TRANSVERSITY 2017

5th International Workshop on Transverse Polarization Phenomena in Hard Processes

INFN - FRASCATI NATIONAL LABORATORIES

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Partonic dynamics and the 3D structure of the nucleon: a global view

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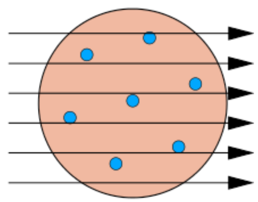
Acknowledgement: Some of the physics presented here are based on the work of EIC White Paper Writing Committee put together by BNL and JLab managements, …

From 3D atomic structure to quantum world, …

- **Atomic structure: dating back to Rutherford's experiment :**

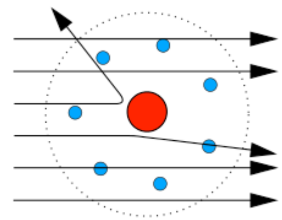
$\alpha + Au \rightarrow \alpha + X$ Over 100 years ago

Atom:



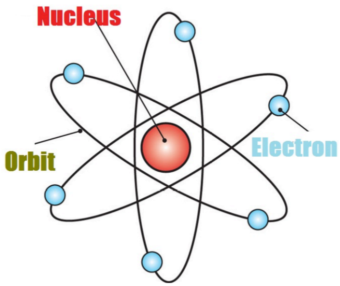
J.J. Thomson's
plum-pudding model

Experiment ➔



Rutherford's
Experiment - Data

Theory ➔



Quantum orbitals

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

From 3D atomic structure to quantum world, ...

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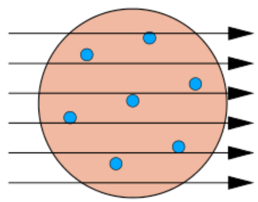

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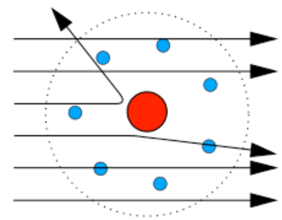

Rutherford's Experiment - Data

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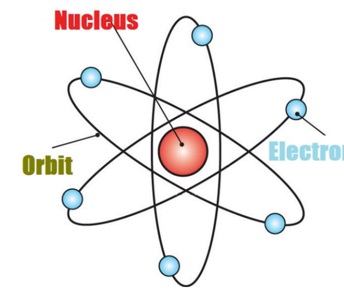
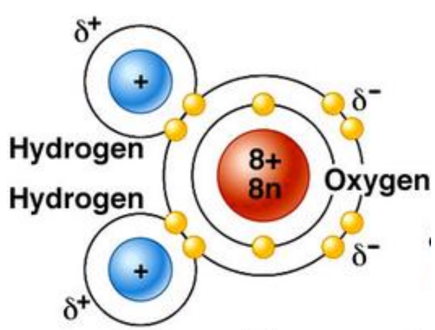


Quantum orbitals

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

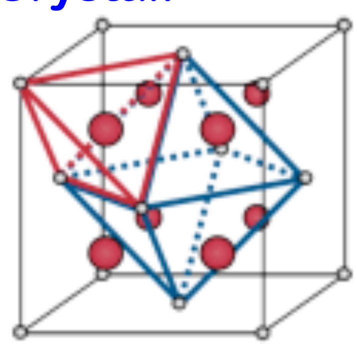
❑ Localized mass and charge centers – vast "open" space:

Molecule:



"Water"

Crystal:



Rare-Earth metal

Nanomaterial:

Carbon-based

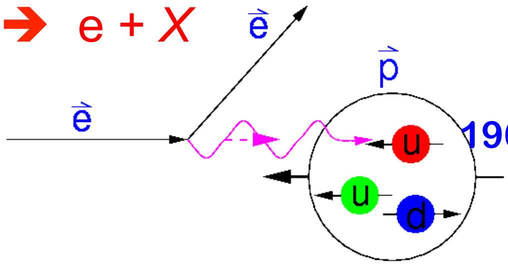
➔ *Infinite opportunities to create & improve ... !*

From 3D hadron structure to QCD, …

❑ **A modern "Rutherford" experiment (about 50 years ago):**

Nucleon: *The building unit of all atomic nuclei*

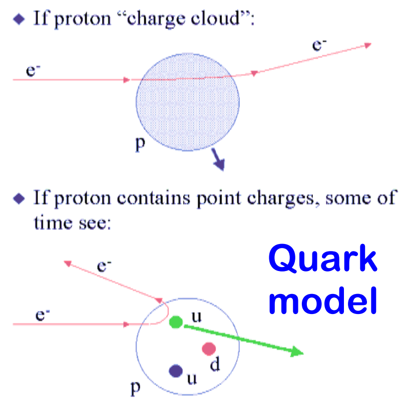
$e + p \rightarrow e + X$



1968

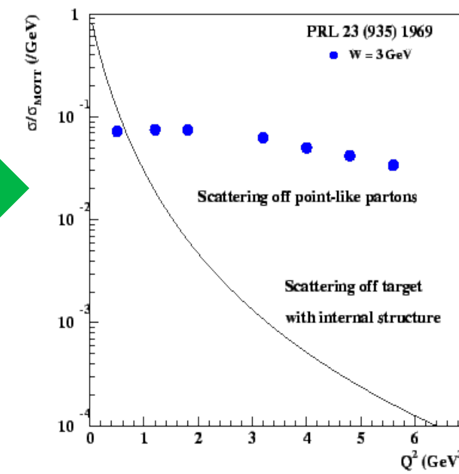
➡ *Discovery of quarks!*

Prediction



Quark model

Discovery



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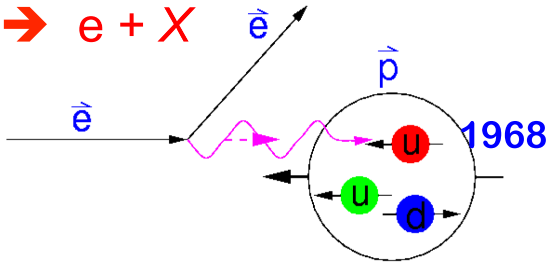

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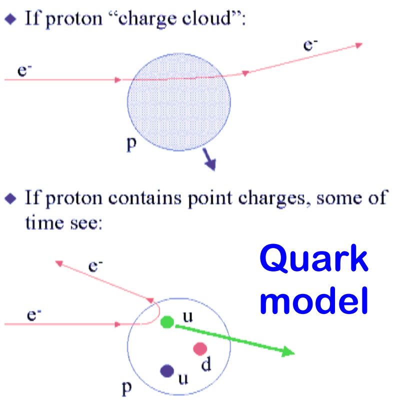
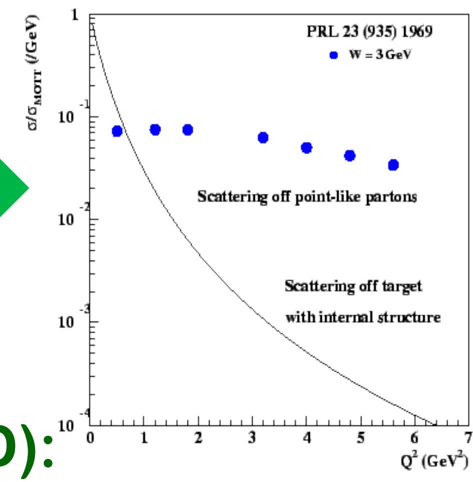
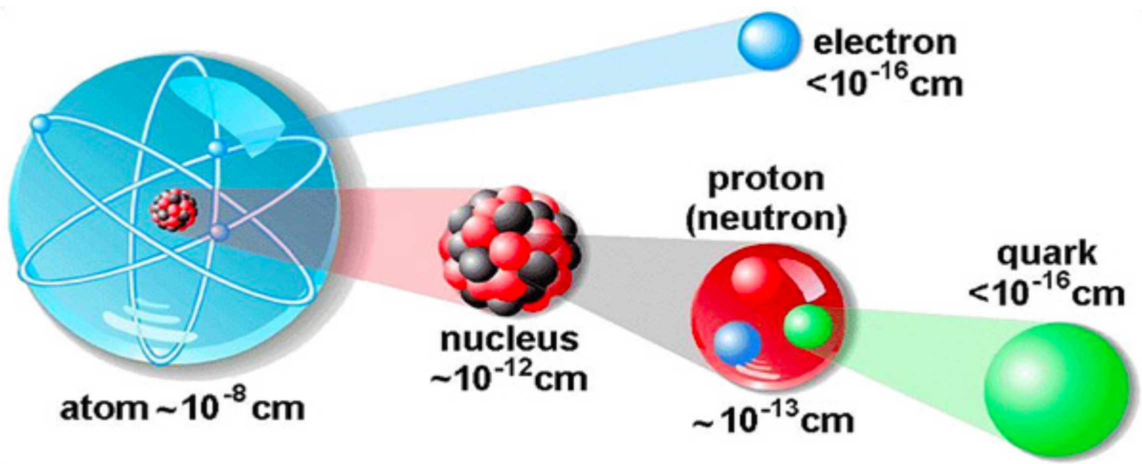


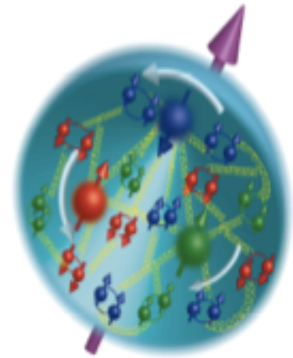
Discovery



❑ Discovery of Quantum Chromodynamics (QCD):



Gluons



No still picture!
No fixed structure!

Nanometer *Femtometer* *Quantum Probability*

From 3D hadron structure to QCD, …

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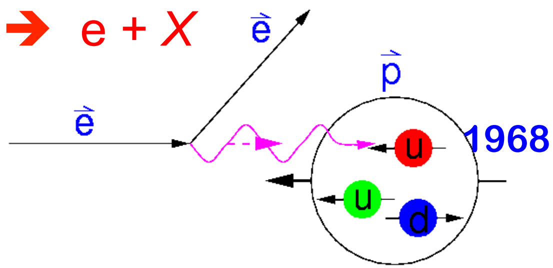

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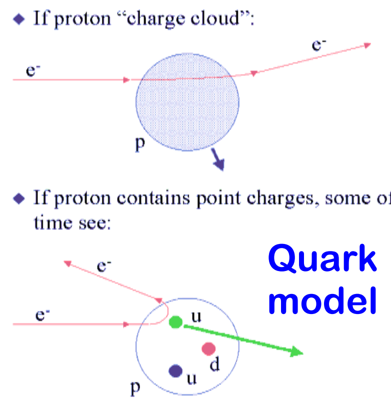

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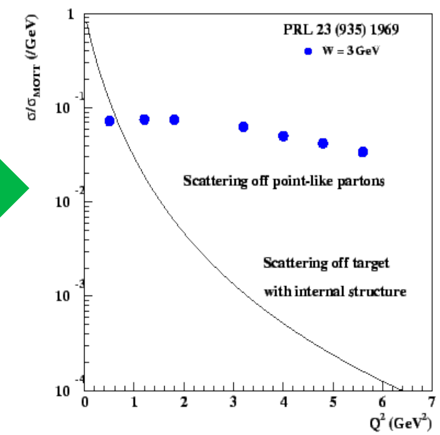
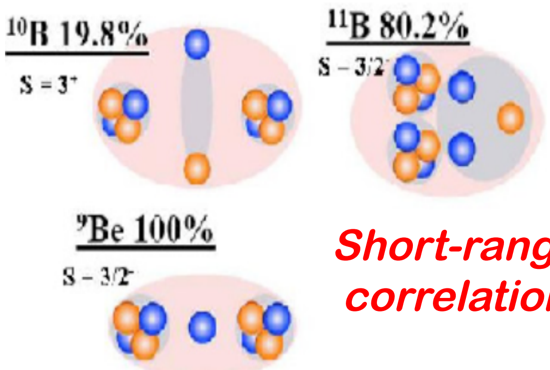


Discovery of quarks!

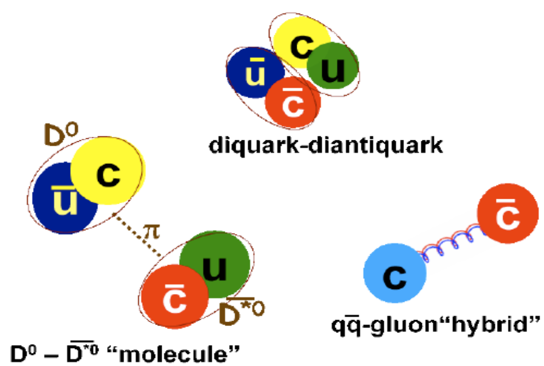
❑ No localized mass and charge centers:

Nuclei – "Molecule"



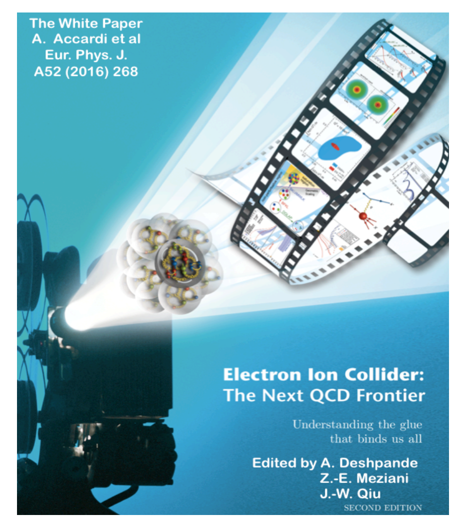
Short-range correlation

XYZ – "Nuclei"



"Light-flavor" **"Heavy-flavor"**

"Femtography"



New frontier of hadron physics … !

Outline of the rest of my talk

- Next frontier of QCD and hadron physics?

  Overarching questions?

- How to "see" the hadron structure?

  See the "unseen"?

- How to quantify the hadron structure in QCD?

  Probabilities to catch the parton and its interaction?

- What do we hope to learn from future facilities?

  From JLab 12 GeV to a future Electron-Ion Collider

  From Lattice QCD – Complementary to experiments

- Summary and outlook

Next frontier of QCD & hadron physics, ...

- How did hadrons, the building blocks of visible world, emerge from quarks and gluons?

  Necessary knowledge for understanding
  where and how did we come from following the “Big Bang?

- What is the internal structure of hadrons, and the dynamics behind the structure?

  Necessary knowledge for understanding
  what are we made of, and
  what hold us together, as well as
  how do we improve and move forward – femtotechnology?

- What is the key for understanding color confinement?

  Necessary knowledge for understanding
  what is the mother nature of the nonlinear,
  strongly interacting dynamics of the color force?

How to "see" the hadron structure?

- **Facts:**

  Gluons are dark!

  No modern detector has been able to see quarks and gluons in isolation!

- **The intellectual challenge:**

  How to probe the quark-gluon dynamics, quantify the hadron structure, study the emergence of hadrons, …, if we cannot see quarks and gluons?

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- **Answer to the challenge:**

  Theory advances:

  QCD factorization – matching the quarks/gluons to hadrons with *controllable approximations*!

  Experimental breakthroughs:

  Jets – *Footprints of energetic quarks and gluons*

  Quarks – *Need an EM probe to “see” their existence, …*

  Gluons – *Varying the probe’s resolution to “see” their effect, …*

  Technology improvements:

  Energy, luminosity, unprecedented resolution, …

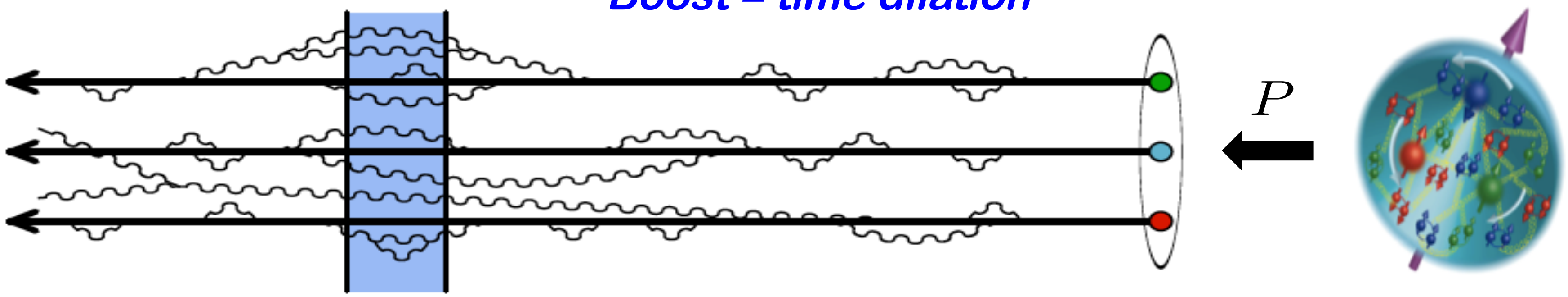
How to “see” the hadron structure?

- **Hard probes to “catch” the quantum fluctuation:**

Lorentz invariant cross sections are frame independent
But, the physical picture of what happened is frame dependent

In any frame in which the proton is moving very fast,

Boost = time dilation



Hard probe (t ~ 1/Q < fm) → *Probability to “catch” the parton!*

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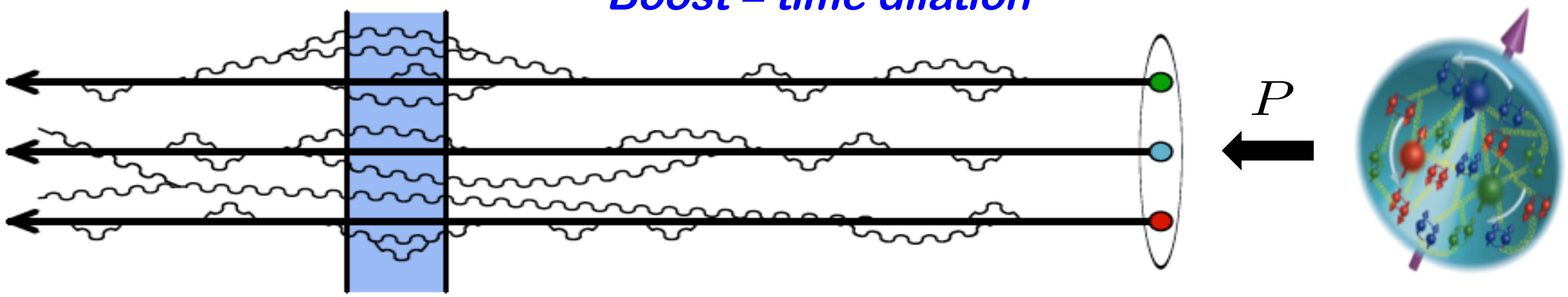


Hard probe (t ~ 1/Q < fm) ➡ *Probability to "catch" the parton!*

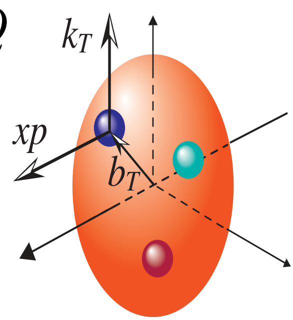
✧ Longitudinal momentum fraction – *x* : $xP \sim Q$ the hard scale!

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

✧ Momentum transfer in diffractive – t : $t \ll Q \quad \Rightarrow 1/b_T$

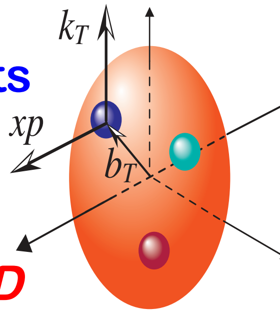
➡ Spatial imaging: ➡

With the collision size: $\sim 1/Q$



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!***

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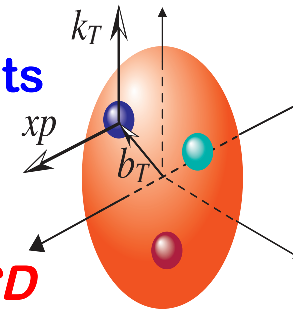

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✧ **BUT:** *None of these matrix elements is a direct physical observable – color confinement!*

✧ **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

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

➡ *Need probes/observables with at least ONE large-scale, & additional controllable small scale(s) to "see" the structure!*

How to quantify hadron structure in QCD?

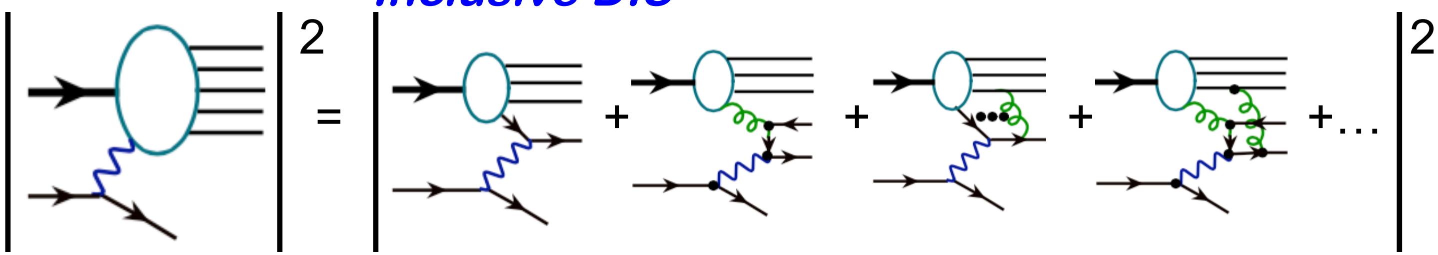
- **Matching the observed hadron to the caught partons:**

Any cross section with identified hadron(s) is NON-Perturbative!

Cross section with ONE identified hadron & ONE large momentum transfer:

Inclusive DIS

$$\sigma_{\rm DIS}(x,Q^2) =$$



$$\approx c_q \otimes q(x,Q^2) + c_g \otimes g(x,Q^2) + \mathcal{O}\left(\frac{\langle k_T^2\rangle}{Q^2}, \frac{\langle F^2\rangle}{Q^2}, ..\right)$$

Probe — **Structure** — **Probe** — **Structure**

Most non-perturbative physics are neglected
Included only those in input PDFs!

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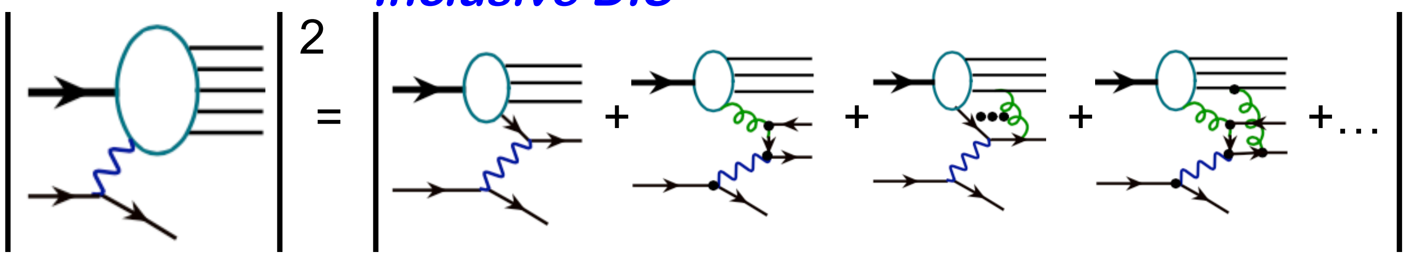

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Probe | Structure | Probe | Structure

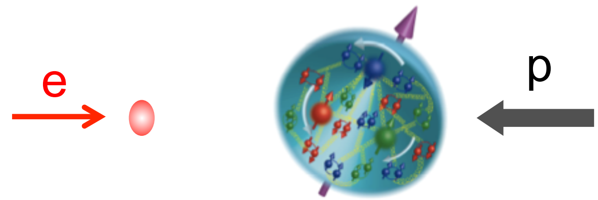
Most non-perturbative physics are neglected
Included only those in input PDFs!

➡ **Leading power/twist factorization – an approximation!**

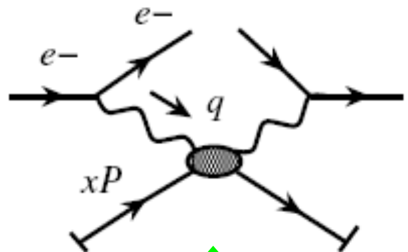
Controllable approximation

if there are more than one identified hadron, …

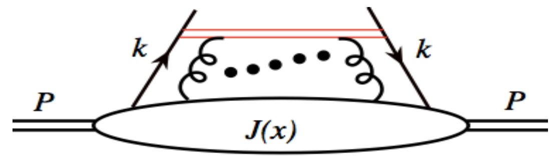
- ❑ **One hadron:**



σ_{tot}^{DIS} :



$\otimes$



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

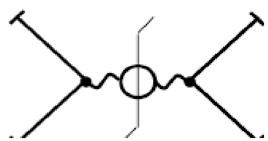
Hard-part
Probe

Parton-distribution
Structure

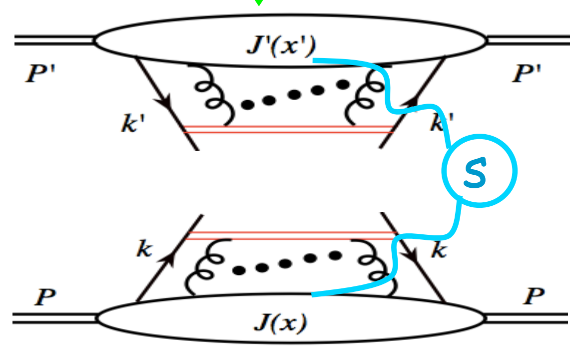
Power corrections
Approximation

- ❑ **Two hadrons:**

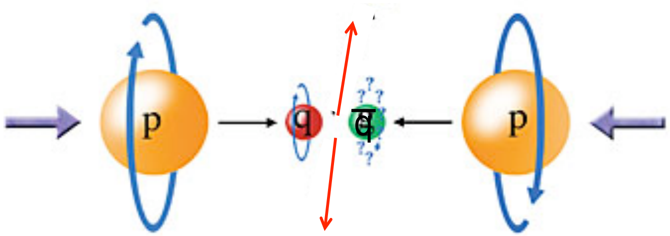
σ_{tot}^{DY} :



$\otimes$



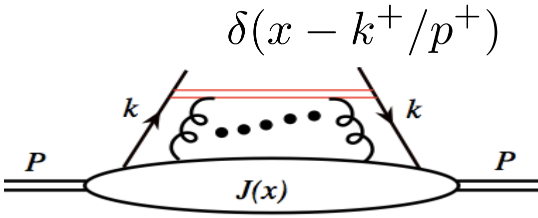
$+ O\left(\frac{1}{QR}\right)$



Predictive power:
Universal Parton Distributions

We have learned a lot for 1D structure, ...

- General expansion of quark distribution:



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

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

- 3-leading power quark parton distribution:

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

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

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

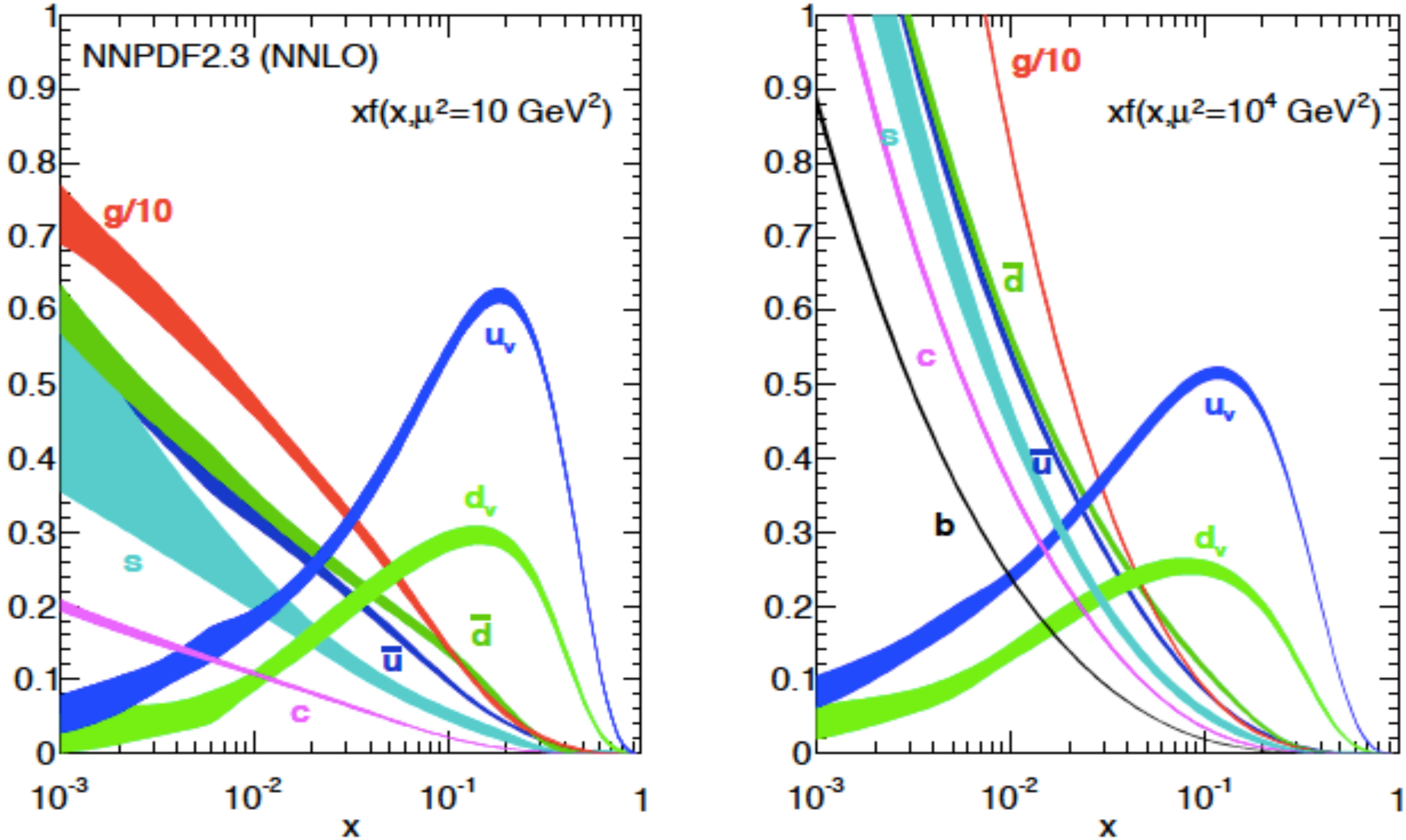
"unpolarized" – "longitudinally polarized" – "transversity"

Probed with observables with a single-hard scale!

- Similar for gluon density and helicity distributions

PDFs of a spin-averaged proton

- Modern sets of PDFs @NNLO with uncertainties:

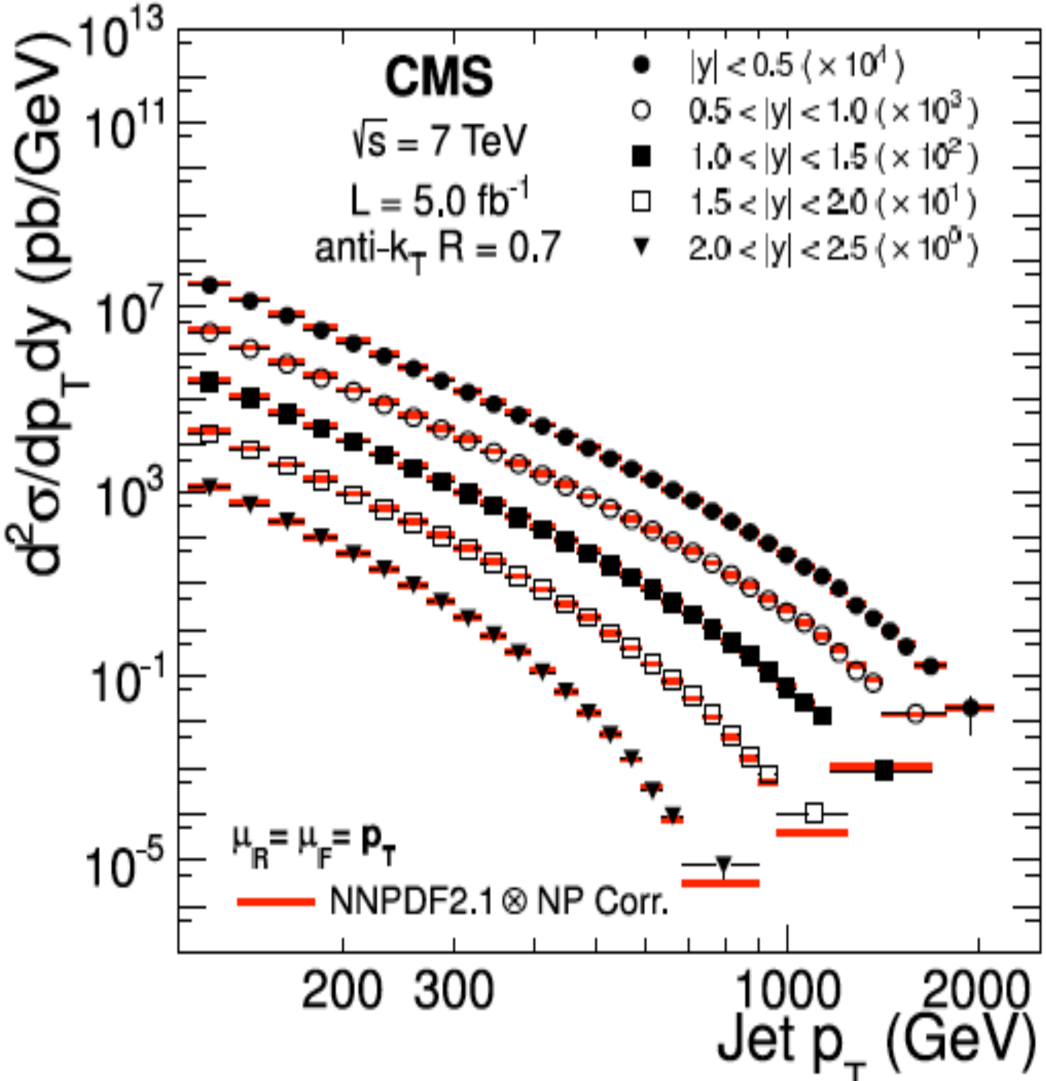


K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014)

Consistently fit almost all data with Q > 2GeV

Role of LHC data

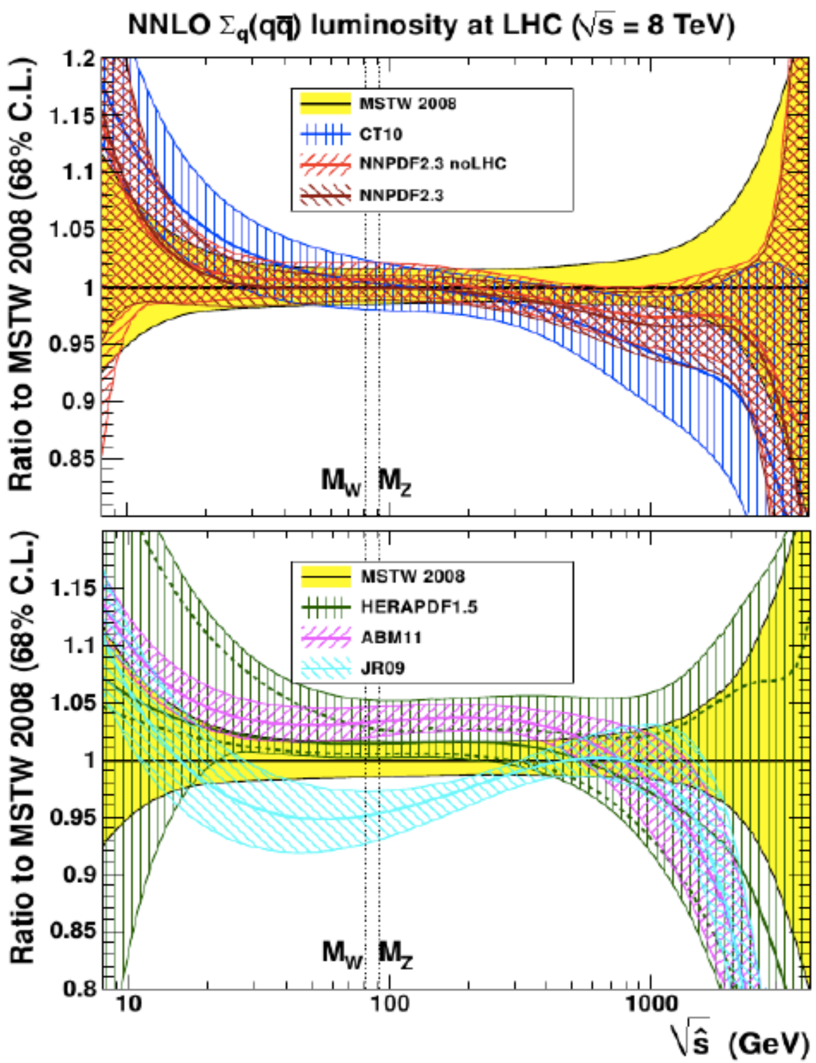
- Inclusive jet production at 7 TeV:



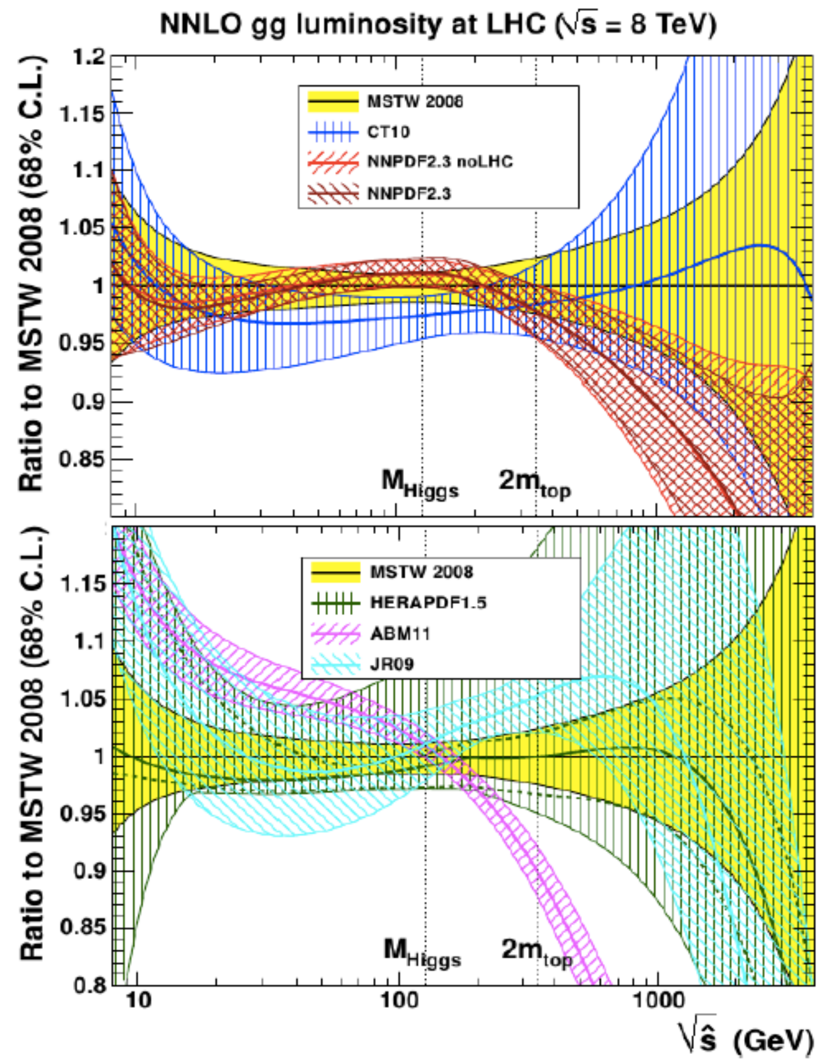
- ✧ Cross sections span 12 orders of magnitude
- ✧ Almost negligible statistical error

Partonic luminosities – Our discovery potential

q - qbar



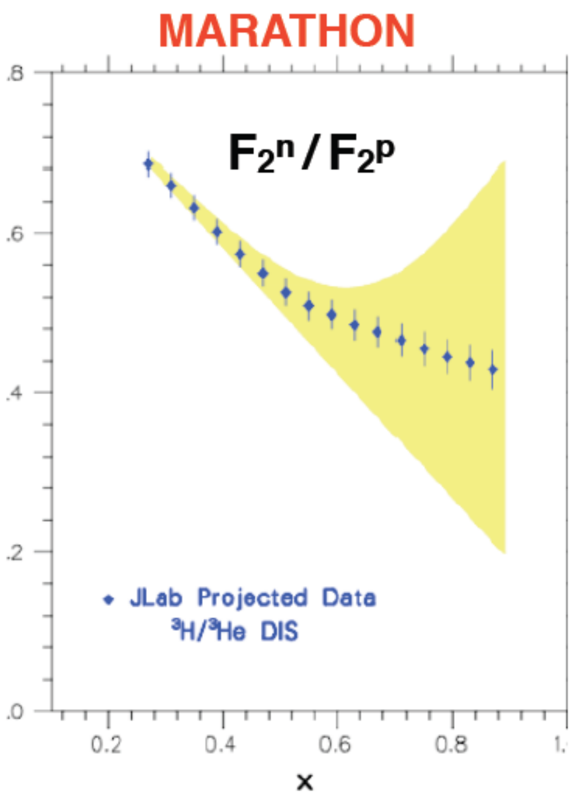
g - g

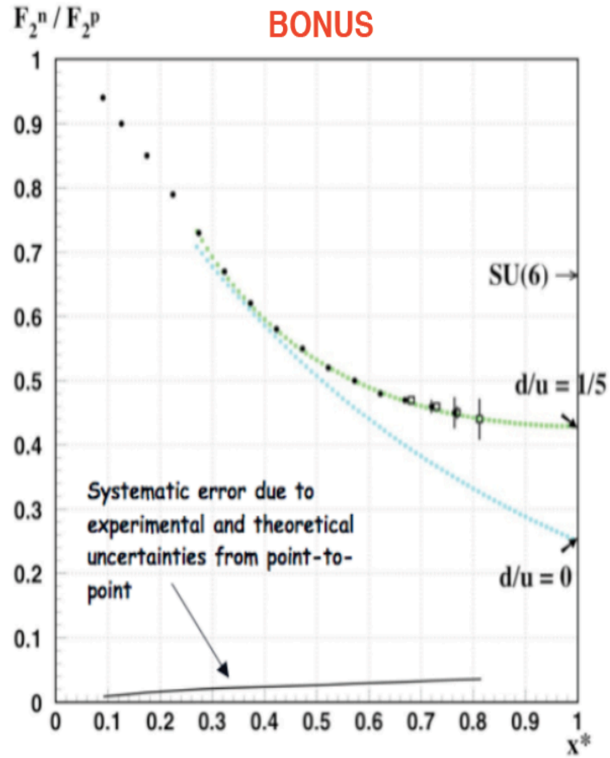


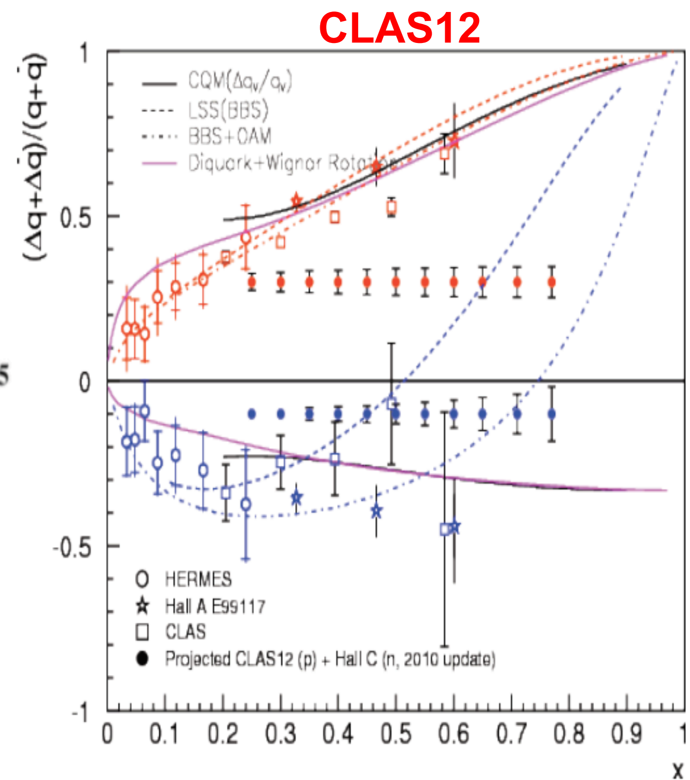
Uncertainties are mainly in large- & small-x regimes – need both JLab12 & EIC

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, …

Future EIC help fix small-x PDFs!

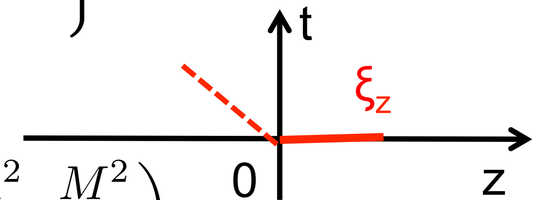
Can lattice QCD help large-x?

Hadron structure from lattice QCD calculation

See talks by Constantinou and Orginos, …

❑ "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:

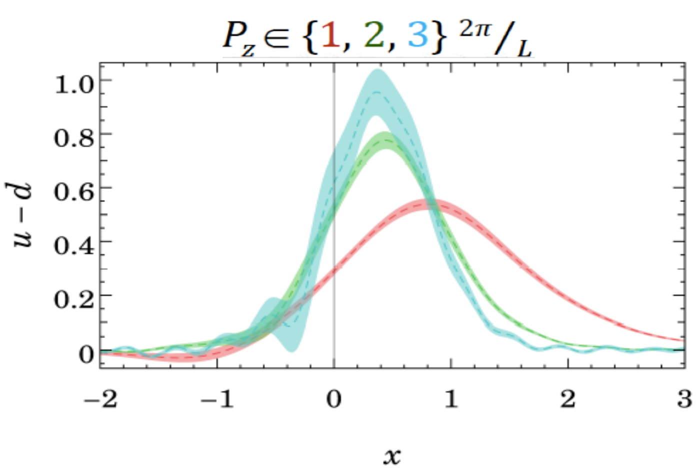
$$\tilde{q}(x,\mu^2,P_z) = \int_x^1 \frac{dy}{y} Z\left(\frac{x}{y},\frac{\mu}{P_z}\right) q(y,\mu^2) + \mathcal{O}\left(\frac{\Lambda^2}{P_z^2},\frac{M^2}{P_z^2}\right)$$

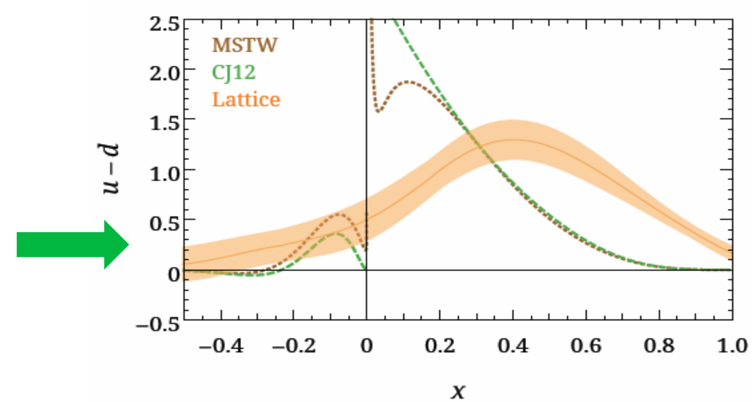
Ji, arXiv:1305.1539

- 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

- **Facts:**
  - ✧ 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

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❑ Beyond the quasi- and pseudo-PDFs:

- ✧ 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

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

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

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

$$\overline{\sigma}_{\mathrm{E}}^{\mathrm{Lat}}(\xi_z, 1/a, P_z) \overset{\mathcal{Z}}{\longleftrightarrow} \sigma_{\mathrm{E}}(\xi_z, \tilde{\mu}^2, P_z)$$

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

$$\Updownarrow$$

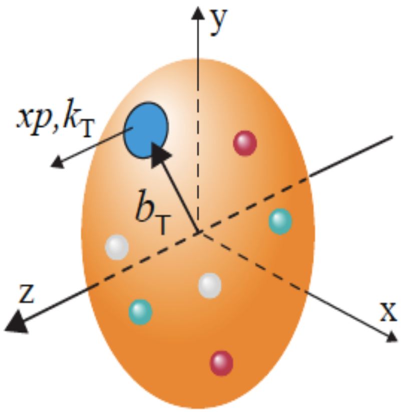
$$\sigma_{\mathrm{M}}(\xi_z, \tilde{\mu}^2, P_z) \overset{\mathcal{C}}{\longleftrightarrow} f_i(x, \mu^2)\,,$$

– Factorization to PDFs (perturbative QCD, …

Paradigm shift: 3D imaging of hadrons

- **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**

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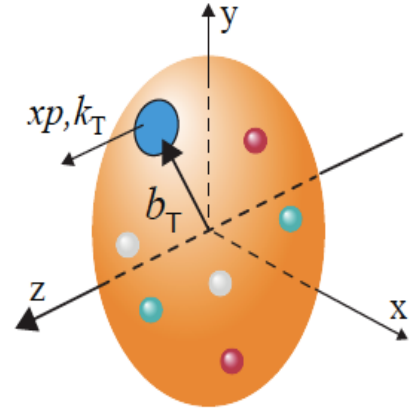

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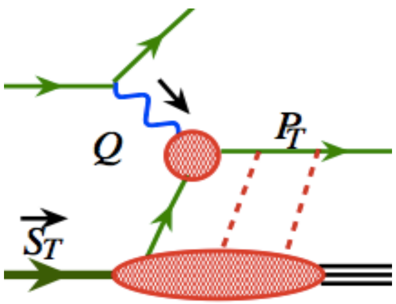
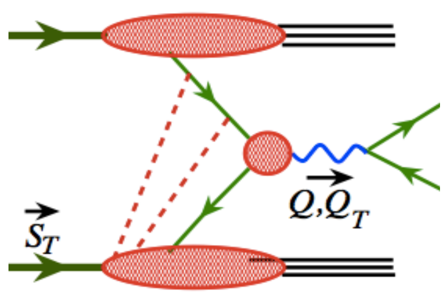
❑ Two-scale observables with the hadron broken:



SIDIS: $Q \gg P_T$

\+



DY: $Q \gg P_T$

\+ Two-jet momentum imbalance in SIDIS, …

✧ Natural observables with TWO very different scales

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

Paradigm shift: 3D imaging of hadrons

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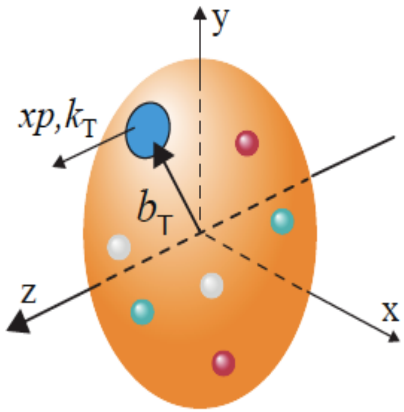

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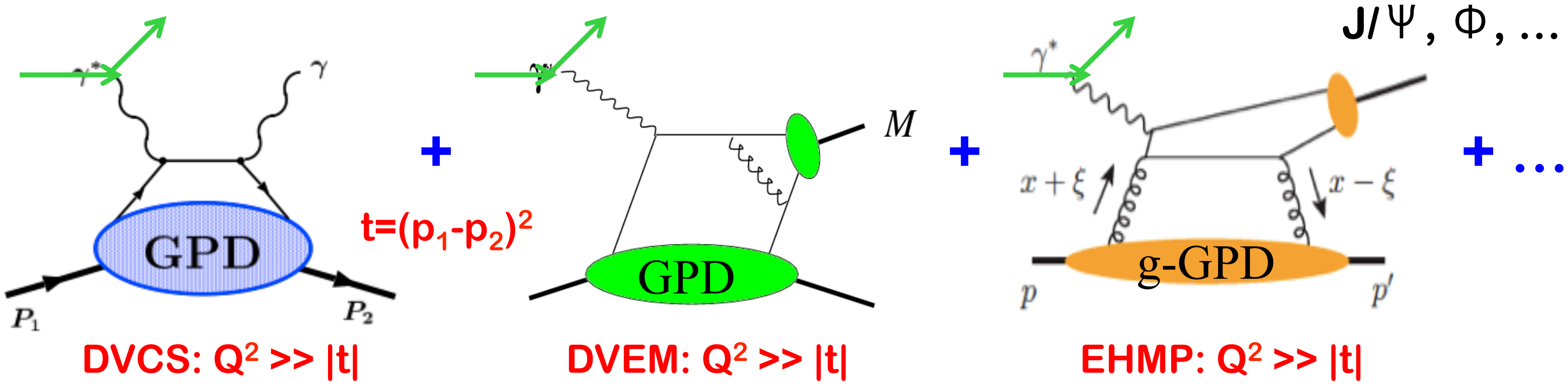
- Two-scale observables with the hadron unbroken:



➡

✧ Natural observables with TWO very different scales

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

Unified description of nucleon structure

See talks by Pasquini, …

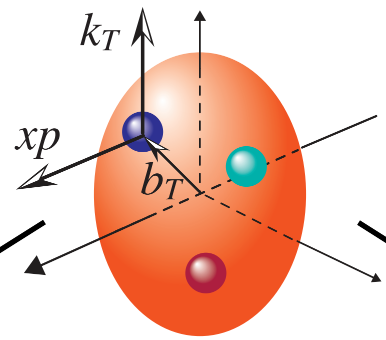
- **Wigner distributions in 5D (or GTMDs):**

Momentum Space

TMDs

Confined motion

$\int d^2 b_T$



$\int d^2 k_T$

Coordinate Space

GPDs

Spatial distribution

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

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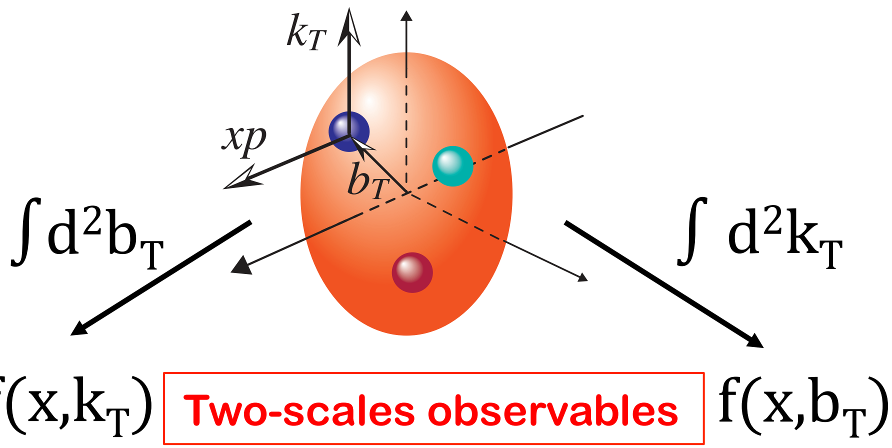


Coordinate Space

GPDs

Spatial distribution

❑ Theory is solid – *TMDs & SIDIS as an example*:

See talks by Rogers, Gamberg, Prokudin, …

✧ **Low P_{hT} (P_{hT} << Q) – TMD factorization:**

$$\sigma_{\rm SIDIS}(Q, P_{h\perp}, x_B, z_h) = \hat{H}(Q) \otimes \Phi_f(x, k_\perp) \otimes \mathcal{D}_{f\to h}(z, p_\perp) \otimes \mathcal{S}(k_{s\perp}) + \mathcal{O}\left[\frac{P_{h\perp}}{Q}\right]$$

✧ **High P_{hT} (P_{hT} ~ Q) – Collinear factorization:**

$$\sigma_{\rm SIDIS}(Q, P_{h\perp}, x_B, z_h) = \hat{H}(Q, P_{h\perp}, \alpha_s) \otimes \phi_f \otimes D_{f\to h} + \mathcal{O}\left(\frac{1}{P_{h\perp}}, \frac{1}{Q}\right)$$

✧ **P_{hT} Integrated - Collinear factorization:**

$$\sigma_{\rm SIDIS}(Q, x_B, z_h) = \tilde{H}(Q, \alpha_s) \otimes \phi_f \otimes D_{f\to h} + \mathcal{O}\left(\frac{1}{Q}\right)$$

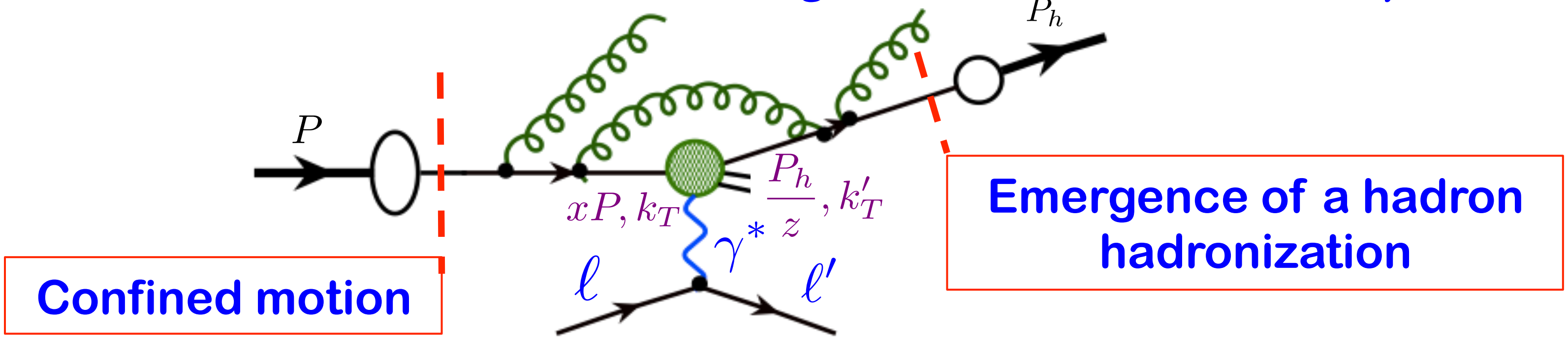
✧ **Very high P_{hT} >> Q – Collinear factorization:**

$$\sigma_{\rm SIDIS}(Q, P_{h\perp}, x_B, z_h) = \sum_{abc} \hat{H}_{ab\to c} \otimes \phi_{\gamma\to a} \otimes \phi_b \otimes D_{c\to h} + \mathcal{O}\left(\frac{1}{Q}, \frac{Q}{P_{h\perp}}\right)$$

Hadron structure and Q^2-dependence

- **Variation of Q^2 at the hard collision:**

Gluon shower – liberation of confined states
– get contributions from all powers



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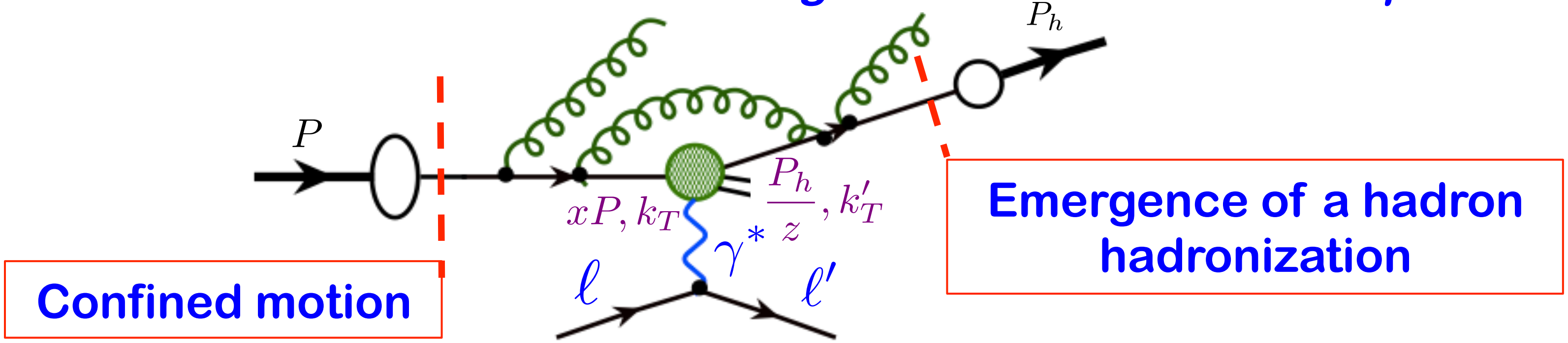

❑ Single hard scale – collinear factorization:

- ✧ DGLAP evolution (LT-approx.) use data at $Q > Q_0$ to help pin down PDFs at Q_0
- ✧ PDFs at Q_0 carry all non-perturbative structure information

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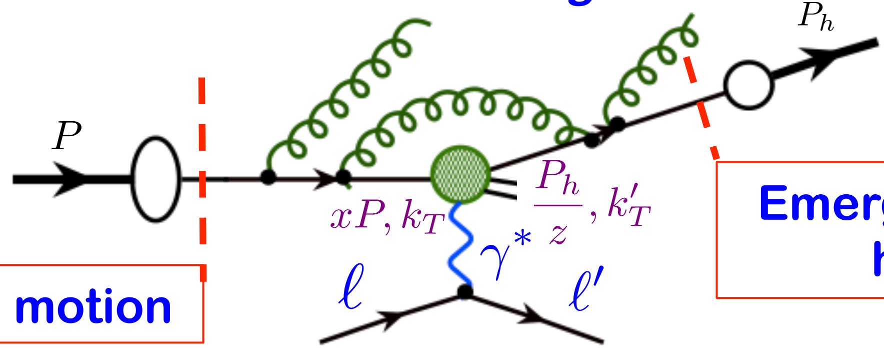


Confined motion

Emergence of a hadron hadronization

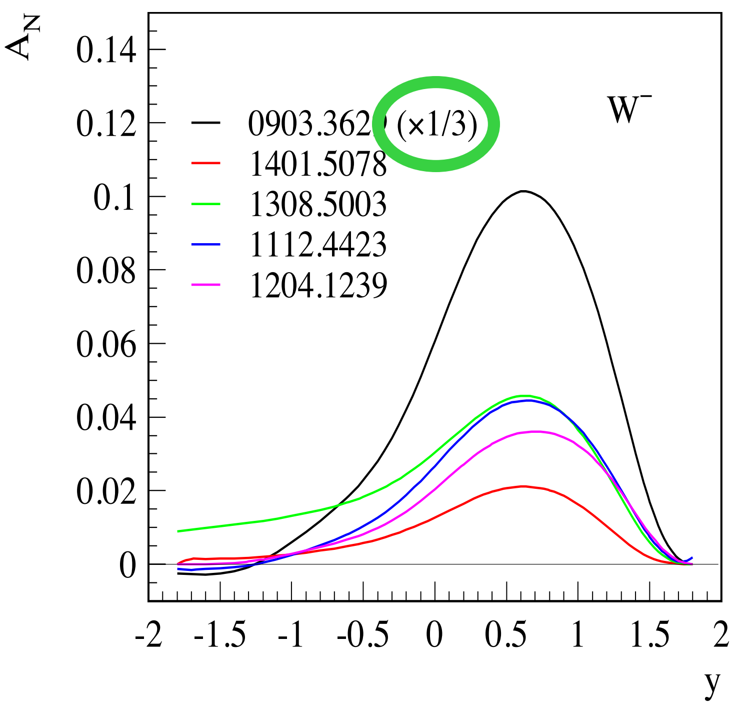
- **Single hard scale – collinear factorization:**
  - ✧ DGLAP evolution (LT-approx.) use data at $Q > Q_0$ to help pin down PDFs at Q_0
  - ✧ PDFs at Q_0 carry all non-perturbative structure information

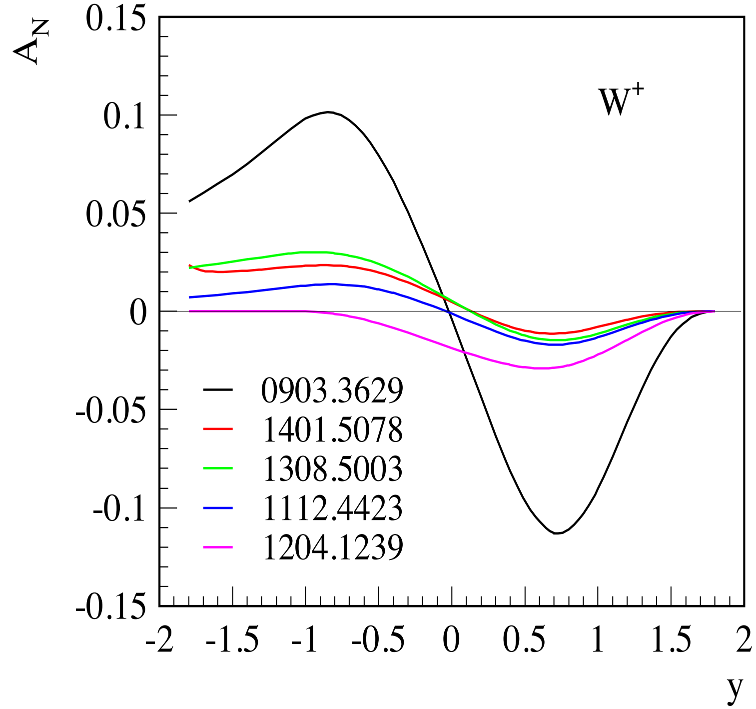
- **Two scales – TMD factorization:**
  - ✧ TMD factorization valid when $P_T << Q$, CS evolution in conjugate b_T-space
  - ✧ When TMDs dominated by small b_T, shower dominated by perturbative logs, CS evolution help use all $Q > Q_0$ data to fix TMDs at Q_0 (Q_0 large, x small)
  - ✧ When TMDs dominated by large b_T region, rich N.P. structure information, CS evolution does not help extract TMDs ⟹ models, new challenge!

Evolution of the Sivers effect

- **Sivers Effect:**
  - Quantum correlation between the spin direction of colliding hadron and the preference of motion direction of its confined partons
  - QCD Prediction: Sign change of Sivers function from SIDIS and DY

- **"Prediction" and large uncertainty of QCD evolution:**



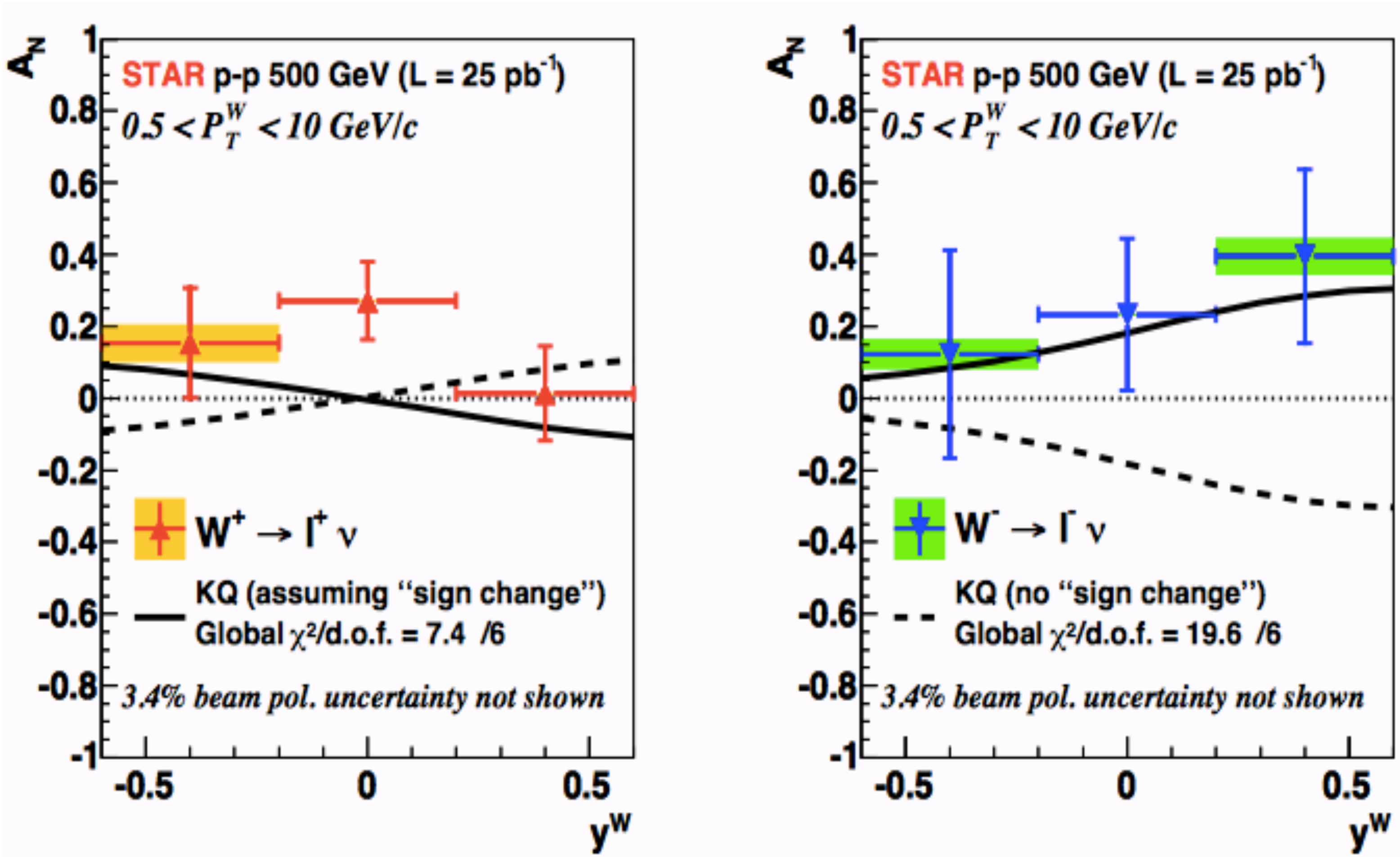


RHIC is an unique facility to test this (W/Z – DY)!

Evolution of the Sivers effect

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

See talk by Aschenauer, …



Theory curves (KQ) = No TMD evolution!

also see M. Anselmino et al. JHEP 1704 (2017) 046

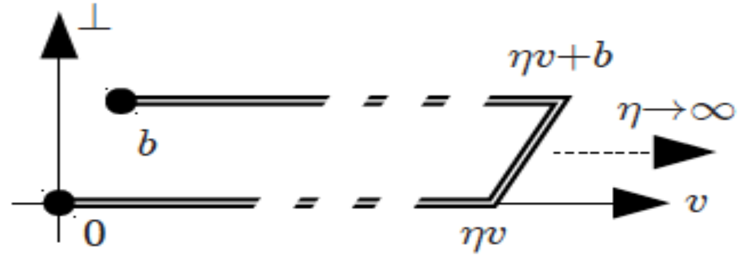
Data from STAR collaboration on A_N for W-production are consistent with a sign change between SIDIS and DY

Hint of the sign change from lattice QCD

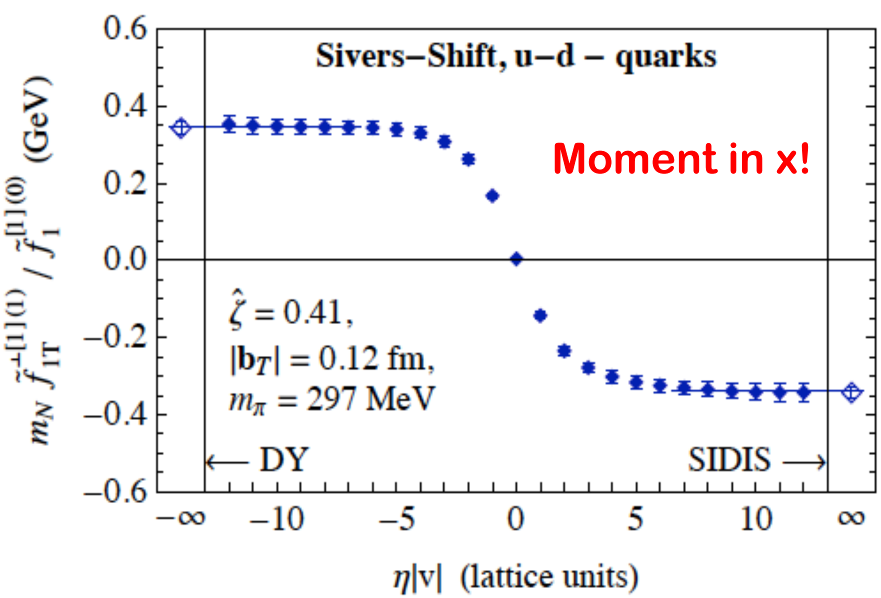
Engelhardt@TMD Collaboration meeting

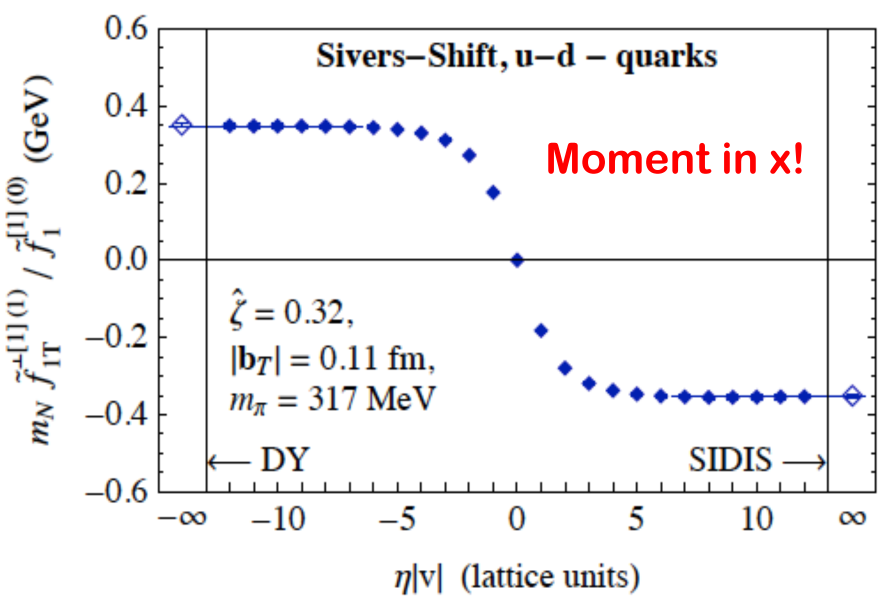
❑ Gauge link for lattice calculation:

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



❑ Normalized moment of Sivers function – at given b_T:

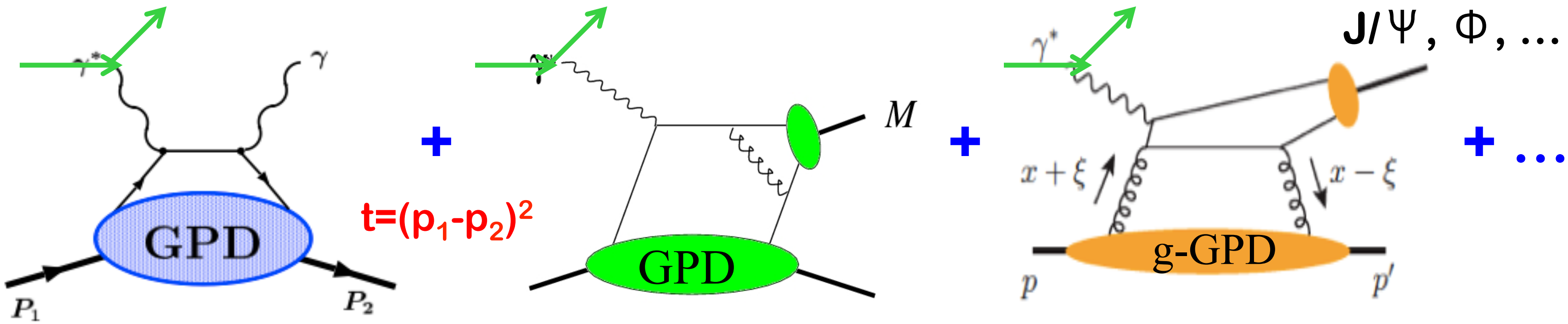




Hunting for GPDs: Exclusive DIS

See talks by Kumericki, Mezrag, Ferrero, Hafidi, Roche, Horn, …

- ❑ **Experimental access to GPDs:**



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

- ❑ **Much more complicated – (x, ξ, t) variables:**
  - ✧ Challenge to derive GPDs from data

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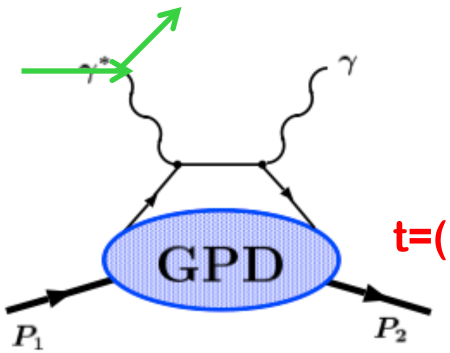
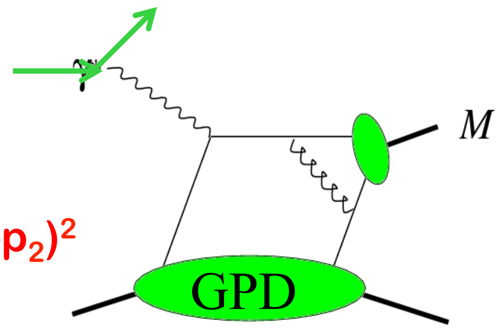
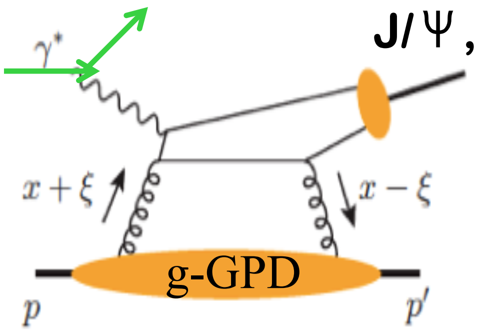


+ $t=(p_1-p_2)^2$



+

J/Ψ, Φ, …



+ …

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

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

✧ Challenge to derive GPDs from data

❑ GPDs could tell us:

✧ Orbital contribution to proton's spin

✧ Proton radius of quark & gluon density

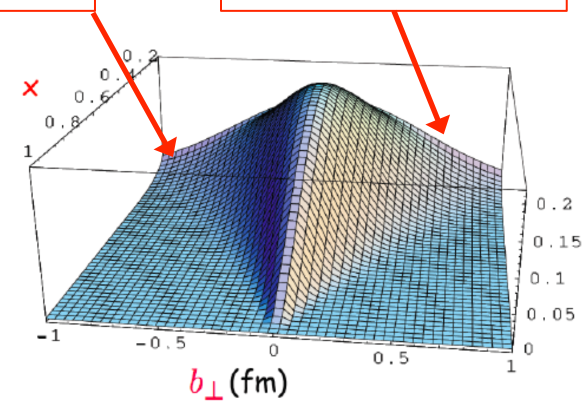
✧ Hints for color confining radius/mechanism

✧ Origin of nuclear force, …

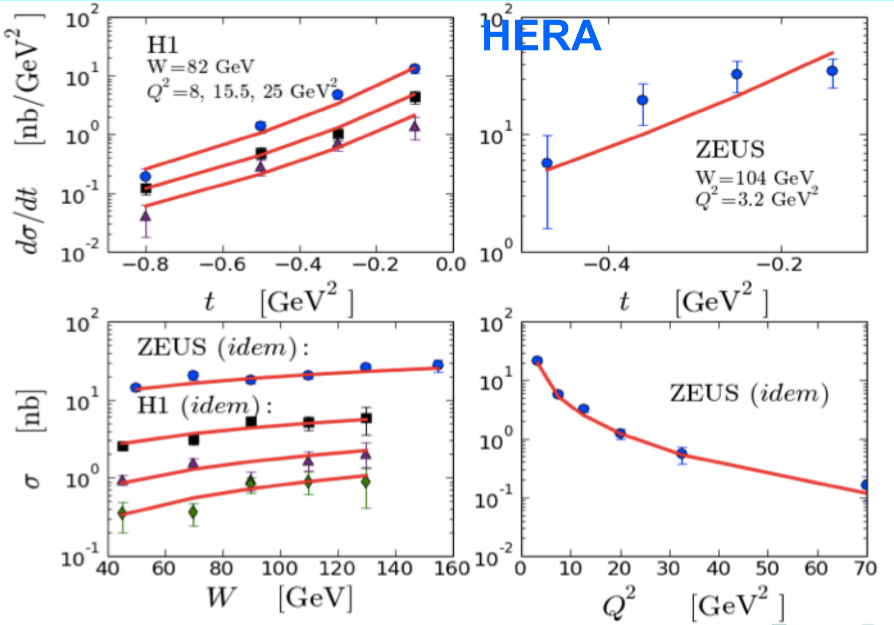
✧ …

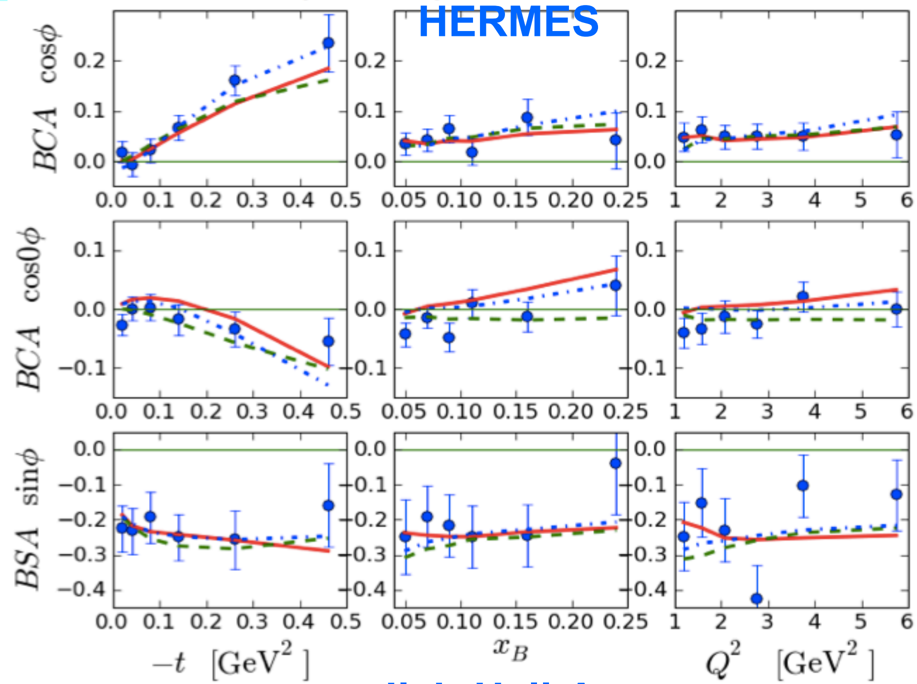
How far does glue density spread?

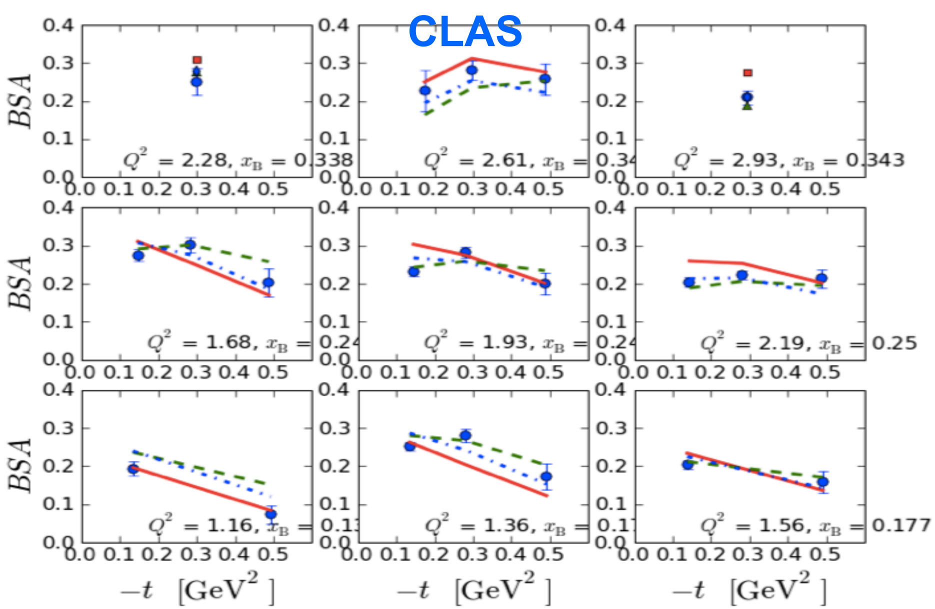
How fast does glue density fall?

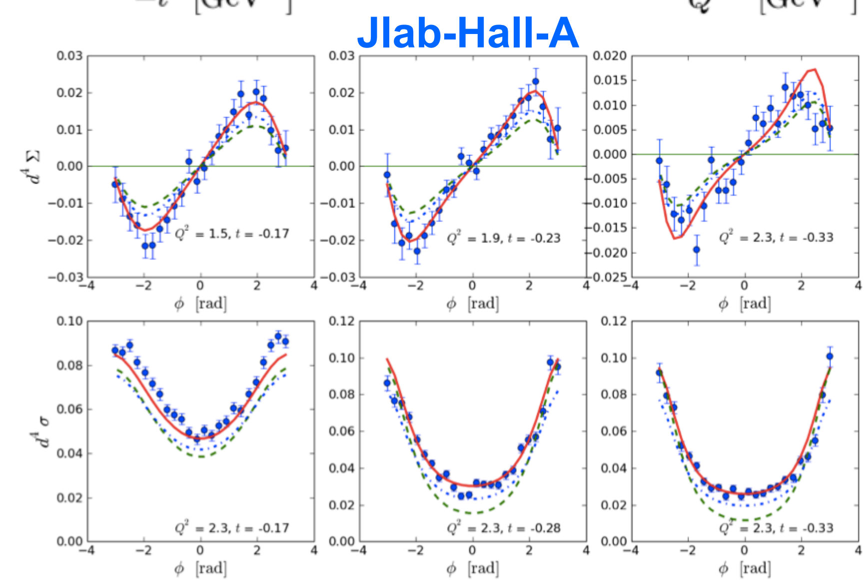


GPDs: just the beginning



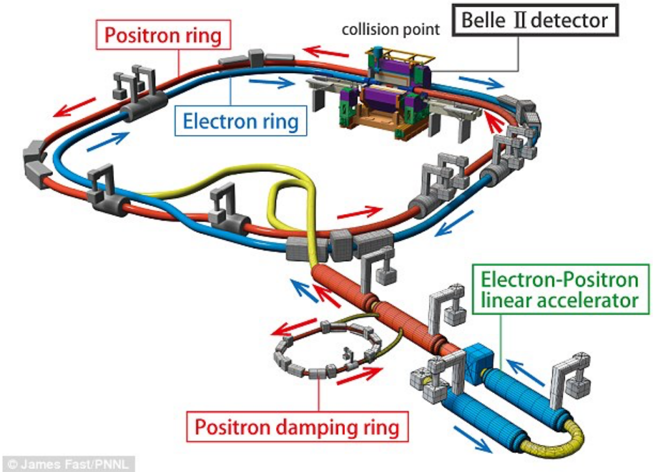


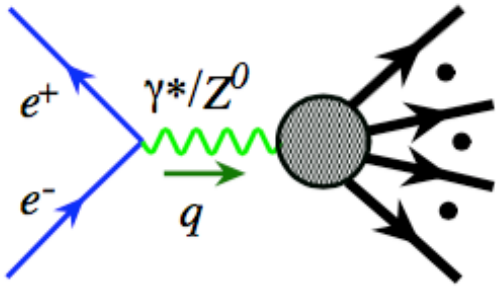




Hard probes from high energy collisions

❑ Lepton-lepton collisions:





Hadrons

- ✧ No hadron in the initial-state
- ✧ Hadrons are emerged from energy
- ✧ Not for studying hadron structure

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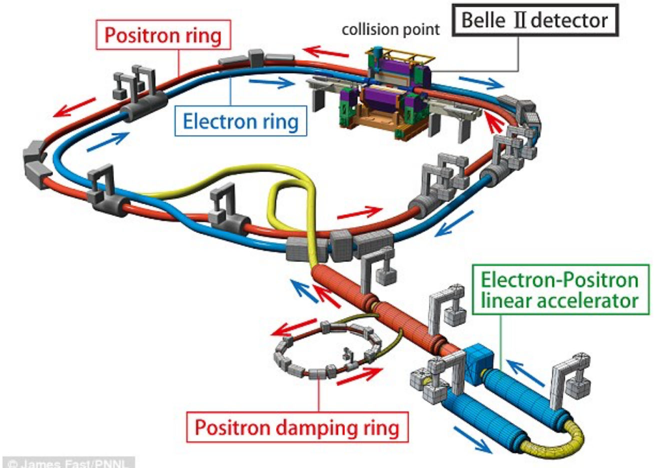

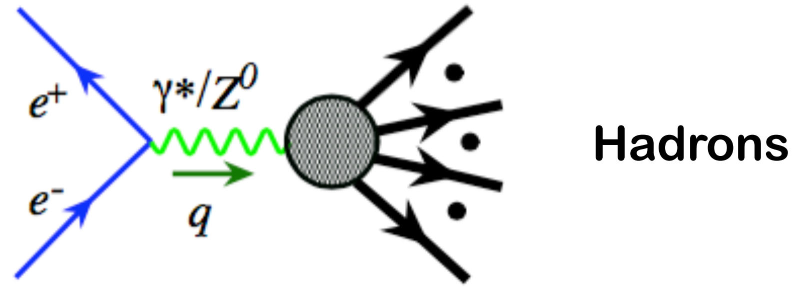

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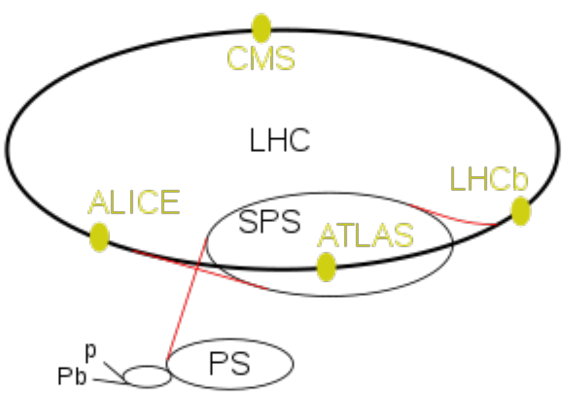

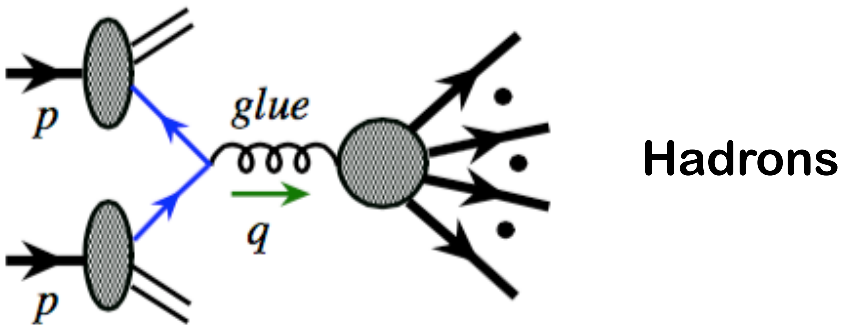

✧ Initial hadrons broken – collision effect, …
✧ Hadron structure – motion of quarks, …
✧ Emergence of hadrons, …

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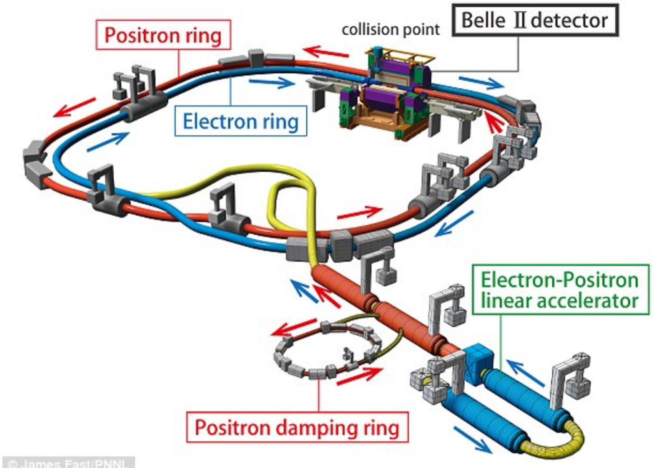

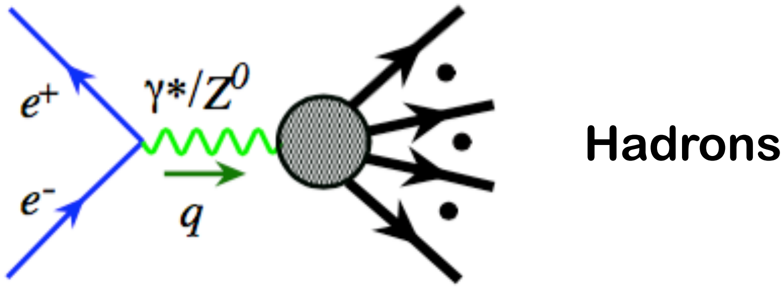

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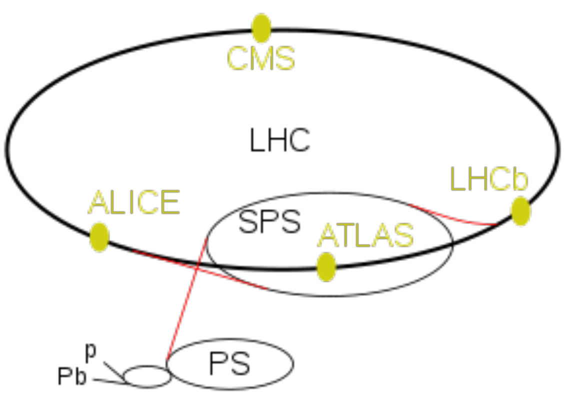

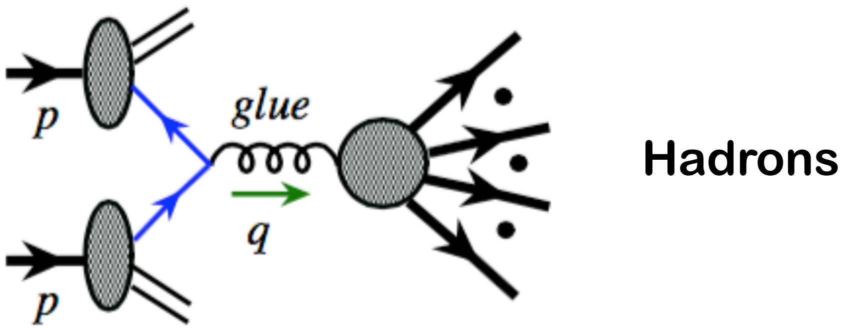

✧ Initial hadrons broken – collision effect, …
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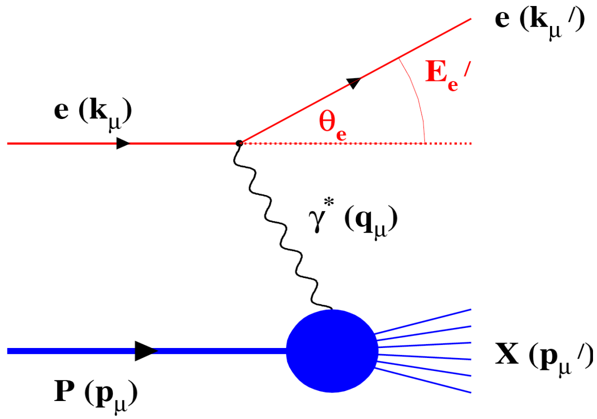
❑ Lepton-hadron collisions:

Hard collision without breaking the initial-state hadron – spatial imaging, …

Many complementary probes at one facility

- **The future "Rutherford" experiment:**



Q^2 → Measure of resolution

y → Measure of inelasticity

x → Measure of momentum fraction of the struck quark in a proton

$$Q^2 = S\ x\ y$$

Inclusive events: e+p/A → e'+X

Detect only the scattered lepton in the detector

(Modern Rutherford experiment!)

Semi-Inclusive events: e+p/A → e'+h(p,K,p,jet)+X

Detect the scattered lepton in coincidence with identified hadrons/jets

(Initial hadron is broken – confined motion! – cleaner than h-h collisions)

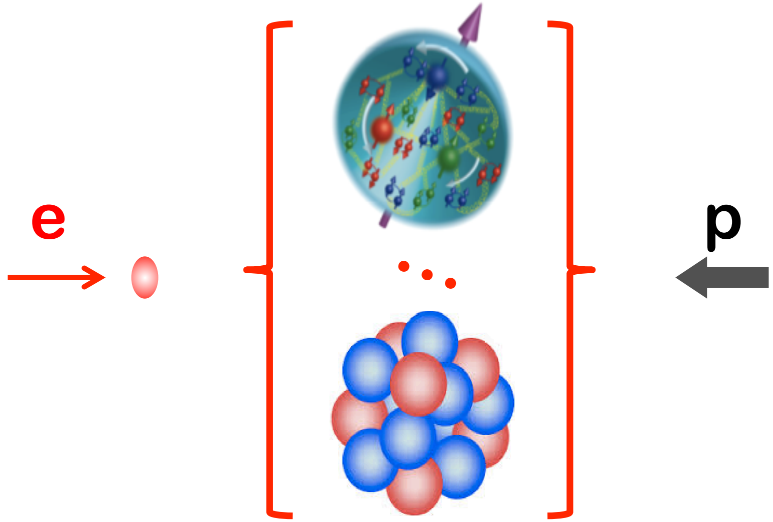
Exclusive events: e+p/A → e'+ p'/A'+ h(p,K,p,jet)

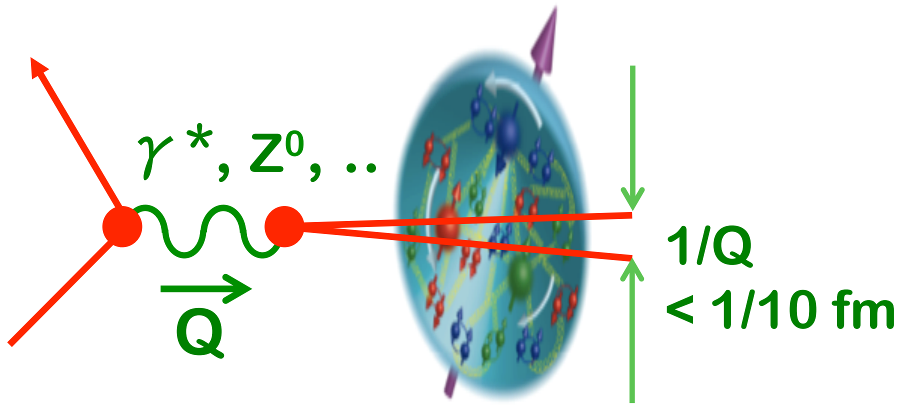
Detect every things including scattered proton/nucleus (or its fragments)

(Initial hadron is NOT broken – tomography! – almost impossible for h-h collisions)

From JLab12 to Electron-Ion Collider (EIC)

❑ **A giant "Microscope"** – "see" quarks and gluons by **breaking** the hadron





To see the dynamics of the glue!

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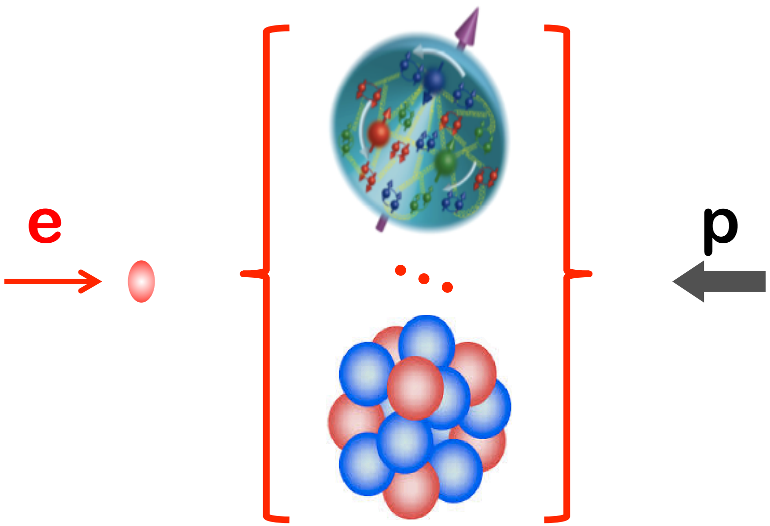

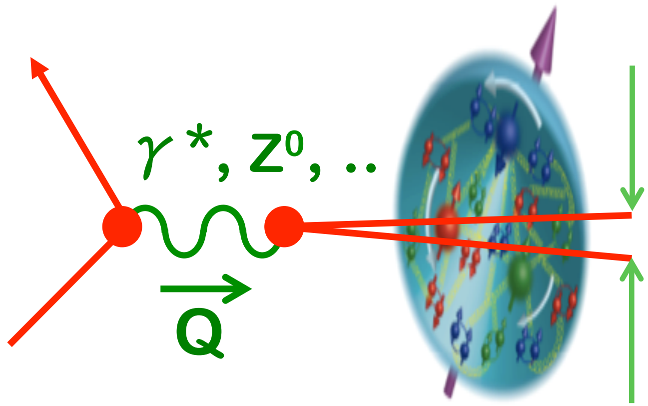

To see the dynamics of the glue!

- A sharpest "CT" – "imagine" quark/gluon structure without breaking the hadron

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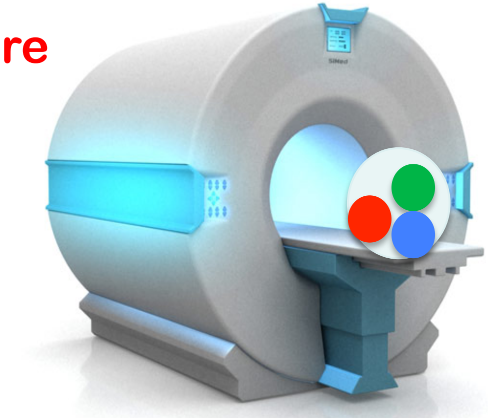
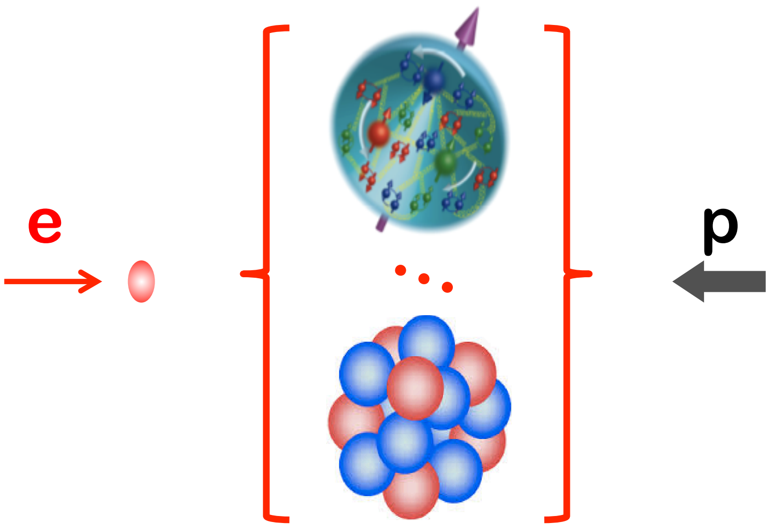
  – "see" proton "radius" of quark/gluon density as a function of "x" – another tunable knob!

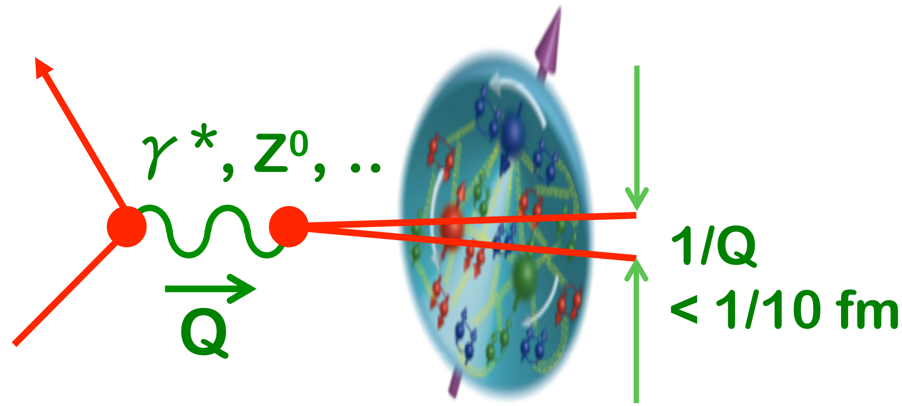


→ *To discover color confining radius, hints on confining mechanism!*

From JLab12 to Electron-Ion Collider (EIC)

- **A giant "Microscope"** – "see" quarks and gluons by **breaking** the hadron





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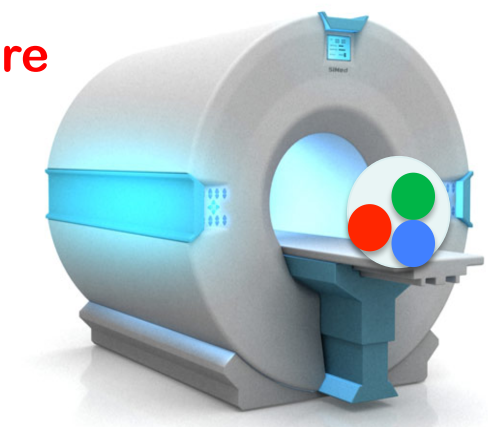

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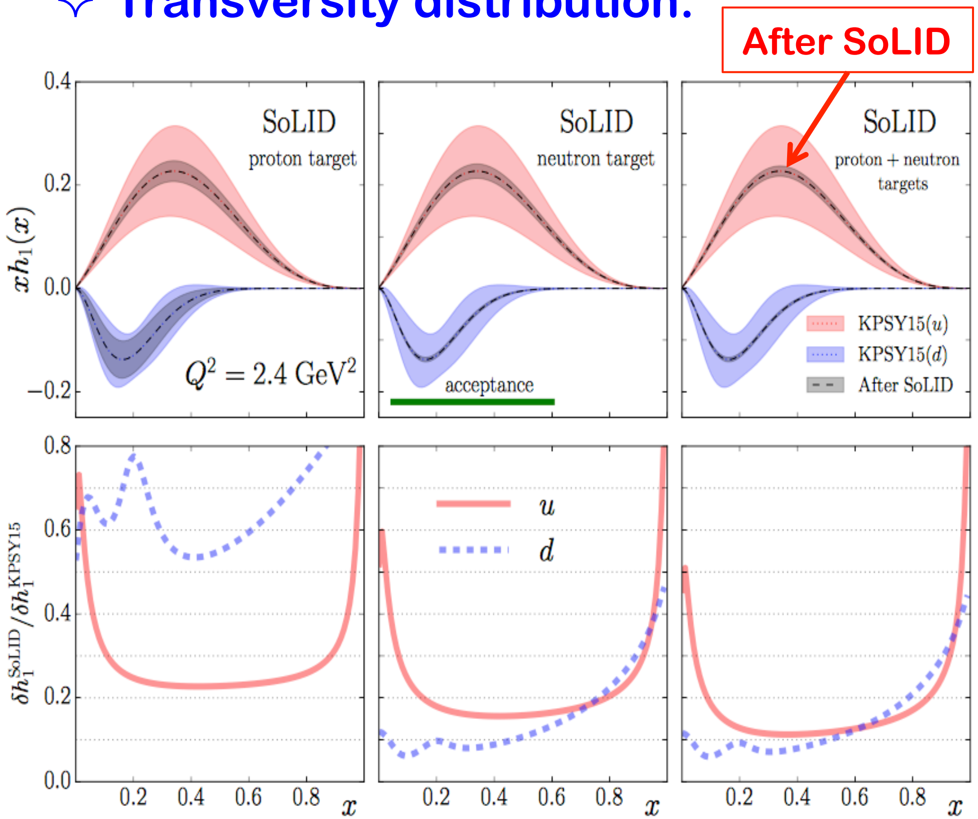
JLab12 – valence quarks, EIC – sea quarks and gluons

Impact of future SoLID at JLab12

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

❑ Transversity & Tensor charge:

✧ Transversity distribution:



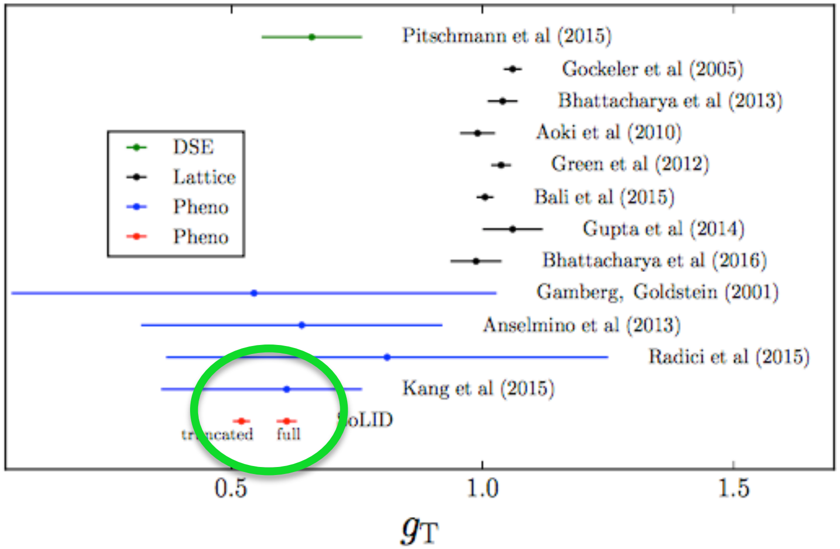
Bayesian statistics is used to estimate the improvement from new data
Current knowledge corresponds to a fit with TMD evolution *Kang et al., P.R. D93 (16) 014009*

Order of magnitude improvement in determining the tensor charge!

✧ 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 $0.05 < x < 0.6$

Why US-EIC can do what HERA can't do?

See talks by R. Ent,

- **Quantum imaging:**
  - HERA discovered: 15% of e-p events is diffractive – Proton not broken!
  - US-EIC: 100-1000 times luminosity – *Critical for 3D tomography!*

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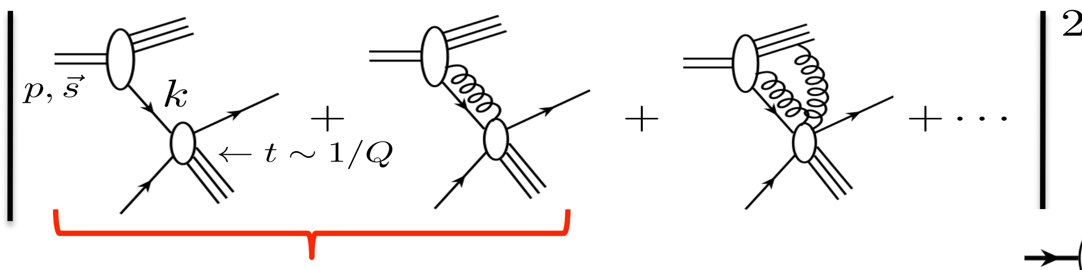
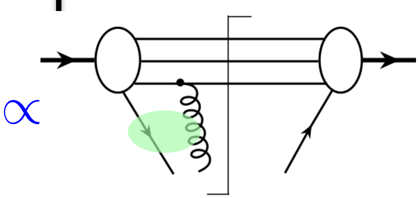
- **Quantum interference & entanglement:**
  - ✧ US-EIC: Highly polarized beams – *Origin of hadron property: Spin, …*
    Direct access to chromo-quantum interference!

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



$\sigma(s) - \sigma(-s)$ ➡ Quantum interference ➡ $T^{(3)}(x,x) \propto$



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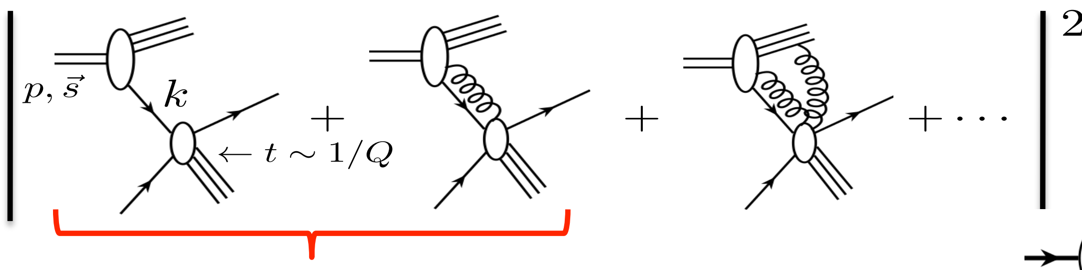

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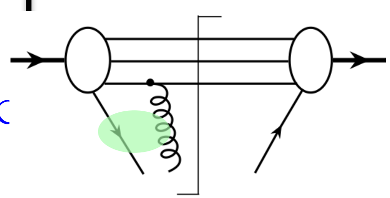


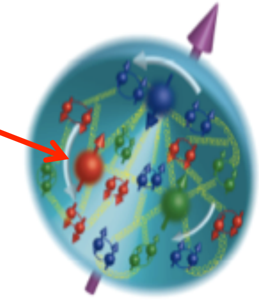
❑ Nonlinear quantum dynamics:

✧ **US-EIC: Light-to-heavy nuclear beams – *Origin of nuclear force, …***
Help Catch the transition from chromo-quantum fluctuation
to chromo-condensate of gluons,
Emergence of hadrons (femtometer size detector!),
– "a new controllable knob" – Atomic weight of nuclei

Summary

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

< 1/10 fm



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

Round table discussion on this Wednesday!

- 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, …

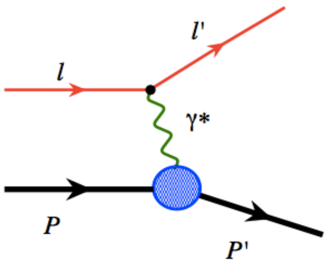
Thank you!

Backup slides

What could we learn about hadron structure?

❑ No elastic color current form factor!

QED:

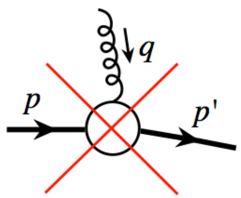


➡ *Form factors*

➡ *Electric charge distribution*

➡ *Proton radius – EM charge*

QCD:



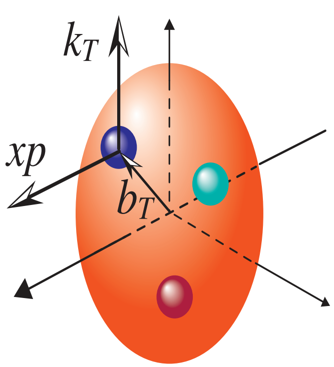
Gluon carries color!

➡ *Parton density distributions*

➡ *Proton radius – quark & gluon density distributions*

❑ 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!*

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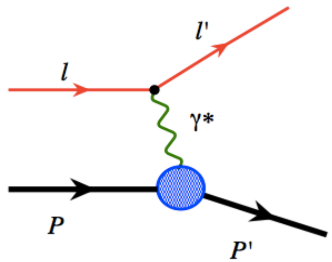

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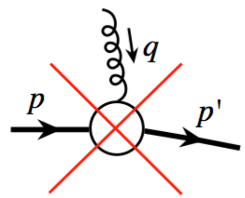


Gluon carries color!

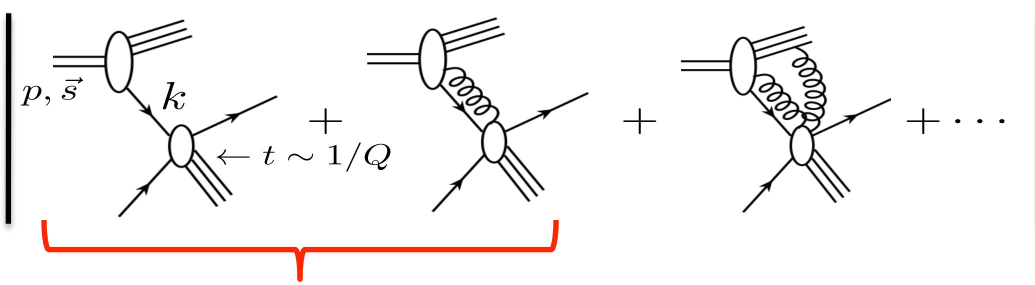
➡ *Parton density distributions*

➡ *Proton radius – quark & gluon density distributions*

❑ Multi-parton, quark-gluon corretions:

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

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



$\Big|^2 \left(\frac{\langle k_\perp \rangle}{Q}\right)^n$ – **Expansion**

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