Explore Hadron Structure by JLab12 Program & Lattice QCD Calculations

Jianwei Qiu

Theory Center, Jefferson Lab

February 15, 2017

Lunch Seminar

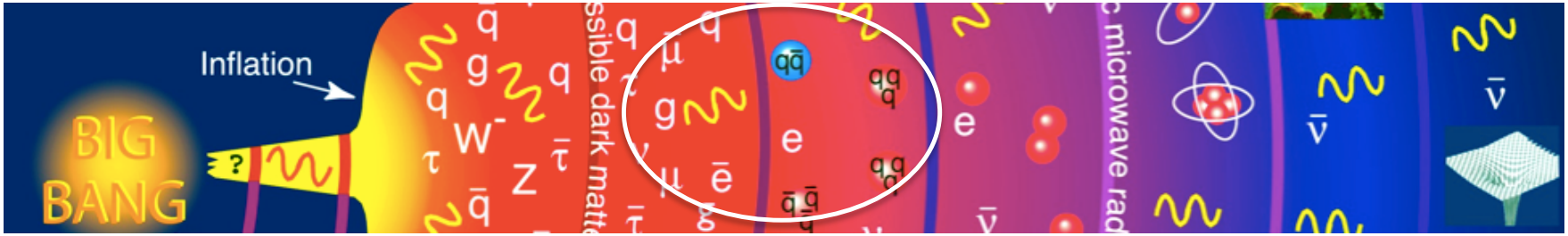
Theory Center

Jefferson Lab

EXPLORING THE NATURE OF MATTER

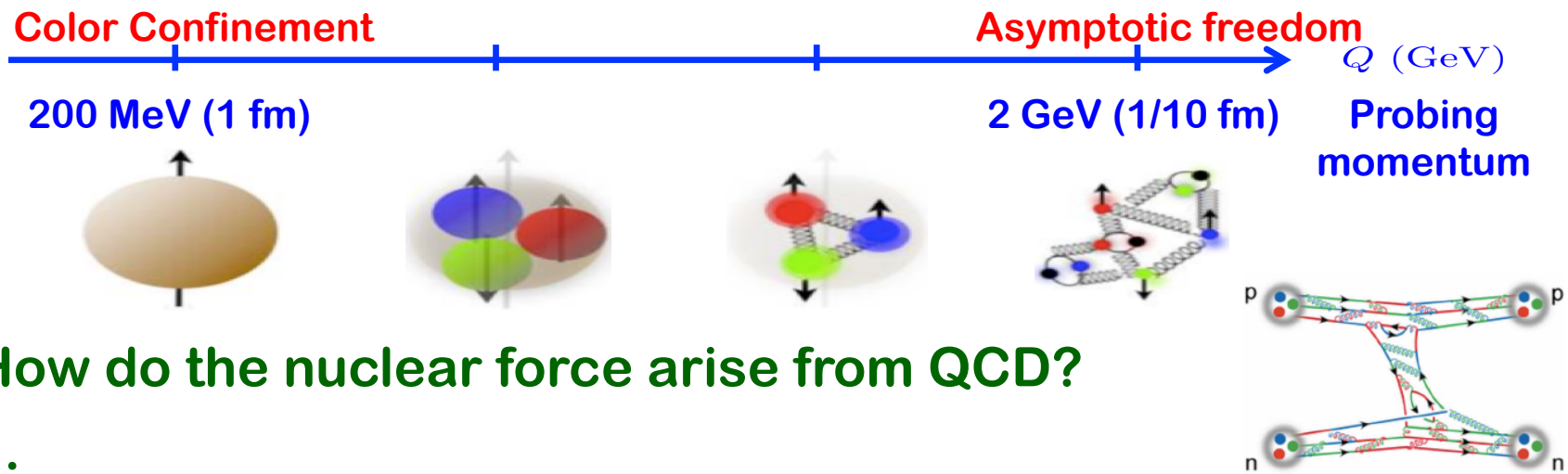
21st Century Nuclear Science

- What is the role of QCD in the evolution of the universe?



- How hadrons are emerged from quarks and gluons?
- How does QCD make up the properties of hadrons?

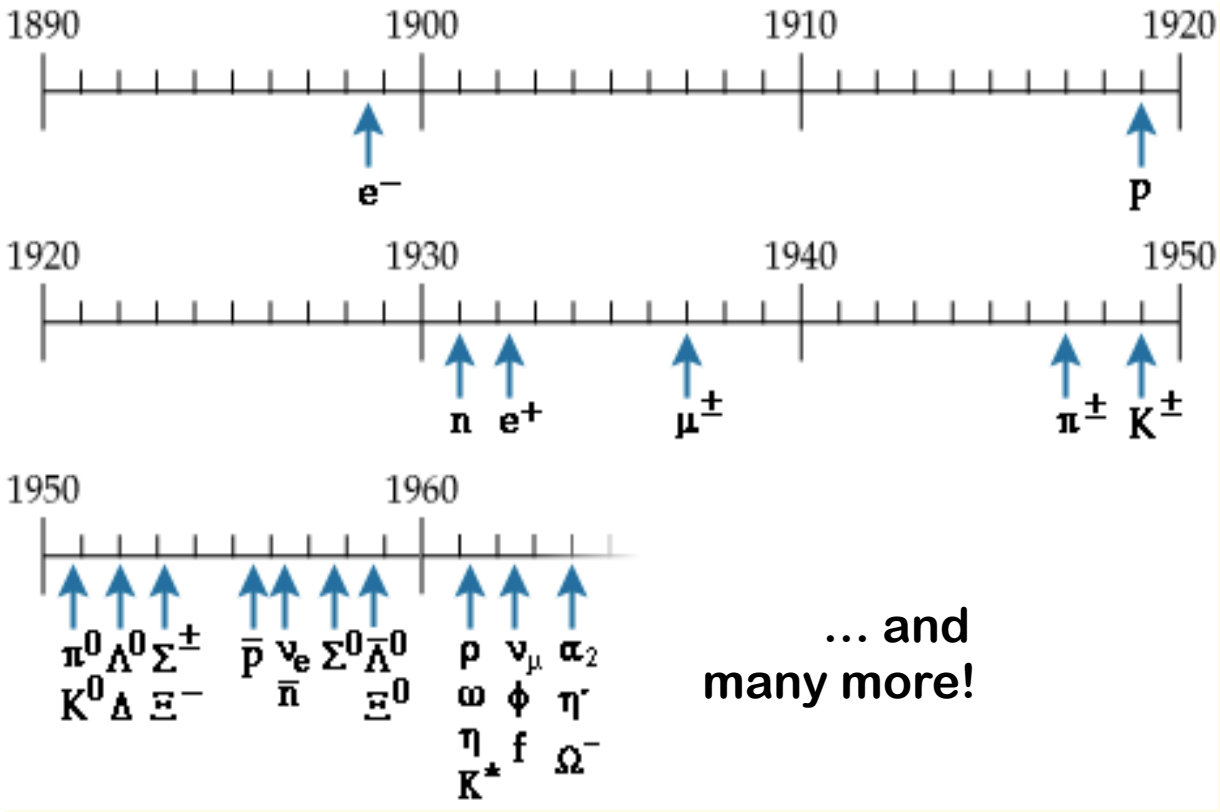
  Their mass, spin, magnetic moment, …
- What is the QCD landscape of nucleon and nuclei?



- How do the nuclear force arise from QCD?
- …

New particles, new ideas, and new theories

- Early proliferation of new hadrons – "particle explosion":



Hadrons have internal structure!

❑ Nucleons cannot be point-like spin-1/2 Dirac particles:

1933: Proton's magnetic moment

Otto Stern

Nobel Prize 1943

$$\mu_p = g_p \left(\frac{e\hbar}{2m_p} \right)$$

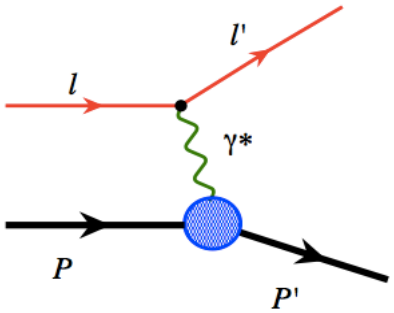
$$g_p = 2.792847356(23) \neq 2!$$

$$\mu_n = -1.913 \left(\frac{e\hbar}{2m_p} \right) \neq 0!$$

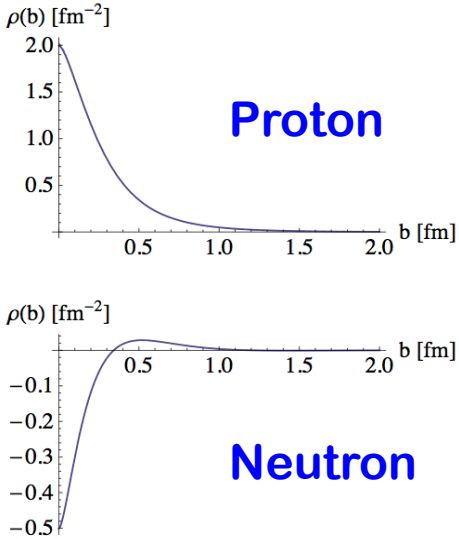
1960: Elastic e-p scattering

Robert Hofstadter

Nobel Prize 1961



Form factors

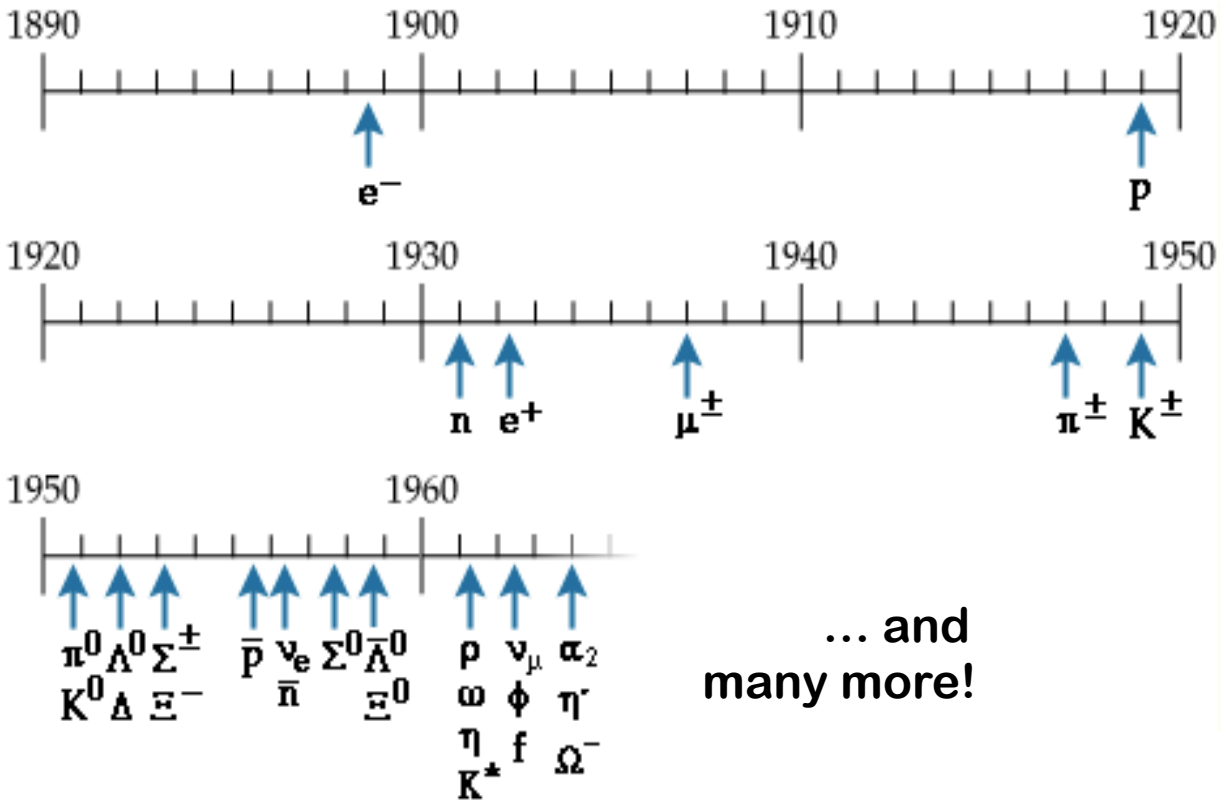


Electric charge distribution

Proton EM charge radius!

New particles, new ideas, and new theories

- Early proliferation of new particles – "particle explosion":

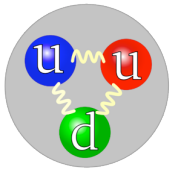


... and many more!

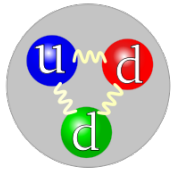
→ Quark Model

Nobel Prize, 1969

Proton



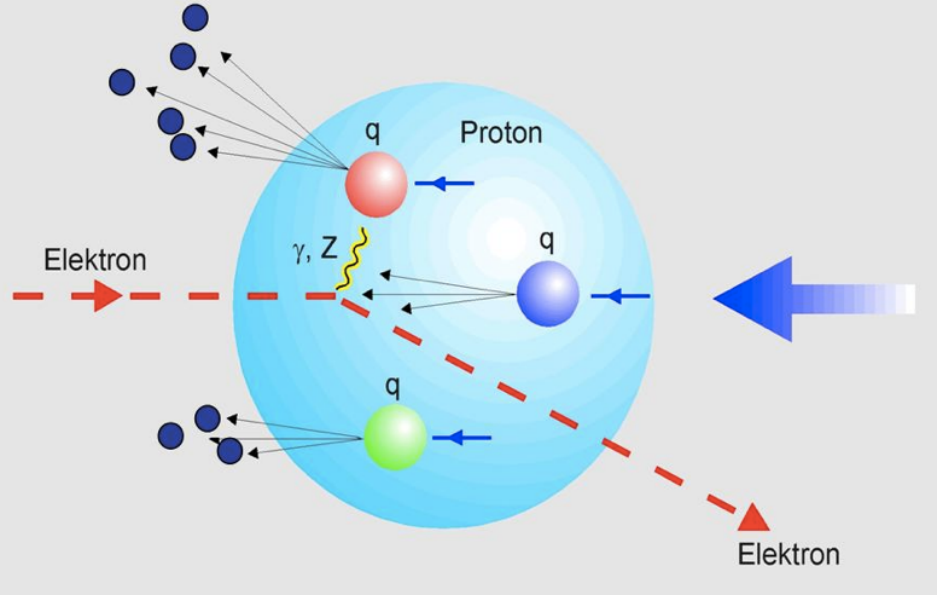
Neutron



Deep inelastic scattering (DIS)

❑ Modern Rutherford experiment – DIS (SLAC 1968)

$$e(p) + h(P) \to e'(p') + X$$



✧ **Localized probe:**

$$Q^2 = -(p - p')^2 \gg 1 \text{ fm}^{-2}$$

$$\Rightarrow \quad \frac{1}{Q} \ll 1 \text{ fm}$$

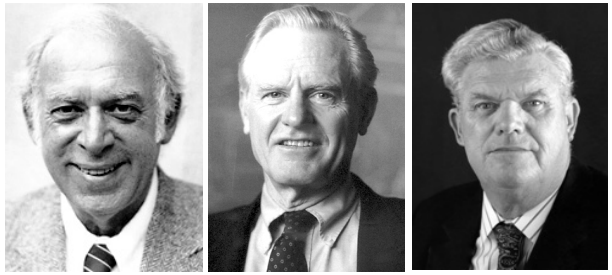
✧ **Two variables:**

$$Q^2 = 4EE' \sin^2(\theta/2)$$

$$x_B = \frac{Q^2}{2m_N \nu}$$

$$\nu = E - E'$$

→ **Discovery of spin ½ quarks, and partonic structure!**



Nobel Prize, 1990

➡ **The birth of QCD (1973)**

– Quark Model + Yang-Mill gauge theory

Quantum Chromo-dynamics (QCD)

= A quantum field theory of quarks and gluons =

- **Fields:**

$\psi_i^f(x)$ **Quark fields: spin-½ Dirac fermion (like electron)**

Color triplet: $i = 1, 2, 3 = N_c$

Flavor: $f = u, d, s, c, b, t$

$A_{\mu,a}(x)$ **Gluon fields: spin-1 vector field (like photon)**

Color octet: $a = 1, 2, ..., 8 = N_c^2 - 1$

- **QCD Lagrangian density:**

$$\mathcal{L}_{QCD}(\psi, A) = \sum_f \overline{\psi}_i^f \left[(i\partial_\mu \delta_{ij} - gA_{\mu,a}(t_a)_{ij})\gamma^\mu - m_f \delta_{ij} \right] \psi_j^f$$
$$- \frac{1}{4} \left[\partial_\mu A_{\nu,a} - \partial_\nu A_{\mu,a} - gC_{abc} A_{\mu,b} A_{\nu,c} \right]^2$$
$$+ \text{gauge fixing} + \text{ghost terms}$$

- **QED – force to hold atoms together:**

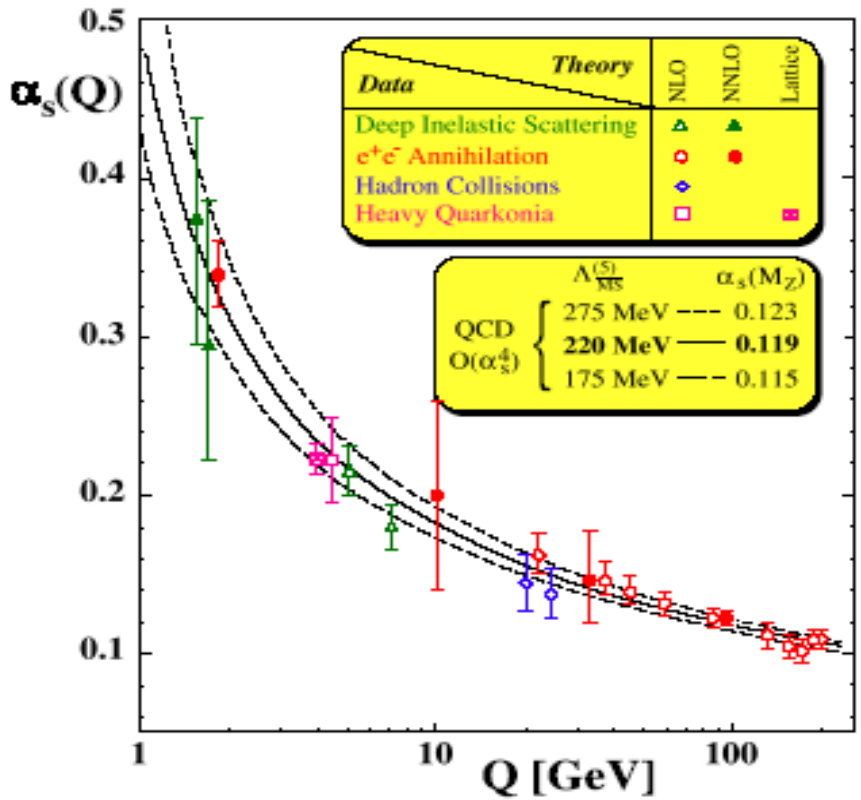
$$\mathcal{L}_{QED}(\phi, A) = \sum_f \overline{\psi}^f \left[(i\partial_\mu - eA_\mu)\gamma^\mu - m_f \right] \psi^f - \frac{1}{4} \left[\partial_\mu A_\nu - \partial_\nu A_\mu \right]^2$$

- **QCD Color confinement:**

Gluons are dark, No free quarks or gluons ever been detected!

QCD Asymptotic Freedom

- **Interaction strength:** $$\alpha_s(\mu_2) = \frac{\alpha_s(\mu_1)}{1 - \frac{\beta_1}{4\pi}\alpha_s(\mu_1)\ln\left(\frac{\mu_2^2}{\mu_1^2}\right)} \equiv \frac{4\pi}{-\beta_1 \ln\left(\frac{\mu_2^2}{\Lambda_{\rm QCD}^2}\right)}$$



μ_2 and μ_1 not independent

Asymptotic Freedom ⇔ antiscreening

QCD: $\frac{\partial \alpha_s(Q^2)}{\partial \ln Q^2} = \beta(\alpha_s) < 0$

Compare

QED: $\frac{\partial \alpha_{EM}(Q^2)}{\partial \ln Q^2} = \beta(\alpha_{EM}) > 0$

D.Gross, F.Willczek, Phys.Rev.Lett 30, (1973)
H.Politzer, Phys.Rev.Lett. 30, (1973)

→ **Discovery of QCD Asymptotic Freedom**

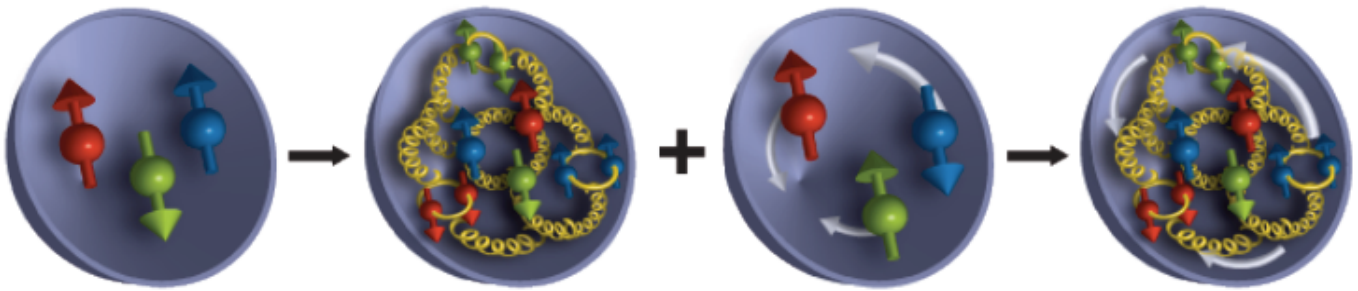
→ **Collider phenomenology**

– Controllable perturbative QCD calculations

Nobel Prize, 2004

Nucleon's properties and internal structure

- Our understanding of the nucleon evolves



1970s 1980s/2000s Now

Nucleon is a strongly interacting, relativistic bound state of quarks and gluons

- QCD bound states:
  - Neither quarks nor gluons appear in isolation!
  - Understanding such systems completely is still beyond the capability of the best minds in the world

- The great intellectual challenge:

Probe nucleon structure without "seeing" quarks and gluons?

How to test QCD dynamics?

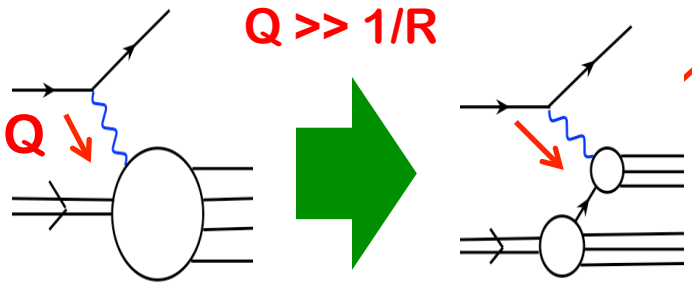
We need the probe!

How to connect QCD quarks and gluons
to observed hadrons and leptons?

QCD factorization
and
Universal distributions and
correlations of quarks and gluons

Connecting hadrons to partons

- Experiments measure hadrons and leptons, not partons
- Large momentum transfer – sensitive to partons:



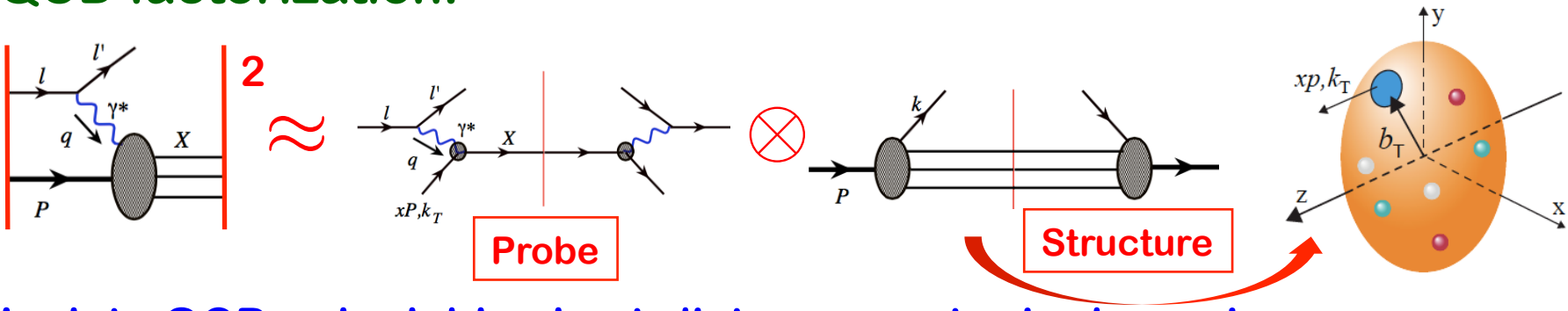
Sensitive to partonic dynamics

+…

(Diagrams with more active partons from each hadron!)

Connection between hadron and parton

- QCD factorization:

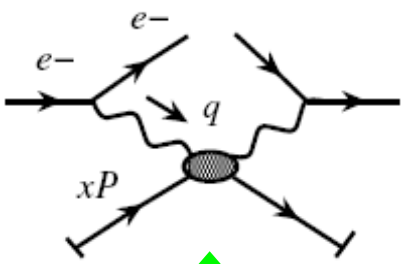


Isolate QCD calculable short-distance partonic dynamics from hadronic matrix elements of parton fields – the structure

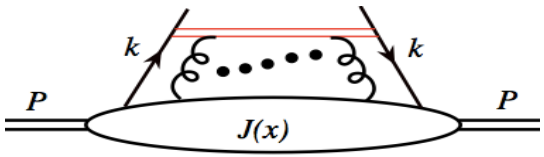
Hard probe and QCD factorization

- **One hadron:**

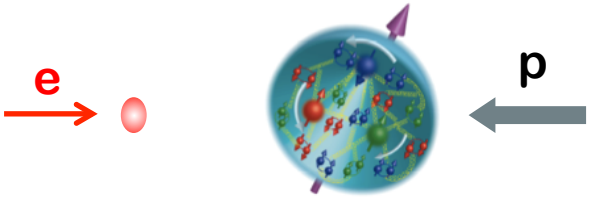
$\sigma_{\text{tot}}^{\text{DIS}}$:



$\otimes$



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



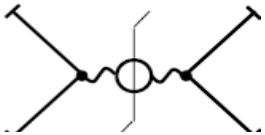
Hard-part
Probe

Parton-distribution
Structure

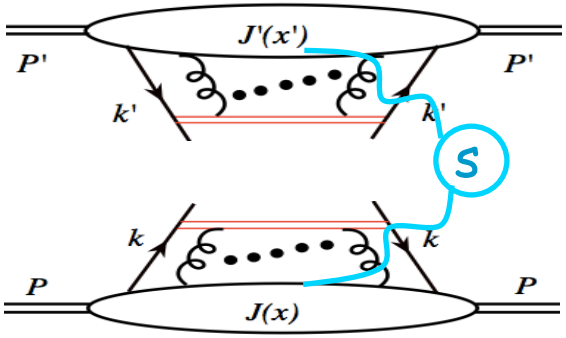
Power corrections
Approximation

- **Two hadrons:**

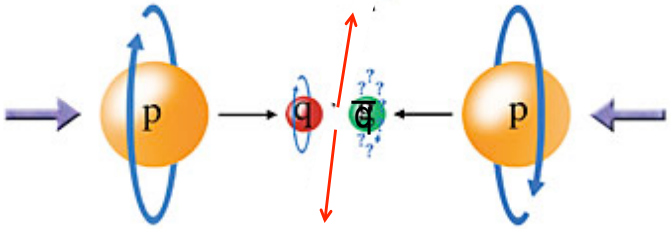
$\sigma_{\text{tot}}^{\text{DY}}$:



$\otimes$



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

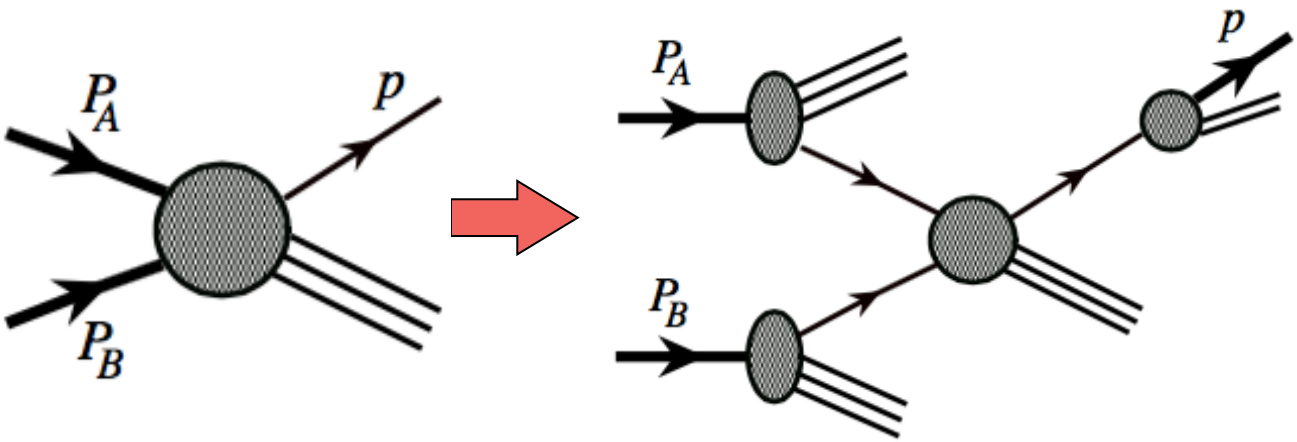


Predictive power:
Universal Parton Distributions

Factorization for more than two hadrons

Nayak, Qiu, Sterman, 2006

❑ Factorization for high p_T single hadron:



$\gamma, W/Z, \ell(s), \mathrm{jet(s)}$
$B, D, \Upsilon, J/\psi, \pi, \ldots$

+ O $(1/P_T^2)$

$p_T \gg m \gtrsim \Lambda_{\mathrm{QCD}}$

$$\frac{d\sigma_{AB\to C+X}(p_A,p_B,p)}{dydp_T^2} = \sum_{a,b,c} \phi_{A\to a}(x,\mu_F^2) \otimes \phi_{B\to b}(x',\mu_F^2)$$

$$\otimes \frac{d\hat{\sigma}_{ab\to c+X}(x,x',z,y,p_T^2\mu_F^2)}{dydp_T^2} \otimes D_{c\to C}(z,\mu_F^2)$$

✧ **Fragmentation function:** $D_{c\to C}(z,\mu_F^2)$

✧ **Choice of the scales:** $\mu_{\mathrm{Fac}}^2 \approx \mu_{\mathrm{ren}}^2 \approx p_T^2$

To minimize the size of logs in the coefficient functions

Hadron properties in QCD

How to understand
the emergent hadron properties,
such as the mass, spin, …,
from QCD dynamics of quarks and
gluons?

Approximated model calculations,
sum rules,
and lattice calculations

Hadron properties in QCD

❑ Mass – intrinsic to a particle:

= Energy of the particle when it is at the rest

✧ QCD energy-momentum tensor in terms of quarks and gluons

$$T^{\mu\nu} = \frac{1}{2}\bar{\psi} i \overleftrightarrow{D}^{(\mu}\gamma^{\nu)}\psi + \frac{1}{4} g^{\mu\nu} F^2 - F^{\mu\alpha} F^{\nu}{}_{\alpha}$$

✧ Proton mass:

$$m = \frac{\langle p| \int d^3x\, T^{00} |p\rangle}{\langle p|p\rangle}\Big|_{\text{Rest frame}} \sim \text{GeV}$$

X. Ji, PRL (1995)

❑ Spin – intrinsic to a particle:

= Angular momentum of the particle when it is at the rest

✧ QCD angular momentum density in terms of energy-momentum tensor

$$M^{\alpha\mu\nu} = T^{\alpha\nu} x^{\mu} - T^{\alpha\mu} x^{\nu} \qquad J^i = \frac{1}{2}\epsilon^{ijk} \int d^3x M^{0jk}$$

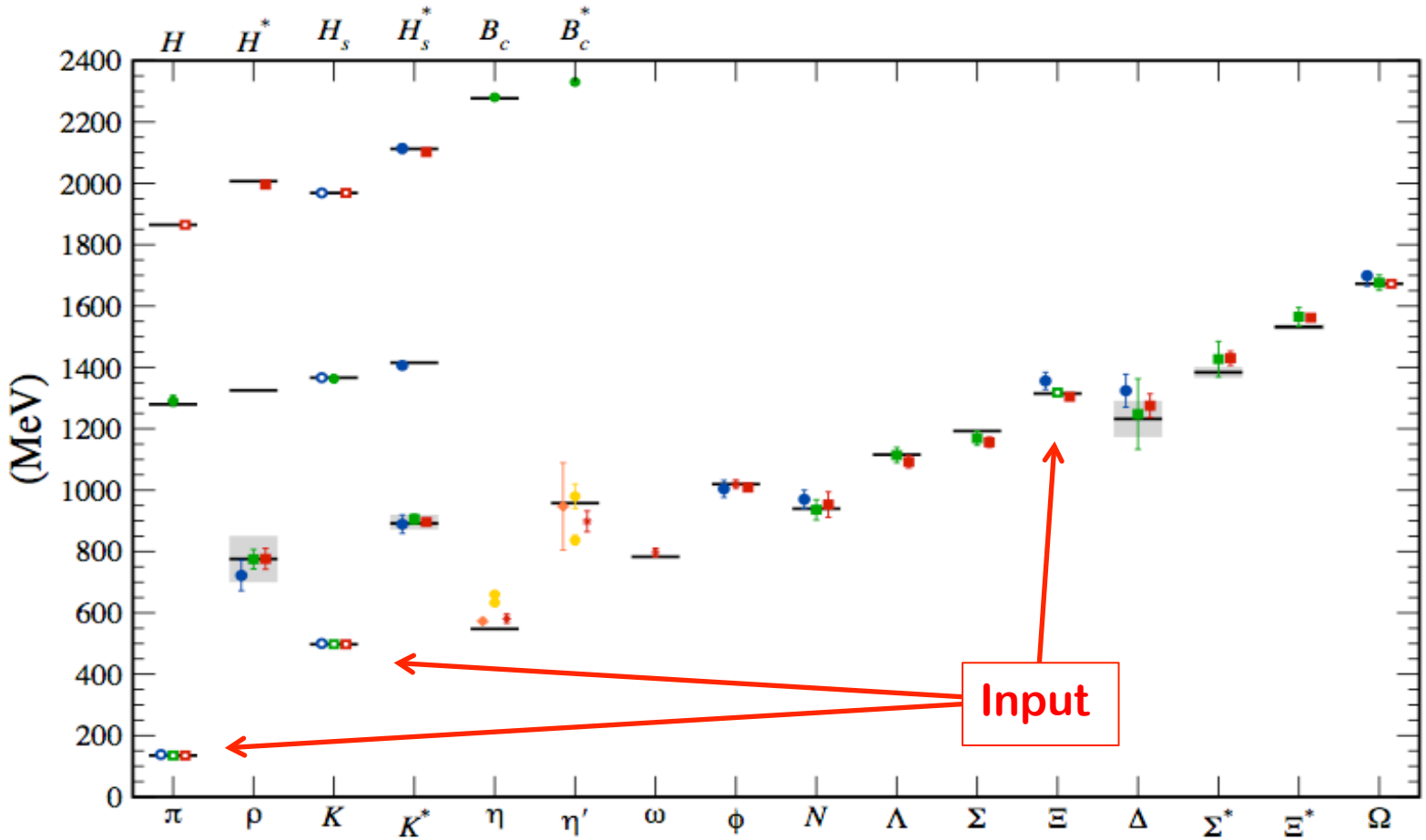
✧ Proton spin:

$$S(\mu) = \sum \langle P, S| \hat{J}^z_f(\mu) |P, S\rangle = \frac{1}{2}$$

We do NOT know the state, $|P, S\rangle$, in terms of quarks and gluons!

Hadron properties in QCD

- **Hadron mass from Lattice QCD calculation:**



A major success of QCD – is the right theory for the Strong Force!

How does QCD generate this? The role of quarks vs that of gluons?

Hadron properties in QCD

❑ Role of quarks and gluons – sum rules:

✧ **Invariant hadron mass (in any frame):**

$$\langle p|\, T^{\mu\nu}\, |p\rangle \propto p^\mu p^\nu \quad \Rightarrow \quad m^2 \propto \langle p|T^\alpha{}_\alpha\, |p\rangle$$

$$T^\alpha{}_\alpha = \underbrace{\frac{\beta(g)}{2g} F^{\mu\nu,a} F^a_{\mu\nu}}_{\text{QCD trace anomaly}} + \sum_{q=u,d,s} m_q(1+\gamma_m)\overline{\psi}_q\psi_q$$

$$\beta(g) = -(11 - 2n_f/3)\, g^3/(4\pi)^2 + \ldots$$

$$\Rightarrow \quad \frac{\beta(g)}{2g}\, \langle p|F^2|p\rangle$$

Kharzeev @ Temple workshop
ECT* workshop on proton mass

➡ ***At the chiral limit, the entire proton mass is from gluons!***

✧ **Hadron mass in the rest frame – decomposition (sum rule):** X. Ji, PRL (1995)

$$M = \frac{\langle P|H_{\rm QCD}|P\rangle}{\langle P|P\rangle}\Big|_{\text{rest frame}} = H_q + H_m + H_g + H_a$$

where $H_q = \sum_q \psi_q^\dagger(-i\mathbf{D}\cdot\alpha)\psi_q$ **– quark energy**

$H_m = \sum_q \overline{\psi}_q m_q \psi_q$ **– quark mass**

$H_g = \frac{1}{2}(\mathbf{E}^2 + \mathbf{B}^2)$ **– gluon energy**

$H_a = \frac{9\alpha_s}{16\pi}(\mathbf{E}^2 - \mathbf{B}^2)$ **– trace anomaly**

Hadron properties in QCD

❑ Role of quarks and gluons – sum rules:

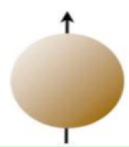
✧ **Partonic angular momenta, the contributions to hadron spin:**

$$S(\mu) = \sum_f \langle P, S | \hat{J}^z_f(\mu) | P, S \rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu)$$

where $\vec{J}_q = \int d^3x \left[\psi_q^\dagger \vec{\gamma} \gamma_5 \psi_q + \psi_q^\dagger (\vec{x} \times (-i\vec{D}))\, \psi_q \right]$ **– quark angular mom.**

$\vec{J}_g = \int d^3x \left[\vec{x} \times (\vec{E} \times \vec{B}) \right]$ **– gluon angular mom.**

✧ **Spin decomposition (sum rule) – an incomplete story:**



Proton Spin

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

Jaffe-Manohar, 90
Ji, 96, …

Different from QM!

Quark helicity: $\frac{1}{2}\int dx \left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s} \right) \sim 30\%$ **– Best known**

Quark helicity: $\Delta G = \int dx \Delta g(x) \sim 20\% (\text{with RHIC data})$ **– Start to know**

Orbital Angular Momentum (OAM): Not uniquely defined – Little known

Gauge field is tied together with the motion of fermion – D^μ !

Hadron properties in QCD

❑ Role of quarks and gluons – sum rules:

✧ **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:**

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

Hatta, Yoshida, Burkardt, Meissner, Metz, Schlegel, ...

✧ **Difference – generated by a "torque" of color Lorentz force**

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

Sum rules are NOT unique – None of these matrix elements are physical!!!

❑ Value of the decomposition – a good sum rule:

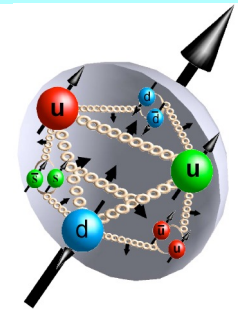
Every term of the sum rule is "independently measurable" – can be related to a physical observable with controllable approximation!

Hadron structure in QCD

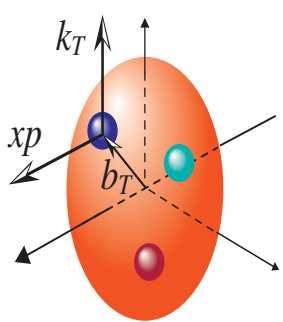
How to understand
the emergent hadron structures,
such as the confined motion,
spatial distributions, and
correlations of quarks and gluons, …,
from QCD dynamics?

Measurements of PDFs, TMDs, GPDs,
quark-gluon correlations, and
Physics behind these functions?

Hadron structure in QCD

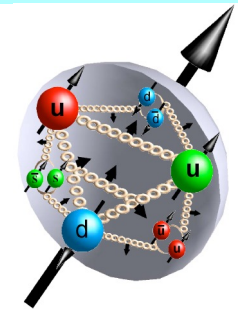


- **What do we need to know for the structure?**
  - **In theory:** $\langle P,S|\mathcal{O}(\overline{\psi},\psi,A^\mu)|P,S\rangle$ – Hadronic matrix elements with all possible operators: $\mathcal{O}(\overline{\psi},\psi,A^\mu)$
  - **In fact:** *None of these matrix elements is a direct physical observable in QCD – color confinement!*
  - **In practice:** Accessible hadron structure = hadron matrix elements of quarks and gluons, which
    1) can be related to physical cross sections of hadrons and leptons with controllable approximation; and/or
    2) can be calculated in lattice QCD
- **Single-parton structure "seen" by a short-distance probe:**
  - **5D structure:**



1) $\int d^2b_T \Rightarrow f(x,k_T,\mu)$ – TMDs: *2D confined motion!*
2) $\int d^2k_T \Rightarrow F(x,b_T,\mu)$ – GPDs: *2D spatial imaging!*
3) $\int d^2k_T d^2b_T \Rightarrow f(x,\mu)$ – PDFs: *Number density!*

Hadron structure in QCD



❑ What do we need to know for the structure?

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

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= hadron matrix elements of quarks and gluons, which

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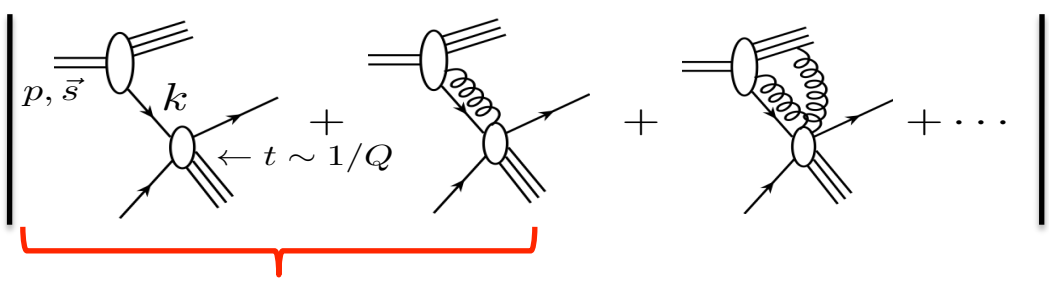
❑ Multi-parton correlations:

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



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

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

Global QCD analyses of PDFs, …

- **Factorization for observables with identified hadrons:**
  - **One-hadron (DIS):**

$$F_2(x_B, Q^2) = \Sigma_f C_f(x_B/x, \mu^2/Q^2) \otimes f(x, \mu^2)$$

  - **Two-hadrons (DY, Jets, W/Z, …) :**

$$\frac{d\sigma}{dy dp_T^2} = \Sigma_{ff'} f(x) \otimes \frac{d\hat{\sigma}_{ff'}}{dy dp_T^2} \otimes f'(x')$$

  - **DGLAP Evolution:**

$$\frac{\partial f(x, \mu^2)}{\partial \ln \mu^2} = \Sigma_{f'} P_{ff'}(x/x') \otimes f'(x', \mu^2)$$

- **Input for QCD Global analysis/fitting:**
  - **World data with "Q" > 2 GeV**
  - **PDFs at an input scale:** $\phi_{f/h}(x, \mu_0^2, \{\alpha_j\})$

Input scale ~ GeV

Fitting paramters

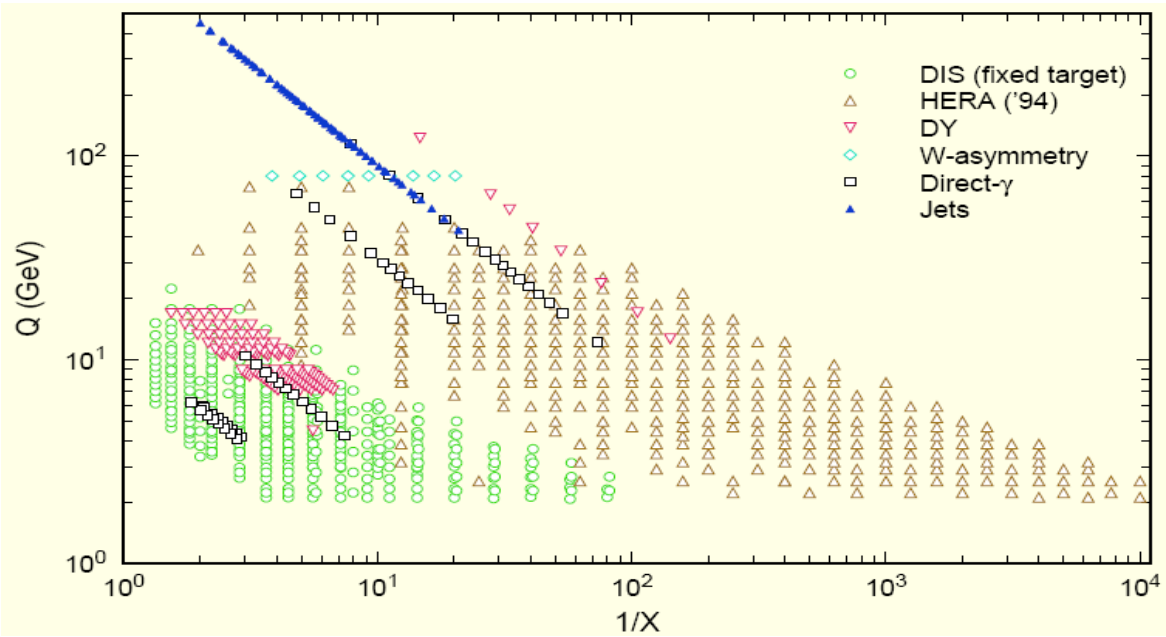
Global QCD analysis – the machinery

Input PDFs at Q_0

$$\varphi_{f/h}\left(x,\{a_j\}\right)$$

Vary $\{a_j\}$

Minimize Chi^2



DGLAP

Q^2 – Evolution

$\varphi_{f/h}(x)$ **at Q>Q_0**

QCD calculation

of cross sections

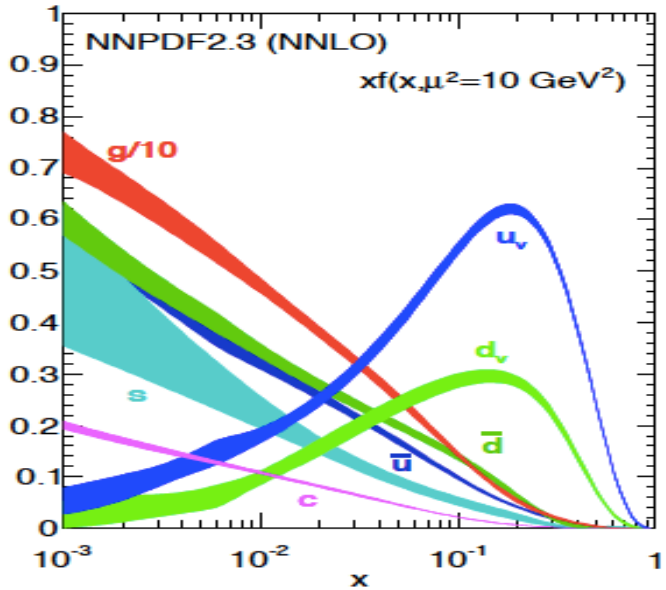
Comparison with Data at various x and Q

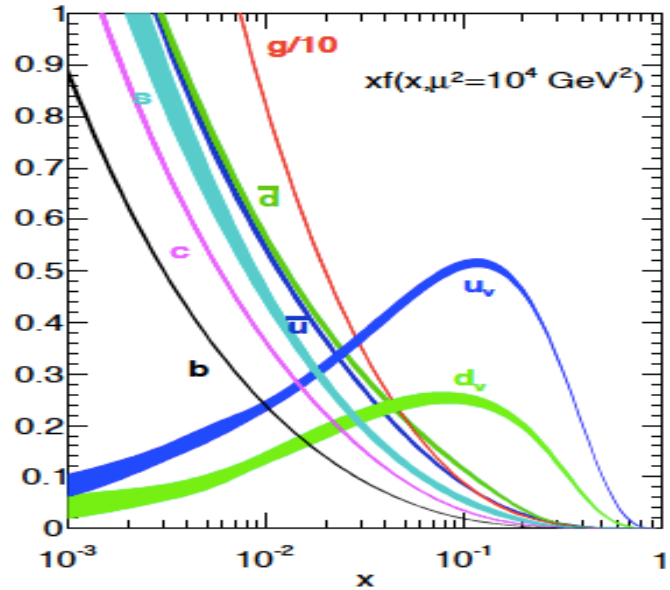
Procedure: Iterate to find the best set of $\{a_j\}$ for the input DPFs

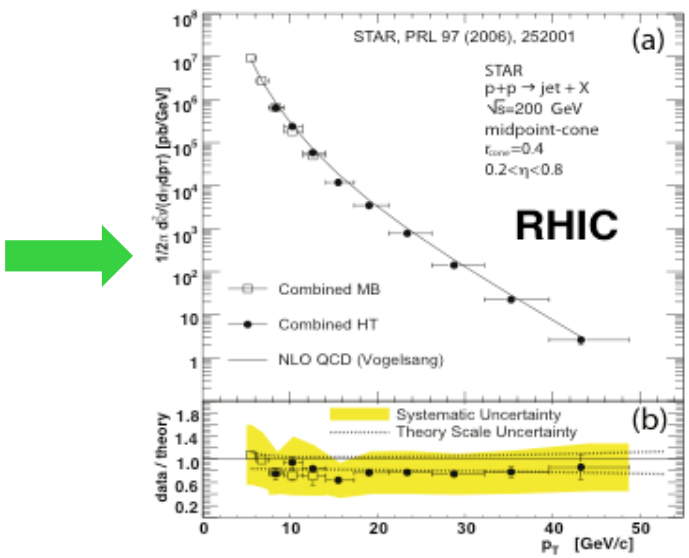
Global QCD analyses – a successful story

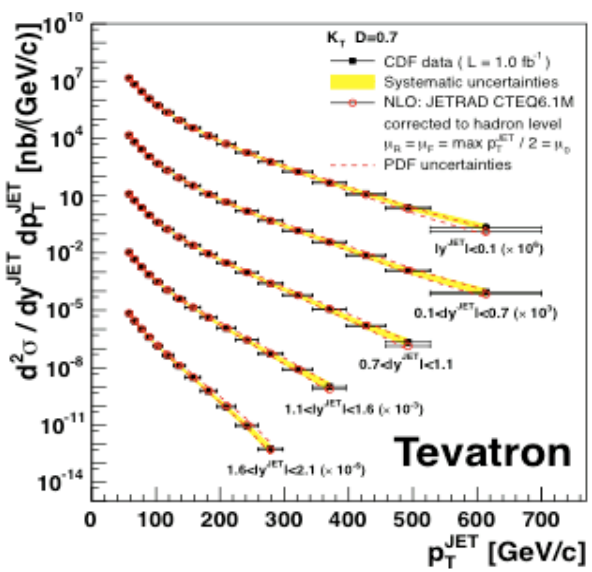
- Modern sets of PDFs @ NNLO:

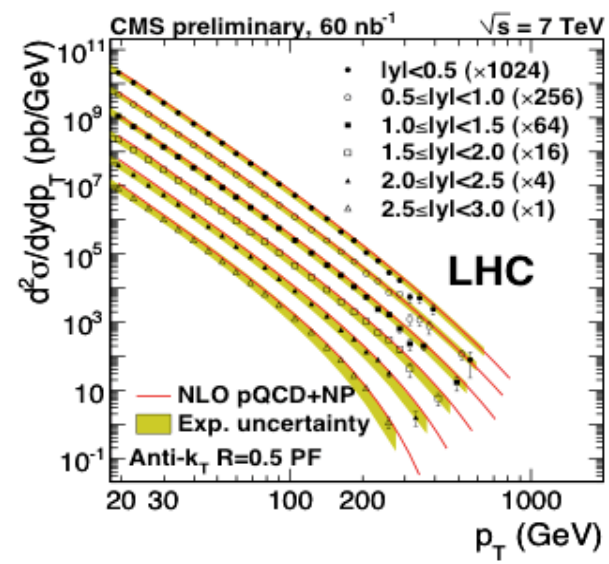
Universal PDFs



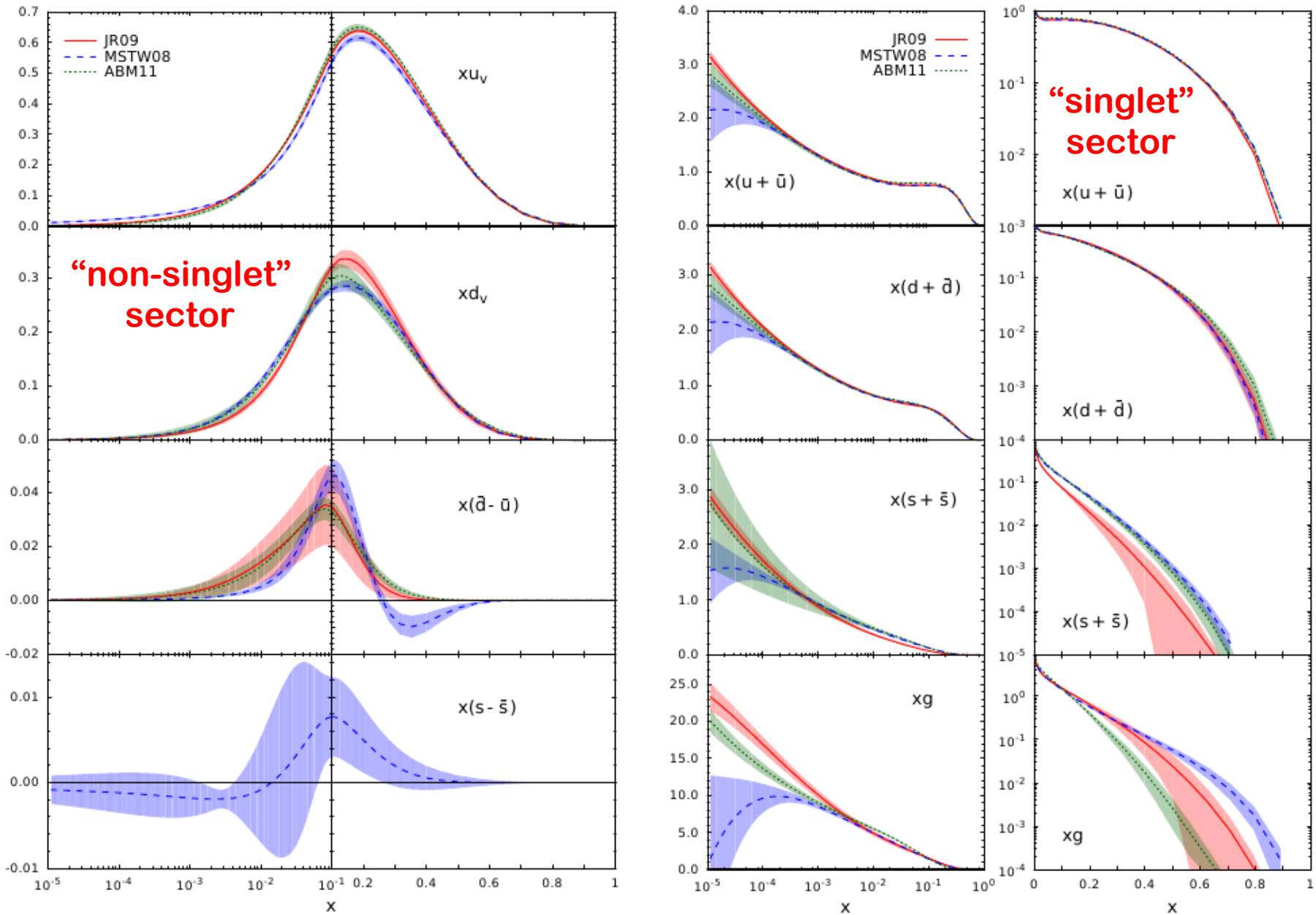






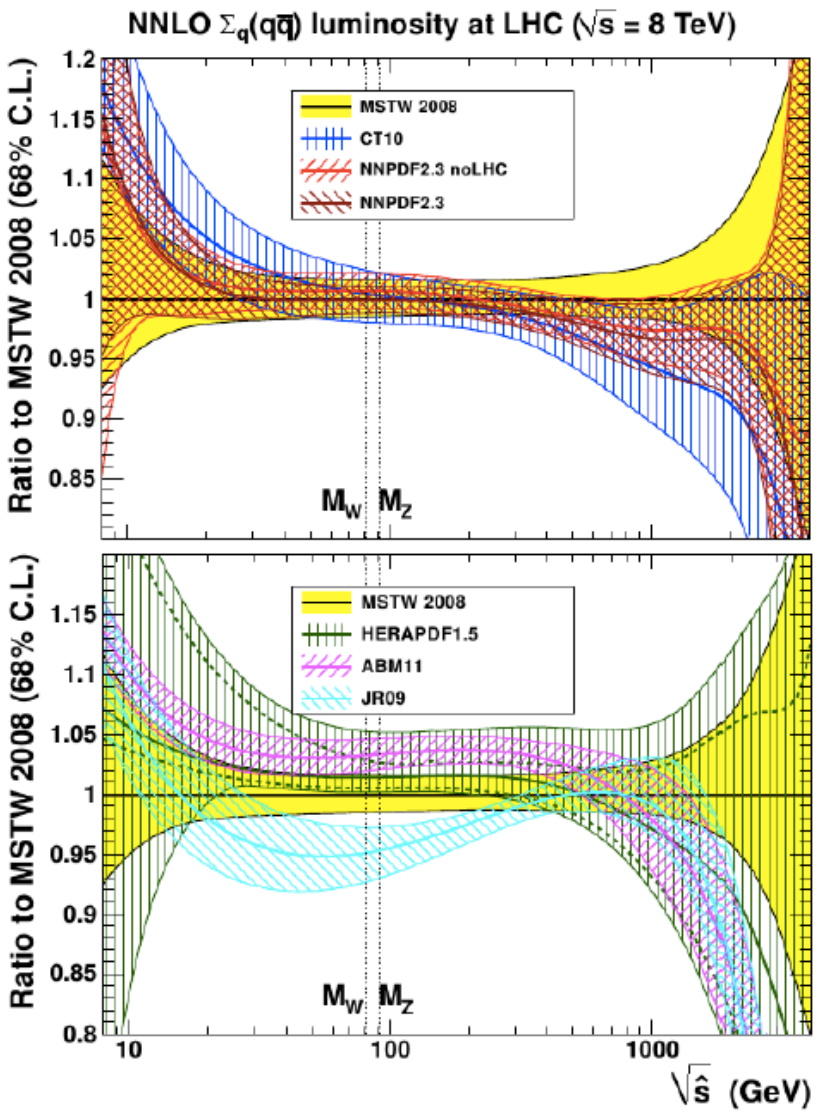


Uncertainties of PDFs

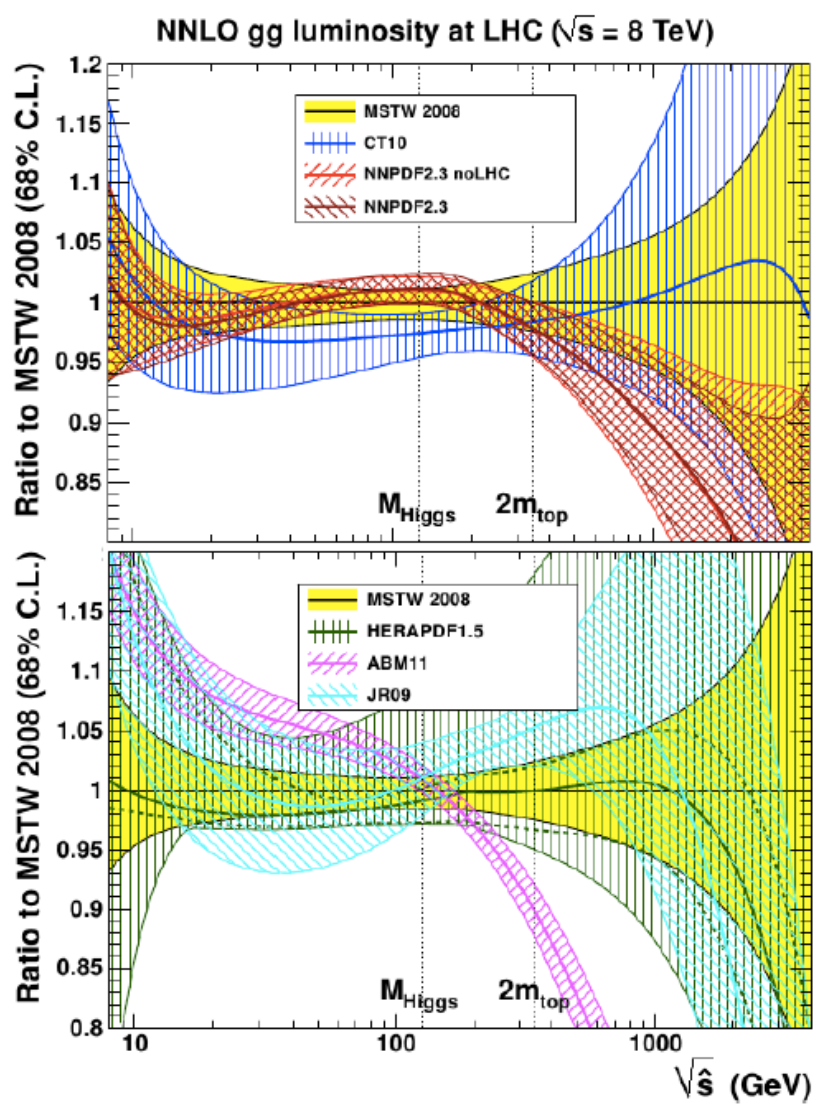


Partonic luminosities

q - qbar



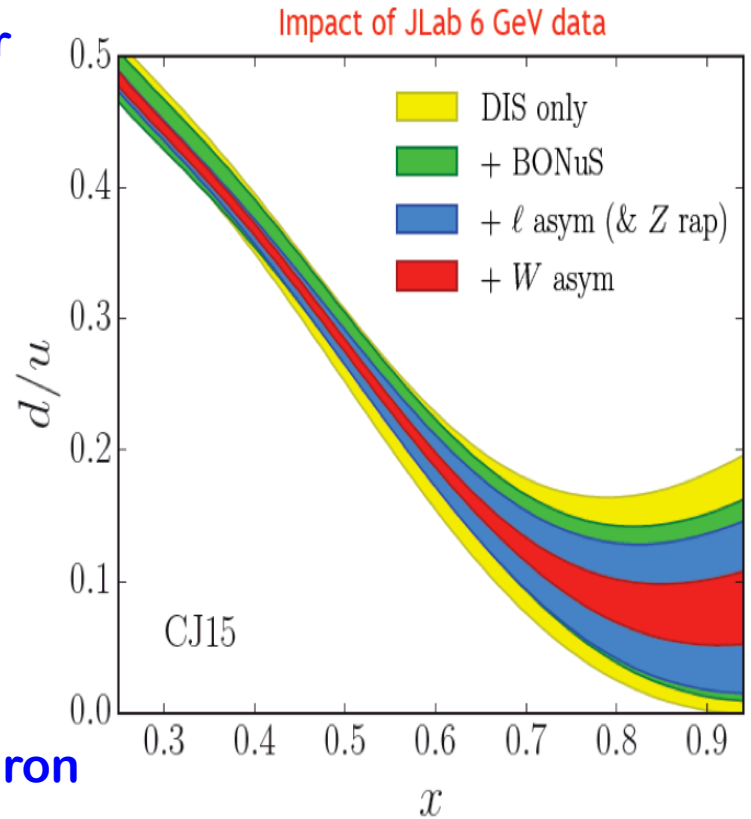
g - g



PDFs at large x

- Testing ground for hadron structure at x → 1:

  - $d/u \to 1/2$ — SU(6) Spin-flavor symmetry
  - $d/u \to 0$ — Scalar diquark dominance
  - $d/u \to 1/5$ — pQCD power counting
  - $d/u \to \dfrac{4\mu_n^2/\mu_p^2 - 1}{4 - \mu_n^2/\mu_p^2} \approx 0.42$ — Local quark-hadron duality



PRD 93 (2016) 074005 & 114017

PDFs at large x

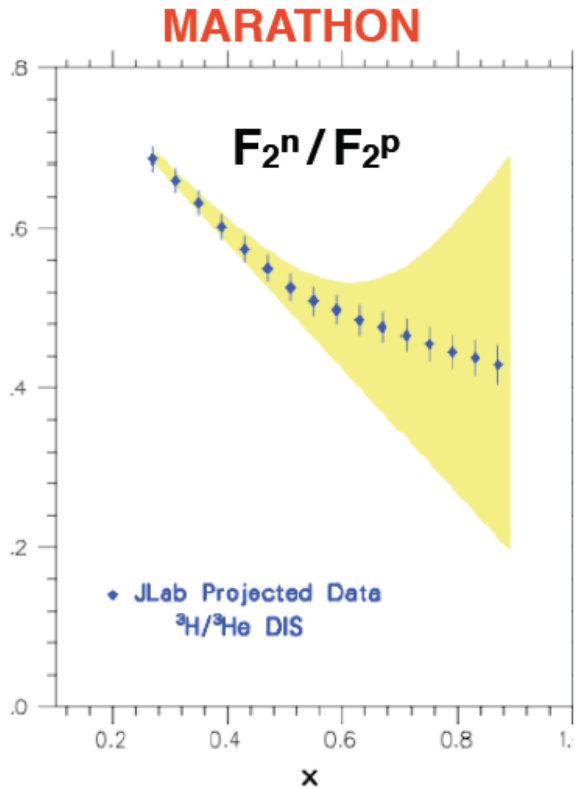
- Testing ground for hadron structure at x → 1:

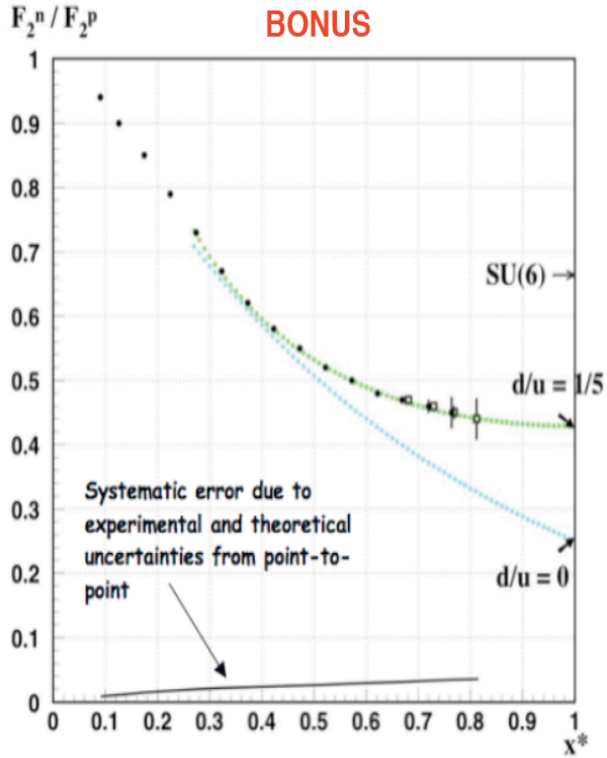
✧ $d/u \to 1/2$	SU(6) Spin-flavor symmetry	✧ $\Delta u/u \to 2/3$ $\Delta d/d \to -1/3$
✧ $d/u \to 0$	Scalar diquark dominance	✧ $\Delta u/u \to 1$ $\Delta d/d \to -1/3$
✧ $d/u \to 1/5$	pQCD power counting	✧ $\Delta u/u \to 1$ $\Delta d/d \to 1$
✧ $d/u \to \dfrac{4\mu_n^2/\mu_p^2 - 1}{4 - \mu_n^2/\mu_p^2} \approx 0.42$	Local quark-hadron duality	✧ $\Delta u/u \to 1$ $\Delta d/d \to 1$

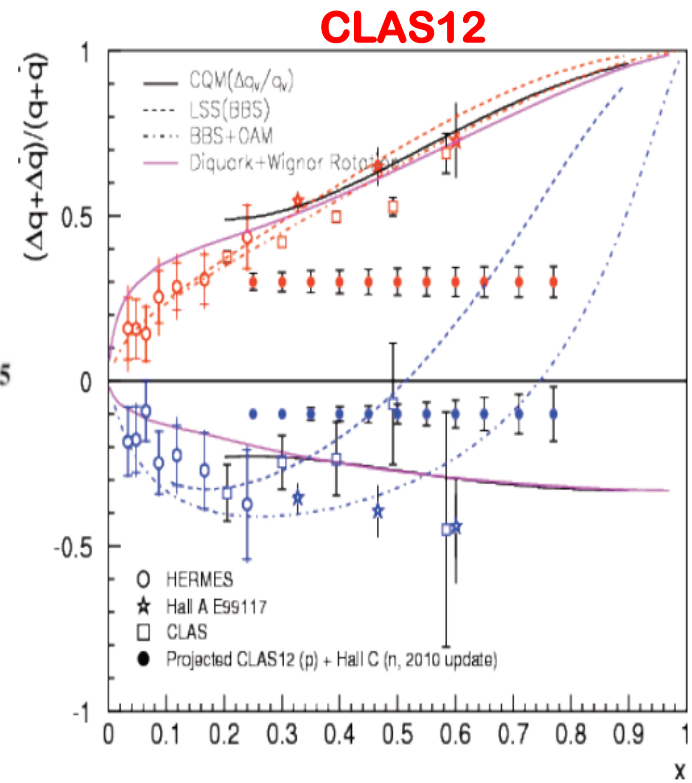
Both JLab12 and lattice QCD can help!

Upcoming experiments – JLab12

- **NSAC milestone HP14 (2018):**







Plus many more JLab experiments:

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

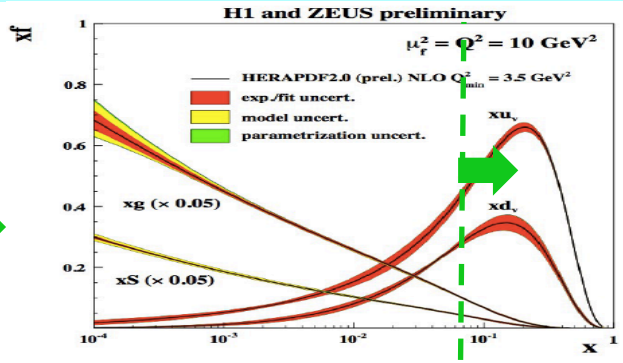
E12-06-109 (CLAS on NH_3, ND_3), …

and Fermilab E906, …

Plus complementary Lattice QCD effort

Lattice calculations of hadron structure

Lattice QCD



X-dep distributions

- **New ideas – from quasi-PDFs (lattice calculable) to PDFs:**
  - **High P_z effective field theory approach:**

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

Ji, et al., arXiv:1305.1539 1404.6680

  - **QCD collinear factorization approach:**

$$\tilde{q}(x,\mu^2,P_z) = \sum_f \int_0^1 \frac{dy}{y} \mathcal{C}_f\left(\frac{x}{y},\frac{\mu^2}{\bar{\mu}^2},P_z\right) f(y,\bar{\mu}^2) + \mathcal{O}\left(\frac{1}{\mu^2}\right)$$

Ma and Qiu, arXiv:1404.6860 1412.2688
Ishikawa, Ma, Qiu, Yoshida, 1609.02018
Monohan, Orginos, 1612.01584
…

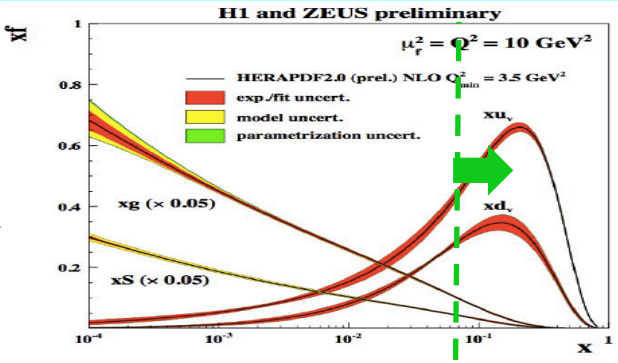
Non-perturbative lattice UV renormalization:
Effective mass renormalization, Gradient flow, …

- **The TMD Collaboration + on-going effort around the world!**

Plus the intense local JLab theory effort!

Lattice calculations of hadron structure

Lattice QCD



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Monohan, Orginos, 1612.01584
…

Non-perturbative lattice UV renormalization:
Effective mass renormalization, Gradient flow, …

- **Tremendous potentials!**

PDFs of proton, neutron, pion, …; TMDs, GPDs, …; JLab12 expts

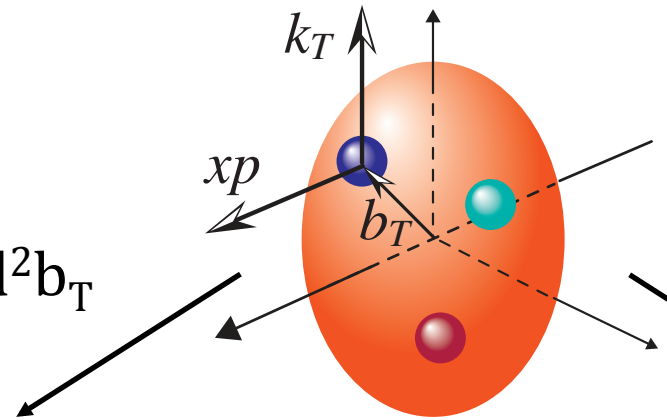
Hadron structure beyond the PDFs

❑ 3D boosted partonic structure:

Momentum Space

TMDs

Confined motion



$\int d^2b_T$

$\int d^2k_T$

$f(x,k_T)$

Two-scales observables

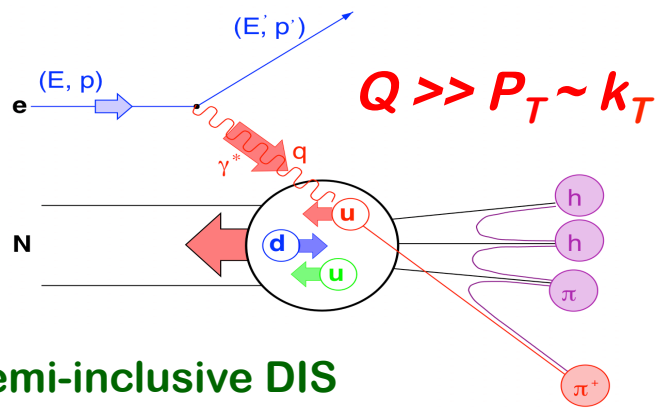
$f(x,b_T)$

Coordinate Space

GPDs

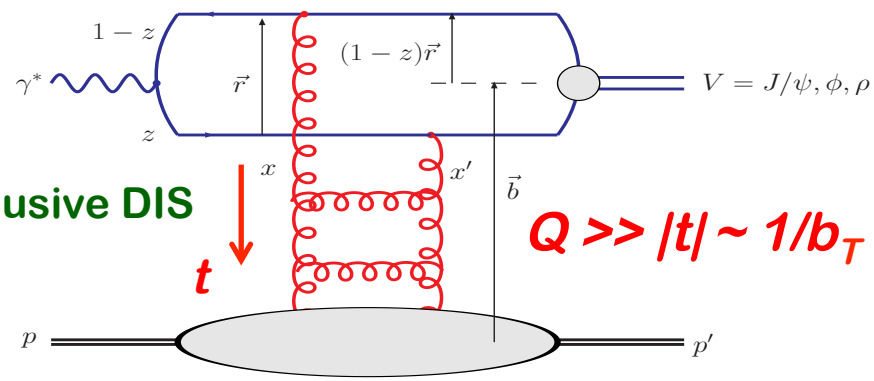
Spatial distribution

3D momentum space images



Semi-inclusive DIS

2+1D coordinate space images



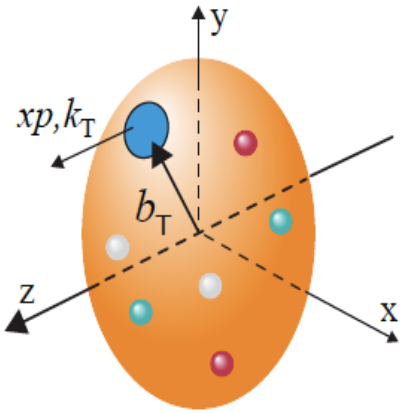
Exclusive DIS

JLab12 – valence quarks, EIC – sea quarks and gluons

Two-momentum-scale observables

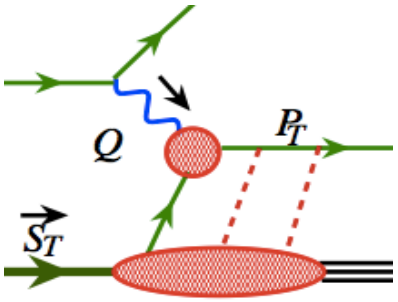
- **Cross sections with two-momentum scales observed:**

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



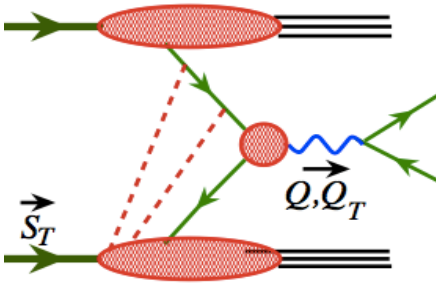
- ✧ **Hard scale:** Q_1 **localizes the probe to see the quark or gluon d.o.f.**
- ✧ **"Soft" scale:** Q_2 **could be more sensitive to hadron structure, e.g., confined motion**

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



SIDIS: $Q \gg P_T$

+



DY: $Q \gg P_T$

+ **Two-jet momentum imbalance in SIDIS, …**

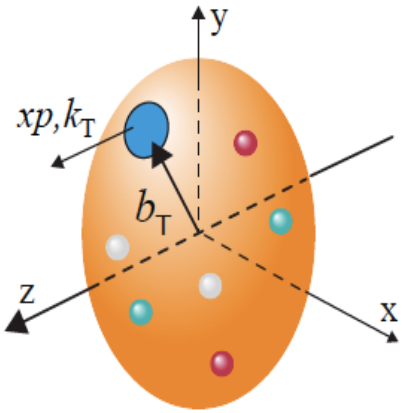
➡

- ✧ **Natural observables with TWO very different scales**
- ✧ **TMD factorization: partons' confined motion is encoded into TMDs**

Two-momentum-scale observables

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

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



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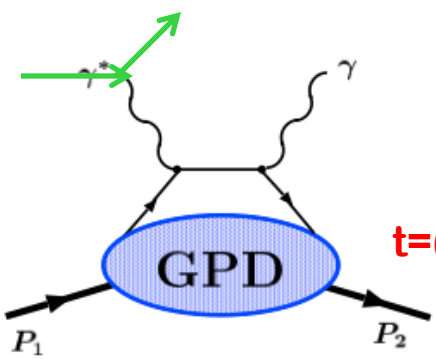
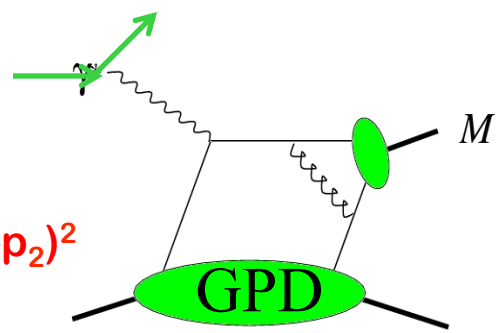
- ✧ **"Soft" scale:** Q_2 **could be more sensitive to hadron structure, e.g., confined motion**

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



+

$t=(p_1-p_2)^2$



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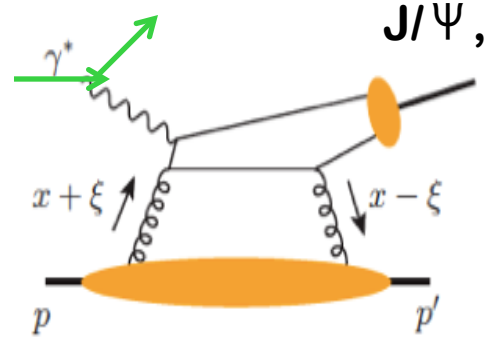


J/Ψ, Φ, …

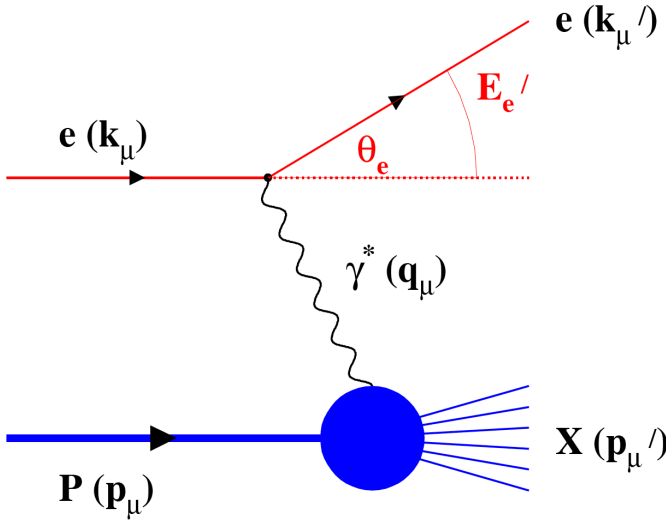
+ …

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**

Lepton-Hadron Facility: from JLab to EIC

- Precision of lepton probe + energy of hadron machine:



Q^2 →Measure of resolution

y → Measure of inelasticity

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

$Q^2 = S \times y$

Inclusive events: e+p/A → e'+X

Detect only the scattered lepton in the detector

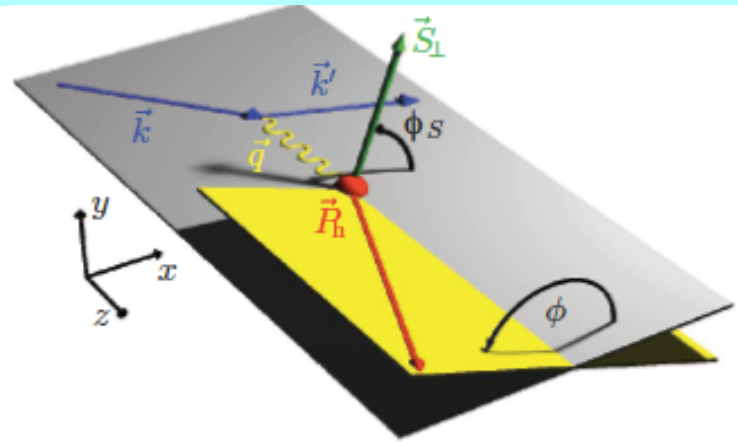
Semi-Inclusive events: e+p/A → e'+h(π,K,p,jet)+X

Detect the scattered lepton in coincidence with identified hadrons/jets

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

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

Semi-inclusive DIS (SIDIS)



- **Process:**

$$e(k) + N(p) \longrightarrow e'(k') + h(P_h) + X$$

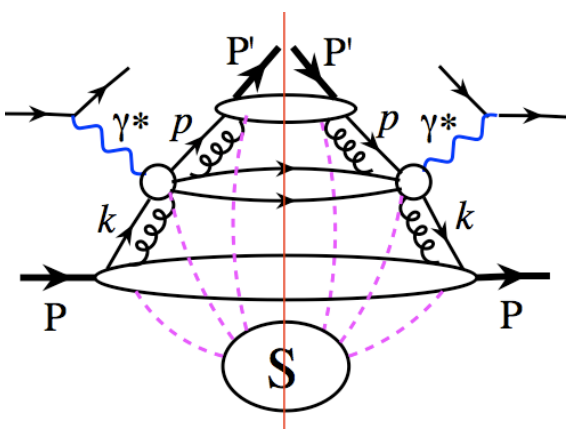
- **Natural event structure:**

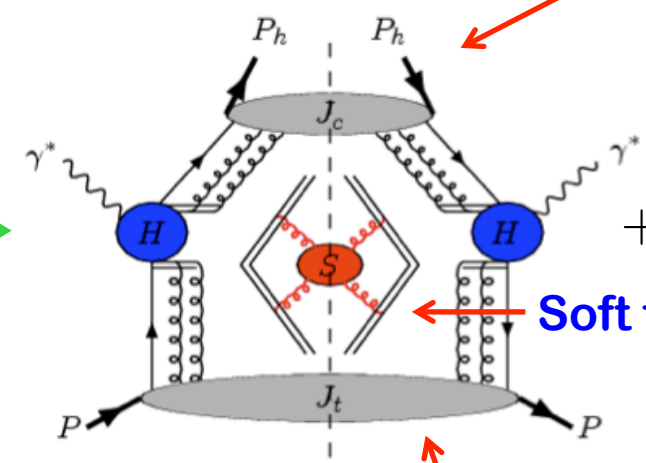
In the photon-hadron frame: $P_{h_T} \approx 0$

Semi-Inclusive DIS is a natural observable with TWO very different scales

$Q \gg P_{h_T} \gtrsim \Lambda_{\rm QCD}$ **Localized probe sensitive to parton's transverse motion**

- **Soft gluons are everywhere:**





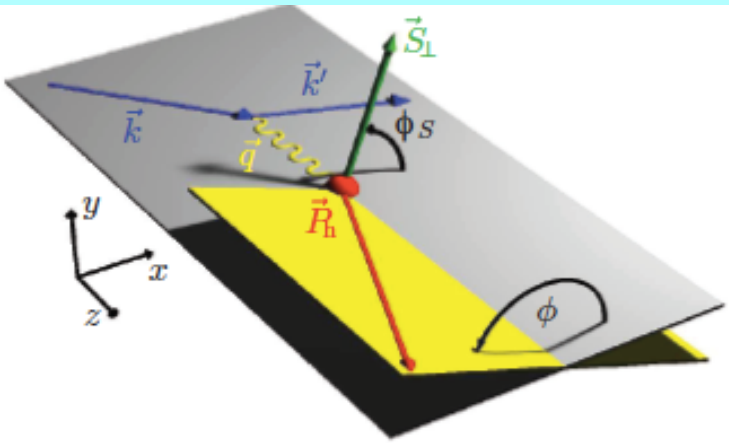
$$+\mathcal{O}\left(\frac{\langle k^2\rangle}{Q^2}, \frac{\langle p^2\rangle}{Q^2}\right)$$

TMD fragmentation

Soft factors

TMD parton distribution

Semi-inclusive DIS (SIDIS)



❑ Process:

$$e(k) + N(p) \longrightarrow e'(k') + h(P_h) + X$$

❑ Natural event structure:

In the photon-hadron frame: $P_{h_T} \approx 0$

Semi-Inclusive DIS is a natural observable with TWO very different scales

$Q \gg P_{h_T} \gtrsim \Lambda_{\rm QCD}$ **Localized probe sensitive to parton's transverse motion**

❑ QCD factorization - approximation:

✧ **Low P_{hT} – 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} – 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:**

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

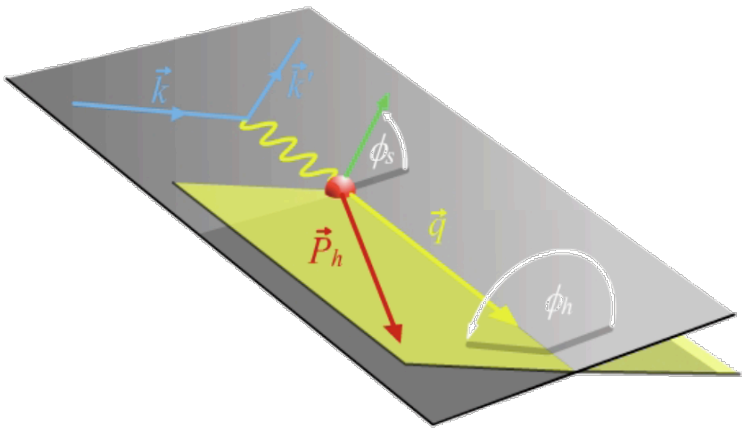
SIDIS is the best for probing TMDs

- **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:**

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

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

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

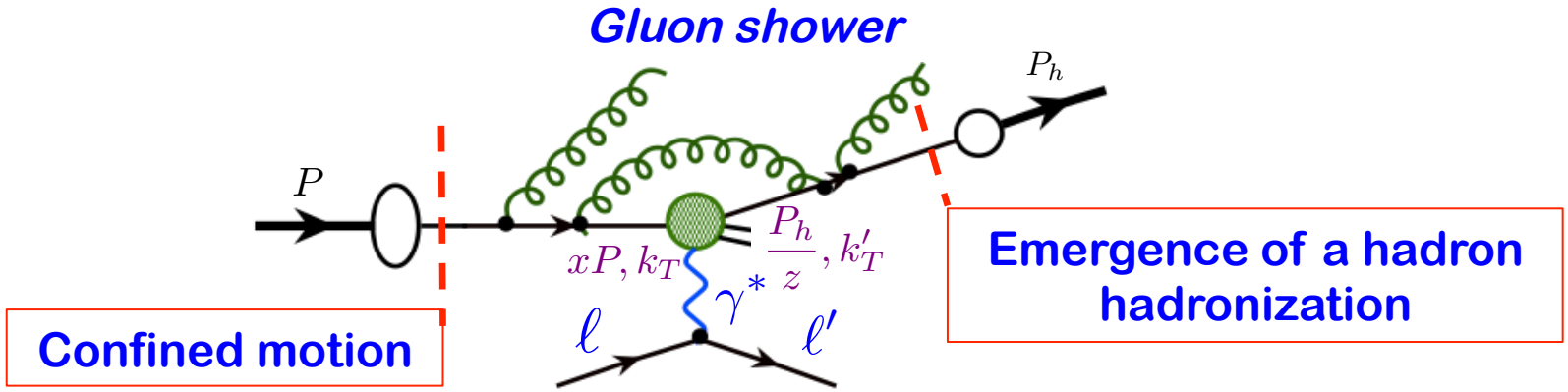
Collins frag. Func. from e^+e^- collisions

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

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

Parton k_T at the hard collision

- Sources of parton k_T at the hard collision:



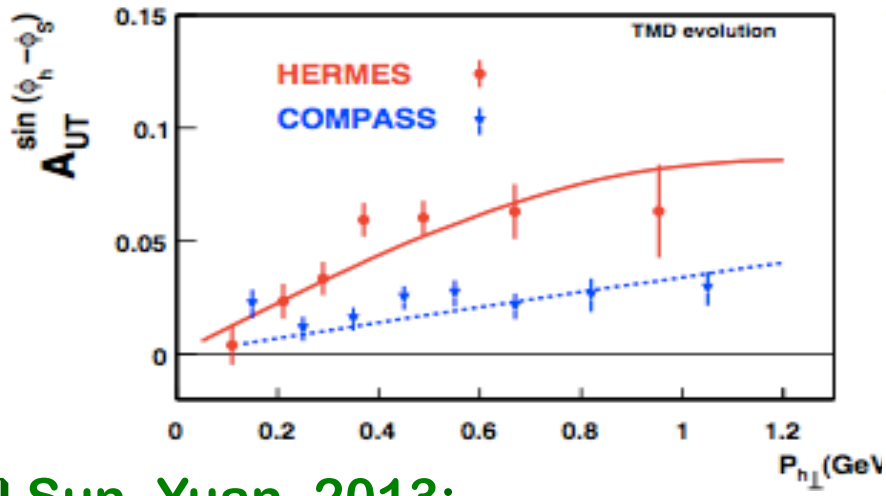
- Large k_T generated by the shower (caused by the collision):
  - Q^2-dependence – linear evolution equation of TMDs in b-space
  - The evolution kernels are perturbative at small b, but, not large b

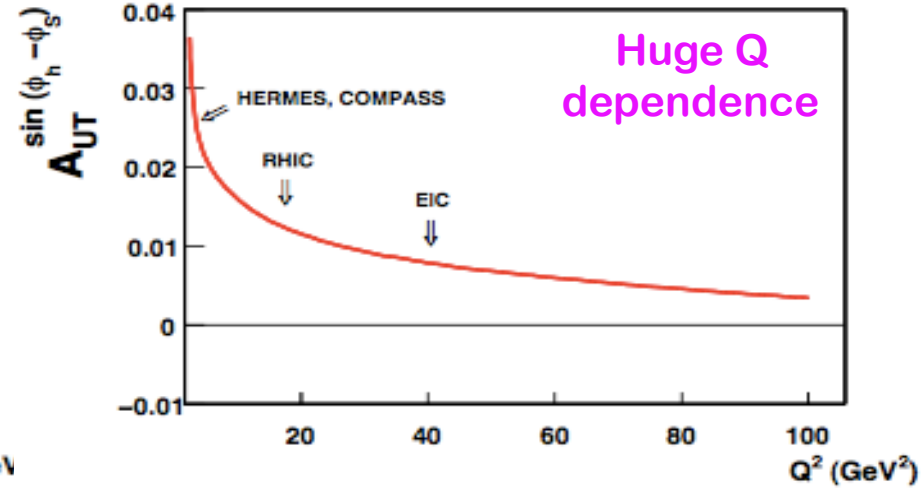
  → The nonperturbative inputs at large b could impact TMDs at all Q^2

- Challenge: to extract the "true" parton's confined motion:
  - Separation of perturbative shower contribution from nonperturbative hadron structure – not as simple as PDFs

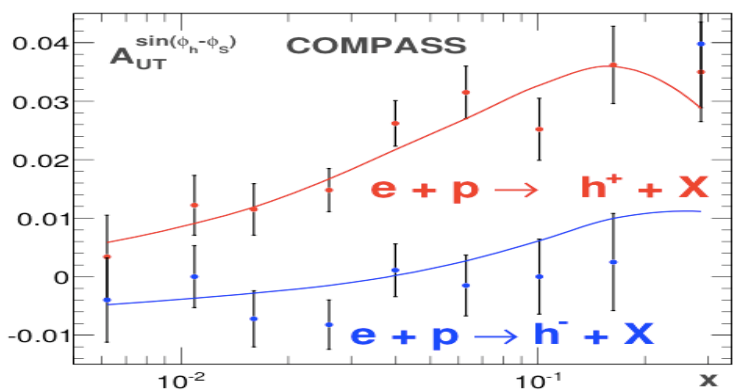
Different fits – different Q-dependence

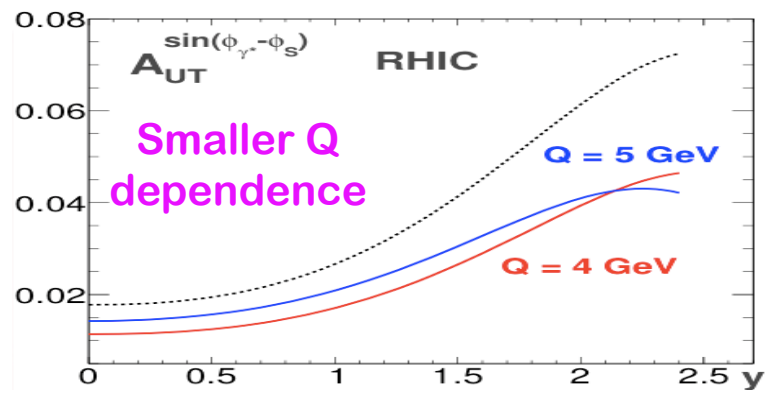
- Aybat, Prokudin, Rogers, 2012:





- Sun, Yuan, 2013:



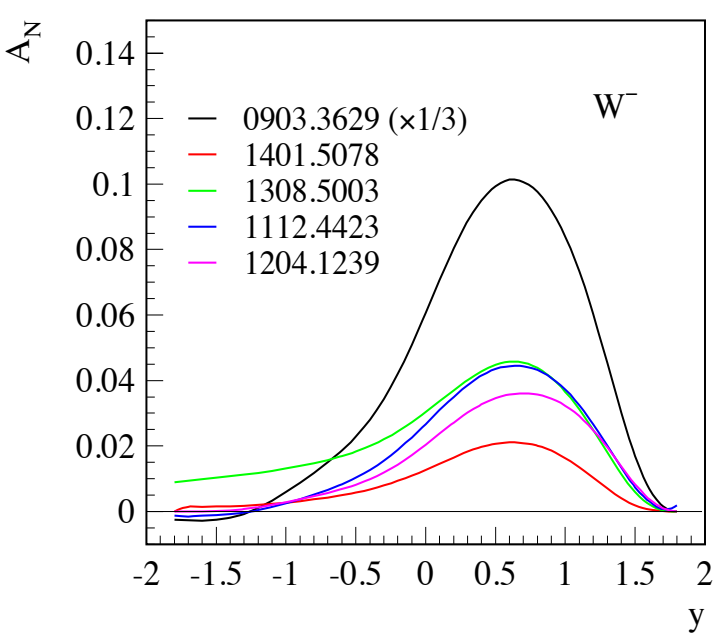


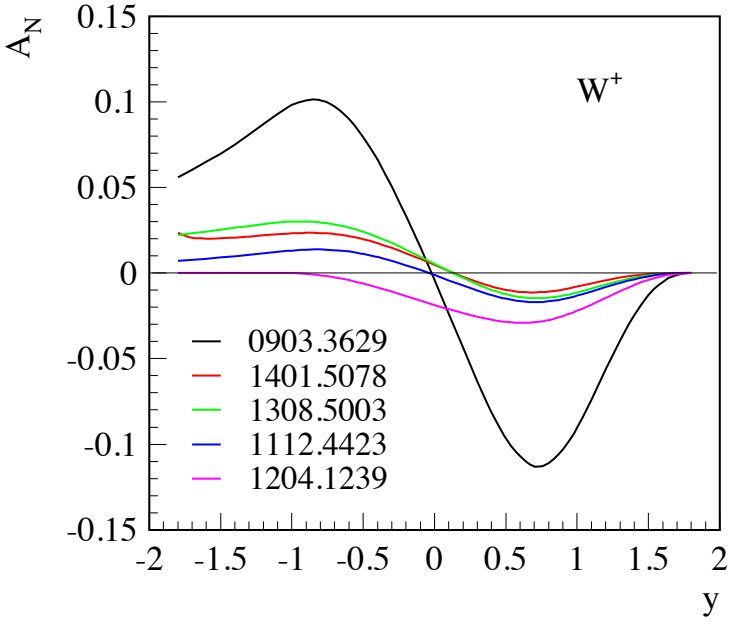
No disagreement on evolution equations!

Issues: Extrapolation to non-perturbative large b-region
Choice of the Q-dependent "form factor"

"Predictions" for A_N of W-production at RHIC?

- **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
- **Current "prediction" and uncertainty of QCD evolution:**





TMD collaboration proposal: Lattice, theory & Phenomenology

RHIC is the excellent and unique facility to test this (W/Z – DY)!

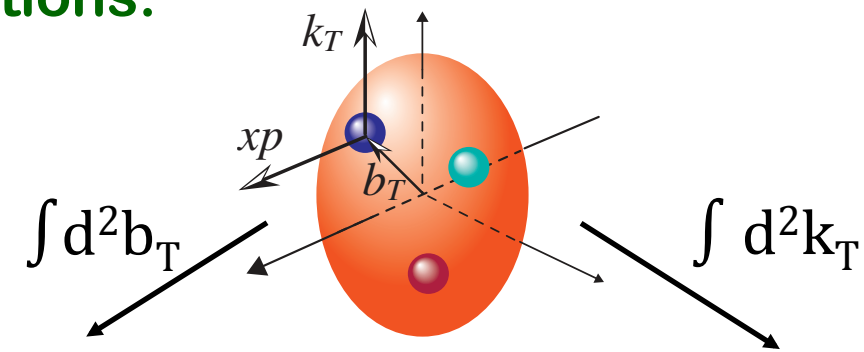
Unified view of nucleon structure

❑ Wigner distributions:

Momentum Space

TMDs

Confined motion



$\int d^2b_T$ $\qquad$ $\int d^2k_T$

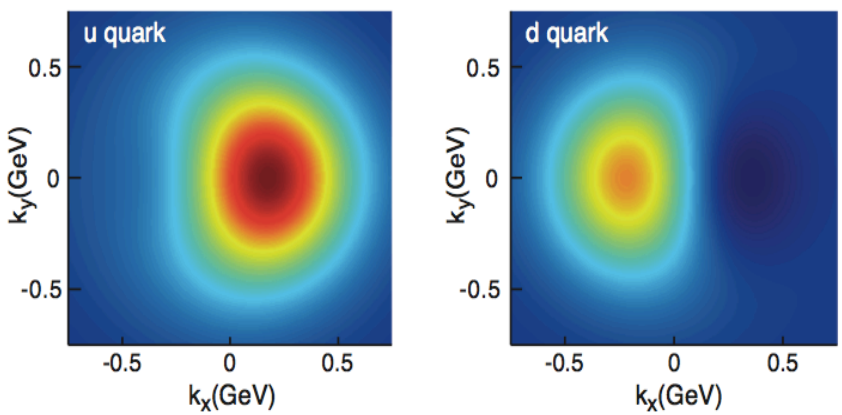
$f(x,k_T)$ **Two-scales observables** $f(x,b_T)$

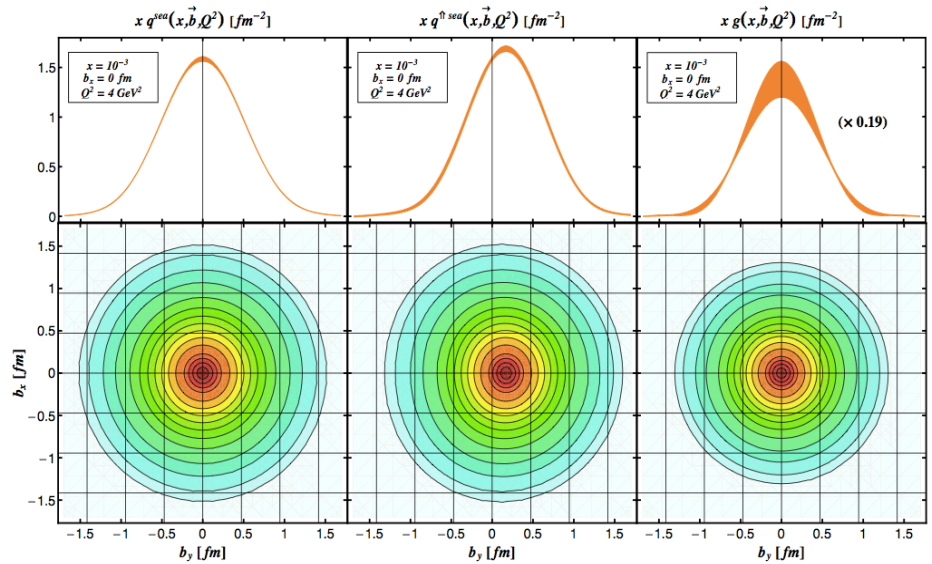
Coordinate Space

GPDs

Spatial distribution

Sivers Functions





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

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

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- **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

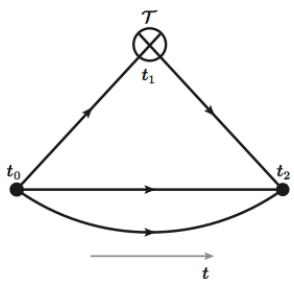
$$\mathcal{L}_q^3 - L_q^3 \propto \int \frac{dy^- d^2 y_T}{(2\pi)^3} \langle P' | \overline{\psi}_q(0) \frac{\gamma^+}{2} \int_{y^-}^{\infty} dz^- \Phi(0, z^-) \times \underbrace{\sum_{i,j=1,2} \left[\epsilon^{3ij} y_T^i F^{+j}(z^-)\right]}_{\text{"Chromodynamic torque"}} \Phi(z^-, y) \psi(y) | P \rangle_{y^+=0}$$

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

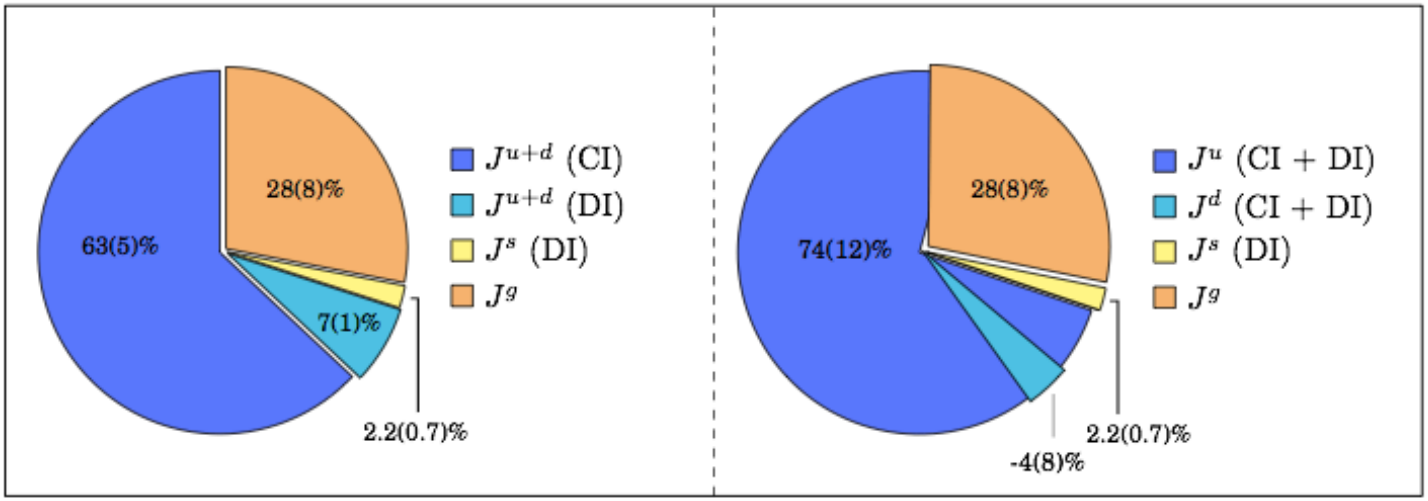
Nucleon spin and OAM from lattice QCD

❑ χQCD Collaboration:

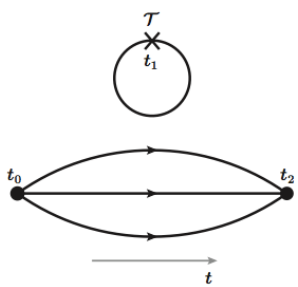
[Deka *et al.* arXiv:1312.4816]



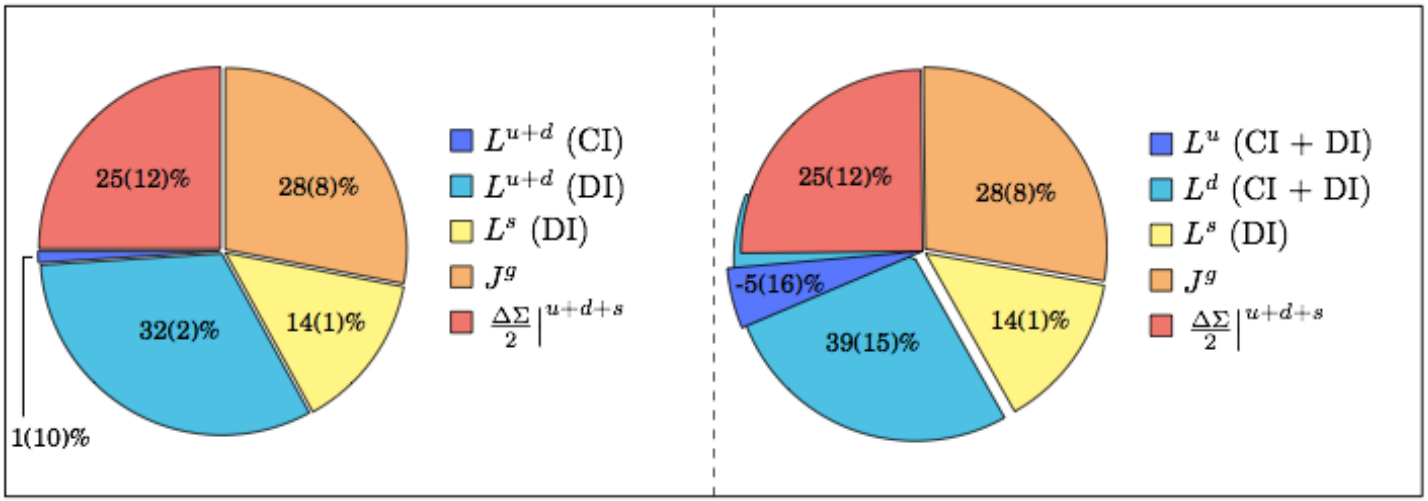
Connected Interaction (CI)



(b)



Disconnected Interaction (DI)

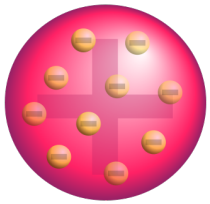


(c)

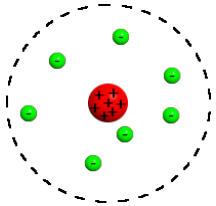
Why 3D hadron structure?

❑ Rutherford's experiment – atomic structure (100 years ago):

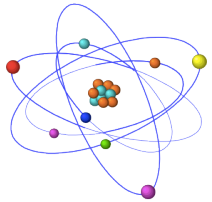
Atom:



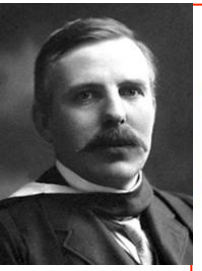
J.J. Thomson's
plum-pudding model

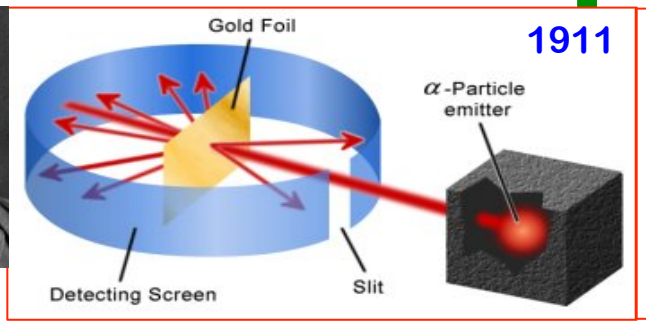


Rutherford's
planetary model



Modern model
Quantum orbitals





Discovery of nucleus
A localized
charge/force center
A vast
"open" space

Discovery of
Quantum Mechanics,
and
the Quantum World!

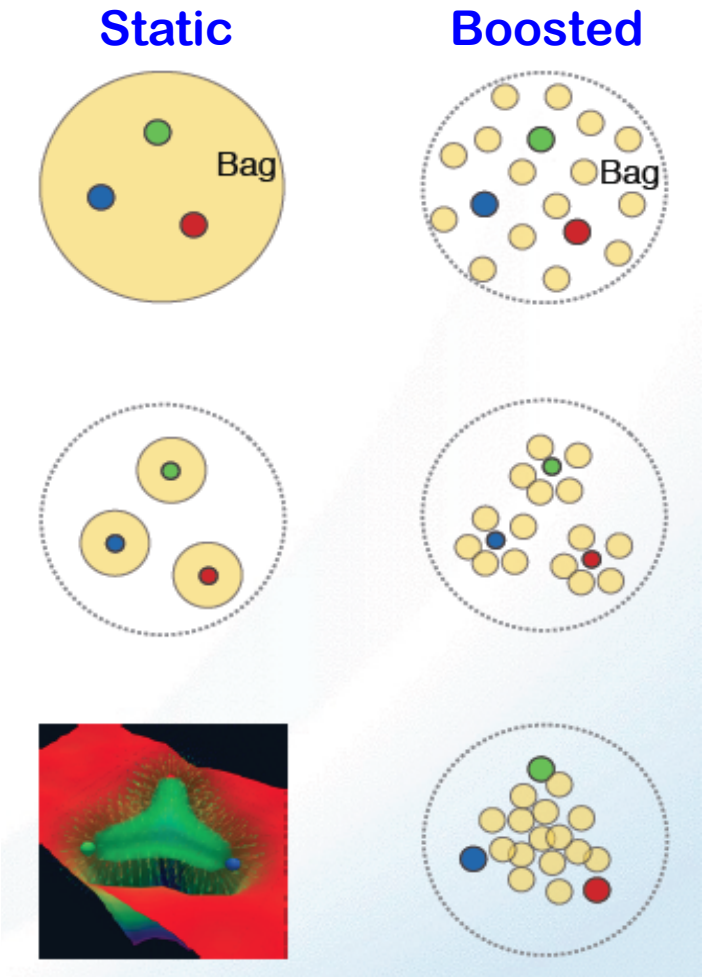
❑ Completely changed our "view" of the visible world:

- ✧ Mass by "tiny" nuclei – *less than 1 trillionth in volume of an atom*
- ✧ Motion by quantum probability – *the quantum world!*
- ✧ Provided infinite opportunities to improve things around us, …

What would we learn from the hadron structure in QCD, …?

Why 3D nucleon structure?

❑ Spatial distributions of quarks and gluons:



Bag Model:

Gluon field distribution is wider than the fast moving quarks.

Gluon radius > Charge Radius

Constituent Quark Model:

Gluons and sea quarks hide inside massive quarks.

Gluon radius ~ Charge Radius

Lattice Gauge theory (with slow moving quarks):

Gluons more concentrated inside the quarks

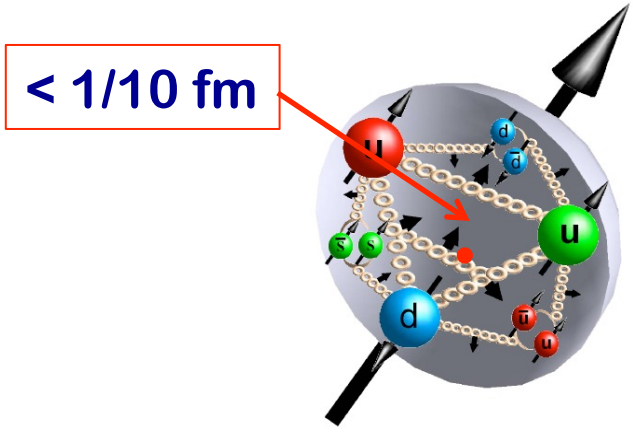
Gluon radius < Charge Radius

3D Confined Motion (TMDs) + Spatial Distribution (GPDs)

Relation between charge radius, quark radius (x), and gluon radius (x)?

Summary

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



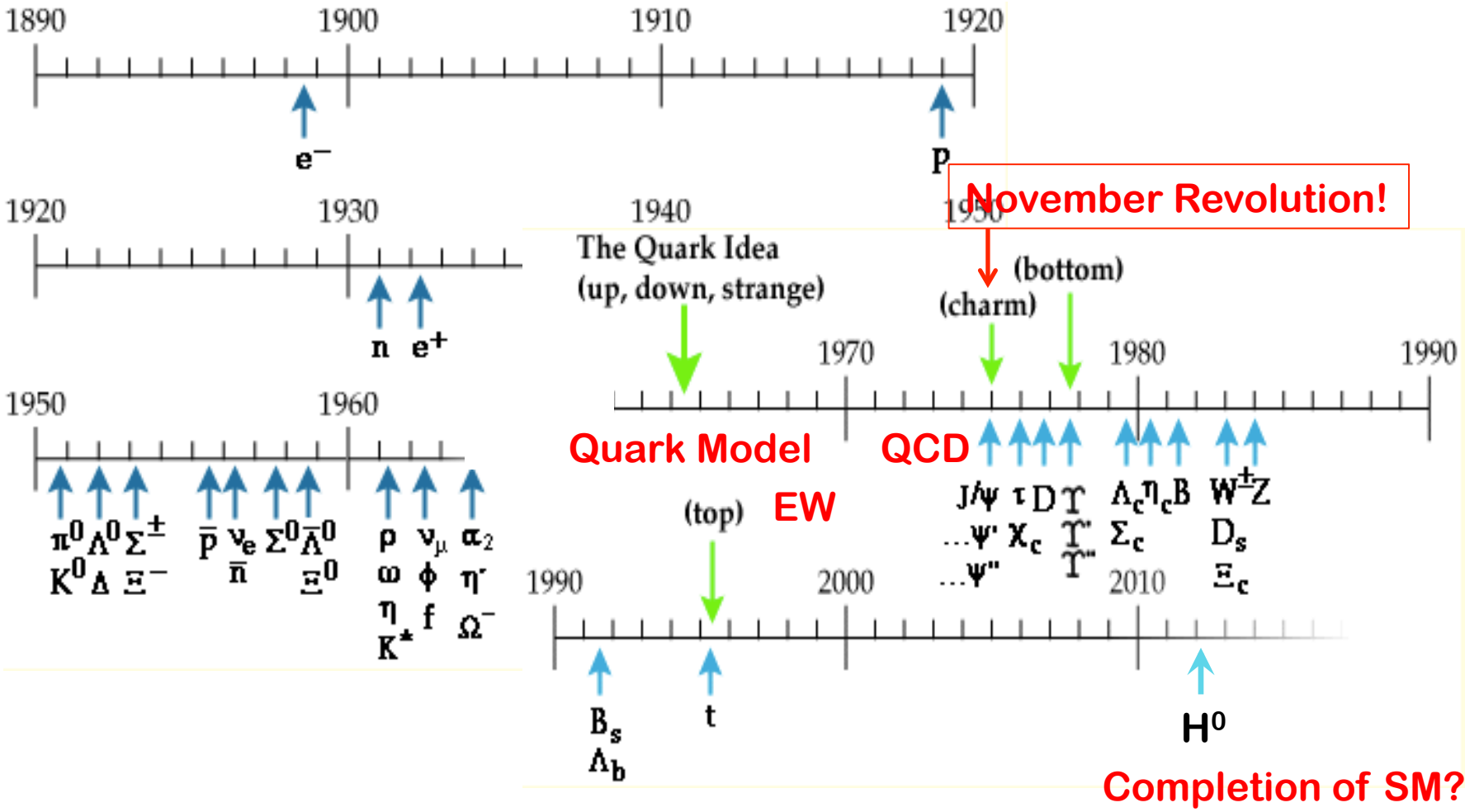
- But, we still do not know much about hadron structure – work just started!
- Cross sections with large momentum transfer(s) and identified hadron(s) are the source of structure information
- QCD factorization is necessary for any controllable "probe" for hadron's quark-gluon structure!
- JLab12/Lattice QCD calculations, plus the future EIC, will provide answers to many of our questions on hadron properties and structure, …

Thank you!

BACKUP SLIDES

New particles, new ideas, and new theories

- Proliferation of new particles – "November Revolution":



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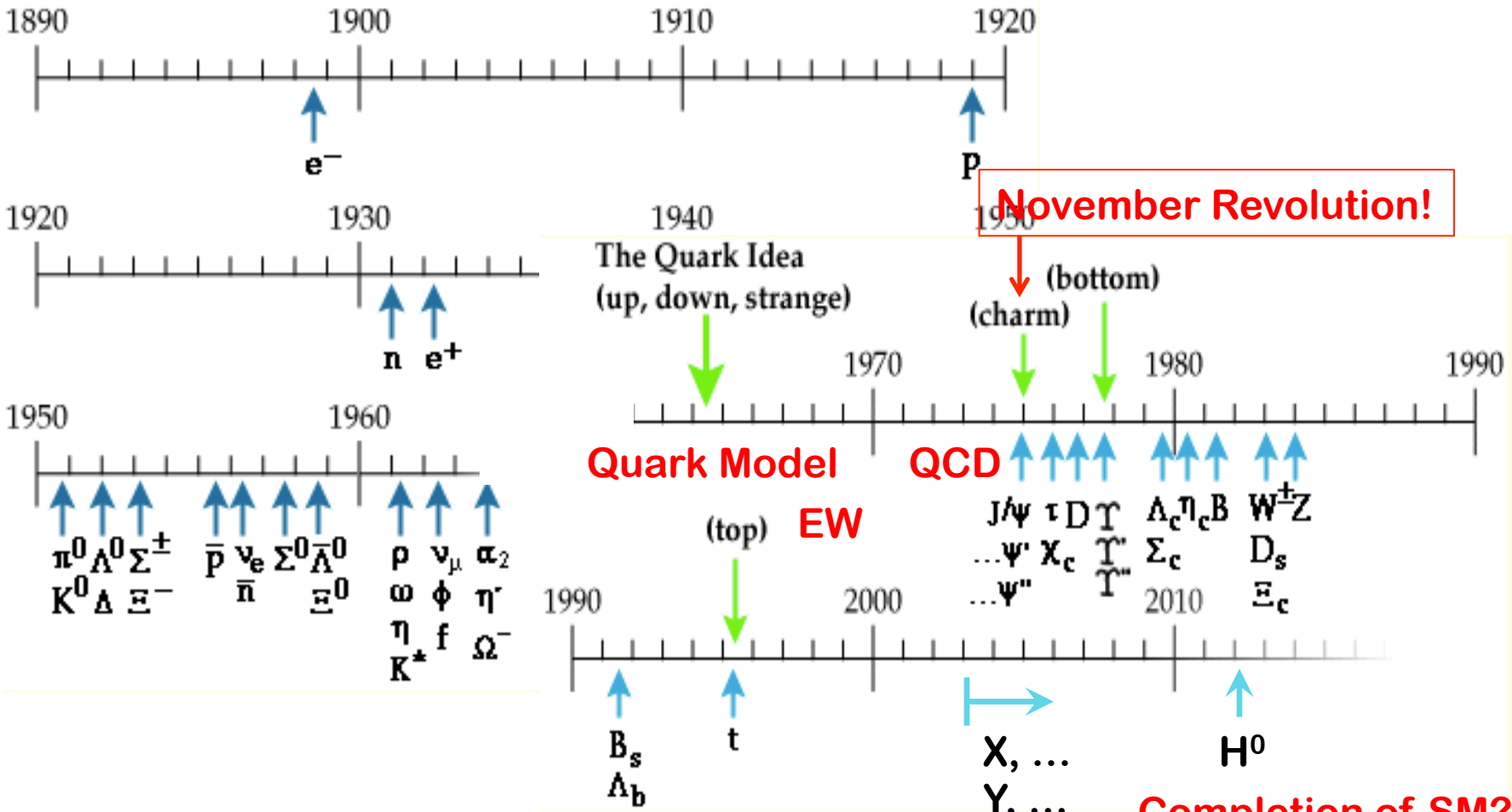
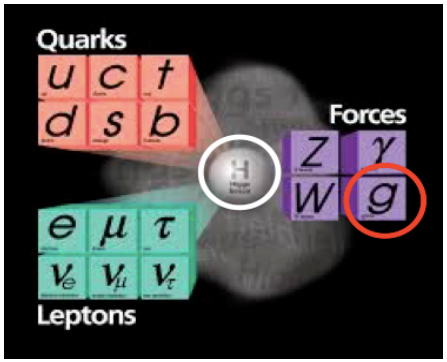
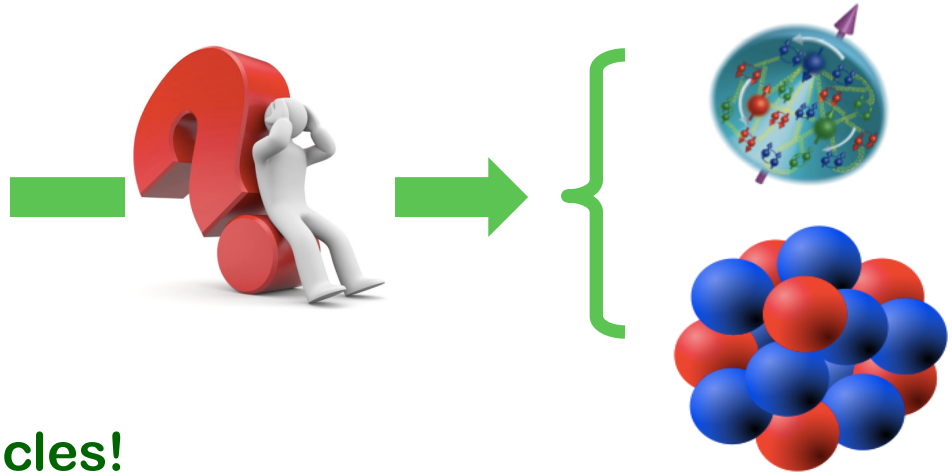


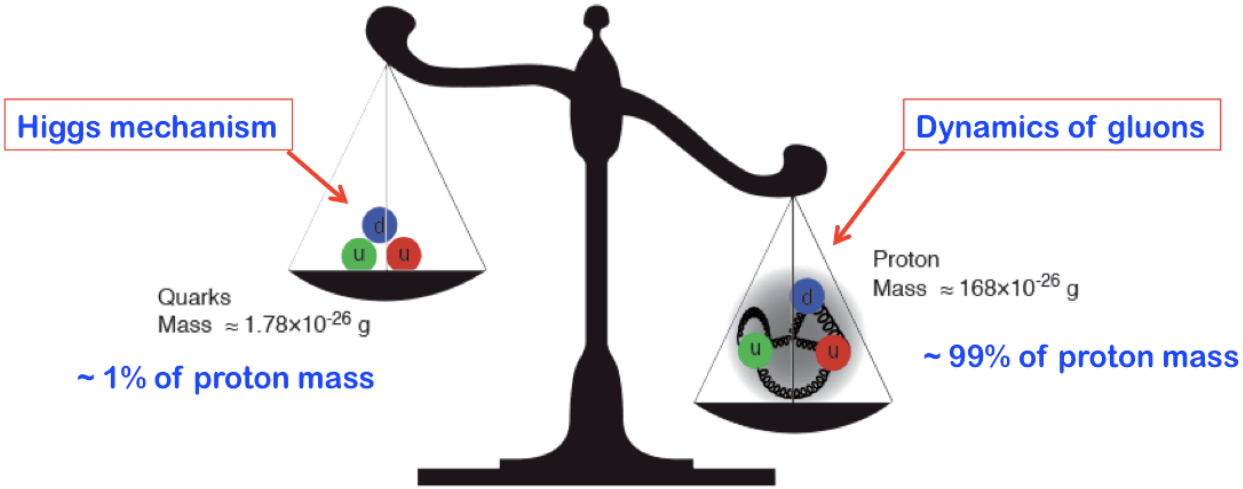
What holds hadron together – the glue?

- Understanding the glue that binds us all – the Next QCD Frontier!

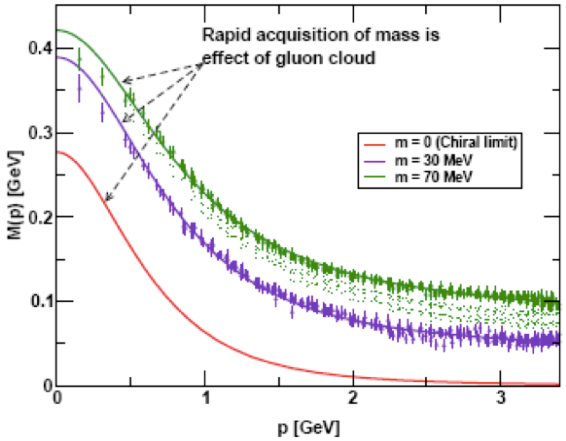




- Gluons are weird particles!
  - Massless, yet, responsible for nearly all visible mass



"Mass without mass!"



Bhagwat & Tandy/Roberts et al

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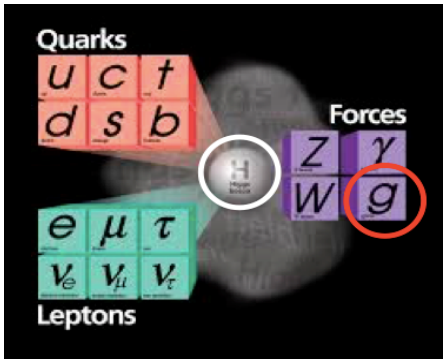

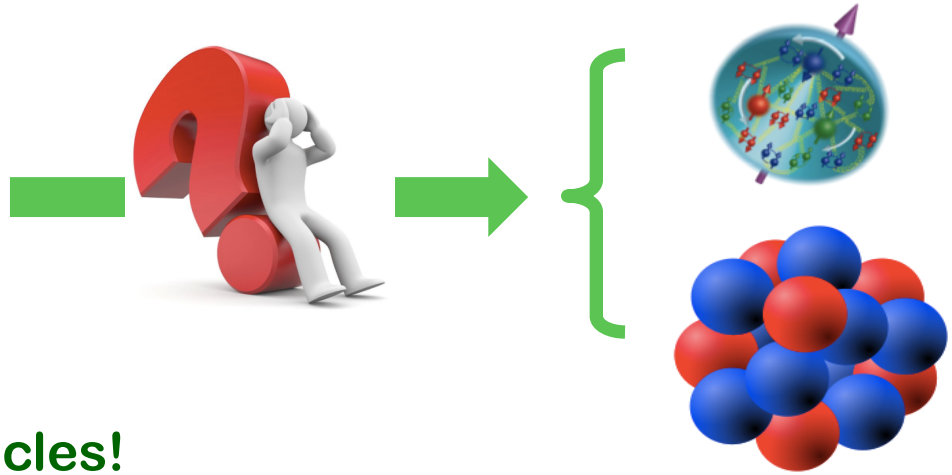

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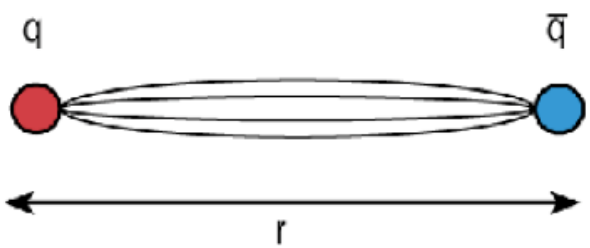
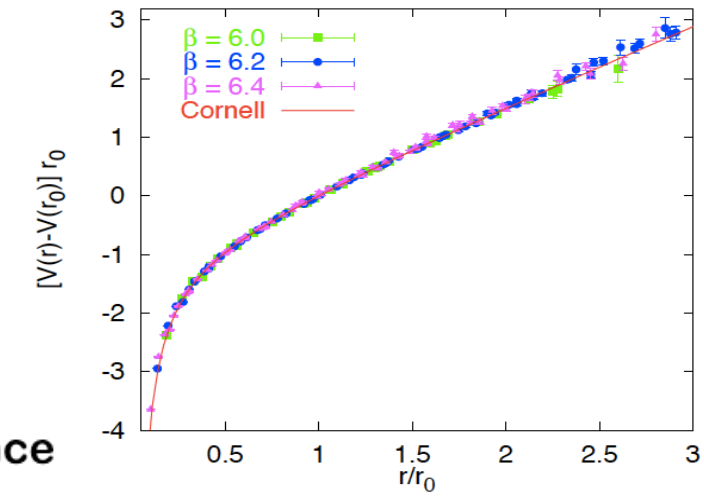
  - Carry color charge, responsible for color confinement and strong force

Force between a heavy quark pair



Heavy quarks experience a force of ~16 tons at ~1 Fermi (10^{-15} m) distance



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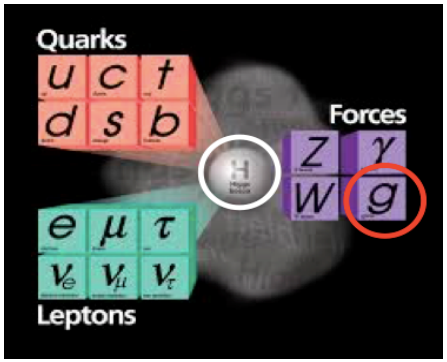

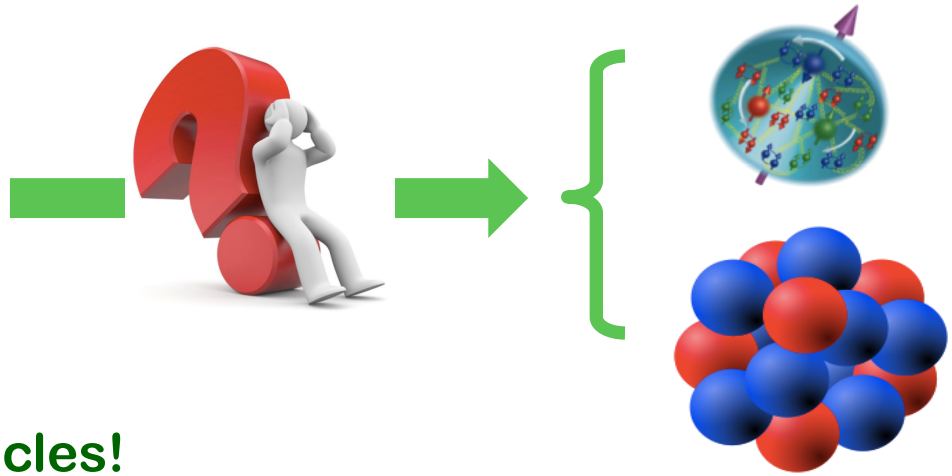

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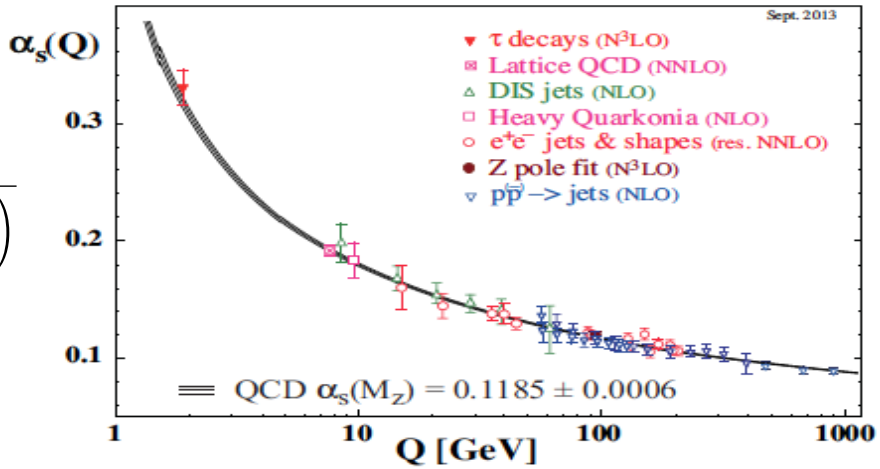
  - Carry color charge, responsible for color confinement and strong force but, also for asymptotic freedom

$$\alpha_s(\mu_2) = \frac{\alpha_s(\mu_1)}{1 - \frac{\beta_1}{4\pi}\alpha_s(\mu_1)\ln\left(\frac{\mu_2^2}{\mu_1^2}\right)} \equiv \frac{4\pi}{-\beta_1 \ln\left(\frac{\mu_2^2}{\Lambda_{\rm QCD}^2}\right)}$$

→ QCD perturbation theory



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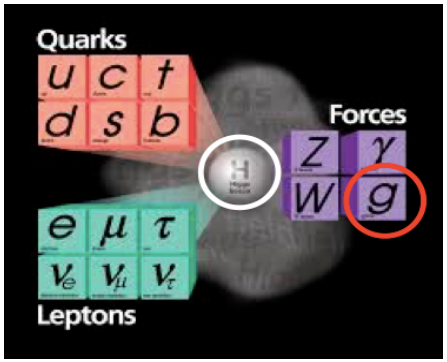

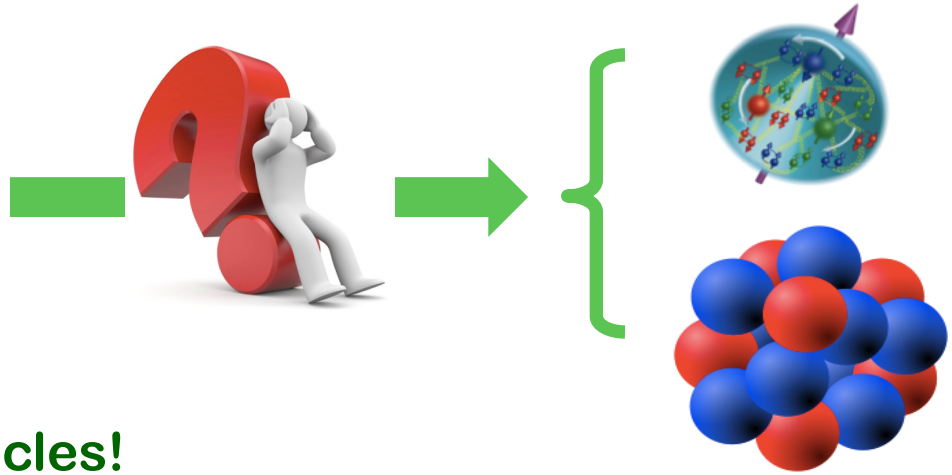

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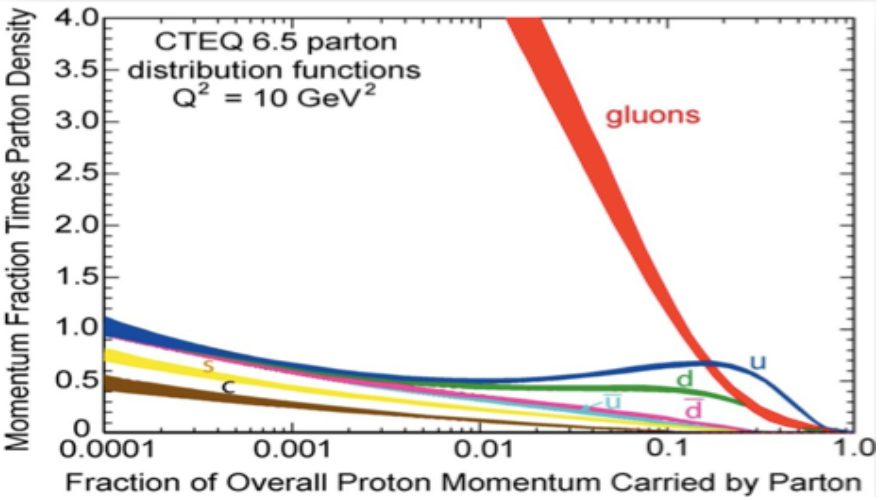

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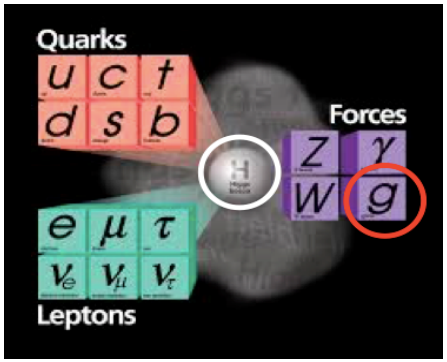

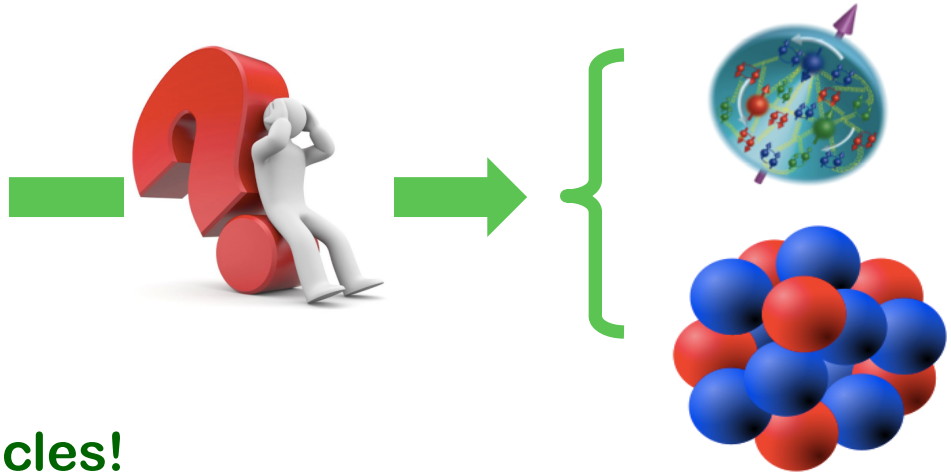

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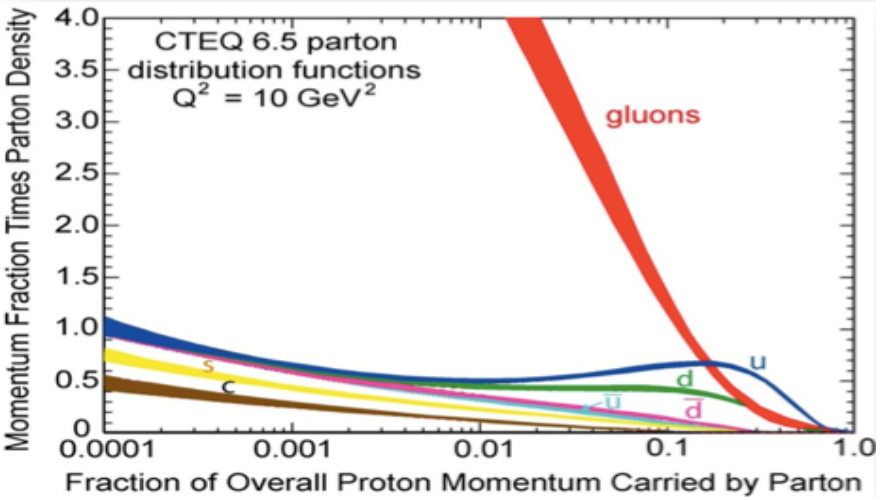

Without gluons, there would be NO nucleons, NO atomic nuclei… NO visible world!

Need an EIC!