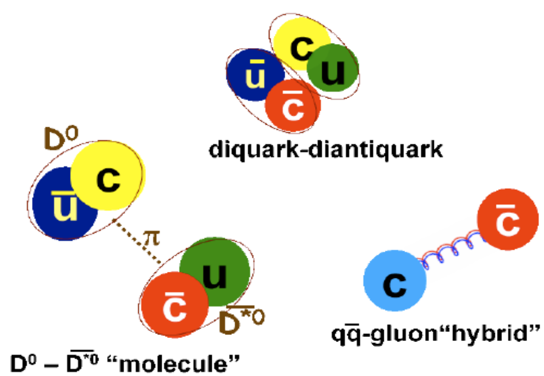
Nuclei – "Molecule"



Short-range correlation

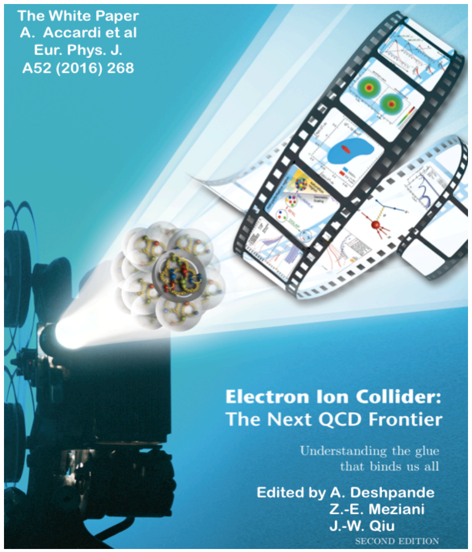
"Light-flavor"

XYZ – "Nuclei"



"Heavy-flavor"

"Femto-technology"



New frontier of hadron physics … !

Outline of my talk

- ❑ How to quantify the hadron structure in QCD?
- ❑ How to "see" hadron structure?
- ❑ What have we learned from existing facilities?
- ❑ What do we hope to learn from future facilities?
  - ✧ From Electron-Ion Collider – Next talk by C. Keppel
  - ✧ From Lattice QCD – Complementary to experiments
- ❑ Summary

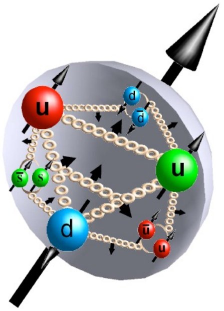
How to quantify hadron structure in QCD?

❑ What do we need to know for the structure?

- ✧ **In theory:** $\langle P, S|\mathcal{O}(\overline{\psi}, \psi, A^{\mu})|P, S\rangle$ **– Hadronic matrix elements**

  of all possible operators: $\mathcal{O}(\overline{\psi}, \psi, A^{\mu})$

  ➡ ***Correlations between any number of fields in QCD***



- ✧ **BUT:** ***None of these matrix elements is a direct physical observable – color confinement!***

How to quantify hadron structure in QCD?

❑ What do we need to know for the structure?

✧ **In theory:** $\langle P,S|\mathcal{O}(\overline{\psi},\psi,A^\mu)|P,S\rangle$ – **Hadronic matrix elements**

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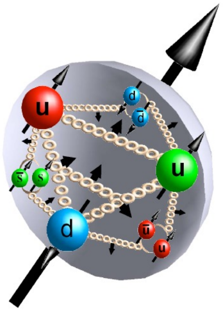


➡ ***Correlations between any number of fields in QCD***

✧ **BUT:** ***None of these matrix elements is a direct physical observable – color confinement!***

✧ **In practice:** **Accessible hadron structure**
= hadron matrix elements of quarks and gluons, satisfying

1) **can be related to physical cross sections of hadrons and leptons with controllable approximation; and/or**

2) **can be calculated/extracted from lattice QCD**

✧ **Resolution:** **Wave vs. particle nature of quarks and gluons?**

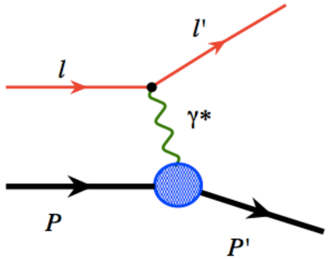
➡ ***Need two-scale probes/observables !***

Large scale – particle nature, small scale – the structure

How to quantify hadron structure in QCD?

- No elastic color current form factor!

QED:

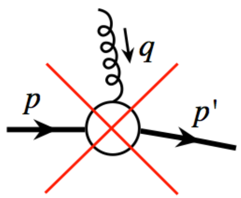


Form factors

Electric charge distribution

Proton radius – EM charge

QCD:



Gluon carries color!

Parton density distributions

Proton radius – quark & gluon density distributions

How to quantify hadron structure in QCD?

❑ **No elastic color current form factor!**

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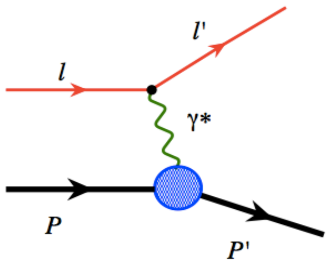
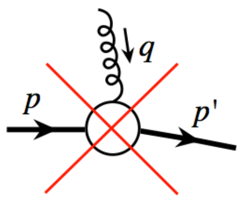


➡ *Form factors*

➡ *Electric charge distribution*

➡ *Proton radius – EM charge*

QCD:



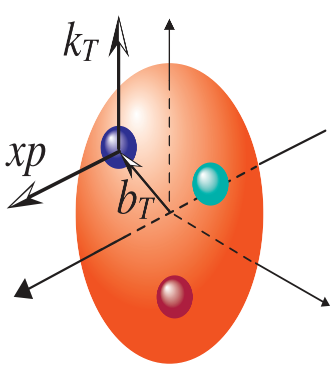
Gluon carries color!

➡ *Parton density distributions*

➡ *Proton radius – quark & gluon density distributions*

❑ **Single-parton structure "seen" by a short-distance probe:**

✧ **5D structure – encoded into the following density distribusions:**



1) $\int d^2b_T$ ➡ $f(x, k_T, \mu)$ – **TMDs:** *2D confined motion!*

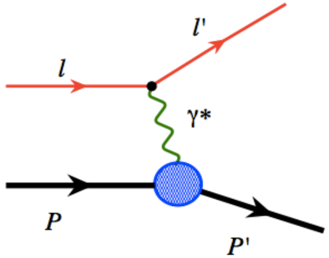
2) $\int d^2k_T$ ➡ $F(x, b_T, \mu)$ – **GPDs:** *2D spatial imaging!*

3) $\int d^2k_T d^2b_T$ ➡ $f(x, \mu)$ – **PDFs:** *Number density!*

How to quantify hadron structure in QCD?

- ❑ **No elastic color current form factor!**

QED:

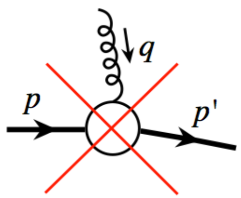


→ *Form factors*

→ *Electric charge distribution*

→ *Proton radius – EM charge*

QCD:



Gluon carries color!

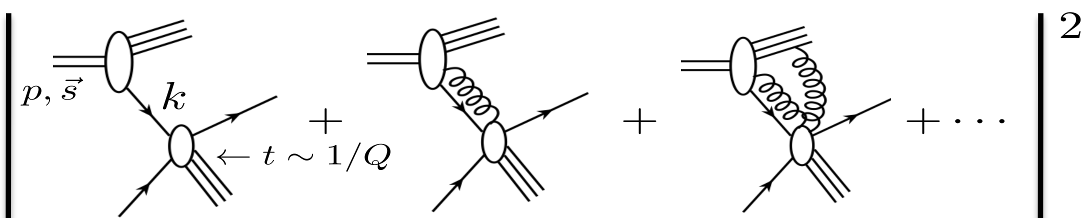
→ *Parton density distributions*

→ *Proton radius – quark & gluon density distributions*

- ❑ **Multi-parton, quark-gluon corretions:**

Single-spin asymmetry: $\propto [\sigma(Q,\vec{s}) - \sigma(Q,-\vec{s})]$

$\sigma(Q,\vec{s}) \propto$



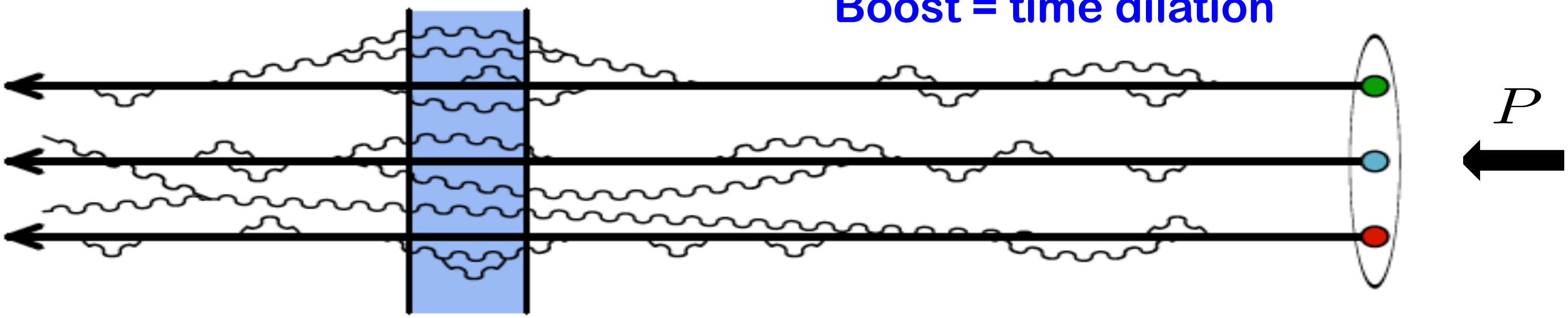
$\left(\frac{\langle k_\perp \rangle}{Q}\right)^n$ **– Expansion**

Quantum interference → **3-parton matrix element – not a probability!**

How to “see” the hadron structure?

- Need high energy probes to “see” the **boosted** structure:

Boost = time dilation



Hard probe (t ~ 1/Q < fm): ***Catches the quantum fluctuation!***

- ✧ **Longitudinal momentum fraction – *x* :** $xP \sim Q$
- ✧ **Transverse momentum – confined motion:** $1/R \sim \Lambda_{\rm QCD} \ll Q$

How to “see” the hadron structure?

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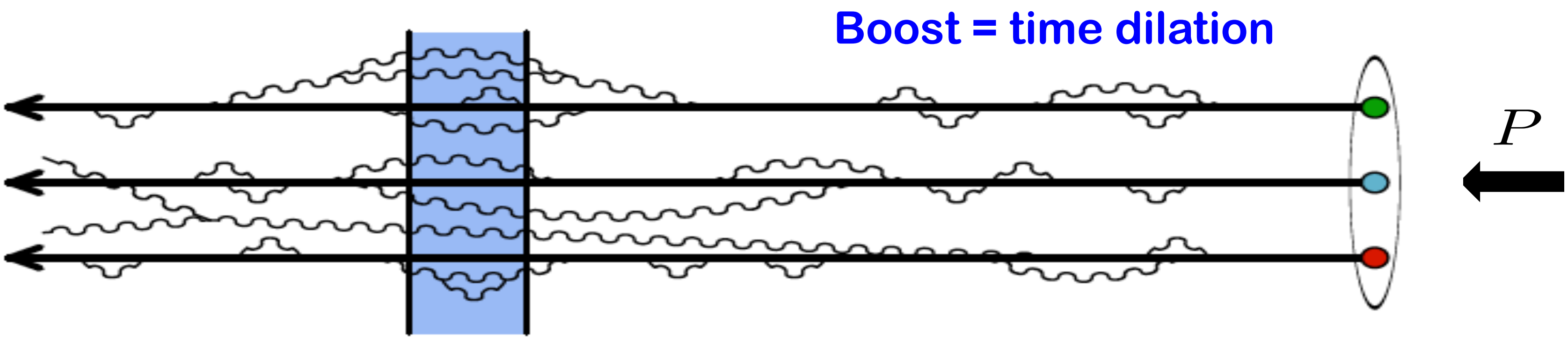


Hard probe ($t \sim 1/Q <$ fm): *Catches the quantum fluctuation!*

✧ Longitudinal momentum fraction – *x* : $xP \sim Q$

✧ Transverse momentum – confined motion: $1/R \sim \Lambda_{\text{QCD}} \ll Q$

- Challenge:

No modern detector can see quarks and gluons in isolation!

- Question:

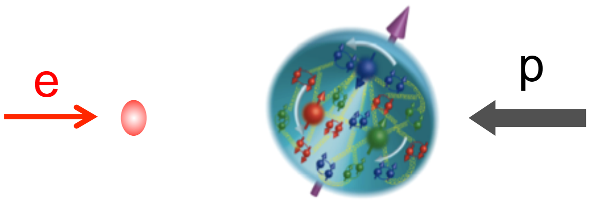
How to quantify the hadron structure if we cannot see quarks and gluons?

- Answer:

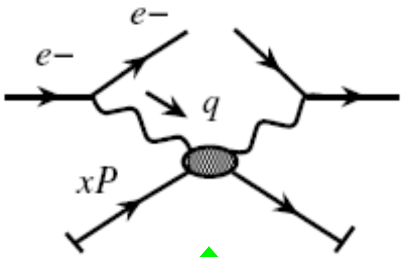
QCD factorization! *Not exact, but, controllable approximation!*

Factorization: connecting hadrons to partons

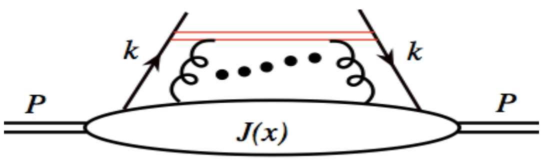
- **One hadron:**



$\sigma_{\text{tot}}^{\text{DIS}}$:



$\otimes$



$+\, O\left(\frac{1}{QR}\right)$

Hard-part Probe	Parton-distribution Structure	Power corrections Approximation

Factorization: connecting hadrons to partons

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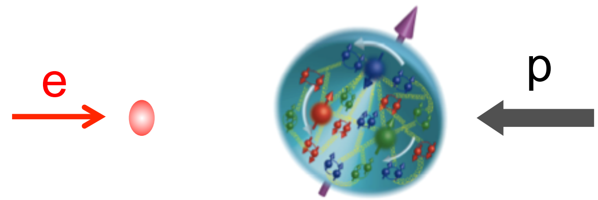
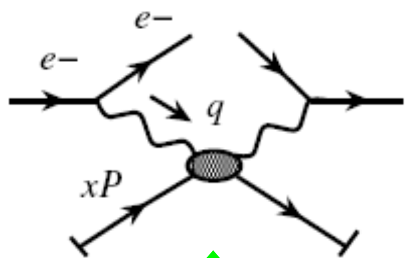
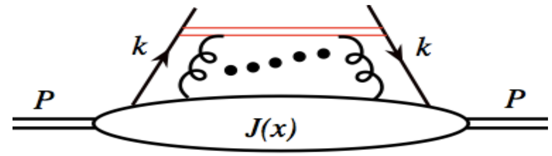


$\sigma_{\text{tot}}^{\text{DIS}}$:



$\otimes$



$+\, O\left(\frac{1}{QR}\right)$

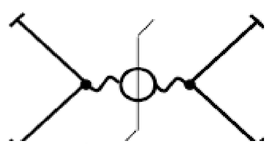
Hard-part
Probe

Parton-distribution
Structure

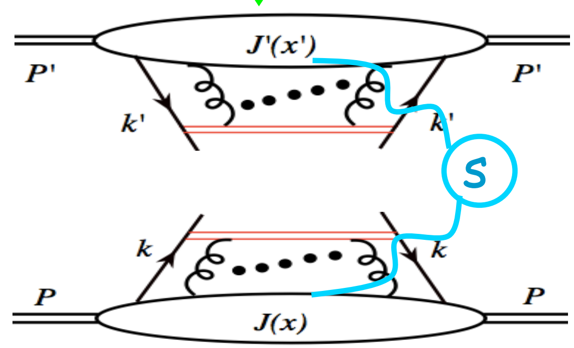
Power corrections
Approximation

❑ Two hadrons:

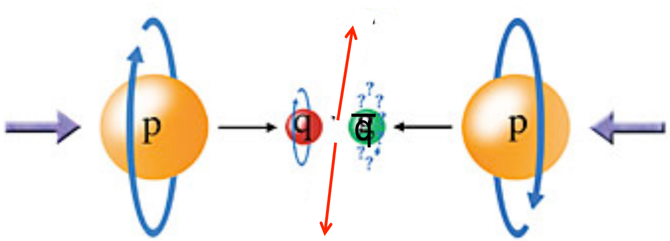
$\sigma_{\text{tot}}^{\text{DY}}$:



$\otimes$



$+\, O\left(\frac{1}{QR}\right)$



Predictive power:
Universal Parton Distributions

Density, helicity, transversity distributions

- **General expansion of quark distribution** $\phi(x)$**:**

must have general expansion in terms of $\not{P}$, $\not{n}$, $\not{s}$ etc.

$$\phi(x) = \frac{1}{2}\left[q(x)\gamma\cdot P + s_{\|}\Delta q(x)\gamma_5\gamma\cdot P + \delta q(x)\gamma\cdot P\gamma_5\gamma\cdot S_\perp\right]$$

- **3-leading power quark parton distribution:**

$$q(x) = \frac{1}{4\pi}\int dz^-\, e^{iz^- xP^+}\,\langle P,S|\bar{\psi}(0)\,\gamma^+\,\psi\left(0,z^-,\mathbf{0}_\perp\right)|P,S\rangle$$

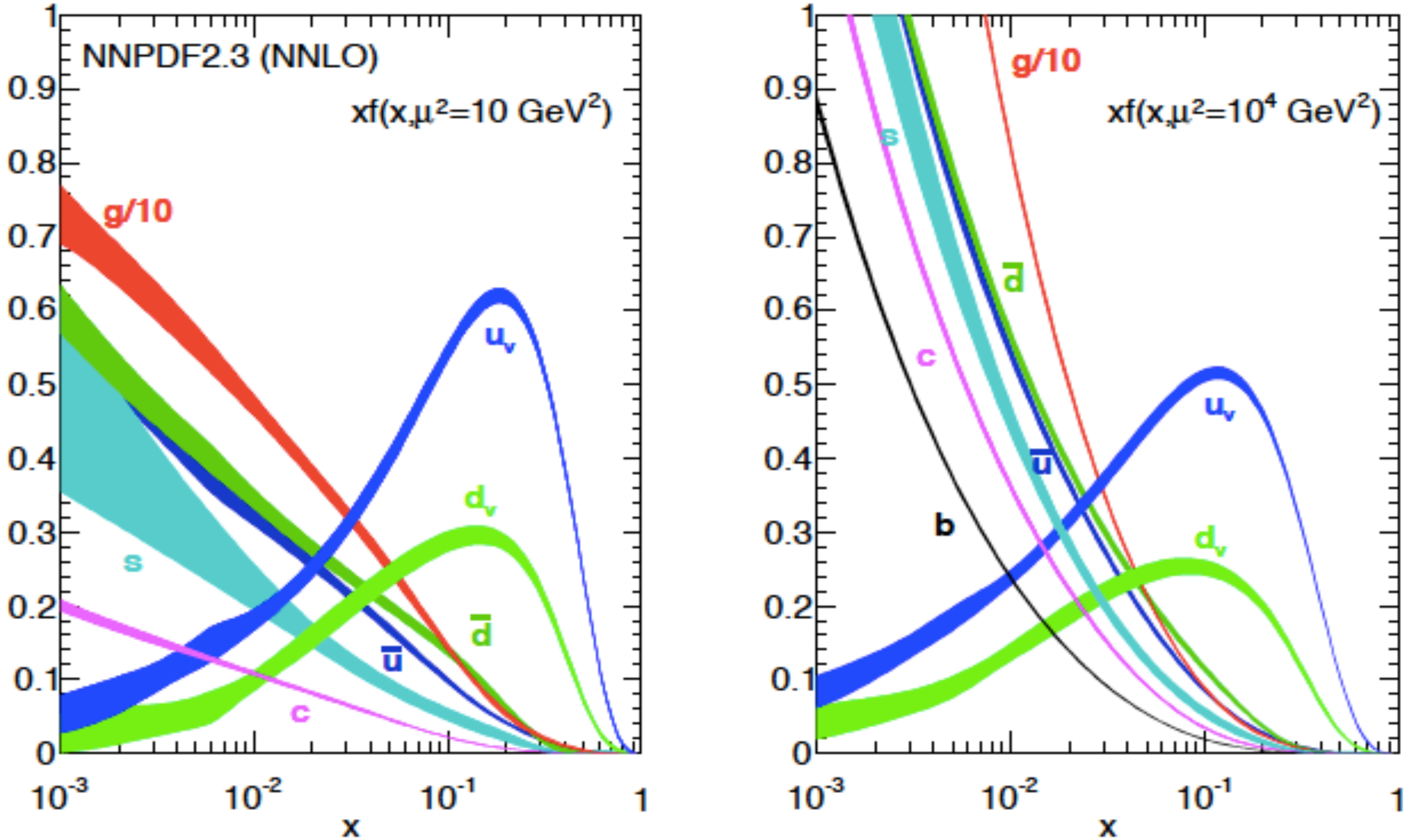
$$\Delta q(x) = \frac{1}{4\pi}\int dz^-\, e^{iz^- xP^+}\,\langle P,S|\bar{\psi}(0)\,\gamma^+\,\gamma_5\,\psi\left(0,z^-,\mathbf{0}_\perp\right)|P,S\rangle$$

$$\delta q(x) = \frac{1}{4\pi}\int dz^-\, e^{iz^- xP^+}\,\langle P,S|\bar{\psi}(0)\,\gamma^+\,\gamma_\perp\,\gamma_5\,\psi\left(0,z^-,\mathbf{0}_\perp\right)|P,S\rangle$$

"unpolarized" – "longitudinally polarized" – "transversity"

PDFs of a spin-averaged proton

- Modern sets of PDFs @NNLO with uncertainties:

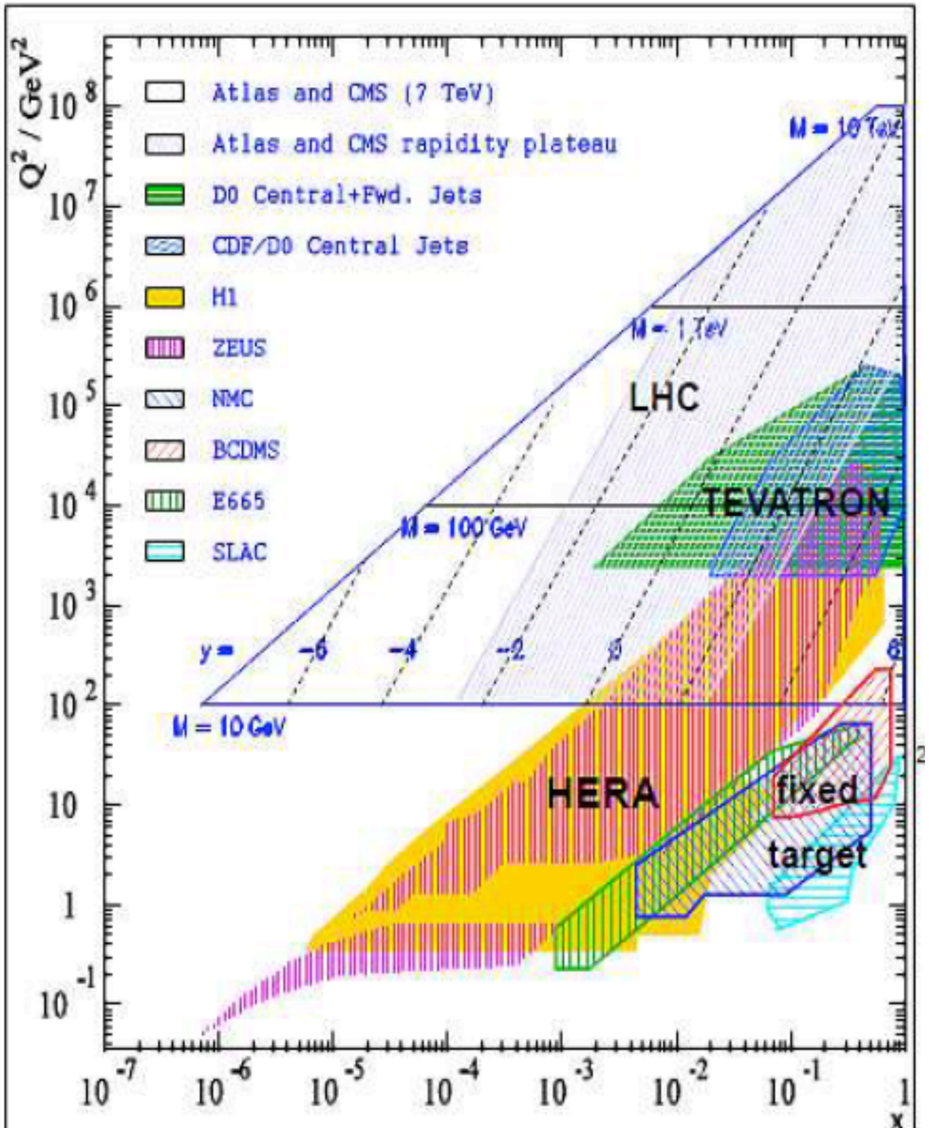


K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014)

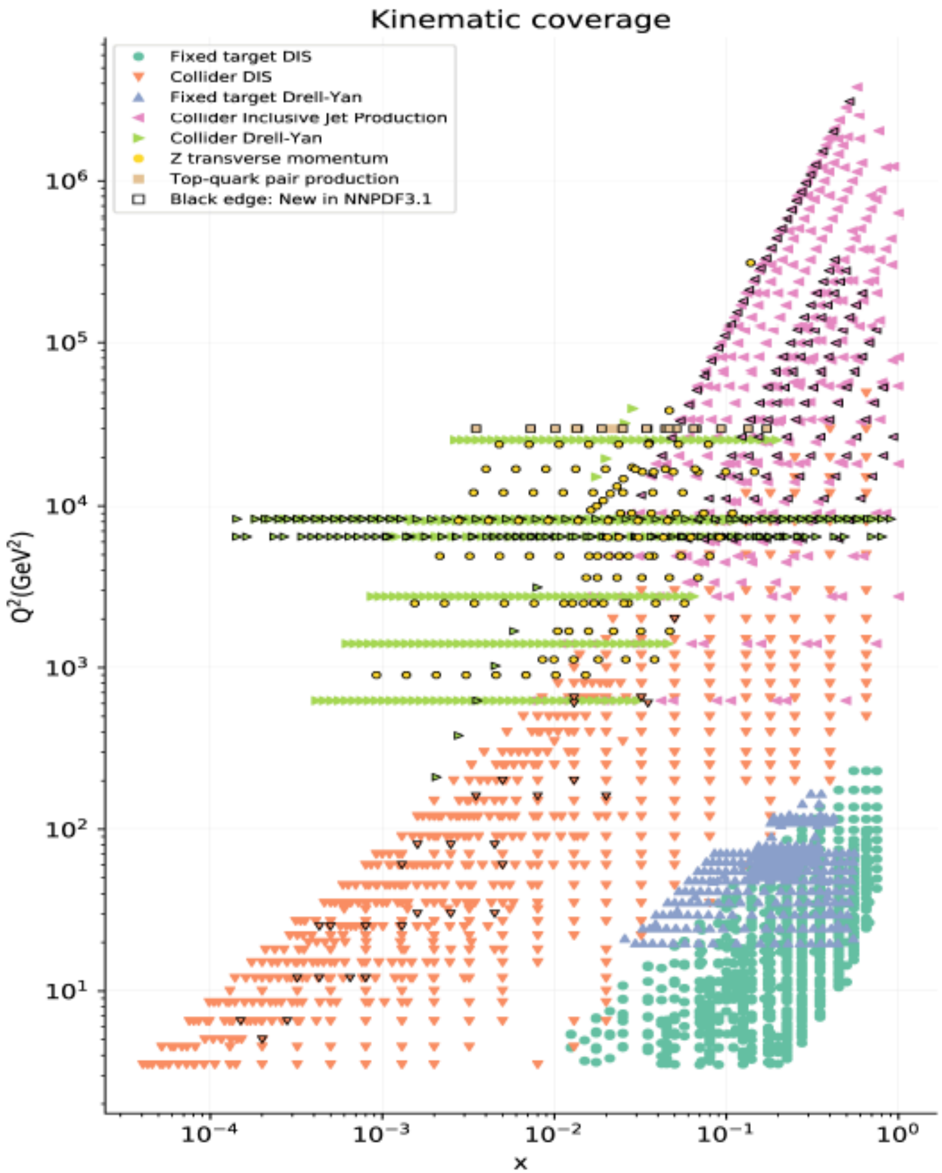
Consistently fit almost all data with Q > 2GeV

New data and kinematic coverage

Experiments and x, Q^2 coverage

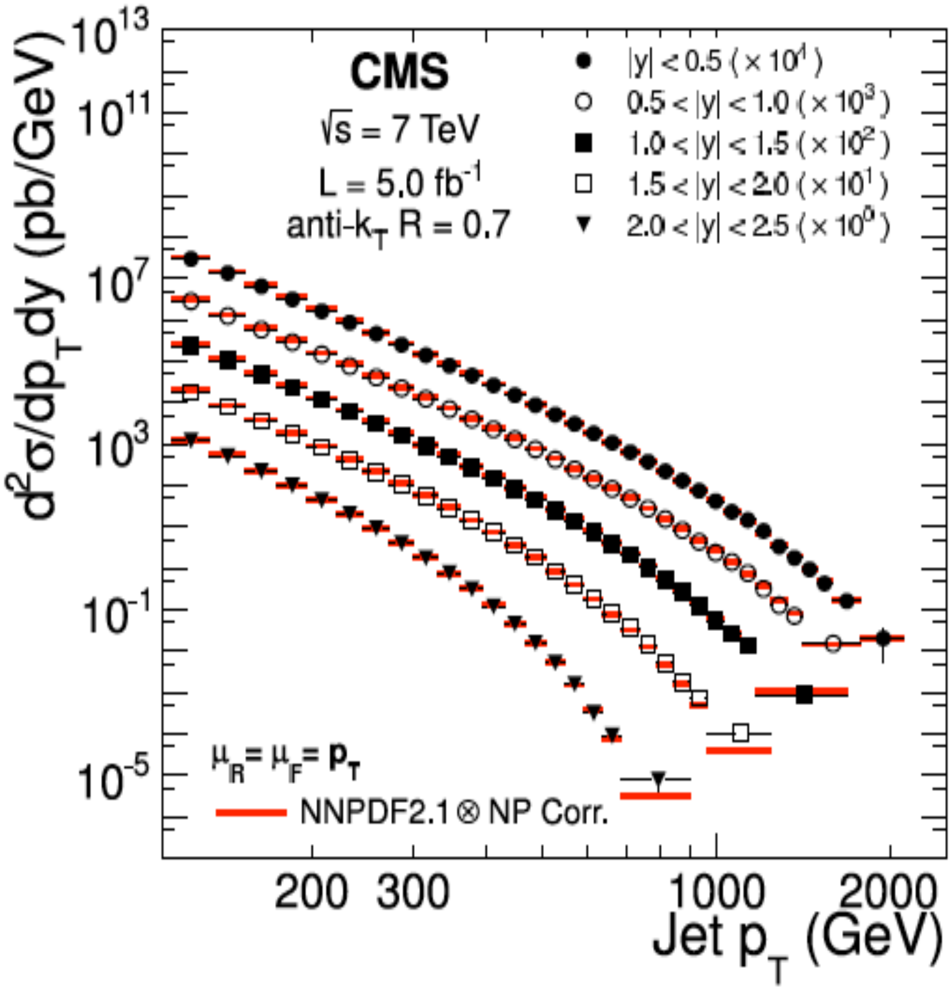


Selection of data doe NNPDF3.1



Role of LHC data

❑ Inclusive jet production at 7 TeV:

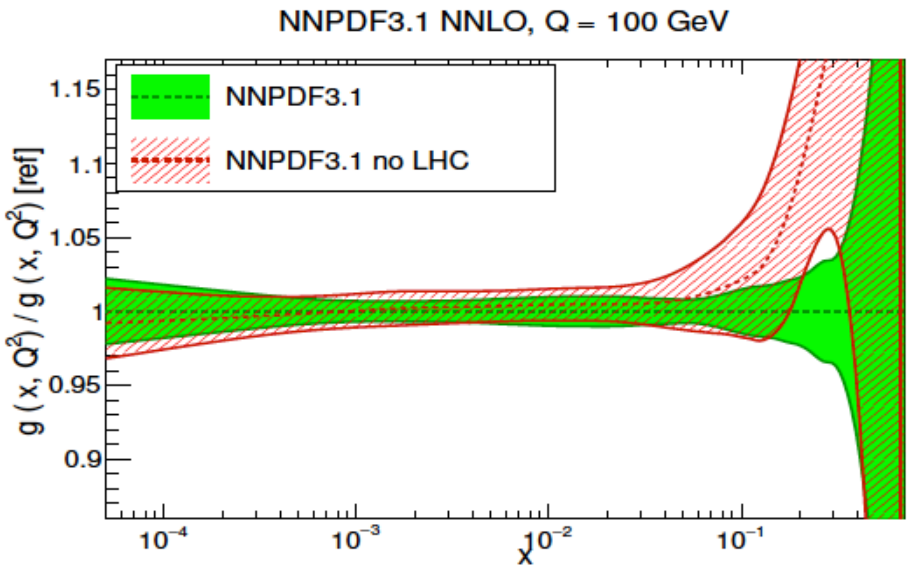


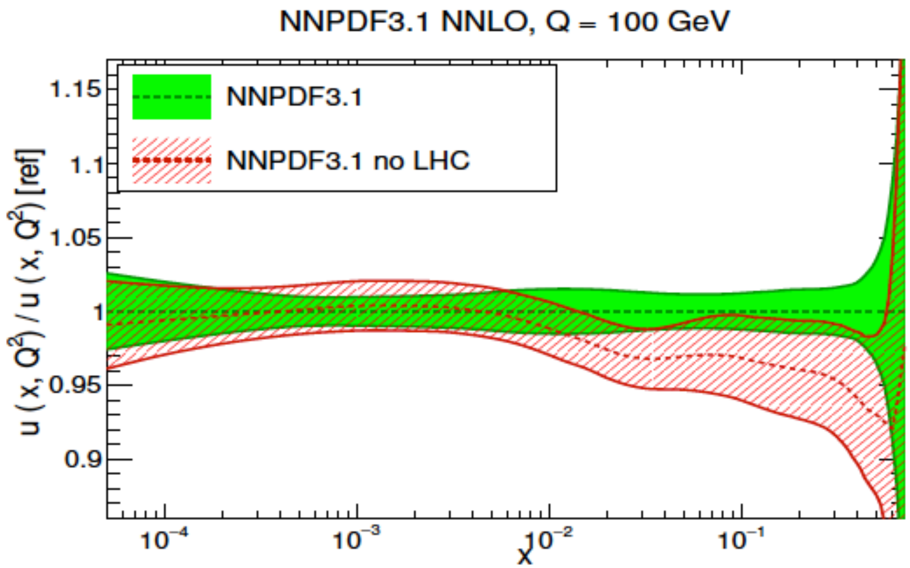
✧ Cross sections span 12 orders of magnitude

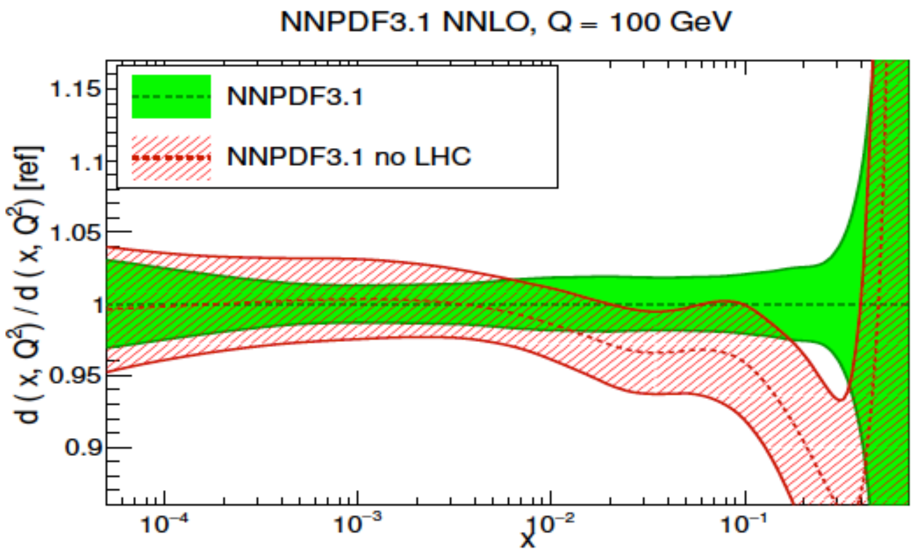
✧ Almost negligible statistical error

Role of LHC data

❑ Impact of the LHC data:



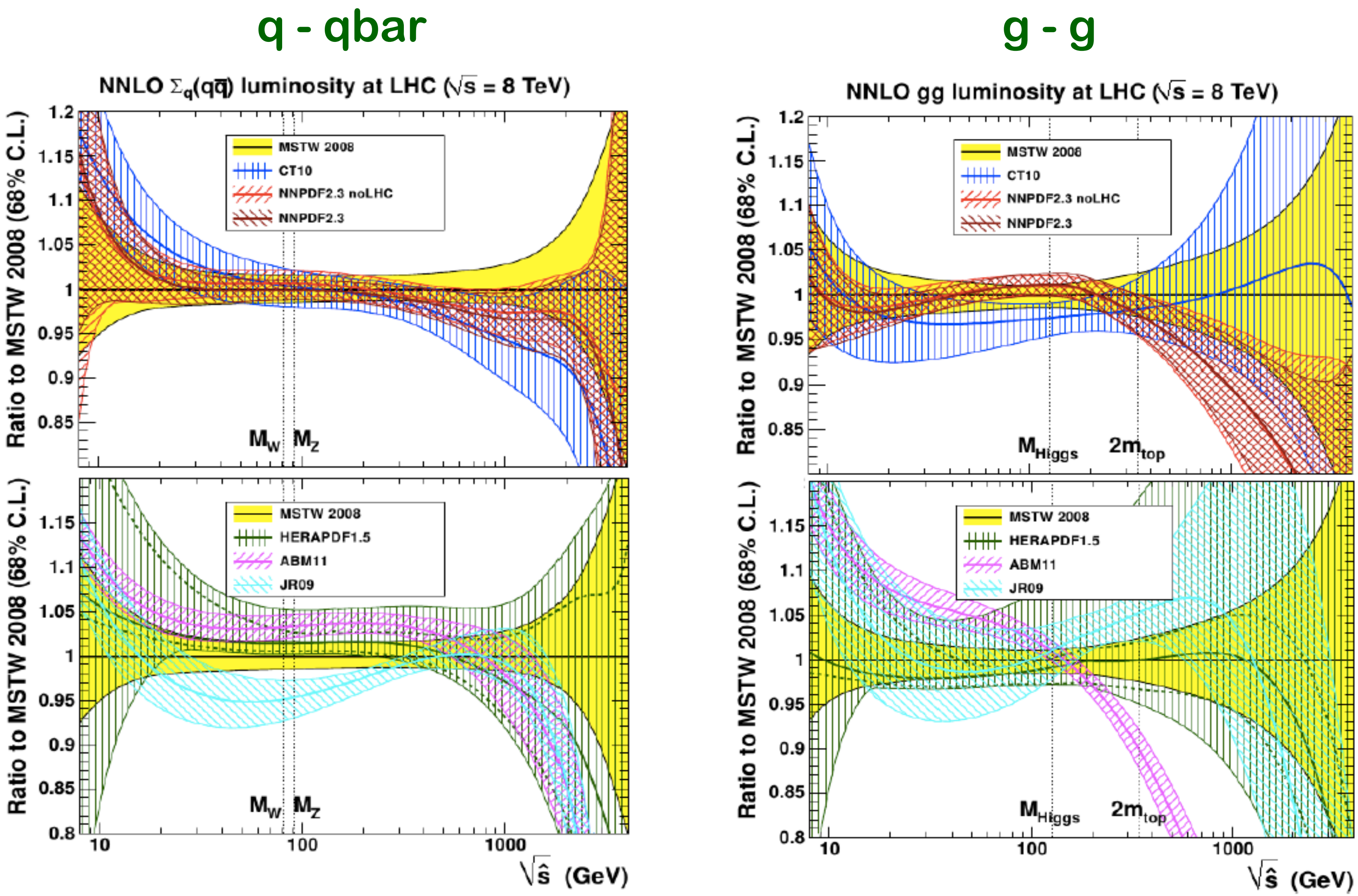




✧ Changes are mainly for large-x region

✧ PDFs are well-determined for intermediate-x region

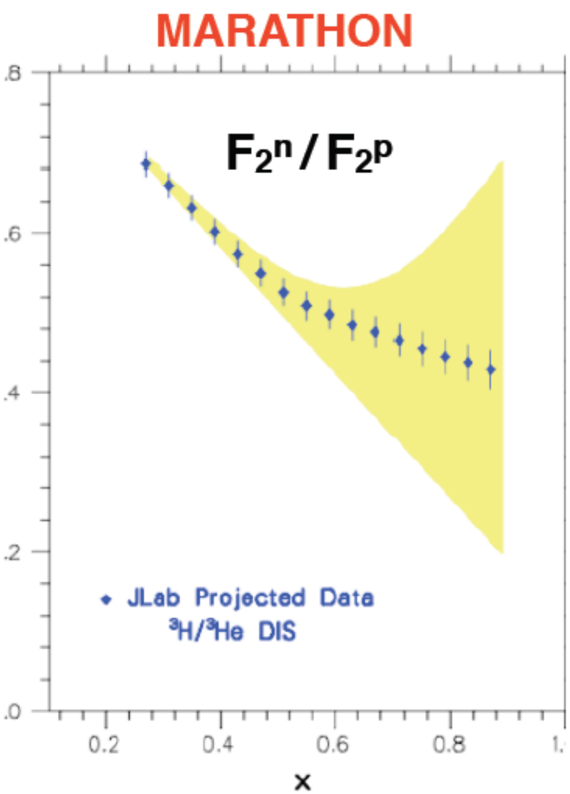
Partonic luminosities

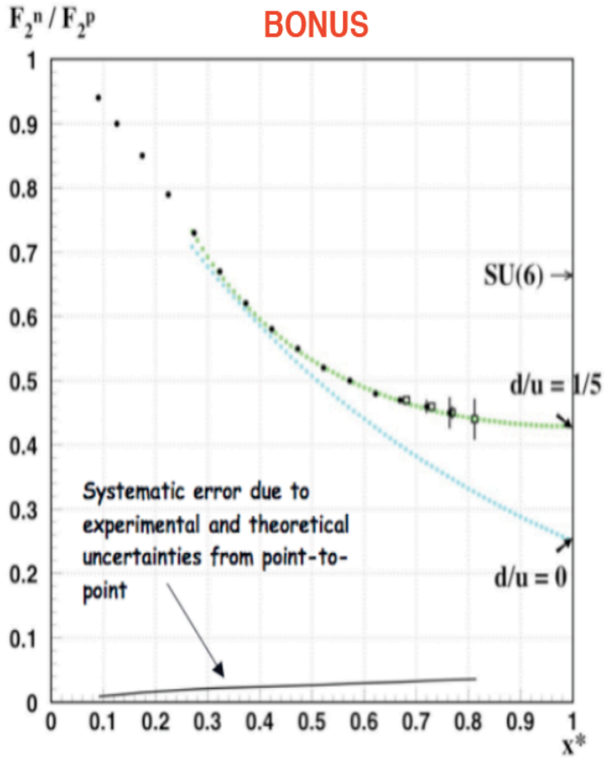


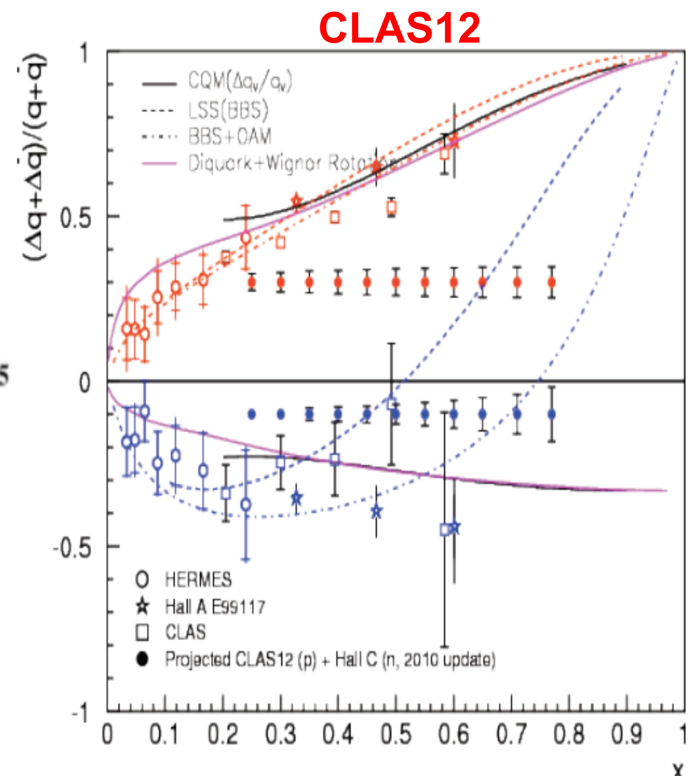
Uncertainties are mainly in large- and small-x regimes

Future large-x experiments – JLab12

- NSAC milestone HP14 (2018):







Plus many more JLab experiments:

E12-06-110 (Hall C on ^3He), E12-06-122 (Hall A on ^3He),

E12-06-109 (CLAS on NH_3, ND_3), …

and Fermilab E906, …

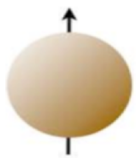
EIC help fix small-x PDFs!

Can lattice QCD help large-x?

Hadron spin

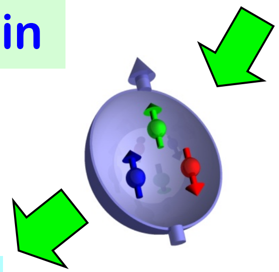
- **How does QCD make up the nucleon's spin?**

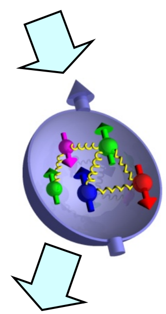
(Proton's helicity structure: $S^z = \sum_f \langle P, S | \hat{J}^z_f(\mu) | P, S \rangle$ **)**

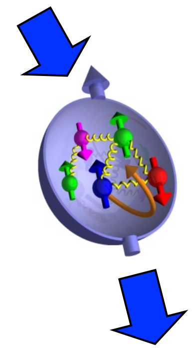


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

Proton Spin







Quark helicity
Best known

$$\frac{1}{2}\int dx \left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$

$$\sim 30\%$$

Spin "puzzle"

Gluon helicity
Start to know

$$\Delta G = \int dx \Delta g(x)$$

$$\sim 20\% (\text{with RHIC data})$$

Orbital Angular Momentum
of quarks and gluons
Little known

If we do not understand proton spin, we do not understand QCD

Polarized deep inelastic scattering

❑ Spin asymmetries – measured experimentally:

✧ **Longitudinal polarization –** $\alpha = 0$

Known function

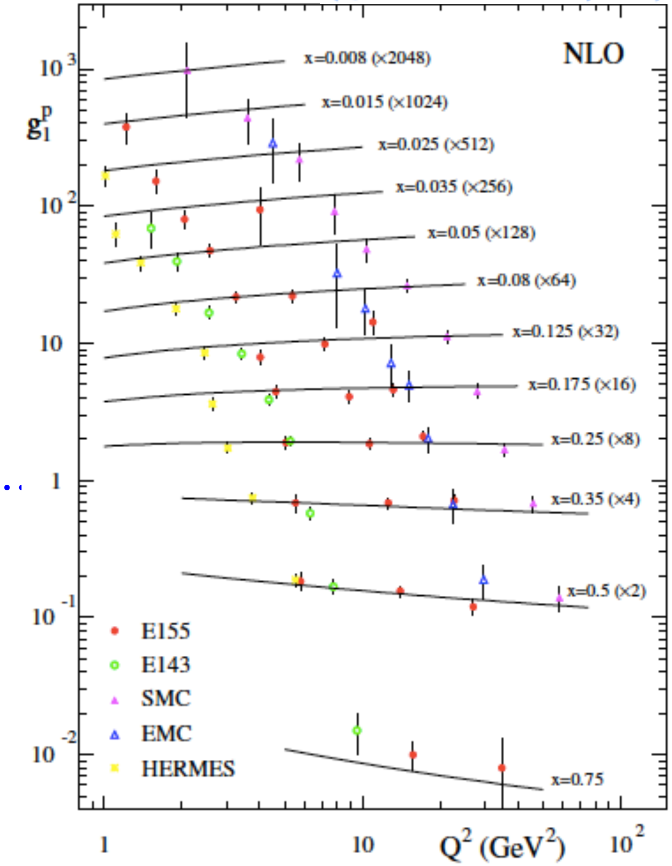
$$A_{\|} = \frac{d\sigma^{(\rightarrow\Leftarrow)} - d\sigma^{(\rightarrow\Rightarrow)}}{d\sigma^{(\rightarrow\Leftarrow)} + d\sigma^{(\rightarrow\Rightarrow)}} = D(y)\,\frac{g_1(x,Q^2)}{F_1(x,Q^2)} \equiv D(y)\,A_1(x,Q^2)$$

$(\,y = 1 - E'/E\,)$

✧ **So far only "fixed target" experiments:**

CERN:	EMC, SMC, COMPASS
SLAC:	E80, E130, E142, E143, E154
DESY:	HERMES
JLab:	Hall A,B,C, many experiments

with various polarized targets: $p,\ d,\ {}^3\mathrm{He}, \ldots$

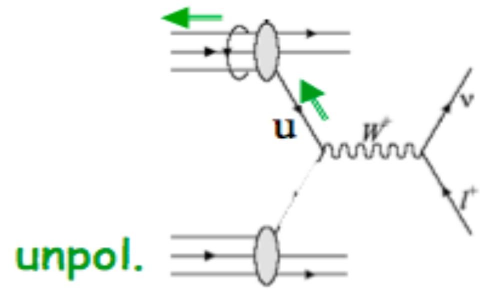


Sea quark polarization – RHIC W program

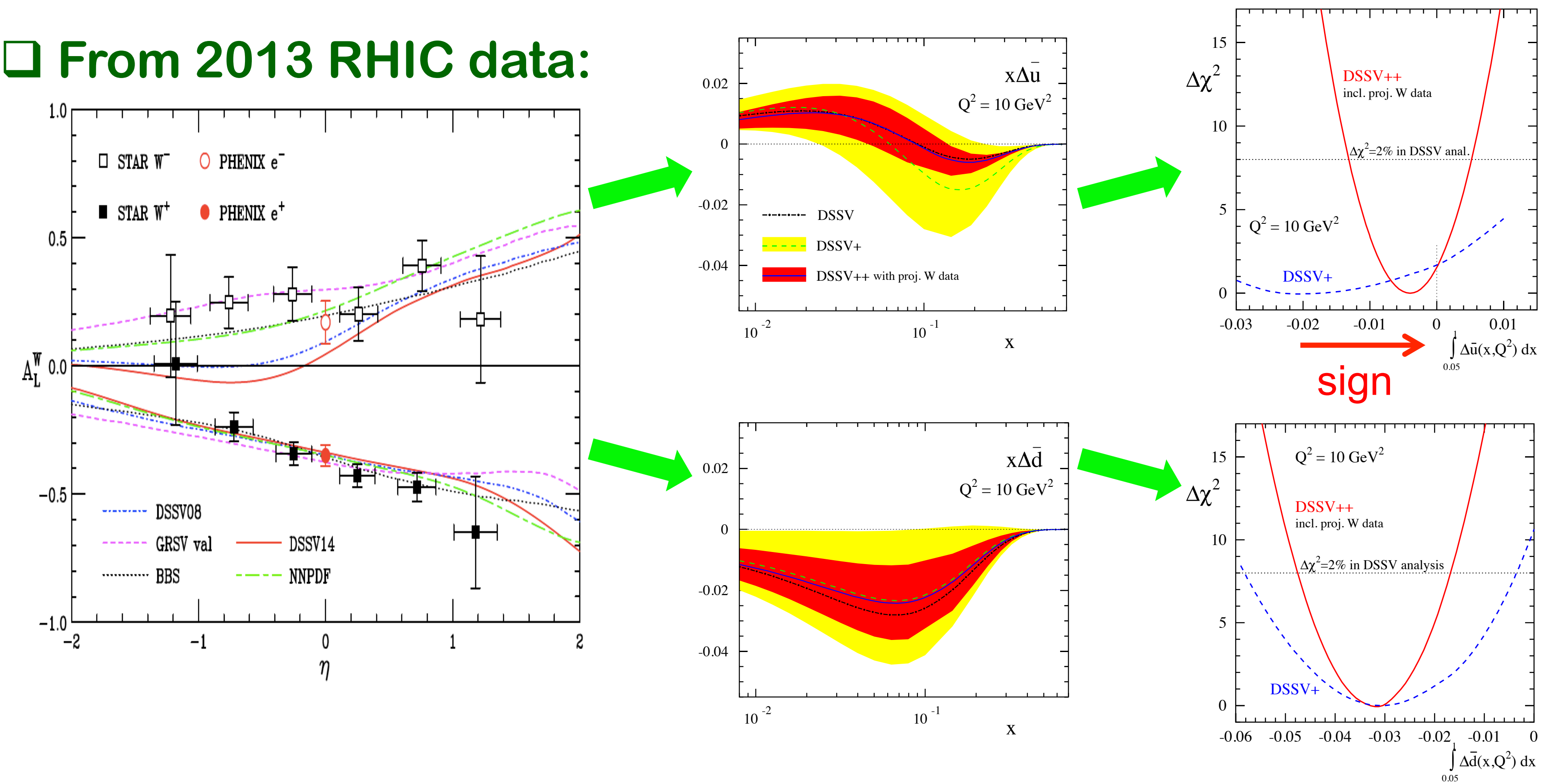
- ❑ **Single longitudinal spin asymmetries:**

$$A_L = \frac{[\sigma(+) - \sigma(-)]}{[\sigma(+) + \sigma(-)]} \quad \text{for } \sigma(s)$$

Parity violating weak interaction

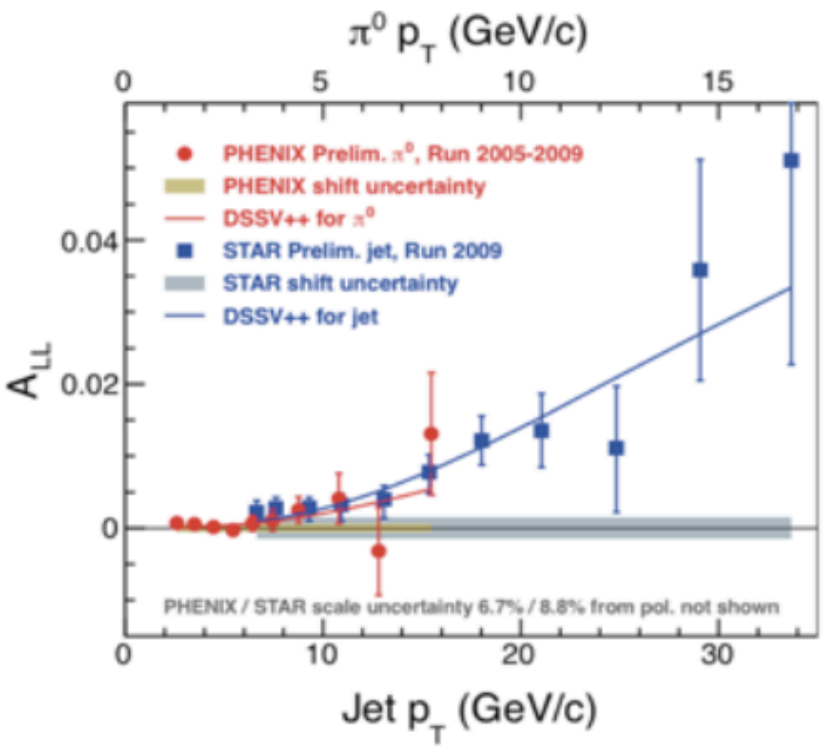


- ❑ **From 2013 RHIC data:**



Impact of RHIC measurements on Δg

new RHIC data included in DSSV++

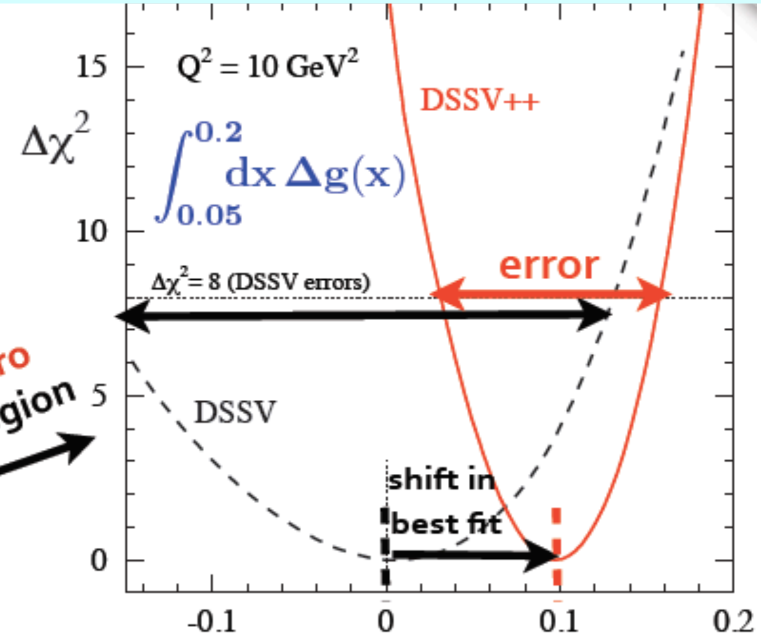


$$\int_{0.05}^{0.2} dx\, \Delta g(x, Q^2 = 10\, \mathrm{GeV}^2) = 0.1^{+0.06}_{-0.07}$$

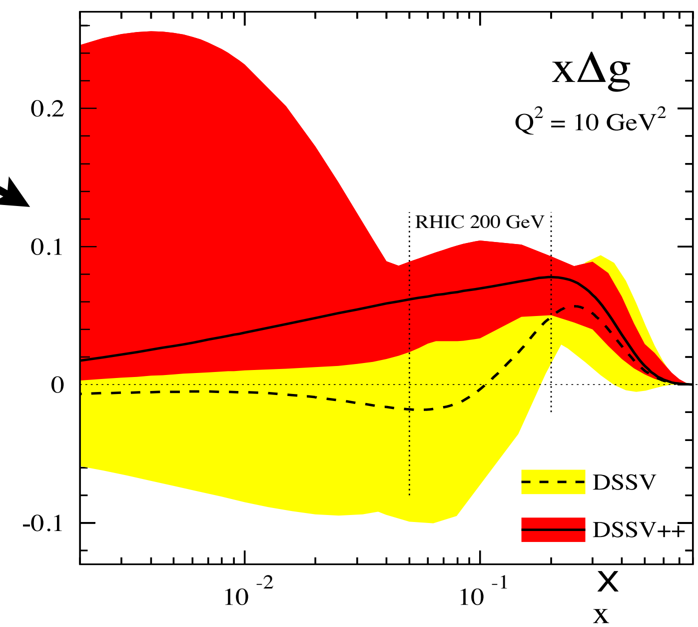
fully compatible with old DSSV error estimate

COMPASS measurement is consistent

lead to non-zero Δg in RHIC x-region



positive Δg in RHIC x-region



Strange quark – combining fits for PDFs & FFs

❑ Strange quark polarization puzzle:

– Global fits for polarized PDFs using inclusive DIS data:

$\Delta s(x) + \Delta\bar{s}(x) < 0$ for all x $\Rightarrow$ $\Delta s + \Delta\bar{s} \approx -0.1$

– Global fits for polarized PDFs with SIDIS data:

$\Delta s(x) + \Delta\bar{s}(x) > 0$ for measured x range

Strange quark – combining fits for PDFs & FFs

❑ Strange quark polarization puzzle:

– Global fits for polarized PDFs using inclusive DIS data:

$\Delta s(x) + \Delta\bar{s}(x) < 0$ **for all x** ➡ $\Delta s + \Delta\bar{s} \approx -0.1$

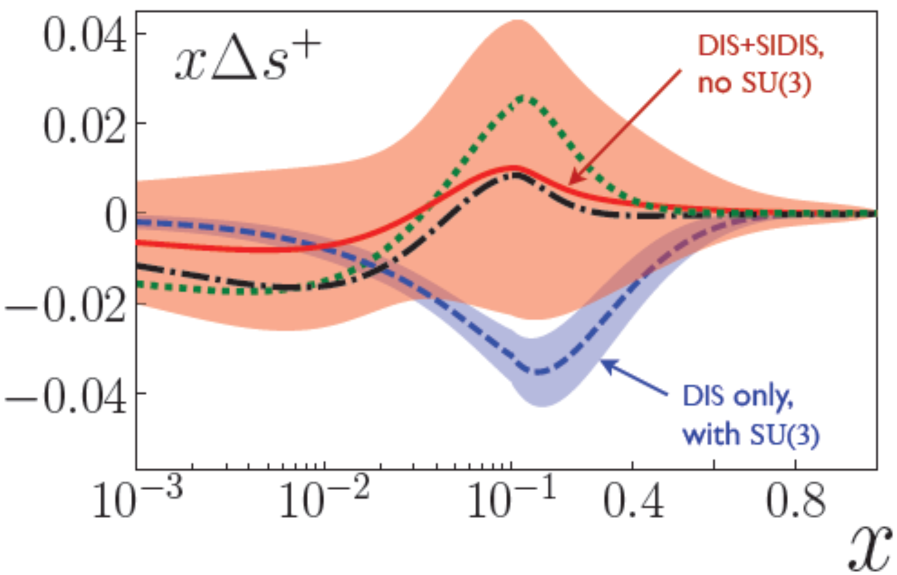
– Global fits for polarized PDFs with SIDIS data:

$\Delta s(x) + \Delta\bar{s}(x) > 0$ **for measured x range**

❑ First simultaneous analysis of spin-PDFs and FFs:

– Both polarized DIS and SIDIS + Single inclusive e+e-, including 6 GeV CLAS data

– Without SU(3) assumption



➡ Resolution of the "puzzle"

$$\Delta s + \Delta\bar{s} = -0.03 \pm 0.10$$

Consistent with lattice result:

$$[\Delta s + \Delta\bar{s}]_{\mathrm{Lattice}} = -0.02(1)$$

Additional quark contribution to Proton Spin:

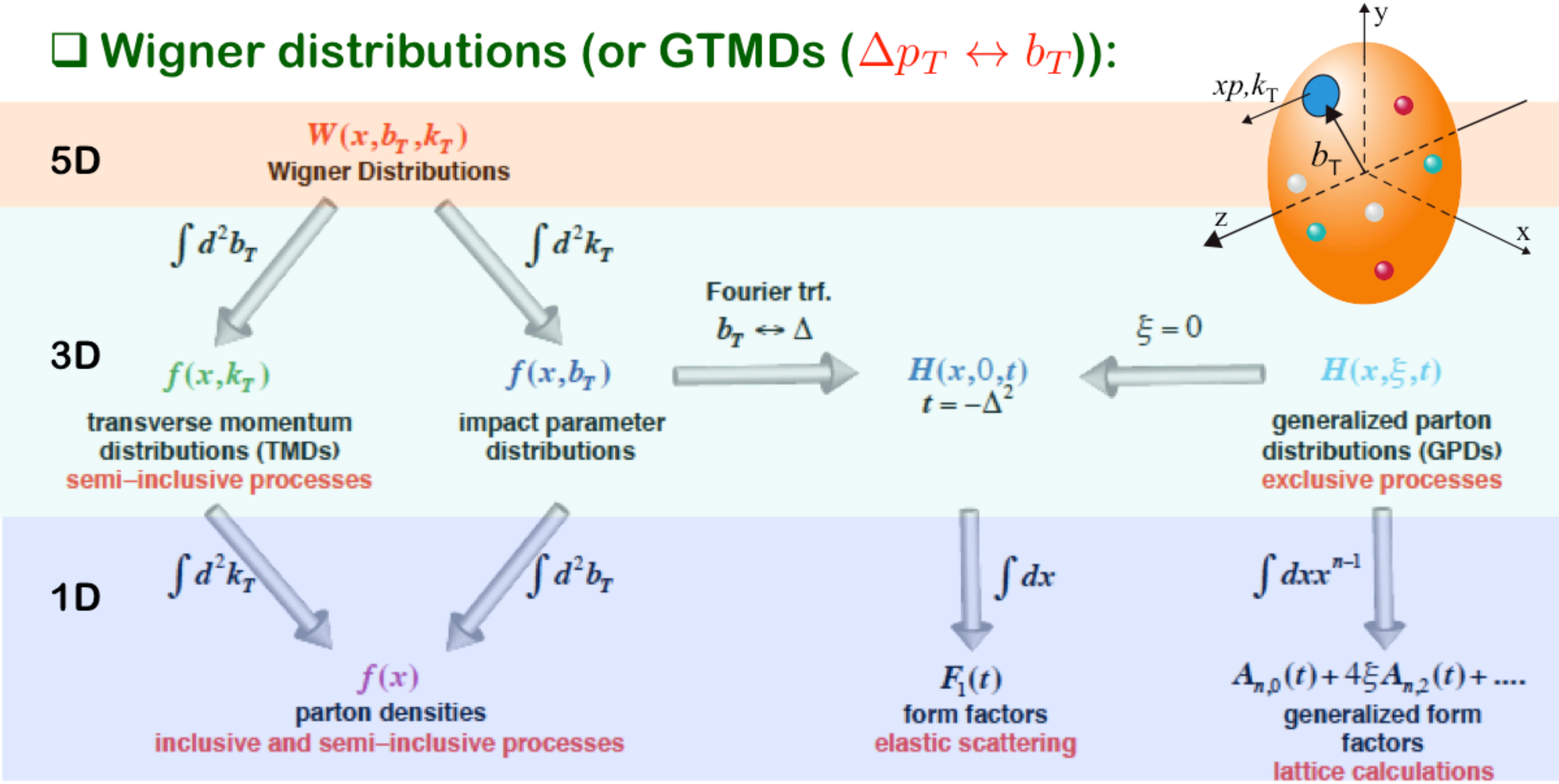
$\Delta\Sigma \approx 0.36 \pm 0.09$ **at 1 GeV**

$\sim 25\%$ larger

J.J. Ethier et al. 1705.05889

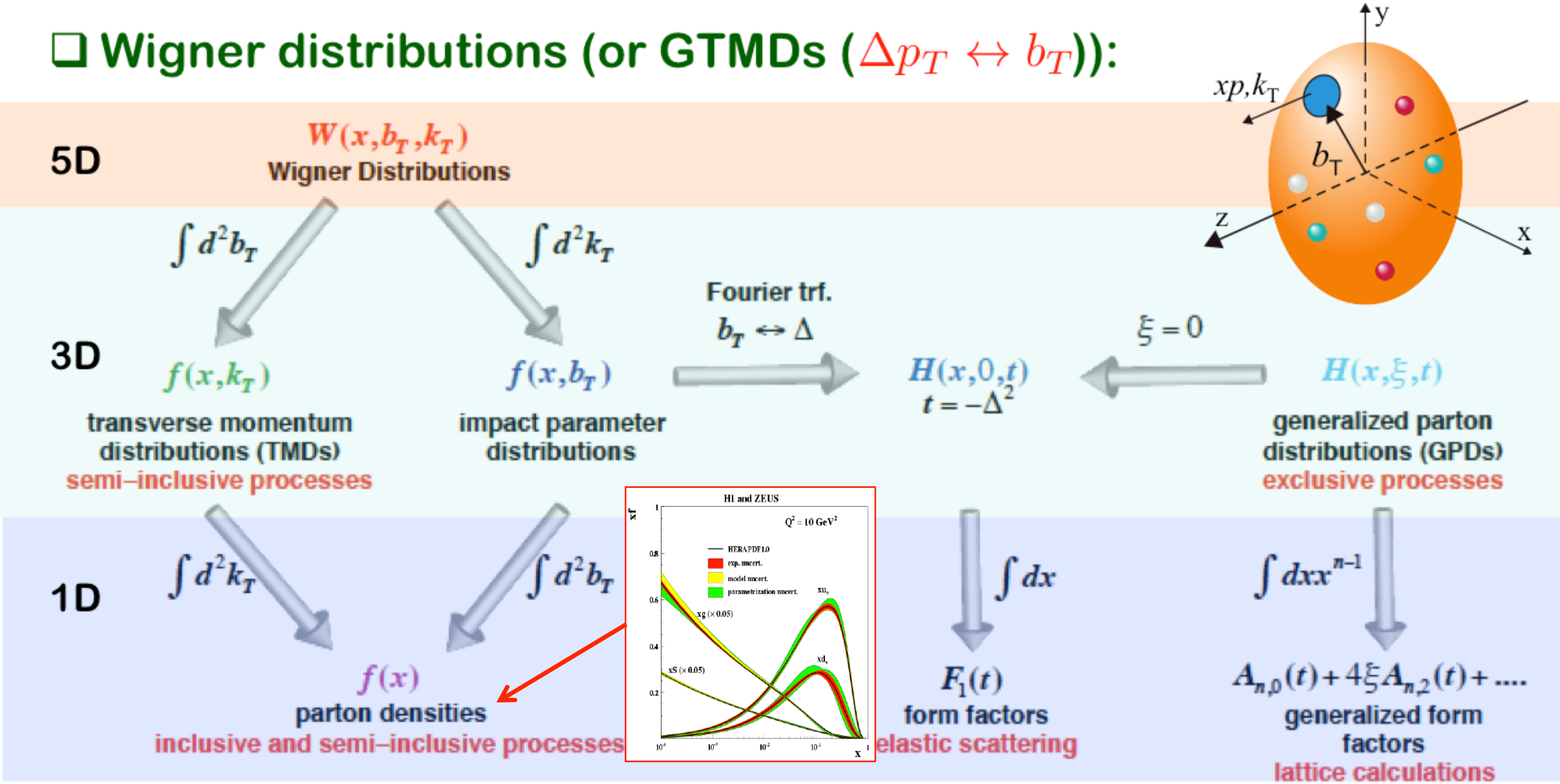
Paradigm shift: 5D imaging of hadrons

- Wigner distributions (or GTMDs ($\Delta p_T \leftrightarrow b_T$)):



Paradigm shift: 5D imaging of hadrons

❑ **Wigner distributions (or GTMDs ($\Delta p_T \leftrightarrow b_T$)):**



❑ **JLab12 + EIC – 3D imaging of quarks and gluons:**

- ✧ **TMDs – Confined motion in a nucleon (semi-inclusive DIS)**
- ✧ **GPDs – Spatial imaging of quarks and gluons (exclusive DIS)**

Paradigm shift: 5D imaging of hadrons

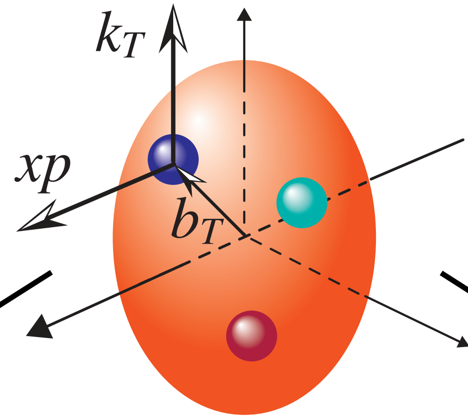
❑ 5D boosted partonic structure:

Momentum Space

TMDs (3D)

Confined motion

$\int d^2 b_T$



$\int d^2 k_T$

Coordinate Space

GPDs (3D)

Spatial distribution

$f(x,k_T)$

Two-scales observables

$f(x,b_T)$

Paradigm shift: 5D imaging of hadrons

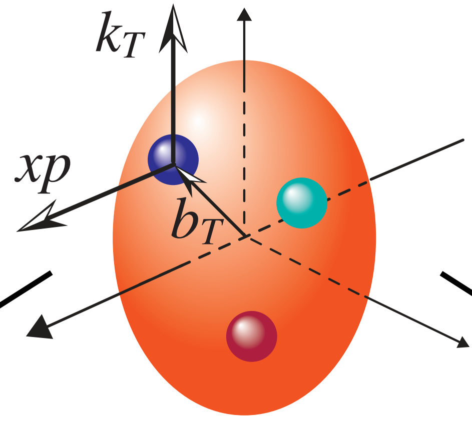
❑ 5D boosted partonic structure:

Momentum Space

TMDs (3D)

Confined motion

$\int d^2 b_T$



$\int d^2 k_T$

Coordinate Space

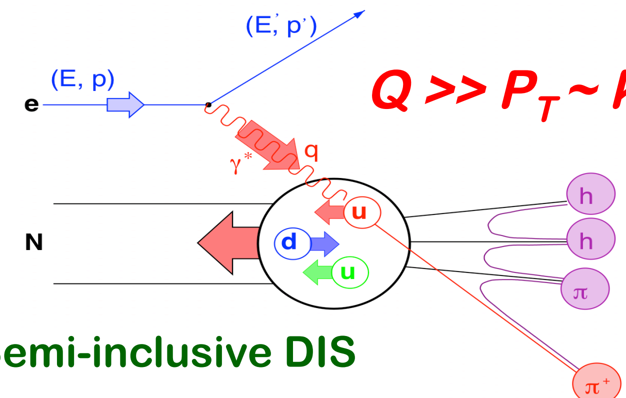
GPDs (3D)

Spatial distribution

$f(x,k_T)$ *Two-scales observables* $f(x,b_T)$

3D momentum space images

$Q >> P_T \sim k_T$



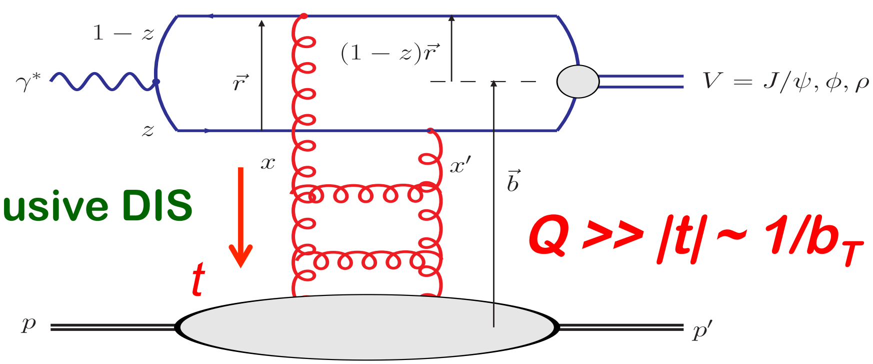
Semi-inclusive DIS

Break the hadron!

2+1D coordinate space images

Exclusive DIS

$Q >> |t| \sim 1/b_T$



Keep the hadron intact!

Position *r* x Momentum *p* → Orbital Motion of Partons

Paradigm shift: 5D imaging of hadrons

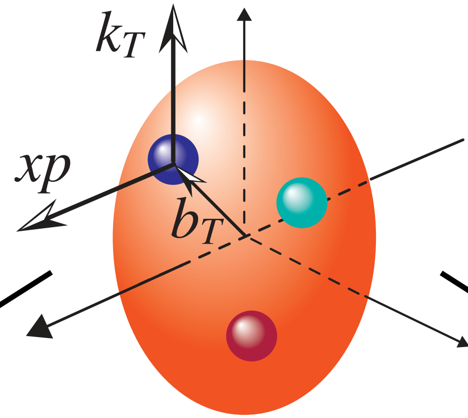
❑ 5D boosted partonic structure:

Momentum Space

TMDs (3D)

Confined motion

$\int d^2 b_T$



$\int d^2 k_T$

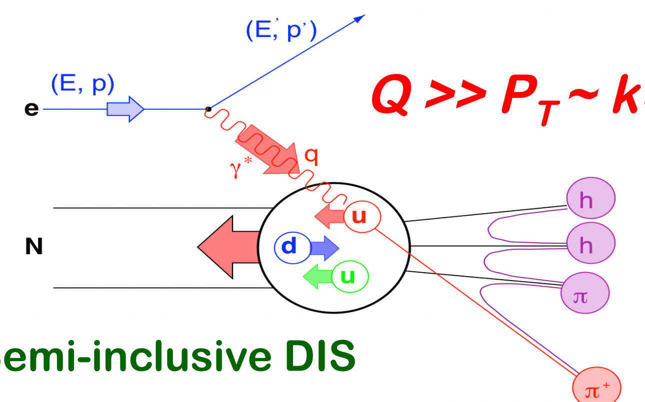
Coordinate Space

GPDs (3D)

Spatial distribution

$f(x,k_T)$ *Two-scales observables* $f(x,b_T)$

3D momentum space images

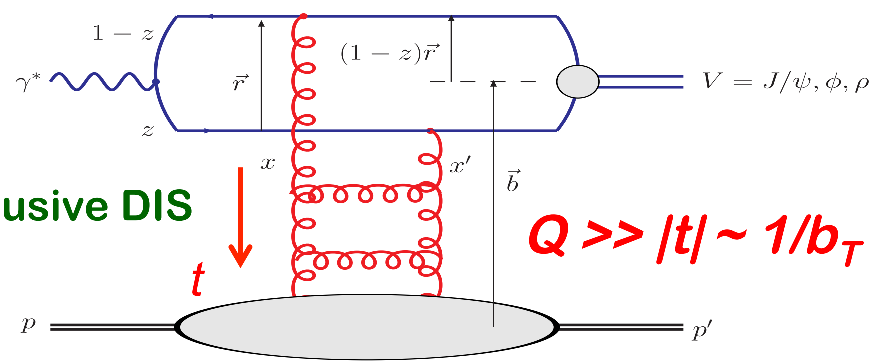


Q >> P_T ~ k_T

Semi-inclusive DIS

Break the hadron!

2+1D coordinate space images



Exclusive DIS

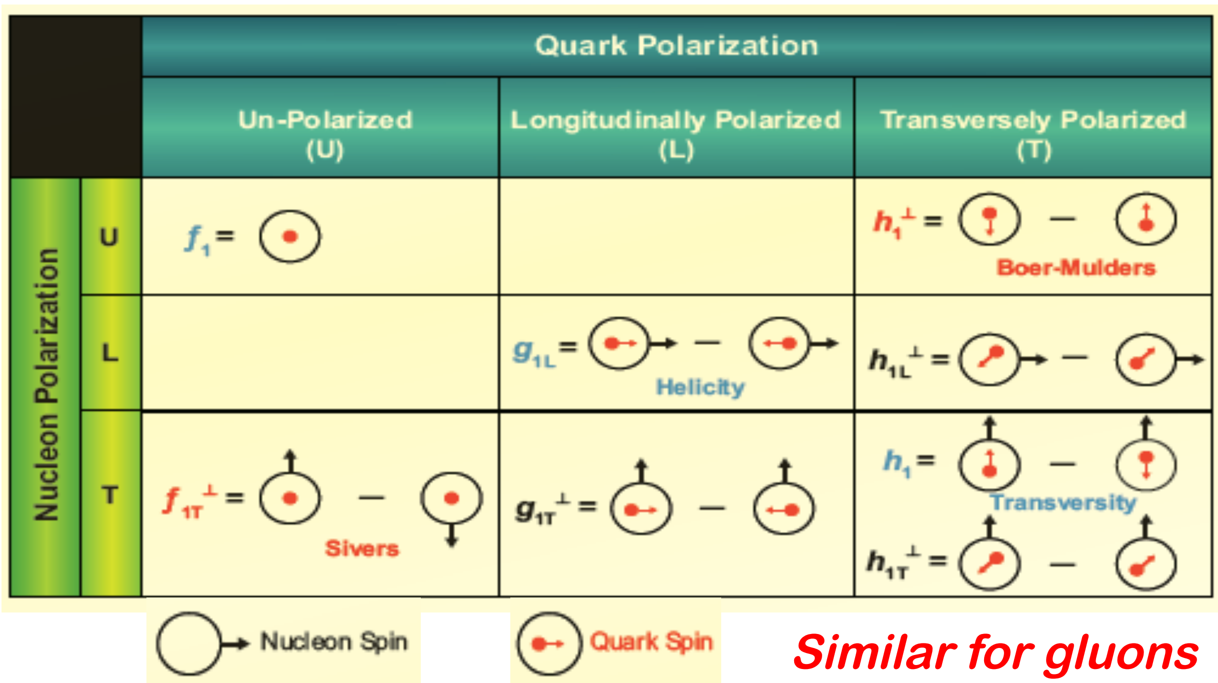
Q >> |t| ~ $1/b_T$

Keep the hadron intact!

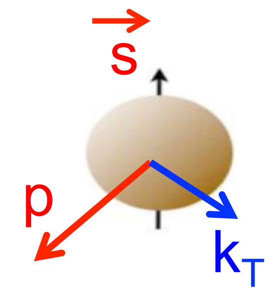
JLab12 – valence quarks, EIC – sea quarks and gluons

TMDs: confined motion, its spin correlation

- Power of spin – many more correlations:



Similar for gluons

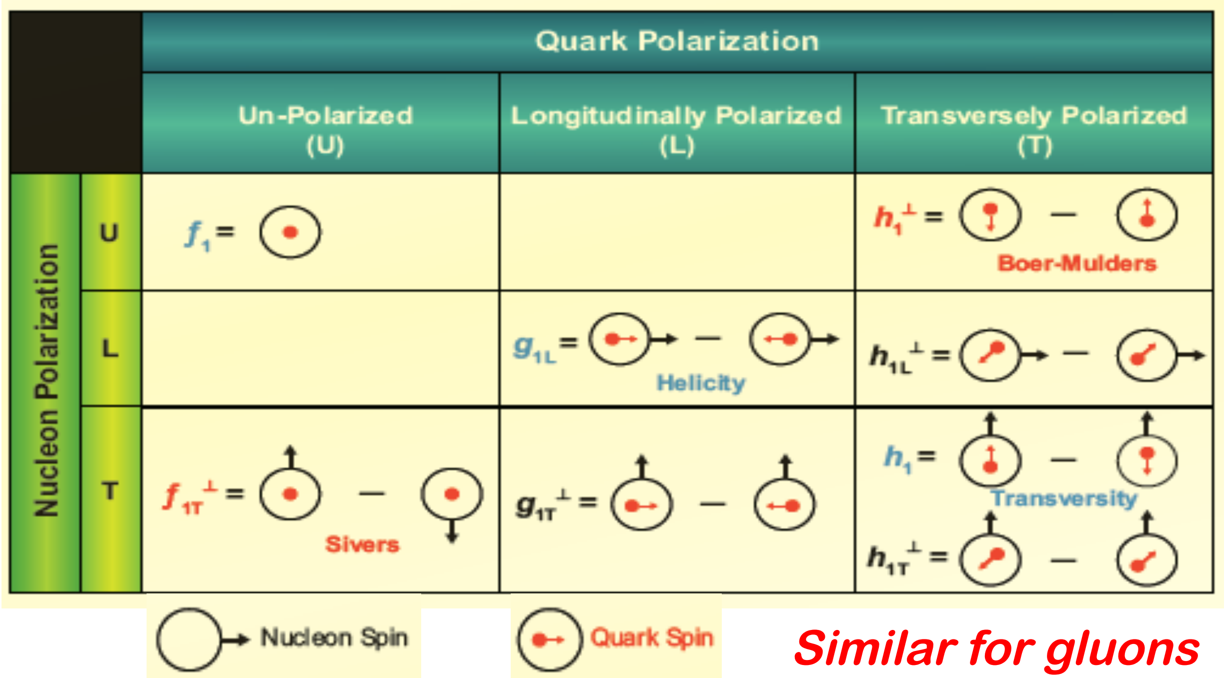


Require two Physical scales

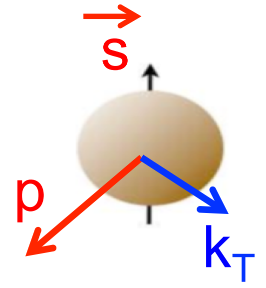
More than one TMD contribute to the same observable!

TMDs: confined motion, its spin correlation

- Power of spin – many more correlations:



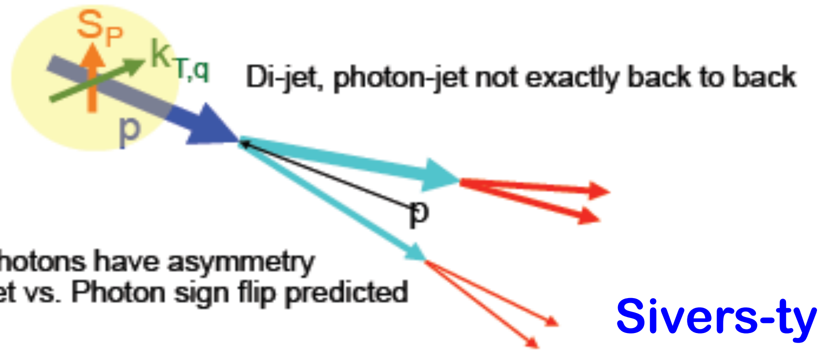
Similar for gluons



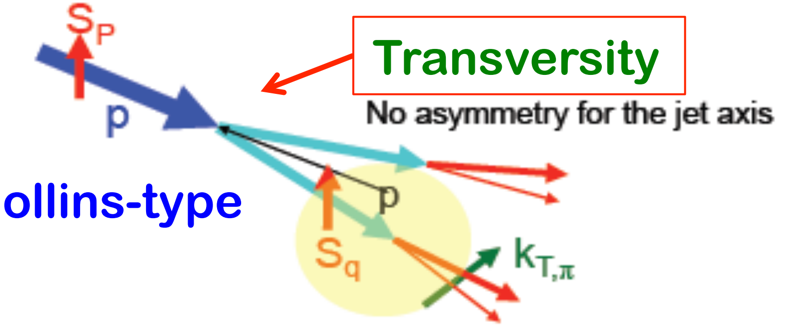
Require two Physical scales

More than one TMD contribute to the same observable!

- A_N – single hadron production:



Sivers-type



Collins-type

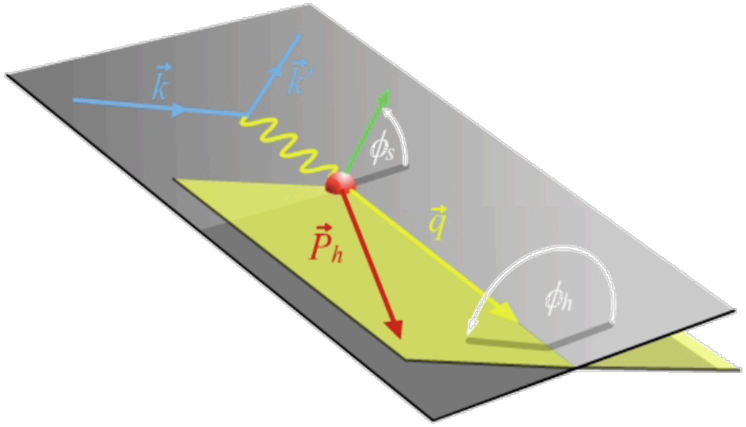
SIDIS is the best for probing TMDs

- Naturally, two scales & two planes:

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

$$= A_{UT}^{Collins} \sin(\phi_h + \phi_S) + A_{UT}^{Sivers} \sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity} \sin(3\phi_h - \phi_S)$$



- Separation of TMDs:

$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

Collins frag. Func. from e^+e^- collisions

Hard, if not impossible, to separate TMDs in hadronic collisions

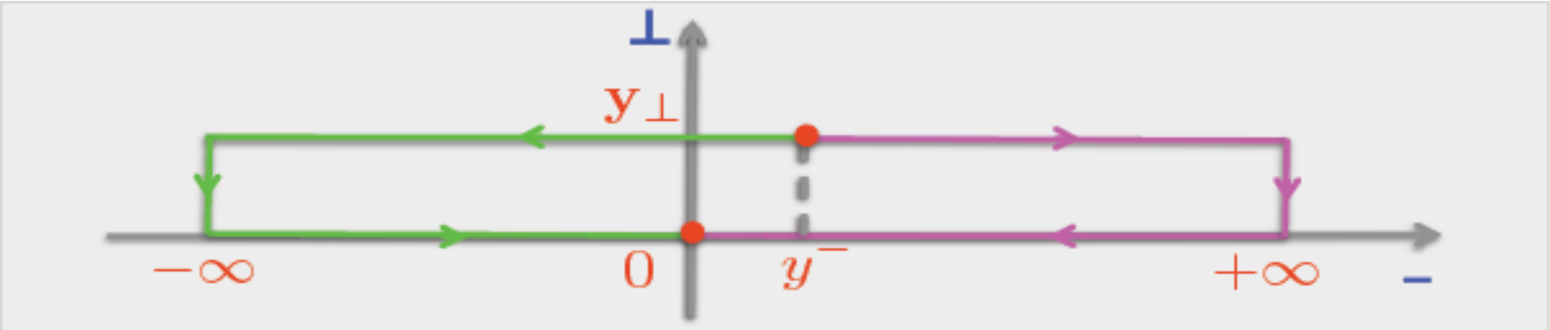
Using a combination of different observables (not the same observable): jet, identified hadron, photon, …

Critical test of TMD factorization

❑ Definition:

$$f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) = \int \frac{dy^- d^2y_\perp}{(2\pi)^3} e^{ixp^+y^- - i\,\mathbf{k}_\perp\cdot\mathbf{y}_\perp} \langle p,\vec{S}|\overline{\psi}(0^-,\mathbf{0}_\perp)\,\boxed{\text{Gauge link}}\,\frac{\gamma^+}{2}\psi(y^-,\mathbf{y}_\perp)|p,\vec{S}\rangle$$

❑ Gauge links:



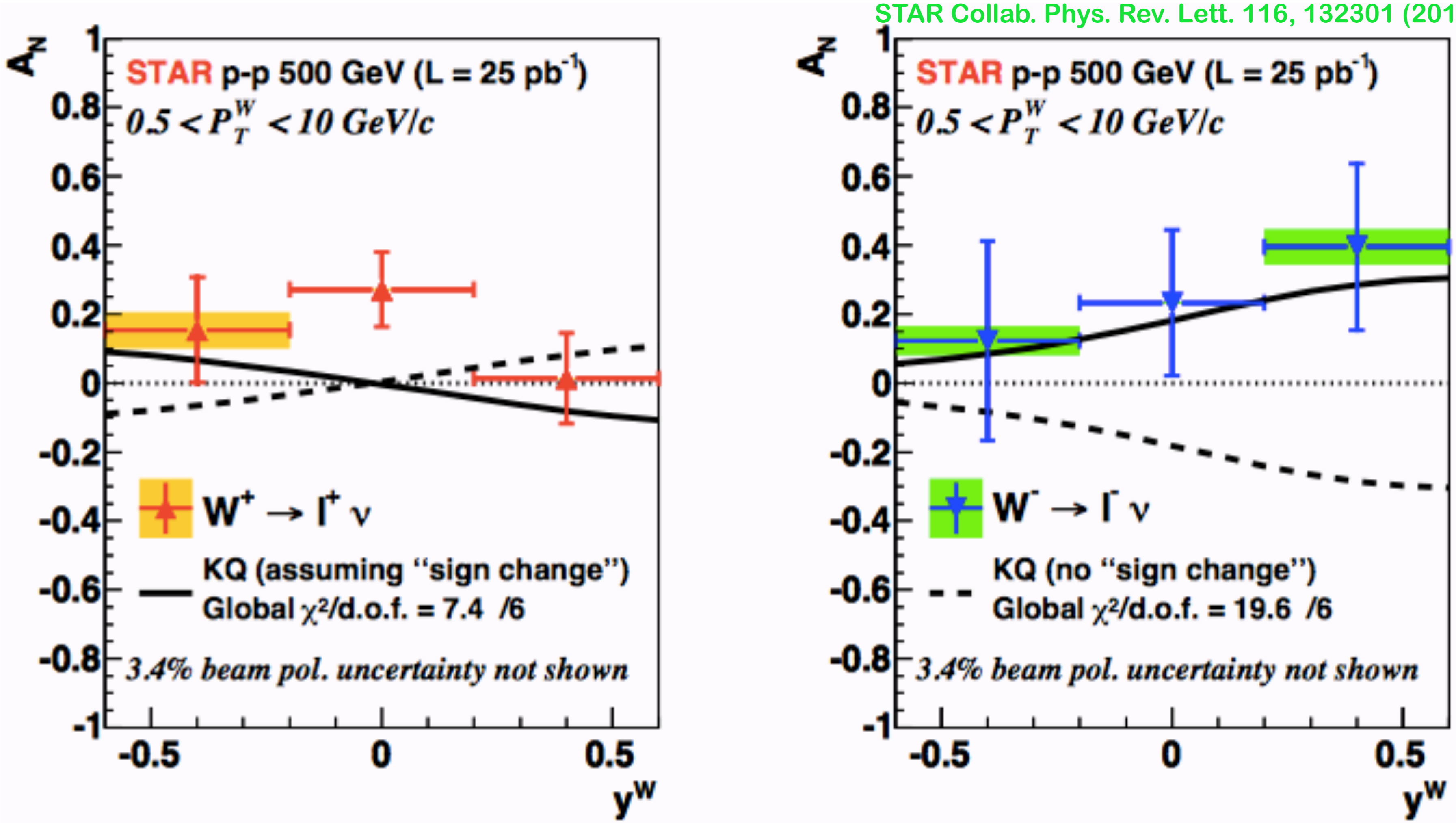
❑ Process dependence:

$$\Delta^N f^{\text{SIDIS}}_{q/h^\uparrow}(x,k_\perp) = -\Delta^N f^{\text{DY}}_{q/h^\uparrow}(x,k_\perp)$$

Sivers function changes sign from SIDIS to Drell-Yan!

Hint of the sign change: A_N of W production

STAR Collab. Phys. Rev. Lett. 116, 132301 (2016)



Data from STAR collaboration on A_N for W-production are consistent with a sign change between SIDIS and DY

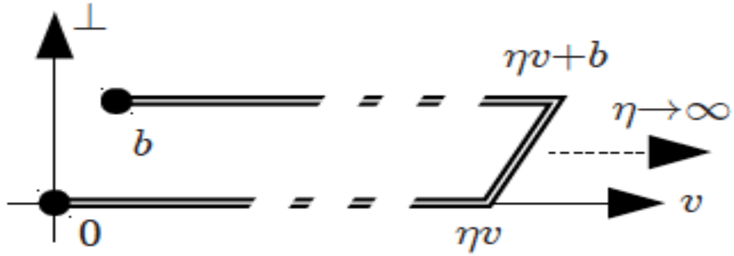
COMPASS Drell-Yan data is consistent

Hint of the sign change from lattice QCD

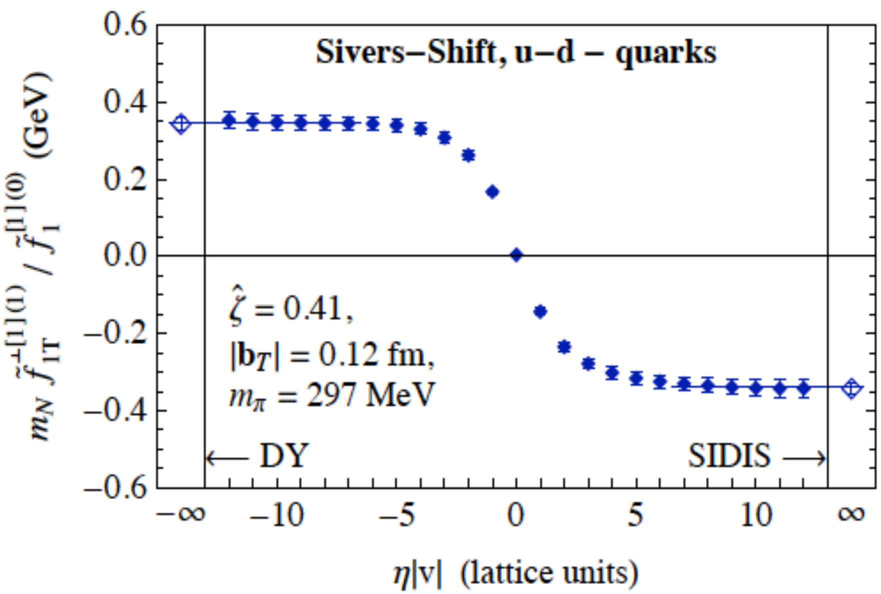
Engelhardt@TMD Collaboration meeting

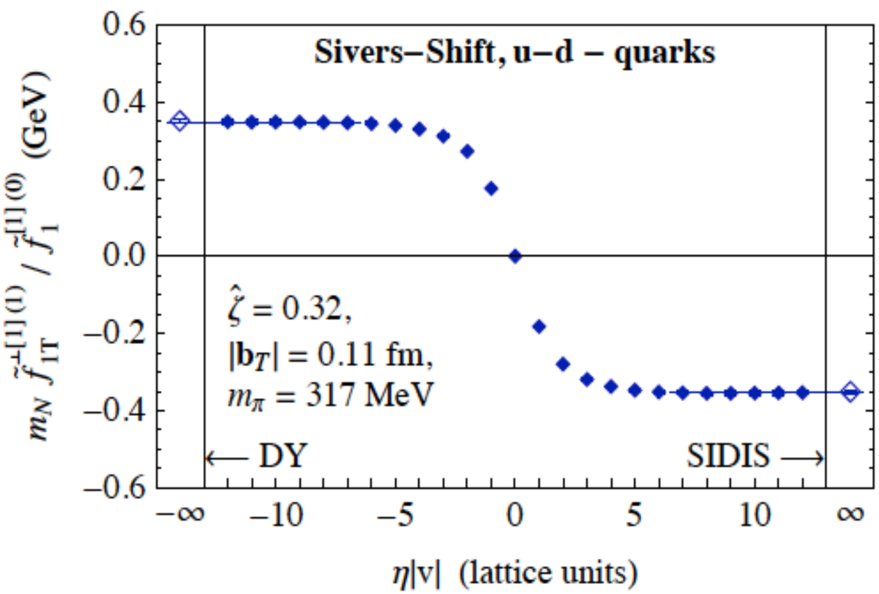
- Gauge link for lattice calculation:

Staple-shaped gauge link $\mathcal{U}[0, \eta v, \eta v + b, b]$



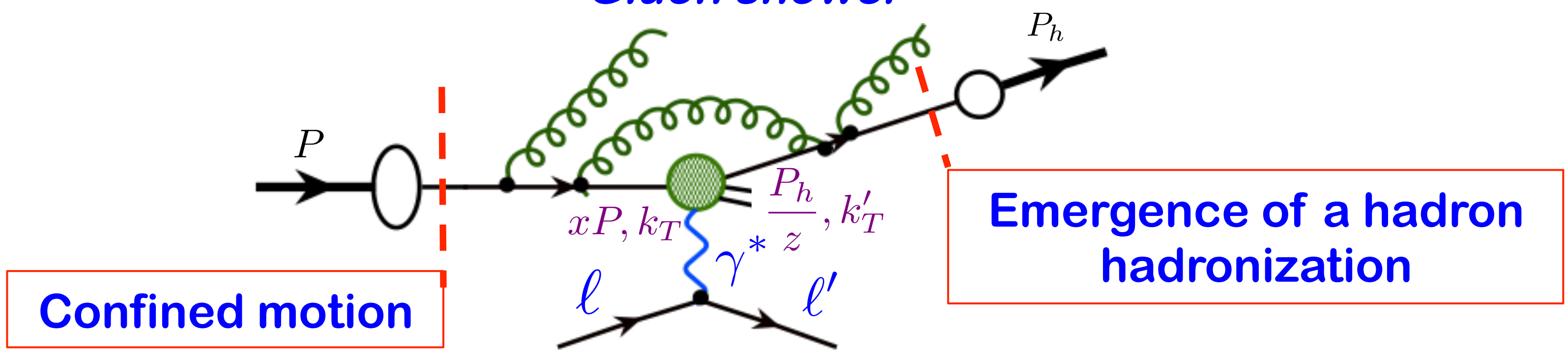
- Normalized moment of Sivers function – at given b_T:





Parton k_T at the hard collision

- ❑ Sources of parton k_T at the hard collision:



- ❑ Large k_T generated by the shower (caused by the collision):
  - ✧ Q^2-dependence – linear evolution equation of TMDs in b-space
  - ✧ The evolution kernels are perturbative at small b, but, not large b

  ➡ The nonperturbative inputs at large b could impact TMDs at all Q^2

- ❑ Challenge: to extract the "true" parton's confined motion:
  - ✧ Separation of perturbative shower contribution from nonperturbative hadron structure – QCD evolution - not as simple as PDFs
  - ✧ Role of lattice QCD?

Task of the DOE supported TMD collaboration

Global QCD analysis: extraction of TMDs

❑ QCD TMD factorization:

– Connect cross sections, asymmetries to TMDs

✧ Factorization is known or expected to be valid for SIDIS, Drell-Yan (Υ^*, W/Z, H^0,…), 2-Jet imbalance in DIS, …

✧ *Same level of reliability as collinear factorization for PDFs, up to the sign change*

❑ QCD evolution of TMDs:

– TMDs evolve when probed at different momentum scales

✧ Evolution equations are for TMDs in b_T-space (Fourier Conjugate of k_T)

FACT: QCD evolution does NOT fully fix TMDs in momentum space, even with TMDs fixed at low Q – large b_T-input!!!

✧ *Very different from DGLAP evolution of PDFs – in momentum space*

FACT: QCD evolution uniquely fix PDFs at large Q, once the PDFs is determined at lower Q – linear evolution in momentum space

❑ Challenges:

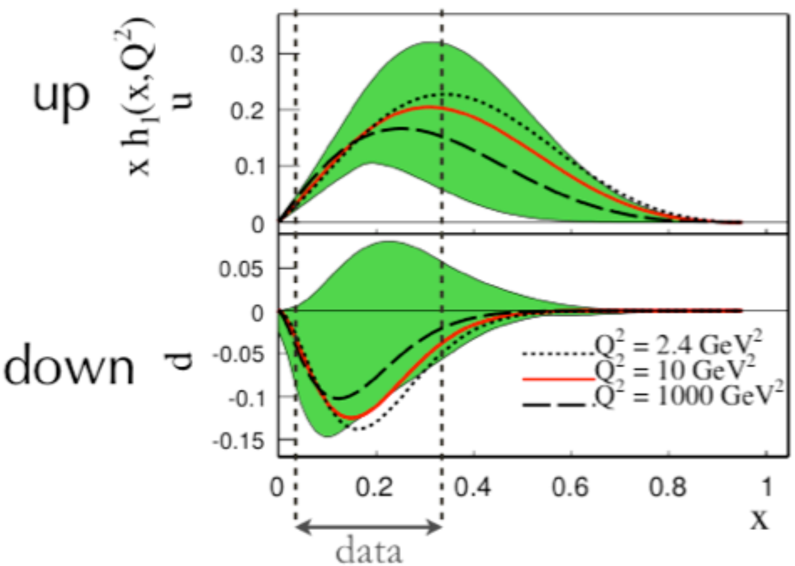
Predictive power, extraction of hadron structure, …

Extraction of TMDs – An Example

❑ Combined fits for the Transversity & Collins FFs:

First Fit using TMD evolution

*Kang et al., P.R. D**93** (16) 014009*



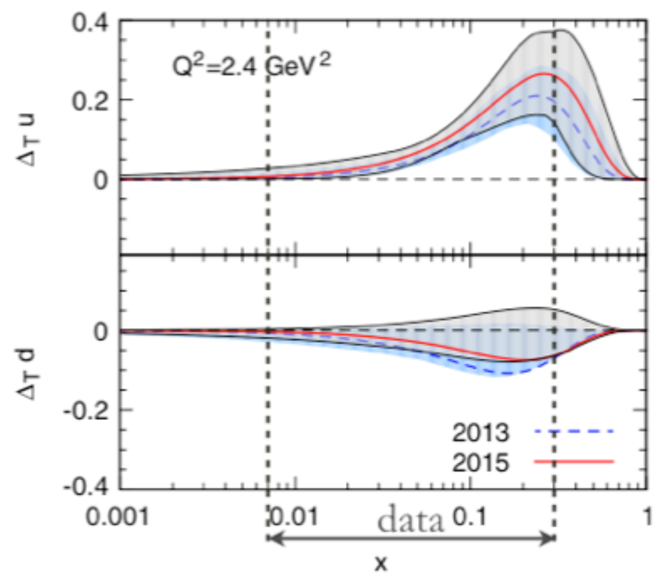
New data:

SIDIS data from hermes and COMPASS and Jefferson Lab

e⁺e⁻ data from BABAR and Belle II

Fits without TMD evolution

*Anselmino et al., P.R. D**93** (15) 034025*



History of upgrading fits:

*Anselmino et al., P.R. D**87** (13) 094019*

*Anselmino et al., P.R. D**92** (15) 114023*

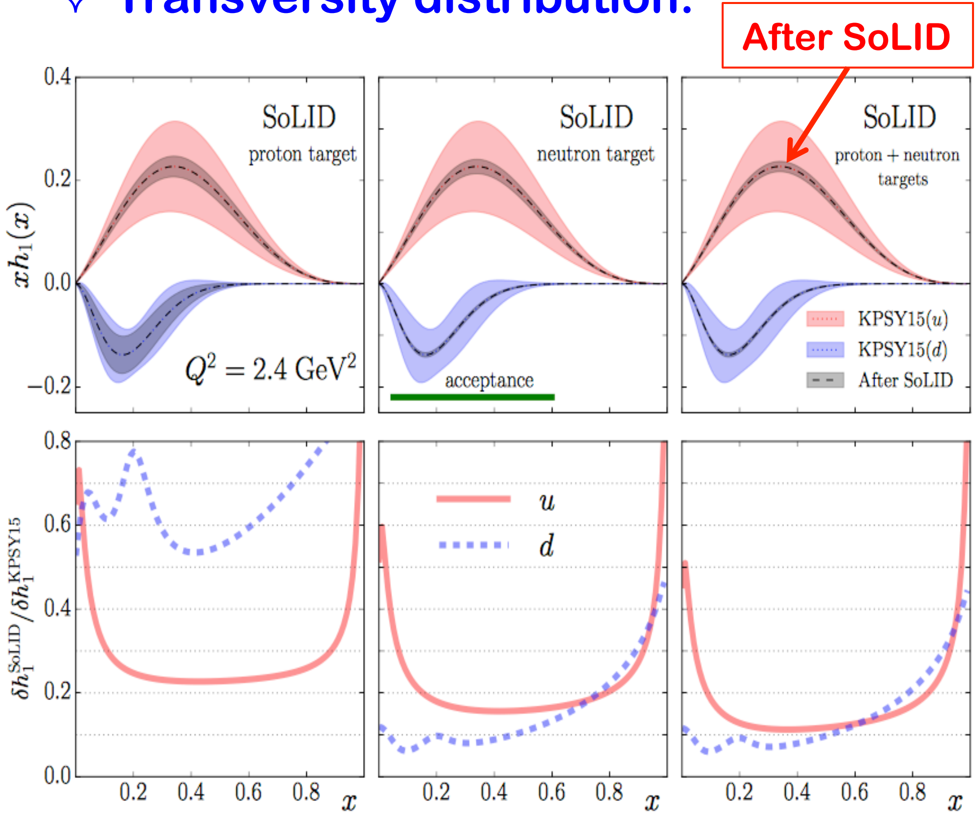
*Anselmino et al., P.R. D**93** (15) 034025*

Extraction of TMDs – An Example

Z. Ye *et al.* Phys Lett. B767, 91 (2017)

❑ Impact of future SoLID at JLab12:

✧ Transversity distribution:

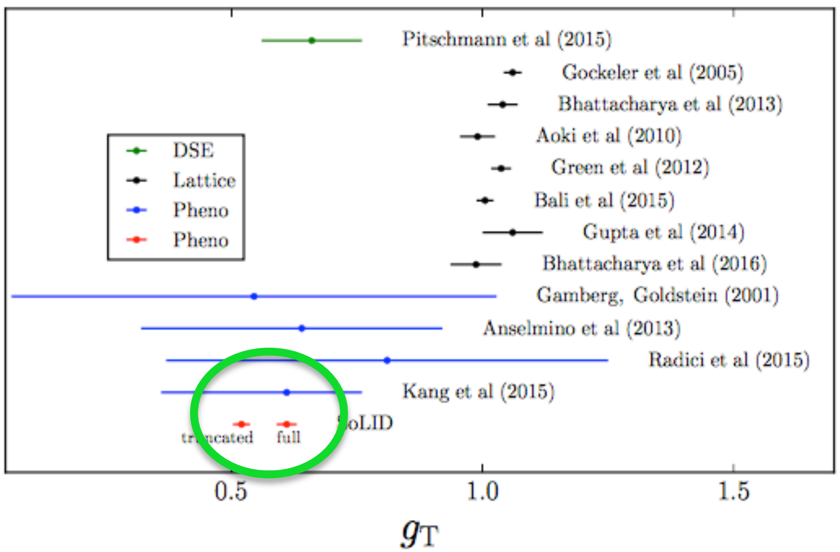


Bayesian statistics is used to estimate the improvement from new data
Current knowledge corresponds to a fit with TMD evolution *Kang et al., P.R. D93 (16) 014009*

✧ Tensor charge:

$$\delta q(Q^2) \equiv \int_0^1 dx\,\left(h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2)\right)$$

$$g_T = \delta u - \delta d.$$



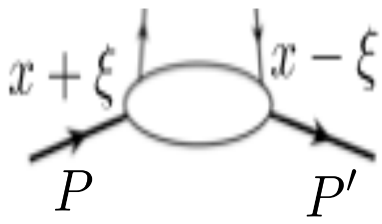
"full" is contribution from $0 < x < 1$ region
"truncated" is contribution from $0.05 < x < 0.6$

Order of magnitude improvement in determining the tensor charge!

GPDs: spatial distribution, its spin correlation

- **Definition – Quark "form factor":**

$$F_q(x,\xi,t,\mu^2) = \int \frac{d\lambda}{2\pi} e^{-ix\lambda} \langle P'|\bar{\psi}_q(\lambda/2)\frac{\gamma\cdot n}{2P\cdot n}\psi_q(-\lambda/2)|P\rangle$$



$$\equiv \quad H_q(x,\xi,t,\mu^2)\,\left[\bar{\mathcal{U}}(P')\gamma^\mu\mathcal{U}(P)\right]\frac{n_\mu}{2P\cdot n}$$

$$+ \quad E_q(x,\xi,t,\mu^2)\left[\bar{\mathcal{U}}(P')\frac{i\sigma^{\mu\nu}(P'-P)_\nu}{2M}\mathcal{U}(P)\right]\frac{n_\mu}{2P\cdot n}$$

with $\xi = (P'-P)\cdot n/2$ and $t = (P'-P)^2 \Rightarrow -\Delta_\perp^2$ if $\xi\to 0$

$\tilde{H}_q(x,\xi,t,Q)$, $\tilde{E}_q(x,\xi,t,Q)$ **Different quark spin projection**

- **Total quark's orbital contribution to proton's spin:** Ji, PRL78, 1997

$$J_q = \frac{1}{2}\lim_{t\to 0}\int dx\, x\,[H_q(x,\xi,t) + E_q(x,\xi,t)]$$

$$= \frac{1}{2}\Delta q + L_q$$

- **Connection to normal quark distribution:**

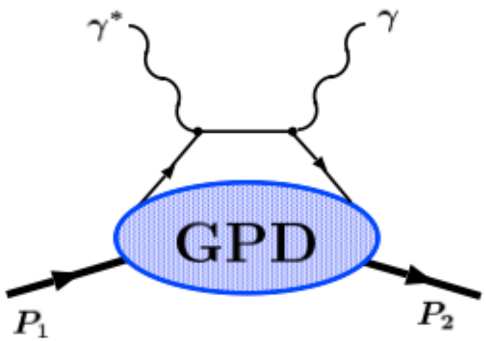
$H_q(x,0,0,\mu^2) = q(x,\mu^2)$ **The limit when** $\xi \to 0$

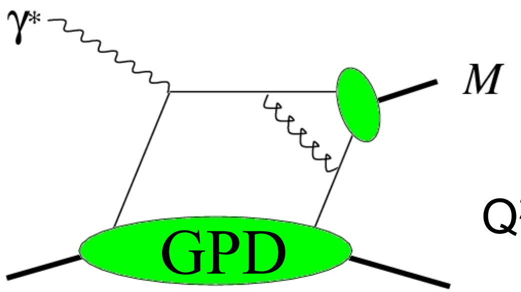
Exclusive DIS: Hunting for GPDs

Mueller et al., 94;
Ji, 96;
Radyushkin, 96

- Experimental access to GPDs:
  - ✧ Diffractive exclusive processes – high luminosity:

    DVCS: Deeply virtual Compton Scattering
    DVEM: Deeply virtual exclusive meson production





Require

$Q^2 \gg (-t), \Lambda^2_{QCD}, M^2$

  - ✧ No factorization for hadronic diffractive processes – EIC is ideal

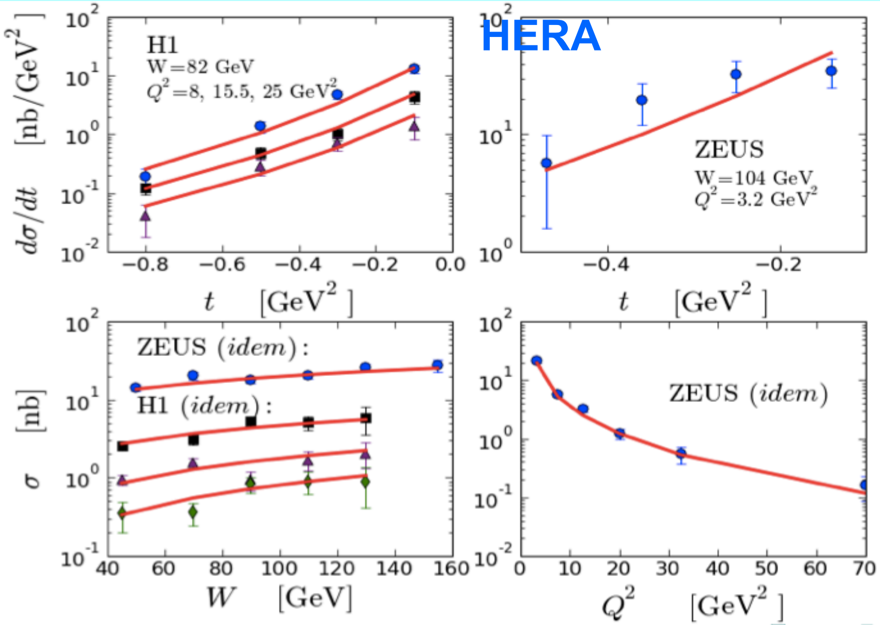
- Much more complicated – (x, ξ, t) variables:

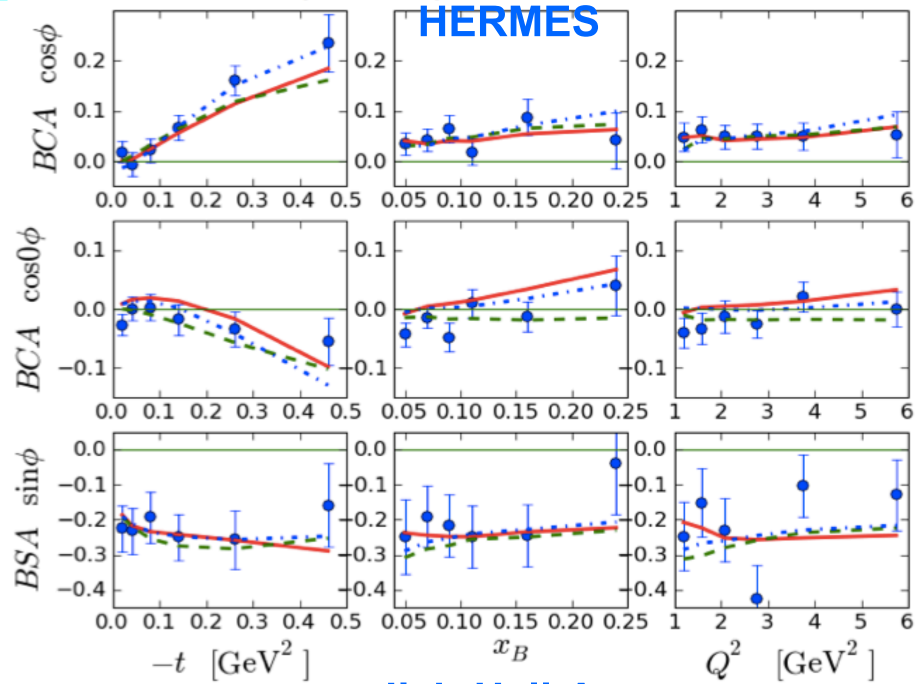
  Challenge to derive GPDs from data

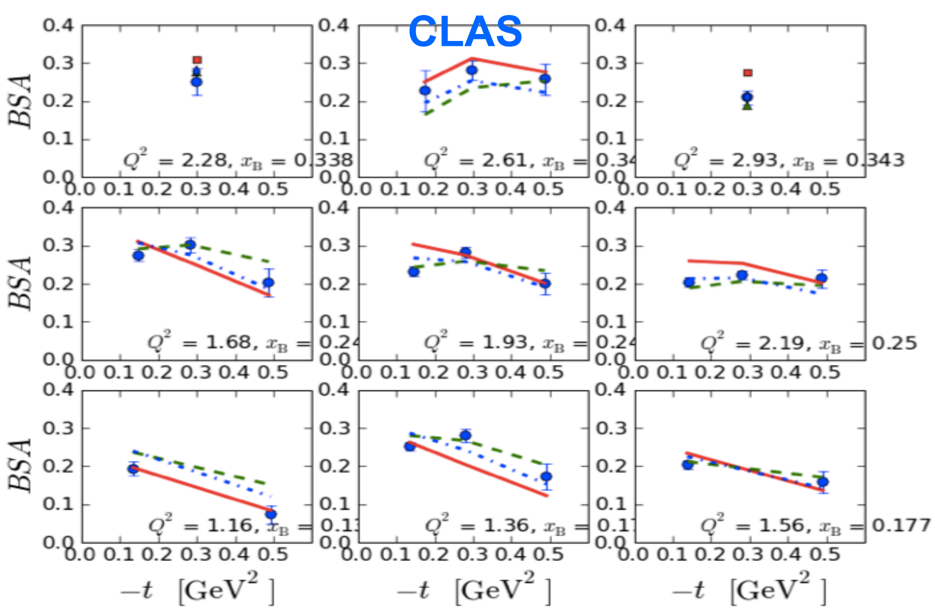
- Great experimental effort:

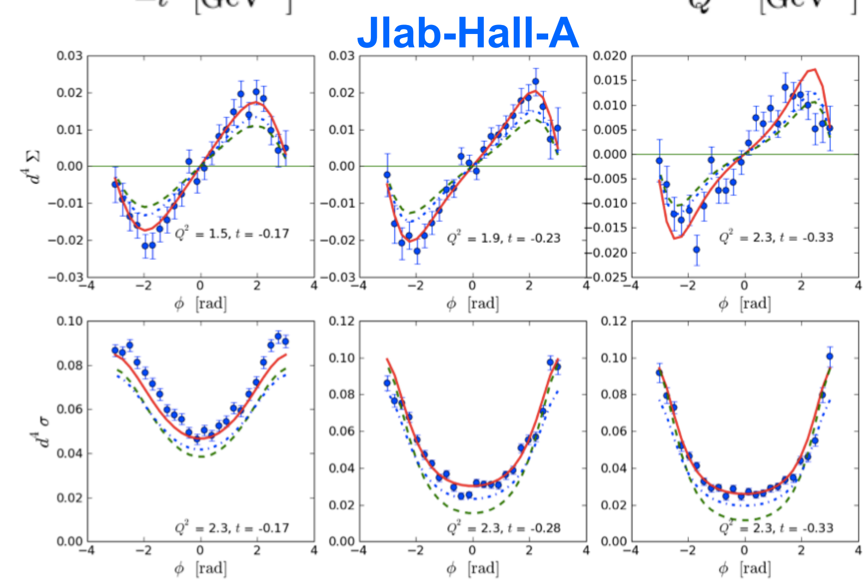
  HERA, HERMES, COMPASS, JLab ⟶ JLab12, COMPASS-II, EIC

GPDs: just the beginning









Unified view of nucleon structure

❑ **Wigner distribution – 5D:**

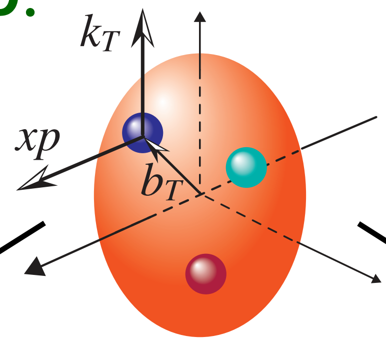
Momentum Space

TMDs

Confined motion

$\int d^2 b_T$

$f(x,k_T)$



$\int d^2 k_T$

$f(x,b_T)$

Two-scales observables

Coordinate Space

GPDs

Spatial distribution

❑ **Note:**

✧ Partons' confined motion and their spatial distribution are unique – the consequence of QCD

✧ But, the TMDs and GPDs that represent them are not unique!

– Depending on the definition of the Wigner distribution and QCD factorization to link them to physical observables

❑ **Can lattice QCD calculate hadron structure?**

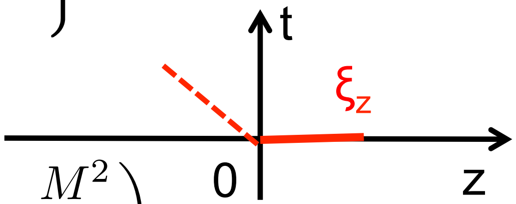
Difficult, but, with tremendous potential – very active now !

Hadron structure from lattice QCD calculation

Ji, arXiv:1305.1539

❑ "Quasi" quark distribution (spin-averaged):

$$\tilde{q}(x,\mu^2,P_z) \equiv \int \frac{d\xi_z}{4\pi} e^{-ixP_z\xi_z} \langle P|\overline{\psi}(\xi_z)\gamma_z \exp\left\{-ig\int_0^{\xi_z} d\eta_z A_z(\eta_z)\right\}\psi(0)|P\rangle + \mathrm{UVCT}(\mu^2)$$



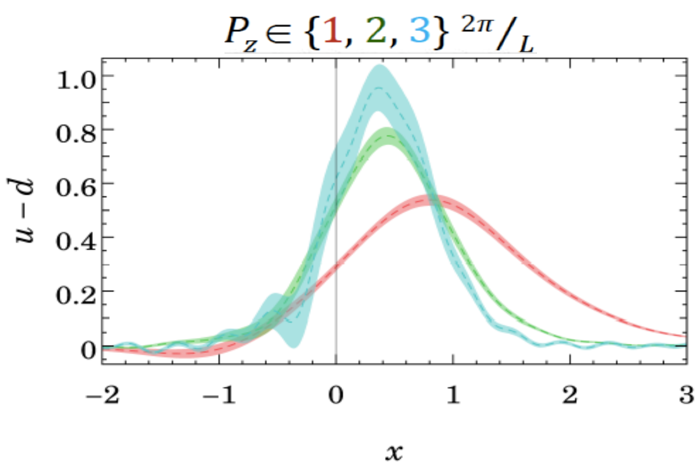
❑ Proposed matching:

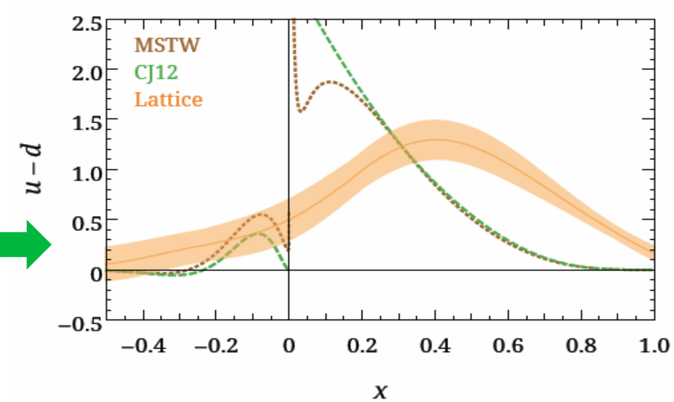
$$\tilde{q}(x,\mu^2,P_z) = \int_x^1 \frac{dy}{y}\, Z\left(\frac{x}{y},\frac{\mu}{P_z}\right) q(y,\mu^2) + \mathcal{O}\left(\frac{\Lambda^2}{P_z^2},\frac{M^2}{P_z^2}\right)$$

- Power divergence – renormalization?
- Mixing with lower dimension operators cannot be treated perturbatively, …

❑ Exploratory effort:

Lin *et al.*, arXiv:1402.1462





Hadron structure from lattice QCD calculation

Ma and Qiu, 2014, 2017
1404.6860, 1709.03018

❑ Our observations:

✧ PDFs are time-independent, so as the factorized cross sections!

✧ The operators, defining PDFs, located on the light-cone is a consequence of the approximation defining the twist-2 factorization

More precisely, the collinear approximation

❑ Our idea:

✧ NOT try to calculate PDFs directly from lattice QCD calculations

✧ Calculate a set of time-independent (fixed or integrated over time) and *good* single hadron matrix elements – "lattice cross sections"

$$\sigma_n(\xi^2,\omega,P^2) = \langle P|T\{\mathcal{O}_n(\xi)\}|P\rangle \qquad \omega = P\cdot\xi$$

with
$$\mathcal{O}_{j_1j_2}(\xi) \equiv \xi^{d_{j_1}+d_{j_2}-2}\,Z_{j_1}^{-1}\,Z_{j_2}^{-1}\,j_1(\xi)\,j_2(0)$$

$$j_S(\xi) = \xi^2 Z_S^{-1}[\overline{\psi}_q\psi_q](\xi),\quad j_G(\xi) = \xi^3 Z_G^{-1}[-\frac{1}{4}F^c_{\mu\nu}F^c_{\mu\nu}](\xi)$$

$$\widetilde{\sigma}_{\rm E}^{\rm Lat}(\xi_z,1/a,P_z) \xleftrightarrow{\mathcal{Z}} \sigma_{\rm E}(\xi_z,\tilde{\mu}^2,P_z)$$

– Renormalization/continuum limit (lattice QCD expertise, …)

$$\Updownarrow$$

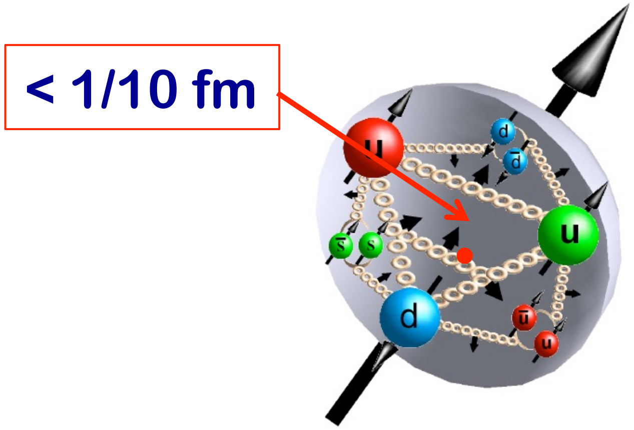
$$\sigma_{\rm M}(\xi_z,\tilde{\mu}^2,P_z) \xleftrightarrow{\mathcal{C}} f_i(x,\mu^2)\,,$$

– Factorization to PDFs (perturbative QCD, …)

✧ Derive PDFs from Global Analysis of "data" on lattice cross sections

Summary

- QCD has been extremely successful in interpreting and predicting high energy experimental data!



- But, we still do not know much about hadron structure – work just started!

- Cross sections with large momentum transfer(s) and identified hadron(s) are the source of structure information

- QCD factorization is necessary for any controllable "probe" for hadron's quark-gluon structure!

- EIC is a ultimate QCD machine, will provide answers to many of our questions on hadron structure, in particular, the confined transverse motions (TMDs), spatial distributions (GPDs), and multi-parton correlations, … NEXT talk!

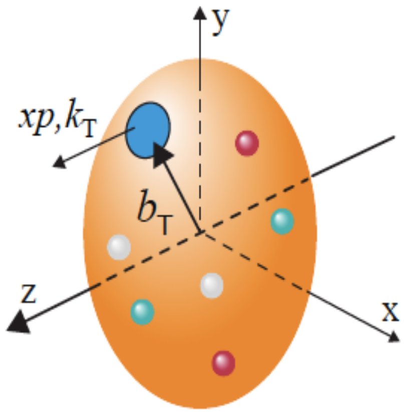
Thank you!

Backup slides

Two-momentum-scale observables

- **Cross sections with two-momentum scales observed:**

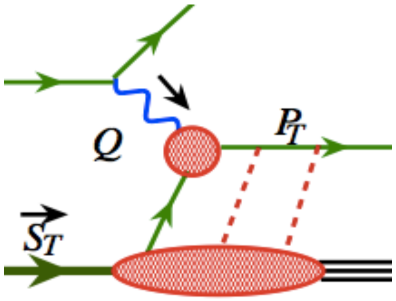
$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\rm QCD}$$



✧ Hard scale: Q_1 localizes the probe to see the quark or gluon d.o.f.

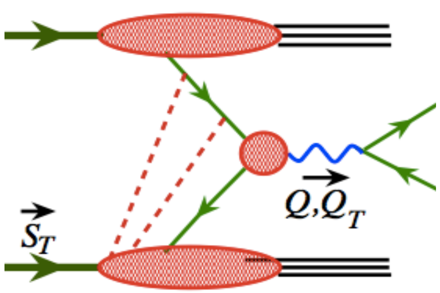
✧ "Soft" scale: Q_2 could be more sensitive to hadron structure, e.g., confined motion

- **Two-scale observables with the hadron broken:**



SIDIS: Q>>P_T

\+



DY: Q>>P_T

\+ Two-jet momentum imbalance in SIDIS, …

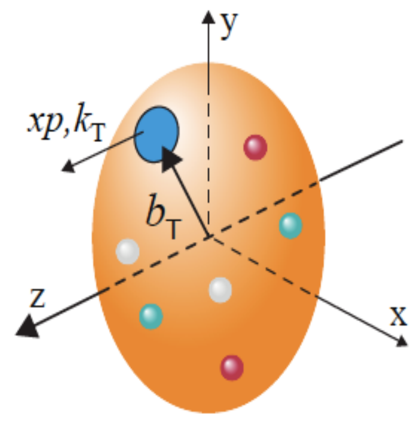
✧ Natural observables with TWO very different scales

✧ TMD factorization: partons' confined motion is encoded into TMDs

Two-momentum-scale observables

❑ Cross sections with two-momentum scales observed:

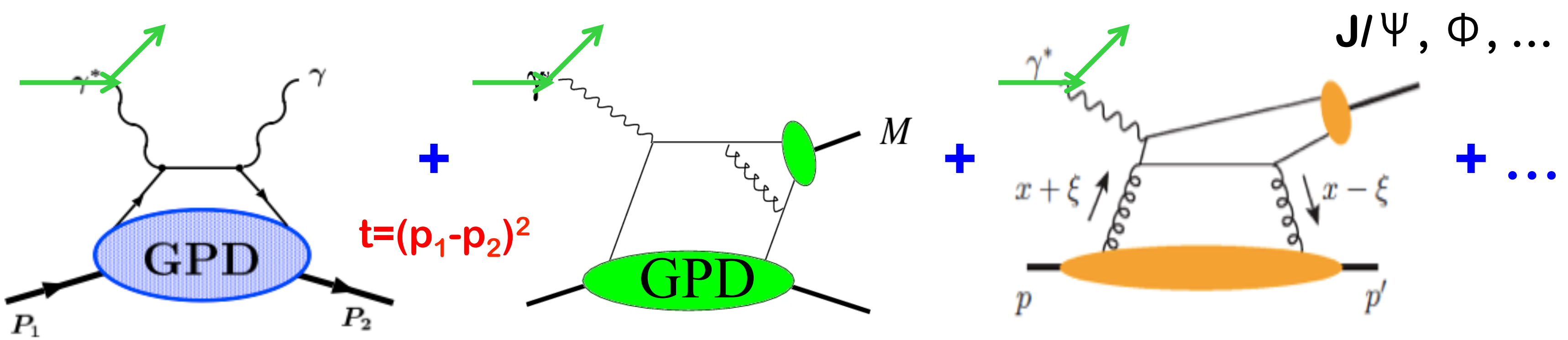
$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\rm QCD}$$



✧ Hard scale: Q_1 localizes the probe to see the quark or gluon d.o.f.

✧ "Soft" scale: Q_2 could be more sensitive to hadron structure, e.g., confined motion

❑ Two-scale observables with the hadron unbroken:



DVCS: $Q^2 >> |t|$ DVEM: $Q^2 >> |t|$ EHMP: $Q^2 >> |t|$

✧ Natural observables with TWO very different scales

✧ GPDs: Fourier Transform of t-dependence gives spatial b_T-dependence

Orbital angular momentum

OAM: Correlation between parton's position and its motion – in an averaged (or probability) sense

- **Jaffe-Manohar's quark OAM density:**

$$\mathcal{L}_q^3 = \psi_q^\dagger \left[\vec{x} \times (-i\vec{\partial})\right]^3 \psi_q$$

- **Ji's quark OAM density:**

$$L_q^3 = \psi_q^\dagger \left[\vec{x} \times (-i\vec{D})\right]^3 \psi_q$$

- **Difference between them:**

Hatta, Lorce, Pasquini, …

- ✧ compensated by difference between gluon OAM density
- ✧ represented by different choice of gauge link for OAM Wagner distribution

$$\mathcal{L}_q^3 \left\{L_q^3\right\} = \int dx\, d^2b\, d^2k_T \left[\vec{b} \times \vec{k}_T\right]^3 \mathcal{W}_q(x,\vec{b},\vec{k}_T) \left\{W_q(x,\vec{b},\vec{k}_T)\right\}$$

with

$$\mathcal{W}_q \left\{W_q\right\}(x,\vec{b},\vec{k}_T) = \int \frac{d^2\Delta_T}{(2\pi)^2} e^{i\vec{\Delta}_T\cdot\vec{b}} \int \frac{dy^- d^2y_T}{(2\pi)^3} e^{i(xP^+y^- - \vec{k}_T\cdot\vec{y}_T)}$$

$$\times \langle P'|\, \overline{\psi}_q(0)\, \frac{\gamma^+}{2}\, \underbrace{\Phi^{\mathrm{JM}\{\mathrm{Ji}\}}(0,y)}_{\text{Gauge link}}\, \psi(y)\, |P\rangle_{y^+=0}$$

JM: "staple" gauge link

Ji: straight gauge link

between 0 and $y=(y^+=0, y^-, y_T)$

Orbital angular momentum

OAM: Correlation between parton's position and its motion – in an averaged (or probability) sense

- **Jaffe-Manohar's quark OAM density:**

$$\mathcal{L}_q^3 = \psi_q^\dagger \left[\vec{x} \times (-i\vec{\partial})\right]^3 \psi_q$$

- **Ji's quark OAM density:**

$$L_q^3 = \psi_q^\dagger \left[\vec{x} \times (-i\vec{D})\right]^3 \psi_q$$

- **Difference between them:**

Hatta, Yoshida, Burkardt, Meissner, Metz, Schlegel, …

✧ generated by a "torque" of color Lorentz force

$$\mathcal{L}_q^3 - L_q^3 \propto \int \frac{dy^- d^2 y_T}{(2\pi)^3} \langle P' | \overline{\psi}_q(0) \frac{\gamma^+}{2} \int_{y^-}^{\infty} dz^- \Phi(0, z^-) \times \sum_{i,j=1,2} \underbrace{\left[\epsilon^{3ij} y_T^i F^{+j}(z^-)\right]}_{\text{“Chromodynamic torque”}} \Phi(z^-, y)\psi(y) | P \rangle_{y^+=0}$$

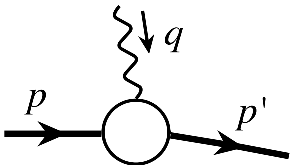
Similar color Lorentz force generates the single transverse-spin asymmetry (Qiu-Sterman function), and is also responsible for the twist-3 part of g_2

Proton’s radius in color distribution?

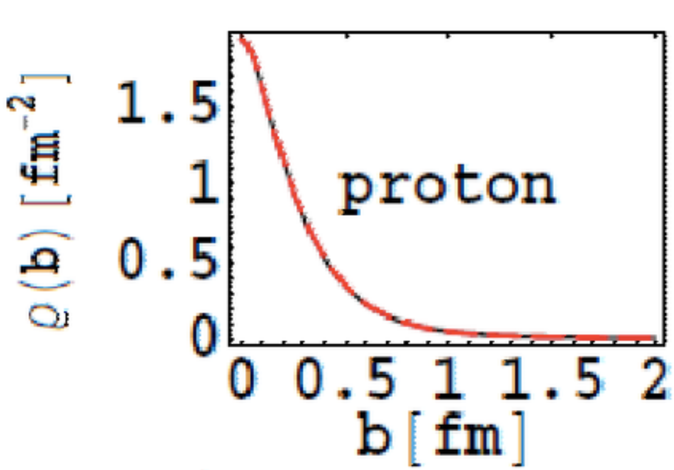
- **The “big” question:**

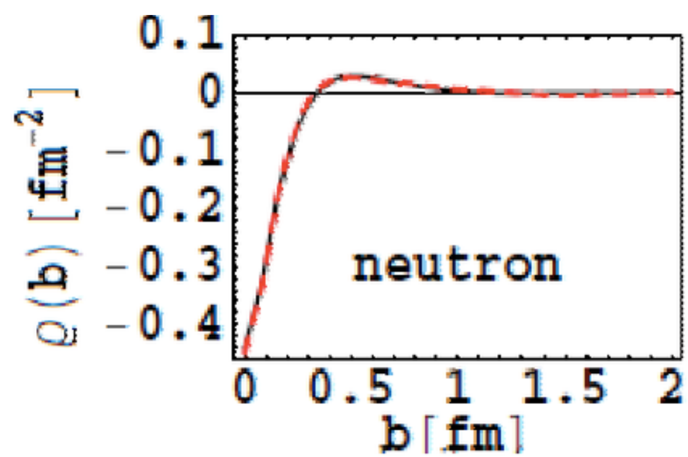
  How color is distributed inside a hadron? (clue for color confinement?)

- **Electric charge distribution:**



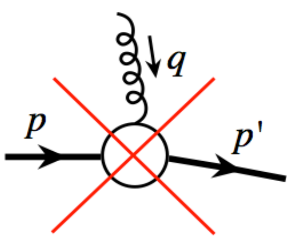
  Elastic electric form factor ➡ Charge distributions





- **But, NO color elastic nucleon form factor!**

  Hadron is colorless and gluon carries color



➡ *Parton density’s spatial distributions – a function of x as well (more “proton”-like than “neutron”-like?) – GPDs*