# The glue that binds us all – physics at a future Electron Ion Collider

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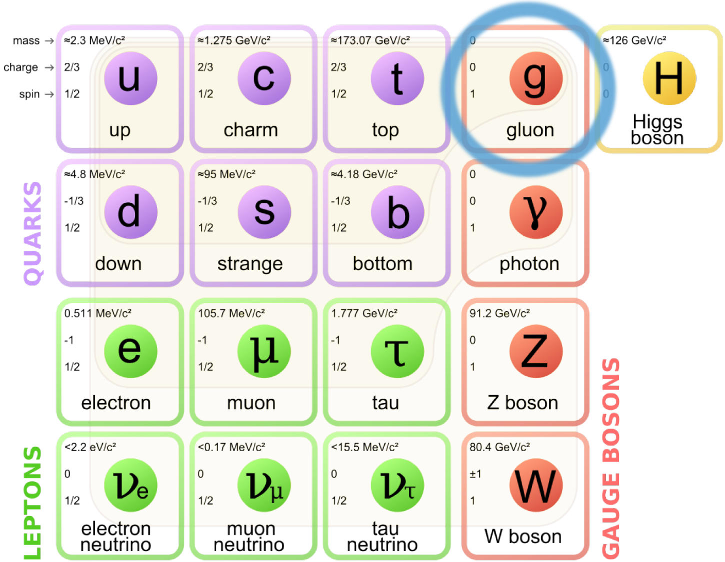
based on the work of many

# Outline

1. The gluon: facts & mysteries
2. Quantum Chromodynamics & the proton: What we know and what we still don't know
3. The Electron Ion Collider: some key measurements
4. Some open challenges in theory & phenomenology (my own work)
5. Summary & Conclusions

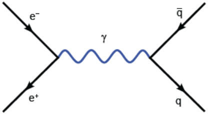
# The gluon - facts & mysteries

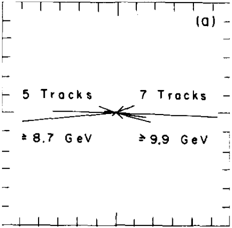



gluon ≡ carrier of strong force & building block of Standard Model

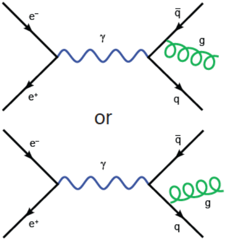
# 1979: Discovery of the gluon @ PETRA/DESY

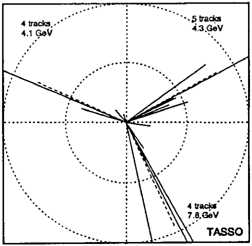
2 jet events:




3 jet events:

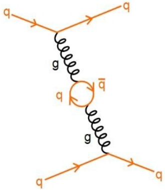


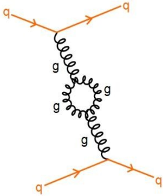

+ confirmation of spin 1 nature of gluon

[TASSO-collaboration, Phys. Lett. B 86, 243 (1979)]

# Asymptotic freedom: the role of glue




screening correction

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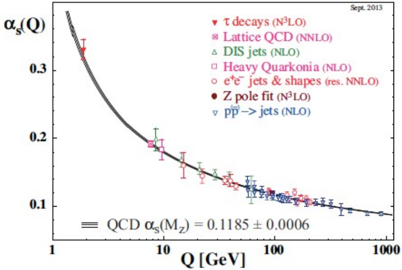




David Gross

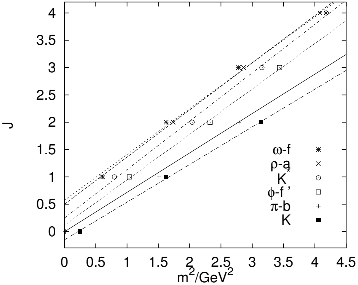

David Politzer


Frank Wilczek

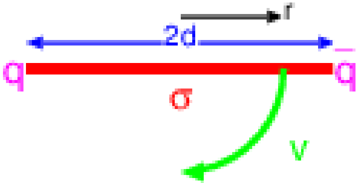
2004

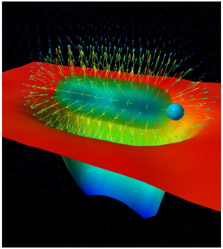
The self-interaction (of color charged) gluons is fundamentally responsible for the asymptotic freedom of quarks and gluons in Quantum Chromodynamics (QCD)

# The gluonic field and confinement ...

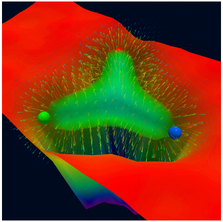



Regge trajectories & its intuitive explanation within the relativistic string model



linear confinement potential between quarks



# Sort of a paradox .....


- gluon is massless, yet responsible for nearly all the mass of visible matter
- Higgs-mechanism provides (through quarks) only 1% of the proton's mass

# The puzzle:

- (Nearly) all visible matter is made up of quarks and gluons
- But quarks & gluons are not visible

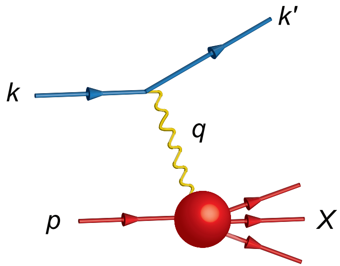
- 98% of the visible mass is generated from quarks & gluons
- but gluons are massless and quarks are so to a good approximation
  ⟶ Strongly interacting matter is consequence of many-body quark-gluon dynamics

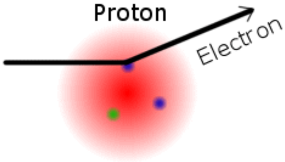
From the EIC white paper arXiv:1212.1701: *"... The current consensus is that the gluons are responsible for both the quark confinement and much of the hadronic mass. The gluons, which bind quarks together into mesons (...) and baryons (...), significantly contribute to the masses of hadrons. At the same time, gluons are significantly less well-understood than quarks .. "*

Understanding the glue ≡ Understanding the origin of matter ⟶ need to develop a deep and manifold knowledge of dynamics of strong interactions

# Quantum Chromodynamics & the proton - what we know and what we don't know

# The Deeply Inelastic Scattering (DIS) femtoscope




$$Q^2 = -q^2 = -(k - k')^2$$
$$Q^2 = E_e E'_e \sin^2 \frac{\theta'_e}{2}$$

**Measure of resolution power**

$$y = \frac{2p \cdot q}{2p \cdot k}$$

**Measure of inelasticity**

$$x = \frac{Q^2}{2p \cdot q}$$

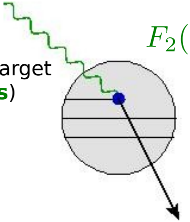
**Bjorken x: Momentum fraction of struck quark**

**= Measure of ($\gamma^* p$) center-of-mass energy at fixed resolution $Q^2$**

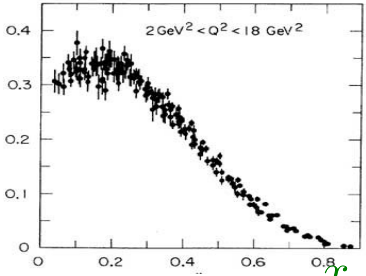
inclusive, unpolarized & no charge: proton structure functions $F_2(x, Q^2)$, $F_L(x, Q^2)$ or reduced cross-section $\sigma_r = F_2(x, Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x, Q^2)$

# The deeply inelastic scattering (DIS) femtoscope

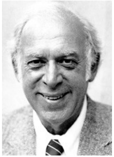
From SLAC fixed target DIS... (**late 1960s**)

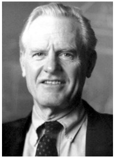


$F_2(x)$




Discovery of quasi-free point-like quarks!



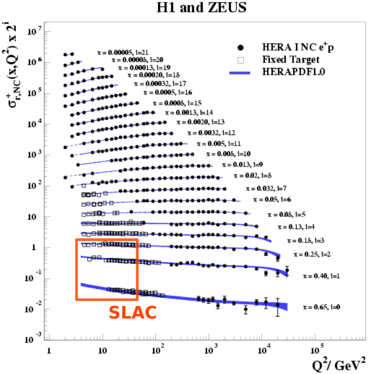


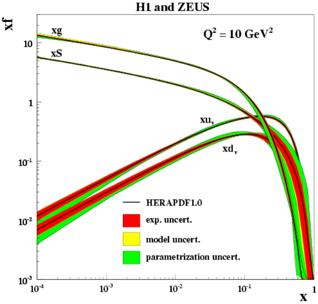
**Friedman** **Kendall** **Taylor**

(**1990**)

# The deeply inelastic scattering (DIS) femtoscope

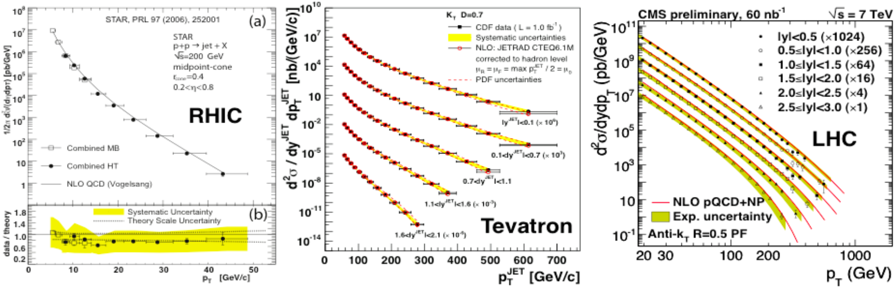
HERA collider at DESY (1992-2007)



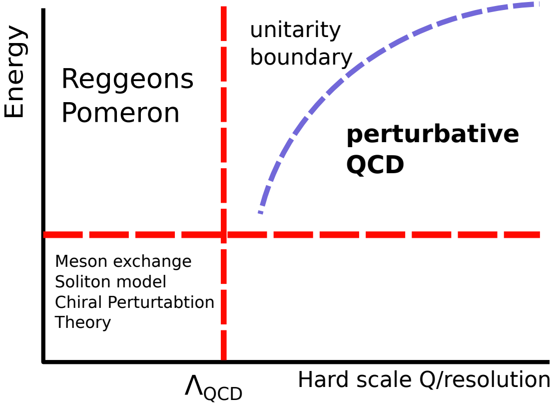

Find: proton at high energies ($\equiv$ small $x$) dominated by gluon & sea-quarks

# Successes of perturbative QCD




- parton distribution functions extracted from HERA data give (together with corresponding partonic coefficients, calculated in perturbation theory) excellent description of hard events in $pp$ and $p\bar{p}$ scattering ($\equiv$ events with scale $Q \gg \Lambda_{QCD} \sim 1/\text{fm}$)
- pQCD as a tool to determine production cross-sections and backgrounds in the search for new physics

# Looks great! - Aren't we done?




- pQCD describes only a small fraction of total cross-section
- Lattice QCD of limited use for scattering processes

# What does the proton look like ?

**Static pictures** | **Glue dominated boosted proton**

## Bag model:

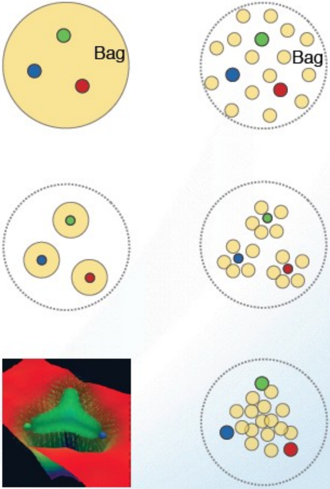
- Field energy distribution is wider than the distribution of fast moving light quarks

## Constituent quark model:

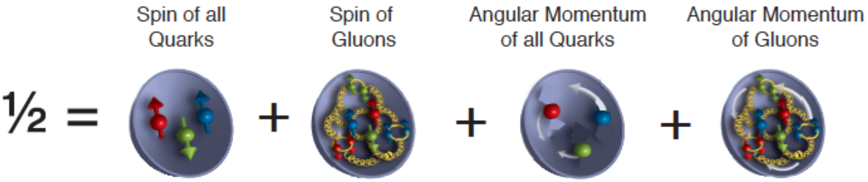
- Gluons and sea quarks “hide” inside massive quarks
- Sea parton distribution similar to valence quark distribution

## Lattice gauge theory:

- (with slow moving quarks)
- gluons are more concentrated than quarks

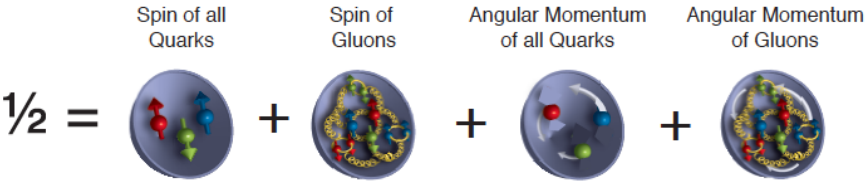


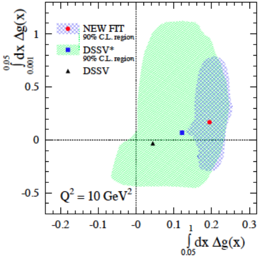
# The proton spin puzzle




- 1987: fixed target DIS experiments → quarks carry only 30% of proton spin
- spin crisis: failure of quark-model picture of proton as 3 constituent quarks

# The proton spin puzzle




- RHIC polarized proton-proton data: strong indication for gluon polarizaiton

[de Florian, Sassot, Stratmann, Vogelsang, PRL 113 (2014) 1 012001]

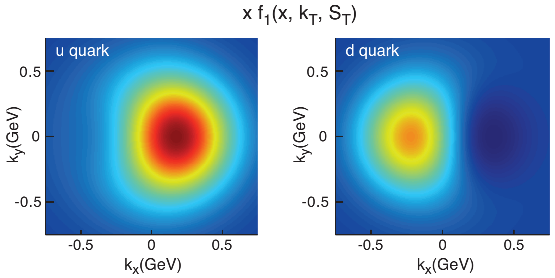
- $\sim 20\%$ by glue, where is the rest?

# What is the confined motion of quarks & gluons in nucleons?

Requires to extend the 1-D picture to $1+2$ dimensions

$$f(x,\mu^2) \to f(x,\boldsymbol{k}_T,\mu^2)$$

Allows to study of correlations between transverse momentum, parton spin & nucleon spin



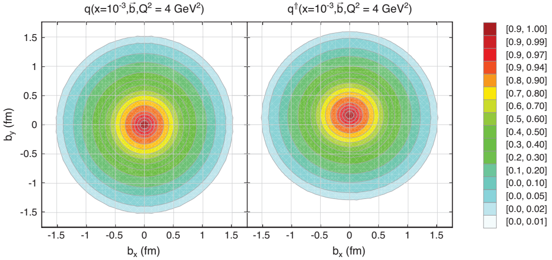

Correlation of proton spin and $u$-quark transverse momentum

# What is the transverse position of quarks & gluons inside the nucleon?

Requires spatial imaging of confined quarks & gluons → Extend the 1-D picture to $1 + 2$ dimensions

$$f(x, \mu^2) \to f(x, \boldsymbol{b}_T, \mu^2)$$

- Allow to study spin-orbit correlations of quarks & gluons
- Determination of total angular momentum carried by quarks & gluons (Ji's sum rule)

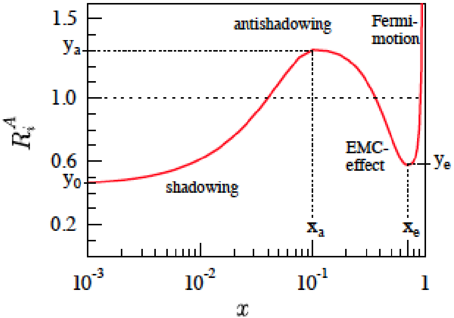


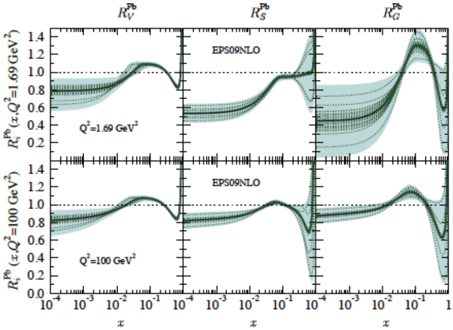

sea quark densities in transverse plane

# Quark & gluon distribution in the nucleus

EMC@CERN: Quark distribution strong affected by binding into nucleus

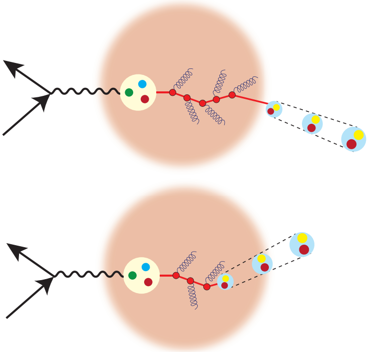
→ Not simply superpositions of distribution functions of individual nuclei




What about gluons? What the spatial distributions of quarks & gluons in the nucleus?

# Fragmentation in and out of a medium

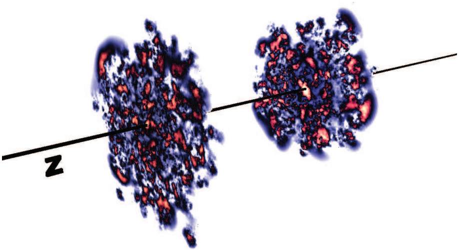


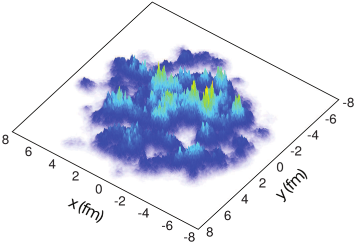
How does a quark/gluon turn into a hadron?

How does color neutralization occur? The key to the formation of hadrons – still not understood within QCD

How does this happen inside the nuclear medium?

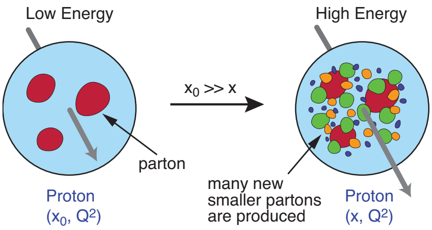
# Initial state of heavy ion collisions



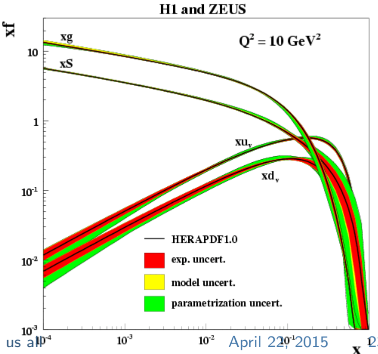




To understand heavy ion collisions and observed phenomena in detail, we need a profound understanding of the properties of their initial state

# The proton at high center of mass energies



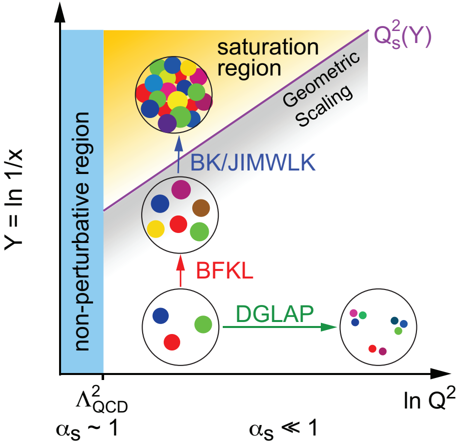

- QCD: proton made up of quanta that fluctuate in and out of existence
- At small $x$: Parton fluctuations time dilated on strong interaction times scales ....




- .... long lived gluons radiate further small $x$ gluons
- power-like rise of gluon and sea-quark distribution & therefore cross-section
- the small $x$ proton an eternal popcorn machine?


POPCORN

# The proton at high energies: saturation

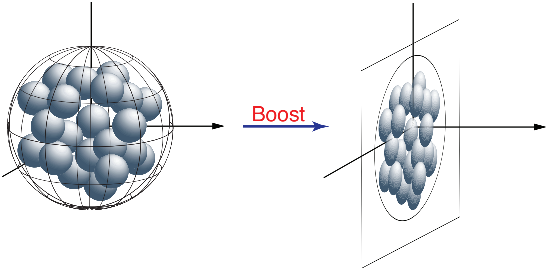



finite size $1/Q$ partons 'overlap' at certain $x$ ➡ saturation scale $Q_s \sim x^{-\Delta}$, $\Delta > 0$

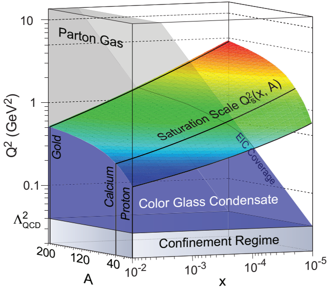
Questions:

- How does this happen? What are the right degrees of freedom?
- How do correlation function evolve in this regime?
- Is there a universal fix point?
- Does the coupling run with $Q_s$?
- How does saturation transition to chiral symmetry breaking & confinement

# Saturation in nuclei: McLerran-Venugopalan model




$Q_s^2 \sim \#$ gluons per unit transverse area $\sim A^{1/3}$




- large gluon density gives large saturation scale $Q_s$
- Dynamically generated saturation scale
  → possible window for weak-coupling $\alpha_s(Q_s) \ll 1$ studies at high densities
- Is this realized like this?

# The Electron Ion Collider: the ultimative(?) QCD machine

- the world's first polarized electron-polarized proton collider
- the world's first electron-heavy ion collider
- luminosity 100-1000 $\times$ HERA luminosity
- considerably extends kinematic range for $eA$, spin, imaging, ...
- timeline: want to start 2025 ...

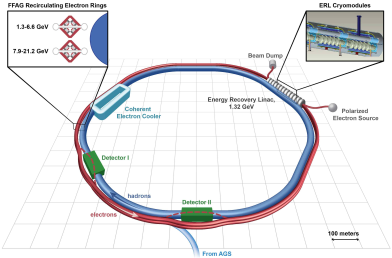
related projects:

- ENC@GSI, EIC@HIAF: time line uncertain; seem not to extend considerably kinematic range
- LHeC/FCC-he@CERN: realiztion unclear ($> 2030$); unpredecented kin. reach

# Accelerator designs

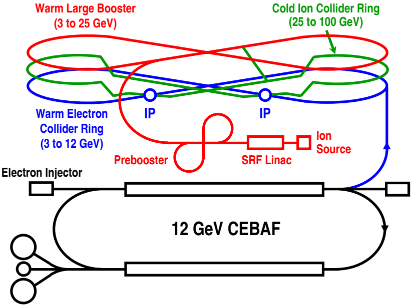
## eRHIC (BNL)

- Add ERL+FFAG recirculating $e$ Rings to RHIC facility
- Electrons 15.9 & 21.2 GeV
- Ions (Au) up to 100 GeV/u
- $\sqrt{s} \simeq 18 - 93\text{GeV}$
- $\mathcal{L} \simeq 1.7 \cdot 10^{33} \frac{cm^{-2}s^{-1}}{A}$ at $\sqrt{s} = 80\text{GeV}$

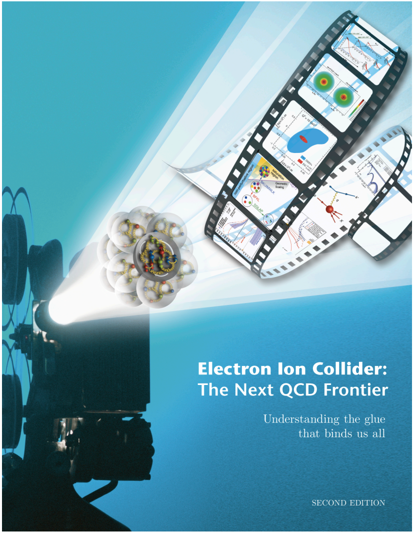



## MEIC (JLab)

- Ring-Ring Collider, use of CEBAF
- Electrons 3-12 GeV
- Ions 12-40 GeV/u
- $\sqrt{s} \simeq 11 - 45\text{GeV}$
- $\mathcal{L} \simeq 2.4 \cdot 10^{34} \frac{cm^{-2}s^{-1}}{A}$ at $\sqrt{s} = 22\text{GeV}$



# Key measurements




Imaging

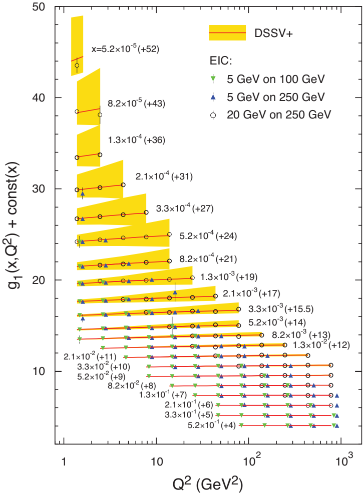
Gluon Saturation

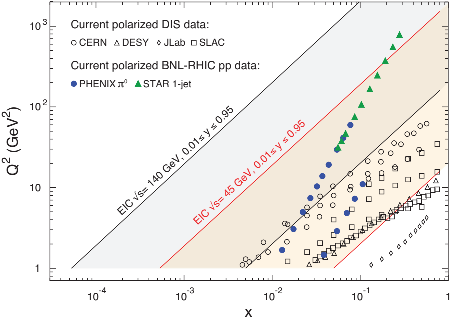
Nuclear Enviroment

Spin

Electroweak

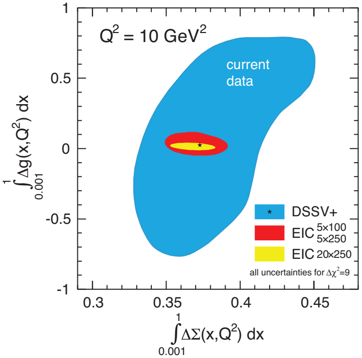
# Resolving the proton's spin puzzle: polarized DIS

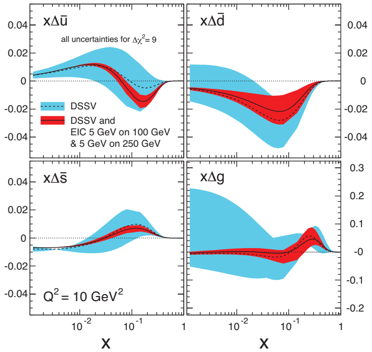



Dramatically extend the exisiting data set

# Resolving the proton's spin puzzle: helicity distributions

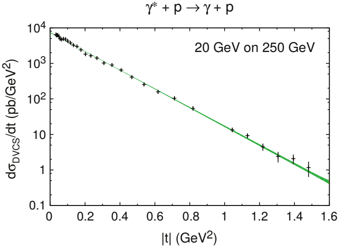


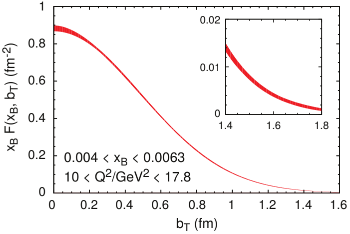




- Increase dramatically our knowledge about valence quark, sea quark and gluon contribution to the proton spin
- Allows to quantify remaining orbital contribution

# Tomography of the nucleon using DVCS

Imaging: from $t$ to spatial distributions



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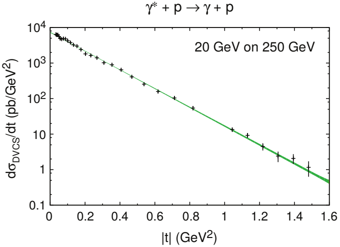
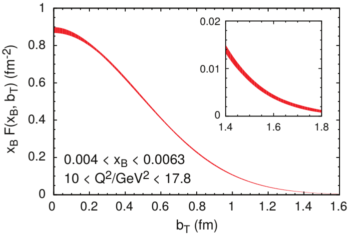
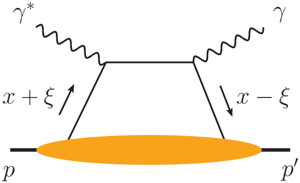
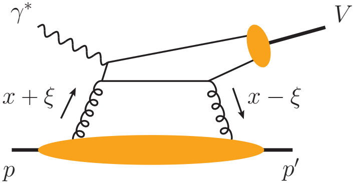



measure in exclusive reactions




Deeply Virtual Compton Scattering (DVCS) & Exclusive Vector Meson Production

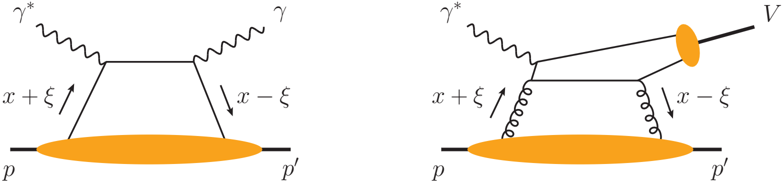
# Tomography of the nucleon using DVCS

experimental challenge:

need almost hermetic detectors

+ high luminosity

measure in exclusive reactions

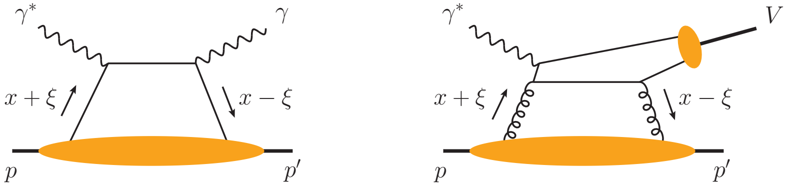



Deeply Virtual Compton Scattering (DVCS) & Exclusive Vector Meson Production

# Tomography of the nucleon using DVCS

theory framework:
constrain so-called Generalized Parton Distribution Functions (GPDs):
combine ordinary pdfs & form factors etc.
+ further constrained from lattice QCD

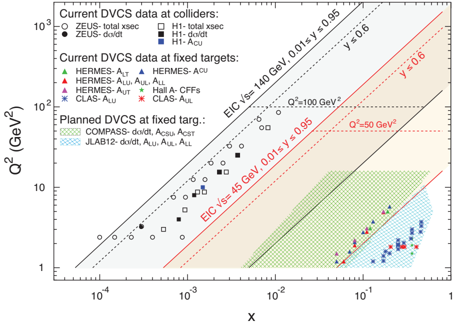
measure in exclusive reactions




Deeply Virtual Compton Scattering (DVCS) & Exclusive Vector Meson Production

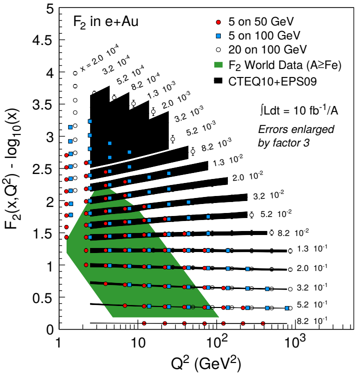
# Tomography of the nucleon using DVCS

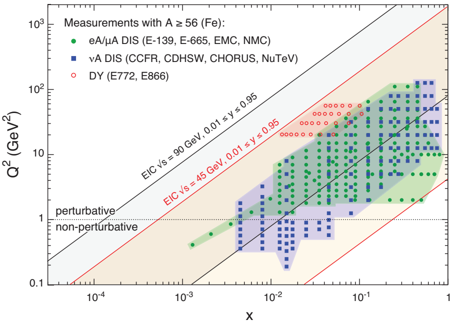
theory framework:
constrain so-called Generalized Parton Distribution Functions (GPDs):
combine ordinary pdfs & form factors etc.
+ further constrained from lattice QCD




At an EIC: considerably extend kinematic range → access to gluon & sea-quarks

# Gluons & sea quarks in nuclei



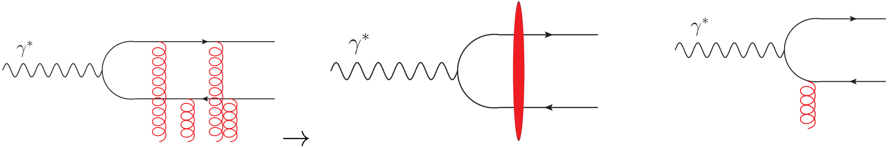




constrain nuclear sea quark and gluon distribution + search for saturation effects in large nuclei

$$\frac{d^2\sigma^{eA\to eX}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[(1+(1-y)^2)F_2(x,Q^2) - y^2 F_L(x,Q^2)\right]$$

# Searching for saturation effects: Dihadron-decorrelation

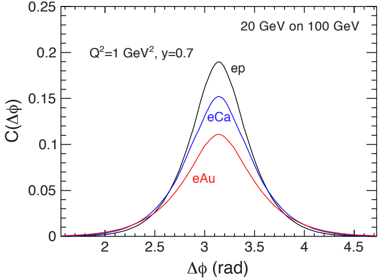
Saturation $\equiv$ high gluon densities ➡ multiple scatterings

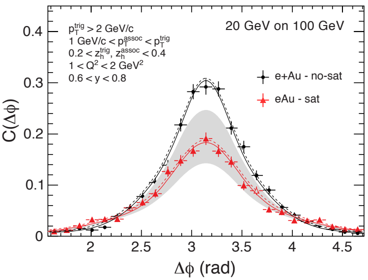



$x \to 0$: a single interaction with a strong & Lorentz contracted gluon field

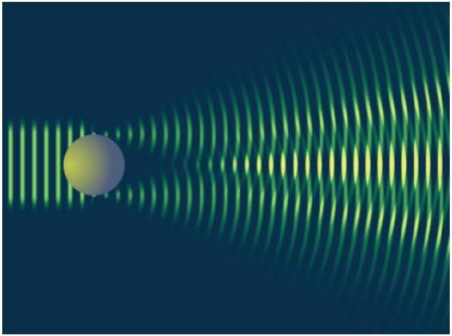
dilute regime: 1 gluon with small $k_T$

➡ expect difference in angular distribution of detected di-hadrons

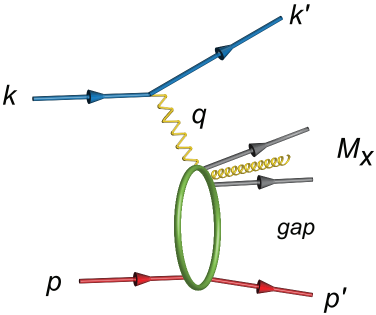


# Diffraction



diffraction in optics

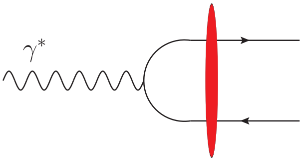



diffraction in DIS

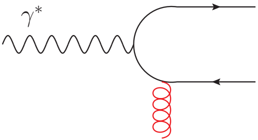
a) coherent: proton/nucleus intact

b) incoherent: break up; rapidity gap definition

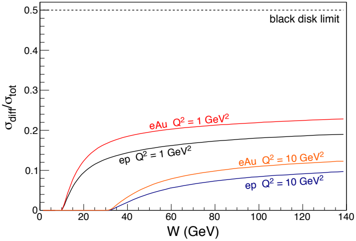
# Searching for saturation effects: Diffraction



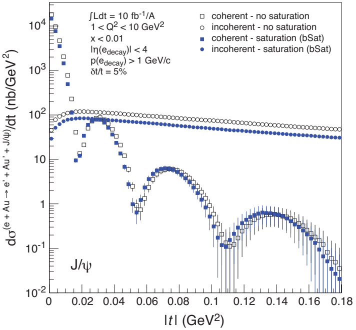

vs.

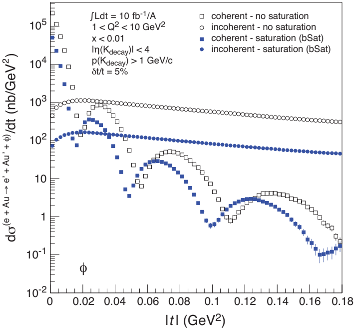



- naïve expecation before HERA: hard diffraction exponentially suppressed
- HERA: 15% of all events diffractivee
- at the saturated fix-point $s \to \infty$: $\frac{\sigma_{\text{diff}}}{\sigma_{\text{tot}}} = \frac{1}{2}$
- expect higher rate for nuclei at EIC



# Searching for Saturation in diffractive VM-production



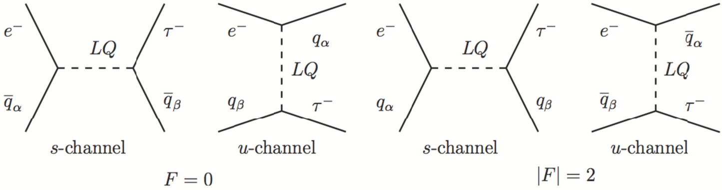




$J/\Psi$: (non-)saturation models very similar ➞ perturbative scale/small size;

$\phi$ (large size object): both models differ significantly

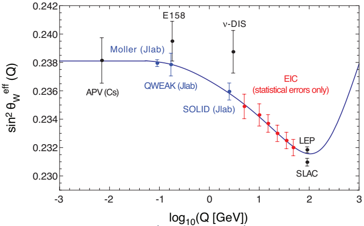
# Electroweak

Neutrino oscillation $\rightarrow$ lepton flavor not conserved




- is there charged lepton flavor violation? through lepto-quarks?
- weakest limits on $e^-\tau^-$ transitions; possible to surpass HERA limits
- potentially competitive with B-factories, but requires further studies

# Weak mixing angle: $\sin\theta_W$




- points aren't hugely precise
- but can scan over a wide range of $Q^2$

# Some (theoretical) challenges on which I am working

- Background to DVCS - the Bethe Heitler process
- Scheme invariant evolution of structure functions
- NLO corrections for DIS cross-sections in presence of high gluon densities

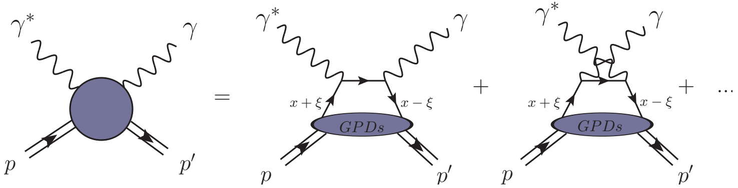
# Background to DVCS - the Bethe-Heiler process

in collaboration with Elke C. Aschenauer (BNL), Marco Stratmann (U. Tübingen) & Hubert Spiesberger (U. Mainz)

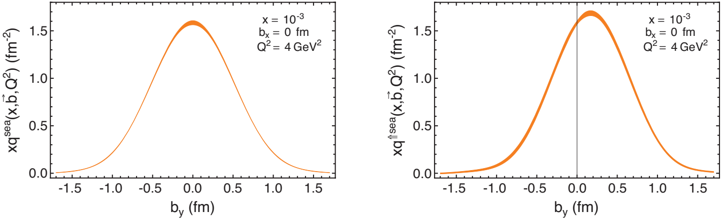
# Deeply Virtual Compton Scattering & GPDs

GPDs (= Generalized Parton Distributions) essential (theoretical) ingredient for imaging/tomography of nucleon

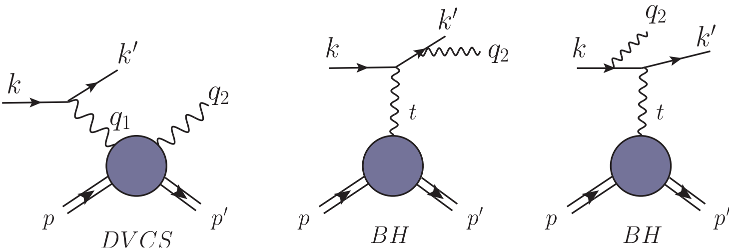
a key process to constrain them: DVCS (Deeply Virtual Compton Scattering)




Their Fourier-transform yields spatial distributions etc.

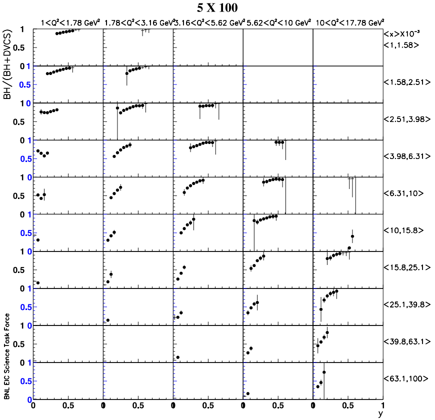


# Complete Cross-section: DVCS + Bethe Heitler



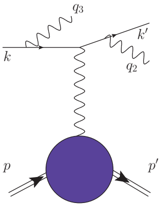

- important background: photon emission from initial/final state electron (=Bethe-Heitler)
- interference term DVCS/BH: important tool to constrain certain asymmetric GPDs
- precision measurement of DVCS: need excellent control of BH

# Ratio of BH to total cross-section




- Simulation by S. Fazio, E. Aschenauer using corrected version of `Milou` Monte-Carlo event generator [Perez, Schoeffel, Favart, hep-ph/0411389]
- larger y: BH dominates
- solution: can find phase-space cut's which reduce BH contribution significantly

# Radiative corrections




2nd undetected photon can lead to a shift in the measured $Q^2$ & $x$ ➡ need to correct for such effects using Monte-Carlos

in adddition:

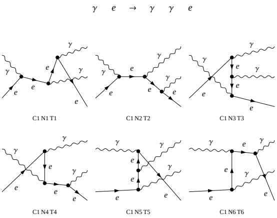
Cuts allow to reduce contamination due to BH-process substantially, but also lose fraction of available data

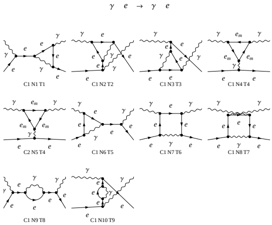
wish high accuracy for BH process to reduce necessary cuts to a minimum

# BH at next-to-leading order

Ongoing project: determination of BH process at NLO

[MH, Spiessberger, Stratmann (soon)]




- not the first *e.g.* Akushevich, Ilyichev;1201.4065], [Vanderhaegen et. al.; PRC 62 025501], but attempt to be the most complete one ...
- full mass dependence of lepton: small, but not always negligble
- soft- & collinear singularities: dipole-subtraction for collinear non-safe observables for maximal exclusive result [Dittmaier, Kabelschacht, Kasprzik; 0802.1405], [Dittmaier, NPB 565 (2000) 69]
- provide full Monte-Carlo realization, which can be directly used for simulations etc.

Work in progress

# Scheme invariant evolution of structure functions

in collaboration with Marco Stratmann (U. Tübingen)

# Collinear factorization in a nut-shell

Observables as convolutions of process-dependent coefficients (calculated order by order in perturabation theory) & universal parton distribution functions

$$F_2(x, Q^2) = \sum_{k=q,g} C_{2,k} \otimes f_k$$

parton distribution functions $f_k$ *non-perturbative*

- cannot be calculated in perturbation theory ➞ fit to data
- BUT: can calculate their evolution w.r.t. the factorization scale $\mu_f^2 \sim Q^2$

$$\frac{d}{d \ln \mu_f^2} f_k(x, \mu_f^2) = \sum_{l=q,g} P_{kl} \otimes f_l(x, \mu_f^2)$$

need only to fit initial conditions at $\mu_{f,0}$ & evolve them to higher $\mu_f$

# Basis: factorization in the limit $Q^2 \to \infty$

- Starting point: factorization into bare pdfs & coefficents
  $F_2(x, Q^2) = \sum_{k=q,g} \hat{C}_{2,k} \otimes \hat{f}_k$ – both are divergent!
- Divergences cancel, but leads to dependence on factorization scale & scheme
  ➡ RG-equation $\equiv$ DGLAP evolution equation
  ➡ pdfs not physical, but a theory definition
- factorization scheme & -scale dependence cancels at each order in perturbation theory (coefficents & splitting kernels), but spurious higher order terms remain

  ➡ if enhanced by *e.g.* small/large $x$ $\ln 1/x$, $\ln(1-x)$ this can imply an substantial uncertainty

# Physical DGLAP Evolution

idea: don't care about pdfs

↓

evolve observable itself

[Furmanski, Petronzio, ZP C 11, 293(1982)], [Catani, ZP C 75, 665 (1997)], [Blümlein, Ravindran, van Neerven, NPB 586, 349 (2000)]

$$\text{“}Q^2 \frac{d}{dQ^2} F(x, Q^2) = K \otimes F(x, Q^2)\text{”}$$

↑

observable itself!

evolution kernels $K$

- physical
- no factorization scheme ambiguity; only renormalization scale

→

equivalent to [Catani, ZP C 75, 665 (1997)]

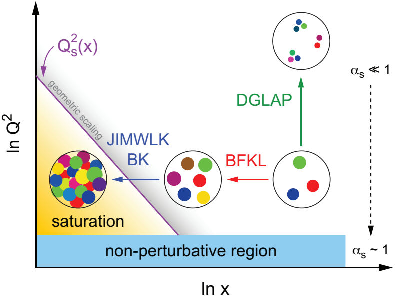
$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

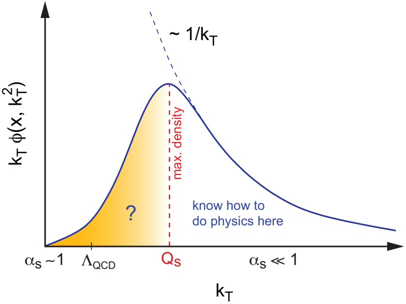
lose universality of pdfs, but gain precision

# Possible applications

Determination of $\alpha_s$ from DIS data (unlike pdf determination no factorization scale ambiguities)

Search for breakdown of linear DGLAP evolution due to higher twist effects ➡ signal for saturation



# Technical Aspects

- work in conjugate Mellin space
  $\otimes \to \cdot$
- Decompose pdfs into flavor singlet & non-singlets

$$\Sigma = \sum_{k}^{n_f} (q_k + \bar{q}_k)$$
$$q_3 = u + \bar{u} - \left(d + \bar{d}\right)$$
$$q_8 = u + \bar{u} + d + \bar{d} - 2\,(s + \bar{s})$$

- matrix valued DGLAP evolution decouples:
  scalar evolution for non-singlets
  + flavor singlet vector $(\Sigma, g)$

$$d_{\ln\mu^2} \begin{pmatrix} \Sigma \\ g \end{pmatrix} = \begin{pmatrix} P_{qq} & nf \cdot P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \cdot \begin{pmatrix} \Sigma \\ g \end{pmatrix}$$

- relate to observables with coefficents:

$$\begin{pmatrix} F_A^{(S)} \\ F_B^{(S)} \end{pmatrix} = \begin{pmatrix} C_{Aq} & C_{Ag} \\ C_{Bq} & C_{Bg} \end{pmatrix} \cdot \begin{pmatrix} \Sigma \\ g \end{pmatrix}$$

- suitable pairs of observables:
  flavor singlet part of $(F_2, F_L)$
  and $(F_2, F_D \sim dF_2/d\ln Q^2)$

From now on: concentrate on singlet; non-singlets *e.g.* [van Neerven, Vogt, NPB 568:263 (2000)]

For a suitable doublet of observables determine (with $a_s = \frac{\alpha_s}{4\pi}$):

$$d_{\ln Q^2} \begin{pmatrix} F_A \\ F_B \end{pmatrix} = d_{\ln Q^2} \left[ C \cdot \begin{pmatrix} \Sigma \\ g \end{pmatrix} \right]$$

$$= \left[ \beta \frac{dC}{da_s} + C \cdot P \right] \cdot \begin{pmatrix} \Sigma \\ g \end{pmatrix}$$

$$= \left[ \beta \frac{dC}{da_s} + C \cdot P \right] C^{-1} \begin{pmatrix} F_A \\ F_B \end{pmatrix} \equiv K \cdot \begin{pmatrix} F_A \\ F_B \end{pmatrix}$$

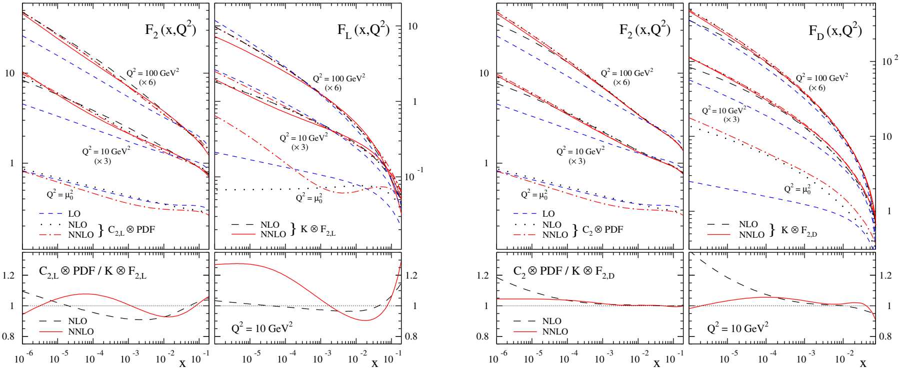
master formula

$$K = \left[ \beta \frac{dC}{da_s} + C \cdot P \right] C^{-1} = a_s K^{(0)} + a_s^2 K^{(1)} + a_s^3 K^{(2)} + \ldots$$

- kernel $K$ independent of factorization scheme & scale order by order in perturbation theory
  [Blümlein, Ravindran, van Neerven, NPB 586, 349 (2000)]
- finite order: dependence on renormalization scale & scheme remains ➡ use for $\alpha_s$ determination

# Numerics with toy input - comparison to pdfs

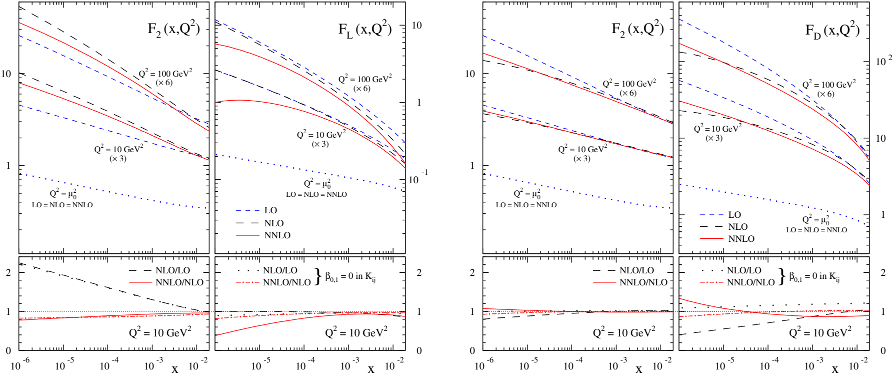
input calculated from realistic toy pdfs (Pegasus default input) & compare LO, NLO & NNLO results resp. - for $(F_2, F_L)$ and $(F_2, F_D \sim \frac{dF_2}{d\ln Q^2})$




Difference pdf/physical anomalous dimensions due to spurious higher order terms; can exclude them in toy input ➡ precise agreement

# Numerics with toy input - K-factors

evolve same (LO input) with LO, NLO, NNLO $\simeq$ real experimental data

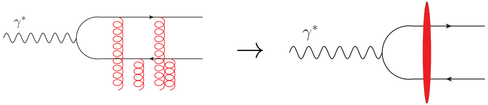



3-loop correction to $F_L$ coefficent very large (esp. at small $x$) ➞ observe instability also reported in pure pdf studies; requires probably resummation

pair $(F_2, dF_2/d\ln Q^2)$ more stable ➞ $\alpha_s$ extraction

# 1st application: evolution of saturation model input

Saturation physics ≡ high gluon densities ➡ multiple scatterings




$x \to 0$: a single interaction with strong & Lorentz contracted gluon field

$$\sigma_{L,T}^{\gamma^* A}(x, Q^2) = 2 \sum_f \int d^2\boldsymbol{b} d^2\boldsymbol{r} \int_0^1 dz \left| \psi_{L,T}^{(f)}(r, z; Q^2) \right|^2 \mathcal{N}(x, \boldsymbol{r}, \boldsymbol{b})$$

dipole amplitude $\mathcal{N}$: interaction of color dipole with target;

(a) solution to BK/JIMWLK evolution equation with fitted input

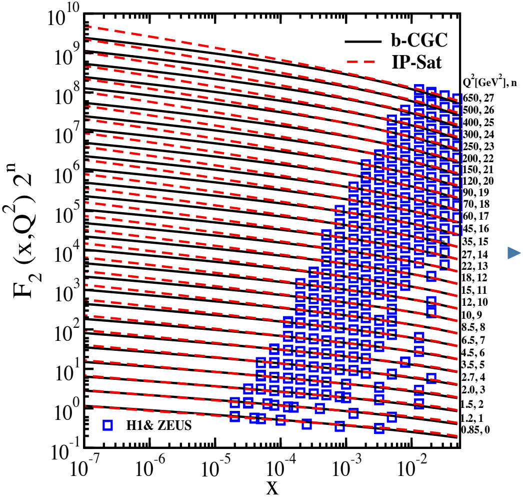
(b) model it ➡ (b)CGC-model [Iancu, Itakura, Munier; PLB 590 (2004)]

$$\mathcal{N}(x, r, b) = \begin{cases} N_0 \left(\frac{rQ_s}{2}\right)^{2\gamma_{eff}} & rQ_s \leq 2 \\ 1 - e^{-\mathcal{A} \ln^2(\mathcal{B} r Q_s)} & rQ_s > 2 \end{cases}$$

$$Q_s^2(x) = \left(\frac{x_0}{x}\right)^\lambda \text{GeV}^2$$

$$\gamma_{eff} = \gamma_s + \frac{1}{\kappa \lambda Y} \ln \frac{2}{rQ_s}$$

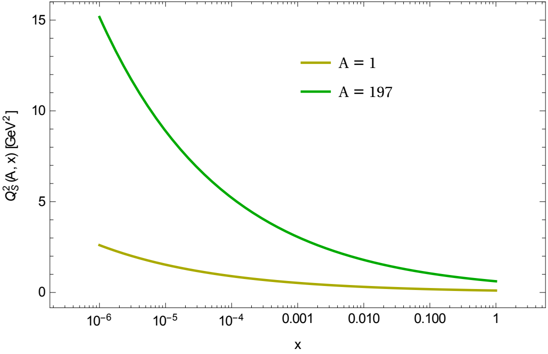
# Recently fitted to combined HERA data .....




- fit [Rezaeian, Schmidt, PRD 88 (2013)]

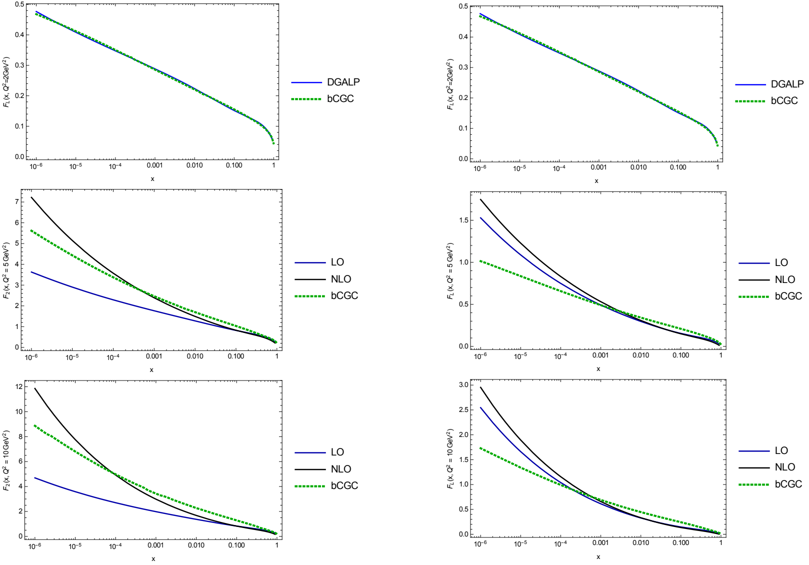
# The idea ...

- simulate DIS on gold nucleus through $Q_s^2 \to Q_s^2 A^{1/3}$ ➡ strong(?) saturation effects at EIC kinematic reach

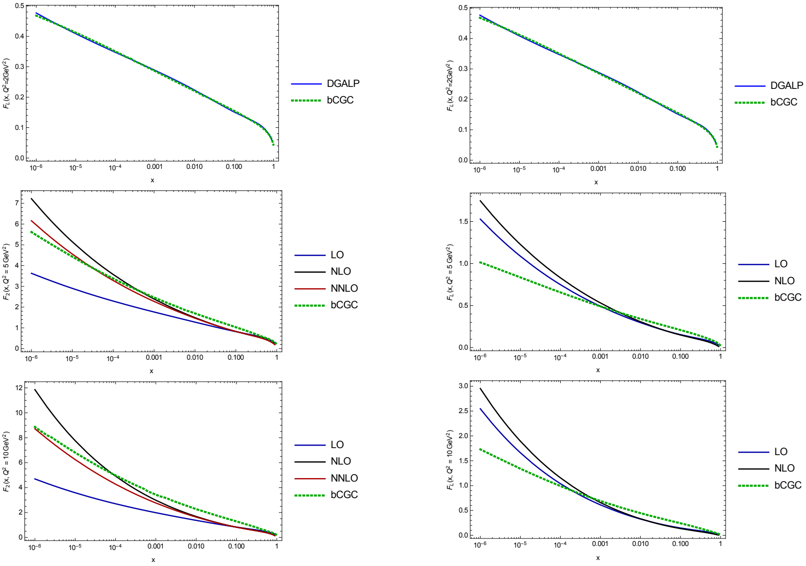



- fit $x$-shape of bCGC at $Q^2 = 2\text{GeV}^2$
- evolve this input with DGLAP
- compare at higher values of $Q^2$
  ➡ deviations $\equiv$ presence of saturation effects

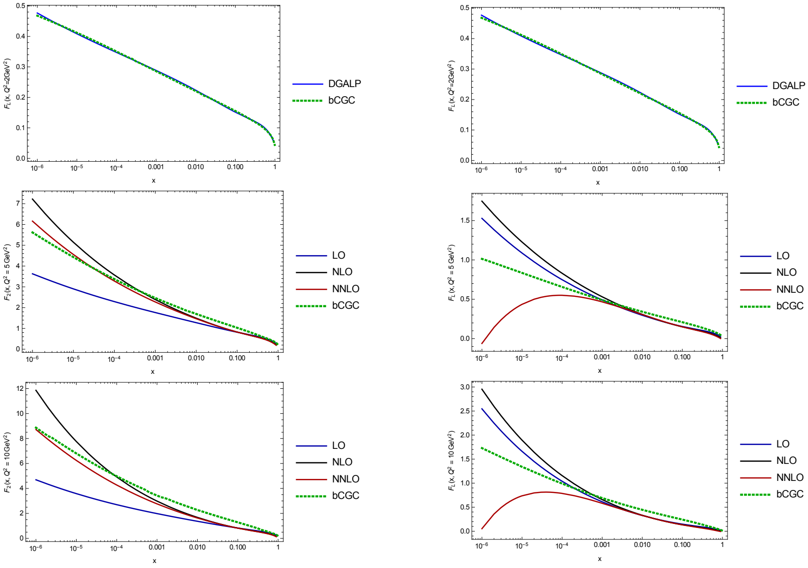
# Results for physical evolution of $(F_2, F_L)$



# Results for physical evolution of $(F_2, F_L)$



# Results for physical evolution of $(F_2, F_L)$



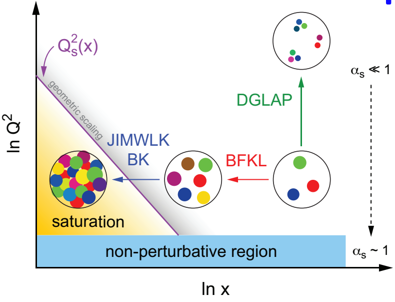
# Comments

- Combination $(F_2, \frac{dF_2}{d\ln Q^2})$ more stable, but also less sensitive to saturation effects
- not a failure of physical anomalous dimensions; only reveals instability of DGLAP evolution at very small $x$ – not at all unexpected
- Resummation of small $x$ logarithms achieved by BFKL; application to pdf exists; to be worked out for physical anomalous dimensions
- realistic phenomenology still requires heavy quarks

# Next-to-leading order (NLO) corrections for DIS cross-sections in presence of high gluon densities

in collaboration with Alejandro Ayala (UNAM), Jamal Jalilian-Marian (Baruch, New York City) & Maria Elena Tejeda Yeomans (Sonora)

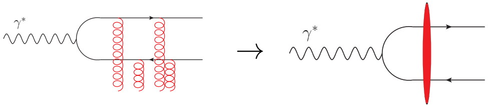
# Search for saturation requires precision on both sides




need:

- high precision for DGLAP evolution ➞ deviations
- high precision of saturated nucleus/DIS in presence of high & saturated gluon densities

Color Glass Condensate formalism (CGC) *e.g.* [McLerran, Venugopalan; PRD 49, 2233 (1994)], ...:

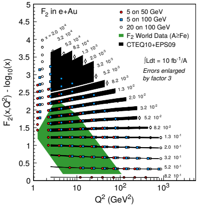



$x \to 0$: a single interaction with strong & Lorentz contracted gluon field

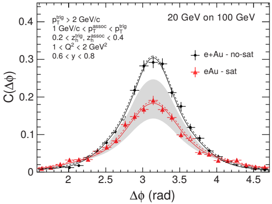
$$\sigma_{L,T}^{\gamma^* A}(x, Q^2) = 2 \sum_f \int d^2\boldsymbol{b} d^2\boldsymbol{r} \int_0^1 dz \left| \psi_{L,T}^{(f)}(r, z; Q^2) \right|^2 \mathcal{N}(x, \boldsymbol{r}, \boldsymbol{b})$$

# Current state of the art

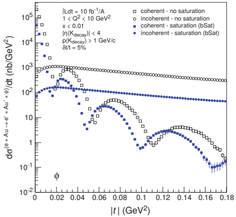
- Evolution of color dipole $\mathcal{N}$ known up to NLO → instabilities [Balitsky, Chirilli; PRD 88 (2013) 111501, PRD 77 (2008) 014019]; [Kovner,Lublinsky, Mulian; PRD 89 (2014) 6, 061704]
- Instabilities getting addressed [Iancu, Madrigal, Mueller, Soyez, Triantafyllopoulos; PLB 744 (2015) 293]
- photon wave function $\left|\psi^{(f)}_{L,T}(r, z; Q^2)\right|^2$ at LO; NLO either not suitable for phenomenology [Balitsky, Chirilli; PRD 87 (2013) 1, 014013] or only real corrections [Beuf; PRD 85 (2012) 034039]
- important for essentially the entire EIC saturation program:




inclusive DIS



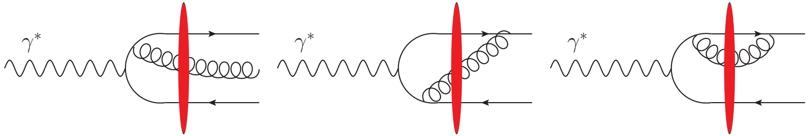

di-hadron correlation



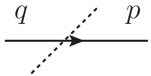

diffraction

# Task: calculate photon wave function in background field

need to calculate:




use propagators in strong background field *e.g.* [Balitsky, Belitsky; NPB 629 (2002) 290],




$$= (2\pi)^d \delta^{(d)}(p-q)\tilde{S}_F^{(0)}(p) + \tilde{S}_F^{(0)}(p)\tau_f(p,q)\tilde{S}_F^{(0)}(q)$$

$$\tilde{S}_F^{(0)}(p) = \frac{i\not{p} + m}{p^2 - m^2 + i0} \qquad \tau_f(p,q) = 2\pi\delta(p^- - q^-)\not{n}^- \int d^{d-2}\boldsymbol{z} e^{-i\boldsymbol{z}\cdot(\boldsymbol{p}-\boldsymbol{q})}\left[V(\boldsymbol{z}) - 1\right]$$

Wilson line resums interaction with target $V(\boldsymbol{z}) \equiv \mathrm{P}\exp ig \int_{-\infty}^{\infty} dx^- A^+(x^-, \boldsymbol{z})$

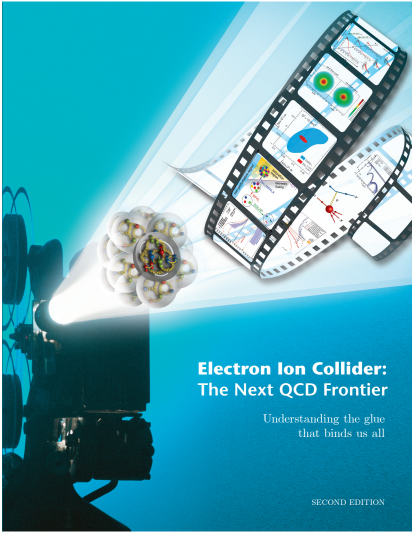
Work in progress ...

# Conclusion

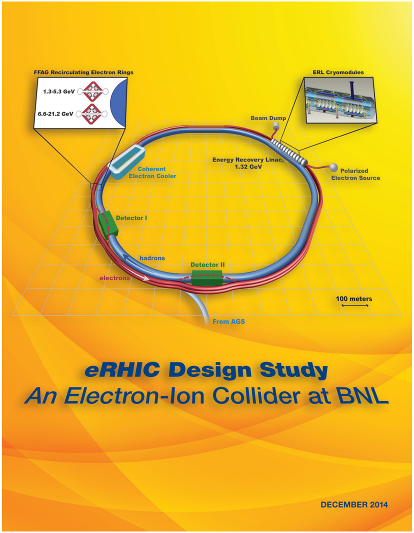
- EIC will be the next generation QCD facility
- Theory: Feasability of EIC program is established; but still work to be done to make use of the full potential of such a machine
- Presented key measurements of the EIC programme whose ability to extract novel physics is beyond question (modulo electroweak)
- In general: Wide-range physics program

**Was never measured before &**
**will be never measured without an EIC**

# Further reading




[arXiv:1212.1701]




[arXiv:1409.1633]

Gracias