Standard Parton Physics and Electron-Ion Collider

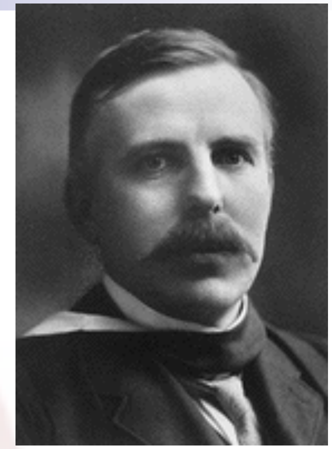
Feng Yuan
Lawrence Berkeley National Laboratory

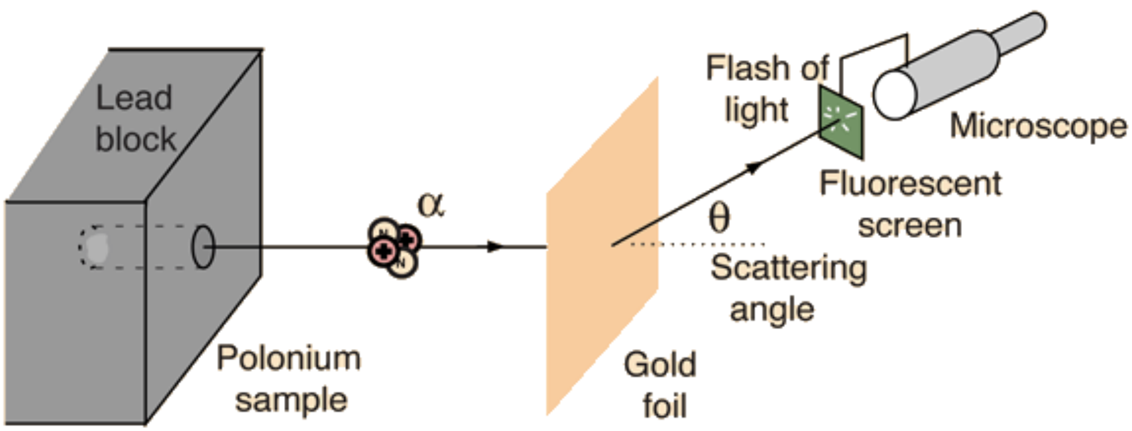
- Parton Physics
  - G. Sterman, *Partons, Factorization and Resummation*, hep-ph/9606312
  - John Collins, *The Foundations of Perturbative QCD*, published by Cambridge, 2011
  - CTEQ, *Handbook of perturbative QCD*, Rev. Mod. Phys. 67, 157 (1995).
- General references
  - CTEQ web site: http://www.phys.psu.edu/~cteq/

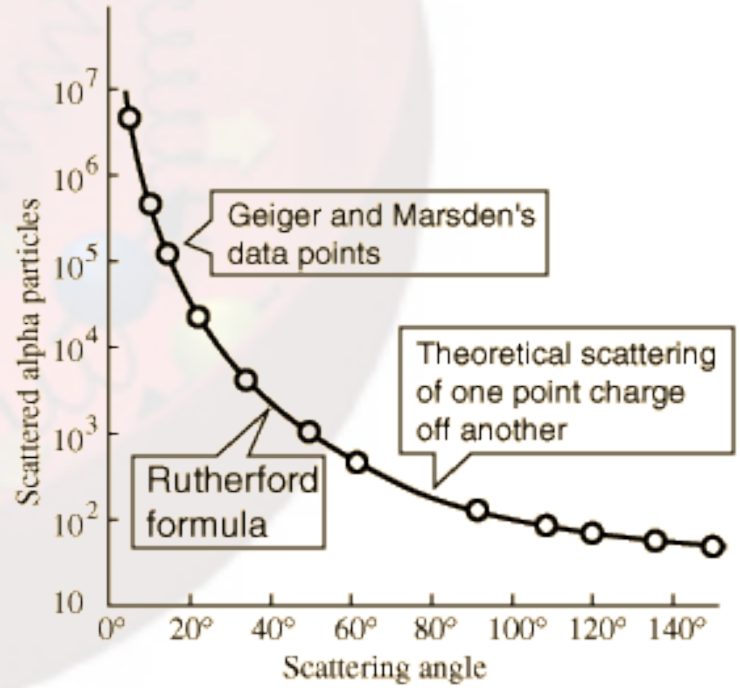
Rutherford scattering

The Scattering of α and β Particles by Matter and the Structure of the Atom

E. Rutherford, F.R.S.*
Philosophical Magazine
Series 6, vol. 21
May 1911, p. 669-688

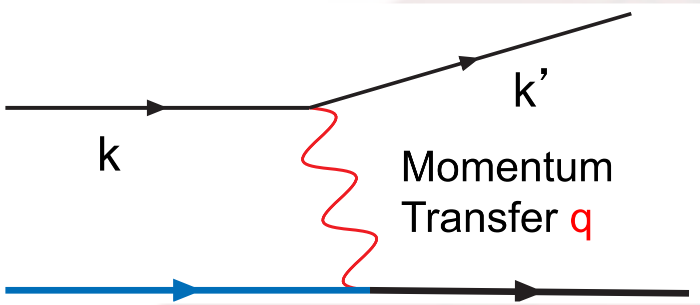






Discovery of Nuclei

Power counting analysis



$$2E_{k'}\frac{d\sigma}{d^3k'} \propto |\mathcal{M}|^2 \quad \mathcal{M} \propto \frac{1}{q^2}$$

$$q^2 = -Q^2 \approx E_k E_k' \sin^2\frac{\theta}{2}$$

- EM interaction perturbation, leading order dominance, potential~1/r
- Point-like structure
- Powerful tool to study inner structure

Basic idea of nuclear science

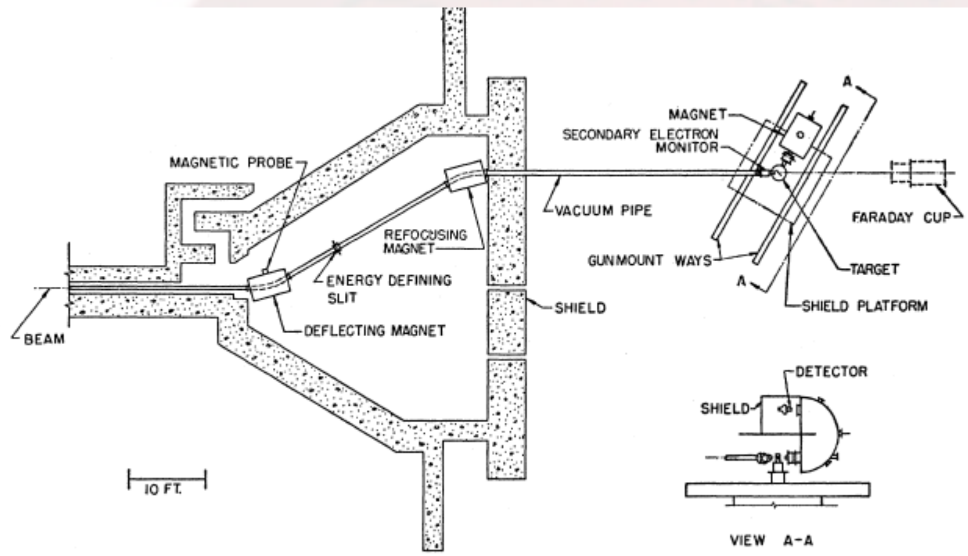
Since the α and β particles traverse the atom, it should be possible from a close study of the nature of the deflexion to form some idea of the constitution of the atom to produce the effects observed. In fact, the scattering of high-speed charged particles by the atoms of matter is one of the most promising methods of attack of this problem. The develop-

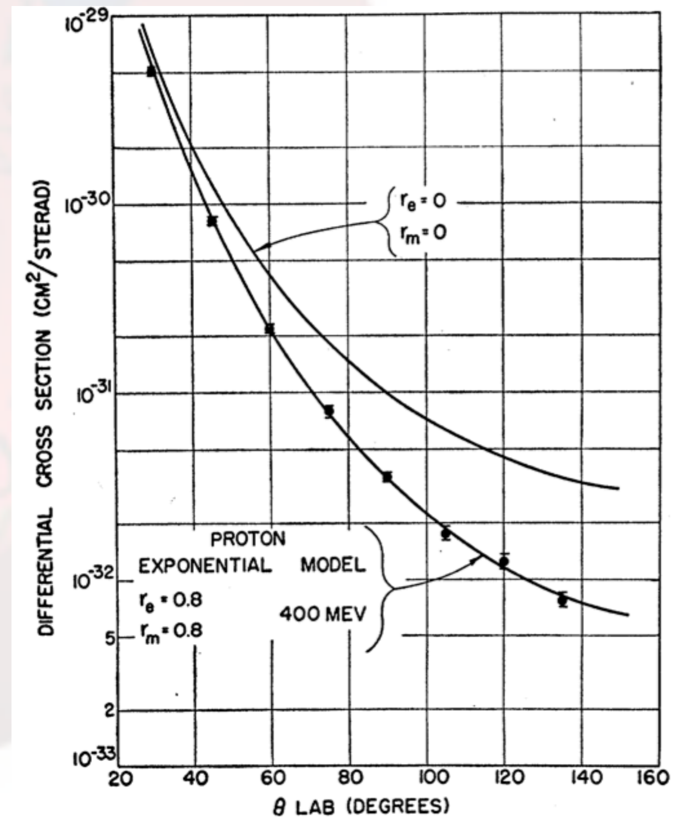
Rutherford, 1911

Finite size of nucleon (charge radius)

Hofstadter

- Rutherford scattering with electron





Renewed interest on proton radius:
μ-Atom vs e-Atom (EM-form factor)

RevModPhys.28.214

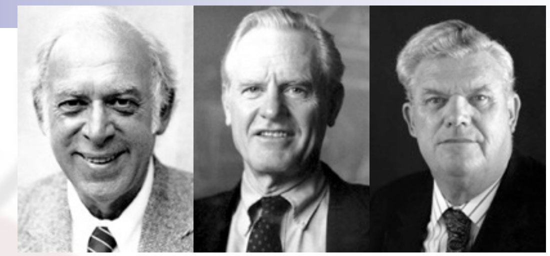
Quark model

Gell-Man

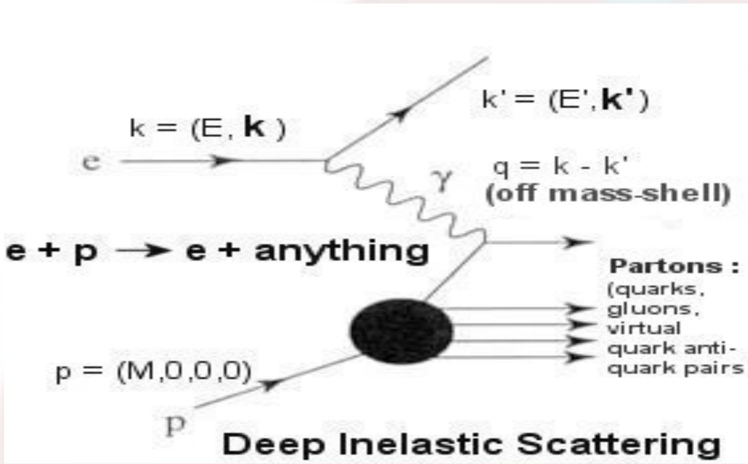
- Nucleons, and other hadrons are not fundamental particles, they have constituents
- Gell-Man Quark Model
  - Quark: spin ½
    - Charges: up (2/3), down (-1/3), strange (-1/3)
  - Flavor symmetry to classify the hadrons
    - Mesons: quark-antiquark
    - Baryons: three-quark
    - Gell-Man-Okubo Formula

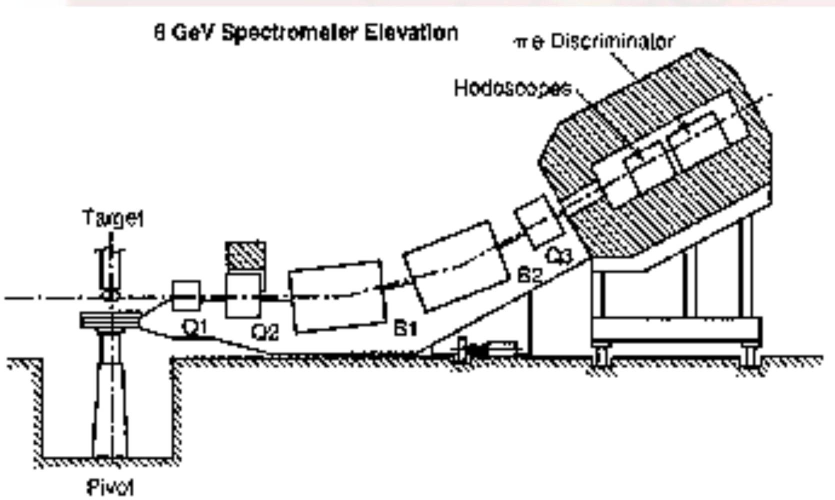
Deep Inelastic Scattering

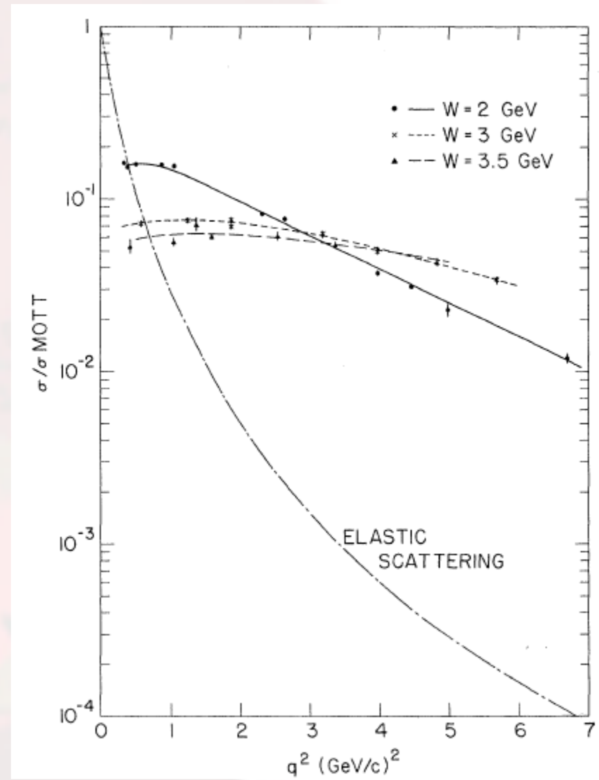
Discovery of Quarks



Friedman Kendall Taylor







Bjorken Scaling: $Q^2 \rightarrow$ Infinity

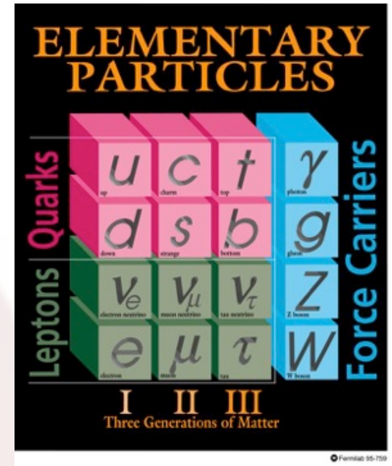
Feynman Parton Model:

Point-like structure in Nucleon

Understanding the scaling

- Weak interactions at high momentum transfer
  - Rutherford formula rules
- Strong interaction at long distance
  - Form factors behavior
  - No free constituent found in experiment
- Strong interaction dynamics is different from previous theory

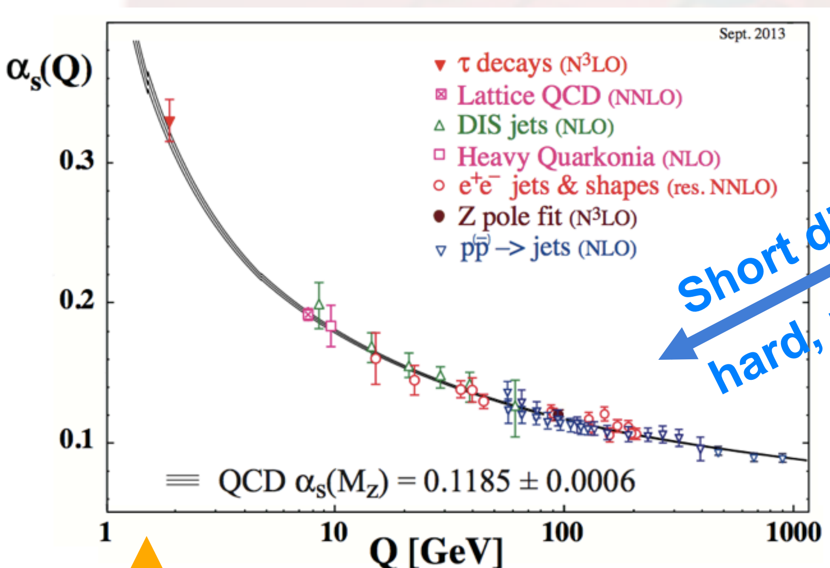
QCD and Strong-Interactions



- QCD: Non-Abelian gauge theory
  - Building blocks: quarks (spin½, m_q, 3 colors; gluons: spin 1, massless, 3^2-1 colors)

$$L = \bar{\psi}(i\gamma\cdot\partial - m_q)\psi - \frac{1}{4}F^{\mu\nu a}F_{\mu\nu a} - g_s\bar{\psi}\gamma\cdot A\psi$$

- Asymptotic freedom and confinement

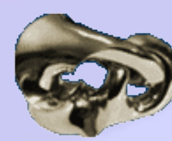


~1/Length

Short distance

hard, perturbative

Long distance:? Soft, non-perturbative



Clay Mathematics Institute Millennium Prize Problem

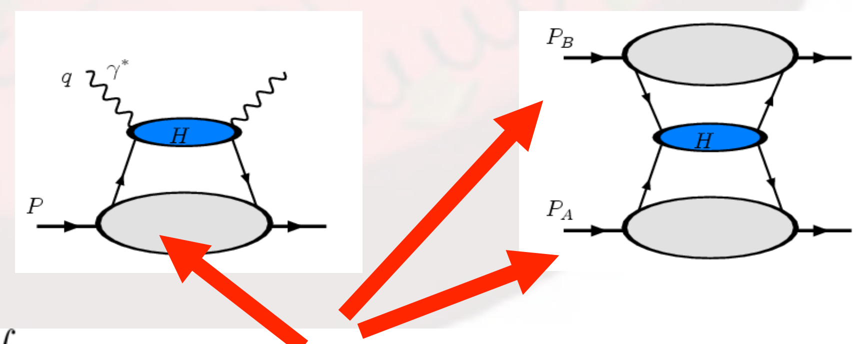
Nonperturbative scale Λ_{QCD}~1GeV

Quantum Chromodynamics

- There is no doubt that QCD is the right theory for hadron physics
- However, many fundamental questions…
- How does the **nucleon mass** generated from massless quarks/gluons?
- How do the fundamental **nuclear forces** arise from QCD?
- We don't have a **comprehensive picture** of the nucleon structure as we don't have an approximate QCD nucleon wave function
- …

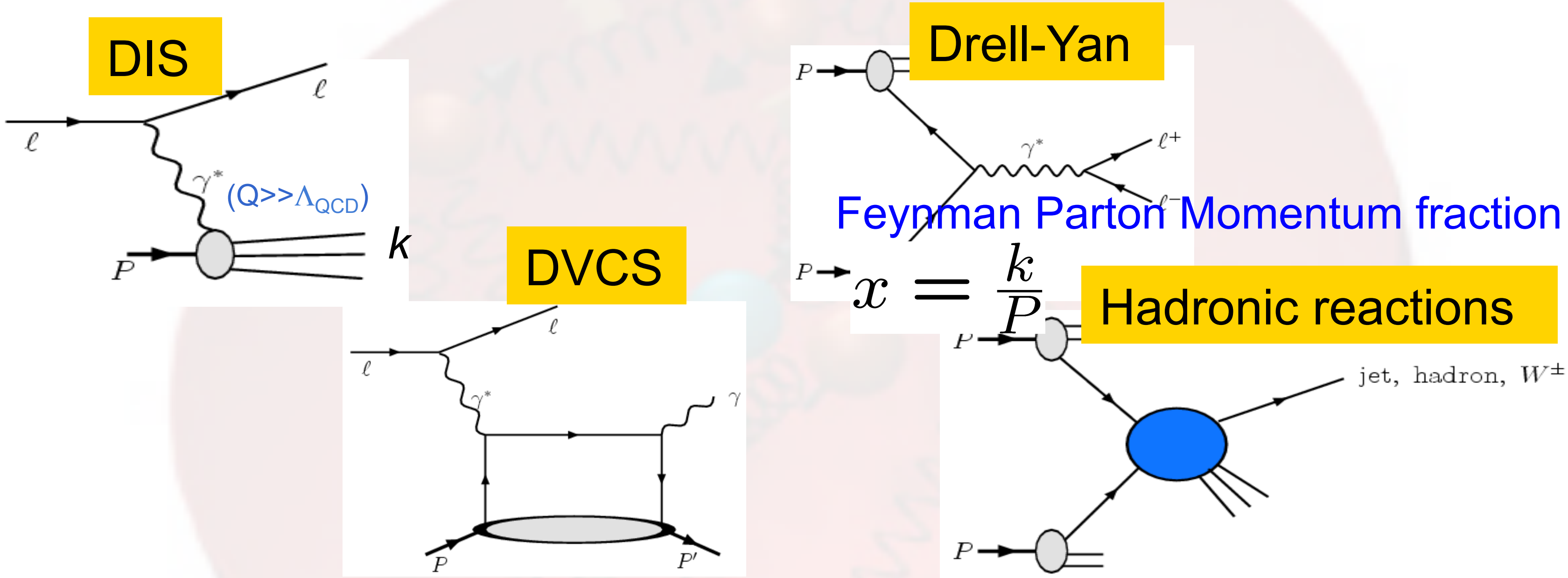
Feynman's parton language and QCD Factorization

- If a hadron is involved in high-energy scattering, the physics simplifies in the infinite momentum frame (Feynman's Parton Picture)
- The scattering can be decomposed into a convolution of parton scattering and parton density (distribution), or wave function or correlations
  - QCD Factorization!



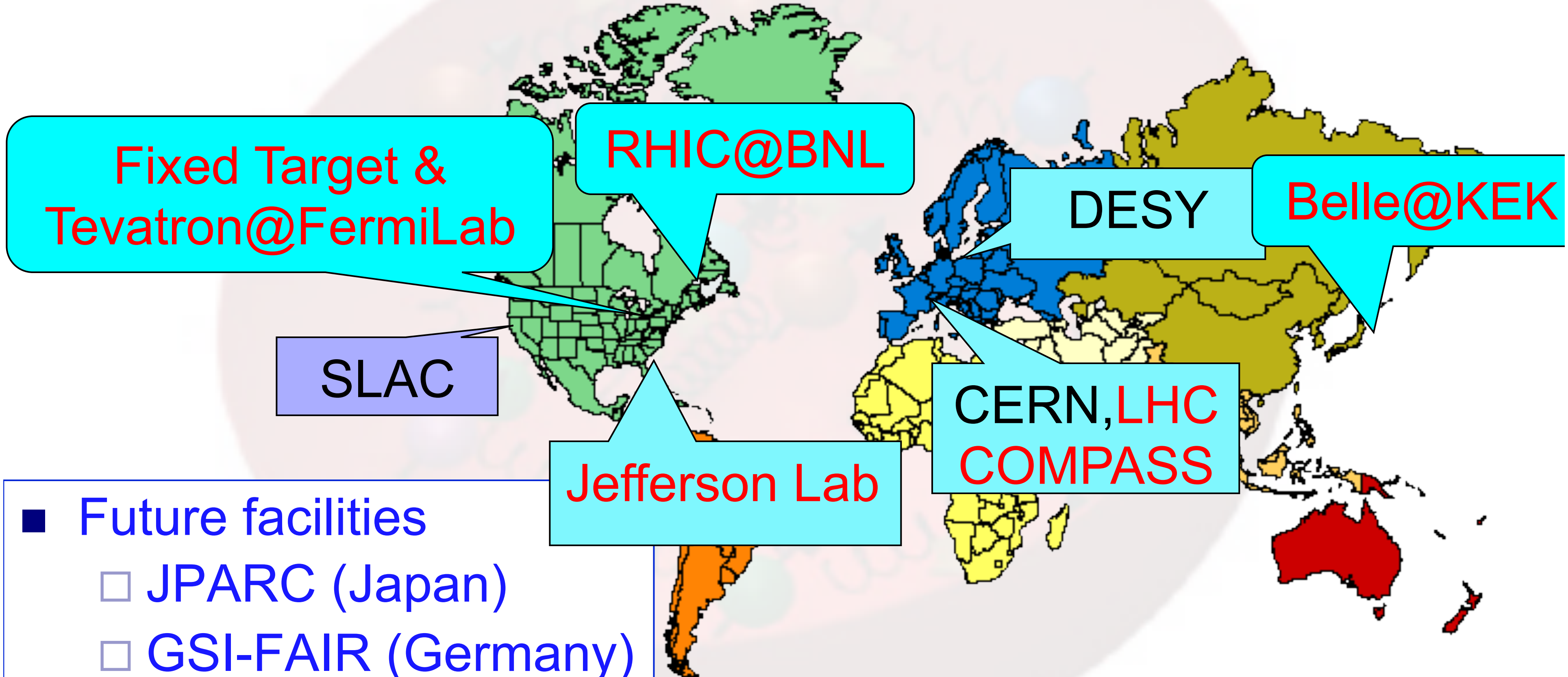
$$\sim \int \text{Parton Distributions} \otimes \text{Hard Partonic Cross Section}$$

High energy scattering as a probe to the nucleon structure



- Many processes: Deep Inelastic Scattering, Deeply-virtual compton scattering, Drell-Yan lepton pair production, pp→jet+X
  - Momentum distribution: Parton Distribution
  - Spin density: polarized parton distribution
  - Wave function in infinite momentum frame: Generalized Parton Distributions

Exploring the partonic structure of nucleon worldwide



- Future facilities
  - JPARC (Japan)
  - GSI-FAIR (Germany)
  - **EIC, LHeC, …**

Perturbative Computations

- Singularities in higher order calculations
- Dimension regularization
  - n<4 for UV divergence
  - n>4 for IR divergence
  - MS ($\overline{\text{MS}}$) scheme for UV divergence

$$\int \frac{d^n k}{k^4} \to \int \frac{dk}{k} k^{n-4}$$

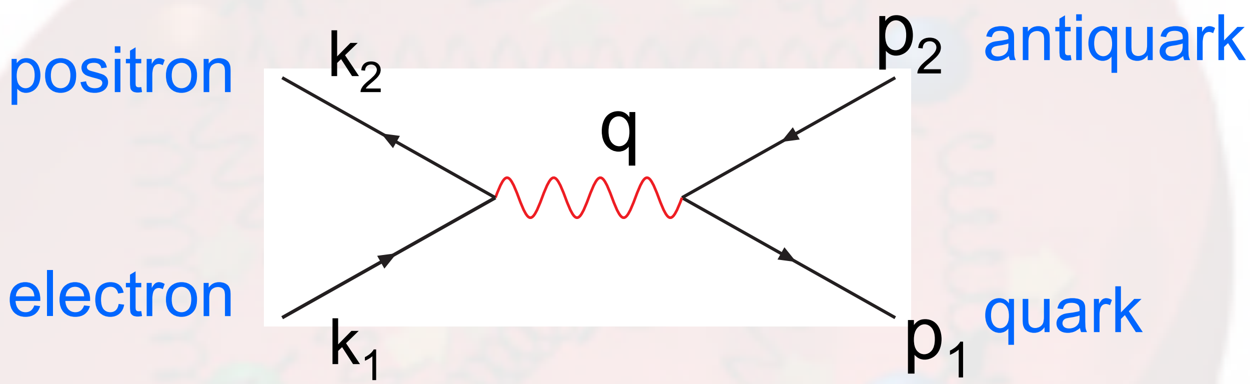
- pQCD predictions rely on Infrared safety of the particular calculation

pQCD predictions

- Infrared safe observables
  - Total cross section in e+e-→hadrons
  - EW decays, tau, Z, …
- Factorizable hard processes: parton distributions/fragmentation functions
  - Deep Inelastic Scattering
  - Drell-Yan Lepton pair production
  - Inclusive process in ep, ee, pp scattering, W, Higgs, jets, hadrons, …

Infrared safe: $e^+e^- \rightarrow$ hadrons

- Leading order



  - Electron-positron annihilate into virtual photon, and decays into quark-antiquark pair, or muon pair
  - Quark-antiquark pair hadronize

- Total cross section

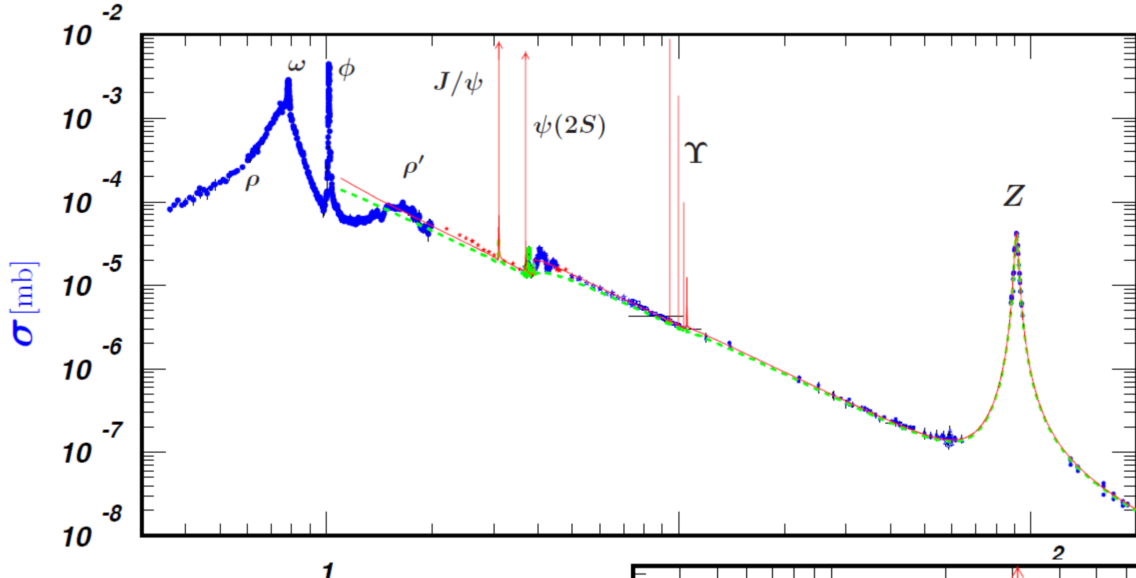
$$\sigma(e^+e^- \to q\bar{q}) = N_c \frac{4\pi}{3}\frac{\alpha^2}{Q^2} e_q^2 \qquad \sigma(e^+e^- \to \mu^+\mu^-) = \frac{4\pi}{3}\frac{\alpha^2}{Q^2}$$

- R ratio

$$R_{EW} = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_c \sum e_q^2$$

  - Depends on the number of colors, electric charge of the quark

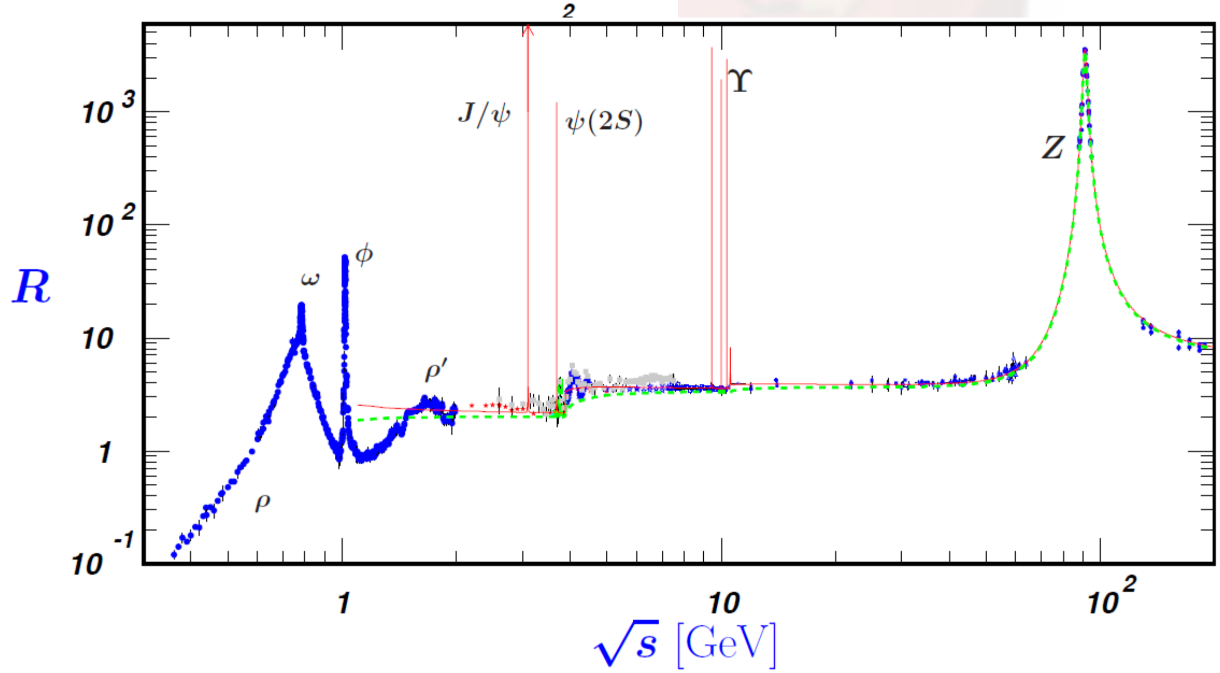
R ratio measurements

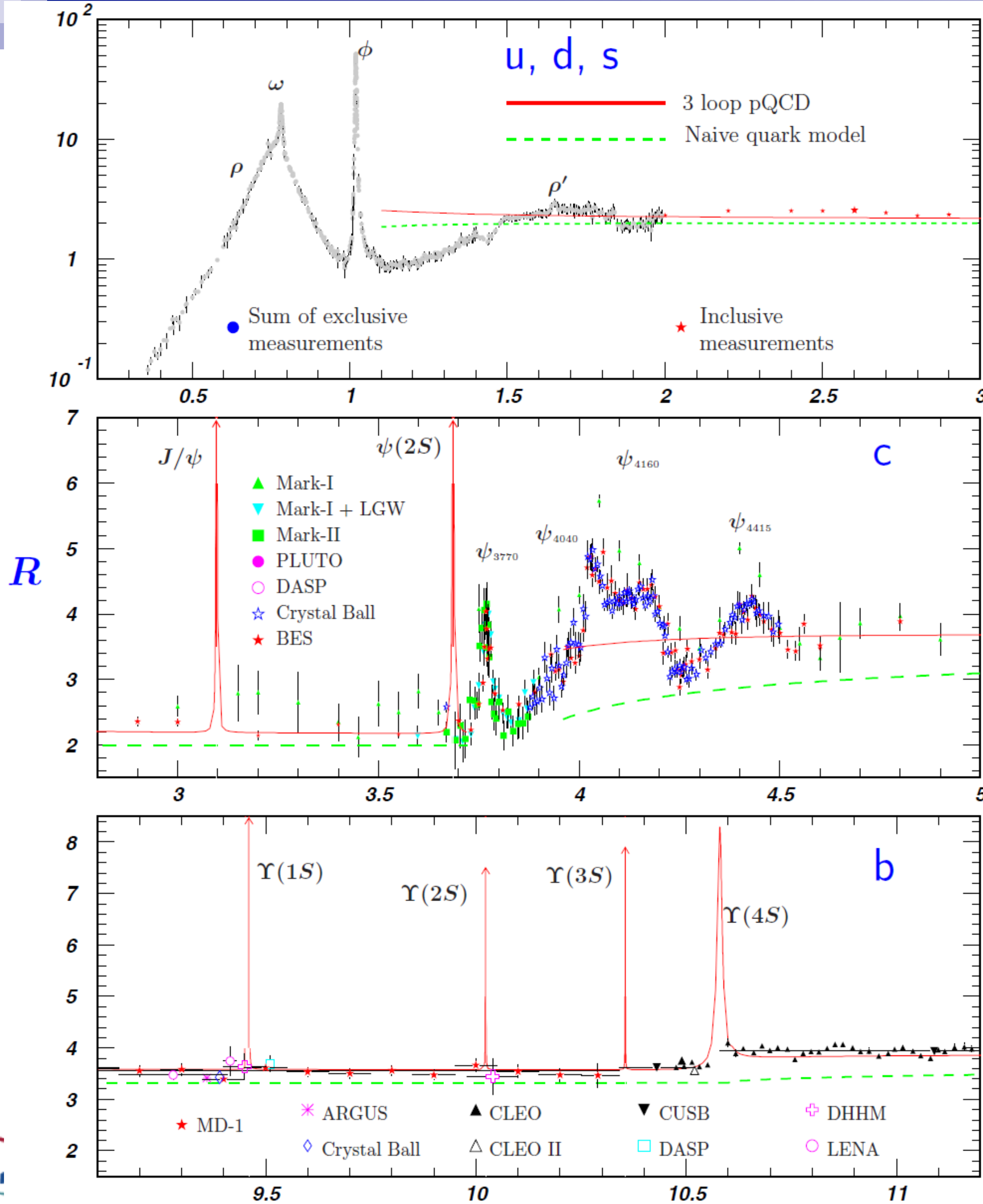


Hadronic cross sections

$e^+e^- \rightarrow$ hadrons

R-ratio





$N_c(e_u^2+e_d^2+e_s^2)=2$

$N_c(e_u^2+e_d^2+e_s^2+e_c^2)=2+4/3$

$N_c(e_u^2+e_d^2+e_s^2+e_c^2+e_b^2)$
$=2+5/3$

Perturbative corrections

- The total cross section is infrared safe

$$\frac{\sigma(e^+e^- \to \text{hadrons}, Q)}{\sigma(e^+e^- \to \mu^+\mu^-, Q)} \equiv R(Q) = R_{\text{EW}}(Q)(1 + \delta_{\text{QCD}}(Q))$$

$$\delta_{\text{QCD}}(Q) = \sum_{n=1}^{\infty} c_n \cdot \left(\frac{\alpha_s(Q^2)}{\pi}\right)^n + \mathcal{O}\left(\frac{\Lambda^4}{Q^4}\right)$$

$$c_1 = 1\,, \qquad c_2 = 1.9857 - 0.1152 n_f\,,$$
$$c_3 = -6.63694 - 1.20013 n_f - 0.00518 n_f^2 - 1.240\eta$$
$$c_4 = -156.61 + 18.77 n_f - 0.7974 n_f^2 + 0.0215 n_f^3 + C\eta\,, \quad \eta = (\sum e_q)^2/(3\sum e_q^2)$$

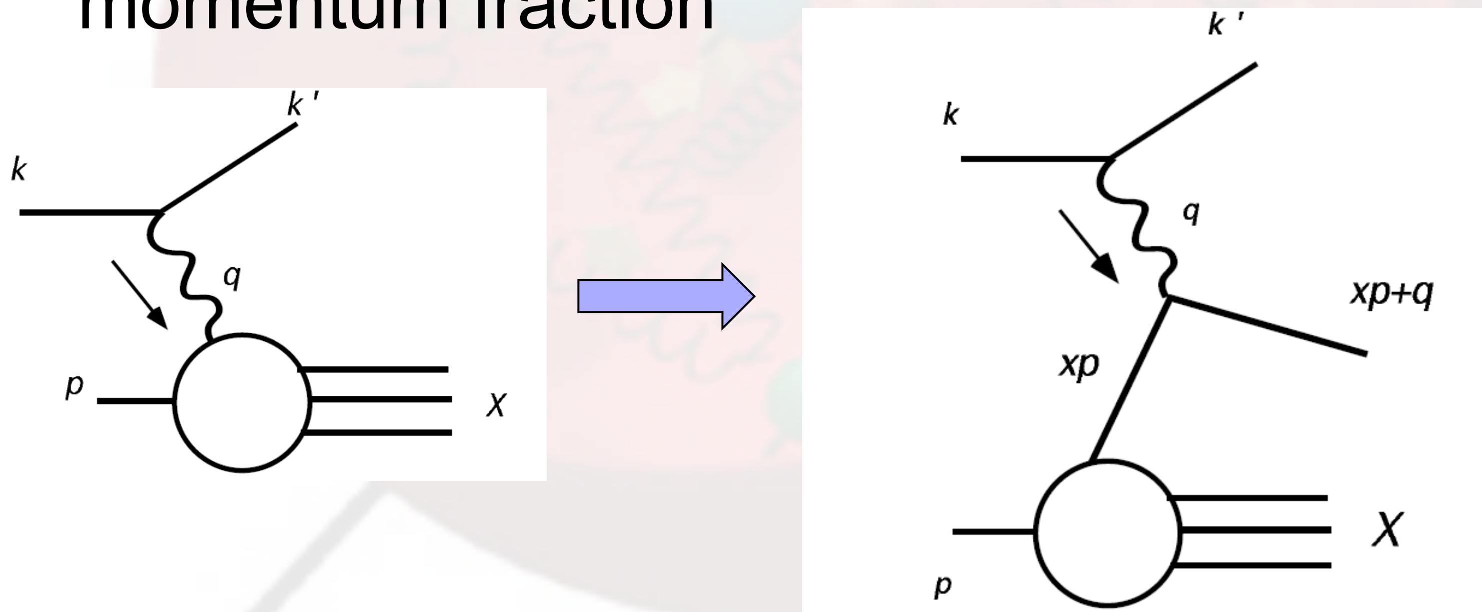
Long distance physics (factorization)

- Not every quantities calculated in perturbative QCD are infrared safe
  - Hadrons in the initial/final states, e.g.
- Factorization guarantee that we can safely separate the long distance physics from short one
- There are counter examples where the factorization does not work

Naïve Parton Model

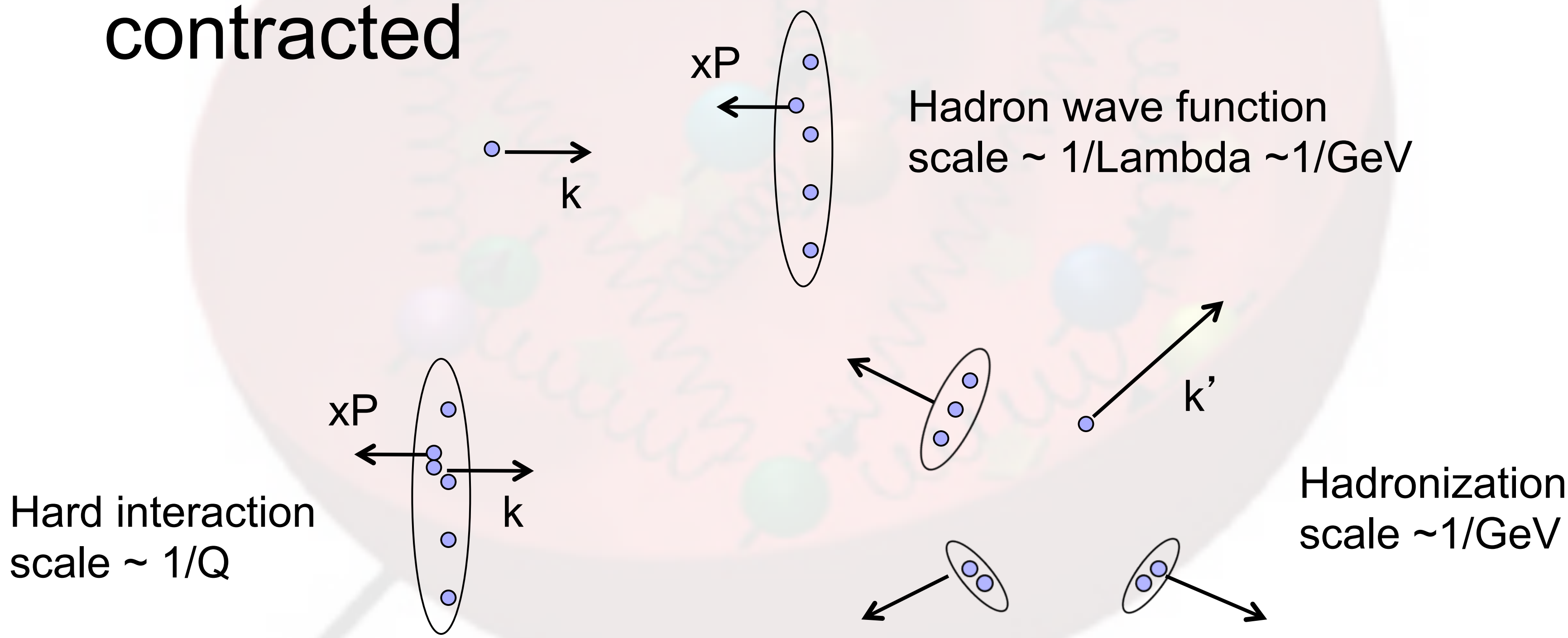
$$d\sigma^{(\ell N)}(p,q) = \sum_f \int_0^1 d\xi \; d\sigma_{\text{Born}}{}^{(\ell f)}(\xi p, q)\phi_{f/N}(\xi)$$

- $\phi_{f/N}(\xi)$ the parton distribution describes the probability that the quark carries nucleon momentum fraction



Intuitive argument for the factorization (DIS)

- In the Bjorken limit, nucleon is Lorentz contracted



Factorization formula

$$F_2{}^{(h)}(x,Q^2) = \sum_{i=f,\bar{f},G} \int_x^1 d\xi\; C_2{}^{(i)}\left(\frac{x}{\xi},\frac{Q^2}{\mu^2},\alpha_s(\mu^2)\right)\phi_{i/h}(\xi,\mu^2)$$

$$F_1{}^{(h)}(x,Q^2) = \sum_{i=f,\bar{f},G} \int_x^1 \frac{d\xi}{\xi}\; C_1{}^{(i)}\left(\frac{x}{\xi},\frac{Q^2}{\mu^2},\alpha_s(\mu^2)\right)\phi_{i/h}(\xi,\mu^2)$$

- Factorization → scale dependence

$$\mu\frac{d^2}{d\mu^2}\phi_{i/h}(x,\mu^2) = \sum_{j=f,\bar{f},G}\int_x^1 \frac{d\xi}{\xi} P_{ij}(\frac{x}{\xi},\alpha_s(\mu^2))\phi_{j/h}(\xi,\mu^2)$$

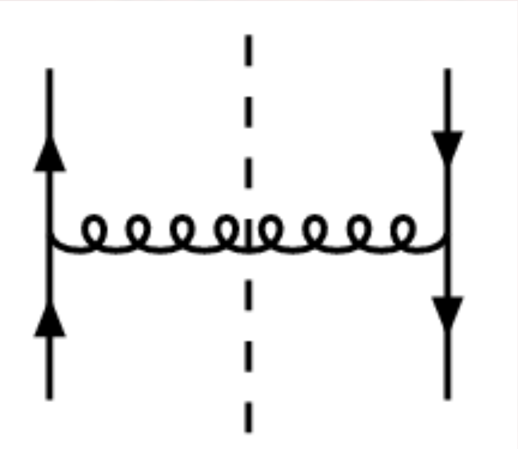
$$\mu\frac{d}{d\mu}\ln\bar{\phi}\left(n,\alpha_s(\mu^2)\right) = -\gamma_n\left(\alpha_s(\mu^2)\right) \qquad \bar{f}(n) \equiv \int_0^1 dx\; x^{n-1} f(x)$$

- Scale dependence → resummation

$$\bar{\phi}^{(\mathrm{val})}(n,\mu^2) = \bar{\phi}^{(\mathrm{val})}(n,\mu_0{}^2)\exp\left\{-\frac{1}{2}\int_0^{\ln\mu^2/\mu_0{}^2} dt\;\gamma_n\left(\alpha_s(\mu_0{}^2 e^t)\right)\right\}$$

anomalous dimension: $\int_0^1 d\xi\,\xi^{n-1}P_{ij}(\xi,\alpha_s) = -\gamma_{ij}(n)$

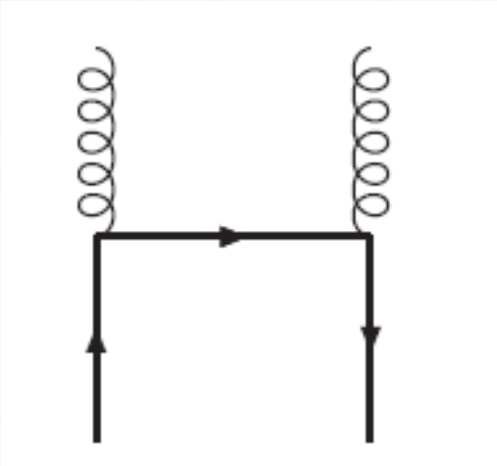
Quark-quark splitting



- Physical polarization for the radiation gluon
- Incoming quark on-shell, outgoing quark off-shell

$$\mathcal{P}_{qq} = C_F \left[\frac{1+x^2}{(1-x)_+} + \delta(1-x) \right]$$

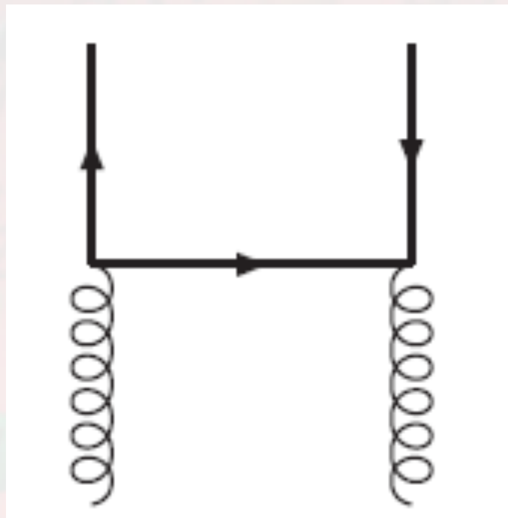
Quark-gluon splitting



- Incoming quark on-shell, gluon is off-shell

$$\mathcal{P}_{g/q} = C_F \left[\frac{1 + (1-x)^2}{x} \right]$$

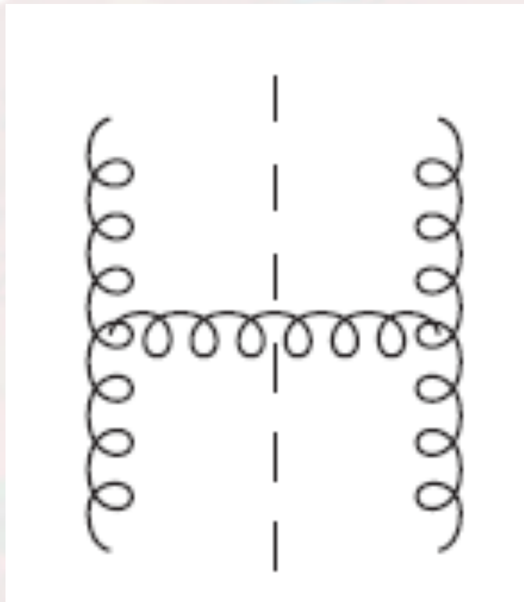
Gluon-quark splitting



- Incoming gluon is on-shell, physical polarization

$$\mathcal{P}_{q/g} = T_F \left[(1-x)^2 + x^2 \right]$$

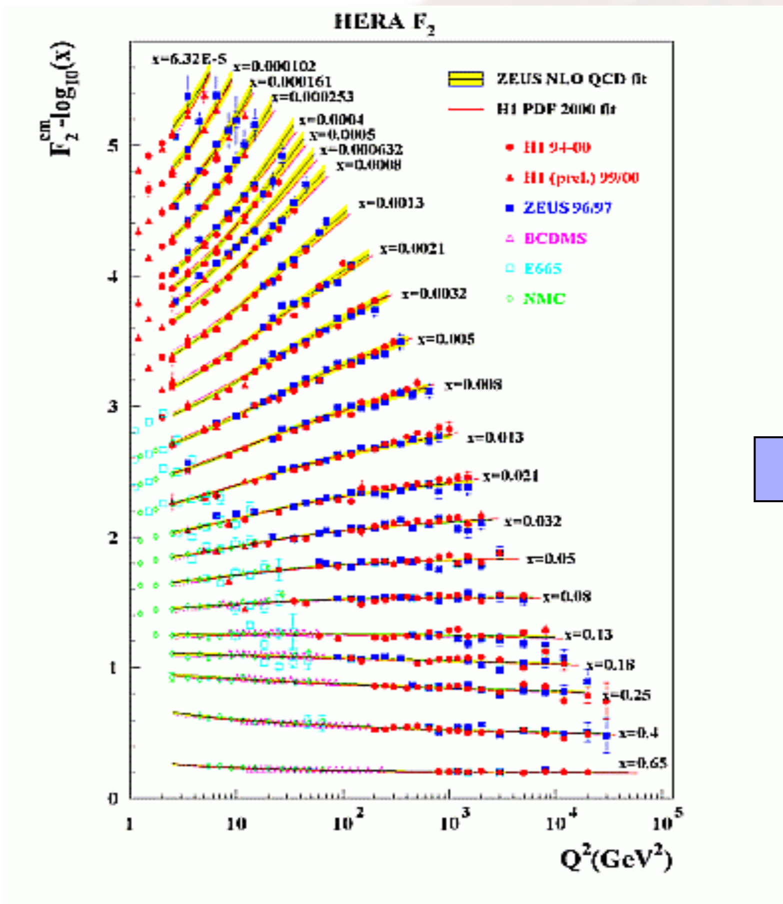
Gluon-gluon splitting

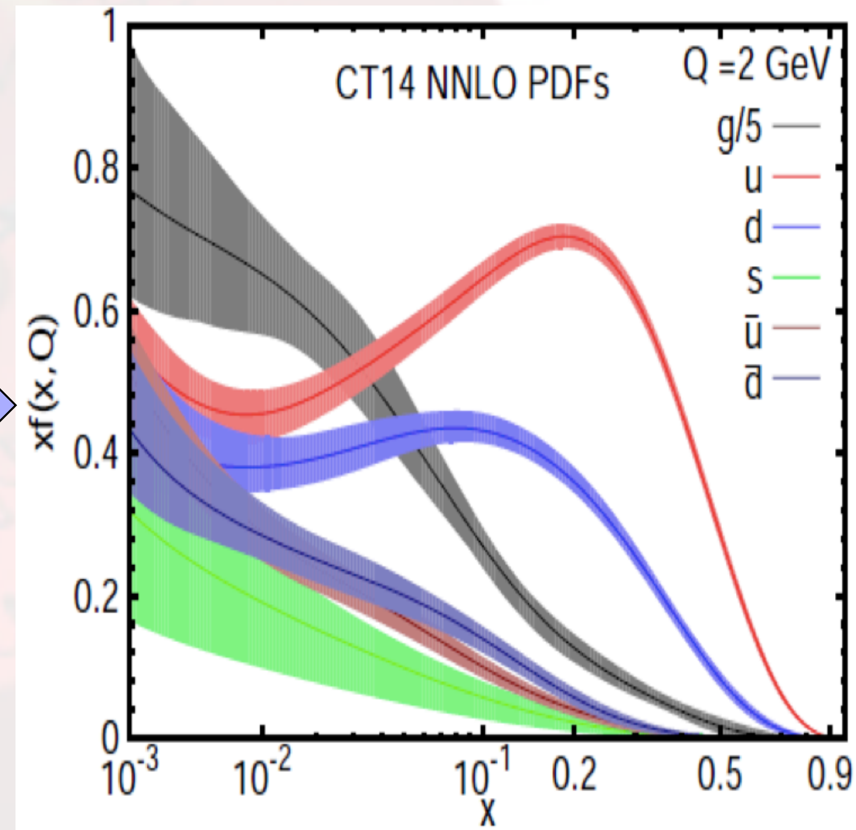


- Physical polarizations for the gluons

$$\mathcal{P}_{gg}(x) = \frac{x}{(1-x)_+} + \frac{1-x}{x} + x(1-x) + \delta(x-1)\beta_0$$

These evolutions describe the HERA data





Reverse the DIS:

Drell-Yan

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)

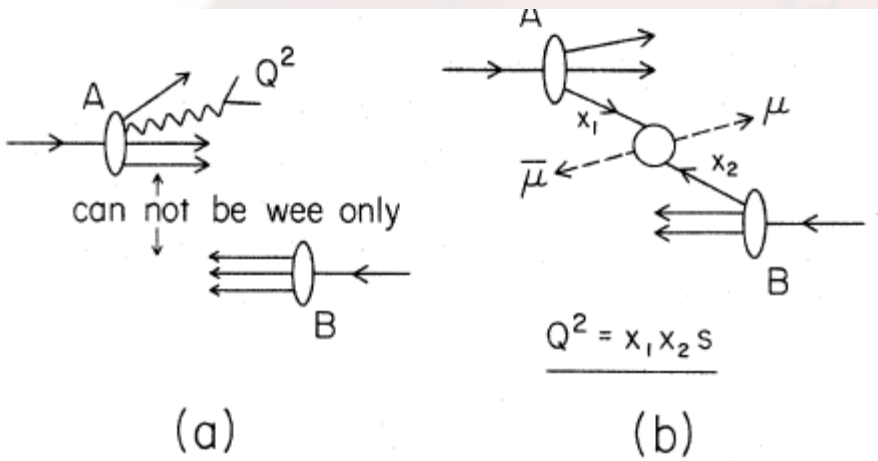
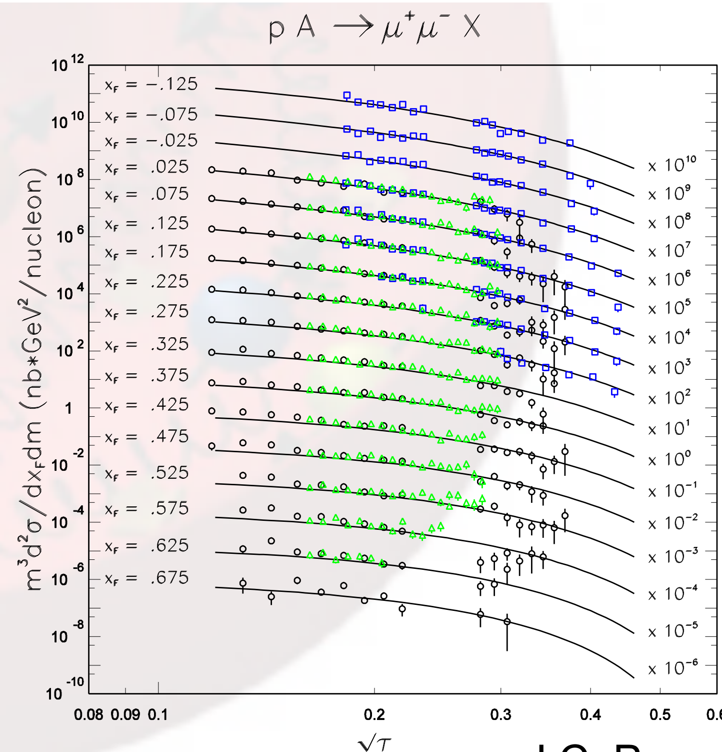
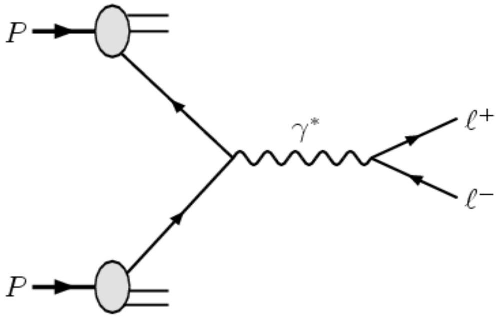


FIG. 1. (a) Production of a massive pair Q^2 from one of the hadrons in a high-energy collision. In this case it is kinematically impossible to exchange "wee" partons only. (b) Production of a massive pair by parton-antiparton annihilation.



J.C. Peng

Drell-Yan lepton pair production



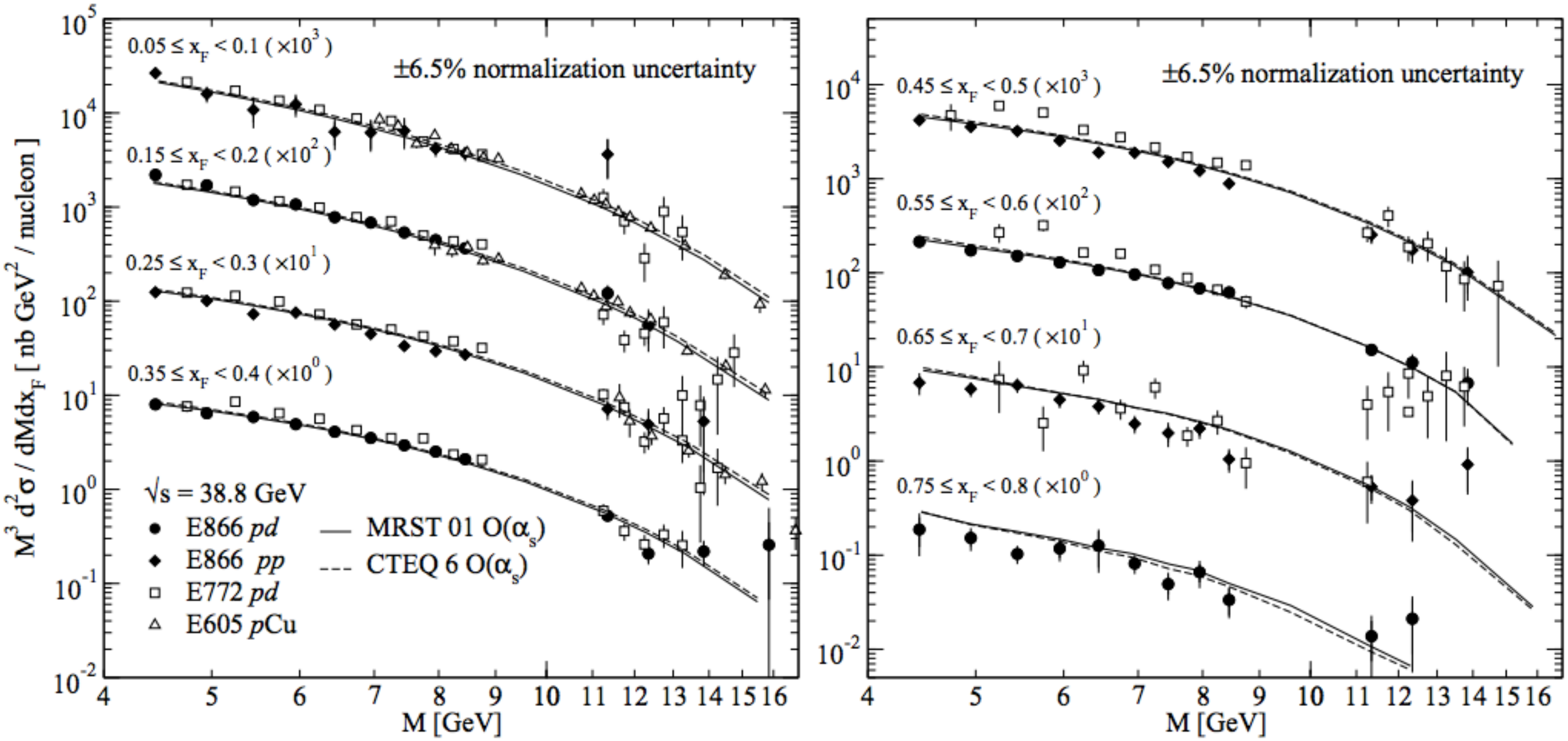
$$\sigma(pp \to \ell^+\ell^- + X) = \int dx_1 dx_2 \phi_{q/p}(x_1)\phi_{\bar{q}/p}(x_2)\hat{\sigma}(q\bar{q} \to \ell^+\ell^-)$$

- The same parton distributions as DIS
  - Universality
- Partonic cross section

$$\sigma(e^+e^- \to q\bar{q}) = N_c \frac{4\pi}{3}\frac{\alpha^2}{Q^2}e_q^2$$

$$\hat{\sigma}(q\bar{q} \to \ell^+\ell^-) = \frac{4\pi}{3}\frac{\alpha^2}{Q^2}e_q^2\frac{1}{N_c}$$

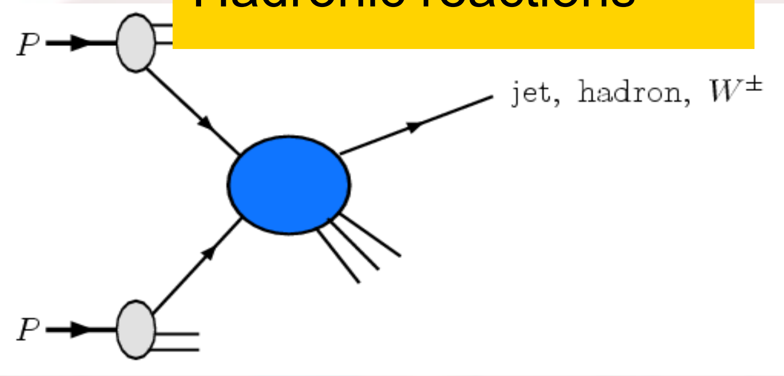
Profound results



- Universality
- Perturbative QCD at work

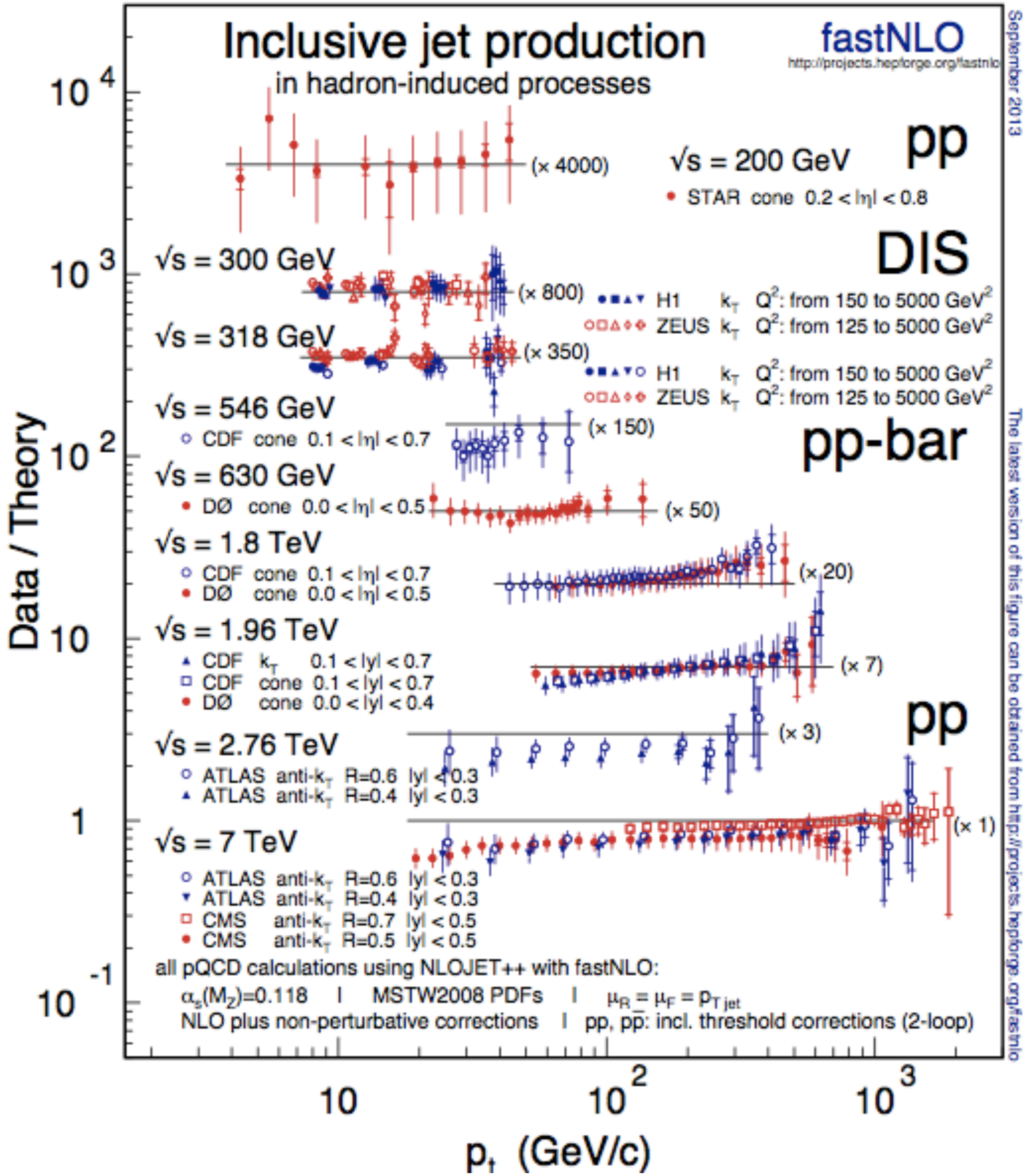
More general hadronic process

Hadronic reactions



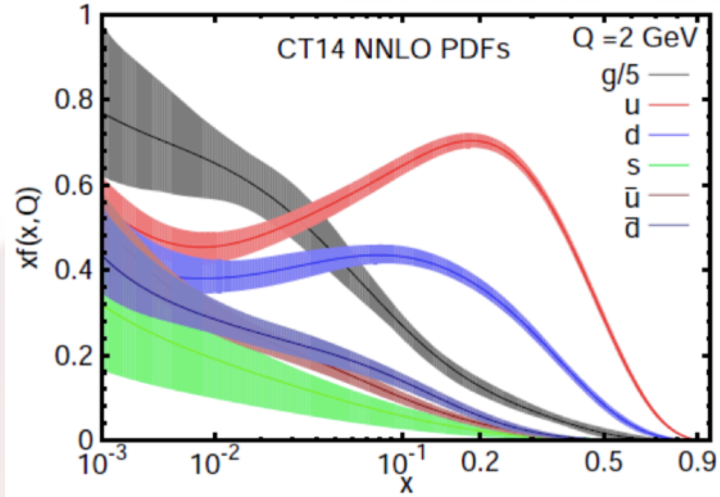
$$\sigma(pp \to c + X) = \int dx_1 dx_2 \phi_{a/p}(x_1)\phi_{b/p}(x_2)\hat{\sigma}(ab \to c + X)$$

- All these processes have been computed up to next-to-leading order, some at NNLO, few at N^3LO


Inclusive jet production
in hadron-induced processes
fastNLO
http://projects.hepforge.org/fastnlo
September 2013
Data / Theory
√s = 200 GeV
pp
STAR cone 0.2 < |η| < 0.8
(× 4000)
√s = 300 GeV
(× 800)
DIS
H1 k_T Q²: from 150 to 5000 GeV²
ZEUS k_T Q²: from 125 to 5000 GeV²
√s = 318 GeV
(× 350)
H1 k_T Q²: from 150 to 5000 GeV²
ZEUS k_T Q²: from 125 to 5000 GeV²
√s = 546 GeV
CDF cone 0.1 < |η| < 0.7
(× 150)
pp-bar
√s = 630 GeV
DØ cone 0.0 < |η| < 0.5
(× 50)
√s = 1.8 TeV
CDF cone 0.1 < |η| < 0.7
DØ cone 0.0 < |η| < 0.5
(× 20)
√s = 1.96 TeV
CDF k_T 0.1 < |y| < 0.7
CDF cone 0.1 < |y| < 0.7
DØ cone 0.0 < |y| < 0.4
(× 7)
pp
√s = 2.76 TeV
ATLAS anti-k_T R=0.6 |y| < 0.3
ATLAS anti-k_T R=0.4 |y| < 0.3
(× 3)
√s = 7 TeV
ATLAS anti-k_T R=0.6 |y| < 0.3
ATLAS anti-k_T R=0.4 |y| < 0.3
CMS anti-k_T R=0.7 |y| < 0.5
CMS anti-k_T R=0.5 |y| < 0.5
(× 1)
all pQCD calculations using NLOJET++ with fastNLO:
α_s(M_Z)=0.118 | MSTW2008 PDFs | μ_R = μ_F = p_T jet
NLO plus non-perturbative corrections | pp, pp̄: incl. threshold corrections (2-loop)
The latest version of this figure can be obtained from http://projects.hepforge.org/fastnlo
p_t (GeV/c)

PDG2014

Parton picture of the nucleon



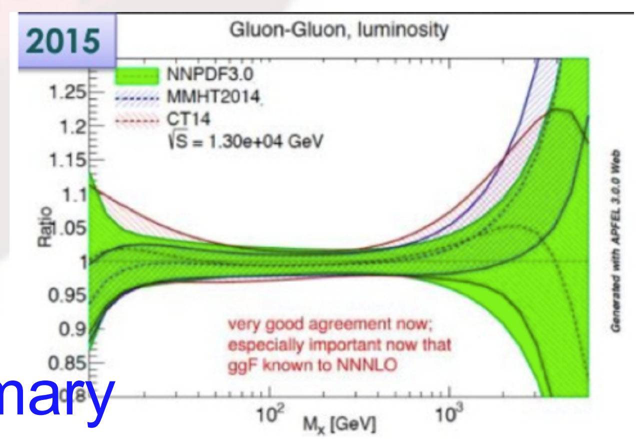
C.-P.Yuan@DIS15

- Beside valence quarks, there are sea and gluons
- Precisions on the PDFs are very much relevant for LHC physics: SM/New Physics

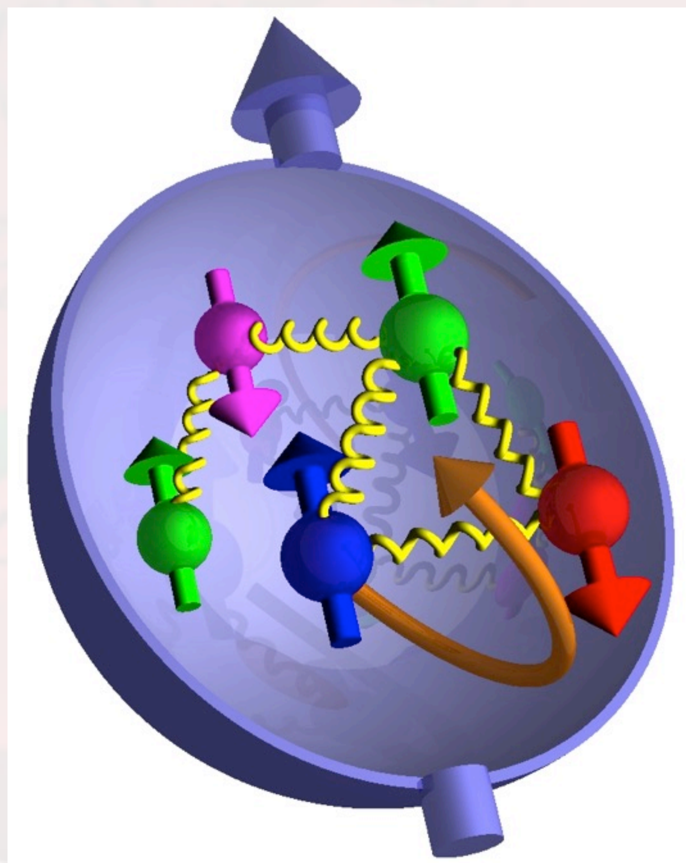
$$\sigma(gg \to H), \sqrt{(s)} = 13\text{TeV}$$

CT14	MMHT2014	NNPDF3.0
42.68 pb	42.70 pb	42.97 pb
+2.0% -2.4%	+1.3% -1.8%	+1.9% -1.9%

DIS summary



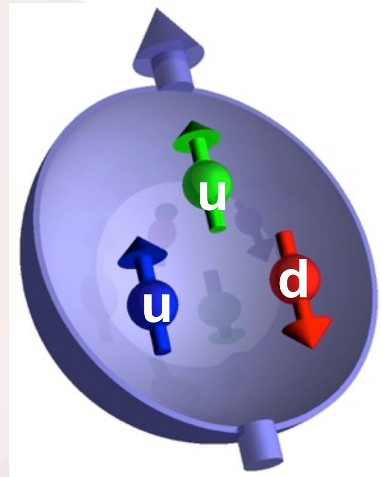
Parton distribution when nucleon is polarized?



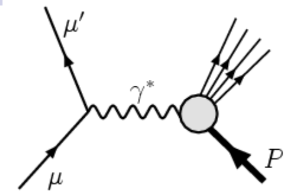
Proton Spin

- The story of the proton spin began with the quark model in 60’s
- In the simple Quark Model, the nucleon is made of three quarks (nothing else)
- Because all the quarks are in the s-orbital, its spin (½) should be carried by the three quarks
- European Muon Collaboration: 1988

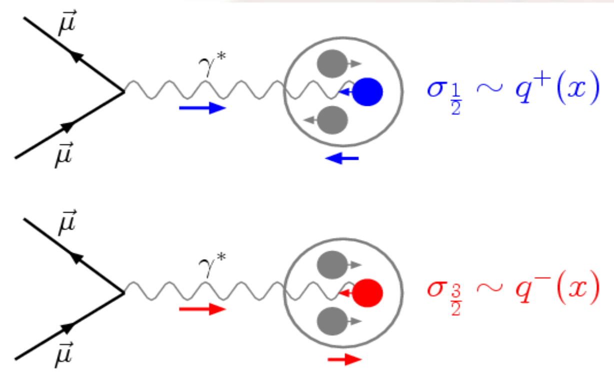
  “Spin Crisis”--- proton spin carried by quark spin is rather small

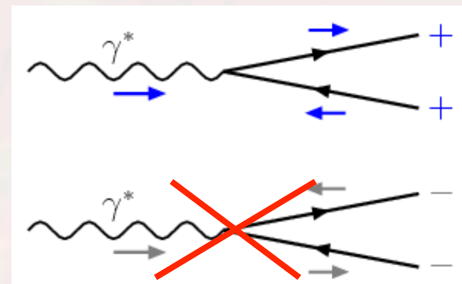


EMC experiment at CERN



- Polarized muon + p deep inelastic scattering,

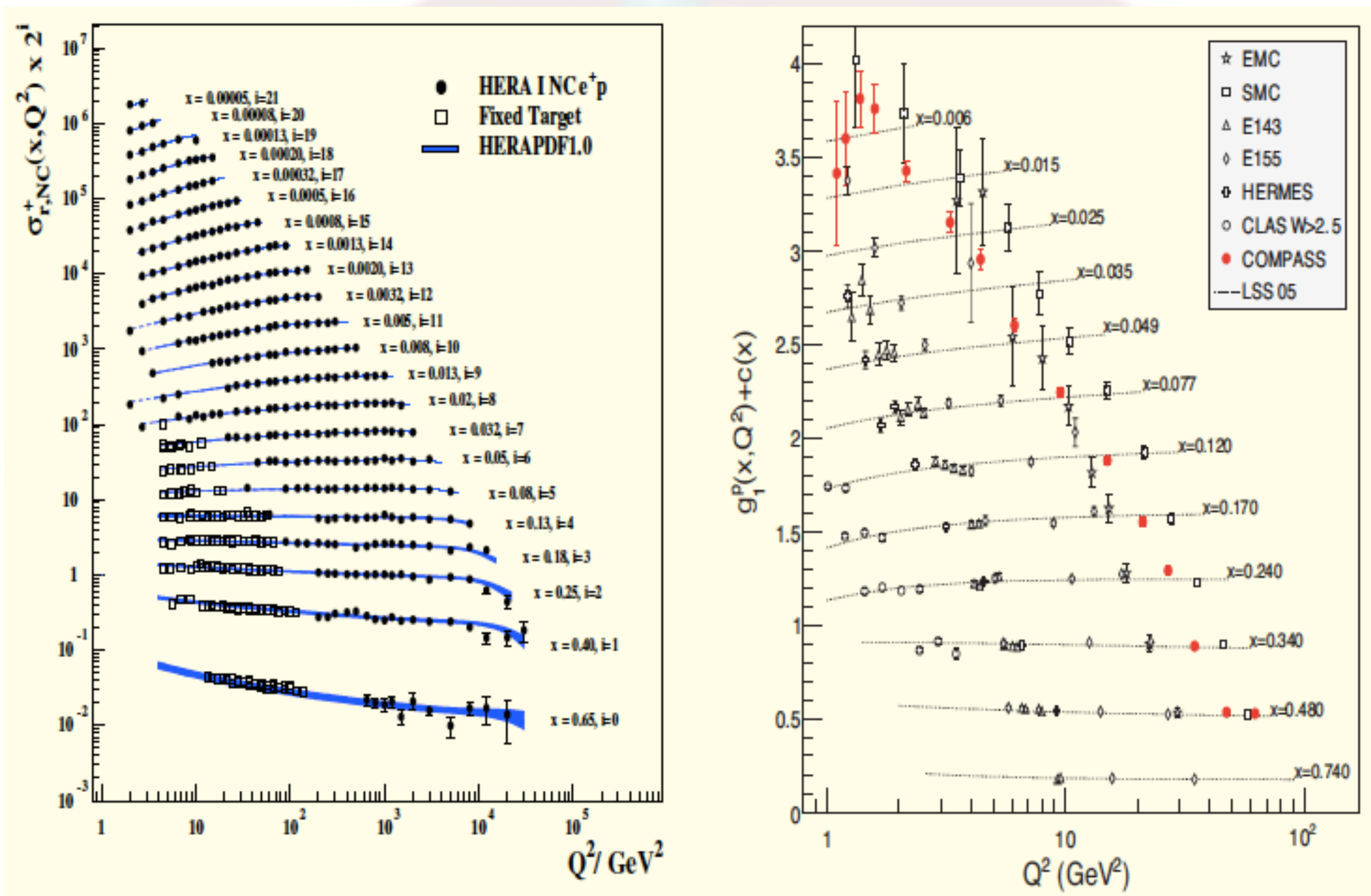




  - Virtual photon can only couple to quarks with opposite spin, because of angular momentum conservation
  - Select $q^+(x)$ or $q^-(x)$ by changing the spin direction of the nucleon or the incident lepton
  - The polarized structure function measures the quark spin density

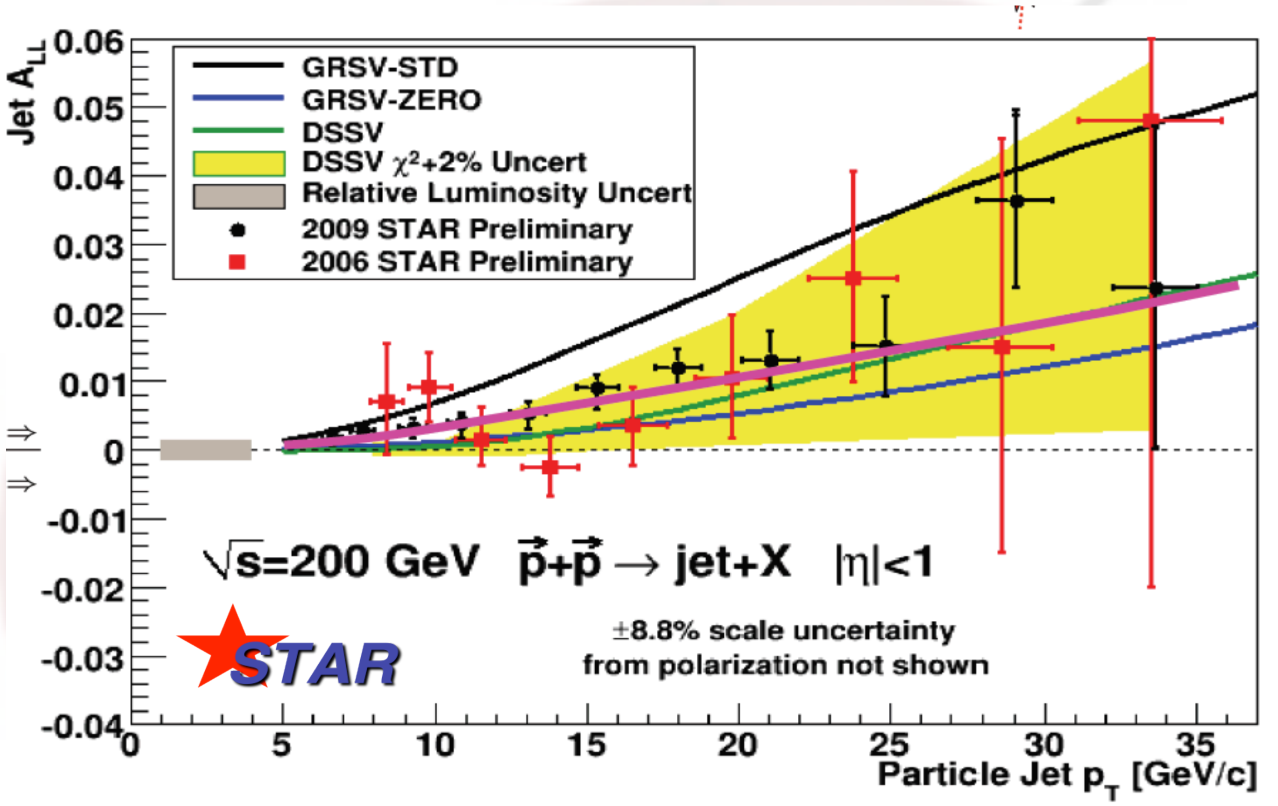
$$g_1(x) \sim \left(\sigma_{\frac{1}{2}} - \sigma_{\frac{3}{2}}\right) \propto \sum_q e_q^2 \left(\underbrace{q^+(x) - q^-(x)}_{\Delta q(x)}\right)$$

Summary of the polarized DIS data



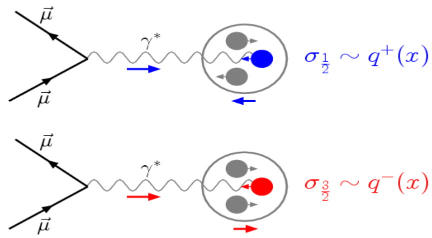
$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$

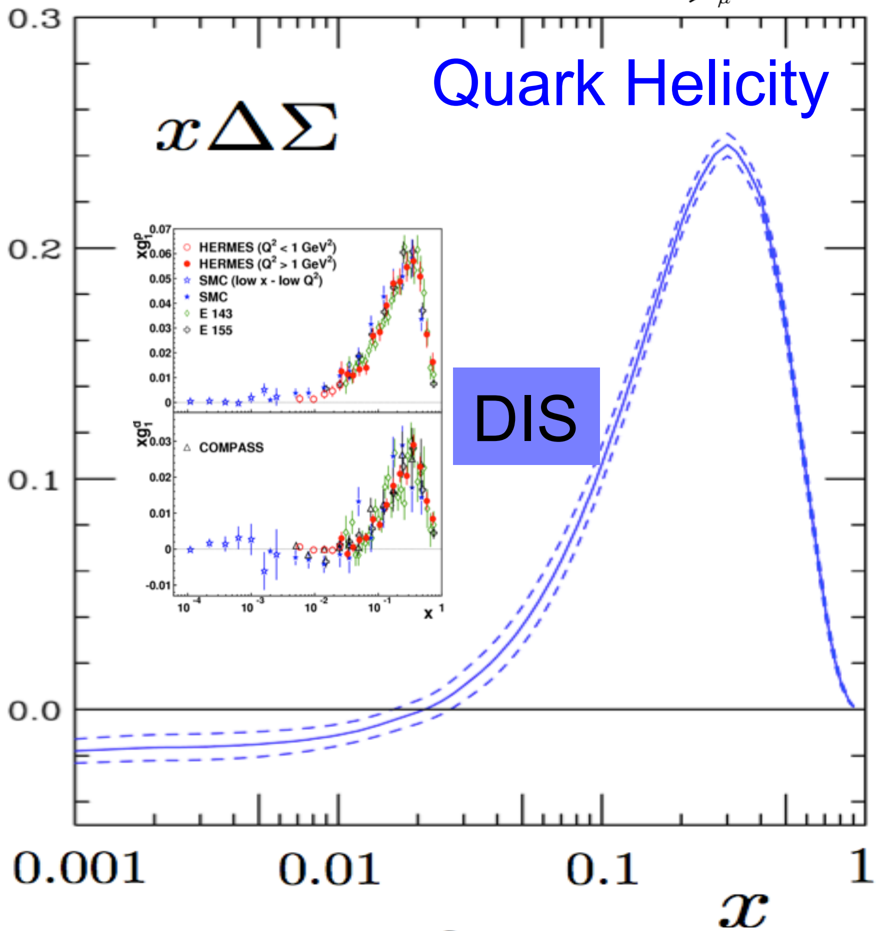
$$\approx \ 0.25$$



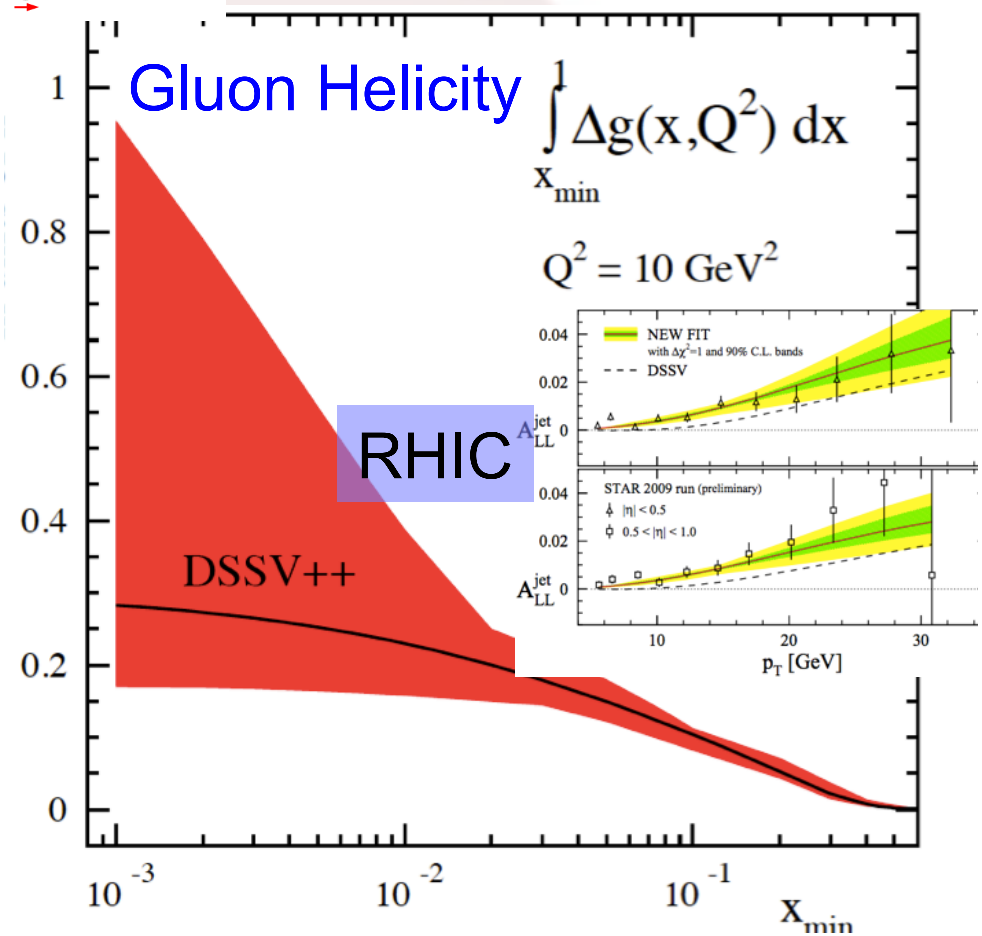
$$\int_{0.05}^{0.2} dx\Delta g \sim 0.1$$

Parton distributions in a polarized nucleon





$Q^2 = 5\,\mathrm{GeV}^2$



de Florian-Sassot-Stratmann-Vogelsang, 2014

Proton spin: $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$ emerging phenomena?

- We know fairly well how much quark helicity contributions, ΔΣ=0.3±0.05
- With large errors we know gluon helicity contribution plays an important role
- No direct information on quark and gluon orbital angular momentum contributions

The orbital motion:

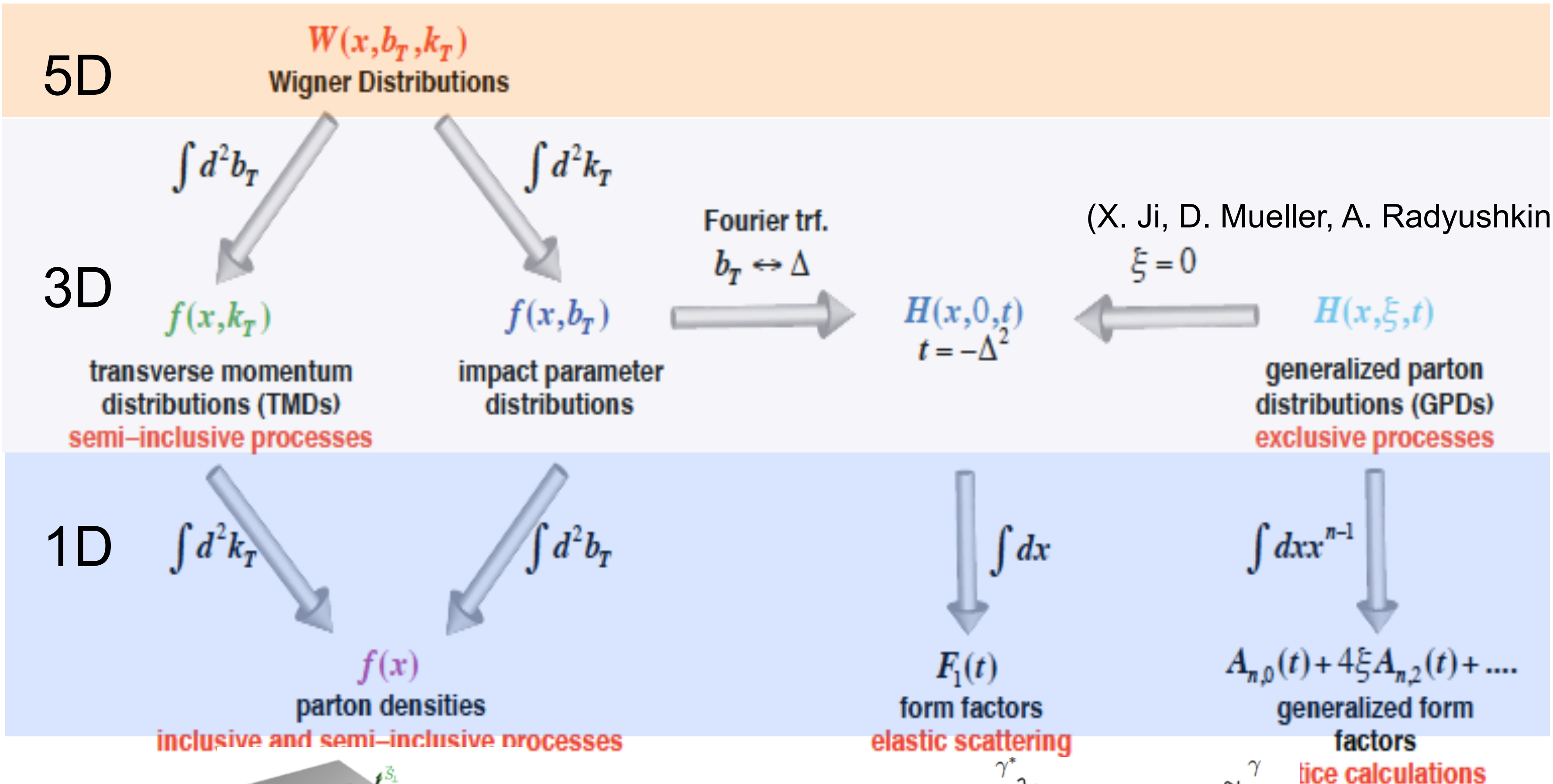
- Orbital motion of quarks and gluons must be significant inside the nucleons!
  - This is in contrast to the naive non-relativistic quark model
- Orbital motion shall generate direct orbital Angular Momentum which must contribute to the spin of the proton
- Orbital motion can also give rise to a range of interesting physical effects (Single Spin Asymmetries)

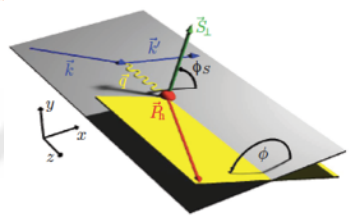
New ways to look at partons

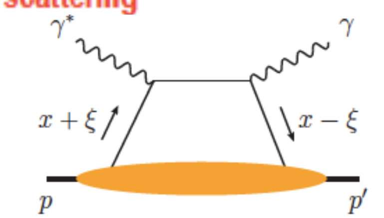
- We not only need to know that partons have long. momentum, but must have transverse degrees of freedom as well
- Partons in transverse coordinate space
  - Generalized parton distributions (GPDs)
- Partons in transverse momentum space
  - Transverse-momentum distributions (TMDs)
- Both? Wigner distributions!

Unified view of the Nucleon

- **Wigner distributions (Belitsky, Ji, Yuan)**



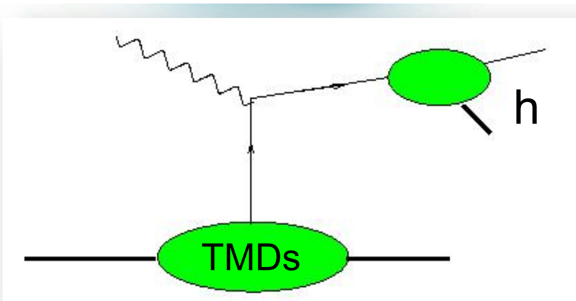


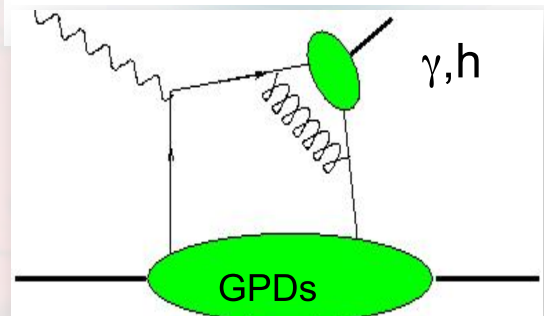


Zoo of TMDs & GPDs

	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	$h_1, h_{1T}^{\perp}$

	U	L	T
U	H		$\mathcal{E}_T$
L		$\widetilde{H}$	
T	E		$H_T, \widetilde{H}_T$



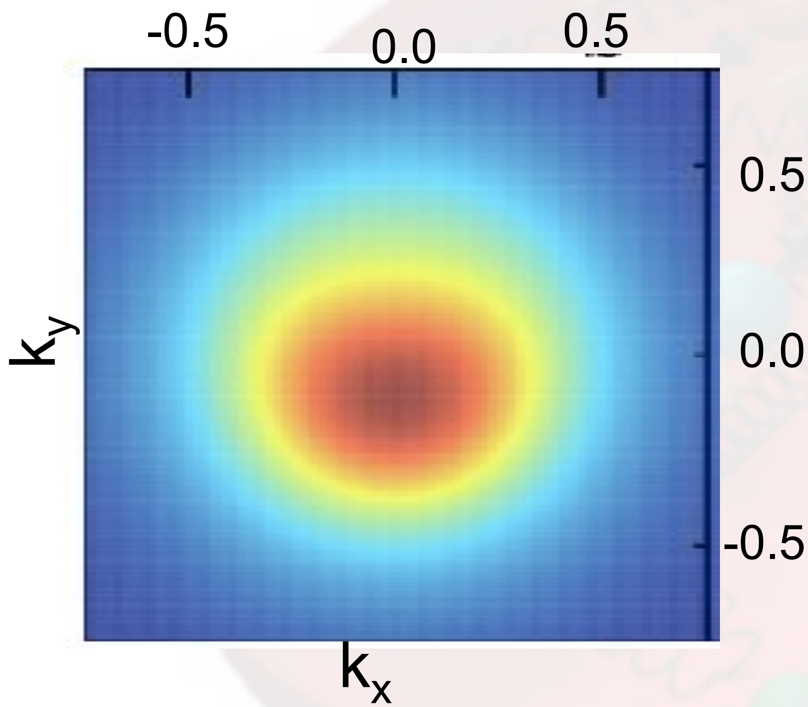


- NOT directly accessible
- Their extractions require measurements of x-sections and asymmetries in **a large kinematic domain of x_B, t, Q^2** (GPD) and **x_B, P_T, Q^2, z** (TMD)

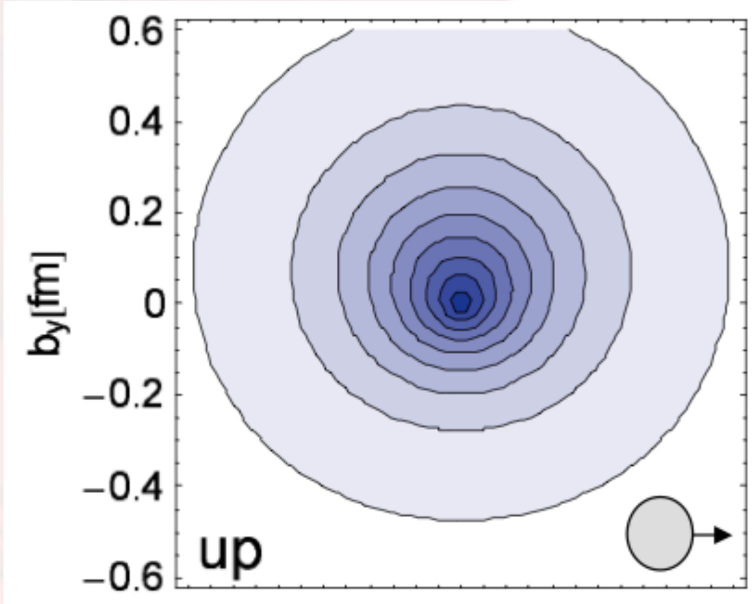
What can we learn

- 3D Imaging of partons inside the nucleon (non-trivial correlations)
  - Try to answer more detailed questions as Rutherford was doing 100 years ago
- QCD dynamics involved in these processes
  - Transverse momentum distributions: universality, factorization, evolutions,…
  - Small-x: BFKL vs Sudakov?

Deformation when nucleon is transversely polarized



Quark Sivers function fit to the SIDIS Data, Anselmino, et al. 2009



Lattice Calculation of the transvese density Of Up quark, QCDSF/UKQCD Coll., 2006

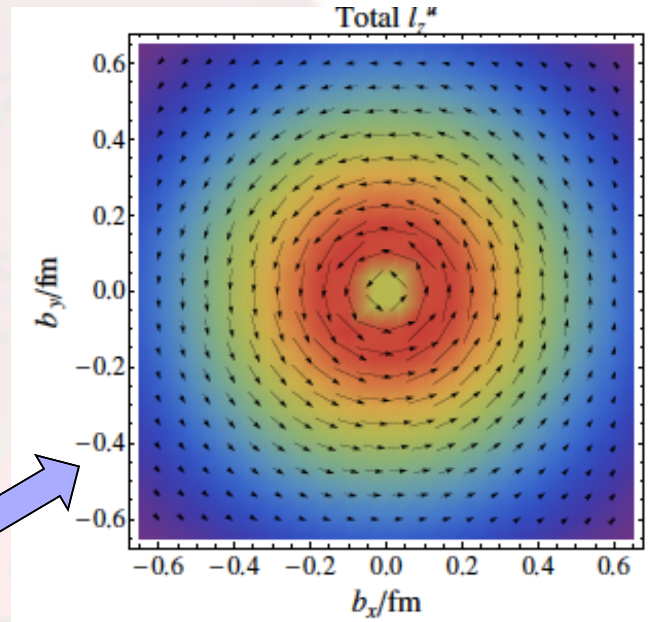
Parton's orbital motion through the Wigner Distributions

Phase space distribution:

Projection onto p (x) to get the momentum (probability) density

Quark orbital angular momentum

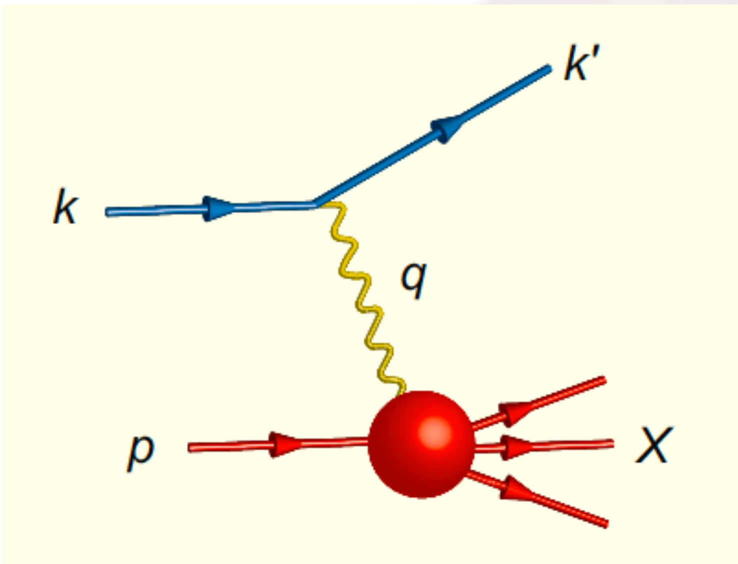
$$L(x) = \int (\vec{b}_\perp \times \vec{k}_\perp) W(x, \vec{b}_\perp, \vec{k}_\perp) d^2\vec{b}_\perp d^2\vec{k}_\perp$$



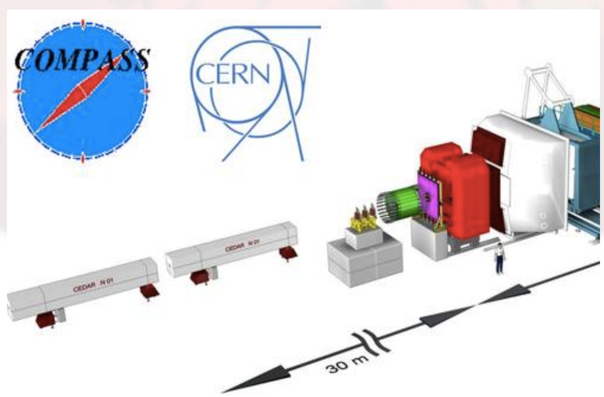
Well defined in QCD:

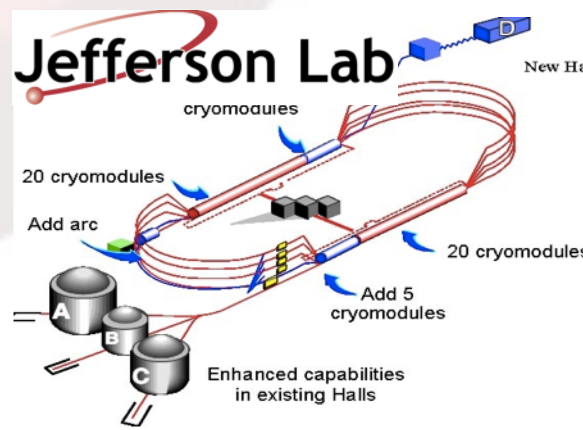
Ji, Xiong, Yuan, PRL, 2012; PRD, 2013
Lorce, Pasquini, Xiong, Yuan, PRD, 2012
Lorce-Pasquini 2011
Hatta 2011

Where can we study: Deep Inelastic Scattering



- Inclusive DIS
  - Parton distributions
- Semi-inclusive DIS, measure additional hadron in final state
  - Kt-dependence
- Exclusive Processes, measure recoiled nucleon
  - Nucleon tomography





Back-up

What we have learned

- Unpolarized transverse momentum (coordinate space) distributions from, mainly, DIS, Drell-Yan, W/Z boson productions, (HERA exp.)
- Indications of polarized quark distributions from low energy DIS experiments (HERMES, COMPASS, JLab)

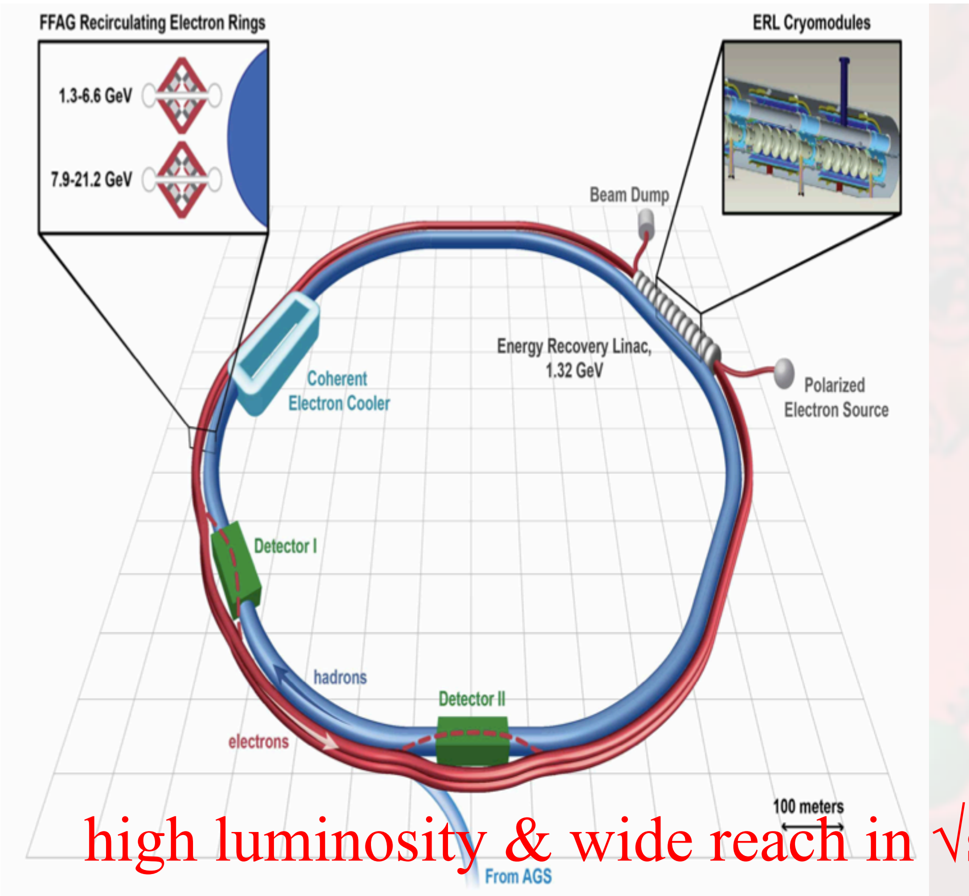
What we are missing

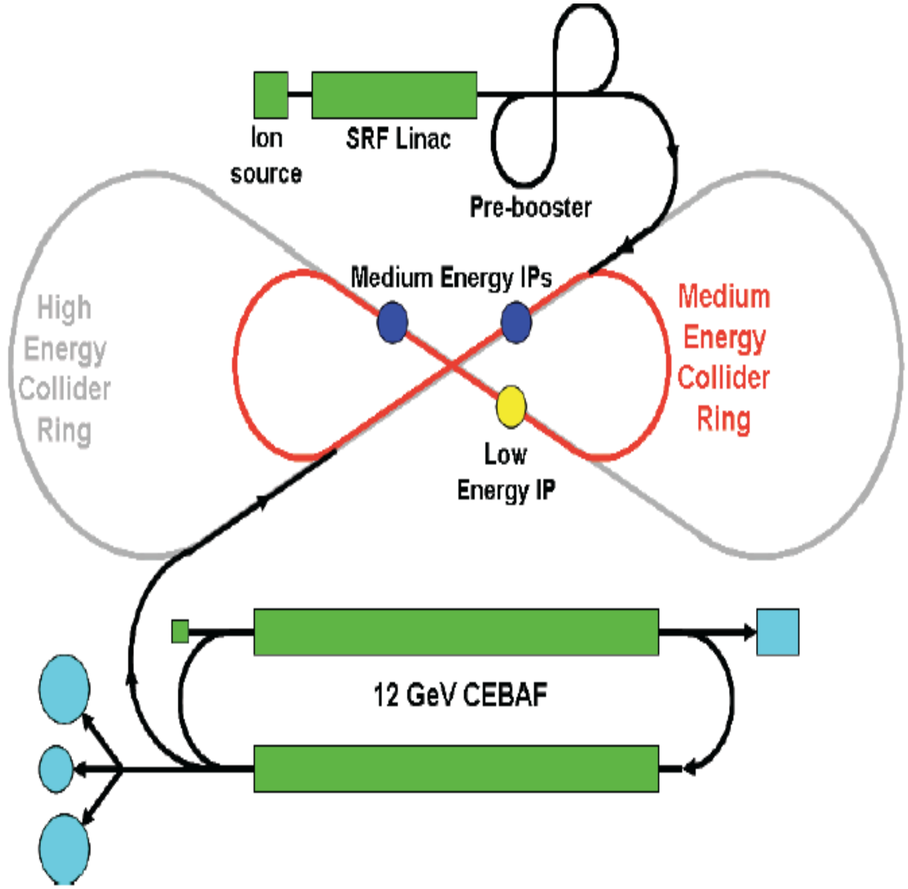
- Precise, detailed, mapping of polarized quark/gluon distribution
  - Universality/evolution more evident
- Spin correlation in momentum and coordinate space/tomography
  - Crucial for orbital motion
- Small-x: links to other hot fields (Color-Glass-Condensate)

Perspectives

- HERA (ep collider) is limited by the statistics, and is not polarized
- Existing fixed target experiments are limited by statistics and kinematics
- JLab 12 will provide un-precedent data with high luminosity
- Ultimate machine will be the Electron-Ion-Collider (EIC): kinematic coverage with high luminosity

We need a new machine: EIC Proposals in US





high luminosity & wide reach in √s

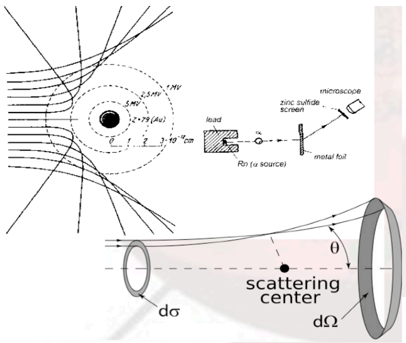
polarized lepton & hadron beams

nuclear beams

arXiv: 1108.1713, arXiv: 1212.1701

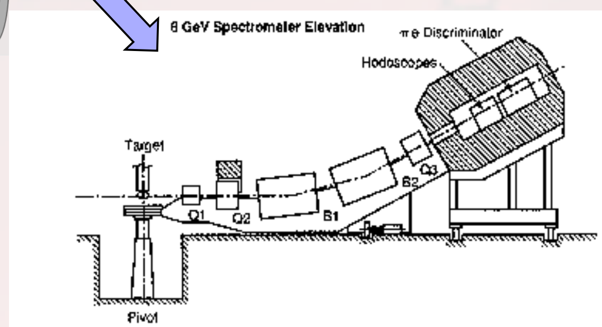
Recap of yesterday

Landscape of Atomic Matter



Rutherford Scattering, 1911

- Discovery of nucleus

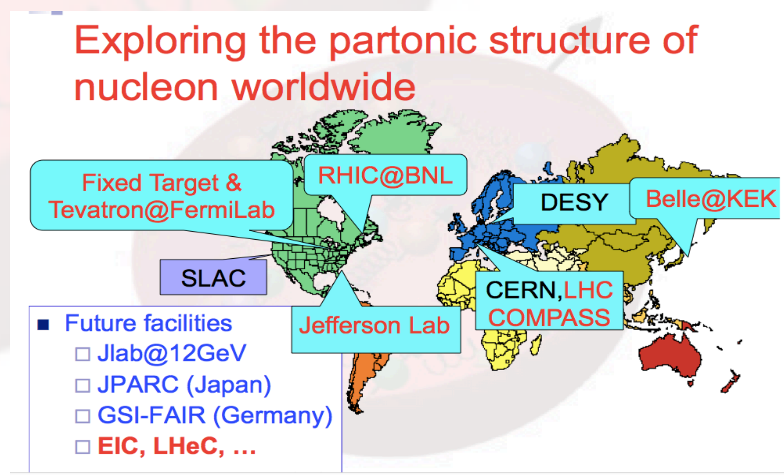


DIS at SLAC, 1960s

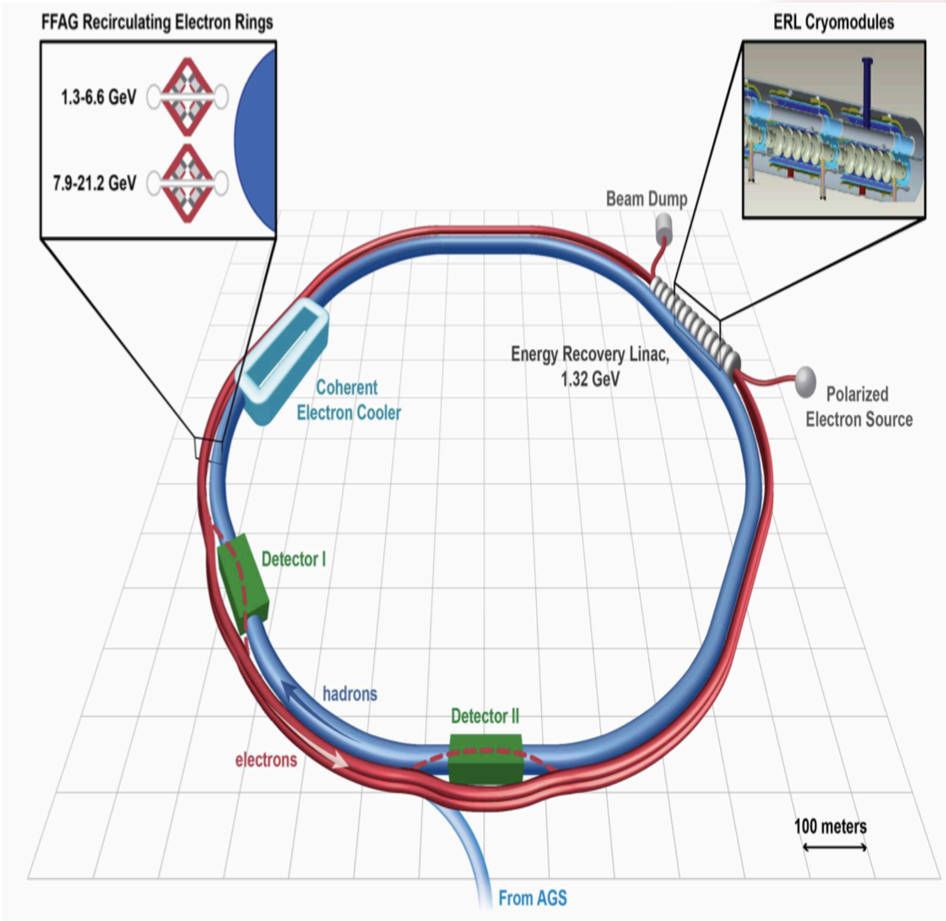
- Discovery of quarks

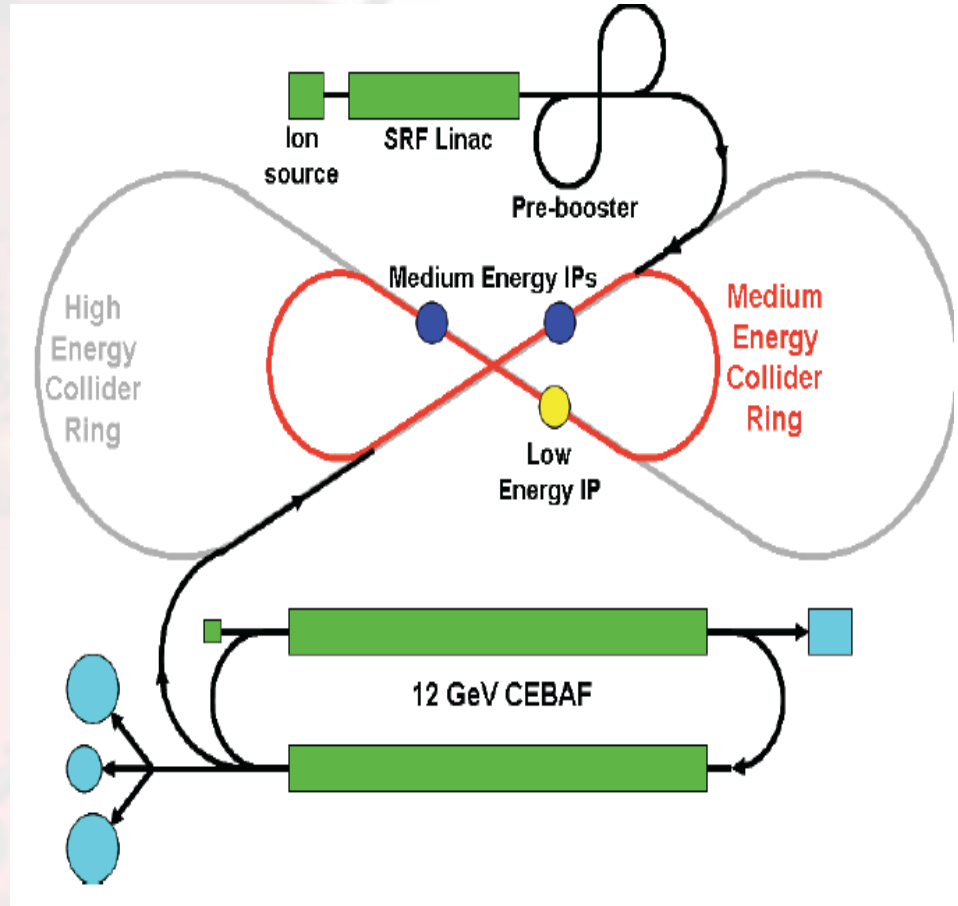
Quantum ChromoDynamics:

$$L = \bar{\psi}(i\gamma \cdot \partial - m_q)\psi - \frac{1}{4}F^{\mu\nu a}F_{\mu\nu a} - g_s\bar{\psi}\gamma \cdot A\psi$$



EIC Proposals in US



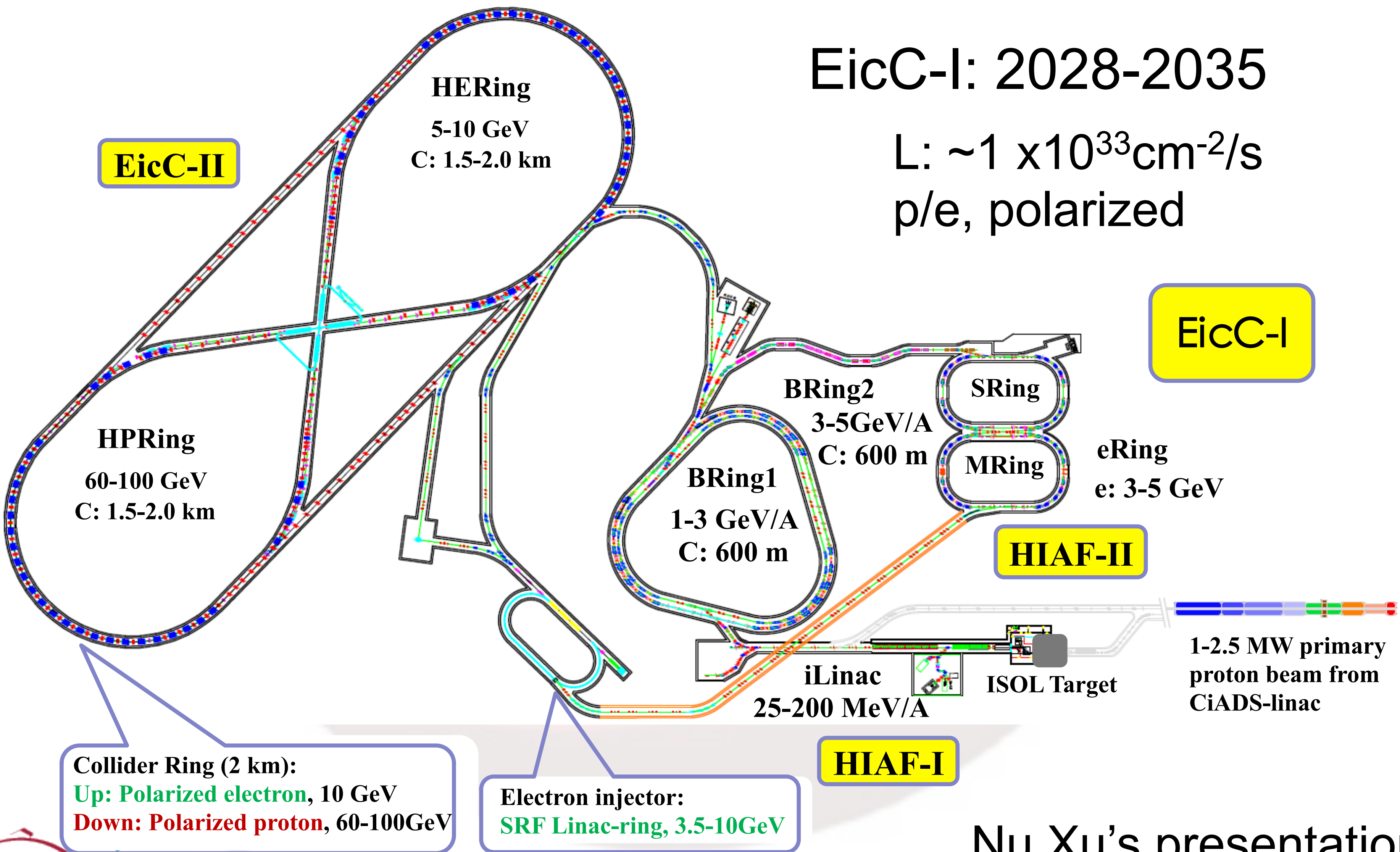


arXiv: 1108.1713, arXiv: 1212.1701

EicC Conceptual Design

EicC-I: 2028-2035

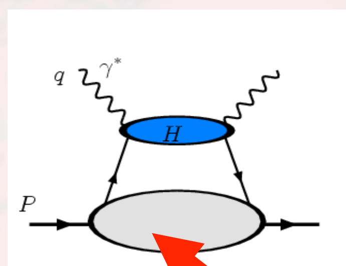
L: ~1 $x10^{33}cm^{-2}/s$
p/e, polarized

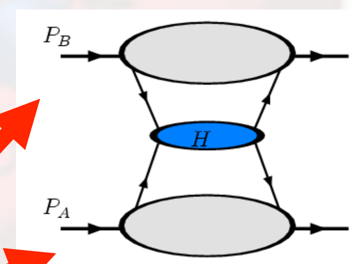


Nu Xu's presentation
at Hadron 2018

Feynman's parton language and QCD Factorization

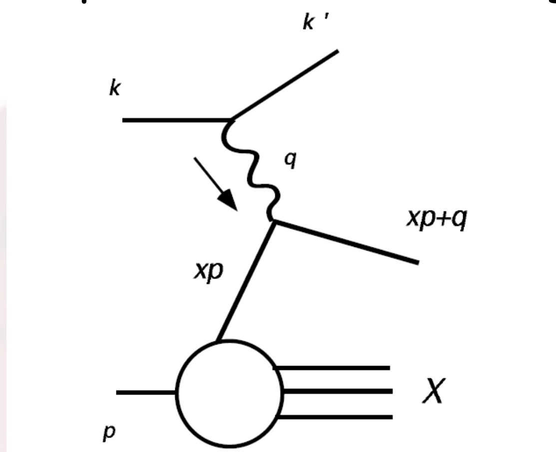
- In high-energy hadronic reactions, the scattering can be decomposed into a convolution of parton scattering and parton density (distribution), or wave function or correlations
  - QCD Factorization!



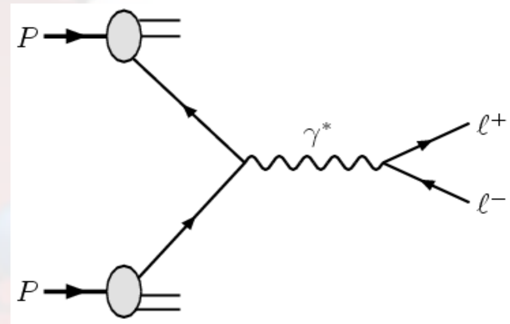


$$\sim \int \text{Parton Distributions} \otimes \text{Hard Partonic Cross Section}$$

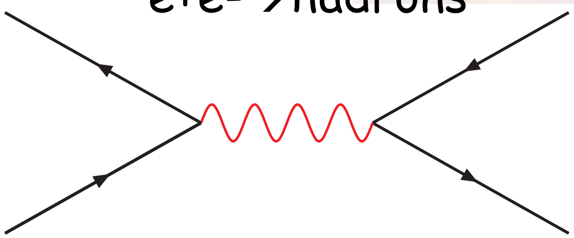
Deep Inelastic Scattering



Drell-Yan Process



e+e-→hadrons

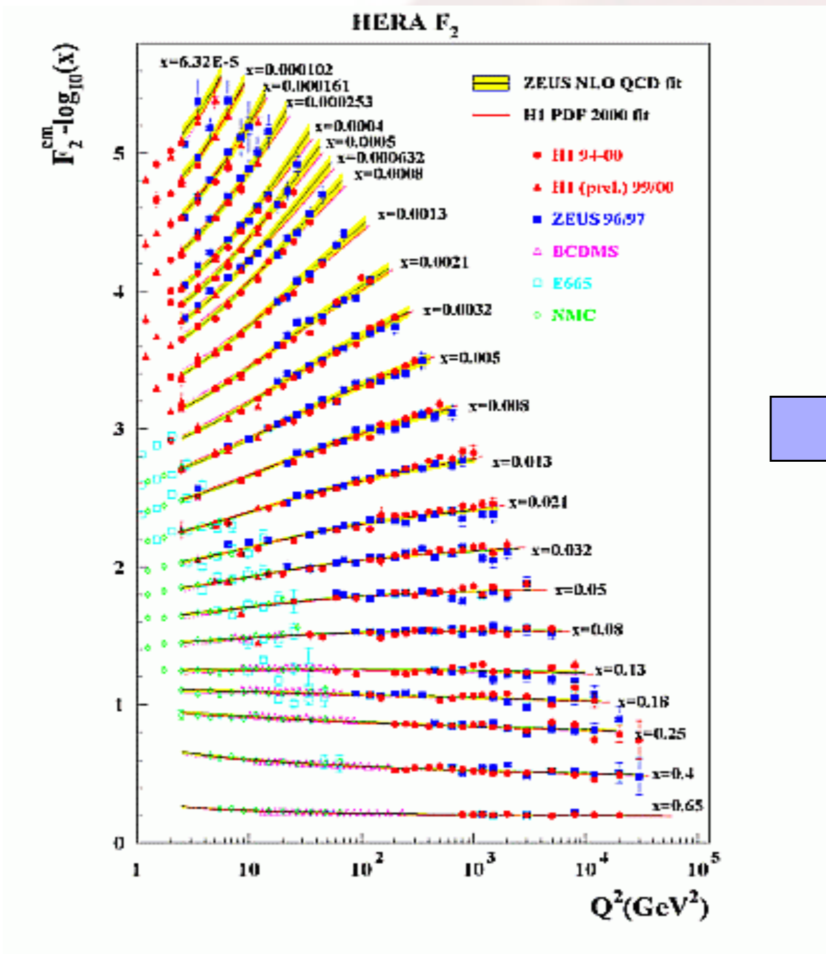


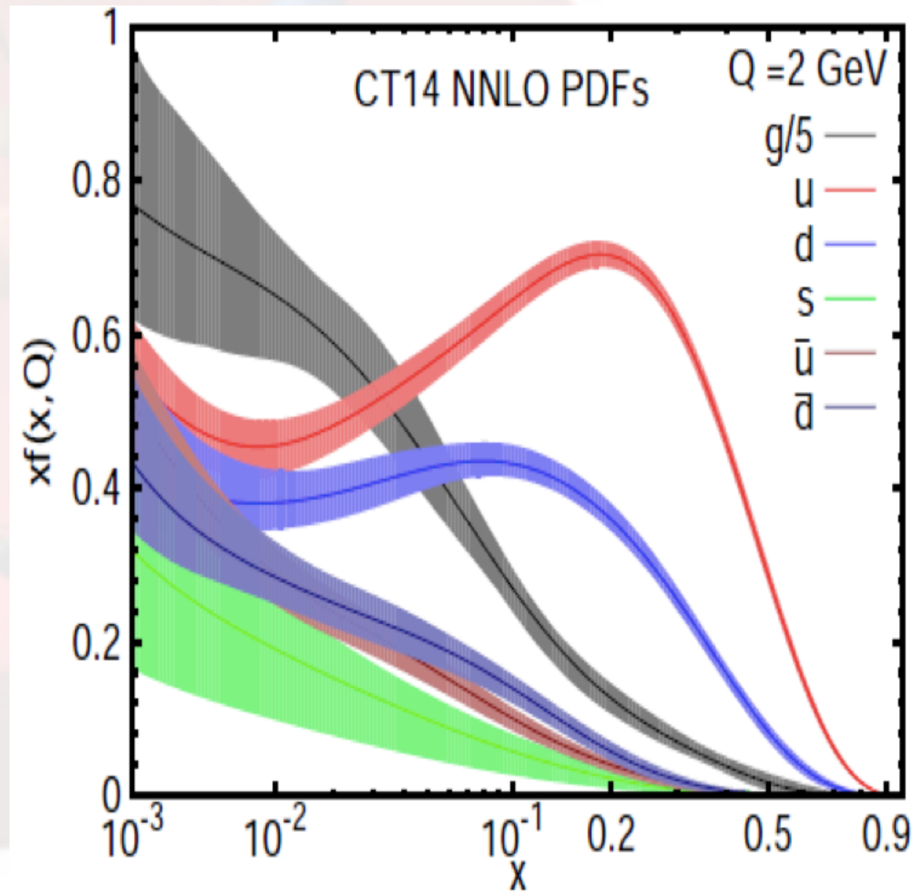
$$\sigma(e^+e^- \to q\bar{q}) = N_c \frac{4\pi}{3}\frac{\alpha^2}{Q^2} e_q^2$$

- Universal parton distributions between DIS and Drell-Yan Processes
- Partonic cross sections can be calculated perturbatively

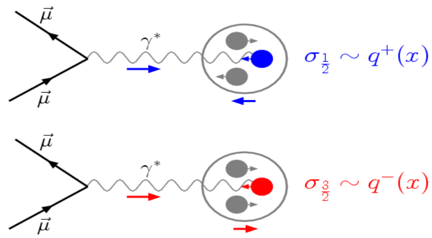
QCD dynamics

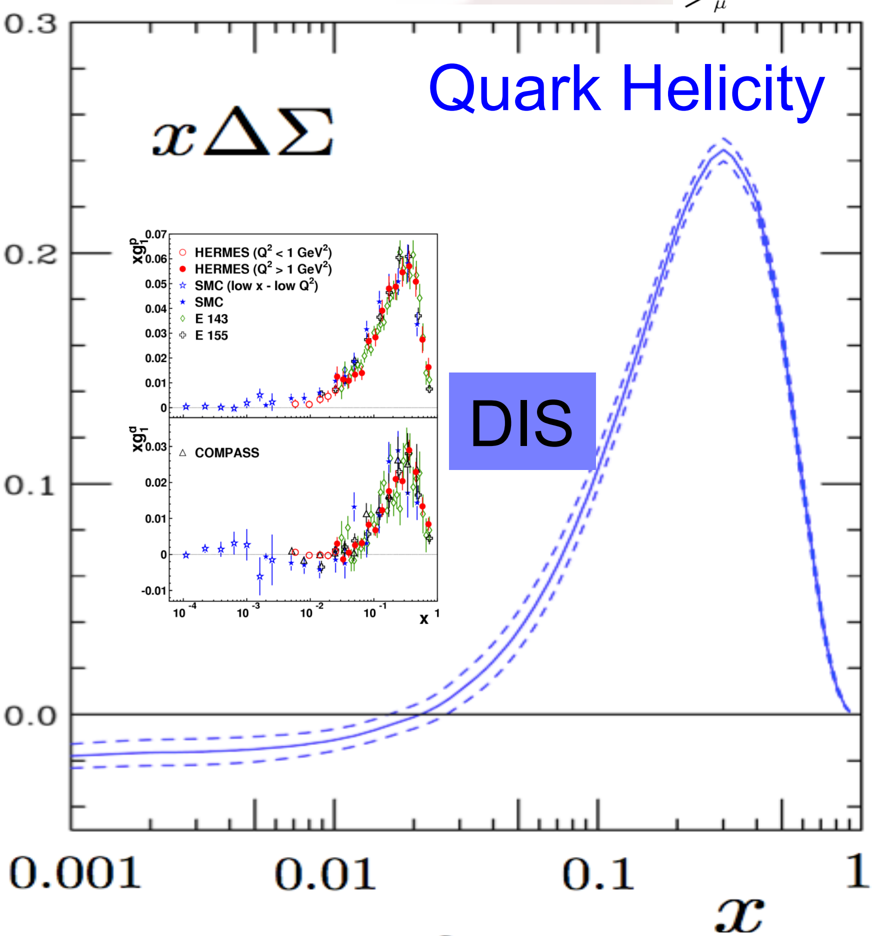
$$\mu \frac{d^2}{d\mu^2}\phi_{i/h}(x,\mu^2) = \sum_{j=f,\bar{f},G} \int_x^1 \frac{d\xi}{\xi} P_{ij}\left(\frac{x}{\xi},\alpha_s(\mu^2)\right)\phi_{j/h}(\xi,\mu^2)$$

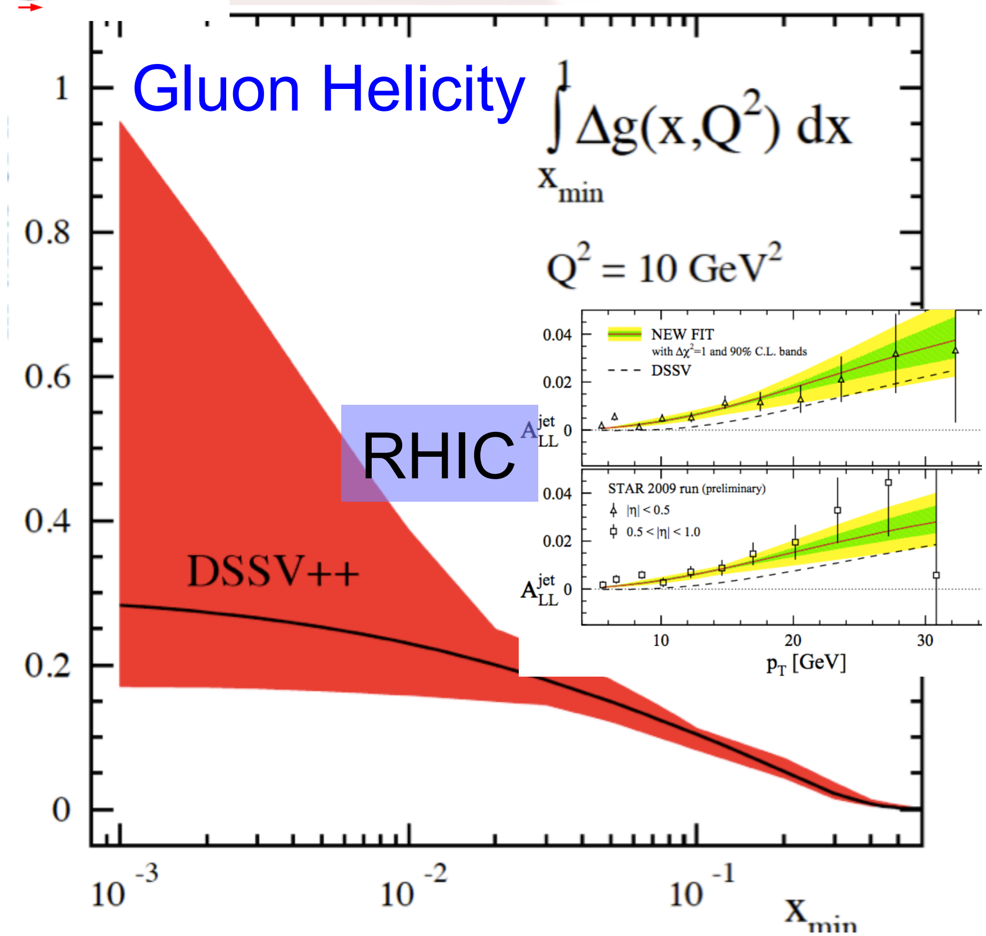




Parton distributions in a polarized nucleon







$Q^2 = 5\,\mathrm{GeV}^2$

de Florian-Sassot-Stratmann-Vogelsang, 2014

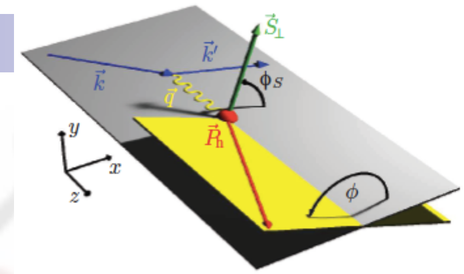
Proton spin: $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$ emerging phenomena?

- We know fairly well how much quark helicity contributions, ΔΣ=0.3±0.05
- With large errors we know gluon helicity contribution plays an important role
- No direct information on quark and gluon orbital angular momentum contributions

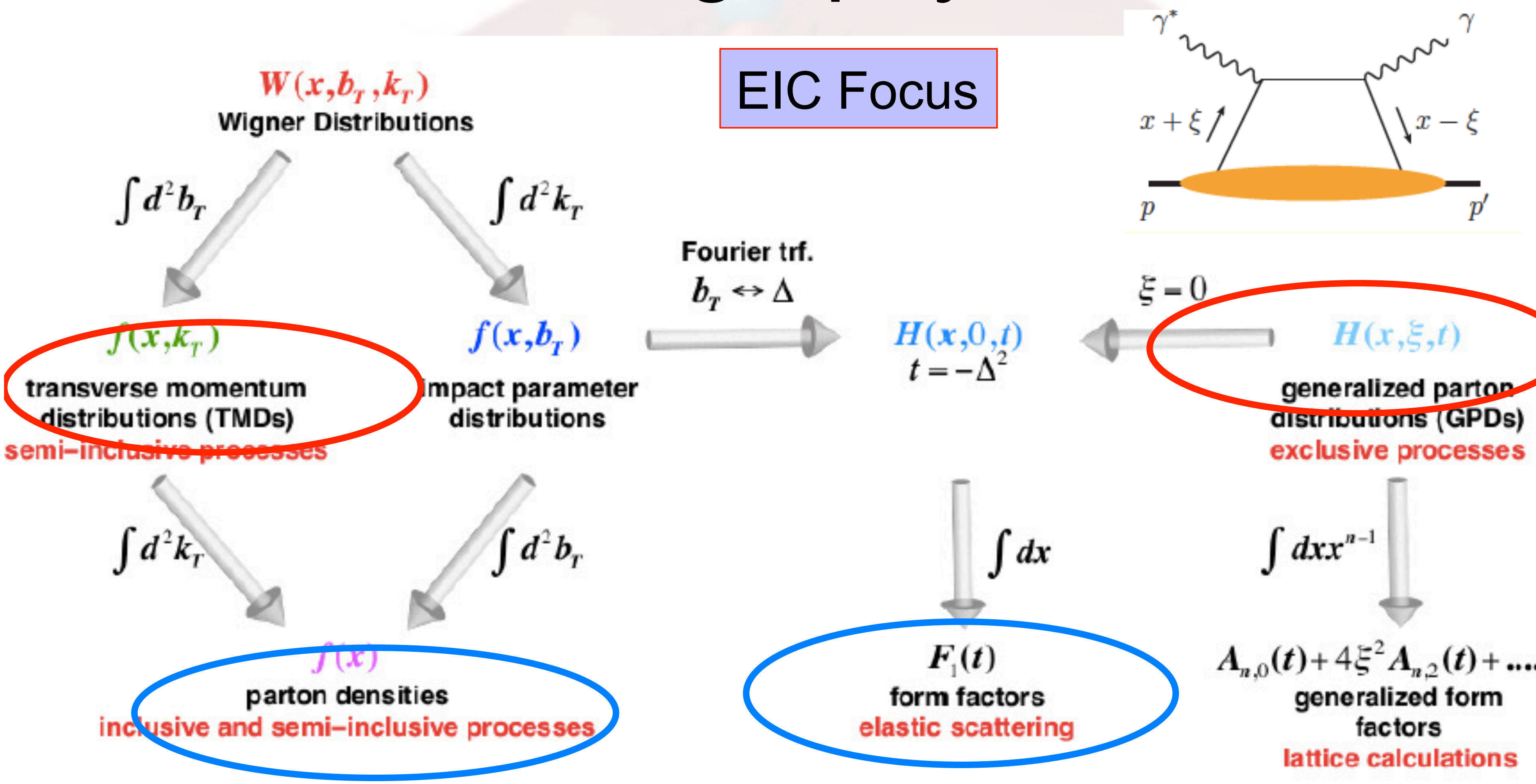
Extension to transverse direction…

- Semi-inclusive measurements (in DIS or Drell-Yan processes)
  - Transverse momentum distributions (TMD)
- Deeply Virtual Compton Scattering and Exclusive processes
  - Generalized parton distributions (GPD)

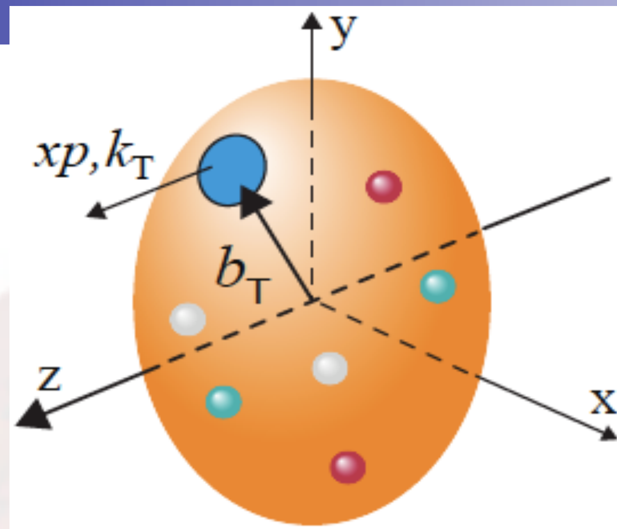
Nucleon tomography



EIC Focus

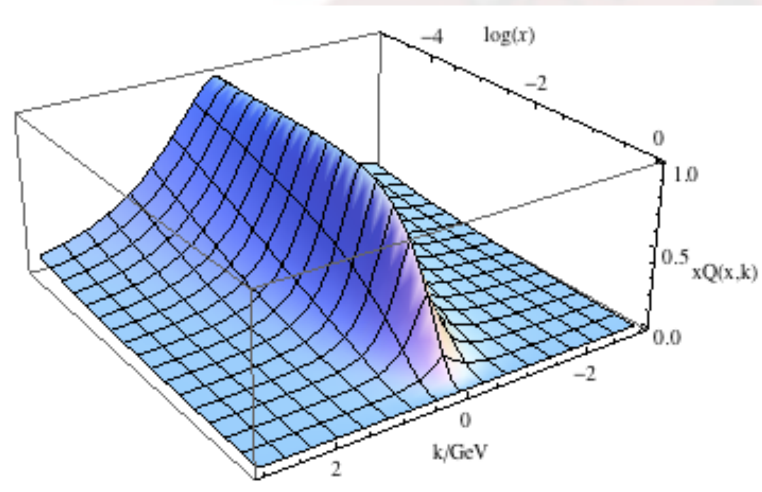


Current Lattice Simulations

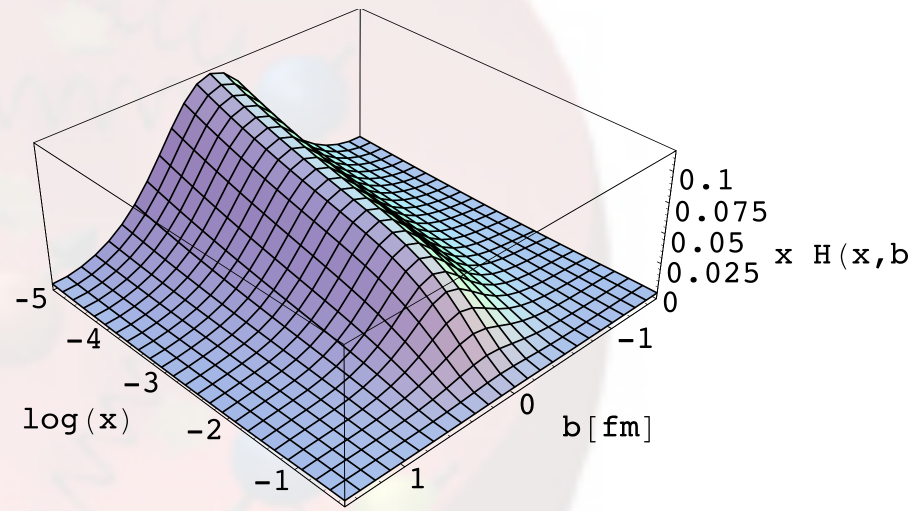


- 3D Imaging from the GPDs and TMDs measurements
  - Try to answer more detailed questions as Rutherford was doing 100 years ago
- QCD dynamics involved in these processes
  - In particular for the TMD part: universality, factorization, evolutions,…

Transverse profile for the quark distribution: k_t vs b_t



Quark distribution calculated from a saturation-inspired model
A.Mueller 99, McLerran-Venugopalan 99



GPD fit to the DVCS data from HERA, Kumerick-D.Mueller, 09,10

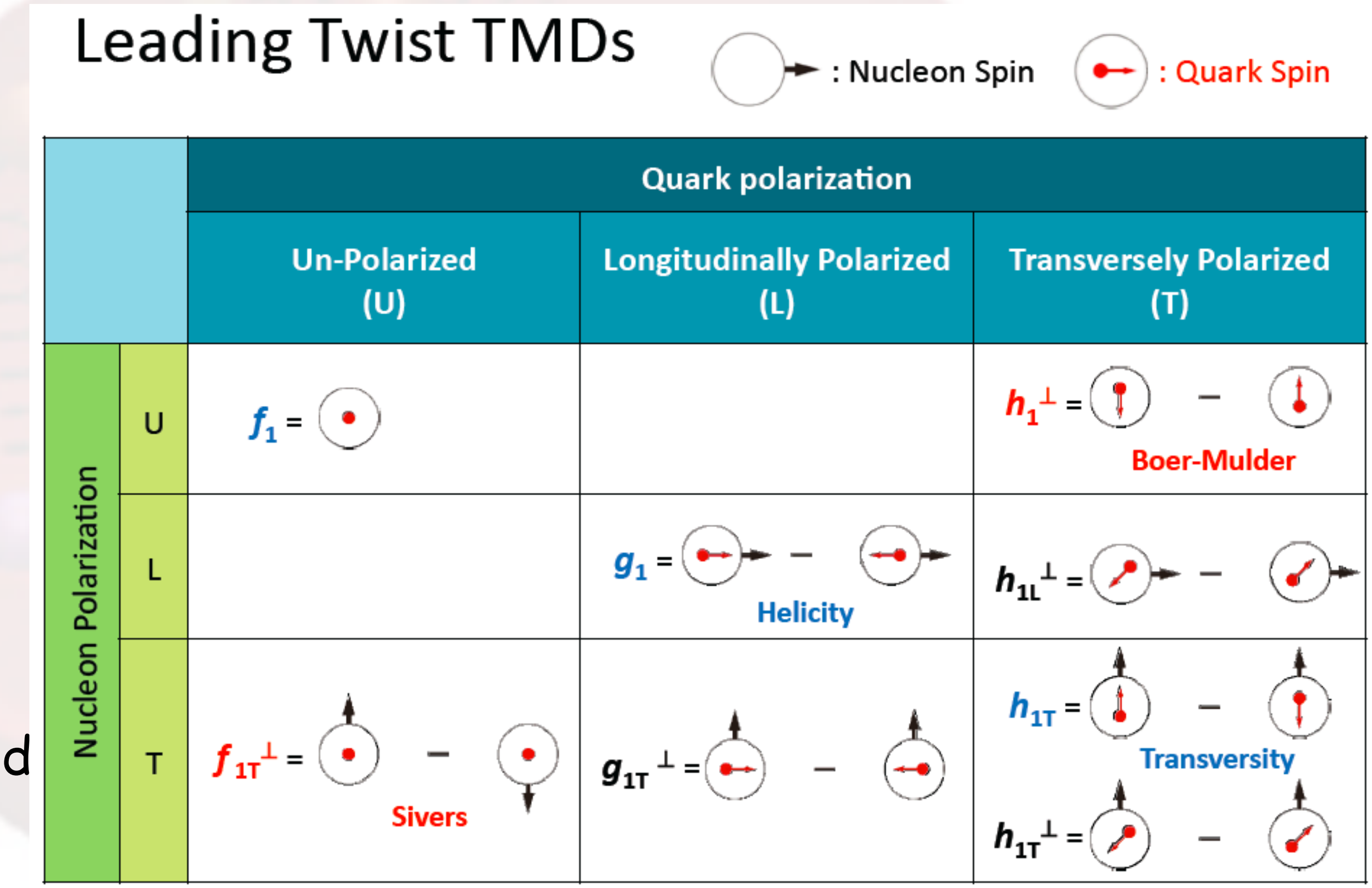
Transverse momentum distribution

Straightforward extension

- Spin average, helicity, and transversity distributions

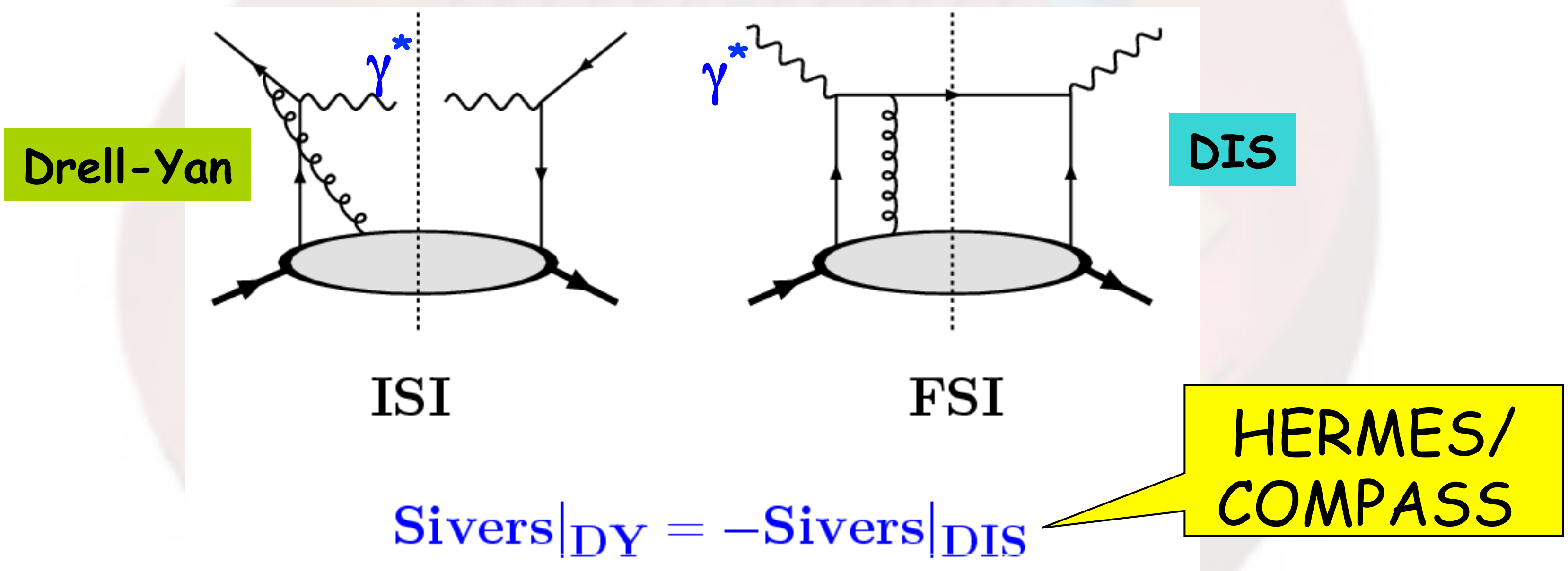
P_T-spin correlations

- Nontrivial distributions, $S_T X P_T$
- In quark model, depends on S- and P-wave interference



Sivers Asymmetries in DIS and Drell-Yan

- Initial state vs. final state interactions



- "Universality": QCD prediction

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- Indications of polarized quark distributions from low energy DIS experiments (HERMES, COMPASS, JLab)

What we are missing

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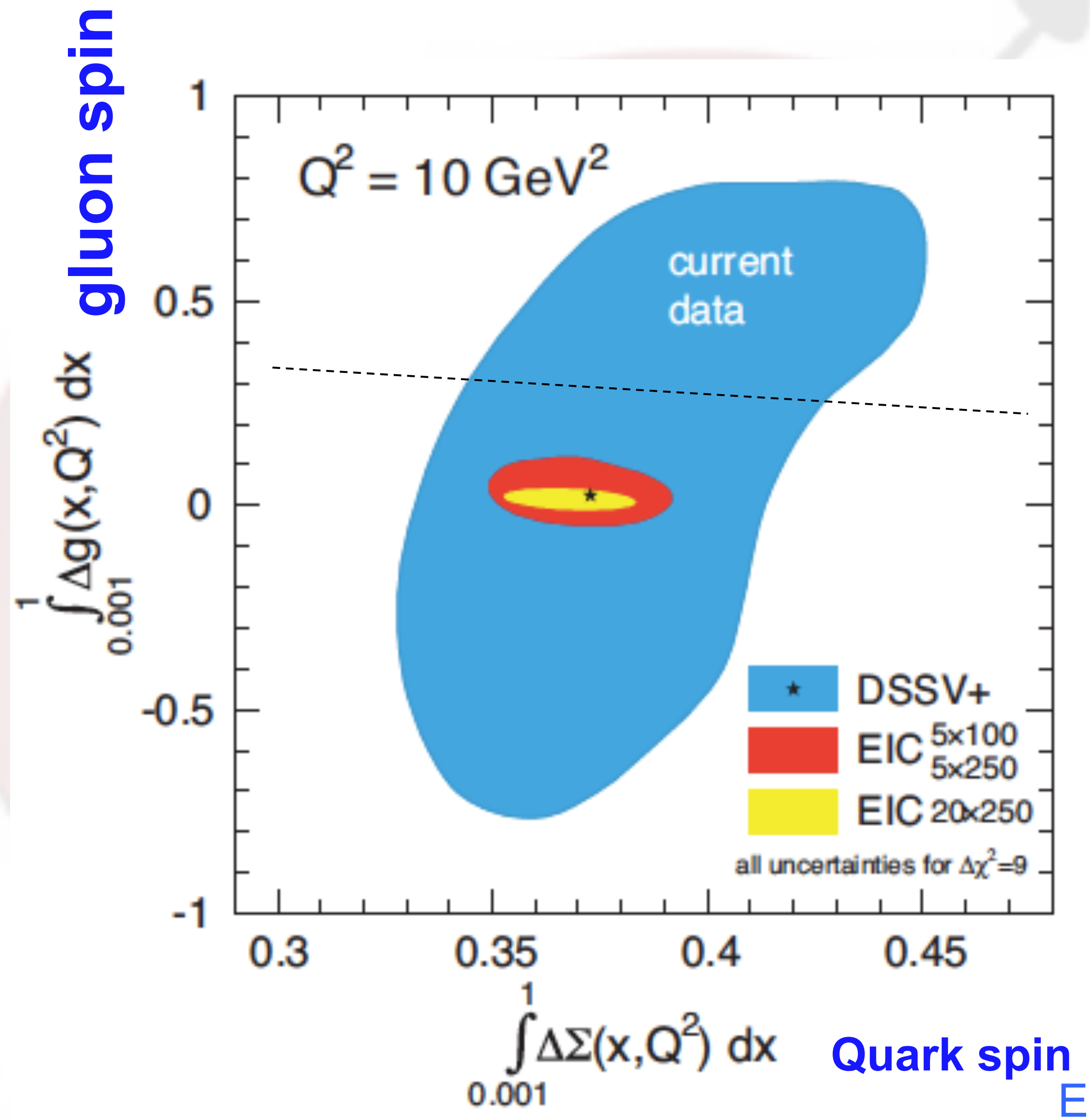
  - Universality/evolution more evident
- Spin correlation in momentum and coordinate space/tomography
  - Crucial for orbital motion
- Small-x: links to other hot fields (Color-Glass-Condensate)

EIC: Understanding the glue that bind us all

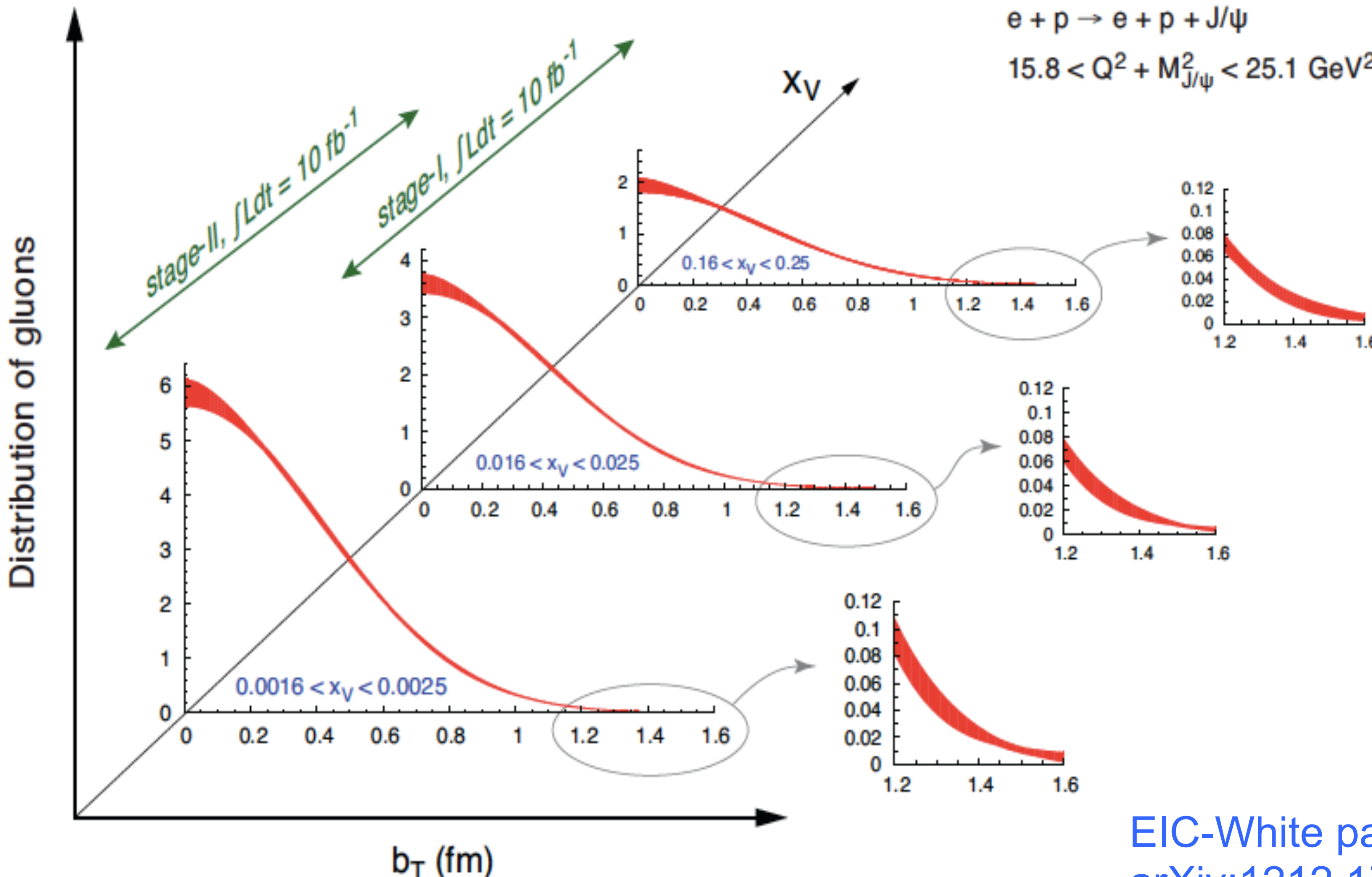
- Gluon plays an important role in the momentum of the nucleon
- Nucleon spin structure through helicity ΔG
- Gluon orbital motion
  - Nucleon tomography (orbital-spin correlations)
- Small x: gluon saturation (CGC)-> a saturated transverse-momentum distribution



Stratmann, et al.
EIC-White Paper

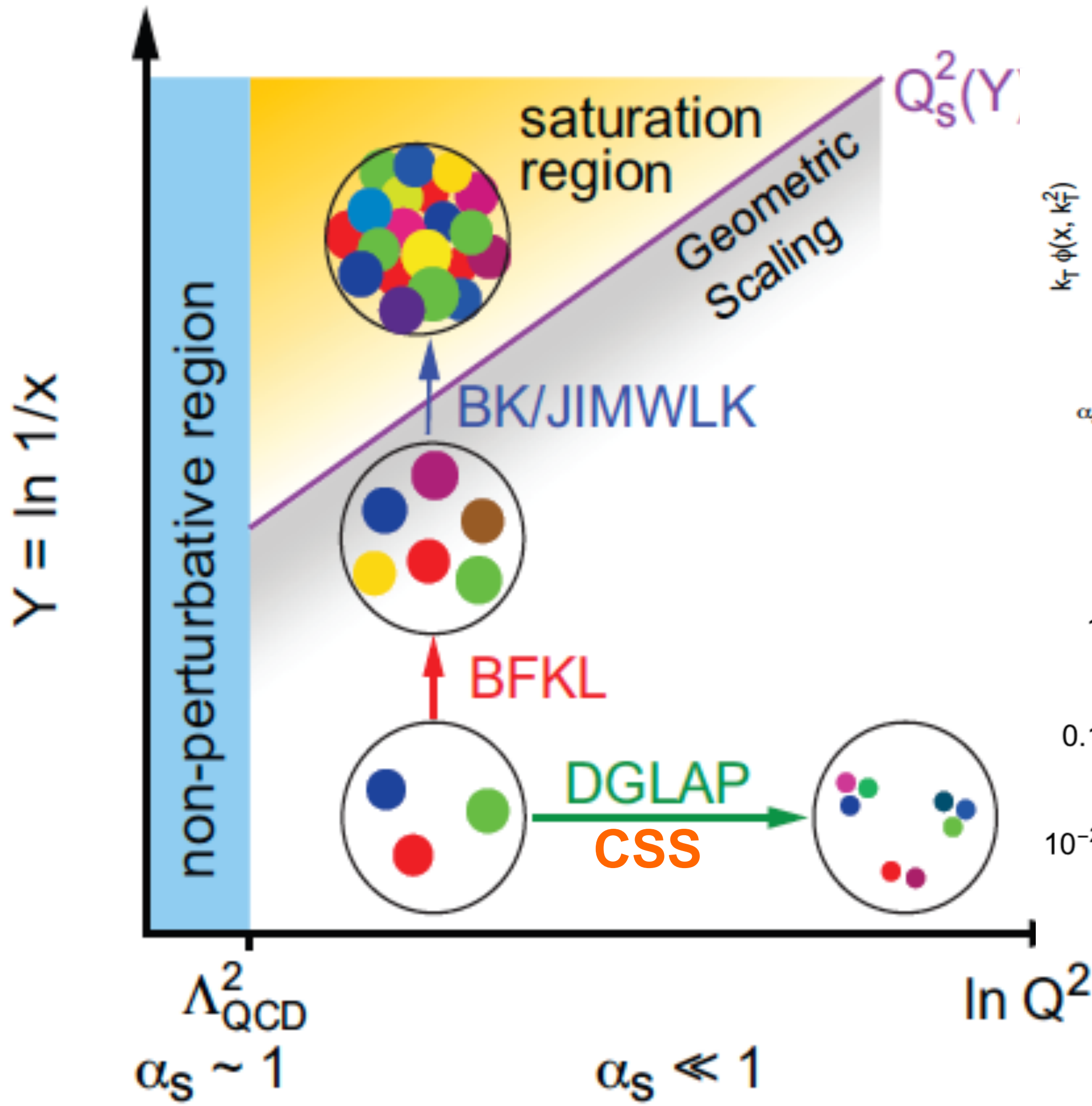
EIC-White paper
arXiv:1212.1701

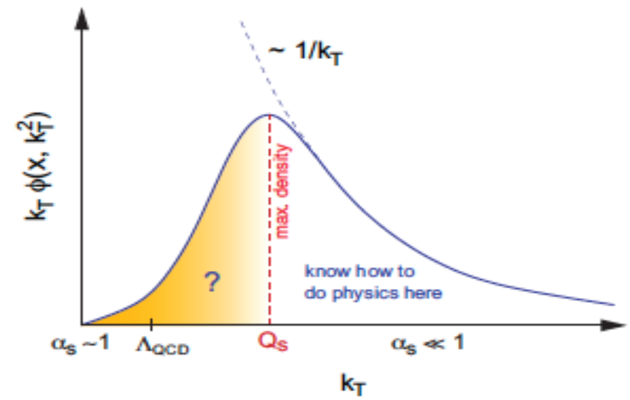
Gluon tomography at small x (GPDs)

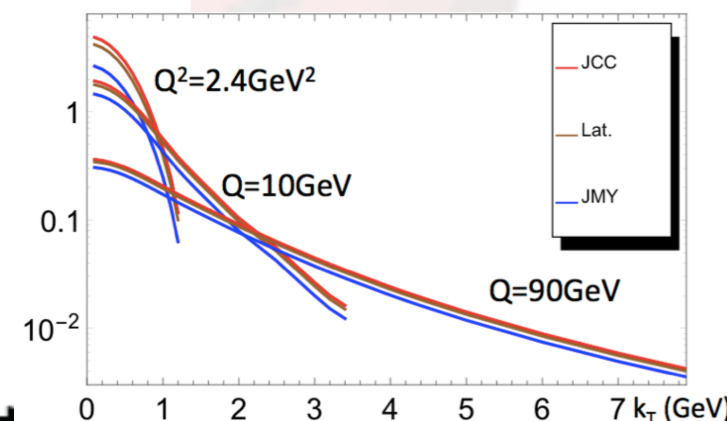


EIC-White paper
arXiv:1212.1701

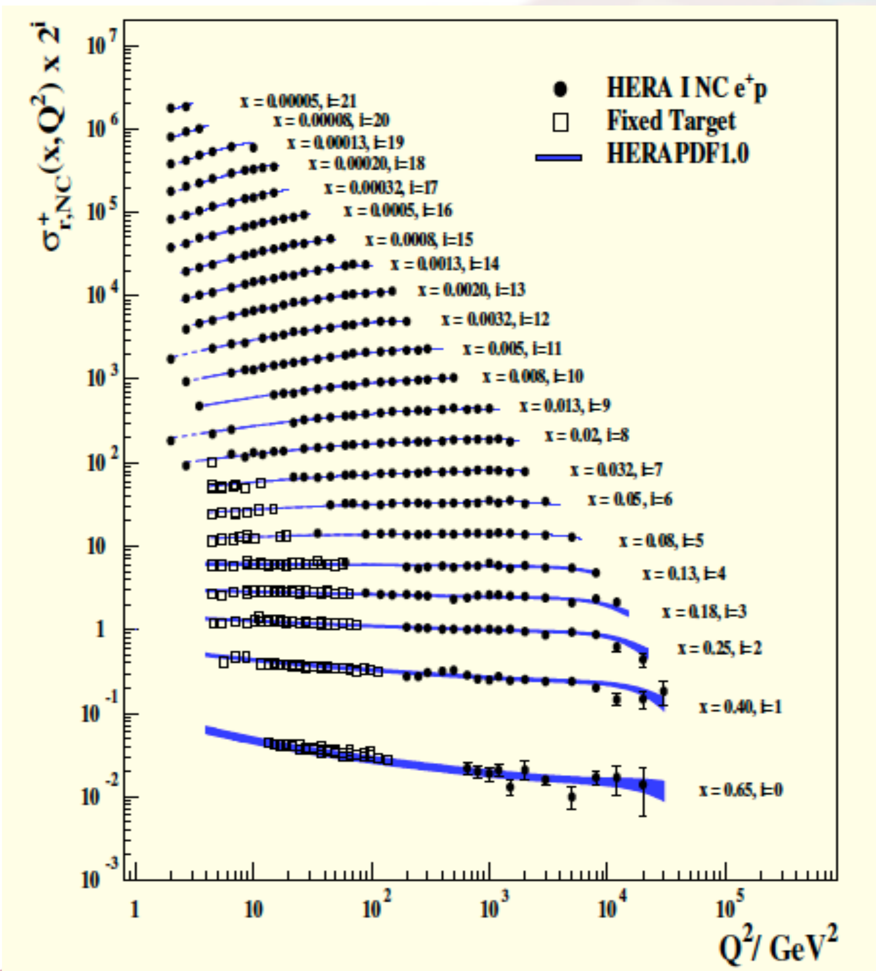
Transverse momentum distributions: A unified picture

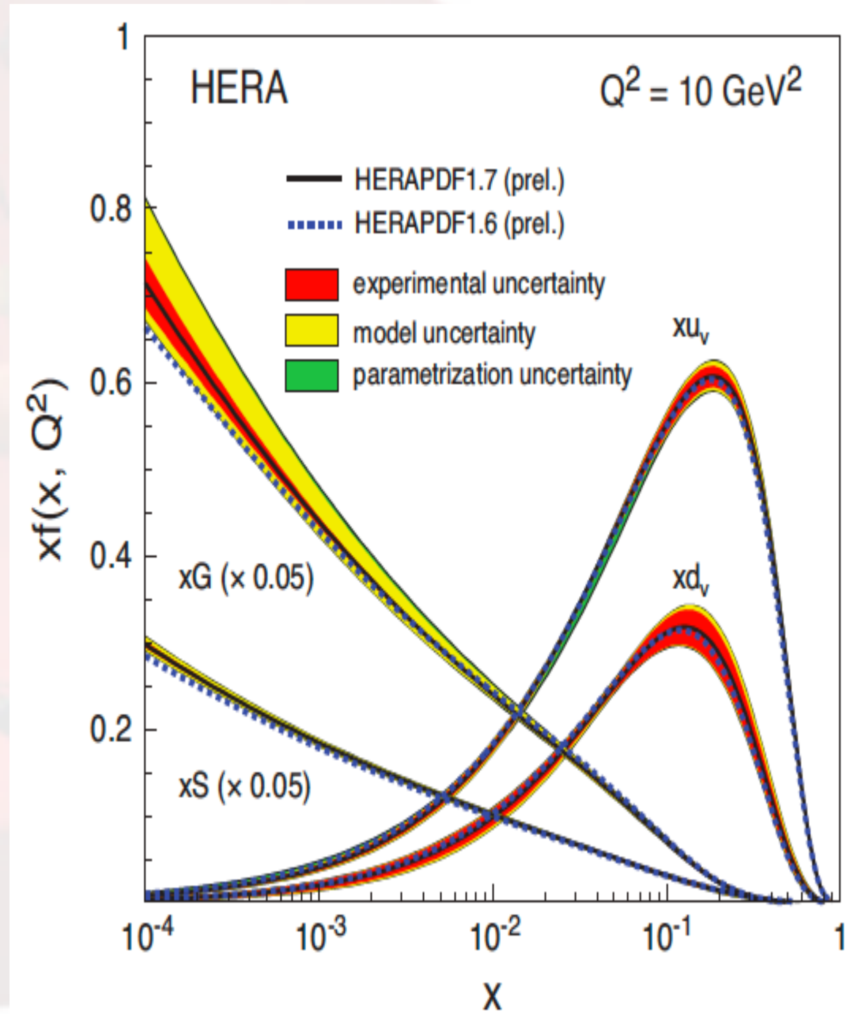






Gluon saturation inevitable at small-x





- QCD evolution drives the gluon distribution rising at small-x

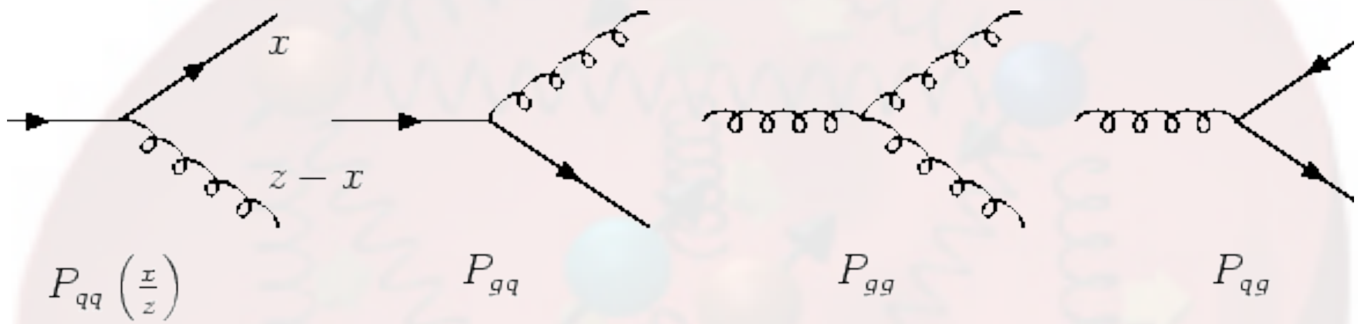


Figure 1.1: *The processes related to the lowest order QCD splitting functions. Each splitting function $P_{p'p}(x/z)$ gives the probability that a parton of type p converts into a parton of type p', carrying fraction x/z of the momentum of parton p*

$$\mu\frac{d}{d\mu}f_{j/h}(x,\mu) = \sum_k \int_x^1 \frac{dz}{z} P_{jk}(z,\alpha_s(\mu))\, f_{k/h}(x/z,\mu)$$

$$\mathcal{P}_{gg}(x) = \frac{x}{(1-x)_+} + \frac{1-x}{x} + x(1-x) + \delta(x-1)\beta_0$$

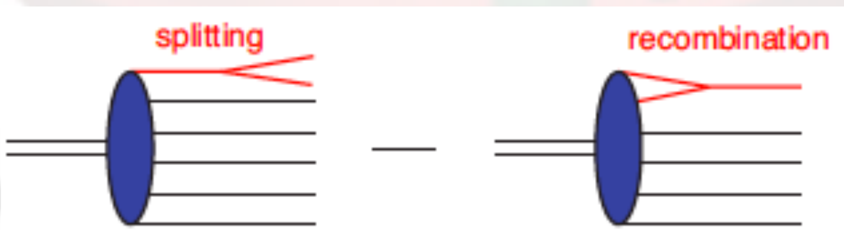
BFKL evolution becomes relevant at small-x

- Balitsky-Fadin-Lipatov-Kuraev, 1977-78

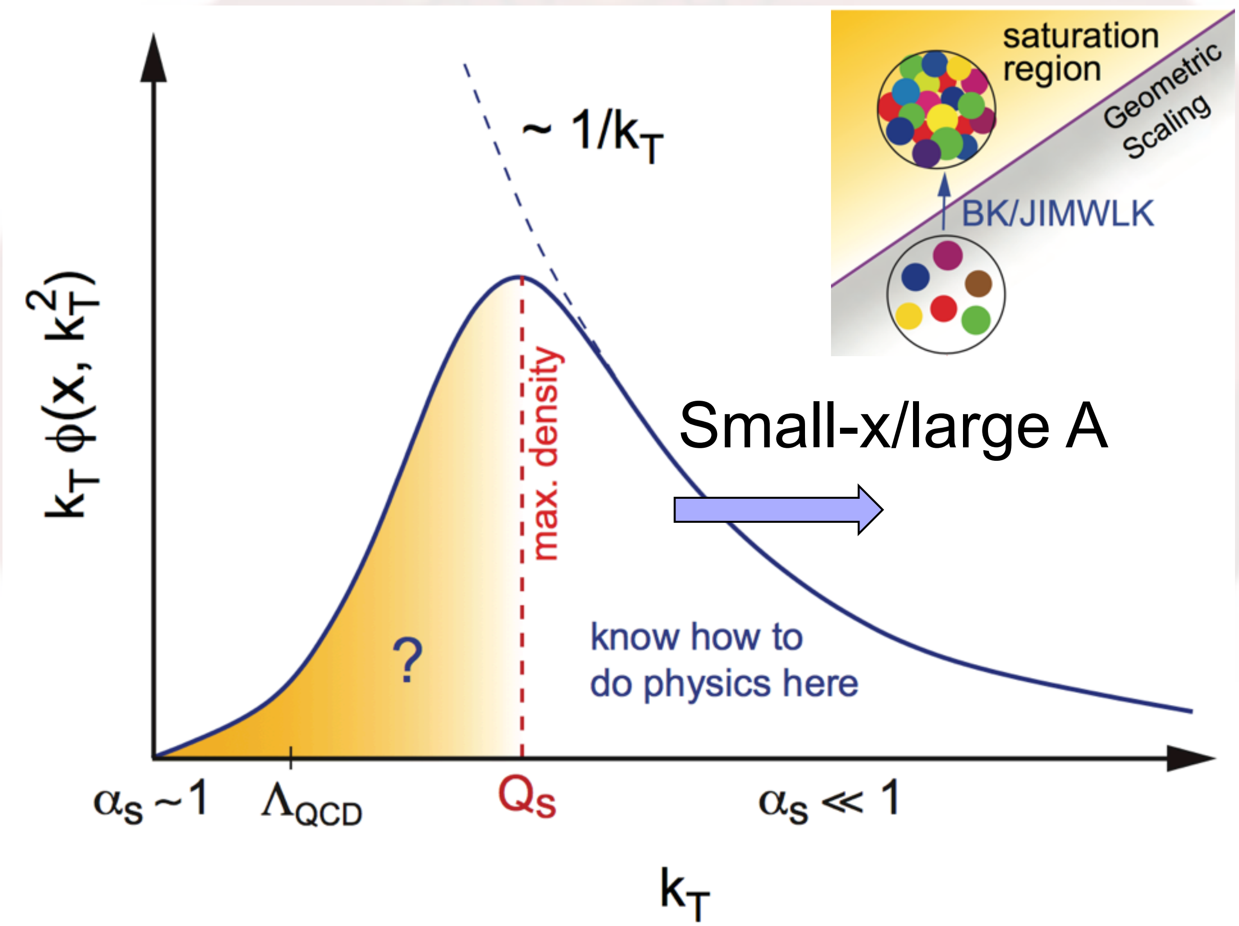
$$\frac{\partial N(x, r_T)}{\partial \ln(1/x)} = \alpha_s K_{\mathrm{BFKL}} \otimes N(x, r_T)$$

- Balitsky-Kovchegov: Non-linear term, 98

$$\frac{\partial N(x, r_T)}{\partial \ln(1/x)} = \alpha_s K_{\mathrm{BFKL}} \otimes N(x, r_T) - \alpha_s \left[N(x, r_T)\right]^2.$$

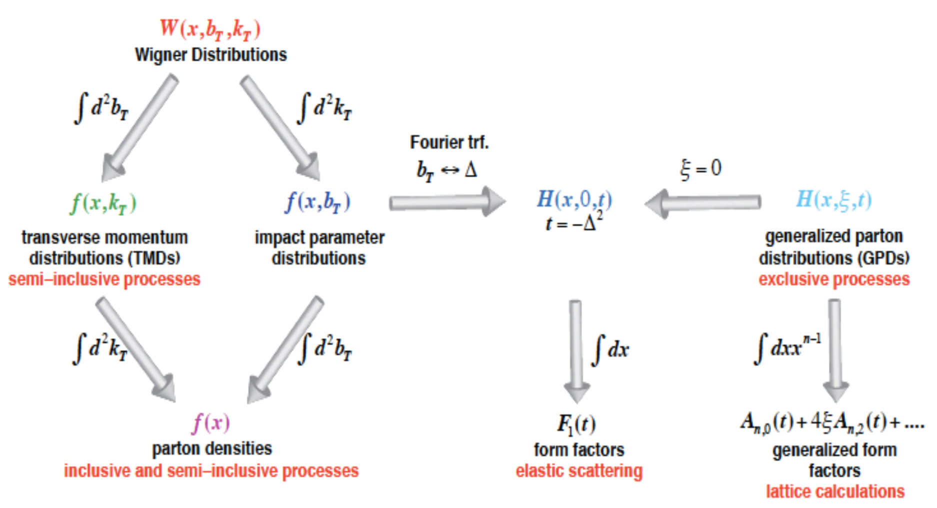


Saturation at small-x/large A



Grand Jewels of Hadron Physics

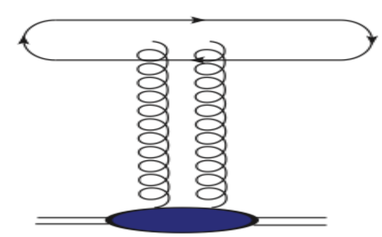
- Wigner distributions (Belitsky, Ji, Yuan)



Small-x

Dipole scattering amplitudes

$$\frac{1}{N_c}\left\langle \mathrm{Tr}\left[U\left(R_\perp\right)U^\dagger\left(R'_\perp\right)\right]\right\rangle_x$$

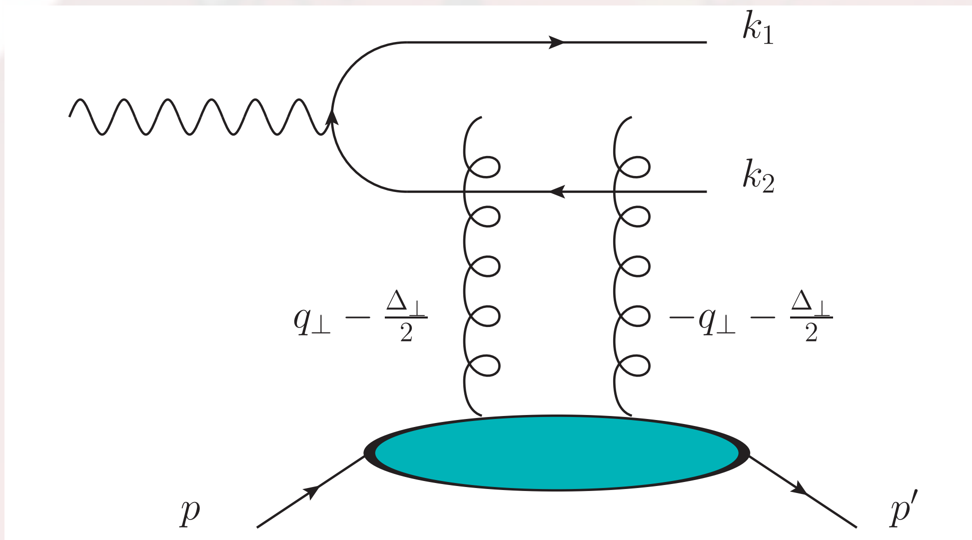


Hatta-Xiao-Yuan,1601.01585
earlier: Mueller, NPB 1999

Probing 3D Tomography of Protons at Small-x at EIC

Diffractive back-to-back dijet productions at EIC:

Hatta-Xiao-Yuan,1601.01585



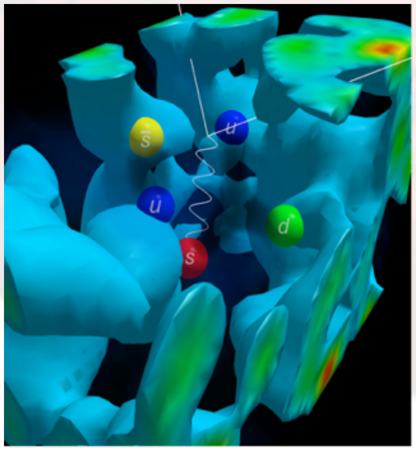
- In the Breit frame, by measuring the recoil of final state proton, one can access Δ_T. By measuring jets momenta, one can approximately access q_T.
- The diffractive dijet cross section is proportional to the square of the Wigner distribution.

Theoretical Issues

- New structure, new dynamics and new phenomena! (ongoing efforts)
  - Structure, probe physics separation and prove QCD factorization
  - New processes to measure novel observables
- Study parton physics on lattice

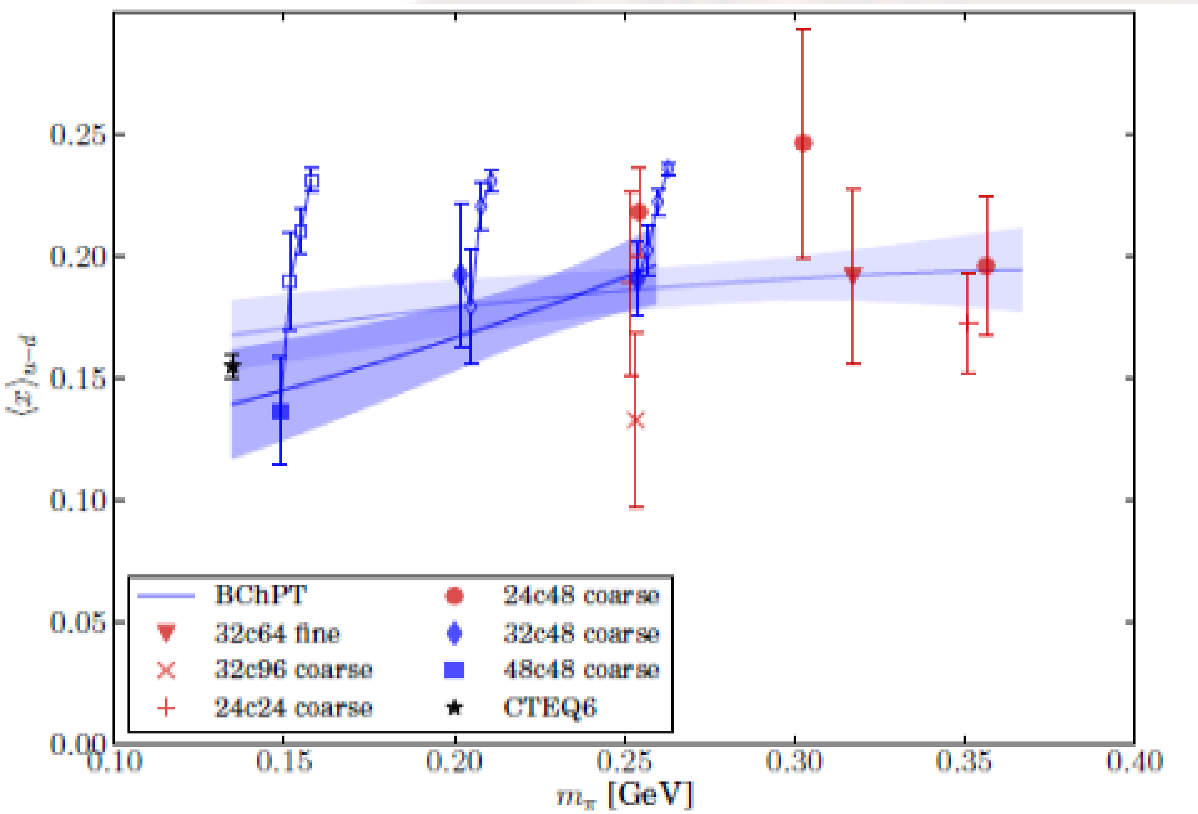
Parton Physics: Lattice QCD

- The only known rigorous framework for *ab-initio* calculation of the structure of protons and neutrons with controllable errors.
- After decades of effort, one can finally calculate nucleon properties with dynamical fermions at physical pion mass!




Nucleon Structure from Lattice QCD

J.R. Green et al, 2012 & 2014

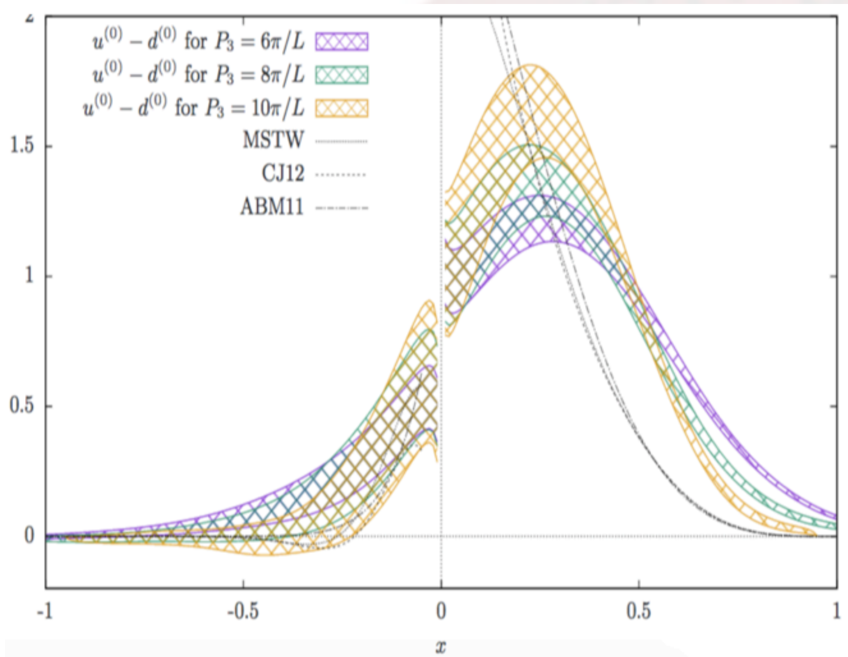


Nearly physical pion mass m_π=149MeV

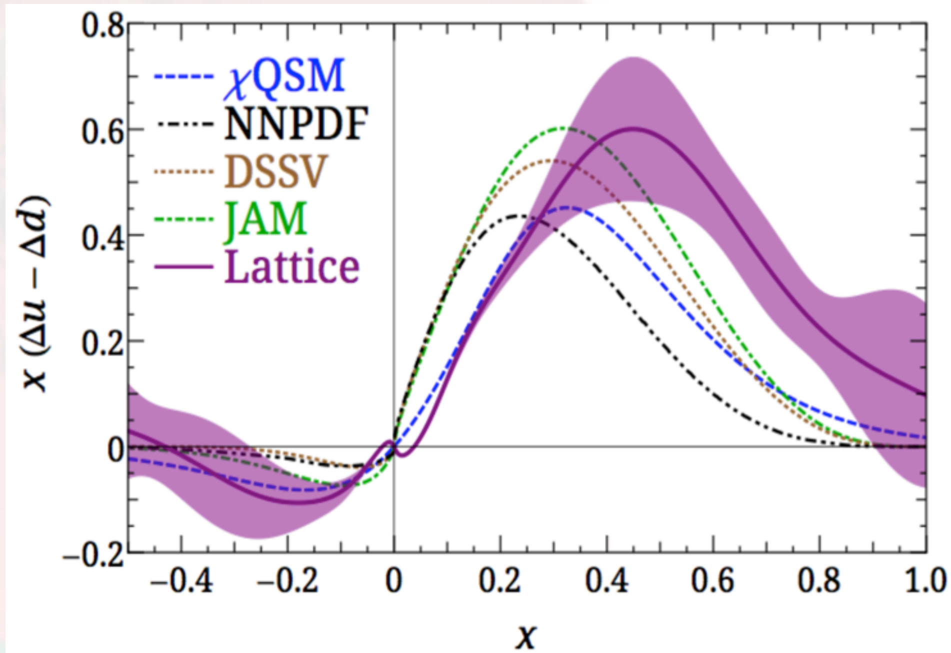
Quark momentum fraction $\langle x \rangle_{u-d} = \int dx\, x\,(u + \bar{u} - d - \bar{d})$

Directly compute PDFs from lattice QCD

Ji, PRL, 2013

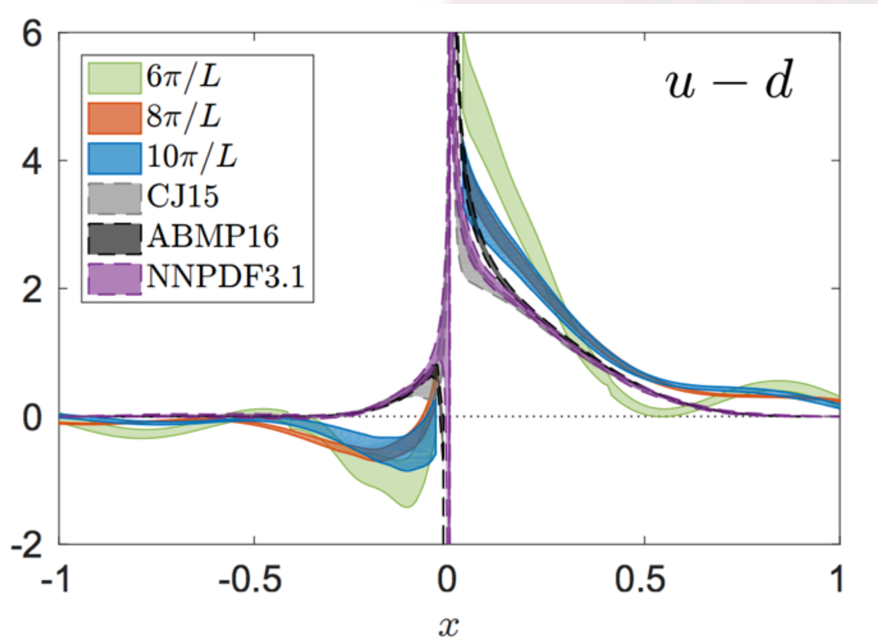


Alexsandrou et al., 2016

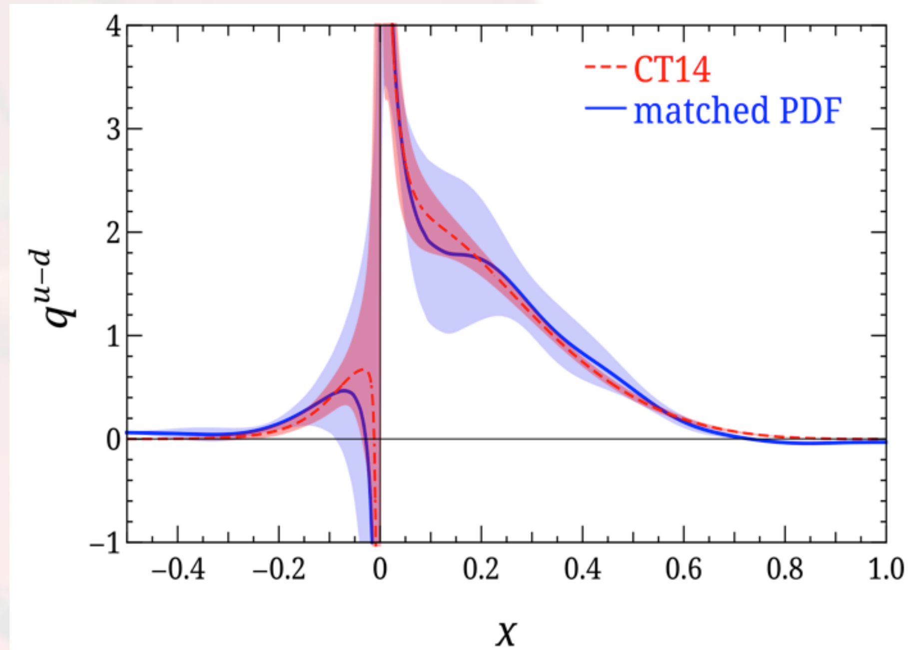


Chen et al., 2016

Directly compute PDFs from lattice QCD at physical pion mass

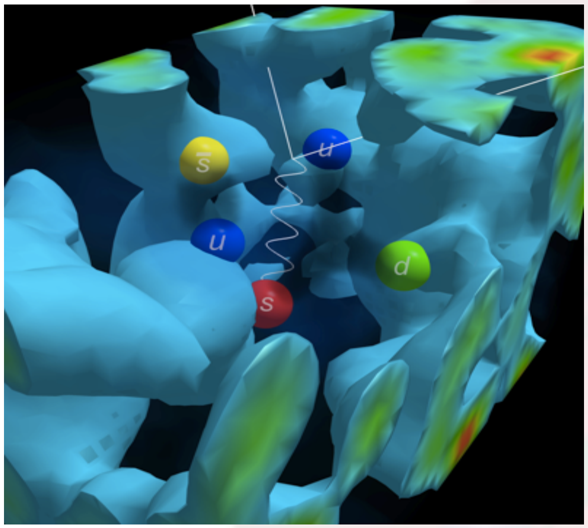


Alexsandrou et al., 2018

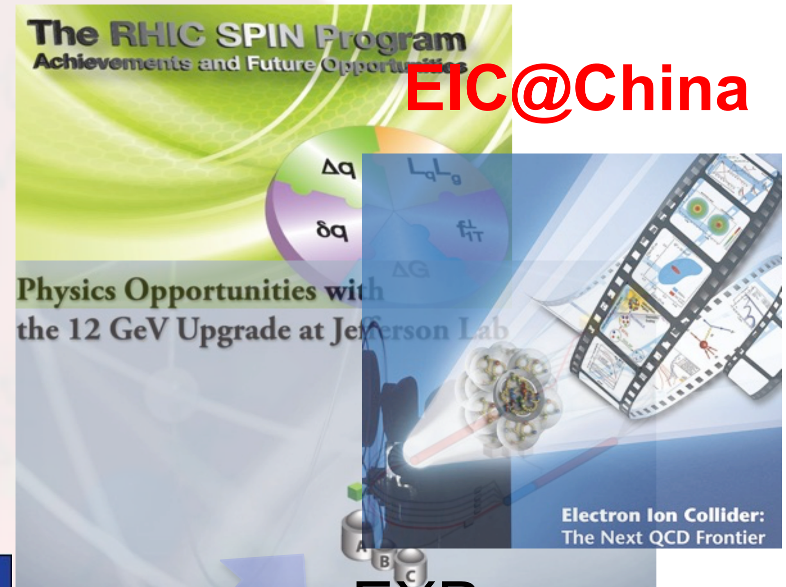


Chen et al., 2018

Fundamental Understanding of the Nucleon Structure in QCD

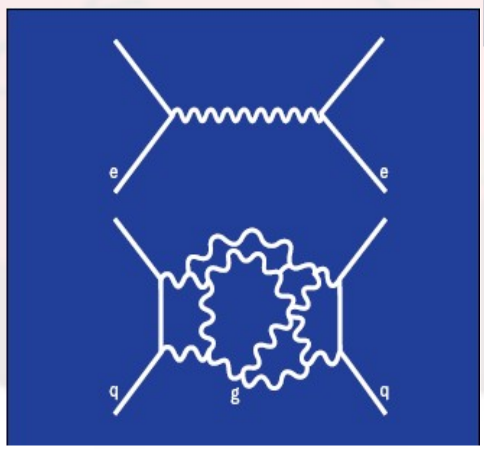


Lattice QCD



EIC@China

EXP. Measurements



Theory/ Phenomenology